# Chapter 15 Uzbekistan

Uranium deposits have been identified in the *Kyzylkum* region in central Uzbekistan and the *Karamazar* region in eastern Uzbekistan (Fig. 7.1). The former contains sandstone-type U mineralization in sedimentary basins as well as carbonaceous (or black) shale-related stockwork-type mineralization in basement uplifts. Volcanic vein-stockwork-type deposits are typical for the Karamazar region.

Remaining in situ resources (status: January 1, 2005) are confined to the Kyzylkum region and amount to 165 000 t U RAR + EAR-I and 220 000 t U EAR-II + SR recoverable at costs of up to $130 per kg U (OECD-NEA/IAEA 2005). (Note: mining and processing losses of 30% have to be deducted to convert from in situ to recoverable resources.)

Mining took place in the Kyzylkum and Karamazar regions. Conventional mining had ceased, however, by 1994. Continued exploitation was restricted to ISL operations in the Kyzylkum basins.

From 1946 through 2004, cumulative production in Uzbekistan amounted to between 105 000 and 110 000 t U (OECD-NEA/IAEA 2003, 2005). The bulk of production came from the Kyzylkum region and an estimated few thousand tonnes U from the Chatkal Range of the Karamazar region (total production from the Karamazar region, including Kyrgyzstan and Tajikistan, was reportedly 20 000 t U). Annual production reached a peak of 3 700–3 800 t U in the 1980s. Since the mid-1990s, production has been on the order of 1 500–2 200 t U $yr^{-1}$. A production of 2 300 t U was expected for 2005.

A hydro-metallurgical plant started operation at *Navoi* in 1964/1965. It has a nominal annual production capacity of 2 300 t U. Molybdenum, vanadium, selenium, rhenium, scandium, yttrium, and REE were recovered as, or are considered potential by-products. Ore from the Karamazar region and Nurabad District was shipped to the *Chkalovsk* mill near Khodzhent (Khudzhand, Chudzand, formerly Leninabad) in Tajikistan.

As of January 2005, uranium production is in the responsibility of three mining divisions of the "Navoi Mining and Milling Integrated Works" (NMMIW) headquartered in Navoi [formerly "Navoi Mining and Milling Combinate" (NMMC) established in 1958 that became a subsidiary of the state corporation "Kizilkumredmetzoloto" upon independence in 1991]. A fourth mining division was closed for economic reasons.

The "State Committee of Geology and Mineral Resources of the Republic of Uzbekistan" formerly carried out uranium exploration. This responsibility is now segmented. Exploration in areas with established deposits is in the hands of the geological divisions of local mining companies, whereas the search for new deposits is the duty of the "State Geological Company Kyzyltepageologia SGE", successor to the "Krasnokholmgeologia" in the late 1990s.

The following description is based on Laverov et al. (1992b, c), OECD-NEA/IAEA (1993–2005), amended by data of other authors cited in the sections of the various uranium regions and districts.



### Historical Review

Several expeditions into the Karamazar region, which extends from eastern Uzbekistan into Tajikistan and Kyrgyzstan, were organized by Vernadsky between 1914 and 1940. These expeditions discovered several U deposits including Taboshar in 1927 (Tajikistan), and Mailuu-Suu in 1933 (Kyrgyzstan); thus establishing the first uranium region in the former USSR.

Systematic exploration for uranium started at the end of World War II. Discoveries in the Uzbekistan sector of the Karamazar region include U-Mo deposits Kattasay and Alatanga in 1949, Chauli in 1952, and Maylikatan and Rizak (Rezak) in 1954–1955. At Adrasman, in nowadays Tadjikistan, a base metal deposit discovered in 1934, uranium associated with bismuth mineralization was found in 1950.

Uranium indications in the Kyzylkum region were first reported in the early 1950s and the first deposit, Uchkuduk, was confirmed in 1952. Subsequent exploration resulted in the discovery of additional deposits in the region including Ketmenchi in 1956, Tokumbet and Bakhaly in 1958, Bukinai in 1959, Sabyrsai in 1960, South Bukinai, Sugraly, Lyavlyakan and Meilysay in 1961, and North Kenimekh in 1980.

