Contributions to Eurasian Geology

Aspects of the Geology of Kazakhstan: A collection of papers honoring the 70th birthday of Academician Aitmukhamed Abdullaevich Abdulin

1995

Occasional Publications ESRI, New Series No. 12B
University of South Carolina
University of Utah

FOREWORD

Academician Aitmukhamed Abdullaevich Abdulin is one of those rare individuals who can anticipate events, and mold them to his desires. When first we met in the late 1980s, almost his first thoughts were how best he could place his cherished Institute of Geology into the mainstream of western analytical and communication highways. He also hoped that there could be a free exchange of ideas between his staff and those of western research units such as the Earth Sciences and Resources Institute (ESRI). It is a testimony to his perception and confidence in his own vision that he insisted that these exchanges involve the younger as well as the senior researchers on his staff, to ensure that the future would be provided for as well as the present.

Throughout the last five years, with an almost constant transfer of personnel and data between the Institute of Geology and various western groups, Aitzhan Abdullaevich's dream of an integrated, earth science-based research unit in the Kazakhstan Academy of Science has become a reality. His insistence on the highest quality technical work from his researchers, those from the west as well as his own staff, his quickness to overlay the best of western technology and communications upon his organization, and his foresight in providing the Institute of Geology with specialists and experts from ESRI and other western groups that complement his local specialists, has made the Institute of Geology one of the best known and respected earth science research institutes in the Former Soviet Union.

At a time in their careers when most scientists are content to rest upon their accomplishments, this quiet giant of Kazakhstan science has moved his institute to the forefront in research programs. May his vision continue and his beloved institute increase in prosperity and recognition.

Dr. William H. Kanes
Director, Earth Sciences and Resources Institute
University of South Carolina
University of Utah

Table of Contents

Aspects of the Geology of Kazakhstan

A collection of papers honoring the 70th birthday
of Academician Aitmukhamed Abdullaevich Abdulin

II. Regional Geology

III. Mineral Resources

IV. Environmental and Engineering

Academician Aitmukhamed Abdullaevich Abdulin: An Appreciation

The outstanding Kazakh geologist and Director of the Satpaev Institute of Geological Sciences of the National Academy of Sciences, Republic of Kazakhstan, Academician Abdulin was born on November 29, 1924, in the Ulytau settlement in western Central Kazakhstan 140 km north of Zheskazgan. After graduation from high school, he served in the Soviet Army from 1942 to 1946 during the Great Patriotic War. In 1953, he graduated from the Geological Faculty, Kazakh State University, Almaty, and was invited to join the Institute of Geological Sciences, Kazakh S.S.R., for post-graduate research.

In the Institute, he rose through the ranks from laboratory assistant to Engineer-geologist, Junior then Senior Research Associate, Chief of Laboratory, Scientific Secretary, to Vice Director, until appointed Director of the Institute in April 1974. He received his Candidate of Science degree in 1958 and his Doctorate of geological and mineralogical sciences in 1971. He was made Professor in 1973, Corresponding Member of the Academy of Sciences, Kazakh S.S.R., in 1975, and elected Academician in 1979. In 1988, he was elected Academician-Secretary of the Earth Sciences Division of the Academy, which unites the institutes investigating earth sciences, and in the same year became Vice President of the National Academy of Science. He was elected to the Parliament of the Kazakh Republic in 1990. In 1992, he was elected Academician of the International Engineering Academy and the Engineering Academy of the Republic of Kazakhstan.

Academician Abdulin is the undisputed leader in regional studies in Kazakhstan. At the very beginning of his professional career, he studied the geology of the gold-copper-tourmaline deposits of Central Kazakhstan. Later, he acted as the initiator and organizer of study of southern (Kazakhstanian) part of Urals — the Mugodzhary Mountains and adjacent territories, which contain important energy resources and metallogenic prospects. He solved the very interesting and important problem of connection of tectonic structures of Urals, Tien-Shan, and Central Kazakhstan, which opened new perspectives for the prospection of new mineral resources.

A.A. Abdulin proposed the rifting-underthrusting model of the geological structure of Kazakhstan. He drew conclusions concerning the origin of the Urals Folded System from the rifts that divide sialic microcontinents.

Later, he deciphered the structure of the Platform cover and folded basement of the North-East part of the Turan Plate. This new tectonic zonation based on their geological structures and types of stratigraphic successions lies at the base of the new complex interpretation of geological and geophysical data.

A.A. Abdulin proposed a riftogenic model of the Torgay depression, and as a result, the South Torgay oil- and gas-bearing basin was discovered. The Kumkol, Aryskum, Nuraly, and other basins belong to this basin.

A new level in the study of geology and minerageny of Kazakhstan and some adjacent territories was carried out under scientific supervision and with personal participation of Acad. Abdulin. The results were published in the set of fundamental monographs and maps. Acad. Abdulin is the Editor and one of the co-authors of the 11-volume monograph "Metallogeny of Kazakhstan", a 6-volume monograph, devoted to the geology of the Chu-Ili Ore Belt, the Tectonic Map of Kazakhstan and adjacent territories, the Map of Caledonian and Hercynian complexes, and maps of oil and gas productivity of Kazakhstan.

A.A. Abdulin participated in All'Union projects, such as compiling the Tectonic map of Precambrian of the U.S.S.R., and the map of metamorphic belts of the U.S.S.R. He presented scientific reports at the XXVI (Paris), XXVII (Moscow), XXVIII (Washington), XXIX (Kyoto, Japan), Sessions of International Geological Congress, and at various international meetings, conferences, and symposiums in Czechoslovakia, Hungary, Yugoslavia, Germany, Israel, China, and elsewhere.

A.A. Abdulin has published more than 300 scientific papers and 10 important monographs, including "Geology of Mugodzhary", "Geology of Kazakhstan", "Tectonics of the region of the connection of the structures of Urals, Tien-Shan, and Central Kazakhstan", "Geodynamics of Kazakhstan", and "Metallogeny and mineral resources of Kazakhstan". In the recent Monograph "Geology and mineral resources of Kazakhstan", he reviewed the modern state of geology of Kazakhstan and future perspectives.

Many well-known geologists in Kazakhstan are students of Academician A.A. Abdulin, including four Doctors of Sciences and more than 20 Candidates. For his outstanding contribution to the geological sciences, Academician A.A. Abdulin was bestowed a State Prize of the U.S.S.R. and of the Kazakhstan, and many orders, medals, and Honorary Degrees. He is "Merited scientist of the Republic of Kazakhstan". He was elected the Honorary Member of the Academy of Sciences of the Republic of Bashkortostan (Bashkiria) and a Foreign Member of several scientific societies.

His organizational talent is one of the most outstanding abilities of Academician A.A. Abdulin, with his ability to organize scientific teams, to outline scientific tasks, and to supervise their performance. He is held in high esteem by scientists generally, and within the geological profession. His colleagues appreciate his interest in their investigations and problems, and his ability to understand and advise.

Selected Publications

1. Abdulin, A.A., 1961. Tourmaline formations of the North-East of Central Kazakhstan. Alma-Ata, Publishing House of the Academy of Science of the Kazak S.S.R., 88 p.
2. Abdulin, A.A., 1973. Geology of Mugodzhary (stratigraphy, tectonics, and magmatism). Alma-Ata, Nauka, 391 p.
3. Abdulin, A.A., Tsirelson, B.S., Bykadorov, V.A. et al., 1976. Tectonics of the area of the Urals, Tien-Shan, and Central Kazakhstan conjunction. Alma-Ata, Nauka, 231 p.
4. Abdulin, A.A., Patalakha, E.I., 1980. Geodynamics of the Earth Crust of Kazakhstan. Alma-Ata, Nauka, 176 p.
5. Abdulin, A.A., 1981. Geology of Kazakhstan. Alma-Ata, Nauka, 303 p.
6. Abdulin, A.A., and Shlygin, A.E., 1983. Metallogeny and Mineral Resources of Kazakhstan. Alma-Ata, Nauka, 311 p.
7. Abdulin, A.A., Shlygin, A.E., and Zhukov, P.K. Most important features of geology and metallogeny of the Urals-Mongolian Folded Belt. Alma-Ata, Nauka, 290 p.

8. Abdulin, A.A., 1989. Rift zones in Kazakhstan, in: Magmatism of rifts, petrology, geodynamics. Moscow, Nedra, p. 49-54.

9. Abdulin, A.A., 1990. Oil and gas-bearing basins of Kazakhstan. Izvestiya of the Academy of Sciences of the Kazak S.S.R., Geological series, N 3, p. 20-24.

10. Abdulin, A.A., 1994. Geology and Mineral Resources of Kazakhstan. Almaty, Gylym, 1994, 400 p.

Publications about Academician A.A. Abdulin

1. Academician Abdulin, A.A. Soviet Geologist. Mining Encyclopedia, 1984, p. 9.

2. Academician Abdulin, A.A. Bibliographic Reference Book "Geologists and Geographers". Kiev, Dumka, 1985, p. 5.

3. Abdulin, A.A. - Geologist, Doctor of the geological-mineralogical sciences, Professor. Alma-Ata. Encyclopedia. Head Editorial Board of the Kazak Soviet Encyclopedia, Alma-Ata, 1983, p. 76.

Kazakhstan Geology: A Perspective

A.A. Abdulin, Director of the Geological Instutute, Kazakh Academy of Science

Abstract

The Republic of Kazakhstan covers more than 2,717 thousand square kilometers at the junction of two great continents, Asia and Europe, and represents an unique province with very complex geologic structure. Kazakhstan is rather well studied but at the present stage of geological development there is little prospect of developing new natural resources. The role of prospecting for new economic deposits, therefore, has greatly increased. The priority directions in stratigraphy, petrology, tectonics, geophysics, and metallogeny in the prospection for oil, gas, coal and oil shale are outlined.

Introduction

Kazakhstan has an area of 2717.3 thousand square miles, which is equal in size to half of Western Europe, or five times the area of France, the largest of the Western European countries. The second largest republic, in terms of area, after Russia, it extends almost 3,000 km from the Lower Volga and Caspian seashores to the Altai Mountains and 1,600 km from the southern part of the West Siberian Lowland to the Tien Shan Mountains and the Kyzyl-Kum Desert.

The frontier is 15,000 km long, bordering on Russia, China, Kirgizstan, Uzbekistan, and Turkmenistan (Fig. 1). Boundless steppes give way to semi-deserts (Sary Arka), and deserts cover most of the Republic, within which are low mountain ranges and smaller hills (melkosopochnik). The Caspian Sea lies on the western border of Kazakhstan, and in the northwestern part of the Turan Plate, the pre-Caspian lowlands is occupied by the shallow, shrinking Aral Sea.

The mountain ranges of the Tien Shan lie in the south and reach elevations of 4,000-5,000 m. The highest peak, Khan Tengry, has a height of 7,000 m. The ranges of the Dzhungar Alatau, Tarbagatai, Saur, and Monrak lie in the eastern part of the country, with the Altai Mountains to the northeast. The principal steppes are bordered to the south and east by these mountains. Major rivers such as the Irtysh, Chu and Syr Darya, and the rivers of the Seminechye (Seven Rivers) area rise in these mountains.

In the north, the Mugodzhary Mountains form the southern extension of the Urals, which extend toward the frontier regions of Kazakhstan, east of which extends the Turgai depression, separating them from central Kazakhstan and connecting the Turan Plate with the West Siberian lowlands.

The country, divided into 19 administrative districts, has a total population of 17.2 million. It is rich in minerals, with large deposits of metallic and nonmetallic minerals as well as appreciable fossil fuel energy resources. Deposits of chrome, iron, titanium, aluminum, copper, lead, zinc, manganese, uranium, barium, boron, fluorine, phosphorus, vanadium, gold, silver, tungsten, molybdenum, and tin have been discovered, explored, and exploited. Ores from many deposits are enriched in rhenium, selenium, tellurium, indium, rare earths, tantalum, scandium, bismuth and other elements that increase their value. Kazakhstan has large reserves of asbestos, wollastonite, industrial diamonds, jadeite, and other types of lithic raw materials. Its large deposits of coal, oil, gas, and oil shale are well known. These, as well as other natural resources, have served as raw materials for the development of non-ferrous and ferrous metallurgy, for the coal, oil, gas, chemical and agrochemical industry, and for the building industry.

At the present level of geological and geophysical development, there is little possibility of opening new industrial ore deposits in outcrop. Replenishment of the mineral and raw-material base is possible, but mainly by searching for concealed ore deposits. The role of scientific prospecting in solving this problem has therefore greatly increased in importance, and replenishment of natural resources has become a key area of study of the K.I. Satpaev Institute of Geological Sciences (National Academy of Science, Kazakhstan Republic), the principal geologic science center in the republic and the main training center for skilled scientific personnel. A wide range of geological exploration and prospecting work is done by large teams of geologists from the Ministry of Geology and Protection of Natural Resources.

Most of Kazakhstan (94%) has been covered by a geological survey on a scale of 1:200,000 and as much as 33% on a scale of 1:50,000. For regions with ore deposits, detailed geological maps on a scale of 1:25,000 and 1:10,000 have been prepared. At present, Kazakhstan is covered by maps of different scales, from 1:2,500,000 to 1:500,000, showing geology, tectonics, geophysics, geomorphology, geoecology, ore deposits, gas- and oil-bearing regions, and metallogenic provinces.

Stratigraphy

Maps have been prepared showing Cambrian, Ordovician, Devonian, Carboniferous, and Permian stratigraphy, and charts with stratigraphic columns have been standardized. The well-studied successions in the Malyi Karatau Range have been proposed as global stratotypes for the Upper Cambrian and the Cambrian-Ordovician boundary. The methodological basis of stratigraphic investigation was and is paleontological in all its aspects — systematic, evolutional, paleobiogeographic, paleoecological, with the various specialized micropaleontological techniques. Physical methods such as stratigraphic lithogeochemistry and seismostratigraphy, especially important in hydrocarbon investigations, have also been carried out.

Stratigraphic and lithologic studies in a number of areas have received special priority, among them:

- stratigraphy and lithology of Precambrian deposits,
- stratigraphy and lithology of Paleozoic marine deposits;
- stratigraphy and lithology of Mesozoic and Cenozoic marine deposits;
- stratigraphy and lithology of continental deposits;
- stratigraphy of Quaternary deposits
- seismostratigraphy

Petrology

In this sphere, the separation and systemization of magmatic formations have been worked out and vertical and lateral extent established. The first edition of a map of igneous rocks of Kazakhstan has been prepared, at a scale of 1:500,000. Investigations in isotopic magmatic geochronology and geophysical mapping of deep-seated and otherwise concealed intrusive bodies are still inadequate and must be sharply increased.

Among the priority directions in petrology are investigation of:

- igneous and metamorphic rock units;
- indicators of geodynamic environments;
- magmatic evolution and significant epochs of magmatic and metamorphic processes;
- rift zone magmatism and metamorphism;
- the origin and distribution in time and space of magmatic and metamorphic rocks;
- magmatic nature of large ore bodies and giant deposits;
- physical and chemical environment of igneous ore-bearing rocks and experimental modelling of conditions of ore formation.

Tectonics

In the early 70s, tectonic maps and charts were prepared on the basis of historical geology. The largest maps of this type are 1:1,500,000 tectonic map of Kazakhstan, and the tectonic maps of the Kazakhstan Caledonides and Hercynides, and a series of regional tectonic maps (Central Kazakhstan, Eastern Kazakhstan, etc.). During the 1980s, subduction zones were shown on some tectonic charts. In other words, interpretations of the tectonic structures of Kazakhstan began to appear in print. From an historical point of view, geosynclinal zones were represented as passive margin deposits on diverging plates. Development of these zones may be linked to an early rifting stage as continental crust separated, with or without ophiolitic magmatism (aulacogene). This interpretation is illustrated by paleotectonic and structural maps, made for 19 Paleozoic levels, and by the structural-formation map of Kazakhstan map, on a scale of 1:500,000. Subsequent investigations will require corrections to the tectonic architecture of Kazakhstan, and it is natural that this will cause changes in concepts of mineral distribution and relationships. In particular, it is now possible to discuss the extraordinary tectonic positions of Kazakhstan oil and coal deposits found in rift structures.

Great attention is paid to tectonofacies analyses in Kazakhstan, and developments in this field may provide the answers to questions on magmatic and ore formations.

Geophysics

In Kazakhstan a large amount of work has been done in manometry, gravimetry, electrometry, thermometry, seismometry, and aeromagnetic and aero gamma-ray surveying. There are now structural-geophysical maps on various scales and maps of deep-seated structures for all of Kazakhstan as well as some adjoining regions. Different interpretations have been placed on the geophysical data, especially of deep-seated structures, and frequently there is a disparity between the results of super deep wells and geophysical well logs. A major project is the development of 3-D seismic models on a regional scale.

Metallogeny

In 1950, Kazakhstan began a program directed toward prediction of mineral deposits through the development of metallogenic-predictive maps. The results of this program, presented in 23 monographs, were recognized by the award of the USSR Lenin Prize (1958) and USSR State Prizes (1958), and three Kazakh SSR State prizes. Such metallogenic maps have sharply increased the reliability of the prediction of metallic mineral deposits. Kazakhstan geologists have shown that the correlation of geological processes with genetic and paragenetically related ore-rock associations can be graphically represented. The reliability of metallogenic analysis requires that all geological formations, including ore formations, be classified by the same features and, most importantly, in the same range scale. However, existing classifications of ore-rock associations and ore formations do not satisfy this condition. In metallogenic analysis the principle is observed that for any one geological formation, there is only one corresponding ore formation. Kazakhstan geologists regard an ore formation as natural association of mineral types, with a stable set of ore elements and with certain quantitative variations. The ore elements are genetically and paragenetically connected only with one geological formation. Statistical analysis, as a basis for distinguishing ore associations and geological formations, has been applied to many deposits and ore manifestations which are classified by quantitative correlation of the principal ore elements (lead, zinc, copper, and others) and subordinant elements (rhenium, indium, tellurium). All manifestations of ore mineralization can be divided into nine groups, which in turn are subdivided into two or three subgroups. A clear connection can be established between groups of deposits distinguished according to the composition and level of alkalinity of the accompanying magmatites. These groups make up evolutional rows and are the objective base for classification of endogenous ore deposits.

Based on this new classification, more than 50 ore formations are distinguished in Kazakhstan. It is suggested that they be referred to as metallogenic complexes (by age and proper name). Systematization of the metallogenic formations reveals more fully and objectively the type and criteria of the relationship between magmatism and ore content, which considerably increases the reliability of predicting deep-seated deposits. Difficulties usually created by the debate over genetic aspects of ore formation are thereby removed. Recent systematization of metallogenic formations substantiates the distinction of ore formations which serve as a key to the development of theoretical questions concerning the genesis of ore. The systematized ore formations are a reliable basis for prediction. The ore formations of any given region are analyzed to determine whether series are complete, and if members are missing the search can be directed toward them.

A map of the Kazakhstan metallogenic complex based on metallogenic zonation aids in estimating the potential ore content of the Paleozoic rocks of Kazakhstan, in indicating metallogenic structural and formational zones, and in distinguishing possible new zones and types of mineralization.

Systematization of endogenous ore formations and the methods applied to metallogenic mapping provide a more objective base for planning exploration and designing a rational trend of research. It also permits an estimate of the general potential of ore resources and of structural-formational zones and mining regions. Lastly, it assists in improving the scientific basis for prediction. The important theoretical and practical results as well as some of the more problematical questions in regional metallogeny are covered in an 11-volume monograph, publication of which was completed in 1983. In addition to metallogenic analyses, the monograph presents information on more than 600 deposits, representing the main raw material base of Kazakhstan.

The other important trend in metallogeny and prediction is the complex of scientific investigations of Kazakhstan mining regions. Practically all regions of Kazakhstan have been covered during these investigations, which have resulted in predictive maps, quantitative estimates of mineral resources, formulation of economic questions and optimal methods for extracting and processing minerals, and long-term planning of prospecting work. Experience in metallogeny and investigations of the mining regions shows the necessity for geological surveys in searching for ore belts and metallogenic zones in each province and helps in recognizing which of the metallogenic formations have the greatest potential. This is reflected in more effective strategies for exploration and prediction of mineral reserves.

The main metallogenic problems are:

- genetic type and geological and physical-chemical conditions of formation of ore;
- sources of ore and ore-forming processes, their evolution and geochronology;
- geological-genetic models of ore formation and endogenous ore-forming systems;
- metallogeny of ore regions, methods of local prediction of mineralization and estimation of mineral reserves;
- conditions for ore formation, principles governing emplacement of deposits, evolutionary series of ore mineral formations.
- paleometallogeny.

Oil and Gas

Kazakhstan has large gas and oil reserves. Some success has been achieved in the search for sub-evaporite oil, and this marks a new stage in the petroleum geology of Kazakhstan. The results of the last few years deserve special mention, particularly the discovery of Jurassic-Cretaceous oil deposits in south Turgai.

The oil and gas potential of the Kazakhstan basins is grouped by rate of deposition into four classes. The first class is characterized by the highest rate of deposition, over 14,000 km^3/my. From 6 to 25 km of sedimentary rocks are in this class, which hosts the largest oil and gas deposits of Kazakhstan, including those of the Pricaspian, Mangyshlak, and Usturt basins. In these basins the location of gas and oil pools in the subsalt beds is controlled by arched uplifts. In suprasalt beds the location of pools is controlled by salt dome tectonics. The second class, in which rate of deposition ranges from 4 to 14,000 km^3/my, is found in the South Turgai and Chu-Sarysu basins. Gas and oil deposits in these basins are on a much smaller scale than in first-class basins.

The third and fourth classes, with low rates of deposition, from 1.5 to 7,000 km^3/my and 1,500 km^3/my, respectively, are found in the Ili, Zaisan, Tekess, and Karkara basins. Gas and oil deposits have not yet been found in these basins, but according to their geological-structural and geochemical conditions, they are potentially gas and oil bearing. The most prospective in the Ili basin is the Horgoss uplift, which complicates the central part of the Panfilovsk depression and, in the north, the underthrust zone.

With the help of seismic investigations by the common depth-point method (CDP), questions not only about the depth structure of the sedimentary basins but also the stratigraphy and prediction of lithological facies of the sedimentary cover section can be successfully solved. Lithofacies maps for certain geological epochs have been prepared, and as a result, zones where carbonate massifs developed have been located as potential gas and oil areas. Fan and basin facies have been distinguished, as well as erosion outliers and large sedimentary accumulations.

Zones with anomalously high pressure (AHP) can be predicted from gravi-electrometric data and hydrodynamic conditions. The APH prediction allows us to avoid various complications and raises the economic effectiveness of prospecting. Based on detailed lithological investigations, the sedimentological conditions during various geological epochs, the spatial distribution of the facies zones, and the paleogeographical environment can be reconstructed. The interdependence of clay transformation and study of the organic content of oil and gas make it possible to distinguish the oil source rock, to explain the mechanism of oil migration, to establish the zones of generation and accumulation of hydrocarbons, to predict phase conditions, and to provide a scientific basis for the direction of oil exploration in Kazakhstan.

A map of gas and oil potential in Kazakhstan on a scale 1:1,500,000 has been constructed showing the following: types of sedimentary basins (according to the volume rate of deposition), age of the oil source beds, the intervals where gas and oil source beds occur, the timing of katagenetic formation of hydrocarbons, zones of oil and gas generation, and accumulation zones (differentiated by differences in phase and genetic conditions).

The following directions have priority in gas and oil exploration and development:

- geodynamic and physical-mathematical models of gas and oil areas,
- the Pricaspian model of megasyneclise with a strategy for the rational use of the hydrocarbon resources,
- geological and geological-economical background of effective gas and oil geological prospecting, with estimates of the potential resources of the South Turgai gas and oil basin,
- the geological basis for distinguishing hydrocarbon resources, the geological and geological-economical basis for effective direction of oil and gas research in the Aral region.

The resolution of these questions by use of such trends will make it possible to clarify much concerning the origin and laws governing the location of gas and oil deposits.

Coal and Oil Shale

Kazakhstan has large (more than 100 billion tons) resources of coking coal and fuel coal concentrated mainly in two stratigraphic levels: Lower Carboniferous and Lower-Middle Jurassic. The principal Carboniferous basins are Karaganda and Ekibastuz; the Jurassic basins are Maikuben, Shubarkul, Turgai, Ili, and Uralo-Caspian. These basins contain all the major coal deposits of Kazakhstan. A significant number (over 100) of relatively small (10-150 million t) deposits are widely distributed throughout the republic. The main source of coking coal is the Karaganda basin. Coal and ashes are enriched in rare earths and scandium (North Kazakhstan deposits), in aluminum and titanium (high-ash coal of the Ekibastuz basin), and in titanium, vanadium, chromium, and nickel (brown coal of the Ural-Caspian basin). The explored reserves of coal will satisfy the demands of the republic for many years to come. Coal shortages result from inadequate mining capacity. A great asset are the oil shales, such as the Kenderlyk deposit, with accumulations of 0.5 billion t, in the Middle-Upper Carboniferous in the east and the Pri-Ural group of Upper Jurassic rocks (Tuksai, Semenovskoe, and others) in the west. An oil content of up to 20-25% is characteristic of these shales.

Conclusion

Kazakhstan has great mineral-raw resources. It occupies the first place in the world in its resources of tungsten, second place with respect to chromite, and fourth place with respect to manganese, copper, lead, molybdenum and phosphorite ores. Kazakhstan occupies first place among Asian countries in the production of chromite, copper, polymetallic ores, molybdenum and tantalum ores and is second in terms of iron, manganese, bauxite, nickel ores and coal production. Kazakhstan also possesses great oil and gas resources. Large deposits of tin, industrial diamonds, silver and gold have been discovered in the northern and central parts of the country, and more new deposits may be discovered using new techniques. The potential of mineral resources may be enhanced by the complex use of raw minerals, the development of no waste technologies, and the extraction of useful components from dumps where large amounts of noble and rare metals and nonmetallic minerals are dispersed.

The mineral resources already discovered should be used with care. They are sufficient not only for internal needs but may form a significant part of the Republic's export, an important economic resource.

Further strengthening of the raw-material base for existing industry, as well as improving exploration quality of industrial mineral resources are necessary.

Precambrian of Kazakhstan: A Review

M.A. Kasymov

Abstract

Both Upper Archean and Proterozoic rocks have been identified in Kazakhstan, as paleorift or median massif deposits. It has been possible to differentiate Archean-Lower Proterozoic rocks and with the help of radiometric dates establish stratigraphic subdivision.

The Ulytau succession has been accepted as the standard for Lower Proterozoic, whilst the Upper Proterozoic has been divided into Lower-Middle Riphean, Upper Riphean and Vendian. In the Kokchetav massif, Lower (Kumdukul Formation) and Upper Archean (Berlyk Formation) have been identified.

Precambrian formations in the Paleozoic geologic structures of Kazakhstan occur in the form of linearly oriented isometric blocks of different sizes. During early investigations of the geology of Kazakhstan, the Archean crystalline complexes and the low grade metamorphosed Proterozoic volcanogenic-sedimentary strata were routinely identified in the Precambrian blocks. Later, geologists studying Precambrian strata concentrated on establishing the Precambrian stratigraphy of Kazakhstan. As a result, in the 60s and 70s two main points of view emerged on the stratigraphy and age of the Precambrian rocks. According to one group (Borukaev, 1955; Shlygin, 1960) highly metamorphosed Archean strata were traditionally separated from Proterozoic volcanogenic-sedimentary deposits; according to the other (Shtreis, 1960), none of the Precambrian rocks were older than Riphean.

A systematic Precambrian stratigraphic scheme was adopted at the 2nd Kazakhstan Interdepartmental Stratigraphic Conference in 1971 (Shlygin, 1976). According to this scheme, the gneisses and crystalline slates of the Zerenda Group of the Kokchetav massif (Fig. 1, no. 7) were provisionally referred to undifferentiated Archean-Lower Proterozoic. The amphibolites and gneisses of the Bekturgan Group of Ulytau (Fig. 1, nos. 2,3) and their stratigraphic analogs were considered to represent the latter part of this age interval, although there is no instance of their direct superposition on metamorphic strata of the Zerenda Group. Age designations of the rocks of the Zerenda and Bekturgan groups are provisional, mainly because of the high grade of regional metamorphism (granulitic and amphibolitic facies) of these rocks and their presence at the base of the Precambrian succession.

For the Lower Proterozoic, the Ulytau succession was accepted as the standard (Filatova, 1983). Here the lower part of the Proterozoic consists of the metadacite-albitophyre slates of the Aralbai Group and the green-slate metabasaltic ferric ore of the Karsakpai Group, followed by the porphyroid strata of the Maitube Group. The upper boundary of the Lower Proterozoic is represented by a porphyroblastic garnet-gneiss complex, which is dated at 1800 My by the uranium-lead-thorium method.

The Upper Proterozoic is subdivided into Lower-Middle Riphean, Upper Riphean, and Vendian (Shlygin, 1976).

Despite great advances in the study of the Precambrian stratigraphy of Kazakhstan during the 1960's, absolute age determinations of Precambrian rocks were few in number and many questions remained. Even now there is no consensus regarding correlation of Precambrian successions of different regions. Paleontology has not been fully utilized in developing a stratigraphy of the Precambrian formations, and the study of lithology, magmatism, and metamorphism is not up to modern standards. Disagreements exist on where boundaries should be drawn and on how large a volume some stratigraphic subdivisions represent. The polycyclicity of the metamorphic and fold-and-fracture changes of Lower Precambrian, pre-Riphean strata, which significantly change original appearances, is not taken into account in the stratigraphic subdivision of the Precambrian of Kazakhstan. Meanwhile, the study of folded regions of Pre-cambrian rocks that have undergone polycyclic development, rocks that were formerly referred to the Paleozoics of Kazakhstan, has shown that superimposed tectono-metamorphic processes conceal the structural, stratigraphical and distinctive lithologic composition carried over from the preceding phases of tectono-magmatic activity in earlier metamorphic cycles. Therefore, to distinguish strata of different ages in heterogeneous formations with highly varied composition, a connection between style of deformation and degree of metamorphic recrystallization must be established and correlated with separate geological bodies, while also defining general

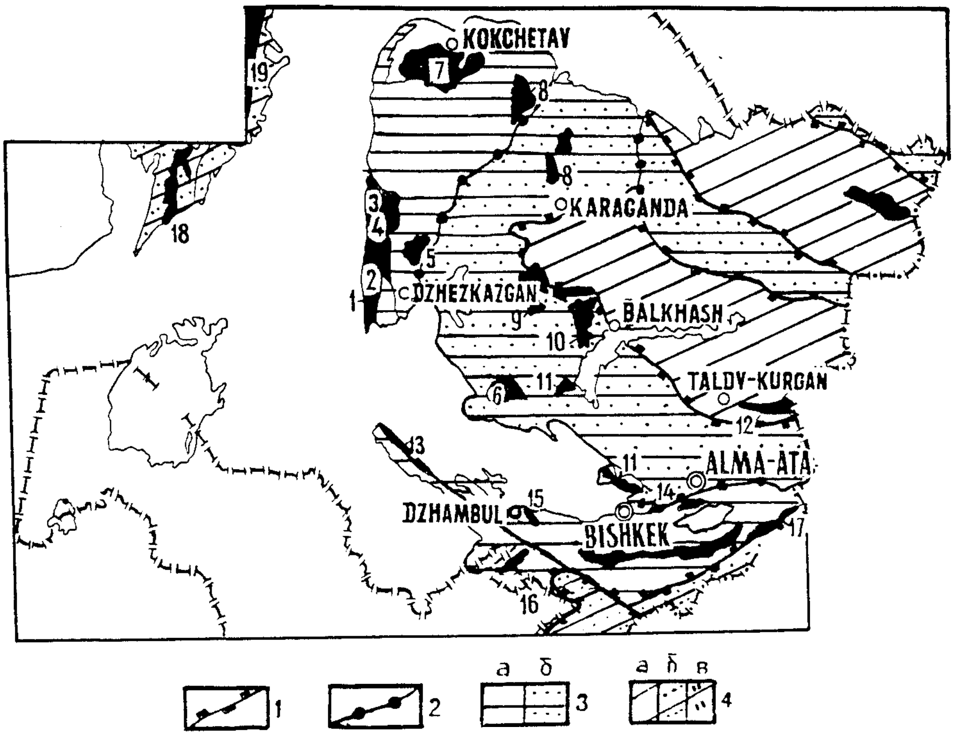


Fig.1. Distribution of successions of Lower Proterozoic deposits of Kazakhstan and Kirgiziya:
1- boundary of folded system; 2- boundary of structural-formational zone; 3- Kokchetav-Tien-Shan folded system of Caledonide (a- Early Caledonian folded complex; folding at the end of Ordovician, b- Late Caledonian folded complex; folding in mid-Silurian); 4- Hercynide Dzhungaro-Balkhash folded system; a- Ural folded system of Hercynides (south f l); b- Southern-Tien-Shan Hercynide fold system. Regions of distribution of Archean and Lower Proterozoic deposits (figures in a scheme): 1-6- Central Kazakhstan (1-2- Karsakpai region: 1- Maitube zone, 2- Karsakpai zone; 3-4- Ulytau region: 3- Northern Ulytau zone, 4- Zhaksy-Arganatin zone; 3- western Sarysu-Teniz region; 6- Chu region; 7-8- Northern Kazakhstan: 7- Kokchetav region, 8- Eshkeolmes, Ermentau-Niyaz regions; 9-12- Central and Southern Kazakhstan: 9- Atasu-Mointy region, 10- Kyzylespe region, 11- Karakamys, Shokpam regions; 12- Boordin region; 13- Bessaz region; 14-15- Northern Tien-Shan: 14- Aktuz-Boordin region, 15- Makbal region; 16-17- Middle Tien-Shan: 16- Chatkal region, 17- Sarydzhaz region; 18-19- Southern Ural: 18- eastern Mugodzhary region, 19- Zaural region.

trends in time and space and the cyclicity of metamorphism and tectonic deformation. Once established in this manner, the age subdivisions of Lower Precambrian metamorphics and magmatites may be shown to correspond to definite tectono-metamorphic and tectono-magmatic cycles.

Subsequently, structural geologic, petrologic, stratigraphic, and radiometric data on the geology of the Precambrian of Kazakhstan began accumulating in the period following the second stratigraphic conference. The studies, by different organizations, including the Satpaev Institute of Geological Sciences (NAS Republic Kazakhstan) made it possible to substantially refine the details of the stratigraphic working scheme of 1971.

New interpretations of a number of Precambrian horizons and new regional correlations have been highlighted in published proceedings of the Kazakhstan Interdepartmental Stratigraphic Conference (Kasymov et al., 1987).

The new working stratigraphic scheme is presented here and can be compared with the scheme that existed in 1971.

On the basis of the cyclicity of endogenic processes of the Precambrian interval, established by geologists of the IGS, NAS Republic of Kazakhstan, it became possible to differentiate crystalline strata, previously referred to as undifferentiated Archean-Lower Proterozoic, into Archean and Lower Proterozoic formations and to define the thermodynamic regimes under which they formed. This differentiation is reflected in the working stratigraphic scheme of the Precambrian of Kazakhstan, adopted at the 3d Interdepartmental Stratigraphic Conference in 1986 (Abdulin et al., 1991).

According to this scheme, the Zerenda Group of the Kokchetav massif (Fig. 1, no. 7), consisting of two parts, a lower part corresponding to the Lower Archean and an upper part , corresponding to the Upper Archean, is provisionally assigned to the Archean. The lower part of the group is represented by the Kumdukul Formation of plagioclase-spinel-quartz granulites, hypergene gneisses, two-pyroxene-spinel slates in association with charnockite-migmatites. The upper is represented by the Berlyk Formation, a body of garnet-sillimanite-biotite gneisses, high-alumina crystalline shales, and quartzite. The Berlyk Formation overlies rocks of the Kumdykul Formation with structural unconformity. Primary (relict) paragenesis of minerals from rocks of the Kumdykul Formation correspond to metamorphism of granulitic facies and Berlyk Formation rocks to the amphibolitic facies. The Archean Zerenda Group is separated from Lower Proterozoic strata by an angular unconformity and metamorphic boundary. Rocks of the Kumdykul Formation, based on composition and relict evidence of granulites and charnockites, are absolutely identical to secondarily metamorphosed granulites and charnockites of the Lower Archean stratotypic regions of the Baltic shield and the Eastern European platform. Similar formations are also widespread within the Aldan shield of the Siberian platform and in Pri-Sayan (southwest) on the marginal extension of the basement of the Siberian platform.

Amphibolite facies granulites of the Lower Archean are exposed in cores of anticlinoria of the Caledonides and Ripheids of the Eastern Sayan folded district, forming from the southwest the Pri-Sayan marginal extension of the basement of the Siberian platform. Upper Archean strata of amphibolite metamorphic facies occur in this ancient folded region, as well as in the basement of the Kokchetav median massif of the Paleozoic of Kazakhstan. The nearest analogs of the Kumdykul Formation of considerably older Early Archean age are the garnet-plagioclase, hypersthene gneisses of the Aidala Formation in the Chu region (Fig. 1, no. 6) in the Kokchetav-northern Tien-Shan folded system of the Caledonides of Kazakhstan, the Shaniken Formation of garnet-plagioclase, biotite-plagioclase, garnet-sillimanite-biotite gneisses of the Eastern Mugodzharian anticlinorium (Fig. 1, no. 18) of the Western Kazakhstan part of the Uralian Hercynides (Kasymov et al., 1987; Abdulin et al., 1991), the Asakarov Formation of plagiogneisses of the Ermentau and Eshkeolmes region (Fig. 1, no. 8), the Borbas Formation of mica gneisses of the Chu region (Fig. 1, no. 6), the Bekturgan amphibolite-gneiss group of the Ulytau region (Fig. 1, nos. 2, 3), the amphibolite-leptite strata of the Anrakhai Group of the Anrakhai region (Fig. 1, no. 11), the Karakamys Group of the Karakamys region (Fig. 1), and finally the Bessaz group of amphibolites of the Bessaz region (Fig. 1, no. 13). In the Caledonides of Kazakhstan, the amphibolite-leptite strata of the Taldyk Group of the Eastern Mugodzharian anticlinorium of the South Uralian Hercynides are analogous to the Berlyk Formation of the Upper Archean. Data on the evolution of tectonic deformation and metamorphism of the Berlyk Formation and Taldyk strata testify to their simultaneous formation. Thus, strata of the Berlyk Formation of the Kokchetav median massif and their stratigraphic analogs in other regions of Kazakhstan form a single band of different but coeval facies, differing in paleotectonic and thermodynamic regimes of formation. The radiometric dates that are available are for superimposed processes, which occurred more than 2 billion years ago and 1950 ± 100 Ma (uranium-lead concordia, metamorphogenic zircon; I.A. Efimov and B.M. Naidenova, oral communication). Ages of the Berlyk Formation are 1797 ± 8 My and 1800 ± 50 My (uranium-lead concordia, metamorphogenic zircon), 1620 ± 70 My (Pb-Pb isochron, metamorphogenic zircon), 1750 My (Pb-Pb isochron, late generation metamorphogenic zircon), and 1755 My. Ages of the Anrakhai Group of gneisses of the Uzunbulak Formation are 1750 My (Pb-Pb isochron, metamorphogenic zircon) and 1755 My, and for the Karakamys Group and accompanying gneiss-granites, 1900 My (uranium-lead concordia, magmatic zircon) (Abdulin et al., 1991; Khalilov et al., 1988).

Southeast of the Kokchetav-Northern-Tien-Shan Caledonide fold system of Kazakhstan and Kirgiziya, in the Aktuz-Boordin region (Fig. 1, no. 14), the Aktuz complex of gneisses, which underwent three stages of metamorphism in the early Precambrian and overlie the Kemin Group of amphibolites, are considered to be Archean. For the Aktuz Formation, Early Proterozoic reworking has been dated at 1140 ± 60 and 1230 ± 50 My on the Pb-Pb isochron and uranium-lead concordia (on late-generation metamorphogenic zircon) (Tokmacheva and Yaroslavtseva, 1983). In the Middle Tien-Shan, in the Sarydzhaz region (Fig. 1, no. 17), amphibolite-gneiss strata of the Kyilu Formation is of Late Archean age. It is dated at 2570 My on the first ratio of lead, and 2600 My on Pb-Pb isochron and uranium-lead concordia (first-generation metamorphic zircon) according to data from the laboratories of the IGS, AS of Republic of Kirgizstan and Kazakh Institute of Mineral Resources (Kisilev et al., 1988). Rejuvenation occurred at 1840-1900 Ma.

To conclude this review of the oldest Precambrian formations of Kazakhstan, it should be noted that resolution of the Early Archean age of the granulite basement of pre-Paleozoic complexes is essential to solving the age problems of pre-Riphean metamorphic strata as a whole, since the age of deposits overlapping on to granulitic basement may be assigned, by analogy with adjacent regions, to the Late Archean and Early Proterozoic. In any case, the geological and petrological data now available do not contradict this assumption.

Lower Proterozoic strata, unlike the Archean, are widespread and their lithological and formational composition show significant variations. In addition to the Ulytau (Karsakpai) succession, a standard Lower Proterozoic succession can be distinguished also in the Kokchetav (Fig. 1,

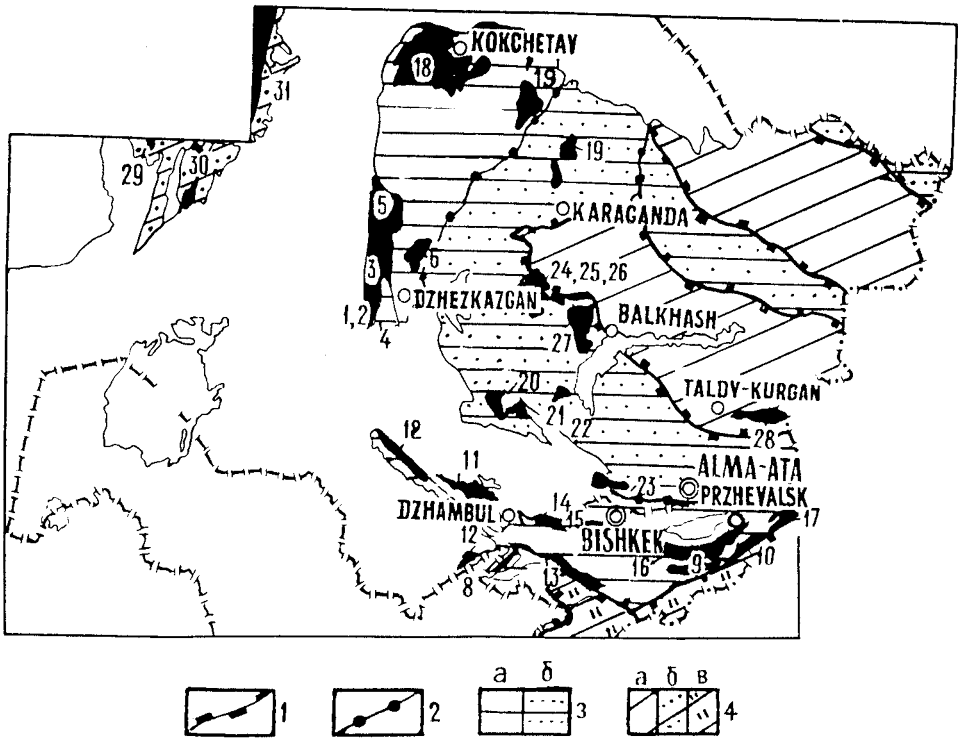


Fig. 2. Distribution of successions of Upper Proterozoic deposits of Kazakhstan and Kirgiziya:
1- boundary of folded system; 2- boundary of structural-formational zone; 3- Kokchetav-Tien-Shan folded system of Caledonides (a- Early Caledonian folded complex, folding at the end of Ordovician; b- Late Caledonian folded complex, folding in the middle Silurian); 4- Dzhungaro-Balkhash folded system of Hercynide; 5- Ural folded system of Hercynide (south flank); 6- Southern-Tien-Shan folded system of Hercynide. Region of distribution of Upper Proterozoic deposits (figures in a scheme): 1-6- Central Kazakhstam: 1-2- Baikonur region: 1- Central zone, 2- Eastern zone; 3-4- Karsakpai region: 3- Maitube zone, 4- Karsakpai zone; 5- Northern-Ulytau region; 6- Western Sarysu-Teniz region); 7-10- Middle Tien-Shan: 7- Bolshekaroi region, 8- Pskem-Sandalash region, 9- Dzhetymtau region, 10- Sarydzhaz region; 11-17- Northern Tien-Shan: 11- Karoi region, 12- Kokdzhot region, 13- Talas region; 14-17- Makbal-Burkhan region: 14- Makbal zone, 15- Ortatau-Uchkoshoi zone, 16- Terskei zone, 17- Karkara zone; 18-19- Northern Kazakhstan: 18- Kokchetav region, 19- Ermentau-Niyaz region; 20-28- Central and Southern Kazakhstan: 20- Chu region, 21- Zhalair-Naiman region, 22- Karakamys region, Sarytym region, 23- Western-Kendyktas region; 24-26- Atasu-Mointy region: 24- Western zone, 25- Central zone, 26- Eastern zone; 27- Kyzylespe region, 28- Tekeli region; 29-31- Southern Urals: 29- Or-Ilek region, 30- Eastern-Mugodzhary region, 31- Zaural region.

no. 7), Chu (Fig. 1, no. 6), Makbal (Fig. 1, no. 15), and eastern Mugodzharian (Fig. 1, no. 18) regions. The Lower Proterozoic of the region as a whole can be divided into two parts according to stratigraphic and radiometric data, with a boundary at about 2000 My. At this boundary, the linear Precambrian structures, the metadacite-albitophyre and metabasaltic ferric-ore groups of the rift phase of development of the porphyroid group of orogenic regimes, replace carbonate-terrigenous strata in median massifs (Kokchetav, Chu, eastern Mugodzhary; see Fig. 1). The latter is metamorphosed to the green slate facies. In the upper part of the Lower Proterozoic, at 1800-1900 My, a regional development of potassic feldspar granitization (up to granite-gneisses) has been found, and this helps to delimit the age of the enclosing strata. The upper limit of the Lower Proterozoic is marked (see Fig. 1) in the Maitube 1 and Karsakpai 2 zones of the Karsakpai region by alkaline granitoids (Karsakpai massif) dated at about 1600-1700 My and in the Lower Proterozoic granitoids at 1800-1950 My (Fig. 2, nos. 9, 23). In the Makbal region, in the upper part of the Lower Proterozoic, which is represented by terrigenous-carbonate deposits, stromatolites of Afebiy age (similar to *Vertexa montrana* Mak., *Columnacollenia* Savajarvia.) were discovered.

The Upper Proterozoic strata of different compositions and genesis reflect different tectonic conditions at the time of their formation. From the underlying metamorphic complexes of Lower Proterozoic carbonates, Upper Proterozoic volcanogenic-terrigenous and carbonate-terrigenous formations are separated by angular unconformities and metamorphic boundaries. Lower-Middle Riphean, Upper Riphean and Vendian strata are recognized in the Upper Proterozoic. Essentially terrigenous and volcanogenic-terrigenous successions are assigned to the Lower-

Middle Riphean. Sedimentary successions are represented by the carbonate strata of the Bakyrly Formation which contain remnants of Middle Riphean stromatolites (Essenov, 1971). This formation correlates with the carbonate-slate Karadzhiga Group of Tien-Shan, underlying radiometrically and paleontologically dated Middle Riphean strata. In northern and central Kazakhstan, analogs of the Bakyrly Formation are the black-slate-carbonate Sharyk Formation of the Kokchetav region, the Kudaly and Kushagyz Formation of the Chu region (Fig. 2, no. 20), and the Niyaz Formation of the Ermentau-Niyaz region (Abdulin et al., 1991). Volcanogenic-terrigenous successions of Lower-Middle Riphean age are represented by formations of the Bozdak Group (Belkuduk, Karasai, and Nadyrbai formations) of the Ulytau region (Fig. 2, nos. 1-4), the Mambetkul and Milysai formations of the eastern Mugodzharian anticlinorium (Fig. 2, no. 30), as well as the Mayzharylgan Group of the Zhalair-Naiman region (Fig. 2, no. 21).

The Upper Riphean of Kazakhstan is represented by subplatform deposits, forming two formational and stratigraphic levels, the lower consisting mainly of quartzite-sandstone and the upper of porphyry. Typical of the lower interval is the Andreev (Kokchetav) Formation. Quartzite-sandstone strata of the Akbastau and Svyatogor formations which occur in the Chu and Ermentau-Niyaz regions are referred to the analogs of this stratigraphic datum. The extent of the quartzitic Ushtobe Formation in southern Ulytau remains uncertain. Here the upper part of the Late Riphean is represented by acid volcanites of the Koksu Group of the Maitube (Fig. 2, nos. 3,4) anticlinorium and basaltoids of the Beleutin Groups of the Karsakpai synclinorium. These groups are correlated with the Orumbai Formation of the Karakamys region (Fig. 2, no. 22), and also the Kainar Formation of the Bolshoi Karatau (Fig. 2, no. 12).

Upper Riphean formations are overlain, with angular unconformity, by Vendian strata. The latter are most complete in the western part of Ulytau (in the Baikonur region, Fig. 2). There, from bottom to top, they consist of terrigenous-tufogenic-silicics and Ulytau terrigenous-carbonate-clay-tilloid groups (Zaitsev and Kheraskova, 1979). A paleontologically defined boundary between the Vendian and Cambrian has been determined only in the Maly Karatau (Fig. 2, nos. 7, 16, 17). Vendian deposits in other regions of Kazakhstan are defined on the basis of their position in a succession and on lithological characteristics (tillite-like conglomerates).

As can be seen from the volume of data presented here, great strides have been made in studying the stratigraphy of the Precambrian of Kazakhstan. First of all, successions of two types of Upper Archean and Lower Proterozoic formations, differing in composition, successions of strata, and thickness have been recognized. One type of succession characterizes paleorift structures (Mugodzharian, Ulytau, Anrakhai, Karatau et al.); the other, structures of median massif types (Kokchetav massif). Revisions have been made in the stratigraphy of deeply transformed strata of crystalline slates and gneisses, previously referred to as undifferentiated Archean-Lower Proterozoic strata. Proper Archean and Lower Proterozoic strata have been recognized. A scheme of stratigraphic differentiation of the Upper Proterozoic has been verified. In recent years, new radiometric dates have been a great help in verifying the age boundaries of the most important stratigraphic subdivisions of Kazakhstan.

Despite significant progress, a number of questions have not been fully resolved. It will thus be necessary to continue investigations of Archean and Lower Proterozoic stratigraphy, using data on formations in metamorphic successions, especially on metamorphic and deformational transformations, and also radiometric data.

Questions also remain regarding the stratigraphy of metamorphic complexes of the lower and upper parts of the Lower Proterozoic, in strata of the Aralbai-Maitube horizons of the Ulytau-Karsakpai regions (Fig. 1, nos. 1-4). They are of special interest because of the discovery of Early Proterozoic stromatolites in terrigenous formations in this stratigraphic interval. It is thus essential to verify the structural position of these terrigenous sediments in the succession and to determine the correlation of porphyroid and porphyritoid strata that are referred in different regions to different stratigraphic levels.

Questions remain as to the age, structural and facial relationships of a number of strata, related to the Lower Precambrian. Biostratigraphic methods will play a major role in in their differentiation.

References

Abdulin, A.A., Kasymov, M.A., and Khaibulin, R.R. 1988. Evolution of endogenic processes in Early Precambrian of Kazakhstan. In A.A. Abdulin (ed.), Petrology and mineragenу of Kazakhstan. Part 1: Alma-Ata, "Nauka", p. 3-4.

Abdulin, A.A., ed. 1986. Geology and metallogeny of Karatau. v. 1: Alma-Ata, "Nauka", p. 20.

Abdulin, A.A., and Abdulkabirova, M.A., 1987, eds. Geology of Northern Kazakhstan (stratigraphy): Alma-Ata, "Nauka", p. 224.

Abdulin, A.A., Nikitin, I.F., et al. (eds.), 1991. Decisions of IIIrd Kazakhstan stratigraphic conference on Precambrian and Phanerozoic (Alma-Ata, 1986) Part I. Precambrian and Paleozoic: Alma-Ata, p. 150.

Borukaev, R.A. 1955. Precambrian and Lower Paleozoic of northeast of Central Kazakhstan (Sary-Arka): Moscow, Gosgeoltekhizdat, p. 407.

Ergaliev, G.Kh, and Pokrovskaya, N.V. 1974. Biostratigraphy of Lower Cambrian of Maly Karatau. In A.A. Abdulin (ed.), Precambrian and Paleozoic of Kazakhstan, v. 1: Alma-Ata, "Nauka", p. 121-124.

Esenov, Sh.E., ed. 1971. Geology of USSR. Southern Kazakhstan, v. 1: Moscow, "Nedra", p. 534.

Filatova, L.I., 1983. Stratigraphy and historic-geological analysis of metamorphogenic strata of Precambrian of Kazakhstan: Moscow, p. 160.

Kasymov, M.A., 1984. Peculiarities of evolution of magmatism and metamorphism of Early Precambrian (Mugodzhary, Chu-Ili mountains, Central Karatau). in A.A. Abdulin (ed.), Problems of petrology of Kazakhstan (magmatism, metamorphism, mineralogy): Alma-Ata, "Nauka", p. 150-151.

Kasymov, M.A. 1988. About structural-age and genetical proportions of Early Precambrian Complexes of Kazakhstan, Part I: Abdulin (ed.), Petrology and minerageny of Kazakhstan, Part I: Alma-Ata, "Nauka", p. 119-120.

Kasymov, M.A., Khaibulin, R.R., 1979. About composition and metamorphism of Precambrian strata of Eastern-Mugodzharian anticlinorium: Alma-Ata, Izvestiya AN KazSSR. Ser. Geol., no. 1, p. 15-25.

Kasymov, M.A., Filatova, L.I., Tokmacheva, S.G., Korolev, V.G., 1987. A state of study and aims of further investigations of stratigraphy of Precambrian of Kazakhstan: Alma-Ata, Izvestiya N KazSSR. Ser. Geol., no. 4, p. 34-39.

Kasymov, M.A., Khaibulin, R.R., 1989. About composition and metamorphism of zerenda group of Kokchetav massif: Alma-Ata, Izvestiya KazSSR, Ser. Geol., no. 6, p. 12-22.

Khalilov, V.A., Zlobin, G.A., Bulina, V.A., Kim, V.S., 1988. Results of geochronological research of Precambrian formations of South Kazakhstan. in A.A. Abdulin (ed.), Petrology and minerageny of Kazakhstan: Abstracts. Alma-Ata. Part 2, p. 21-22.

Kisilev, V.V., Apayarov, F.A., Komarevtsev, V.T., et al., 1988. Uranium-lead age of zircons from strata of Precambrian basement of Hercynide of Median of Tien-Shan: Izvestiya AN Kirg. SSR, no. 4, p. 76-82.

Korolev, B.G., Maksumova, R.A., Mambetov, A.M., 1974. Vendian and Tommotian stage of Lower Cambrian in Middle Asia and south of Kazakhstan. In A.A. Abdulin (ed.), Precambrian of Kazakhstan, v. 1: Alma-Ata, "Nauka", p. 141-144.

Korolev, V.G., Ogurtsova, R.N., Maksumova, R.A., 1986. Chichkan biota--Evidence of an important biotic event in Upper Proterozoic: Izvestiya AN Kirg. SSR., no. 4, p. 17-20.

Missarzhevskiy, V.V., Mambetov, A.M., 1981. Stratigraphy fauna of boundary layers of Cambrian and Precambrian of Maly Karatau. in A.V. Peive (ed.), Proceedings GIN AN USSR, issue: Moscow, p. 90.

Ogurtsova, R.C., Sergeev, V.A., 1988. Microbiota of Chichkan Formation of Upper Precambrian of Maly Karatau: Paleontological journal, no. 2, p. 106-116.

Shlygin, E.D., 1960. Archean and Proterozoic deposits of Northern Kazakhstan. In Zh.A. Italiev, R.A. Borukaev (ed.), Proceedings of conference on unification of stratigraphic scheme of Precambrian and Paleozoic of Eastern Kazakhstan: Alma-Ata, v. 1, p. 64-74.

Shlygin, E.D., ed. 1976. Decisions of interdepartmental conference on working out of unified stratigraphic scheme of Precambrian and Paleozoic of Eastern Kazakhstan: Leningrad, p. 97.

Shlygin, A.Ye., Kasymov, M.A., Khaibulin, R.R., and Yaroslavtseva, N.S., 1992. The high-grade metamorphic rocks of the Ural-Mongolian fold in Kazakhstan. In S.S. Aygustinis, et al. (eds.), High-grade metamorphic: Athens 622. Greece, p. 477-504.

Shopf, Dz.V., Sovetov, Yu.K., 1976. Microfossils in stromatolites from Vendian deposits of South Kazakhstan: DAN USSR, v. 230, p. 1448-1450.

Shtreis, N.A., 1960. Riphean of eugeosynclinal districts, using Central Kazakhstan as an example: Dokl. sov. geol. Problem 8, "Stratigraphy of Late Precambrian, Precambrian and Cambrian", Intern. geol. congr., XXI session, p. 55-63.

Tokmacheva, S.G., Yaroslavtseva, N.S., 1983. Peculiarities of composition and reconstruction of initial composition of ancient formation of North Ulytau. In M.K. Serdukov (ed.), Problems of regional geology and geophysics of Kazakhstan: Alma-Ata, "Nauka", p. 40-51.

Zaitsev, Yu.A., Kheraskova, T.N., 1979. Vendian of Central Kazakhstan: Moscow, Izdatelstvo of Moscow University, p. 251.

Zykov, S.I., Stupnikova, H.I., Filatova, L.I., et al., 1977. Lead-uranium thorium dating of Precambrian metamorphic rocks of Central Kazakhstan: Moscow, Izvestiya AN USSR. Ser. Geol., no. 5, p. 20-37.

Zykov, S.I., Stupnikova, N.I., Zaitsev, Yu.A., et al., 1981. Uranium-lead age of Proterozoic acid volcanites and granite-gneisses of Atasu-Mointy watershed (Central Kazakhstan): Vestnik Moscow university, Ser. geol., no. 3, p. 55-63.

Problems in the Cambrian Stratigraphy of Kazakhstan

G.Kh. Ergaliev

Abstract

Information on the Cambrian deposits of the various structural-formational zones is briefly summarized, and two independent stratigraphic schemes for the Karatau terrigenous-carbonate and Boschekul volcanogenic-sedimentary type sections are presented. The Kyrshabakty section (Malyi Karatau) is a probable stratotype for subdividing stages of not only the Upper Cambrian but the Middle Cambrian as well. Problems requiring further investigation of the Cambrian deposits of Kazakhstan are outlined.

Results of Cambrian studies in Kazakhstan were presented in "The Geology and Metallogeny of Kazakhstan" (Abdulin, 1989), commemorating the 90th birthday of Academician K.I. Satpaev and the 70th Anniversary of the Geological Institute of the Kazakhstan Academy of Sciences. Much is known about the Cambrian rocks of Kazakhstan. Among the monographs and articles that have been published are works by Sidorenko (1971, 1972), Abdulin (1986), and Abdulin and Abdulkabirova (1987). The development of Cambrian stratigraphy is traced in a number of reports — Borukaev (1970), Ivshin (1953, 1956, 1961, 1978, 1983), Ergaliev and Pokrovskaya (1977), and Ergaliev (1980), among others — as well as in the Proceedings and Resolutions of the I, II and III Interdepartmental Stratigraphic Conferences (Aitaliev and Borukaev, 1960; Abdulin, 1974; Shlygin, 1976; Nikitin, 1991). The regional correlation schemes that were outgrowths of these conferences became the basis of small- and medium-scale geologic maps of Kazakhstan.

The Cambrian rocks of Kazakhstan belong to the early-geosynclinal complex of Paleozoic (Caledonide) complexes and are closely connected with late Baikalian formations. They occur in the Kokchetav-Tien Shan fold systems, at the boundary between the Caledonian and Variscan orogens, and also in the Boschekul-Chingiz geosyncline. During the Cambrian those regions were sites of a series of depressions and uplifts that originated in the Vendian, probably with leptogeosynclinal, geanticlinal, platform, and eugeosynclinal sedimentary regimes. According to the composition of the formations of which they are comprised, these units are grouped into the Ishim-Karatau, Malyi-Karatau, Chu-Kendyktas, Zhalair-Naiman, Sarytuma, Aktau-Dzhungaria, Teniz-Stepnyak, Ishke-olmes, Selety-Boschekul, Chingiz-Tarbagatai and Ordatas tectono-stratigraphic units (Fig. 1). Each unit is distinguished by a characteristic sedimentary, volcanogenic, and magmatic composition, deep-seated structure, and distinctive faunal content and distribution.

Within eastern Kazakhstan, the two types of Cambrian section are the Karatau and Boshchekul-Chingiz. The Karatau-type sections have a uniform, terrigenous-carbonate composition, persistent facies, and an absence of effusive rocks. Thin sequences are common. The Boshchekul-Chingiz is distinguished by widespread volcanogenic and terrigenous-siliceous-volcanogenic rocks, great thicknesses, complex composition, and nonpersistent facies (Fig. 2).

Of special significance in the study and correlation of Cambrian rocks are the continuous Karatau and Ulytau sections located within the Ishim-Kazatau and Malyi Karatau structural-formational zones (southwestern Central Kazakhstan) (Fig. 1). The striking similarity of the sections of these regions with the deposits of the Kupriyanovka district, the Ishim river meander, the Kendyktas mountains, the Dombralytau mountains, and the Sarytuma and Aktau-Dzhungarian zones allows reliable correlation. The Karatau and Ulytau sections are also important because they are very rich in diverse faunal groups of all three Cambrian series and have precise interrelations with under- and overlying units. The Ayusokkanian, Sackian, and Aksaian stages of the Upper Cambrian were first established in the stratotype section along the Kyrshabakty River in Malyi Karatau, South Kazakhstan (Fig. 3) (Ergaliev, 1980). At present the Kyrshabakty section of the Malyi Karatau, 28 km east of Zhanatas-city and 150 km north-west of the Zhambyl (Dzhambul)-city in the Sarysu district of the Zhambyl (Dzhambul) region, is one of the potential stratotypes for subdividing the Middle and Upper Cambrian into stages and zones (Fig. 1) (Ergaliev, 1990, 1991). In 1985 the Kazakh S.S.R. Government designated the area in which this section occurs as the Aksai State Geological Reserve. The stratigraphy of the Cambrian deposits of the aforementioned areas of western and southern parts of Central Kazakhstan was described using the Karatau section as the prototype.

The Ishim-Karatau zone is the site of the most extensive distribution of Cambrian black shales and siliceous-carbonate rocks. Stable, uncompensated sedimentation is peculiar to this extensive zone. Also common here are persistent strata and members of siliceous-carbonaceous phthanites (siliceous shales), shales with vanadium and rare metal mineralization, and a small thickness of thin-bedded dark carbonaceous-argillaceous limestones with a stunted fauna in which benthic organisms are lacking.

The Cambrian rocks of Malyi Karatau differ considerably from those of other zones. Although mainly carbonates, they show considerable variability in lithological composition, structure, and depositional environment. The rocks are characterized by platform-type sedimentation, an approximate doubling in the thickness of phosphorite deposits, the diversity of the carbonate facies, and the presence of various faunas, including benthic ones. Conditions of sedimentation within the different parts of the carbonate submarine mountain "Aisha-Bibi" (Fig. 3) determine the lithological and biofacial variability of the Cambrian sections in individual blocks (Cook, Taylor et al., 1989, 1991): slope conditions in the Aksai and Ushbulak blocks and platform conditions in the Bolshekaroi and Malokaroi blocks. It should be noted that according to the results of reliable measurements of the paleocurrent directions in the imbricate-bedded plano-clastic breccias of the Arpaozen section, the total area of the submarine Aisha-Bibi belt should be widened up to include Bolshoi Karatau (the Ishim-Karatau zone) where its south-western slope probably existed (Figs. 1, 4) (Ergaliev, 1992).

In the Chu-Kendyktas zone, the Cambrian rocks consist mainly of sandstones and siltstones with subordinate phthanites and carbonates. The thin-bedded phosphorites are connected with the sandstones and siltstones, and the concentration of vanadium and other components with the phtanites. A stunted Middle-Upper Cambrian trilobite fauna is observed in the limestones.

In the Zhalair-Naiman zone, the structure of the Cambrian section appears to be identical with that of the Chu-

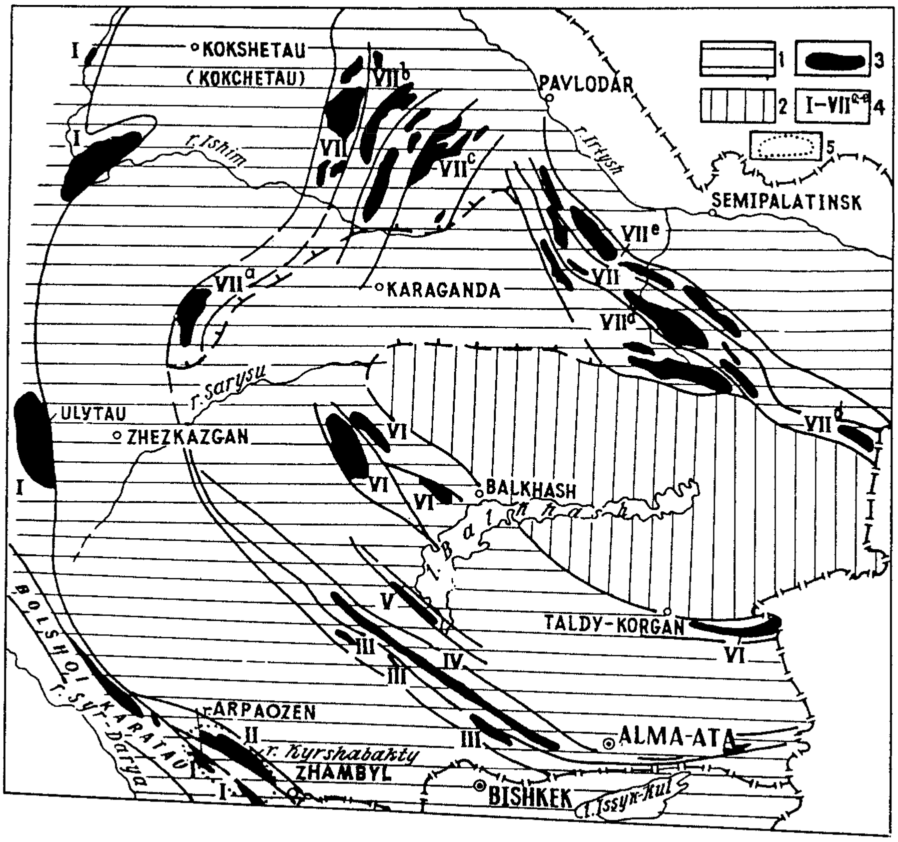


Fig. 1. Distribution of the Cambrian deposits of Kazakhstan: 1- areas of distribution of early geosynclinal complexes of the Paleozoics (Caledonides); 2- area of distribution of the late geosynclinal complexes of the Hercynides; 3- area of Cambrian exposures; 4- structural-formational zones: I- Ishim-Karatau zone; II- Malyi Karatau zone; III- Chu-Kendyktas zone; IV- Zhalair-Naiman zone; V- Sarytuma zone; VI- Aktau-Dzhungar zone; VIIa- Tengiz-Stepnyak zone; VIIb- Ishkeolmes zone; VIIc- Selety-Boshchekul zone; VIId- Chingiz-Tarbagatai zone; VIIe- Ordatas zone; 5- the area of the location of the submarine mountain Aisha-Bibi.

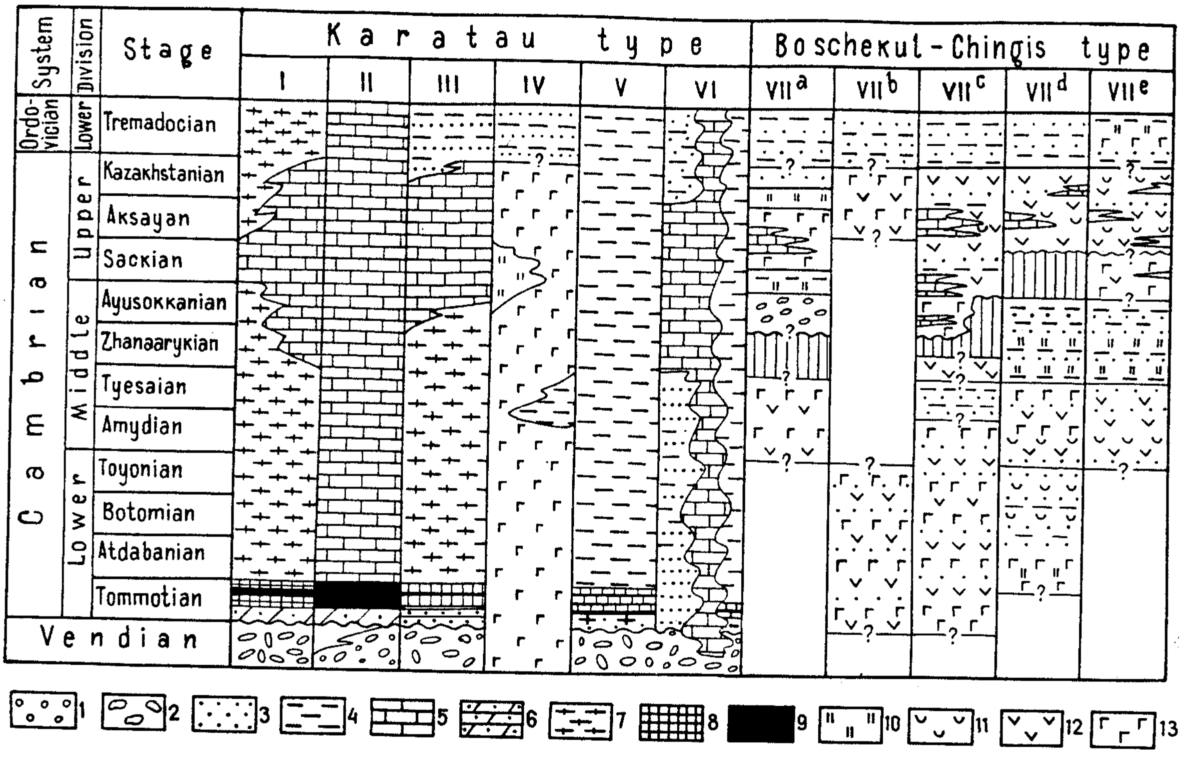


Fig. 2. The summary stratigraphic columns of the Cambrian deposits of the Kazakhstan structural-formational zones. Symbols: 1- conglomerates; 2- tillite-like conglomerates; 3- sandstones; 4- siltstones and mudstones; 5- carbonate rocks; 6- dolomites with fragments of underlying rocks; 7- phtanites and jasper-like, siliceous-carbonaceous, carbonaceous-argillaceous, siliceous-argillaceous rocks; 8- vanadium-bearing carbonaceous rocks; 9- phosphorites and siliceous-phosphate rocks; 10- jaspers; 11- tuffs and tuffites; 12- acidic and intermediate volcanites; 13-basic volcanites.

Kendyktas zone. Genetically heterogeneous ophiolites here have been ascribed to the Cambrian by practically all researchers, but this assignment is somewhat tentative, as a Late Cambrian fauna has not been found. The inarticulate brachiopods in cherts from the Zhambyl (Dzhambul) mountain area, which have been considered to be Late Cambrian, are in fact Early Ordovician and occur in the uppermost part of the ophiolite section.

In the Sarytuma zone, unlike sections in the previous zones, Cambrian sediments are represented mainly by unfossiliferous carbonaceous-argillaceous shales, siltstones, and sandstones, with high concentrations of lead, zinc, and barite, and minor phosphorite and vanadium. Carbonate rocks are practically absent.

The Cambrian rocks of the Aktau-Dzhungarian zone are characterized by siliceous-terrigenous and carbonate deposits. In terms of depositional environment, they have much in common with the black shales of the Ishim-Karatau and Malokaratau sections. Compared with the Malyi Karatau zone, the Cambrian section here is not as rich in phosphorites and vanadium and less fossiliferous. In some regions (southern Dzhungarian) the fauna is absent.

For all the tectono-stratigraphic zones characterized by Karatau-type sections, a uniform regional Cambrian correlation scheme was established at the 3d Kazakhstan Stratigraphic Conference (Nikitin, 1991) (Fig. 4), which used the well exposed, continuous, completely carbonate, structurally simple Malokaratau section as a base. Four zones are distinguished on the basis of problematic fossils (Missarzhevsky and Mambetov, 1981) and 27 zones on the basis of trilobites (Ergaliev, 1967, 1980, 1981, 1987). Of these, 12 zones and 3 stages are subdivisions of the general Cambrian scale in the Commonwealth of Independent States (Sokolov, 1983). However, the lack of generally accepted Cambrian stages recognized by the International Geological Congress and debatable Cambrian division boundaries, led the author of the present article to propose a four-stage division of the Middle Cambrian and a three-stage division of the Upper Cambrian in the Kyrshabakty section.

According to this scheme, the Amgian and Mayan stages of the Middle Cambrian were made superstages and subdivided into Amydaian, Tyesaian, Zhanaarykian, and Ayusokkanian stages, as Repina and Rosova (1984) believed they should be, and the Upper Cambrian was divided into Sackian, Aksaian, and Kazakhstanian (Batyrbai stage, according to Apollonov and Chugaeva, 1984) stages (Ergaliev, 1990a, 1990b) (Fig. 4).

System	Subdivision	Stage	Karatau type / Zone	Boshchekul type / Horizons
Cambrian	Upper	Kazakhstanian *	Lotagnostus hedini	Kanchingiz
			Micragnostus mutabilis	
			Trisulcagnostus trisulcus	
		Aksayan	Agnostus scrobicularis	
			Neoagnostus quadratiformis	Lermontova
			Eurudagnostus ovaliformis	
			Eurudagnostus kazachstanicus	
			Pseudagnostus pseudangustilobus	
		Sackian	Jvshinagnostus ivshini	Selety / Aksak-Kuyandy
			Pseudagnostus curtare	
			Acutatagnostus acutatus	
			Jnnitagnostus inexpectans	
			Glyptagnostus reticulatus	Akmola
	Middle	Ayusokkanian	Glyptagnostus stolidotus	
			Kormagnostus simplex	
		Mayan	Lejopyge laevigata	„Alkamergen"
			Lejopyge armata	Boschesor
			Goniagnostus nathorsti	
			Ptychagnostus punctuosus	Chingiz
		Amgian	Ptychagnostus atavus	Maidan
			Ptychagnostus intermedius	
			Peronopsis ultimus	Zhangabul
			Schistocephalus	
	Lower	Toyonian	Probowmania asiatica	Akzhar
				Shiyli
		Botomian	Redlichia chinensis	Bayanaul
			Ushbaspis limbata	
			Hebediscus orientalis	
		Atdabanian	Ushbaspis sp. 1	Bakanas
			Rhombocorniculus cancellatum	
		Tommotian	Bercutia cristata	
			Pseudorthotheca costata	
			Tiksitheca licis	

* Batyrbaian, after Apollonov M.K. and Chugaeva M.N.

Fig. 3. Regional stratigraphy of the Cambrian deposits of Kazakhstan.

The Boshchekul-Chingiz zone, occupying northern and northeast parts of Central Kazakhstan, includes several large areas of Cambrian rocks (from west to east): Tengiz-Stepnyak, Ishkeolmes, Selety-Boshchekul, Chingiz-Tarbagatai, and Ordatas (Fig. 1). Within all these regions, typically in the development of Lower Cambrian volcanogenic formations, basalts in a rhyolite-dacite-basaltic series, predominate. The volcanogenic Middle Cambrian formations are notable for basalts of more varied composition (alkaline and tholeiitic), as a rule, giving way to andesitic series, towards the end of the Middle and Late Cambrian. Carbonate and terrigenous clastic rocks are less important. On the whole, the Cambrian is distinguished by widespread distribution of shallow-water terrigenous-carbonate facies with a rich coquina fauna. As is generally known, the stratigraphic correlation scheme for this part of Kazakhstan, accepted at the 3rd Kazakhstan Stratigraphic Conference (Nikitin, 1991) (Fig. 4), is based on work of Ivshin (1953-83). Unfortunately, the scheme was constructed mainly from separate outcrops of trilobite-bearing rock. In contrast to the Karatauian scheme, it covers 14 horizons, with diverse trilobite complexes and, to a lesser extent, other fauna (archaeocyathids, brachiopods, and conodonts).

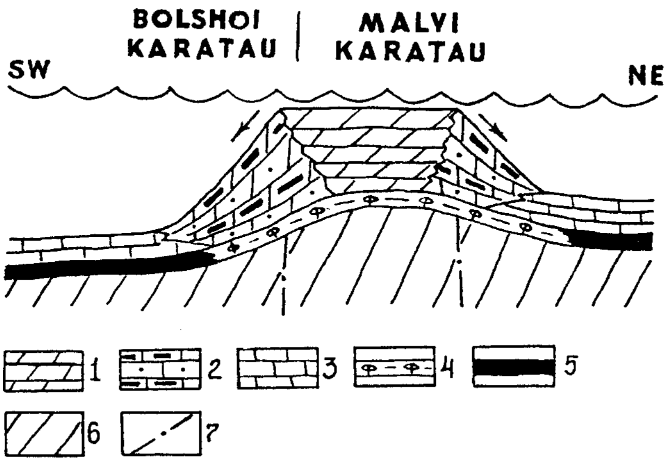


Fig. 4. The model of the Early Paleozoic submarine mountain Aisha-Bibi (after H. Cook et al., 1989, with alterations by F.G. Ergaliev, 1992). Symbols: 1-3- carbonate deposits of the Shabakty series of Malyi Karatau and the Kokbulak series of Bolshoi Karatau: 1- shallow water, 2- slope, 3- basin; 4- the Chulaktau (phosphorite-bearing) series deposits of Malyi Karataua, 5- the Kurumsak (vanadium-bearing) series deposits of Bolshoi Karatau, 6- the Precambrian complex, 7- synsedimentary faults.

Based on this brief description of the Cambrian sections as displayed in large tectono-stratigraphic zones, it may be concluded that the rocks were integral to the development of the geological structure of Kazakhstan. Associated with them are Kazakhstan's largest deposits of phosphorite, vanadium, polymetallic ores, barite, and other commercial minerals which in many respects determine the mineral and raw-material base of the Republic. From this, the importance of correlating the two regional scales of Cambrian deposits in Kazakhstan becomes obvious. To accomplish this, the position and stratification of isolated Cambrian exposures such as olistostromes characteristic of eugeosynclinal sections, should be determined. Some formations, such as the volcanogenic-siliceous and siliceous-volcanogenic strata of northeast part of Central Kazakhstan, may be found to be Ordovician when the sections are studied in detail. The Cambrian sections of the Zhalair-Naiman zone are insufficiently studied and require special attention. The sections of the Aktau-Zhungarian zones of southern Kazakhstan have not yet been fully studied. Exploration of the latter is needed in order to supply essential biostratigraphic data.

The unique trilobite and conodont faunas of the Kyrshabakty section in Malyi Karatau can be seen in lists published with in-depth determinations of the volumes and boundaries of the 6 stages and 21 zones of the Middle and Upper Cambrian. At present, it is necessary to carry out a biofacies study of the Cambrian index fossil groups to improve the basis of zonal schemes and for worldwide correlation.

References

Abdulin, A.A., ed., 1974. Pre-Paleozoic and Paleozoic of Kazakhstan, v. 1: Alma-Ata, Nauka, p. 105-115 (in Russian).

Abdulin, A.A., ed., 1986. Geology and metallogeny of Karatau, v. 1: Alma-Ata, Nauka, p. 35-45 (in Russian).

Abdulin, A.A., ed., 1989. Geology and metallogeny of Kazakhstan: Alma-Ata, Nauka, 344 p. (in Russian).

Abdulin, A.A., and Abdulkabirova, M.A., eds., 1987. Geology of Northern Kazakhstan (stratigraphy): Alma-Ata, Nauka, p. 48-77 (in Russian).

Abdulin, A.A., Apollonov, M.K., and Ergaliev, G.Kh., eds., 1990. Guide-Book. The Third International Symposium on the Cambrian System. Excursion 2. Kazakh S.S.R. Malyi Karatau: Alma-Ata, p. 18-37.

Aitaliev, Zh.A., and Borukaev, R.A., eds., 1960. The proceedings of the conferences on the unification of the stratigraphic schemes of the pre-Paleozoic and Paleozoic of Eastern Kazakhstan, Part 1: Alma-Ata, Publishing House Akademiya Nauka Kazakh S.S.R., p. 78-174, p. 297-298 (in Russian).

Apollonov, M.K., and Chugaeva, M.N., 1984. Cambrian-Ordovician boundary problem, in Apollonov, M.K., Bandaletov, S.M., and Ivshin, N.K., eds., Lower Paleozoic stratigraphy and paleontology of Kazakhstan: Alma-Ata, Nauka, p. 16-25 (in Russian).

Borukaev, R.A., 1970. Selected works, v. 1: Alma-Ata, Nauka, 246 p. (in Russian).

Cook, H.E., Taylor, M.E., Zhemchuzhnikov, V.G., Apollonov, M.K., Ergaliev, G.Kh., Dubinina, S.V., Melnikova, L.M., Sargaskaev, Zh.S., and Zakharov, A.V., 1989. Evolution of an early Paleozoic carbonate seamount, Malyi Karatau Range, Southern Kazakhstan, U.S.S.R.: New evidence for early history of Kazakhstania: Abstracts, 28th International Geological Congress, Washington, D.C., v. 1, p. 322-323, authorship corrected, in Hanshaw, B.B., 1990. General Proceedings, 28th International Geological Congress, Washington, D.C., p. 81.

Cook, H.E., Taylor, M.E., Zhemchuzhnikov, V.G., Apollonov, M.K., Ergaliev, G.Kh., Sargaskaev, Zh.S., Dubinina, S.V., and Melnikova, L.M., 1991. Comparison of Two Early Paleozoic Carbonate submarine fans - Western United States and Southern Kazakhstan, U.S.S.R., in. Cooper, J.D., and Stevens, C.H., eds., Paleozoic Paleogeography of the Western United States - II: Los Angeles, California, the Pacific Section Society, Economic Paleontologists and Mineralogists, v. 2, p. 847-872.

Ergaliev, G.Kh., 1967. Stratigraphy and biostratigraphy of the Cambrian and Tremadocian of the Baikonur-Karatau-Zhabagly zone of eastern Kazakhstan. Unpublished Cand. Sc. Theses: Alma-Ata, 19 p. (in Russian).

Ergaliev, G.Kh., 1980. Trilobites of the Middle and Upper Cambrian of Malyi Karatau: Alma-Ata, Nauka, 211 p. (in Russian).

Ergaliev, G.Kh., 1981. Upper Cambrian biostratigraphy of the Kyrshabakty section, Malyi Karatau, Southern Kazakhstan, in Taylor, M.E., ed., Short Papers of the Second International Symposium on the Cambrian System: U.S. Geological Survey Open-File Report 81-743, p. 82-88.

Ergaliev, G.Kh., 1987. Cambrian of Kazakhstan (the Karatau type of sections): Izvestiya academii Nauk Kazakh S.S.R., seriya geologicheskaya, no. 4, p. 40-43 (in Russian).

Egaliev, G.Kh., 1990a. Kyrshabakty section in Malyi Karatau as a stratotype for stage and zonal subdividing in the Middle and Upper Cambrian. The Third International Symposium on the Cambrian System. 1-9 August 1990: U.S.S.R., Novosibirsk, Abstracts, p. 90.

Ergaliev, G.Kh., 1990b. Stage and zonal scale of the Middle and Upper Cambrian exemplified by the Kyrshabakty section in Malyi Karatau, in Abdulin, A.A., Apollonov, M.K., and Ergaliev, G.Kh eds., Guidebook, The Third International Symposium on the Cambrian System. Excursion 2. Kazakh S.S.R., Malyi Karatau: Alma-Ata, p. 18-27.

Ergaliev, G.Kh., 1990c. Kyrshabakty stratotype section of the Middle and Upper Cambrian, in Abdulin, A.A., Apollonov, M.K., and Ergaliev, G.Kh., eds., Guidebook, The Third International Symposium on the Cambrian System. Excursion 2. Kazakh S.S.R. Malyi Karatau: Alma-Ata, p. 27-37.

Ergaliev, G.Kh., 1991., Cambrian of Karatau as a potential standard for planetary stratigraphic correlations: Vestnik Akademii Nauk Kazakh S.S.R., no. 8, p. 23-27 (in Russian).

Ergaliev, F.G., 1992. On the paleogeography of Karatau in the Middle Cambrian-Early Ordovician (Southern Kazakhstan): Izvestiya Akademii Nauk Kazakh S.S.R., Seriya geologicheskaya, no. 6, p. 51 (in Russian).

Ergaliev, G.Kh., and Pokrovskaya, N.V., 1977. Lower Cambrian trilobites of Malyi Karatau: Alma-Ata, Nauka, 98 p. (in Russian).

Ivshin, N.K., 1953. Middle Cambrian trilobites of Kazakhstan, Part 1 (the Boshchekul faunal horizon): Alma-Ata, Publishing House of the Academy of Sciences of the Kazakh S.S.R., 253 p. (in Russian).

Ivshin, N.K., 1956. Upper Cambrian trilobites of Kazakhstan, part 1 (the Kuyandy faunal horizon between the rivers of Olenty and Shiderty): Alma-Ata, Publishing House of the Academy of Sciences of the Kazakh S.S.R., 120 p. (in Russian).

Ivshin, N.K., 1961. Correlation of the faunal scale of the Cambrian of Kazakhstan with the scales of Eastern Siberia, Western Europe and Northern America in Shatsky, N., Rodgers, J., and Menner, V.V., eds., The Cambrian System, its paleogeography and the problem of the lower boundary. The International Geological Congress, Session 20, Mexico, Symposium, Part III: Moscow, p. 303-329 (in Russian).

Ivshin, N.K., 1978. Biostratigraphy and trilobites of the Lower Cambrian of Central Kazakhstan: Alma-Ata, Nauka, 127 p. (in Russian).

Ivshin, N.K., 1983. Upper Cambrian trilobites of Kazakhstan, part II, Seletinian horizon of the Kuyandinian stage of Central Kazakhstan: New Dehli, Amerind Publishing Co. Pvt. Ltd., 432 p. (translated from Russian).

Missarzhevsky, V.V., Mambetov, A.M., 1981. Stratigraphy and fauna of the Cambrian and Precambian strata of Malyi Karatau: Moscow, Nauka, 90 p. (in Russian).

Nikitin, I.F., Ergaliev, G.Kh., et al., 1989. Knowledge and problems of the Kazakhstan Paleozoics, in Abdulin, A.A., ed., The geology and metallogeny of Kazakhstan: Alma-Ata, Nauka, p. 32-43 (in Russian).

Nikitin, I.F., ed., 1991. Resolutions of the III Stratigraphic Conference on the Precambrian and Phanerozoic, 1986. Part 1, the Precambrian and Paleozoic: Alma-Ata, p. 40-67 (in Russian).

Rosova, A.V., and Repina, L.N., 1984. Cambrian. The Middle and Upper divisions, in Yanshin, A.V., ed., The Phanerozoic of Siberia, v. 1, Vendian, Paleozoic: Novosibirsk, Nauka, p. 25-29 (in Russian).

Shlygin, E.D., ed., 1976. Resolutions of the Interdepartmental Conferences on the elaboration of the unified stratigraphy schemes of the Precambrian and Paleozoic of Eastern Kazakhstan, 1971: Leningrad, p. 21-32 (in Russian).

Sidorenko, A.V., ed., 1971. Geology of the U.S.S.R., v. 20, Southern Kazakhstan, Part I: Moscow, Nedra, p. 67-108 (in Russian).

Sidorenko, A.V., ed., 1972. Geology of the U.S.S.R., v. XL, Central Kazakhstan, Part I: Moscow, Nedra, p. 93-153 (in Russian).

Sokolov, B.S., ed., 1983. Resolutions of the Interdepartmental Stratigraphy Committee and its commissions: Leningrad, no. 21, p. 29-31 (in Russian).

Early Geosynclinal Ordovician Siliceous and Jasper-Basaltic Formations of Kazakhstan

I.F. Nikitin

Abstract

The stratigraphy of the Ordovician siliceous and siliceous-volcanogenic deposits of Kazakhstan is summarized, and the significance of the conodonts found in these deposits is discussed. New stratigraphic data enable more precise determinations of age, succession, and correlation, and corroborate the validity of singling out two types of sediments — jasper-basaltic and mainly siliceous. The jasper-basaltic type is characteristic of the inner part of the folded Paleozoic structures of Kazakhstan and is common in the Dzhungar-Balkhash zone and on the periphery of the Chingiz-Tarbagatai zone. Its age range is from Early-Middle Ordovician (on the periphery) to Late Ordovician and Early Silurian in the inner part. The second or siliceous type is most widespread and thickest in the Ermentau-Chuili zone. These deposits are Early and early Middle Ordovician in age. They become thinner to the west and southwest. In the inner part of the Kazakhstan Paleozoics the jasper-basaltic formations are invariably associated with olistostromes and tuff-siliceous-terrigenous sediments, and in each instance present unique spatial and age combinations. Characteristics of the volcanism of the jasper-basaltic groups and their spatial interrelations with various kinds of mainly siliceous sediments are the basis for paleogeographic and paleotectonic reconstructions in which the Paleozoics of Kazakhstan represented a marginal basin of the Pacific Ocean type, with island arcs, inter-arc, and back-arc depressions. Ore deposits of iron, manganese, polymetallic, vanadium, phosphorite, barite, etc. are associated with the siliceous and jasper-basaltic formations. By analogy with modern marginal seas, above-average concentrations of gold may also be found.

Introduction

The siliceous and jasper-basaltic early geosynclinal complexes of the Paleozoics of Kazakhstan (Fig. 1) represent closely connected successions that alternate or show other kinds of changes in the vertical direction as well as laterally and are considered to be members of an ophiolite association (Avdeyev, 1984, and others). The siliceous Akdym group (Borukaev and Lyapichev, 1957) and the jasper-basaltic Urtynzhal group (Bogdanov, 1959) are representative of such successions.

These deposits have long attracted attention as it is thought that they reflect the formative stage of the geosynclinal systems of the Paleozoics of Kazakhstan as well as of the entire Ural-Mongolian geosynclinal belt. Their age and genesis have long been the subject of intense debate. Only when conodonts began to be found in the cherts (Gridina and Mashkova, 1977) did it become obvious that most of the aforementioned deposits are of Ordovician age. The possibility then arose of studying their original composition and of linking their origin with tectonic structures.

A number of published reports deal with specialized but exceptionally important questions regarding the age and stratigraphic succession of these deposits within different structures or regions (Dvoichenko, 1974; Gerasimova et al., 1977; Nikitin et al., 1980; Novikova et al., 1980; Novikova et al., 1983; Gerasimova et al., 1984; Besstrashnov et al. 1985; Borisyonok, 1985; Borisyonok et al., 1985; Gerasimova, 1985; Novikova et al., 1985; Dvoichenko and Abaimova, 1986; Novikova et al., 1991; Gerasimova et al., 1992; Nikitin et al., 1992). Other reports summarize what is known about the stratigraphy and volcanism or paleogeography and paleotectonics (Zvontsov, 1973; Borisyonok e al., 1979; Kheraskova, 1979; Babichev et al., 1980; Kurkovskaya, 1985; Kheraskova, 1986; Gerasimova et al., 1988). Despite all that has been published, this complex problem must be addressed once more, in the light of new data that have led the author to interpret the paleogeographical environments in which these deposits accumulated, and their paleotectonic positions, in ways that differ from previous interpretations.

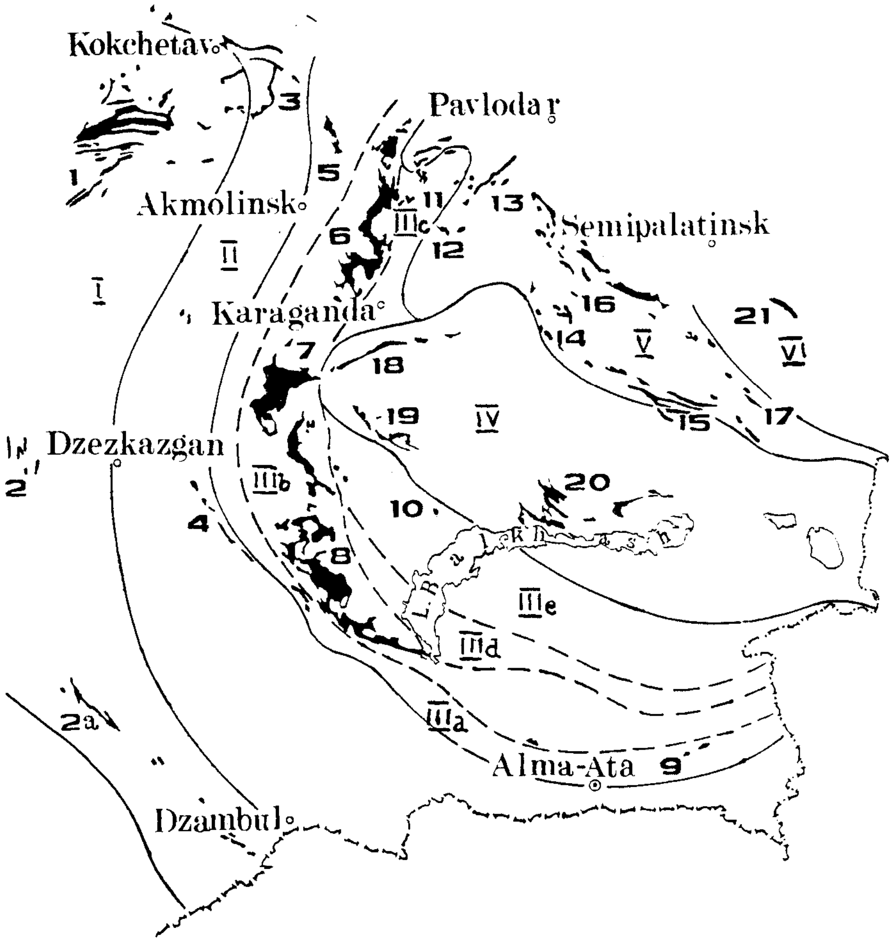


Fig. 1. Distribution of Ordovician siliceous and siliceous-basaltic formations in Kazakhstan (black): I- Ishim-Karatau zone, II- Stepnyak-Betpakdala-North Tien-Shan zone, III- Ermentau-Chuili zone: IIIa- Selety-Sugaty subzone, IIIb- Ermentau-Burultas subzone, IIIc- Shiderty subzone, IIId- Mynaral-South Dzhungarian subzone, IIIe- Mointy-Tekeli subzone, IV- Dzhungar-Balkhash zone, V- Chingiz-Tarbagatai zone, VI- Zaisan zone: 1- Kokchetau-Kalymkul, 2- Baikonur, 2a- Bolshoi Karatau, 3- Shat, 4 - Betpakdala, 5- Ishkeolmes, 6- Ermentau, 7- Atasu, 8- Burubaital, 9- Boguty, 10- Mointy, 11- Shiderty, 12- Karaulcheku, 13- Maikain, 14- Egendybulak, 15- Akchatau, 16- Naimanzhal, 17- Tarbagatai, 18- Tekturmas, 19- Agadyr, 20- Itmurundy, 21- Char.

Stratigraphy

The jasper-basaltic formations are most widespread and show the greatest contrasts in age and composition in the Dzhungar-Balkhash zone and along the periphery of the Chingiz-Tarbagatai zone (Fig.1) (Nikitin, 1991). Here they are part of an ophiolite association and, according to some authors, lie on a melanocratic foundation, forming the base of the oceanic crust of the eugeosynclinal area of the Paleozoics of Kazakhstan (Antonyuk et al., 1976; Antonyuk et al., 1977 and others).

Mainly siliceous Ordovician sediments are found on the western and southwestern margins of the Ermentau-Chuili zone. In these sections, basalts occur only sporadically. The deposits here are believed to rest directly on sialic basement.

Everywhere they occur, the Ordovician deposits are in overthrust slabs stacked one upon another, forming allochthonous terranes split into nappes within which complex often isoclinal folds are dislocated by faults, or are represented by accumulations of detached blocks and olistoliths in diamictites (Fig. 2).

The deposits are divided into formations in which the dominant lithologies are volcanics, tephra, siliceous rocks, olistostromes, and terrigenous components. However, with rare exceptions, no stratigraphic contacts of these formations are exposed. They are bounded by faults and related to each other in as yet undetermined ways. The discovery of conodonts has made it possible to define the general age succession of certain units, thereby filling in some of the gaps.

Kurkovskaya (1985), who studied the conodonts of Kazakhstan, singled out six complexes after generalizing all the data from the more than 150 localities then available (see also Gerasimova et al., 1988). The first complex, with *Prioniodus evae* Lind. and others, and the second, with *Periodon aculeatus zgierzensis* Dzik and others, are Arenigian. The third, characterized by *Prioniodus alatus parvidentatus* (Sergeeva), is Arenigian-Llanvirnian. The fourth, in which *Histerodella holodentata* Ethington et Clark and *Prioniodus alatus* Hading are present, and the fifth, with *Pygodus serrus* (Hading), are Llanvirnian; and the sixth, with *Pygodus anserinus* Lamont et Lind., is Llandeilian. Later this succession was supplemented by the discovery of Tremadocian complexes, the lower one with *Drepanodus numarcuatus* (Lind.) and a Caradocian complex comprising *Hamarodus europeus* (Serpagli) and other forms (Nikitin, 1991).

Fig. 2. Compound-dislocated cherts of the Akdym formation in the northern part of the Ermentau mountains in the northeast of Central Kazakhstan (aerial photograph).

Zhilkaidarov (in Nikitin et al., 1992), studying continuous sections within stratigraphic levels comparable to these complexes, attempted to distinguish local zonal sequences of Arenigian and Llanvirnian conodonts in the siliceous and siliceous-basaltic formations of an area to the southwest of the Chingiz region.

The generalized succession of the conodont complexes and zones in the siliceous and siliceous-basaltic formations of Kazakhstan thus extends throughout most of the Ordovician, from the Tremadocian to the Caradocian, and serves as a basis for correlating these deposits with each other and for comparing them with units of the standard scale. Radiolarians (Nazarov and Popov, 1980) and graptolites are as yet poorly studied and thus less useful in this respect. The latter are traced in the siliceous formations mainly in the west of central Kazakhstan in the Stepnyak-Betpakdala, northern Tien-Shan, and Ishim-Karatau-Naryn zones (Nikitin, 1991).

As already noted, in the north of the Ermentau-Chuili zone, in the Ermentau-Niyaz anticlinorium, the aforementioned deposits are typically represented by the Akdym group (Fig. 3) (Borukaev, 1955; Dvoichenko, 1971; Novikova et al. 1978, Novikova et al., 1986), in the Atasu anticlinorium, by the Karatas and Mynadyr formations (Gerasimova et al., 1971), and in the south, by the Burubaital formation. (Nikitin et al., 1980). They consist

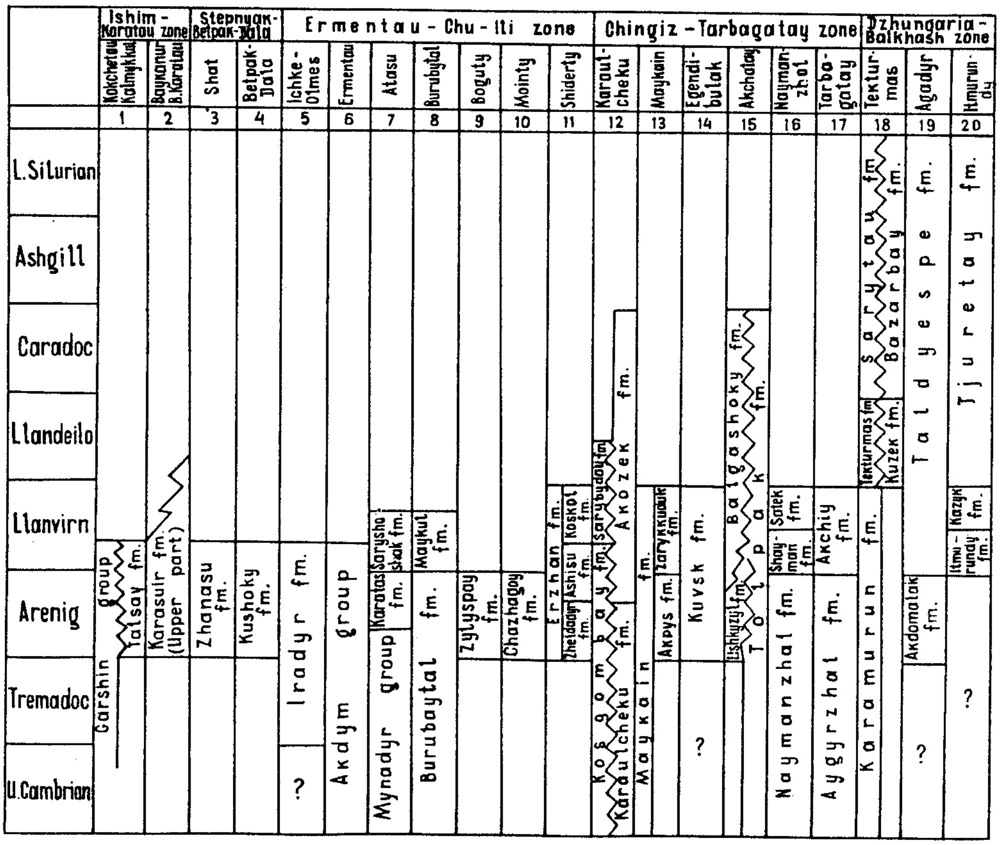


Fig. 3. Correlation chart for the Ordovician siliceous and siliceous-basaltic formations of Kazakhstan.

of microquartzites, jaspers, phthanites, siliceous siltstones, quartzites, siliceous-clastic and quartz sandstones, and include vanadium-phosphatic shales, ferromagnesian and manganese ores, and stratified barite ore. The volcanic rocks, chiefly basalts, form rare interbeds and lenses but make up 15-20% of the thickness of these formations in certain sections (Novikova et al., 1988). Remnants of more intensive volcanism are found on the western edge of the zone, where they may be restricted to the east by the Ermentau-Buruntas subzone.

In the north, the siliceous Iradyr Formation, consisting of multicolored jaspers and quartzites and containing Arenigian conodonts, is distinguished in the Ichkeolmes anticlinorium (Borisyonok, 1981). Underlying this unit is the mostly basaltic Sazy Formation, which is up to 500 m thick. To the south, a similar position is apparently occupied by the basalts and siliceous rocks of the Ashchisu Formation, exposed in the Chu ophiolite belt (Akishev et al., 1992). Siliceous-volcanogenic formations of similar composition remain along the eastern foothills of the Ermentau mountains and on the right bank of the Olenty River in the Semizbugu hills (Borisyonok et al. 1985; Gerasimova et al. 1988). Whether these mainly basaltic formations, ascribed to the Ermentau group, belong to the Ordovician has not yet been proven, and a Cambrian age is also possible, as reflected in the Resolutions of the 3d Kazakhstan Stratigraphic Conference (Nikitin 1991).

Conodonts have been found in the Akdym group and the Iradyr, Burubaital, Maikol, and other formations at many localities throughout the Ermentau-Chuili zone. The oldest ones, *Prooneotodus tenus* (Müller) and *P. gallatini* (Müller), indicate a Late Cambrian age. The Tremadocian conodonts *Cordylodus* cf. *proavus* Müller and *Drepanodus numarculatus* (Lind.) occur in different successions of Ordovician cherts that have not yet been correlated with each other. The most widespread is the Arenigian level with *Paracordylodus gracilis* Lind., *Prioniodus evae* Lind., *Periodon flabellum* (Lind.), and others. Conodont associations typical of the Late Arenigian — *Microzarkodina flabellum* (Lind.), *Periodon intermedius* Serpagli, and others — are observed more rarely. Strata containing Early Llanvirnian conodonts such as *Cordylodus horridus* Barnes et Poplav. and *Periodon aculeatus* Hading are evidently confined to the upper part of these formations. In the northern part of the zone, in the Ermentau mountains, these sediments are overlapped by the Teleskol formation, consisting of tuffstones, tuff siltstones, and tuffites alternating with basic and acid volcanics tentatively dated as Middle Ordovician. In the south, the Burubaital formation is overlain and partially replaced along strike by the Maikul formation (Fig. 4), consisting chiefly of quartz sandstones, siltstones, gritstones, and conglomerate with strata and members of cherts similar to those in the Burubaital formation. The cherts have yielded the Late Llanvirnian conodonts *Pygodus serra* (Hading), *P. anserinus* Lamont et Lind., *Periodon aculeatus* Hading, and *Panderodus gracilis* (Branson et Mehl.). There is some disagreement as to the position that these cherts occupy in the Maikul formation. According to one opinion, they are detached blocks of the Burubaital formation and form klippes among the terrigenous rocks of the Maikul formation. The thickness of the Akdym group and Burubaital formation is usually given as from 700 to 1300 m. These figures are undoubtedly many times too large, and the true thickness of these deposits probably does not exceed a few hundreds of meters and may be only dozens of meters. The Llanvirnian cherts of the Maikul formation are not more than 50-100 m thick.

Fig. 4. Ridges of light chert with Llanvirnian conodonts among sandstones of the Maikul group in southwestern Balkhash Region.

West of the Ermentau-Chuili zone, in the Stepnyak-Betpakdala-Northern Tien-Shan and Ishim-Karatau-Naryn zones, siliceous deposits of Ordovician age have limited distribution. To the north they are represented by the Zhanasui formation (Kopyatkevich and Tsai, 1974), consisting of phtanites, red jaspers, sandstones, and siliceous siltstones with interlayers of trachybasalt, trachydacite, and tuffite. These sediments contain graptolites (*Tetragraptus* sp.) and the conodont *Periodon flabellum* (Lind.). To the south, in Betpakdala, the siliceous sediments occur in the upper part of the Kushoky formation, forming a 270-m-thick member of dark-grey and black phthanites, alternating with quartz and quartz-feldspathic sandstones and siltstones. Arenigian graptolites can be traced here too. In the lower part there are *Didimagraptus protobifidus* Elles, *Expansograptus extensus* (Hall.), *Phyllograptus angustifolius* Hall (the *D. protobifidus* zone), and in the upper part, *Isograptus maximodivergens* (Harris), *Dichograptus maccoyi* H. et al., *Phyllograptus* Hall (the *I. maximodivergens* zone). Conodonts have also been found at these levels. Higher in the section are siltstones and mudstones with a 40 - 50 m thick member of red and yellowish jaspers containing the Llanvirnian graptolites *Glyptograptus dentatus* (Brongn.) and others (the *P. tentaculatus* zone). Graptolites are also found in the Kushoky formation in the Sarysu-Teniz watershed. In the lower part of the formation there are *Tetragraptus quadribrachiatus* (Hall), *Phyllograptus anna* (Hall), *Corymbograptus deflexus* E. et W., *Isograptus maximodivergens* (Harris), *I. gibberulus* (Nich.) (the *I. maximodivergens zone*), and higher there are *Pseudotrigonograptus ensiformis* (Hall), *I. divergens* (Harris), and *Glossograptus acantus* E. at W. (the *D. hirundo* zone). The thickness of these deposits does not exceed 250 - 300 m.

In the central parts of the Stepnyak-Betpakdala-Northern Tien-Shan zone, these formations are overlapped by the typically island arc volcanics of the Saga group or the Savid formation, and in the north, along the western periphery, by the terrigenous sediments of the Stepnyak and other formations.

Westward in the Ishim-Karatau-Naryn zone, the thickness of siliceous deposits diminishes to 30 m or less. There they are represented by a member consisting of greenish, dark-grey, almost black jaspers in the upper part of the Kamal formation of Bolshoi Karatau and the Karasu formation of the Baikonur synclinorium. This member has yielded the Lower Llanvirnian graptolites *Pseudotrigonograptus ensiformis* (Hall), *Glyptograptus dentatus* (Brongn.), and *Paraglossograptus tentaculatus* (Hall) (the *P. tentaculatus* zone) as well as conodonts. A member consisting of red and greenish mudstones is distinguished in the upper part of the Karasu formation. In western exposures of this unit, red jaspers containing the Llanvirnian and Llandeilian conodonts *Pygodus anserinus* Lamont et Lind. and others occur, along with ferromagnesian concretions (Azerbaev, 1990).

The thick siliceous-basaltic deposits assigned to the Bratolyubovka, Garshin, and Nikolsko-Buruluk formations and also the siliceous and siliceous-terrigenous deposits of the Shinsai and Talsai formations are restricted to the northwestern margin of the zone, in the Dzharkainagach anticlinorium, the Kalmykkul synclinorium, and along the western and northern margins of the Kokchetav massif (the Konstantinovka and other anticlinoria) (Ivanov et al., 1988). The siliceous rocks in the Bratolyubovka, Garshin, and Nikolsko-Buruluk formations consist mainly of red jaspers and are prevalent in the upper part of the section. The lower part is composed of greyish-green aphyric basalts, with some pillow lavas.

Conodonts (of Late Arenigian age) have only been found in the upper part of the siliceous beds of the Garshin and Nikolsko-Buruluk formations. In the Bratolyubovka formation only fragments of radiolarians are recorded. Fossils have not been found in the lower, chiefly volcanogenic parts of these formations, and many investigators consider these rocks Cambrian and even Vendian in age (Kheraskova, 1986; Novikova et al., 1988). In the Shinsai formation, along with sandstones and limestones, members consisting of dark siliceous-carbonaceous mudstones are recognized. In the upper part of the formation, radiolarians and Tremadocian inarticulate brachiopods are indicated. The lower part of the formation is thought to be Cambrian (Nikitin, 1991). In the Talsai and Tasoba formations, red jaspers and argillaceous-siliceous mudstones predominate. The latter formation is characterized by Arenigian graptolites and conodonts (Khabelashvili and Tsai, 1966; Ivanov et al., 1988). The thickness of Ordovician siliceous rocks in these formations apparently does not exceed a few dozen meters, and in the Bratolyubovka, Garshin, and Nikolsko-Buruluk formations, perhaps a few hundred meters.

On the eastern border of the Ermentau-Chuili zone, in the Shiderty and Mointy-Tekeli subzones, the thickness of the Ordovician deposits is sharply reduced. In the north they are represented by the Erzhan formation — red argillaceous ash, jasper, cherts, trachydacites, trachyte porphyrites, and tuffs in the lower part of dark carbonaceous phthanites.[1] The lower part of the Erzhan formation has yielded the Arenigian conodonts *Paracordylodus gracilis* Lind., *Periodon flabellum* (Lind.), *Oistodus gracilis* Lind., *O. forceps* Lind., *Oneotodus gracilis* (Furnish), and the upper part the Llanvirnian conodonts *Periodon aculeatus* Hading, *Scolopodus cornuformis* Sergeeva, and others. In the south, in the Mointy-Tekeli subzone, the dark carbonaceous cherts and mudstones of the Chazhagai formation have yielded the Arenigian conodonts *Prioniodus* (*O.*) *evae* Lind., *Paracordylodus gracilis* Lind., and *Periodon flabellum* (Lind.) and the graptolites *Tetragraptus bigsbyi* (Hall) and *Phylograptus angustifolius* Hall (Apollonov et al., 1990). Red siliceous mudstones are recorded in the Ortan formation (Nikitin, 1991). The thickness of the entire succession is approximately 200 m.

In east-central Kazakhstan, in the Chingiz-Tarbagatai zone, the siliceous-basaltic complex is widespread. These deposits make up the structures bordering the inner, island arc part of the zone (Zvontsov and Frid, 1988). In the southwestern region, near Chingiz, the complex is typically represented by the Ushkyzyl and Bolgashoky formations (Figs. 5, 6) of the Balkibek anticlinorium (Nikitin et al., 1992). The Ushkyzyl formation overlies Cambrian Balkibek basalts disconformably and consists of alternating striated light grey black and greenish jaspers in the

---

[1] Khromykh (1986) assigns the mainly siliceous lower part of the formation to the Zheltau formation, trachydacites and trachytes to the Ashchisu formation, and the siliceous-terrigenous upper part of the formation to the Koskol formation.

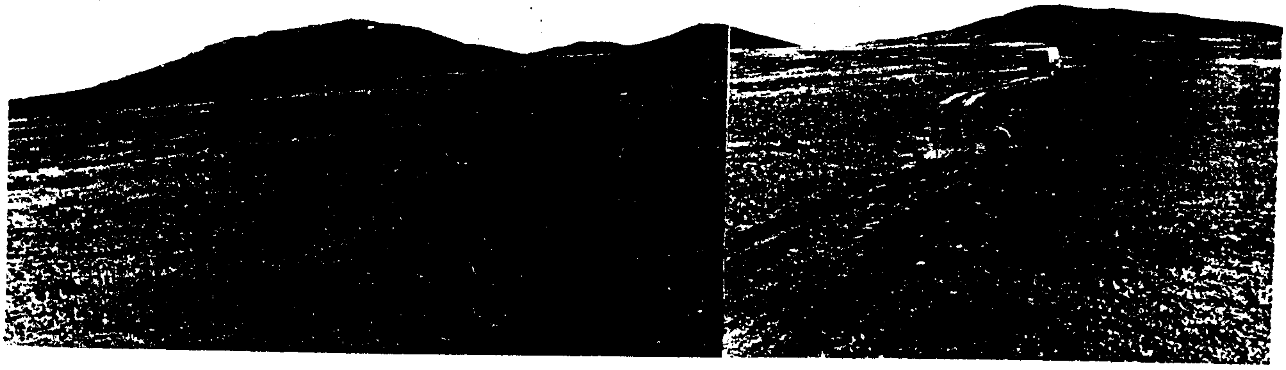


Fig. 5. Ushkyzyl hills in southwestern Chingiz Region, composed of jaspers of the Ushkyzyl Formation.

Fig. 6. Kyzylzhal mountains in southwestern Chingiz Region. Dark (1) and red (2) cherts of the Ushkyzyl Formation on the left; valley with outcrops of basalts of the Bolgashoky formation (3) in the center; ridges (4) of Bolgashoky jaspers with Llanvirnian conodonts on the right.

lower part. Two complexes of Early Arenigian conodonts have been identified, the lower one belonging to the *Prioniodus elegans* zone and the upper to the *Prioniodus* (*O.*) *evae* zone. The middle part of the zone comprises brown-red and sealing-wax-colored jaspers, with greenish and light-grey interlayers. In terms of conodont stratigraphy, this part of the formation corresponds to a combination of the *Prioniodus triangularis*, *P. navis*, *Paroistodus originalis* zones and possibly to part of the *Microzarkodina parva* zone. The upper part of the formation is composed of meat-red jaspers with Late Arenigian-Early Llanvirnian conodonts (the upper part of the *M. parva* zone and the *Eoplacognatus variabilis* zone). In the northwestt, in the Tokai mountains, analogous deposits are identified in the Tokai formation.

The Bolgashoky formation consists mainly of dark, greyish-green aphyric basalts in the lower part of the section. Beds of striated red and greenish jaspers occur among the basalts. The upper part of the formation consists of a chaotic accumulation of olistoplacs and olistoliths of red jaspers in a tephroid, arenaceous, or siltstone matrix. Conodonts indicate that the age of the formation is Middle Arenigian-Llanvirnian. According to A.M. Zhilkaidarov, fragments of *Periodon aculeatus* Hading have been found in the jaspers; in the lower part of the olistostrome member, in the olistoplacs of the jaspers, conodont fragments described from the Llanvirnian deposits of Baltoscandia (*Pygodus* sp. "C" Longren.) have been found. The age of the upper part of the formation is still not defined. Southeastward, at the southwestern foot of the Tarbagatai Ridge, the Naryn formation (Zvontsov and Frid, 1991), in which Zhilkaidarov found Ordovician-like conodonts, is apparently an analogue of the Bolgashoky formation.

Northwestward, in the Otyzbes mountains, on the left bank of the Balatundyk river, the composition of the deposits changes, and the Ushkyzyl and Bolgashoky formations are replaced by the Kuvsk formation, which was considered Late Ordovician before conodonts were found in it (Nikitin, 1972). The lower part of the Kuvsk formation consists predominantly of tephroid sandstones, siltstones, andesitic and basaltic porphyrite lavas and their tuffs; the middle part of terrigenous sandstones, thin-bedded grey or brown, siliceous radiolarian-spongilite shales, and tuff-silicites; and the upper part of meat-red massive jaspers with which ferriferous and ferromanganiferous ores are associated. Arenigian conodonts were discovered in thin interlayers of striated jaspers, in the blood part of the middle member, and Llanvirnian conodonts in the massive jaspers of the upper part of the formation. In the Otyzbes mountains, the formation is overlapped by an Upper Ordovician olistostrome.