Taboshar (Tajikistan) and Tyuya-Muyun (Kyrgyzstan) provided U ore for the first Soviet radium production in a special plant close to Taboshar during the 1930s. Actual mining for uranium started in the Karamazar region in 1946, first at Shakaptar (mined to 1958) and again at Taboshar in 1952; in the early years the ore was leached in pachucas close to the mines and the leachate was treated at the mill at Leninabad (now Chkalovsk) formerly called Combinate # 6. Mining of the U-Mo deposits in Karamazar and other parts of the former USSR served as the prime source of uranium in the Soviet Union until the mid 1960s.

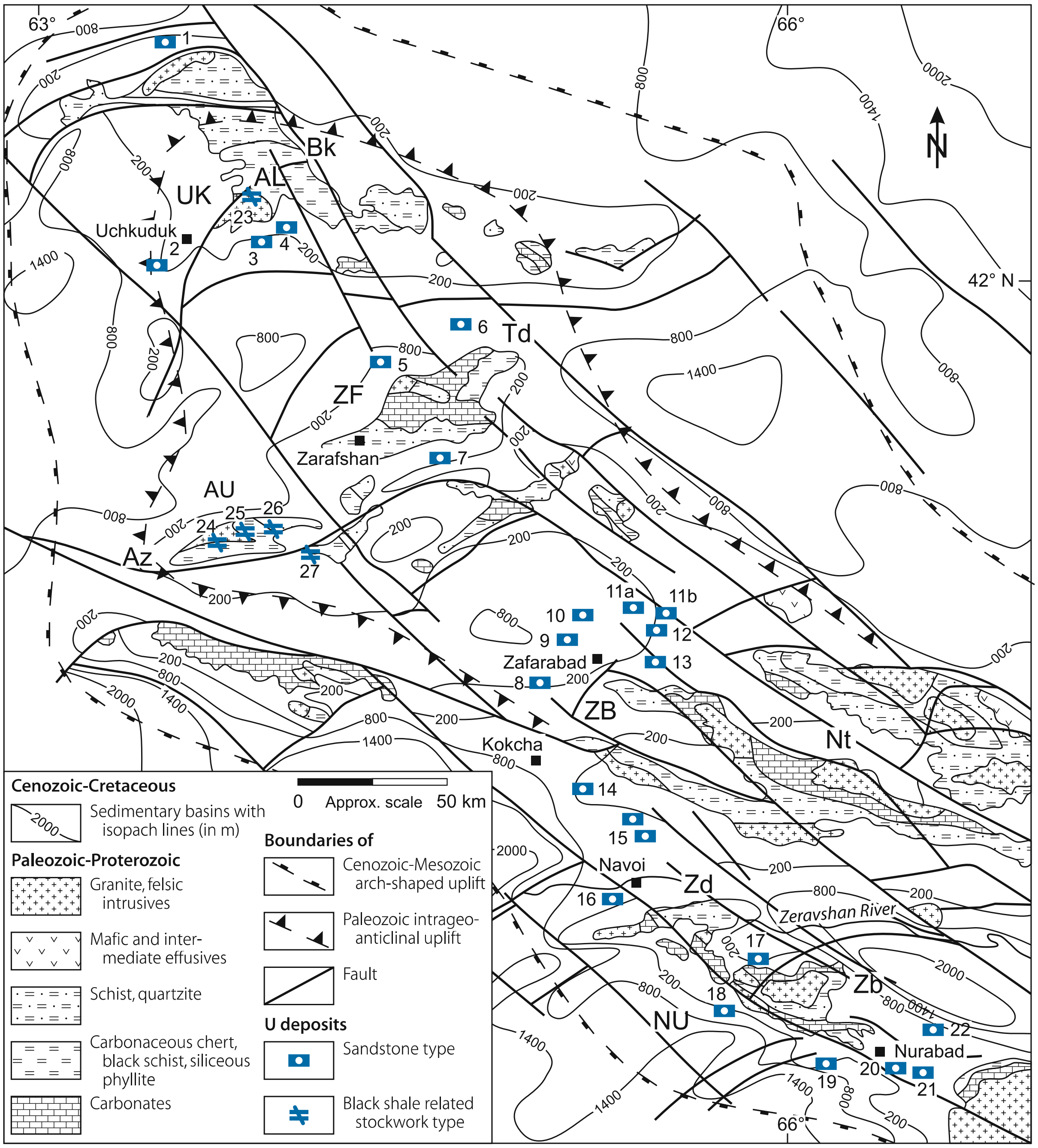
Development of open pit and underground mines commenced in the Kyzylkum region at Uchkuduk in 1958. Ore was initially stockpiled until the new mill at Navoi, located some 300 km SE of Uchkuduk, became operational in 1964/1965. Conventional underground mining operations began at the Sabyrsai and Sugraly deposits in 1966 and 1977, respectively. All conventional mining ceased in the Kyzylkum region in 1994, and only ISL operations continued. Testing of ISL techniques was carried out first in 1961 at the Uchkuduk deposit. Commercial ISL U production followed in 1965. ISL methods were subsequently applied at nine deposits (see next chapter).

Four mining towns, Uchkuduk, Zarafshan, Zafarabad, and Nurabad were established to serve the four mining districts of the Kyzylkum region.

## 15.1 Kyzylkum Region

The Kyzylkum region is located in arid country of the Kyzylkum Desert in central Uzbekistan. U deposits occur in a 125 km wide belt, which extends for about 400 km from Uchkuduk in the northwest to Nurabad in the southeast. Navoi is the largest town in the region and is located about 65 km NE of Bukhara. A basin and range morphology as reflected by broad valleys separated by ranges of low relief characterizes the landscape.

**Fig. 15.1.**
**Uzbekistan. Kyzylkum uranium region, generalized geological map with location of sandstone-type U deposits in Tertiary-Cretaceous basins and black shale-related stockwork-type U deposits in uplifted blocks of the Paleozoic-Proterozoic basement (after Shchetchkin and Kislyakov 1993 amended from OECD-NEA/IAEA 1995). Mountain ranges: *Az* Auminzatau, *Bk* Bukintau, *Nt* Nuratau, *Td* Tamdytau, *Zd* Ziatdin, *Zb* Zirabulak. U districts/deposits in Tertiary-Cretaceous basins: *UK* Uchkuduk District: *1* Bakhaly, *2* Meylisai, *3* Uchkuduk, *4* Kendyktyube; *ZF* Zarafshan District: *5* Sugraly, *6* Aktau, *7* Amantai. *ZB* Zafarabad District: *8* Bukinai (North) and Tokumbet, *9* Alendy, *10* Beshkak, *11a* Lyavlyakan, *11b* Aulbek, *12* Terekuduk, *13* Varadzhan, *14* Bukinai South, *15* Kenimekh North and South. *NU* Nurabad District: *16* Maizak North, *17* Ketmenchi, *18* Tutly, *19* Agron, *20* Sabyrsai, *21* Shark, *22* Nagornoye. Kyzylkum basement area: *AL* Altyntau ore field: *23* Khodzhaakhmet. *AU* Auminza-Beltau ore field: *24* Dzhantuar, *25* Rudnoye, *26* Kostcheka, *27* Voskhod**




Four districts with 25 sandstone- and 6 black shale-related stockwork deposits have been established in the region since the discovery of uranium at Uchkuduk in 1952. These districts group around four mining towns (mentioned as second names) and include – from NW to SE: *Bukantau or Uchkuduk, Auminza-Beltau or Zarafshan, West-Nuratau (Nurantinsky) or Zafarabad*, and *Zirabulak-Ziatdin or Nurabad)* (Fig. 15.1). Deposits are often closely spaced, a circumstance, which permits a grouping of, deposits into ore fields in which the deposits exhibit similar structural and litho-geochemical features.

Prominent uranium deposits are of *rollfront sandstone type* hosted in small Tertiary-Cretaceous basins at depths from 50 to 610 m on the western and southwestern side of the Bukantau-Aristantau-Nuratau Ranges of the northwestern spur of the Tien Shan mountains. Most deposits occur in Upper Cretaceous and a few in Lower Cretaceous and Upper Eocene strata.

*Uranium grades* of sandstone deposits are highly variable ranging in average from 0.026 to 0.18% U. Associated elements include Se, V, Mo, Re, Sc and lanthanides in potentially economic concentrations.