In the northern part of the zone, the siliceous-basaltic deposits make up a portion of the Maikain-Kyzyltas ophiolite belt and are traced from the Kyzyltas mountains and the Agyrek mountains in the south northeastward to the edge of Central Kazakhstan, north of the Maikain mine. In recent years, investigation of the region has been given high priority, and the rocks there have been studied in great detail. According to V.G. Stepanets (Turmanidze et al., 1991), in the Karaulcheku mountains the siliceous-basaltic formations are components of the pseudostratified ophiolite association, the lower members of which are represented by laminated basite-hyperbasites, diabases-keratophyres and plagiogranites, and the upper part by the Karaulcheku formation of basaltic and andesite-basaltic lavas with tuffs and red jaspers. The age of the formation is tentatively considered Tremadocian-Early Arenigian. Higher in the section is the Akozek formation, the lower part of which consists of variegated siliceous siltstones, tuffosilicites, acidic ash tuffs, jaspers, gritstones, and lenses of limestone. The upper part is composed of basalts and andesite-basalts. The lower part of the formation has yielded the Arenigian-Llanvirnian conodonts *Cordylodus horridus* Barnes et Poplav., *Paroistodus parallelus* (Pander), *Periodon flabellum* (Lind.), and *P.* cf. *aculeatus* Hading; the middle part the Llandeilan conodonts *Periodon aculeatus* Hading, *Prioniodus* sp., and *Panderodus gracilis* (Branson et Mehl.); and the upper part the Caradocian-Ashgillian conodonts *Panderodus* cf. *mutatus* (Branson et Mehl.) and *Protopanderodus* sp.

In the Tolpak, Kosgombai and Agyrek mountains and in the northeastern extremity of the zone, in the Zhamanbugembai and Zhaksybugembai and Adelbek mountains, in the area of the Angrensor and Kudaikol lakes, the Ordovician deposits are components of intricately combined slices of imbricated ophiolites and are represented by the chiefly siliceous Kosgombai formation and volcanics coeval with it. The Kosgombai formation of microquartzites, red jaspers, and siliceous mudstones is similar to the Ushkyzyl formation and contains the conodont succession *P. elegans, P. evae, P navis-P. triangularis, P. originalis, A. variabilis-M. ozarkodella* and, possibly, *P.serra* zones, too. In one of the slices comprising the Agyrek, Kosgombai, and Kyzyltumsyk formations, the succession of these zones is observed in an uninterrupted section of chert only 18 m thick. In other slices of the same group of formations, conodonts of the *P.evae, P.navis-P. triangularis* and *A. variabilis-M. ozarkodella* zones have been found only in the jasper strata among basalts and tuffs about 144 m thick. In the Tolpak formation, conodonts of the *P. navis-P. triangularis* and *A.variabilis-M. ozarkodella* zones occur in jaspers among the pillow basalts of the shoshonite group and tuffosilicites (200 m thick) overlain by siliceous siltstones, ash tuffs and tuffites (300 m thick). In other slices of the same group of formations, conodonts of these zones are distinguished in the Tolpak siliceous-tuffite formation.

The fact that in every group of imbricated ophiolites the same or similar successions of conodont complexes are distinguished in different formations (i.e., basaltic, siliceous, or tuffaceous) may indicate that they accumulated within different parts of the basins, and that the sediments from these various parts were later superimposed on one another tectonically.

Eastward around the Maikain mine, the base of the section is composed of basalts, microdiabases, and siliceous siltstones interbedded with andesite-basalts, all of which total about 400 m in thickness. Higher in the section is the Alpys formation (300 m thick) of andesite-basalts, tuffs, breccias and siliceous mudstones and jaspers in which two complexes of Arenigian conodonts have been identified: the lower including *Prioniodus evae* Lind. and the upper including *Microzarkodina flabellum* (Lind.) and *Periodon flabellum* (Lind.) (Nikitin, 1991). At the Maikain mine itself, at the base of the Zhyrikuduk formation (300-500 m) of trachyandesite-basalts, tuffs, siliceous tuffites, brown and greyish- green radiolarian jaspers with the Llanvirnian conodonts *Oistodus venutus* Stauffer and *Periodon* cf. *aculeatus* Hading (Mikhailova et al., 1981) are exposed.

A belt of siliceous-basaltic deposits analogous to the Kyzyltas-Maikain belt is traced along the northeastern flank of the Chingiz-Tarbagatai zone from the northeastern foot of the Tarbagatai Ridge to the Alkamergen lake in the northeast, but owing to poor exposure, fragmentary outcrops, and complex structure, these deposits have not been studied to the same extent. According to V.Ya. Glukhenky and N.K. Dvoichenko (Nikitin, 1991), in the northeastern part of the band the oldest rocks are cherts (microquartzites, jaspers, siliceous mudstones) with interlayers of basalts, andesites and tuffs composing the upper part of the Naimanzhal formation.

In the lower part of this formation the Tremadocian conodonts *Drepanodus numarkuatus* (Lind.), *D. bisimmetricus* Viira, and *Cordylodus rotundatus* Pander occur; in the upper part, the conodonts of the *P. evae* zone. The thickness of these deposits, estimated to be 800 m, may be highly overstated. The basalts, andesitic basalts, dacites and trachydacites with cherty members, sandstones and siltstones are divided into the Shaiman and Satek formations and ascribed a Llanvirnian age. The latter formation contains conodonts including *Ptyloconus* sp. and *Subcordylodus* sp. The thickness of these formations totals 2200 m. Deposits with the same composition as the aforementioned formations are exposed on the northeastern slopes of the Tarbagatai Ridge. At that location, V.S. Zvontsov and N.M. Frid (1991) mapped the Aigyrzhal formation, consisting of cherts (about 500 m thick) containing the Arenigian conodonts *Oistodus lanceolatus* Pand., *O. parallelus* Pand., *Microzarkodina flabellum* (Lind.), *Paracordylodus gracilis* Lind., *Oelandodus elongatus* (Lind.), *Drepanodus arcuatus* Pand. and so on. Higher in the section they mapped the supposedly Arenigian Akchy formation (more than 1000 m thick), consisting of trachybasalts, agglomerate tuffs and tuffoglomerates with black cherts and mudstones.

In the inner part of the Central Kazakhstan Paleozoics, in the Dzhungar-Balkhash zone, the siliceous-basaltic formations are more widespread and encompass a greater age range.

Many investigators have studied the ophiolite complex in the Tekturmas anticlinorium (Bogdanov, 1939; Zvontsov, 1967; Pupyshev et al. 1971, Smirnova, 1971; Antonyuk, 1974; Kheraskova, 1986, and others). The most reliable data on its structure, succession of deposits, and age have been obtained through work conducted by Novikova, Gerasimova and Kurkovskaya (Novikova et al., 1985; Novikova, 1991; Gerasimova et al., 1992). According to them, the cherty-basaltic formations, together with the underlying serpentinite melange, gabbroids and sheeted dike complex, make up a group of deformed nappes thrust over each other and the Silurian deposits from south to north.

In the southern nappes, the deposits are divided into the mainly basaltic Karamurun formation and the siliceous Tekturmas formation, as conventionally mapped there, and are overlapped by the olistostrome Sarytau formation. In the northern nappes they consist of the basaltic Kuzek formation, coeval with the Tekturmas formation and the volcanogenic-terrigenous Bazarbai formation, the greater part of it coeval with the Sarytau formation. The mainly amygdaloidal basalts (spilites) with subordinate strata of red, rarely striped (red, greenish and grey) jaspers, tuffosilicites and ferruginous rocks help make up the Karamurun and Kuzek formations. Lenses of lithoclastic tuffs and lava breccias are exposed here and there. In the upper part of this complex, evidently in the Kuzek formation, a member has been distinguished that is made up of pillow lava sheets (spilites and microdiabases) 10-100 m thick that alternate with beds of tuffosilicites and jaspers 3-10 m thick (Kheraskova, 1986).

In the jaspers of the Karamurun formation, inarticulate brachiopods and conodonts (Nikitin, 1991) have been found. Oldest are the Tremadocian brachiopods *Lingulella ferruginea* Salt., *Z. bella* Walcott and the Arenigian conodonts *P. evae* and so on. The youngest conodonts are Llanvirnian: *Pygodus serra* (Hading), *Periodon aculeatus* Hading, and *Paracordylodus* sp. The thickness of the formation totals 600 m.

The Tekturmas formation comprises dark-red jaspers, and light-colored microquartzites; the siliceous-clastic rocks and brown and greenish siliceous siltstones are rare. The Llandeilian conodonts such as *Pygodus serra* (Hading) and *P. anserinus* Lamont et Lind.,are found in the jaspers. The thickness of the formation reaches 200 m. The same conodonts occur in the jaspers interbedded with basalts of the Kuzek formation to the north.

The Bazarbai formation overlaps the Kuzek basalts and is composed of red, frequently dark-red ash jaspers, thin-bedded tuffo-silicites, mediosilicic and acidic ash tuffs, and siltstones. In the lower part of the formation the Caradocian conodonts *Paraconodontus similis* (Rhodes), *P. mutatus* Branson et Mehl., *Prioniodus grandis* (Ethington) and others were discovered, and in the upper part the Llanvirnian graptolites *Monograptus triangularis* (Hark.), *Glyptograptus tamariscus* Nich., *Climacograptus normalis* Nich., and *Coronograptus gregarius* (Lapw.). The Sarytau formation, coeval with the Bazarbai according to its stratigraphic position, encloses siltstones, siliceous mudstones and sandstones in which olistoliths of Tekturmas jaspers, basalts, diabases and gabbros are immersed. Detached blocks of Tekturmas jaspers, up to hundreds of meters long, are especially numerous in the lower part of the formation.

Along the northwestern margin of the Dzhungar-Balkhash zone, the siliceous-basaltic complex crops out in the area of the Agadyr railway station, where it forms the northwest-trending belt that Streis and Kolotukhina (1948) named the Burnazar-Karagan anticline zone. In this zone the siliceous-basaltic complex forms isolated massifs separated by the terrigenous sediments of the Silurian and consists of slices and nappes thrust over each other and over the Silurian deposits.

At first these deposits were designated by Streis and Kolotukhina as the Kyzyltau formation and were assigned an Ordovician age. As a result of later investigations by VSEGEI geologists, they were redefined as Silurian, divided into the Naizakesken, Taldyespe and Naizakara formations (Pupyshev, 1974), and then supplanted by the Akdomalak formation. At present, a bipartite division of these deposits into Akdomalak and Taldyespe formations seems the most substantiated.

The Akdomalak formation crops out in a narrow zone extending from the Akdomalak hills to the Kirei valley, where all the rocks are intensively dislocated and metamorphosed in small slices together with gabbroids and amphibolized rocks and also Silurian sandstones and limestones. They comprise light-grey, whitish semitransparent quartzites, rarer greenish-grey or brown indistinct striped cherts, and greyish-green aphyric basalts, spilites, and tuffs. Zhilkaidarov found the Arenigian conodonts *Periodon flabellum* (Lind.), *Paracordylodus* cf. *gracilis* Lind.?, *Paroistodus parallelus* (Pander)?, *Acantiodus accantus* Lind. s.f., *Colocerodon* sp. s..f, and *Ozorkodina* sp. s.f. in the light semitransparent quartzites. The thickness of the deposits has not been determined.

The Taldyespe formation is more widespread. Greyish-green aphyric basalts with massive and pillow structure represent the chief component of the formation. Variolites, usually forming crusts in the pillow lavas, are rarer, and amygdaloidal basalts are sparse. The jaspers form separate, very often lens-like strata 4-5 m thick; they are brownish-red, dark-red or thin-bedded (stratification arises from the distribution of radiolarians and hematite). The dark, almost black jaspers are colored black by magnetite.

The upper part of the formation, like the Tekturmas, is composed of an unusual "bedded" member, consisting of rhythmically alternating basalts and red striped jaspers or greenish thin-bedded siliceous siltstones. The thickness of the jasper strata and the siliceous siltstones does not exceed 0.5-2 m, and the basalts 5-10 m. The thickest strata of the brown striped ferruginous jaspers are assigned to the upper part of the formation, to the boundary with overlying terrigenous Silurian deposits. In some places, in the transitional zone between these formations, the jaspers alternate with sandstones and siltstones, but it is not clear whether this is interbedding or the repetition of rocks of different ages by faults. In the jaspers the Caradocian conodonts *Protopanderodus* cf. *insculptus* (Branson et Mehl), *Icrodella superba* (Rhodes), *Panderodus similis* (Rhodes), *Skandodus dulkumaensis* Mosk., *Rhynchognatus tipica* Ethington, *Distacodus vistrix* Mosk., *Hamarodus europaeus* (Serpagli) were discovered.

In the uppermost part of the formation, in a stratum of greyish-green siltstones among basalts, Middle Llandoverian graptolites were found. The thickness of the Taldyespe formation totals about 300 m. It is overlain by unusual red and green mudstones in which Silurian conodonts are found.

In the northern Balkhash area, the jasper-basaltic complex is widespread in the Itmurundy-Tyulkulam anticlinorium. These deposits are usually divided here into three formations (Antonyuk, 1974; Koshkin, 1987): Itmurundy, Kazyk, and Tyuretai.

The Itmurundy formation mainly consists of amygdaloidal basalts with individual beds of red jasper and siliceous siltstones that usually display boudinage. The Kazyk formation mainly comprises red, sparsely striped yellowish and greenish jaspers, aleuropelites, siliceous-clastic breccias, and unusual whitish and turquoise siliceous tuffites and acid tuffs. The Tuyretai formation is represented by aphyric pillow basalts, red and greyish-green jaspers, sandstones and siltstones.

Conodonts, numerous in the red jaspers of all three formations (Novikova et al., 1983; Nikitin, 1991), resemble those typical of the Llandeilian stage: *Pygodus serra* (Hading), *P. anserinus* Lamont et Lind., *Periodon aculeatus* Hading, and so on. The thickness of the Itmurundy formation is estimated to be 1000 m, the Kazyk about 600 m, and the Tyuretai about 450 m.

On the northern limb of the Itmurundy-Tyulkulam anticlinorium, the Itmurundy and Kazyk formations are overlapped disconformably by the Dzhamanshuruk formation, consisting of conglomerates, siltstones, siliceous siltstones, basalts, andesites, tuffs and the limestones with Late Ordovician corals, brachiopods and trilobites. The normally bedded strata of these rocks alternate with chaotic accumulations of the same deposits.

On the southern limb of the Itmurundy-Tyulkulam anticlinorium, the Tyuretai formation is overlain by a flyschoid terrigenous formation. The contact is marked by olistoliths and large blocks of jasper with the Llandeilan conodonts *P. serra* (Hading), *P. anserinus* Lamont et Lind., and others. At several localities, the terrigenous matrix contains the Middle Llandoverian graptolites *Demirastrites triangularis* (Harken.), *Glyptograptus tamariscus* Nich., *Coronograptus gregarius* (Lapw.), *Pristiograptus* cf. *concinnus* (Lapw.), *Pribilograptus* cf. *incommodus* (Tornq.) and others. These interrelations are complicated by the thrust zone confined to the southern limb of the anticlinorium. As a result, a complex picture has emerged, prompting different views on how the Tyuretai formation and the Silurian terrigenous complex relate to each other. Koshkin et al. (1987) contest the validity of the age of the Kazyk and Tyuretai formations determined from conodonts, and they consider the Kazyk formation Upper Ordovician and the Tyuretai Lower Silurian. They place the terrigenous formation with the detached blocks of Middle Ordovician jaspers positions higher in the section, assigning these deposits to the Ashchiozek formation and stating their belief that all these formations are connected by gradual transitions.

Taking into account the same set of conodonts in the Itmurundy, Kazyk, and Tyuretai formations and also the variability in facies of similar deposits in other regions, it may be that all these formations, one way or another, are coeval and that facies of one replace facies of another. At the same time, along the southern limb of the anticlinorium (the Ashchiozek anticline and so on) there are Upper Ordovician siliceous-basaltic formations that should be distinguished as a separate stratigraphic unit.

In addition to the aforementioned regions, the siliceous-basaltic complex occurs in the Zaisan zone. It has not yet been studied in detail there. Separate finds of radiolarians and organic material of indeterminant systematic position (*Ulkundia incomperta* Nazarov) are the only basis for the Middle Ordovician age of the basalts and cherts that are found there among the ophiolites. The succession of these deposits and their structures remain unclear.

The stratigraphic data presented here for the Ordovician siliceous, siliceous-volcanogenic deposits of Kazakhstan substantiate their subdivision into two types: chiefly siliceous and siliceous-basaltic (Novikova, 1985; Gerasimova et al., 1988 and others). The mainly siliceous deposits with their small terrigenous and volcanogenic (chiefly basaltic) component are widespread in the Ermentau-Chuili zone. Among them, aphanitic variegated cherts, light quartzites, red, rarer yellow, greenish striped jaspers predominate. The mainly aphanitic greenish and black radiolarian jaspers and the phthanites are less extensive, as are the siliceous-clastic breccias and sandstones, terrigenous quartz-feldspathic sandstones and silstones. Dark-colored cherts (jaspers, phthanites), as a rule, are distinguished by regular horizontal bedding; in the red and variegated cherts, besides horizontally bedded structures, varied ripples and also unidirectional crossbedding, and turbidite hieroglyphs are observed (Zhemchuzhnikov and Petrova, 1990).

In regard to age, these formations are limited to the Early Ordovician and the beginning of the Middle Ordovician, creating two maxima in the Middle Arenigian and at the end of the Arenigian, at the beginning of the Llanvirnian.

West of the Ermentau-Chuili zone the siliceous deposits occur mainly at the same stratigraphic levels, but they are thinner in this direction, and greenish-black jaspers and phthanites, together with the red jaspers, are predominant. In all sections where reliable stratigraphic successions are clearly transgressive, phthanites and black jaspers lie chiefly at the base of such sequences and are overlain by red jaspers. Among the aphyric and amygdaloidal volcanics, pillow basalts are commonly prevalent. Tuffs occur sporadically.

Jasper-basaltic sections are indicative of the inner and the eastern part of the Paleozoics of Central Kazakhstan — the Dzhungar-Balkhash and Chingiz-Tarbagatai zones. The principal components of these formations are aphyric or amygdaloidal basalts and red jaspers. The phthanites and black jaspers are limited in extent and, as in the west, mainly confined to the lower parts of the formations.

The jasper and basaltic members form complex combinations in which the former may underlie the latter, replace them along strike, alternate with them, or form thick overlying members.

Paleogeographic and Paleotectonic Reconstructions

The Ordovician siliceous formations were deposited in the deepest hemipelagic and bathyal environments. This is as true of the eastern and inner parts of the Paleozoics of Kazakhstan and the northern Tien-Shan (the Chingiz-Tarbagatai and Zaisan zones) as in the external parts (the Ishim-Karatau-Naryn, Stepnyak-Betpakdala-northern Tien-Shan zones). Most of the silica may have been generated by deep-seated processes, in areas of intensive volcanic activity; transportation and deposition of silica would have occurred biogenically (Nikitin, 1973; Zhemchuzhnikov and Petrova, 1990). Dark-colored cherts accumulated in relatively stagnant deep-water depressions, in still waters rich in organics.

The sediments from which variegated cherts and red radiolarian jaspers formed were deposited by currents of cold, oxygenated bottom water, as indicated by evidence of a high-energy depositional environment (Zhemchuzhnikov and Petrova, 1980).

The basalts of the Dzhungar-Balkhash zone and its margins are closest to basalts of marginal seas, judging from petrochemical characteristics and paleotectonic environment (Novikova et al., 1988; Novikova et al., 1991; Nikitin et al., 1991). In the basaltic formations there are numerous subvolcanic bodies, mainly dikes and diabase sills, which are often distinguished from the basalts with difficulty. Apart from the basic volcanics and subvolcanic formations, mediosilicic and acid volcanics, commonly ash tuffs, are present in small quantity. Such combinations are typical of the basins of some modern marginal seas (Frolova et al., 1989). Along the periphery of the Dzhungar-Balkhash zone the basalts are represented mainly by aphyric varieties, whereas in the inner part (the Itmurundy-Tyulkulam and Tekturmas anticlinoria), amygdaloidal basalts (spilites) predominate, as in the case of the basins of modern marginal seas.

The jasper-basaltic associations are invariably combined with olistostromes and tuff-siliceous-terrigenous formations (Avdeyev and Seitov, 1984), producing unique spatial and age combinations in each case. In such combinations the jasper and basalts, as a rule, are older, but they may be replaced on one side of the basin (supposedly the inner one) by chaotic accumulations created by submarine volcanism and on the other side by tuff-siliceous-terrigenous deposits transported from the Chingiz-Tarbagatai island arc (Fig. 7).

Within the Dzhungar-Balkhash zone, jasper-basaltic deposits and accompanying sediments (olistostromes and tuff-siliceous-terrigenous) comprise the entire Ordovician section and, in some cases, the earliest Silurian. In the region of the Chingiz- Tarbagatai zone they are restricted to the Early and Middle Ordovician.

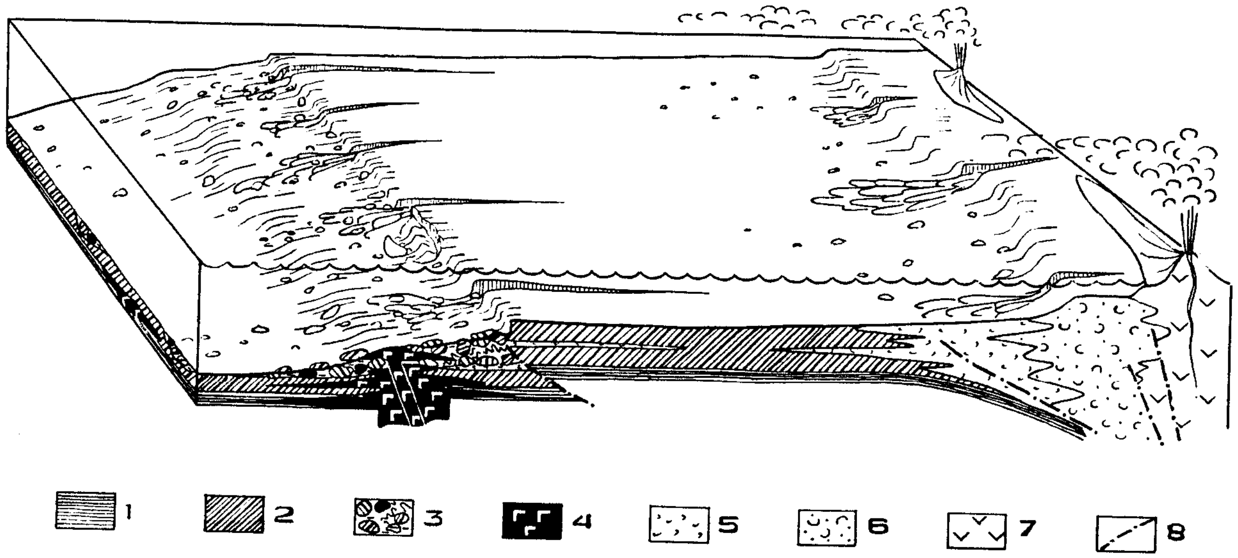


Fig. 7. Schematic model of volcanic arc-spreading zone system in the Ordovician marginal basin of Kazakhstan: 1- phthanites and black jaspers; 2- red and striped jaspers; 3- olistosromes; 4- basalts; 5- vitric tuffs and tuffites; 6- tuffs and tephroids; 7- andesites; 8- faults.

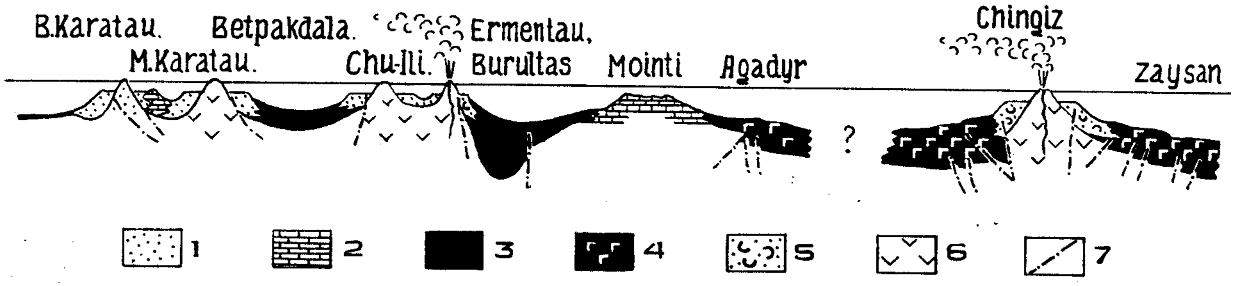


Fig. 8. Schematic cross-section of the Kazakhstan marginal basin in Arenigian-Llanvirnian time: 1- clastic sediments; 2- limestones; 3- siliceous sediments; 4- jaspers and basalts of spreading zones; 5- volcanic-clastic sediments; 6- andesites, volcanics, and tuffs; 7- faults.

The type of volcanism recorded by the jasper-basaltic complexes and spatial combinations within the mainly siliceous and other sediments correspond, on the whole, to paleogeographic and paleotectonic reconstructions (Nikitin et al., 1991) for which modern ocean margins — marginal seas and volcanic island arcs — serve as a model (Fig. 8). In addition, the Ordovician basin of Kazakhstan displays marked similarities to modern marginal seas surrounded by complex island arc systems like those of the Philippine Sea and the Izu-Bonin-Marianas island arc. Regions in which chert accumulated evidently represented depressions, preceding island arc uplift and forming the active Stepnyak-Betpakdala-Northern-Tien-Shan island arc within the Ishim-Karatau-Naryn, Stepnyak-Betpakdala-Northern Tien-Shan and Ermentau-Chuili zones in the Early Ordovician. The Ermentau-Burultas subzone, to which maximum chert accumulation was then confined, may have represented a system of riftogenic interarc depressions situated between the volcanic arc and inner amagmatic Shdiderty-Mointy-Dzhungarian relic arc.

In the Ishim-Karatau-Naryn zone, thin cherty sediments accumulated on the external slope of the frontal amagmatic island arc and in the riftogenic structures adjacent to it.

The Dzhungar-Balkhash zone represented a back-arc basin with peculiar "blurred" spreading in the Early Ordovician. Deposition of the jasper-basaltic groups of the Chingiz-Tarbagatai zone may have been connected with the riftogenic structures surrounding the central part of the zone, which became an active volcanic island arc in latest Cambrian time.

At present there are no data from which to reconstruct the paleotectonic conditions of deposition of the Ordovician siliceous-basaltic complexes of the Zaisan zone. One can only suggest that the back-arc basin of the Chingiz-Tarbagatai island arc system, which was later regenerated by Hercynian activity, would also have existed in the Zaisan area.

Economic Geology

Small deposits of iron, manganese, copper, polymetals, vanadium, phosphorites and barite are associated with the cherty and siliceous basaltic formations of the Ordovician in Kazakhstan (Apollonov, 1992). The majority are confined to Arenigian-Llanvirnian strata (Kayupov et al., 1989). Interbedded vanadium-phostphate-bearing shales, sandy phosphorites, iron-manganese and manganese ores have all been found in the Akdym group in the Ermentau and Atasu anticlinorium, in zones 100-120 km long, but the deposits of iron and manganese are small and isolated (Kumdykol and Kosagaly and others). Workable deposits associated with the Ordovician siliceous formations are confined to stratified lead-zinc deposits of the Tekeli group, which occur only in the carbonaceous Tekeli formation, and also stratified deposits of barite in the Burubaital formation of the Ermentau-Chuili zone (Azerbaev and Kuznechevsky, 1974) and in the Kamal formation of Bolshoi Karatau.

In conclusion, it should be noted that discovery of large gold and silver deposits and sulfide ores (Cu, Pb, Zn, Sn, etc.) (Levin, 1991; Lisitsin, 1991) in modern sediments of some marginal seas provides incentive for exploration of analogous deposits in ancient siliceous-basaltic formations, developed under similar conditions. In this respect, the jasper-basaltic formations of the Dzhungar-Balkhash and Chingiz-Tarbagatai zones appear to be the most promising

Acknowledgments — The author sincerely expresses his gratitude to his colleagues V.S. Zvontsov and N.M. Frid, who read the article and made many useful comments, and to I.L. Bryzgalova, who did much of the work of translating it into English.

References

Akishev, T.A., Bykadorov, N.A., Smagulov, R.A., and Shevchuk, S.I., 1992. The Chu ophiolite belt: Izvestiya Akademii Nauk Kazakh S.S.R., seriya geologicheskaya, no. 1, p. 18-25.

Antonyuk, R.M., 1974. The oceanic belt of the eugeosyncline region of the east of Central Kazakhstan, in Muratov, M.V., ed., The tectonics of the Ural-Mongol folded belt: Moscow, Nauka, p.67-73.

Antonyuk, R.M., Glukhan, I.V., and Klimakhina, Z.A., 1976. The early geosyncline magmatic formations of Central Kazakhstan paleozoids: Izvestiya Akademii Nauk Kazakh S.S.R., seriya geologicheskaya, no. 4, p. 81-85.

Antonyuk, R.M., Lyapichev, G.F., and Markova, N.G. et al., 1977. The structure and evolution of the Earthís crust of Central Kazakhstan: Geotektonika, no. 5, p. 71-82.

Apollonov, M.K., 1992. Mineral resources in the Ordovician of Kazakhstan and Kirgizia: Izvestiya Akademii Nauk Kazakh S.S.R., seriya geologicheskaya, no. 3., p. 12-23.

Apollonov, M.K., Zhemchuzhnikov, V.G., and Dubinina, S.V., 1990. The Ordovician of the North-Western Balkhash region: Izvestiya, Akademii Nauk Kazakh S.S.R., seriya geologicheskaya, no. 4, p. 3-17.

Avdeyev, A.V., 1984. The ophiolite zones and the history of the geological development of Kazakhstan from the mobilistic positions: Sovetskaya Geologiya, no. 4, p. 63-72.

Avdeyev, A.V., and Seitov, N.S., 1984. The standard model of the development of the ophiolite zones of Kazakhstan, in Abdulin, A.A. ed., v.1, The theses of the III Kazakhstan Petrographical Conference: Alma-Ata, Nauka, p. 30-311.

Azerbaev, N.A., Kirichenko, I.V., 1990. The ferromanganesian concretions in the, Ordovician deposits of the Baikonur synclinorium, in Lisitsin, A.P., ed., The geology of oceans and seas. The theses of the reports of the 9th All-Union School of the sea geology: Moscow, v. 3, p. 89-90.

Azerbaev, N.A., and Kuznechevsky, A.G., 1974. Some peculiarities of the Chiganak barite deposit, in Abdulin, A.A., ed., the Informational multiauthor volume of the Geological Institute of the Kazakh S.S.R. Academy of Sciences: Alma-Ata, Nauka, p. 182-183.

Besstrashnov, V.M., Gerasimova, N.A., and Novikova, M.Z., 1985. The reference section of the Lower and Middle Ordovician of Northern Betpakdala, in Zaitsev, Yu.A., ed., the geology of the early geosyncline complexes of Central Kazakhstan: Moscow, Moscow State University, p. 96-132.

Bodganov, A.A., 1959. Main features of the Paleozoic structure of Central Kazakhstan, Byuleten Moskovskovo Obshchestva Ispytatelei prirody (geological section), v. 34, no. 1, p. 3-38.

Borisyonok, V.I., 1981. The siliceous-terrigenous formations in the early geosyncline complex of the northeast of Central Kazakhstan: Vestnik Moskovskogo Gosudarstvennogo Universiteta, no. 4, p. 81-84.

Borisyonok, V.I., 1985. The stratigraphy of the early geosyncline complex of the Ishkeolmes anticlinorium, in Zaitsev, Yu.A., ed., The geology of the early geosyncline complexes of Central Kazakhstan: Moscow, Moscow State University, p. 132-164.

Borisyonok, V.I., Gerasimova, N.A., Zaitsev, Yu.A., Zardiashvili, N.I., Minervin, O.V., Novikova, M.Z., Rozanov, S.B., Tenyakova, R.G., and Kheraskova, T.N., 1979. On the stratigraphy of the Lower Paleozoic volcanogenic-siliceous formations of Central Kazakhstan: Byulleten Moskovskogo Obshchestva ispytatelei prirody, v. 54, no. 4, p. 54-66.

Borisyonok,V.I., Gerasimova, N.A., Zaitsev, Yu.A., Novikova, M.Z., and Rozanov, S.B., 1985. The new data on the stratigraphy of the Lower Paleozoic of the Ermentau-Niyaz anticlinorium, in Zaitsev, Yu.A., ed., The geology of the early geosyncline complexes of Central Kazakhstan: Moscow, Moscow State University, p. 10-53.

Borukaev, R.A., 1955. The Pre-paleozoic and Lower Paleozoic of the northeast of Central Kazakhstan (Sary-Arka): Moscow, Gosgeoltekhizdat, 407 p.

Borukaev, R.A., and Lyapichev, G.F., 1957. The Upper Proterozoic of the north and the east of Central Kazakhstan, in Medoev, G.Ts. ed., the theses of the reports of the Conference on the unification of the stratigraphic schemes of the Pre-paleozoic and Paleozoic of Eastern Kazakhstan: Alma-Ata, p. 40-42.

Dvoichenko, N.K., 1971. The Cambrian stratigraphy of Ermentau, in Zaitsev, Yu.A., ed., the stratigraphy of the Precambrian of Kazakhstan and the Tien-Shan. The materials of the stratigraphy conference in Karaganda: Moscow, Moscow State University, p. 161-163.

Dvoichenko, N.K., 1974. The ancient formations within the Ermentau-Niyaz anticlinorium, in Abdulin, A.A., ed., The prepaleozoic and Paleozoic of Kazakhstan. V. I., the sratigraphy of the Prepaleozoic, Cambrian, Ordovician and Silurian of Kazakhstan: Alma-Ata, Nauka Kazakh S.S.R., p. 118-120.

Dvoichenko, N.K., and Abaimova, G.A., 1986. The conodonts and biostratigraphy of the volcanogenic-siliceous formations of the Lower Paleozoic of Central Kazakhstan, in Kanygin, A.V., ed., The microfauna and biostratigraphy of the Phanerozoic of Siberia and adjacent regions: Trudy Instituta geologii i geofiziki Sib. Otdeleniya Akademii Nauk S.S.S.R., no. 651, p. 160-178.

Frolova, T.I., Perchuk, L.A., and Burikova, I.A., 1989. The magmatism and the transformation of the Earth's Crust of the active margins: Moscow, 261 p.

Gerasimova, N.A., 1985. The Ordovician stratigraphy of the Atasu anticlinorium, in Zaitsev Yu.A., ed., The geology of the early geosyncline complexes of Central Kazakhstan: Moscow, Moscow State University, p. 53-96.

Gerasimova, N.A., Dubinina, S.V., and Zardiashvili, N.I., 1977. About the age of the siliceous-terrigenous complex of the Atasu anticlinorium (Central Kazakhstan): Doklady Akademii Nauk S.S.S.R., v. 235, no. 1, p. 151-154.

Gerasimova, N.A., Zaitsev, Yu.A., Kurkovskaya, L.A., and Novikova, M.Z., 1988. The problems of the stratigraphy of the Lower Paleozoic of Central Kazakhstan, in Zaitsev, Yu.A., ed., the geology and commercial minerals of Central Kazakhstan: Moscow, Nauka, p. 30-41.

Gerasimova, N.A., Novikova, M.Z., Kurkovskaya, L.A., and Yakobchuk, A.S., 1992. The new data on the stratigraphy of the Lower Paleozoic of the Tekturmas ophiolite belt: Byulleten Moskovskogo Obshchestva ispyatelei prirody (geological section), v. 67, no. 3, p. 60-76.

Gridina, N.M., and Mashkova, T.V., 1977. The conodonts from the siliceous-terrigenous formations of the Atasu anticlinorium: Izvestiya Akademii Nauk Kazakh S.S.R. seriya geologicheskaya, no. 6, p. 47-48.

Ivanov, K.S., Sakharov, V.A., Nasedkina,V.A., and Muzyka, M.I., 1988. About the age of the volcanogenic-siliceous formations of the surroundings of the Kokchetav massif (Northern Kazakhstan): Doklady Akademii Nauk S.S.S.R., v. 301, no. 2, p. 158-163.

Kayupov, A.K., Benevolensky, I.P., Zhukov, M.I., and Tsai, D.T., 1988. The minerageny of the carbonate-siliceous formations of the Vendian-Ordovician of the Atasu-South Dzhungar median massif: Izvestiya Akademii Nauk Kazakh S.S.R., seriya geologicheskaya, no. 5, p. 3-15.

Khabelashvili, A.I., and Tsai, D.T., 1966. The Lower-Middle Ordovician deposits of the Dzharkainagach anticlinorium (the Ishim River Bend: Sovetskaya Geologiya, no. 10, p. 36-38.

Kheraskova, T.N., 1986. The Vendian-Cambrian formations of the caledonids of Asia. Trudy Geologicheskogo Instituta Akademii Nauk S.S.S.R.: Moscow, Nauka, v. 386, 245 p.

Kheraskova, T.N. Novikova, M.Z. and Zardiashvili, N.I. 1979. The peculiarities of the content of the early geosyncline volcanogenic formations of Central Kazakhstan: Izvestiya Akademii Nauk S.S.S.R. seriya geologicheskaya, no. 6, p. 47-61.

Khromykh, B.F. 1986. The new data on the Vendian-Early Paleozoic development and metallogeny of the Boshchekul ore region: Izvestiya Akademii Nauk Kazakh S.S.R. seriya geologicheskaya, no. 6, p. 20-34.

Kopyatkevich, R.A., Koneva, S.P., and Nazarov, B.B. 1974. On the problem of the age and stratigraphical position of jaspers of the Ushkyzyl mounains, in Abdulin, A.A. ed. The Prepaleozoic and Paleozoic of Kazakhstan, v. I: Alma-Ata, p. 116-117.

Kopyatkevich, R.A. and Tsai, D.T. 1974. About the age of the volcanogenic- jasper formation of the Stepnyak synclinorium, in Abdulin, A.A. ed. The Informational research multiauthor volume: Alma-Ata, Nauka, p. 194-196.

Koshkin, V.Ya., Abdrakhmanov, B.M., Volkov, V.V., 1987. The stratigraphy of the terrigenous-siliceous-basaltic formation of Ordovician and Silurian of the Norhern Balkhash Region in Bekzhanov, G.R., ed. The regional geology and geophysics of Kazakhstan: Alma-Ata, Kazakh Institute of Mineral Raw Materials, p. 6-15.

Kurkovskaya, L.A., 1985. The conodont complexes from the siliceous and volcanogenic-siliceous formations of Central Kazakhstan, in Zaitsev, Yu.A. ed. The geology of early geosyncline complexes of Central Kazakhstan: Moscow, Moscow State University, p. 164-171.

Levin, L.E., 1991. The extremely high concentrations of gold on the sea bottoms: Priroda, no. 3, p. 109-110.

Mikhailova, N.F., Shebunyaev, M.P., Zhukovsky, V.I., and Moskalenko, T.A., 1981. About the find of the Middle Ordovician conodonts in the Maikain ore field (the northeast of Central Kazakhstan): Izvestiya Akademii Nauk Kazakh S.S.R., seriya geologicheskaya, no. 1, p. 34-35.

Nazarov, B.B., 1975. The radiolarians of the Lower-Middle Paleozoic of Kazakhstan: Moscow, Nauka, p. 201.

Nazarov, B.B., and Popov, L.E., 1980. The stratigraphy and fauna of the siliceous-carbonate formations of the Ordovician of Kazakhstan: Moscow, Nauka, 290 p.

Nikitin, I.F., 1972. The Ordovician of Kazakhstan. Part I, Stratigraphy: Alma-Ata, Nauka, 240 p.

Nikitin, I.F., 1973. The Ordovician of Kazakhstan. Part II, Paleogeography and Paleotectonics: Alma-Ata, Nauka, 98 p.

Nikitin, I.F., ed., 1991. Resolutions of the III Kazakhstan Stratigraphy Conference on the Precambrian, and Phanerozoic. Part I, The Precambrian and Paleozoic: Saint-Petersburg, VSEGEI, 147 p.

Nikitin, I.F., Apollonov, M.K., Tsai, D.T., Burenin, V.M., Dubinina, S.V., and Kuznechevsky, A.G., 1980. About the age of the siliceous formations of the Lower Paleozoic of the Southwestern Near Balkhash Region: Izvestiya Akademii Nauk Kazakh S.S.R., seriya geologicheskaya, no. 3, p. 42-50.

Nikitin, I.F., Ergaliev, G.Kh., Marfenkova, M.M., Palets, L.M., Salmenova, K.Z., and Shuzhanov, V.M., 1989. The knowledge and the problems of the stratigraphy of the Paleozoic of Kazakhstan, in Abdulin, A.A., ed.,The geology and metallogeny of Kazakhstan: Alma-Ata, Nauka, p. 32-43.

Nikitin, I.F., Frid, N.M., Zvontsov, V.S., 1991. Paleogeography and main features of volcanicity in the Ordovician of Kazakhstan and North-Tien-Shan, in Barnes, C.R., and Williams, S.H., eds., Advances in Ordovician Geology: Geol. Surv. Canada Paper 90-9, p. 259-270 (in English).

Nikitin, I.F., Zhilkaidarov, A.M., and Frid, N.M., 1992. The Ordovician siliceous-basaltic complex of the Southwestern Near Chingiz Region: Izvestiya Akademii Nauk Kazakh S.S.R., seriya geologicheskaya, no. 4, p. 57-70.

Novikova, M.Z., 1985. The information on the knowledge of the stratigraphy of the early geosyncline volcanogenic- and terrigenous-siliceous complexes of the Lower Paleozoic of Central Kazakhstan, in Zaitsev, Yu.A., ed., The geology of the early geosynline complexes of Central Kazakhstan: Moscow, Moscow State University, p. 7-10.

Novikova, M.Z., Rezantsev, A.V., and Dubinina, S.V., 1978. About the age of the Akdym group of the Ermentau-Niyaz anticlinorium: Doklady Akademii Nauk S.S.S.R., v. 241, no. 2, p. 453-455.

Novikova, M.Z., Gerasimova, N.A., Borisyonok, V.I., Buyakovska, K., Dubinina, S.V., and Minervin, O.V., 1980. The new data on the the early geosyncline volcanogenic-siliceous formations of the Lower Paleozoic of the Ishkeolmes and Ermentau-Niyaz anticlinoria, in Zaitsev, Yu.A., ed., The problems of the geology of Central Kazakhstan: Moscow, p. 85-102.

Novikova, M.Z., Gerasimova, N.A., and Dubinina, S.V., 1983. The conodonts from the volcanogenic-siliceous complex of the Northern Near Balkhash Region: Doklady Akademii Nauk S.S.S.R., v. 271, no. 6, p. 1449-1451.

Novikova, M.Z., Gerasimova, N.A., and Kurkovskaya, L.A., 1985. About the finds of conodonts in the volcanogenic-siliceous complex of the Tekturmas anticlinorium: Izvestiya Akademii Nauk Kazakh S.S.R., no. 2, p. 63-66.

Novikova, M.Z., Kuznetsov, I.E., Ryakhovsky, V. Ya., and Sigachev, S.P., 1988. The Lower Paleozoic early geosyncline volcanism of Central Kazakhstan, in Zaitsev, Yu.A., ed., The geology and commercial minerals of Central Kazakhstan: Moscow, Nauka, p. 44-71.

Novikova, M.Z, German, L.A., Kuznetsov, I.E., and Yakobchuk, A.S., 1991. The ophiolites of the Tekturmas zone, in Abdulin, A.A., ed., The magmatism and ore content of Kazakhstan: Alma-Ata, p. 92-102.

Puchkov, V.N., 1986. The conodont finds in the Lower Paleozoic siliceous formations of the Baikonur Synclinorium and their stratigraphical meaning: Izvestiya Akademii Nauk Kazakh S.S.R., seriya geologicheskaya, no. 1, p. 53-57.

Pupyshev, N.A., 1974. The stratigraphy of the Upper Zhaman-Sarysu and Sherubai- Nura Rivers, in Abdulin, A.A., ed., The Prepaleozoic of Kazakhstan, v. I: Alma-Ata, Nauka, p. 248-250.

Pupyshev, N.A., Zaichikina, A.V., Zaikanova, V.S., and Smirnova, N.A., 1971. The stratigraphy of the ancient formations of the Ermentau-Zaili and Dzhungar-Balkhash folded system, in Zaitsev, Yu.A. ed., The stratigraphy of the Precambrian of Kazakhstan and the Tien-Shan. The materials of the Karaganda Stratigraphy Conference: Moscow, Moscow State University, p. 164-174.

Streis, N.A., and Kolotukhina, S.E., 1948. The geological structure of the Ortau and Kosmurun mountains of the Zhana-Arka region of the Karaganda area: Trudy Geologicheskogo Instituta Akademii Nauk S.S.R., seriya geologicheskaya, v. 101, no. 32, p. 69-124.

Turmanidze, T.A., Grishin, D.V., Pechersky, D.M., and Stepanets, V.G., 1991. Paleomagnetism of the Orovician ophiolites from the allochthonous massifs of Central Kazakhstan: Geotektonika, no. 4, p. 54-69.

Zaitsev, Yu.A., Babichev, E.A., Borisyonok, V.I., Gerasimova, N.A., Minervin, O.V., Novikova, M.Z., Protasevich, L.T., and Rozanov, S.B., 1980. The structural-facial zonation and paleotectonic environments of the sedimentation of the Lower Paleozoic eugeosyncline complexes of Kazakhstan, in Zaitsev, Yu.A., ed., The problems of the geology of Central Kazakhstan: Moscow, Moscow State University, p. 56-85.

Zhemchuzhnikov, V.G., and Petrova, N.N., 1990. The quartz from the siliceous formations of the Ordovician of northwestern Balkhash region. The petrology and minerology of Kazakhstan and Central Asia, in Laumulin, T.M., ed., The theses of the reports on the Conference of the young geology investigators: Alma-Ata, p. 83.

Zvontsov, V.S., 1967. The siliceous-spilite formation of the Tekturmas anticlinorium, in Borukaev, R.A., ed., the volcanogenic-formations of Kazakhstan: Alma-Ata, p. 11-25.

Zvontsov, V.S., 1973. The Early and Middle Cambrian siliceous-basaltic formations of Central Kazakhstan and their tectonic position, in Abdulin, A.A., ed., The tectonics and magmatism of Kazakhstan: Alma-Ata, Nauka, p. 21-40.

Zvontsov, V.S., and Frid, N.M., 1988. About the Vendian-Early Paleozoic volcanism of Kazakhstan (the zonation and main peculiarities of the development): Izvestiya Akademii Nauk Kazakh S.S.R. seriya geologicheskaya, no. 6, p. 48-61.

Zvontsov, V.S., and Frid, N.M., 1991. The Early Paleozoic of the Northeastern Near Chingiz Region and western Tarbagatai — stratigraphy, formations, some peculiarities of the volcanism: Izvestiya Akademii Nauk Kazakh S.S.R., seriya geologicheskaya, no. 4, p. 23-42.

Devonian of Central Kazakhstan

V.M. Shuzhanov

Abstract

The complicated geological development of Kazakhstan during the Devonian Period is of great interest. The oceanic eugeosynclinal zones of the Southern Urals and Zaisan region, miogeosynclinal Zhungar and Balkhash zones, orogenic continental formations of Sary Arka, Betpak-Dala, and Northern Tien Shan, and marine and continental complexes of the Pre-Caspian and Pre-Aral buried platforms are all situated within Kazakhstan. The polyformational composition of Devonian deposits was responsible for a wide spectrum of mineral resources, from the large industrial deposits of Atasu-type ferrous ores to the lead-zinc and multi-element platinum-gold-silver-polymetallic deposits of Karatau, Mugodzhary, Central Kazakhstan, and Rudny Altai. The fact that most of Kazakhstan is well exposed and easily accessible makes it unique as a place for determining patterns of terrestrial geological evolution in the middle Paleozoic as well as the geological history of the area.

The Devonian of Kazakhstan is distinguished lithologically, paleogeographically, and tectonically. The Devonian rocks attract special attention in view of the fact that the principal uranium, polymetallic, iron-manganese and pyrite ore deposits occur within the sedimentary-volcanogenic formations of this age.

The Devonian sedimentary, volcanogenic and intrusive rocks of both continental (orogenic) and marine (geosyncline and subplatform) origin are widespread in Kazakhstan, and their analogs are found in different parts of Asia. The Devonian-Lower Carboniferous deposits form the deformed "cover" from under which the lower Paleozoic and Precambrian blocks crop out. This "cover" occupies approximately a third of the area of outcrop of the Paleozoic, up to 500,000-600,000 km^2 in the more eroded parts of Central Kazakhstan.

The Devonian sedimentary and volcanic rocks have been studied by Bublichenko (1945, 1974), Bogdanov (1965), Mazarovich (1976), Markova (1969), Kaplun and Senkevich (1977), Shuzhanov (1984), Yurina (1988), and others. The principal results are presented in medium-scale geological surveys. Regional investigations were discussed at the Stratigraphic Meeting in 1971 and the results included in the monograph "Geology of the USSR" with geological maps of Kazakhstan on a scale of 1:50,000 and 1:1.5 million.

The detailed geological surveys and research work provided a wealth of interesting detail on the stratigraphy and lithologic composition of the volcanogenic and sedimentary deposits and on Devonian tectonics. The analysis and general conclusions drawn from this new research work have contributed greatly to an understanding of Devonian sedimentation and magmatism.

Zonation of the Kazakhstan Paleozoics

Based on the lithology and petrography of the widespread Devonian formations, the history of development of the Paleozoics of Kazakhstan is subdivided into the Kokchetav-Northern Tien Shan, Central Kazakhstan, and Zhungar-Balkhash fold systems (Fig. 1). The folded zones of Rudnyi and Gornyi Altai are exposed in the east of Kazakhstan and in the west in the southern Urals and Mugodzhary.

The Kokchetav-Northern Tien Shan system includes the Kokchetav, Ulutau, Chu, Karatau, and Trans-Ili blocks as well as the buried Paleozoic structures of the Turgai, Teniz, and Chu-Sarysu troughs. They are attributed to the Early (or stable) Caledonian fold system (Markova, 1964).

The Kokchetav-Northern Tien Shan system in the pre-Devonian formed a large-scale arched uplift more than 2000 km long and up to 300-400 km wide. The general uplift occurred during the Silurian and was accompanied by folding and intrusion of granitoids. Orogenesis appears to have been the primary determinant of the final form of the main tectonic structures with thick continental crust. During the Devonian, the Kokchetav-Northern Tien Shan system was subjected to steady uplift. In piedmont depressions and intermontane plains, red sandy-pebble deposits accumulated, and small volcano-tectonic structures formed. The Devonian deposits of this system are represented by continental molasse of the Old Red Sandstone type similar to deposits in the British-Scandinavian orogenic belt and volcanogenic formations of mixed composition (from alkali-basalt to rhyolites). The thickness of the deposits is not great, and successions are incomplete and interrupted by unconformities and hiatuses (Fig. 2).

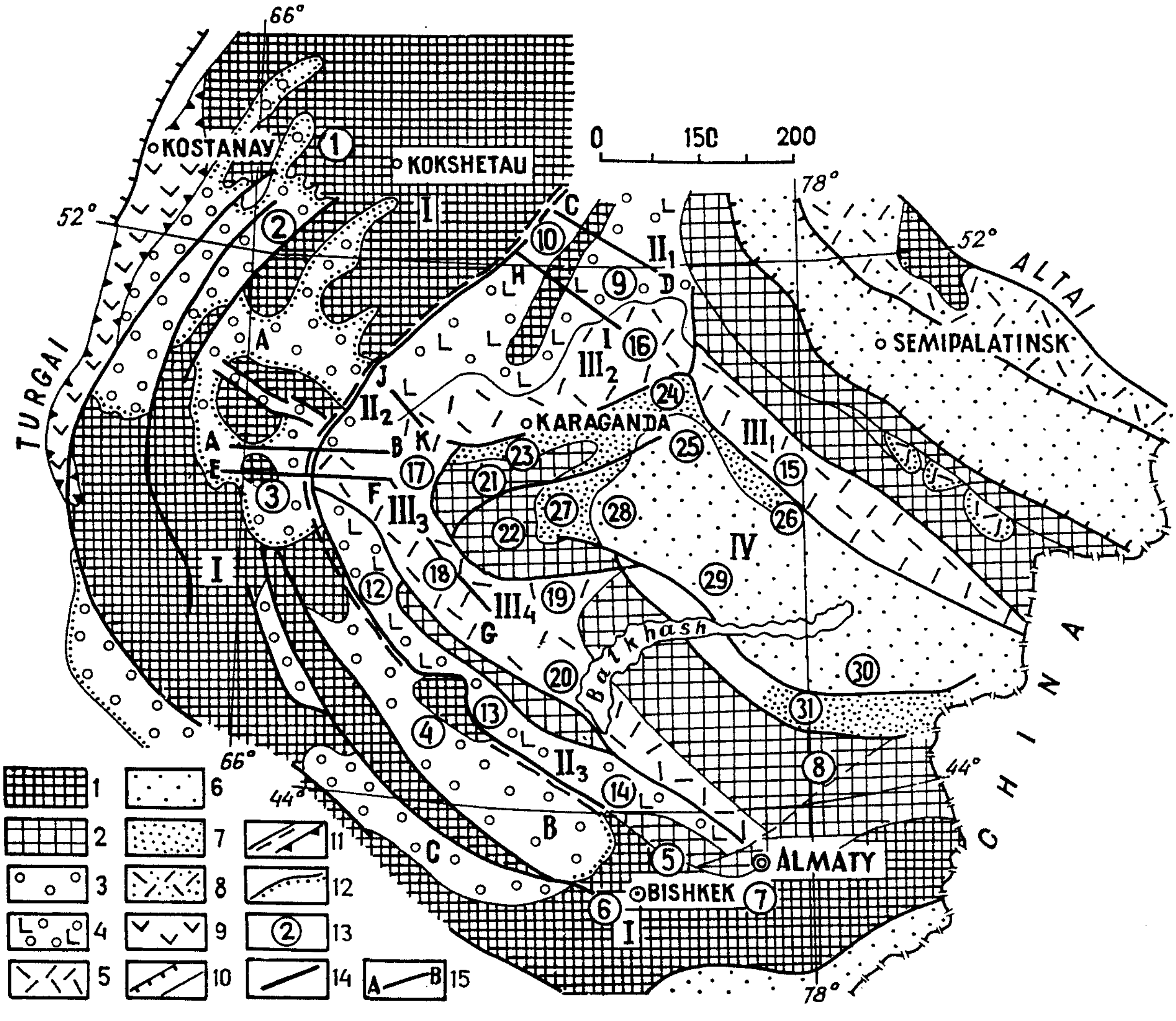
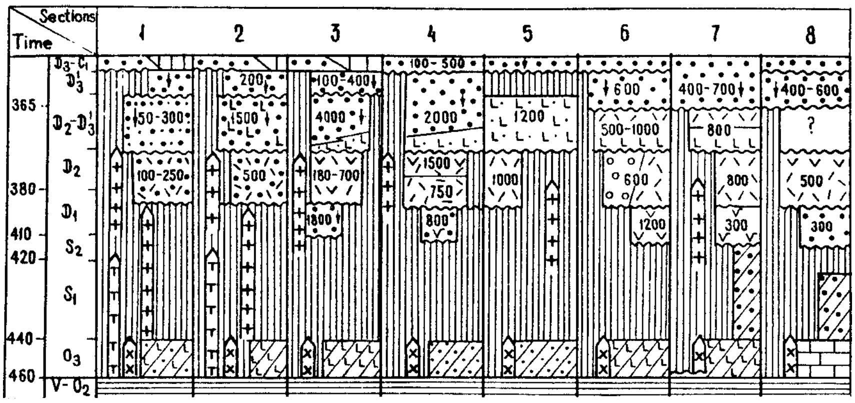


Fig. 1. Scheme of structure-facial zones of the Devonian of Kazakhstan. 1-2- Early Caledonian (1) and Late Caledonian geosynclinal (2) complexes; 3- Middle-Late Devonian molasse basins: A- Teniz, B- Taldybulak, C- Karatau; 4- Devonian intermontane depressions, filled by continental volcanic and molasse deposits; 5- Devonian volcano-plutonic belt; 6- depressions, composed of terrigenous and tuff-terrigenous marine deposits; 7-8- peripheral basins, composed of coastal-marine terrigenous and volcanic deposits of acidic composition, allochthonous (7), autochthonous (8); 9- depressions with continental effusives and coastal-marine terrigenous carbonate deposits; 10, 11- boundaries between: 10- marine geosynclinal (a) and continental (b) zones; 11- structural-facial continental zones (a) depressions and volcano-plutonic belts (b); 12- boundaries of depressions; 13- numbers of columns on Figs. 2, 3, 4; 14- fractures; 15- paleoprofile. I- Kokchetav-Northern Tien Shan system, II-III- Central Kazakhstan system, IV- Zhungar-Balkhash system, V- Chingiz-Tarbagatai system.

The Central Kazakhstan folded region is located in the inner part of Kazakhstan. It covers the western, southern, and eastern part of the Central Kazakhstan and Chingiz-Tarbagatai region (Fig. 1). It is horseshoe-shaped, 2500 km long and 200-300 km wide, and is attributed to the Late Caledonian fold system (Markova, 1964).

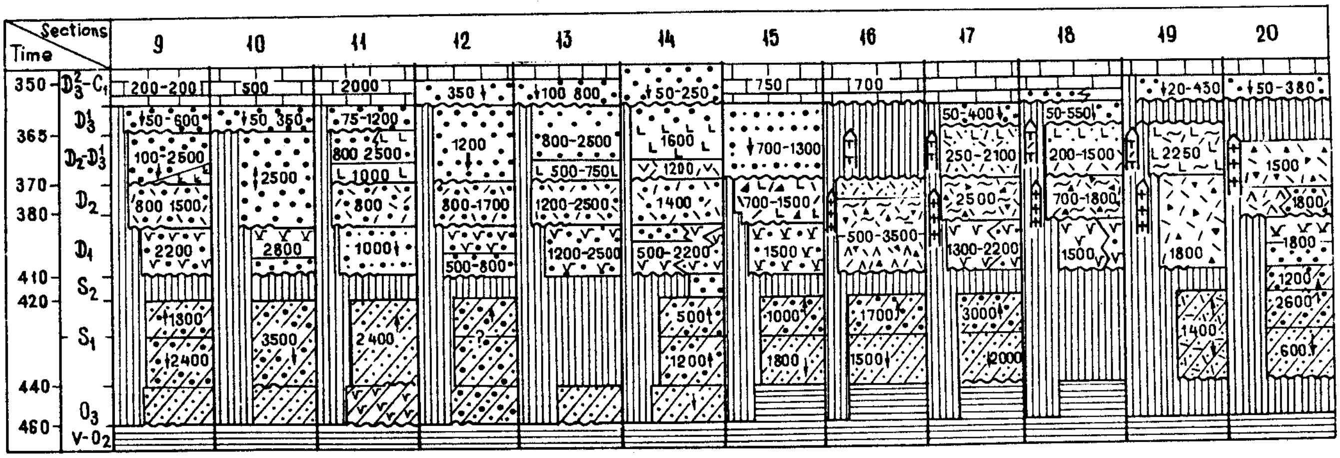
The pre-Devonian development of Central Kazakhstan was considerably different from that of the outer arc of the Caledonides. Molasse deposits accumulated in Late Ordovician-Early Silurian time, gradually covering the region with coarse clastics derived mainly from the Kokchetav-Northern Tien Shan uplift (Bandaletov, 1969). The supply of clastic material was so copious that sedimentation was not compensated by downwarping, with the result that basins grew shallower, gradually becoming transformed into piedmont depositional plains.

Late Silurian time in the Central Kazakhstan region was marked by epeirogenic uplift (Fig. 3). Consequently, the Late Silurian interval, which spans more than 10 million years, is not represented in the stratigraphic column.



Fig, 2 (left). Formational series of orogenic structures on the blocks of Kokchetav-Northern Tien Shan region. The numbered columns refer to the succession of locations indicated on Fig. 1.

Fig. 3 (below). Formational series of orogenic structures of Central Kazakhstan.



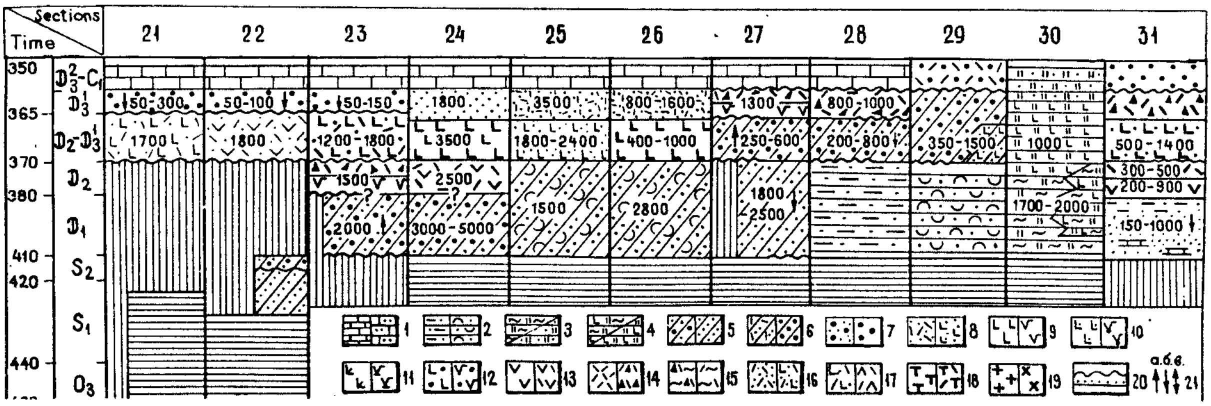


Fig. 4. Formational series of structures of the Zhungar-Balkhash system.

Quasi-platform complex, formations: 1- carbonate, terrigene-carbonate. **Geosynclinal complex, formations:** truly geosynclinal-horizontal hatching; 2- aleurolite-sandstone and tuff-terrigenous; 3- siliceous shale and terrigenous siliceous; 4- basaltic-siliceous-shale and siliceous-basaltic, molasse complex, formations; 5- molasse mottled and grey-colored; 6- molasse grey-colored tuff-terrigenous and red-colored. **Orogenic complex, formations:** 7- molasse mottled and red-colored; 8- liparite-terrigenous and basalt-terrigenous; 9- basaltic and andesite-basaltic; 10, 11- trachybasaltic and trachyandesite-basaltic more potassic (10) and sodic (11); 12- basaltic and andesite-basaltic with volcanomict sedimentary material; 13- andesitic and andesite-rhyolite; 14-15- rhyolite: 14- lava and tuff, 15- ignimbrite-tuff and ignimbritic; 16- terrigenous and basalt-terrigenous with allochthonous tuffs; 17- andesite-basalt-rhyolite and dacite-rhyolite. **Intrusive formations:** 18- granosyenites, monzonites, trachyrhyolites subvolcanic comendites; 19- granites and granodiorites; 20- continued break (a), plicated unconformity (b); 21- structure of molasse formation: regressive (a), transgressive (b), transgressive in the lower and regressive in the upper parts (v).

No sedimentary deposits nor magmatic formations of this age have been found. Central Kazakhstan and the Early Caledonian fold belt formed together a single continental massif (Bogdanov, 1965). At the beginning of the Devonian, long, narrow rifts, small grabens, and intermontane basins developed and were filled with coarse red clastics and (or) the products of basanitoid volcanism. Analogues of these formations are found in southern Siberia, Great Britain, Scandinavia, Spitsbergen, and Greenland. A volcano-plutonic belt with very thick volcanogenic formations, mainly of dacite and rhyolite, began to form in the mid-Early Devonian within blocks unaffected by rifting (Fig. 3).

The Zhungar-Balkhash fold system is located in northeastern Central Kazakhstan and extends eastwards to northwestern China (Fig. 1). The boundaries of this region in Kazakhstan were determined in the latter part of the Silurian, after which a Devonian median massif formed. The Zhungar-Balkhash is regarded as a Variscan fold system (Markova, 1964; Bogdanov, 1965). In the Late Silurian-Early Devonian, the region was an intracontinental shallow-water marine basin connected with the Zaisan-Southern Mongolian geosyncline. It probably began forming in the Late Ordovician and continued to develop until the Middle Devonian. Most of the Zhungar-Balkhash depression was situated over buried blocks of a Precambrian median massif. All the available data suggest that both Central Kazakhstan and the Zhungar-Balkhash region were continental areas in Devonian time.

Stratigraphy

Topical problems of Devonian stratigraphy are a reflection of the composition and variability of Devonian facies and the paucity of paleontological data. Through geologic surveys and thematic research work, the Devonian continental volcanogenic and sedimentary accumulations were subdivided into formations and their distribution outlined. Stratigraphic position, relations with underlying and overlying deposits, the character of facies changes, thickness, texture, and structural features have been established for every formation.

The Northern Balkhash marine deposits are subdivided into regional biostratigraphic horizons which can be faunally correlated with units of the International Stratigraphic scale (Bublichenko, 1945, 1973; Kaplun, Senkevich, 1974, 1977). The presence of benthic shelly fauna and macroflora in sections of both Northern Balkhash and Central Kazakhstan has served as the basis for a floral zonal scale (worked out by M.A. Senkevich and A.L. Yurina) and for correlation of marine and continental deposits (Bakhteev et al., 1984; Yurina, 1988). The results of detailed investigations were summarized in the stratigraphy of the Devonian of Kazakhstan (Shuzhanov, 1984).

Devonian geological events correspond in the Caledonides to four stages of sedimentation and volcanism separated by regional unconformities and granitoid intrusion. Sedimentation in the Variscides occurred in three tectonic stages, and the stage boundaries correspond to those in the Caledonides (Figs. 3, 4). The Early Devonian, Emsian-Eifelian and Givetian-Frasnian are the main stages. The boundaries between them are the same in the Caledonides and Variscides and are marked by transgressive overlap and by abrupt changes from rhyolitic to basaltic volcanism.

Early Devonian. Lower Devonian deposits in the Kokchetav-Northern Tien Shan and Central Kazakhstan systems consist of sedimentary molasse and essentially volcanogenic and volcanogenic-sedimentary sections. A gradual transition from one type to the other has been traced back in a number of areas. Sedimentary successions are characteristic of the small grabens within the Ulutau, Chu, and Erementau uplifts (Fig. 2). They consist of red and speckled sandstones, mudstones, gravelstones, and conglomerates with thicknesses from 100-200 m to 2 km. The conglomerates in the basal units of the sections are gradually replaced upwards by gravelstones and sandstones. The latter are distinguished by parallel and lens-like bedding and variable granulometric and lithological composition. Facies change gradually along strike and vertically. Clastic material of terrigenous rocks consists of quartz, feldspar, mica, and fragments of crystalline schists, quartzites, effusive rocks, and granitoids of the Precambrian and early Paleozoic. The deposits contain an impoverished flora, among which endemic forms of the Early Devonian predominate, with infrequent occurrences of *Drepanophycus* and *Zosterophyllum.*

Lower Devonian volcanogenic successions are characteristic of the Central Kazakhstan region (Fig. 3). The volcanics of the Koktas, Zharsor, and Aigyrzhal formations fill narrow relatively elongated rifts (Zhalair-Naiman, Aigyrzhal-Zhumak) (Fig. 5) and an isometric intermontane area (Shyderty). They are represented by andesite-basalts, andesites and basalts, lava breccias, and tuffs of intermediate to basic composition. Volcanogenic rocks are interbedded with conglomerates, gravel and sandstones. The clastic material of the sedimentary rocks was generated *in situ* from erosion and redeposition of pyroclastics and lavas. A coarse and lens-like bedding is typical of these deposits. Flows are replaced by tuffs and lava breccias, pyroclastic rocks, and volcanogenic conglomerates and gravelstones along strike. The qualitative and quantitative ratios of volcanogenic and sedimentary rocks vary, with the latter making up from 10 to 40% of total volume. The total thickness of the deposits is 1.2-2.5 km.

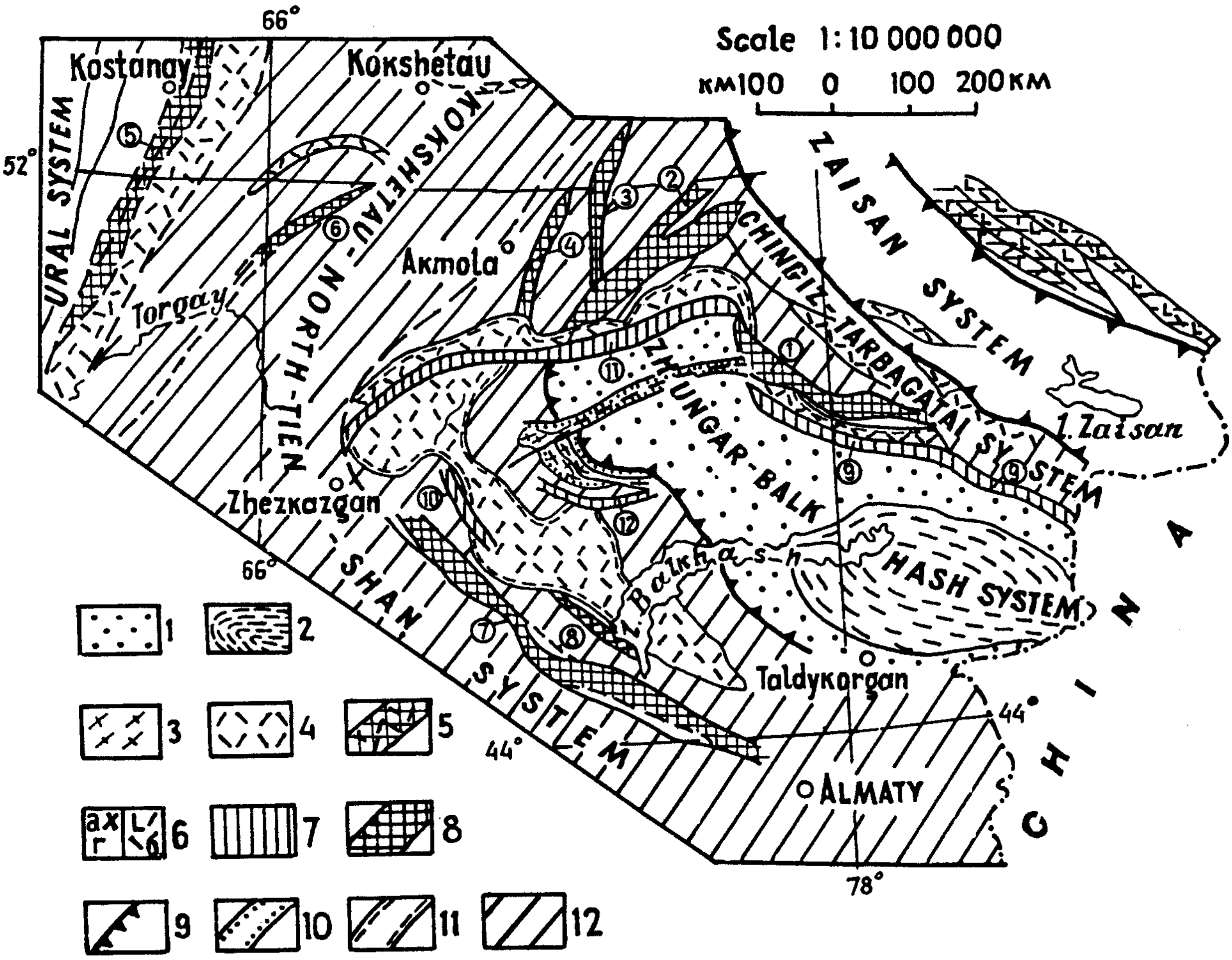


Fig. 5. Distribution of zones of continental volcanism and areas of marine sedimentation during the Devonian.
Areas of accumulations: 1- sandy-clayey deposits; 2- clayey-siliceous deposits.
Zones of volcanism: 3- The Late Devonian andesite-rhyolites; 4- The Early-Middle Devonian rhyolitic; 5- The Early Devonian andesite-basalt and Early-Middle Devonian rhyolite; 6- Late Devonian (a) and Middle Devonian (b) basalt-rhyolite; 7- Givetian basalts; 8- Early Devonian andesite-basalt.
Boundaries: 9- between the Caledonian and Hercynian systems; 10- of the Frasnian volcanic belt; 11- of the Early-Middle Devonian volcano-plutonic belt; 12- area of the uplift without volcanism and sedimentation.
Rifts with basaltoid volcanism: 1- Aigyrzhal; 2-3- Shyderty; 4- Selety; 5- Turgai; 6- Ishim; 7- Zhalair-Naiman; 8- Mynaral; 9- Dagandaly; 10- Atasu; 11- Spassk; 12- Akbastau.

In a few localities (12), Lower Devonian sandstones and aleurolites contain a macroflora consisting of *Cooksonia* sp., *Zosterophyllum* sp., *Drepanophycus* sp., *Taeniocrada dubia* Kr. et W. and endemic forms of *Jugumella burubaeasis* Senk., *J. jugata* Seak., *Maubasia natabilis* Senk. Early Devonian spores were also discovered there.

The lower boundary of continental molasse and volcanogenic deposits in Central Kazakhstan is transgressive, with Lower Devonian unconformably overlying pre-Silurian but resting conformably on Silurian, which makes mapping this boundary rather difficult. Paleontological data are lacking, so the stratigraphic level of the lower boundary has not been determined with certainty. It is quite possible that Early Devonian sedimentation and volcanism originated in different structures at the same time and that the lower boundary is diachronous.

Marine deposits of the Lower Devonian are characteristic of the Zhungar-Balkhash region (Fig. 4). They are exposed in northern Zhungar, northern Balkhash, and south of Karaganda and are overlain by upper Paleozoic rocks throughout the rest of the region. The Lower Devonian rocks are conformable upon the Upper Silurian, and the boundary in the northern part of the Zhungar-Balkhash region (Nura synclinorium) is drawn between the Lochkov and Pridoli stages, and in the central part of the region it coincides with the top of the Tokrau horizon. However, the coastal-marine deposits are transgressive on the Lower Silurian and still older formations along the southern periphery of this region.

The marine deposits of the inner part of the Zhungar-Balkhash region consist of grey sandstones, mudstones, tuffites, and acidic pyroclastics, which total 2-5 km in thickness. They are one continuous series but can be divided into three formations:a lower, carbonate-terrigenous unit with reefal limestones; a middle, sandstone tuff-tuffite unit; and an upper, tuff-sandstone with conglomerate and gravelstone lenses. Five horizons are distinguished according to benthic fauna and flora. The upper boundary of the lower series is drawn where *Protolepidodendron scharianum* first appears, since shelly fauna of the upper (Kazakh) horizon has a mixed composition in which Lower Devonian taxa were recorded together with typical Middle Devonian taxa (Kaplun, Senkevich, 1977). Conodonts and graptolites have not yet been found, and the zones in the Lower and Middle Devonian series have been established on the basis of brachiopods, tabulates, crinoids, and macroflora.

Early-Middle Devonian. Volcanogenic formations of dacite-rhyolite and red molasse-type sedimentary deposits, attributed to the Emsian and Eifelian stages, are widespread in Central Kazakhstan, where volcanites and comagmatic granitoids form the Devonian volcano-plutonic belt. Perivolcanic basins are filled with molasse (Bogdanov, 1965; Mazarovich, 1976; Shuzhanov, 1984; Fig. 1). Such deposits occur locally in the Kokchetav-Northern Tien Shan region. Effusive rocks are remnants of small volcanoes. Molasse deposits are well represented in small grabens on the Kokchetav, Chu, and Ulytau uplifts (Fig. 2).

Volcanogenic deposits of the Devonian volcano-plutonic belt form a flat-lying cover in southwestern Predchinghiz northeast of Karaganda, in the Sarysu-Teniz watershed, and in western Balkhash (Figs. 5, 8). The beds lie without apparent unconformity on the Lower Devonian or are unconformable on Silurian and older rocks. Volcanic rocks form thick groups consisting of two formations: the Semizbugy Formation and, overlying it, the Zhilandybulak Formation. The Semizbugy and its correlates are characterized by homogenous massive structure and composed of red clastic lavas and tuffs, often with ignimbrite texture, agglomerate lapilli, thin clastic tuff, and acidic tuffites (dacite and rhyolite). Lens-shaped bodies with a cover of andesite, dacite, tuff-sandstone, mudstone, and gravelstone are found in some regions in the lower part of this formation. The terrigenous rocks and tuffites yield Early Devonian plant remains such as *Drepanophycus spinaeformis* Goepp., *Cooksonia crassipariatilis* Jur., and *Blasaria sibirica* Zal., as well as eurypterids of the Rhenopteridae Storner family and *Bunodes* sp. (Mazarovich et al., 1985). The thickness of these rocks reaches a maximum of 3.5 km. The upper, Zhilandybulak Formation, is characterized by bedded pyroclastic rocks analogous in composition to the underlying effusive rocks showing exfoliation and by tuff-sandstones and tuffites, lenses of volcanic conglomerates and gravelstones, and sometimes by strata and sills of andesite and basalt. Their thickness reaches from 800 to 2500 m. Macrofloral elements consist of Eifelian endemic types of genus *Tamarella, Artschaliphyton* et al., and *Protolepidodendron scharianum* Krejci, *Blasaria sibirica* (Krysht) Zal., *Calamophyton primaevum* Kr. et W.

Volcanogenic deposits in the Kokchetav-Northern Tien Shan region are composed of lavas, various acidic tuffs, and lesser amounts of andesite. Some massive and coarse-bedded members contain stratified sills and lens-shaped subvolcanic beds. Thickness ranges from a few hundred meters to 1.2 km. These deposits do not usually contain organic remains; only in terrigenous rocks in some regions of Trans-Ili Alatau have *Taeniocrada decheniana* (Goepp) Kr. et W. and *Lycopsida* sp. been found.

The greatest development and maximum thickness of molasse deposits occur in the Degress Formation and its analogues of Lower-Middle Devonian age found in depressions surrounding the volcano-plutonic belt and in rifts of earlier Devonian deposits (Shiderty, Zhalair-Naiman) (Figs. 3, 5). The beds overlie the Lower Devonian with a hiatus and transgressively overlap older formations. Interformational conglomerates are found at their base. The main molasse components are various red and multicolored sandstones, conglomerates, and gravelstones; the secondary components are mudstones, tuffs, acidic tuffites, and sometimes local amygdaloidal basalts and chemical limestones. The molasse deposits are transgressive and have a complex inner structure. Conglomerates are replaced along strike by gravelstones and coarse-grained sandstones, and sandstones by mudstones. Closer to the volcano-plutonic belt the terrigenous deposits become gradually dominated by reworked volcanoclastic and juvenile acidic pyroclastic material. Volcanogenic rocks make up a greater part by volume (up to 50%) of the molasse sediments in successions adjacent to volcanic structures. Porphyritic crystallinoclastic as well as ignimbrite lavas and coarse tuffs and subvolcanic and extrusive bodies of rhyolite pinch out in depressions at a distance of 2-5 km, and only thin-bedded tuffs can be traced for tens of kilometers. Terrigenous molasse near structures of the volcano-plutonic belt consists of coarse, red volcano-clastics up to 100 m thick (Figs. 6, 8).

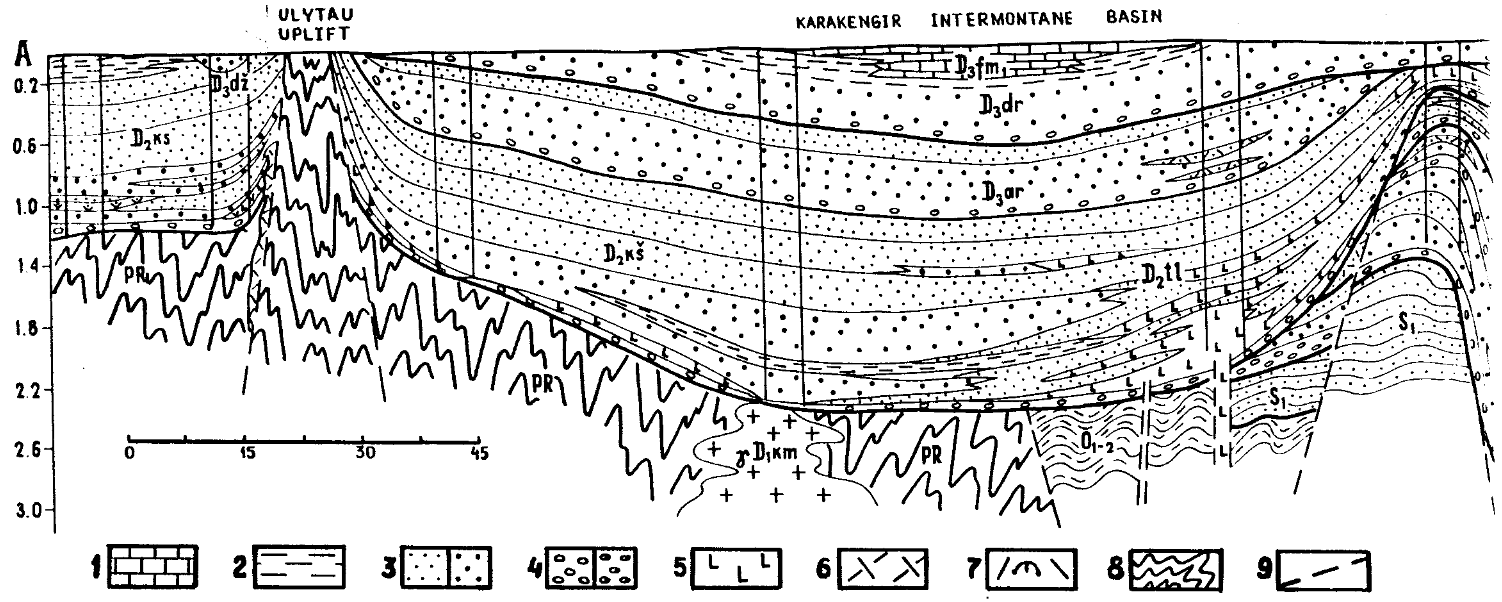


Fig. 6. Schematic facies profile (A-B) of the Devonian formations of the Ulytau region and Sarysu-Teniz uplift (in the west - Tamdy and Karakengir molasse depressions; in the east - volcanic belt). 1- limestones; 2- siltstones; 3- sandstones (a), gravelly and course-grained sandstones; 4- conglomerates; 5- basalts, andesite-basalts, trachybasalts; 6- tuffs and lavas of rhyolite and dacite composition; 7- ignimbrites, ignispumites, aggluminates of rhyolitic and dacitic composition; 8- Precambrian; 9- faults.

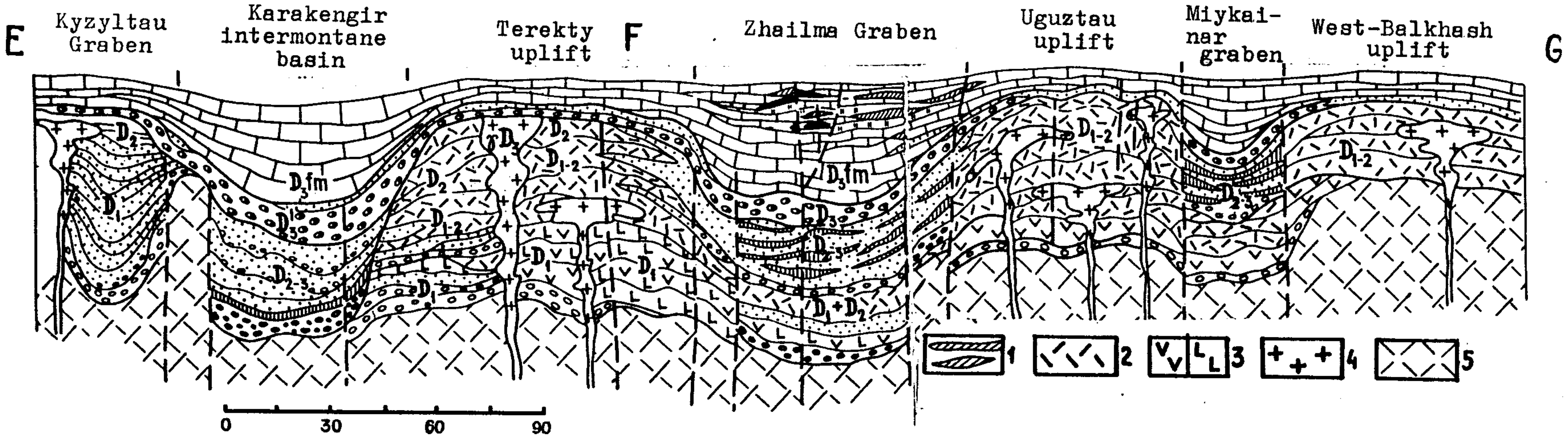


Fig. 8. Structure and relations of magmatogenic uplifts with intermontane basins (grabens- in Central Kazakhstan, Profile E-F-G). The profile stretches in latitude from the Ulytau Mountains to the Sarysu-Teniz uplift and further to the southeast into the West Balkhash region. 1- basalts, trachybasalts, cherts, and iron-manganese ores of the Upper Devonian; 2- effusives of rhyolitic and dacitic composition of the Lower and Middle Devonian; 3- andesites, andesite-basalts, and basalts of the Lower Devonian; 4- Middle and Late Devonian granitoids; 5- Pre-Devonian formations. (For the rest of the legend, see Fig. 6.)

The lower part of the Degress Formation contains plant remains in the lower (Sardzhal) horizon. Endemic plants such as *Maubasia natabilis* Senk., *Jugumella burubaensis* Senk., and *Cooksonia cassiparietilis* Jur. are found here together with *Zosterophyllum australianum* Lanng et Cookson, *Z. renanum* et W., *Drepanophycus spinaeformis* Goepp., and *Gosslingia brecopensis* Heard. In the uppermost beds, Senkevich described Middle Devonian forms such as *Protolepidodendron scharianum* Kr., *Artschaliphyton unicum* Senk., and *Tamarella taeniata* Senk.

Middle-Late Devonian. Deposits of this age in the Caledonian region of Kazakhstan are composed of a heterogenous series ranging from Givetian-Frasnian continental volcanogenic-molasse to Upper Devonian-Lower Carboniferous marine terrigenous-carbonates (Figs. 2, 3). In the Zhungar-Balkhash region, the lower series corresponds two groups of marine volcanogenic-sedimentary deposits and the upper one to a regressive group of volcanogenic-terrigenous Famennian-Tournaisian deposits (Fig. 4).

Givetian-Frasnian deposits in the Caledonian region are attributed to the Zhaksykon group. They fill the intermontane, foothill, and perivolcanic basins and grabens in the northwestern and western parts of Central Kazakhstan, the Turgai trough, Chu-Sarysu, and Teniz depressions (Figs. 6, 7). Lithostratigraphic analogues of these groups may be found in the British-Scandinavian and Altai-North Mongolia Devonian orogenic belts. The only difference between the Zhaksykon group and its analogues in Europe and southern Siberia is that basalts and trachy-basalts are widespread in Givetian horizons in Kazakhstan. A number of strata, members or several members are interbedded with red deposits. Homogenous rock masses composed of effusive rocks are combined in formations. The Zhaksykon group and its analogues rest without conspicuous unconformity on terrigenous rocks of the Eifelian stage, with erosional channeling of the Lower-Middle Devonian acidic volcanogenic formations but with a sharp unconformity on the lower Paleozoic and Precambrian (Figs. 3, 6).

The molasse deposits consist of red and multicolored sandstones, mudstones, gravel-stones, and conglomerates. Lenses and thin strata (up to 0.5-1 m) of limestones, marls, and cupriferous aleuro-sandstones are present in members of grey- and wine-colored sandstones and mudstones. All these rocks belong to a single transgressive-regressive complex, with complicated internal structure, facies replacement, and pronounced (200-500 m) thickness variations (Figs. 6, 7).

Givetian-Frasnian terrestrial rocks occur in two main lithological successions: volcanogenic-sedimentary and terrigenous molasse. The first is typically found in the west and south, the second in northeastern Central Kazakhstan (Figs. 6, 9, 10).

Complete successions of volcanogenic-sedimentary deposits of the Zhaksykon group within the Sarysu-Teniz uplift are subdivided into three parts. In the lower part, an effusive rock mass (up to 1.2 km thick) is purported to overlie thin red sandstone, conglomerate, and gravelstone units. The middle part, 800-1200 m thick, consists predominantly of grey-greenish, grey, and wine-colored sandstones, mudstones, small lenses of gravelstones, with intercalations of ash-flow tuffs, limestones, marls, argillites with abundant Givetian plant and fish remains. The upper part consists of red sandy-gravelstone-conglomerate beds ranging in thickness from 100 to 1,200 m. The lower effusive rock mass is replaced northwards towards the Turgai trough by speckled terrigenous rocks, within which single basalt flows are preserved (Fig. 6). Lenses of cupriferous sandstones and mudstones are found in these successions among wine-colored and grey sandy-clayey rocks.

The terrigenous clastic deposits are united in the Chadra group in the Shiderty and Selety depressions. This group is subdivided into two formations, the lower composed of red and multi-colored poorly sorted polymict sandstones and mudstones, ranging in thickness from 700 to 2300 m. Thick beds (250 m) of bouldery and coarse pebble conglomerates in the lower part of the succession grade upward into fine pebblestones, gravelstones, and poorly sorted sandstones. The mudstones yield *Protolepidodendron scharianum* Krejci and other species. In some parts of the Shiderty depression (Lake Kumkol) the succession includes lenses, strata, and sills of basalt with thicknesses of up to 100-200 m. The upper formation consists of a 450-1500 m thickness of grey terrigenous rocks,

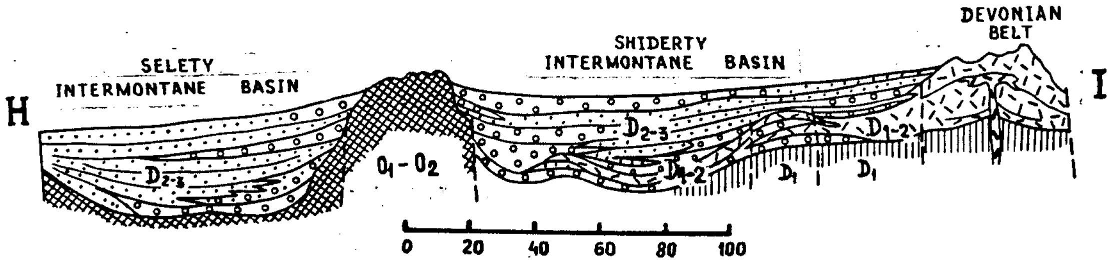


Fig. 7. Structure of the Lower Devonian formations in the Selety and Shiderty intermontane basins. Profile C-D. (For legend, see Fig. 6.)

including grey limestones, marls, cupriferous sandstones, and mudstones. *Mucrospirifer seid* (Nal.), *Spinocyrtia ali* (Nal.), and *Cyrtospirifer acmet* Nal., as well as endemic Late Devonian fauna and flora., were found in carbonate rocks of the May horizon of the Frasnian stage.

Givetian-Frasnian deposits fill small depressions along the strike of the Devonian volcano-plutonic belt, some (in the Sarysu-Teniz watershed) passing into large troughs that offset the belt. The deposits are composed of red clastics, dark violet-grey basanitoids, tuffs, and red-brown rhyolitic flows. The terrigenous rocks show weathered lava clasts and include tuffs, ignimbrites, and juvenile acidic pyroclastics. The red rocks contain a number of bedded limey sandstones and gray-green tuffites, with abundant Givetian plant remains. The thickness varies from 1.2 km to 120-200 m where effusive rocks pinch-out.

The Middle-Upper Devonian is exposed in the Zhungaro-Balkhash region, bordering the Caledonian massif, and in northern Balkhash. Offshore-marine volcanogenic-terrigenous rocks are found on the periphery of this region, passing into marine carbonate-terrigenous rocks toward the center. Volcanogenic-terrigenous deposits in the Karaganda region (Spassk rift) in southwestern Predchinghiz and in northern Zhungar comprise two formations: Lower Givetian andesite-basalt (Dagandaly) and Upper Givetian-Frasnian terrigenous or tuff-terrigenous (Akbastau and its analogues, Fig. 4). The lower formation lies conformably on Eifelian sedimentary deposits and with an erosional unconformity on continental rhyolitic volcanics.

The Dagandaly formation (columns 23, 24, 26 in Fig. 4) consists of andesite-basalts, basalts, and andesites of normal and higher alkalinity. Effusive rocks in the succession alternate with thin members of tuff-sandstones, mudstones and conglomerates, which also include lenses of limestone, cherts, and tuff that persist along strike, dacites and diabases of subvolcanic facies, sills, and stocks of andesite. The lavas and tuffs are replaced laterally (up to 10 km) by volcanomict tuff-sandstones and tuffites of moderately basic composition. The sedimentary rocks and tuffites yield a macroflora that includes *Protolepidodendron scharianum* Krejci, *Berrandsina dusliana* (Krejci) Stur, *Hostinella* sp., and *Artschaliphyton unicum* Senk. Rare finds of Givetian conodonts occur in the limestones to the south of Karaganda. The thickness, ranging from 600 to 1800 m, is reduced where effusive rocks pinch out.

The Upper Givetian-Frasnian deposits of the Akbastau formation rest transgressively on volcanics of the Eifelian stage and the Lower Givetian. Basal conglomerates are of interformational type — boulder and coarse pebble polymict units with clastic rocks from the underlying Devonian volcanogenic rock masses, quartzites, Ordovician jaspers, and granitoids. The cover consists of multicolored sandstones and mudstones. Cherty, calcareous, and carbonaceous rocks with pyrite, chalcocite, and bornite occur within the sandy-clayey sediments higher in the section. The upper part consists of green-grey terrigenous rocks with thin interbedded limestones and fine-grained acidic tuffs. The thickness reaches 1200-1500 m. Calcareous and argillaceous sediments contain brachiopods, corals, crinoids, and bryozoans and a Givetian and Frasnian flora (Mazarovich et al., 1985).

The Middle-Upper Devonian rocks of northern Balkhash and northern Zhungar comprise two formations: one lower Givetian, the other upper Frasnian. They are not much different from the Akbastau formation of the Spassk zone and the Chinghiz foreland in regard to lithology, structure, and faunal and floral content.

Late Devonian. The Upper Devonian is represented by transgressive marine deposits with a diachronous lower boundary in the Caledonides of Kazakhstan. At the base are red conglomerate-sandstone deposits (Dairy formation) (Fig. 6). These grade upward into terrigenous-carbonate rocks of Famennian-Tournaisian age. The diachronous lower boundary of carbonate sediments with a rich and varied macro- and microfauna coincides with the base of the Famennian stage in Central Kazakhstan but rises to the Lower Tournaisian in northern and southern Kazakhstan.

The Upper Devonian and Tournaisian deposits form a mildly dislocated quasi-platform cover in Central Kazakhstan. They transgressively overlie Devonian volcanogenic and intrusive beds, the lower Paleozoic, and the Precambrian. Carbonate sediments of different origin predominate, with terrigenous rocks concentrated around the uplifts. Silty siliceous deposits, sodic basalts, and stratified iron-manganese and lead-zinc ores (Atasu, Altau regions) are widespread in stagnant basins. The red conglomerate-sandstone masses of western and southern Central Kazakhstan contain stratified manganese deposits.

The Upper Devonian in the Zhungar-Balkash system is represented by deposits of various facies, mainly carbonate and argillaceous sediments (up to 250 m) in the northwest and clay schist-siliceous and tuffite deposits with lenses of basic composition and limestones in the Uspenka zone. In northern Balkhash the Famennian stage is represented by a thick stratum of andesite-basalt, rhyolite, and terrigenous rocks. Tuffites, schists and siliceous rocks with basalt lenses, the totalling over 3 km thick, are widespread in northern Zhungar. The Famennian age of the multifacial complex of the Zhungar-Balkhash region is distinguished on the basis of conodonts, ammonoids, brachiopods, and tabulate and rugose corals.

From the available stratigraphic data, Devonian continental deposits can be assigned to four stages of sedimentation and volcanism, with regional unconformities delimiting deposits of each stage (Figs. 2, 3). Basaltoid volcanism and accumulation of lower red molasse are peculiar to the Early Devonian stage of Central Kazakhstan. The Emsian-Eifelian is represented by rhyolitic volcanism and granitic magmatism, with accumulation of volcanomict red molasse in perivolcanic troughs. The Givetian-Frasnian stage records resumption of basanitoid volcanism and accumulation of the upper red molasse. The Late Devonian-Early Carboniferous was a time of carbonate quasi-platform sedimentation.

Marine transgressions occurred twice in Kazakhstan. From the Middle Givetian up to the Early Frasnian, shallow seas invaded the continental zones of northeastern Central Kazakhstan. The second more extensive transgression of the Famennian-Tournasian covered almost all of Central Kazakhstan.

Devonian Volcanism and Ore Mineralization

Much petrographic/petrochemical data has been gathered during more than 50 years of research on volcanogenic complexes, as summarized in monographs by Sergiev (1948), Abdulin (1982a), Shuzhanov (1984), and others. Recent progress in stratigraphic and formational analysis of the Devonian has made it possible to specify:

1) stratigraphic position of volcanogenic complexes;
2) formational associations of volcanic rocks;
3) petrographic/petrochemical features of volcano genic series and their metallogeny;

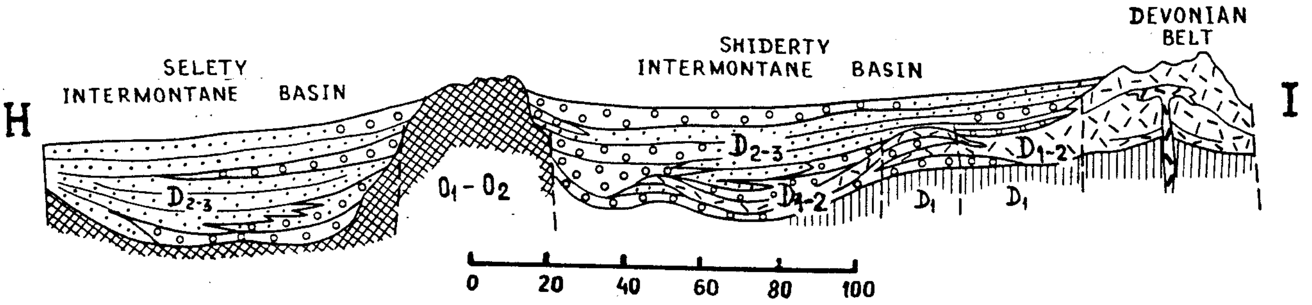


Fig. 9. Replacement of volcanogene formations of volcano-plutonic belt by red molasse deposits in the northeast of Central Kazakhstan. Profile H-I. (For legend, see Fig. 6.)

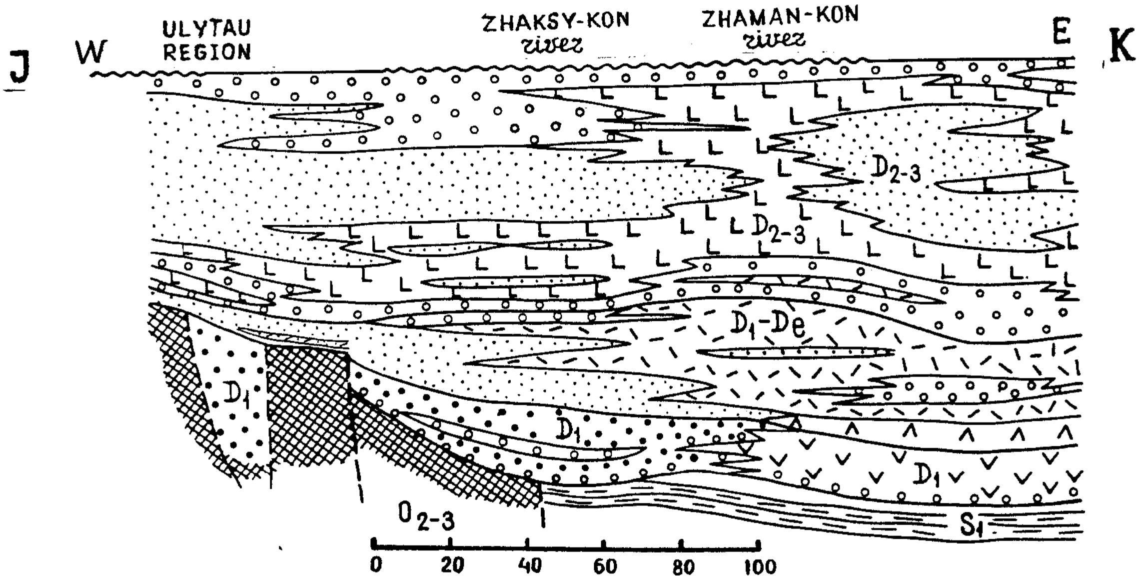


Fig. 10. Replacement of volcanogenic rocks by molasse deposits in the west of Central Kazakhstan. Profile J-K. (For legend, see Fig. 6.)

4) evolution of Devonian volcanism in time and regularities in the spatial distribution of volcanic rocks (Paleozoic structure).

The volcanogenic successions of Kazakhstan are subdivided into the following formations (Figs. 2, 3): andesite-basalt with two petrochemical series of gradually differentiated rocks with normal or higher (subalkaline) alkalinity; andesite-dacite-rhyolite, dacite-rhyolite with alkali-calcic and subalkalic series (Abdulin, 1982b; Shuzhanov, 1984). Besides these widespread formations, alkaline basalt and trachyrhyolite formations are distinguished in rare volcanogenic structures. Formational analogues of the Devonian volcanics of Kazakhstan in the Altai-Sayan region and Mongolia were described in detail by Luchitskii et al. (1966), Mossakovskii (1975), and Markova (1969).

Early Devonian basanitoid volcanism is characteristic of rift structures[1] such as Aiugryrzhal, Shiderty, and Zhalair-Naiman (Fig. 5). They represent narrow (up to 30-40 km), long (up to 300-800 km) synsedimentary structures bounded by deep fractures. Grabens developed in molasse basins during the Late Ordovician-Silurian, and also on consolidated blocks of lower Paleozoic and Precambrian rock. They were filled with volcanic products and lesser amounts (5-20%) of clastic material derived from adjacent uplifts. Volcanogenic deposits rest without apparent unconformity on Silurian molasse inside grabens but are transgressive over older deposits. Volcanism was localized along the marginal rift faults and to a lesser degree along the rift axes. The total area covered by Early Devonian volcanism was about 70-80,000 km^2, and the volume of igneous material exceeded 150,000 km^3. The volcanogenic index is 50-80, and the explosive index is 10-60. The quantitative ratio of lavas to tuffs is different in different rifts: the explosive index (the percentage of pyroclastics compared to the volume of volcanogenic rocks) is 60-70 in Aigyrzhal-Zhumak and 30 in Shiderty; in Zhalair-Naiman it is 10-15 and in Mynaral 0.

Volcanogenic rocks are represented mainly by andesite-basalts and andesites, and to a lesser extent by basalts and dacites, all displaying differences in subalkaline composition, as well as tuffs of corresponding composition. Lavas and tuffs are interbedded in succession with volcanomict conglomerates, tuff-gravelstones, and tuff-sandstones. Volcanogenic rocks are replaced along strike and laterally by volcanogenic-sedimentary rocks (Figs. 7, 10). Lavas form bedded bodies and lenses with thicknesses of from 3 to 60 m.

Effusive rocks have porphyritic textures, with plagioclase phenocrysts of labradorite and andesine. Among dark-colored minerals, pyroxenes predominate: augite, titanium-augite, diop-side, lesser pigeonite and hypersthene. Olivine occurs in basalts and trachybasaits in small grains (up to 1 mm). Amphiboles and biotite are rare in andesites, latites, and dacites. Alkaline minerals are lacking in subalkaline rocks of basic and intermediate composition.

Tuffs occur as beds and lenses with thicknesses varying from 1-2 to 150 m. They are mostly agglomerates, with fragments up to 20-30 cm. Much rarer are lithoclastic and crystalline rocks with psammite-size clasts. Tuffs have andesitic, dacitic, and basaltic compositions. Stratified volcanogenic deposits are cut by subvolcanic bodies of basalt, diabase, andesite, and dacite. These are in the main rocks with porphyritic and aphyric textures, and with massive amygdaloidal and fluidal structure. Subalkaline megaporphyritic diabases, basalts, and andesites with very large (1-2 cm) phenocrysts of plagioclase are abundant. Stratified sills that cut dikes and stocks are seldom composed of these rocks.

The products of Early Devonian volcanism are represented by all transitional types of rocks from basalt to dacite and by subalkaline rocks from trachybasalt to trachydacite. Quantitative ratios of rocks with normal and higher alkalinity are highly variable, but rocks with normal alkalinity predominate as a whole. Rocks of the sodic series (Na_2O/K_2O = 4) have a high titanium content with a K_2O/TiO_2 ratio of 0.8, and the potassic-sodic series (Na_2O/K_2O = 1-4) has a K_2O/TiO_2 ratio of 1. All rocks from basalts to dacites correspond to meso- and leucocratic types with high alumina contents.

Formation of copper and polymetallic sulfide ores was closely connected with the Early Devonian basanitoid volcanism. Many small deposits occur in the Shiderty and Aigyrzhal-Zhumak rifts of northeastern Central Kazakhstan. All the known copper (Kondzhanchad group, Berkara, etc.) and polymetallic (Abyz, Mizek, etc.) ore deposits are found in successively differentiated Lower Devonian dacite-andesite-basalt formations (Aigyrzhal, Zhumak). They are confined to zones of tectonic dislocation and metasomatism. The most favorable are volcanogenic deposits with high porosities and aureoles of subvolcanic bodies and small intrusions.

Ore beds are found among crushed and exfoliated alloclastic breccias of various tuffs and lavas altered to propylites, quartz-sericite-chlorite and quartz-sericite rocks, and monoquartzites. They are conformably enclosed by metasomatically altered volcanogenic rocks of intermediate and basic composition, as well as by weakly altered subvolcanic bodies of andesite, diabase, dacite, and rhyolite.

---

[1] In Kazakhstan, Devonian riftogenesis developed on geosyncline-folded basement with continental crust. The continuous continental crust was disturbed by steeply dipping faults but kept its integrity.

Copper ore deposits are composed of chalcopyrite, chalcocite, bornite, and minor pyrite. Malachite and azurite are well developed in the oxidation zone.

The occurrence of massive polymetallic sulfide mineralization in continental volcanogenic deposits of the Lower Devonian was established in Kazakhstan not many years ago. This type of ore mineralization is obviously characteristic only of volcanogenic formations of eugeosynclines and island arcs.

Massive sulfide base metal deposits are represented by pyrite, copper-pyrite, copper-lead-zinc, and lead-zinc ores. The basic ore minerals are chalcopyrite, sphalerite, galena, pyrite, fahlore (sulfantimonides or sulfarsenides of copper), electrum (argentiferous gold), and hessite (Ag_2Te). Gold and silver are present in all sulfides, especially in pyrite and fahlore. Ores are massive and intervein-impregnated. Distribution of ore bodies and metasomatites is very compact. There are gradual transitions between different ore types and sericite-quartz and chlorite-sericite-quartzites. The following succession in formation of deposits has been established: propylitization and metasomatic regeneration of volcanogenic rocks, then gradual formation of massive sulfide, chalcopyrite-pyrite, sphalerite-chalcopyrite, and galena-sphalerite ores. The process is completed by the emplacement of quartz and calcite-quartz veins with gold and sulfides. Massive sulfide polymetallic deposits are attributed to a class of postvolcanogenic types.

Early-Middle Devonian Rhyolitic Volcanism. This type of orogenic volcanism manifested itself throughout a vast area of the Central Asian fold belt, covering an area of over 150,000 km^2 in Kazakhstan and over 200,000 km^2 in the Altai-Mongolia region. The total volume of igneous material in zones of active volcanism (Central Kazakhstan) is about 300-400 km^3.

Rhyolitic volcanism and accompanying granitic magmatism were confined to a tectono-magmatic zone of the volcano-plutonic type in Central Kazakhstan, where comagmatic volcanic and intrusive sialic complexes are combined. The volcano-plutonic belt includes a number of magmatogene uplifts (West Balkhash, Sarysu-Teniz, etc.; Figs. 5, 8). The belt is over 2,000 km long and 50-200 km wide.

Rhyolitic volcanism began in the Emsian and continued in northeastern central Kazakhstan until the Late Eifelian, and in the southwestern part until the Givetian (Fig. 3, columns 15-20). The products of short-lived rhyolitic and dacitic eruptions are observed in the Eifelian section in the Spassk zone, and in the Upper Devonian in the Uspensk-Aksoransk zone (Fig. 4., columns 23, 27, 28). Analogous rejuvenation of rhyolite complexes took place in Rudnyi Altai as well (Kuzebny, 1975).

Volcanogenic formations are represented by various tuffs, porphyritic crystallinoclastic lavas, ignimbrites, spherulitic and fluidal dacites, and rhyolites with normal or higher alkalinity. Crystallinoclastic tuffs and lavas with massive and ignimbrite texture are typical of the lower part of the rhyolites. These rocks contain large (up to 5-6 mm) numerous (up to 50-60%) phenocrysts of quartz and feldspar and small fragments of lava and volcanic glass, as well as small crystals of biotite and amphibole. These rocks constitute thick members that fill large calderas and lens-shaped and stratal bodies as well. They are traced for tens of kilometers along strike and then pinch out. The thickness of these homogenous strata is measured in kilometers; foliation is absent and sedimentary rocks are uncommon. Series of crystalline tuffs, ignimbrites, and porphyritic lavas are cut by subvolcanic bodies of rhyolite and comagmatic granitic plutons. It is obvious that in the volcano-plutonic belt they both form a common magmatic system (a volcano-plutonic association) (Fig. 8).

The upper part of the rhyolites differs from the lower in having a thin-bedded structure, caused by frequent alternation of pyroclastic and terrigenous rocks. Typical volcanogenic rocks are thin fragmental vitrocrystallinoclastics, ash, and pisolitic tuffs and tuffites.

As indicated by petrochemical composition, volcanogenic rocks belong to the calc-alkalic and subalkalic series. Potassium and sodium contents are approximately equal, totaling not more than 6-8%; in subalkalic rocks they make up more than 9-10%.

Formation of highly aluminous quartzites (Semizbugu deposit) and numerous noncommercial occurrences of uranium-molybdenum and rare earth mineralization are connected with rhyolite volcanism. Commercial uranium deposits are confined to perivolcanic zones. The pinch-out and substitution of volcanogenic facies by terrigenous rocks and concentrations of subvolcanic dacites, trachydacites, and trachyrhyolites are both observed.

Givetian and Late Devonian Basanitoid Volcanism. Givetian andesite-basaltic formations (Dagandaly) form tilt-block structures resembling continental rifts. The Spassk and Dagandaly rifts originated in deep-fault zones of the early Paleozoic separating the Zhungar-Balkhash and Central Kazakhstan sectors (Fig. 5). The great rifts formed in heterogenous structures of the Caledonian massif and volcano-plutonic belt.

The Dagandaly rift is traced in modern structures for as much as 600 km and is outlined by individual outcrops of basalt forming long, narrow northwest-facing tectonic blocks. Linearly stretched subvolcanic bodies of basalt, diabase, dacite, and rhyolite and zones of syn- and postvolcanic metasomatism (epidotization, chloritization, propylitization) are confined to these strips of effusive outcrop. Outcrops of lava and subvolcanic rocks in the rift zone are about 7-10 km wide; these units are 800-1200 m thick. Outside the rift, lava thicknesses are distinctly reduced, to tens of meters.

The Spassk rift extends for 400 km (Fig. 5). The northern flank of this rift is traced along the deep fault crossing the structures of the volcano-plutonic belt. The southern flank is traced along the Spassk fault zone. The Spassk rift is composed of andesite-basalt and basalt, with lesser amounts of andesite and andesite tuff, allochthonous fine fragmental tuffs of dacite and rhyolite composition, and tuffaceous volcanomict conglomerates and sandstones.

Givetian volcanism is represented by fissure eruptions of andesite-basalt, basalt, and andesite lavas with normal or higher alkalinity (subalkaline). Tuffs of basic and intermediate composition occur near small volcanic cones. Effusive thicknesses are as much as 2.5 km.

Small rifts with basanitoid volcanics are clearly distinguished in the western and southern parts of Central Kazakhstan (Fig. 5). Some occur in structures of the volcano-plutonic belt, others in structures of the early Paleozoic. The andesite-basalt formations are uncomformable on effusive rocks and granitic plutons of the Lower-Middle Devonian.

Volcanogenic formations are represented here by basalts and andesite-basalts, with lesser amounts of andesite and trachyte. Lavas are associated with red sandstones, gravelstones, and conglomerates. Effusive thicknesses reach a few tens of meters on the uplifts, and in grabens are as much as 1.2 km.

Basalts and andesite-basalts are porphyritic and less frequently aphyric, with amygdaloidal and massive texture. Phenocrysts are represented by labradorite and augite, less frequently by hypersthene and olivine. Potassium feldspar is well developed in subalkaline rocks. Effusive rocks are attributed to the potassic-sodic (Na_2O/K_2O = 1-3) and potassic series with high alumina content. Titanium contents vary from 1% in Dagandaly rift rocks to 1.5% in effusive rocks of the Spassk rift and 2-3% in structures of Central Kazakhstan. Givetian volcanics are distinguished from the Lower Devonian by higher basicity, titanium, and potassium contents.

Numerous copper and gold-silver deposits (over 800) are attributed to Givetian volcanism. Ore deposits with intervein-impregnated copper mineralization (chalcopyrite, chalcocite, bornite) are traced in the form of lenses, stratified, and columnar bodies in altered andesite-basalts, andesites, and tuffs and in silicified graywacke tuff-sandstones as well. Pre-ore alteration of effusive rocks is represented by intensive epidotization, chloritization, silicification, and pyritization. Secondary changes are often accompanied by thin impregnations of pyrite and chalcopyrite. Some copper deposits are attributed to the copper-pyrite type. Quartz veins occur in volcano-sedimentary deposits and subvolcanic andesites and dacites of Givetian age.

The aforementioned copper and gold deposits are found in the Spassk and Dagandaly rifts. Numerous occurrences of sedimentary-type copper mineralization are well known in Givetian deposits in Central Kazakhstan. Cupriferous sandstones are located among coastal-marine and lacustrine speckled terrigenous rocks. Basanitoids are present in successions of ore fields. Copper was probably supplied to terrigenous sediments by hydrothermal fluids of volcanic origin.

The products of Late Devonian volcanism are well exposed in the latter parts of the Frasnian and Famennian. Earlier basalt flows are associated with accumulations of red molasse, and later flows with marine siliceous-carbonates deposited in silted stagnant basins. Upper Devonian volcanic rocks are confined to small disjointed rifts from 10 to 100 km long (Figs. 5, 8). In the western part of Central Kazakhstan (the Atasu, Ulytau regions), rifts face northeastward; in the central part (Uspenka sector) they have a sublateral orientation. Active volcanism is represented by quiet fissure eruptions of lava and by episodic explosive eruptions of basic pyroclastics. Lava flows have thicknesses of from 1 to 50 m and extend as much as 4-6 km. Coarse clastics (up to 8 cm) are represented by tuffs, and fine clastics by ash rocks and tuffites. The first form strata with thicknesses of from 2 to 15 m; the second form bands that are millimeters thick. The thickness of lavas and tuffs ranges from 150-250 m near eruptive centers to zero 5-7 km away, where they are replaced by tuffites and banded ash-flow tuffs, siliceous rocks, and iron-manganese ores.

According to petrochemical composition, the Upper Devonian rocks are composed of basalts, trachybasalts, subvolcanic bodies of trachytes, and gabbro-diabases. Basalts of the Frasnian stage are potassic, and those of the Famennian belong to the K-Na series. Albitized plagioclase, pyroxene, and olivine form well developed phenocrysts. The effusive rocks have been extensively affected by alkaline autometasomatism.

Basic industrial deposits of stratified iron-manganese ore and superimposed lead-zinc ores of the Atasu type are all connected with Late Devonian volcanism. The lead-zinc deposits of Karatau are traced in the Famennian stage. Their connection with volcanogenic processes is problematic. Syngenetic iron-manganese and lead-zinc mineralization in the Late Devonian rift structures may have had a global origin.

Acknowledgments — The author is grateful to Svetlana Popova for the English translation and to Drs. M.K. Apollonov and A.E.M. Nairn for help in editing the text.

References

Abdulin, A.A., ed., 1982. Magmatic complexes of Kazakhstan. Chingiz-Tarbagatai folded systems Alma-Ata, Nauka, 1966 p.

Abdulin, A.A., ed, 1982. Kokchetav-North-Tien-Shan folded system: Alma-Ata, Nauka, 235 p.

Bakhteev, M.K., Senkevich, M.A., and Yurina, A.L., 1984. Paleofloristic division of continental sedimentary-volcanogenic deposits of the Devonian in Kazakhstan; Bulletin MOIP, ser. geol., v. 59, no. 5, p. 82-92.

Bandaletov, S.M., 1969. Silurian of Kazakhstan: Alma-Ata, Nauka, 155 p.

Bogdanov, A.A., 1965. Tectonic zonation of Paleozoics of Central Kazakhstan and Tien-Shan: 1. Bulletin MOIP, ser. gool., v. 5, p. 40-68, 2 vol. 6, p. 8-38.

Bublichenko, N.L., 1945. New stratigraphic scheme of the Devonian deposits of the Northeastern part of Kazakhstan. Doklady Akademii Nauka SSSR, no. 5, p. 361-365.

Bublichenko, N.L., 1974. Devonian of Kazakhstan, in Borukaev, R.A., ed, Pre-Paleozoic and Paleozoic of Kazakhstan, v. 11: Alma-Ata, Nauka, p. 5-14.

Bublichenko, N.L., and Kaplun, L.I., 1973. Kazakhstan geosyncline region, in D.V. Nalivkin, ed., Stratigraphy of the USSR. Devonian system, Book 1: Moscow, Nedra, p. 462-474.

Kaplun, L.I., and Senkevich, M.A., 1927. New data on stratigraphy of the Middle Devonian of Central Kazakhstan. V.P. Sapelnikov, ed., Paleontology of the Lower Paleozoic of Urals, Sverdlovsk.

Luchitskiy, I.V., 1966. Comparative paleovolcanology of the Middle and Upper Paleozoic in Northern Siberia and Eastern Kazakhstan, Novosibirsk.

Marinov, N.A., ed., 1973. Geology of the Mongolian People's Republic, Moscow, Nedra, v. 1, 582 p.

Markova, N.G., 1969. The regularities of distribution of folded zones of different age with Central Kazakhstan as an example, in M.V., Muratov, ed., Folded regions of Eurasia. Moscow, Nauka, 376 p.

Mazarovich, O.A., 1976. Geology of the Devonian molasse, Moscow, Nedra, 204 p.

Mazarovich, O.A., Malinovskaya, S.P., Yurina, A.L., Belyaev, O.E., Vorontsova, T.N., Martynova, M.V., Ryazanova, A.V., Phedorov, T.O., 1985. Modern state of the stratigraphic scheme of the Devonian of the Central Kazakhstan. Bulletin MOIP, ser. geol., v. 60, no. 6, p. 71-93.

Mossakovskiy, A.A., 1975. Orogenic structures and volcanics of Eurasian Paleozoics and their role in the process of formation of continental Earth's crust. Moscow, Nauka, 315 p.

Nikitin, I.F., 1991. Conclusions of the third Kazakhstan Stratigraphic Meeting on Precambrian and Phanerozoic. Part 1, Precambrian and Phanerozoic, Alma-Ata, Nauka, 150 p.

Sergiev, N.G., 1948, Effusive rocks of the Central Kazakhstan. Alma-Ata, publishing house of the Academy of Sciences of the Kazakh SSR, 256 p.

Shuzhanov, V.M., 1984. The Devonian formations: Alma-Ata, Nauka, 221 p.

Sidorenko, A.V., ed., 1971. Geology of the USSR. South Kazakhstan: Moscow, Nedra, v. 50, 531 p.

Sidorenko, A.V., ed., 1972. Geology of the USSR. Central Kazakhstan: Moscow, Nedra, v. 20, Book 1, 582 p., Book 2, 380 p.

Yurina, A.L., 1988. Flora of the Middle and Late Devonian of Northern Eurasia: Moscow, Nauka, 176 p.

Development of the Famennian-Early Carboniferous Chu-Sarysu Basin and Its Hydrocarbon Potential

T.M. Shlygina

Abstract

The structure of the Famennian-Lower Carboniferous sediments of the Chu-Sarysu depression is analyzed. Study of this succession of strata in vertical sections reveals patterns of alternation of one sedimentary unit with another. Using the analytical methods of historical geology, the stages in the geological development of the region are established. Sedimentological characteristics of hydrocarbon reservoirs and the conditions governing their development are determined.

Introduction

The Chu-Sarysu basin is a large sedimentary depression in southern Kazakhstan where the presence of commercial deposits of hydrocarbons and of nitrogen and helium has been established. These deposits are confined to sedimentary rocks of late Paleozoic age. The rocks with the greatest potential are formations of Famennian-Early Carboniferous age. Most researchers consider these to be the main gas- and oil-bearing complex.

The depression is situated between exposures of the Precambrian rocks of the Bolshoi and Malyi Karatau mountains, Kirgizian Range, Ghu-Ili mountains, "Chu-Ili massif", and Sarysu-Teniz uplift. The geological structure of the depression reflects its connection with the Kokchetav-Northern Tien Shan system of the Caledonides of the Urals-Mongolian folded belt (Abdulin, 1981), having originated during the quasi-platform stage of development of the stable Caledonides (Shlygin, 1964). A major influence on the development of the depression was the presence of Precambrian crystalline blocks in the basement. Rocks of Caledonian age are of limited extent: on the pre-Mesozoic surface their outcrop is restricted to the Tasty elevation (Fedorenko, Azbel et al., 1991). The orogenic stage of development, represented by Lower and Middle Devonian sedimentary-volcanic rocks in the area of the Zhalair-Nayman fault and by thick red molasse of Middle and partly Late Devonian age, is reflected in the structure of the basement (Lee, 1975). Thick (up to 5 km) upper Frasnian-Permian deposits, represented by terrigenous carbonate salt-bearing rocks, are identified as an epi-Caledonian quasi-platform sedimentary cover, mantled by rocks of Mesozoic and Cenozoic age.

The basement of the Chu-Sarysu depression is divided into individual blocks by large, deep Caledonian faults. The differentiation and development of these blocks determined to a marked degree the structural plan of the region. The Talas-Tasty uplift in the central part of the depression created two trough systems — one northeastern, including the Tasbulak and Moinkum depressions, and one southwestern, made up of the Kokpansor and Suzak-Balkadam depressions (Fig. 1).

To understand how the basin developed, we must first study the sedimentary formations, which are considered integral units of the structure from an historical and geological point of view. Studies of the Famennian-Lower Carboniferous section have identified formations corresponding to particular periods and stages of the development of the basin. This information makes it possible to define stratigraphic volumes and depositional environments (Sinitsyn and Khromova, 1970) and to recognize new subunits and cyclothems. The terrigenous evaporites of the Famennian stage consist of three cyclothems, whereas the terrigenous carbonates of the Lower Carboniferous comprise Tournaisian dolomite, lower Visean cherty-clay-carbonate, lower and middle Visean carbonate, and Serpukhovian carbonate-evaporites.

A model of the Famennian-Early Carboniferous development of the Chu-Sarysu sedimentary basin has been constructed by analyzing the historical geology represented in the stratigraphic record. According to the data obtained, the basin originated during the Famennian stage, coinciding with deposition of evaporites, and achieved its final form during the Early Carboniferous marine transgression.

Evaporite Stage

By the beginning of the Frasnian, the orogenic movements that created the Caledonides of the Kokchetav-Northern Tien Shan massif had come to an end. Throughout the massif, orogenic uplift gave way to epeirogenic depression, ushering in a period of marine transgression.

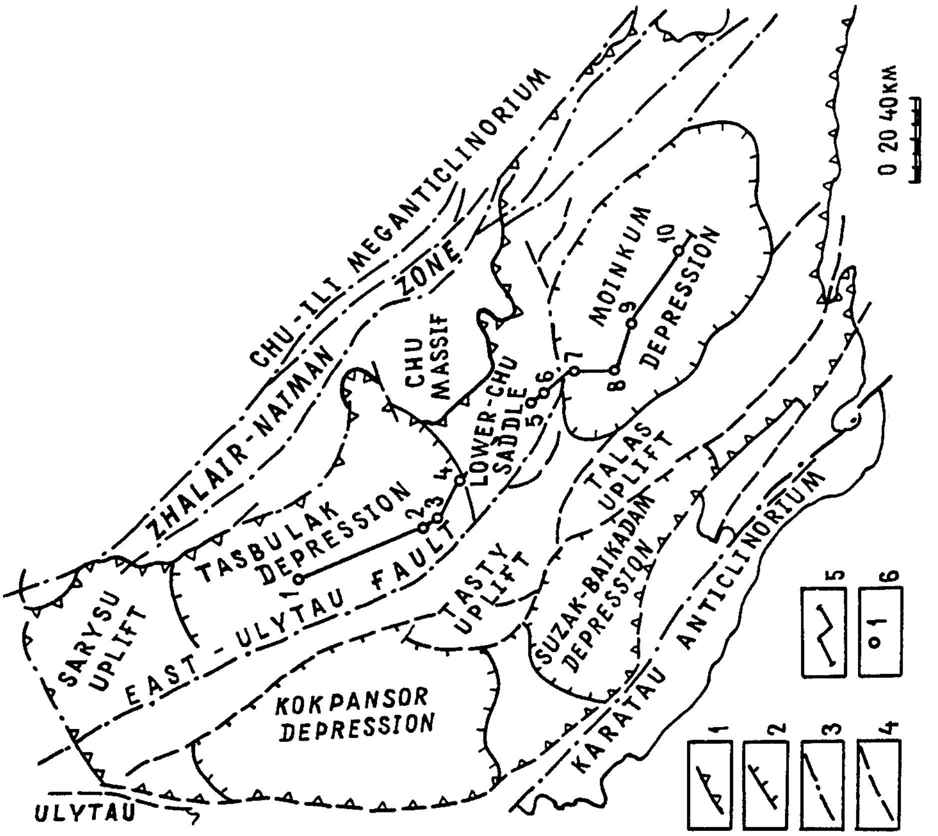


Fig. 1. Tectonic scheme of the Chu-Sarysu depression. Symbols: 1- boundaries of the depression; 2- boundaries of subsidence; 3- deep fault structures of the ancient initial stage; 4- tectonic displacement; 5- profile line of the section; 6- local structures: 1- North Karakoin, 2- North Izykyr, 3- Izykyr, 4- Sokyr-Toube, 5- Chuiskoye, 6- South Chuiskoye, 7- Barkhan, 8- Orynbai, 9- Ayrakty, 10- Karamatau.

Subsidence began in the northeast, in the Dzhungaro-Balkhash geosyncline, in the northwest, in the region of the Urals geosyncline, and also in the south, in the southern Tien Shan geosyncline. During the Famennian, seas entered the basin through a narrow strait joining it to the Dzhungaro-Balkhash geosyncline, in the eastern part of the modern Sarysu-Teniz divide (Vlasov, 1977). With a hot climate and low relief, the stable tectonic regime of the Chu-Sarysu sedimentary basin provided conditions favorable for deposition of evaporites.

Thus, in the northern part of the basin, three interconnected saline lagoons appeared. The sediments deposited in these lagoons are represented in the stratigraphic column by three salt-bearing cyclothems in which salt deposits are interbedded with terrigenous and carbonate rocks (Fig. 2). Such structures are characteristic of lagoonal evaporite basins and reflect the stages in the development of the basins. In evaporite basins, by analogy with coal-bearing basins, the carbonate and terrigenous beds within cyclothems (Sonnenfeld, 1988) represent periods during which the concentration of salt brine is reduced. Synchroneity of the evaporite cycles is established by dating ash-rich interbeds in sections deposited in individual lagoons (Fig. 2).

The lower cyclothem has a characteristic structure. It is formed of a thick terrigenous carbonate stratum and a thin horizon of anhydrite. The carbonate section is underlain by a bed of arkosic sandstone, representing alluvial-lacustrine sediments deposited on a littoral plain. Upwards in the section the sandstone gradually gives way to fine-grained, red carbonate rocks, which were deposited under hot climatic conditions in shallow basins, during a period when not even fine clastic sediment was carried into the basin and conditions favored carbonate deposition. With further increases in salt concentration, the waters of the lagoons became saturated in sulfate ions and gypsum was precipitated. The final, uppermost stratum of the lower cyclothem is a thin but widespread anhydrite horizon, which covers the northern and central parts of the Kokpansor and Tasbulak depressions.

This lower cyclothem corresponds to the earliest stage in the development of a salt basin, during which terrigenous sedimentation is gradually replaced by chemogenic sedimentation in some non-compensated basins. During this stage, the underlying, pre-evaporite marl stratum — a basic element of lagoonal salt basins (Sonnenfeld, 1988) — is succeeded by salt sedimentation.

The second cyclothem began with deposition of a thin bed of carbonate, reflecting a brief period when brine concentrations within the basin dropped because of a renewed influx of seawater. This increased inflow was apparently connected with a eustatic rise of sea level, in turn related to tectonic movements outside the Chu-Sarysu sedimentary basin. Breakup of the basin into separate areas with different rates of subsidence and the increase of brine concentrations in the lowest areas led to deposition of halite interbedded with gypsum in the Moinkum and central Betpak-Dala depressions. Rates of subsidence were also large in the Tasbulak depression, but because of the magnitude of this structure, salt concentrations decreased more slowly, and a thick formation of gypsum formed as a result. The second cyclothem, as the first, corresponds to the formative stages of development of a salt basin.

The third cyclothem represents the primary period of evaporite deposition in all three basins, and so the largest volumes of halite and gypsum are found within it. As Sonnenfeld (1988) noted, for thick beds of halite to form in an evaporite basin, it is necessary to have a hot climate, an imbalance between influx and evaporation, and uncompensated subsidence to generate large basins with areas of rapid synsedimentational subsidence. Shelf and shoal areas represent the passive margins of the salt basin, where brine can become concentrated and where gypsum can be accumulated. According to Sonnenfeld's calculations, these areas must be 2.5-4 times greater than the area of halite deposit. The next requirement for thick halite deposits to form is rapid subsidence of part of the basin. This is because halite precipitates very rapidly and quickly fills the basin. In order for the parts of the basin in which halite has been deposited not to become full and for precipitation to continue, the rate of sedimentation must be 5-7 times greater than the rate of subsidence of the passive margins. As Sonnenfeld (1988) noted, thick salt formations almost always form in regions with the highest rates of subsidence. Thus, salt basins tend to form in the atrophied branches of aulacogens and troughs, defined by systems of deep, almost vertical faults, as well as in depressions bordering mountain fronts.

These preconditions for deposition of thick beds of halite were certainly met in the Chu-Sarysu depression, where salt-generating lagoons formed above deeply subsident blocks that were separated from uplifted blocks by large synsedimentary faults. The most active of these was the East Ulytau fault (Fig. 1).

The third cyclothem represents the final stage, covering the "halite" phase in the development of the basin. By this time, the Chu-Sarysu basin was distinctly differentiated into vast areas with high rates of subsidence, in which thick halite formations accumulated, and areas with low rates of subsidence, the passive margins, where brine was being concentrated.

The evaporite section of the Chu-Sarysu depression is transgressive. It is capped by a surface of solution and overlapped by marine sediments (Figs. 2, 3).

Marine Stage

During the Early Carboniferous, the Chu-Sarysu marine basin completed the full cycle of development, in the course of which it evolved from the salt lagoons of the Famennian to the continental plain of the mid-Carboniferous. All of this is reflected in the development in stages and orientation of sedimentational processes. Based on the historical and geological analysis, four subformations have been distinguished, namely, dolomite, cherty-argillaceous-carbonate carbonate, evaporite-terrigenous-carbonate (Fig. 3), and accordingly four stages in the development of the Early Carboniferous marine basin, namely, transitional, initial, main, and final, are recognized.

A dolomite subformation is distinguished in the lower part of the Lower Carboniferous terrigenous-carbonate formation, which overlies, with erosional contact, terrigenous Famennian evaporites and transgressively overlaps eroded basement rocks in some places. The stratigraphic position of the dolomite subformation corresponds to the Tournaisian stage. It is readily distinguished within the limits of the salt-generating basin and differentiated from the overlying and underlying formations. Uniform facial composition and stable thickness in some depressions, which are characteristic of the subformation, were the result of infilling of the basin by Devonian salts and the simultaneous lowering of brine concentrations throughout the basin, except for basin margins and isolated parts.

The dolomite subformation was deposited during a transitional stage in the development of the Chu-Sarysu sedimentary basin (from evaporitic to marine), an interval corresponding to the Tournaisian. During this time, marine transgression expanded far beyond the basin and there was a renewed influx of seawater, bringing brine concentrations to lower and lower levels until seawater reached normal levels of salinity. The drop in brine concentration halted salt precipitation and led to the partial solution of Devonian salt. When the situation reversed, the chemical precipitation of salt resumed. This process, described by Sonnenfeld (1988), characterizes the "regressive salinity phase" of Richter-Bernburg (1977) and the "transgressive phase" of Hite (1970). As a result of salt precipitation, the dolomite content gradually decreased from the lower parts of the subformation to the upper, and limestone and marl took its place. Analytical data show that dolomite in the lower part of the section amounts to about 70% and in the

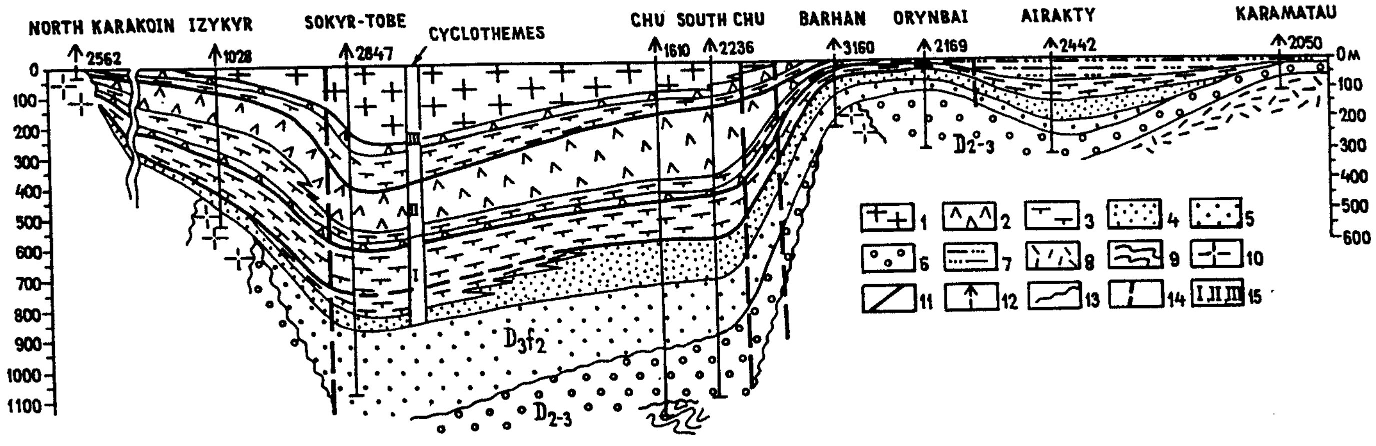


Fig. 2. Lithofacies profile of pre-Tournaisian, Upper Devonian deposits. Symbols: 1- rock salt (halite); 2- massive anhydrites; 3- pre-evaporite terrigenous-carbonate deposits; 4- arkose sandstones, alluvial-lacustrine formations of the littoral plain; 5- upper Famennian deposits; 6- Middle-Upper Devonian deposits; 7- continental red beds; 8- sedimentary-volcanogenic formations of the Middle-Upper Devonian; 9- metamorphic rocks; 10- magmatic rocks; 11- interlayers enriched with ash; 12- wells; 13- erosional surfaces; 14- synsedimentary faults; 15- cyclothems.

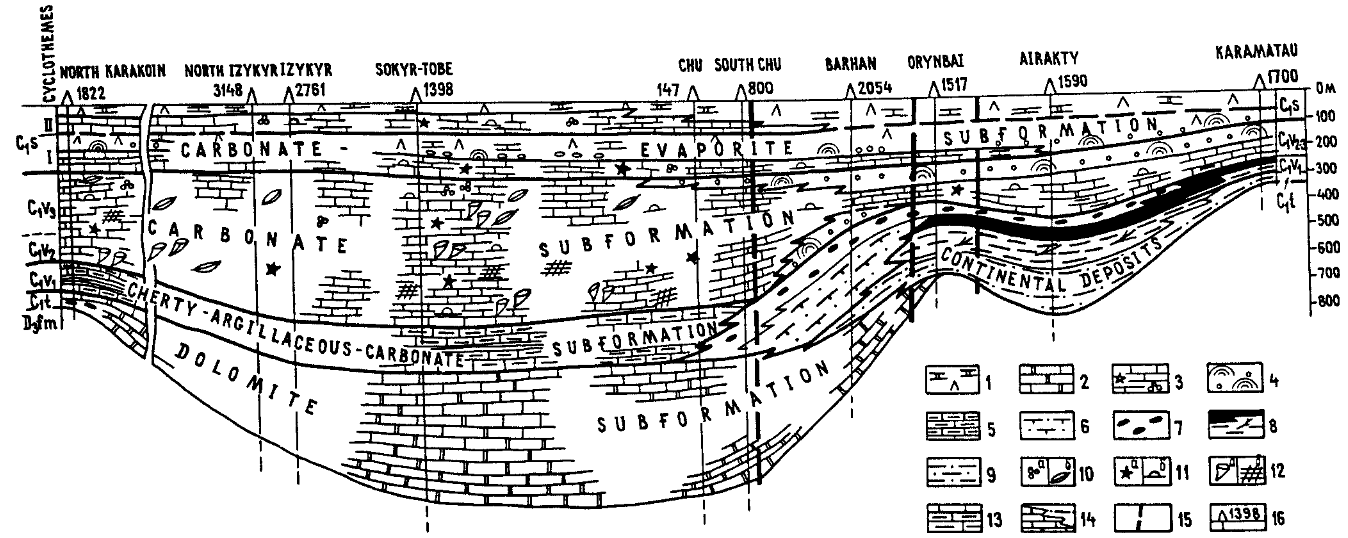


Fig. 3. Lithofacies profile of the Lower Carboniferous deposits. Symbols: 1- microgranular dolomites and anhydrites, formations of saline basins; 2- dolomites and dolomitic limestones, formations of the desalinization of saline basins; 3- marine massive limestones; 4- oolitic-algal limestones, formations of the nearshore marine and shoals; 5- black argillaceous limestones and marls, formations of a stagnant basin; 6- undifferentiated carbonate-terrigenous deposits of littoral lagoons and gulfs; 7- differentiated marine sandstones, bar deposits and beaches; 8- aleuro-argillites with carbonized plant remnants; deposits of the alluvial-lacustrine littoral plains, grading into aleuro-argillites with interlayers of coal, deposits of the lacustrine-swampy littoral plains; 9- sandy-argillaceous multicolored deposits of the alluvial-lacustrine plains; 10- foraminifera (a), ostracods (b); 11- echinoderms (a), brachiopods (b); 12- corals (a), bryozoan (b); 13- boundary between subformations; 14- facies replacement; 15- synsedimentary faults; 16- wells, showing depth to top of the Serpukhovian deposits.

upper part 0%, while the calcite content increases from 2-3% in the lower part to 70% in the upper.

Reduction of brine concentration in the basin was a lengthy process. The greater the volume of brine, the more water and time are needed before precipitation of one of the evaporite minerals is replaced by precipitation of another, and these factors account for the difference in thickness of the dolomites deposited in the Tasbulak and Kokpansor depressions (in the former 0.5 km and in the latter a maximum of 150 m).

During the Tournaisian stage, deposition of dolomite was widespread. Dolomite has been recorded in the eastern sections of Betpak-Dala and Malyi Karatau, but the thickest formations (up to 1.5 km) accumulated in the Bolshoi Karatau (Marfenkova and Valeev, 1986). In the northern part of the Chu-Sarysu depression and also along the Sarysu-Teniz uplift, irregular dolomitic limestones developed.

The dolomite subformation is conformably overlapped by the cherty-argillaceous-carbonate subformation, which transgressed over the terrigenous Tournaisian formations of the eastern Betpak-Dala, Kirgizian mountains, and some outcrops of eroded basement within the depression. The stratigraphic level of the cherty-argillaceous-carbonate subformation corresponds to the early Visean stage. The facies are very stable, and the subformation has a distinctive character that sets it apart from the underlying and overlying deposits. It is represented mainly by black, often silicified, thin argillaceous-carbonate, carbonate-argillaceous rocks in which phosphatic material and large numbers of siliceous sponges are present.

The aforementioned deposits represent the initial stage in development of the Chu-Sarysu marine basin, during which a normal marine regime was established throughout most of the Chu-Sarysu depression. Low relief, even during the Devonian, accelerated marine transgression. Continental terrigenous sedimentary environments existed only in the southeastern part of the depression and to the east and south of it, partially occupying the area of the modern Dzhalair-Naiman elevation and the Kirgizian mountain range. On the west, the sea was separated from the Central Asian sea by a narrow belt of islands, represented now by Malyi Karatau and Ulytau; to the north and northeast, beside the modern Sarysu-Teniz uplift and Dzhungaro-Balkhash geosyncline, it was open.

In early Visean time, deposition of the distinctive black argillaceous carbonates, referred to as "black shales", occurred throughout the basin. Analyses of the available data show that one of three models (Hallam, 1983) for deposition of "black shales" (i.e., formation in shallow epicontinental seas during periods of transgression, where stagnant conditions are promoted by high organic productivity, warm damp climate, and limited water circulation) is fully applicable to the early Visean Chu-Sarysu sea basin, where the climate was humid (Vlasov, 1977) and, with uninterrupted transgression, large areas of coastal plain were submerged and produced great quantities of organic and argillaceous material. Gradually subsiding, low, swampy plains were the source of supply for organic material. The plains were situated in the southern and southeastern parts of the basin, within the Moinkum depression and Chu massif. These conditions led to establishment of a stagnant water regime, characterized by an oxygen deficit and the generation of hydrogen sulfide by sulfate-reducing bacteria. Decay of organic material caused the decrease in oxygen concentration (Tisso and Velte, 1978).

The presence of phosphatic material in the central part of the basin and glauconite in the nearshore zone (the area of transition between the Tasbulak and Moinkum depressions) confirms the above, because these materials tend to occur in horizons formed in reducing environments during periods when marine organisms are undergoing mass die-off (Leeder, 1982).

During the second half of the early Visean, an influx of abundant detrital volcanomictic material (tephrites) from the region of the Chu-Ili uplift transformed the coastal zone at the boundary between the shallow epicontinental sea and the wide coastal plain (an area now situated within the modern Moinkum depression) to a shoreline characterized by offshore bars, barrier islands, near-shore bars, spits, and low ridges behind which lagoons, bays, coves, and tidal flats formed. During transgression, the barrier islands were displaced toward land or breached by erosion. As a result, sedimentary facies migrated landwards by the lateral displacement of the different sedimentary environments. At the end of the early Visean, the sea "overlapped" the region of the present-day Moinkum depression, and the lacustrine and paludal sedimentational environment was transformed into a shallow nearshore-marine environment.

Thus, during an initial stage in its development, in the early Visean, the Chu-Sarysu sea assumed the form of a shallow-water basin in which carbonate clay were deposited from oxygen-deficient seawater. Although these muds were rich in organic matter, the oxygen-poor zone was not very deep, and as a result of uplift, in places the oxygen content was subject to periodic increases and organic-detrital argillaceous limestones accumulated. As in previous periods, the region of maximum subsidence lay in the Tasbulak depression.

The cherty-argillaceous-carbonate subformation is conformably overlapped by the carbonate subformation, uniting middle and upper substages of the Visean stage. Typically, this subformation contains an abundance of organic-detrital and biomorphic limestones and relatively little terrigenous material. Deposition of the carbonate subformation coincides with the main stage in development of the marine regime during middle-late Visean time. Sea level reached a maximum at the beginning of the middle Visean, bringing an end to the influx of terrigenous material and ending transgression in the Chu-Sarysu depression. The sea then gradually became clear and active precipitation of carbonates began. Later in the middle Visean, regression began, and sea levels continued to fall until the end of the Visean.

The main stage in development of the marine regime occurred under hot climatic conditions, when the influx of terrigenous material was at a mimimum. In the Chu-Sarysu basin, this created an environment favorable for the growth of marine organisms. Thus, various carbonate structures developed and bioherms became numerous, although they did not grow beyond a certain size because sea level remained stable throughout most of the middle Visean.

In middle and late Visean, deposition of organogenic and detrital limestones was widespread, and these rocks constitute most of the sections of the Bolshoi and Malyi Karatau, East Betpak-Dala, and Kirgizian ranges, where, up until the end of the Visean, the tendency to regression is also evident because unlike the rocks of the Chu-Sarysu basin, the aforementioned sections also contain terrigenous sediments. To the north, in the region of the Sarysu-Teniz uplift, the terrigenous rocks became more widely developed, forming interlayers among the limestones of the middle Visean and dominating the upper Visean section.

The final stage in development of the Chu-Sarysu sea basin coincides with the Serpukhovian stage. During this time, regression, already evident toward the end of the Visean, intensified, so that by the mid-Carboniferous, in most of the Chu-Sarysu basin, the marine regime had given way to a terrigenous depositional environment. The deposits of this final, Serpukhovian stage consist of a cyclical sequence of carbonate-evaporites that is distinguished as an independent subformation. The carbonate-evaporite subformation rests conformably, with rare, insignificant erosion, on upper Visean sediments and overlaps the multicolored, mainly sulfate-terrigenous rocks of the Middle Carboniferous. It is readily distinguished from the aforementioned units because of the variety of facies that it encompasses.

In the sections of the Serpukhovian stage, two transgressive-regressive cycles are evident; however, the initial transgressive phases were relatively short, and the bulk of the rocks reflect long regressive phases. The transgressive-regressive cycles that developed in the Chu-Sarysu basin during Serpukhovian time correspond to the type 1 and 2 cycles of Wilson (1975). Both cycles are peculiar to shallow epicontinental seas that are in the process of becoming shallower. The lower cycle begins with marine organic-detrital limestones and ends with the deposits of lagoons and subsaline sabkhas. Thin carbonate muds accumulated only in the southeastern and southern parts of the paleodepressions, within the modern Moinkum depression and the eastern part of the Talass uplift, which represented relatively uplifted parts of the sea bottom with limited circulation. In contrast, during the Late Serpukhovian cycle, thin carbonate and carbonate-sulfate formations were the most widespread types of sediment. This is evidence that Late Serpukhovian transgression was not significant and that with sufficiently rugged relief, which formed during early Serpukhovian time due to the growth of organogenic structures, conditions were favorable for the formation of partly isolated and isolated basins. The latter, thanks to the rapidity of carbonate formation, became filled with the thin carbonate sediments. Marine conditions lasted longest in the southwestern parts of the basins, which were open to the Bolshoi Karatau depression, and in the northern part of the Tasbulak depression.

To the end of Serpukhovian time the Chu-Sarysu paleobasin was a vast nearshore plain, sabkha-like, with separate lagoons and salt lakes. On the south, east, and north the Chu-Sarysu paleobasin was surrounded by alluvial plains, and only in the west, in the Bolshoi Karatau, did the relic sea basin remain.

Historical geological analysis thus shows that during Famennian-Early Carboniferous time, the Chu-Sarysu depression was a typical shallow epicontinental sea basin that had developed in a hot climate and under a stable quasi-platform regime, which in its formative stage was characterized by the deposition of salt.

Sedimentological Characteristics of Reservoir Rocks

Numerous exploratory and research studies conducted by the Geological Ministries of the Kazakh SSR and USSR (former) and also by the National Academy of Sciences of the Republic of Kazakhstan have established the presence of gas in the Chu-Sarysu sedimentary basin. The calculated resources of gaseous hydrocarbons are respectable, but large deposits have not been found yet and preparation for exploratory drilling has been inadequate, so work was suspended in 1984. The main difficulties in finding hydrocarbon accumulations in the basin are connected with determining the drilling targets and with establishing criteria for predicting where reservoir rocks might form.

Studies of reservoir characteristics of productive horizons and the physical properties of impermeable caprocks were conducted by several organizations. Based on laboratory studies, different types of reservoirs were distinguished and characterized.

The most permeable rocks in the Chu-Sarysu depression are in pore-type and cavernous-pore type reservoirs in organic and organic-detrital limestones of the Visean and

Serpukhovian stages, where the open porosity varies from 2.5 to 35%, averaging 5-13.2%.

The best terrigenous reservoirs in the Chu-Sarysu depression are fine- and medium-grained sandstones with low cement content. Porosity in these rocks is more than 18%, and the gas-saturation coefficient is 0.7-0.9, which places them in the N 3-4 class by Khanin's (1965) classification. It has also been established that reservoirs of the first type are prevalent within depressions and that these have relatively high permeability (>10-100 md) and porosity (18-25%). In more tectonically mobile structures, such as the slopes of the depression, rocks with poor reservoir characteristics (porosity 6-8%, permeability <1 md) have developed (Filipyev and Kusherbayev, 1983). Reservoirs are not distributed throughout the entire basin.

Different types of rocks in which systems of interconnected pores have developed may serve as reservoirs. Selley (1981), who studied the morphology of pore spaces, found that there are two main genetic groups of pores: primary, or primary-sedimentary, and secondary, or post-sedimentary. However, the mechanism of formation of primary and secondary pore space is controlled by the composition and content of the rocks, and is thus predetermined by sedimentational processes. For this reason, the reservoir characteristics can be predicted only with the help of detailed lithologic-petrographic, facies-paleogeographic, and historical-geological analyses.

Famennian-Lower Carboniferous sediments of the Chu-Sarysu depression are represented by various sedimentary rocks. The composition of these rocks is closely connected with their stratigraphic position in the section, and this is a function of the stage of development of the basin. Thus, inquiries into how porosity formed in the rocks must be made in terms of the formations and subformations that have been distinguished.

Famennian Terrigenous Evaporite

The structure of the Famennian terrigenous evaporite, consisting of three cyclothems, beginning with the terrigenous or carbonate-terrigenous sediments and ending with salts, predetermines the possibility of reservoirs forming in the lower parts of the cyclothems. Rocks with primary reservoir characteristics could only have formed in the salt-generating basins during the initial stage of the development of the basins. In the Chu-Sarysu basin, arkosic sandstones formed at this stage, but intense silicification and intensive secondary alteration with the formation of secondary textures conforming to the preserved primary textures and stylolitic contacts have made them impermeable. Microgranular limestones, dolomites and marls, which developed in the lower parts of the first and second cyclothems, cannot be considered as potential reservoirs because the pores in these rocks became filled by early diagenetic dolomite or gypsum. Thus, interest focuses on the sandstones and aleurolites at the base of the third cyclothem, formation of the interstices of which is connected with dissolution of carbonates, sulfates, and rarely halite cement by subsalt water within the rocks. In the presence of hydrocarbons, calcite and anhydrite are dissolved in greater quantity (Chepikov et al., 1972).

Lower Carboniferous Terrigenous/Marine Carbonates

In the dolomite subformation of the Tournaisian stage, rocks with poor primary reservoir characteristics prevail. This is connected with the fact that primary dolomites developed in the lower parts of the subformation, and microdetrital, mud, ballstone limestones, with a large content of thin matrix, developed in the upper parts. All the joints and small stylolitic sutures are "healed" by calcite, anhydrite, and rarely silica.

Lower Visean Cherty Argillaceous Carbonates

The lower Visean cherty carbonate subformation is represented by metachert limestones and marls with interlayers of argillites and spongolites (rocks composed largely of fossil sponges). The abundance of thin beds of argillaceous and carbonate-argillaceous material gives the subformation a low primary porosity. Authigenic mineralization is widely developed in the rocks of the lower Visean (silica, pyrite, feldspar, phosphate minerals), which is why the presence of joints and numerous microstylolites does not improve the porosity or the permeability. During the early Visean, in the southeastern part of the depression, a coast with offshore bars had formed, with sand bars and barrier islands, etc., situated subparallel to the coastline. Subsequent transgression partially destroyed these. In addition, the most porous deposits were intensively silicified. Thus, in this subformation the best reservoir characteristics are found in sediments deposited in gulfs, bays, and tidal zones, represented by fine-grained sandstones and aleurolites formed by the reworking of volcanic materials.

Middle-Upper Visean Carbonates

The middle-upper Visean carbonate subformation consists of limestones that generally contain large quantities of thinly bedded carbonate mud, which reduces the overall porosity of the subformation to zero. Within the region of the Moinkum depression, which represented an uplifted part of the sea bottom, leaching processes were widespread owing to the porosity of accumulations of oolitic limestone and calcareous and shelly sandstones. The lower parts of the carbonate subformation in this region also contain accumulations of graywacke and arkosic sandstones. The graywackes, as in the lower Visean, are weakly cemented and serve as reservoirs; however, the arkosic sandstones are practically impermeable. In the carbonate sediments of the middle-upper Visean, authigenic mineralization is weakly developed, and open joints and stylolites are characteristic features.

Serpukhovian Carbonates and Evaporites

Among the sediments of the Serpukhovian carbonate and evaporite subformation, deposited during a period of marine regression, of greatest interest are the oolitic, algal, stromatolitic limestones, shelly, calcareous sandstones, and gritstones of the upper parts of the lower cycle, which have numerous leaching cavities and desiccation fissures. On the other hand, terrigenous sulfatic formations of the upper parts of the lower cycle are largely impermeable. In the Tasbulak-Moinkum depression, tuffaceous argillites and sandstones situated in the upper parts of the lower cycle may be regarded as cap rocks. Rocks in the upper cycle that may serve as reservoirs include clayey limestone, calcareous gritstones, and pelitomorphic limestones with numerous leached cavities, all of which are developed in the Kokpansor and Tasbulak depressions. In the Moinkum depression, these rocks form the entire section.

The primary reservoir rocks in the carbonate sediments of the Lower Carboniferous are thus to be found in a regressive series of sediments, represented by oolitic and algal limestones and shelly, calcareous sandstones and siltstones. Of greatest interest are the sediments of the upper part of the lower transgressive-regressive cycle of the Serpukhovian stage.

References

Abdulin, A.A., 1981. Geology of Kazakhstan. Alma-Ata, Nauka, 312 p. (in Russian).

Chepikov, K.P., Ermolova, E.P., Orlova, N.A., and Surkova, G.I., 1972. Postsedimentational Transformations of the Reservoir Rocks. Moscow, Nauka, 90 p. (in Russian).

Fedorenko, O.A., Azbel, K.A., Marchenko, I.S., and Neganov, Yu.K., 1981. The peculiarities of the formation and mineralogy of quasiplatform cover of the Chu-Sarysu depression. In: Geology and Mineral Resources of South Kazakhstan (edited by E.D. Shlygin). Alma-Ata, Nauka, p. 203-218 (in Russian).

Filipyev, G.P., and Kusherbaev, A.M., 1983. Main gas reservoir types in the middle-upper Paleozoic deposits of the Chu-Sarysu syneclise. In: Reservoirs of Oil and Gas and Fluid Impermeability (edited by F.G. Gurari and M.K. Kalinko). Novosibirsk, Nauka, 137 p. (in Russian).

Hallam, A., 1981. Facies Interpretation and the Stratigraphic Record. Oxford and San Francisco, W.H. Freeman and Co., 291 p.

Hite, R.J., 1970. Shelf carbonate sedimentation, controlled by salinity in the Paradox Basin, Southeast Utah. 3rd Symp. on Salt, v. 1, Cleveland, Ohio, p. 48-66.

Khanin, A.A., 1965. Basic Studies on Reservoir Rocks of Oil and Gas. Moscow, Nedra, 342 p. (in Russian).

Lee, A.B., 1975. Tectonics and Prospects for the Gas and Oil Presence of the South Kazakhstan. Alma-Ata, Nauka, 320 p. (in Russian).

Leeder, M.R., 1982. Sedimentology — Process and Product. London, George Allen and Unwin, 439 p.

Marfenkova, M.M., and Valeev, F.Ya., 1986. Bolshoi Karatau Tournaisian stage. In: Geology and Metallogeny of Kazakhstan, v. 1: Geology (edited by A.A. Abdulin). Alma-Ata, Nauka, p. 68-74 (in Russian).

Richter-Bernburg, G. , 1977. Einflusse progressiver Salinitat auf Entstehung und Strukturformen von Salzgesteinen — eine Problematik des Muschelkalksalzes. Jahresber. Mitt. Oberrhein. Ver., 59, 273-301 (in German).

Selley, R.C., 1976. An Introduction to Sedimentology. London, Academic Press, Inc., 408 p.

Shlygin, E.D., and Shlygin, A.E., 1964. Some principles of geotectonic zonation of Kazakhstan. In: Folded Regions of Eurasia (edited by M.B. Muratov). Moscow, Nauka, p. 78-93 (in Russian).

Shlygin, E.D., ed., 1982. The Tectonic Development and Prospects for Gas and Oil Presence of the Chu-Sarysu Depressions. Alma-Ata, Nauka, 160 p. (in Russian).

Sinitsyn, F.E., and Khromova, N.R., 1970. Epigeosynclinal formations of the middle-upper Paleozoic of the Chu-Sarysu syneclise and prospects for gas and oil presence. In: Geology and Prospects for Gas and Oil Presence in Middle Asia (edited by G.A. Arzhevskyi). Moscow, VNIGNI, p. 141-163 (in Russian).

Sonnenfeld, P., 1988. Brines and Evaporites. London, Academic Press, Inc., 480 p.

Tissot, B.P., and Welte, D.H., 1978. Petroleum Formation and Occurrence. New York, Springer-Verlag, 463 p.

Vlasov, V.I., 1977. Paleogeography and prospects for gas and oil presence of the middle and upper Paleozoic of the Chu-Sarysu depression. In: Geology and Oil and Gas Presence of Kazakhstan (edited by S.E. Chakabaev). Alma-Ata, Nauka, p. 122-128 (in Russian).

Wilson, J.L., 1975. Carbonate Facies in Geologic History. New York, Springer-Verlag, 471 p.

Evolution of Paleozoic Magmatism of Kazakhstan

G.F. Lyapichev, E.Yu. Seitmuratova, B.I. Rusanov

Abstract

The analysis of the Paleozoic magmatic rocks of Kazakhstan shows the regular character of the evolution of their natural associations-formations. All magmatic formations lie in one of three vertical successions: ortho-, medio- and para-geosynclinal, according to the present authors. Every group is characterized by a definite composition and sequence of formations.

In the Paleozoic history of the Kazakhstan part of the Urals-Mongolian fold belt, the groups of formations changed, one to another, in a regular succession from orthogeosynclinal to parageosynclinal, reflecting a constructive tendency in the evolution of the Earth's crust. The evolution of the structural-compositional features of the magmatic formations is reflected by silicic-potassic tendency of the change in their geochemistry. In time, that tendency is characteristic for any vertical formation succession and for every magmatic formation, which is part of a succession.

This regularity is characteristic for the Urals-Mongolian folded belt as well as for the magmatism of any folded belt on Earth.

Introduction

Kazakhstan lies in the southwestern part of the Paleozoic Urals-Mongolian fold belt, one of the largest tectonic structures of the Eurasian continent. Deep, transverse fault zones divide the belt into two branches: the meridional Ural and the latitudinal Mongolian (Fig. 1).

The history of formation of the Paleozoic structures of the belt is characterized by a complex combination of constructive (reflecting a general trend in crustal evolution) and crustal destructive processes, each of which followed its own unique course. The Kazakhstan segment is regarded as including two groups of differentiated fold systems — Caledonide and Hercynide (Shatskiy, 1936; Kassin, 1952; Bogdanov, 1965; Bespalov, 1971) — each divided into tectono-stratigraphic zones with a definite succession and age of formation. The boundaries between these systems and tectonic-stratigraphic units are interpreted differently. In this article, magmatic evolution is addressed based upon the following assumptions:

1. magmatic rocks are direct indicators of processes operating within the planetary interior, including changes in structure and composition of the crust;
2. as a result of magmatic processes, natural associations (i.e., magmatic complexes) develop, and in conjunction with sedimentary and metamorphic rocks, provide material evidence of former magmatic (and general geological) evolutionary processes in the earth's crust;

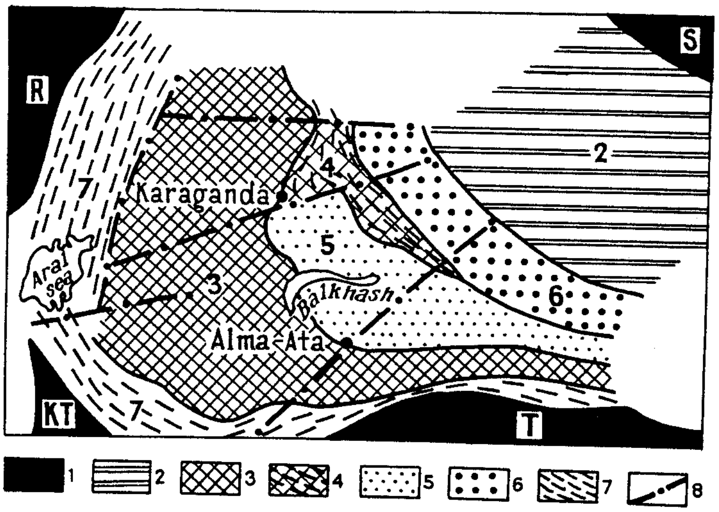


Fig. 1. The Kazakhstanian part of the Urals-Mongolian folded belt. 1- Platform and platform massifs: R- Russian Platform, S- Siberian Platform, KT- Karakum-Tadzhikian massif; 2-4- Caledonian folded systems: 2- Altai-Sayan system, 3- Kokchetav-Northern Tien-Shan system, 4- Chingiz-Tarbagata system; 5-7- Hercynian folded systems: 5- Dzhungar-Balkhash system, 6- Zaisan system, 7- Ural and Median-Southern Tien-Shan system; 8- megablock boundaries.

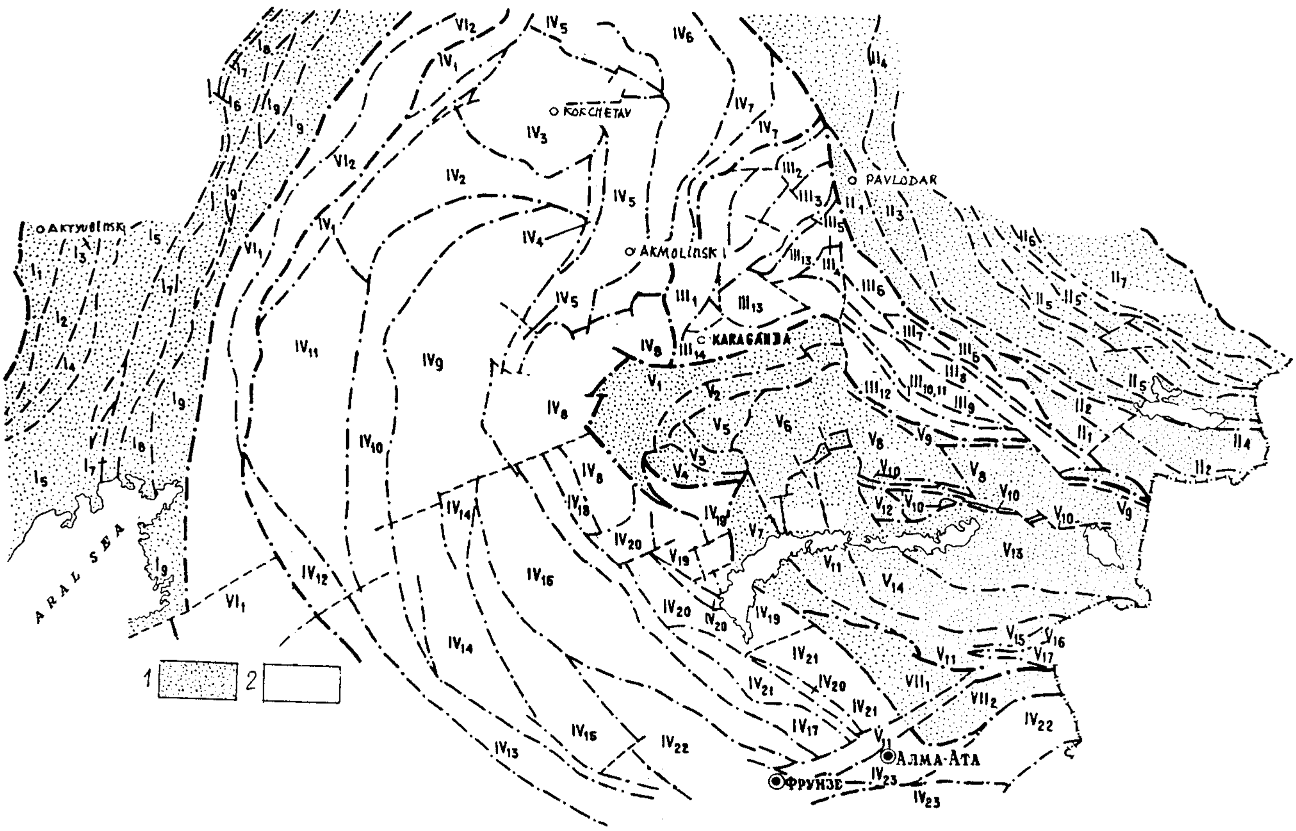


Fig. 2. Folded systems and structural-formational zones of Kazakhstan Paleozoics. 1- Hercynian folded systems: I- Uralian, II- Zaisan, V, VII- Dzhungar-Balkhash; 2- Caledonian folded systems: III- Chingiz-Tarbagatai, IV, VI- Kokchetav-Northern Tien-Shan. Figures on the scheme correspond to: I- Uralian system, zones: I1- Zilair, I2- Sakmara, I3- Uraltau, I4- Western Mugodzhary, I5- Urals-Tobolsk, I6- Kartaly-Bredin, I7- Ulgasyn-Dzhetygara, I8- Troitzk, I9- Kustanay; II- Zaisan system, zones: II1- Zharma (Zharma-southern Saur), II2- Sarsazan-Northern Saur, II3- Koyandy-Arkalyk, II4- Chara, II5- Kalba-Narym, II6- Irtysh, II7- Rudnyi-Altay group; III- Chingiz-Tarbagatay system zones: III1- Ermentau, III2- Boshchekul, III3- Kendyktas, III4- Bayanaul, III5- Maikain, III6- Arkalyk, III7- Chunai, III8- Central Chingiz, III9- Sargaldak, III10- Koksengir, III11- Akchatau, III12- Kosmurun, III13- North Karaganda, III14- Temirtau; IV- Kokchetav-Northern Tien-Shan system zones: IV1- Mar'evka, IV2- Kalmakkol, IV3- Kokchetav, IV4- Stepnyak, IV5- Stepnyak-Zhaksykon, IV6- Aksu, IV7- Bestyube and Priselety, IV8- Priatasu, IV9- Ulytau, IV10- Baikonur, IV11- South Turgai, IV12- Median Syrdar'ya, IV13-Karatau, IV14- Malyi Karatau, IV15- Terskei, IV16- Chu, IV17- Zhalair-Naiman, IV18- Kenzhebai, IV19- Western Mointy, IV20- Sarytuma, IV21- Zheltau, IV22- Agalatas-Chonkemin, IV23- Issykkul; V- Dzhungar-Balkhash system zones: V1- Atasu-Nura, V2- Southern Uspenka, V3- Akzhal-Aksoran, V4- Atasu-Mointy, V5- Zhaman-Sarysu, V6- Tokrau, V7- Eastern Mointy, V8- Kalmakemel-Bakanas, V9- Prichingiz, V10- Northern Sayak, V11- Kotyrasan, V12- Northern Balkhash, V13- Northern Dzhungar, V14- Sarkand, V15- Central Dzhungar, V16- Borotaly, V17- Southern Dzhungar.

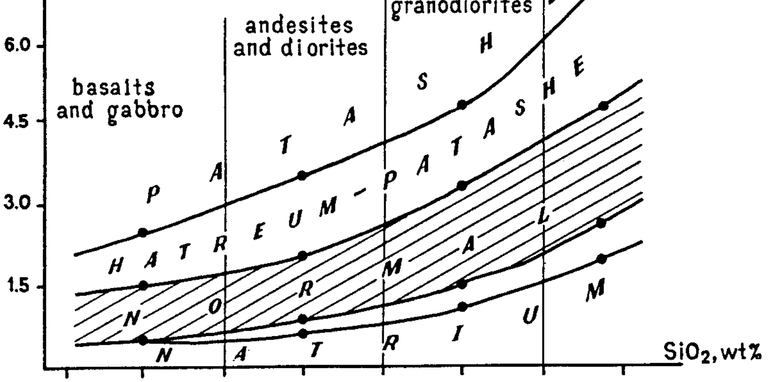


Fig. 3. Classification of mesocratic (normal) magmatic rocks.

3. the dynamic cycle of tectonic activity, from the onset until complete cessation, is recorded in the compositional and structural characteristics to which the magmatic rock groups correspond;
4. the nature of changes in magmatism and the silicic-potassic tendency that reflects a stable evolutionary trend of magmatic chemistry within developing fold belts are keys to an understanding of the dynamics of magmatic activity (Antonyuk et al., 1977).

Before passing to the characteristics of magmatic evolution, refer to the scheme used to classify magmatic rocks and formations, shown on Figs. 2, 3. Numerous histograms of volumetric proportions of rocks in actual magmatic complexes (Fig. 4), which in Kazakhstan are mainly volcanogenic, were used to create this classification.

Types of Magmatic Formations

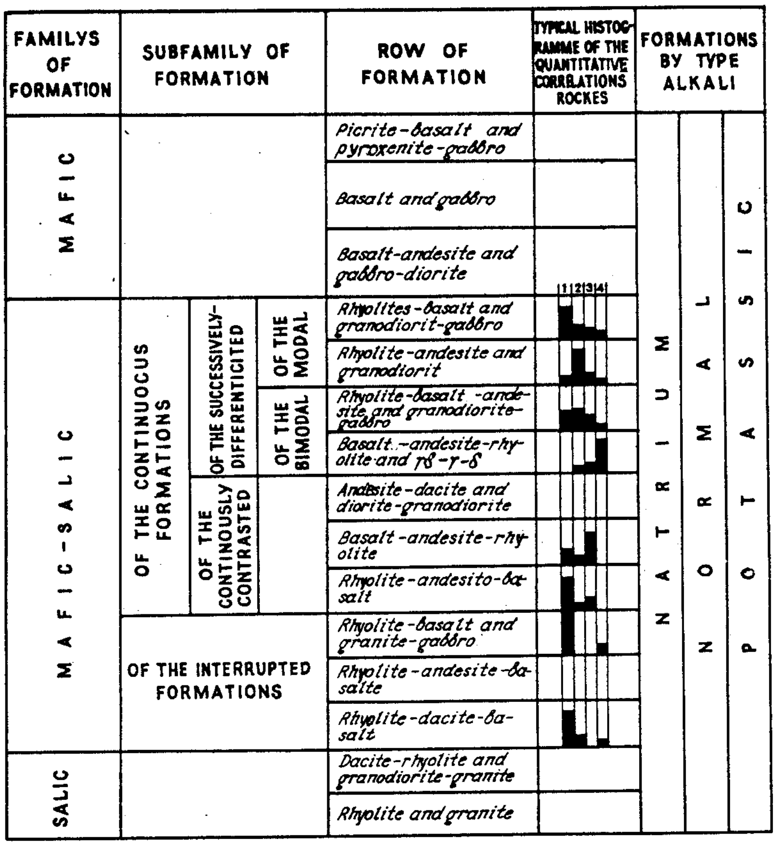
Three vertical successions of magmatic formations (Fig. 5) are distinguished within the Kazakhstan segment of the Urals-Mongolian fold belt. Their distribution is shown on Fig. 6. Corresponding to them are three groups of tectonic structures, which tectonists have referred as ortho-, medio- and para-geosynclinal (Sheinmann, 1968; Peive, 1961, 1972; Alektorova and Fogelman, 1979; and others). The groups are distinguished by the differences in the primary volcanogenic rocks of which they are comprised. One succession is characterized by volcanogenic members of the ophiolite association, the second by bimodal contrasts in rocks of sodic and potassic alkalinity, which can be associated with basalts of sodic or normal alkalinity. Trachybasalt or successively differentiated formations of normal and potassic alkalinity are typical of the third group. Such successions are based on actual structural-material features that are easily recognized and uniformly interpreted by many researchers (Stille, 1964; Kuznetsov, 1964, etc.). In this case, the successions are outlined without regard to hypothetical concepts or petrogenetic models. Following traditional terminology, the group of structures characterized by ophiolite magmatism will be referred to as orthogeosynclinal (Kolman, 1979; Peive et al., 1977); these structures associated contrasting formations in the basal part of succession as mediogeosynclinal, and a group of structures with basal units of potassic basalt or continuous basalt-rhyolite as parageosynclinal (Lyapichev, 1976). Many years of research on the Paleozoic magmatism of Kazakhstan have shown the authors that specific geosynclinal structures are characterized by specific sequences of formations and that the typing of geosynclinal structures can only be made if based on magmatic evolution.

The orthogeosynclinal group (Fig. 7) is divided into two subgroups. One, the pliomagmatic subgroup, incorporates volcanics of successively differentiated formations, repeated more than once (Fig. 8-12). In the miomagmatic subgroup, ophiolitic magmatism is virtually suppressed, and there are only sporadic developments. In terms of basalt composition, three types of pliomagmatic successions are established (Kutolin, 1972). Basalts of the Chingiz type resemble island-arc basalts, and basalts of the Boshchekul type resemble volcanics of intraoceanic uplifts (Borukaev, 1955). Continuous volcanic series of these two types are chemically similar to alkaline-basalt complexes of intraoceanic islands, or to successively differentiated island-arc formations. The third type includes an ophiolitic association of dunite-harzburgite type (Lyapichev, 1955, 1956), in which the volcanogenic member differs from that given above, resembling instead tholeiite of a mid-oceanic ridge. Because of their low alkalinity and potassium content, successively differentiated and contrasting volcanogenic formations of this type are closer to sodic branches of differentiated formations of mid-oceanic islands than to island arc formations (Bevzenko, 1979).

The miomagmatic subgroup of orthogeosynclinal successions is also quite diverse (Figs. 13-15). According to chemical composition of successively differentiated formations, two types are distinguished. In one (Ermentau and Chara zone), the tendency toward sodic alkalinity is dominant (Dvoichenko, 1976; Novikova et al., 1980); in the other (Northern Balkhash, Atasu-Nura zone) (Bogdanov et al., 1955), normal and potassic-sodic alkalinity are dominant. Volcanic geochemistry and paleogeographical reconstruction suggest that the two types of formational successions examined belong to two groups of structures — oceanic (Chara and Erementau zones) and intracontinental (Antonyuk, 1974).

Mediogeosynclinal successions are less diverse than orthogeosynclinal successions (Figs. 16-19). Early geosynclinal volcanogenic formations are divided by chemistry into two types. Volcanics of one type (Prechingiz zone) are characterized by potassic-sodic or sodic alkalinity; volcanics of the other type (Krykkuduk zone) are noticeably less potassic (Lyapichev et al., 1976). Successively differentiated formations of mediogeosynclinal successions are chemically similar to continuous island arc series and, in contrast with differentiated basalt-rhyolites, approach the types of volcanogenic complexes that form in continental rifts. Their distribution between orthogeosynclinal and parageosynclinal zones is typical of the paleotectonic position of structures where mediogeosynclinal successions were formed.

Parageosynclinal successions of magmatic rock groups are also subdivided into two subgroups (Figs. 20-23). Successions of one are characteristic of stable Paleo-



FAMILYS OF FORMATION	SUBFAMILY OF FORMATION			ROW OF FORMATION	TYPICAL HISTOGRAMME OF THE QUANTITATIVE CORRELATIONS ROCKES	FORMATIONS BY TYPE ALKALI
MAFIC				Picrite-basalt and pyroxenite-gabbro		NATRIUM NORMAL POTASSIC
				Basalt and gabbro		
				Basalt-andesite and gabbro-diorite		
MAFIC-SALIC	OF THE CONTINUOCUS FORMATIONS	OF THE SUCCESSIVELY-DIFFERENTICITED	OF THE MODAL	Rhyolites-basalt and granodiorit-gabbro		
				Rhyolite-andesite and granodiorit		
			OF THE BIMODAL	Rhyolite-basalt-andesite and granodiorite-gabbro		
				Basalt-andesite-rhyolite and γδ-γ-δ		
		OF THE CONTINOUSLY CONTRASTED		Andesite-dacite and diorite-granodiorite		
				Basalt-andesite-rhyolite		
				Rhyolite-andesito-basalt		
	OF THE INTERRUPTED FORMATIONS			Rhyolite-basalt and granite-gabbro		
				Rhyolite-andesite-basalte		
				Rhyolite-dacite-basalt		
SALIC				Dacite-rhyolite and granodiorite-granite		
				Rhyolite and granite		

Figure 4

Fig. 4. Classification of magmatic formations. 1- basalts and gabbro; 2- andesites and diorites; 3- dacites and granodiorites; 4- rhyolites and granites.

Fig. 5. Type histograms of the volumetric relations of rocks in the volcanic formations. B- basalts; A- andesites; D- dacites; R- rhyolites. Volcanic complexes: 1-7- "continuous" (successively differentiated) unimodal rhyolite-basalt complexes (1, 2), basalt-rhyolite complexes (3, 4), rhyolite-andesite complexes (5), andesite-rhyolite complexes (6), rhyolite-basalt-andesite complexes (7); 8-10- "continuous" bimodal complexes; 11-16- continuous-contrast bimodal complexes; 17-20- continuous-contrast-unimodal complexes; 21-23- contrast-bimodal complexes; 24-27- contrast-unimodal complexes; 28- contrast complexes with two continuous maxima.

Fig. 6. Distribution in Kazakhstan successions of magmatic formations. 1- orthogeosynclinal successions; 2- mediogeosynclinal successions; 3- parageosynclinal successions; 4- some faults.

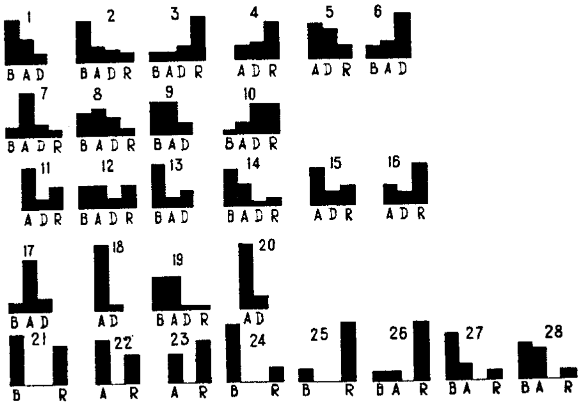


Figure 5

Figure 6

Fig. 7 (left). Scheme of orthogeosyncline structural-formational zones. Orthogeosyncline zones: I- Chingiz-Tarbagatay type: perioceanic (a), peri- and intracontinental (b); II- Uralian type: 1-17- structural-formations zones: 1-3- perioceanic insular arc: Eastern-Asian (Ia), Andean (Ib); 4- insular arc of margin seas; 5-6- interarc and intra-arc basin; 7-8- margin sea; 9-10- rift of the margin sea: flange parts (9a), axis parts (9b), parts manifesting themselves on continental slopes (9c); 11-13- continental slope: with a part of shelf (13a), with a part of a slope foot (13b); 14-15- oceanic rift: oceanic parts (15a), intracontinental margins (15b); 16-17- oceanic basin.

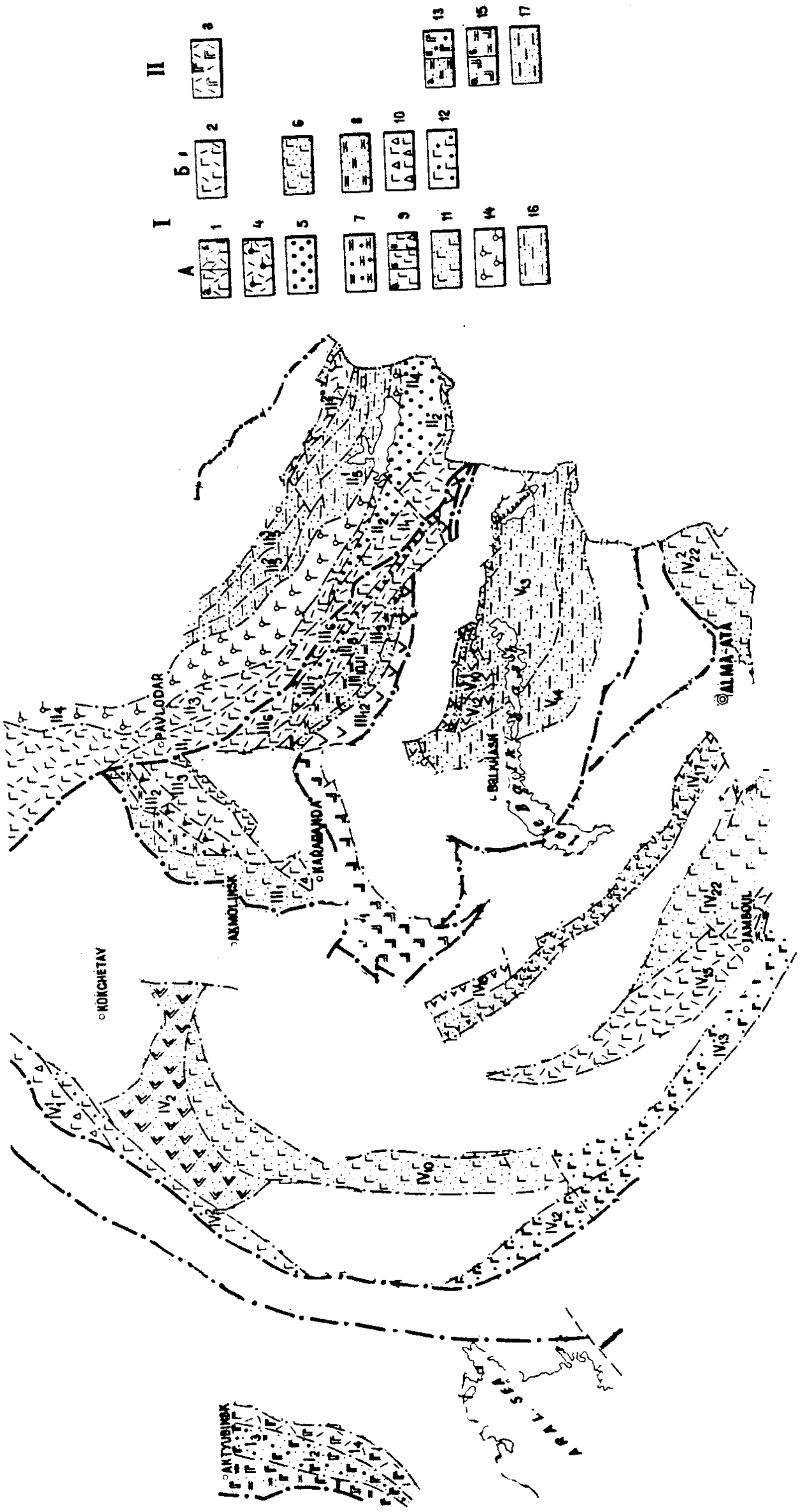
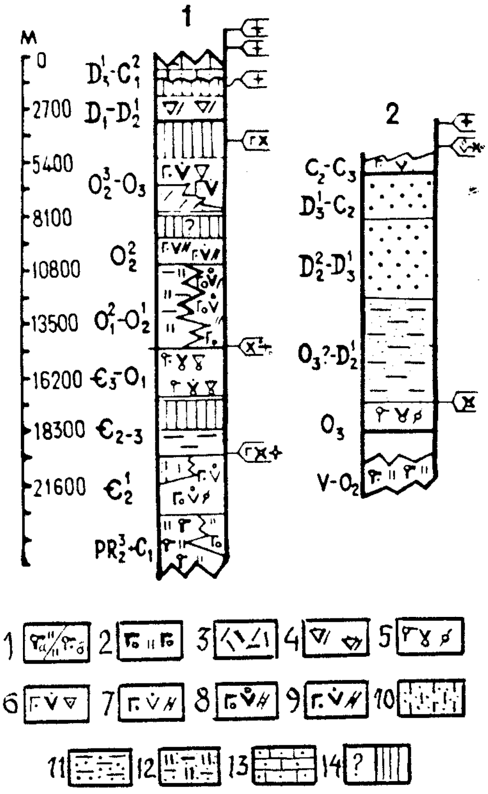
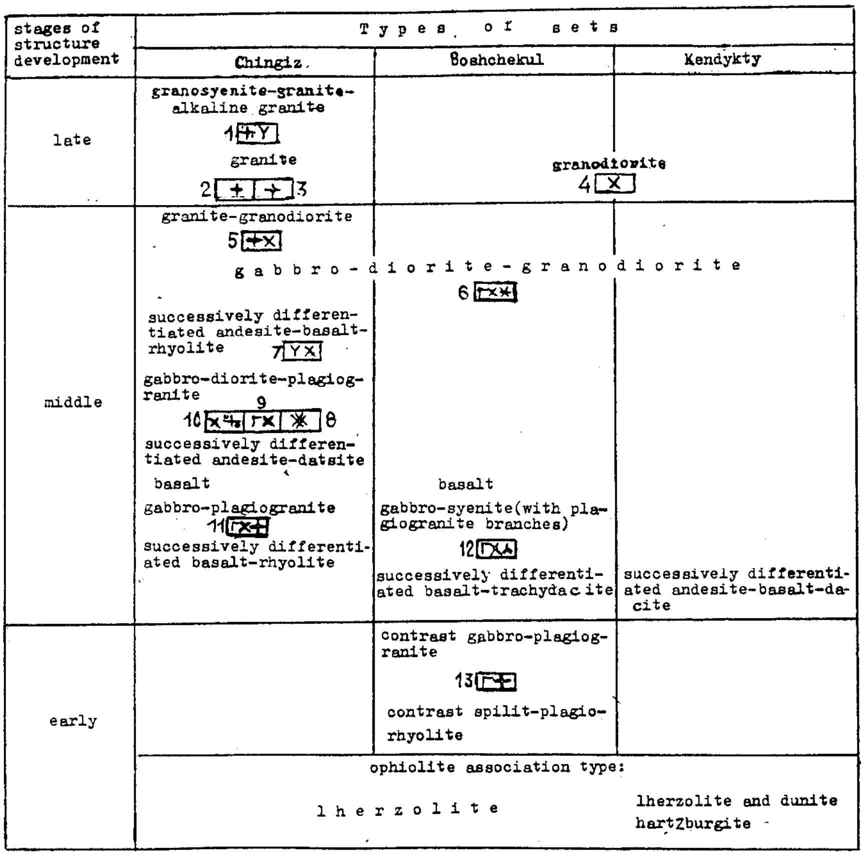


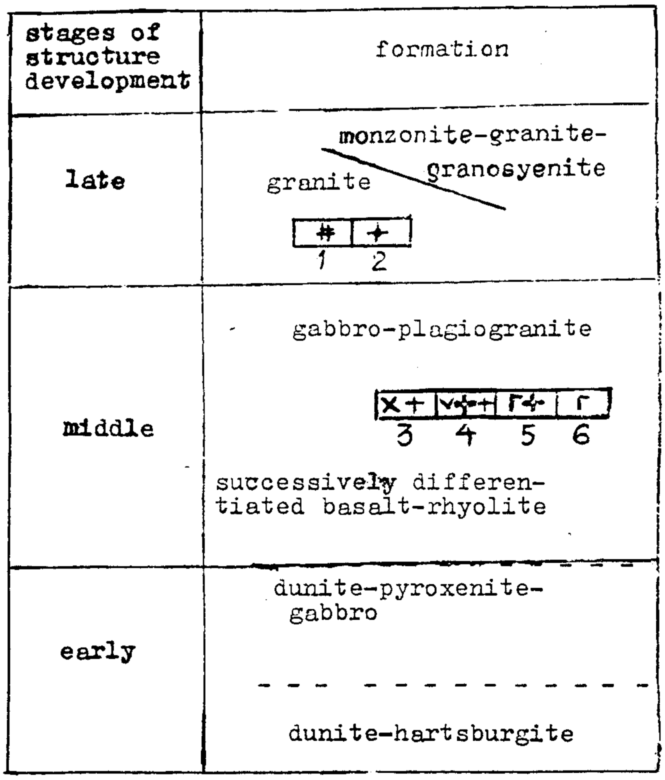
Fig. 8 (below). Vertical successions of orthogeosynclinal magmatic formations. 1- siliceous-basaltic formation of sodic (a), and sodic and potassic (b) alkalinity; 2- siliceous-basaltic formation of sodic and normal alkalinity; 3- formations of normal rhyolite; 4- formation of dacites and rhyolites; 5- andesite-rhyolite formation of sodic and potassic alkalinity; 6- andesite-dacite normal and potassic alkalinity; 7- basalt-rhyolite formation of normal potassic alkalinity; 8- basalt-andesite-rhyolite formation of sodic and normal alkalinity; 9- basalt-andesite-rhyolite of normal and potassic alkalinity; 10- arenaceous-polymictic formation; 11- flyschoid formation of the regressive type; 12- siliceous-terrigenous formation with olistostrome-like horizons; 13- carbonate formation; 14- tilloid formations. Successions correspond to structural-formational zones: 1- Central Chingiz, 2- Sarcand.





stages of structure development	Types of sets		
	Chingiz	Boshchekul	Kendykty
late	granosyenite-granite-alkaline granite 1 +Y granite 2 + + 3	granodiorite 4 X	
middle	granite-granodiorite 5 +X gabbro-diorite-granodiorite 6 ГX✳ successively differentiated andesite-basalt-rhyolite 7 YX gabbro-diorite-plagiogranite 9 10 X+ ГX ✳ 8 successively differentiated andesite-datsite basalt gabbro-plagiogranite 11 ГX+ successively differentiated basalt-rhyolite	basalt gabbro-syenite(with plagiogranite branches) 12 ГX٨ successively differentiated basalt-trachydacite	successively differentiated andesite-basalt-dacite
early		contrast gabbro-plagiogranite 13 Г+ contrast spilit-plagiorhyolite	
	ophiolite association type: lherzolite		lherzolite and dunite hartZburgite

Fig. 9 (right). Generalized succession of magmatic formations in the pliomagmatic subgroup of orthogeosynclinal successions. 1- granosyenite-granite-alkaline granite; 2- potassic granite; 3- normal granite; 4- granodiorite; 5- granodiorite-granite; 6- monzonite-granite-granosyenite; 7- granodiorite-granosyenite; 8- diorite-granodiorite-granite bimodal; 9- gabbro-granodiorite; 10- granodiorite-plagiogranite-granite; 11- gabbro-plagiogranodiorite-plagiogranite continuous bimodal; 12- gabbro-plagiogranodiorite-granite continuously contrast bimodal; 13- gabbro-plagiogranite contrast unimodal.



stages of structure development	formation
late	monzonite-granite-granosyenite granite # + 1 2
middle	gabbro-plagiogranite X+ V+ Г+ Г 3 4 5 6 successively differentiated basalt-rhyolite
early	dunite-pyroxenite-gabbro - - - - - - - - - - - - - dunite-hartsburgite

Fig. 10 (left). Generalized succession of magmatic formation in pliomagmatic subgroup of orthogeosynclinal successions (Uralian type). Intrusive formations: 1- alkaline granite and alaskite; 2- potassic granite; 3- granite-granodiorite; 4- diorite-granite-plagiogranite continuous; 5- gabbro-plagiogranite contrast bimodal; 6- gabbro.

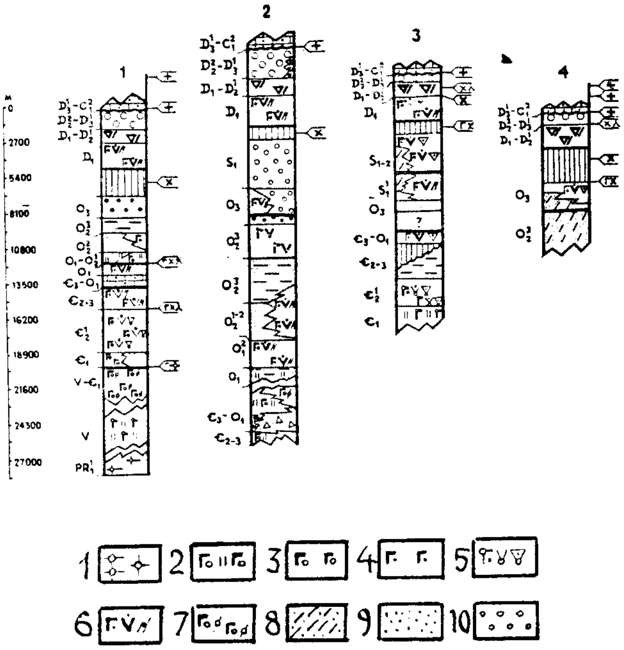


Fig. 11. Vertical successions of orthogeosynclinal magmatic formations (pliomagmatic subgroup). 1- plagiogneiss-amphibolite; 2- siliceous-basalt of sodic and normal alkalinity; 3- normal and sodic basalts; 4- normal and potassic basalts; 5- basalt-dacite of sodic and potassic alkalinity; 6- basalt-andesite-rhyolite of normal and potassic alkalinity; 7- rhyolite-basalt of sodic alkalinity; 8- siltstone-arenaceous-polymictic; 9- terrigenous, essentially graywacke; 10- arenaceous, conglomeratic variety of regressive type. For other symbols, see Fig. 9. Successions of structural-formational zones are numbered: 1- Boshchekul; 2- Kendykty; 3- Koksengir; 4- Sargaldak.

zoic blocks and correspond to structures in which highly potassic basalt-trachyte and monzonite-syenite-granosyenite form, as well as alkaline granite. Successions of the other are developed in zones of Precambrian consolidation and include three types:

1. Buruntas, characterized by widespread rhyolite and granite (Abdulin, 1980);
2. Kokchetav, which includes only intrusive rocks, characterized by mafic complexes and a widespread granodiorite-granite association, as well as normal and highly potassic granites, alaskites, and alkaline and subalkaline granites (Abdulin, 1982a); and
3. Balkhash, in which basalt-rhyolite and andesite-dacite-rhyolite of normal and potassic alkalinity are common and always accompanied by comagmatic monzonite-granosyenite, granodiorite-granite, and granite complexes (Abdulin, 1983). The chemical composition of magmatic formations changes with time in the direction of highly alkaline successions. The same appearance is typical of petrochemical trends of parageosynclinal volcanogenics as well as trends of mid-Cenozoic East Asian island arc formations. A higher level of alkalinity distinguishes them from Kazakhstan volcanics.

The three types of magmatic groups examined clearly differ in structure and composition, and in quantitative relationships as well. Thus, the ratio of thicknesses of volcanogenic and sedimentary rocks in Paleozoic volcanogenic-sedimentary formations in ortho-, medio- and parasets is 1.5:1:5; the corresponding explosive indices [the explosive index - the percentage of tuff (pyroclastics) to volume of volcanic rocks] are 37, 41 and 69 respec-

Table 1

Family of rock types	**Lithologic members (Formations)***		
	Orthogeosynclines	***Mediogeosynclines***	***Parageosynclines***
Gabbro-monzonite-granite	Gabbro-plagio-granite, gabbro-syenite	Tonalite-plagio-granite-granite	Monzonite-syenite
Granodiorite	Gabbro-diorite-granodiorite	Tonalite-diorite-granodiorite	Granodiorite
Granodiorite-granite	Diorite-grano-diorite-granite		Granodiorite-granite

* The term "formation" is used in the Russian sense.

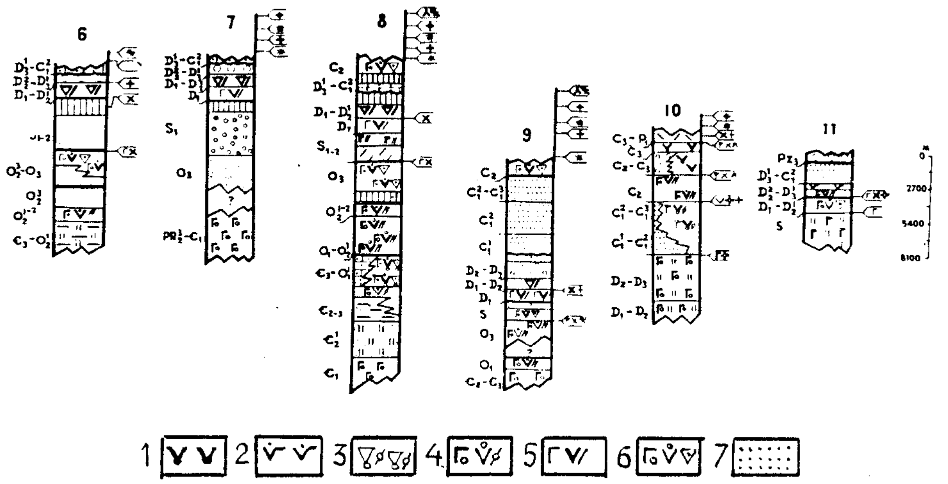


Fig. 12. Vertical successions of orthogeosynclinal magmatic formations (pliomagmatic subgroup). 1- formations of potassic andesites; 2- andesite-basalt of normal and potassic alkalinity; 3- sodic dacites and rhyolite; 4- basalt-rhyolite of sodic and normal alkalinity; 5- andesite-rhyolite; 6- basalt-dacite of sodic and normal alkalinity; 7- non-dismembered sedimentary formations. For other symbols, see Figs. 9 and 11. Successions of structural-formational zones are numbered: 6- Chunai; 7, 8- Arkalyk (7- northern block; 8- southern block); 9- Zharma-South Sauri; 10- Sarsazan-North Sauri; 11- Western Mugodgary.

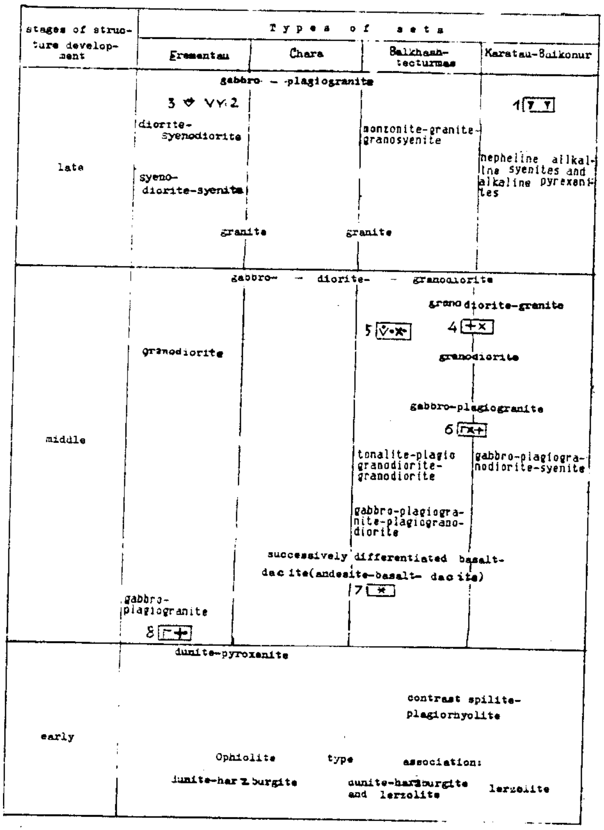


Fig. 13. Generalized succession of magmatic formations in pliomagmatic subgroup of orthogeosynclinal successions. Intrusive formations: 1- nepheline and alkaline syenites and alkaline pyroxenites; 2- syeno-diorite-syenite; 3- diorite-syeno-diorite; 4- granodiorite-granite; 5- tonalite-plagiogranodiorite-granodiorite; 6- gabbro-plagiogranite-plagiogranodiorite continuously unimodal; 7- granodiorite-adamellite-granite; 8- gabbro-plagiogranite contrast

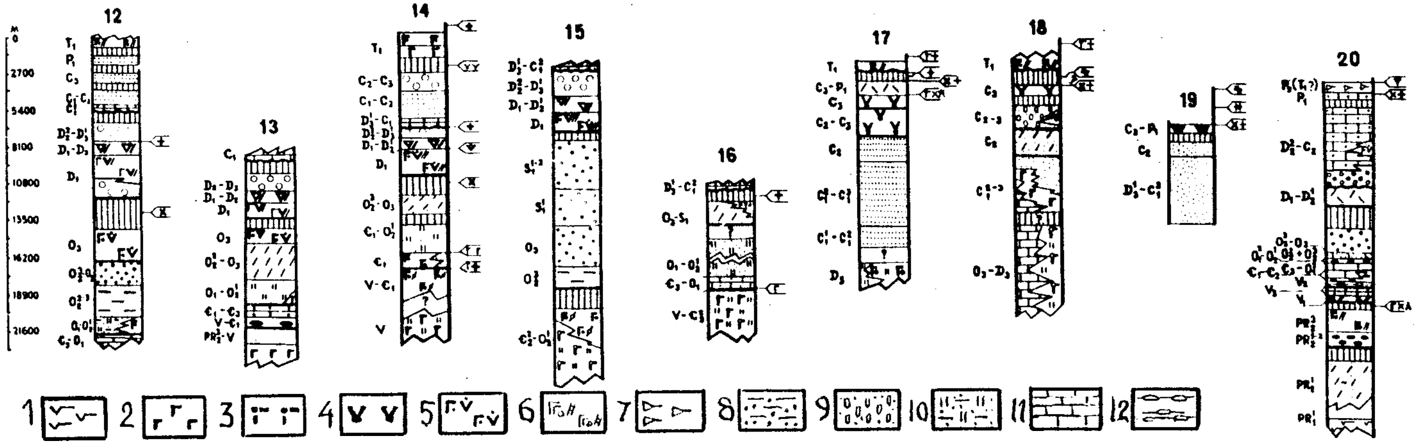


Fig. 14. Vertical successions of orthogeosynclinal magmatic formations (pliomagmatic subgroup). 1- shale-amphibolite and serpentinite-gabbro-amphibolite non-dismembered; 2- normal basalts; 3- potassic basalts and trachybasalts; 4- potassic andesites; 5- normal and potassic basalts and andesites; 6- basalt-liparite of sodic and normal alkalinity; 7- alkaline basalts and trachybasalts; 8- flysch and flyschoid of regressive type; 9- siltstone arenaceous variegated of transgressive type; 10- siliceous-terrigenous with the olistostrome-like horizon; 11- conglomerate-arenaceous-carbonate; 12- tilloid. For other symbols, see Figs. 9, 11, 12. Successions of structural-formational zones are marked by figures: 12- Mar'evka; 13- Kalmakkol; 14- Ermentau; 15- Baiakhmet-Koskombai; 16- Akchatau; 17- Koyandy-Arkalyk; 18- Chara; 19- Kalba-Narym; 20- Bolshoi Karatau.

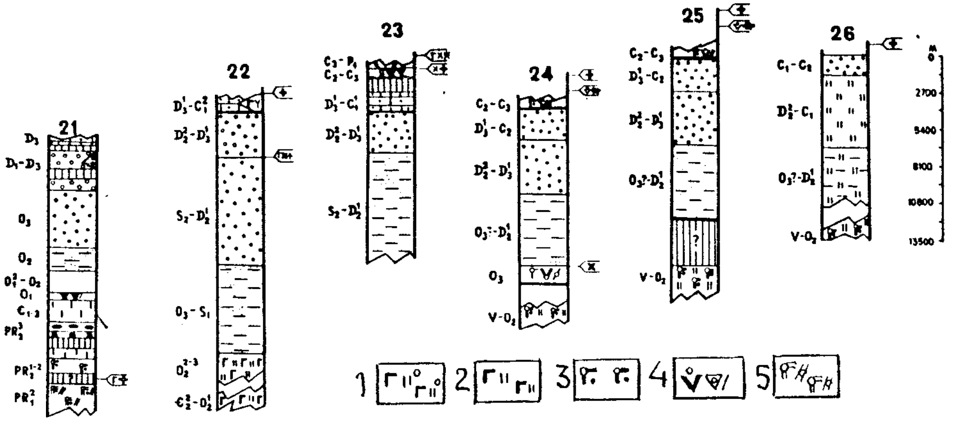


Fig. 15. Vertical successions of orthogeosynclinal magmatic formations (pliomagmatic subgroup). 1- non-dismembered terrigenous-siliceous-basaltic; 2- sodic-normal alkalinity; 3- sodic and potassic basalts; 4- andesite-dacite of normal and potassic alkalinity; 5- basalt-rhyolite of sodic and potassic alkalinity. For other symbols, see Figs. 9, 11, 12, 14. Successions of structural-formational zones are marked by figures: 21- Zhapair-Naiman; 22, 23- Atasu Nura: 22- western block, 23- eastern block; 24- Sarkand; 25- Northern Balkhash; 26- Northern Dzhungar.

tively. The three groups of successions are clearly distinguished also in the ratios of total thicknesses of volcanics of different composition. Thus, the ratio of basalts, andesites, dacites and rhyolites in orthosets of rocks is 55:20:8:15; in mediosets it is 46:20:14:20; and in parasets it is 20:14:23:43. Although the generalizations smooth over real differences, it is nevertheless obvious that in parastructures, acidic rocks are twice as abundant as in ortho- and mediostructures, and basalts and andesites are two times less abundant.

From detailed analysis, it is clear that in orthosets, undifferentiated basalt-andesite and successively differentiated basalt-rhyolite are distinctly predominant, and uninterrupted contrasting formations are completely absent; in mediosets, both the contrasting interrupted and continuous formations prevail; in parasets, dacite-rhyolite formations are distinctly predominant. The three kinds of rock successions are clearly distinguished by alkalinity (Fig. 24). In ortho- and mediosets, sodic and normal formations predominate; and the normal, potassic and also proper-potassic ones sharply prevail in parasets. So, whereas the ratio of sodic and normal formations to potassic and normal is about 0.5 in ortho- and mediosets, it is 25 times less in parasets. There are no proper-potassic formations in orthosets, but in parasets they are 5 times as abundant as in mediosets. The evolution of the petrochemical features from the orthostructures through mediostructures to the parastructures consists in increasing significance of acidic varieties with a parallel decrease in significance of basalts. The contrast in differentiation of the formations increases; potassic alkalinity increases on a level with the increase in general alkalinity; and the tendency of acidity to increase manifests itself in the same way, provided that the different successions of the rocks are not compared in terms of silicic acid but instead by acidity-basicity.

Intrusive formations display the same tendencies in evolution of structure and composition as those described for volcanics. These are reflected both in regular lithologic change within every plutonic family, tallying with the ortho-medio-paraset type succession, and by trends in the chemical differences exhibited by different formations of a family. These tendencies are especially well expressed in the granodiorite and granodiorite-granite families. In orthogeosynclines, the gabbro-diorite-granodiorite formation is somewhat prevalent over the diorite-granodi-orite-granite. In mediogeosynclines, on the average, the formations of both the granodiorite and granodiorite-granite families are developed equally; in parageosynclines, the granodiorite formation is clearly predominant, and proper-granodiorite occurs sporadically. In the granite family, the granites of all the three types of tectonic structures are clearly distinguished, especially by the type of alkalinity, despite similarities in composition. Comparison of the distribution of the products of proper-granitic plutonism in tectonic structures of different types shows that normal granites prevail in orthogeosynclines; both normal granites and essentially potassic granites are widely developed in mediogeosynclines; and potassic granites are especially significant in parageosynclines.

Effusive Magmatism

Cessation of volcanic activity common in all the Paleozoic systems of Kazakhstan occurred simultaneously, in the early Mesozoic. In Caledonian systems, new volcanic zones appeared during two intervals: Late Riphean-Vendian and Late Cambrian-Early Silurian, separated by a period of 55 My, during which time tectonic activity culminated. This period corresponds to the time of formation of the granitic basement in the Baikalides of the Urals-Mongolian belt (Abdulin, Avdeev, Patalakha, 1976). The same situation is observed in the Hercynian fold systems. New centers of volcanism appeared in two epochs, one in the Late Cambrian-Early Ordovician and one in the Early-Middle Devonian, supposedly separated by a 55 My interval. The two maxima, at the appearance of new volcanic zones in the Hercynides, are delimited by the time of formation of the granite basement of the Caledonides. In both the Caledonides and Hercynides, activity in the earlier volcanic zones began with eruption of ophiolitic volcanics that are not characteristic of the later volcanic zones.

Basalts (Fig. 25) make up about half of the thickness of the volcanogenic formations and are the predominant volcanics of the Caledonides and Hercynides. The proportion of andesites is the same, but the Hercynides contain almost twice as much rhyolite. The ratio of volcanogenic and sedimentary materials is lower by a factor of almost 2 in the Caledonides than in the Hercynides (0.39 and 0.75). In the Caledonides, the ratio of lavas and tuffs is smaller (1.59 and 1.96, respectively). The average rate of accumulation of volcanic rocks is almost the same (719 and 685 m/My) in the Caledonides and Hercynides, but the rate of formation of sedimentary rocks is about 2.5 times higher in the Caledonides than in the Hercynides (1502 and 611 m/ My) compared with corresponding average rates of rock formation (703 and 548 m/My).

Judging from the overall picture of volcanism, the Caledonian and Hercynian fold systems of Kazakhstan exhibit similarities (such as the almost equal intensity of the volcanogenic rock-formation, the regular repetition of the sequence of formations, the similar volumetric ratios of rocks of various compositions, etc.) as well as differences (different intensity of the sedimentary rock-formation, different ratio of volcanogenic and sedimentary material, different explosive coefficient, etc.) reflecting cyclic recurrence on the one hand and volcanic and magmatic trends on the other.

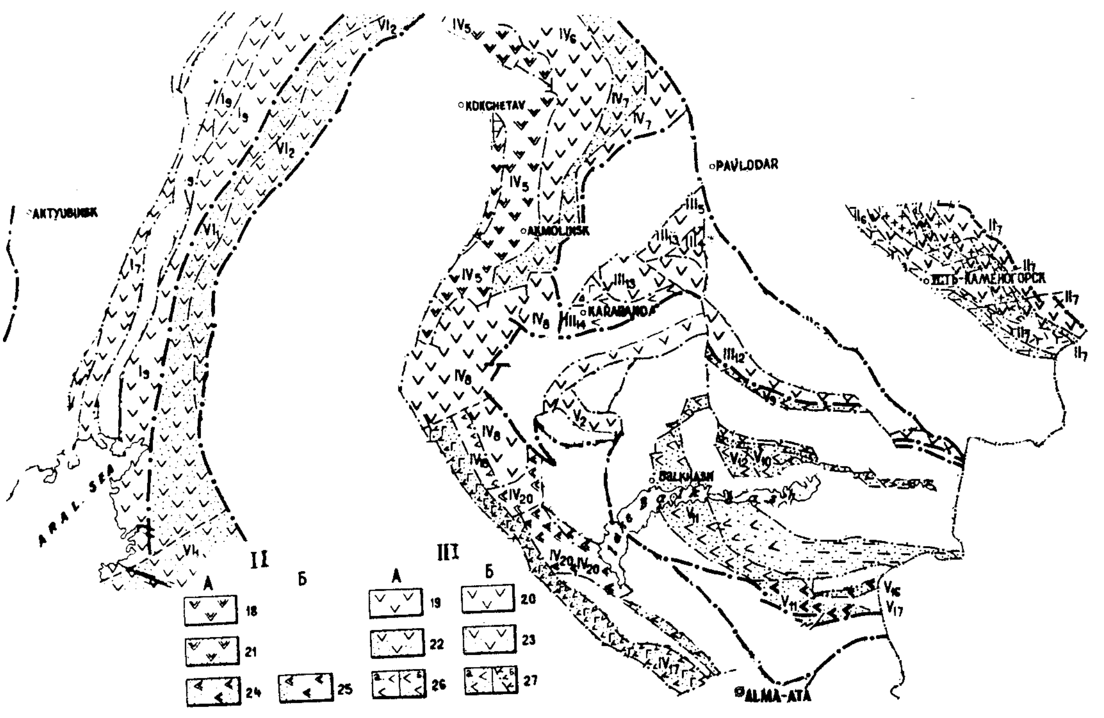


Fig. 16. Scheme of mediogeosyncline structural-formational zones. Zones: III- newly formed structures; IV- regenerated structures: pericontinental (c), intracontinental (d); 18-27- structural-formational zones: 18-20- insular arc, 21-23- inter-arc and intra-arc basin, 24-27- rift: 26a- essentially with effusive volcanism, 26b- essentially with intrusive magmatism; 27a- essentially with effusive magmatism, 27b- essentially with intrusive magmatism.

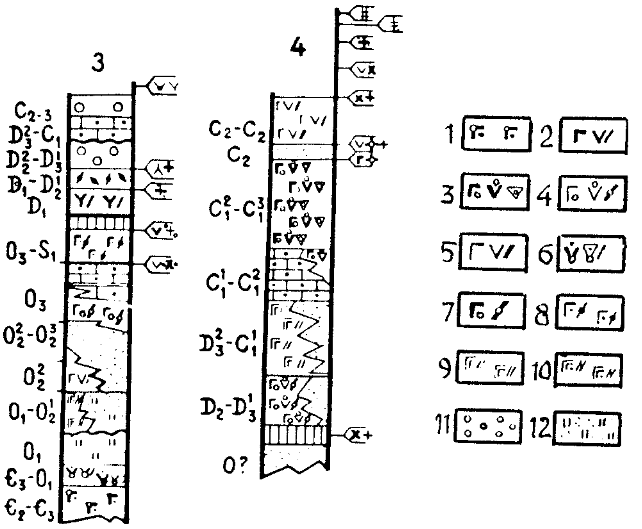


Fig. 17. Vertical successions of magmatic formations in mediogeosynclines. Formations: 1- sodic and potassic basalts; 2- basalt-rhyolite (general basalt); 3- basalt-dacite of sodic and normal alkalinity; 4- quartz-keratophyre (basalt-rhyolite of sodic and normal alkalinity); 5- basalt-rhyolite (general rhyolite); 6- andesite-dacite of sodic and potassic alkalinity; 7- basalt-rhyolite of sodic and normal alkalinity; 8- basalt-rhyolite of normal and potassic alkalinity; 9- basalt-rhyolite bimodal; 10- basalt-rhyolite bimodal of normal and potassic alkalinity; 11- terrigenous red-colored continental; 12- terrigenous-siliceous. Successions correspond to structural-formational zones: 3- Krykkuduk-Zhaksykon; 4- Rudny Altay zone group.

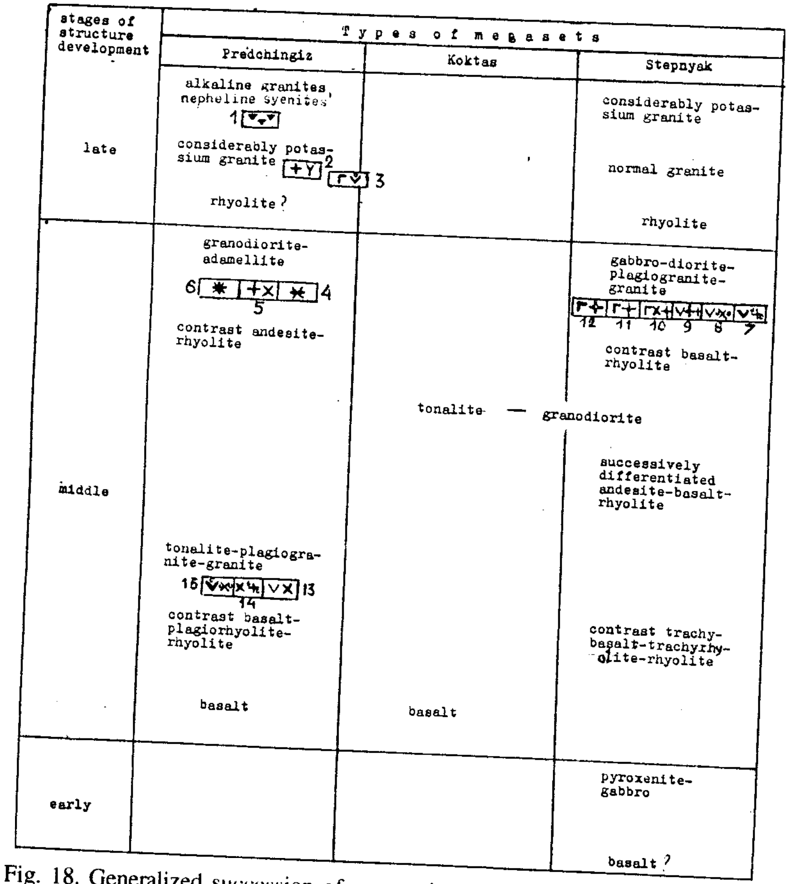


Fig. 18. Generalized succession of magmatic formations in mediogeosyncline successions. Intrusive formations: 1- alkaline and nepheline syenites; 2- granosyenite-granite; 3- diorite-syenodiorite-gabbro; 4- granodiorite-adamellite-granite; 5- granodiorite-granite; 6- granodiorite-granite bimodal; 7- granite-plagiogranite-diorite continuous unimodal; 8- diorite-plagiogranodiorite-granodiorite continuous bimodal; 9- diorite-granite-plagiogranite continuous; 10- gabbro-plagiogranite-plagiogranodiorite continuously unimodal; 11- plagiogranite-gabbro contrast unimodal; 12- gabbro-plagiogranite contrast bimodal; 13- diorite-granodiorite; 14- granodiorite-plagiogranite-granite; 15- granodiorite-plagiogranodiorite-tonalite.

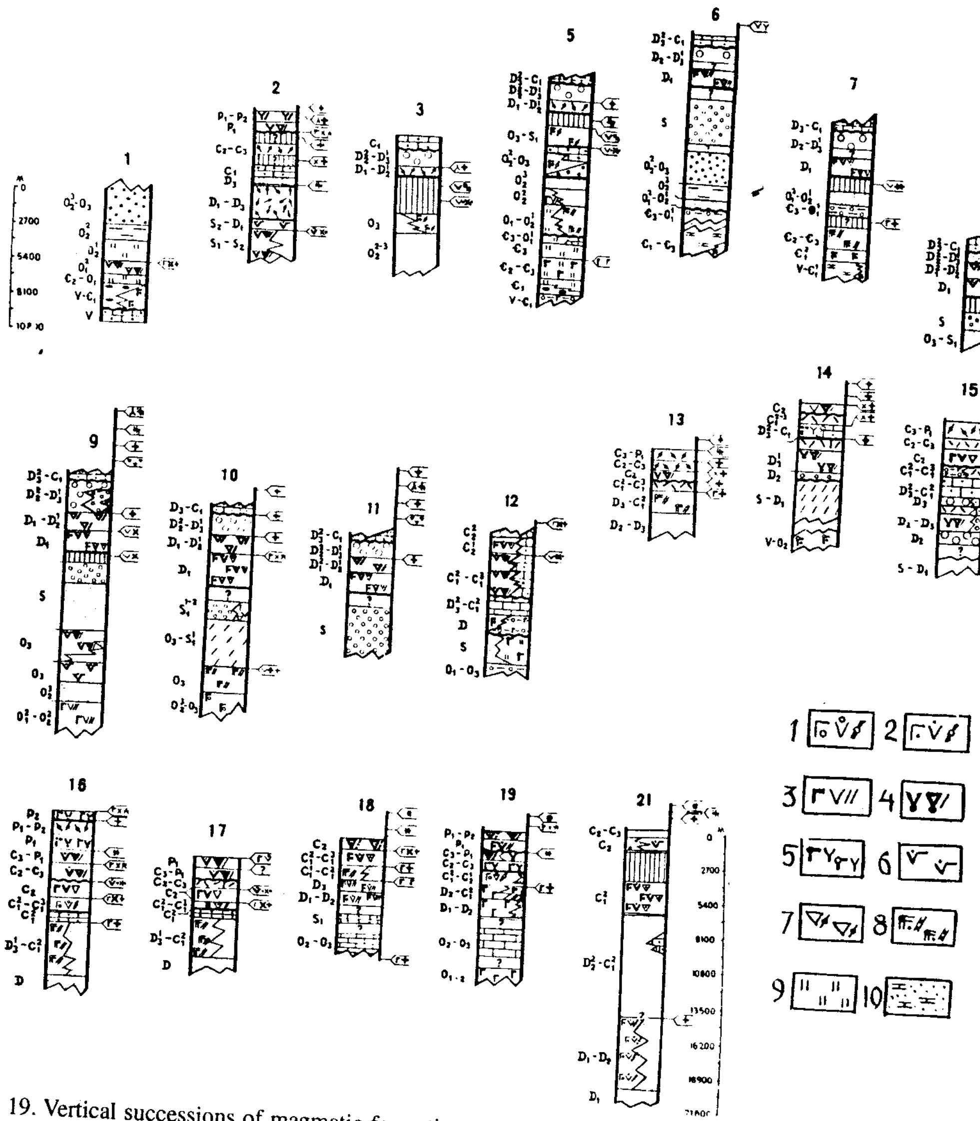


Fig. 19. Vertical successions of magmatic formations in mediogeosynclines. Formations: 1- quartz-keratophyre (basalt-rhyolite sodic and normal alkalinity); 2- basalt-rhyolite of normal and potassic alkalinity; 3- basalt-rhyolite; 4- andesite-dacite potassic alkalinity; 5- potassic basalts and trachytes; 6- andesite-basaltic of normal and potassic alkalinity; 7- normal dacites and potassic rhyolite; 8- basalt-trachy-basalt-rhyolite-trachyrhyolite; 9- siliceous; 10- arenaceous-carbonate. Successions of structural-formational zones: 1- Sarytuma; 2- Kyzylespe; 3- Stepnyak; 4- Krykkuduk-Zhaksykon; 5- Aksu; 6- Bestyube; 7- Priseletiy; 8- Priatasu; 9- Maikain-Alexandrovka; 10- Kosmurun; 11- Bayandul; 12- Kustanai; 13- South Upsenka; 14- Akzhal-Aksoran; 15- Chiyozek; 16- Eastern Kotyrasan; 17- North Sayak; 18- South Dzhungar; 19- Borotaly; 20- Rudny-Altay zone group; 21- South Altay zone group.

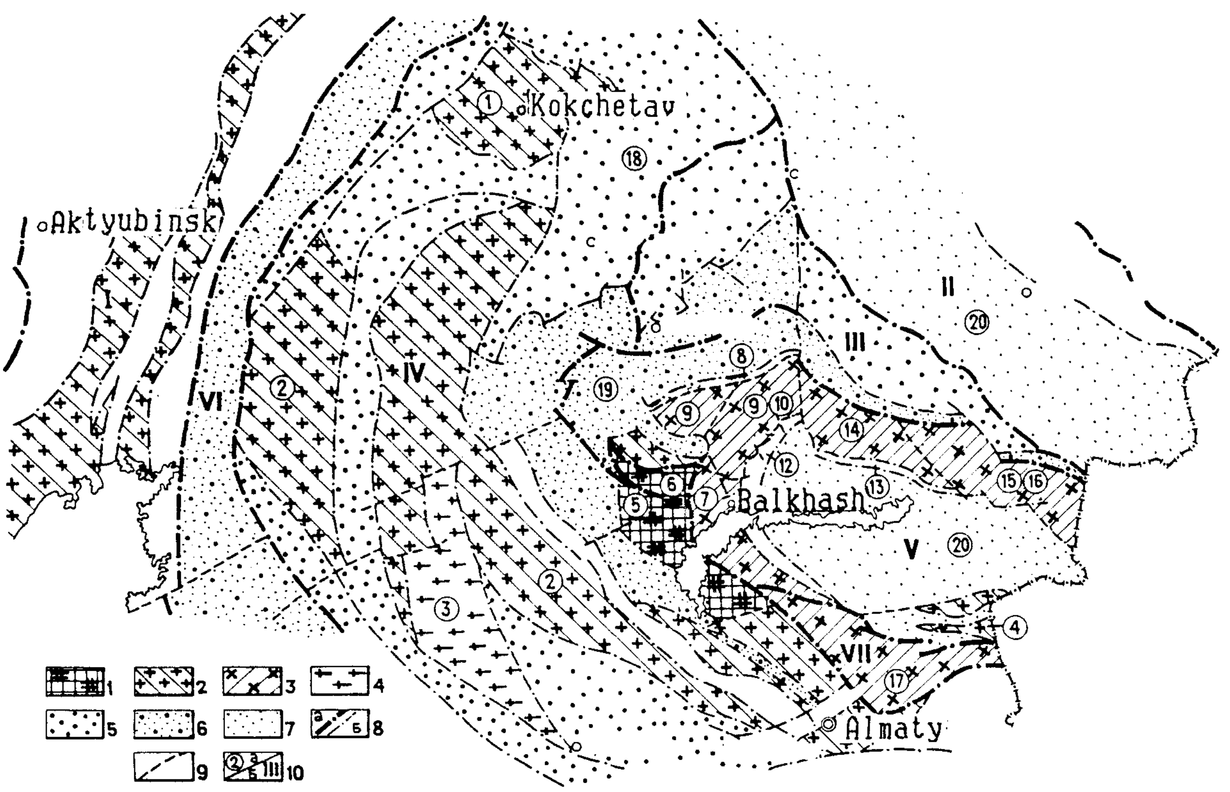
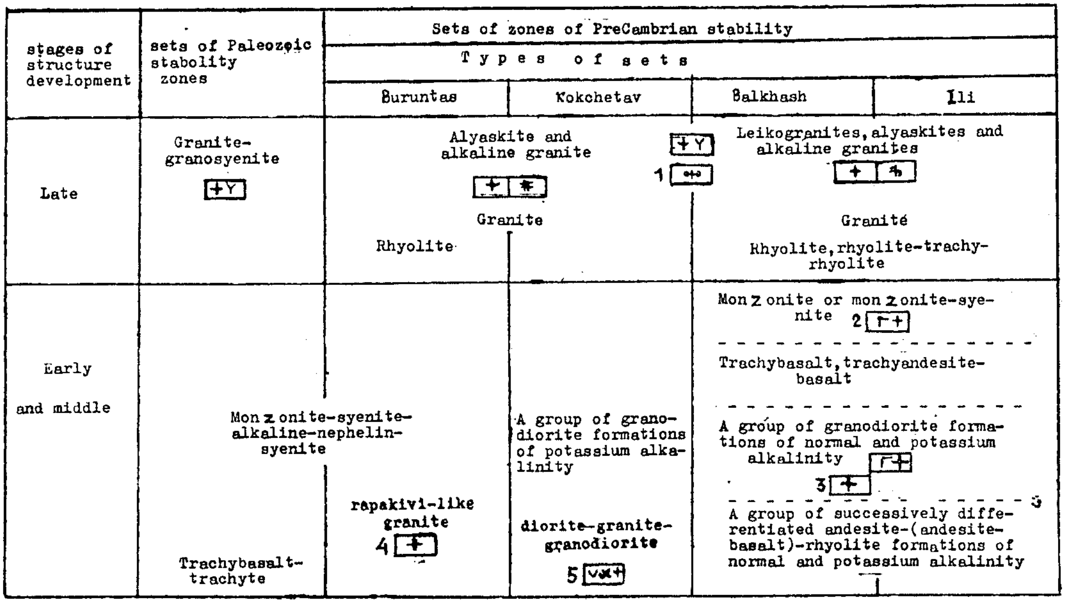


Fig. 20. Structural-formational zones with parageosynclines vertical successions of magmatic formations. 1-4- zones with Late Cambrian continental basic type: 1- Burultau, 2- Kokchetav, 3- Balkhash and Ili, 4- Maly-Karatau; 5-7- zones with Paleozoic-early Mesozoic continental basic: 5- Caledonian (central Kazakhstan type), 6- late Caledonian (Zhailma type), 7- Hercynian (east Kazakhstan type); 8- borders of folded systems (a), and structural-formational zones (b); 9- some faults; 10- normal of formational columns (a), and indices of zones on figure scheme of structural-formational distribution (b).



stages of structure development	sets of Paleozoic stabolity zones	Sets of zones of PreCambrian stability			
		Types of sets			
		Buruntas	Kokchetav	Balkhash	Ili
Late	Granite-granosyenite +Y	Alyaskite and alkaline granite + ✱ Rhyolite	Granite +Y 1 ⊶	Leikogranites, alyaskites and alkaline granites + ⁴ Granité Rhyolite, rhyolite-trachy-rhyolite	
Early and middle	Monzonite-syenite-alkaline-nephelin-syenite Trachybasalt-trachyte	rapakivi-like granite 4 +	A group of granodiorite formations of potassium alkalinity diorite-granite-granodiorite 5 v✱+	Monzonite or monzonite-syenite 2 Γ+ Trachybasalt, trachyandesite-basalt A group of granodiorite formations of normal and potassium alkalinity Γ+ 3 + A group of successively differentiated andesite-(andesite-basalt)-rhyolite formations of normal and potassium alkalinity	

Fig. 22. Generalized succession of magmatic formations of parageosyncline successions. Formations: 1- albite-alaskite; 2- monsonite-granite; 3- plagiogranite; 4- rapakivi granite; 5- diorite-granodiorite-granite.

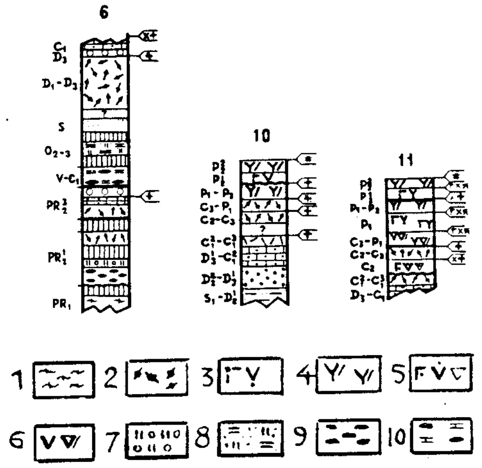


Fig. 21 (left). Vertical successions of magmatic formations in parageosynclines. Formations: 1- siliceous-carbonate-amphibolite-gneisses; 2- normal and potassic rhyolites; 3- potassic basalts and andesites; 4- rhyolites and orthophyres; 5- basalt-dacite normal and potassic alkalinity; 6- andesite-dacite; 7- quartz-arenaceous; 8- arenaceous-carbonate-siliceous; 9- carbonate-siliceous-carboniferous-shale; 10- siliceous-carboniferous-shale and terrigenous-siliceous-carboniferous. Formational columns of structural-formations zones are marked by figures: 6- West Mointy; 10-11- Tokrau: 10- blocks, 11- interblock fractures.

Fig. 23 (below). Vertical successions of parageosyncline magmatic formations. Formations: 1- granite-gneiss; 2- non-dismembered associations of diabase and argillo-arenaceous-conglomerate; 3- andesite-dacite of normal and potassic alkalinity; 4- normal and potassic basalts and andesites; 5- basalt-dacite; 6- non-dismembered argillo-arenaceous conglomeratic transgressive type. Figures correspond to successions of structural zones: 1-17- with late Precambrian continental basis: 1- Ulutau-Kokchetav (Kokchetav block); 2- Chu; 3- Malyi-Karatau; 4- Tekeli; 5-6- West Mointy: 5- Burultau, 6- Kyzylespe block; 7- Eastern Mointy; 8- Berkuty-Kentyube; 9- Zhaman-Sarysu; 10-11- Tokrau: 10- blocks, 11- interblock suture; 12- West-Kotyrasan; 13- Akshoky-Kokdala; 14-16- Kotanamel-Bakanas: 14- Kotanamel block, 15- Bakanas block, 16- interblock suture; 17- Ili; 18-20- zones with Paleozoic-early Mesozoic continental basic: 18- central Kazakhstan type (on Caledonic crust), 19- Zhailma (on Late Caledonic crust), 20- eastern Kazakhstan type (on Hercynide crust).

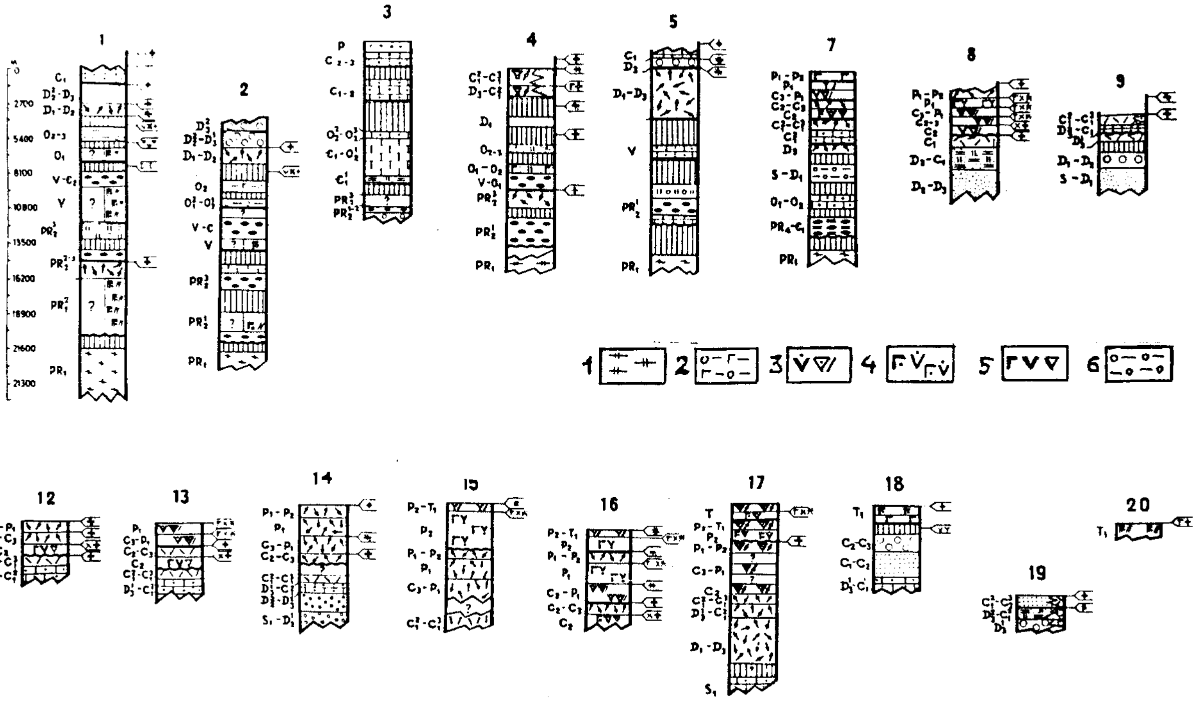
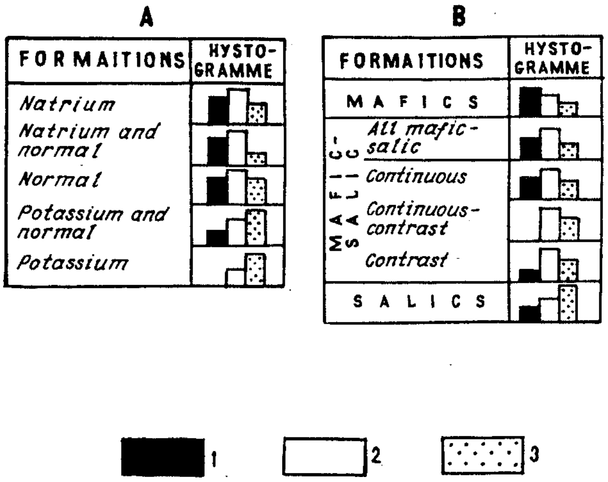
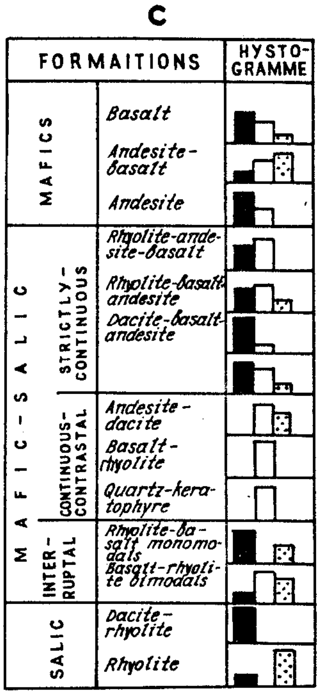


Fig. 24. Comparative characteristics of structures by the peculiarities of the volcanogenic formations. A- potassic alkalinity of formations; B- quantitative relations of families of formations; C- quantitative relations of types of formations. Structures: 1- orthogeosynclinal; 2- mediogeosynclinal; 3- parageosynclinal.





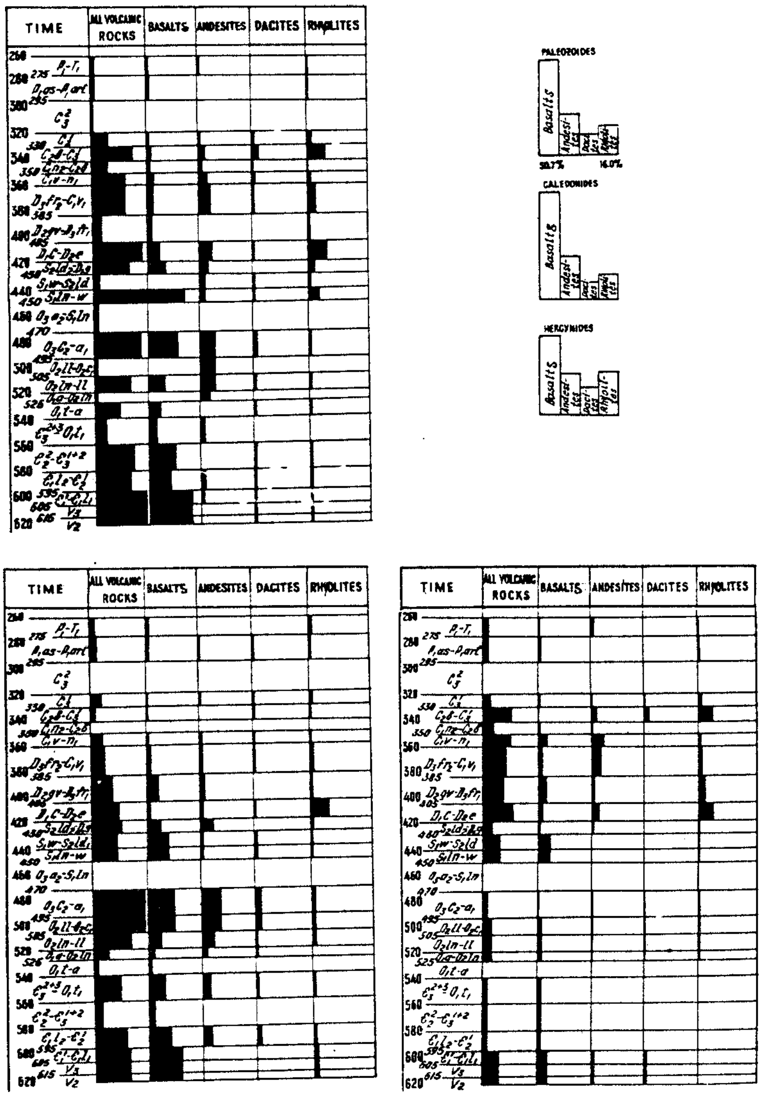


Fig. 25. Relations of average thicknesses of volcanics in Paleozoic sequences and temporal variations in average thicknesses of volcanics in the Caledonides (2), and Hercynides (3) of Kazakhstan: 1- basalts; 2- andesites; 3- dacites; 4- rhyolites.

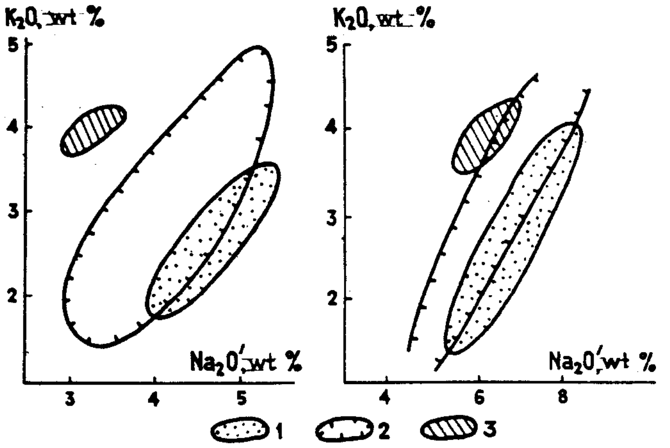


Fig. 26. Type and degree of alkalinity of granodiorites of the granodiorite family of different types of tectonic structures: 1- orthogeosynclines; 2- mediogeosynclines; 3- parageosynclines.

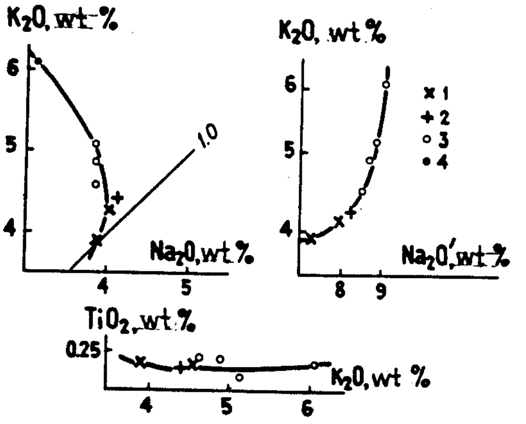


Fig. 27. Variations in chemistry of granites of different types of tectonic structures: 1- orthogeosynclines; 2- mediogeosynclines; 3- parageosynclines of the Pribalkhash area (near Balkhash area) type: 4- parageosynclines of Kokchetav-Chu type.

Titanium, aluminum and potassium contents, general alkalinity, and the ratio of potassium to sodium increase in the basalts in different types of successions from the beginning to the end of a geosynclinal cycle. The greatest range in contents is found in potassium and the least in aluminum; but the tendency for contents to decrease is observed in all the elements considered toward the end of each geosyncline cycle (Lyapichev et al., 1981).

Analysis of the chemistry of the volcanic rocks shows, on the whole, that the evolution of composition is regular both in time and space and correlates with such geological features as a type of succession and the position of formations within the vertical succession, which are characteristic for a given tectonic zone. The differentiated formations of the same name in the different successions are clearly distinguished by chemistry and especially by degree and type of alkalinity. Ophiolitic basalts of the Kazakhstan Paleozoics are chemically similar to but not identical with oceanic tholeiites, having more in common with the tholeiites of oceanic islands. In terms of chemical composition, the successively differentiated sequences of both the orthogeosynclinal and mediogeosynclinal rocks fully correspond to the standard of the calc-alkali volcanic series of the island systems of East Asia. Similarly, the contrasting mediogeosynclinal and parageosynclinal volcanic formations resemble the volcanics of island-arc structures in terms of petrochemical tendencies. At the same time, the parageosynclinal formations differ in having a higher degree of the alkalinity and a significantly more rapid increase in potassic alkalinity (Lyapichev and others, 1981).

Intrusive Magmatism

Sialization, which takes place in the process of building continental crust, is reflected in the evolution of plutonic formations (Peive, Knipper, Markov and others, 1984). It shows both in successive changes of some magmatic formations (examples in Table 1) by others and alterations in the volumetric relations of rocks of the same name formations and composition.

In the gabbro-monzonite-granitoid succession, changes in composition from orthogeosynclinal to parageosynclinal formations clearly reveal a tendency toward an increase in the volume of more acidic rocks and decreases in general and potassic alkalinity (Table 1).

The essential characteristic of the granodiorite family is that granodiorites comprise not less than 70-75% of the total volume. In mediogeosynclinal formations, the second element of the association, by volume, is represented by diorite; and gabbro is only sporadically present, whereas in orthogeosynclines both gabbro and diorite are typical components.

Members of the granodiorite-granite family are closely associated with those of the granodiorite family. In orthogeosynclines, granodiorites are predominant, whereas in medio- and parageosynclines, granites are equally significant, volumetrically.

In orthogeosynclines, the gabbro-diorite-granodiorite member tends to be more common than diorite-granodiorite-granite. The granodiorite and granodiorite-granite families, on average, are developed equally in mediogeosynclines, but in parageosynclines, granodiorite-granite is clearly predominant, even though granodiorite itself occurs only sporadically. All the aforementioned formations differ considerably in chemical composition (Fig. 26). The silicic-potassic tendency of petrochemical evolution is clearly expressed, as exemplified by the most widespread intrusive rocks — granodiorites (Fig. 26).

The granite family comprises two main types: normal granites and essentially potassic granites and alaskites. Despite similarities in chemical composition, granites in the three types of geosynclinal structures are clearly different, especially in the degree and type of alkalinity (Fig. 27). Granites of the ortho-, medio- and parageosynclines form an unbroken series reflecting increasing sialization of new continental crust. Comparison of the distribution of the products of granite plutonism proper in different tectonic structures shows that in orthogeosynclines, normal granite prevails; and in mediogeosynclines, both normal granites and essentially potassic granite are widely developed; but in parageosynclines, the latter play a greater role. Analysis of the chemistry of magmatic rocks (Abdulin, 1982, 1983, 1984; Serykh et al., 1976; Kazmin et al., 1977) shows that the evolution of magmatic composition is regular both in time and space and correlates with the type of formation succession and with the vertical position of a formation. The silicic-alkaline-potassic tendency in magmatic evolution, a reflection of the general evolution of the Earth's crust, thus seems indisputable.

Structures such as mid-oceanic ridges, rifts in the continental slope and foot, oceanic rifts that propagate into the continent, initial island arcs, and marginal seas may be distinguished by the chemistry of basalt and the successively differentiated volcanic rocks in the orthostructure of the Kazakhstan Paleozoics, according to present-day interpretation. With due regard for such interpretations and existing paleogeographical reconstructions, the most probable picture of the principal stages of formation of the continental crust of Kazakhstan fully corresponds to the development of marginal-continental geosyncline systems, according to the tectonic model of lithospheric plates, and does not contradict the geosyncline hypothesis.

Conclusion

Considering the course of evolution of the Kazakhstan Paleozoics leads to the following conclusions:

1. Based upon composition and structure, the plutonic rocks of the Kazakhstan Paleozoic sequence are subdivided into three groups, distinguished not only by the definite combination and the definite succession of magmatic types, but also by petrochemical character, key formations and intensity of magmatism. The vertical successions of magmatic formations reflect the stages of construction and destruction of continental crust. Volumetric relations of the magmatic rocks and their chemistry display tendencies of direction, cyclicity and rhythm in development of tectonic structures. General laws of geosynclinal magmatism are determined by the joint and, as a rule, coordinated effect of the known laws governing a) the silicic-alkaline tendency of chemical changes; b) the increase of the degree of alkalinity and replacement of sodic-type alkalinity by potassic; c) homogeneity and magmatism; and d) the increase of the degree of differentiation of magmatic formations with time. These tendencies are traced both in time in the vertical successions and in space as they increase from the orthogeosynclinal successions through the mediogeosynclinal ones to the parageosynclines.

2. In some zones, the chemistry of orthogeosynclinal basaltic volcanics in successively differentiated formations of the Kazakhstan Paleozoics is the same as that of basalts of typical island arc formations of East Asia. In other zones, no similarity to the basalts of the inner-oceanic islands or the islands of the mid-oceanic ridges is recognized. The successively and contrastingly differentiated volcanogenic formations of the mediogeosynclinal structures appearing in the course of destruction of blocks of both Precambrian and Paleozoic crust exhibit petrochemical trends identical with those of island arc formations, but a higher degree of general alkalinity. The silicic-potassic petrochemical tendency and also tendencies toward increasing degree of general alkalinity, the degree of the contrast range of the differentiation, and increase in the proportion of acid differentiates in magmatic formations manifest themselves in the variety of magmatic formations of the Kazakhstan Paleozoics, from the early elements to the late ones, and, on the whole, from orthogeosynclinal megasets to parageosynclinal ones. These tendencies reflect trends in the evolution of the Earth's crust and in the differentiation of the substance of the planet.

3. The normal and essentially potassic granites form the final products of the evolution of the granodiorite formations; the latter are closely connected with successively and contrastingly differentiated basaltic and andesite formations in space and in time. The petrochemical trends of the volcanic and plutonic rocks coincide, which emphasizes the causal, genetic relations of the above-mentioned volcanic and intrusive formations and restricts the use of all hypotheses of crustal transformation and magma development,

on the one hand, and supports the leading role of the subcrust fluids comprising the spectrum of the petrogenic elements.

4. Consideration of data on the evolution of the Paleozoic magmatic formations of Kazakhstan testifies that normal geosyncline magmatism gives rise to a definite order of regularly organized vertical successions of magmatic formations. These correspond to definite geotectonic environments: ortho-, medio- and parageosynclines.

Acknowledgments — The authors express their gratitude for help in the preparation of this paper to Dr. L.M. Paletz and F.F. Saidasheva (print), to translators I.L. Bryzgalova and R.K. Nurbaeva and the draughtsman L.S. Bokhanko. The authors also thank Prof. A.E.M. Nairn and Dr. M.K. Apollonov for editing the paper and improving the English.

References

(all papers in Russian)

Abdulin, A.A., ed., 1980. The Geology of the Chu-Ili Region. Alma-Ata, Nauka, 503 p.

Abdulin, A.A., ed., 1982a. The Magmatic Complexes of Kazakhstan, v. 1: The Kokchetav-Northern Tien-Shan Folded System. Alma-Ata, Nauka, 235 p.

Abdulin, A.A., ed., 1982b. The Magmatic Complexes of Kazakhstan, v. 2: The Chingiz-Tarbagatai Folded System. Alma-Ata, Nauka, 167 p.

Abdulin, A.A., ed., 1983. The Magamatic Complexes of Kazakhstan, v. 3: The Dzungar-Balkhash Folded System. Alma-Ata, Nauka, 215 p.

Abdulin, A.A., ed., 1984. The Magmatic Complexes of Kazakhstan. The Urals and Zaisan Folded Systems. Alma-Ata, Nauka, 223 p.

Abdulin, A.A., Avdeev, A.V., and Patalakha, E.I., 1976. The magmatism of Kazakhstan from the position of the modern geotectonic conceptions. In: The Problems of the Petrology (edited by V.S. Sobolev). Moscow, Nauka, p. 18-36.

Alektorova, E.A., and Fogelman, N.A., 1979. About the tectonic zonation of the paleozoids of central Kazakhstan. Geotektonika, v. 4, p. 117-121.

Antonyuk, R.M., 1974. The oceanic crust of the eugeosyncline area of the east of central Kazakhstan. In: The Tectonics of the Ural-Mongol Folded Belt. Moscow, Nauka, p. 67-74.

Antonyuk, R.M., Lyapichev, G.F., Markova, N.G., et al., 1977. The structure and the evolution of the Earth's crust of central Kazakhstan. Geotektonika, v. 5, p. 71-82.

Bespalov, V.F., 1971. The Geological Structure of the Kazakh S.S.R. Alma-Ata, Nauka, p. 347-361.

Bevzenko, P.E., 1979. The Magmatic Evolution of the Floor and Folded Surroundings of the Pacific Ocean. Moscow, Nauka, 320 p.

Bogdanov, A.A., 1965. The tectonic zonation of the paleozoids of Central Kazakhstan and Tien-Shan. Byull. Mosk. Obschestva ispytatelei prirody (Geol. Sec.) 40, p. 3-38.

Bogdanov, A.A., Mazarovich, O.A., Mikhailov, A.E., and Chetverikova, N.P., 1955. The new data on the geology of the Precambrian and Paleozoic deposits of the Atasu region (central Kazakhstan). Sovetskaya Geologiya, 4, 48 p.

Borukaev, R.A., 1955. The Prepaleozoic and the Lower Paleozoic of the Northeast of Central Kazakhstan (Saryarka). Moscow, Gosgeoltekhizdat, 408 p.

Dvoichenko, N.K., 1991. The stratigraphy of the Cambrian of the Erementau. In: The Stratigraphy of the Precambrian of Kazakhstan and the Tien-Shan (edited by A.A. Bogdanov), 161-163, Moscow.

Kassin, N.G., 1951, 1952. The development of the geological structures of Kazakhstan: Izv. AN SSSR., Ser. Geol., 14, 3025, 15, 3-18.

Kazmin, V.N., Chernopolsky, Yu.A., Shulga, V.I., and Glukhan, I.V., 1977. The average content of some slight elements in the main types of granitoids of central Kazakhstan. Izv. AN SSSR, Ser. Geol., 4, p. 16-38.

Kolman, R.G., 1979. The Ophiolites. Moscow, Mir, 320 p.

Kutolin, V.A., 1972. The Problems of Petrochemistry and Petrology of Basalts. Moscow, Nauka, 208 p.

Kuznetsov, Yu.A., 1964. Main types of magmatic formations. Moscow, Nedra, 387 p.

Lyapichev, G.F., 1955. The Intrusive Complexes of the Prepaleozoic and the Cambrian of the Boshchekul Region. Alma-Ata, Izdatelstvo Akademii Nauk Kazakh SSR, 132 p.

Lyapichev, G.F., 1956. Some peculiarities of the geological mapping of the basic and ultrabasic intrusions of central Kazakhstan. Izv. AN SSSR, Ser. Geol., 24, p. 26-39.

Lyapichev, G.G., 1976. The regularities of the development of the volcanism of Kazakhstan. In: The Problems of Petrology (edited by V.S. Sobolev). Moscow, Nauka, p. 149-166.

Lyapichev, G.F., 1977. The evolution of the Earth's crust and the tectonic zonation. In: The Metallogeny of Kazakhstan: The Types of the Structural-Formational Complexes (edited by A.A. Kayupov), 9-22, 164-189. Alma-Ata, Nauka.

Lyapichev, G.F., Nurlybaev, A.N., Starov, V.I., Panchenko, A.G., Seitmuratova, E.Yu., Sergieva, M.N., Telguziev, A.T., and Fedko, V.P., 1981. Plutonism and tectonics. In: The Problems of the Tectonics of Kazakhstan (edited by A.A. Abdulin). Alma-Ata, Nauka, p. 101-132.

Novikova, M.Z., Gerasimova, N.A., Borisyonok, V.I., Buyakovska, K.S., Dubinina, S.V., and Minervin, O.V., 1980. The new data on the stratigraphy of the early geosyncline volcanogenic-siliceous formations of the Paleozoic of the Eshkiolmes and Erementau-Niyaz anticlinoria. In: The Materials on the Geology of Central Kazakhstan, 30, p. 85-102, Moscow.

Peive, A.V., 1961. The tectonics and Magmatism. Izv. AN SSSR, Ser. Geol., 3, p. 36-54.

Peive, A.V., et al., 1972. The paleozoids of Eurasia and some questions on the evolution of the geosyncline process. Sovetskaya Geologiya, 12, p. 7-22.

Peive, A.V., et al., 1977. The ophiolites: The modern knowledge and the aims of the investigations. Geotektonika, v. 6, p. 4-14.

Peive, A.V., Knipper, A.L., Markov, M.Z., et al., 1984. The regularities of the formation of the continental crust in the Phanerozoic. In: The Reports of the XXVIIth International Geological Congress, v. 7 (Tectonics). Moscow, p. 3-9.

Serykh, V.I., et al., 1976. The Mineral and Chemical Content of the Ultra-Acid Granitoids of Central Kazakhstan. Alma-Ata, Nauka, 195 p.

Shatsky, N.S., 1938. About the tectonics of central Kazakhstan. Izv. AN SSSR, Ser. Geol., 5b, p. 3-7.

Sheinmann, Y.M., 1968. The Sketches on the Depth Geotectonics. Moscow, Nedra, 231 p.

Stille, H., 1964. Selected papers. Moscow, Mir, 887 p.

Late Paleozoic Balkhash-Ili Volcanic-Plutonic Belt (Central and South Kazakhstan)

E.Yu. Seitmuratova, M.R. Borukaeva, G.F. Lyapichev

Abstract

This article summarizes the current state of knowledge concerning the magmatic complexes of Kazakhstan. The newly developed correlations of the Late Paleozoic volcanogenic and volcanogenic-sedimentary rocks and volcanogenic-plutonic associations presented are based on the authors studies. Four formational families are distinguished: mafic, continuously differentiated mafic-salic, contrastingly differentiated mafic-salic, and salic. A short description of each family is presented with an overview of the evolution of Late Paleozoic volcanism.

Introduction

The problem of the relation of magmatism with depth is of fundamental importance. Naturally, volcanic-plutonic belts, regions of widely distributed volcanic and plutonic rocks, provide a lot of information concerning the inner regions of the Earth. This information is supplied by the composition of igneous instrusions and volcanos which accompanied the magmatic processes and is an important aid in the solution of some of the problems concerning the genesis of ores and in discovering the rules controlling the distribution of mineral deposits.

The Late Paleozoic Balkhash-Ili volcano-plutonic belt attracted the attention of many geologists of the former USSR (Abdulin et al., 1972, 1973, 1976; Azbel et al., 1971; Azbel, Borukaeva, 1969; Afonichev, 1967; Bakhteev, 1966; Bespalov, 1956, 1971; Bogdanov, 1959; Borukaeva, Azbel, 1965; Fremd, 1971; Fremd, Rybalko, 1971; Gayek, 1967; Kepezhinskas, 1969; Koptev-Dvornikov, Yakovleva, Petrova, 1967; Kopteva, 1974; Koshkin, 1962, 1974; Kumpan 1966; Kumpan et al., 1969; Kurchavov, 1984; Lyalin, 1971; Lyapichev et al., 1971, 1976, 1989, 1991; Monich et al., 1960, Mossakovskyi, 1975; Myasnikov, 1974; Perekalina, 1966; Radchenko, 1967; Shcherba, 1969; Shcherbakova, 1969; Sharpyonok, 1979; Skrinnik, Tkachenko, 1980; Radchenko, Rozenkrantz, 1968; Tashchinina, 1965; Timofeeva, 1976; Yakovleva, 1963; Zeilik, 1968). However, despite the many intensive investigations, many problems of the geology, stratigraphy and metallogeny of the Late Paleozoic magmatic rocks have not been resolved.

Late Paleozoic (and Early Triassic?) magmatic rocks are known over much of Kazakhstan, but prolonged and intensive continental volcanism and contemporary intrusive activity are concentrated in the Hercynian Dzhungar-Balkhash folded system (Figs. 1, 2). The Dzhungar-Balkhash fold system may be divided into four megazones: (1) the Outer Nura megazone, adjoining the Caledonides, 2) and 3) two Median megazones, united into a single Balkhash-Ili volcanic-plutonic belt (Afonichev, 1967) and (4) Inner Sayak-North Dzhungar megazone.

Late Paleozoic magmatic rocks of the Balkhash-Ili belt can be traced (with some interruptions) into South-East Mongolia, up to the meridian of Lake Baikal. Thus, the Kazakhstanian magmatic area forms only the extreme northwestern part of a single Dzhungar-Mongolian volcanic-plutonic mega-belt. According to the majority of investigators of the Late Paleozoic belt, the North Balkhash and Ili megasynclinoria can be distinguished as the middle megazone in the modern folded structure of the belt. The megasynclinoria, in turn, are subdivided into Uspenka, Tokrau, Kotanemel-Bakanass, Alakol, Saryozek and Panfilov synclinoria.

The synclinoriums are gently dipping structures, lying on the Early Hercynian folded structural complex. Within them, isometric volcano-tectonic depressions differing in time of formation are common and characteristic morphostructures. An uninterrupted succession of Late Paleozoic volcanic rocks from Visean-Serpukhovian to Early and Late Permian in age can be studied in the many existing magmatic structures (Zhanet, Kyzyladyr, Arkharly, Saryozek, Degerez, Arkalyk, etc.).

Traditionally, most investigators consider that the Late Paleozoic formations began only during Visean-Serpukhovian, from the so-called Karkarala formation in the northern part of the belt and from the Batpak group in the southern part. There are many problems in subdividing the Late Paleozoic volcanic rocks in the dating and correlation of the formations, especially in the North Balkhash area (Lyapichev et al., 1989; Seitmuratova, 1992). During the last decade, the authors have studied and revised the subdivisions and formations of all the type sections in the belt

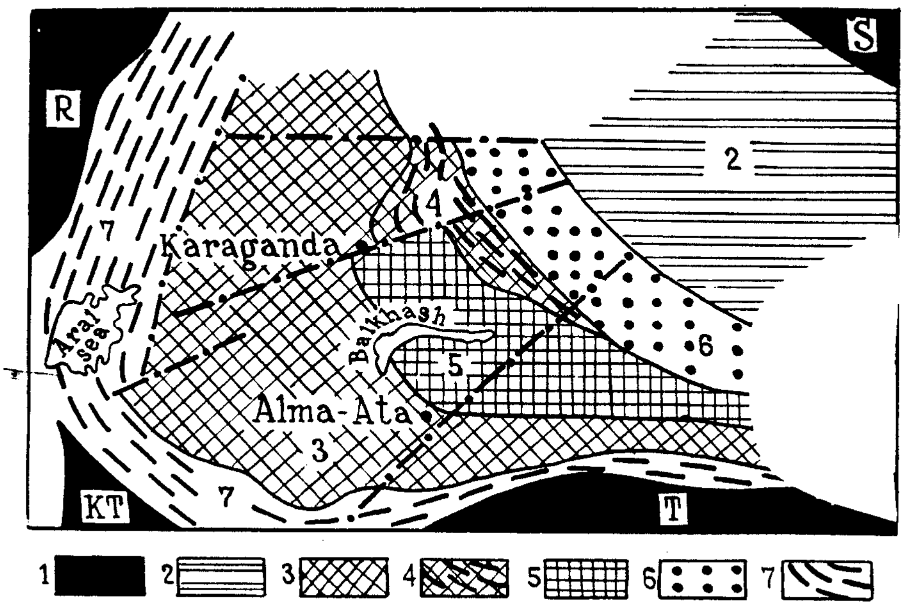


Fig. 1. The position of the Balkhash-Ili volcanic-plutonic belt (Dzhungar-Balkhash system) in the Paleozoic structure of Kazakhstan: 1- platforms: R- Russian, S- Siberian, T- Tarimian, KT- Karakum-Tazhykian; 2-4- Caledonian fold systems: 2- Altai-Sayan, 3- Kokchetav-North Tien-Shan, 4- Chingiz-Tarbagatai; 5-7- Hercynian fold systems: 5- Dzhungar-Balkhash (Balkhash-Ili volcanic-plutonic belt), 6- Zaisan, 7- Urals and Median-South-Tien Shan.

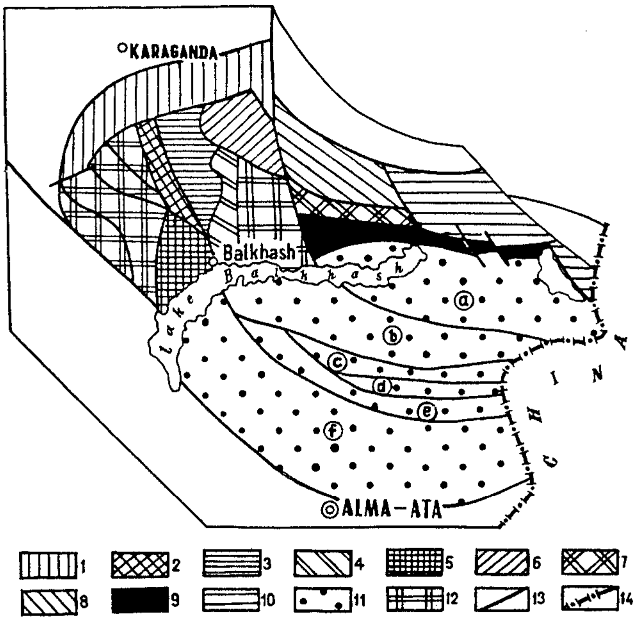


Fig. 2. The structural-formational zonation of the Late Paleozoic Balkhash-Ili volcanic-plutonic belt: 1- Uspenka; 2- West Tokrau; 3- Zhantau; 4- Kotyrasan; 5- South Tokrau; 6- East Tokrau; 7- Kalmakemel; 8- Kotanemel; 9- Sayak; 10- Bakenass; 11- Ili (with subzones): a- North Dzhungar, b- Sarkand, c- Central Dzhungar, d- Borotaly, e- South Dzhungar, f- Ili; 12- the structural-formational zones with or without weakly developed Late Paleozoic volcanism; 13- the boundary of the structural-formational zones and subzones; 14- state boundary.

and made modern interzonal correlations (Fig. 3) with the object of resolving the most disputable problems. These investigations were carried out as a part of the Project "Geology and Metallogeny of the Balkhash segment of the Earth crust of Kazakhstan" of the Satpaev Institute of Geological Sciences of the National Academy of Sciences of the Republic of Kazakhstan. Because of the uncertainty of some of the paleontological data, radiolometric data were widely used to assign ages and to correlate the Late Paleozoic volcanic rocks and the comagmatic intrusions of the Balkhash-Ili volcanic-plutonic belt. The cyclic character of magmatic processes was recognised (Azbel, Borukaeva, 1966; Lyapichev et al., 1976). From these results, a correlation chart of the Late Paleozoic magmatic rocks of the belt (Fig. 4) was compiled by G.F. Lyapichev, E.Yu. Seitmuratova, M.R. Borukaeva and E.N. Timofeeva, using the data of L.A. Goganova, A.K. Myasnikov, Yu.I. Lyalin, A.M. Kurchavov, V.Ya. Koshkin, M.M. Marfenkova, O.E.

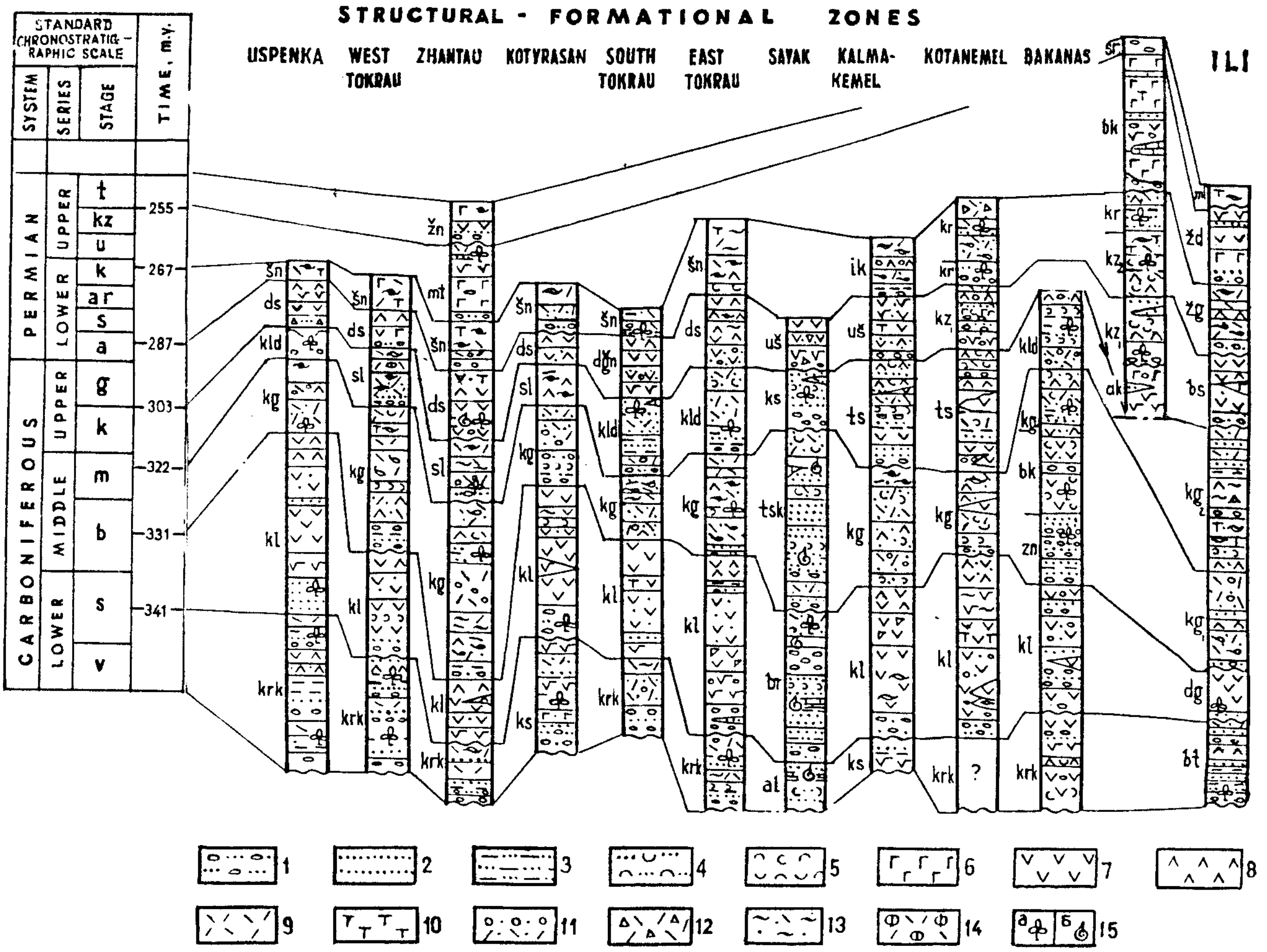


Fig. 3. The correlation of the Late Paleozoic deposits of the Balkhash-Ili volcanic-plutonic belt: 1-3- Sedimentary rocks: 1- conglomerate and gravelstone; 2- sandstone; 3- silty sandstone, muddy, carbonaceous, and muddy-carbonaceous siltstone, limestone; 4-5- volcanogenic-sedimentary rocks: 4- tuffaceous sandstone, tuffaceous siltstone; 5- tuffite; 6-14- volcanic rocks: 6- basalt, andesito-basalt; 7- andesite, trachy-andesite, andesito-dacite; 8- dacite; 9- rhyodacite, rhyolite; 10- trachyte, trachy-rhyolite; 11- lithocrystallineclastic, vitrocrystalline clastic, crystalline clastic, and welded vitrocrystalline clastic tuffs; 12- agglomerate tuff and volcanic breccia; 13- ignimbrite, ignispumite, tafflava, fluidal lava; 14- spheroidal lava; 15- fossils: flora (15a), fauna (15b).

Indexes of formations: P2zn- Zhan; P2sr- Seirektau; P2ml- Malaisara; P1-2mt- Maitas; P1-2bk- Bakaly; P1-2zd- Zheldykora; P1sn-Shangelbai; P1ik- Ikbai; P1kr- Karairek; P1kz2- Upper Kyzylkiya; C3-P1ds- Dostar; C3-P1dgn- Zhangeldy; C3-P1us- Ushmola; C3-P1kz1- Lower Kyzylkiya; C3-P1ak- Akshoky; C3-P1bs- Beskainar; C2-C3kld- Koldar; C2-C3sl- Slushoky; C2-C3ks- Koskyzyl; C2-C3ts- Taskora; C2-3bk- Bakenas; C2-C3kg2- Upper Kugaly; C2-C3ks- Kungisayak; C2kg- Keregetas; C2tsk- Tastykudak; C2zn- Zhamenka; C2kg1- Lower Kugaly; C1-2kl- Kalmakemel; C1-2 br- Burultas; C1-2dg- Degeres; C1krk- Karkarala; C1ks- Kusak; C1a- Alabyal; C1 bt- Batpak.

Belyaev and others. The Carboniferous-Permian boundary was dated in the chart as 287 m.y., in accordance with the Central Asiatic standard. This is the age of granites which are overlapped by the Schwagerina Horizon (Polevaya, 1974). The same figure is accepted in the International radiometric scale (Harland et al., 1982).

The standard radiometric data used in this chart, given below, are figures obtained during the recent investigations (Lyapichev, Seitmuratova, Starov et al., 1991).

252 ± 12 m.y. — the age of the potassic granitoids of the Kyzylkainar (Taskora) igneous complex which penetrates the basalts of the Bakaly formation. The formation has a Late Permian flora.

267 ± 16m.y. — the age of the subalkali granosyenite of the Kokdala complex.

275 ± 10 m.y. — the age of the granosyenite of the Trangalyk complex which penetrates the Shangelbai formation and granitoids of the Kokdombak complex.

291 ± 12 m.y. — the age of the granite of the Aschisu complex, covered by the Kyzylkiya formation in the Arkharly structure. The overlying Karmys formation contains a Late Permian floristic association.

290 ± 12 m.y. — the age of the syenogranodiorite of the Kokdombak complex which penetrates the Zhangeldy formation and is penetrated by subvolcanic bodies of the Shangelbai formation. The Zhangeldy Formation rests on the Kokkyzyl formation which contains a dateable flora.

299 ± 14 m.y. — the age of a granitoid of the Sayak complex which penetrates volcanic rocks, which overlie the Kungisayak Formation with its fauna of Moscovian age and with a Koldar floral association.

303 ± 2 m.y. — the age of the granite of the Kaldynna complex.

340 ± 355 m.y. — the age of the granitoids of the Balkhash and Muzbel (Serpukhovian) complexes.

The figures for the rubidium-strontium ages of the Kaldyrma pluton (303 m.y.) and Sayak pluton (299 m.y.) are especially important because the plutons are intruded into faunistically and floristically dated formations; also of importance is the age of the Akchatau complex (287 m.y.). The Sayak pluton cuts through the whole marine succession found in the Sayak syncline and is unconformably overlain by volcanic rocks of the Ushmola formation. The upper part of the marine succession can be assigned to the Lower Moscovian stage based on faunal evidence (foraminifera, etc.). The floral remains are characteristic of the so-called Koldar horizon (Itkuduk formation) of the Middle or Upper Carboniferous. The Kaldyrma pluton cuts formations containing the flora of the Kaldyrma horizon.

These data show that in Kazakhstan there exists a reliable framework for a regional radiometric scale. The basis of this scale is the boundaries between tectono-magmatic microcycles, corresponding to the comagmatic pairs of Dobretsov and Donskikh (1966). The duration and location of the boundaries of the tectono-magmatic microcycles recognized correlates well with the global standard radiometric scale.

Eight intervals of tectono-magmatic activity can be distinguished in the belt. The intensity of magmatism in the belt, both vertically and laterally, is very variable, as recorded both by the thickness of the volcanic formations, the ratio of rock types in them (Fig. 5) and their areal distribution. The ratio of volcanic to intrusive magmatism is very variable and changes from zone to zone.

Two assumptions were made in compiling the chart, the first concerning the continuity of magmatic activity in the belt during the Late Paleozoic, and the second on the simultaneity of the youngest formation of potassic andesitic basalts, basalts and andesites over the belt (Bakaly, Maitas, Zheldykora formations). Both assumptions are based on mapping and interzonal correlation. This chart was the basis for our study of the Late Paleozoic rocks of the belt. Formations were distinguished as lithological-petrographical rock units. The volcanic rock units distinguished in the chart correspond to suites in the Stratigraphic Code of the USSR, 1975, to the "concrete formation" of Yu.A Kuznetsov, 1964, and to the "magmatic complex" of V.S. Koptev-Dvornikov, 1967. We believe that the formations (complexes, suites) distinguished are characterized as follows:

1. every formation represents a natural association of rocks that can be traced for long distances and may be characterized by some feature of rocks content and by a single petrochemical trend;
2. the ratio of the rocks comprising each trend is characteristic for each formation;
3. gradual transitions between magmatic formations are excluded, and boundaries between rock associations are drawn at sharp changes in their lithological-petrographical composition.

The present authors did not observe continuous transitions between formations, and believe that development of magmatism as comagmatic pairs of volcanic and intrusive complexes is the most probable ("as a rule"). This idea is represented in the correlation scheme of magmatic com-

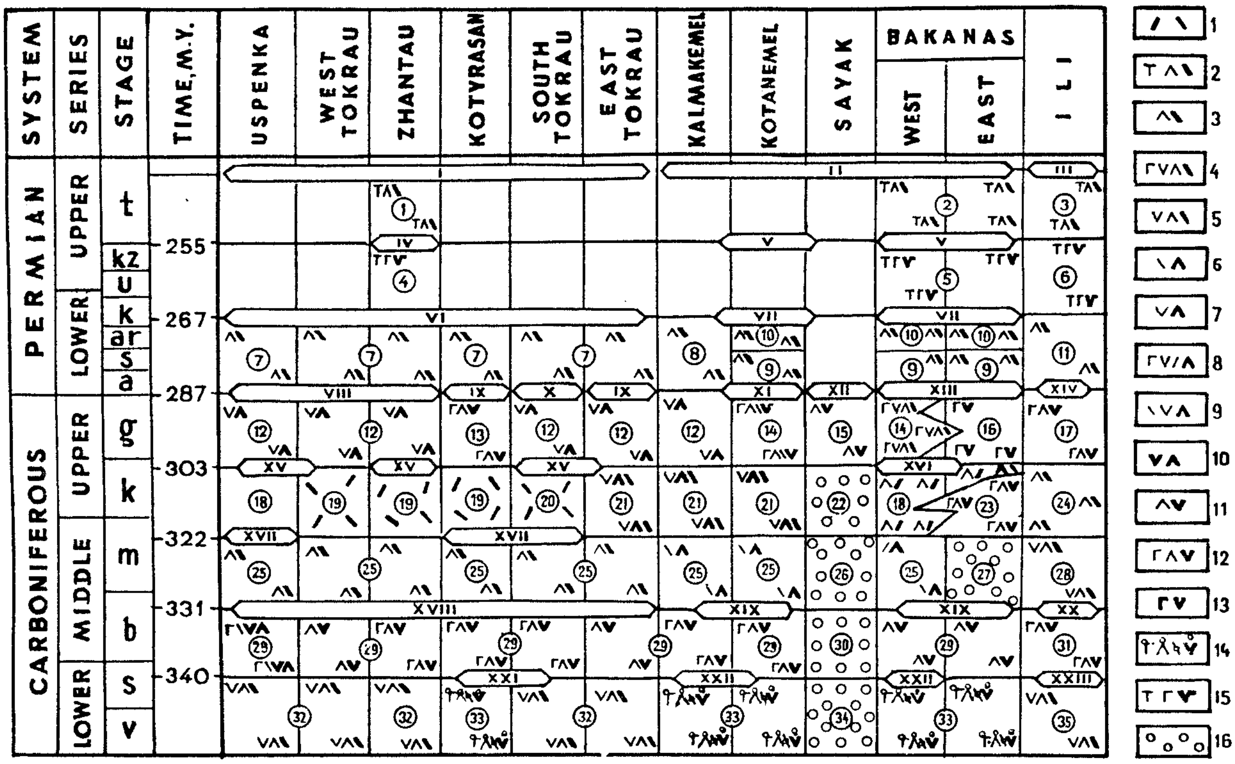


Fig. 4. The vertical successions of Late Paleozoic magmatic and sedimentary formations of the Balkhash-Ili volcanic-plutonic belt: Volcanic formations: 1- rhyolite of normal and potassic alkalinity; 2- trachydacite-rhyolite of potassic alkalinity; 3- dacite-rhyolite of potassic alkalinity; 4- the successively differentiated andesito-basalt-dacite-rhyolite potassic and normal alkalinity; 5- andesito-dacite-rhyolite of normal alkalinity; 6- rhyodacite of normal alkalinity; 7- andesite-dacite of normal and potassic alkalinity; 8- andesito-basalt-rhyolite-dacite of normal and potassic alkalinity; 9- rhyolite-andesite-dacite of normal alkalinity; 10- andesite-dacite of normal and potassio alkalinity; 11- dacite-andesite of normal alkalinity; 12- basalt-dacite-andesite of normal alkalinity; 13- basalt-andesite of normal and potassic alkalinity; 14- basalt-dacite-rhyolite-andesite of sodium alkalinity; 15- trachybasalt-andesito-basalt of potassic alkalinity; 16- sedimentary formations.

Arabic numerals designate volcanogenic and volcanic-sedimentary formations: 1- Zhan; 2- Seirektau; 3- Malaisara; 4- Maitass; 5- Bakaly; 6- Zheldykora; 7- Shangelbai; 8- Ikbeit; 9- Upper Kyzylkiya; 10- Karairek; 11- Zhalgyzagash; 12- Dostar; 13- Zhangeldy; 14- Ushmola; 15- Lower Kyzylkiya; 16- Akshoky; 17- Beskainar; 18- Koldar; 19- Slushoky; 20- Koskyzyl; 21- Taskora; 22- Kungisayak; 23- Bakanas; 24- Upper Kugaly; 25- Keregetas; 26- Tastykuduk; 27- Zhamenka; 28- Lower Kugaly; 29- Kalmakemel; 30- Burultas; 31- Degerez; 32- Karkaraly; 33- Kusak; 34- Alaba; 35- Batpak.

Roman numerals designate intrusive complexes: I- Kyzylrai, essentially potassic granites; II- Bakanas granites; III- South Dzhungar (Lepsy) granites; IV- Kyzyladyr, gabbro-monzonite-grano-syenites; V- Kyzylkainar (Taskora) gabbro-monzonite-granosyenites; VI-Tarengalyk syeno-granodiorite-granosyenite-granites; VII- essentially potassic granites; VIII- Saryolen monzonite-syeno-granodiorites; IX- Akohatau granites; X- Kokdombak monzonite-syeno-granodiorites; XI- granites; XII- Sayak gabbro-monzonite-granodiorite-granites; XIII- Aschysai (Kumzhal) granites; XIV- Katutau gabbro-granodiorites; XV- Kaldyrma leucogranites; XVI- Koldar gabbro-diorite-granodiorites; XVII- Kuttuadam adamelite-granites; XVIII- Topar diorite-granodiorite-granites; XIX- Kokdala gabbro-diorite-granodiorites; XX- Central Dzhungar (Altynemel) granodiorite-granites; XXI- Balkhash gabbro-diorite-plagio-granodiorite-plagiogranites; XXII- Muzbel gabbro-diorite-plagiogranites; XXIII- Terekty-Usek gabbro-diorite-granites.

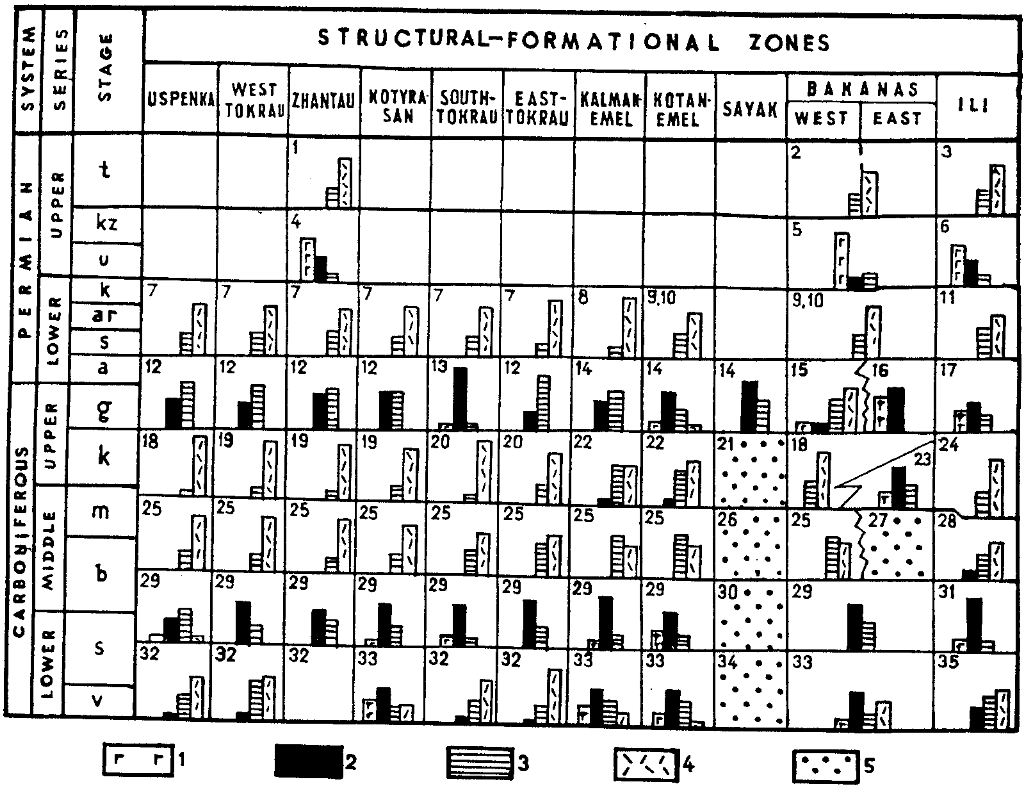


Fig. 5. The volume balance of the different volcanic rocks in the Late Paleozoic formations of the Balkhash-Ili volcanic-plutonic belt: 1- basalt; 2- andesite; 3- dacite; 4- rhyolite; 5- sedimentary rocks. Arabic numerals (1-35) correspond to the volcanogenic and sedimentary formations of Fig. 4.

plexes in the Balkhash-Ili volcanic-plutonic belt (Fig. 4). The scheme is based on data from E.Yu. Seitmuratova (Uspenka and Tokrau megazone B), E.N. Timofeeva (Kalmakemel and Katanemel zones), G.F. Lyapichev and A.K. Myasnikov (Bakanas zone) and M.R. Borukaeva, K.A. Azbel and Yu.I. Lyalin (Ili megazone) (Fig. 4).

During the study of the magmatic complexes of the belt, particular attention was paid to volcanic complexes which provide information concerning the evolution of magmatism. Detailed study of structure, composition and relations of volcanic-plutonic associations mapped in the belt permit us to characterize formations and to unite them into four families: mafic, mafic-salic showing continuous differentiation, mafic-salic with contrasting differentiation, and salic formations. This grouping of contrasting associations is distinguished for the first time.

The Mafic Family

The andesite-basalt association of normal and potassic alkalinity includes early-Late Permian complexes in the Zhantau zone (Maitas formation) and Bakanas zone (Bakaly formation) and also in the Ili megazone (Zheldykora formation).

The formation is represented by beds of andesitic-basalts, basalt and trachy-andesitic basalts alternating with horizons of tuff and more rarely of tuffstone and tuffite. The lava and tuff ratio varies in different sections. Aphyric basalts with amygdaloidal texture are the predominant lava types. They have a high alkalinity (from 5.0 to 8.8%) and typically a 1 to 4.9% of potassium oxide and high alumina. Of the metalliferous association, there are found small native copper and copper zeolites.

The Mafic-Salic Continuously Differentiated Family

Dacite-basalt-andesite with a sodic alkalinity are found in the Kusak complex (C1v-s), which is distributed widely in the Kotyrasan and Ealmakemel zones. The type section is located in the Kusak Syncline. The formation consists of andesite and andesitic basalt lava and tuff to a lesser degree. Acidic volcanic rocks (mainly tuff) constitute 10-15% of the formation by volume. Sedimentary rocks, mainly as conglomerate and sandstone, and coal-bearing beds play a noticeable role in some successions.

The proportion of the principal lithologies is very variable laterally. Distinct sodic rich and normal alkalinity is a typical petro-chemical feature of the formation. The geochemical identity of the formation is emphasized by a comparatively high copper content. A dacite-basalt-andesite formation with normal and potassic alkalinity is represented by the Kalmakemel complex (C1s-C2b) in the South Tokrau zone and by the Degerez formation of the same age in the Ili megazone. The formations consist mainly of andesite-basalt, more rarely of dacitic volcanic rocks. Lava predominate, and tuff are more rare. According to their chemical composition, the rocks form an uninterrupted sequence from andesito-basalt to dacite. A variation in alkalinity from normal to potassic is usual for all types of volcanic rocks.

Basalt-andesites of potassic and normal alkalinity are also found in the Kalmakemel complex (C1s1-C2b), in the Zhantau and Kotyrasan zones, the Bakanas complex (C2-C3) of the Bakanas megazone and also in the Upper Carboniferous-Early Permian Zhangeldy complex in the South Tokrau zone, the Akshoky complex in the Bakanas megazone and the Beskainar complex in the Ili megazone. The prevalence of andesito-dacite and the insignificant quantity of andesito-basalt and dacite is characteristic of the formation. In most complete successions, the formation shows a two part composition. The lower member, a volcanogenous-sedimentary sequence, consists of tuffaceous conglomerates, tuffites, and sandstones interbedded with lavas and andesitic- and andesitic-dacite tuffs. The upper, volcanic member is represented by interbedded andesites, andesitic basalts, andesito-dacite lavas, tuffs and tuff lavas in a general homodromic succession.

An andesite-dacite formation of normal and potassic alkalinity is also found in the Kalmakemel (C1s-C2b) and Buguly (C3-P1) complexes in the Uspenka zone and in the Dostar complex (C3-P1) in the West and East Tokrau, Zhanatau and Kotyrasan zones.

The Kalmakemel complex in the Uspenka zone differs from the same rocks in other zones by a higher acidic content (dacites predominate over andesites) and by the presence of andesito-dacites and trachyandesites, as well as by the appearance of layers of rhyodacites. The sections in the Nurbai and Karabasan structures are type sections. Together with lavas, the crystallinoclastic and lithoclastic tuffs, are more rare tufflavas. The contribution of volcanogenic sedimentary rocks is unimportant in terms of the general thickness. The subvolcanic facies is represented by andesito-dacite sills, very similar to lava.

The Dostar and Buguly complexes are represented mainly by lavas and tuffs, and to a lesser degree by andesito-dacite and andesito-tuff-lavas. Dark red in colour, the presence of feldspar and biotite porphroblasts, elevated alkalinity in the andesites (up to trachyandesite) is characteristic for the rocks. Sedimentary rocks are few or absent.

In the petrochemical sense, the prevalence of the potassic alkalinity in most types of rocks is characteristic. Correlation of the average andesite composition with the world standards demonstrates that the alkalinity of the volcanic rocks is high (6 to 8%) and depends on the high potash content (K20-3.01%). Dacite-andesites of normal and potassic alkalinity are represented in the Kalmakel complex (C1s-C2b) in the Kalmalemel, West and East Tokrau zones and in the Bakanas megazone. Insignificant quantities of volcanogenic-sedimentary rocks and the predominance of andesite and trachyandesite lavas are a characteristic of the formation. Tuffs are of lesser importance. The wide distribution of plugs and subvolcanic intrusions, gold, polymetallic and copper deposits are connected with the Zhusabai, Ozyornoye and other subvolcanic intrusions.

An andesite-dacite-rhyolite sequence with normal and potassic alkalinity is found in the Karkarala formation (C1 v2-s) in the Uspenka and West Tokrau zone and in the Batpak complex (C1v2-s) in the Ili megazone. Type sections were selected in the Kadyp-Oguztau, Sarygylzhan and Chiiozek structures. The volcanic rocks of the formation constitute a progressively differentiated series from andesite and andesito-dacite to rhyolite. The rocks are found in practically all volcanic facies, plug, subvolcanic and nappes. In the nappes, tuffs, ignispumites, and ignimbrites, characteristically grey-black and dark grey-green in colour, are widely represented together with lavas. The presence of volcanogenic-sedimentary rocks, tuffites, tuffstones, conglomerates, carbonaceous and carbonaceous-cherty mudstones is characteristic of the formation. The ratio of volcanogenic-sedimentary and volcanic rocks in the Uspenka zone shows remarkably wide lateral variations. The volume of the sedimentary rocks clearly decreases from southwest to northeast.

With respect to the petrochemistry, the rhyolites and dacites belong to the class of normal rhyodacites with a rather unstable type of alkalinity (from sodic normal to potassic). In comparison with global standards, the principal rocks in the formation are richer in alumina and poorer in titanium.

The Salic Formation Family

A rhyolitic-dacitic assemblage of normal and potassic alkalinity is represented in the Keregetas (C2 -xx) in the Kotanemel and Kalmakemel zones. The prevalence of dacites is a characteristic of the formation. In the type section, in the southern part of the Kalmakemel syncline, crystalline-clastic tuffs of the rhyolite-dacite composition are interbedded with thin-bedded rhyolitic tuffs, ignimbrites and tuffites. Tuffaceous-sedimentary rocks lie at the base. The instability of the facies is shown by the wedging out of some horizons and members over short distances. A wide variation in the silica content (from 65% to 73%) has been recorded.

Dacite-rhyolites of normal and potassic alkalinity are very widely distributed in the belt. They include the Middle Carboniferous Keregetas complex in the Zhantau, Kotyrasan and South Tokrau zones, and almost all the Lower Permian volcanic complexes, the Berkuty complex in the Uspenka zone, the Shangelbai complex in the Tokrau megazone, the Karairek complex in the Bakanas megazone, and the Zhalgyzagash complex in the Ili megazone. Lithoclastic and ash tuffs, interbedded with fluidal and spherolithic lavas, tufflava, and ignimbrites of rhyodacite and rhyolitic composition, are characteristic of the Middle Carboniferous complexes. Thin members of red colored volcanogenic-sedimentary rocks occur. Variation of the alumina content (from 66% to 76%) is a characteristic feature of the chemical composition.

The Lower Permian complexes are characterized by a two part composition. The lower section is represented by ash, welded lithoclastic and vitrocristalline tuffs, and more rarely by tufflavas and ignimbrites of rhyodacitic, rhyolitic and trachy-rhyolitic composition. Lavas are very rare. The upper part consists mainly of nappes of brownish black, pinky-grey, or light-brown ignispumites and ignimbrites. Volcanogenic-sedimentary rocks are rare. The wide distribution of subvolcanic and plug facies and close association of volcanic rocks of the formation with granitoids of the granite-grano-syenite formation of Permian age are very characteristic.

Dacite-rhyolites of potassic alkalinity are represented by the Late Permian complexes, the Siireektau complex in the Bakanas zone, the Kyzyladyr complex in the Zhantau zone, and the Malaisary complex of the Ili megazone. In the nappe facies, welded and agglomerated tuffs, ignimbrites, and more rarely ignispumites of trachy-rhyolitic and trachydacitic composition predominate. The thin-bedded tuffaceous conglomerates, sandstones, and mudstones are common at the base of many sections. They are of arkosic composition with fragments of basalt, andesitic-basalt and trachy-andesite from the underlying andesite-basalt complex. Fragments of basalt were observed also in the lower acidic tuff nappe which is an easily traced marker horizon. Craters are filled with extrusions of ignispumites, and dykes of grano-syeniteporphyre occupy faults radiating from the volcanoes. The chemical composition is rather homogeneous; the potassic alkalinity is high; and the alumina content is rather low.

Rhyolites are distributed rather widely in the belt. They include the Middle and Upper Carboniferous Kaldar complex of the Uspenka and Bakanas zones, the Slushoky complex of the Zhantau, Kotyrasan and West Tokrau zones, the Koskyzyl complex of the South and East-Tocrau zones, the Upper Kudaly complex of the Ili megazone and also the Middle Carboniferous Keregetas complex of the Uspenka, East Tocrau and West Tocrau zones, the Early Permian Karmys-Kyzylkiya complex of the Kotanemel zone. The predominance of rhyolite over dacite distinguishes the formation from the previous formations. Rhyolite rarely forms less than 90% of all successions. Sedimentary arkosic rocks of appreciable thicknesses are notable; only the Slushoky complex is an exception. The latter complex consists of volcanic rocks, ignimbrites, welded tuff, tuff-lava of acidic and ultra acidic composition. According to the general chemical composition of the formation, the rocks are ultraacidic of normal (potassic-sodic) alkalinity.

Associations of Contrasting Formations

These associations are characterized by their complex petrography and their great lateral variability. Such associations were described by V.F. Bespalov (1971) in the North Balkhash region as the Arkharly formation. He stated that "in the usual stratigraphic understanding, any distinct typical succession for the Arkharky formation is lacking". Really, the question of formational unity of this rock association is debatable, because of the combination of the two very different groups of rocks forming the association. Such associations appear in transitional zones, in which basalt volcanism from one side and rhyolitic volcanism from the other side took place synchronously. Such associations are not widely distributed and were observed only in some isolated structures of the Zhantau, Kotanemel and Bakanas zones in complexes of Late Carboniferous-Early Permian and early Late Permian age.

The basalt-rhyolite association of the Upper Carboniferous-Lower Permian-Lower Kyzylkiya formation is represented in the Kotanemel and Bakanas zones (Arkharly, Saryoba and Taskora volcano-tectonic structures). In the Arkharly structure, deposits of the Arkharly complex belong to the association. Volcanic rocks occur in the lower part of the Kyzykkiya formation with predominantly volcanogenic-sedimentary rocks and litho-vitro-crystallineclastic tuffs of rhyolitic and rhyodacitic composition with crystalline clasts of quartz and are included in the Arkharly complex. Light grey, greenish grey, and light green colours are typical of the rocks. Dacitic ignimbrites and tuffs are rather rare. Andesito-basalt, rare trachy-andesito-basaltic lava members are usually thin, and are sometimes lenticular. The quantity of such members is variable, and two members are known in some sections, as in the Arkharly structure, for example. The total thickness of the basalt may constitute half of the total thickness in some successions (Buzhurtau m.t.). The basalts are usually aphyric with amygdaloidal texture.

A trachybasalt-trachyandesite-rhyolite association of Early and Late Permian age (Maitas fomation) is known in the Arkharly, Karakiya, Shangraktas and Dostar volcanic structures in the Zhantau zone. The successions in these structures are polyrhythmic in many cases and are represented mainly by volcanogenic-sedimentary rocks of acidic and basic composition and more rarely by volcanic rocks. Every rhythm is marked by the interbedding of thin horizons of tuffaceous conglomerates, gravelstones, sandstones, mudstones of greywacke and arkosic composition, sometimes with limestones and subordinate tuffs and tuffites of rhyolitic composition, andesito-basalts and aphyric and amygdaloidal basalts. Tuffaceous-sedimentary rocks with basaltic clastics are replaced laterally by basalts and andesito-basalts (southern slopes of Karakiya mountain and the northern part of the Shangraktas structure).

Petrochemically, the basalts of the Early and Late Permian association demonstrate a considerable similarity to basalts and andesito-basalts of the Zhantau (Maitas) and Bakaly complexes. The SiO_2 content (49.3-55%) is standard for basalts and andesito-basalts, but the alkalinity range (from 4 to 8.8%) is high, and the potassium content is high (from 1.3 to 4.9%).

The andesite-dacite association of Middle and Upper Carboniferous (Taskora formation.) is widely distributed in the Kotanemel and Kalmakemel zones. Rocks of dacite-trachydacite pyroclastic facies, composing the middle part of the succession, predominate. Andesite and andesito-basalt lavas also play an important role. As single horizons, they occur in all the succession but are best represented in the upper part. Volcanic rocks of acidic composition (rhyolitic and rhyodacitic tuffs) are subordinate (less than 5% of the total thickness). Dark brown and reddish brown colour, agglomerate structure, allochthonous pyroclastics, abundant ignispumites and auto-magmatic breccia are the characteristics of the formation. The

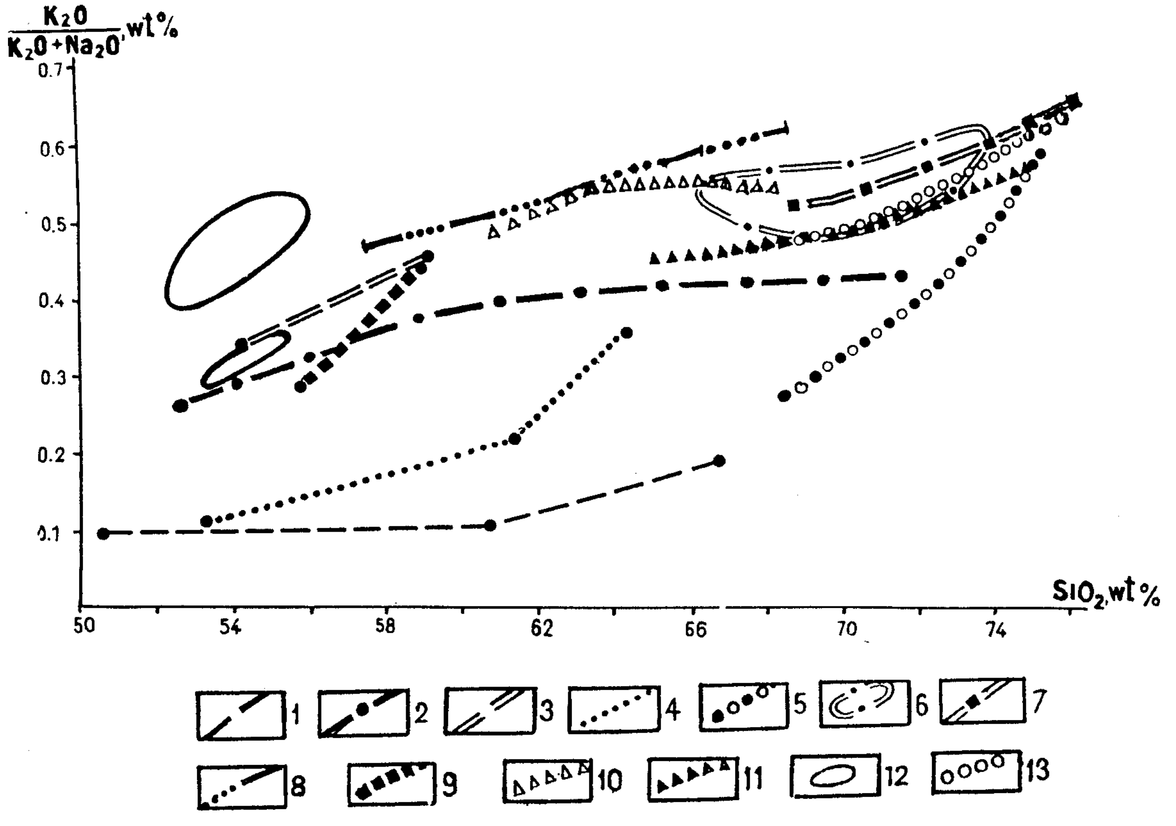


Fig. 6. Potassium content in the volcanic complexes of the Northwest sector (part) of the Balkhash-Ili volcanic-plutonic belt: 1-13- petrochemical trends of the Late Paleozoic volcanogenic formations in the different structural-formational zones: 1- Kusak Formation of Kotyrasan zone; 2- Karkaraly Formation in all zones; 3- Kalmakemel Formation of the Uspenka zone; 4- Kalmakemel Formation of Tokrau, Zhantau, Kalmakemel, and Kotanemel zones; 5- Keregetas Formation in all zones; 6- Koldar and Slushoky formations of Uspenka, Zhantau, and West Tokrau zones; 7- Loskyzyl Formation of South and East Tokrau zones; 8- Doatar Formation of Uspenka zone; 9- Zhangeldy Formation of South Tokrau zone; 10- Dostar Formation of Zhantau, West and East Tokrau, and Kotyrasan zones; 11- Zhangeldy Formation of all zones; 12- Maitas Formation of Zhantau zone; 13- Zhan Formation of Zhantau zone.

amount of sedimentary material is not large, and as a rule, its role increases with increasing distance from volcanic and volcano-tectonic structures. Subvolcanic, plug and extrusive facies are widely distributed. Chemically, normal calc-alkali and high alkalinity varieties (owing to potassium) can be distinguished among the rocks of the complex.

The volcanogenic complexes just described in the Balkhash-Ili belt have a very distinctive petrochemical composition, particularly in the type and level of their potassic content (Fig. 6). Two structural megazones are very different in the succession of formations. The first, the Kotyrasan-North Sayak median megazone, adjacent to the inner Sayak-North Dzhungar megazone, is one in which the formational sequence began with terrigenous clastic formations followed by contrasting basalt-rhyolite association with a strong sodic alkalinity (Kusak complex). The contrasting formation is replaced higher in the succession by the successive (continuously) differentiated complex, of sodic or normal alkalinity. The late complex is always potassic-sodic and never sodic-potassic. The second, the Carboniferous-Permian part of the formational sequence of the Tokrau-Bakanas-Ili megazone, began with successively differentiated basaltic-andesitic-dacitic formations with normal or potassic alkalinity. These differentiated formations (the Kalmakemel complex and its analogues) rest on the essentially rhyolitic Karkaraly complex.

There is a clear distinction between these successions. An essentially sodic alkalinity is characteristic of the first (Kotyrasan-North Sayak) megazone, and an essentially potassic alkalinity is characteristic of the second (Tokrau-Bakanas-Ili) megazone. In the first megazone, the volcanogenic succession overlies a clastic, terrigenous formation. In the second megazone, the volcanogenic succession rests on rhyolites covering the Medium massif. The succession begins with contrasting formations in the first megazone and with successively differentiated formations in the second megazone.

It must be emphasized that petrochemical differences between megazones become progressively less clear higher in the section, and the successions and youngest formations are very similar petrochemically in all megazones.

The petrochemical zonation of magmatic complexes of the Dzhungar-Balkhash Variscides is very similar to the zonation found in modern transitional zones between continents and oceans.

Acknowledgments — The authors gratefully acknowledge the help of Dr. L.M. Paletz and Eng. F.F. Saidasheva in the preparation of the text, of translators I.L. Bryzgalova and R.K. Nurbaeva, and of draughtsman L.S Bokhanko for the figures. The authors also thank Drs. M.K. Appollonov and A.E.M. Nairn for editing the text and improving the English.

References (all in Russian)

Abdulin, A.A. ed., 1977. Metallogeny of Kazakhstan. Types of the structure-formation complexes and tectonic zonation of Paleozoics. Alma-Ata, Nauka, 190 p.

Abdulin, A.A., Abdrakhmanov, K.A., and Avdeev, A.V., 1972. Central ring-shaped structures of Kazakhstan, their type and the mechanism of their formation. Izvestiya AN Kazakh S.S.R., Seriya geologicheskaya, no. 1, p. 11-16.

Abdulin, A.A., Avdeev, A.V., Abdrakhmanov, K.A., and Skublov, G.T., 1973. Orogenic central ring-shaped tectonomagmatic structures of Kazakhstan, in: A.A. Abdulin, ed., Tectonics and magmatism of Kazakhstan. Alma-Ata, Nauka, p. 67-96.

Abdulin, A.A., Cholpankulov, T.Ch., Azbel, K.A., Zvontsov, V.S., Lyalin, Yu.I., Nikitina, L.G., and Frid, N.M., 1976. Main features of the evolution of the Paleozoic volcanism of Kazakhstan, in: A.A. Abdulin, ed., Magmatic and metamorphic complexes of Kazakhstan, v. 1. Alma-Ata, Nauka, p. 122-132.

Afonichev, N.A., 1967. Main stages in the evolution of the Dzhungar-Balkhash geosynclinal system (paper 1). Sovetskaya geologia, no. 2, p. 33-53.

Afonichev, N.A., 1967. Main stages in the evolution of the Dzhungar-Balkhash geosynclinal system (paper 2). Sovetskaya geologia, no. 3, p. 61-82.

Antoyuk, R.M., Lyapichev, G.F., Markova, N.G., Paylova, G.G., Rosen, O.M., Samygin, S.G., Tokmacheva, S.G., Shuzhanov, V.M., Shcherba, I.G., 1977. Structures and evolution of the Earth's crust of Central Kazakhstan. Geotectonica, no. 5, p. 71-82.

Azbel, K.A., and Borukaeva, M.R., 1966. On the problem of the recurrence in Paleovolcanology (with South Dzhungaria as example), in: Borukaev, R.A., ed., Geology and ore potential of volcanogenic formations of Kazakhstan. Alma-Ata, Nauka, p. 68-75.

Azbel, K.A., Borukaeva, M.R., Kovalevski, A.F., and Sterkin, V.D., 1971. Main features of orogenic magmatism of the Balkhash-Ili volcanic belt (with North-East Balkhash region and South Dzhungaria as examples), in: Shlygin, A.E., ed., Materials on geology and mineral resources of South Kazakhstan. Alma-Ata, Nauka, p. 183-192.

Bakhteev, M.K., 1966. On the peculiarities of the Upper Paleozoic porphyre formation in the southern part of the Tokrau synclinorium (Central Kazakhstan). Bulletin of MOIP, geol. section, no. 5, p. 76-89.

Bespalov, V.F., 1956. Upper Paleozoic of East Kazakhstan. Sovetskaya geologia, no. 52, p. 47-55.

Bespalov, V.F., 1971. Geological structure of the Kazakh S.S.R. Alma-Ata, Nauka, 363 p.

Bogdanov, A.A., 1959. Main features of the paleozoic structure of Central Kazakhstan. Bulletin of MOIP, geol. section, v. 34, p. 3-38.

Borukaeva, M.R., and Azbel, K.A., 1965. About the final stage of the Late Hercynian magmatism of South-West Dzhungaria, in: Shlygin, A.E., ed., Materials on the geology and mineral resources of South Kazakhstan. Alma-Ata, Nauka, p. 104-113.

Dobretsov, G.L., and Donskikh,V.V., 1966. Volcanic formation of the North Balkhash region and Dzhungaria and their relation to intrusive magmatism, in: R.A. Borukaev, ed., Materials of the Symposium on volcanic-plutonic formations and their ore potential. Alma-Ata, Nauka, p. 73-78.

Fremd, G.M., 1971. Typing and genesis of paleovolcanos and depressive volcanic-tectonic structures, in: I.V. Luchitskti, ed., Paleovolcanos and volcanic-tectonic structures. Vladivostok, p. 7-25.

Fremd, G.M., and Rybalko, V.I., 1971. Orogenic volcanism of the South-Dzhungar and East-Sikhote-Alin belts. Tomsk Publishing House (Tomsk University), 150 p.

Gaek, O.Y., 1967. New data on the stratigraphy of the volcanogenic formations of the Tokrau-Tarangaluk watershed. Izvestiya AN Kazakh S.S.R. geol. ser., no. l, p. 76-77.

Harland, W.B., Cox, A.V., Llewellyn, P.C., Pickton, C.A.G., Smith, A.G., and Walters, R., 1985. A geologic time scale. Moscow, Mir, 139 p.

Kayupov, A.K., ed., 1983. Metallogeny of Kazakhstan: Metallogenic complexes and regularities of their appearances. Alma-Ata, Nauka, 208 p.

Kepezhinskas, V.V., 1969. Late Paleozoic volcanism of the Tokrau synclinorium. Novosibirsk, Nauka, 196 p.

Koptev-Dvornikov, V.S., Yakovleva, E.B., and Petrova, M.A, 1967. Volcanogenic rocks and methods of their study. Moscow, Nedra, 331 p.

Kopteva, I.V., 1974. Late Paleozoic volcano-tectonic structures of the North Balkhash region. Moscow, Nauka,164 p.

Koshkin, V.V., 1962. On the stratigraphic position of the Sayak formation. Izvestiya AN S.S.R. geol. ser., no. 5, p. 76-84.

Koshkin, V.Ya., 1974. The stratigraphy of the Late Paleozoic of the northern part of the Balkhash-Ili Hereinian volcanic basin, in. A.A. Abdulin, ed., Prepaleozoic and Paleozoic of Kazakhstan, v. 2. Alma-Ata, Nauka, p. 154-162.

Kumpan, A.S., 1966. The Upper Paleozoic of East Kazakhstan. Moscow, Nedra, 247 p.

Kumpan, A.S., Dobretsov, G.L., Mitrofanova, K.V., 1969. Late Paleozoic formations of East Kazakhstan. Leningrad, Nedra, 921 p.

Kurchavov, A.M., 1984. Zonation of orogenic volcanic rocks of Kazakhstan. Moscow, Nauka, 205 p.

Kuznetsov, Yu.A., 1964. Main types of magmatic formations. Moscow, Nedra, 387p.

Lyalin, Yu.I., 1971. About the velocity of displacing of magmatism in Central Kazakhstan. Vestnik AN Kazakh S.S.R., no. 4 (312), p. 17-24.

Lyapichev, G.F., Seitmuratova, E.Yu., Borukaeva, M.R., Timofeeva, E.N., Lyalin, Yu.I., Bekmagambetov, D.B., and Leonov, A.V., 1991. Late Paleozoic volcanogenic formations of the Dzhungar-Balkhash folded system, in: A.A. Abdulin, ed., Magmatism and ore potential of Kazakhstan. Alma-Ata, Gylym, p. 77-85.

Lyapichev, G.F., Seitmuratova, E.Yu., and Timofeeva, E.N., 1989. The status of problems of the stratigraphy of continental volcanogenic formations of the Late Paleozoic of the North Balkhash region, in: E.P. Pushko, ed., Stratigraphy of the Paleozoic of Kazakhstan. Alma-Ata, Kazakhstan Scientific Research Institute Mineral Res., p. 111-119.

Lyapichev, G.F., Seitmuratova, E.Yu., Starov, V.I., Belmagambetov, B., Telguziev, A.T., Ill'in, V.A., and Morokov, V.D., 1991. Some questions of isotope geochronology of magmatic complexes of Kazakhstan, in: A.A. Abdulin, ed., Magmatism and ore potential of Kazakhstan. Alma-Ata, Gylym, p. 153-159.

Monich, V.K., Bedrov, G.T., and Bolgozhina, A.G., 1960. Geology and petrology of the Bainazar ring-shaped system of magmatic rocks, in: V.V. Galitzltyi, ed., Materials on the stratigraphy and petrology of Kazakhstan, v. 3. Alma-Ata, Nauka, p. 139-157.

Mossakovskyi, A.A., 1975. Orogenic structures and volcanism of the Eurasian Paleozoides and their place in the process of the formation of the continental crust. Moscow, Nauka, 316 p.

Myasnikov, A.K., 1974. Late Paleozoic of the Balkhash synclinorium (North-East Balkhash Region), in: A.A. Abdulin, ed., Prepaleozoic and Paleozoic of Kazakhstan, v. 2. Alma-Ata, Nauka, p. 162-166.

Mychnik, M.B., 1971. New data on the Permian of the Northeast Balkhash region. Izvestiya AN Kazakh S.S.R., geol. ser., no. 4, p. 72-74.

Perekalina, T.V., 1966. Geology of the Hercynian granitoid intrusions of Central Kazakhstan. Leningrad Publishing House, 240 p.

Polevaya, N.I., ed., 1974. Geochronology of the USSR, v. 2, Phanerozoic. Leningrad Nedra, 344 p.

Radchenko, A.I., 1967. Carboniferous flora of South-East Kazakhstan. Alma-Ata, Nauka, 75 p.

Radchenko, G.P., Rozenkrants, A.A., Kovalyova, V.V., and Smelovskaya, M.M., 1968. On the question of the age of the upper part of the continental volcanogenic group of the North-East Balkhash Region. Sovetskaya geologiya, no. 6, p. 138-141.

Seitmuratova, E.Yu., 1992. The Kokdombak Late Paleozoic volcano-tectonic structure (Central Kazakhstan). Izvestiya AN Kazakh S.S.R., geol. ser., no. 2, p. 29-38.

Sharpyonok, L.N., 1979. Magmatogenic ring-shaped structures. Leningrad, Nedra, 231 p.

Shcherba, I.G., 1969. Hercynian structure of the North Balkhash Region. Moscow, Nedra, 163 p.

Shcherbakova, M.N., Bakhteev, M.K., Kurchavov, A.M., Mikhailov, A.E., Polozhihina, A.I., Sharpyonok, L.M., and Shchegoleva, L.A., 1977. Late Paleozoic of the western and northern parts of the Dzhungar-Balkhash geosyncline, in: Zaitsev, Yu.A., ed., Geology and mineral resources of Central Kazakhstan. Moscow, Nauka, p. 184-202.

Skrinnik, L.I., and Tkachenko, K.N., 1980. Petrochemistry of the volcanogenic formations of the Ili belt. Sovetskaya geologiya, no. 7, p. 91-97.

Tashchinina, M.V., Rozenkrant, A.A., 1965. Volcanogenic formations of the Middle and Upper Paleozoic of the north part of the Dzhungar-Balkhash fold system, in: Magmatism and metamorphism of East Kazakhstan, Abstract from the first petrographical conference, (Kazakhstan). Alma-Ata, Nauka, p. 114-118.

Timofeeva, E.N., 1976. Evolution of the chemical composition of Late Paleozoic volcanism in the North Balkhash region. Izvestiya AN Kazakh S.S.R., geol. ser., no. 2, p. 46-52.

Yakovleva, E.B., 1963. Automagmatic breocia of Kazakhstan. Sovetskaya geologiya, no. 8, p. 119-123.

Zeilik, B.S., 1968. About relicts of large Paleozoic volcanoes in Central Kazakhstan. Izvestiya AN Kazakh S.S.R., geol. ser., no. 4, p. 74-90.

Non-marine Cretaceous Basins of Kazakhstan

B. Tsirelson

Abstract

The Central Eurasian platform occupies most of Kazakhstan and is mantled by Mesozoic-Cenozoic sediments lying unconformably over pre-Mesozoic fold structures.

The Cretaceous sediments are of platform character throughout Kazakhstan, although they may vary considerably in facies. They primarily are coastal-marine, shallow-water deposits. Only during the Barremian in the east are non-marine sandstones and clay found.

There are three principal structural units over which Cretaceous deposits are found:
a) the Pricaspian Depression, with an almost completely shallow-marine section showing regular facies variations from the margin to the central part of the depression.
b) the Turanian Plate, where the Cretaceous sequence is thickest and has its greatest areal extent. Five subbasins can be recognized.
c) the Kazakh Shield, where Cretaceous sediments are confined to small, isolated erosional and tectonic depressions.

In addition, Cretaceous deposits occur on the West Siberian Plate, a small area of which lies within Kazakhstan.

Introduction

Kazakhstan covers an area of about 3 million square kilometers in western Asia and parts of Eastern Europe. It stretches from the Volga River and Caspian Sea in the west to the Altai Mountains in the east, and from the extreme south of the Western Siberian Lowlands in the north to the Tien Shan in the south (Fig. 1). Geologically, it contains parts of several different tectonic units. In the west, Kazakhstan includes the Caspian Depression, which is the southeastern termination of the "old" Eastern European Platform. This depression is not only Eurasia's, but also the world's largest non-marine basin, with an area of half a million square kilometers and a total sediment thickness in excess of 20 km. The sediments range from Late Proterozoic to Quaternary. The greater part of the country, however, is occupied by the young Central Eurasian Platform, which is characterized by a widespread mantle of Mesozoic-Cenozoic rocks resting unconformably over pre-Mesozoic, folded structures of the Ural-Mongolian belt. This "young" platform is bordered by the "old" Eastern European Platform and to the east by the Eastern Siberian Platform. It is limited to the south by the young fold mountains of the Alpine-Mediterranean Belt, and by the mountain ranges of the Tien Shan-Altai (Garetskii, 1972).

Three major structural elements, distinguished by their tectonic development, can be recognized as forming the Central Eurasian Platform. These are the Turanian and West Siberian plates, separated by the Kazak shield. From the outset, it is apparent that the Turanian and West Siberian plates are regions where subsidence prevailed during the Mesozoic-Cenozoic and where thicknesses of up to 12 km accumulated. The Kazakhstan shield was a region of prevailing uplift, and sediments accumulated either on the slopes or in small depressions in the central part of the platform. The sedimentary section is, therefore, stratigraphically incomplete and composed of no more than a few hundreds of meters at the maximum. Thus, the Cretaceous sediments are of platform character throughout Kazakhstan, and the lithofacies composition and stratigraphic continuity are quite variable (Aubekerov et al., 1989; Krassilov et al., 1992; Tsirelson, 1987). In the following sections, the Cretaceous deposits will be described on a regional basis.

Pricaspian Depression

This structure, although large (Fig. 2), was essentially a single depositional basin during the Cretaceous. The basin received a regular lithofacies sequence from margin

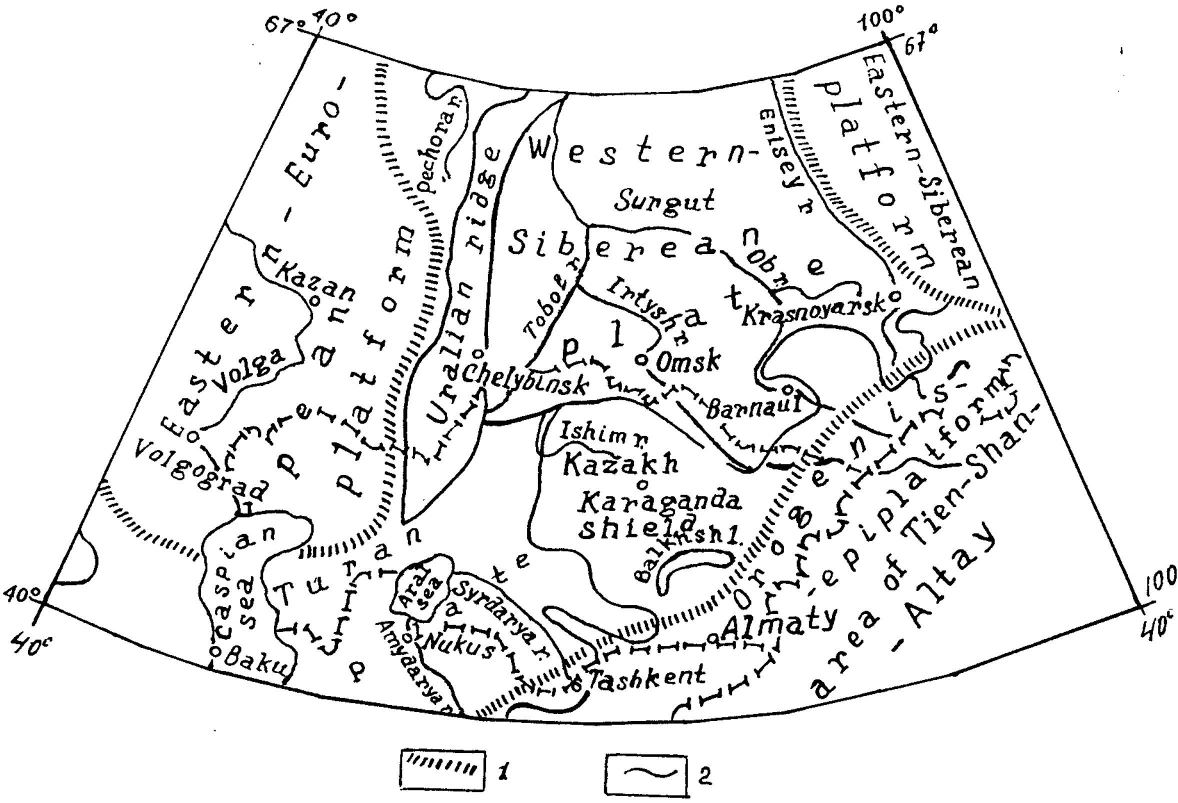


Fig. 1. Tectonic position of Kazakhstan in Eurasia. 1- Tectonic province boundaries; 2- Boundaries within the young Central Eurasian platform.

to basin center (Zhuravlev et al., 1970). Since the basin was tectonically stable and subsided gradually, the sedimentary succession is both thick and complete in the Kazakhstan part of the depression. Almost the whole thickness of the Cretaceous succession is made up of coastal-marine and shallow-water deposits. The only clearly distinguishable, non-marine beds are the Barremian in the eastern near marginal zone, where variegated and aleurolitic clays with sandstone interbeds are found. These beds have yielded ostracods and palynomorphs.

In the central part of the basin, the succession is exclusively marine and can be divided into four parts. The lower part consists of terrigenous, green-colored beds of Berriasian-to-Barremian age, which accumulated on a shallow, near-shore, marine shelf and contains a benthic fauna. Higher in the section, there is a sequence of dark-grey and black clays with a layer of carbonate concretions (septarian nodules). These are dated as Aptian-Albian. The fauna and the lithology of the beds are consistent with deposition on the deeper parts of the shelf.

The succeeding unit is dated as Late Albian-Senonian. In the central part of the basin, it differs from the underlying unit of dark-grey shales only in the more significant role of sandstones within the clays, indicative of a shallowing of the basin. At the eastern margin of the basin, the clays are replaced by a sandy unit with numerous molluscan remains and distinctive cross-bedding.

The uppermost member of the Cretaceous section consists of white limestones, chalk, and marls with an abundant fauna dated as Turanian-Maastrichtian. Usually at the base of the carbonates, there is a thin, sandy unit clearly discordant upon the underlying beds.

The Cretaceous section in the Pricaspian basin thus marks a Berriasian-Barremian transgression followed by a slight, regressive phase beginning in the Late Albian with a return to renewed transgression in the Turanian to Maastrichtian (see Fig. 3).

An important modifier in the sedimentation history of the region is the influence of the halokinetic activity of the thick (several kilometers) Kungurian evaporites, which are superposed over the stable, subsiding margin. The relatively rapid growth of salt domes and associated subsidence of the interdomal troughs resulted in the deposition of thick clays in the troughs, which can reach as much as 1 to 1 1/2 kilometers. As the salt domes grew at different times in different places, the effects on sedimentation in different troughs are equally variable.

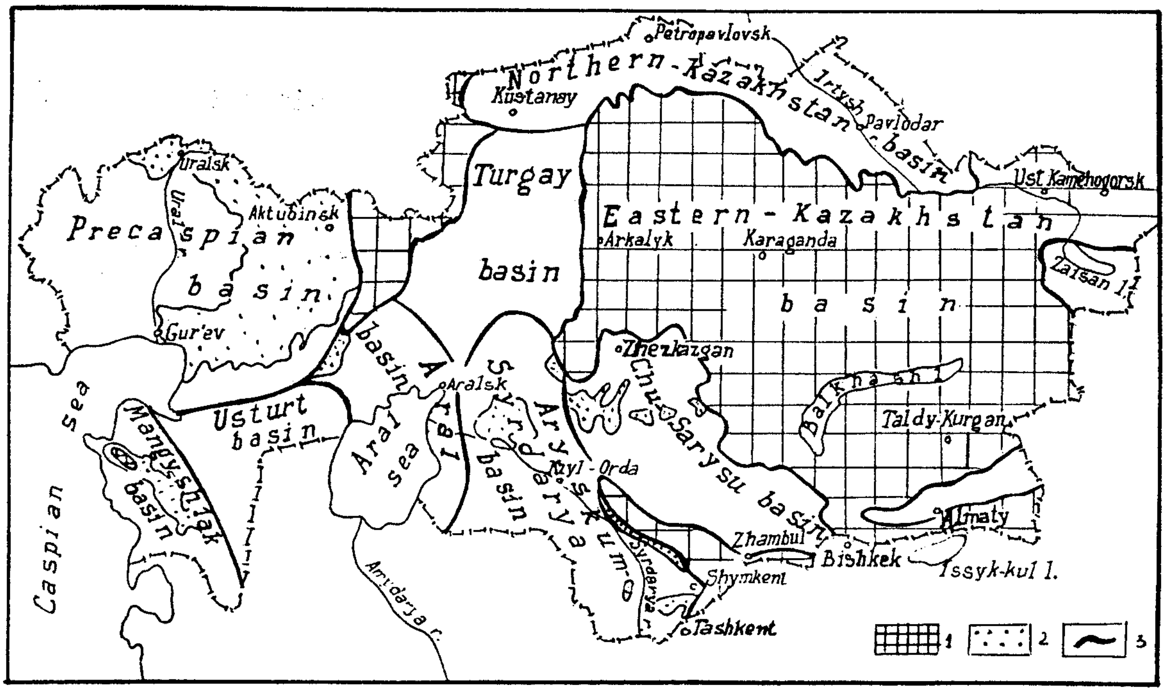


Fig. 2. Outline of the Cretaceous sedimentary basins of Kazakhstan. 1- Exposures of Pre-Mesozoic basement; 2- Exposed Cretaceous sediments; 3- Exposed Cretaceous sedimentary basins.

Turanian Plate

The greatest area of Cretaceous deposits lies on the Turanian plate, which has an areas of 1,000,000 sq. km. and lies in Kazakhstan. Cretaceous deposits are nearly omnipresent, with thicknesses ranging from 1500 to 1800 m in the deepest depressions to a few hundred meters on the uplands and peripheral zones. Based upon the lithofacies and stratigraphic completeness, five sub-basins are recognized: the Mangishlak, Ust'-Urt, Aral, Turgay, and Aryskum-Syr-Darya basins (Fig. 2).

Mangishlak Basin. The basin lies in the southwestern part of the plate, the region closest to the Mediterranean belt. It contains the most complete section and has a substantial thickness (1500 m) and a minimum of non-marine beds. It is thus closely similar to the Pricaspian (Zhuravlev et al., 1970; Naidin et al., 1984) and is distinguished from it only in the greater, non-marine character of the Barremian sediments, a more extensive time range for the coastal to marine sands of the Albian-Cenomanian by the inclusion of the Middle Albian, and by a thinner Turanian-Maastrichtian carbonate sequence. The Lower Turanian is here represented by six coastal-marine clays.

Ust'-Urt Basin. The basin lies to the east of the Mangishlak and is characterized by a growth in the coastal-marine and non-marine deposits (Zhuravlev et al., 1970). In the lower part of the section, not only the Barremian but also the Hauterivian and Valanginian stages are represented by non-marine red beds. In the middle part of the section, the stratigraphic range of the Albian-Cenomanian coastal and shallow-marine sands is expanded to include almost all of the Albian, excluding only the lowermost part. The range of carbonates in the uppermost part of the section is likewise reduced, and in the northeastern part of the basin includes only sediments from the Upper Santonian to Maastrichtian, with the Turanian-Lower Santonian consisting here of coastal and shallow-marine sand and clay.

Aral Basin. The Aral Basin provides the key to understanding the marine-non-marine facies relationships. In the western part of the basin, the beds are predominantly marine; but in the east, they are mainly non-marine (Zhuravlev et al., 1970; Tsirelson et al., 1982). The western part of the section differs very little from the Ust' Urt; only in the lower part of the section does the non-marine part extend from Berriasian to Barremian inclusively. Further to the east, in the East and northeast Aral Basin, the section is rich in non-marine beds, which cover the Aptian, Albian, Cenomanian, and Coniacian and may also include the upper Turanian. Only the Aptian sediments possess the grey colors characteristic of lake, swamp, and deltaic deposits formed in a humid environment; all the remaining non-marine beds are variegated or red, reflecting the existence of arid climatic conditions.

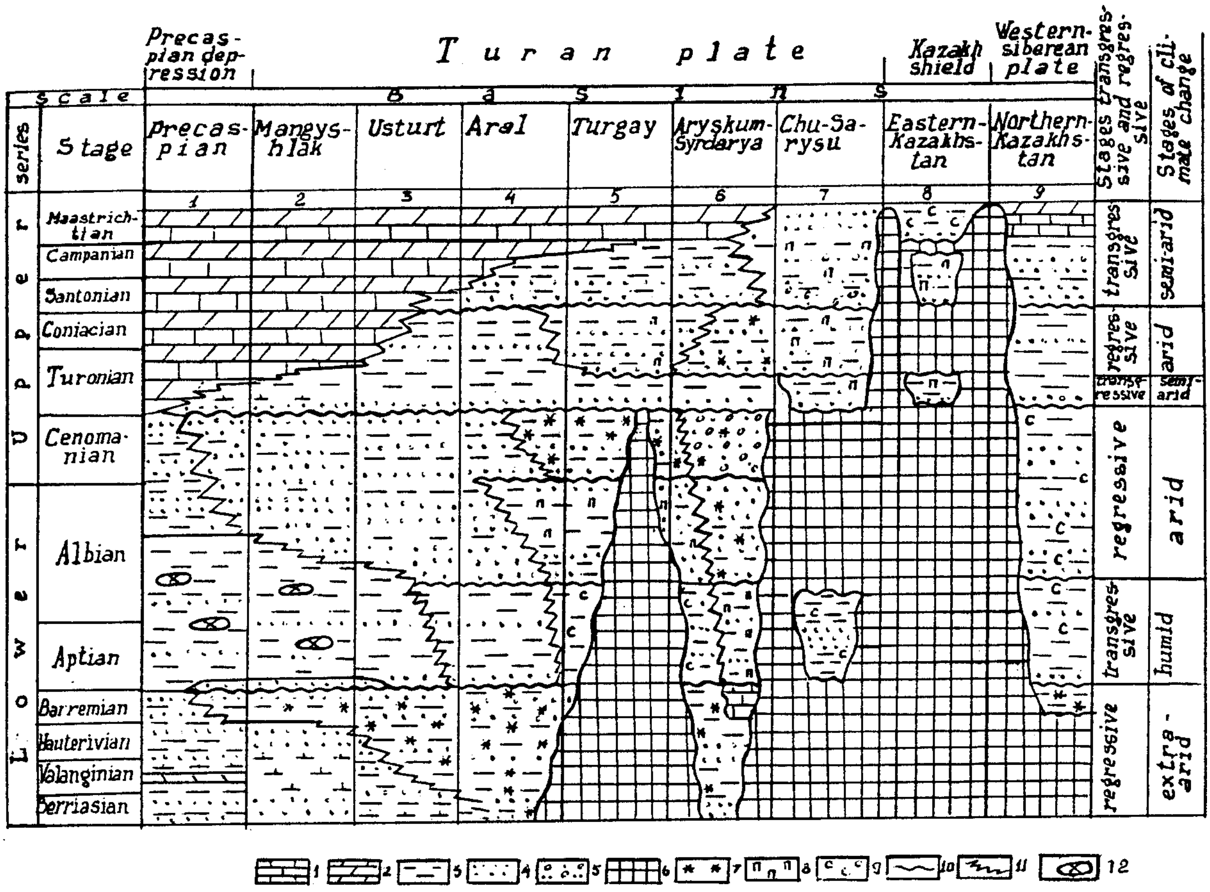


Fig. 3. Cretaceous sedimentary lithofacies in the basins of Kazakhstan. 1- marine limestones; 2- marine marls; 3- littoral-marine clays, littoral-marine, and continental sandstones; 5- continental gravel and conglomerates; 6- Pre-Mesozoic basement; 7- continental, red-colored sediments; 8- continental, vari-colored sediments; 9- continental, grey-colored sediments; 10- stratigraphically non-conformable boundaries; 11- boundaries of sedimentary lithofacies.

Within the section, the Lower Turanian and Santonian-Lower Campanian beds are shallow-marine, green-grey, argillaceous deposits. The Upper Campanian-Maastrichtian is represented by carbonates, as in the western regions of Kazakhstan, although occupying a narrower time range.

Turgay Basin. The position of the basin, between the Urals and the Kazakh Shield and as a zone of transition between the Turan Shield and the West Siberian Plate, gives the stratigraphic sequence its distinctive character (Abdulin et al., 1984; Kirpol et al., 1971; Nesterova et al., 1990). The section in the southern, more subsident part of the basin is virtually identical with that found in the northeast Aral section, which is with the greater part being represented by non-marine sediments except for the Lower Turanian and the Santonian-Maastrichtian. In the northern, more elevated part of the basin, the Cretaceous section is stratigraphically reduced due to the absence of the lower Cretaceous section, including the Cenomanian. Here, Lower Turanian coastal and shallow-marine deposits rest directly upon folded, pre-Mesozoic basement. Still further to the north, in the region of the Kustanav saddle, the lowest part of the Cretaceous is represented by shallow-water marine deposits of the Santonian-Campanian. These sediments mark the existence for the first time during the Mesozoic-Cenozoic of the Turgay Channel connecting the Turanian and West Siberian epi-continental seas with the warm waters of the northern Tethys shelf, which is a link between the Boreal and Tethys seas of northern Europe and Siberia.

Aryskum-Syrdarya Basin. The southernmost basin discussed, its location near the western spur of the Tien Shan controls the character of the Cretaceous section (Abdulin et al., 1984; Kostenko et al., 1971; Nesterova et al., 1990). As in the Turgay Basin, the Lower Turanian, Santonian-Campanian, and Maastrichtian are the only intervals represented by shallow- and coastal-marine deposits. The remainder of the succession is made up of continental beds; and, as in the Turgay, there is a marked change between the nearly complete section in the more subsident zones (Syrdarya depression, and the Aryskum trough) and the stratigraphic pinch-out of the Lower Cretaceous and Cenomanian, the more elevated regions. An additional characteristic is that the sequence includes coarse clastics, and almost all the continental beds are red, indicative of an arid environment in the nearby source areas.

Chu-Sarysu Basin. The basin can be regarded as either the eastern periphery of the Turanian plate or the southwestern slope of the Kazakh shield. As such, the sequence is entirely continental and of restricted range (almost everywhere, only the Turanian-Maastrichtian is represented) and thin (reaching a maximum thickness of the order of 300-400 m) (Kostenko et al., 1971). Only in a few places are pockets of grey Albian sediments preserved. The basin lies to the north of the Syrdarya basin; perhaps this location accounts for the dominance of variegated rock presumably accumulated under arid climatic conditions.

Kazakh Shield

Within the shield area, Cretaceous sediments accumulated only in small, isolated erosion valleys and tectonic depressions. Their thickness is invariably small, measured in a few tens of meters (Ponomarenko et al., 1972). Through plant impressions and palynomorph complexes, it has been possible to assign a variety of ages to the deposits. Lower Turanian, Santonian-Campanian, and Maastrichtian forms have been identified. Thus, the sediments are coeval, with the times of maximum transgression recorded on the neighboring Turanian plate. The Turanian and Santonian-Campanian sediments are variegated and accumulated under semi-arid conditions. The Maastrichtian sediments are grey and relatively rich in plant remains, reflecting the onset of more humid conditions (or possibly lower temperatures?).

West Siberian Plate

Only a small part of the West Siberian Plate lies within Kazakhstan and may be considered a single basin from the point of view of Cretaceous sedimentation. The nature of the deposits is closely related to the tectonic history of the basin. In the subsident, basinal section, nearly all the zones of the Cretaceous from Barremian to Maastrichtian are represented. In the south, in the more uplifted part of the basin, the section is reduced in thickness, and no sediments older than Santonian have been recorded on the northern slope of the Kazakh Shield (i.e., the southern margin of the basin). In this same direction, the sediments show evidence of a change from shallow-water passing to a more coastal-marine, then to a continental environment.

The basin marks the southern limit of the Boreal Sea, with non-marine Aptian and younger sediments accumulating on the continental margin. The nature of the sediments suggests a generally humid climate, and only the Barremian rocks are red, similar to those on the Turanian plate. The Turanian is thus regarded as the period of maximum aridity in Kazakhstan and the neighboring regions of Siberia.

Conclusion

The following summarizes the conclusions that may be drawn from this brief review of the Cretaceous sediments of Kazakhstan:

1. The Cretaceous sediments accumulated in an epicontinental shallow marine basins, on wide shelves, and on broad continental plains.
2. Kazakhstan is one of the few regions in Eurasia where a transition from marine to continental deposits can be observed. It also shows the transition from the warm waters of Tethys to the colder Boreal seas of Siberia. This provided the potential for detailed correlation between these two, different, paleogeographic provinces. The principal paleontological groups for this correlation are the spores and pollen, which are widely distributed in all lithologies.
3. The correlation of the Cretaceous basins of Kazakhstan show some distinct paleogeographic changes within the region. As elsewhere in the world, the increasing transgression of the younger rocks, which reached its peak during the Maastrichtian, marked the change from a geocratic to thalassocratic stage of development. The transgression was intermittent, with maxima in the Late Aptian-Early Albian, Turanian (possibly Early Turanian), and Santonian-Maastrichtian. The progressive reduction of relief and the generally more humid climate followed in step with these changes. There is also a distinct contrast between the greater aridity in the southwest regions in comparison with those to the northeast (or could this simply be a temperature effect?).
4. The paleotectonic and paleogeographic conditions described for the Cretaceous of Kazakhstan help determine the location of important economic minerals, from gas and oil to bauxite, phosphorites, and heavy-mineral placer deposits, as well as underground water.

References

Abdulin, A.A., Tsirelson, B.S., et al., 1984. Geological composition and useful minerals southeast of the Turgay trough and northern Ulutau. V.1, Geological composition, Almaty, Nauka, 232 p.

Aubekerov, B.Zh., Buvalkin, A.K., Tsirelson, B.S., 1989. The main problems of the stratigraphy of the Mesozoic-Cretaceous deposits of Kazakhstan, in: Geology and Metallogeny of Kazakhstan. Almaty, Nauka, 44-57.

Garetskii, R.G., 1972. Tectonics of the young platforms of Eurasia. Nauka, 300 p.

Kirpol, G.P., Khatskevich, V.A., Falkova, Yu.G., 1971. Cretaceous System, in: Geology of the USSR. V. XXXIV, Turgay Trough 1M, Nedra, p. 2328-298.

Kostenko, N.N., Kovrizhnykh, Yu.B., Nikitin, E.A., Polumiskova, L.N., Federenko, O.A., 1971. Geology of the USSR. V. XL, South Kazakhstan, 1M, Nedra, p. 389-420.

Krassilov, V.A., Bugdaeva, E.A., Andreev, Yu.N., et al., 1992. The non-marine Cretaceous of the USSR: Review. in: Aspects of non-marine Cretaceous geology. China Ocean Press, p. 110-129.

Naidin, D.P., Benjmovsky, V.N., Kopaevich, L.F., 1984. Methods of transgression and regression study (exemplified by late Cretaceous basins of West Kazakhstan). Moscow Univ. Publ. Ho., 162 p.

Nesterova, E.V., Tsirelson, B.S., Shilin, P.V., 1990. Stratigraphy and fossil flora of the Cretaceous and fossil flora of the Cretaceous deposits in the northeastern part of the Turgay Plateau, in: Fauna of the vertebrates and flora of the Mesozoic and Cenozoic of Kazakhstan. Almaty, Nauka, p. 121-132.

Ponomarenko, Z.K., Shilin, P.V., 1972. Cretaceous System, in: Geology of the USSR. V. XX, Central Kazakhstan 1M, Nedra, p. 426-437.

Tsirelson, B.S., Shtyrenko, L.S., Bykadorov, V.A., Nesterova, E.V., 1882. New sata on the stratigraphy of the Neocomian-Lower Turanian deposits of the northern Kusul-Kum and eastern Priaralie, 1982. Izvestiya AN Kazak SSR. ser. geol. p. 10-81.

Tsirelson, B.S., 1987. Cretaceous and Paleogene deposits of Kazakhstan. Izvestiya, AN Kazakh SSR. ser. geol. 4, p. 85-89.

Zhuravlev, V.S., Garetskii, R.G., Zhelezko, V.I., Kiselev, L.I., Samodurov, V.I., Segedin, R.K., Koltshyin, S.N., Klycheva, N.Yu., Benenson, V.A., Trifonov, N.K., Kirukhin, L.G., Petrov, C.E., Yanshin, A.L., 1970. Geology of the USSR, v. XXI, Western Kazakhstan, 1M, Nedra, p. 475-625.

On the Study of Microcontinents and Ophiolite Zones in Kazakhstan

A.A. Abdulin, A.V. Avdeev, N.S. Seitov

Abstract

This geodynamic approach to the geology of Kazakhstan began with a reinterpretation of two problems raised by N. G. Kassin and R. A. Borukaev: the geology of the Precambrian and of the siliceous-basic-serpentine belts. Mapping the Atasu-Mointy microcontinent and the Sakmarian ophiolite zone resulted in the discovery of the triad of the Riphean continentalization developed in many "insular blocks" of the Precambrian in Kazakhstan, and the Steinmann ophiolite triads, corresponding to the relics of the oceanic crust in 15 relatively independent sutures separating those blocks.

The various stages that make up the Wilson Cycle — rift, oceanic, island arc, pre-collision, collision, and post-orogenic — can each be distinguished in most of the ophiolite zones related to these sutures. Based on data revealing the independence of the ophiolite zones, one of us recognizes evidence of a regional, but not global, plate tectonics in the Paleozoic; the others consider the ophiolite "Kazakhstanica zones" to be the result of closing of the Paleo-Ural and Paleo-Asian oceans.

We then discuss the principles of the compilation and the details of the small-scale paleogeodynamic maps of Kazakhstan accompanied by geological-geophysical section columns, which are the fruition of the geodynamic ideas. Some of these maps have been published and are omitted here.

Problems in radiometric dating of the Precambrian rocks and the Paleozoic ophiolites following from the geodynamic map compilation are dealt with. For the Precambrian of Kazakhstan, 6 isochrons — 2000±100, 1800±100, 1300±100, 900±80, 750±50, 650±20 My — have been established by uranium-lead isotope methods, and each corresponds to a unique geodynamic event. Isotopic analysis of the oldest lead in ore depostis in Kazakhstan made it possible to distinguish six epochs — 1060, 680, 580, 520, 490, 360 My — conforming to the epochs of separation of the lead ore, possibly during opening of the rifts.

Data are presented on the geochemistry of the magmatic association of the Kazakhstan ophiolite zone with regard to both the rock-forming oxides and microelements which, probably indicate their association with supra-subduction zone ophiolites. Utilization of diagrams by De la Roche and A. N. Zavaritsky in estimating the geodynamic relationships of the total set of magmatic associations is demonstrated.

In discussing the uncertainty principle in geology, attention is focused on the unreliability of stratigraphic schemes previously worked out for the supra-subduction accretion prisms and the abundance of the diamond-bearing, protrusive bodies of the basite-ultramafite, sialic, and mixed composition taken for the intrusive and other formations along the frame of the sutures in the collision zones. Weaknesses in the concept of paired metamorphic belts and the graduality of metamorphism in application to the compressional structures in Kazakhstan are also discussed.

Introduction

Views on the geology of Kazakhstan, once studied exclusively from the standpoint of classical geosyncline theory, which was traditionally developed by many of the schools of the former Soviet Union, are experiencing a major about-face.

This about-face is connected with the change in approach to Precambrian geology and the ophiolite zones of Kazakhstan. The importance of these problems was fully realized in the past by geologists such as N.G. Kassin and R. A. Borukaev. The former noted the almost general presence of the "insular blocks" of the Precambrian (Kassin, 1934), and the latter distinguished linear geosyncline belts (Borukaev, 1955). Work with the Kazakh SSR Science Academy Geological Institute by R. A. Borukaev led to the concept of numerous Sinian geosyncline depressions, transformed into anticlinoria and separated by the Presinian median masses on the shoulders of which the

Cambrian geosynclines with their intensive volcano-terrigenous sedimentation developed (Borukaev, 1970, 1971).

At the time of the Glomar Challenger voyages and the publication of the well-known article by A.V. Peive (Peive, 1969) in the USSR, several geologists from Kazakhstan came to recognize the particular significance of the Steinmann triad as evidence of the presence in Kazakhstan of broad basins with oceanic type crust. Those conclusions were stimulated by an appreciation of the extraordinary structural complexities of the ophiolite zones and their immediate surroundings, including, of course, many Precambrian outcrops. The deciphering of these complexities, not reflected on maps of different scales even now, also led to the restoration of the triad of the Precambrian continentalization peculiar to Kazakhstan. The trend comprises (in ascending order) mature shale-carbonate-orthoquartzite strata, potassic rhyolite strata (and comagmatic plutons of rapakivi-type granites rich in potassium) and the overlapping strata of immature volcanomictic arkoses (Avdeev, 1968). Incidentally, this triad of ancient platforms, somewhat rejuvenated and becoming younger from the center to the edges (within the span of approximately 2-1 billion years for the rhyolite-granite member) is characteristic of Laurasia. In the western USA, the equivalents are the Belt orthoquartzites, the red porphyries of Arizona, and the arkose-carbonate sediments of the Upper Precambrian sections.

Application of the key ideas of the Precambrian continental and Steinmann oceanic triads, based on detailed mapping of the Atasu-Mointy (Avdeev, 1968) and the Or'-Ilek (Abdulin, Avdeev, Seitov, 1977) regions, permitted the rapid revision of the geology of key Kazakhstan regions (Avdeev, 1984) and the rejection of previously established stratigraphic schemes of the Precambrian and the lower Paleozoic.

Microfossils played a major role in the revision of ophiolite zone stratigraphy, especially the abundant conodonts in the cherty rocks of the upper member of the Ordovician ophiolite triads (The Problems of Modern . . ., 1990). Despite abundant new finds of conodonts in cherts from almost every zone (Vasiliev, 1991; Zhilkaidarov, 1991; Stepanets, 1992), the problem of the ophiolite age diapason has not been fully solved.

Ophiolite Sutures of Kazakhstan

Within Kazakhstan, there are over a dozen ophiolite sutures (Fig. 1). The age of these ophiolites ranges within broad limits from Early Cambrian to Middle Devonian (Early Carboniferous). Restored to their original dimensions, these structures have different orientations. As a rule, they are restricted on both sides by deep faults to which the large and small blocks of the older, often Precambrian, mature continental crust (probably fragments of the margins of former micro-oceans) gravitate. We suggest that the initial location, development, and formation of the ophiolite sutures are connected with the lateral mobility of the Precambrian microcontinents, as the fragments of Kazakhstanica are an essential part of Laurasia (Fig. 2).

The exposed Paleozoic ophiolite sutures of Kazakhstan are usually less than a few dozens of kilometers in width and hundreds of kilometers (rarely a thousand kilometers) long. According to the set of geological formations and the character of their location, every Paleozoic ophiolite suture of Kazakhstan corresponds to a miniature fold belt, developed "as a result of the horizontal juxtaposition of rocks of different ages and different tectonic nature" (Peive et al., 1985, p. 75). They include a series of the geological formations developed in various tectonic-magmatic and paleofacies settings, but juxtaposed in space during the next stage of development and shaping of the belt. Signs of the juxtaposition can be found in the interrelations of different geological formations in fragments that are characterized by extraordinary complexity. However, in practically all cases one common feature is observed: subhorizontal disruptions are always complicated by late subvertical folding. Such regularity suggests that the spatial juxtaposition of different zones through the subhorizontal disruptions, as the isoclinal crumpling following thrust plate movements and orogenic uplift of the newly formed microbelt, resulted from tangential compression, probably caused by sublithospheric convectional currents (Seitov, 1988, 1989). In the course of geological mapping it is very difficult to single out each of these formations from the whole unit of the geological body creating the ophiolite suture. These difficulties are connected with the imperfection of the methodological principles of establishing the stratigraphic units, which are still based on ignoring the significance of the subhorizontal disruptions and the facts of the "mixing" of fragments of juxtaposed formations under the conditions of late isoclinal and subvertical folding (Seitov, 1988, 1989).

Based on formational content and the structure of exposed Paleozoic ophiolite sutures of Kazakhstan, six main stages of the transformation of the earth's crust may be distinguished within such belts (Seitov, 1988, 1989). The first, the rift stage, is characterized by the breakup of the mature continental lithosphere under tensional conditions. The initial location and development of the intracontinental rift are reflected in the formation of a characteristic set of volcanic and sedimentary rocks (Grachev, 1977; Milanovsky, 1983; Rumberg and Morgan, 1984; Mirlin, 1985; and others), which may be isolated into the independent set of rift formations (Seitov and Avdeev, 1983; Seitov, 1987, 1988, 1989).

Next, the oceanic stage is connected with subsidence of the continental lithosphere, oceanic expansion under

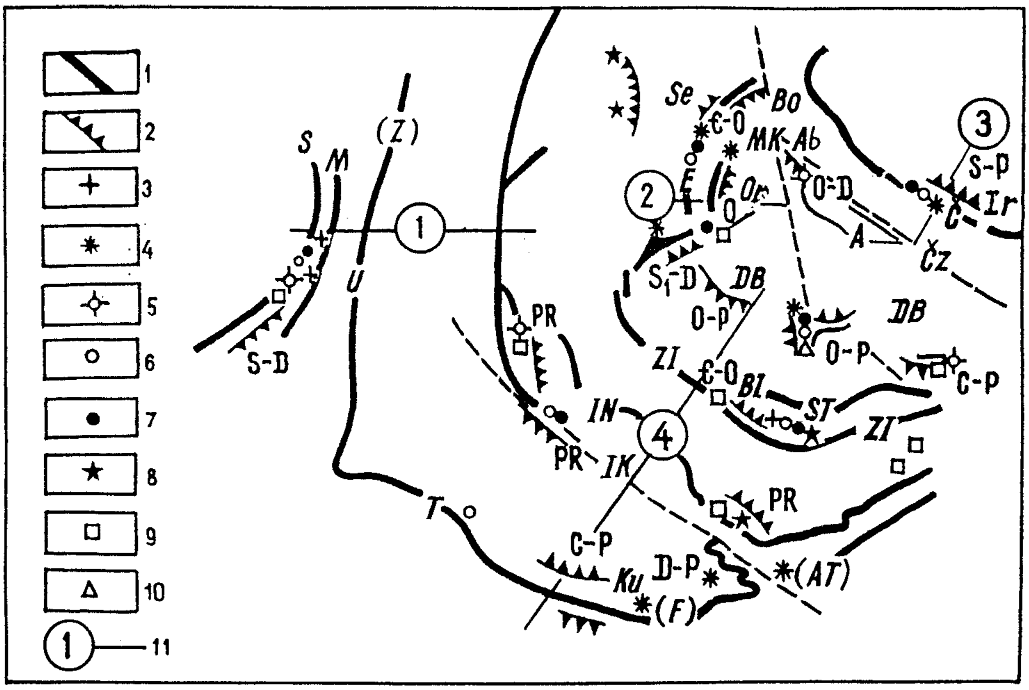


Fig. 1. Distribution of the main ophiolite sutures of Kazakhstan and zones with indications of underthrust metamorphism. Legend: 1- ophiolite sutures: S- Sakmar; M- Mugodzhar; Zh-F-At- Zhetygarinian-Ferganian-Atbashian; U-T- Ural-Turkestan; IK- Ishim-Karatau; IN- Ishim-Naryn; Zh-I- Zhalair-Ili; ST- Sarytum-Tekeli; DB- Circum-Dzhungarobalkhash; E- Erementau; MK- Maikain-Kyzyltas; CI- Chingizian; A- Akchatau; Ch- Charian; Z- Zaisan; 2- overthrust zones with metamorphites and indication of dip direction, age diapason of subduction in generally accepted indexes and designation of some zones: K- Kurama; Bl- Bolgozha; Se- Selety; Bo- Bozshakol; Or- Oroi; Ab- Abraly; I- Irtysh; 3-10- points of recording the data transmitters of the subduction processes: 3- glaucophane and lawsonite in the aposiallites; 4- glaucophane in the apobasites; 5- winchite; 6- hydrogranulites; 7- hydroeclogites; 8- eclogites; 9- rodingites; 10- jadeites; 11- profiles across the main ophiolite zones (see Fig. 2).

conditions of persisting extension, and spreading-center activity. This stage is characterized by creation of two types of geological formations — the amagmatic terrigenous-carbonate deposits of the passive continental margins and three-layered oceanic crust (the ophiolite association). The latter usually consist of cherts, pillow lavas, basalt dikes and sills, and cumulose and restite gabbro-ultramafites. The regions of sedimentation and the paleofacies conditions under which these formations are created are sharply different.

The island arc stage is the beginning of "continentalization" of the "ocean-continent" area at the expense of island-arc volcanism and accretion of ophiolite and other rock associations under compressional conditions. Island-arc volcanics form at the expense of subducting oceanic lithosphere or obduction of solid lithosphere mantle of the continental shoulder of the ocean (Seitov, 1988, 1989). The accretion of the ophiolite and other formations of the continental shoulder of the ocean is realized at the expense of the thrust plates, obducting on the same shoulders from the side of the closing ocean.

The precollision stage is characterized by a practically complete closure of the ocean under conditions of continuing tangential compression, accompanying the juxtaposition of all the above-mentioned formations initially built in the different tectono-magmatic and paleofacial conditions, through thrusting of the fragments. The development of thrusts is accompanied by olistostrome formation. In the back-arc basins the particular formation of high potassium basaltoids is generated and is conformably overlapped with the flysch formation.

The collision/orogenic stage marks the sharp conjunction of former ocean shoulders (collision) and transformation of horizontal motion in the asthenosphere into vertical motion in the lithosphere. The orogenic microbelt and the deep "roots" of the orogen are formed. Paleozoic complexes generated during previous stages and metamorphosed in the mesozone and katazone play an important role in the composition of these "roots." This leads to the cleavage linearization of the belt, intrusion of the granitoid batholiths, general metamorphism, and disturbance of the unity of the thrust plates. Molasse is deposited in the intermontane depressions.

The post-orogenic stage completes the formation of the folded structure and exposes the abyssal parts of the orogen. At this stage the movement of the blocks of the Earth's lithosphere, disturbed by the abyssal faults, is mainly vertical, caused by movement in the microbelt to

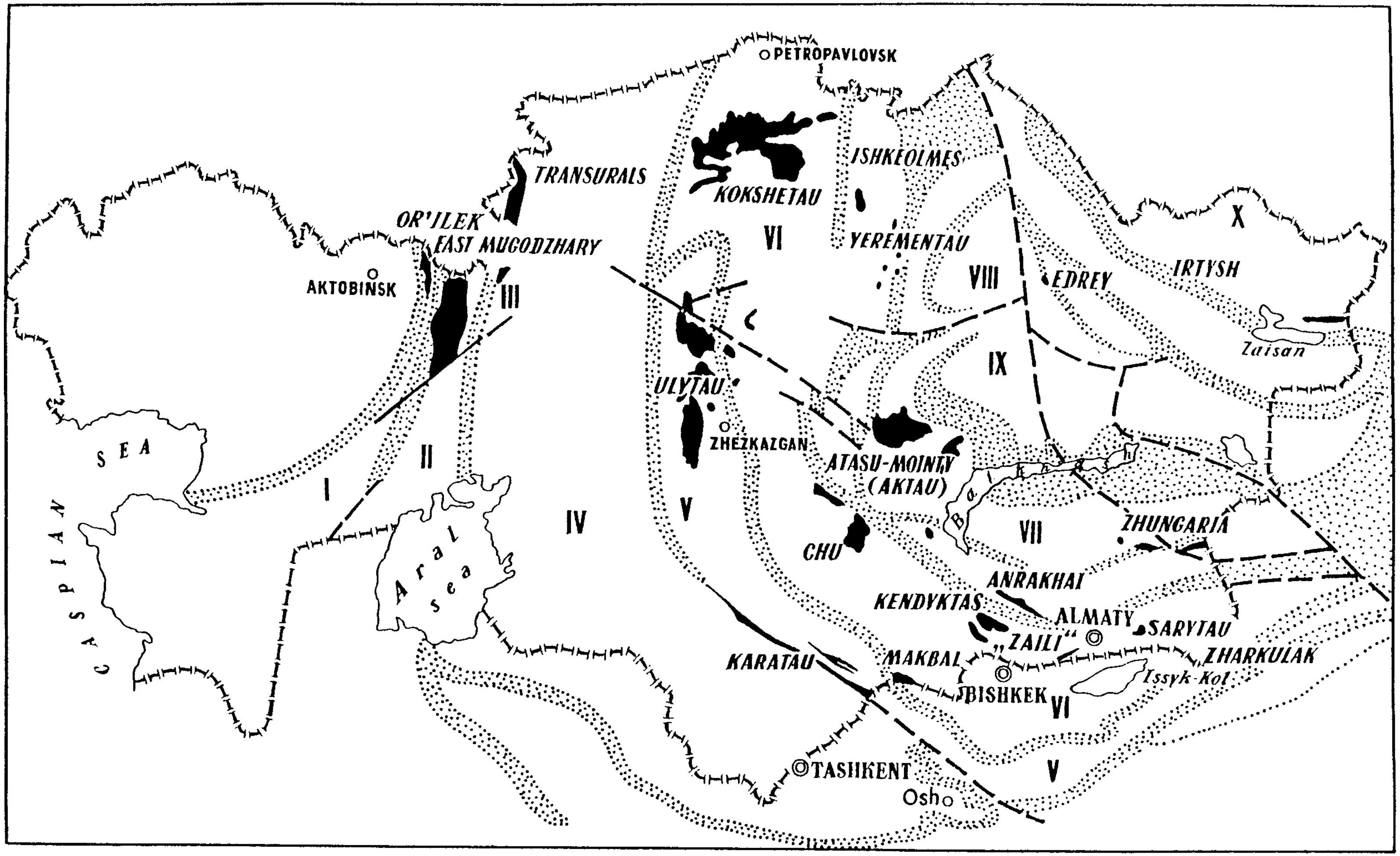


Fig. 2. Schematic map of Precambrian outcrops in Kazakhstan (generalized outline shown in black with geographical names, usually anticlinoria). The main Precambrian sialic microcontinents partially concealed are marked by Roman numerals: I-Uraltau (in Kazakhstan-Or'Ilek); II-East Mugodzhary-Northern Ustyurt; III-Transurals; IV-Tobol-Syrdar'ya; V- Ulutau-Sarydzhaz; VI- Kokchetav-Northern Tien-Shan: VIa- Anrakhai (Zheltau)-Altynemel; VII- Atasu (Aktau)-Zhungarian; VIII- Bayanaul; IX- Balkhash, X- Altay. The main ophiolite zones (see Fig. 1) of Kazakhstan and adjacent Republics are stippled, and young strike-slip faults are indicated by broken lines.

restore isostatic balance, which had been disturbed by erosion of the orogen.

The totality of the stages of development of the Paleozoic ophiolite paleostructure is identified as a Wilson cycle and corresponds to the whole geotectonic cycle of the paleo-ocean development, which leads to the formation of new continental crust (Seitov, 1988, 1989). The formation of such small sutures is interpreted with difficulty notwithstanding the attempts of the devoted supporters of the mobilistic schools of the CIS (Zonenshain, 1976; Bespalov, 1974; Antonyuk, 1974; Markova et al., 1982; Peive et al., 1971; Ruzhentsev, 1976; and others) to explain them as belonging to two large oceans — one paleo-Asian, the other paleo-Uralian. If one considers the variable age of the ophiolite complexes of the indicated sutures and their alternation in the space with the blocks of the ancient continental crust, the shortcomings of such an explanation should be obvious.

The arguments adduced above for the relative independence of development of each Paleozoic ophiolite suture of Kazakhstan provided Seitov with a basis for demonstrating the regional character of Paleozoic plate tectonics (Seitov, 1988, 1989). According to his view, the peculiarities of the lithosphere and asthenosphere of the Paleozoic Earth, specifically their thinness in comparison with the Mesozoic-Cenozoic (Seitov, 1989), are the basis of this regional (not global) plate tectonics.

Recent investigations of the well-exposed non-coeval (from Karelian and Late Riphean to Late Carboniferous) ophiolite sutures of Kazakhstan corroborate the model of their development, worked out first in the Sakmar zone, from the initial rifting of the continental crust, spreading and drawing apart of the microcontinental blocks, formation of oceanic crust and its subsequent or parallel submergence under conditions of variable double-sided subduction of the Malaccan Sea type, thrusting over the cover of the microcontinents, and the appearance of the early island arcs and back-arc ophiolite and non-ophiolite basins and so on (Abdulin, Avdeev, Seitov, 1977; Avdeev and Kovalev, 1989).

According to Avdeev, data on the positive magnetic and gravitational anomalies of the concealed areas of the western, northern and eastern margins of Kazakhstanica and adjacent parts of Uzbekistan, Kirgizstan, the Russian Federation, and China, reveal a system of extended sutures — the Ural-Turkestan-Singtzan-South Mongolian and, probably, Irtysh-Dzhungar-South Mongolian sutures corresponding to two large oceans. The circum-Balkhashian sutures through the western Dzhungarian sutures of China join the Irtysh-Zaisanian ones in eastern Kazakhstan. Thus, on the whole, for Kazakhstan the Sakmar zone model can be amplified by considering destruction of the Precambrian craton, with formation of marginal oceans and micro-oceans, and the centripetal migration, deep into Kazakhstanica (within the interval of the Late Riphean-Late Ordovician-Carboniferous), of the ophiolite and non-ophiolite basins right up to the closure of the oceans and back-arc seas, their integration into Pangea by means of progressive collision of the continents, the repeated rebuilding of the subduction zones, the rise of the orogenic thermal fronts and the mass melting of the thickened continental crust over the late Benioff and Ampferer paleozones with the formation of marginal magmatic belts and the hetero-ordered ring structures of volcano-plutonic origin (Avdeev, 1965) (Fig. 3).

Paleogeodynamic Maps

Mobilistic concepts are realized through the compilation of paleogeodynamic maps. The first such map was compiled by us in 1976 for the Kempirsai mine area on the scale of 1:100,000 (Abdulin, Avdeev, Seitov, 1977). Geodynamic maps of all or parts of Kazakhstan at a scale of 1:2,500,000 were compiled and published in 1989-1990 (Geodynamic Map of USSR, 1989; Atlas of Maps of South Kazakhstan, 1990) and, using the same symbols — for separate regions and areas at more detailed scales (1:1,000,000, 1:50,000, and 1:10,000). In comparison with ordinary geological maps, based on a "plutono-neptunic" categorization, the geodynamic maps contain essentially new information.

As a departure from traditional geologic maps, our geodynamic maps attempt to correlate formations with actual analogues, giving them the corresponding symbols and portraying them not in random colors but by a regular succession of all the colors of the spectrum. For example, at one end of the spectrum, red denotes mature continental crust of the ancient and late collision zones of Laurasia, and violet at the other end — three-layered oceanic crust of the oceans and margin seas. In between, there is a regular sequence of transitional colors — orange (the continental rifts), yellow (mainly carbonate early Paleozoic passive margins of the Precambrian microcontinents of the Aisha-Bibi type (Cook et al., 1991), which, like the carbonate cover of the Devonian-Carboniferous at the stages of transformation into the active margins, generated unique skarn accumulations of wollastonites at contacts with non-coeval granitoid intrusives), green (active continental margins of the Devonian and late Paleozoic volcano-plutonic belts with mass developments of the ring-structure type), blue (flysch of the residual basins, the Dzhungar-Balkhash type, and also fore-arc and back-arc basins), dark blue (island arcs), and white (late polymictic molasse, reflected in a mixed color). By means of such colors, a geodynamic map can depict the genetic significance of the physical matrix, and complete indices (for instance, iD_3 — the island arc of the Late Devonian) and additional symbols enable us to depict the entire spectrum of information — lithological-petrographical, metamorphic, structural-tectonic, minerogenic, etc.

The paleogeodynamic maps of southern Kazakhstan at a scale of 1:1,000,000 and 2,500,000 are accompanied by the scheme of distribution of the main geodynamic elements, depicting eight microcontinental blocks with the Precambrian continental crust, manifesting the full or partial triad of the Riphean continentalization or riftogenesis, twelve sutures or suture zones, including accretion prism and residual basins with non-coeval zones (from the Karelian and late Riphean to the Early Carboniferous) that migrated in time and space as ophiolite triads, two dozen of the non-coeval (from the Karelian to the Late Permian-Triassic) zones of the oceanic crust or lithosphere intake, with an indication of the paleosubduction and main transform faults. The geologic-geophysical columns on five main approaches of the geophysical profiles are also supplemented to this map. On three of them we have comprehensive data on magnetic and gravitational fields, allowing E.A. Zazubin to show the main continental and ophiolite lithoplates in the third dimension. Despite closure of most of the ophiolite basins in Kazakhstan by two-sided subduction, the direction of prevailing or late subduction is revealed in sections around the sutures by the gently sloping orientation of the nappes in one direction.

Geodynamic Proving Grounds

The idea of organizing geodynamic proving grounds to which the concepts of plate tectonics could be applied belongs to the Ministry of Geology of USSR. At a meeting in Tashkent in 1985 we proposed the following sites in Kazakhstan: 1- the Kempirsai ophiolite, with its unique chromite deposits; 2- Zhezkazgan-Atasu, with secondary

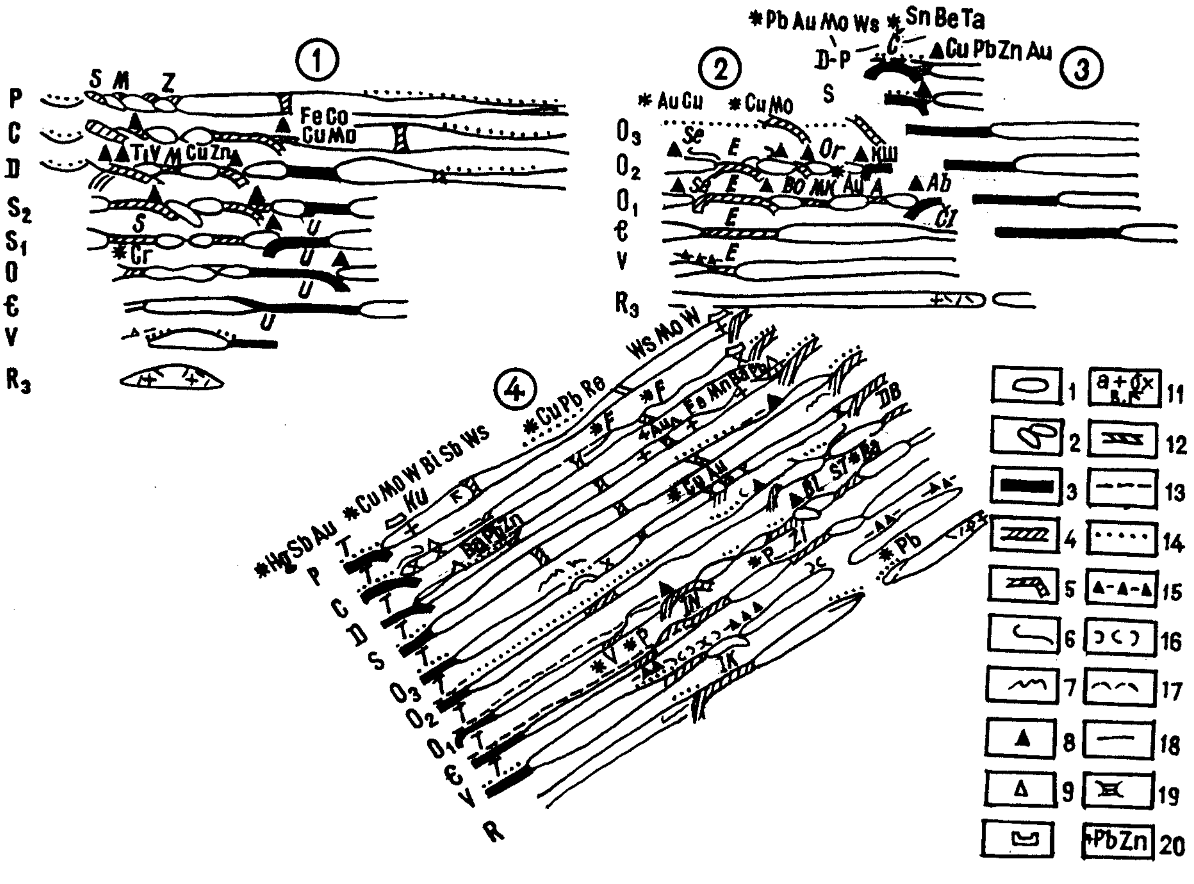


Fig. 3. Schematic model of development of ophiolite zones in Kazakhstan. 1- microcontinents; 2- microcontinents involved in subduction; 3- oceanic crust of large basins; 4- oceanic crust of micro-oceans; 5- oceanic crust involved in subduction; 6- overthrusts; 7- folding; 8- early volcanic and volcano-plutonic (island) arcs; 9- late orogenic volcano-plutonic belts and areas; 10- late orogenic ring volcano-plutons; 11- plutons: a- leucogranites, b- granodiorites, c- alkaline gabbroids; 12- carbonate covers of the microcontinents; 13- argillo-siliceous rocks; 14- arenaceous formations; 15- tilloids; 16- tuffites; 17- Riphean rhyolites; 18- Riphean basalt; 19- ophiolite sutures; 20- symbols of some deposits. Figures in circles correspond to the profiles on Fig. 1 — on the left, indices of the Precambrian and Phanerozoic systems.

back-arc rifts (Atasu) and ferromanganesian and fluorite-barite-polymetallic deposits of the Red Sea type and epicontinental basins (Zhezkazgan) with unique rhenium-lead-copper deposits ("cupriferous sandstone"); 3- the Bozshakol island arc with its large porphyry copper deposits; 4- the southern Kazakhstan complex with the Karatau stratiform barite-polymetallic deposits, the Akbakai hydrothermal gold deposits, the Boguty scheelite stockwork, the Bizhe-Koksai porphyry copper and skarn-polymetallic deposits, the Tekeli polymetallic deposits in noncoeval black shales, and the northern Balkhash-Aktogai copper deposits of skarn and porphyry types; and 5- the Chingiz ophiolite-island arc with undefined potential. In the end, the Geology Ministry chose the Kirgizian geodynamic proving ground because of its compactness and good exposure.

Before the disintegration of the USSR, the following geodynamic complexes within the Osh geodynamic proving ground in the foothills of the Alai Range were studied at academic seminars:

1. Fragments of oceanic crust, the first bed of which in the narrow foothills bend is dated as the Vendian-Cambrian (Kirgizata), Ordovician (Sortale); Silurian, Devonian and Early Carboniferous (Sortale, Khadzhi-Gair).
2. Silurian listric olistostromes with large blocks of Vendian-Cambrian ophiolites, overlapped by Cambrian-Ordovician flysch with eroded island arc volcano-plutonic complexes (Kirgizata).
3. The continuous shale-carbonate pelagic section within the Silurian-Devonian-Lower Carboniferous, adjoining the same, but highly disturbed pelagic and shallow carbonate platforms of the passive margins (Peshkaut).
4. Delaminated olistostromes of the Moscovian stage, crumpled into a complex of recumbent folds with multistoried olistoplates of the Visean-Serpukhovian carbonates (Kharangly).
5. Terrigenous mixed and ophiolite mélanges with blocks of sedimentary rocks (from Vendian to the Middle Carboniferous), island arc volcanics, and complete ophiolite rocks with wedges of lawsonite-glaucophane shales in a matrix of black Silurian shales (the Tulian and Kanian mélanges).
6. Nine intrusive complexes of three "pure" and six mixed series, considered by Nenakhov (1988) as the products of postsubduction collision and occupying a steeply south-dipping subduction paleozone active from the end of the Carboniferous to the beginning of the Late Permian.

The presence of these complexes corroborates the idea of existence of the Ural-Turkestan Ocean in the Late Riphean-Vendian-Early Carboniferous. The margins of this ocean correspond to two belts of compressed ophiolite fragments extending from Sultanuizdag through the Tamdytau Mountains, northern Nuratau, the Turkestan Range, southern and eastern Fergana, and farther to the east over the line of 200-km right-striking slip fault in the direction of the Atbashi Range (Fig. 2). Upon closure of this ocean through two-sided subduction, its northern margin passive, under conditions of left-lateral oblique subduction,became active in the Middle-Late Carboniferous, when it was a Nevada-type margin, and continued active in the Late Carbonif-erous-Early Permian, when it was an Andean type. In the Permian it underwent syncollision riftogenesis (Seliverstov, 1992), forming the unique Kurama minerogenic province (Figs. 1, 3). The unique gold deposits of the more restricted Muruntau fragment are connected with the penetration into the oceanic crust nappe of syn-collision granitoid batholiths and post-orogenic upper Paleozoic plutons.

According to the results of recent investigations, the history of the development of the Irtysh-Zaisan ocean of eastern Kazakhstan (which ended with the carbonate flysch and upper Paleozoic molasse) came to a close through two-sided subduction under fragments of the microcontinents of Kazakhstan and Altai, with development of nappes of oceanic and sland arc nature and the opening, mainly in the Early-Middle Ordovician, of back-arc seas (Tulian and Kanian mélanges). Exploration work by geologists in the Chingiz geodynamic proving ground (also the Semipalatinsk nuclear testing ground) led to the discovery of a new minerogenic province, with the rich mineral resources of the Kurama deposits both in reserves and value of raw materials, and to the Rudny Altai and Kalbin deposits, overlying the Benioff paleozone on the other side of the closed ocean.

Radiochronology of Precambrian Microcontinental Rocks and Paleozoic Ophiolites

Precambrian

Work on compiling the various geodynamic maps of the Kazakhstan fragment of the Ural-Mongolian folded belt corroborated the idea that Precambrian protoliths were intensively reworked by Phanerozoic geodynamic processes, especially over the Benioff paleozones. The processes consisted of intensive crumpling, metamorphism (and metasomatism), melting, and consequent tectonization, accompanied by disturbance of the initial geochemistry, magnetic peculiarities, and isotopic imbalances. Many of the published radiometric dates for Precambrian formations of Kazakhstan (Filatova, 1983) and Kirghizia (Kiselev, 1991) should therefore be considered outmoded, and paleomagnetic data and geochemical correlations with actual analogues should be regarded with caution.

Recent uranium-lead isotope studies of substantial samples of zircon, and sufficient admixtures of non-radiogenic lead, have revealed only six more or less reliable age limits: 2000±100, 1800±100, 1300±100, 900±80, 750±50, 650±20 My (Fig. 4). We correlate the 2000±100 and 1800±100 My ages with late Karelian "jasperite" riftogenesis and collision; 1300±100 My, with the Middle Riphean accumulation of orthoquartzite formations; 900±80 My, with the Late Riphean acid potassic collisional volcano-plutonism (Avdeev, Zlobin, Kim, Khalilov, 1990); 750±5 My, with the Late Riphean contrast rift magmatism, marking the destruction of Laurasia; 650±20 My, with the Vendian subduction metamorphism of the Riphean underthrust plate of the Kirgizian Range. The oldest ages, 2570 My, have not been replicated. They were from gneisses of the Kuilyu Formation of the northern Tien Shan. The discordant ages of the clastic zircons from the orthoquartzites of the Riphean of the Kirgizian Range, previously considered Early Proterozoic, correspond to this age.

Paleozoic Ophiolites

An attempt was made to determine the age of the plutonites of the ophiolite association, and the metamorphites that developed after them, in some of the largest massifs of Kazakhstan —the Kempirsai (Sakmar suture) body, the Karaarcha (western Ishim-Naryn suture) body, the Sarytau (eastern Zhalair-Ili suture) body, as well as some mélanges. Zircon samples were taken only from the gabbro-norite pegmatites of the Talpakian complex of the Maikain-Kyzyltas suture (Stepanets, 1992); U-Pb analysis of the zircon suggested an Early Ordovician age (471-480 My). In the other ophiolites, because of the paucity of zir-

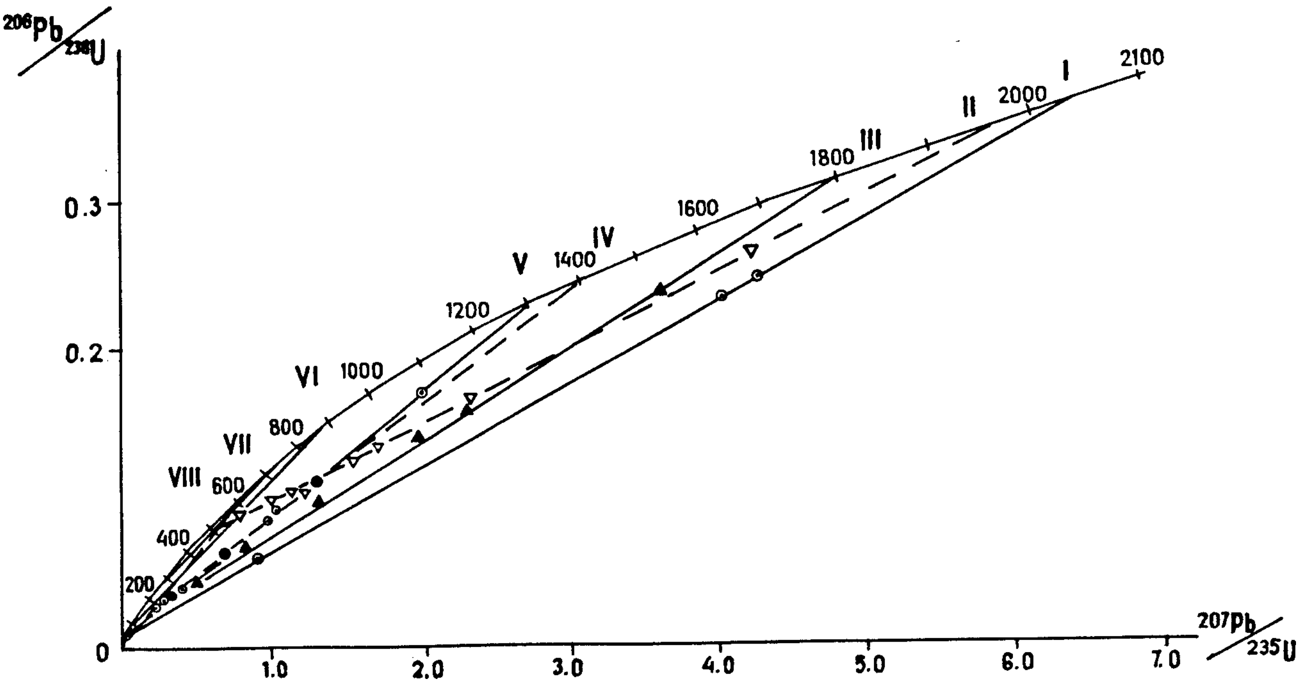


Fig. 4. Diagram showing discordia for the zircons of the Precambrian rocks of South Kazakhstan. The concordia curves and the points of intersection of the curve with straight lines are (Roman numerals for upper points): I-y=(0.00554±0.00024)+(0.051175±0.00002)x, T_1=2028±11 My, T_2=56±20 My. From the Makbal Riphean orthoquartzites of the west Kirgizian Range; II-y=(0.0046048±0.000271)+(0.05242±0.00005)x, T_1=1963±5 My, T_2=485±6 My. From the metamorphic schists and gneisses of the Kendyktas Mountains; III-y = (0.00797 ± 0.00013) + (0.06708 ± 0.00012)x, T_1=1797±8 My, T_2=95±15 My. From the metamorphic schists and gneisses of the Anrakhai and the Chu Rises; IV-y=(0.0083±0.000051)+(0.07935±0.00001)x, T_1=1388±11 My, T_2=112±18 My. From the metamorphic schists and gneisses of the Zhungaria Ranges; V-y=(0.001931±0.000051)+(0.0853787±±0.000019)x, T_1=1297±4 My, T_2=28±6 My. From the granite-gneisses (*in situ*) of the Transilialatau and Sarytau Ranges; VI-y = (0.000264 ± 0.00072) + (0.10416 ± 0.00002)x, T_1=880±11 My, T_2=53±8 My. From the Late Riphean potassium porphyroids and schistose granites of the Atasu-Mointy region (Avdeev et al., 1990); VIII-y=(0.010365±0.00016)+(0.103135±0.00001)x, T_1=757±4 My, T_2=238±5 My. From subalkaline granophyres of the KuMysty complex of the Karatau Range; VIII-y = (0.00094± 0.00012) + (0.11794 ± 0.00009)x, T_1=637±5 My, T_2=25±6 My. From Late Riphean granites of the Makbal Rise, involved in subduction metamorphism.

con, only hornblende was sampled for K-Ar analysis. Radiometric data were found to coincide with geological estimates in 30% of the tests conducted; a greater rate of coincidence was noted for the rocks of Kempirsai, largest of the massifs of Kazakhstan. Ages obtained for the gabbro, 407±20 or 385±15 My, and for hydroeclogites formed after them, 355±15 My, correspond to the results of the laboratory studies of Kempirsai rocks by G. J. Wasserburg (Lawrence and Wasserburg, 1984), which determined an isochrone of 385±22 My by the samarium-neodymium method. For the rocks of the massif and mélanges of southern Kazakhstan, only one satisfactory datum in seven was obtained — 607±50 My for the pegmatoid gabbro of the Karaarcha massif of the Kirgizian Range.

Laboratory analysis of the isotopy of lead in galena from Kazakhstan ore deposits may help to date the rift opening of the main and daughter (back-arc) ophiolite and non-ophiolite basins during the epoch of separation of the most ancient lead. The early epochs we preliminarily denote as: 1- Tekeli (1060 My, middle-Late Riphean boundary); 2- Karatau (680 My, Late Riphean-Vendian boundary); 3- Zhalair (580 My, Vendian-Cambrian boundary); 4- Sarytum (520 My, Late Cambrian); 5- Kendyktas (490 My, Early Ordovician); 6- Atasu (360-330 My, Late Devonian-Early Carboniferous) (Fig. 5).

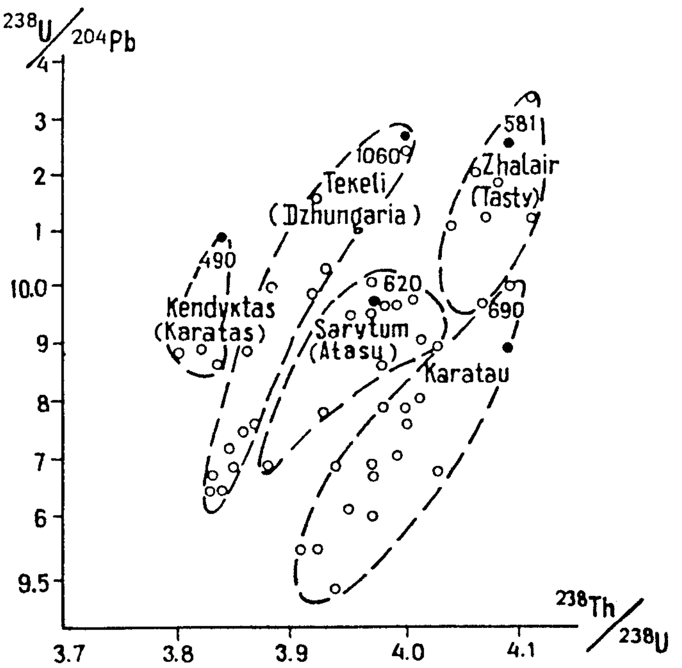


Fig. 5. Diagram showing lead isotopic ratio of galena from some of the polymetallic provinces of South Kazakhstan. Areas of oldest lead (black circles with figures in My) are outlined; named groups of lead deposits are bracketed.

Geochemistry of Igneous Rocks

Ophiolite Associations, Rock-forming Oxides

On an AFM diagram the basalts are grouped along the border of the tholeiite and calc-alkali series (Irvine and Baragar, 1971), with extensions into the pure tholeiite field and rarely into the calc-alkali series. On an MgO-FeO-Al_2O_3 diagram (Pearce, Gormann, Birkett, 1977) one-third of the basalts correspond to basalts of mid-oceanic ridges, one-third to oceanic islands, partially in the spreading centers, and one-third to continental rifts and traps. On an MnO_2-TiO_2-P_2O_5 diagram (Mullen, 1983) a third of the basalts also correspond to basalts of the mid-oceanic ridges, a third to the oceanic islands (with a predominance of alkaline basalts), and a third to tholeiites of the island arcs. Note, however, that more than a third of all analyses plot in indeter-minate positions on the lines of demarcation. In terms of oxides such as MgO and TiO_2 that are most resistant to metamorphism, the basalts of the ophiolite zones of Kazakhstan tend to resemble the traps or basalts of Iceland but not the oceanic basalts; they occupy the same position on the MgO-FeO diagram, where they are characterized by the high iron content peculiar to trap rock. The position of Kazakhstan basites as oceanic units is clearer on our CaO/Na_2O-K_2O diagram, where the trap area and trends of inequitype island arc basalts are also exhibited rather well.

Ophiolite Associations, Minor Elements

On the Ti-Zr diagram (Pearce and Cann, 1973), most analyses are for tholeiite basalts of the spreading zones of oceans and marginal seas of the Seimal, Oman and Maram, New Guinea type; on the Cr-Y diagram (Pearce et al., 1981) the majority are inclined to the ophiolite areas of the mid-oceanic ridges, and only on the scheme of fixed to MORB contents of the 15 elements with large and small ionic radii (Pearce, Lippard, and Roberts, 1987) — to the area of supra-subduction zone ophiolites (Fig. 6). This corroborates the idea of full submergence of ophiolite plates of the aforementioned oceans which may have existed around the periphery of Kazakhstanica.

Other Complexes

The magmatic associations of all non-coeval geodynamic settings of Kazakhstan are more reliably discriminated on the diagrams by Zavaritsky (1944; Fig. 7) and de la Roche et al. (1980; Bathelor and Bouden, 1985) on coordinates R1-R2. Even more pronounced are the different depths of formations by the downward orientation of the R2 axis. The proximity of the intermedi-ate compositions of granitoids of type I, S and A to the unitectic oval of these diagrams indicates the intracontinental crustal origin of the most of the granite magma, which is also corroborated by the geological data. Most Kazakhstan granitoids belong to syncollisional, orogenic, and postorogenic formations; probably, only basic initial and early phases had an "island arc" origin (Fig. 8).

The Uncertainty Principle in Geology

In compiling the differently scaled geodynamic maps of Kazakhstan, uncertainties proliferated during detailed analysis of the stratigraphy, magmatism, and metamorphism of formations belonging not only to the lowermost Precambrian but also to the Paleozoic ophiolites and adjacent zones involved in underthrust shifts. We deal here only with some of the principal uncertainties, ones requiring field revision, and with the record of possible alternatitives for map symbols.

Accretion Prisms

A major uncertainty is peculiar to the stratigraphic schemes established by the "non-standard" zones of tectonic congestion through traditional geological methods. Along the Zhalair-Naiman fragment of the Kazakhstan Erementau-Zhalair-Ili ophiolite arc, almost 400 km long, there is an unimaginable jumble of heterogeneous, noncoeval cataclasite-Mylonites, comparable only to the chaotic exposures of the Sultan-Uizdag-Muruntau fragment of the Turkestan ocean suture. Even a single thin section reveals fragments of the plicated lamina and streams of three suites and, along their borders, relics from the replacement of small glaucophane and stilpnomelane crystals of the greenschist paragenesis. On old maps, diorite porphyrites are scattered boudins of glaucophanized rhyolites and granophyres of the Late Riphean, extending into the Arenigian-Llanvirnian conglomerates (Fig. 9: 7,8). Here as in many other parts of Kazakhstan, we are dealing with a series of crumpled rocks with linearized kink-bands, cleft by the late faults of plate tectonics: from the problematic Vendian-Cambrian tuffites, mélanges of coeval ophiolite triads, Ordovician island-arc volcanics, quartz graywacke from the clasts of the Precambrian gneisses, and so on. All of this jumble has travelled from the paleozone of northeast-dipping subduction, mixed

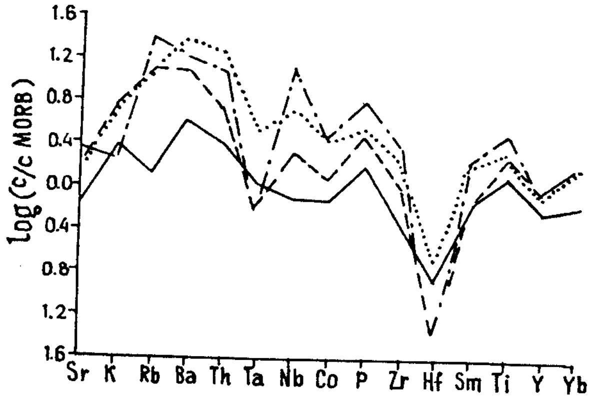


Fig. 6. Content of elements with large ionic radii and elements with high field strength in basalts of some ophiolite zones of South Kazakhstan (determined at United Institute GGM RAS, Novosibirsk). Unbroken outline: Cambrian pillow-lavas of the Ishim-Naryn suture, Karaarcha locality, west of the Makbal Precambrian Rise, western Kirgizian Range; hatched line: Cambrian pillow-lavas, eastern Yermentau-Zhalair-Ili suture, Sarytau Massif and Mountains, eastern Transilialatau Range; hatched-dotted line: Cambrian pillow-lavas of the Zhalair fragment of the Ermentau-Zhalair-Ili suture; dotted line: Late Riphean porphyrytoids of the riftogenic bimodal Kopa group near the Zhalair fragment.

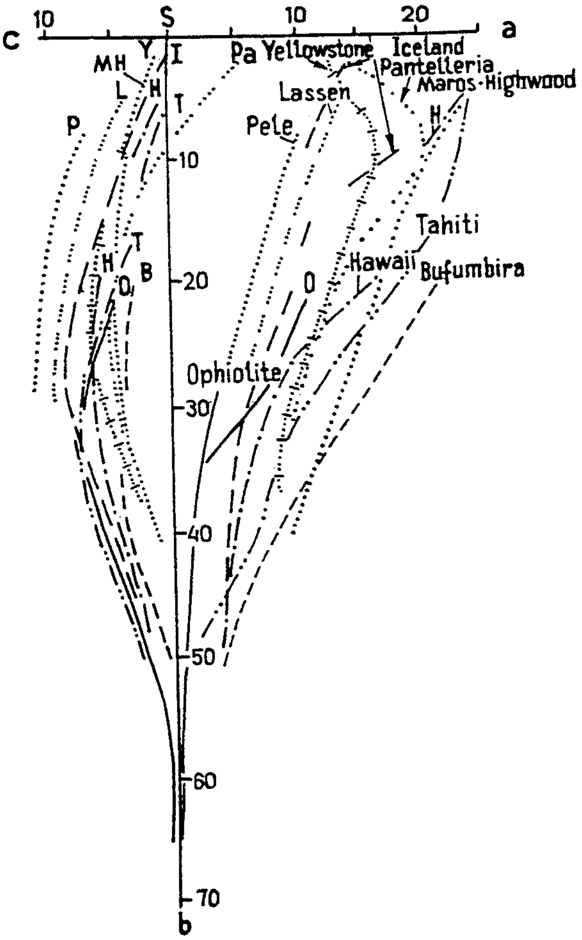


Fig. 7. Zavaritsky diagram (Zavaritsky, 1944) showing the main volcanic association and basites of ophiolitic associations of Kazakhstan with calculated calcic (c), alkalinic (a), and melanocratic (b) characteristics.

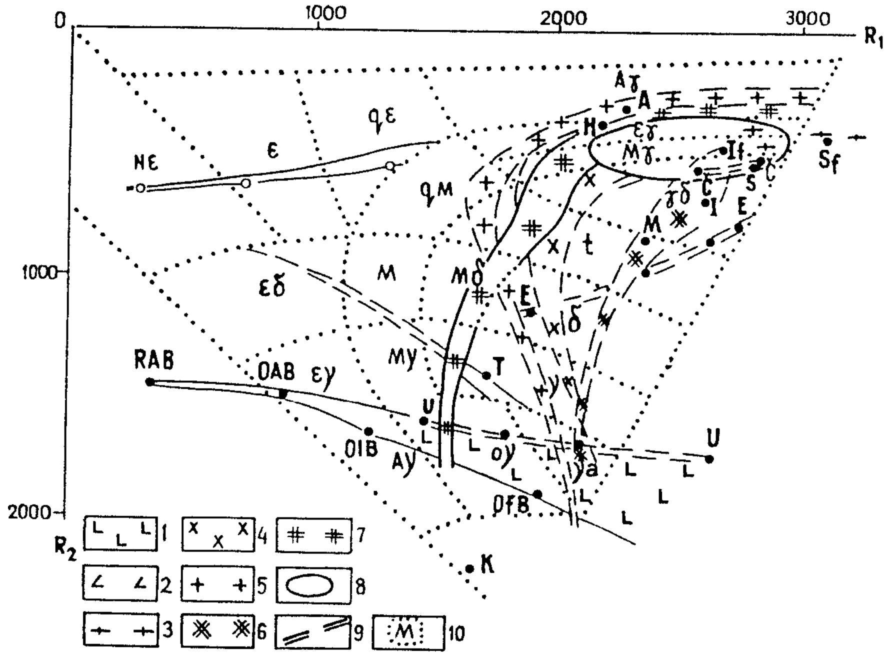


Fig. 8. De la Roche diagram (De la Roche et al, 1980) showing igneous rocks of South Kazakhstan and other regions of the earth. 1- igneous rocks from different ophiolitic zones of Kazakhstan; 2- volcanites of Ordovician shoshonitic island arc association, same locality; 3- igneous rocks of acid and potassic Late Riphean continental volcano-plutonic association, same locality; 4- subductional and syncollision Late Ordovician plutonites, same locality; 5- igneous rocks of Devonian active continental margin of the Kazakhstan area; 6- Early Carboniferous synorogenic plutonites of Kazakhstan; 7- igneous rocks of the Late Paleozoic-Early Triassic active continental margin of the Kazakhstan area; 8- ellipse of syncollisional anatectic granitoids (Batchelor and Bouden, 1972); 9- trends of metamorphogenic ultramafites (U), enderbites (E), and charnockites (C) of the Antarctic Continent (Kamenev and Ravitch, 1972); 10- fields of typical rocks of the A.A. Strekeisen classification. Position of average composition of various typical igneous rocks (various publications): K- kimberlite, OFB- ocean-floor basalts, OIB- oceanic island basalts, OAB- oceanic alkaline basalts, RAB- riftogenic African basalts, T- traps; M, I, I_f, S, S_f, A H- granitoids of different types according to new classifications (Pearce et al, 1984).

with Ordovician terrigenous rocks, been emplaced almost vertically, and in its present state yields no clues to the initial stratigraphy, which has to be restored from fragments by non-traditional methods, with no certainty as to the reliability of reconstructions.

Collisional Zones

In Kazakhstan, Patalakha (1970) worked out a method of tectonofacies analysis of widespread "zones of crumpling," establishing the main structural paragenetic types and 10-12 tectonofacies, which indicate the intensity of deformational processes. Along these zones, usually also enclosing the ophiolite sutures and their settings, there are a great number of rootless protrusive bodies. The small protrusives often "fill" larger low-viscosity masses. The large and small protrusives, until now, were mapped as intrusives, meta-intrusives, meta-sediments, and so on. Among them, several types can be distinguished: 1- apogabbro-serpentinite-listvenite Or'-Ilek type, squeezed out of subducted oceanic plates (Fig. 9: 1, 2) in the plates of the Precambrian continental crust from the glaucophanized Riphean triad; 2- apogranulite-gneiss protrusives of Anrakhaian type (Fig. 9: 3, 4), represented mainly by diamond-bearing porphyroblastic staurolite-garnet quartz-micaceous shales, rich in boudins, lenses and streaks of carbonatites, serpentinites, and apoeclogite metamorphites, replaced by glaucophane, zoisite, winchite, and other minerals, with a maximum of progressive metamorphism of continental crustal rocks around apobasite protrusives — all these types are the products of the viscous-inversional intermixture (Patalakha and Avdeev, 1975) of subducting oceanic and continental fluidized plates; for the serpentinites of the Or'-Ilek and Anrachaian types the liquid crystal state (Avdeev, 1984; Khodyrev and Agashkov, 1986); and 3- blastocataclastite-Mylonite of granitoid type, developed after the Precambrian gneisses and granulites and squeezed from the partially melted subducted continental plates (Fig. 9: 5, 6). The last may be referred to as the Irtysh, from the broad development of isoclinal nappes, together with the enclosing "hornfelsed" Devonian shales of the linear ramparts in the Irtysh zone of crumpling, where they were assigned to one or the other of the late Paleozoic stress-granitoids, the Precambrian meta-

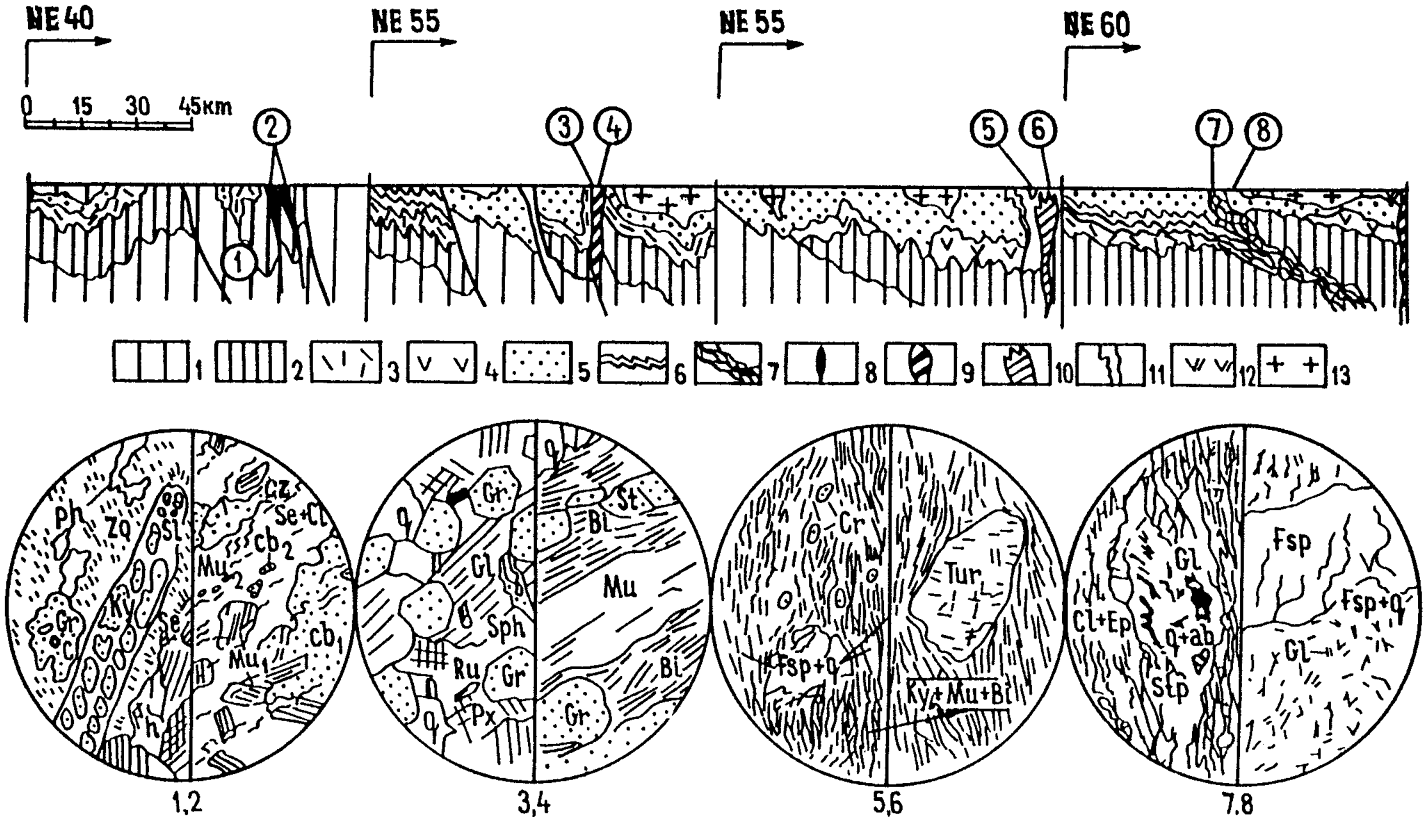


Fig. 9. The main types of anomalous geological bodies in sections across the ophiolite sutures of Kazakhstan (figures in circles): 1, 2- Sakmara zone; 3, 4- Zhalair-Naiman zone (across from the railway station at Otar); 5, 6- Chara zone; 7, 8- Zhalair-Naiman zone (across from the railway station at Chiganak). 1- Paleozoic oceanic crusts in the nappe or underthrust bedding; 2- Precambrian continentalized crusts, predominantly of gneissic composition; 3- metamorphosed contrast volcanites of Late Precambrian rifts; 4- volcanics of early island arcs; 5- crumpled and jointed terrigenous formations, including the Caledonian and Hercynian flysch and molasse; 6- isoclinal tectonic nappes of continental-slope and oceanic deposits; 7- metamorphosed tectonic mixtures of accretionary prism; 8- protrusive of the hot serpentinites and listvenites with gabbroid ballast; 9- protrusives apogranulite-gneiss shales with boudins of the glaucophanized eclogites; 10- folded protrusives of hot retrogranulites; 11- intrusives of gabbro-diabases (metamorphosed); 12- volcanites; 13- granitoids of active continental margins.

Symbols for sketches of the thin sections (diameter of field of vision = 2.2 mm, the numbers of the microsections correspond to the sections): 1- thin section N39/4-73, hydro-eclogite with disthene, garnet and diamond; 2- N14/10-75, listvenite; 3- N38/2-81, glaucophanized eclogite; 4- N41/2-82, enclosing it porphyroblast apogneiss quartz-micaceous shale; 5- N143/32-84, Mylonites with fragmented porphyroblasts of garnet; 6- N143/41-84, blasto-Mylonite with deformed metacrystal of tourmaline (kyanite grew synchronously with striae); 7- N4544/2-89, relics of stilpnomelane and glaucophane in the green shale cataclasite-Mylonite; 8- N58/20-82, lawsonite-glaucophane shale on the Upper Precambrian porphyroid, from pebbles of the Llanvirnian conglomerates.

Mineral abbreviations: Ru- rutile; Sph- sphene; Gr- garnet; Ky- kyanite; St- staurolite; C- diamond; Px- pyroxene; h- hornblende; Gl- glaucophane; CZ- clinozoisite; Zo- zoisite; Ep- epidote; Tur- tourmaline; Bi- biotite; Mu1-2- muscovite of two generations; stp- stilpnomelane; cb1-2- breunnerite of two generations; Cl- chlorite; Se- serpentine; ph- prehnite; q- quartz; ab- albite; Fsp- feldspars; Sl- sillimanite.

morphites, the Paleozoic arkose forma-tions, or the olistostromes.

Most of the anomalous bodies of the underthrusting zones, preceding the present syncollisional magmatism, are characterized by thermal activity during injection into the alien enclosing environment, with the amplitude of uplift in dozens of kilometers, reflected in extreme irregularity of metamorphic/metasomatic mineral associations and their telescopic character and making it impossible to describe these geological and corresponding physical systems with classic certainty.

Paired Metamorphic Belts

Applied to the Paleozoics of the Ural-Mongolian fold belt, the validity of the concept of paired metamorphic belts (Miashiro, 1976) is called into question. In connection with the collisional phases of the several Wilson cycles, exposures in the "shagreen" crust of Kazakhstan reveal the coincidence of metamorphites and signs of high pressure and temperature in the ophiolite sutures themselves, attested to by the presence of small diamonds in the underthrust metamorphites and planar structures in the plagioclases of the apobasite metamorphite, previously found only in astroblemes. Planar structures in the underthrust metamorphites and diamonds were discovered long ago (Efimov, 1972), but publication of such findings is a recent development, reflecting the activity of young academicians who were the first to breach the walls of secrecy (e.g., Sobolev and Shatsky, 1990). In the setting of the ophiolite sutures, the paired belts alternate in space, replacement of the glaucophane metamorphism by the Barrovian type having wiped out signs of the early metamorphic history; differences in gradation between various types of meta-morphism have also disappeared.

Conclusion

In an article of this length, we cannot deal comprehensively with questions raised by all aspects of paleogeodynamics, having to rely on maps which can generally be comprehended only through colored symbols. Fortunately, much data on particular zones and paleogeodynamic maps at a scale of 1:2,500,000 have already been published, and the following conclusions can be drawn:

1. In organizing the store of data bearing on the trend of mobilism, the key ideas of the Riphean continental and Steinmann oceanic triads, elaborated through detailed mapping of the Atasu-Mointy microcontinent and the Sakmar ophiolite suture, are of considerable help.
2. From fragments of the strongly deformed formations inside the ophiolite sutures, we can restore, with greater or less certainty, the riftogenic, oceanic, island arc, precollisional, collisional and postorogenic stages of their development, comprising the Wilson cycle, and indicate the relative independence of each zone. The problems of migration in time and space of these zones within Kazakhstanica and their connection with the progenitor oceans need firmer grounds for solutions.
3. The mobilist approach to the geology of any region may followed by compiling geodynamic maps and geological columns in colored patterns, indexes, and symbols denoting ancient geodynamic settings, correlated with the modern ones but strongly tectonically disturbed. This approach can be realized, according to our experience, on maps scaled from 1:2,500,000 to 1:10,000, the latter for especially complex sutures.
4. The success of new approaches to compiling maps, geological columns, and, based on these, minerogenic prognoses will depend on collaborative efforts by geologists studying the standard structural-material complexes on the proving grounds. The Osh (Aksu) geodynamic proving ground and the structures of the closed Turkestan Basin have played a large role in raising geologists' qualifications. The Kazakhstan proving grounds, with its unique deposits of different types, may play a similarly important role.
5. As the experience of the geodynamic mapping showed, considerable reworking of the Precambrian protoliths and the ophiolite suture rocks above the Benioff paleozones demands the utilization for radiometric purposes of isotopy on the isochrone level and also a search for new ways of dating the magmatic members of the ophiolite associations and riftogenic processes. The age limits of 2000±100, 1800±100, 1300±100, 900±80 (acid potassic volcano-plutonism), 750±50 (riftogenic contrasting magmatism), 650±50 My were determined by the isochronous uranium-lead isotopy of Kazakhstan zircons, and the isotopy of the lead of galenas allowed discrimination of the epochs of separation of the ancient leads dating 1060, 680, 520, 490, 360-330 My, probably recording the events of the initial location of aulacogens, rifts, and back-arc seas.
6. Data on the geochemistry of the magmatic associations of the ophiolite zones of Kazakhstan present a very contradictory picture of different

geodynamic settings, but relate, on the whole, to subduction zones where the plates of the main oceans submerged. The most likely diagram of the separation of all magmatic associations is that of de la Roche.

7. In compiling paleogeodynamic maps, maximum uncertainty attaches to the stratigraphy of the accretion prisms and dismemberment of intrusives, metamorphites, and protusives of the supersubduction collisional zones. In Kazakhstan, among the protrusives, it was possible to distinguish apogabbro-serpentinite-listvenite bodies, ramparts of the apogranulite-gneiss, and apophyllite diamond-bearing micaceous shales with apoeclogite boudins, and also ramparts of apogranulite-gneiss-blastocataclasite-Mylonites. In the strongly deformed zones, concepts of paired metamorphic belts and gradual metamorphism become increasingly tenuous.

Acknowledgments — The authors express their thanks to V.A. Khalilov for presenting the materials on the isotopy of zircons and galena, and also to D.T. Vasiliev, A.M. Zhilkaidarov, V.V. Kiselev, V.M. Nenakhov, K.V. Seliverstov, and V.G. Stepanets for putting at our disposal synopses of theses of their dissertations dealing with the problems considered in the article.

References

Abdulin, A.A., Avdeev, A.V., Seitov, N.C., 1977. The Tectonics of the Sakmara and Or'-Ilek zones of the Mugodzhary. Alma-Ata, Nauka, 240 p. (in Russian).

Anonymous, 1990. Atlas of Maps of South Kazakhstan — Scale 1:2,500,000. Alma-Ata, 17 p. (in Russian).

Antonyuk, R.M., 1974. The oceanic crust of the eugeosyncline area of the eastern central Kazakhstan. In: The Tectonics of the Ural-Mongolian Folded Belt. Moscow, p. 67-74 (in Russian).

Avdeev A.V., 1965. On the ring structures of the magmatic complexes. Soviet Geology, 10, p. 50-66 (in Russian).

Avdeev, A.V., 1968. The geology and magmatism of the Atasu-Dzhamshy watershed (central Kazakhstan). Cand. Sc. thesis (Geol. and Miner.). Alma-Ata, 27 p. (in Russian).

Avdeev, A.V., 1984a. Ophiolite zones and the geologic history of Kazakhstan from the mobilist standpoint. Int. Geol. Rev., v. 26, no. 9, p. 995-1005 (in English).

Avdeev, A.V., 1984b. The ichnology of the conodont animal as the key to the cognition of their nature. Paleontological Sbornik, 21, p. 78-80 (in Russian).

Avdeev, A.V., and Kovalev, A.A., 1989. The ophiolite and evolution of the southern-western part of the Ural-Mongolian folded belt. Moscow, 229 p. (in Russian).

Avdeev, A.V., Zlobin, G.A., Kim, V.S., Khalilov, V.A., Shuvalov, I.G., 1990. New data on the age of the Precambrian rhyolite-granite association of the Atasu-Mointy watershed (Central Kazakhstan). Dokl. Akad. Nauk SSSR, 311, 3, p. 685-689 (in Russian).

Batchelor, R.A., Bouden, P., 1985. Petrogenetic interpretation of granitoid rock series using multicationic parameters. Chemical Geol. 48, p. 43-55.

Bespalov, V.F., 1974. The development of conceptions on the tectonics of Kazakhstan. Izv. Akad. nauk of Kazakh SSR, Ser. Geol., 3, p. 30-39 (in Russian).

Borukaev, R.A., 1955. The pre-Paleozoic and lower Paleozoic of the northern-eastern central Kazakhstan (Sary-Arka). Moscow, Gosgeoltekhisdat, 408 p. (in Russian).

Borukaev, R.A., 1970. Selected Papers. Alma-Ata, Nauka., v. 1, 1970, 248 p., v. 2, 1971, 188 p. (in Russian).

Cook, H.E., Taylor, M.E., Zhemchuzhnikov, V.G., Apollonov, M.K., Ergaliev, G.Kh., Sargaskaev, Zh.S., Dubinina, S.V., Melnikova, L., 1991. Comparison of two Early Paleozoic carbonate submarine fans — Western United States and Southern Kazakhstan, Soviet Union. In: Paleozoic paleogeography of the Western United States. J.D. Cooper and C.H. Stevens (eds). Pacific Section SEPM, v. 67, p.847-872.

De la Roche, H., Leterrier, J., Grand Claude, R., Marchall, M., 1980. A classification of volcanic and plutonic rocks using R-1/R-2 diagrams and major element analyses—its relationships with current nomenclature. Chem. Geol. 29, p.183-210.

Efimov, I.A., 1972. The ancient rocks of Kazakhstan and northern Kirgizia. Doct. Sc. thesis (Geol. and Mineral.). Alma-Ata, 51 p. (in Russian).

Filatova, L.I., 1983. Stratigraphy and historical-geological analysis of the metamorphic formations of the Precambrian Central Kazakhstan. Moscow, Nedra, 160 p. (in Russian).

Grachev, A.V., 1977. Rift zones of the Earth. Leningrad, Nedra, 248 p. (in Russian).

Irvine, M.N., Baragar, W.R.A., 1971. A guide to the chemical classification of the common volcanic rocks. Canad. J. Earth Sci. 8, p. 523-548.

Kamenev, E.N., Ravitch, M.G., 1972. The Crystallinicum of the Antarctic Platform. Leningrad: Hydrometeoizdat. 659 p. (in Russian).

Kassin, N.G., 1934. The sketch on the tectonics of Kazakhstan. In: The Problems of the Soviet Geology. Moscow, 11, 161-181 (in Russian).

Khodyrev, O.Yu., and Agashkov, V.M., 1986. Phase transformations of serpentine in the system MgO-SiO2-H2O in the interval of pressures 40-80 kbar. Geochemistry, 2, p. 264-269 (in Russian).

Kiselev, B.B., 1991. The Precambrian of the paleosoids of Tien-Shan. Dr. Sc. thesis (Geol. and Miner.). Bishkek, 65 p. (in Russian).

Markova, N.G., Rozen, O.M., Pavlova, T.G., Samygin, S.G., Kheraskova, T.N., Antonyuk, R.M., Shcherba, I.G., 1982. The tectonics of Kazakhstan (Explanatory note on the Tectonic Map of Eastern Kazakhstan on the Scale 1:2,500,000). Moscow, Nauka, 140 p. (in Russian).

Milanovsky, E.E., 1983. The riftogenesis in the history of the Earth. Moscow, 280 p. (in Russian).

Mirlin, E.G., 1985. On moving apart the lithosphere plates and riftogenesis. Moscow, 250 p. (in Russian).

Miyashiro, A., 1976. The metamorphism and the metamorphic belts. Moscow, Mir, 536 p. (in Russian).

Mullen, E., 1983. $MnO-TiO_2-P_2O_5$: a major element discriminant for basaltic rocks of ocean environments and its implications for petrogenesis. Earth Planet Sci. Lett., 65, p. 41-58.

Nenakhov, V.M., 1988. The collisional (orogenic) magmatism of Turkestan-Alai. Cand. Sc. thesis (Geol. and Miner.). Leningrad, 16 p. (in Russian).

Patalakha, E.I., 1970. The mechanism of the current structures in the zones of crumpling. Alma-Ata, Nauka, 216 p. (in Russian).

Patalakha, E.I., Avdeev, A.V., 1975. On the mechanism of magma elevation. Izv. Akad. Nauk USSR, Ser. Geol., 5, p. 132-136 (in Russian).

Pearce, J.A., Alabaster, T., Shelton, A.W., Searle, M.P., 1981. The Oman ophiolite as a Cretaceous arc basin complex: evidence and implications. Philos.Trans.R.Soc., London, no. 300, p. 299-317.

Pearce, J.A., Cann, J.R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analysis. Earth Planet Sci. Let., 19, no. 1, p. 290-300.

Pearce, J.A., Gormann, B.E., Birkett, T.C., 1977. The relationship between major element chemistry and tectonic environment of basic and intermediate volcanic rocks. Earth Planet Sci. Lett., 36, no. 1, p. 121-132.

Pearce, J.A., Harris, N.B.W., Tindle, A.C., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. J. Petrol., 25, p. 956-983.

Pearce, J.A., Lippard, S.J., Roberts, S., 1987. The peculiarity of the composition and the meaning of supra-subduction zone ophiolites. In: The Geology of the Margin Basins. Moscow, Mir, p. 134-165 (in Russian).

Peive, A. V., 1969. The oceanic crust of the geological past. Geotectonics, 4, 5-23. (in Russian)

Peive, A.V., Shtreis, N.A., Perfiliev, A.C., et al., 1971. The structural position of ultrabasites on the western slope of the South Urals. In: The Problems of Theoretical and Regional Tectonics. Moscow, p. 9-24 (in Russian).

Peive, A.V., Knipper, A.L., Markov, M.S., et al., 1985. The formation of the Earth continental crust. Geotectonics, 3, p. 75-76. (in Russian)

Problems of Modern Micropaleontology. Leningrad, Nauka, 1990, 232 p. (in Russian).

Ramberg, I., and Morgan, P., 1984. The physical characteristics and direction of the continental rift evolution. Tectonics (Rep. at the 27th Internat. Geol. Congr.). Moscow, p. 78-106 (in Russian).

Ruzhentsev, S.V., 1976. The margin ophiolite allochtons. Moscow, 171 p. (in Russian).

Seitov, N.S., 1987. On some aspects of the problem of the riftogenesis. Izv. Akad. Nauk Kazakh SSR, Ser. Geol., 5, p. 35-44 (in Russian).

Seitov, N.S., 1988a. The Riphean-Paleozoic ophiolite zones of Kazakhstan as the microoceanic sutures. Izv. Akad. Nauk Kazakh SSR, Ser. Geol., 4, p. 25-33 (in Russian).

Seitov, N.S., 1988b. The possible ways of solving the problems on the plate tectonics from the position of the trend of development of the planet. Vestnik Akad. Nauk Kazakh SSR, 11, p. 31-37 (in Russian).

Seitov, N.S., 1988c. The tectonics of plates and the ophiolite zones of Kazakhstan (the principles of the moderate mobilism). Alma-Ata, Nauka, 112 p. (in Russian).

Seitov, N.S., 1989. The geological basis of the Paleozoic regional tectonics of the minor plates (according to the peculiarities of the ophiolite zones of Kazakhstan). Dr. Sc. thesis (Geol. and Miner.). Alma-Ata, 38 p. (in Russian).

Seitov, N.S., 1992. The plate tectonics: The possible sources and peculiarities (the materials on the ophiolite zones of Kazakhstan). Alma-Ata, Galym, 200 p. (in Russian).

Seitov, N.S., and Avdeev, A.V., 1983. The possible nature of the intracontinental paleorift structures of some regions of Kazakhstan. Izv. Akad. Nauk Kazakh SSR, Ser. Geol., 4, p. 9-17 (in Russian).

Seliverstov, I.V., 1992. The late Paleozoic dynamics and the metallogeny of the Chatkal region. Cand. Sc. thesis (Geol. and Miner.). Bishkek, 20 p. (in Russian).

Sobolev, N.V., Shatsky, V.S., 1990. Diamond inclusions in garnet from metamorphic rocks: a new environment for diamond formation. Nature, 343, p. 742-745.

Stepanets, V.G., 1992. The petrology and the geological position of the ophiolites of northern-eastern central Kazakhstan. Cand. Sc. thesis (Geol. and Miner.). Alma-Ata, 20 p. (in Russian).

Vasiliev, D.G., 1991. Volcanic formations in the history of the geological development of the caledonides of the northern Tien-Shan. Cand. Sc. thesis (Geol. and Miner.), Leningrad, 18 p. (in Russian).

Zavaritsky, A.N., 1944. Introduction to the petrochemistry of igneous rocks. Izd. AN USSR. Sverdlovsk. 324 p. (in Russian).

Zhilkaidarov, A.M., 1991. The conodonts and the stratigraphy of the volcanogeno-siliceous deposits of the Ordovician of the southwestern Pre-Chingiz. Cand. Sc. thesis (Geol. and Miner.). Novosibirsk, 20 p. (in Russian).

Zonenshain, L.P., 1976. The reconstruction of the Paleozoic oceans. In: The Drift of the Continents. Moscow, p. 28-71 (in Russian).

Zonenshain, L.P., Mezhelovsky, N.V., and Natapov, L.M. (eds.), 1989. Geodynamic Map of the USSR and adjacent seas. Scale 1:2,500,000. Moscow, Tsentrgeologiya (in Russian).

Introduction to the Geological Structure, Mineral Resources, and Metallogeny of Kazakhstan

T.M. Laumulin and T.M. Zhautikov

Abstract

Tectonically, Kazakhstan consists of a number of stable Precambrian massifs separated from one another by sutures and marginal sedimentary wedges of early and middle Paleozoic rocks, which were consolidated after Middle Carboniferous to Permian times and subsequently covered by quasi-platform terrigenous-volcanogenic molasse. A platform regime became established during the Mesozoic. The history of the Cenozoic culminated in Alpine tectonic events of the end of the Neogene and Quaternary. These events are reflected in the richness and heterogeneity of the mineral deposits of both igneous and sedimentary origin.

A brief review of the principal mineral deposits by age precedes an evaluation of the classification, research and exploration strategies in Kazakhstan.

Introduction

In Kazakhstan, with an area of more than 2.7 million km^2, practically all geological formations (and their mineral deposits), differing in composition, age, and genesis, are represented. The distribution of geological formations is determined by the geologic history of the region and by its structural characteristics (Abdulin et al., 1971, 1976, 1980, 1981, 1983, 1989; Bespalov, 1965, 1971; Esenov, 1967, 1970, 1971, 1972; Gerasimov, 1969; Esenov et al., 1968; Kayupov, 1971, 1978, 1979, 1980, 1981, 1983; Kunaev, 1976; Kurskeev, 1977; Satpaev, 1959, 1968; Shlygin et al., 1964; Shcherba, 1983; and others).

The Republic (Fig. 1) occupies an epi-Hercynian platform massif, parts of which (the mountain systems of Tien-Shan and Altai) were subjected to strong orogenic movements. The basement of this epi-Hercynian platform is composed of Precambrian (presumably Archean and Proterozoic) and Paleozoic (and including Lower Triassic in some places) sedimentary, magmatic, and metamorphic rocks strongly deformed and intruded by igneous rocks. The tectonic structure of Kazakhstan is complicated and controlled by the presence of a number of stable Precambrian massifs (plates and microplates), separated from each other by sutures and by marginal sedimentary wedges that accumulated during the Early and Middle Paleozoic. Consolidation through sutures, from the Late Ordovician until the Early Carboniferous, resulted in formation of a uniform massif which, after the Hercynian orogeny (in the Middle Carboniferous and Permian), was transformed into a uniform platform. Part of the ancient massifs and suture zones was subsequently covered by quasi-platform terrigenous-volcanogenic molasse.

The Kazakhstan shield, the largest tectonic unit in the region, consists of the Dzhungar-Balkhash and Teniz-Kokchetav blocks, which are surrounded by fold belts. In the southwest lies the Karatau-Ulutau fold belt, and in the northeast lies the Chingiz-Tarbagatai and Zharma-Saur belts. The Zharma-Saur is separated from the Rudnyi Altai by the Rudnyi-Altai suture zone.

In the north, the Kazakhstan shield is bordered by the West Siberian lowland, which grades into the Turgai depression in the south. Further to the south-southwest, the shield passes into the Turan Platform. These physiographic features separate the shield from the Mugodzhary Mountains at the southern end of the Urals. Further to the west is the Caspian depression, on the edge of the Russian Platform.

Precambrian

Four Precambrian massifs occur within the Kazakhstan shield: Kokchetav, Ulutau, Atasu-Moiynty, and Chu. Caledonide and Hercynide orogenic zones developed over the sutures, separating the ancient massifs, engulfing their margins, and penetrating the massifs as zones of tectonomagmatic activity (Abdulkabirova, 1975, 1987, 1988, and others).

Rocks of the ancient massifs are metamorphosed in varying degree. The older Upper Archean or Lower Proterozoic rocks are represented by a gneiss-amphibolite

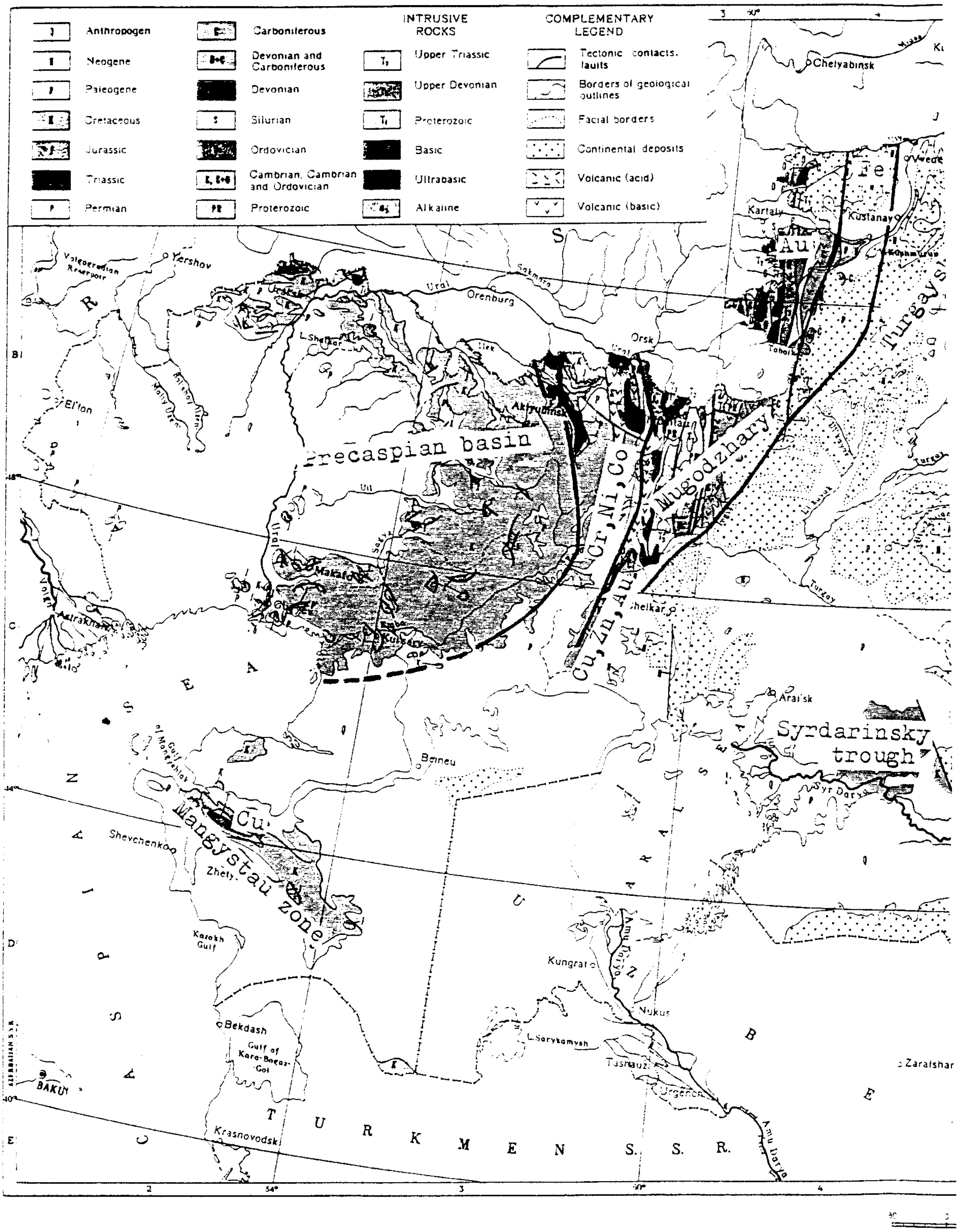
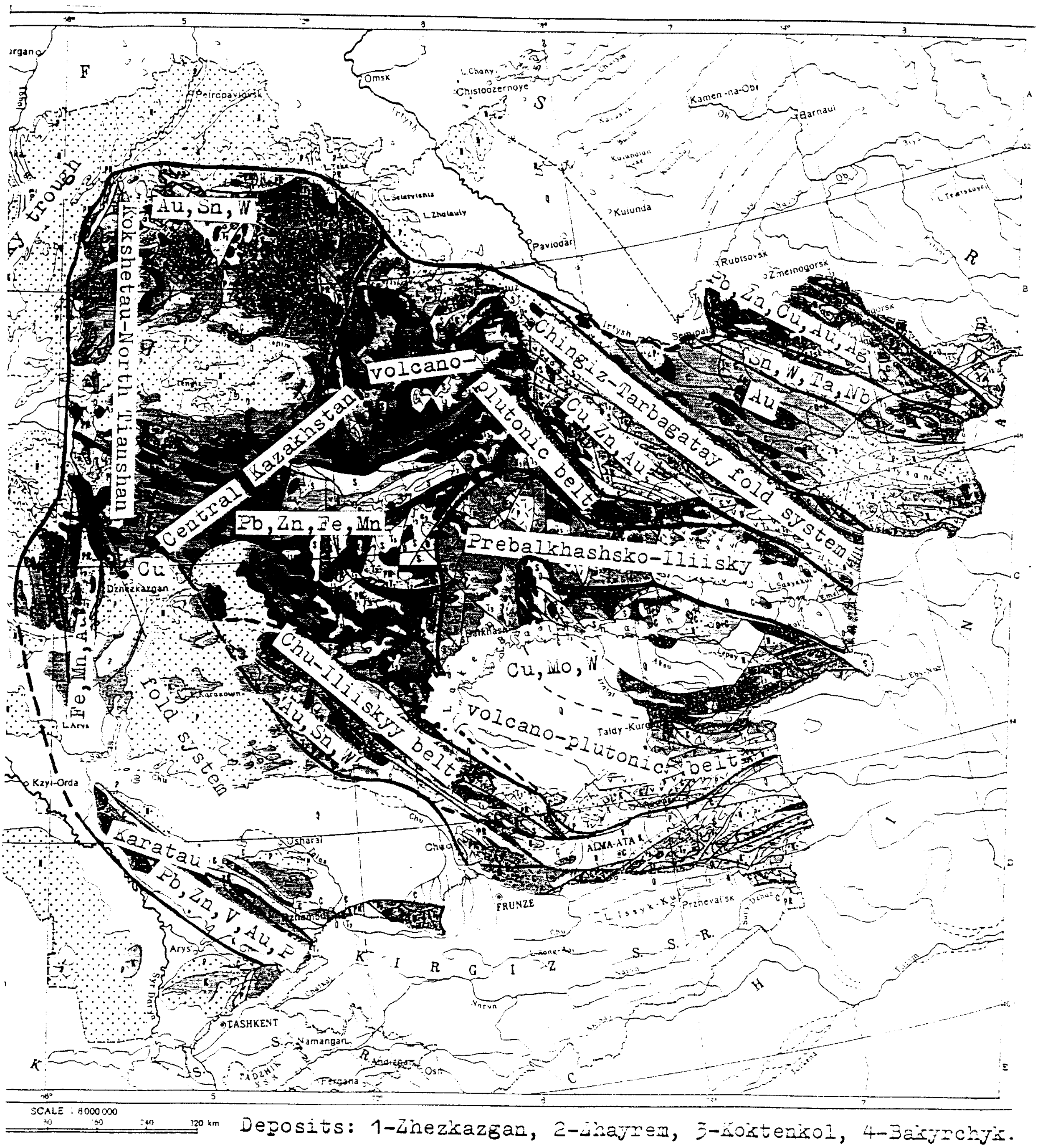


Fig. 1. Sketch of the geological structure and structural-metallogenic zoning of Kazakhstan. Deposits: 1- Zhezkazgan; 2- Zhayrem; 3- Koktenkol; 4- Bakyrchyk.



Deposits: 1-Zhezkazgan, 2-Zhayrem, 3-Koktenkol, 4-Bakyrchyk.

complex. Rocks comprising the Ulutau are metamorphosed to a lesser degree and consist of metavolcanics, ferruginous quartzites, and greenschists (Nurlybaev, 1984). Upper Proterozoic rocks cover the ancient Precambrian craton. Typical of these rocks are blastopsammitic quartzites, micaceous quartzites, porphyroids, quartz-sericite-chloritic schists, and carbonates. The uppermost Proterozoic (Vendian?) consists of carbonates, weakly metamorphosed sandstones, and aleurolites with tillite horizons.

Paleozoic

The rocks of Central Kazakhstan are predominantly Paleozoic (Abdulin, 1983, 1984, 1986, 1987, 1988, 1990, 1991; Bok, 1966,1977; Borukaev, 1967, 1968, 1969; Esenov, 1971, 1972; Kazanin, 1976; Shcherba et al., 1968, 1979-1980).

Cambrian rocks of the suture zone (geocline) are represented essentially by altered greenstone basic volcanics, siliceous and silico-carbonate rocks, ophiolites with ultramafics, and quartz-feldspathic sandstones. Carbonate, terrigenous, and lesser siliceous rocks predominate on the stable Cambrian massifs. Ordovician sediments have a different array of facies. Stable massifs are characterized by the presence of Lower Ordovician carbonate rocks and by Upper Ordovician sandstones and aleurolites. Mainly andesite volcanics, as well as silico-carbonate and carbonate-terrigenous strata, were deposited near the suture zones during the middle geoclinal period. Ophiolites formed in subduction zones in the Early Ordovician, but were succeeded by predominantly volcanic and siliciclastic formations during the Middle and Late Ordovician.

Cambrian gabbronorites (stratified lopoliths), small bodies of gabbro and pyroxenite, and large Ordovician batholiths were intruded into the Kokchetav massif.

The Silurian Period was characterized by consolidation accompanied by widespread orogenic Caledonian intrusions in marginal zones of central Kazakhstan. Silurian sediments are known in the inner Dzhungar-Balkhash basin as well as in the Zaisan-Irtysh basin. Andesitic volcanics, sedimentary formations, and granitoid intrusions formed in the intermediate Chingiz zone, between the Dzhungar-Balkhash and Zaisan-Irtysh zones.

The Devonian was characterized by development of a marginal volcanic belt (with numerous granitoid intrusions) around the Dzhungar-Balkhash basin, in which mainly sandstones, aleurolites, and small quantities of siliceous rocks and intermediate volcanics accumulated. During the Late Devonian-Early Carboniferous, Caledonide rocks of Central Kazakhstan were subjected to marine transgression, and limestones and to a lesser extent dolomites were widely deposited in depressions, especially during the Tournaisian and Visean. Grey, coal-bearing, terrigenous rocks accumulated in the nearshore areas, along with salt in lagoons, and red sandstones and conglomerates on the margins of nearby uplifts. Characteristic Famennian formations containing siliceous rocks, ferromagnesian ores, pyritic rhythmites, and sedimentary barites formed in the Uspenka zone. Active sedimentation occurred during the Devonian in the Dzhungar-Balkhash basin, resulting in deposition of sandstones, aleurolites, siliceous tuffites, and silico-argillaceous slates, superseded by overlying coarser clastics and limestones. Lower Lower Carboniferous basic volcanics, associated with siliceous rocks, characterize the sutural zone in the Irtysh-Zaisan Basin.

Consolidation occurred throughout Central Kazakhstan, beginning at the end of the Early Carboniferous and continuing through the middle of the period. During the Late Paleozoic, the inner Dzhungar-Balkhash volcanic belt originated. It consists of alternating intermediate-basic and acid lavas, tuffs, ignimbrites, and products of their erosion. Upper Paleozoic granitoids are widespread. The previously consolidated Teniz and Chu-Sarysu depression became filled with a sub-horizontal complex of brown and red sandstones, conglomerates, argillites, aleurolites, limestones, dolomites, gypsum, anhydrites, and halite.

Mesozoic and Cenozoic

The platform regime in the region became established during the Middle Triassic. Mesozoic sediments have a restricted distribution. Rhaetian-Jurassic synclines consist of terrigenous beds, which include coal. Cretaceous rocks (clays, sands, marls) are exposed along the margins of the Kazakhstan shield. Alluvial valleys, limnic depressions of different sizes, and flat-lying areas were covered by Neogene clays and different unconsolidated, Quaternary sedimentary lithologies.

The mountainous relief in southern and eastern Kazakhstan, which formed at the end of the Paleogene-Neogene, achieved its present-day appearance during the Quaternary. These regions had been part of the Kazakhstan shield until the end of the Neogene; then, differential movement of blocks created a system of uplifts (ridges), intermontane and piedmont depressions, which became the sites for deposition of thick terrigenous deposits of clay (some evaporitic), rock debris, and erosion products including sands, loams, and volcanic pebbles. The accumulated sediments have a total thickness of several kilometers. In piedmont areas, thick beds of eolian loess were deposited.

Geology and Mineral Resources

Tertiary deposits of the northern parts of the Tien-Shan are similar to those that surround the Kazakhstan shield. Stable massifs are characterized by carbonate and siliceous Cambrian and Lower Ordovician rocks; terrigenous rocks of the Middle and Late Ordovician; suture zones composed of Vendian and Cambrian ophiolites; and volcanic, silico-terrigenous, and carbonate terrigenous Ordovician rocks. Silurian rocks are silico-terrigenous carbonates except in Tarbagatai, where they are volcanogenic.

The orogenic Caledonides are represented by contrasting Devonian volcanics and sediments. The quasi-platform Caledonides (Famennian-Late Devonian) are composed of red, salt-bearing sandstone, aleurolite, clay, limestone, dolomite, and gypsum. Nearby, in the Hercynide succession, Lower Carboniferous rocks consist of andesite and dacite, with the upper Paleozoic represented by intermediate basic and acid volcanic flows and tuffs.

The Hercynides of the Dzhungar Alatau (Devonian, Carboniferous) are represented by marine geosynclinal argillaceous and siliceous shale, and some zones of intermediate volcanic rocks, as well as Lower-to-Middle Carboniferous limestones, conglomerates, and sandstones.

The Upper Proterozoic consists of orogenic volcanics of contrasting composition, and coarse-clastic terrigenous rocks.

Of the intrusive rocks, Upper Ordovician, Devonian, and Upper Devonian granitoids are widespread in the mountain areas, but ancient ultramafic and basic rocks are less common.

The Mesozoic and younger platform deposits occur locally, including a coal-bearing, terrigenous Rhaetian-Jurassic complex, a rather thin Upper Cretaceous and Paleogene-Eocene quartzose sand, and white and multicolored clays. Oligocene red clays and Neogene-Quaternary proluvial, alluvial, and limnic deposits reach great thicknesses in the intermontane depressions.

Among the mineral resources of the region, Carboniferous coking coals (Karaganda, Ekibastuz, and others) are of great importance (Abdulin, 1986, 1988, 1991; Kushev, 1971; Laumulin, 1977; Satpaev, 1968; Shcherba, 1960, 1988; etc.). Cupriferous sandstones of Zhezkazgan (Figs. 2, 3, 4) formed in a Middle-Late Carboniferous quasi-platform environment, and porphyry copper ores are associated with small intrusions of Late Paleozoic (Lounrad, Aktogai, and others) and Ordovician (Bozshakol) age. Iron (Karazhal), manganese (Zhezdy), and lead-zinc ores (Zhairem) (Figs. 5, 6) are associated with Famennian depressions and are of hydrothermal-sedimentary origin.

Tungsten-molybdenum stockwork and vein deposits are related to Paleozoic granites (Fig. 7), some of Devonian age (Karaoba) and others of Permian age (Vostochhyi Kounrad, Akchatau, Koktenkol — Figs. 8, 9 — and Zhanet, among others). Ordovician, Devonian, and upper Paleozoic gold deposits predominate over gold deposits of other ages. Chief among the nonmetallic minerals are deposits of corundum (Semizbugy) and pyrophyllite (Sheshenkora).

South Kazakhstan (Miroshnichenko, 1987; Shcherba, 1968; and others) is known for its sedimentary phosphorites, vanadium-bearing siliceous slates (Karatau), copper (Shatyrkol, Koksai, and others), and gold deposits associated with Ordovician and upper Paleozoic granitoid intrusions, stratiform lead-zinc pyrite deposits in Famennian and Lower Carboniferous carbonates (Karatau, Ketmen) and in lower Paleozoic silico-carbonates (Tekeli in Dzhungar Alatau), and Devonian stockwork tungsten deposits in Ordovician sandstones (Boguty). Aktogai porphyry copper deposits occur in upper Paleozoic rocks.

There are deposits of coal and oil shale (Kendyrlyk in the Saur ridge, coal deposits in the Ili and Alakul depressions and Ketmen ridge) and building materials (Shcherba, 1976) in upper Paleozoic, Triassic, and Jurassic strata located between Tarbagatai ridge and Dzhungar Alatau.

Rudnyi Altai is structurally distinctive (Esenov, 1971; Kayupov, 1977, 1978, 1979, 1982, 1983; Nekhoroshev, 1958-1966; Shcherba, 1984; etc.). There, predominantly terrigenous Lower Carboniferous rocks, and intermediate and moderately acid Devonian volcanics, intruded by upper Paleozoic granitoids, overlie a basement composed of folded lower Paleozoic rocks (albite-epidote-chlorite, and quartz-albite-sericitic schists, which are metamorphosed sandstones and aleurolites) and Caledonian granitoids. The Cenozoic is represented by intermontane alluvial deposits. There are almost no Mesozoic rocks. Predominantly stratiform pyrites and polymetallic deposits (Zyryanovskoye, Tishinka, Ridder-Sokolno, Nikolaev, and others) in volcanics formed by volcanogenic-sedimentary and hydrothermal-metasomatic activity are of great importance in Rudnyi Altai. Volcanogenic-sedimentary iron-ore (Holzun) and vein tungsten-molybdenum ores (Chindagatui) occur in the adjacent eastern areas of Gornyi Altai. Tin-tungsten vein mineralization is associated with Permian granites in the west, in the Kalba and Narym ridges. The West Kolbin gold belt (Fig. 10) lies further to the southwest.

The West Siberian lowland surrounds the northern part of the Kazakhstan shield. The structure of the folded basement of this part of the West Siberian lowland can be understood only by taking into consideration adjacent regions of northern Kazakhstan. The sedimentary cover is composed of Quaternary deposits, Neogene, Paleogene, and Cretaceous rocks and lesser Jurassic alluvial and limnic clays, sands, aleurolites, and terrigenous shallow-water sediments. Economic mineral resources are of limited extent (sedimentary iron-ore and building materials).

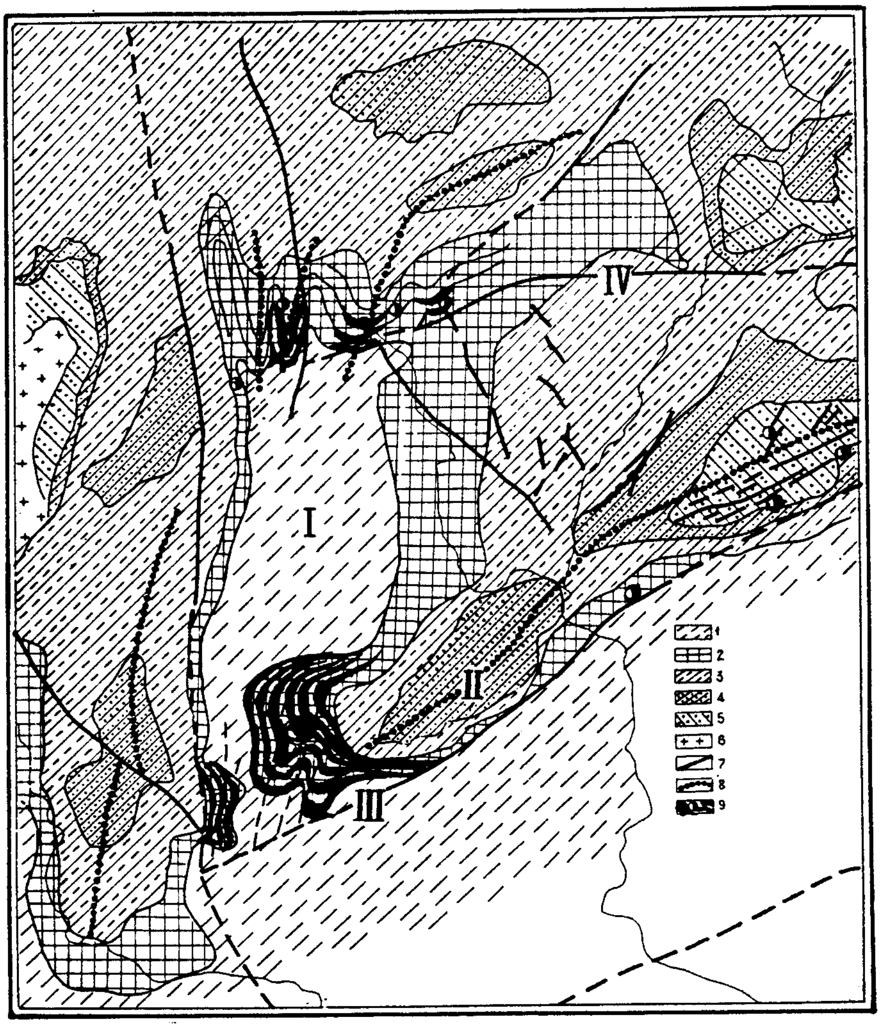


Fig. 2. Geologic-structural sketch of the Zhezkazgan ore region (extracted from K.I. Satpayev, S.Sh. Seifulin, V.F. Bespalov, N.N. Nuralin). 1- red aleurolites, sandstones, and limestones (C-P); 2- gray, red sandstones, and aleurolites (C-C) of the Zhezkazgan productive bed; 3- gray limestones, sandstones, aleurolites, and argillites (C-v); 4- gray, crystalline limestones, dolomites, and marls (C-t); 5- red sandstones and slates, conglomerates (D); 6- bedded intrusions-granodiorites; 7- faults; 8- fold axis; 9- copper ore occurrences and deposits. Structural elements: 1- Zhezkazganskaya syncline; 2- Kengyrskaya anticline; 3- Terektinsky fault; 4- Terektinsky northern fault branch.

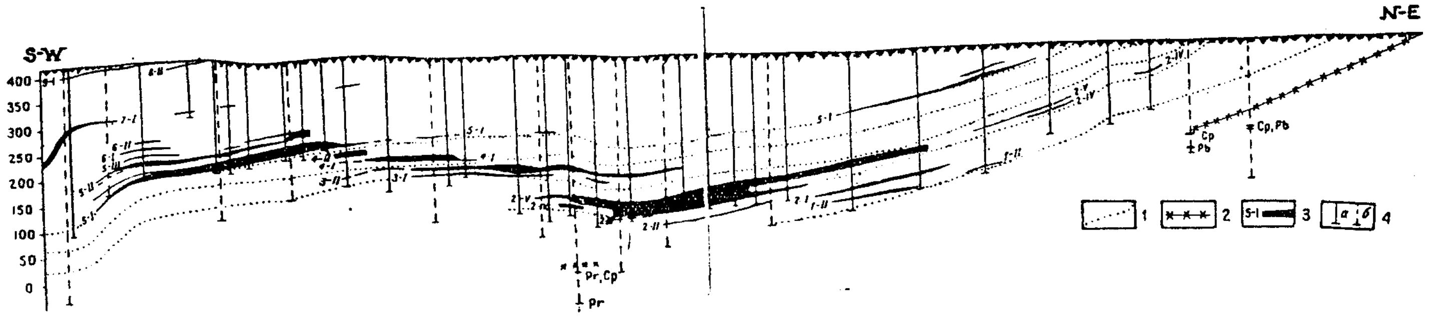


Fig. 4. Section along line through the Zhegkazgan ore region: 1- floor of host rocks; 2- floor of Zhezkazgan formations; 3- contour.

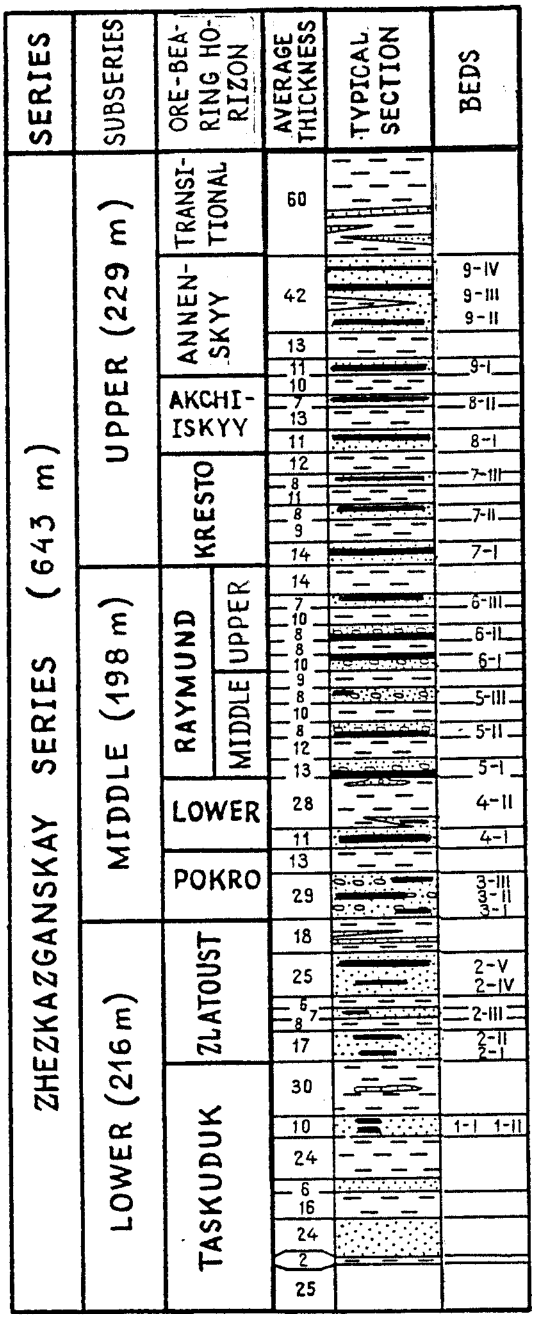


Fig. 3. Stratigraphic column showing Zhezkazgan ore-bearing formations: 1- gray sandstones; 2- red sandstones, aleurolites, and argillites; 3- raymundovsky conglomerates; 4- silicified limestones; 5- rock types.

The Turgai depression (Bekmukhametov, 1987; Nurlybaev, 1984; and others) is composed of thin beds of Mesozoic-Cenozoic platform cover that overlies the Paleozoic basement, the composition of which is similar to that in adjacent regions of Central Kazakhstan and Mugodzhary. During the Cretaceous-Paleogene, the depression connected marine basins of the West Siberian and Turan lowlands.

The basin of the eastern part of the depression contains an orogenic molasse of red Devonian and Carboniferous carbonates. Precambrian and Paleozoic rocks typical of Mugodzhary (metamorphic schists, basic and intermediate volcanics, sandstones and shales, carbonates, granitoids and ultramafics) lie west of the depression. A belt on the boundary between these structural zones is characterized by widespread volcanics (dacites, andesite flows, and tuffs), small comagmatic intrusions, carbonates, and moderate-sized massifs of upper Paleozoic granitoids. Magnetitic iron ores (Kachar, Sokolovskoye, Sarbaiskoye, and others) occur as skarns and hydrosilicate deposits. In the west, there are also deposits of asbestos (Zhetygora), gold, and copper in the basement of the zone.

The oldest basin-filling deposits are contrasting basic and acid volcanics of Triassic age, which occur in graben-like depressions. Terrigenous, coal-bearing sediments of Jurassic age were deposited in depressions whose depocenters had migrated from these Triassic grabens. Lower Cretaceous deposits are also continental, consisting of sandstones and multicolored clays. Upper Cretaceous marine and Paleogene deposits consisting of quartzose sands with glauconite, aleurites, multicolored clays, sandstones, aleurolites, and siliceous shales cover nearly all of the depression. The upper part of the succession is composed of Neogene clays and Quaternary valley alluvium (sands, loams, aleurites, and other building materials). Economically important Jurassic brown coals and oil and gas deposits were found in the South Turgai depression. Brown iron ores of limnic and valley types occur in the Upper Cretaceous and Paleogene deposits. Some bauxite deposits that originated in the weathered zone of crystalline rocks have been redeposited along the margins of the depression.

Mugodzhary, since it is the southern part of Urals, is also characterized by meridionally elongated, structural facies zones, composed of Precambrian-Carboniferous rocks. The western foothills are composed mainly of Permian and Triassic rocks (Abdulin, 1973, 1977, and others).

The Precambrian metamorphic rocks are represented by gneiss-amphibolite and schist complexes and gneiss-like granitoids. The rocks of the early Paleozoic are primarily metamorphosed sandstones, schists, and carbonates, but the Silurian and Upper Devonian rocks are greenstone basalts, spilites, diabases, and siliceous rocks — formations characteristic of a suture zone. Upper Devonian and Lower Carboniferous deposits in the western part of the region are represented by sandstones, shales, and bituminous strata; but in the east, they consist mostly of andesites, dacites, lesser volumes of basalt, and their erosional products, together with carbonate and siliceous rocks.

Mugodzhary is noted for the presence of ultramafics. The large and famous Kempirsai massif (Fig. 1) is an Ordovician and Silurian intrusion. Younger, Lower Car-

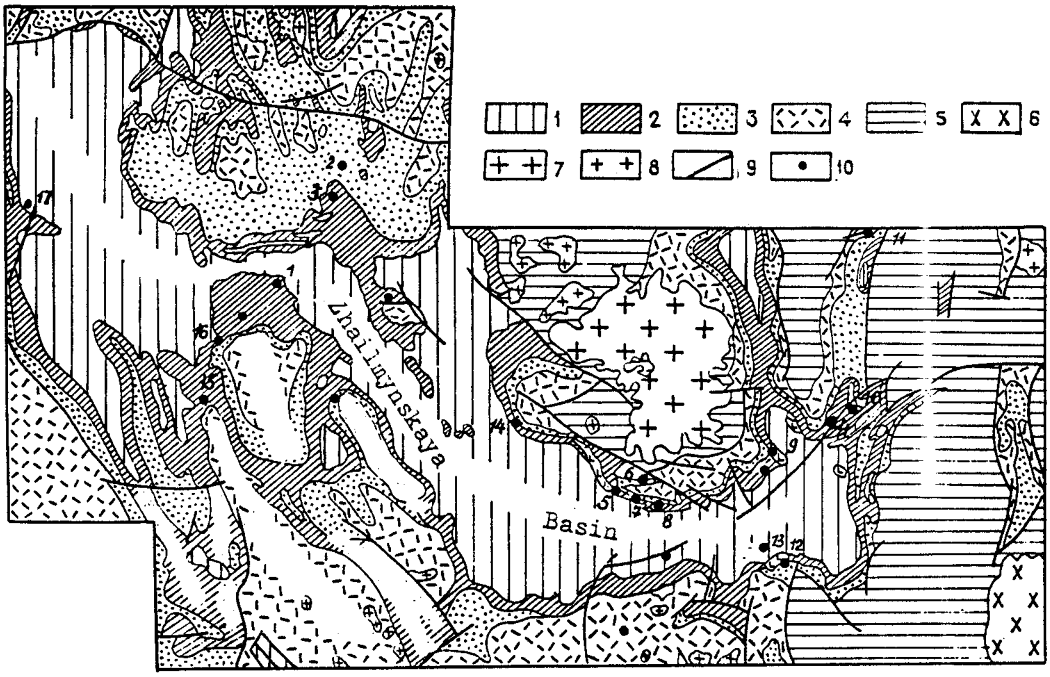


Fig. 5. Geological-structural sketch of Zhailmynskoi Basin (Atasusky ore-bearing region). Extracted from E.E. Buzmakov, V.I. Shibryn. 1- limestones, argillites, sandstones (C_1); 2- limestones, clayey-siliceous-carbonate rocks (D_3fm) hosting ferromanganese and polymetallic ores; 3- red conglomerates, aleurolites, sandstones, lenses of trachydacitic porphyries (D_3fr); 4- terrigeno-volcanogenic complex (D_{1-2}); 5- metamorphosed volcanogeno-terrigenous formations (PZ_1); 6- granites (C_{2-3}); 7- granitoids (D_{2-3}); 8- subvolcanic quartz porphyries (D_2); 9- faults; 10- deposits: 1- Zhayrem; 2, 3- Ushkatin I and III; 4- Bestube; 5-8- Karazhal-Zapadny (5), Severny (6), Vostochny (7), and Uzhny (7), Dalne-Vostochny (8); 9- Ktai; 10- Kentube; 11- Keregentas; 12, 13- Klych-Uzhny and Severny; 14- Altyn Shoki; 15- Zhumart; 16- Tamara; 17- Kamis.

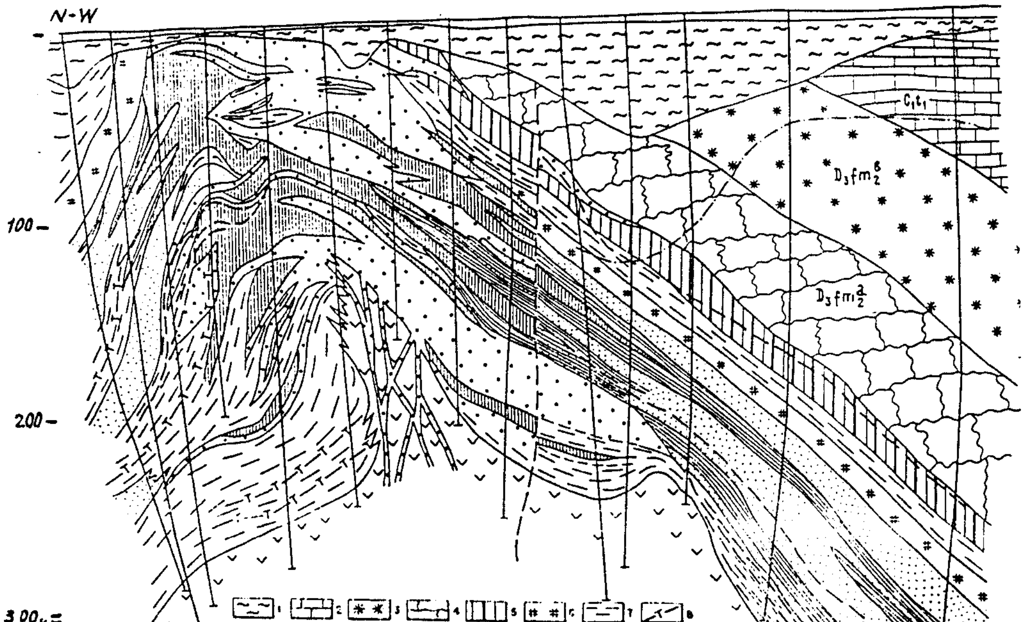


Fig. 6. Section of Zhayrem deposit. Taken from A.A. Rozhnov. 1- Cenozoic sands, loam, clay; 2- black, coaly, limestones; 3- red limestones; 4- gray, nodular-bedded rocks; 5- ferriferous horizons; 6- black, coaly, carbonate-feldspar-siliceous rocks with pyrite concretions (marker horizon); 7- barren rocks within ore-bearing beds; 8- tuff; 9- trachytic porphyries; 10-13- ores: 10- Pb-Zn (hydrothermal-sedimentary), 11- Pb-Zn (barytized), 12- Zn-Pb-barite (hydrothermal-metasomatic), 13- copper-barite (hydrothermal); 14- faults; 15- boreholes.

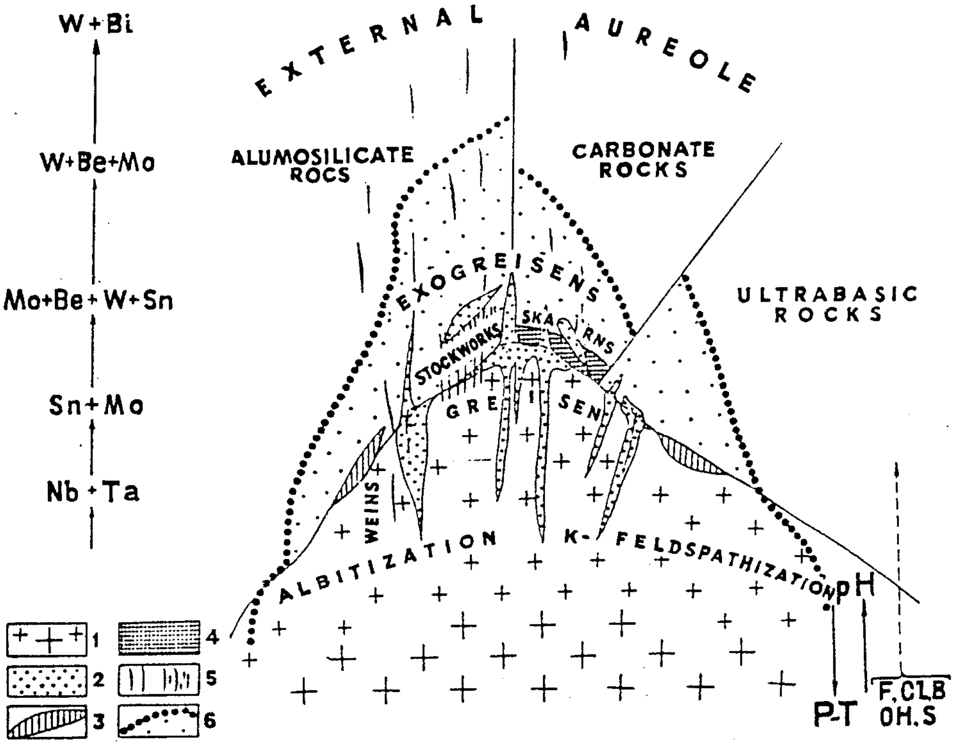


Fig. 7 (left). Generalized sketch of ore-metasomatic zoning within the dome structure-host rocks (with varying composition). Taken from G. Sherba. 1- granites; 2- greisen; 3- pegmatites; 4- skarns; 5- quartz veins and stockworks; 6- zone of development of rare metals, mineralization, and accompanying processes.

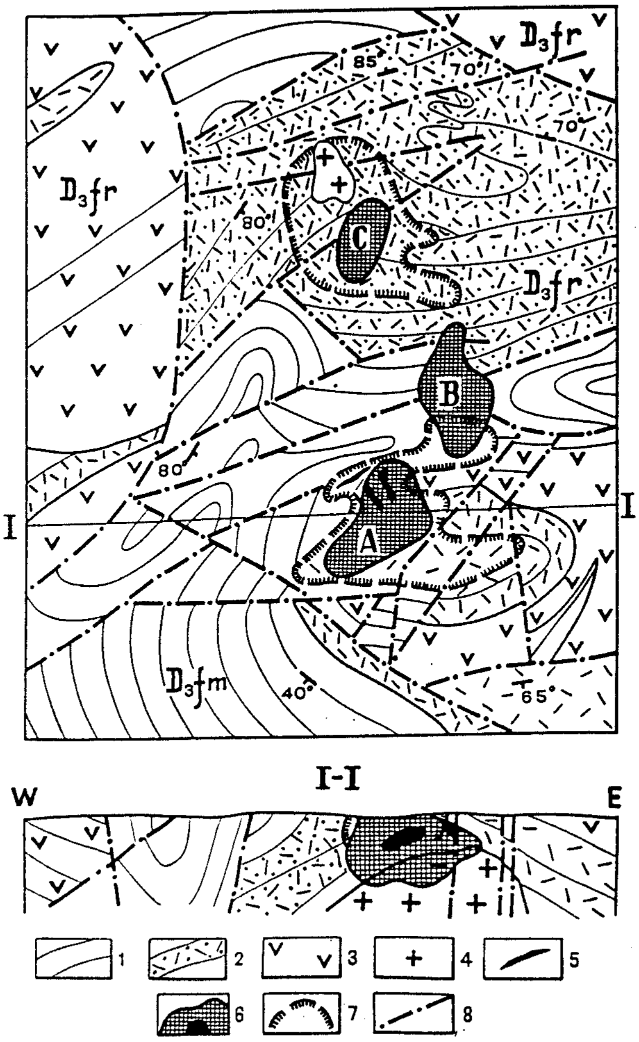


Fig. 8 (right). A geologic-structural sketch and section along I-I of the Koktenkol ore field. Extracted from G. Bedrov, A. Parkadze, K. Fatkulin, Yu. Nenashev. Stratified rock complexes: 1- Famennian limestone-schist; 2- Frasnian terrigeno-volcanogenic; 3- Frasnian effusive blanket; 4- Granites; Ore bodies: 5- quartz vein; 6- stockwork; 7- outlines of hydrothermal alteration zones; 8- faults. Zones: A- Uzhny, B- Promezhutochny, C- Severny.

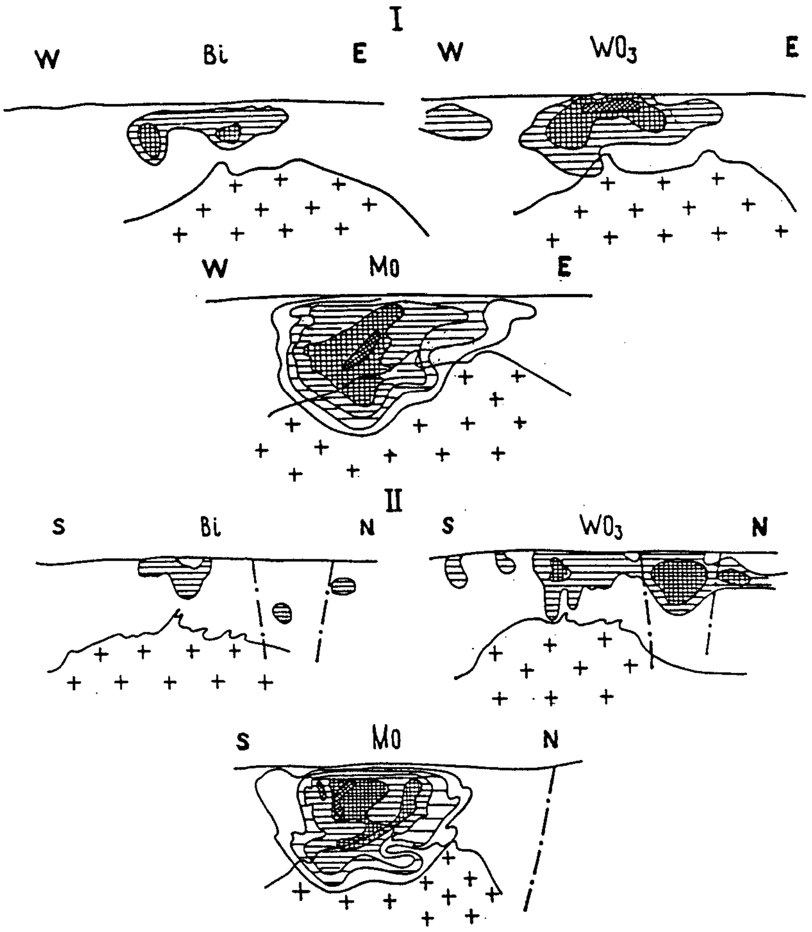


Fig. 9. Distribution of mineralization in the Koktenkol stockwork. The density of ruling corresponds to the intensity of mineralization.

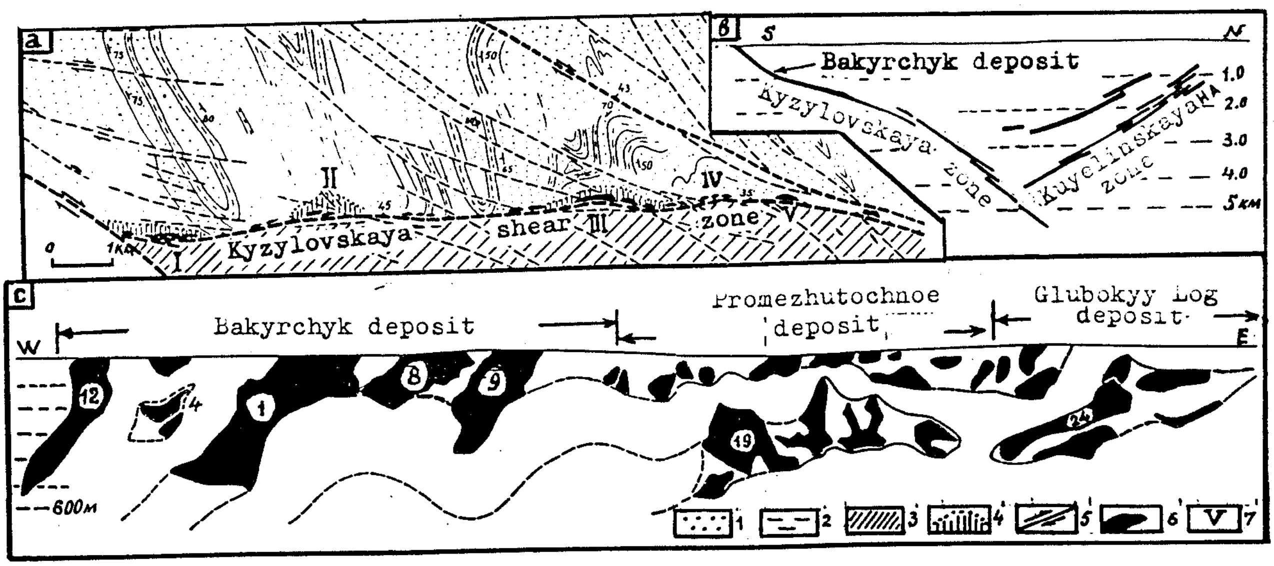


Fig. 10. Geologic-structural sketch (a), seismic cross section (b), and longitudinal projection (c) showing the ore bodies of the deposits of the Bakyrchyk ore field. Taken from T.M. Zhautikov. Terrigeno-molassic complex (C_{2-3}): 1- polymictic sandstones; 2- lime and coaly-argillaceous aleurolites; 3- flyschoid complex (C_1sp); 4- plastic deformation of rocks in the shear zone; 5- displacement; 6- longitudinal section showing ore bodies and their numbers; 7- deposits: I- Bolshevik, II- Kholodny Kluch, III- Bakyrchyk, IV- Promezhutochnoe, V- Gluboky Log.

boniferous ultramafics lie east of it. Small intermediate-basic intrusions, genetically related to comagmatic effusive rocks, are reported in the Silurian-Devonian greenstone zone. Upper Paleozoic granitoids occupy a considerable area. Mugodzhary also has small nepheline-syenite massifs.

The mineral resources of Mugodzhary are represented by chromite deposits (Kempirsai and others) related to Carboniferous ultramafics and by asbestos deposits, nickeliferous, ultramafic, weathering crusts, and bauxites. Copper-pyrites and gold deposits are associated with greenstone volcanics.

The Pricaspian lowland (a marginal part of the Eastern European Platform) is underlain by diapiric salt domes (Aznabaev, 1978; Dzhumagaliev, 1969; Zholtaev et al., 1975; and others). A thick succession of horizontally bedded Upper Proterozoic, Paleozoic, Mesozoic, and Cenozoic, predominantly shallow-water, nearshore, lagoon-continental limestones, marls, clays, sandstones, aleurolites, and lesser coals and oil shales have accumulated there. A thick bed of rock salt of Permian (Kungurian) age that underlies the entire depression has given rise to numerous salt domes and ridges that intrude Mesozoic and some Cenozoic deposits, creating the low hills of the area. Tremendous reserves of rock salt exist here. There are in addition numerous deposits of concretionary phosphorite of Cretaceous and Paleogene age along the eastern margin of the depression near Mugodzhary, while deposits of oil shale, bitumen (kerogen), and various building materials occur in the depression and along its margins.

The Turan Platform (lowland), the Ustyurt Plateau, and the Mangystau Peninsula occupy the southwestern part of Kazakhstan, the relief of which is controlled by horizontally bedded Cenozoic rocks. The Mangystau Peninsula is formed of blocks of Permian and lower Mesozoic rocks that have been exposed by uplift and erosion. The Ustyurt Plateau, which is absolutely flat and arid, without permanent rivers and streams, occupies the area between the Caspian and Aral seas and is covered by Neogene limestones. The plateau and some areas east of the Turan Platform (southwest of the Ulutau-Karsakpai region) are bounded by high erosional scarps called “chinks” composed of compact, hard, sometimes gypsiferous Paleogene clays and weakly lithified carbonates. The Aral Sea is in the center of the platform. The relief of the Karakum Desert, which spreads south of the Aral Sea, is characterized by isolated, low hills rising from the flat desert surface. Nearshore plains are covered by saline Quaternary “marine” sediments along the eastern shore of the Aral Sea and in places along the shores of the Caspian Sea, as on the Buzachi Peninsula.

The structure of the pre-Mesozoic basement of the Turan Platform and all of western Kazakhstan is complex. Presumably, there is a stable Precambrian massif under the Ustyurt Plateau, as well as east of the Aral Sea (pre-Syrdarya depression). Upper Paleozoic granitoids, penetrated in bore holes, provide evidence of Hercynian folding and intensive intrusive magmatism in this region. The folded structures of Mugodzhary probably do not extend southward to the Aral Sea, where wells penetrate Upper Carboniferous volcanics, nor southwestward to the Caspian Sea, between the Pricaspian depression and the Ustyurt Plateau.

The Mesozoic-Cenozoic cover of the platform is composed of subhorizontally bedded shallow marine and nearshore marine aleurites, sands, limestones, and lesser compact sandstones and aleurolites. The thickness of the cover reaches 4 km.

On the Turan Platform in Mangystau, economically important resources include oil and gas deposits, phosphorites, building materials, cupriferous sandstones, sedimentary iron and manganese deposits, titanium-bearing placers, rock salt, and sulfates (pre-Aral).

Metallogeny

One of the world’s first metallogenic prospecting maps, at a scale 1:500,000 (Satpaev, 1957, 1968), was the one prepared for central Kazakhstan. In preparing this map, tectonic epochs (pre-Paleozoic, Caledonian, Hercynian) and zones of tectonic-magmatic activity were defined. In a practical sense, the map shows all occurrences of ore minerals; and, through the characterization of potentially exploitable types of deposits, it provides a basis to distinguish regions with first, second, and third exploration potential.

First-rank prospective areas correspond, as a rule, to areas with large mineral deposits. Areas with only a limited number of the criteria used to determine the likelihood of mineralization are regarded as second or third rank. Preference is given to ore-bearing intrusive complexes — the most productive being at the intersection of deep mobile zones.

Most investigators have based interpretations of their observations on the linear-block tectonic model of Kassin (1934, 1947), in which stable Precambrian blocks (median massifs) were separated by mobile zones (geosynclines). These two basic structures determine the focus of metallogenic investigation and zonation of Kazakhstan, using data on tectonics, lithogenesis, magmatism, and ore formation. Cycles (periods) and stages (phases) in development of ore-bearing, structural-metallogenic zones can be defined, as well as the relations of ore-bearing bodies to geochemical types of magmatites. The first round of research in the Uspenka zone, conducted in 1960 by a large group of specialists at the Institute of Geology and other organizations, marked the beginning of detailed systematic investigations of the most important ore-bearing regions of the Republic. Expansion of metallogenic research in the 1970s was based on the accumulated results of large and small-scale research as well as the opportunities afforded by new analytic methods. These new techniques permitted large-scale investigations in isoptopic geochronology (argon, lead, strontium, uranium, osmium), geochemistry (sulfur), electronic microscopy, and thermo-baro-geochemistry. Microprobe and neutron-activation analysis with modern Japanese equipment helped extract more data from ore material, and the spectrographic methods developed at the Institute extended the range of elements subject to geochemical study (rhenium, platinum, germanium, and others).

Metallogenic investigations developed in two directions. The most important of these were the detailed investigations of the main ore-bearing regions of Kazakhstan: the Uspenka zone, Chu-Ili, Mugodzhary, Kalba, Rudnyi Altai, Zharma-Saur, Karatau, Zhezkazgan, Balkhash, and Kokchetav, the results of which were presented in a number of monographs, containing much new data on the geology, history of development, regularities in the distribution of mineral deposits, and the potential of structural-metallogenic zones, ore concentrations, and fields. An attempt was made to evaluate specific regions quantitatively with the help of computers. In principle, each monograph is a comprehensive survey of the geology and mineral deposits of a particular ore region. The main results of the investigations were presented in an 11-volume monograph, "Metallogeny of Kazakhstan" (Kayupov, 1977-1983).

The relationship between tectonic development and metallogeny in Kazakhstan has proved to be the key to understanding genetically and paragenetically related ore deposits. All geological formations, including those containing ore, are classified on the basis of the same features in a single interval, which means that a single unique interval of ore formation corresponds to one geological formation. The association of ore and geological formations is designated as a "metallogenic formation", but if there is a concrete indication of multiple formative events, as provided by age dating, it is designated as a "metallogenic complex". This system of defining metallogenic formations makes it possible to distinguish lines of evolution of ore formations essential to solving theoretical problems of ore genesis and provides a reliable basis for prediction. Analysis of the evolutionary trends in a particular area may reveal whether a complete mineralogic sequence is represented. Members identified as absent then can be sought after. Mapping of the metallogenic complexes (or series) of Kazakhstan (at scales of 1:1,500,000; 1:1,000,000; and 1:500,000) and the metallogenic zonation based on it permits an estimate of the potential ore content of the Paleozoic rocks as well as the characterization of structural-formational zones and indication of new zones and new types of mineralization as potential prospects for the discovery of economically important mineral deposits.

In addition to regional metallogenic analysis, more than 600 types of mineral deposits are described in the 11-volume "Metallogeny of Kazakhstan", the principal reference source on the ore deposits of Kazakhstan. Abdulin and Shlygin's "Metallogeny and Mineral Resources of Kazakhstan" (1983) resembles Kayupov's monograph in organization and concept. Data are presented on all the economic geologic resources of Kazakhstan, both of exogenic and endogenic origin, including energy resources, ores, nonmetallic minerals, building materials, and ground water.

Shcherba et al. (1970, 1983) analyzed the metallogeny of Kazakhstan from a different point of view, distinguishing ore belts and provinces that correspond to linear and regional tectogens. The evolution in composition of the mineralization of metallogenic cycles and epochs of geotectonogens in oceanic, intermediate, and continental crust and in different types of orogens are discussed. The early epochs of every cycle show a tendency toward siderophility; all the later ones, toward lithophility. The general vertical mineral zonation is characterized by definite trends in the qualitative composition of minerals and ore bodies in intermediate metabasaltic, metadioritic, metagranitic, and volcanogenic-sedimentary rocks. In analyzing ore belts and provinces, ore zones are distinguished, and ore "pockets" within zones, subordinate to, or corresponding with, areas of contact and areas of intersection of longitudinal faults with meridional zones. The metallogeny of provinces and belts is polycyclic. Qualitatively, the ore mineralization of provinces developed in Proterozoic continents is chalco-lithophilic, but the ore mineralization of subduction zones is sidero-chalco-lithophilic. Metallogenic analysis of geotectonogens allows the extension of prognoses of hidden mineralization and volume to significantly greater depths than was possible with the former geosynclinal concept.

Further development of metallogenic research in the Republic will continue with formational analysis by delineating ore formations and ore associations to elucidate their evolution and mineralogical type as a basis for assessing their mineral content and deficiencies. At the same time, the investigation of stages and polycycles of development and metallogeny of mobile zones and median massifs requires an understanding of the role of rift processes and tectonomagmatic activation at different stages of development. Advances in regional and local mineral exploration are impossible without a complete investigation of the primary and secondary geochemical characteristics of geological formations and their mineral potential, and without distinguishing the structural, petrological, and geomorphological conditions with quantitative estimates of prospective reserves.

References

Abdulin, A.A., ed., 1971, 1976. Tectonic Maps of Kazakhstan. Scale 1:1,500,000. Moscow.

Abdulin, A.A., 1973. Geology of Mugodzhary. Alma-Ata, Nauka, 391 p.

Abdulin, A.A., 1981. Geology of Kazakhstan. Alma-Ata, Nauka, 312 p.

Abdulin, A.A., ed., 1984-1991. Geology and metallogeny of the Balkhash segment of the Earth crust in Kazakhstan, v. 1-7. Alma-Ata, Nauka.

Abdulin, A.A., ed., 1986. Geology and Metallogeny of Karatau, v. 1. Alma-Ata, Nauka, 239 p.

Abdulin, A.A., ed., 1987. Geology and Metallogeny of Karatau, v. 2. Alma-Ata, Nauka, 246 p.

Abdulin, A.A., ed., 1989. Geology and Metallogeny of Kazakhstan. Alma-Ata, Nauka, 344 p.

Abdulin, A.A., Baidildin, E.A., Kasymov, M.A., et al., 1976. Metallogeny of Mugodzhary. Alma-Ata, Nauka, 280 p.

Abdulin, A.A., and Patalakh, E.I., 1980. Geodynamics of the Earth Crust of Kazakhstan. Alma-Ata, Nauka, 176 p.

Abdulin, A.A., and Shlygin, A.E., 1983. Metallogeny and Mineral Resources of Kazakhstan. Alma-Ata, Nauka, 312 p.

Abdulkabirova, M.A., 1975. Fault-Block Structure and Endogenic Mineral Deposits of North Kazakhstan. Alma-Ata, Nauka, 240 p.

Abdulkabirova, M.A., ed., 1988. Geology and Metallogeny of North Kazakhstan, v. 1-3. Alma-Ata, Nauka.

Aznabaev, E.K., 1978. Conditions of Formation of Oil and Gas Deposits of the Pricaspian Depression. Alma-Ata, Nauka, 188 p.

Bekmukhametov, A.E., 1987. Magmatogenic Iron-Ore Formations. Moscow, Nedra, 212 p.

Bespalov, V.F., ed., 1965. The Geologic Map of Kazakhstan. Scale 1:1,500,000.

Bespalov, V.F., 1971. Geological Structure of Kazakhstan. Alma-Ata, Nauka, 363 p.

Bok, I.I., ed., 1966. Geology and Metallogeny of Dzhungar Alatau. Alma-Ata, Nauka, 255 p.

Bok, I.I., ed., 1977. Geology and Metallogeny of Zhaman-Sarysu Mega-Anticlinorium. Alma-Ata, Nauka, 222 p.

Borukaev, R.A., and Shcherba, G.N., ed., 1967-1969. Geology and Metallogeny of the Uspenka Tectonic Zone, v. 1-6. Alma-Ata, Nauka.

Dzhumagaliev, T.N., ed., 1969. Geology and Oil and Gas Deposits of the Pricaspian Depression. Moscow, Nedra, 177 p.

Esenov, Sh.E., ed., 1967, 1971, 1972. Geology of the USSR Kazakhstan. Moscow, Nedra.

Esenov, Sh.E., 1972. Tectonics and Oil and Gas Deposits of Mugodzhary and Ustyurt. Moscow, Nedra, 240 p.

Esenov, Sh.E., 1972. Geology and Metallogeny of Northern Pre-Balkhash. Alma-Ata, Nauka, 268 p.

Esenov, Sh.E., Kunaev, D.S., and Mukhamedzhanov, S.M., 1968. Mineral Resources of Kazakhstan. Alma-Ata, Nauka, 550 p.

Gerasimov, I.P., 1969. Natural Conditions and Resources. Moscow, Nauka, 482 p.

Kayupov, A.K., ed., 1977-1983. Metallogeny of Kazakhstan. Alma-Ata, Nauka, 11 vols.

Kunaev, D.S., 1976. Metallogenic and Geochemical Zonation of the Territory of Kazakhstan. Alma-Ata, Nauka, 256 p.

Kurskeev, A.K., 1977. Geophysical Characteristics of the Earth's Crust in Kazakhstan. Alma-Ata, Nauka, 192 p.

Kushev, G.A., 1971. Coal Resources of Kazakhstan. Alma-Ata, Nauka, 57 p.

Laumulin, T.M., 1977. Rare-Metallogenic Structures in the Geotectonogens of Kazakhstan. Alma-Ata, Nauka, 200 p.

Muldagaliev, I.G., and Kozenkov, V.S., 1977. Occurrences of Mercury in Kazakhstan. Moscow, Nedra, 150 p.

Nekhoroshev, V.P., 1958. Geology of Altai. Moscow, Nedra, 262 p.

Nekhoroshev, V.P., 1966. Tectonics of Alta. Moscow, Nedra, 306 p.

Nurlybaev, A.N., ed., 1984. Geology and Mineral Deposits of the Turgai Region. Alma-Ata, Nauka, v. 1, 2, 232 p., 200 p.

Satpaev, K.I., ed., 1959. Metallogenic and Prognostic Maps. Alma-Ata, Nauka, 395 p.

Satpaev, K.I., ed., 1968. Selected Works, v. 3. Problems of the Metallogeny and Mineral Resources of Kazakhstan. Alma-Ata, Nauka, 313 p.

Shcherba, G.N., 1960. Formation of Rare-Metal Deposits of Central Kazakhstan. Alma-Ata, Nauka, 381 p.

Shcherba, G.N., ed., 1967. The Zharma-Saur Geotectonogens. Alma-Ata, Nauka, 200 p.

Shcherba, G.N., ed., 1968. Geology and Rare-Metal Mineralization of South Kazakhstan. Alma-Ata, Nauka, 226 p.

Shcherba, G.N., ed., 1979-1980. Geology and Metallogeny of the Chu-Ili Ore Belt, v. 1-6. Alma-Ata, Nauka.

Shcherba, G.N., ed., 1983. Metallogenic Provinces and Belts. Alma-Ata, Nauka, 240 p.

Shcherba, G.N., 1984. Metallogeny of Rudnyi Altai and Kalba. Alma-Ata, Nauka, 240 p.

Shcherba, G.N., ed., 1988. Rare-Metal Mineralization of Kazakhstan. Alma-Ata, Nauka, 218 p.

Shcherba, G.N., Laumulin, T.M., and Bolshakov, N.I., et al., 1968. Geology and Metallogeny of Northwestern Pre-Balkhashye. Alma-Ata, Nauka, 228 p.

Shlygin, E.D., and Shlygin, A.E., 1964. Some Principles of Tectonic Zonation of Kazakhstan, in Folded Areas of Eurasia. Moscow, Nauka, 376 p.

Zholtaev, G.Zh., and Bulekbaev, Z.E., 1975. Tectonics and Oil and Gas Deposits of the Flanks of the Pricaspian Syneclise. Alma-Ata, Kazakhstan, 202 p.

Stratiform Mineralization in Kazakhstan

L.A. Miroshnichenko and N.M. Mitryaeva

Abstract

Stratiform mineralization is found at many Phanerozoic horizons, particularly in beds of Lower Cambrian, Middle and Upper Devonian (Eifelian and Famennian), and Carboniferous beds. Kazakhstan contains some of the largest-known deposits of copper, lead, zinc, barium, strontium, phosphorus, vanadium, iron, and manganese. There also are important vanadium, yttrium, and molybdenum deposits.

The mineralizations are associated with four tectonic regimes — rift, geosyncline, platform, and tectonomagmatic (continental rift) — with mineral composition related to the tectonic regime. These asssociations may prove valuable in attempting to locate new deposits. Stratiform ore deposits also may be characterized by rhythmic distribution and zonation in the Atasu and Rudnyi Altai regions.

The analysis of the origin and distribution of deposits contributes to an objective assessment of economic mineral potential, which in Kazakhstan favors the discovery of moderate-sized copper-pyrite, copper-zinc, and polymetallic ores rich in gold and silver.

Introduction

The term "stratiform" emphasizes the subordination of ore accumulation to the stratification of volcanogenic-sedimentary rocks. The term has been applied to a number of deposits that are not temporally related to ore-enclosing geological formations, and this has resulted in some uncertainty as to how to classify stratiform deposits. In Kazakhstan, such deposits are considered to include ores that originated in the sedimentary or volcanogenic-sedimentary geological formations that they are spatially associated with and thus to have a temporal connection as well. The term "stratiform mineralization" would otherwise be meaningless. Thus, ore mineralization that postdates the formation of ore-bearing strata but is confined to the strata because of sedimentary structure, lithology, or some other factor is not considered stratiform.

Kazakhstan is one of the largest known provinces of stratiform ore deposits of copper, lead, zinc, barium, strontium, phosphorus, vanadium, iron, and manganese. The deposits have been studied for many years, and vast amounts of information have been assembled on different aspects of their formation and distribution. Recent studies have added tungsten, fluorite, and gold to the list of stratiform ore minerals.

Stratigraphy

Stratiform ore is found in polychronic, multistage deposits. Sedimentary and epigenetic ore facies are distinguished by features related to their formative processes. Sedimentary ores are bodies of stratified rock and are an integral part of the ore-bearing formation, equivalent to other components. Their formation is subject to the laws of sedimentation. Epigenetic ores, on the other hand, are produced by metasomatic processes (magmatogenic, metamorphogenic, etc.) that control the pathways of ore-bearing solutions. These ores may be in sheet-like deposits concordant with bedding, as well as in bodies that transect bedding. Karst cavity ores are also epigenetic.

The major ore elements in economically important deposits are Cu, Pb, Zn, Ba, P, V, Fe, Mn, F, W; associated with these are Mo, Au, Ag, Tr, Sr, Cd, Re, Ge, W, Co, Mn, Ti, Se, Te, Ta, Pt, In, Sb, As, Ag. Concentrations of associated elements are distributed as follows: Mo, Ti, in sedimentogenic vanadium ore; Au, Se, Te, Ti, In, Hg, in epigenetic lead-zinc and pyrite-polymetallic ores; Ag, Re, in rhenium lead-zinc-copper (cupriferous sandstone) ores. The distribution of economically important ore deposits is as follows: sedimentary, P, V, Fe, Mn, Cu, Pb, Zn, Ba, F; and epigenetic, Cu, Pb, Ba, F, Zn. The largest concentrations of Cu, Pb, Zn, Ba, Fe, Mn, F and associated elements (Hg, As, Sb, Ag, Au, Re, Sc, Te, Ti, Ge, In) are in upper Paleozoic rocks (Zhezkazgan, Atasu, Karatau, and Atasu horizons). High concentrations of V and P (Chulaktau-Kurumsak horizon) and Ba, Pb, and Zn (Karatas-Tekeli horizons) are confined to lower Paleozoic rocks (Cambrian and Ordovician).

Stratiform mineralization is found at many Phanerozoic stratigraphic levels (Fig. 1), but deposits in four Paleozoic horizons are particularly rich: Lower Cambrian, Middle Devonian (Eifelian), Upper Devonian (Famennian), and Carboniferous. The largest deposits of vanadium (Balasaus-kandyk, Zhebagly) in Bolshoi Karatau and phosphorus (Zhanatas, Chulaktau) in Malyi Karatau are in Lower Cambrian strata. Vanadium ores are rich in yttrium, molybdenum, and silver, and phosphorus deposits in argillaceous-siliceous shales are rich in platinum (up to 80%). The Devonian is characterized by a high degree of saturation of ores of the stratiform type. Two horizons are distinguished in the Devonian: Eifelian and Famennian (Lee, Mitryaeva, Pokrovskava, 1979; Kayupov, 1978, 1982). The bulk of pyrite-zinc-copper (Mugodzhary) and pyrite-gold-silver-lead-zinc (Rudnyi Altai, pre-Chinghiz) mineralization took place during Eifelian time. In terms of the degree of saturation and economic value of these deposits, the Eifelian stage is the "pyrite epoch" in Kazakhstan.

The Famennian horizon is distinguished by rich deposits of zinc, lead, barium, manganese, and iron in carbonate and carbonaceous-siliceous-carbonate rocks (Atasu, Karatau). Five-element paragenetic associations of this sort are a recurrent feature of certain geochronological horizons in Kazakhstan (Miroshnichenko, Mitryaeva, Pokrovskaya, 1979; Kayupov, 1978, 1982).

The next epoch of stratiform ore formation, the Carboniferous, is characterized by high-grade copper deposits in sandstones (Zhezkazgan) (Fig. 2). Economically important concentrations of lead, zinc, silver, and rhenium are a distinctive feature of these cupriferous sandstone ores (Satpaeva, 1985).

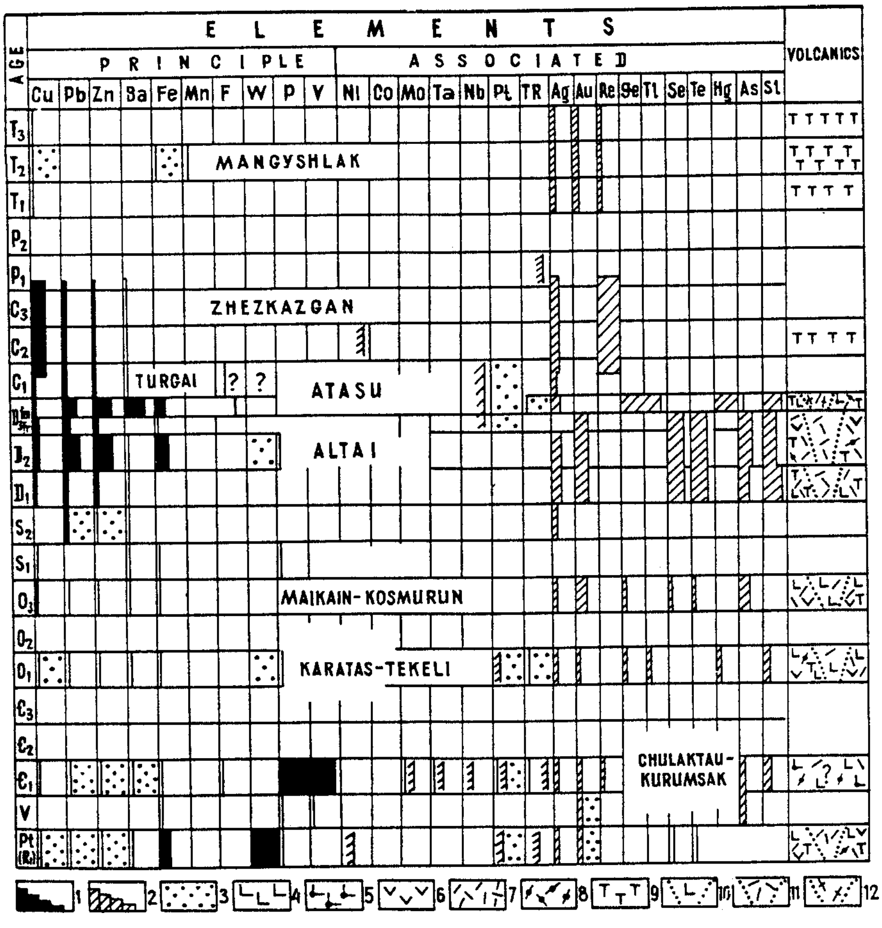


Fig. 1. Levels of stratiform mineralization in Kazakhstan. 1-2- the relative degree of element accumulation: 1- basic, 2- secondary; 3- element accumulation on new levels; 4-9 volcanics: 4- basalts, 5- trachybasalts, 6- andesites, 7- rhyolites, 8- trachyrhyolites, 9- tuffs; 10-12- subvolcanic rocks: 10- basalts, 11- rhyolites, 12- syenites and monzonites.

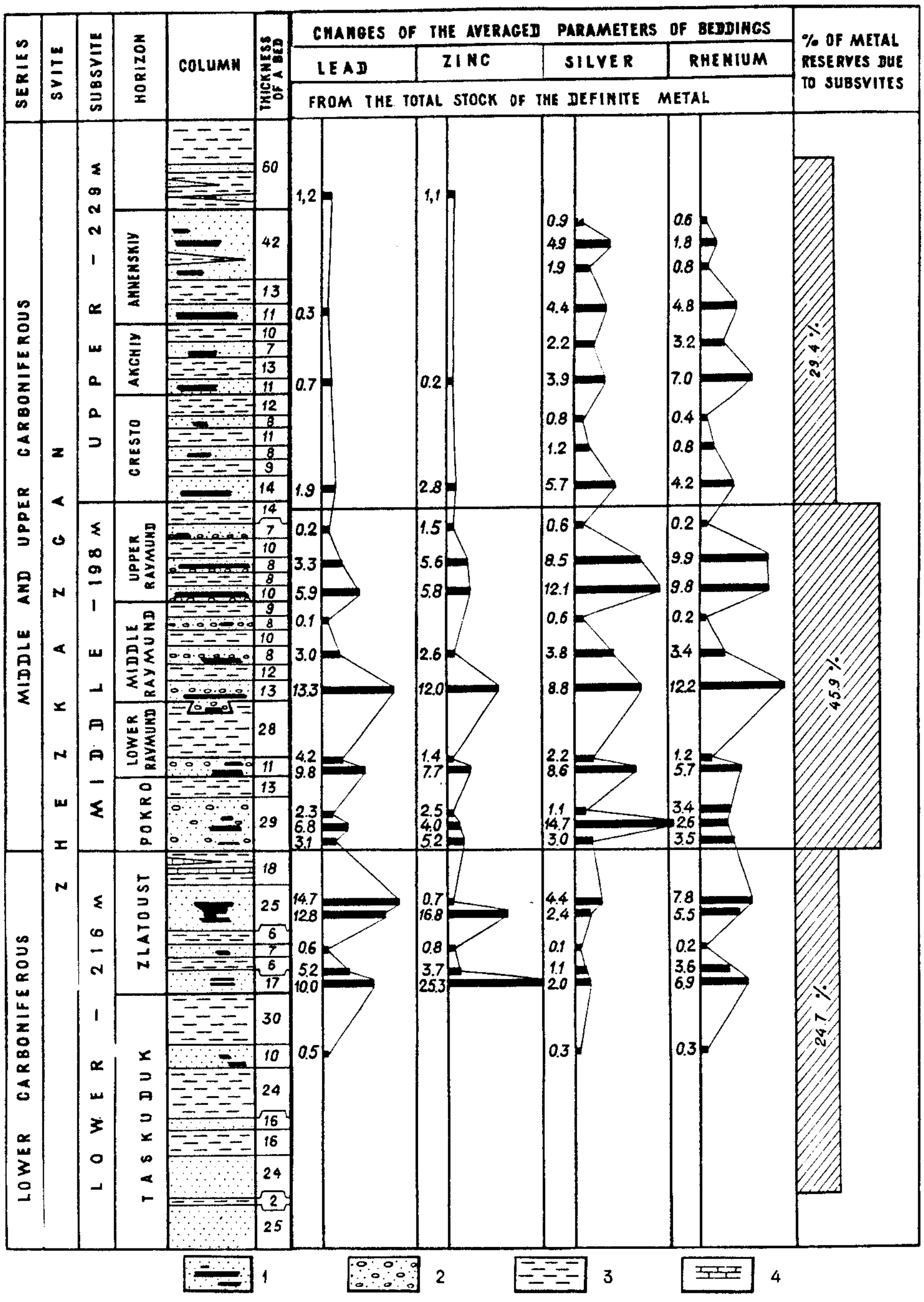


Fig. 2. Schematic stratigraphic column of the Zhezkazgan formation in the central ore field (after K.I. Satpaev et al., revised by L.V. Kopyatkevich, 1985). 1- grey sandstones; 2- Raymond conglomerates; 3- red mudstones, siltstones, and fine-grained sandstones; 4- siliceous layers; 5- alteration curves of ore- (dotted line) and metal-bearing (continuous line) layers of grey sandstones; mean copper contents of ore deposits.

Amongst the youngest Paleozoic rocks, thin (5-25 cm) beds of limestone in Permian mudstones of the Teniz basin are of considerable interest because of their high silver contents (tens and hundreds of grams per tonne). The beds can be traced with breaks for some tens of kilometers and are characterized by "silver monometallicity." Economically important metamorphic scheelite ores accompanied by ancient tungsten deposits have been found only in Precambrian rocks. These horizons also contain polymetallic ores rich in rare earths, lead-zinc deposits in carbonaceous-carbonate rocks, and gold in carbonaceous terrigenous rocks. Precambrian stratiform mineralization in Kazakhstan has not received enough attention and should thus be targeted for future study.

Tectonic Regimes

Stratiform mineralization is a feature of four tectonic regimes: rift (pre-geosyncline), geosyncline, platform, and tectono-magmatic (continental rift) activity. In Devonian rocks, moderate-size pyrite-zinc-copper deposits and small manganese ore deposits rich in tungsten and phosphorus (Mugodzhary) are related to ophiolite sodic-rhyolite-sodic-basalt-basaltic magmatism in rift zones (pre-geosyncline). Large deposits of vanadium and phosphorus ore (Chulaktau-Kurumsak type) are distinguished in zones with epigenetic basaltoid magmatism and high-grade siliceous and carbonate rocks in the Lower Cambrian. A quite different ore composition is characteristic of the geosynclinal regime of stratiform deposits. Two groups of ore-bearing tectonic zones are typical of this regime of island arc and marginal volcanic belts. In the island-arc group, pyrite gold-silver-lead-zinc mineralization is most pronounced in zones with Devonian basalt-rhyolite (quartz-keratophyric) magmatism. Pyrite-type deposits of this group are widely developed in Rudnyi Altai (Altai type), where they constitute the largest reserves of copper, lead, zinc, gold, silver and a whole series of accompanying elements (selenium, tellurium, indium, bismuth, etc.) in commercial concentrations. Another group of zones (marginal volcanic belts) differs from the preceding one by consisting chiefly of copper and pyrite ore, often with considerable concentrations of gold and silver. These developed in zones of basalt-andesitic volcanites, with a small percentage of acid differentiates (Spassk and pre-Chinghiz zones). The largest deposits of cupriferous sandstones of the Zhezkazgan type were formed during the next platform regime, in the Carboniferous. Lead, zinc, silver, and rhenium reach economic concentrations in paragenetic sequences with copper.

Large-scale stratiform deposits of ores of five elements (zinc, lead, barium, iron, and manganese of the Atasu and Karatas-Tekeli types) are associated with intracontinental rifting or tectono-magmatic activity (postorogenic rifting) in fold belts. Lead-zinc ores of this type are rich in silver, thallium, and mercury, and the iron ores in germanium. All economically valuable deposits of this type are associated with Famennian carbonaceous-carbonate sediments (Zhairem, Karazhal, Ushkatyn, Mirgalimsai, Shalkiya) (Fig. 3).

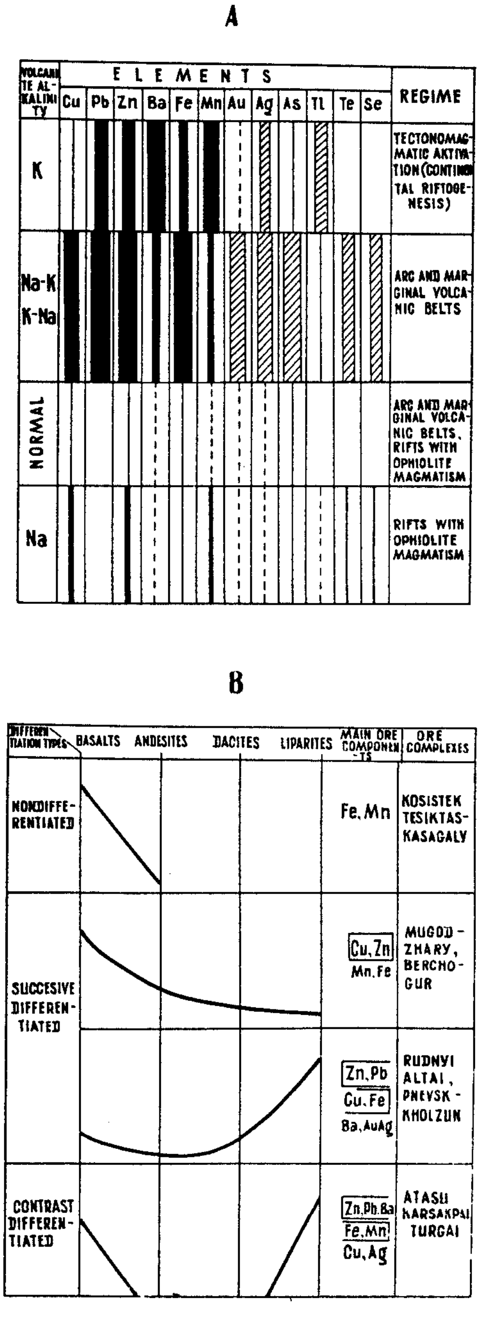


Fig. 3. Composition of stratiform mineralization according to type of tectonic regime and volcanic alkalinity (A), and volcanic differentiates (B).

Two distinctive features in the composition of ore mineralization emerge from comparison of stratiform ore deposits of different tectonic regimes: 1) a femic profile of mineralization in structures of all tectonic regimes and the restriction of most deposits to the flanks of riftogenic structures (Fig. 4), and 2) a qualitative differentiation in the composition of mineralization depending on the tectonic regime. Lead mineralization is not associated with rift structures nor with ophiolitic magmatism. Copper pyrite and zinc-copper deposits are of only moderate size. Differences in composition and scale of mineralization are typical of structures developed in continental crust, where high-grade ore deposits of zinc, lead, copper, barium, manganese, and iron are found. Included among these are the pyrite deposits of Rudnyi Altai (rich in gold and silver) and five-element (lead, zinc, barium, manganese, iron) ores of the Atasu type.

Mineralogenic specificity of "continental" structures consists in the absence of vanadium and phosphorus mineralization.

Further investigations directed towards the paleotectonic analysis of different horizons will help to elucidate the paleometallogeny of stratiform mineralization and provide opportunities for regional study and for assessing the prospective quality and quantity of ores, thereby enriching our understanding of the history of stratiform ores.

Economically important stratiform ores have been studied mainly in tectonically faulted successions, especially at the intersection of deep fractures or where conjugate faults cut anticlinal structures. Hydrothermal-sedimentary and metasomatic ores are confined to the first setting, and metasomatic ores of magmatic and metamorphic origin are confined to the second. In rift structures, for example, evidence of hydrothermal-sedimentary mineralization is found scattered for up to 10 km along the axis of a rift, but ore deposits of sedimentary and epigenetic origin are found only in the conjugate fractures that intersect the axis.

Recent studies of mineralization processes in the Red Sea rift have shown a connection between ore-bearing troughs and the places where northwest- and northeast-trending faults intersect. In the Midcontinent of North America, an old mining region, many ore deposits, including those of the stratiform type, are associated with rift structures (Ramberg and Morgan, 1984). Likewise, ore deposits are also clustered along rifts in the French Alps, Atlantic sea floor, Galapagos, and many other rift structures.

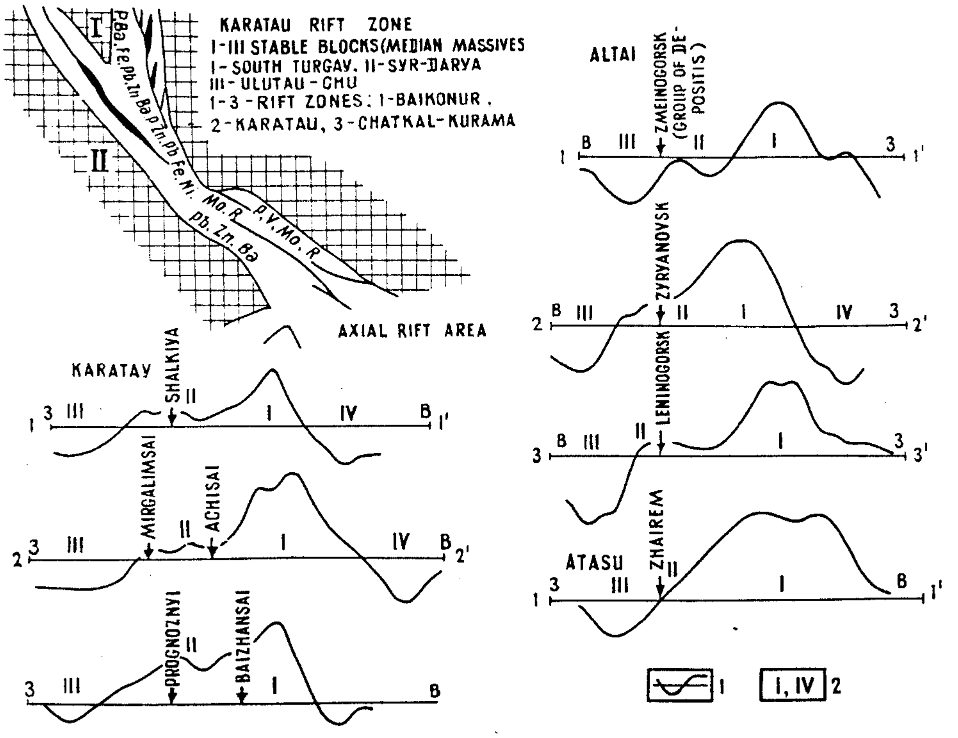


Fig. 4. Distribution of Fe mineral forms in deposits of various types.

We believe that the structural knots that form at the intersection of tectonic zones provide an explanation for the clustering of deposits with basic features common to different tectonic regimes. These knots are considered to have localized the vigorous circulation of different solutions and, thereby, the accumulation of ore deposits, with the ensuing extraction, redeposition, and sedimentation of ore matter. The fact that ore fields are confined to the intersection of tectonic zones helps in analysis of the lithostratigraphic, geochemical, and other criteria which may be used to locate new ore concentrations, including ones buried under Mesozoic-Cenozoic sedimentary cover.

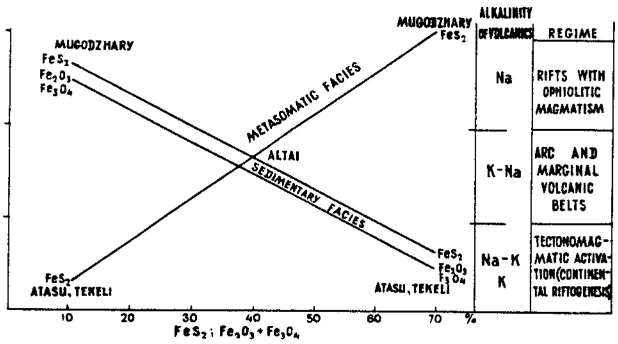


Fig. 5. Distribution of lead-zinc deposits in Kazakhstan according to gravimetric data (after V.N. Lyubetskii). 1- projections on the lines of gravity profiles of stratiform lead-zinc (Karatau, Atasu) and pyrite-polymetallic (Altai) deposits; 2- types of gravity anomalies.

Classification of Ore Deposits

A new system of classifying ore deposits has been worked out at the K.I. Satpaev Institute of Geological Sciences, based on the principle that a metallogenic formation or ore complex comprises both geological units and ore deposits (Kayupov, 1978, 1982). An ore complex consists of a number of mineral types, reflecting variations in composition of sedimentogenic and epigenetic facies. A system that establishes connections between geological units and ore deposits excludes from analysis the large variety of other types of systematized ore classification. This analysis of ore deposits is especially useful for stratiform mineralization. Two groups are distinguished among ore-bearing geological units: sedimentary and volcanogenic. The sedimentary group comprises carbonate and terrigenous subgroups. Carbonaceous-siliceous-argillaceous-carbonate formations are the ore-bearing units of the carbonate subgroup. Large deposits of lead, zinc, barium, manganese, and iron (Atasu type) are associated with tectono-magmatic activity in rift regimes, where mineralization is confined to carbonaceous carbonate-siliceous rhythmites and dolomite lithologies. The terrigenous subgroup, represented by platform red-beds, comprises two subformations: mottled beds and red beds. Sandstones of the Zhezkazgan type (the indicator element is rhenium) rich in copper, lead, zinc, and rhenium belong to the mottled subunit, and sandstones of the Tyulkubash type with rare deposits of manganese ore (Zhezdy) poor in copper belong to the red subunit.

The volcanic group unites three subgroups of ore-bearing formations. Volcanics become more potassic from riftogenic structures with ophiolitic magmatism to continental rift structures, with the ore content varying from zinc-copper through polymetallic to lead-zinc, barium and iron-manganese. Thus, pyrite-zinc-copper mineralization is associated with structures in which rhyolite-andesite-basalt is the predominant rock type (Mugodzhary ore complex). Basalt-rhyolite units with an irregular alkaline ratio are accompanied by pyrite-gold-silver-copper-lead-zinc mineralization in island-arc structures (Rudnyi Altai, Kosmurun and other complexes). With an increase in potassium and in the presence of basalt-rhyolite units, mineralization tends to be characterized by lead-phosphorus-iron ore deposits (Pnevsko-Kholzun ore complex). Potassic volcanogenic formations mainly of trachyrhyolite composition are characteristic of structures with tectono-magmatic activity. In contrast to the mineralization of volcanogenic formations of the preceding structures, barium-lead-zinc, manganese and iron mineralization is widespread here (Atasu ore complex). Potassic volcanogenic formations are intensively mineralized only in association with essentially carbonate rocks. A relatively high organic content and a high silica content are characteristic of sedimentogenic ore facies in these formations.

Analysis of volcanogenic formations of different types reveals the following characteristics in composition and in scale of associated mineralization: 1) small deposits of iron, manganese (often with tungsten), and copper are associated with non-differentiated basaltic and andesite-basaltic formations (especially in orthostructures); 2) differentiated volcanogenic formations are subdivided into two groups based on composition and ore-mineralization — formations in which basalts predominate and mineralization is essentially copper-zinc, and formations in which rhyolites predominate over basalts, ores become copper-lead-zinc, and concentrations of phosphorus-iron ores are observed; 3) stratiform mineralization in contrast-differentiated volcanogenic formations is notable for the wide spectrum of ore components. Large deposits of lead-zinc, barium-iron, and manganese ores are associated with these formations.

A succession of mineral forms of iron depending on facies characteristics, volcanic alkalinity, and structure types has been established (Fig. 5). In metasomatic facies,

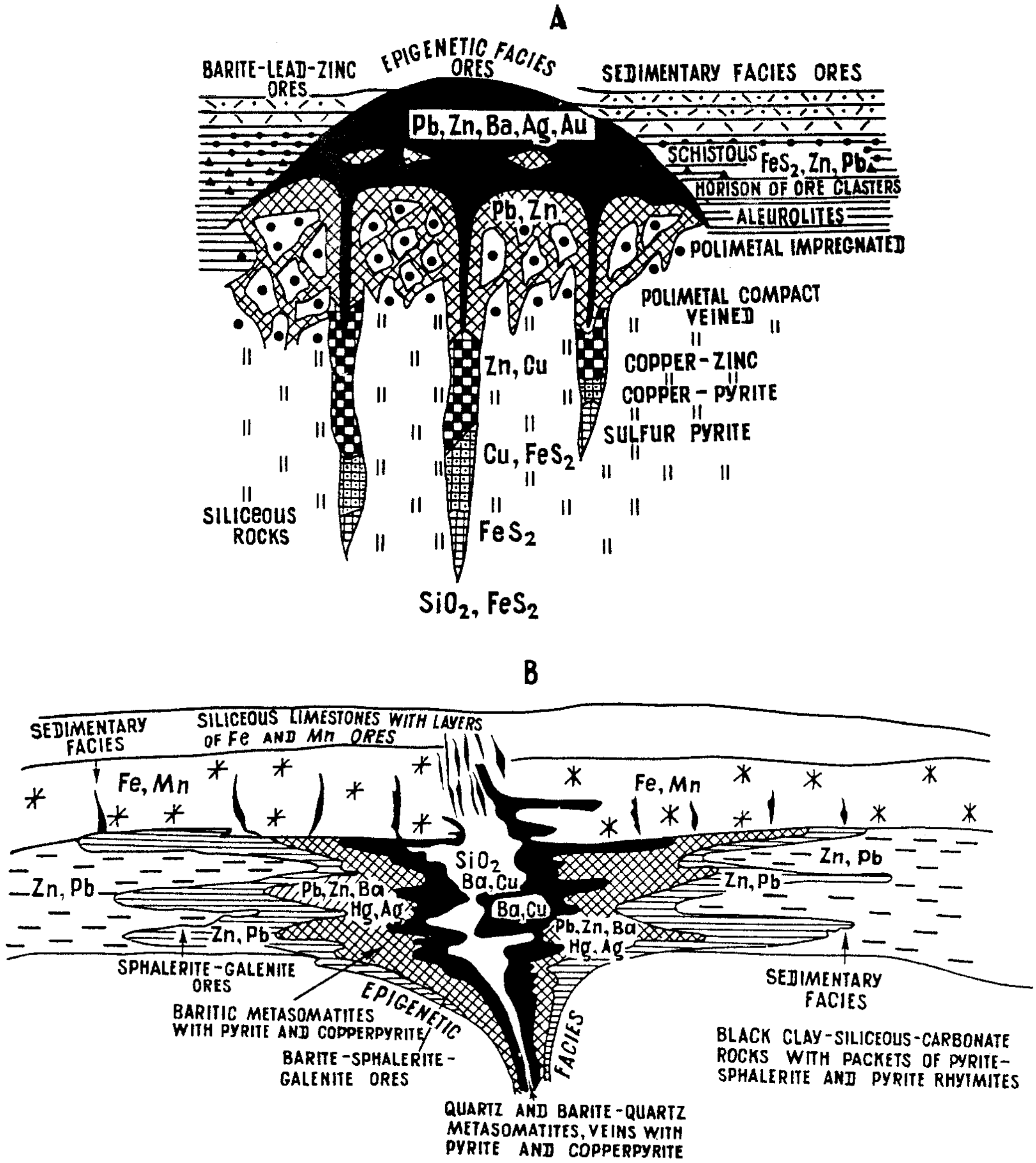


Fig. 6. Types of zonation in stratiform mineralization. A- Rudnyi Altai, B- Atasu.

the quantity of sulfide ore increases as potassium decreases and sodium increases. The maximum pyrite content occurs in deposits associated with sodic volcanics in ophiolitic formations (Mugodzhary ore complex). A somewhat different picture is seen in sedimentary facies, where the pyrite content increases with the decrease in sodium, and is highest in potassic volcanogenic formations (Atasu ore complex). Ferrous-ferric oxide minerals are distributed in much the same way as pyrite in sedimentogenic facies. The highest concentrations of these minerals (basically hematite) are also associated with potassic volcanics (Atasu, Pnevsko-Kholzun ore complexes).

Rhythmic Distribution and Zonation

Stratiform ore deposits are characterized by rhythmic distribution and zonation at scales ranging from the megascopic to the microscopic. In the ore-bearing basalt-rhyolite rocks of Rudnyi Altai, the rhythmic distribution of ores that vary in composition depending on horizon is regulated by the alkalinity of the host rocks. Barite-polymetallic ores are associated with more potassic volcanics lower in the section; volcanics of intermediate horizons with approximately equal potassium and sodium contents host massive sulfide-polymetallic mineralization. Both polymetallic sulfide and copper-zinc sulfide deposits are associated with basic andesitic-dacitic volcanics of upper horizons. The role of potassium diminishes and that of sodium increases from lower to upper horizons as the basicity of volcanics and their acidic differentiates increases. The copper, zinc, and pyrite content of the ores show a steady increase.

In Famennan-Tournaisian sediments of the Atasu region, rhythmic distribution takes the form of alternation of flysch-like horizons with pyritic and pyrite-sphaleritic ore (Lower element) and nodular-bedded siliceous limestones with iron and manganese ores (Upper element). Five rhythms can be distinguished in ores of the Atasu region. Rhythmic distribution in other deposits is less clearly defined (Southern Dzhungaria, Akzhal-Aksoran zone, Bolshoi Karatau).

Two types of zonation have been established in polymetallic stratiform deposits: the Rudnyi Altai type, and the Atasu-Mirgalimsai (Fig. 6). The Rudnyi Altai type is peculiar to volcanogenic pyrite-polymetallic deposits of epigenetic facies. From the bottom to the top of the deposit, zoning is represented by a successive change from pyritic ores to chalcopyritic, copper-zinc, polymetallic, and barite-polymetallic ores. Veined bodies of the roof of the deposit alternate with streaky ores of the stockwork type passing upward into lenticular-stratified massive ore bodies. Bedded ores with alternating horizons of ore-clasts occur in the roof of the deposit and along the flanks. The Atasu-Mirgalimsai type is restricted to ore-bearing carbonates. Concentric zonation is observed in which a quartz nucleus is sequentially surrounded by zones of quartz-barite, barite-sphalerite-galena, and sphalerite-pyrite.

Metamorphism

Stratiform primary mineralization has been affected by dynamometamorphic and thermal metamorphic processes. Dynamometamorphism caused by folding in zones of compression and fracturing of suture structures has produced changes in the form of ore bodies and in the textures and structures of ores. Schistosity, plication, striations, boudinage, recrystallization, and indications of plastic flow where minerals were forced into the curves of microfolds can all be observed. The role of processes connected with dynamometamorphism, the redeposition of ore matter, and formation of ore deposits is especially great, as for example, in the case of roscoelite stockworks formed in zones of intensive compression and fracturing by remobilization of vanadium in carbonaceous-siliceous rocks (Balasauskandyk, Kurumsak deposits, etc.). High concentrations of lead-zinc ores (Tekeli, Usek deposits), numerous baritic, calcite-galena-sphalerite, quartz-hematitic veins, and veinlets inheriting the composition of primary mineralization are associated with this type of metamorphism.

Thermal metamorphism has rearranged ore matter within the thermal fields of magmatic bodies, along with forming new mainly veined and nested, aggregated barite, lead-zinc, magnetite, and fluorite deposits (Zhundy, Kaskaigyr, Kurgasyn deposits, etc.). New high-temperature ore minerals such as mangan-hedenbergite, bustamite, wollastonite, quartz-magnetite, and garnet-magnetite are also observed.

Galena veins are attributed to regenerated plutonometamorphism in the Zavodinsk 1 lead-zinc and Parygin deposits (Altai) and in the scheelite deposits of Bayan (North Kazakhstan).

Genesis

The origin of most stratiform deposits is still open to debate. Results of current research confirm Smirnov's conclusions on the polygenetic character of stratiform ores, both sedimentogenic and epigenetic ores. According to geological and analytical data, two groups of deposits with different sources of ore material are distinguished. In zones where the products of volcanism are displayed, the composition of ores and the ratio of ore components correlate with type of structures, composition, degree of differentiation, and alkalinity of volcanic rocks, and ore deposits are distinctly zoned. There, the age of lead-isotope-bearing ores is close to the age of the volcanic rocks, according to L.I. Shilov, 1971, but older according to N.G. Syromyatnikov, 1979. The sulfur component has a crustal origin. Ores of both sedimentogenic and epigenetic facies are associated with volcanism (Rudnyi Altai, Mugodzhary, Atasu, Altai ore complexes, etc.). The second group unites ore-bearing formation zones developed mainly in magmatic rift structures. In these essentially carbonate formations, the lead-isotope age of sedimentogenic and epigenetic ore facies is greater than the age of the enclosing rocks (Karatau, Karatas-Tekeli ore complexes). Mineralization here is related to remobilization of ore components from older stratigraphic levels (Karatau ore complex).

Some consider stratiform copper, rhenium, lead, and zinc ore deposits to be epigenetic and to have formed as a result of removal of other minerals, whereas others associate the primary deposition with sedimentation. Ensuing redistribution of copper and metamorphogenic ore deposition are quite possible.

Ore deposits in the essentially terrigenous formation of the Mangyshlak Karatau, where cupriferous sandstones occur at different stratigraphic levels of the Triassic, are noteworthy. Copper mineralization is confined to siliceous aleurolites rich in iron, nickel, zinc and gold in the lower part of the formation. Horizons of rhyolitic tuff and dolomite are encountered in the upper part. Sedimentary iron-manganese mineralization in tuff horizons and sideritic iron in sandstones with jasper seams have been identified in this part of the section, along with the cupriferous sandstones. Lead, zinc, barium, arsenic, and gold occur with the copper in these ores. It is difficult to explain mineralization of this type in terms of common sedimentary processes (weathering and erosion).

Prospects

The analysis of the origin and distribution of deposits of different types of minerals contributes to an objective assessment in the search for economic stratiform mineralization. There are many prospects for distinguishing stratiform ores of a particular composition in particular tectonic structures in which a series of stratigraphic levels in geological formations are potential stratiform deposits distinguished in these structures. The principal potential is for moderate-size deposits of pyrite-copper and copper-zinc ore (Mugodzhary type) in rifts with ophiolitic magmatism; large deposits of pyrite-polymetallic ores rich in gold and silver (Altai type) in island arc structures with unimodal basalt-rhyolitic volcanism; unique accumulations of copper in sandstones (Znezkazgan type) in mottled platform formations; large-scale deposits of five-element paragenesis of lead, zinc, barium, iron, manganese (Atasu type) in continental rifts. Along with the prospects for finding new deposits, the mineralized strato-levels are very important from a genetic point of view. The list of lead, zinc, copper, tungsten, etc. deposits that owe their origin to processes connected with dynamometamorphism and regeneration of intrusive rocks continues to grow.

Prospects of stratiform mineralization in Kazakhstan are far from limited, and the process of study and prospecting for such promising types of deposits has only begun.

References

Abdulin, A.A., 1985. On stratiform mineralization in Kazakhstan and main ways in further studying. Izvestiya Akademii Nauk KazSSR, ser. geol., no. 5, p. 3-8.

Abdulin, A.A., ed., 1987. Geology and Metallogeny of Karatau; v. 2. Alma-Ata, Nauka, 246 p.

Lee, V.G., Mitryaeva, N.M., and Pokrovskaya, I.V., 1979. Stratiform polymetallic and lead-zinc deposits in Kazakhstan, in: Yanshin A.L., ed., Metallogeny and ore formation. Alma-Ata, Nauka, p. 81-94.

Kayupov, A.K., ed., 1978. Metallogeny of Kazakhstan ore formations. Lead and zinc ore deposits. Alma-Ata, Nauka, 266 p.

Kayupov, A.K., ed., 1982. Metallogeny of Kazakhstan ore formations. Iron and manganese ore deposits. Alma-Ata, Nauka, 206 p.

Miroshnichenko, L.A., Mitryaeva, N.M., Pokrovskaya, I.V., and Patalakha, G.B., 1985. Stratiform mineralization in Kazakhstan, in: Smirnov, B.I., ed., Basic regularities in distribution of commercial minerals, X1Y. Metallogeny of Uralo-Mongol Belt. Moscow, Nauka, p. 57-68.

Ramberg, I.B., and Morgan, P., 1984. Physical character and orientations of continental rift evolution. 27th Internat. Geol. Congr. Tectonics. Section C.07. Reports, v. 7, Moscow, August 4-14, 1984, 12. ***(Page 12 or 12 pages????)***

Satpaeva, M.K., 1985. Zhezkazgan ores and modes of their origin. Alma-Ata, Nauka, 208 p.

Shilov, L.I., 1971. Isotopic lead composition of Ridder-Sokolnoe and Tishinka deposits (Rudnyi Altai). Geochemistry, No. 1.

Smirnov, V.I., 1982. Geology of mineral resources. Moscow, Nedra, 422 p.

Syromyatnikov, N.G., 1979. The epochs of origin of lead ore concentrations in polymetallic deposits in Kazakhstan according to isotopic data. Izvest. Akad. Nauk KazSSR, ser. geol., no. 2, p. 4-18.

Atasu-type Ore Deposits in Central Kazakhstan

G.N. Shcherba and N.M. Mitryaeva

Abstract

The deposits described as of Atasu type were first distinguished by the senior author in 1962. They are named after a locality in Central Kazakhstan and have the following characteristics:

1. There are stratiform sulfide ores of zinc and lead and oxide ores of iron and manganese which formed within continental rifts during a single mineralic process linked with Early Hercynian (Famennian - Tournaisian) orogenesis. The process was completed by hydrothermal metasomites and baryte veins with chalcopyrite all within a single ore-field.
2. Ores of different composition form separate layers which alternate with, and are enclosed within, an argillaceous-siliceous-carbonate sequence. The latter have a chemical-volcanic character of a relatively marine basin with a changing sulfide to oxidation condition.
3. Hydrothermal (volcanogenic) sedimentary ore deposits later were remobilized as hydrothermal-metasomatic deposits with vein and cavity filling with an increasing Ba, Pb, Cu content.

The mineralization can be regarded as polymetallic as radially distributed (linear) or concentric around a focal area (a volcanic center or a hydrothermal ocean floor vent). Different groups of ore bodies may be separated in space, but the zonation permits some definition of zones of ore concentration.

At the time such Atasu-type mineralization was defined, there appeared to be no analogues in the literature, and the separate phases were apparently considered to be independent deposits.

Introduction

Deposits and ores of the Atasu type (AT) are lenticular and bedded accumulations of submarine stratiform oxides of iron-manganese and barite-lead-zinc sulfide ores that alternate with and are enclosed by stratigraphic units comprised of argillaceous-siliceous-carbonaceous rock. Iron-manganese and barite-zinc ores may occur together or separately. They are located within a single chronostratigraphic section. The name "Atasu" was first applied to these deposits in 1962, during studies of the metallogeny of the Uspenka sublatitudinal ore belt in Central Kazakhstan (Borukaev and Shcherba, 1967-69; Mitryaeva et al., 1962; Shcherba, 1967). The deposits are situated on the western flank of the belt, with the main ore accumulations concentrated in the Zhailma graben-syncline, a western extension of the Uspenka graben. The first reports on the iron ores date to 1911. Later geological investigations, carried out in three periods (1911-1927, 1930-1950, and 1960-1990), resulted in discovery of hundreds of ore-bodies and uncovered large resources of Zn, Pb, Ba, Mn, and Fe.

Regional geological investigations were carried out at different times under the guidance of I.S. Yagovkin, N.G. Kassin, and D.G. Sapozhnikov (metallogenic); K.I. Satpaev and G.N. Shcherba (regional investigation); I.V. Dugaev, V.I. Kavun, and A.A. Rozhnov (prospecting); N.L. Kheruvimova, M.M. Kayupova, and N.M. Mitryaeva (mineralogical); M.D. Morozov, A.V. Stroiteleva, and D.N. Kazanly (geophysical), and many others whose names appear in the numerous publications, particularly monographs, of the last three decades (e.g., Borukaev and Shcherba, 1967-69; Kayupova, 1974; Mitryaeva, 1979; Shcherba, 1964).

The Zhailma graben-syncline has a well-defined outline in which the conjunction of four major structural elements is apparent (Fig. 1). Two of these are sublatitudinal (eastern and central) and 45-30 km long, and two trend northwest, with lengths of 40 and 50 km. The total length of the graben-syncline is 130 km, the width from 10 to 30 km. Small synclinal troughs with submeridional and northwestern trends (Fig. 1) branch off the main structure.

The Zhailma is troughlike in cross section, lying within a Caledonian complex block. It is more than 2 km deep, bordered by steep faults, and filled with Famennian-Tournaisian sediments. At the base and along the margins are consolidated lower Paleozoic volcanogenic-sedimentary rocks, overlain by dacite-rhyolite volcanics of Frasnian and upper Caledonian red molasse.

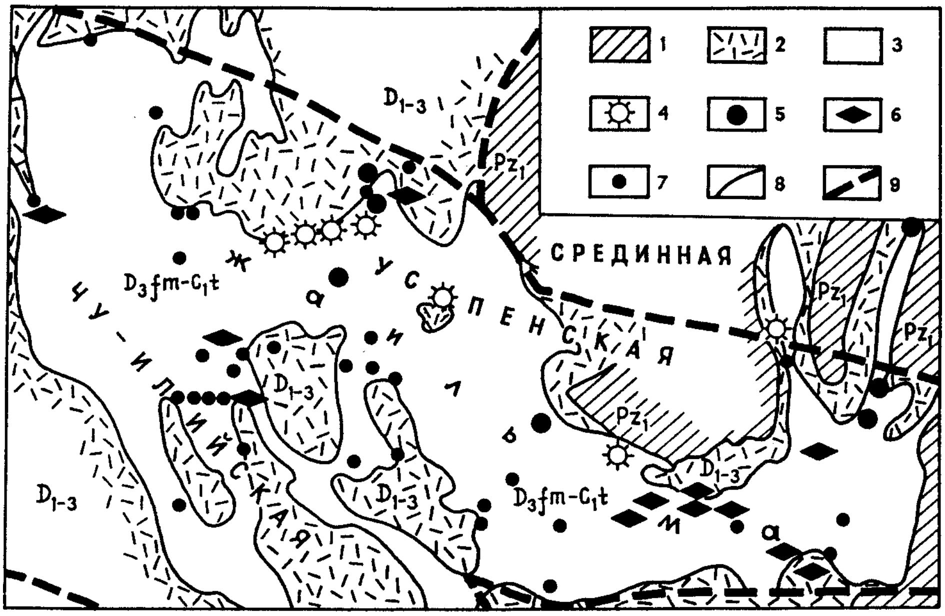


Fig. 1. Geologic sketch of the graben-syncline of Zhailma. 1- volcano-terrigenous strata, P_z; 2- volcanics D_{1-3}; 3- marine volcano-terrigenous-carbonaceous formation, D_3 fm-C_1t; 4- established Famennian volcanic centers; 5-6- Atasu-type deposits; 5- iron-manganese-lead-zinc; 6- iron-manganese; 7- ore manifestations; 8- outline of the graben; 9- boundaries of deep mobile zones.

Paleotectonic Conditions

Irregularities in the outline of the Zhailma graben and its extensions are explicable in terms of its origin as a rift. The graben was formed at a triple junction where deep mobile zones — the sublatitudinal Uspenka and northwestern Chuili — intersect the ancient submeridional Median Zone. During Early Hercynian extensional movements, parallel rifts which subsided to different depths formed in the continental crust. Along deeper, nearside faults, basaltic volcanics, small gabbroic intrusions (within meridional branches of the graben), and deposits of Atasu-type ore were emplaced.

Geophysical data reveal that the earth's crust in this region is at least 42.5-45 km thick and reaches 47-52 km where a layer of metabasalt has been uplifted under Zhailma and the overlying succession records a rise in femic composition. At the basement of the Phanerozoic is an amphibolite-gneiss layer, whereas in the surrounding block granite-gneiss marks the basement. This difference reflects the influence of the Proterozoic Kunek-Karazhal polyrift greenstone zone, an element of the Median geotectonogene, which passes through the basement.

Synchronization of destructive tectonic movements of crustal blocks, a regime of relative tension during the Famennian-Tournaisian, and numerous faults that dissect the continental core into blocks may be attributed to radial spreading, accompanied by basaltic diapirism, expansion of the sides of the main and parallel rifts, and core sinking, with subsidence of the graben. The continental regime of the Frasnian was replaced by a shallow sea in the early Hercynian of the Famennian-Tournaisian which spread across large parts of Central Kazakhstan and in which were deposited shallow-coastal facies sediments.

Later, beginning in the Middle Carboniferous, general uplift occurred, and the marine regime gradually reverted to continental. The rift system was shortened, with the change from tensional to compressional conditions, and complexly folded linear brachiosynclines formed. The width of the main Zhailma graben-syncline was reduced an average of 1.5 times and that of its separate branches by up to 3 times. Strata near the boundary faults were compressed into steep linear folds with limbs dipping as much as 80-90°. Towards the middle of the syncline, less steeply dipping brachioform structures of the second order were created (Mitryaeva et al., 1962; Rozhnov et al., 1983; Shcherba, 1969). Contemporaneous with folding, a complex system of longitudinal, transverse, and diagonal normal and thrust faults was reactivated, with a general displacement of masses and separate plates from southeast to northwest (Uspenka fold belt). Later, magmatic activity resumed, with volcanism and intrusions of intermediate to acid composition, which continued in the east and south especially, until the end of the Hercynian and into earliest Triassic time.

Kimmerian Alpine movements occurred with continental uplift, accompanied by considerable subaerial denudation and the accumulation of a detrital cover and the formation of weathering crusts under a climate that was first humid and then arid.

Geological Formations

As previously noted, the accumulation of shallow-coastal marine sediments was synchronous with the movements of Caledonian basement blocks. The largest movements were localized in axial near-fault rift segments, where igneous activity consisting of subalkaline basaltic-trachyrhyolitic volcanism and volcano-chemical sedimentation (siliceous, manganese-carbonaceous), associated with deposition of volcanoclastic strata, was most intense. This activity resulted in emplacement of small subvolcanic bodies, sills and flows of diabase, porphyries, tuffs, stocks of gabbro-diorites, and monzo-diorites with increased sodium and potassium alkalinity, all typical of intercontinental rifts (Borukaev and Shcherba, 1967-69).

Lower Famennian pelitomorphic and aleurolitic rocks of varied lithology and facies — clay-siliceous, calcareous, coal-aleurosiliceous-carbonaceous — were unconformably deposited over Frasnian molasse. Upwards in the section, they are replaced by frequent thinly bedded flysch-like rhythmites of variable thickness, overlain by calcareous sandstones, then succeeded by aleurolites, siliciclastics, limestones, or coal aleurolites (depending on position, i.e., in the center of stagnant depressions, on the flanks of uplifts, near rift structures, or within volcanic centers of the northern nearfracture zone) (Rozhnov et al., 1983; Shcherba, 1967; Figs. 1, 2). The volcano-chemical sediments and ores and volcaniclastics form as rhythmites. The total thickness of ore enclosed in Famennian sediments amounts to 1 km.

The appearance of layers of red rock within the section, an increase in thickness of horizons in depressions, and the existence of rifts, fans, and slumps testify to sedimentation coeval with vertical movements.

At the base of insular volcanic centers, coal-marl strata, siliciclastics, and welded tuffs of Early Famennian age were deposited, succeeded upwards in the section, during the Late Famennian, by alternating siliceous limestones and tuffs, including also bombs and flows of albitized andesite and diabase porphyrites. At the center of the northern Shairem volcanic field there are sills and stocks of syeno-diorites, subalkaline diabases, and younger porphyrites and trachyrhyolites (Mitryaeva et al., 1962). The volcanics all contain Ba, Pb, Zn, Fe, Mn, more rarely some Ge, Ag, Cu, Ni, V, Rb, and Co .

The total thickness of the volcanics is 300 m. Sodic alkalinity in early trachyrhyolites gives way in later rocks to potassic alkalinity. The Famennian stage is conformably overlain by terrigenous-siliceous-carbonaceous rocks of Early Carboniferous age. The sediments are thus interpreted as marine-terrigenous-siliceous, coal-siliceous-clays deposited in warm shallow seas and the volcanics as subalkaline basalt-andesite-trachyrhyolites characterizing rifting in continental crusts (at an early stage of the Hercynian cycle).

Types of Ores and Conditions of Formation

The graben-syncline contains more than 50 Atasu-type deposits, including Zhairem, Ush-katyn I, Ukatyn III, Karazhal, Ktay, and Bestobe. More than ten such deposits (Usynzhal, Akzhal, Kara Gayly, Kentobe, Bogach, and

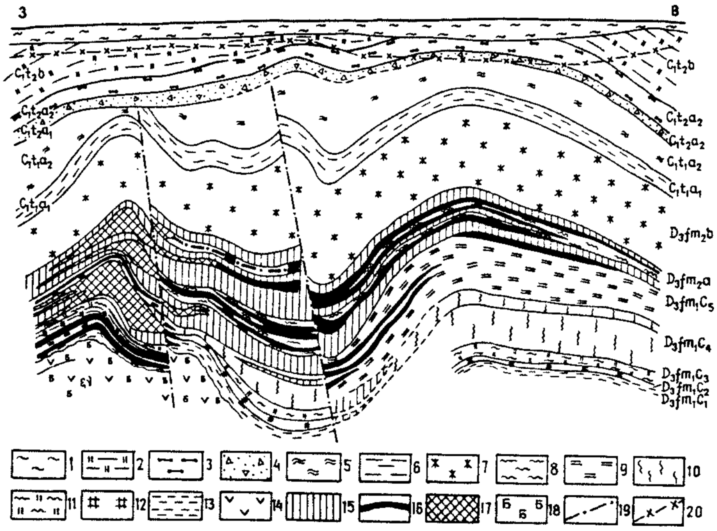


Fig. 2. Zhairem deposit, eastern section (from Rozhnov et al., 1983). 1- clays N_{1-2}; 2- grey siliceous-carbonate rocks, C_1t_2b; 3- siliceous nodular limestones, $C_1t\ _2a_2$; 4- sedimentary breccias with barite-sulfide mineralization, $C_1t_2a_1$; 5- coal-bearing flysch, $C_1t_1a_2$; 6- alternating wave-layer limestones and flysch, $C_1t_1a_1$; 7- limestones, siliceous red and grey, nodular-layered, D_3fm_2b; 8- limestones, siliceous nodular-layered, limestones organogenic-detritic, clay-siliceous-limestones, D_3fm_2a; 9- organogenic-detritic limestones, alternating with dark-grey, clay-siliceous-carbonaceous rocks, $D_3fm_1C_5$; 10- clay-siliceous-carbonaceous rocks with layers of lean iron ore, $D_3fm_1c_4$; 11- rhythmic-layered clay-siliceous-carbonaceous rocks with pockets of pyrite and pyrite-sphalerite rhythmites, $D_3fm_1c_3$; 12- black carbonaceous-feldspathic-siliceous ores, $D_3fm_1c_2$; 13- irregularly alternating coal-siliceous-limestones, organogenic detrital limestones, pelitolites with coal and pyrite rhythmites, $D_3fm_1c_1$; 14- trachytic porphyries, EV; 15- lean iron ore; 16- lead-zinc hydrothermal-sedimentary ore; 17- barite lead-zinc hydrothermal-metasomatic ore; 18- baritized ore; 19- faults; 20- boundary of weathering crusts.

other smaller ones) are known in the Uspenka ore belt east and west of Zhailma (Fig. 1).

In Atasu deposits, the variability of ore type within even a single ore horizon, let alone in different layers and ore bodies, is typical. The following main ore types are distinguished by composition and qualitative proportions of components: iron, iron-manganese, manganese, lead-zinc, barite-lead-zinc, barite, sometimes with copper (all of these represented in large deposits). There are in addition the following subordinate varieties, which make application of metallurgical processes more difficult: lead-manganese (coronadite, kentrolite), zinc carbonate (complex carbonates of Zn, Mn, Fe, Mg, and Ca), and fluorite-barite-lead.

The content of the chief economic ore components varies within wide limits: Fe 15-20 to 50%, Mn 5 to 45%; in lead-zinc ore Pb 0.5-1.5% and Zn 3-5%; in barite-sulfide ore Pb 0.5-4%, Zn 0.7-15%, and Ba 5-50%. The accessory element content is equally variable.

In terms of mode of deposition, ores can be categorized as follows: 1) volcanogenic (hydrothermal)-sedimentary ores of Fe and Mn, Pb and Zn, with minor barite; 2) hydrothermal-metasomatic barite-zinc-lead; and 3) hydrothermal barite veins with copper.

Volcanic-sedimentary Ore Formation

Stratigraphic arrangement is typical of ores of iron and manganese and persists throughout the trough. The deposits are located within five horizons of grey and red flysch units (Fig. 2). Economic Pb-Zn mineralization is concentrated mainly in a grey flysch unit and in rhythmite units within flysch-like horizons.

Replacement ores may still retain obvious sedimentary features. Oxide and carbonate ores of Fe and Mn form pockets and layers in dark nodular and hummocky-bedded limestones and in siliceous limestones with layers of ferruginous jasper and pelite (Table 1). Superimposed metamorphism has subsequently resulted in the formation of silicates of manganese (rhodonite, bustamite, tephroite), garnets, epidote group minerals, and other minerals. Additional hydrothermal activity resulted in deposition of ores with unique iron-manganese mineralogy containing Br, Cl, Ar, Pb, and layers of barite, pyrite, and chalcopyrite.

Lead-zinc sulfide ores are black or colored dark-grey by carbonaceous substances in clayey-siliceous-carbonaceous rocks with layered sulfide impregnations and contiguous units of pyrite-sphalerite and pyrite rhythmite. The latter are composed of normally alternating rock layers, saturated with sulfides, and monomineralic (pyrite, sphalerite) or polymict (pyrite-sphalerite and others). Some ore deposits contain layers of barite. Individual lay-

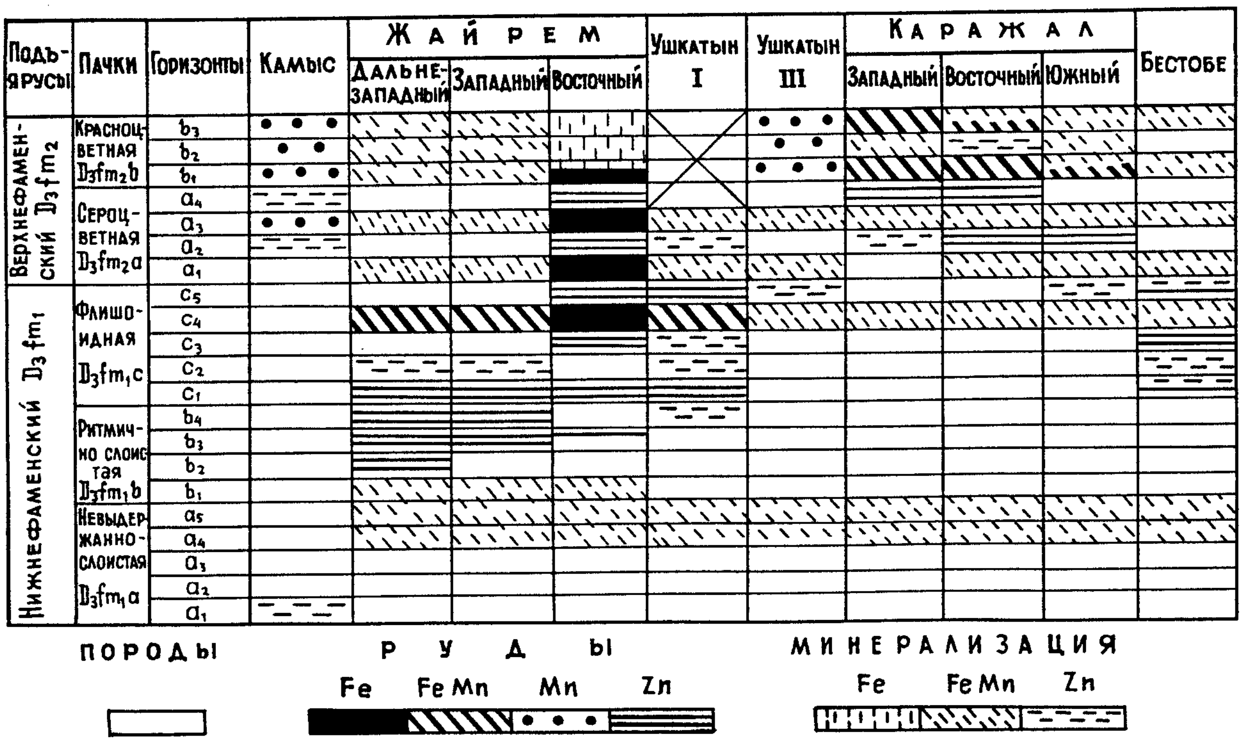


Fig. 3. Ore megarhythms in Famennian Atasu-type deposits.

ers of ore minerals are up to 10 mm thick and more. The number of such layers ranges from many tens to even hundreds. Zinc is prevalent over lead, with the Zn:Pb ratio ranging from 3:1 to 5:1.

The normal process of sedimentation was punctuated by the influx, in pulses, of ore-bearing hydrothermal fluids. Pulsation was the main cause of rhythmicity in ore deposits and in formation of mega-rhythms. Horizons of flysch composition repeatedly alternate with sulfide mineralization (lower element of a mega-rhythm) and horizons of nodular and hummocky-bedded limestones with layers of iron and manganese ore (upper element of a mega-rhythm). Macro-rhythms are expressed by the alternation of ore and rock layers. Microrhythms are especially widespread in sulfide ores.

The rate of sedimentary ore accumulation varied, owing to the episodic influx of ore material. Thus, it took 1.5-2 My for mega-rhythms to form, a thousand or tens of thousands of years for macrorhythms, and tens of years or even less for microrhythms.

Ore-bearing hydrothermal solutions, upon reaching the benthic area of the basin, became mixed with marine waters, and because of differences in fluid density and the environment, layering inevitably occurred, with the oxidative zone predominant in the upper part and a reducing zone below. Zn, Pb and some Fe precipitated in stagnant depressions, while Mn and most Fe (due to its mobility in a reducing environment) remained in solution. Sulfide deposition ceased upon reaching the oxidizing-reducing interface, above which ores of Fe and Mn were deposited.

Horizontal zonation is determined by differences in mobility of the chemical components. For ores of Fe and Mn, it is seen in the successive replacement of ferric jaspers, iron, iron-manganese, and manganese ores from the center of deposition outward toward the margins. In sulfide ores, lead-zinc (galena-sphalerite) ores were replaced by pyrite rhythmites from the center of deposition outward. Primary zonation in these ores is complicated by superimposed hydrothermal processes. Differentiation of ore material and the formation of different kinds of concretions was facilitated by the activity of sulfate-reducing bacteria.

Hydrothermal Ore Formation

Hydrothermal-metasomatic mineralization is superimposed on volcanic-sedimentary ores. The mineralogy of barite-lead-zinc ores is complex, comprising some 70 minerals (Table 1). In some deposits an abundance of barite and fluorite is typical. Pb, Cu, and Ag are dominant among sulfides of galena and different sulfosalts in concordant ore bodies and subconformable lenses with numerous apophyses and in bodies of mineralized breccia, grading into sedimentary deposits. The main mass of hydrothermal-metasomatic ore deposits formed under the influence of hydrothermal fluids on rocks and ores synchronous with them. Alkaline metasomatism-albitization, potassic feldspathization, and dolomitization preceded deposition. Relatively hotter, more dilute solutions introduced the mobile elements As, B, Cl, Na, K, and Mg, as well as small amounts of S. Neomineralization was most extensive in those horizons in which Mn was the more reactive element. Silicates and manganese and lead oxides (kentrolite, coronadite, etc.) and minerals containing chlorine (friedelite, pyrosmalite) and arsenic (sarkinite, manganberzeliite, etc.) were the next to be deposited (Kayupova, 1974). With the arrival of chalcophiles such as As and Zn, galena, pyrrhotite, chalcopyrite, and sphalerite began to be deposited in small quantities in feldspathic quartz and barium veins.

Solutions of the succeeding major stage of ore deposition were rich in Pb, Ba, and S and contained Sb, As, Cu, and other elements. Hydrothermal fluids caused recrystallization and redeposition of sedimentary ores. Carbonates were removed, and iron moved into solution. Part of the iron was removed from the zone of ore deposition and part redeposited in the form of colloidal pyrite. Almost all the sphalerite formed at this stage resulted from recrystallization of early sphalerite (Fig. 4D).

Metallogenesis occurred in a low-temperature oxygen-rich environment. Fluid inclusions contain little volatile matter but an increased concentration of salt.

The hydrothermal-metasomatic process was of prolonged duration. In the opinion of some, the process was synchronous with sedimentation (Shcherba, 1969), while others believe that the main mass of hydrothermal-metasomatic ores formed in the Late Tournaisian. Taking into account the maximum thickness of Upper Tournaisian deposits (300 m), the depth of hydrothermal-metasomatic mineralization could not have exceeded 500 m.

Late hydrothermal ores of the third stage are represented by intersecting lenticular bodies and veins of coarse-grained white barite with pockets of pyrite, hematite ore, and chalcopyrite. Rare inclusions of Co and Ni minerals are typical. Veins and lenses cut all the earlier deposits, including hydrothermal-metasomatic ores, and even penetrate rocks of Visean age in some places.

Sericitization and silicification of volcanogenic-sedimentary rocks and potassic feldspathization of subvolcanics preceded mineralization. Hydrothermal fluids introduced Ba, Cu, Ag, and Co. Simultaneously with deposition of late barite, early barite was recrystallized and partly redeposited. Ore deposition occurred as the oxidation potential (Eh) gradually rose to high levels. Solutions in inclusions possess very high concentrations of $(HCO_3)^{2-}$ and $(SO_4)^{2-}$, and the $(SO_4)^{2-} + SO_2 : H_2S$ ratio ranges from 10 to 210.

Table 1. Types of ore and conditions of formation.

Stages of mineralization	I. Hydrothermal-sedimentary	II. Hydrothermal-metasomatic	III. Hydrothermal vein
Age of mineralization	Famennian	Famennian-Tournaisian	Probably up to Visean inclusive
Character of ore-forming process	Submarine deposit of rhythmically alternating layers of Fe, Zn, Pb, and Ba sulfides and oxides and carbonates of Fe and Mn in silty siliceous-carbonaceous mass	Hydrothermal replacement and deposits of sulfides of Zn, Pb, Ba, and others, often within horizons of hydrothermal-sedimentary mineralization, and also in and near rift structures.	Deposition and redeposition of barite, quartz with inclusions of sulfides of Fe, Cu, and others, in zones of brecciation, often outside ore bodies (vertical or horizontal) of ores of I and II stages, minor metasomatism
Forms of ore bodies	Layered; length, hundreds of m and more; thickness, up to tens of m	Subconcordant lenses, mineralized zones of brecciation. Extension of lenses.	Veins, small lenses
Principal useful elements	1. Fe, Mn 2. Zn, Pb	Pb, Zn, Ba	Ba, partly Cu
Chief ore-forming minerals	1. In iron ores hematite, magnetite, siderite; in manganese braunite, hausmannite; in iron-manganese jacobsite, magnetite, hematite, braunite, hausmannite. 2. In lead-zinc ores pyrite, sphalerite, galena	Galena, sphalerite, barite, sometimes fluorite	Barite (with nests of pyrite and chalcopyrite).
Typomorphic minerals	Framboidal pyrite	Co-arrangement of barite and sulfasalts of Zn, Cu, Ag, and pyrite in metacrystals	Minerals of Co and Ni
Elements-mixtures	In ores of Fe; in ores of Mn-Zn, Pb, less Co, Ni; in ores of Zn-Pb-Cd, Fe, Ti, As, Hg	Cd, Cu, Ag, Hg, Ge, As, Sb, Sr. In ores of Fe and Mn-As, S (at the expense of Ba).	Ag, As, Co, Ni, Hg, Sr
Texture of ores	Rhythmic-layered, irregular layered, cretion-layered, brecciated, and others.	Layering inherited, massive, brecciated and others	Massive, brecciated, vein
T^{o}C of ore deposition (vacuum decrepitation)	40-70^{o}	150^{o}	300-175^{o}

Table 1. Types of ore and conditions of formation.

Ore-forming fluids (mainly on Gzh-inclusions)	In brine-saturated sulfide ores, large volatile component, 725-980 g/kg (mostly water, with H_2S, CO_2, N_2). Salts = 276 g/kg. Sulfate-chloride solution of iron-calcium-sodium with notable silicic acid. Eh low. For ores of Fe and Mn acid environment with high Eh.			For leading ore association, highly concentrated fluids of brine-melt type, high Eh						
				Small volatile component, 29 g/kg (mostly water, minor CO_2, H_2S, N_2). Salts = 970 g/kg. Solution sulfate-hydrocarbon calcium-ferric, relatively high Eh.				Small volatile component, 90-115 g/kg (H_2O, CO_2, N_2). Salts = 885-910 g/kg. Solution ferric-calcium-sodium, very high Eh.		
Isotopes of Zn:	Zhairem	Ushkatyn	Bestube	Zhairem	Ushkatyn I	Ushkatyn III	Bestube	Zhairem	Ushkatyn I	Bestube
Pb^{206}/Pb^{204}	17.98	18.00	18.03	18.02	18.05	18.04	18.02	18.03	18.05	18.04
Pb^{207}/Pb^{204}	15.65	15.60	15.64	15.63	15.63	15.63	15.62	15.65	15.64	15.65
Pb^{208}/Pb^{204}	38.09	37.99	38.10	38.09	38.16	38.03	38.13	38.10	38.08	38.03
Isotopes of S: ^{34}S (%)	-1.9	-8.1	-12.0	+0.8	+6.2	-7.1	-0.8	+6.6	+11.7	+10.9
Depth of ore deposition	First hundreds of m (bottom sediments)			Not more than 500 m						

The main mass of hydrothermal-metasomatic ore is found in areas of volcanogenic-sedimentary sulfide mineralization, and the latest ores are at the focus of zones in which the distribution of hydrothermal-metasomatic mineralization decreases progressively from one stage to the next. Concentric zonation is manifest in the successive arrangement of zones from barite or quartz-barite metasomatites, to barite-galena, barite-galena-sphalerite, galena-sphalerite, sphalerite-pyrite, and finally pyrite rhythmites (the order corresponding to the distance of penetra-tion of hydrothermal fluids).

Reasons for the combination of all three stages of mineralization were: 1) preservation of the main paths of hydrothermal fluids throughout the period of ore formation; 2) the presence of a sequence of carbonaceous matter containing framboidal pyrite, which served as a geochemical barrier; and 3) the abundance of zones of brecciation in physico-chemically heterogeneous flysch horizons. In the more homogeneous iron-manganese horizons, hydrothermal-metasomatic ores occur only in zones of maximum brecciation. For all stages of ore deposition, there was probably only a single source of ore material, as attested to by the isotopic composition of lead ore (Table 1). From stage to stage there was a tendency for sulfides to become progressively heavier, iso-topically. During the sedimentary stage, isotopically light sulfur is typical, reflecting a sedimen-tary-diagenetic mode of ore formation. The isotopic sulfur composition of sulfides of the next stage is homogeneous, close to that of meteorites, which may reflect connection with a deep, probably sub-crustal magma chamber. As the sulfur in late-stage vein sulfides is enriched in heavy isotopes, two different sources of sulfur are suggested: magmatic and marine.

Zonation

Lateral zonation is generally concentric. Volcanic centers are the focal areas around which the principal ores are arranged, with increasing distance, in the following order: vein and hydrothermal-metasomatic, Cu, Ba, Zn, Pb; hydrothermal-metasomatic and volcanogenic- sedimentary, Zn, Pb, Ba (Fe, Mn); volcanogenic, Fe, Pb, Zn (Ba, Mn), and Fe, Mn, (Pb, Zn), and Mn (Fe) (Shcherba, 1967). The size of ore deposits varies from a few kilometers to tens of kilometers. Some ore bodies were depleted by deep fault channels, connected with depleted magma chambers.

Small-scale zonation is displayed in the transition from mixed complex sedimentary-hydrothermal mineralization to outlying areas of layered sedimentary iron ore in which first iron-manganese and then manganese replace the original material.

A general vertical zonation of a general nature is shown by the alternation of ore layers and bodies with volcano-chemical precipitates and clastics and also of ore

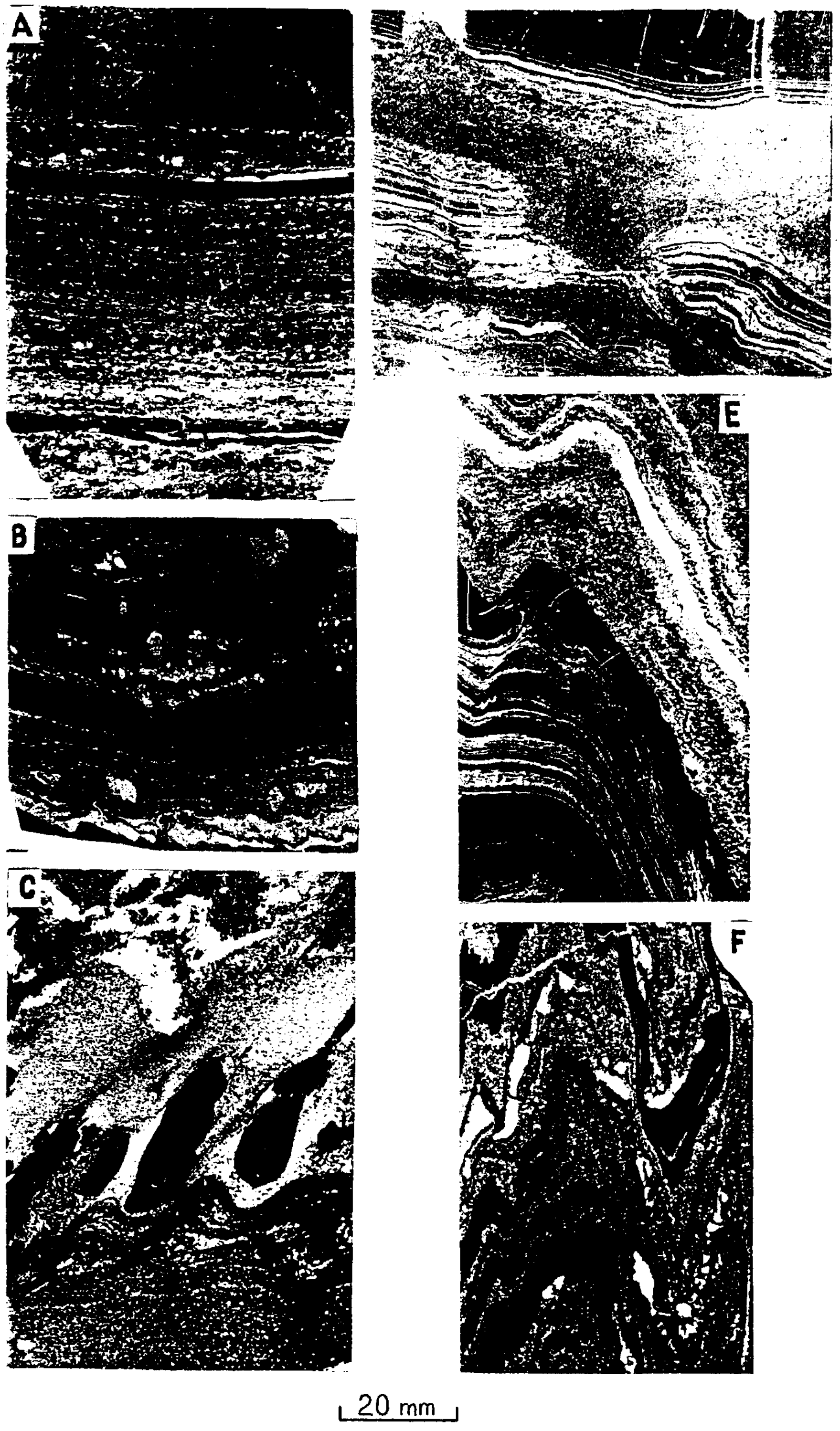


Fig. 4. Ores of the Atasu type. A- rhythmites of sulfide ores (bright) in carbonaceous argillites; B- carbon-bearing concretion in stratified ores; C- deformation in shale-carbonaceous rock with concretions; above sulfide layers with calcite (white); D- stratified sulfide ores in replaced by a barite-pyrite paragenesis; a fringe of the regenerated pyrite and sphalerite is seen at the boundary; E- conformal folded deformation of the sediment and metasomatic ore (more wide layers); F- carinate folds, boudinage in sulfide ores; bright-calcite separation, dark coaly argillite.

bodies of different composition within a distance of a few meters to tens of meters (Fig. 3). Macrorhythmicity of this sort may have been produced by pulsation not only of the volcanogenic-sedimentary process but of all processes of ore deposition. Of particular interest is the observation that instead of simple replacement, there is an alternation of iron-manganese oxide ore horizons and lead-zinc sulfide ores displaying different degrees of hydrothermal metasomatism.

In the Zhairem ore body, the basal zone is represented by lead-zinc ore. Above this, lead-zinc (5 horizons) alternates with iron ore (4 horizons) interbedded with coal-siliceous-carbonate beds. eplacement occurs inside even the thicker layers of iron ore (Fig. 2). In Ushkatyn, the tops of macrorhythms are represented by iron ores. Beneath this, they are replaced by alternating iron and manganese ores (13 layers). Lead-manganese ores along the strike are replaced by iron-manganese (8 horizons). Still lower are a few layerlike bodies (up to 7) of barite-lead ores (Rozhnov et al., 1983).

Zonation within ore layers and horizons studied in detail by N.S. Scripchenko (1980) is evidently rhythmic. The composition of ore-rock rhythmites in sulfide deposits is as follows: pyrite-bearing limestone, galena-sphalerite in massive carbonates, barite-sphalerite-galena in carbonates with layers of aphanitic limestone. Boundaries between layers may be gradual or contrasting, and the thickness of layers from a few millimeters to a few centimeters. Each ore layer consists of many tens of rhythmites. Strict layering of ores of the first stage is disturbed by superposed layers, lenses, and pockets of sulfides of the second stage. In the focal zones of ore fields, deposits of both stages are crossed by veins, mineralized breccias, columnar bodies of quartz-barite, and rare pockets of chalcopyrite, galena, and pyrite.

The intermittent character of ore deposition, which evidently followed active phases of volcanism (after eruption of main mass of basalts and pyroclastics), is quite obvious. In many deposits, ore deposition began in the form of layers of sulfides of lead and zinc coeval with the accumulation of layers of volcano-chemical sediment (siliceous, manganese-carbonaceous) consisting of terrigenous pelitomorphs with minor pyroclastics. Later, deposition of sulfide ores alternated with iron-manganese oxide ores, and manganese itself was deposited on the periphery of these ore deposits — a peculiarity probably connected with periodic dormancy of the volcanic magma chamber. The third stage of ore deposition marked the end of the process. Linear or concentric zonation was determined by the arrangement of volcanic centers (nearside or central). Deposits that formed during the main interval of ore deposition are restricted to Famennian-Tournaisian strata.

Superimposed Processes

Autometamorphism, a diagenetic process where with each pulse of the convective regime, rocks and ore were

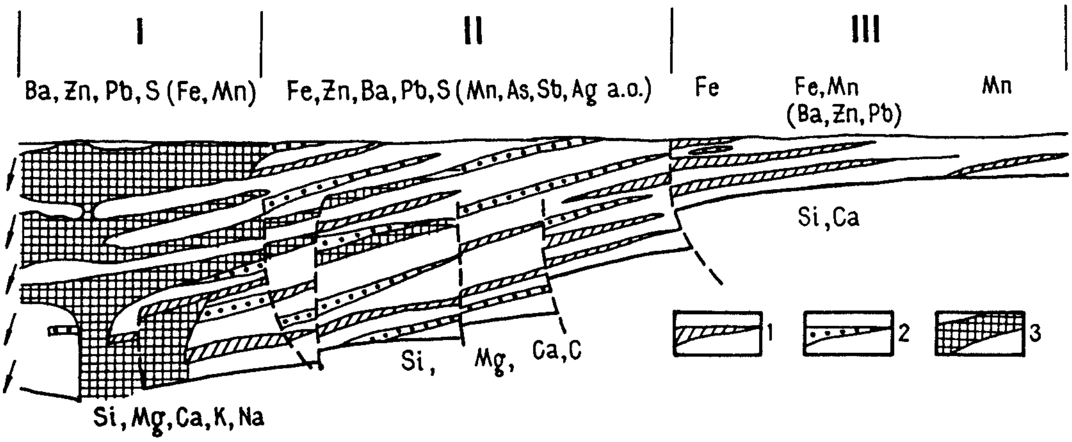


Fig. 5. Generalized scheme of radial (linear)-concentric zoning of the Atasu type deposits. I- inner focal zone (2-3 km); volcanites are widely developed, dominate hydrothermal-metasomatic partly regenerated sulfide ores, barites; II- middle zone (2-4 km); few volcanites — lavas, pyroclastics, tuffites; sedimentary sulfide and oxide ores, volcano-chemical sediments dominate; III- outer zone (3-7 km); terrigene rocks, volcano-chemical sediments, sediments oxide iron-manganese bodies: 1- sediment oxide ores of iron and manganese, 2- sediment sulfide ores, 3- hydrothermal-metasomatic (including a regenerated) ores and vein bodies. Rhythmics of the rift bottom sinking defining a change of acid-restoring conditions is shown conventionally by arrows.

bathed in solutions somewhat cooler than the preceding ones, must first be noted.

After they formed, ores in the Middle Carboniferous were subjected to dynamometa-morphism, in which congruent folding was accompanied by boudinage and thermal effects (Fig. 4). Finally, in some ore fields there is evidence of contact metamorphism along the borders of intrusions in post-volcanic rocks, especially middle-late Hercynian granitoid intrusions.

In addition to ore regeneration (transformation of hematite into magnetite, psilomelane into braunite, etc.), there is evidence of direct absorption of ore by invading granitic melts, creating what has been mistaken for mineralization connected with granitoids. Such occurrences had been identified as contact-metasomatic (false skarn), particularly where iron-manganese ores were involved, on the basis of carbonates of "ore-bearing" magnesian skarns, recrystallization, and appearance of secondary thermal and mineralogic zonation. Only the discovery of ore xenoliths in granites, and the intersection of the former by apophyses, laid to rest this erroneous concept (Shcherba, 1967, 1969) and revealed the true origin of the ores.

In considering the practical effects of superimposed processes, it should be noted that metamorphism improved the metallurgical properties of some ores, and that surficial processes such as denudation, oxidation, and formation of weathering crusts have affected ores within the near-surface zone.

Distribution of Mineralization of the Atasu Type

Atasu type (AT) deposits are located in chains and accumulations throughout the Uspenka ore belt (500 km) and its branches and in neighboring ore provinces and belts (Balkhash, Chu-Ili, Chingiz-Tarbagatay, northern Tien-Shan). Volcanogenic stratiform deposits of the same composition but different age in the Urals, Caucasus, Western Europe, Anatolia, and China may also be of this type. Combinations of stratiform volcanogenic lead-zinc and iron-manganese ores are also known in deposits of older, Proterozoic metallogenic epochs (e.g., at Broken Hill in Australia and in Brazil, India, Canada, and the US).

It was noted above that with increasing distance from the source, complex ores are replaced by iron oxides and carbonates and then by distal iron-manganese and manganese (a series of deposits with Fe, Ba, Pb, Zn). Manganese deposits of Tethys, the older Proterozoic deposits of South America, South Africa, and probably the giant Kalahari deposits are of this kind (Fig. 5).

From the time that AT deposits were first discovered, work done in re-evaluating them and identifying their peculiarities has been taken into account in the course of ongoing exploration and prospecting, with the result that new ore bodies have been found and resources increased more than tenfold.

The widespread distribution of AT ores is explained by recourse to standard theories of basaltic-rhyolitic volcanism in submarine rifts, the composition of the products of such processes, and the course of their differentiation in magma chambers, with distillation of "excess" products into hydrothermal solutions and substantial involvement of marine waters in the convection currents that distributed these solutions.

Stratiform AT ores occupy a notable place in the world reserves of Mn, Zn, Pb, sometimes forming large, even gigantic and unique accumulations.

Problems of Genesis

At present, there are two hypotheses offering competing explanations of the origin of AT ores, both of which acknowledge volcanogenic and sedimentary-metasomatic modes of ore deposition. One hypothesizes filtrational leaching and transport of ore-forming and lithogenic elements from underlying volcanics, with submarine recycling. According to the other hypothesis, intermediate volcanic basins were the source of metals and primary ore-bearing solutions. Owing to disequilibrium, liquation created contrasting sets of mantle melt within a basalt-rhyolite system, and these were differentiated by distillation. Excess liquation products were entrained in solutions that escaped through open faults on the sea bottom. Lithogenic solutions containing Ca, Mg, and Si gave rise to limestone, dolomite, and siliceous rocks, whereas ore-forming solutions containing Fe, Mn, Pb, Zn, Ba, Cu, and other elements gave rise to sedimentary and hydrothermal ores (Shcherba, 1964, 1967). This hypothesis is supported by the absence in most cases of thick volcanic strata beneath ore deposits (such strata being an essential requirement of the first hypothesis), by evidence of considerable leaching, and, lastly, by the evidence of pulsational ore deposition in response to volcanic periodicity.

Impressive contrasts in vertical and horizontal zonation of composition and ore types, and localization of late-stage deposition around volcanic centers, serve as major guides to exploration. Alternating variations in composition, modes of deposition, and paragenesis distinguish AT ore bodies from other types of deposits.

Accepted models of submarine rifting and the inevitable differentiation of basaltic melts expelled from the magma chambers associated with such rifts explain the compositional variations of hydrothermal fluids and the widespread distribution in time and space of the AT ores that were deposited by these fluids. Volcanogenic pyrite ores were formed at greater depths in closing rifts, under increased pressure and temperature, where more sulfur was available and less oxygen. Under intermediate less extreme conditions, alternating ore types tended to form.

References

Borukaev, R.A., Shcherba G.N. (eds.). Geology and metallogeny of the Uspenka tectonic zone. Alma-Ata, Nauka, v. 1, 1967, 372p.; v. 2, 1967, p. 302; v. 3, 1967, p. 260; v. 4, 1968, p. 158; v. 5, 1969, p. 166; v. 6, 1968, p. 180.

Kayupova, M.M., 1974. Mineralogy of iron and manganese ores of Western Atasu (Central Kazakhstan). Alma-Ata, Nauka, p. 230.

Mitryaeva, N.M., 1979. Mineralogy of barite-lead-zinc ores of the Atasu region deposits. Alma-Ata, Nauka, p. 220.

Mitryaeva, N.M., Rozhnov, A.A., Shcherba, G.N., 1962. To the genesis of polymetallic ores of Atasu region (Central Kazakhstan). Izvestiya AS KazSSR, ser. geol. 1962, no. 6 (51), p. 53-64.

Rozhnov, A.A., Bigaliev, M., Buzmakov, E.I., Lytkin, V.A., Sereda, V.Ya., Taranushich, F.F., Shibrik, V.I., 1983. Deposits of the Atasu type. In: Ivanov, S.N. (ed.), Pyrite deposits of the USSR. Moscow, Nauka, p. 198-204.

Shcherba, G.N, 1964. Some peculiarities of study of the Atasu type deposits. Izvestiya AS KazSSR, ser. geol., No. 59, p. 15-33.

Shcherba, G.N., 1967. Deposits of the Atasu type. Geology of ore deposits, no. 5, p. 106-114.

Shcherba, G.N., 1969. Deposits of the Atasu type in Kazakhstan. International geological congress, XXIII session, Delhi, p. 84-94.

Skripchenko, N.S., 1980. Hydrothermal-sedimentary polymetallic ores of limestone-slate formations. Moscow, Nedra, 215 p.

Rhenium and Radiogenic Osmium in the Stratiform Copper Deposits of Kazakhstan

S.K. Kalinin and E.E. Fine

Abstract

Data are presented on the abundance and distribution of rhenium in the stratiform copper deposits of west-central Kazakhstan. The Zhezkazgan ore region is identified as a rhenium province. Characteristics of ^{187}Os distribution in these ores are discussed. This radiogenic osmium isotope is proposed as a new species of natural resource.

Introduction

Widespread copper mineralization is a characteristic feature of sedimentary rock complexes of Mid- and Late Carboniferous age in west-central Kazakhstan. The rocks are composed of grey and red sandstones, conglomeratic sandstones, siltstones, and argillites, of which only the grey sandstones and grey conglomerates are ore-bearing. The largest deposit in the region is Zhezkazgan, a very thick, stratiform, multilayered body. The principal ore bodies are chiefly stratiform deposits (Satpayeva, 1985) of complex composition but with ore minerals consisting chiefly of chalcocite, bornite, chalcopyrite, galena, and sphalerite, with pyrite in very small quantities.

A number of smaller deposits (e.g., Sorkuduk, Zhartas, Itauz, Sary-Oba, Kipshakpai) and shows of ore (e.g. Kenen, Kopkazgan, Kokpecty) resemble Zhezkazgan in terms of structure and mineralization and are located up to 300-400 km both to the north and to the south of it (Fig. 1a, b).

Rhenium

High concentrations of the rare element rhenium are characteristic of the sulfide ores. The presence of rhenium is so typical that it may be regarded as a distinguishing feature of this type of copper deposit (Kalinin and Fine, 1977). It is found in sulfide ores of all mineralogical types. The ores generally contain 0.00005-0.0005% Re, but zones heavily impregnated with copper sulfides may contain as much as 0.001-0.002% (Fig. 2). The Re/Cu ratio in the ores varies widely. While in some ores, especially chalcocite, the Re/Cu ratio is very low, other ores are enriched in rhenium and cases have been found of bornite-chalcocite nested accumulations in which the Re/Cu ratio reaches 1:100 or more. The mean ratio of these elements in the Zhezkazgan deposit is 1:5700.

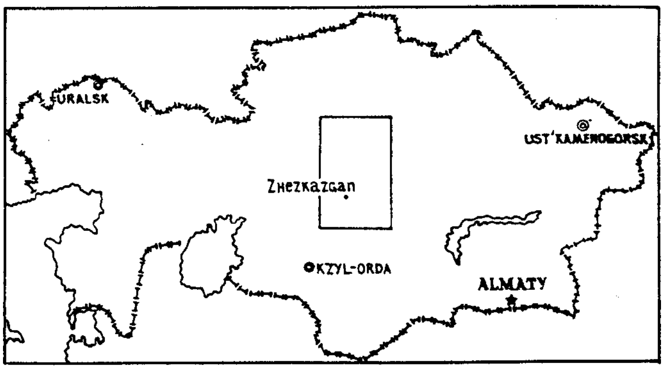
The molybdenum content of the ores is close to the rhenium content. The Re/Mo ratio varies over a range of 1:0.3-1:75, in contrast to the average crustal ratio of these elements, which is 1:1500. The geochemical concentration coefficient for rhenium here is three orders of magnitude higher than that of molybdenum.

Mineralogical studies of ore samples from this region of Kazakhstan reveal the presence of the rhenium mineral zhezkazganite in rocks highly enriched in rhenium (Fig. 3). Under the microscope, at magnifications of ×100-300, the mineral has the shape of semi-elliptical veinlets that form rims peripheral to bornite grains. More rarely, the mineral is found in aggregates of bornite with chalcocite (Fig. 4). Thin intergrowths of zhezkazganite with bornite, chalcocite, and galena can be observed at magnifications of ×1500-2000. Detailed study of their structure can only be done with an electron microscope, which provides an image of the smallest grains of zhezkazganite, i.e., 0.1-0.01 μ (Satpayeva et al., 1962; Satpayeva, 1985). Grains of this size cannot be isolated from the ore for chemical analysis, but by using an indirect method of selective dissolution of ores of different mineral composition, it is possible to determine that this mineral is a rhenium-molybdenum sulfide, $(Re,Mo)S_2$.

Ultrasonic probes of inclusions of zhezkazganite reveal that in addition to molybdenum and sulfur, lead is present (Kosyak, 1968), as well as copper (Ivanov et al., 1967). As a result, the formulas $Pb_4Re_3Mo_3S_{16}$ and $CuReMo_4S_4$ were proposed for this mineral. Because of the complexity of the problem, the composition and structure of zhezkazganite are the subject of on-going studies.

Ore deposits of the Zhezkazgan region display highly unusual geochemical evidence of rhenium mineralization. The mantle is obviously the primary source of this rhenium, judging from the high rhenium contents of certain ultrabasic rocks, chondrites, and especially iron meteorites. In meteorites, rhenium concentrations are tens and hundreds of times higher than the mean content in the

Fig. 1a. The location of the study area in Kazakhstan.



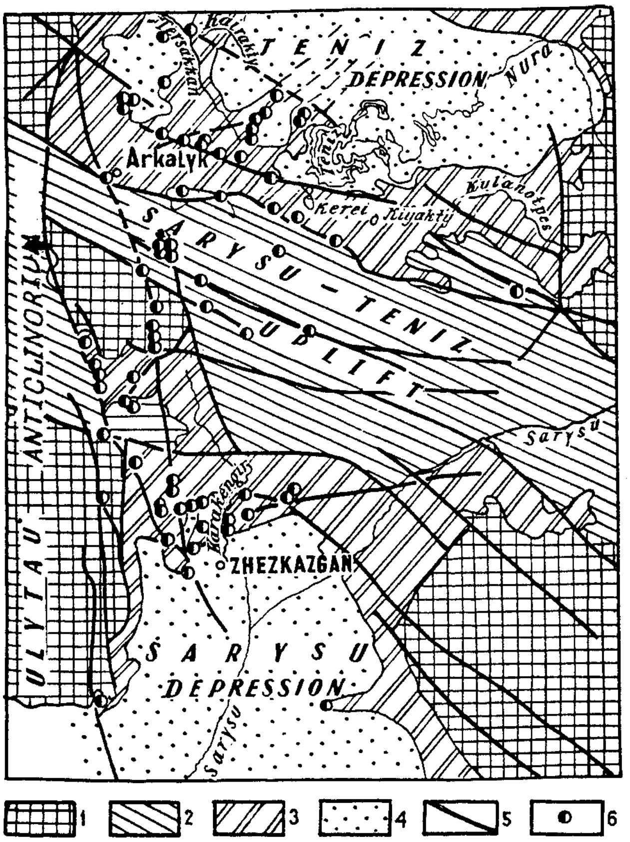


Fig. 1b. Schematic map of the Zhezkazgan ore region. 1- lower structural stage; 2-4- upper structural stage: 2- Sarysu-Teniz zone of block faulting, 3- zones of marginal brachy-fold and linear structures, 4- Teniz and Sarysu depressions, filled with Permian sediments; 5- dislocations with a break in continuity; 6- copper deposits and ore shows.

earth's crust (0.0007 ppm). The mantle of the earth, the composition of which reflects that of meteorites to a certain degree, also contains a high concentration of rhenium. The element may migrate into the crust and be concentrated there by locally favorable geological conditions. A process promoted by the volatility and solubility of some rhenium compounds, aided by the potential for migration along large tectonic fractures which can be traced to great depths, would also have promoted deposition of sulfide ore, as at Idygey and in Eastern Ulutau. Thus, data on the rhenium content of ores, combined with other geological and geophysical evidence, may be regarded as an additional tool for charting deep crustal disturbances. On the other hand, structural factors must also be taken into account in searching for rhenium-enriched ore bodies.

A unique combination of geologic, geochemical, and physico-chemical conditions has resulted in the development of this rhenium-bearing province. The province stretches from the Teniz group of ore bodies in the north to the Zhaman-Ibat deposit in the south. Although the outlines of the province could be more precisely defined, its economic importance is indisputable. The fact that rhenium is enriched in all the ore deposits of the province, combined with its unique mode of occurrence, leads to recognition of these deposits as constituting a special type, which may be referred to as zhezkazgan deposits.

The Osmium Isotope

The presence in ores of this region of an increased concentration of rhenium, one of whose isotopes is radioactive, raises the possibility of studying the daughter product of the radioactive decay of ^{187}Re, the isotope ^{187}Os ($^{187}\mathrm{Re}_{75} \rightarrow {}^{187}\mathrm{Os}_{76} + \beta$- particle + anti-neutrino), which has been found in the copper and complex copper-lead-zinc ores of Zhezkazgan (Kalinin et al., 1975). Studies of Zhezkazgan ore were conducted using highly sensitive spectroscopic methods, which were an effective means of detecting and measuring rhenium and osmium, as well as all the elements accompanying them (Kalinin and Fine, 1969).

Fig. 5 shows how osmium content is related to the concentration of the parent element in a number of samples. As seen in the diagram, the osmium concentration of the ores increases in proportion to the rhenium content, and in one sample reached 1-2 g/t. When the absolute content of rhenium and osmium changes from 10.0 to 1100 g/t Re and from 0.04 to 2.4 g/t Os, the ratio between them

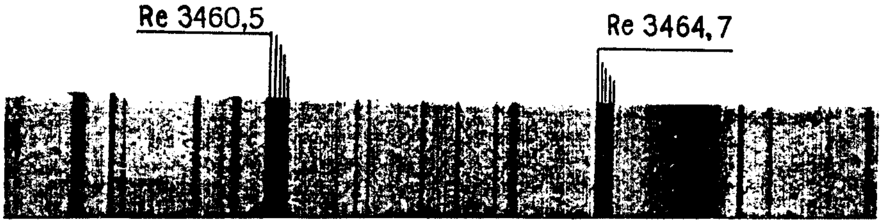


Fig. 2. Spectrogram of copper ore containing 0.002% Re.

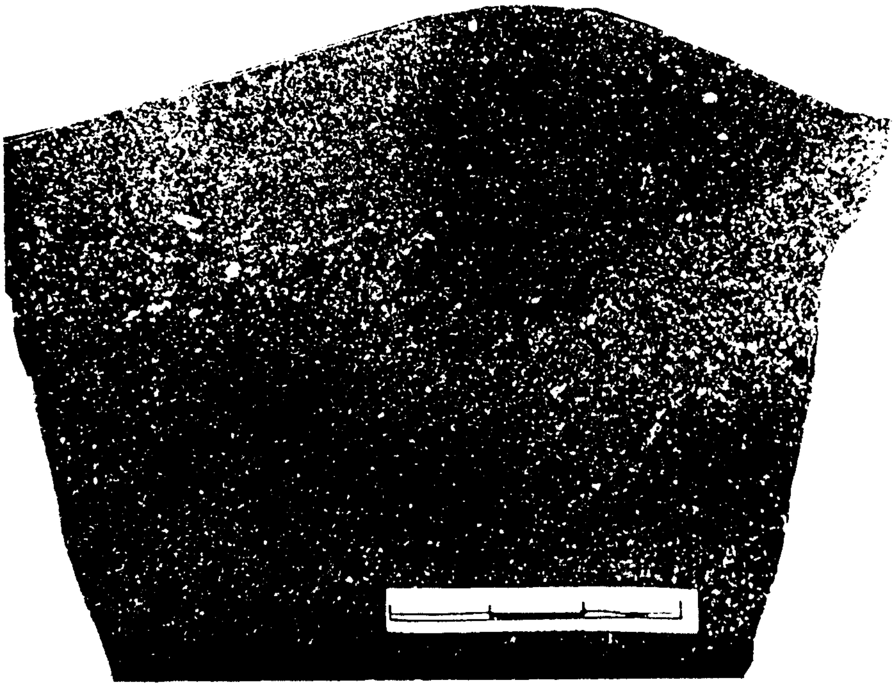


Fig. 3. Photograph of an ore sample; the dark material is a sulfide nest with a high rhenium content.

Fig. 4. Filiform-looped inclusions of zhezkazganite in bornite (white, rhenium mineral; gray, bornite). Magnification x450.

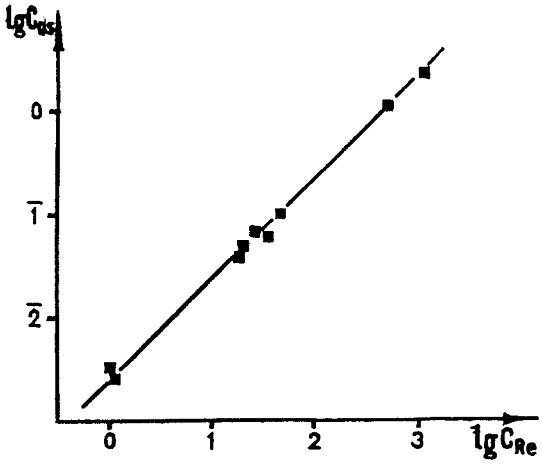


Fig. 5. Re/Os ratio in ore samples.

becomes relatively constant, averaging 1:460, with a variation coefficient equal to 17.1%. The constancy of this ratio is an effect of the radioactive decay law, according to which the accumulation of isotope ^{187}Os in rhenium-bearing ores is governed by the following formula:

$$^{C}187_{Os} = {}^{C}187_{Re} \times (e^{\lambda t}-1) = 0.626 \times C_{Re} \times \lambda t$$

where λ = a decay constant of ^{187}Re, and t = absolute geological age of the deposit.

The fact of constancy of decay makes it possible to evaluate the resources of radiogenic osmium in ores of individual deposits on the basis of the Os/Re ratio.

The isotopes ^{187}Os and ^{187}Re are a unique isobaric pair. Their study in ore deposits is not only of industrial value but also has important metallogenic and geochemical implications.

The isotope content in samples of ore from the Zhezkazgan deposit varies from 0.0025 to 0.003 g/t, which is an average of only one atom of ^{187}Os in some billions or milliards of atoms of the other elements. In the process of metallurgical treatment, osmium is concentrated in particular materials, from which it can be obtained in practically pure form. The isotopic composition of one of the osmium samples from Zhezkazgan ore is given in Table 1. It is considerably different from the isotopic composition of non-radiogenic osmium (Fig. 6).

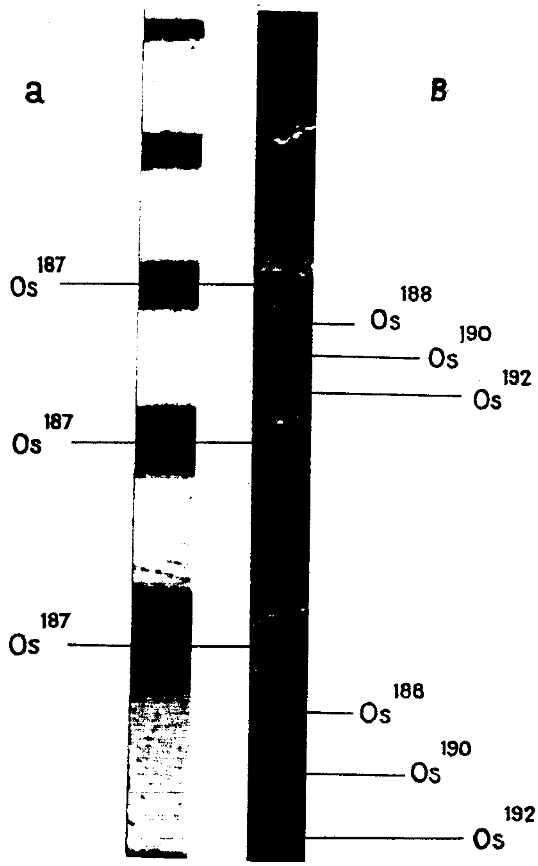


Fig. 6. Os 4420.468. Å line in the spectrogram of radiogenic (a), and ordinary (b) osmium (Fabry-Perot interferometer, t=18 mm, i=50 ma).

Table 1

Isotopic composition of osmium sample obtained from rhenium-bearing ores of the Zhezkazgan deposit (at.%)

Os	184	186	187	188	189	190	192
Radiogenic osmium	n.d.	0.01	99.57±0.05	0.06±0.02	0.07±0.02	0.11±0.02	0.17±0.02
Ordinary osmium*	0.018	1.59	1.64	13.3	16.1	26.4	41.0

*See Nier, 1937.

The possibility of extracting radiogenic osmium from rhenium-bearing ores in significant quantities raises the aformentioned isotope to the category of a new natural resource. Data on the level of concentration, combined with the relationship among the other elements and isotopic composition of osmium, constitute valuable sources of information about processes of ore formation, migration, and differentiation of a mineral species and help to establish the geological age of mineralization.

Acknowledgments — The authors are grateful to Prof. A.E.M. Nairn and Dr. M.K. Apollonov for editing the paper and improving the English. We also acknowledge with thanks our colleagues T.A. Ozerova and E. Kh. Kim, who participated in the study of isotopic and elemental composition.

References

Ivanov, V.V., Poplavko, E.M., Gorokhova, V.N., 1967. On the geochemistry of rhenium in the ore deposits. Geochimyia, no. 12, p. 1430-1444.

Kalinin, S.K., Fine, E.E., 1969. The emission spectral analysis of mineral products. Moscow, Nedra, 248 p.

Kalinin, S.K., Fine, E.E., Egizbayeva, K.E., 1975. Stable isotope osmium-187. Alma-Ata, Nauka, 95 p.

Kalinin, S.K., Fine, E.E., 1977. Occurrence of rhenium in natural objects. Alma-Ata, Nauka, 144 p.

Kosyak, E.A., 1968. The composition of the rhenium mineral from the Zhezkazgan ores. Zapiski of all-Union Mineralogical Society, 97.2, p. 213-216.

Nier, A.O., 1937. The isotopic constitution of Osmium. Phys. Rev., 8, 885.

Satpayeva, M.K., 1985. The ores of Zhezkazgan and conditions of its formation. Alma-Ata, Nauka, 208 p.

Satpayeva, T.A., Kalinin, S.K., Satpayeva, M.K., Marzuvanov, V.L., 1962. The peculiarity of manifestation of rhenium in the ores of Zhezkazgan deposit. Vestnik of the Academy of Science of Kazakh SSR, no. 12, p. 58-65.

Kazakhstanite, a Hydrated Ferrovanadate from Cambrian Black Shales of Northwest Karatau, South Kazakhstan

E.A. Ankinovich, G.K. Bekenova, and N.I. Podlipaeva

Abstract

Kazakhstanite has been found in the weathering zone of the carbonaceous vanadium-bearing Kurumsak Formation of Cambrian age in northwest Karatau (NWK) and in the Zhabagly Mountains of southern Kazakhstan. The mineral is a powder, occurring as tiny grains (0.01 mm) in rounded or elongated kidney-like pockets and thin crusts and films with radiaxial or spherulitic structure and cleavage is perfect, parallel to (001). The mineral is black, with a black-brownish streak, adamantine luster. D (meas.) = 3.4-3.6, D (calc.) = 3.65 g/cm^3. The symmetry is monoclinic, space-group C2/c or Cc, with *a* 11.84 (1), *b* 3.6500 (4), *c* 21.27 (1) Å, β 100.0 (1)°, V 905.5 (1.9) Å^3, Z=1. The strongest lines in the X-ray powder diffraction pattern (d in Å (I) (hkl) are: 10.51 (10) (002), 3.484 (6)(110), 2.915 (3) (400), 2.756 (3) ($\bar{1}$15), 2.606 (4) (311), 2.095 (2) (00.10), 1.971 (2) ($\bar{5}$13), 1.825 (2) (020). The chemical formula, derived from electron-microprobe (valence of vanadium and its quantative content chemically analyzed), is:

$$\mathrm{Fe}^{3+}_{5}\mathrm{V}^{4+}_{3}\mathrm{V}^{5+}_{12}\mathrm{O}_{39}(\mathrm{OH})_9 \cdot 8.55\,\mathrm{H_2O}$$

The infrared absorption spectrum includes bands at 470, 510, 715, 860, 1000, 1615, 3230, 3460 cm^{-1}. The thermal curve shows four broad maxima: 85-160, 370-490, 630 and 700° C. Goethite, bokite, jarosite, alunite, barnesite, hewettite, metahewettite, variscite, vashegyite, and kaolinite are associated with kazakhstanite. By genesis, chemical composition and structural characteristics, kazakhstanite is identified as one of the phyllovanadates. Comparative data on the phyllovanadates are presented. The mineral is named after Kazakhstan. The type material is deposited at the Fersman Mineralogical Museum of the Russian Academy of Sciences and at the Geological Museum of the Satpaev Institute of Geological Sciences of the National Academy of Sciences of the Republic of Kazakhstan, Almaty.

Introduction

Investigations of the mineral composition of vanadium-bearing deposits in northwest Karatau (NWK) and in the Zhabagly Mountains (Fig. 1) have resulted in identification of over 100 mineral species, among them the vanadium minerals satpaevite, alvanite, bokite, gutsevichite, rusakovite, and vanalite. The general lack of studies of these minerals (except for the vanadium-bearing mica, chernykhite) may be explained by difficulties arising from the small quantities available for investigation, their occurrence in powder form with fine mineral intergrowth, complications of chemical composition, and low degree of structural order. Investigation of such minerals has recently become possible as a result of the application of a complex of modern methods. Determination of new mineral species and varieties is a very important task, along with revision of the data on previously studied vanadium minerals. Kazakhstanite, a hydrated ferrovanadate, is one of the new species, discovery of which was reported to the International Commission on New Minerals and Mineral Names, which approved the name. The type material is deposited at the Fersman Mineralogical Museum of the Russian Academy of Sciences, Moscow, and the Geological Museum of the Satpaev Institute of Geological Sciences of the National Academy of Sciences of the Republic of Kazakhstan, Almaty.

Occurrence and Associated Minerals

Kazakhstanite is not rare but is usually found as mm-sized rounded spheroidal or oval grains disseminated on the bedding planes of phthanites. Sometimes, mineral intergrowths form as small botryoidal crusts in cavities (Fig. 2). In one specimen, crusts reach 0.5-1.5 cm in thickness, in common with bokite aggregates. Goethite, bokite, jarosite, alunite, barnesite, hewettite, metahewettite, variscite, vashegyite, and kaolinite are associated with kazakhstanite.

There is an entire series of secondary vanadium-bearing minerals, formed in a definite paragenetic sequence. In the carbonaceous-argillosiliceous vanadium-bearing shales, kazakhstanite can be distinguished as dendritic streaks or as a cement in brecciated areas. The internal structure of rounded grains is spherulitic or radiate-fibrous. However, they occur more commonly as an aggregate of tight isometric grain intergrowths. Crusts and

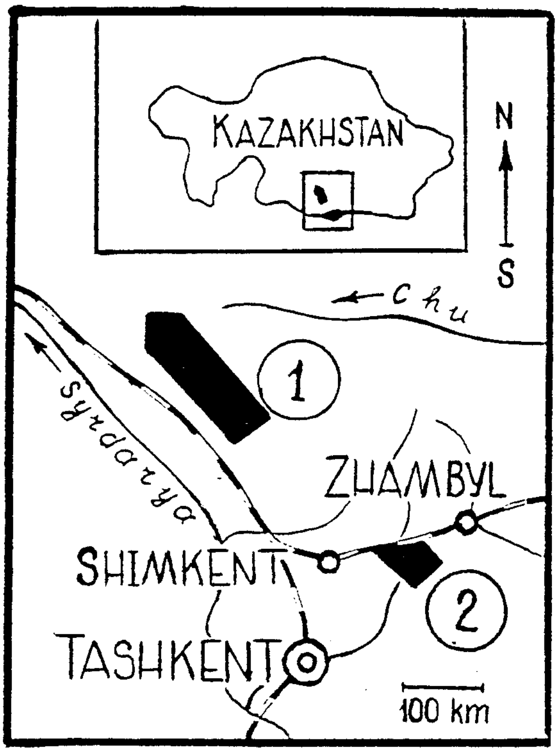


Fig. 1. Locations of mineralogical study: 1- northwest Karatau; 2- Zhabagly Mountains.

streaks consist of parallel crystal slices (elongated along a and b, flattened along c).

Physical Properties

Kazakhstanite is black; the powder is black with a brownish hue. Crystalline aggregates have an adamantine luster; dense aggregates in which crystallinity is indistinct have a dull luster. Mm-size crystals have perfect cleavage on (001). The mineral is dissolved by cold acids. Diluted KOH reveals grain boundaries in polished sections. After heating, the mineral loses 12.30% of its water. At 630°C the mineral fuses. The magnetic properties of the mineral cause mineral grains to cake. The crystals are too small for an accurate determination of hardness. The measured density (Dmeas.) is 3.4-3.6, the calculated (Dcalc.) density 3.65 g/cm^3.

Chemical Composition

Kazakhstanite crystals were analyzed with a JEOL 733 electron microprobe (Table 1). The chemical formula is:

$$Fe^{3+}_{5} V^{4+}_{3} V^{5+}_{12} O_{39} (OH)_9 \bullet 8.55 H_2O, Z=1$$

Thermal Data

The TG curve of a 38.8 mg sample shows continuous loss of mass. Four broad endothermic effects are marked on curve DTA at temperatures of 85°-160°, 370°-490°, 630° and 700° C. The first has two maxima (curve DTG): the main one at 115° and a weaker one at 160°C, with losses of mineral mass of 5.55 and 2.20%, respectively. The second has a series of weak endothermic maxima, divided by small temperature intervals. It was observed for vanadates (for instance, hewettite), as a result of combined phenomena of loss of water of hydration and oxidation of V^{4+} cations with formation of new phases. The TG curve shows that during heating at higher temperatures, there is a small but uniform loss of mineral mass, which is the result of the emission of water of hydration and volatility of vanadium. The endothermic peak 630° C is connected with fusion of the mineral. Total loss of mineral mass during heating is 13.50% (Table 2), including vanadium volatility. Data on thermal and thermo-X-ray diffraction analyses are given in Table 2.

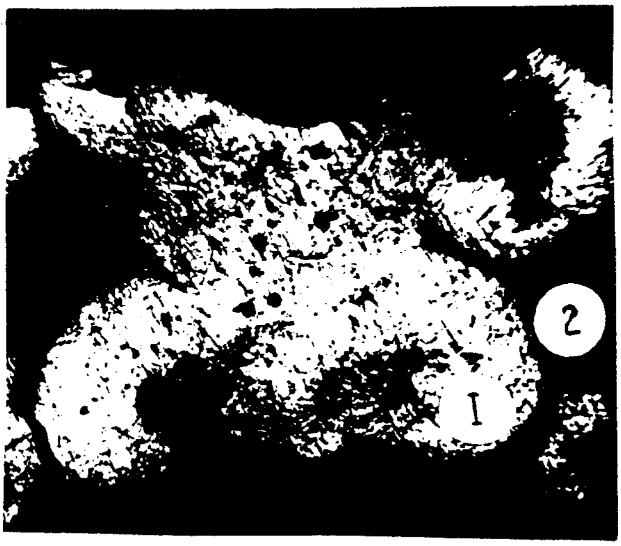


Fig. 2. Rounded formation of kazakhstanite: 1- on bedding plane of phthanite; 2- Polished section x 120.

Table 1. Chemical composition of kazakhstanite (wt%).

	1	2	3	4
K_2O	0.14	0.20	0.12	0.15
CaO	0.09	0.01	0.16	0.09
Fe_2O_3[3]	19.88	19.35	20.65	19.88
V_2O_4	12.88[1]			
	71.19	71.80	71.18	71.39
V_2O_5	55.10[1]			
P_2O_5	0.17	0.08	0.22	0.01
H_2O	12.50[1,2]			
Total	100.76			

[1] Data from wet analyses; [2] Data from thermal analyses - 12.30%;
[3] Mössbauer spectrum shows absence of Fe^{2+} in kazakhstanite structure.

Table 2. Loss of mass of kazakhstanite during heating.

Temperature °C	Loss of mass,%	Type of water, volatility of vanadium
20-80	—	—
80-115	5.55	water of crystallization
115-180	2.20	water of crystallization
180-300	1.10	water of crystallization
300-490	2.85	water of hydration
490-630	0.60	water of hydration
630-700	0.30	volatile
700-1000	0.90	volatile
Total	13.50	

Infrared-Absorption Spectroscopy

The infrared-absorption spectrum of kazakhstanite, obtained with a "Specord-75JR" spectrophotometer and recorded over the region 400-3800 cm^{-1} (Fig. 3), is distinct from published vanadate spectra, with absorption maxima at 470, 510, 715, 860, 1000 cm^{-1}, corresponding to vibrations of bonds V-O, Fe -O on polyhedrons in the lattice vibration region. The coordination number of the vanadium is difficult to ascertain, because it is necessary to take into consideration valence and the degree of polymerization in the crystal structure of the mineral in order to make a correct interpretation. For example, the band with a 1000 cm^{-1} maximum may belong to valence vibrations of bonds V-O in the chains of dipyramids (Povarennykh, Gevorkjan, 1970). Within valence band OH-groups, there are diffuse weak maxima at 3460, 3230, and 1615 cm^{-1}.

Crystallography

Electron microscopy reveals that crystals of kazakhstanite are subject to the influence of vacuum and electron beams, as expressed by shifts of extinctional contours (Fig. 4). This phenomenon can be explained by the irregular emission of water of crystallization without disturbance of the crystal structure of the mineral. Evidence of this fact is the lack of variability in electron diffraction patterns of a selected area of a single crystal exposed for a relatively long period to the influence of an electron beam (Fig. 5a).

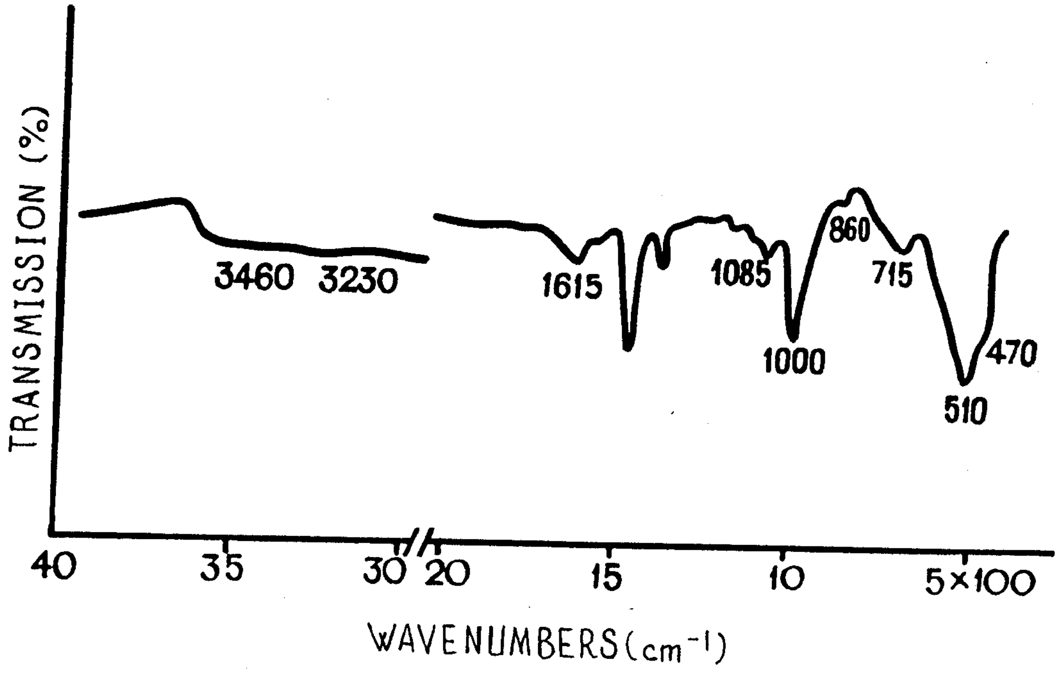


Fig. 3. Infrared-absorption spectrum for kazakhstanite.

Vanadates of NWK, such as bokite, Ca-barnesite, and hewettite, have similar selected-area electron diffraction patterns (Fig. 5b) because they have perfect (001) cleavage (crystals lie on (001)) and the a, b dimensions of the unit cell have similar values. In the electron diffraction patterns of kazakhstanite, 0k0, h00 reflections with k, h odd are absent. But oblique texture electron diffraction patterns (Wenk, 1976, p. 63) of the above-mentioned vanadates are distinctly different because of differences in values of parameters of the unit cell c and angle β.

The hk - indices of each ring node were deduced by comparing a normal texture pattern (Fig. 6a) with a selected-area pattern of a single crystal (Fig. 5a). Totality of ring nodes on normally oriented electron diffraction patterns (or arcs on the minor axis of obliquely oriented patterns, given by lengths of minor (tilt) axis b_{hk}), can be obtained from the common formula: where a, b, c, angle γ

$$b_{hk} = \frac{L\lambda}{\sin\gamma}\sqrt{\frac{h^2}{a^2}+\frac{k^2}{b^2}-\frac{2hk\cos\gamma}{ab}}$$

are parameters of the unit cell, Lλ is the camera constant, and hkl the indices (Zvyagin, 1967; Wenk, 1976). In the case of kazakhstanite, the length of the minor axis, b_{hk}, is proportional to the square root of $N=h^2 + 11\ k^2$, for an orthogonal (γ = 90°) base (Table 3).

Analysis of the oblique texture pattern (Fig. 6b) shows that the height of the maximum (Wenk, 1976, p. 64)

Fig. 4. TEM micrograph of kazakhstanite.

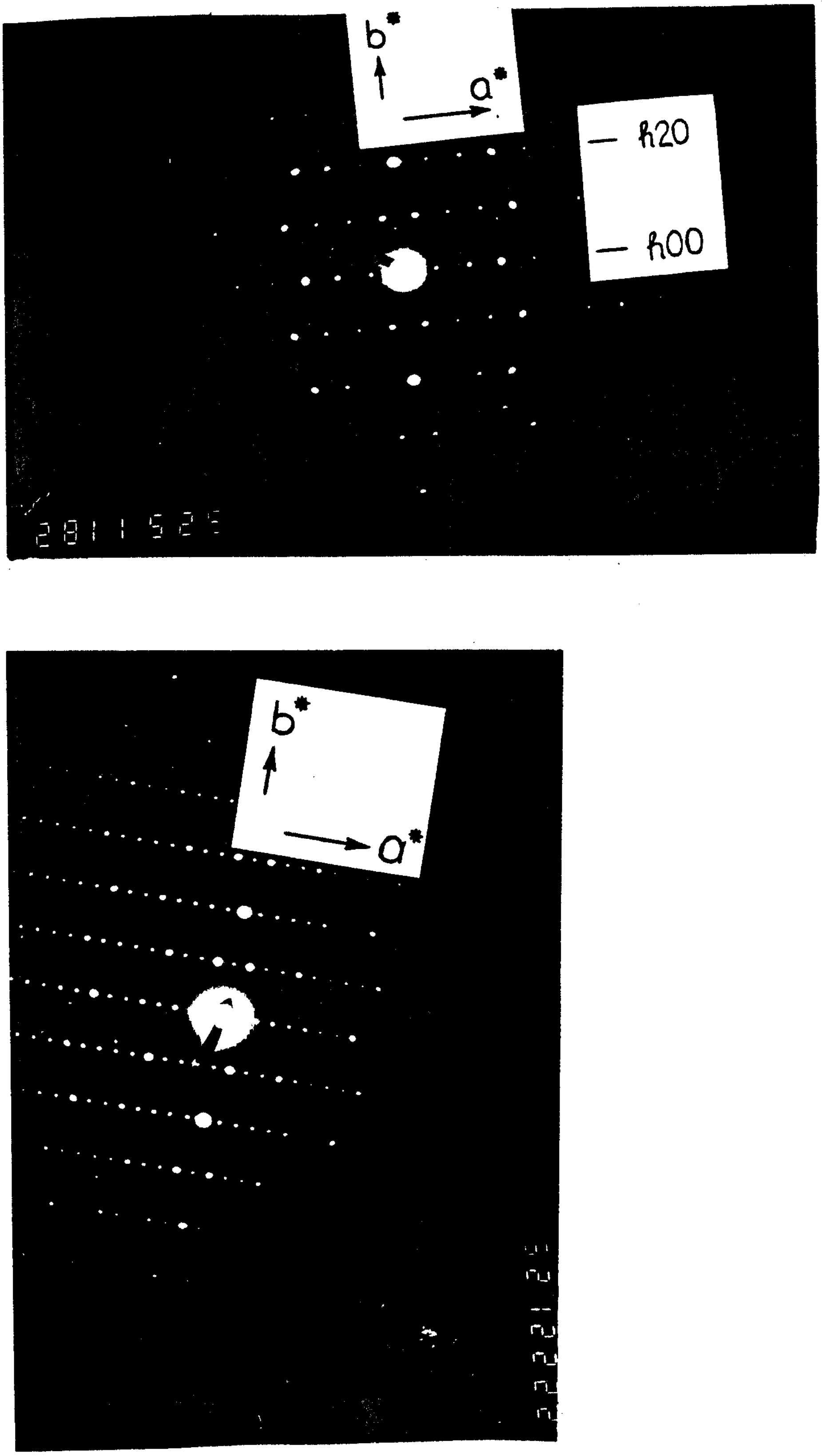


Fig. 5. Selected-area electron diffraction pattern: a- kazakhstanite; b- bokite.

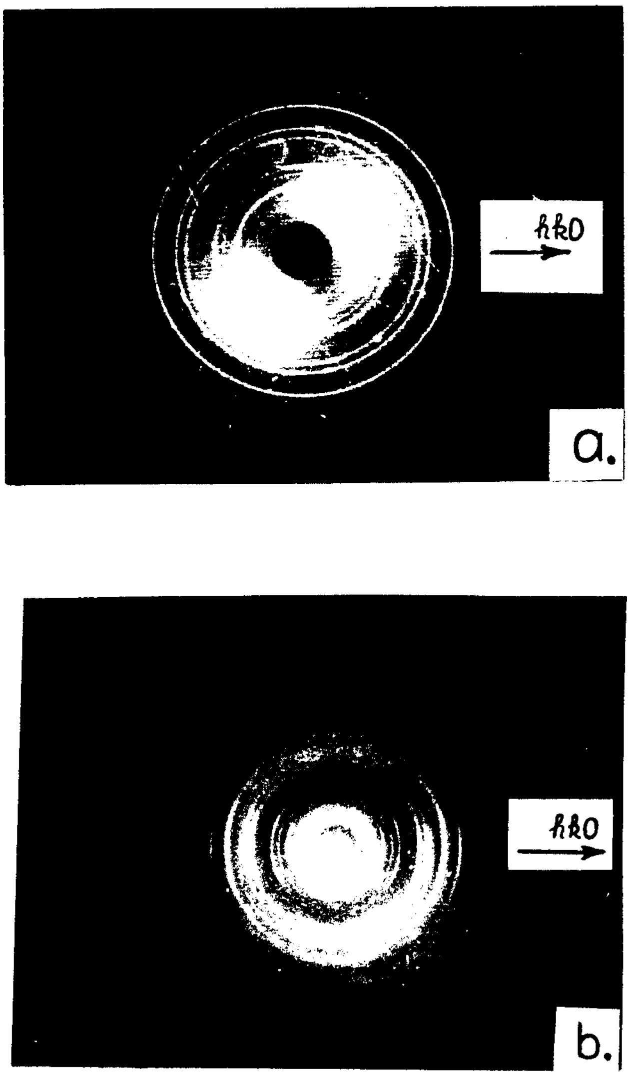


Fig. 6. a- normal texture electron diffraction pattern; b- oblique texture electron diffraction pattern of kazakhstanite.

of the arc above the minor axis is D=hp+lq, where p, q were measured in mm on the diffraction pattern. All arcs were then indexed, and *a, b, c*, β and V parameters of the unit cell were measured. The refined unit cell parameters on X-ray powder data (Table 4) Fig. 7) are a = 11.84(1), b =3.6500(4), c = 21.27(1) Å, β = 100.0(1)°, V = 905.5(1.9) Å^3. To establish the space-group of kazakhstanite, the observed reflections hkl, hol, 0k0 were compared. On the X-ray powder diffraction pattern, electron diffraction pattern reflections hkl, h+k=2n; h01, h,1=2n; 0k0, k=2n are represented. Hence it follows that the space-group of the mineral is C2/c or Cc.

Table 3. Sequence of ellipses of kazakhstanite.

	hk	N	d(meas.) Å
1.	20	4	
2.	11	12	3.463
3.	40	16	2.891
4.	31	20	2.581
5.	60,51	36	1.977
6.	02	44	1.825
7.	22	48	1.733
8.	71, 42	60	1.537
9.	80	64	
10.	62	80	1.342
11.	91	92	1.210
12.	10.0, 31	100	
13.	82, 33	108	1.156
14.	53	124	1.082
15.	11.1	132	1.033
16.	12.0, 10.2	144	0.988
17.	73	148	
18.	04	176	0.9138
19.	13.1, 93, 24	180	0.8868
20.	12.2	188	0.8669
21.	44	192	
22.	14.0	196	
23.	64	212	0.8286

Table 4. X-ray powder diffraction data for kazakhstanite.

Note: Operating condition — 35 kV, 20 mA, Cu-radiation. Intensities are estimated visually.

I	d(meas.) Å	khl	d(calc.) Å
10	10.51	002	10.466
1	5.527	$\bar{2}02$	5.527
1	3.593	204	3.587
6	3.484	110	3.483
		006	3.489
2	3.184	$\bar{1}13$	3.185
3	2.915	400	2.913
3	2.756	$\bar{1}15$	2.751
		404	2.763
1	2.691	$\bar{3}11$	2.680
		402	2.685
4	2.606	311	2.599
		115	2.610
2	2.095	0.0.10	2.093
2	1.971	$\bar{5}13$	1.970
1	1.931	511	1.929
2	1.825	020	1.825
1	1.792	408	1.794
1	1.528	1.1.12	1.527
		$\bar{7}11$	1.528

The values obtained for unit cell parameters c and angle β differ, depending on whether they are calculated from electron diffraction data or from x-ray powder diffraction data. For example, X-ray spacing d_{002} = 10.51Å, but spacings d_{002}, calculated from oblique texture and selected-area electron diffraction data, are 9.26 and 8.9 Å respectively. Similar values were obtained by X-ray diffraction at temperatures of 100° and 180°C. In order to determine the form of the water contained in the kazakhstanite crystal structure, X-ray diffraction patterns were obtained of the mineral as it was being heated. Temperatures were selected from thermal data. Fig. 8a-g shows X-ray diffraction patterns of oriented specimens of kazakhstanite. Heating to a temperature of 180°C, given the unstable crystal structure of kazakhstanite, causes changes connected with a loss of water of crystallization. On the X-ray diffraction pattern there is a decrease in the value of d_{002}, an expansion of lines, and a drop in intensities. Prolonged heating of the specimen causes additional loss of intensity of lines, a further decrease in the value of d_{002}, and the appearance of new lines (with d = 7.15 Å). These changes may reflect the transformation to a new structure. At a temperature of over 630°C, the mineral is destroyed. When cooled to 20°C, recrystallization occurs and a new phase (akin to schubnelite) appears.

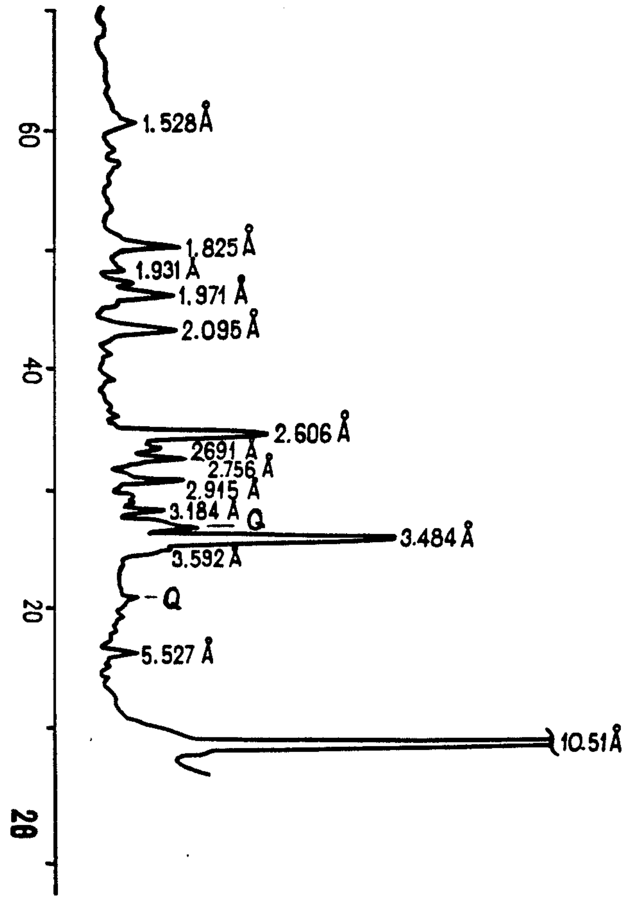


Fig. 7. X-ray powder diffraction pattern of kazakhstanite. Values of d are marked; Q denotes reflection from quartz.

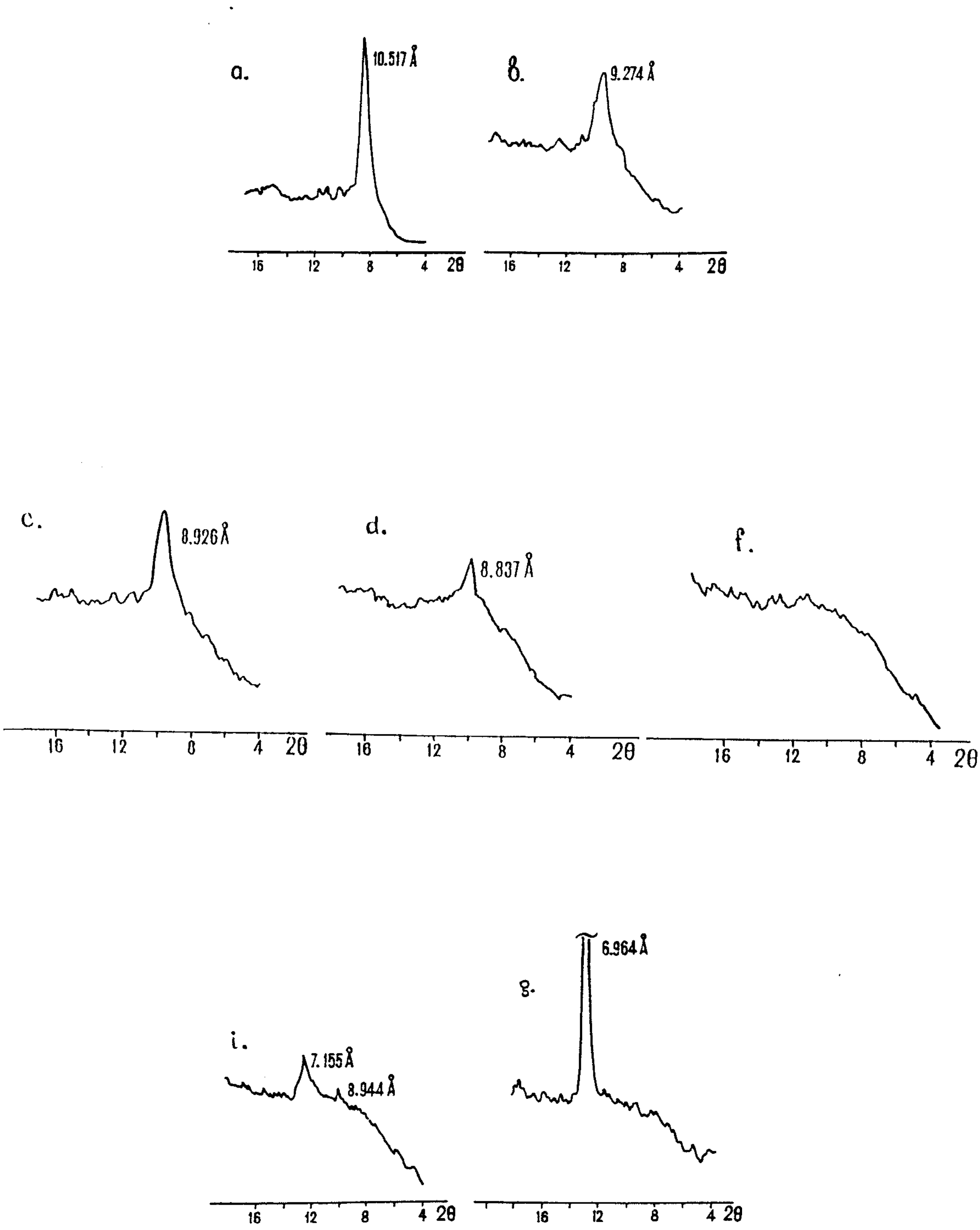


Fig. 8. X-ray powder diffraction patterns of kazakhstanite upon heating to different temperatures: a- 20°; b- 100°; c- 180°; d- 410°; e- 470°, f- 670°; g- 20°C.

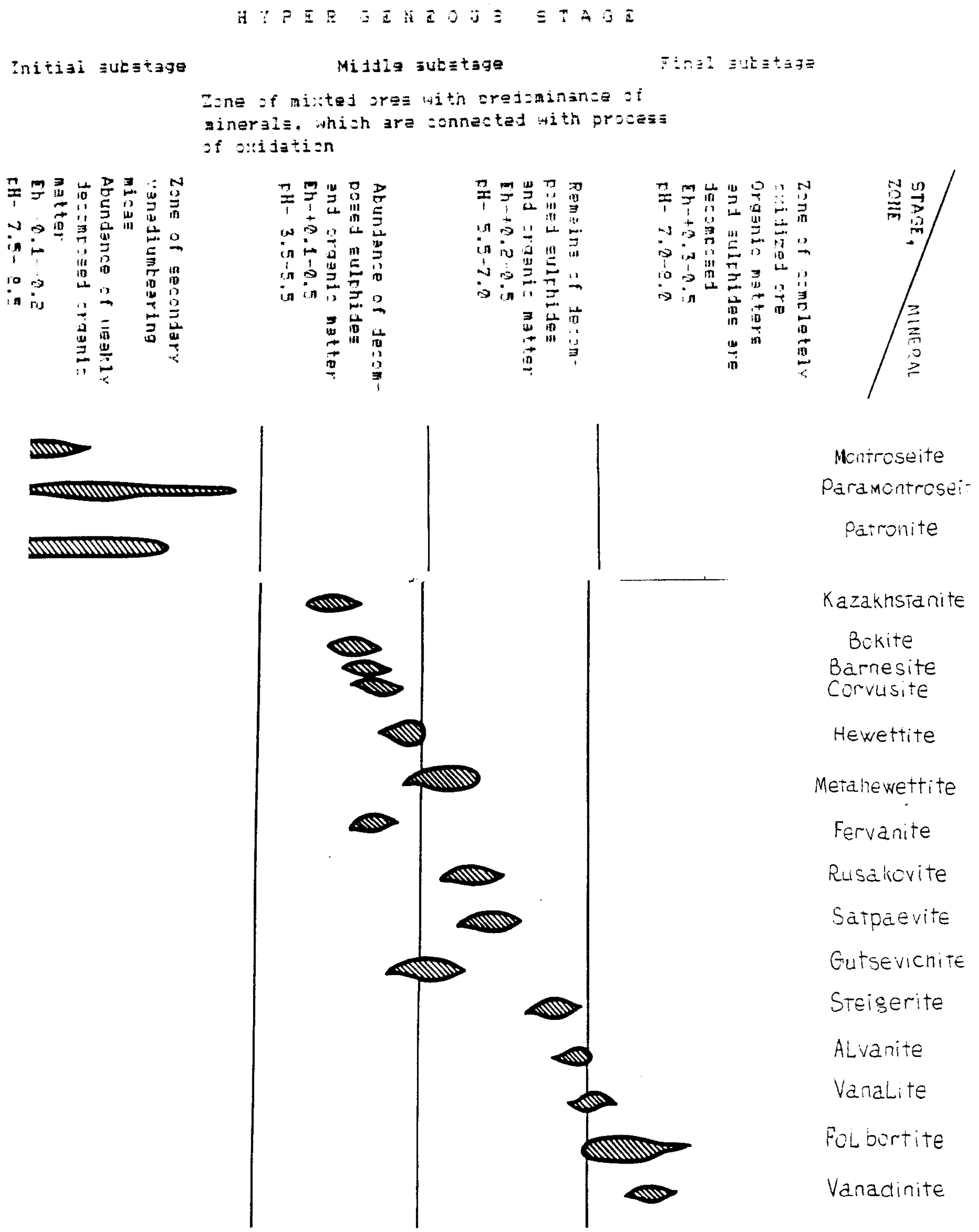


Fig. 9. Scheme of typical formation of vanadates in weathering zone of the vanadium-bearing deposits of NWK and Zhabagly Mountains.

The different values of unit cell parameters c and angle β, calculated from X-ray diffraction and electron diffraction data, can be explained by the influence of an electron beam and the vacuum of the electron microscope on the structure of kazakhstanite, which undergoes compression as water of crystallization is driven off.

These characteristics are typical of polyvanadates (for example, hewettite). Among the phyllovanadates that have been studied, under the influence of a high vacuum and an electron beam, barnesite is the most stable mineral.

Conditions of Formation

Kazakhstanite is typical of vanadium-bearing black shales that have been subjected to the relatively short but intense influence of surface agents (Fig. 9). Such conditions are typical of rocky outcrops in the Kurumsak, Balasauskandik, and Ran ore fields and in the Zhabagly Mountains. When a carbonaceous substance and dispersed patronite, as well as disseminated pyrite, are exposed to rapid oxidation under such conditions, sulfate solutions tend to form which are enriched in vanadium and iron and very mobile. Solutions deposit kazakhstanite and goethite in cracks as a result of the relatively abrupt knickpoint of the pH curve. Some solutions are especially reactive to certain carbonaceous pelitic shales, forming patches of metasomatites as a result. Later, as a result of the influence of HCO_3 and destruction of the micaceous substance of shale, crusts of bokite, jarosite and alunite begin to form, closely interlacing to aggregates. At a more advanced stage in the process and in a more oxidative environment, barnesite with tetravalent vanadium as a minor constituent crystallizes from solution. Hewettite and metahewettite then form in a loose aggregate of kaolinite, vashegyite, and variscite, with an abundance of silico-phosphor-vanadium-aluminium-bearing colloids, when calcic carbonic acid solutions are introduced.

Correlation with Other Mineral Species

Kazakhstanite belongs to the polyvanadates (Evans, 1959), and to the phyllovanadate structural group (Shtruns, 1989). All vanadates of this group have similar unit cell parameters, *a* 11.6-12.6 Å, *b* 3.59-3.67 Å, because their structure is based on V_6O_{16} layers. Phyllovanadates are listed in order of increasing parameter *c* in Table 5. Kazakhstanite is difficult to distinguish from bokite (Ankinovich, 1963) because the two are so closely intergrown. They may be differentiated by the application of the diffraction method of electron microscopy. Comparison of selected-area diffraction patterns of kazakhstanite (Fig. 5a) and bokite (Fig. 5b) shows that, unlike the former, bokite has all reflections (even, odd) h00, 0k0. The presence of all reflections explains the larger number of ellipses on the electron diffraction pattern of bokite compared with the pattern of kazakhstanite. But it is impossible to determine unit-cell parameter *c* and angle β of bokite, because it is difficult to obtain good obliquely oriented electron diffraction patterns, perhaps because of bokite's imperfect structure or its water of crystallization, which is emitted under vacuum and the high temperature of the electron beam. Although the values of the unit-cell parameters *a* and *b* of both minerals are similar (bokite has d_{100} =12.25, d_{010} = 3.64Å, according to selected-area diffraction data and d_{001} =10.19Å, according to X-ray diffraction data), their space-groups are different, as in the case of minerals such as hewettite and metahewettite.

Acknowledgments — We gratefully acknowledge Dr. B.B. Zvyagin and colleagues of the laboratory of electron microscopy of the Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry (Moscow) for assistance in obtaining obliquely oriented electron diffraction patterns of kazakhstanite, and T.A. Shabanova, S.L.Terekhovich, I.B. Samatov, P.E. Kotelnikov, T.D. Netalieva, B.A. Savostin, and N.M. Mitryaeva of the Institute of Geological Sciences of the National Academy of Sciences of the Republic of Kazakhstan, who collaborated with us in this study of kazakhstanite. We are also grateful to A.E.M. Nairn, Peter Margolin, and M. K. Apollonov for improving the English of this paper.

Table 5. Comparative data on the phyllovanadates.

N	Mineral	Chemical formula, z	Density g/cm^3
1.	Barnesite	$Na_2V_6O_{16} \bullet 3H_2O$	
2.	Ca-barnesite	$(Na_{2-2n}Ca_n)(V^{4+}V^{5+})(O_{16-n}OH_n)_{16} \bullet 2.5\ H_2O$, 1	3.09
3.	Na-Ca-metahewettite	$NaCa_{0.5}V_6O_{16} \bullet 2H_2O$, 1	2.89
4.	Alaite	$V_2O_5 \bullet H_2O$, 3	
5.	Grantsite	$Na_4CaV_{12}O_{32} \bullet 8H_2O$, 1	2.94
6.	Metahewettite	a. $CaV_6O_{16} \bullet 3H_2O$, 2; b.	2.942 2.94
7.	Bokite	$(Al,Fe)_3(V^{4+}, V^{5+})_9O_{26} \bullet 10H_2O$	
8.	Kazakhstanite	$Fe^{3+}_5 V^{4+}_3 V^{5+}_{12} O_{39} (OH)_9 \bullet 8.55H_2O$, 1	3.52
9.	Hewettite	a. $CaV_6O_{16} \bullet 9H_2O$; b.; c.	2.51
10.	Bariandite	$V_5O_{12} \bullet 6H_2O$, 2	2.7
11.	Navajoite	$\div V_2O_5 \bullet 3H_2O$, 6	3.04
12.	Hendersonite	$Ca_2V^{4+}_{1+x} V^{5+}_{8-x} O_{24} \cdot 8H_2O$, 4	2.79

Note: 1- Weeks et al., 1963; 2- Ankinovich and Podlipaeva, 1986; 3- Bachmann and Barnes, 1962; 4- Annenkova et al., 1976; 5- Weeks, 1961; 6a- Hillebrand et al., 1914, Qurashi, 1961; 6b- Bayliss and Warne, 1979; 7- Ankinovich, 1963; 8- Ankinovich et al., 1989; 9a- Hillebrand et al., 1914; 9b- Bayliss, 1982; 9c- Evans, 1989; 10- Cesbron and Vachey, 1971; 11- Weeks and Thompson, 1954; 12- Lindberg et al., 1962; Ross, 1959.

Table 5 (continued)

	Color	Optical Data			Unit-cell parameters			
		Ng	Np	Nm	a, Å	b, Å	c, Å	β, °
1.	dark red	>2.0	1.797	2.0	12.17	3.602	7.78	95°2'
2.	cherry red, brown-red	2.04-2.08	1.80	2.01-2.04	12.152	3.590	7.908	95°48'
3.					12.26	3.58	8.11	92.5
4.	violet-brown	2.06	1.774		12.66	3.61	8.30	98
5.	green	>2.0	1.83	2.0	12.41	3.60	17.54	95.25
6.	red	2.23	1.70	2.10	12.25	3.615	18.54	118
		2.23	1.70	2.10	12.15	3.607	18.44	118°02'
7.	brown-black				d_{100} = 12.25	d_{010}= 3.64	d_{001}= 10.19	
8.	black				11.84	3.650	21.27	100
9.	red	2.4	1.77	2.18	12.56	3.615	11.47	97
					12.25	3.497	11.174	97.25
					12.29	3.590	11.174	97.24
10.	black		>1.85		11.70	3.63	29.06	101.5
11.	gray-brown	2.02		1.905	12.25	3.65	17.43	97
12.	green-black	>2.01	<2.0	>2.01	12.40	18.92	10.77	90

	Space-group	X-ray diffraction data, Å
1.	P2/m, P2	12.28-7.9-3.12-3.45-2.27-1.800
2.	P2/m, P2	12.09-7.84-3.89-3.455
3.	P21/m, P21	
4.		8.22-4.18-3.47-3.12-3.04-1.805
5.	C2/m, Cm, Cc	12.4-8.76-4.34-3.67-2.715-2.24
6.	A2/m	8.19-3.578-3.062-2.812-2.295-2.206
7.		10.19-3.44-2.91-1.826
8.	C2/c, Cc	10.51-3.484-2.915-1.825
9.	P2/m	11.03-5.63-5.53-3.66-3.093-2.574
10.	C2/c, Cc	14.2-5.72-3.48-3.43-2.85
11.		12.1-10.6-5.79-4.35-2.90
12.		9.45-4.70-3.24-3.11-2.79

References

Ankinovich, E.A., 1963. A new vanadium-bearing mineral — bokite: Zapiski of All-Union Mineralogical Society, v. 1 p. 57-59 (in Russian).

Ankinovich, E.A., and Podlipaeva, N.I., 1986. Ca-variety of barnesite from rocks of carbonaceous-siliceous vanadium-bearing formation of Southern Kazakhstan: Zapiski of All-Union Mineralogical Society, v. 3, p. 345-351 (in Russian).

Ankinovich, E.A., Bekenova, G.K., and Podlipaeva, N.I., 1989. A new hydrated ferro-vanadium-bearing mineral kazakhstanite, from a carbonaceous-siliceous formation of northwest Karatau (southern Kazakhstan): Zapiski of All-Union Mineralogical Society, v. 5. p. 95-100 (in Russian).

Annenkova, G.A., Organova, N.I., Rudnitskaya, E.S., Platonov, A.N., Dobrovolskaya, M.G., Dmitrik, A.L., 1976. Alaite from Mineralogical Museum of Academy of Sciences USSR: New data on minerals of USSR, Issue 25, p. 117-123 (in Russian).

Bachmann, H.G., and Barnes, W.H., 1962. The crystal structure of a sodium-calcium variety of metahewettite: Canadian Mineralogist, 7, p. 219-235.

Bayliss, P., 1982. X-ray powder data for hewettite: Mineralogical Magazine, 46, 341, p. 503-504.

Bayliss, P., Warne, S.S., 1979. X-ray powder data for metahewettite: Mineralogical Magazine, 43, p. 550.

Cesbron, F., Vachey, H., 1971. La bariandite, nouvel oxide hydrate de vanadium (4), (5): Bulletin de la Societe francaise de Mineralogie et de Cristallogr., 94, 1, p. 49-54.

Evans, H.T., 1959. The crystal chemistry and mineralogy of vanadium. Part 7: US Geological Survey Prof. Pap. 320, p. 91-102.

Evans, H.T., 1989. The crystal structure of hewettite: Canadian Mineralogist, 27, 2, p. 181-188.

Hillebrand, W.F., Merwin, H.E., and Wright, F.E., 1914. Hewettite, metahewettite and pascoite, hydrous calcium vanadates: Proceeding American Philosophical Society, 53, p. 31-54.

Lindberg, M.L.,Weeks, A.D., Thompson, M.E., Elston, D.P., and Meyrowitz, R., 1962. Hendersonite, a new calcium vanadyl vanadate from Colorado and New Mexico: American Mineralogist, v. 47, p. 1252-1272.

Povarennykh, A.C., and Gevorkjan, S.V., 1970. Peculiarities of infrared-absorption spectra: Mineralogical Issue Lvov' University, 24, v. 3, p. 254-260 (in Russian).

Ross, M., 1959. Mineralogical applications of electron diffraction. 2. Studies of some vanadium minerals of the Colorado Plateau: American Mineralogist, 44, p. 322-341.

Strunz, H., 1989. Versuch einer Klassifikation der Vanadate: Ber. Dtsch. Mineralog. Ges, 1, p. 214-215.

Weeks, A.D., 1961. Mineralogy and geochemistry of vanadium in the Colorado Plateau: Journal Less Common Metals, 3, p. 443-450.

Weeks, A.D., and Thompson, M.E., 1954. Identification and occurrence of uranium and vanadium minerals from Colorado Plateau: US Geol. Survey Bulletin, 1009-B, p. 13-62.

Weeks, A.D., Ross, D.R., and Marvin, R.F., 1963. The occurrence and properties of barnesite $Na_2V_6O_{16} \cdot 3H_2O$, a new hydrated sodium vanadate mineral from Utah: American Mineralogist, v. 48, p. 1187-1194.

Wenk, H.R. (ed.), 1976. Electron Microscopy in Mineralogy: Springer-Verlag, Berlin, Heidelberg, New York, 564 p.

Zvyagin, B.B., 1967. Electron-diffraction analysis of clay minerals: New York, Plenum Press, 282 p.

Mineral Resources of Ordovician Rocks in Kazakhstan and Kirgizia

M.K. Apollonov

Abstract

Ordovician mineralization (lead, zinc, copper, gold, barite, phosphate, etc.) plays an important role in the mineral resources of Kazakhstan and Kirgizia. The distribution of Ordovician mineral deposits was clearly influenced by the character of the paleotectonic structures. There were two geological and metallogenic epochs — Early Ordovician (including Llanvirnian) and Late Ordovician — both associated with a characteristic tectonic regime and metallogeny. Mineralization in the Ordovician sialic median massifs, ocean-like basins, and volcanic arcs is comparable to analogous modern structures.

Introduction

Few, if any, papers have been published on the mineral resources of the Ordovician in Kazakhstan and Kirgizia. Descriptions of Ordovician mineral deposits are scattered in many publications on mineral resources of the Precambrian and Paleozoic of Kazakhstan and Kirgizia. The most important is the 10-volume monograph "Metallogeny of Kazakhstan", edited by A.K. Kayupov and published from 1977 to 1983. Short reviews of Ordovician mineralization are included in some generalized monographs and papers (Abdulin and Shlygin, 1983; Abdulin, 1987; Abdulin et al., 1987; Asanaliev, 1984; Kayupov et al., 1989; Nikitin, 1973).

The purpose of this paper is to give a short review of Ordovician mineral resources in Kazakhstan and Kirgizia.

Mineral Resources

The various types of Ordovician mineralization in Kazakhstan and Kirgizia are clearly associated with regional geologic structures of definite genesis and age. Such relationships have long been the basis of study of the metallogeny of Kazakhstan (Satpaev, 1953; Kayupov et al., 1989a, b), but association of mineralization and paleogeographical and paleotectonic environments has not been as intensively studied in Kazakhstan and Kirgizia as it has in many other regions of the world (Kovalyov, 1985; Mitchell and Garson, 1984) (see Fig. 1).

The geological history of the Ordovician in Kazakhstan and Kirgizia is divided into two distinct epochs: Early (including the Llanvirnian) and Late Ordovician. The epochs have different tectonic regimes and are separated by a major geotectonic reorganization (Apollonov and Patalakha, 1989), and the paleotectonic environments and mineralization are distinct in each epoch.

Two ancient sialic median massifs (microcontinents) — the Kokchetav-Issykkol and Balkhash massifs — formed the general framework of the tectonic structure of Kazakhstan and Kirgizia in the Early Ordovician (Fig. 2). The massifs were divided by a wide, ocean-like basin (inner sea). The present Ermentau-Buruntau fold zone corresponds to this ancient basin. The Urals ocean existed to the west, and the Chingiz-Tarbagatai ocean-like basin with its island chain existed to the east. The epoch was characterized by an extensional tectonic regime.

Thin, deep-water, black shales, cherts, and limestones were deposited on the submerged parts of the median massifs (shelf, continental slope, and adjacent parts of basinal plain-Ishim-Karatau-Naryn and Atasu-Dzhungar zones). The large deposits of lead, zinc, some barite, minor manganese, and iron mineralization poor in nickel, copper, and cobalt are related to these sediments. Black metalliferous shales with moderate amounts of vanadium, molybdenum, phosphorous, and other elements are common. Dispersed gold was deposited in terrigenous and carbonaceous-cherty sediment on the outer parts of the Kokchetav block.

Large hydrothermal-sedimentary barite deposits and smaller deposits of iron-manganese ores poor in nickel, copper, and cobalt formed in deep-water cherty and cherty-terrigenous sediments in the Ermentau-Buruntau Basin. Such mineralization occurs in oceans along fracture zones under extensional conditions (Mitchell and Garson, 1981; Kovalyov, 1985). Early Ordovician (including Llanvirnian) mineral deposits are rare in the ocean-like Chingiz-Tarbagatai Basin and are represented by poor, iron-manganese mineralization.

Regional extension was superseded by compression in the Late Ordovician. The geological structure of Kazakhstan and Kirgizia was utterly changed as a result of this

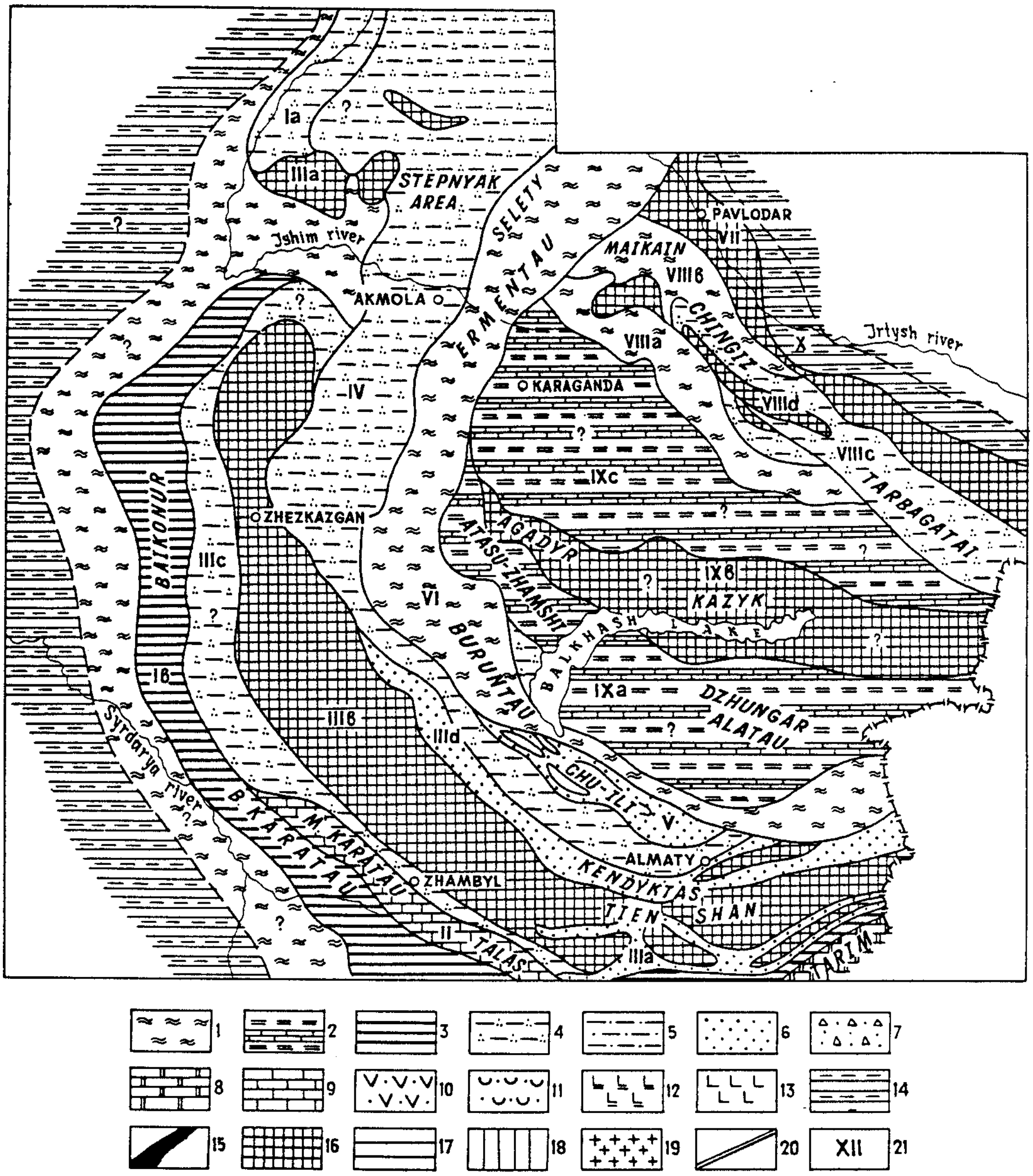


Fig. 1. 1:10,000,000- Paleotectonic map of Early Ordovician (Tremadocian, Arenigian, and Llanvirnian). 1- deep-water red jaspers, green, grey, and white cherts with layers of siliciclastics and (rare) volcanic rocks; 2- deep-water phthanites, black shales, and carbonates; 3- mainly deep-water green, yellow, and black shales, members and layers of black cherts and limestones; 4- moderately deep-water and shallow-water, mainly light quartz-feldspathic sandstones, siltstones, mudstones, layers of acidic tuffs, and tuffites; 5- mainly deep-water alterations of green and grey sandstones, mudstones with conglomerate layers and lenses (flysch); 6- mainly shallow-water grey sandstones and mudstones with carbonate buildups (marine mollasse); 7- mainly deep-water conglomerates, sandstones, mudstones, olistostromes; 8- shallow-water carbonates (cover of Precambrian massif); 9- carbonates of the sea mounts; 10- volcanic rocks of variable composition and siliciclastic rocks of volcanic arcs; 11- tuffs, siliciclastic, and tuffogenous rocks; 12- jasper-basaltic association; 13- basalts; 14- presumed deep-water, oceanic-like deposits in pure exposed areas; 15- exposed ophiolites; 16- denudated Precambrian covered by shallow-water marine; 17- denudated cover of Precambrian sialic massifs; 18- denudating or covered by shallow-folded and uplifted marine beds; 19- Late Ordovician granodiorite massives; 20- presumed position of the Benioff zone; 21- numbers of main zones: I- Ishim-Karatau-Naryn Zone: Ia- Maryevka Subzone, Ib- Karatau-Naryn subzone; II- Malyi Karatau-Talas Zone; III- Kokchetav-Issyk-Kul Massif: IIIa- Kokchetav Block, IIIb- Ulutau-Issyk-Kul Block, IIIc- west slope, IIId- east slope; IV- Akmola-Almaty Zone; V- Zheltau Massif; VI- Ermentau-Buruntau Zone; VII- Pavlodar Massif; VIII- Chingiz-Tarbagatai Zone: VIIIa- Akchatau Basin, VIIIb- Maikain-Kendykty Basin, VIIIc- East Chingiz-Tarbagatai Basin, VIIId- Kanchingiz Uplift; IX- Balkhash Massif: IXa- Atasu-Dzhungar Basin, IXb- Agadyr-Kazyk Uplift, IXc- Area of presumed Cambrian-Lower Ordovician cover of the Balkhash Massif; X- Zaisan Zone.

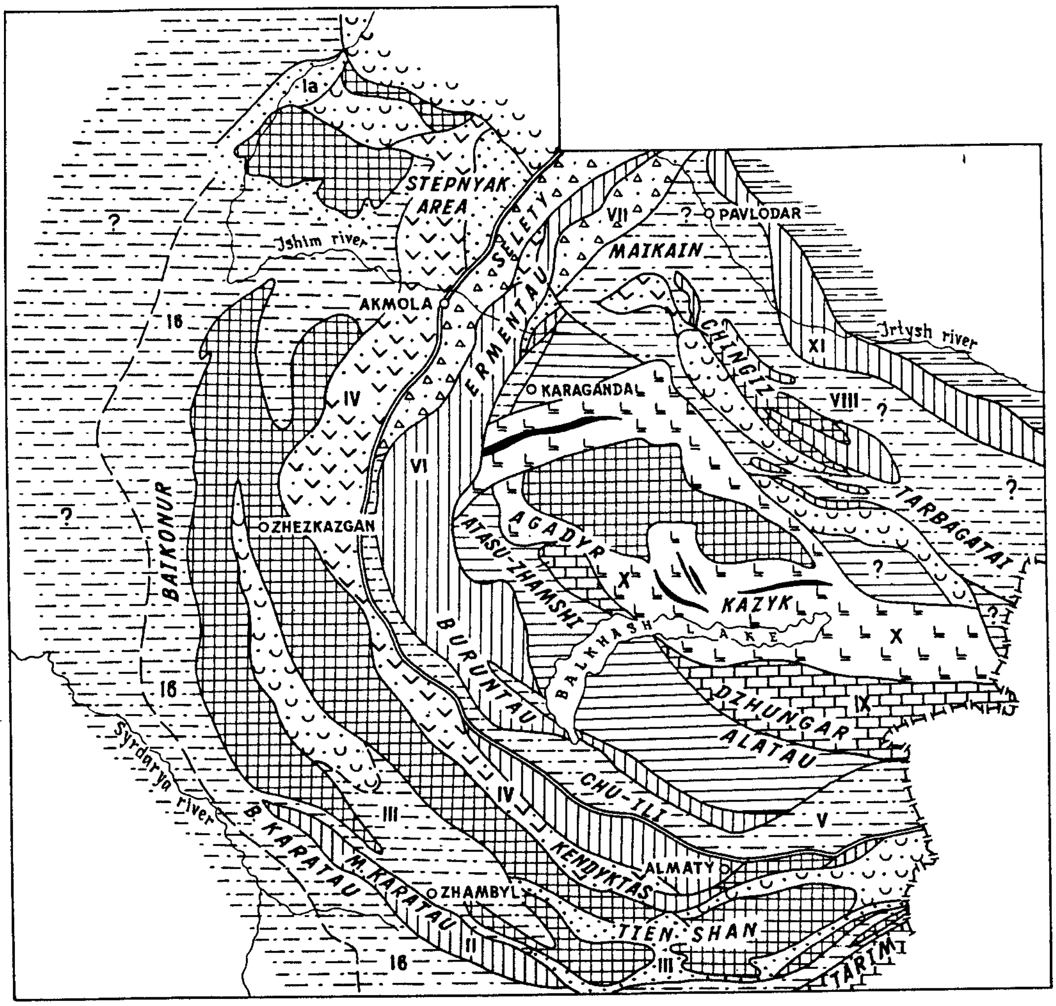


Fig. 2. Paleotectonic map of early Late Ordovician (Llandeilian). Lithological explanations are the same as Fig. 1. Main structures: I- Ishim-Karatau-Naryn Zone: Ia- Maryevka Subzone, Ib- Karatau-Naryn Subzone; II- Malyi Karatau Zone; III- Eskuly-North Tien Shan Zone; IV- Stephyak-Betpakdala Zone; V- Selety-Syugaty Zone; VI- Ermentau-Buruntau Zone; VII- Shiderty Zone; VIII- Chingiz-Tarbagatai Zone; IX- West Balkhash (Atasu-Dzhungar) Zone; X- East Balkhash (Agadyr-Kazyk) Zone; XI- Zaisan Zone.

compression (Figs. 2, 3). The oceanic crust of the Ermentau-Buruntau Basin began to be buried under the Kokchetav and Ulytau-Issykkol massifs along a Benioff zone. The Lower Ordovician (including Llanvirnian) deep-water, cherty deposits were separated from the basalt base and compressed and uplifted into a high cordillera. The cordillera was framed by the deep Selety-Chu-Ili flysch and olistostrome basin in the west. The Stepnyak-Betpakdala volcanic island arc formed along the eastern edge of the Kokchetav and Ulytau-Issykkol massifs far to the west. An analogous arc formed in place of the Chingiz-Tarbagatai Basin. The oceanic-like Agadyr-Kazyk belt was created in the Middle Ordovician as a result of disruption of the Balkhash massif. The generalized Ordovician stratigraphy of Kazakhstan is outlined in Fig. 4, where the attempt is made to show the location and the characteristic mineralization in time and place.

Gold-tellurium, gold-quartz, iron-skarn, and copper-porphyry mineralization are characteristic of the volcanic arcs. Phosphate deposits were formed in carbonate build-ups over the volcanic uplifts. Gold of possible alluvial origin is characteristic of the terrigenous sediments of the Selety-Chu-Ili Basin.

Pyrite, copper-polymetallic mineralization with gold, and barite were formed in volcanic formations of contrasting compositions in the Chingiz-Tarbagatai volcanic island arc. Deposits of lead and zinc became associated with thick carbonate formations in the outer parts of the Balkhash massif in the Dzhungar Alatau and northern Balkhash regions. Deposits of iron, manganese, and cop-

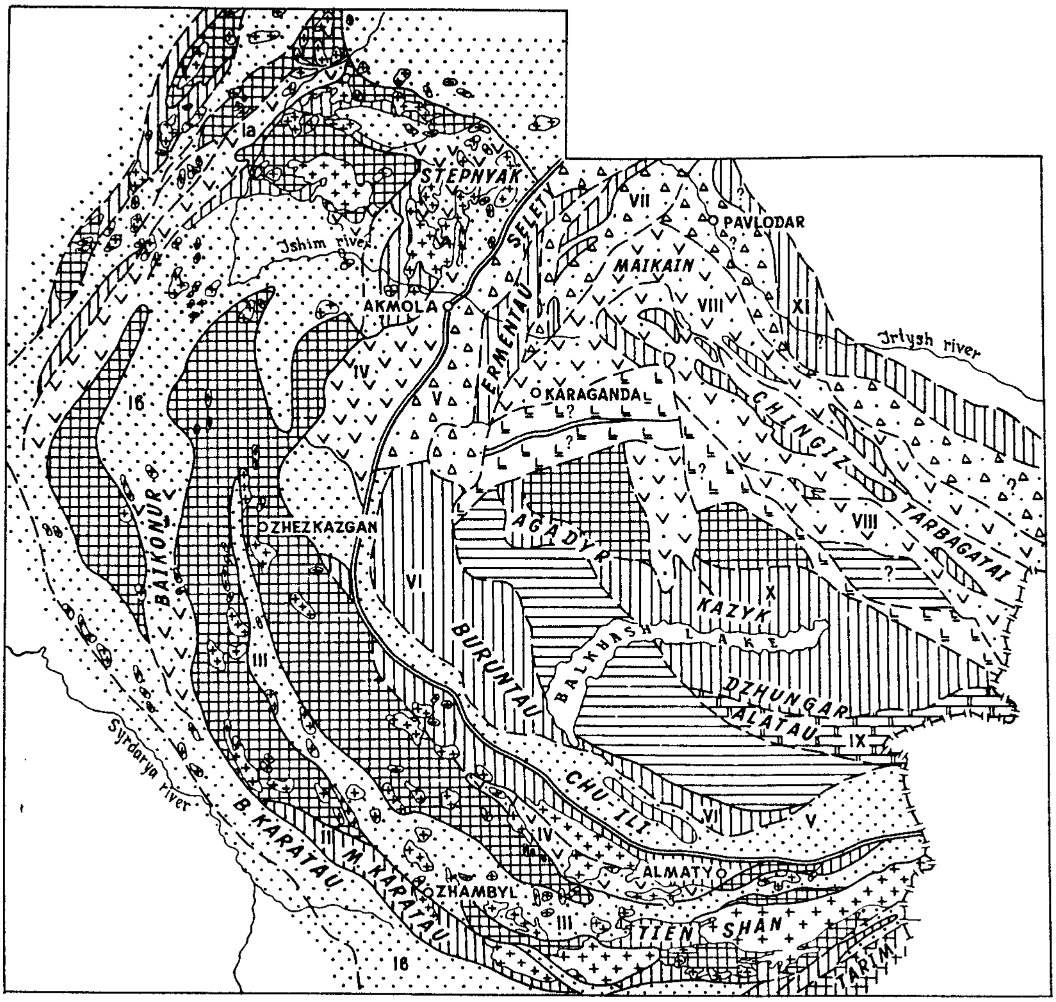


Fig. 3. Paleotectonic map of late Late Ordovician (Caradocian and Ashgillian). Explanations are the same as Fig. 2.

per, characteristic of the oceanic-like Agadyr-Kazyk Basin, are common in such structures (Mitchell and Garson, 1981; Kovaljov, 1985). The stratigraphic position of main types of mineralization is shown in Fig. 4.

Gold

Most Ordovician gold deposits in Kazakhstan are located in the northern region, north of the Stepnyak-Betpakdala and Selety-Chu-Ili belts (Abdulkabirova et al., 1971). Small gold deposits are known to the south in the Chu-Ili and Kendyktas Mountains and also in the northwestern part of the Chingiz-Tarbagatai belt (Tortkuduk and Maikain areas).

Northern Kazakhstan is one of the ancient centers of gold mining. Ancient excavations have been found in practically all gold deposits.

Many of the small- and medium-sized deposits (such as Stepnyak, Zholymbet, Aksu, Kvartsitovyye gorki, Zhanatobe, Danilovka, and Bestobe) constitute the Stepnyak (or Stepnyak-Bestobe) group of gold-sulfide-quartz deposits (Abdulkabirova et al., 1971). Most gold deposits are connected with terrigenous, sometimes cherty, Lower and Upper Ordovician rocks. In some cases, gold is associated with carbonaceous sediments. Gold deposits are represented by zones of enrichment in dispersed gold, metamorphic ore-bearing veins, and vein zones and ore folds. The quartz vein type predominates (Maulenov, 1969, 1991). Antimony, arsenic, and tellurides are associated with the gold.

The most typical Stepnyak deposit is localized in hornfelsic terrigenous lower part of the Upper Ordovician rocks, intruded by diorites of the Stepnyak complex. The deposit is formed by quartz veins with beresite halos. Pyrite, arsenopyrite, and tellurides are typical of this deposit.

The genesis of gold mineralization in the region is under review. The majority opinion is that all deposits are hydrothermal and that the Stepnyak diorites are the source of the gold (Abdulkabirova et al., 1971; Kayupov et al.,

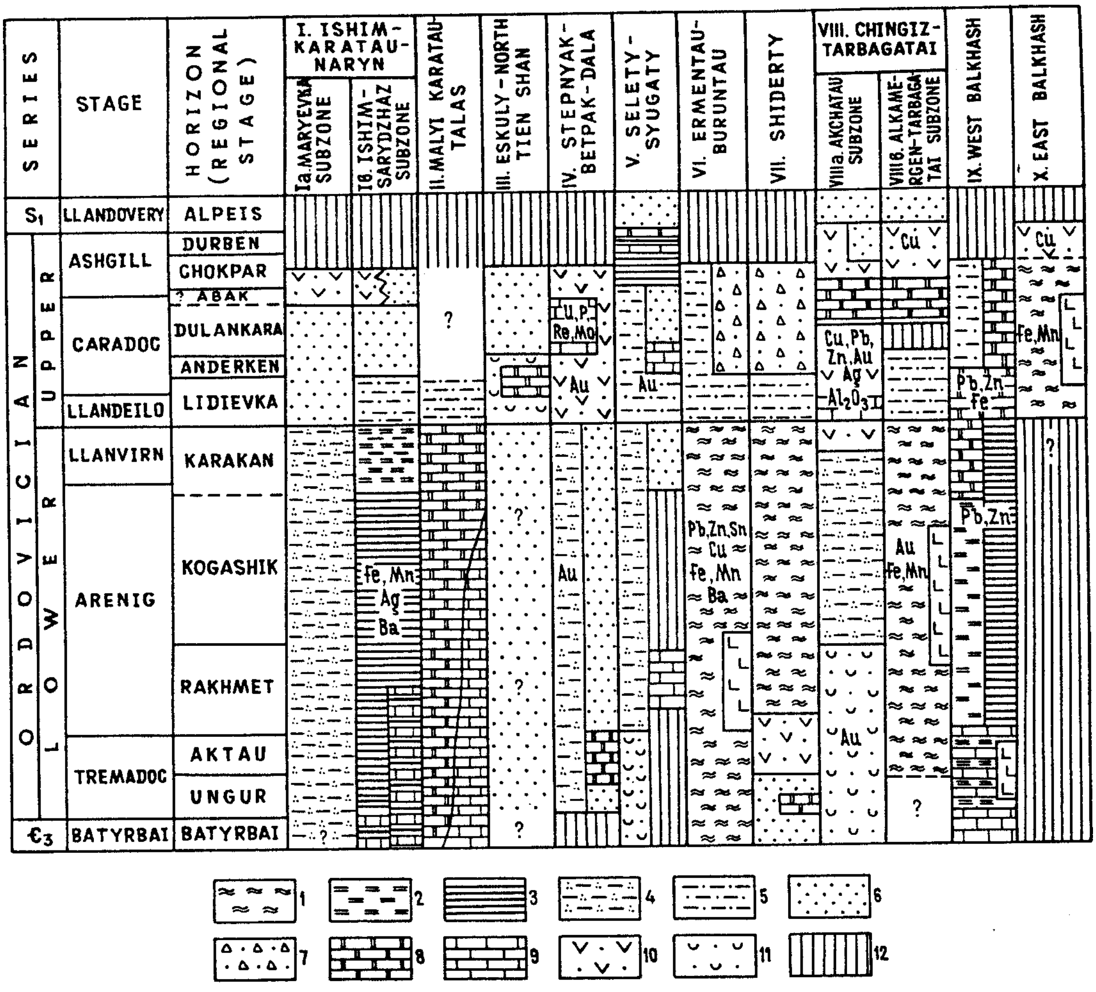


Fig. 4. Generalized Ordovician successions of Kazakhstan showing the most characteristic ore mineralization. 1- deep-water red jaspers; green, grey, and white cherts with layers of siliciclastics and (rare) volcanic rocks; 2- deep-water phthanites, black shales; 3- mainly deep-water green, yellow, black shales with layers of black cherts and limestones; 4- moderately deep-water and shallow-water mainly light quartz-feldspathic sandstones, siltstones, mudstones, layers of acidic tuffs, and tuffites; 5- mainly deep-water alterations of green and grey sandstones, mudstones with conglomerate lenses and layers (flysch); 6- mainly shallow-water grey sandstones and mudstones with carbonate buildups (marine molasse); 7- conglomerates, sandstones, mudstones, olistostromes; 8- deep-water carbonates; 10- volconic rocks of various composition and siliciclastic rocks of volcanic arcs; 11- tuffs, Euffaceaus, and siliciclastic rocks; 12- periods of non-deposition; Ag- silver; Au- gold; Al_2O_3- bauxite; Ba- barium; Cu- copper; Fe- iron; Mn- manganese; Mo- molybdenum; P- phosphorus; Pl- lead; Re- rhenium; U- uranium; Zn- zinc.

1989; and others). Some geologists (e.g., Maulenov, 1969, 1991) object that intrusive rocks are absent in many deposits. Nevertheless, intrusions were probably the heat source, permitting regeneration of dispersed gold and the formation of economic concentrations.

Sulfide minerals (usually pyrite and arsenopyrite) are always associated with and are bearers of gold. Some deposits are connected with highly carbonaceous black shales, but most vein-type, gold deposits are tied to moderately or weakly carbonaceous formations (Maulenov, 1991).

Copper

Copper, usually in combination with other metals, is rather common in the Ordovician of Kazakhstan and Kirgizia. The most important deposits are in the Chingiz-Tarbagatai belt; lesser deposits are found in northern Kazakhstan and in the northern Balkhash regions, and also in the Kendyktas Mountains in southern Kazakhstan.

Pyrite-polymetallic deposits are known in northeast-central Kazakhstan in the central and northwestern areas of the Chingiz-Tarbagatai belt (Kaipov and Kayupov, 1971; Kayupov et al., 1978; Khisamutdinov et al., 1981;

Zvontsov, 1981, 1990). They are connected with volcanogenic Ordovician formations. The Akbastau-Kosmurun group of medium-sized deposits (Akbastau, Mizek, Kosmurun), connected with a basalt-rhyolite formation of the Upper Ordovician, was studied in the southwestern Chingiz region. The Bayanaul-Maikain group of small-to-medium-sized deposits (Aleksandrovka, Souvenir, Zhusaly, Maikain), are connected with the trachydacite-basalt Aleksandrovka and Maikain formations of Middle Ordovician age and occur north of the Chingiz-Tarbagatai belt. Mineralization is localized in volcano-tectonic structures.

As a rule, weak, disseminated, volcano-sedimentary mineralization is widespread in the ore fields. Rich, economically important, hydrothermal-metasomatic mineralization is superimposed on it. Metalliferous deposits occur in interstratal displacements, crush zones in volcano-tectonic structures. The predominant minerals are pyrite, chalcopyrite, sphalerite, galena, barite, and quartz. Bornite, chalcosite, magnetite, gold, silver, and pyrrhotite are the chief secondary minerals.

The ore deposits were probably formed in two stages. Dispersed mineralization was syngenetic with Ordovician volcanic rocks, and rich ores were formed later (Kayupov et al., 1978; Khisamutdinov et al., 1981), during the Early or Middle Devonian, as a result of powerful hydrothermal-metasomatic processes. Ores of this stage are rich in gold and silver.

Pyrite-polymetallic deposits are rare in the Ordovician in the Stepnyak area of northern Kazakhstan. However, the widespread volcanic rocks and the presence of shows of ore (Atan locality) make the area a rather prospective one.

Most copper-sulfide deposits are very small. They are connected with jasper-basalt formations of the Lower or Upper Ordovician in the Ermentau-Buruntau, Chingiz-Tarbagatai, and Agadyr-Kazyk belts and conform to the Central Kazakhstan (or Cyprus) type.

Mineralization is connected with jaspers and basalts of the Itmurundy and Kazyk formations of the Upper Ordovician (Llandeilian-Caradocian), and with the basalt-andesite-dacite of the Zhamanshuruk Formation of the Upper Ordovician (Tesiktas deposit) in the Kazyk branch of the northern Balkhash anticlinorium.

Besides copper, these ores contain zinc, lead, arsenic, cobalt, silver, molybdenum, cadmium, gallium, germanium, tin, and mercury (Kayupov, 1978b).

Copper-Porphyry Deposits

The small Kyzyltu deposit and some shows of ore are known in the Ordovician of the Selety and Stepnyak areas, northern Kazakhstan (Kolesnikov, 1981, 1991). The primary ores consist of pyrite and chalcopyrite. Hydrothermal alteration is represented by orthoclazation, albitization, biotitization, and beresitization. Explosive breccias are very characteristic. The molybdenum to copper ratio is 1:32, and lead, zinc, bismuth, tellurium, rhenium, and other metals also occur in the ores.

Small, copper-porphyry deposits are also known in the Ordovician of Kirgizia (Igemberdiev et al., 1985).

Lode Copper Deposits

This type of mineralization occurs in the Kendyktas Mountains, where the deposits are connected with Upper Ordovician granitoid plutons (Chatyrkol, Ungurlyu, East Kurdai, and other deposits). In the Chatyrkol deposit, copper-rich, calcite-chalcopyrite ores are widely distributed. Quartz-magnetite ores are rarer (Kayupov, 1978b).

Shows of copper ore of the cupreous sandstone type are known in terrigenous sediments of the Upper Ordovician in Kirgizia (Asanaliev, 1984). Carbonaceous shales of the Lower Ordovician Kamal Formation in Bolshoi Karatau are notable for their rather large copper content (Abdulin, 1987).

Lead and Zinc

Lead and zinc deposits connected with Ordovician formations are concentrated in the Dzhungar Alatau Range, southern Kazakhstan, near Tekeli township (Bok, 1966; Veitz, 1972; Kayupov, 1978a; and others). Shows of lead and zinc ores are also known in the northeastern Balkhash region.

Tekeli and Suuktobe (or Koksu-Suuktobe) are two ore fields in the Dzhungar Alatau. Each consists of a group of deposits. The first, the Tekeli group, consists of the Tekeli, Yablonovoye, and Aleksandrovskoye deposits and some smaller ore bodies and is associated with black shales of the Tekeli Formation of the Lower Ordovician. The ore is composed mostly of galena, sphalerite, and pyrite. The ratio of lead to zinc is approximately 1:2. The content of molybdenum, barium, thallium, antimony, and germanium is considerable. The second group, that of Suuktobe, comprises the Suuktobe, Koksu, Kokkus, Kyuely, and Telman deposits and is associated with the carbonate Suuktobe Formation (Llandeilian-Caradocian). Galena is so important in these deposits that lead mineralization predominates in some (Suuktobe, Kyuely). However, barite-zinc mineralization predominates in Kokkus, and zinc-copper predominates in Koksu. The lead-to-zinc ratio is approximately 4:1. Because of the abundance of pyrite, the ores are considered to be pyrite-lead-zinc, but there is no connection with volcanism, a characteristic of such ore.

Deposits of both groups are of economic importance, but the Tekeli group is the more important (Bok, 1966; Veitz, 1972; Patalakha, 1985; Kayupov, 1978a).

The Tekeli Formation, which hosts the Tekeli deposit, consists of strongly metamorphosed, carbonaceous argillites with layers of carbonaceous-siliceous and carbonaceous-calcareous slates, phthanites, and lenses of carbonaceous limestones and dolomites. Some investigators believe the formation to be Riphean in age (Nikitchenko, 1979, and others). Others refer this formation to the lower part of the Ordovician (Llanvirnian) on the basis of Arenigian graptolites from underlying strata and chitinozoans in the Tekeli Formation (D.T. Tsay, pers. comm.).

The ores are very simple in composition, the most important minerals being galena, sphalerite, and pyrite. The galena/sphalerite ratio is 1:2. Dispersed fluorite is found associated with sphalerite and galena at the Yablonovoye deposit (Patalakha, 1985).

Ore-bearing formations in the Ordovician of the northwestern Balkhash region (Atasu-Zhamshi zone) are rather similar to those in Tekeli. The mineralized Chazhagai Formation of carbonaceous phthanites, siliceous argillites, and limestones is similar to the Tekeli Formation, and the carbonaceous Shundy Formation is closely related to the Suuktobe Formation (Kayupov et al., 1988).

Mineralization at some ore localities in the northwestern Balkhash region is connected with the carbonaceous Shundy Formation (Shundy deposit). Ores there consist of galena. Ores in the northwestern Balkhash region (as well as in the Dzhungar Alatau) are of hydrothermal-sedimentary origin.

Unusual for Kazakhstan, the pyrite-polymetallic mineralization is distributed as localized deposits in the Buruntau anticlinorium in the western Balkhash region (Kayupov et al., 1976). Mineralization is connected with carbonaceous aleurolites and fine-grained sandstones in the upper part of the Maikol Formation of jaspers and terrigenous rocks (Llanvirnian). The ores consist of pyrite, pyrrhotite, galena, sphalerite, chalcopyrite, bornite, and arsenopyrite. The lead content ranges from 1.5 to 11%; zinc is up to 2.5%, rarely to 8.8%; and tin is up to 1%. Stannous-polymetallic ores contain cassiterite and stannite. The deposit is most likely of hydrothermal-sedimentary origin.

Manganese and Iron

Exhalative-sedimentary and probably sedimentary manganese, iron deposits, and shows are widespread in the Ordovician of Kazakhstan and Kirgizia, but the ores are mostly of low quality, and the deposits are not of economic importance. Mineralization occurs in the Arenigian and Llanvirnian in the Ishim-Karatau-Naryn and Ermentau-Buruntau belts and in the Llandeilian and Caradocian of the Agadyr-Kazyk belt. Mineralization is associated only with deep-water, siliceous strata. Small, skarn-magnetite deposits occur in northern Kazakhstan.

Distribution of the iron and manganese ores is associated with three major structural zones, as follows:

Ishim-Karatau-Naryn Belt. Mineralization was discovered within the Ishim and Baikonur areas and in the Bolshoi Karatau and Middle Tien Shan ridges. In the Ishim area, small deposits and many ore shows were discovered in the lower part of the Tasoba Formation in brown and gray argillites of Arenigian and Llanvirnian age (Karimov, 1967; Gavrilov, 1972; Kayupov, 1982; Ivanov et al., 1984; Veimarn and Kapsamun, 1984). Of these, the Zhaksy and Tasoba deposits are the most important. Silver is known to accompany the manganese-iron in some places within the belt.

In the Baikonur area, iron-manganese nodules and crusts are found in Lower Ordovician deposits (N. Azerbaev, pers. comm.). In the Bolshoi Karatau range, iron-manganese deposits are found in the Lower Ordovician Kamal Formation, in which an ore bed 20-90 m thick can be traced for tens of kilometers (Kyzylata and Koskol deposits) (Abdulin, 1987).

Iron-manganese mineralization is widespread over the middle Tien Shan from the Chatkal Range to the Saryzhaz Range. It is connected with the Lower Ordovician Kamal, Olzhobai, and Kokbel formations of deep-water sediments. This type of mineralization has been thoroughly studied in the Zhetym-Too Range (Adyshev, 1974; Asanaliev, 1984).

Ermentau-Buruntau Belt. Along the eastern slope of the Ermentau-Niyaz anticlinorium, the zone of manganese-bearing rocks stretches for 100-120 km. The Kumdykol deposit and some shows of mineralization have been studied there (Ivanov et al., 1984; Bekmukhametov and Nogospaev, 1990). This mineralization is associated with jaspers of the Lower Ordovician Akdym group.

Along the eastern Atasu anticlinorium, the iron-manganese mineralization zone is about 100 km long. The Kosagaly, Tuyak, Koyandy, and other deposits and some shows of mineralization are connected with this zone (Borukaev and Shcherba, 1967; Ivanov et al., 1984; Veimarn and Kapsamun, 1984; Bekmukhametov and Nogospaev, 1990). This mineralization is localized in the siliceous Karatas Formation (Llanvirnian) of the Akdym group.

Agadyr-Kazyk Belt. Some small deposits and shows of mineralization are known in siliceous-volcanogenic rocks of the Agadyr-Kazyk belt. The Toimasshoky deposit and Karabaishoky, Ushkyzyl, and other shows are found in the Akchatau-Agadyr horst-anticline. They are associated with jaspers, cherts, and basic volcanics of the Taldyespe Formation (Borukaev and Shcherba, 1967; Ivanov et al., 1984). The small Karashat deposit in the northern

Balkhash region is associated with volcanics and jaspers of the Upper Ordovician Itmurundy Formation, intruded by upper Paleozoic granites (Ivanov et al., 1984). The average manganese content at the locations listed varies from 2-3 to 28%, and iron makes up 25-30%, rarely as much as 40-60%.

Chingiz-Tarbagatai Belt. Only poor iron-manganese-gold mineralization is known in the red jaspers of Arenigian age in the northern part of the belt.

Skarn-Magnetite Deposits

The Atansor group of deposits (Atansor, Kuzgan, Tlegen) consist of more than 30 shows of skarn-magnetite mineralization in the Stepnyak area, northern Kazakhstan (Kayupov, 1982). The mineralization is associated with the Upper Ordovician Krykkuduk granodiorites and occurs in the granodiorite-Upper Ordovician limestone contact zone.

The small titanomagnetite Otaidy-Karasu deposit is located in the gabbroid phase of the Krykkuduk granodiorites (Abdulin and Shlygin, 1983).

Barite

Barite mineralization is found in the Lower Ordovician sedimentary formations in the western Balkhash region (Buruntau anticlinorium), central Kazakhstan, and in the Bolshoi Karatau Range of southern Kazakhstan. Barite mineralization in the Upper Ordovician is associated with sulfide-gold-barite-polymetallic deposits, connected with volcanogenic and volcanogenic-sedimentary formations in northern and northeastern Kazakhstan.

The very important Chiganak deposit and smaller Eastern Chiganak, Zheleznodorozhnoye, Ulekensai, and Suykadyr deposits are found in the Lower Ordovician in the western Balkhash region, west of the Chiganak Railway station (Kayupov et al., 1976; Kulinich, 1989). Ore deposits are represented by barite beds and lenses up to 0.5-2.0 km long and from 5-to-30 m thick. The barite content is from 30 to 90%.

The ore bodies are concordant with jaspers, siliceous aleurolites, siliciclastic rocks, and polymictic sandstone, with aleurolite intercalations. Barites are accompanied by phosphatic sandstones (P_2O_5-32%) and vanadium-bearing, carbonaceous siliceous aleurolites (Kayupov et al., 1976).

The mineralization is found in the lower part of the Lower Ordovician Kamal Formation in carbonaceous siliceous and aleuritic, and in some cases quartz-sericitic shales and slates, ferruginous quartzites, and limestones southeast of Koskol Lake in the Bolshoi Karatau Range, southern Kazakhstan (Abdulin, 1987). The ore band, 50 m thick, is persistent along strike. The thickness of barite layers varies from some millimeters to tens of centimeters, with the total thickness of barite-bearing carbonates being about 15-20 m. The barite content is from 5 to 60%. Copper and silver are also present; and cobalt, molybdenum, and arsenic are found in the carbonaceous rocks.

Vanadium

Vanadium is widely distributed in Lower Ordovician black shales in Kazakhstan and Kirgizia, often together with molybdenum and phosphorous; however, none of it occurs in economically significant amounts (Ankinovich, 1961; Adyshev, 1974; Nikitin, 1973; Asanaliev, 1984). Vanadium-bearing, carbonaceous formations are distributed along the length of the Ishim-Karatau-Naryn belt. They are especially characteristic of the South and Middle Tien-Shan. Stratiform, vanadium-molybdenum mineralization is known in the Lower Ordovician part of the carbonaceous Berkut Formation in the Saryzhaz and Zhetym-Too Ranges, Kirgizia (Asaneliev, 1984). Vanadium-bearing rocks are also known in the northwestern Balkhash region (Chazhagai Formation) and in the Tekeli area (Zakharov and Tekeli formations).

Phosphorite

Economically important Ordovician phosphorites are distributed in the north of Kazakhstan. Koksor, Zaozyornoye, Tastykol, Mailisor, Karabai, and other deposits; and mineral shows are known in the Stepnyak area, in a zone 200 km long and 20-30 km wide. Only sparse shows are known in other areas (Sagunov et al., 1990).

The mineralization is connected with shallow-water volcanogenic sedimentary and sedimentary deposits of the upper parts of the Lidievka and Mailisor formations of the Late Ordovician and with the carbonate Mayatas Formation of Late Ordovician age. The richest ores are usually localized in limestones and, more rarely, in mudstones and sandstones. Ore bodies form lenses or beds from 2-3 to 5-10 m thick and 200-400 m long. Some beds can be traced along strike for 2.5 km and for 500 m downdip. The limestones contain 20-35% P_2O_5, and the mudstones 12-14% (Sagunov et al., 1990). Uranium, rhenium, and molybdenum are known to occur with phosphorite.

Small shows of phosphorite are also known in the northern part of the Selety-Chu-Ili zone, in the Selety synclinorium (Selety and Akzhar deposits), and in the northern part of the Chingiz-Tarbagatai belt (Nikitin, 1973).

Bauxite

Minor bauxite shows have been discovered in the Stepnyak area (Taskol locality) and in the Chingiz Range

(Shagan locality) (Dolgopolov, 1975). In the Taskol locality, diaspore bauxite fills karst caverns in Upper Ordovician limestones. The Al_2O_3 content reaches 46%. Bauxite, also containing 45% Al_2O_3, has been discovered in Upper Ordovician (Llandeilian) limestones along the bank of the Shagan River, Chingiz Range.

Gemstones

A small, jadeite deposit and shows of nephrite, chrysoprase, chrysopal, moss agate, and cacholong (pearl opal) occur in ultrabasites in central Kazakhstan. The Itmurundy jadeite deposit in the northern Balkhash region is associated with the Kenterlau ultrabasite body. The body, 30 km long and 1.5 km wide, is localized between jaspers and jasper-volcanics of the Itmurundy and Kazyk formations of Upper Ordovician (Llandeilian-Caradocian) age. It consists of chrysotile-antigorite serpentinites with relics of harzburgites, dunites, wehrlites, and pyroxenites (Samsonov and Turingue, 1984).

The jadeite-bearing zone is approximately 400 m long and 40 m wide. The jadeite bodies are found as veins, lenses, and stocks. Typical bodies measure 9 x 27 m, 17 x 38 m, and 8-18 x 60 m. Ore bodies are formed by monomineralic white and gray jadeite. Green bodies occur only in contact zones. Veinlets of green to bright emerald-green jadeite, in some cases transparent ("Imperial"), also occur (Samsonov and Turingue, 1984).

Jadeite of the Itmurundy deposit is characterized by very high quality and was considered to be a standard of quality in the USSR (Kornilov and Solodova, 1992). The mineral is used in jewelry and is a popular collector's item.

Building Materials

Ordovician limestones are used as raw material for cement, lime, and building aggregate in many areas of Kazakhstan and Kirgizia. Most decorative marble deposits in the region are Ordovician (Taskol, Ekpendy, Karatau et al.). Granitoids are used as building and decorative materials. Siliceous rocks are used in the chemical industry and in metallurgy (Chiganak deposit and others). Upper Ordovician hydromicaceous argillites (Adensu) are used for manufacturing keramzite, a light, porous artificial material used for heat and sound insulation and in production of concrete (Abdulin and Shlygin, 1983; Alyokhin et al., 1973).

Acknowledgments — I should like to express my thanks to Dr. V.V. Kolesnikov and Dr. L.A. Miroshnichenko, who have read drafts of this paper and provided many useful comments. Dr. A.M. Maulenov provided some data on gold deposits.

References

Abdulin, A.A. (ed.), 1987. Geology and metallogeny of Karatau, v. 2. Alma-Ata, Nauka, 246 p. (in Russian).

Abdulin, A.A., and Shlygin, A.Ye., 1983. Metallogeny and Mineral Resources of Kazakhstan. Alma-Ata, Nauka, 312 p. (in Russian).

Abdulin, A.A., Shlygin, A.E., and Zhukov, P.K., 1987. Major Features of Geology and Metallogeny of the Urals-Mongolian Folded Belt. Alma-Ata, Nauka, 280 p. (in Russian).

Abdulkabirova, M.A., Ankinovich, O.S., Grishin, V.M., Kayupov, A.K., and Kudaibergenova, A.K., 1971. Gold Fields of Kazakhstan. Alma-Ata, Nauka, 167 p. (in Russian).

Adyshev, M.M., 1974. Sedimentary metallogeny of Tien-Shan. In: Geology and Mineral Resources of Kirgizia (M.M. Adyshev, ed.), p. 9-22. Frunze, Ilim (in Russian).

Alyokhin, Yu.A., Duysenbaev, A.D., Ismailov, M.A., and Sagunov, V.G., 1973. Reserves of Building Materials of Kazakh SSR. Alma-Ata, Kazakhstan, 591 p. (in Russian).

Ankinovich, S.G., 1961. Lower Paleozoic of the Vanadium-Bearing Basin of North Tien-Shan and western outskirts of Kazakhstan, Part I. Alma-Ata, Publishing House of Academy of Sciences of Kazakh SSR, 272 p. (in Russian).

Apollonov, M.K., and Patalakha, E.I., 1989. Tectonics of paleozoides of Kazakhstan - fixism or mobilism? In: Geology and Metallogeny of Kazakhstan (A.A. Abdulin, ed.), p. 146-162. Alma-Ata, Nauka (in Russian).

Asanaliev, U., 1984. Regularity of Distribution of Sedimentary Mineral Resources in Tien-Shan. Frunze, Ilim, 289 p. (in Russian).

Bekmukhametov, A.Ye., and Nogospaev, B.G., 1990. Ermentau-Chu-Ili ore belt of manganese-iron-siliceous formation and its perspectives. Izvestiya AN Kazakh SSR. Geol. Series, 2, p. 50-60 (in Russian).

Bok, I.I. (ed.), 1966. Geology and Metallogeny of Dzhungar Alatau. Alma-Ata, Nauka, 255 p. (in Russian).

Borukaev, R.A., and Shcherba, G.N. (eds.), 1967. Geology and Metallogeny of the Uspenka Tectonic Zone (Central Kazakhstan), v. 2, Part 1. Alma-Ata, Nauka, 169 p. (in Russian).

Dolgopolov, V.F., 1975. Ordovician bauxite and prospects for its discovery in the USSR. Doklady AN USSR, 224, p. 1417-1420 (in Russian).

Gavrilov, A.A., 1972. Exhalation-sedimentary deposition of manganese ores (with Urals and Kazakhstan as examples). Moscow, Nedra, 216 p. (in Russian).

Igemberdiev, S.A., Malyshev, A F., and Osmonbaev, K.O., 1985. Porphyry copper mineralization in North Kirgizia. In: Regularity in the Stuctures of the Earth's Crust in Tien-Shan and Its Metallogeny (A.V. Barikov, K.Zh. Bokonbaev, V.G. Korolyov, and V.V. Kiselyov, eds.), p. 90-100. Frunze, Ilim (in Russian).

Ivanov, O.V., Kaymakov, A.K., Kuznetsov, I.I., and Solton, S.A., 1984. Manganese deposits of Kazakhstan and perspectives of their practical use. In: Manganese ore deposition in the Territory of the USSR (D.G. Sapozhnikov, ed.), p. 21-29. Moscow, Nauka (in Russian).

Kaipov, A.D., 1971. Ordovician Volcanism and Copper-Pyrite Mineralization in the Yakbastau-Kusmurun Ore Field. Alma-Ata, Nauka, 191 p. (in Russian).

Karimov, A.G., 1967. On manganese mineralization of the Tasoba Formation of Lower-Middle Ordovician, North Kazakhstan. In: Manganese Deposits in the USSR (D.G. Sapozhnikov, ed.), p. 3233-3336. Moscow, Nauka (in Russian).

Kayupov, A.K. (ed.), 1977. Metallogeny of Kazakhstan. Types of Structural-Formational Complexes and Tectonic Zonation of Paleozoides. Alma-Ata, Nauka, 192 p. (in Russian).

Kayupov, A.K. (ed.), 1978a. Metallogeny of Kazakhstan. Ore Formations. Lead and Zinc Deposits. Alma-Ata, Nauka, 267 p. (in Russian).

Kayupov, A.K. (ed.), 1978b. Metallogeny of Kazakhstan. Ore Formations. Copper Deposits. Alma-Ata, Nauka, 191 p. (in Russian).

Kayupov, A.K. (ed.), 1982. Metallogeny of Kazakhstan. Ore Formation. Iron and Manganese Deposits. Alma-Ata, Nauka, 208 p. (in Russian).

Kayupov, A.K., Benevolenskiy, I.P., Zhukov, P.K., and Tsay, D.T., 1988. Metallogeny of carbonate-carbonaceous-silicic formations of Vendian-Ordovician of Atasu-South Dzhungar massif. Izvestya AN Kazakh SSR, Geol. Series, 5, p. 3-15 (in Russian).

Kayupov, A.K., Lee, V.G., Lyapichev, G.F., and Miroshnichenko, L.A., 1989a. Paleometallogeny of Kazakhstan. In: Geology and Metallogeny of Kazakhstan (A.A. Abdulin, ed.), p. 197-206. Alma-Ata, Nauka (in Russian).

Kayupov, A.K., Lee, V.G., Lyapichev, G.F., and Miroshnichenko, L.A., 1989b. Ore formations of Kazakhstan. In: Geology and Metallogeny of Kazakhstan (A.A. Abdulin, ed.), p. 206-220. Alma-Ata, Nauka (in Russian).

Kayupov, A.K., Zhautikov, T.M., and Kaipov, A.D., 1978. Metallogenic peculiarities of pyrite-bearing regions of East Kazakhstan. In: Regularities of Distribution of Mineral Deposits (V.I. Smirnov, ed.), p. 151-156. Moscow, Nauka (in Russian).

Kayupov, A.K., Zhukov, P.K., Kuznechevskiy, A.G., Sidnevets, G.Z., and Shlygin, A.E., 1976. Major features of formation of mineral resources. In: Geology and Metallogeny of Sarytuma Zone (West Balkhash Region) (A.K. Kayupov, ed.), p. 197-206. Alma-Ata, Nauka (in Russian).

Khisamutdinov, M.G., Belyaev, A.A., Kaipov, A.D., and Taran, A.N., 1981. Pyritaceous mineralization of Chingiz and Maikain ore regions. In: Volcanogenic-Sedimentary Ore and Lithogenesis (A.A. Abdulin, ed.), p. 116-124. Alma-Ata, Nauka (in Russian).

Kolesnikov, V.V., 1981. Main types of porphyry copper deposits of Kazakhstan. Izvestia AN Kazakh SSR, Geol. Series, 6, p. 23-33 (in Russian).

Kolesnikov, V.V., 1991. Non-Ferrous Metal Deposits. Balkhash Segment. Alma-Ata, Nauka, 192 p. (in Russian).

Kovalyov, A.A., 1985. Mobilism and Criteria of Geological Search. Moscow, Nedra, 223 p. (in Russian).

Kulinich, V.V., 1989. Epochs and stratigraphic levels of economically important deposition of barites in Kazakhstan. Izvestiya AN Kazakh SSR, Geol. Series, 2, p. 58-66 (in Russian).

Maulenov, A.M., 1969. On the connection of gold mineralization with flyschoid formations in North Kazakhstan. In: Geology and Geochemistry of the Noble Metal Deposits in Kazakhstan (M.I. Kazantsev, ed.), p. 39-40. Alma-Ata, Nauka (in Russian).

Maulenov, A.M., 1991. Gold-bearing formations and facies in North Kazakhstan and its postsedimentation transformation. I. Izvestiya AN Kazakh SSR, Geol. Series, 2, p. 16-31 (in Russian).

Mitchell, A.H.G., and Garson, M.S., 1981. Mineral Deposits and Global Tectonic Settings. London, Academic Press.

Nikitchenko, I.I., 1979. Carbonaceous depositions of Precambrian and lower Paleozoic in Dzhungar Alatau and their ore mineralization. Izvestiya AN Kazakh SSR, Geol. Series, 2, p. 62-67 (in Russian).

Nikitin, I.F., 1973. Ordovician of Kazakhstan, II. Paleogeography, Paleotectonics. Alma-Ata, Nauka, 99 p. (in Russian).

Patalakha, G.B., 1985. Reconstructions of processes of ore formations in deeply metamorphosed stratiform lead-zinc deposits. Izvestiya AN Kazakh SSR. Geol. Series, 5, p. 50-57 (in Russian).

Sagunov, V.G., Virt, G.R., Nesipbaev, A.N., et al., 1990. Phosphate Rocks in Kazakhstan. Alma-Ata, Nauka, 200 p. (in Russian).

Samsonov, I.P., and Turingue, A.P., 1984. Gems of the USSR. Moscow, Nedra, 335 p. (in Russian).

Satpaev, K.I., 1953. On metallogenic epochs, formations and belts in Central Kazakhstan. Izvestiya, AN USSR, Geol. Series, 17, p. 9-26 (in Russian).

Veimarn, A.B., and Kapsamun, V.I., 1984. Ore formations of iron and manganese in central Kazakhstan. In: Manganese Ore Deposition at the Territory of the USSR (D.G. Sapozhnikov, ed.), p. 29-35. Moscow, Nauka (in Russian).

Veitz, B.I., 1972. Mineralogy of Main Deposits and Localities of Mineralization in Tekeli Zone, Dzhungar Alatau. Alma-Ata, Nauka, 136 p. (in Russian).

Zvontsov, V.S., 1981. On geological position of the pyrite-polymetallic Maikain deposit (northeast of Central Kazakhstan). Izvestiya AN Kazakh SSR, Geol. Series, 1, p. 46-51 (in Russian).

Zvontsov, V.S., 1990. Alexandrovskoye pyrite-polymetallic deposit in the northeast of central Kazakh. Izvestiya AN Kazakh SSR, Geol. Series, 2, p. 16-23.

Coal Resources of Kazakhstan

T.M. Azizov and V.I. Vlasov

Abstract

Six stages can be traced in the development of coal formations in Kazakhstan. Devonian coal formations occur in small areas of east-central Kazakhstan and are of sporadic character. The Early Carboniferous Epoch was the first in which coal formation reached a peak. Karaganda, Ekibastuz, and hundreds more small coal deposits that make up the main resources of high quality coal formed at this time. Late Paleozoic (C_2-C_3, P) coal accumulation was considerably reduced from the Early Carboniferous and took place mainly in east Kazakhstan. The beginning of the next peak in coal formation, equivalent to the Early Carboniferous, occurred in the Early-Middle Jurassic. Large basins such as Turgai, Maikyuben, Ili, Urals-Caspian and Shubarkol, Jubileinoye contain the deposits of this epoch. In the Paleocene (Oligocene), coal formation was less intense than in the preceding epochs, although peat accumulated in vast territories of southwest, north and east Kazakhstan. More than 300 coal and oil shale deposits are known in Kazakhstan. General coal resources total more than 170 billion tons, irregularly distributed over a large area. The main coal resources are found in central and north Kazakhstan, where coking coals are also concentrated.

The Republic of Kazakhstan covers 2.7 million km^2, equivalent in area to the combined territories of France, Spain, Norway, Germany, Poland, Italy and Great Britain. Within this vast territory, along with many kinds of minerals, more than 300 deposits and shows of coals of various ages and oil shales have been found.

The geological history of Kazakhstan records several stages of coal formation: Middle-Late Devonian, Early Carboniferous, Middle-Late Carboniferous, Permian, early Mesozoic, and Paleogene. The process of coal formation reached a peak in the Early Carboniferous and early Mesozoic and was distinguished by special paleogeographic and paleotectonic conditions of sedimentation and peat formation.

Devonian coal formation occurred sporadically in small areas in the eastern part of central Kazakhstan. During the Carboniferous, particularly in the Early Carboniferous (Visean-Serpukhovian), coal formation was widespread in almost all of central Kazakhstan, and in the main coal basins (Karaganda and Ekibastuz) numerous coal deposits formed. This epoch recorded the first maximum in coal formation, much of it of coking quality. Toward the end of the Carboniferous and again in the Permian, the area of peat formation was considerably reduced, becoming concentrated mainly in east Kazakhstan, where considerable volumes of oil shales formed in continental environments.

The next peak in coal formation, equivalent in magnitude to the Early Carboniferous, began in Early-Middle Jurassic time. At this time, in the large basins such as Turgai, Maikyuben, Ili, Urals-Caspian, numerous deposits of high quality coal with a high calorific content and low ash were formed under continental limnic-marsh conditions. Coal formation ended at the beginning of the Late Jurassic and did not resume until Paleogene time, when deposits formed in the vast areas of southwest, north and east Kazakhstan. The extent of coal formation, however, was less than in preceding epochs. Changes in the main coal-bearing parameters in time are presented in Fig. 1.

The geology, conditions of coal formation, quality of coal, and resources of the Kazakhstan coal deposits have been described in numerous monographs and articles. Basic works by Golitsin et al. (1973), Yegorov (1945), Kushev (1963), Kustov (1947), and Orlov et al. (1972) were drawn on in preparing this survey.

The coal resources of Kazakhstan exceed 170 billion tons, including 18 billion tons of coking coals and other high-calorific coals. The resources of other varieties of coal are 67 billion tons, of which more than 9 billion tons are suitable for surface mining. The resources of brown coals are estimated to be 106 billion tons, of which 28 billion tons may be suitable for surface mining. Most of the coal fields are of Early Carboniferous (Visean-Serpukhovian) or Early-Middle Jurassic age, and their resources total tens and hundreds of million tons. Only the largest basins contain billions of tons of coal. The main coal basins are situated in the central and northern coal-bearing provinces. The southern and western ones contain considerably fewer coal resources (Fig. 2).

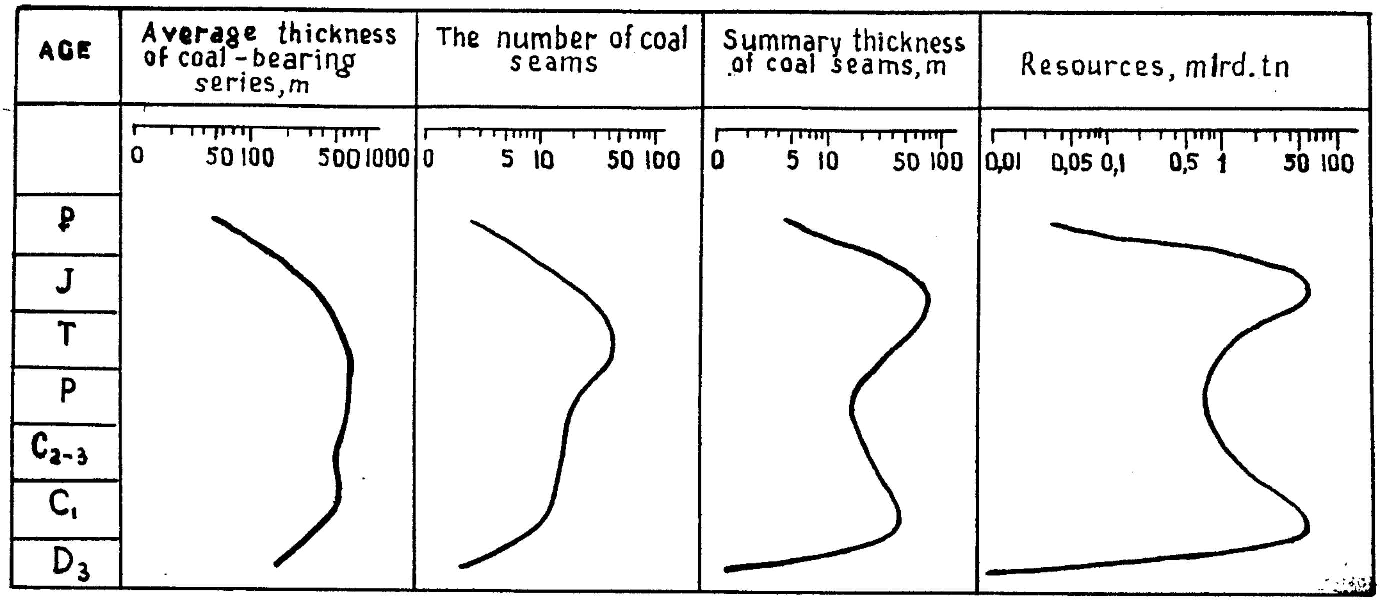


Fig. 1. Changes in main coal-bearing parameters in time (logarithmic scale).

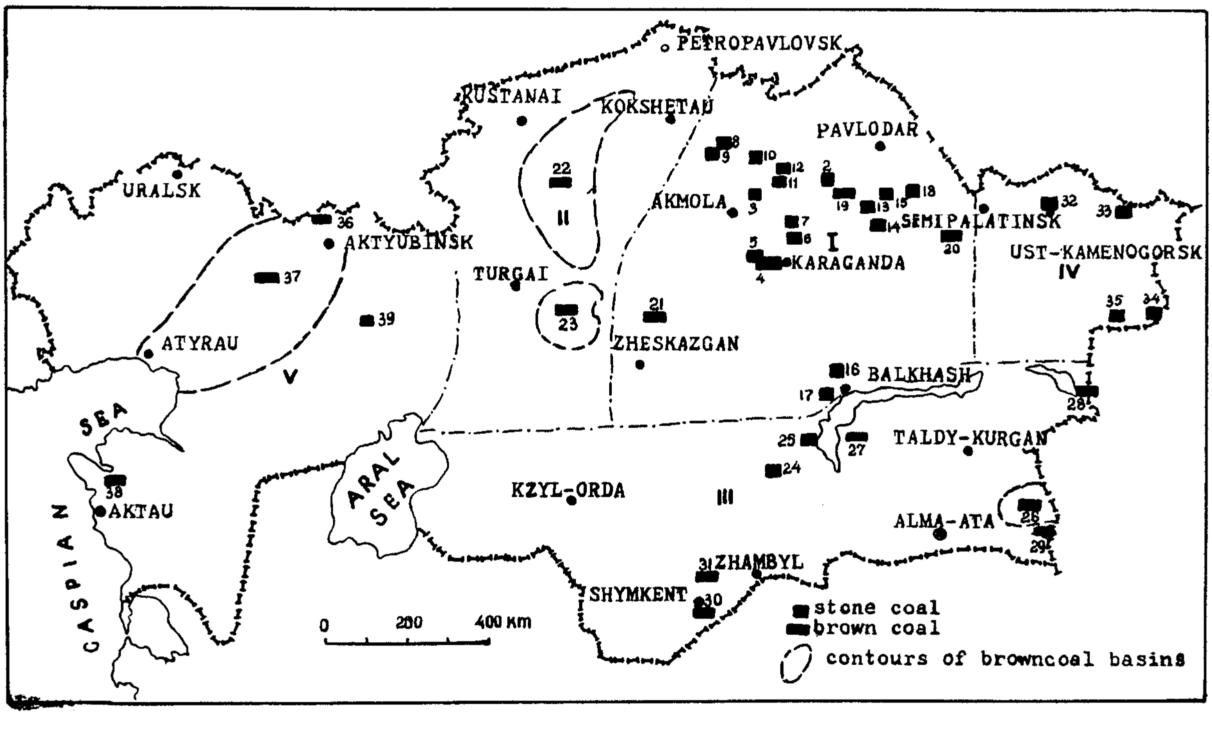


Fig. 2. Location of the main coal deposits of Kazakhstan.

The central Kazakhstan province[1] is the site of large Carboniferous and Jurassic coal basins and fields; the basins include Karaganda, Ekibastuz, and Teniz-Kordzhuncol, and the fields include Samarka, Zavyalovka, Kuu-Cheku, Nurynskoye, Borly, Koitas, Kokshenghir, and Zhamantuz. Among the Jurassic coal basins, those with greatest commercial value are Maikyuben, Shubarkol, Jubileinoye, and Koitas.

The Karaganda coal basin (1) is a deep synclinal structure, stretching 120 km in a sublatitudinal direction, with an average width of 30 km. From west to east, the basin encloses three large basins separated by domes and complicated by smaller structures (Fig. 3). The Carboniferous coal-bearing deposits are nearly 4000 m thick and are divided in seven formations, four of which contain industrial quality coal with up to 80 workable seams. The total thickness of all coal seams is of the order of 110 m. Most of the working coal seams lie in the Karaganda (C_1), Dolynka (C_2) and in the lower part of the Tentek (C_{2-3}) formations. The thickness of individual seams varies from 0.7 to 3.5 m, rarely exceeding this. Within the basin, coal content of the formations decreases from east to west and from south to north. The humic coals of the basin change from gassy to lean. Lean coke and fat coals predominate. The ash content of the coals varies from 10-15 to 25-35%. The coal resources of the basin total nearly 43 billion tons, of which 24.6 billions tons are recoverable.

In the Karaganda basin, the Lower Jurassic (Kumyskuduk and Dubovka coal fields) and Middle Jurassic (Mikhailovka coal field) deposits are coal-bearing. The first contains 5 coal-seams from 2 to 12 m thick; 3 coal-seams (2-4 m thick) lie within the Middle Jurassic deposits. The coal is brown, with an ash content of 16-25%. Average brown-coal resources total more than 2 billion tons.

In the Ekibastuz basin (2), 130 km southwest of the city of Pavlodar, Carboniferous coal-bearing deposits (1700 m thick) fill an asymmetrical graben-syncline, stretching 24 km in a northwesterly direction, with a width of 8.5 km (See Fig. 4). The maximum depth to the base of the main productive horizon is 700 m in the deepest, northeasterly part of the structure. Maximum thickness of coal occurs in Visean-Serpukhovian deposits (Ashlyarik and Karaganda formations), where total thickness is nearly 1000 m. Of the six coal-beds of workable thickness, two are situated in the top part of the Ashlyarik formation and four belong to the Karaganda formation. The uppermost deposits of the Middle and Upper Carboniferous contain 15 thin nonindustrial coal seams. The Ashlyarik formation coal-beds (6 and 5) are up to 8-10 m thick but have a complicated structure and high ash content and therefore have no commercial value. Coal seams 3, 2, 1 in the top part of the formation are combined to form a single productive horizon from 130 to 210 m in thickness, worked at present in large-scale open-cast sites. The coals of the basin range from gas to coking type, humic, have a high ash content (30-40%), are difficult to extract, and include many nonproductive horizons. The ash content of minable coal is nearly 40%. The general coal resource in the basin totals 9.7 billion tons. Ekibastuz coals are utilized in large thermal electric power stations, where they are ground into powder before combustion.

The Teniz-Kordzhunkol basin (3) lies 150 km northeast of the town of Akmola. The Visean-Serpukhovian age coal-bearing deposits fill a brachysyncline structure (25 × 25 km), complicated by secondary folding. The Kosmurun and Saryadyr coal fields have received the most study. The main coal horizon lies at the base of the upper Visean section and consists of three clusters of coal seams from 60 to 80 m thick in the south to 20-30 m thick in the north. A higher proportion of coal is seen in the Saryadyr field and in the southern part of the Kosmurun field, where total thickness of workable coal beds reaches 20 m. The coal of the basin has a high ash content (to 45%), yields high energy, and ranges from gases to cokes and anthracite. The general coal resource is calculated to be more than 2.6 billion tons.

The Samarka (4) and Zavyalovka (5) deposits lie 25 and 60 km respectively west of the Karaganda coal basin and contain the most valuable coking coal seams. The coal-bearing series fill narrow graben-synclines, stretching in a submeridional direction, which are limited to the west and the east by fractures. The Karaganda and Dolynka Formations in the Samarka field contain 4 coal-beds with ash contents of between 20-28%. The coals rank from gas to coke. The general resources of the Samarka field total 1.3 billion tons of coal. In the Zavyalovka field, the Karaganda formation also contains four coal-beds with a thickness of 1-1.3 m; the Dolynka Formation, two seams (0.8-1.5 m); and the Tentek, two seams (0.7-1.8 m). The range of ash content varies between 25 to 30%. The coals are coking and bituminous grade. General coal resources total nearly 530 million tons, 240 million tons of which are coking coal.

The Kuu-Cheku coal field (6) lies 60 km northeast of Karaganda. Like the Samarka and Zavyalovka fields, it is a satellite of the Karaganda basin. Coal-bearing sediments of Visean-Serpukhovian age form a northwesterly trending brachysyncline 8 × 20 km in extent. In the upper part of the Ashlyarik formation there are five coal layers from 1.3 to 26 m thick with an ash content of 35-44%. The grade of the coal ranks from coking to caking. The coal seams of the Karaganda formation are suitable for open mining. General coal resources total 650 million tons.

The Borly field (7) is 100 km north of the Karaganda basin. The Visean-Serpukhovian coal-bearing series form

---

[1] Coal provinces and deposits are shown on Fig. 2.

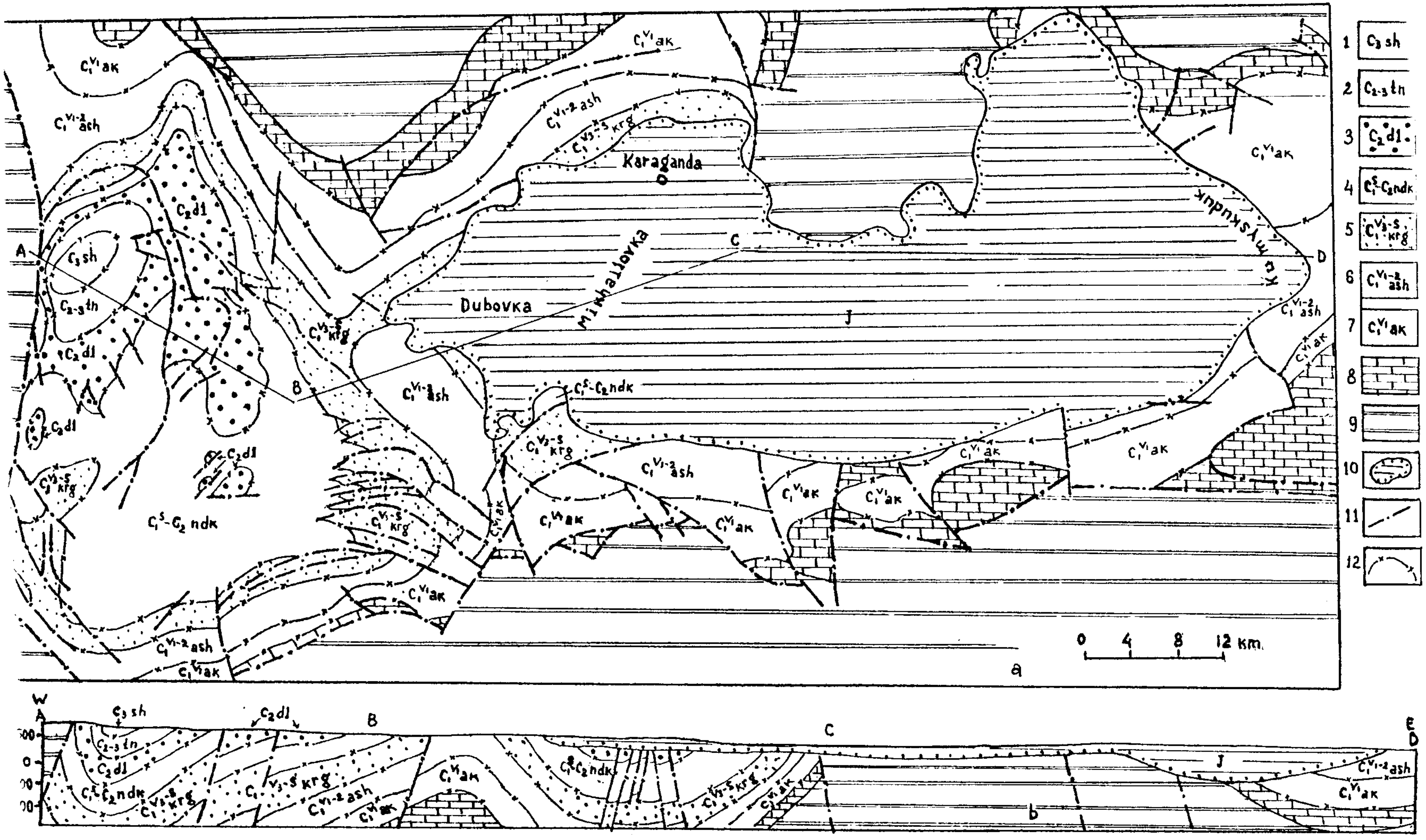


Fig. 3. Geologic map (**a**), and cross section (**b**) on A-B-C-D of the Karaganda coal basin. Coal-bearing formations: 1- Shakhan; 2- Tentek; 3- Dolinka; 4- Nadkaraganda; 5- Karaganda; 6- Ashlyarik; 7- Akkuduk. Geologic formations: 8- Tournasian-Famennian carbonates; 9- pre-Famennian formations. Miscellaneous: 10- extent of Jurassic sediments; 11- faults; 12- extent of coal-bearing formations.

an east-west-trending, gently sloping syncline 2.5 x 6.5 km in size. At the base of the Karaganda formation there is a group of three structurally complex coal seams. From the bottom to top, the seams are 25-35, 10-25, and 1.5-2 m thick. The coal has a high ash content (32-45% and more). General coal resources total 350 million tons. All resources lie at a 200 m depth and can be reached by open-cast mining. The deposit is now being mined in a large open pit.

In the central Kazakhstan coal-bearing province, in addition to the Early Carboniferous basins described, there is a large number of smaller coal fields. In the northern part of the province there are the Koksengir (8), Yablonovka (9), Bogembai (10), Samaisor (11), and the Koitas (12), and others. At the base of the Visean-Serpukhovian coal-bearing formation of Early Carboniferous age there are one or two coal beds from 1-2 to 3-5 m thick, with a high ash content. The resources of these fields are small.

In the eastern part of the province, Visean coal-bearing deposits total 100-400 m in thickness and occur in a number of coal fields, including the Ayakmalaisor (13), Kyzyltau (14), and Zhamantuz (15) fields. There are 3-6 coal layers totalling up to 30 m in thickness. The coals again have a high ash content. The limited resources of these deposits and difficult mining and geological conditions severely diminish the prospects of the region.

There are several small Visean coal fields, including the Akmayasarycol (14) and Sarykum (17) fields in the southern part of the province. A volcano-sedimentary sequence contains from 2 to 5 coal seams, 0.8-3.5 m thick, with a variable but high ash content (to 40-50%).

In the northeastern part of central Kazakhstan (left bank of the Irtysh River) the Lower Permian coal-bearing sediments are up to 1000 m thick. Among the largest fields are Kainama, Belogorka, and Sarydala. The Kainama deposit (18) is 140 km southeast of Pavlodar. The two coal layers are 3 m and 0.9 m in thickness and are found at depths of as much as 600 m. The ash content is 15-20%. The general coal resources total 650 million tons.

During the Early and Middle Jurassic epochs, several of the largest coal basins and deposits of the central Kazakhstan coal province formed, among them Maikuben and Shubarkol.

The Maikuben basin (19) is 60 km southeast of Ekibastuz. The 1800-m-thick coal-bearing series is divided into four formations. The two middle formations (Taldykol and Shoptykol) contain the main coal seams.

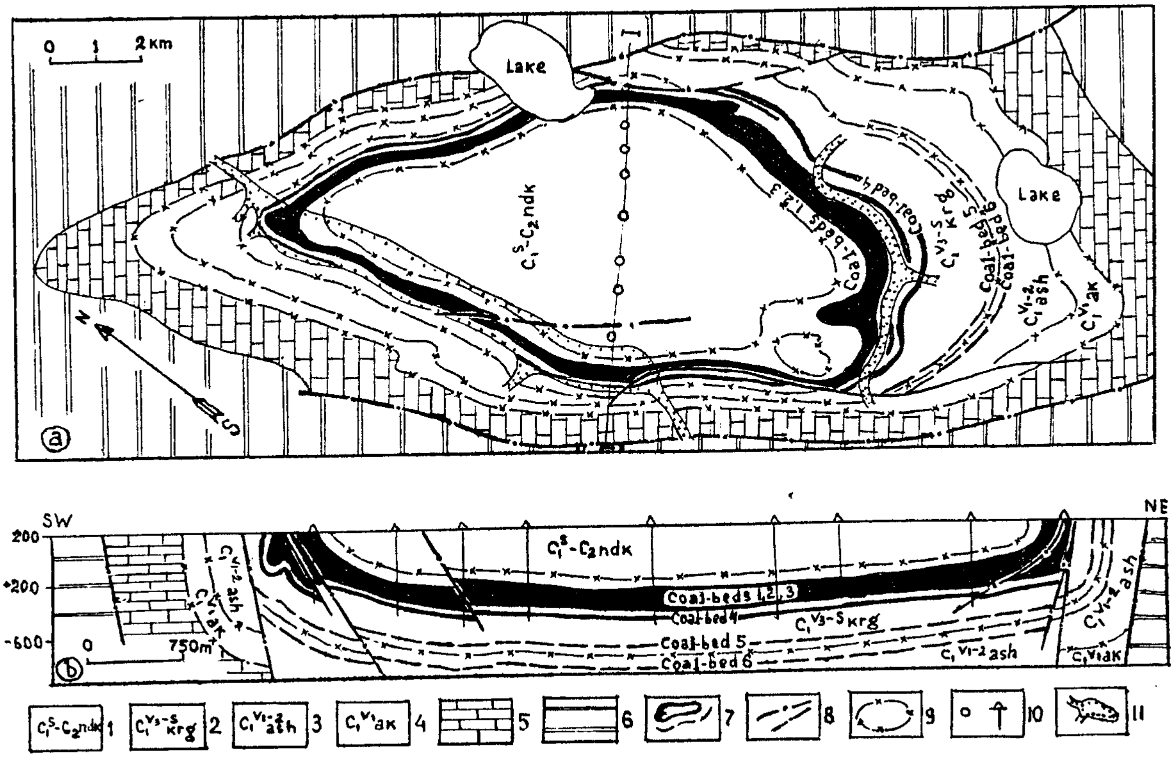


Fig. 4. Geologic map (**a**), and cross section (**b**) on I-I of the Ekibastuz coal basin. Coal-bearing formations: 1- Nadkaraganda; 2- Karaganda; 3- Ashlyarik; 4- Akkuduk. Geologic formations: 5- Tournasian-Famennian carbonates; 6- pre-Famennian formations. Miscellaneous: 7- coal beds; 8- faults; 9- extent of coal-bearing formations; 10- wells; 11- quarries.

The coals are brown with an ash content of 25-28% and are used as high-quality fuel for electric power stations. Some may be used for gasification. The general coal resources of the basin total 5.3 billion tons.

The Yubileinoe coal field (20) is 110 km southwest of Semipalatinsk. The Lower and Middle Jurassic coal-bearing series form a gently sloping northwest-trending syncline 5 × 15 km in extent. The coals are concentrated in two packets, the lower, 35-90 m thick, containing five coal seams and the upper three seams. The thickness of the seams varies from 3-5 to 9-13 m, and rarely to as much as 23-33 m. The seams, at depths of from 5 to 260 m, consist of brown coal with an ash content of 14-19%. Dry distillation of the coal yields 6-12% primary resin. General coal resources total nearly 1.5 billion tons.

The Shubarkol coal field (21, Fig. 5) is 130 km northeast of Zheskazgan. The Lower Jurassic coal-bearing series, 330 m thick, forms a sublatitudinal syncline structure (7 × 16 km) plunging west and east at 5-10° and 5-15°, with steeper southern and northern limbs (to 20-45° or 40-90°). There are three coal horizons: Lower, Middle, and Upper. The Upper, 32 m thick, is a simple structure mined at present by open-cast mining. The general coal resources total more than 1.5 billion tons. Coals with low ash content (average 11%) coalify to the flame stage with a low sulfur output, so they serve as raw material for producing liquid fuel by hydrogenation.

The Koitas coal field (12), 200 km northeast of Akmola, resembles the preceding field. The coal-bearing series are of Lower-Middle Jurassic age. There are two complex coal horizons, 17-45 m (Lower) and 18-75 m (Upper) thick. The coals are brown and the ash content is 10-12% to 30-35% range. The general coal resources total 1.3 billion tons.

In the North Kazakhstan coal province (II) there are two large brown-coal basins, Turgai and Zhylanshyk. The Turgai basin (22) covers more than 150,000 km^2, extending 700 km from north to south. The coal-bearing series of Triassic and Jurassic age are in isolated graben-synclines. There are more 20 coal fields in these structures, among them Kushmurun, Egynsai, Priozernoye, Orlovskoye, and Kyiakty. Each is suitable for open-cast mining.

According to the coal-bearing nature and the character of the locality, all the coal-bearing structures fall into six groups, three of which — Ubagan, Pryishym, and Baiconur — are of considerable industrial importance. The Ubagan group is found in the northwestern part of the Turgai basin, in the Kushmurun, Egynsai, Priozernoye, Chernigovka, and Kharkovka coal fields. There are two coal-bearing formations: Kushmurun and Duzbai. The first contains the principal coal seams. The total thickness of Kushmurun coal beds ranges from 10-20 to 85 m (Egynsai) and 120 m (Kushmurun). The ash content of these coals ranges from 14-18% to 22-29%. The general resources of the Ubagan coal fields total 8 billion tons.

The Pryishym group of coal-bearing structures is situated in the eastern part of the Turgai basin. Among them the largest coal fields are Zhanyspai, Kysyltal, Orlovskoye, Savinkovskoye, and Mkhatovskoye. The main body of the coal belongs to the Duzbai formation. The total thickness of coal seams ranges from 30 m in the zone where coals are superseded by sedimentary rocks to 147 m in the central parts of the fields. Coal-bearing beds of the Middle Jurassic Kushmurun formation are known only in the Savinkovka and Zhanyspai coal fields. There are up to 10 coal seams here, with thicknesses of 15-29 m. The ash content is 14-22%. The general coal resources total more than 52 billion tons.

The Baiconur group of coal-bearing structures, in the southeastern part of the Turgai Basin, lie in the Baiconur and Kyiakty coal fields. The first has already been mined. In the second field, Middle Jurassic sediments contain four complicated coal seams ranging from 1-2 to 5-8 m in thickness. The average ash content is 20%; resources total 113 million tons.

The general resources of high quality coals of the Turgai basin to a depth of 600 m are estimated at 62 billion tons.

The Zhylanshyk basin (23) contains 20-45 m of continental sediments of Oligocene age (Chylikty formation). A brown coal seam 0.7 to 14 m thick occupies the middle of the formation and lies at depths of from a few meters to as much as 110 m. The ash content is 22-24%, and the primary resin near 10%. The general coal resources are 14.5 billion tons, of which nearly 9 billion tons is suitable for open-casting mining. Brassy coal (containing pyrite) is common.

In the South Kazakhstan coal-bearing province (III), nearly 25 deposits of coal occur in Lower Carboniferous or Lower-Middle Jurassic sediments. The largest coal basin and deposits lie in the Lower-Middle Jurassic sediments.

The Chu basin (24) is in the northern part of the Chu depression, 120 km southwest of the south shore of Lake Balkhash. The lower Visean coal-bearing series, 300-400 m in thickness, contains 2-5 coal seams and occupies the Karakol brachysyncline and Moynkum depression. The thickness of coal seams ranges from 1-2 to 5 m, rarely 7-15 m. The coal seams grade from bituminous through coking coals. The high ash content averages from 40-45%. The resources of the basin are huge; however, they have no commercial value because of the great depth at which they lie.

The Kulan coal field (25) is 30 km southwest of Lake Balkhash. It contains Visean coal-bearing sediments with two coal seams, one 12-27 m and the other 10-20 m thick. The thickness of the intervening sediments ranges from 7

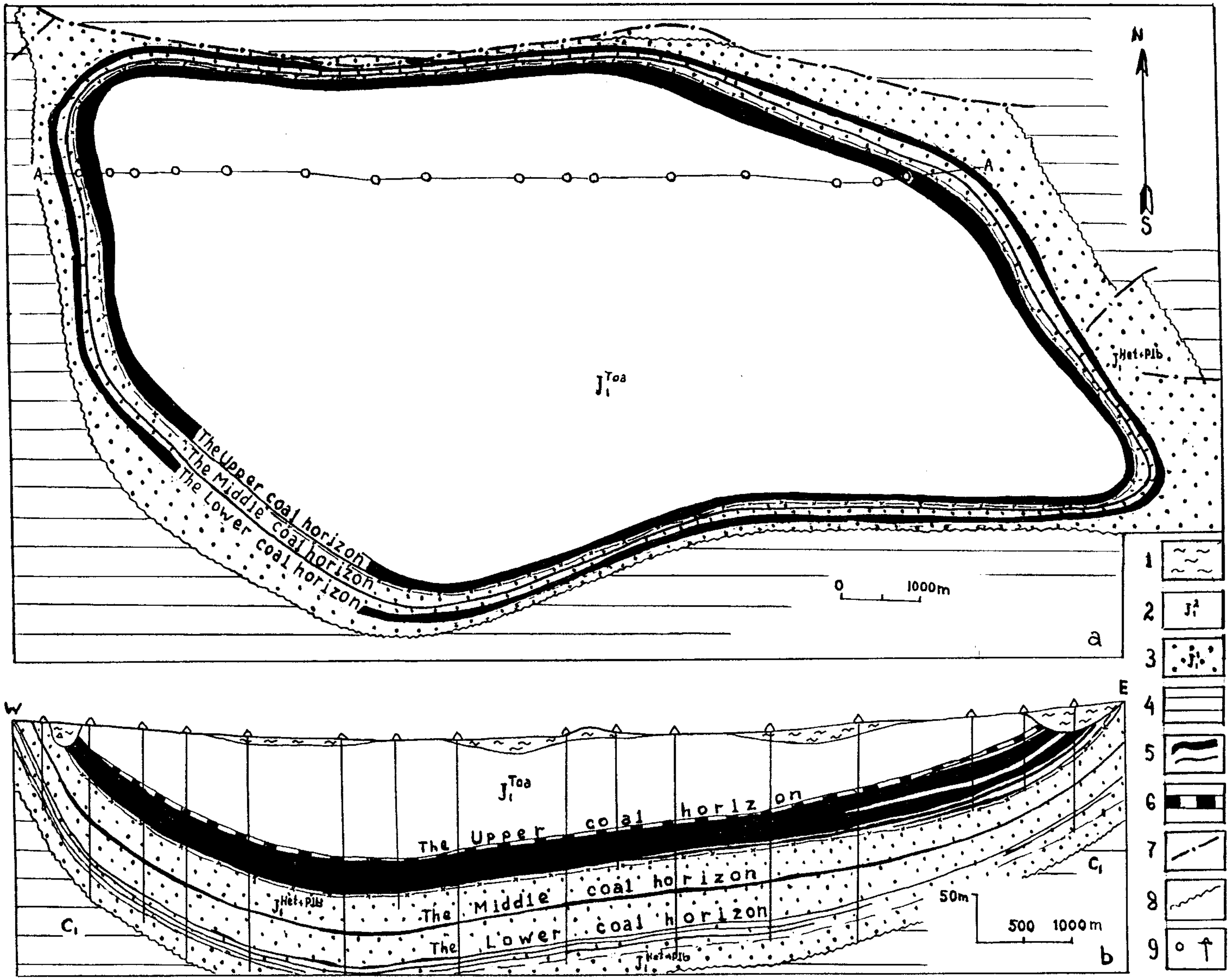


Fig. 5. Geologic map (**a**), and cross section (b) on A-A of Shubarkol coal field: 1- Neogene clays; 2- upper coal-bearing member; 3- lower coal-bearing member; 4- pre-Jurassic formations; 5- coal horizons; 6- oil shale; 7- faults; 8- pre-Jurassic surface; 9- wells

to 20 m. The ash content is 35-40% and resources total nearly 70 million tons.

The Visean Karasai group of coal deposits are widespread in South Jungaria (Karasai, and Muckry coal fields, near Taldy-Kurgan; Sulubukan, Burkhan, and Tyshkan in the eastern part of the region). There are from 15-25 coal seams ranging from 0.2 to 1.5 m in thickness in the western part to 2 coal seams from 0.7-3 to 7-15 m thick in the eastern part. The coals have a high ash content, and the resource is small.

The Ili brown coal basin (26) is in the eastern part of the Ili depression, near the Kazakhstan-China border. The coal-bearing sediments are of Lower-Middle Jurassic age. There are two coal beds, 2 and 2.5 m thick, in the Lower Jurassic, and 5 coal seams 0.7-22 m thick in the Middle Jurassic. The coal has a low ash content (8-13%), the primary resin forms nearly 11.5%. Coal resources to a depth of 800 m total 1.8 billion tons. Coal resources of the Kazakhstan part of basin are projected to total nearly 44 billion tons.

The Lower Ili brown coal basin (27) is west of the Pribalkhash depression, above the lower Ili River. The Lower-Middle Jurassic coal-bearing series is up to 200 m thick filling a shallow graben-like structure (20x80 km) which trends in a northwesterly direction and contains one coal seam from 1-2 m to 58 m thick. The coal forms a single sequence in the northwestern part of the basin, but splits into two in the southeast. The average ash content is 15%. Coal resources total nearly 10 billion tons.

The Alakol coal field (28) is in the southeastern part of the Alakol depression, 15 km southeast of Lake Alakol. In a coal-bearing formation 120 m thick, there are 8 coal seams ranging from 1 to 5.7 m thick. The upper coal seam is the thickest (2.8-10.1 m) and most uniform. The ash content is 6.5-9.6%, the primary resin content is from 9.3 to 10.5%. Coal resources total more than 51 million tons.

The Oikaragai coal field (29) is 300 km east of Alma-Ata, near the China-Kazakhstan frontier, where it occupies a high mountain depression. Middle Jurassic sediments from 45 to 110 m thick contain a structurally simple coal seam from 4.5 to 23.5 m thick. There are three coal-bearing areas, isolated by the erosion of mountain streams. The coals are brown, with a low ash content (6-16%). Resources total 70 million tons.

The Lenger coal field (30) is 35 km east of Shymkent. A100-300 m thick coal-bearing formation of Early Jurassic age contains 10 beds. Individual beds range from 1.5-2.5 m to 15 m thick. The ash content is 19-21%. Coal resources to a depth of 900 m total 750 million tons.

The Karatau group of coal deposits (31) occurs in Jurassic sediments along a major fault-bounded trough (5-7 × 125 km) which trends northwestwards. The Lower Jurassic sediments contain 12-14 coal beds from 0.6 to 2.1-3.6 m thick (Taskomyrsai, and Shokpak fields), and the Middle Jurassic 5-9 coal layers from 0.6 to 3 m thick (Bugun, Orlovka, Kitayevka and other fields). The coal seams of all fields have complex structures, and a low ash content (10-15%). The resources of these fields are of no commercial value. The resources of the South Kazakhstan coal-bearing province are estimated as 14 billion tons.

In the East Kazakhstan coal-bearing province (IV), small coal fields are known. Using structural-formational and territorial criteria all the coal fields fall into three groups; the Kokpeckty, Belokamenka, and Kenderlyk.

The coal fields of the first group are very small and of no practical importance.

In the second group, the Belokamenka coal field (32) is highly significant. It is situated 25 km north of Ust-Kamenogorsk. The Middle-Upper Carboniferous coal-bearing sediments, fill a narrow fault-bounded graben (2-3 × 15 km) with a northwestern trend, and contains nearly 13 coal seams from 0.5 to 30 m in thickness. The coals have a high ash content (25-40%) and rank from coking coal to subanthracite. Coal resources total 957 million tons.

The Cheremoshynka coal field (33), 130 km east of Ust-Kamenogorsk, is within Middle-Upper Carboniferous sediments that fill a narrow fault-bounded graben (2 × 9 km) with a northeastward trend. The coal-bearing formation contains 2-3 steeply dipping coal seams from 0.6-2.3 to 3.2-4.4 m in thickness. Coal ranks from subanthracite to anthracite, with an ash content of 15-25%. Coal resources total nearly 15 million tons.

The Kenderlyk group of coal fields comprise the Kenderlyk, Manrak, Tologoi, and other small fields. Productive horizons lie in the Middle-Late Carboniferous to Permian sequence but in the Kenderlyk and Sarybulak fields, coal-bearing sediments of Triassic-Jurassic age are also found.

The Kenderlyk coal field (34), 60 km southeast of Zaisan, is one of the largest deposits of East Kazakhstan. Productive sediments occupy a northwestward-trending syncline. In addition to coal, the deposits contain oil shales. The coals are Late Carboniferous, Late Permian, and Late Triassic; the oil shales are Early Permian and Late Carboniferous. There is one coal seam 2.1-2.7 m thick, and at higher levels two seams of oil shale 1.8-2.6 (lower) and 0.9-1.2 m (upper) thick in the Upper Carboniferous coal-bearing formation. Ten coal beds from 0.6-1.5 to 5 m thick are contained in the Upper Permian coal sequence.

Upper Triassic coal-bearing sediments are widespread in the central part of the syncline and contain 48 layers of brown coal. The total thickness of the coal is near 40 m.

The Paleozoic coals have a high ash content (from 19-30 to 45%). The ash content of the brown coal is 10-55% (average 34 %). Hard coal resources total 600 million tons, brown coals 1 billion tons.

The Lower Permian sediments include three horizons containing 9, 3, and 6 beds of oil shales. Thicknesses range from 0.6-2.5 to 7-9 m. Oil shale resources total 700 million tons. The primary resin ranges from 12-17 to 24%.

The Manrak coal field (35) is 60 km south Lake Zaisan. Here Upper Carboniferous coal-bearing sediments, up to 700 m thick, fill a small northwesterly trending graben (0.5-1 × 8-10 km) with four coal seams (from 0.8-1.5 to 2.3-3 m, rarely 7 m). The coal layers have a compound structure, variable thickness, and a high ash content (30-45%). Resources total 40 million tons.

The western Kazakhstan coal-bearing province (V) is characterized by mainly Jurassic coal-bearing sediments and the occurrence of small brown-coal fields. It is the poorest province, in terms of coal resources. There are three coal-bearing regions, as follows:

The Orsk coal-bearing region (36) is in the South Priuralye. The Lower Mesozoic continental sediments which fill the Or depression (20-35 × 150 km) have a submeridional trend. The southern part is in the Aktobe oblast. The largest brown-coal field (Mamyt) lies in the central part of this depression. The lowest coal horizon of the field contains 4-8 coal seams, the thickest of which reaches 1-2 m. The middle coal horizon contains 10-15 seams, among which are three seams 6-8 m thick. The upper coal horizon consists of 3-4 coal seams locally from 1 to 3 m in thickness. The coal layers have a complex structure, and the ash content is 10-30%. Coal resources total nearly 1.5 billion tons. Other coal fields of the region are small and of no practical significance.

The Urals-Caspian coal-bearing region (37) is in the western part of the Pricaspian depression (from the western slope of Ural and Mugodzhary to the northern coast of the Caspian Sea). There are more than 100 coal fields here, in Upper Triassic and the Middle Jurassic sediments. The number of coal seams ranges from 3 to 10, sometimes reaching 20-24. The ash content is 17-35%, rarely 45%. The total resources of the Urals-Caspian region coals are estimated at 1.5 billion tons.

The Mangyshlak coal-bearing region (38) is in the southwestern part of Kazakhstan. There are more than 100 small coal fields, working Lower and Middle Jurassic sediments. The coal-bearing formations contain 2-3 coal seams 0.4-0.8 m, rarely 1 m, in thickness. The ash content is 10-20%. Coal resources total 400 million tons.

An Early Carboniferous coal field, Berchogur (39), is also part of the West Kazakhstan coal-bearing province. It is situated on the eastern slope of Mugodzhary. The coal-bearing formation contains 20-25 coal seams. The thickness of the seams range from 0.6 to1.5 m. The coal is ranked as bituminous. Coal resources total 47 million tons.

Thus, within the West Kazakhstan province, only the Mamyt (Eastern Urals) brown-coal field is prospective for industrial development.

In summary, of all the Kazakhstan coal basins and fields, the central and northern provinces have the highest fuel-energy potential, the southern and the eastern provinces have a lower potential and the western province has no fuel base. All of the Kazakhstan coke resources in the Karaganda coal basin and Samarka and Zavyalovka coal fields, essential to development of the metallurgical industry, are also concentrated in the central province.

References

Golitsin, M.V., Dumler, L.F., and Orlov, I.V., eds., 1973. Geology of Coal and Oil Shale Deposits of the USSR, v. 5. Kazakhstan Coal Basins and Deposits. Nedra, Moscow, Book 1, 720 p., Book 2, 432 p. (in Russian).

Kushev, G.L., 1963. Karaganda Coal Basin. Publ. House of the Kazakh Academy of Sci., Alma-Ata, 344 p. (in Russian).

Kustov, B.I., and Kushev, G.L., 1947. Kazakhstan Coal, Its Quality and Classification. Publ. House of the Academy of Sci. of the USSR, Moscow, 180 p. (in Russian).

Orlov, I.V., Kushev, G.L., Dumler, L.F., and Golitsin, M.V., eds., 1972. Geology of Karaganda Coal Basin. Nedra, Moscow. 416 p. (in Russian).

Yegorov, A.I., 1945. The Carboniferous Coal Accumulation in the North-East Kazakhstan. Publ. House of the Kazakh Academy of Sci. of the USSR, Alma-Ata, 179 p. (in Russian).

An Assessment of Oil and Gas Prospects in Kazakhstan

A.A. Abdulin and E.S. Votsalevsky

Abstract

The major part of oil and gas production in Kazakhstan and of the known reserves is accounted for by some 11 or 12 fields. These fields are concentrated in west Kazakhstan. All of the giant fields are in west Kazakhstan in the Pricaspian and Mangyshlak basins, in regions where the potential for new discoveries is greatest.

The major problems facing the oil and gas industry are twofold. The first is the technological problem of maintaining oil production and reducing the production decline, together with intensified exploration to maintain high-level production after the year 2005. The second concerns transporting oil for export. Both problems involve not only improved technology, but a massive injection of capital.

The rise of the Caspian Sea level poses an additional, natural hazard, for it threatens to inundate some of the oil-producing areas.

Major reserves of oil, gas, and condensate have been discovered in Kazakhstan, most of which have not yet been developed or are in the initial stage of development. By the beginning of 1993, 188 fields had been discovered. These include 94 oil, 21 gas, 11 gas condensate, 25 oil and gas condensate, and 37 oil/gas and gas/oil fields. In 1993, 66 fields produced 21.9 million tons of oil, 3.3 million tons of condensate, and 6.4 million tons of gas. Eleven of the fields — Tengiz, Uzen, Kalamkas, Zhetybay, Zhanazhol, Karazhanbas, North Buzachi, Karachaganak, Kumkol, Kenbay, and Kenkiyak — contain more than 85% of all the discovered oil reserves. Twelve fields — Karachaganak, Zhanazhol, Tenge, Zhetybay, Imashev, Urikhtau, South Zhetybay, Kalamkas, Chagyrly-Chumyshty, West Prorva, Uzen, and Amangeldy — contain about 95% of discovered gas reserves as gas reservoirs and gas caps.

The above-mentioned fields determine the level of oil, gas, and condensate production at present and in the near future.

In Kazakhstan, there are 13 sedimentary basins with different oil and gas potential, such as the Pricaspian, South Mangyshlak, North Ustyurt-Buzachi, Priaral, South Turgay, Kustanay, Sredne-Syrdarya, Chu-Sarysu, Tengiz, North Kazakhstan, Zaysan, Alakol, and Ili (Fig. 1). The Pricaspian, North Ustyurt-Buzachi, South Mangyshlak, and South Turgay basins have proven oil and gas potential, but other fields have not been studied sufficiently, nor explored for oil and gas.

In exploring the oil and gas potential of the Republic, it is usually divided into West and East Kazakhstan, separated by the Urals fold system.

West Kazakhstan, including the Pricaspian, North Ustyurt-Buzachi, and South Mangyshlak sedimentary basins, is the major area in the Republic in terms of discovered reserves and potential oil and gas resources. It contains approximately 93% of liquid hydrocarbons and about 96% of gas reserves. Out of 188 fields discovered in Kazakhstan by January 1, 1993, 166 are located in the western sector, including such giants as Tengiz, Karachaganak, Uzen, and the major fields Zhanazhol, Korolev, Kalamkas, Karazhanbas, and Zhetybay.

The sedimentary basins of Kazakhstan differ in structure and age of sedimentary cover, structural development, thickness of the sedimentary cover, oil and gas potential, types of and formation conditions of traps and reservoirs, and other geological parameters.

All of those basins are confined to major isometric or linear negative structures, with distinct linear elements in the zones adjacent to the Caledonian or Hercynian fold structures. The volume of the basinal sedimentary cover varies from 200-300 thousand cubic kilometers to 7.5 million cubic kilometers.

The basement of the basins is heterogeneous and characterized by blocks of various shapes. The block structure of the basement induces dramatic faulting in the lower portion of the sedimentary cover and affects the morphology of structural elements in the overlying sedimentary formations (linear anticlinal zones, major struc-

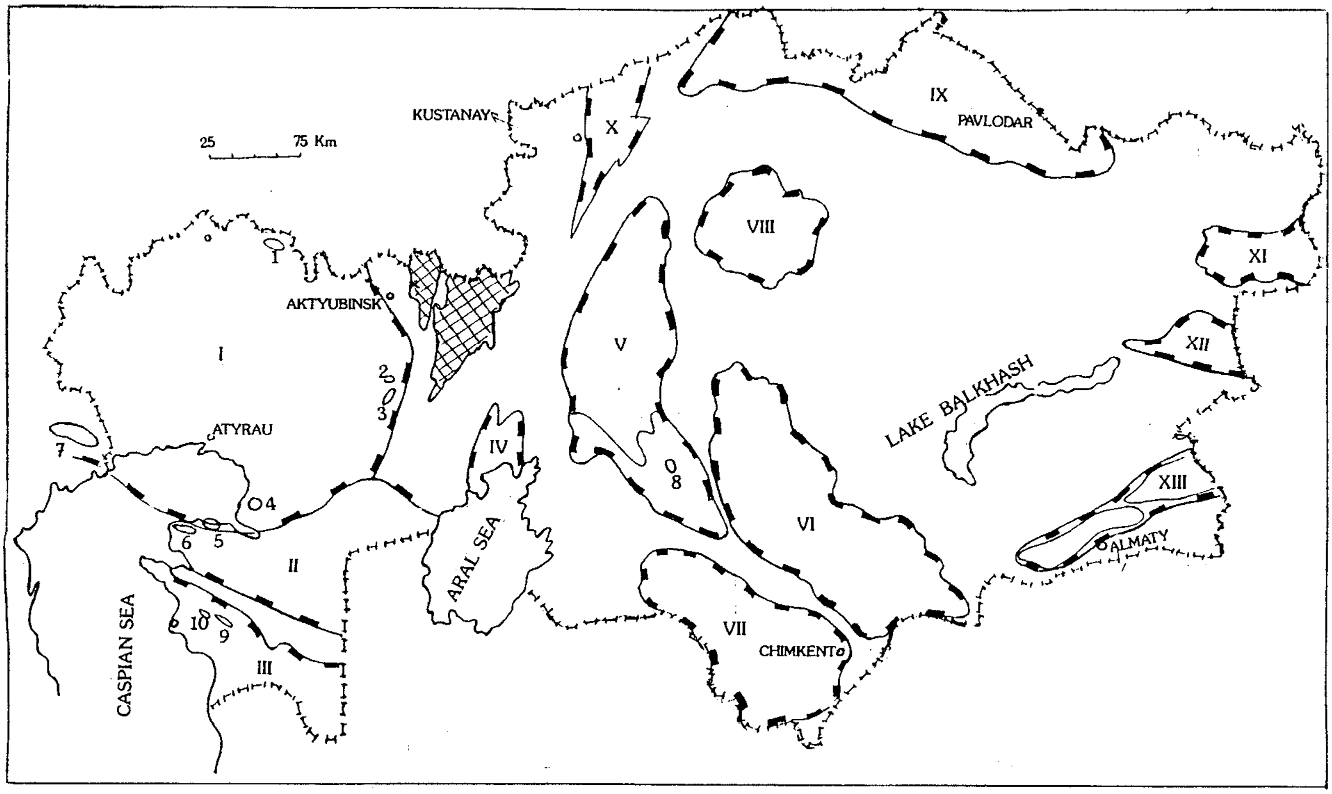


Fig. 1. The sedimentary basins and principal oil and gas fields of Kazakhstan. The sedimentary basins: I- Pricaspian, II- North Ustyurt-Buzachi, III- South Mangyshlak, IV- Priaral, V- Turgay, VI- Chu-Sarysu, VII- Sredne-Syrdarya, VIII- Teniz, IX- North Kazakhstan, X- Kustanay, XI- Zaysan, XII- Alakol, XIII- Ili. The oil and gas fields: 1- Karachaganak, 2- Kenkiyak, 3- Zhanazhol, 4- Tengiz, 5- Kalamkas, 6- Karazhanbas, 7- Astrakhan, 8- Kumkol, 9- Uzen, 10- Zhetybay.

tures of isometric shape, steep flexures, sedimentary escarpments, etc.).

Lithologically, the sedimentary cover in almost all of the basins is composed of clastic and carbonate rocks of various genesis and wide stratigraphic range.

In all of the basins, the sedimentary section can be subdivided clearly into reservoir and seal horizons. Reservoirs are composed of sand-silt and carbonate deposits, while seals consist of halite sulphate, clay-shale, and sometimes clay-carbonate deposits. Regional seals insulating some portion of the sedimentary cover are developed primarily in the sedimentary basins of western Kazakhstan.

The permeability properties of reservoirs are characterized by sharp horizontal and vertical variations. Permeability varies from 1 millidarcy to 1.5-2.0 darcy. The most complex reservoir type is related to the clastic and clastic-carbonate pre-Kungurian Paleozoic in the Pricaspian, Triassic in South Mangyshlak, middle Jurassic in North Ustyurt, and Paleozoic in the Chu-Sarysu basin. The porosity of the reservoir rocks is mostly intergranular, sometimes augmented by fracturing, although fractured reservoirs are quite rare.

Chu-Sarysu is the only basin containing only gas. All of the other basins with proven oil and gas potential have oil, oil with free gas in the form of gas caps, or individual gas accumulations. The concentration of condensate in the gas condensate portion of the pre-Kungurian Paleozoic in the Pricaspian is up to 850-1000 g/m^3.

Jurassic oil in South Turgay and South Mangyshlak contains up to 11.5-25% of paraffin. The Pre-Kungurian Paleozoic in the Pricaspian is characterized by the presence of hydrogen sulphide in free and dissolved gas, whose concenration may reach 22 to 24%. Heavy oil on the Buzachi peninsula contains commercial concentrations of vanadium and nickel.

Giant fields have been discovered only in the Pricaspian and South Mangyshlak basins. In the Pricaspian, they are related to major tectonic-sedimentary traps in the middle and lower Carboniferous carbonate deposits; in the South Mangyshlak basin, they are related to the Middle and Upper Jurassic sandy-silt deposits. The oil and gas column varies from 450 m to 2000 m in the giant fields. The pre-Kungurian Paleozoic in the north-northwestern portion of the Caspian Sea is predicted to have a very good potential for the discovery of new giant and major fields.

The sedimentary basins in Kazakhstan are characterized by variability of trap types. There are faulted anticlines, traps in the arches and near-arch portions of salt domes sealed by faults, steep slopes of salt cores and salt overhangs, traps confined to stratigraphic unconformities, traps related to lithological pinch-outs, and traps confined to various types of tectonic-sedimentary structures. The most complex and variable traps are confined to supra-salt and sub-salt complexes of the Pricaspian basin.

The pressures and temperatures found in the sedimentary basins in Kazakhstan vary considerably. In the pre-Kungurian Paleozoic, temperatures of 110-120^{O} are recorded at the depth of 5000 to 5500 m. Reservoir pressures vary from 65 to 95 mPa. Anomalously high temperatures also are in the supra-salt complex, where they may reach 210-247^{O} at the depth of 3500 to 4000 m.

One of the peculiar features of the Kazakhstan basins is that there is no active hydrodynamic drive in most complexes in the region. Hydrogeological systems generally are characterized by highly mineralized formation water, which sometimes contains commercial concentrations of iodine, bromine, boron, lithium, caesium, and strontium.

A long and complex history of development of East European and Siberian Plate margins, as well as the development of Ural-Mongolian fold zone (its Altay and Kazakhstan branches in particular) is the cause of such a variety of sedimentary basin types in Kazakhstan.

Global tectonics during the lower-middle Paleozoic, together with the transformations during the Caledonian and Hercynian stages of tectonic activity, contributed to the formation of the present-day sedimenatry basins. Practically every basin is geologically unique, and those with a long history of development covering the time interval from the Paleozoic through Meso-Cenozoic have a more complex structure.

Analyzing geological criteria, we can predict the discovery of new fields in the basins with proven oil and gas potential, and major discoveries may be anticipated in the north-northeastern portion of the Caspian Sea.

In order to solve the problems of energy supply in Kazakhstan, the Republic should pursue the following objectives.

First, it is necessary to significantly improve the technology of oil-field development in the major oil-producing regions in order to reduce the decline in oil production and eventually to stabilize it.

Second, it is important to intensify oil and gas exploration, with the aim of discovering and evaluating the reserves at the new fields.

Third, it is critical to solve the problem of oil transport, both within the Republic and outside of it, as soon as possible.

The above objectives are extremely important, because more than 50% of Kazakhstan oil is produced from four fields — Uzen, Zhetybay, Kalamkas, and Karazhanbas — in the South Mangyshlak and North Ustyurt-Buzachi sedimentary basins. In the Uzen and Kalamkas fields, where the total annual oil production is approximately 10 million tons, the production rate is declining by more than 1 million tons per year. However, recoverable oil reserves in those fields are very significant, and production can be stabilized if engineering problems can be solved. The situation is very similar in the Karazhanbas field and other oil-producing regions of Kazakhstan, where technological problems limit the production rate. The introduction of new technologies may allow the utilization of non-producing hydrocarbon reserves, which is equivalent to the development of new major fields. As the financial and technological resources of Kazakhstan are insufficient to permit the Republic to solve the problems, foreign investments will be crucial.

Another problem is that in the last two-three years, the exploration for oil and gas has declined dramatically, even in the most prospective regions of the Pricaspian basin. If not reversed, this tendency will affect the production of potential oil reserves; after the years 2005-2010, Kazakhstan may not be able to maintain high annual oil-production rates. The policy of encouraging foreign investments has as its objective the signing of agreements with foreign companies to develop the fields already discovered and prepare for production rather than exploration of new fields. Recently, this was initiated by the consortium "Kazakhstancaspishelf", and agreements were signed with a number of foreign companies to explore the Pricaspian basin. However, this has not occurred in the east Kazakhstan basins, resulting in the reduction of exploration in those areas of the Republic.

Oil transport is a vital problem for Kazakhstan. The fact that the major resources are concentrated in western Kazakhstan while the industry is developed in its central and eastern areas creates an imbalance in the production and consumption of oil and oil products. There are two refineries in the eastern regions, with the capacity of approximately 13 million tons of crude oil per year, which utilized oil from West Siberia. At present, these refinery complexes have been practically closed down due to the irregularity of oil supplies from Siberia. This problem could be solved if a pipeline from western Kazakhstan to its eastern regions was to be constructed and connected to the Pavlodar-Chimkent pipeline. Export of liquid hydrocarbons is another very critical issue for Kazakhstan once the giant fields of Tengiz and Karachaganak have been brought into full production; but, there is no high-capacity pipeline system in Kazakhstan, and the use of the Russian export pipeline is very limited. As a consequence, the oil production rate at Tengiz was reduced, and production of gas and condensate at Karachaganak was stopped.

Thus, Kazakhstan cannot significantly increase hydrocarbon production, although it has major oil, gas, and condensate reserves ready for production, as well as considerable oil and gas potential in most sedimentary basins. In recent years, the situation has been aggravated by natural global phenomena, such as the continuous rise of the Caspian Sea level. Since 1978, the level of the Caspian Sea has risen by 2 meters, inundating more than 25 thousand square kilometers of the Atyrau and Mangistau lowlands in western Kazakhstan. Some important oil-producing areas are in the flooded zone already or will be flooded in the near future. If the sea level continues to rise, the most promising oil fields, such as the Martyshy, Tengiz, Prorva, and Buzachi groups, will be in the zone of inundation. Their total production in 1993 was about 8 million tons per year. This situation has contributed to the acceleration of exploration in the northeastern area of the Caspian Sea, which may offset the negative effect of the sea-level rise on oil production in Kazakhstan.

All this allows us to make the following conclusions:

1. Major explored reserves of oil, gas, and condensate, together with enormous potential resources, form a good basis for a significant increase in liquid hydrocarbon production compared to the present-day level.
2. The development of the petroleum industry in Kazakhstan depends on technological and engineering improvements in field development, as well as a solution to the oil- transport problem within the Republic and outside of it.
3. In order to solve the technological problems of field development and export of oil, Kazakhstan will need major foreign investments.
4. Since there is a risk of oil-production decline due to the potential for inundation of some oil-producing regions by the Caspian Sea, contingency plans for accelerated exploration of the offshore Caspian and Aral areas must be prepared.

Human Impact on the Environment of the Aral Sea Region

B.K. Bekniyazov

Abstract

A series of maps has been generated to display geological, geomorphological, hydrological, and engineering-geological effects in the Aral Sea region. The environmental effects of hydrological, and climatic changes can be demonstrated on dynamic, cartographic maps, such as the drying up of tugai, the growth of solonchaks, the fall in lake and groundwater levels, the conversion of lake beds to arable land, and the growth of areas covered by aeolian sand.

Introduction

The Aral Sea continues to dry up, affecting more and more aspects of the environment and influencing social, economic, medical, biological and political spheres of human life. The various geological-ecological problems in the Aral Sea region have been the subject of intensive study (Abdulin and Bochkarev, 1989, 1990; Bochkarev, 1989). The complexity of these problems depends primarily on the ability of the environment to resist or recover from anthropogenic (technological) developments, and the duration and character of these effects. The environment of the Aral Sea region is susceptible to such influences because of the arid climate and the fragile desert and semi-desert conditions (Bochkarev, Pozdnysheva, Karazhanov, 1982). Even short-term, localized influences can change conditions over large areas. The anthropogenic factor makes itself felt through irrigation, agricultural development, stock-breeding, construction, and the spread of towns and villages, railroads and motor-roads, canals and water pipes, and electric lines. Meanwhile, the level of the Aral Sea continues to drop, exerting influences that result in radical changes in the environment.

Analysis of ecological investigations indicates that attempts to solve the problem of assessing environmental conditions and predicting tendencies toward change have not been undertaken upon a firm conceptual basis and are flawed by neglect of the time factor. Existing small-scale maps do not represent these changes. The ultimate goal is to establish recommendations for the rational use of the environment and to organize engineering and ecological monitoring of the Aral Sea region. Estimating anthropogenic regional changes and their prognosis is the immediate task.

The methodological basis of the investigations follows the new direction of engineering geology/engineering ecology. Up until now, it has been used only in industrial regions and large urban centers, so it needs to be adjusted for application to desert conditions with active agricultural development. The engineering-ecological functional method is based on the idea of close mass-energy connections of the environment with other external media, and requires regular investigation of all the components. Compiling a volumetric and dynamic cartographic model of the territory as an atlas of basic and auxiliary maps is the main aspect of these investigations (Golodkovskaya and Eliseev, 1989). The maps were compiled using modern surface and aerial methods, including computers for processing information.

Classification of Regional Environment and Technosphere

The environment of the Aral Sea region (Fig. 1) was studied separately. Geological, geomorphological, hydrological, geodynamic, and engineering-geological conditions, as well as those factors that influence them (climatic, botanical, hydrographic, anthropogenic) were taken into account. A series of analytical maps was compiled to display this information, these include an engineering-geological map, a map of exogenous geological processes, a map of the geological environment, and a map showing technogenic loads (irrigation canals, settlements, agriculture, etc. Fig. 3). Maps previously compiled and ready for publication were also used. Among them there are geomorphologic and hydrogeologic maps and a map showing neotectonic structures (Bochkarev et al., 1991).

Classification was carried out at the level of districts according to the lithology of rocks and geomorphologic classification of topography on the basis of an engineering-geological map of the Aral Sea region. The following classes and types of environment are shown: classes — mainly clayey soils, sandy-clayey and sandy soils; types

Fig. 1. General map of the Aral Sea region. A- western Kazakhstan; B- Kazakhstanian part of the Aral Sea region; C- modern delta of the Syrdarya River; D- Malyye Barsuki sandy massif.

— Quaternary eolian plains (I), Quaternary lacustrine-alluvial plains (II), Quaternary marine plains (III), continental pre-Quaternary denudational plains (IV), and marine pre-Quaternary denudational plains (V) (Fig. 2). Figure 2 shows a small portion of the map of the Syrdarya River delta environment.

The "technosphere" of the region is represented mainly by agricultural types. Five classes and fifteen subclasses are distinguished on the map of varieties of technogenic loads (Fig. 3). The classes are 1) land reclamation (main and irrigation canals, irrigation networks), 2) residential areas (towns, villages), 3) stock-breeding areas (pastures, winter quarters, watering places, haymaking places), 4) transport network (railroads and motor roads, water pipes, electric lines), and 5) extractive industries-exploraion and operating deposits (salts, building materials, underground water).

Regional Changes in the Environment and Technosphere

The aforementioned maps represent the environment in a static, fixed state. For reliable prognoses, however, dynamic cartographic models must be constructed. In order to do this, we must first consider the changes in factors that influence the environment (climate and hydrosphere) and the environmental consequences of these changes (hydrogeology, geomorphology, geodynamics) within the technosphere of the region.

Semyonov, Tulina and Chichasov (1989), recording climatic changes beginning in the 60s, showed that the drop in the level of the Aral Sea has been accompanied by reduction of relative humidity to unprecedented values, lower even than during the driest months and years. Lacking the moderating effect of the sea and deltas, July temperatures have increased by 2-2.5°C and January temperatures have fallen by 1-2°C, and the frost-free period has been reduced by 20-25 days. Statistically, wind velocity is considerably reduced, and wind directions have become more erratic. The atmosphere has become laden with dust removed from the dry sea bed.

Climatic changes negatively influence the environment, and changes in, and reduction of, the vegetative cover influence the dynamics and stability of that part of the environment closely dependent upon the atmosphere and biosphere of the region.

Changes in the hydrosphere have a particularly great impact on human living conditions. The deterioration of Aral Sea water quality, the drying up of *tugai* (lakes or shallow, slow rivers, overgrown with bushes and trees) and inundated areas, reduction of river runoff, a falling water table, and pollution of water resources are problems that have been tackled by many researchers. The dynamics of the changes need to be ascertained and depicted on maps. For this purpose a map of regional hydrospheric changes has been compiled using topographic maps and satellite imagery. It reveals the following: lakes, which were terminal runoffs of the temporary water courses in the north Aral Sea region, have turned into *solonchaks* (salt marshes, or dry lake beds covered with solonchak soils which have a high salt content) and lakes within the delta and inundated areas have shrunk 20-100% in area, while spring flooding of the rivers has nearly ceased. Saline lands and *sors* (salt flats, playas covered by clay with a high salt content, etc.) have formed in the lowlands of the dried sea bed and in isolated gulfs. Perenially wet areas on the north Aral seashore, kept wet by under-ground water, have shrunk in size. Numerous lakes have appeared, fed by excess water from irrigation and filtration along canals as well as by reservoirs of fresh and salt water near flowing wells. Many river beds, especially the Kuvandarya bed, have been straightened by canals and partitioned by dams. Many natural wells and springs have dried up.

Changes in hydrogeological conditions have been ascertained by hydrogeologists. The extensive drop in the Aral Sea level and the opening and exploitation of ground water have led to considerable changes in hydrogeological conditions. First of all, the level and hydrochemical regime of the ground water of the area have changed. Ground water levels near the Aral Sea have dropped as much as 3-

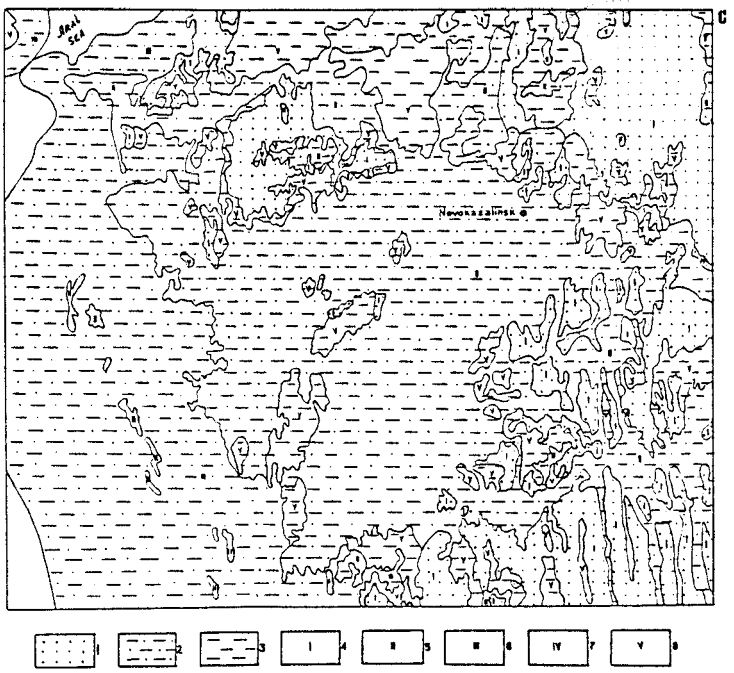


Fig. 2. Portion of the environment classification map (delta of the Syrdarya River). 1- mainly sandy soils; 2- sandy-clayey soils; 3- mainly clayey soils; 4- Eolian Quaternary depositional plains; 5- lacustrine-alluvial Quaternary depositional plains; 6- marine Quaternary depositional plains of the dessicated part of the Aral Sea shelf; 7- continental pre-Quaternary denudation plains; 8- marine pre-Quaternary denudation plains.

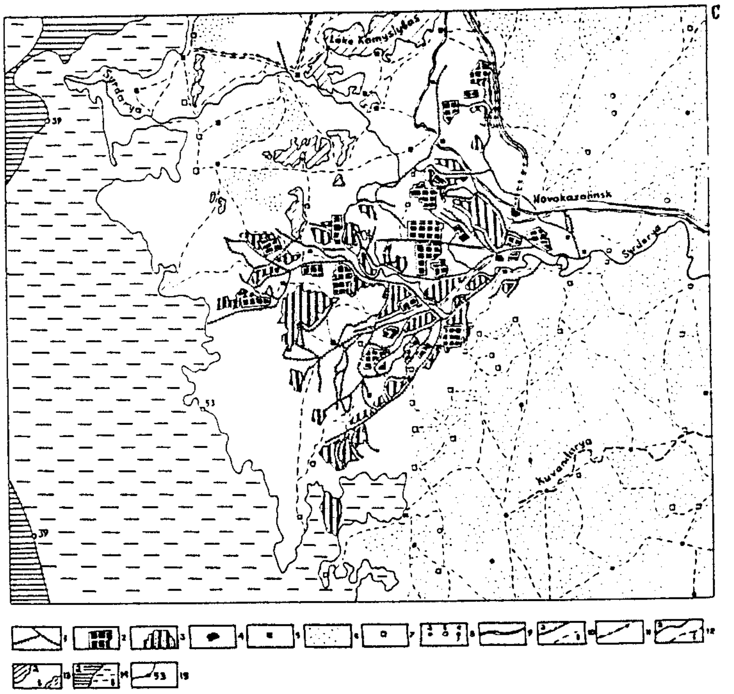


Fig. 3. Portion of the map of technogenic load classification (delta of the Syrdarya River). Land reclamation class: 1- main and irrigation canals, irrigated massifs; 2- river plantations; 3- melons and kitchen gardens. Residential class: 4- towns; 5- settlements. Cattle-breeding class: 6- pastures; 7- winter and summer ranges; 8- watering places (a- bore holes, b- wells, c- springs). Transport class: 9- railroads; 10- motorcar roads (a- paved, b- dirt); 11- water pipes. Other symbols: 12- river beds (a- permanent, b- temporary); 13- the Aral Sea aquatorium (a- existing, b- former); 15- shoreline of the Aral Sea with elevation in meters.

5 m. Further from the sea the amplitude diminishes, but it is still observed at a distance of 7-10 km in the northern part of the Aral Sea region and 60-80 km in the eastern direction. The fall in ground water level is due not only to the decline in Aral Sea level but also to aridization of the climate and falling piezometric water levels in the marine Paleogene sediments. During the past 30 years, this decline has reached 3-4 m in a zone that has increased in width from 9-10 km up to 40-60 km. The greatest amplitude decline in the Senonian-Turonian water level in the eastern and southeastern Aral Sea region amounts to 7-14 m. Thus the total quantity of underground and saltwater runoff in the Aral Sea region has been reduced by hydrogeological changes (Akhmedsafin, 1983).

Changes in geomorphological conditions are particularly obvious in the eolian massifs both on the continent and on the dried shelf of the sea. According to our data, replacement of eolian relief forms in the Aral Karakum and Kyzylkum sands takes place according to the following succession: cover sands, cumulose sands, ridge-honeycomb sands, and ridge sands. Sandy relief on the dried sea bed is transformed much more quickly because the material is unconsolidated.

Changes in the technogenic load on the environment of the Aral Sea region are traced on topographic maps and satellite photographs during different years. The most considerable changes are in irrigated land. At present, nearly all of the Syrdarya River delta is used for rice and melon cultivation and for haymaking. The former large lakes, Kokshkol and Makpal, have now become arable lands. Rice plantations can be recognized in the Syrdarya River delta on space photographs; from year to year they have grown in area, occupying lands situated to the west near the dried Aral Sea bed. They are twice as large now as formerly. The network of irrigation and drainage canals has greatly increased, and new settlements have appeared. Slightly salty artesian water was found in Kyzylkum, so pasturage expanded, and the area of former pastures has also increased. The network of motor roads and of cattle trails linking watering places (artesian wells) broadened. New areas of winter and summer range have been opened for cattle. Exploitation of salt and building material deposits, construction of railways and motor roads, towns and settlements have a less obvious influence. But in most cases such effects have far-reaching consequences, with deep penetration into the environment, and that is why they are not easily reversible.

Changes in the geodynamic state result in activation of exogenous geological processes. Large-scale expansion of natural processes takes place in sandy areas. There are two eolian processes: transportation and accumulation of sand. The accumulation of sand in interridge *takyr* (intermittent lakebeds or clay-silt playa) is observed in Kyzylkum, with the result that territories occupied by sand enlarge. Sand transportation takes place in Malyye Barsuki and Priaral Karakum, parts of the northern Kyzylkum Desert where there are Paleogene-Neogene sandy deposits and Quaternary alluvium, covered by soil and formerly showing no eolian features. The main reason for sand activation and transport is in all cases economic activity.

A scheme of environmental changes of the Aral Sea region (scale 1:200,000, from satellite photographs) was drawn up, and special attention was given to changes in sandy massifs. The scheme represents various periods of time (1948, 1957, 1974, 1985). The problem of recent sand movement in the Karakum up to the present time remains debatable (Sadov, 1988). Analyzing data obtained at different times, we can define the mechanism of regional movement of sandy massifs (increase or decrease of eolian sands areas), the direction and velocity of movement, and the reasons for its mobility. The mechanism of sand mobility may be considered as follows: sands accumulate on loamy or clayey surfaces as small massifs, at first isolated from each other. As sands accumulate, separated bodies join together, gradually forming an unbroken sandy cover. At the next stage of movement this process recurs. The general direction of sand movement is to the north.

Figure 4 is a schematic representation of environmental changes in the sandy Malyye Barsuki massif. Broadening of eolian sands area occurs owing to transportation of formerly compact Paleogene sands. Changes that occurred throughout the Quaternary Period were analyzed, and the area of the territory exposed to these changes was defined. The average rate of growth of the eolian sand area has been 12-14 km^2 per year. Proportions of areal enlargement are shown on the histogram. The direction of movement varies, depending on the location of sites where the sandy cover is disturbed. Specific reasons for the spread of eolian sands may become apparent when the scheme of changes of technogenic loads is superimposed on that of environmental changes. For the Malyye Barsuki massif, the main reasons are overgrazing, road construction, and too high a concentration of cattle at watering places. However, the spread of winnowed sands in the eastern part of the massif is the result of extensive mining during the prospecting for mineral resources, when the surface cover of Paleogene sands was destroyed by numerous excavations, ditches, and well bores.

The same picture is observed in the Kyzylkum sands. Eolian processes were activated not so much by the drop in ground water level caused by decline in the Aral Sea level as by ordinary economic activity. The more intensive and prolonged the technogenic influence, the stronger is the process of sand transportation.

Models of environment change for different periods are the basis for estimating the extent of modern changes and environmental stability. Using these maps and infor-

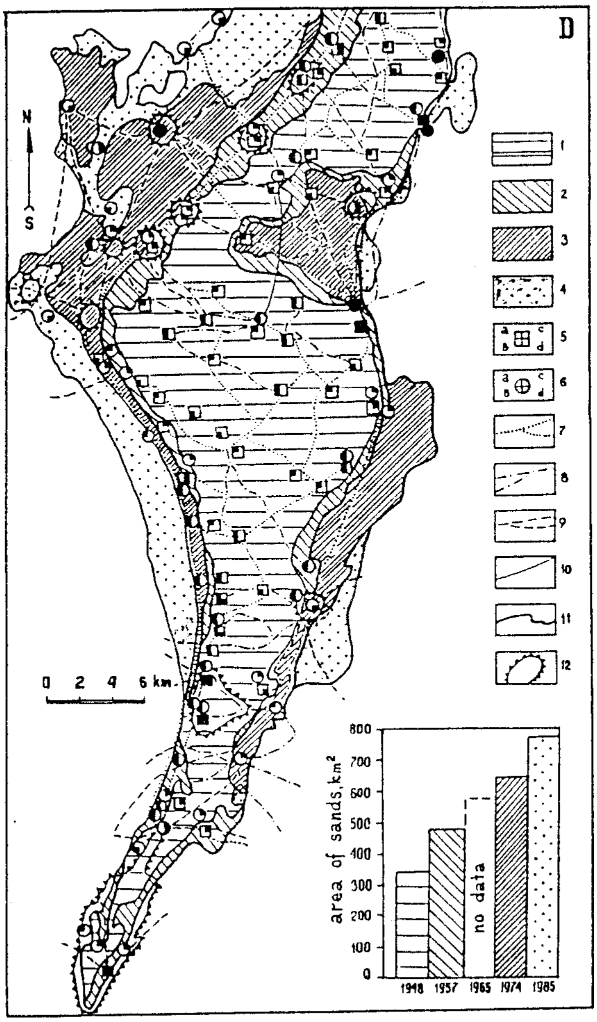


Fig. 4. Map of environmental changes of the sandy Malyye Barsuki massif. Areas of sand transportation and their expansion in: 1- 1948; 2- 1957; 3- 1974; 4- 1985. Highest concentrations of domestic cattle (winter and summer quarters in: 5a- 1948; 5b- 1957; 5c- 1974; 5- 1985. Functioning watering places (wells) in: 6a- 1948; 6b- 1957; 6c- 1974; 6- 1985. Dirt roads in: 7- 1948; 8- 1957; 9- 1974; 10- 1985; 11- boundaries of sand transportation areas in different years; 12- areas of activation of modern deflation processes.

mation from plans for regional economic development, a promising predictive matrix of environmental changes and a map for its rational use is being compiled. Research on the preparation of a cartographic ecological model of environmental use goes on. A system of engineering-geological monitoring will be worked out, permitting redetermination of prognoses for geological environment changes in the Aral Sea region and recommendations for its protection and rational use.

References

Abdulin, A.A., and Bochkarev, V.P., 1989. Problems of rational use of geological environment of Kazakhstan. Abstracts of 28th International Geological Congress, v. 1, Washington, DC, July 9-19, 1989, p. 1-3.

Abdulin, A.A., and Bochkarev, V.P., 1990. Problems of rational use of Kazakhstan environment. Engineering Geology, 3, p. 3-7 (in Russian).

Akhmedsafin, U.M. (ed.), 1983. Underground Water and Salt Runoff in the Aral Sea Basin. Alma-Ata, Nauka, 160 p.

Bochkarev, V.P., 1989. Engineering-geological problems of the arid zones of Kazakhstan. In: Engineering Geology of the Earth (W.R. Dearman and E.M. Sergeev, eds.), p. 86-90. Moscow, Nauka.

Bochkarev, V.P., Pozdnysheva, D.P., Bekniyazov, B.K., and Marinenko, G.A., 1991. Set of maps of environment dynamics in the Aral Sea region. Scientific News of Kazakhstan (Express Information), 2, p. 15-17 (in Russian).

Golodkovskaya, G.A., and Eliseev, U.B., 1989. Environment in Industrial Regions. Moscow, Nedra, 220 p. (in Russian).

Medoev, G.Ts. (ed.), 1982. Problems of Part of Siberian Rivers Runoff Transfer to Kazakhstan and Central Asia. Engineering-Geological and Soil Reclamation Conditions in Kazakhstan. Alma-Ata, Nauka, 232 p. (in Russian).

Sadov, A.V., 1988. Aero-Space Methods in Engineering Geodynamics. Moscow, Nedra, 207 p. (in Russian).

Semyonov, O.E., Tulina, L.P., and Chichasov, G.N., 1980. Aral: Tragedy exists. Man and Natural Disaster, p. 102-105 (in Russian).

Paleokarst of South Kazakhstan and Its Influence on Engineering Geology

V.P. Bochkarev, A.S. Menshikova, and V.G. Shipulina

Abstract

Paleokarst of the Karatau Range is a unique feature of the exogenous macro-structure of rocky carbonate massifs. Aligned with a network of fissures, it defines the anisotropy of physical-mathematical properties, and the stability of artificial slopes and underground workings in urban and industrial regions. An engineering-geological assessment of paleokarst is given, based on the results of intensive investigations and mapping of mines, quarry fields, artificial basins, and underground workings.

For many years there were no engineering-geological investigations of karst terrane in Kazakhstan because the carbonate formations lie in a desert and karst features are largely subterranean (Sokolov, 1967). In southern Kazakhstan, paleokarst has been recognized only in the Karatau Range, the northwestern spur of the northern Tien Shan. Despite its relatively low altitude (500-2170 m), the Karatau Range stands above the surrounding low-lying desert-steppe areas of the Syrdarya and Chu-Sarysu basins. The Karatau comprises two ranges — Bolshoy and Malyi Karatau, separated by the Leontievskaya depression (Fig. 1). On the basis of its physiographic form along strike, the Bolshoy Karatau is subdivided into northwestern (west of long. 68°E), central, and southeastern (east of long. 69° E) segments. The Malyi Karatau includes the axial part of the asymmetric Kokdzhon Range (up 1200-1614 m), the front ranges of the Bolshoy and Malyi Aktau, separated by the longitudinal Bolshoy, Malyi Karoy (800-820 m), and Aksai (520 m) valleys.

The monoclinally folded and disjunctive structures of the Karatau Range were developed during the Baikalian, Caledonian and Hercynian phases of tectogenesis. The Bolshoy Karatau is a Hercynian-Caledonian-Baikalian folded anticlinorium, whereas the Malyi Karatau is Caledonian-Baikalian.

The modern Karatau Range is a typical epiplatform orogenic area of the North Tien Shan, with deformation of a pre-Neogene surface which was reduced to 2000 m by erosion during the Neogene-Quaternary.

All the conditions favorable for development of both modern and ancient buried karst are present: the widespread occurrence of carbonate formations of different ages, the high permeability of rocks due to extensive tectonic jointing, an active hydrodynamic system in a mountainous rugged relief, vigorously circulating underground water capable of agressively dissolving limestone (including hydrothermal solutions active in the past, which formed stratiform deposits of polymetallic ores and cavities of ore karst).

This article reports unpublished information from engineering-geological evaluations of paleokarst in the Karatau Range. It is based on lengthy investigations and detailed mapping of quarry and mining operations in the Karatau phosphorite deposits and on examination of roadcuts, and it incorporates previously published data.

Morphogenesis and Paleokarst Occurrence

Paleokarst is common in upper Riphean, lower and middle Paleozoic carbonate formations.

a. Riphean: Paleokarst of the carbonate (dolomitic-calcareous) formation of the Toguzbai suite (R_3 tg) of Late Baikalian geosynclinal type occurs along the watershed of the Bolshoy Aktay range in the Zhanatas tectonic block. The rocks of the formation form a gently dipping undulating monocline with the steeply dipping limb (75-85°) inclined 10-25° NE. The limestones are gray, slightly pink-gray and dark red to red when intensive hematization of clayey and aleuritic material has occurred. Stratified and columnar-stromatolitic structure, thin striation and wave-like banding with small intricate dentation are present. Limestones are composed principally of calcite grains with rare rhombohedrons of dolomite and abundant hydrous ferric oxides, and aleuritic admixtures of quartz, chlorite and phosphatic clay. The dolomites are gray, light gray, grayish brown, slightly pink-gray, with varied structures (micro-fine grained, pelito-morphic, inequigranular). The bedding is massive and flaggy, and coarse-bedded or thin, wavy, laminated, and cellular. Rocks of this suite are exposed on the southwestern side of quarries working the Zhanatas phosphorite deposit, where numerous paleokarst cavities of different size and form, and filled with loose disperse and detrital material, have been mapped.

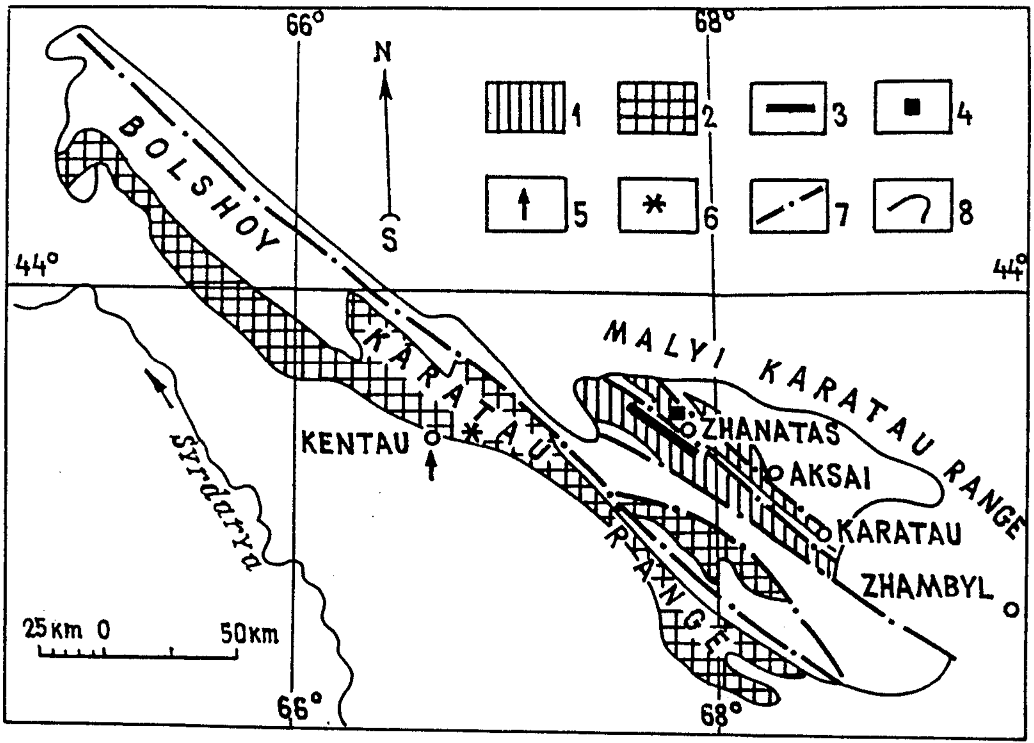


Fig. 1. Area of carbonate karst rocks: 1- Shabakty (C_1l-O_2) and Toguzbai (R_3tg) suites; 2- carbonate formation (D_3fm-C_1); 3-6- areas of karst that have been investigated: 3- Zhanatas phosphorite quarries (Fig. 2), 4- Koksu mine (Fig. 3), 5- karst suffusional sinkholes in Kentau area (Mirgalimsai mine, Fig. 4), 6- sulfate ore karst in Achisai mine; 7- regional fault traces; 8- outline of the Bolshoy and Malyi Karatau ranges.

Cavities are rare in the limestone and consist of oval caverns from 0.2-0.3 m to 1-1.2 m in size, filled with red clay.

In the massive, thick-flaggy, calcareous dolomites there are many karst areas extending from 40 to 250 m where cavities (from 3-7 m and up to 40 m) and sinkholes are separated by outcrops of non-karstic rocks (5-15 m). In most cases they are situated in the near-surface part of the quarry face, and they are covered by a thin cover of loam or soil. There are also local linear karst zones up to 40 m wide, which follow zones of cross fractures. The cavities are varied and complex in form and are branching, rectangular, or trapezoidal in shape. They may narrow or widen downwards with a 20-44 m width. There are in addition niches, caverns (0.3-1.5 m) and honeycomb (cellular dolomites) structures. The paleocavities are filled with sand, siliceous gravel and pebbles, gravelly sandstone, and a conglomerate with a ferruginous-clayey cement, boulders of flint, slightly pink-gray dolomitic powder containing secondary phosphorites, brick-red clays with gravel and pebble inclusions of siliceous rocks, and finally fragments and blocks of karstic dolomites. At the surface of the dolomites there are traces of active leaching, small hollows, cavities, trenches with gouges, sandy material and dolomitic powder.

b. Early Paleozoic: Paleokarst occurs in the Caledonian parageosynclinal carbonate (calcareous-dolomitic) formations of the Shabakty suite (C^1_1 - O_2 — Lower Cambrian - Middle Ordovician) — thick (2000 m) homogeneous carbonates extending the entire length of the Malyi Karatau Range (120 km). The suite is composed of dolomites, and more rarely limestones. There are occasional interbedded marls, argillites, and flints. The chemical composition of the rocks is diverse. In 10 samples, calcite forms 6.22-91.55%, and dolomite about 7.06-91.62%, with an insoluble residuum of 0.98 - 14.48%. Paleocavities are exposed everywhere in excavation: in phosphorite quarry faces, in roadcuts, construction pits, and in boreholes into the Koksu deposit.

The paleocavities in quarries up to 150 m deep in the Zhanatas deposit have been investigated in detail. Here the karst rocks in the lower part of section of the Shabakty suite are represented by light-gray calcareous dolomites of the "G" packet and fine-grained black dolomites of the "B" packet (Fig. 2). They are separated by almost karst-free, thinly laminated dolomites with interbedded argillite and marl of the "V" packet. Linear karst zones and fissures (0.1-10 m wide) cut across the entire quarry face. The largest cavities are in the "G" unit, which is more than 60 m thick. The continuous and "skeletal" karst fields 100-250 m long along the slope front, are controlled by cross fractures. Local karst cavities (fissures and irregular, pear shaped hollows) cut across bedding structures or may extend along them for 2-10 m, with widths of 0.1-2.5 m. In the "B" packet black dolomites, cavities are small and of rectangular (up to 15 m), conic, or elongated in form. These karst cavities may be filled with red clay, dolomitic powder, dull-gray disseminated clays with blocks of secondary phosphorites ("refuse" filling), quartz sand with gravel and pebbles of siliceous rocks, and secondary pale-yellow limestone. Almost all kinds of cavity fill include inclusions of large blocks and fragments of karstic rocks, formed by failure of underground cavern walls and roofs.

Paleokarst in the area of the Koksu mine was found as a result of drilling numerous wells 20-22 m deep which revealed 139 karst shows. Soluble rocks are represented by Middle Ordovician carbonate formations. Their chemical composition (68-71% calcite, 29-32% dolomite) indicates that the rocks are medio-dolomitic limestones. Most interstices are cavernous (0.5-1 m). One cave, at a depth of 3.5 m below the surface, is 7.5 by 3.0 m in plan and 1.6 by 1.8 m in height.

The upper parts of the karst cavities were breached by Eocene marine erosion, and many cavites (karst fissures, sinkholes) were filled with dolomitic powder, sand, and loose and dense sandstone blocks, although red clay is rare. Fill of every sort contains gravel and pebbles of karstic limestone and gypsum (Fig. 3).

c. Late Paleozoic: Paleokarst also occurs in the geosynclinal carbonate (dolomitic-calcareous) formations of the Upper Devonian-Lower Carboniferous (Hercynian stage). On the southwestern slope of the Bolshoy Karatau Range, these rocks are more than 4000 m thick. Soluble carbonates are part of a shallow-water facies, including organogenic-detrital (lithobioclastic) rocks with graded bedding and massive reefal structures. Characteristic of this formation is the variability in facies, structural-textural features, and thickness in different parts of the Bolshoy Karatau Range. Large stratiform deposits are associated with this formation. They form a system of asymmetric synclinal

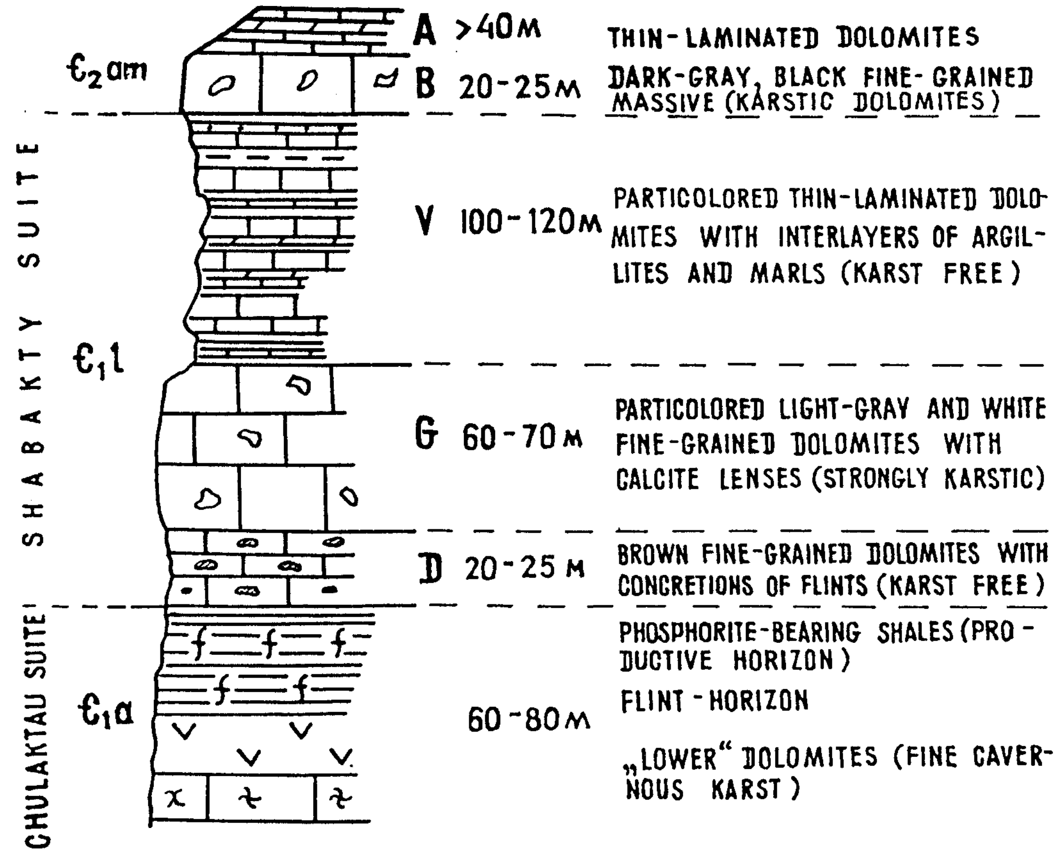


Fig. 2. Schematic section of the NE slope of the Zhanatas phosphorite quarry. A, B, V, G, D- lithological units of the Shabakty suite (B, G- karst horizons).

and anticlinal folds broken by fractures and with limbs inclined at angles ranging from 10 to 75°. The mineralogical composition of the rocks is given in Table 1.

In the Famennian part of the section, dolomites predominate (35 samples). In the late Famennian and early Tournaisian, there are both limestones and dolomites, but in the later Tournaisian-Visean there are only limestones. Silica concentration is highest in the calcareous rhythmites.

According to Olli (1958), paleokarst in central and southeastern Karatau is indicated by buried sinkholes along the Biresek-Boyaldyr divide, on the Balmazar and Dzhamanktai plateau, and in Boroldaitau (Ulken Tura Mountain).The sinkholes are 25-50 m in diameter, with an average depth of 10-15 m (the deepest is 50-60 m). Sinkholes on the plateau are seen in the rough areas in rocky Paleozoic terrane.

Rocks of the sinkhole walls and floor have disintegrated to a dolomitic powder, and the sinkholes are filled with material from the overlying Cretaceous. Pliocene-Quaternary loams with lenses of "pale-yellow" limestone also occur. On the right bank of the Biresek River these sinkholes are filled with red clays (K_1), but by sands and sandstones (K_2) on the Dzhamanktai plateau. On Ulken Tura Mountain, sinkholes are elongated along bedding fissures and filled with K_2 sands. Within the mining excavations of the Mirgalimsai deposit, ancient karst cavities, filled with red clays and sands with sharks' teeth, were exposed by wells at a depth of 800 m (Galitsky). Erosional-karst basins at the top of the upper Paleozoic car-

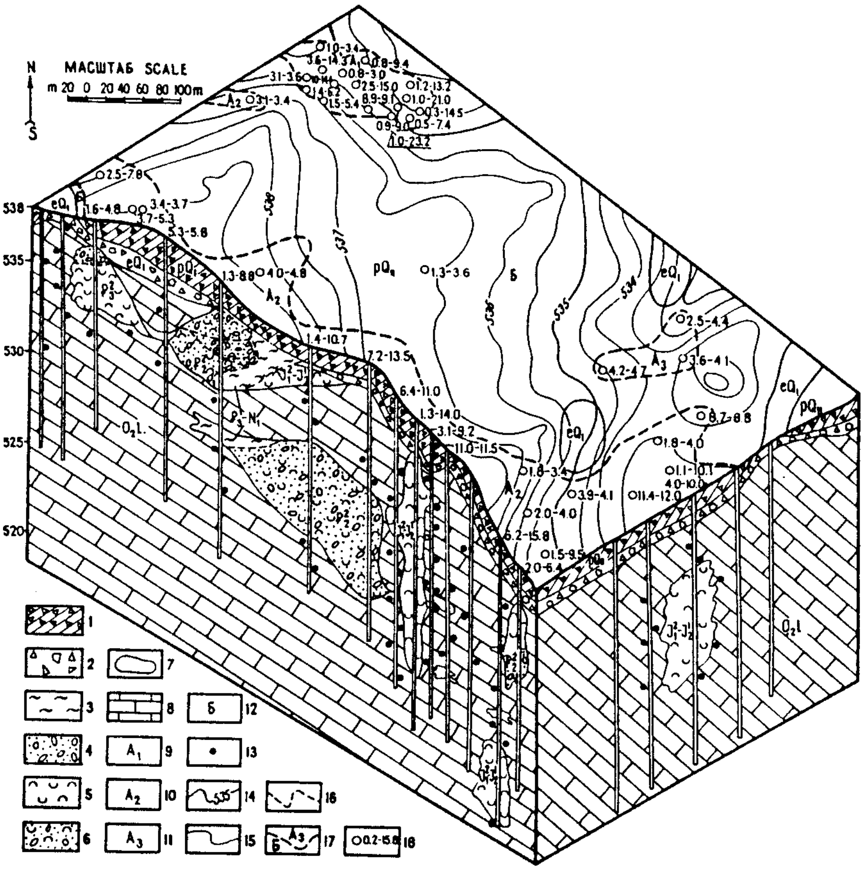


Fig. 3. Engineering-geological map (block-diagram of karst territory of the Koksu mine central industrial area (Malyi Karatau). 1- mid-Quaternary proluvial deposits — loams with gruss; 2- Lower Quaternary eluvial deposits — gruss, rock debris, and blocks of carbonate rocks; 3-6- fillings of ancient karst cavities: 3- Oligocene-Miocene influvium from continental deposits of the Besharyk suite (clays are red-brown), 4- Eocene marine influvium — quartz sands with gravelstones and pebblestones of siliceous rocks, 5- Lower-Middle Jurassic autochthonous filling — dolomitic powder, 6- mixed autochthonous-allochthonous fillings — sands with gravelstones and pebblestones of siliceous rocks with admixture of dolomitic powder and gypsum; 7- hollow cavities of ancient karst; 8- karstic mid-dolomitic limestones of Middle Ordovician (Llanvirnian stage) of the Shabakty suite; 9-13- zonation according to extent that paleocavities have spread: 9-11- areas of extensive karst: 9- area of strongly karstic rocks, K=36%; 10- area of average karst, K=25%; 11- area of poorly karstic rocks, K=10%; 12- area of weak karst manifestation, K <10%; 13- predominant development of caverns; 14-18- additional symbols: 14- horizontal lines with section 0.5 m, 15- borders of stratigraphic-genetic complexes, 16- borders of lithotypes of fillings; 17- borders of areas with different degrees of development of karst, 18- wells and exposed karst cavities with depth intervals (meters).

Composition of Carbonate Rocks (D_3-C_1) NW Karatau

Petrographic Type	Number of Samples	Mineralogical Composition %			
		Calcite	Dolomite	Argillaceous	Siliceous
Macrofacies of rocks with gradational lamination					
Dolomites	18	1.52-5.34	86.97-97.22	0.22-3.11	0.03-4.29
Argillaceous dolomites	1	0	89.62	7.33	2.20
Poorly silicified dolomites	2	4.12-5.30	78.79-88.85	0.15-2.75	6.77-11.12
Argillaceous poorly silicified dolomites	2	0.91-4.76	73.67-78.29	10.11-10.56	8.54-9.24
Weakly calcareous dolomites	11	5.8-10.32	84.05-91.00	0.02-2.23	0.64-4.8
Medium calcareous dolomites	1	30.70	64.43	1.72	3.22
Strongly calcareous, poorly silicified dolomites	1	32.55	57.98	3.85	5.79
Limestones	6	92.05-93.78	2.74-5.21	0.86-1.31	1.0-2.39
Siliceous limestones	1	77.59	3.84	0.86	19.56
Strongly siliceous limestones	4	62.35-63.59	3.34-6.40	1.49-2.10	29.21-31.6
Limestones with nodules and interlayers of flints (rhythmites)	4	38.37-55.39	4.96-14.36	1.82-2.8	24.46-54.33
Poorly dolomitic limestones	22	81.36-92.71	5.58-14.27	0.63-3.72	0.79-4.85
Poorly dolomitic, poorly silicified limestones	9	73.38-86.84	3.69-16.60	0.93-3.69	6.58-10.38
Limestones with thin interlayers of flints (rhythmites)	3	59.92-76.08	6.12-10.28	1.87-3.12	13.92-34.4
Moderately dolomitic limestones	4	64.84-73.0	18.52-30.09	1.31-3.44	1.84-5.93
Strongly dolomitic limestones	3	49.44-53.73	42.71-46.00	0.53-0.61	1.08-2.46
Macrofacies of reefogenic structures (Talapskyi reefoid)					
Dolomites	7	2.30-4.99	91.55-97.17	0.28-1.36	0.26-1.55
Poorly calcareous dolomites	1	7.23	91.64	0.58	0.35

bonate basement were discovered by Dzhumabaev (Abdulin, 1987) on the southwestern slopes of Boroldaitau and in the Kentau district (Boksitovyi area). These karst basins are elongate (length, 2-2.5 km; width, 0.2-1.0 km) with gentle slopes. In the Boksitovyi area, a karst sinkhole with a diameter of 25 m and a depth of 7.5 m was found. The basins and sinkholes are filled with bauxitic clays of the Nautskaya suite (T_3). In addition to the regional spread of paleokarst in carbonate deposits (D_3fm-C_1), ore karst occurs locally with lead and zinc sulfide ores. Ore karst has not been studied in detail (Makarenko, 1962). Referred to as "thermokarst", it is briefly mentioned in articles by Olli (1958) and Chepizhnaya (1963) and in a monograph on the metallogeny of the Karatau Range (Abdulin, 1987).

The genetic peculiarities, stage of formation, and relative age of ore karst may be determined by the intensive study of the entire range of geological and geochemical conditions of development (the genesis and age of polymetallic sulfide ores must also be taken into account). Ores of the Karatau complex have stratiform, polygenic, and polychronal character. In all deposits the main ore minerals are sphalerite, galena and pyrite; the non-metalliferous minerals are carbonates, quartz, and in some deposits of barite. Sulfides of syngenetic hydrothermal sedimentary deposits form thin impregnations and small layers; epigenetic (hydrothermal - metasomatic) ores make up thick veins and lenses, and small irregular bodies that conform to fracture zones or are localized in ancient pre-ore karst cavities, whose form they acquire. Polychronism of ore accumulation is determined by the different stratographic levels of metallization at which it occurs, beginning with the early Famennian (the Shushakovskaya suite) through the Visean (Akuyuk suite). Ore shows in karst were found in the Achisai, Visean, and Kastymkamal deposits and with barite ores of Kokkiya and Burabai-Zhayagyzagysh (Abdulin, 1987). The formation of rich lead-zinc, pyrite (Achisai) and barite deposits (Kokkiya) from poorly manifested syngenetic hydrothermal sedimentary mineralization is the special feature of these deposits. Mineralization is localized in karst cavities formed in the dolomites and limestones by hydrothermal ore-bearing solution during the second stage of ore formation; the solution temperature was 200-60° C, water content 71-85%, gas 1-6%, and salts 14-25%. Although ore was deposited in carbonate rocks, the components of these rocks (Ca, Mg, CO_2) were not as abundant in solution as chlorides, fluorides, and sulfates of sodium and potassium, which played the leading part in the process. Among the gasses, SO_2, H_2S, CO_2, and N_2 predominate.

According to Olli (1958) empty karst caves developed by leaching were found in the Achisai deposit at the contact with oxidized lead-zinc ores. Some of the karst caves at the Achisai deposit have a volume of several tens of thousands cubic meters. The largest cave (4 m wide, 42 m long, 10 m high) is situated between horizons 5 and 6 of the ore deposit workings at a depth of 165 m. The karst cave of horizon 7, at a depth of 180 m, is 4 m wide, 8 m long, and 15 m high. On the walls of caves there are crusts of porous oxidized ores and brown iron ore with residual galena and sphalerite. Formation of these karst caves is associated with manifestation of post-ore sulfide or sulfate karst. The agent of karst corrosion is underground water enriched with free sulfuric acid (Kolodyazhnaya, 1962). "Sulfate" karst is distinguished from common non-metalliferous carbonate karst by its rapid development and its spatial localization in zones of ores oxidation. At the Kokkiya barite deposits in the limestones and dolomites of the Shushakovskaya suite (D_3fm), residual zones of the pre-Cretaceous karst occur at a depth of 5-10 m and for 2 km along the strike of the enclosing rocks. Karst cavities at outcrops contain barite, barite-siderite and barite-sulfide veins, and are filled with eluvial fragments of barite and enclosing rocks, cemented by argillo-arenaceous material from the Cretaceous-Paleogene deposits. An intensive barium aureole coincides with karst zone outcrops. Blocks and fragments of coarsely crystalline white barite have been discovered in trenches in the lower part of the karst zone. A complex karst field 600 m wide and 1200 long, with barite-siderite, and barite hematite veins has been mapped in outcrop in the Karstovyi area in the nodular limestones of the Achisai suite. The largest karst cavity, measuring 300 × 70 m, is consistent in plan with barite outcrops. The average depth of karst cavities is about 10 m, and the cavities occupy about 15-30% of the area. The barite content is 30-35%. In the Burabai-Zhalgyzagysh deposit, the oxidation zone is associated with numerous karst hollows and caverns, created by leaching of dolomite where crossed by fissures, and of organic remains. Crystalline crusts of ore minerals occupy the hollows. Ore karst at these deposits may be classified as follows:

1. primary pre-ore (Achisai) and pre-barite (Kokkiya) which formed in chambered cavities and karst fissures in massive limestones in which limestone was replaced by iron ores and barites of epigenetic hydrothermal-metasomatic origin.
2. secondary vadose post-ore (post-barite) old pre-Cretaceous karst, forming karst zones (sinkholes, concordant with crosscutting karst fissures), buried under fragments of enclosing rocks and barite and cemented by argillo-arenaceous material of Cretaceous-Paleogene (Kokkiya) age.
3. secondary (modern) post-ore vadose sulfate karst, exposed in the zone of sulfide mineral oxidation, forming porous brown iron ore in pyritic-sideritic ores and chambered cavities (Achisai, Visean, etc.).

Composition and Properties of Paleokarst Cavity Fills

In the Karatau Range, three genetic groups of karst cavity fillings are distinguished: autochthonous, allochthonous, and mixed. They are also subdivided according to age and lithological-facies composition.

The products of solution and corrosional mechanical destruction of karstic rocks, which remained in place or were redeposited in karst cavities, are related to the autochthonous group of karst fill. They include the following:

1. residual, insoluble, monomineralic components of carbonates as terrigenous admixtures of aleuropelitic material, enriched with hydrous ferric oxides, sometimes forming cavern fillings with orange-red terra rossa type powder.
2. residual products of solution and mechanical corrosion of high dolomitized rocks, represented by dolomitic powder with gruss and fragments of karstic rocks.
3. redeposited lacustrine aleuropelitic formations with typical thin ribbon bedding.
4. products of cavern collapse, such as talus and large fallen blocks of karstic rocks.

Allochthonous fills are considered as a special type of continental deposit, related to karst, called influvium by G.F. Lungersgauzen. We may subdivide influvial formations into two genetic types: hydrothermal, which flowed from sources deep in the interior of the earth (endogenous origin), and vadose, infiltering from the surface through overlying deposits (exogenous origin). The first is localized, and is found as polymetallic ores deposits, the second is widespread. Hydrothermal influvium is represented by accumulations of ore minerals (galena, sphalerite, pyrite, barite, etc. and accessory minerals), filling chambers and fissure cavities with pre-ore and syn-ore primary karst deposits of epigenetic hydrothermal metasomatic origin. The age of hydrothermal influvium is usually determined as Late Permian in agreement with the supposed time of epigenetic ore formation (Galitsky, 1967).

Yadose influvium may be of different ages:

1. Upper Triassic filling of ancient karst basins and sinkholes with red bauxite clays.
2. Cretaceous-Paleogene argillo-arenaceous filling of karst cavities of pre-Cretaceous karst and middle Paleozoic carbonate rocks.
3. Eocene marine deposits of the last transgression, mainly sandy with gravel and pebbles of siliceous rocks, sometimes with boulders of flint; sandstone, gravelstone, and conglomerate with an argillo-carbonate cement.
4. Oligocene-Miocene red filling, formed by influx of Besharyk suite deposits (P_3-N_p — Paleogene-Neogene).
5. Pliocene — Lower Quaternary loams and "straw-colored" limestones.

Accompanying unconsolidated marine and continental sediment filling on the walls of hollows, and in the filling itself, is a sinter consisting of amorphous and crystalline Neogene minerals: calcite, gypsum, hydrous ferric oxides, secondary apatite, psilomelane, etc. Physical-mechanical properties of the filling have been studied in the laboratory and *in situ*.

Dolomitic powder is typical of the autochthonous group. Until now, the mechanism of its origin was not quite clear. In an attempt to explain the origin of the powder, attention was focused on peculiarities in the mineral composition of karstic rocks and on the calcite and dolomite solubility ratio, all of which reveal the selective nature of the karst process in dolomitic rocks. According to Rodionov (1958), selective solubility causes structural change in the carbonates, with an increase in porosity and the number of caverns at the same time as the volumetric strength of soil decreases. Concurrently, mineral composition changes, dolomitic limestones change to calcareous dolomites, and the latter to pure dolomites. At a certain stage in karst development, selective solution induces rock failure, which then becomes more important than solution. Rocky dolomitic material, having reached critical porosity, turns to powder. Its composition is the same as that of calcareous-dolomitic powder (in dolomitic limestones which have inclusions of gruss and rock debris from incompletely decomposed karstic rocks). According to Yakich (1979), moderately dolomitic rock often contains more calcite than the theoretical norm (54.35% $CaCO_3$ and 45.65% $MgCO_3$). The excess $CaCO_3$ forms a calcitic cement, cementing the rhombohedral crystals of the double carbonate. A moderately dolomitic solution forms under the influence of the two parallel processes, each of which proceeds at its own rate: calcite solution in cement and solution of the double salt (much slower). The end product of selective corrosion is the same: powdery dolomite and dolomitic fragments.

In local areas of modern and ancient hydrothermal activity, the influence of temperature and chemistry on dolomitic rocks is of great importance in karst corrosion. Numerous experiments by Yanatieva (Sokolov, 1962) and by Mandi (Yakich, 1979) indicate a marked increase in solubility of dolomite when water temperatures reach 40-55°C and above, while at the same time the solubility of calcite decreases (other conditions being equal). Yakich concluded that "Hot water (thermal spring) does not initiate selective solution, because the rate of solution of the double carbonate crystals is higher than the rate of calcite solution." In the case under consideration, the chemical activity of hydrothermal solutions containing silicic acid, ferrous sulfide, sulfates and chlorides of alkaline metals plays a very important role in formation of dolomitic powder. These components favor transformation of calcite cement into siderite and gypsum when ferrous sulfate is present. Formation of such mineral components in karstic rocks induces them to swell and then to crumble to dolomitic powder. Dolomitic powder can thus be produced by a variety of processes.

According to granulometric and material composition, the powdery infill contains varying amounts of dolomitic powder and is of two types: 1) pure dolomitic powder, and 2) an admixture of dolomitic powder with quartz sand. Depending on the ratio of sand and dolomitic powder and the gypsum content, there are two types of filling: 1) dolomitic powder with quartz sand (10-30%) and a small amount of gypsum (0.4-29.0%, average 14.3%); and 2) quartz sand with dolomitic powder (10-30%), with a large amount of gypsum (25.31-61.82%, average 44%).

Pure dolomitic powder has a disperse argillo-aleuritic composition and a dense structure. It has a dusty appearance, resembling sandy loam of white, gray, slightly yellow or slightly pink-gray color. It can contain inclusions of karstic rock gruss and crystals and druses of gypsum. It contains 61-87% of powdery carbonate and 12-38.9% of insoluble mineral admixture, 6.2-36.8% of fine dust and argillaceous particle size, 1.1-13.1% coarse and sandy particles, rarely 0.2-4.5% of gruss particles. Judging by plasticity index (26-10%) such material may be classified as clay or loam. It has a rather high density of soil particles (2.74-2.52, averaging 2.66 g/cm^3) and moderate soil density (1.69-1.34, averaging 1.53 g/cm^3). The modulus of deformation under naturally humid conditions varies from 3.6 to 93.2 MPa; water saturation may reduce this to 3.5-10.4 MPa.

A mixture of dolomitic powder and quartz sand with a different ratio and variable gypsum content (0.4-61.8%) shows high average values of density (particle density 2.56, soil density 1.67, dry soil density 1.50 g/cm^3. The modulus of deformation with natural humidity varies over a wide range (2.8-156.3 MPa), diminishing with water saturation to 3.8-17.1 MPa. Angles of internal friction and cohesion under different experimental shear conditions change accordingly: 24-31° and 0.02-0.12 MPa. With water saturation, soil cohesion is three times lower.

An admixture of dolomitic powder with quartz (10-30%) and a small amount of gypsum has higher density. The average density of soil particles is 2.64 and soil density is 1.65 g/cm^3; modulus of deformation 30-42 MPa, relative subsidence 0.007-0.0001. Angles of internal friction and cohesion with natural humidity have large values - 30-38°, 0.058-0.32 MPa.

An admixture of quartz sand and dolomitic powder with a large amount of gypsum has the lowest density value (average density of soil particles 2.42, soil density 1.51, and dry soil density 1.42 g/cm^3). The modulus of deformation with natural humidity is 30-50 MPa; relative subsidence with prolonged wetting (16-21 days) increases to 0.04-0.1. A high concentration of gypsum reduces density characteristics of soil admixtures and promotes relative subsidence increase due to leaching of gypsum during wetting.

The general physical-mechanical properties of pure dolomitic powder and its mixtures with allochthonous fill are as follows: 1) high porosity - average values 40.6-41.1%; 2) extreme values of modulus of deformation (93.2-156.3 MPa), close to that of semi-rocky soils; 3) high variability of resistance to shear index, increased internal friction (24-42°) and relatively small cohesion owing to sandy admixtures (0.017-0.04 MPa).

The allochthonous group is represented by clays of brown, red-brown, brick-red, reddish-brown, orange, brown, light-brown, gray-green colors. This filling consists of bodies of quartz sand and karstic rock debris as gravel or flint, and gypsum. Based on their granulometric composition, the following groups may be distinguished: 1 - dusty-argillaceous soils (particles with a diameter of <0.01 mm, 56.3-84.3%); 2- clays (particles <0.005 mm in diameter, 36.5-74.9%); 3- heavy and moderately heavy dusty loams; 4- dusty sandy loams.

Depending on the plasticity index and gypsum content, there are two kinds of red-colored argillaceous filling: 1- clays and heavy loams with a plasticity index of 13-29% and small dispersed gypsum content; 2- highly plastic brown clays (30-40%) with large amounts of gypsum present as patches, lenses, and interlayers.

The general characteristics of argillaceous allochthonous fillings are as follows: 1- high density values (density of particles, 2.70-2.76 g/cm^3; dry soil density, 1.38-165 g/cm^3), sharply different from all other fillings of allochthonous and mixed genetic groups; high porosity values (maximum 42.9-57.8%) and porosity coefficients (average, 0.78); brown and gray-green clays have the highest porosity coefficients (0.75-1.37), which is evidence of their unconsolidated state; 2- clays with average natural humidity, 14.2-20.6% and low plastic limit - 11.7-30% is hard, semi-hard, and, rarely, plastic; 3- clays which do not posses subsidence properties and according to relative swelling index (0.05-0.09) swell poorly; 4- modulus of general deformation of red-colored clays at the Zhanatas deposit with natural humidity and pressure is 0.1-0.2 MPa, 3.8-34.7 MPa; in the Aksai area under the same conditions it is 3.2-29 MPa, water saturation reduces it to 2.9-12.6 MPa, with higher pressure (0.0-0.4 MPa) modulus of deformation with natural humidity increases to 30-71 MPa (under high pressure and after water saturation, modulus of deformation is 2-4 times higher); 5- indexes of resistance to shear of the argillaceous filling cover a wide range, depending on soil peculiarities and experimental conditions (angle of internal friction 7-19° and up to 40°, cohesion — 0.001-0.005 to 0.047-0.14 MPa). A distinctive feature of karst cavity fillings is the non-uniformity of granulometric and material composition, which impedes testing them for engineering geology and complicates interpretation of the results.

Paleogeographic Conditions of Karst Development

The most favorable conditions for karst development in the Karatau Range and in other areas of the Northern Hemisphere occurred during the Liassic (and the first half of the Middle-Jurassic; Strakhov, 1960). The Karatau region then had low to moderately mountainous relief of as much as 1600-2000 m and was rather dissected and topographically heterogeneous. Mountains came into being in areas of local uplift. In the enormous Leontievskaya depression (180 km long) a Jurassic fresh-water lake formed. A warm (annual average temperature 22-24° C) and humid (annual precipitation 2000-3000 mm), almost tropical, climate favored the formation of a thick soil layer and luxuriant vegetation. Differentiation of relief, which began in the Late Triassic and lasted until Early Jurassic, promoted active circulation of poorly mineralized underground water, enriched with carbon dioxide of meteoric and soil origin, and with sulfuric acid in areas of ore deposits and in their oxidation zones.

The local base level of groundwater discharge was situated at the level of the Jurassic lake. Relief, climate, and hydrodynamic conditions favored the solution of carbonate beds of different ages. In the second half of the Middle Jurassic, arid conditions began to suppress the karst process. By the beginning of the Early Cretaceous the surface of the Bolshoy Karatau had become a peneplain. During the Early Cretaceous, continental red clays began accumulating and in the relatively low-lying areas, ancient karst sinkholes became filled with these clays and were buried by them. During the Late Cretaceous the Bolshoy Karatau region became a deltaic coastal plain, and mainly sandy material was deposited in sinkholes. During the last transgression of the Eocene sea, large numbers of of ancient sinkholes were cut by erosion, leaving only their "roots," with its fill of Cretaceous and Paleogene sediments. In Malyi Karatau, transgression of the Eocene sea is demonstrated by paleocavities filled with sandy material, with gravel and pebbles of siliceous rocks, and with red clays of the Besharyk suite (P_3-N_1). Ancient karst probably developed during the earlier periods of long continental evolution, but under less favorable conditions as, for example, during the Late Carboniferous and Permian. Karst basins and sinkholes, filled with red bauxite clays of the Nautskaya suite (T_3), are indicative of a possibly pre-Jurassic paleokarst in the Bolshoy Karatau Range. The oldest is pre- and syn-ore hydrothermal karst, consistent with Permian hydrothermal-metasomatic lead-zinc and barite metallization (Galitsky, 1967). Ore karst cavities were filled with these ores and buried under Cretaceous-Paleogene deposits.

Analysis of the tectonic evolution of the Karatau range during the Alpine stage and study of karst cavities fillings permitted Razumova and Olli (1958) to distinguish two main stages in karst development: pre-Cretaceous, most likely Jurassic, and Pliocene-Quaternary. In Malyi Karatau, the first stage of karst development can be determined more exactly as pre-Paleogene (pre-Eocene) on the basis of karst cavity filling properties. The exposure of sinkholes at the level of the denudation (abrasion) surface of the Bolshoy Aktau and Malyi Aktau is indicative of an older origin, meaning that karst forms existed before the the Eocene sea began its advance. Thus, local karst in Bolshoy and Malyi Karatau is most likely Jurassic (Lias-Dogger) in age.

Influence of Paleokarst on Engineering Geology

Karst cavities, both filled with loose material and hollow, are an element of exogenous macrostructure and cause anisotropy in physical-mechanical properties of rocky carbonate massifs. With respect to engineering geology, the stability of artificial slopes and underground workings in urban and industrial areas is decreased in massifs with widespread karst. The state of strain of the massifs and mechanism of deformation of industrial construction and slopes depends on how much karst is present. Strain and strength properties of karst cavities fillings, particularly of clayey and sandy composition, are always much lower than the properties of the original rocky massif. Quarry slopes and roads in areas of paleokarst are easily washed away and crumble, causing argillization of berms and subgrades. Design work and estimation of slope stability become complicated because different approaches are taken in selecting slope angles in varying geological conditions. In quarries at the Zhanatas deposit, angles of stable slopes in a rocky massif with steep monoclinal mode of occurrence are 75-55°, in dolomitic powder and sandy-argillaceous fillings they are 35-40°.

When driving underground workings in the Aksai and Molodyezhny mines, paleokarst cavities, filled with water-saturated sand, caused outbreaks of quicksand and extensive inundation of these workings. Where karst underlies the basements of heavy industrial construction, foundations may settle irregularly, causing such buildings to list dangerously. Part of the central industrial area of the Koksu mine may be an example, where high, heavy cylindrical ore towers were designed. Drilled wells (383) uncovered 139 karst cavities, filled with dolomitic powder and sand.

The area covered by karst in quarry facies of the Zhanatas deposit varies from 1.95-7.5 to 9.05-20.3%, reaching a maximum in calcareous dolomites of "G" packet of the Shabakty suite. The average value of the linear coefficient of karst (based on vertical extent of cavities) in the Koksu mine industrial area in dolomitic limestones (O_2l) is 10-36%. In individual wells it varies from 1-6 to 75-90%. Two plots were singled out in this area: one of strongly karstic rocks and one of weakly karstic rocks. The former is divided in three, according to the average values of K^1_3: extensive karst (K^1_3 =36%), moderate karst (K^1_3 =25%) and infrequent karst (K^1_3 =10%) (Fig. 1).

Paleokarst cavities, as deep sinkholes, formed in carbonate rocks (D_3-C_1) on the southwestern slope of Bolshoy Karatau during the pre-Cretaceous, formed through anthropogenic activation of the karst-diffusional process within the town of Kentau (Fig. 4). Long-term dewatering of a considerably flooded deposit resulted in formation of a huge sinkhole, 100 m long and 300-450 m deep in the center. Within the same region, during 1958-78 systematic subsidence occurred over an area of 2.5 km^2. Subsidence of 0.5-5 m occurred over an area of 6600 m^2. Two infiltration sinkholes and more than 13 large and small karst holes appeared. The maximum depth of the holes is 20-55 m, the diameter 10-28 m, and the area 11.3-615.4 m^2. (The general area of karst holes amounted to 5825.5 m^2.) Using Savarensky's formula we have determined average annual probability of karst-diffusional holes appearing (B) as 0.0013% per year. The value of "B" is an order of magnitude greater for the whole area and smaller by a factor of two in the strongly karstic region (Rastyapino settlement, B=0.002%). Kentau, where over a 20-year period two infiltration sinkholes formed in a 2.5 km^2 area, is classified as having average stability according to Makeev's system. Ancient sinkhole fillings show a tendency to mechanical diffusion, which makes the appearance of karst holes possible. This possibility can be estimated by calculating diffusion stability, based on the diameter and percentage of diffusional particles (d_{si}, mm). All the lithological of filling variants contain particles with d=d_{si} from 4 to 52%, which is greater than the critical value (3%).

The Kentau area was divided into zones according to the hazard that development of infiltration sinkholes and karst holes posed to existing constsruction. Four zones were distinguished, the second being the most dangerous. In this second zone, in northeastern Kentau, large deep karst holes may appear that are now covered by deposits up to 15 m thick.

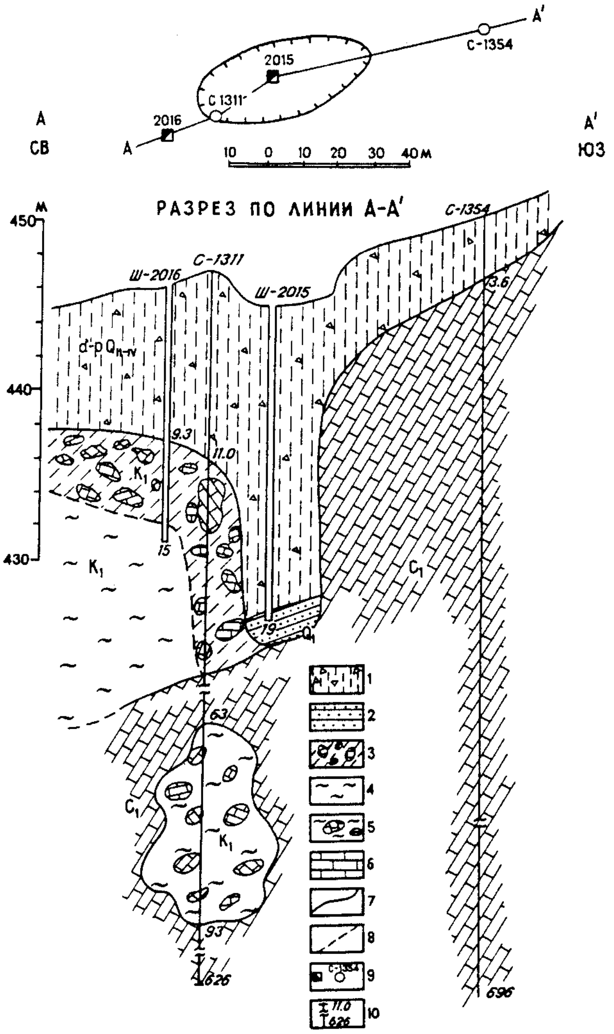


Fig. 4. Karst suffusional sinkhole — karst hole above an ancient karst cavity, Kentau area. Plan and section of infiltration sinkhole, ancient karst cavities; 1-5- allochthonous and mixed fillings of paleocavities: 1- Middle Quaternary modern deluvial-proluvial loess-like loams, 2- Lower Quaternary (?) sandstones, 3- sandy loam with fragments and blocks of limestone, 4- Lower Cretaceous red-colored clays, 5- the same clays with fragments and blocks of limestones; 6- Lower Carboniferous limestones; 7- borders of stratigraphic-genetic complexes of rocks; 8- borders of fillings lithotypes; 9- exploration shaft, well, and their number; 10- well (exploration shaft) in the section; figures denote depth of the main borders and depth of the working face in meters.

Conclusion

Regionally ancient carbonate karst is encountered in carbonate formations of the Caledonian Shabakty suite in the Malyi Karatau and in the Famennian-Lower Carboniferous of the Hercynian.

Karst is developed mainly in the massive, thick-bedded, flaggy calcareous-dolomitic rocks. The influence of the carbonate rock composition on the expansion of paleocavities is less distinct. Increased siliceous (particularly the presence of flint beds) and argillaceous content prevent karst from developing. Karst develops in NW Karatau in large reef massifs where these admixtures are absent.

The spread of paleokarst is controlled by fractures, tectonic fissures, and bedding planes, complicating the monoclinal-folded structures of carbonates. Paleokarst may be found particularly at the intersection of NW (310°) and NE (25°) trending fractures, and especially in zones of brecciation. Bedding structures contribute to the development of paleocavities and are concordant with them.

Besides the regional spread of paleocavities, there is also a localized development. This occurs in polymetallic ore deposits as primary hydrothermal pre- and syn-ore karst and secondary vadose sulfide karst (in the zones of ore oxidation).

Paleokarst is difficult to identify at the surface where it is buried below a soil layer and by overlying deposits. It may be exposed in artificial slopes (road cuts and quarries) and penetrated in wells. Near-surface and deep-seated paleocavities, represented by mega-, macro-, and microforms, are distinguished. Paleocavities are often filled; only 20-30% are empty. Paleocavity fillings are represented by autochthonous (dolomitic powder), allochthonous (influvium of covering deposits) and mixed genetic groups.

Information on the paleogeography of the region permits the recognition of two stages in ancient karst development: Late Carboniferous-Permian (local hydrothermal karst) and pre-Cretaceous to Early-Middle Jurassic (regional karst). Accordingly, paleokarst cavity fillings of local ore karst are allochthonous-endogenic in origin (lead, zinc, barite, etc.), and fillings of regional-exogenic origin were derived from Cretaceous-Paleogene deposits.

Paleokarst has a direct influence on engineering-geological conditions. It results in formation of a complicated exogenous macrostructure and in anisotropy of the properties of carbonate massifs. There are considerable differences in the properties of karstic rocks and paleocavity fillings. These promote formation of anthropogenic karst-diffusion sinkholes and contamination of underground water, and they decrease the stability of slopes and underground workings, leading to the possibility of irregular subsidence and collapse of heavy industrial construction.

References

Abdulin, A.A. (ed.), 1987. Geology and Metallogeny of Karatau, v. 2: Metallogeny. Alma-Ata, Nauka, 224 p.

Chepizhnaya, E.A., 1963. Peculiarities of karst manifestation at the Achisai deposit. In: Natural Physical-Geological and Engineering-Geological Processes and Phenomena (F.V. Kotlov and A.A. Makovejeva, eds.), p. 114-121. Moscow, Publishing House AN SSSR.

Galitsky, V.V., 1967. Tectonics of the Karatau Range (South Kazakhstan). Alma-Ata, Nauka, 47 p.

Il'in, A.N., Kapustin, A.P., et al., 1960. Karst Phenomena in the Dzerzhinsk Town Area, Gorky District. Moscow, Publishing House AN SSSR, 119 p.

Kolodyazhnaya, A.A., 1962. Formation aggressive components in underground water of the North Urals karst region. In: Voprosy of Hydrogeology and Hydrothermy (G.V. Bogomolov and J.A. Makarenko, eds.), p. 18-24. Moscow, Publishing House AN SSSR.

Makarenko, J.A., and Chepizhnaya, E.A., 1962. About ore karst study. In: Voprosy of Hydrogeology and Hydrothermy (G.V. Bogomolov and J.A. Makarenko, eds.), p. 3-9. Moscow, Publishing House AN SSSR.

Olli, E.I., 1958. Karst of the Bolshoy Karatau Range. Bulletin MOIP, Geological Series, 3, p. 73-89.

Rodionov, N.V., 1958. Engineering-Geological Investigations in Karst Regions. Moscow, Gosgeoltekhizdat, 182 p.

Sokolov, D.S., 1962. Main Conditions of Karst Development. Moscow, Gosgeoltekhizdat, 286 p.

Sokolov, D.S. (ed.), 1967. Karst of Kazakhstan. Explanatory Note to the Map of Karst Rock and Karst Phenomena. Moscow, Nedra, 96 p.

Strakhov, N.M., 1960. The Base of the Theory of Lithogenesis, v. 1. Moscow, Publishing House AN SSSR, 235 p.

Yakich, L., 1979. Morphogenesis of Karst Regions. Moscow, Progress, 354 p.