Two modes of deposits are distinguished. Deposits of lower grade such as Beshkak, Bukinai, Lyavlyakan and others are controlled by "normal" redox fronts that were presumably exclusively generated by the reaction of oxygenated groundwater with synsedimentary organic debris reductants. Better grade ore bodies with an average of several tenths of a percent U and more are typically associated with zones, which have been additionally affected by epigenetic extrinsic reductants. Such ore bodies are known from Uchkuduk, Sugraly, and Sabyrsai where the higher grade and tonnage permitted conventional mining as outlined further below.

Compared with sandstone-type U deposits in the USA, the Kyzylkum rollfront deposits resemble in their regional geological setting those in the Wyoming Basins while at some locations hydrogeochemical processes related to the influx of extrinsic reductants tend to be more similar to those in the South Texas U region.

Basement uplifts contain small *stratiform and stockwork-type* U or U-V-phosphate deposits in tectonically deformed carbonaceous and siliceous metasediments of Precambrian to Lower Paleozoic age (locally referred to as "black shale" type). Deposits of this type are reported from two ore fields: *Altyntau* in the Bukantau/Uchkuduk and *Auminza-Beltau* in the Zarafshan District. The average U grade is between 0.06 and 0.132%. Associated metals occur in concentrations of 0.1–0.8% V, 0.1–0.2 g Au $t^{-1}$, and up to 0.024% Mo and 68 g Y $t^{-1}$.

Remaining *in situ U resources* (status: January 1, 2005) contained in *sandstone-type deposits* amount to 118 000 t U RAR + EAR-I and 166 000 t U EAR-II + SR in the up to $130 per kg U cost category. Combined with past production of some 100 000 t U from sandstone deposits, the original uranium endowment of the Kyzylkum basins would total almost 400 000 t U or some 280 000 t U of recoverable uranium based on mining and processing losses of ca. 30%. Resources of black *shale-related stockwork deposits* total 47 000 t U RAR + EAR-I and 54 000 t EAR-II + SR (OECD-NEA/IAEA 2001–2005).

Only sandstone-type ore bodies were or are exploited. *Conventional mining* methods have been used at three deposits: open pit methods at Uchkuduk beginning in 1958, and underground methods at Sugraly and Sabyrsai beginning in 1966 and 1977, respectively. Nine deposits were subject to *ISL exploitation* since 1961 including ore bodies at the aforementioned deposits. In 1975, the ISL technique began to replace underground mining at Sabyrsai; conventional mining came to a complete halt in 1983. All conventional mining ceased in the Kyzylkum region when the mines at Uchkuduk and Sugraly were added to the closure list in 1994. Also in this same year, ISL operations at Sugraly were terminated.

In 2005, nine *ISL operations* were active in three districts: at Uchkuduk and Kendyktube in the Uchkuduk District (operated by the Northern Mining Division); at Bukinai North, Bukinai South, Beshkak, Lyavlyakan, and Tohumbet in the Zafarabad District (Mining Division # 5); and at Ketmenchi and Sabyrsai in the Nurabad District (Southern Mining Division). The maximum depth of ISL extraction is 700 m.

Total uranium production of the Kyzylkum region is some 103 000 t through 2004. The three conventional mines at Uchkuduk, Sugraly and Sabirsai delivered almost 56 000 t U for the years between 1958 and 1994 while ISL operations produced about 47 000 t U from 1961 through 2004. Annual production peaked in the 1980s when 3 700–3 800 t U $yr^{-1}$ were recovered. Current ISL production is on the order of 2 000 t U $yr^{-1}$ (2 087 t U in 2004) (OECD-NEA/IAEA 2001–2005). Mo, Se, Re, and Sc were recovered as by-products, whereas V, Y, and REE are considered potential by-products at some deposits. Final processing is centralized at the Navoi mill. Mining and milling operations are the responsibility of NMMIW.

**Sources of information.** Karimov et al. 1996; Kislyakov and Shchetochkin 2000; Kuchersky 1997; Laverov et al. 1992a-c; Mashkovtsev et al. 1979; OECD-NEA/IAEA 1995–2005; Shchetochkin and Kislyakov 1993; Venatovsky 1993; and other sources as noted. Note Worthy is the work by Karimov et al. (1996) who describe the known geology of the kyzylkum uranium region adequately and present on comprehensive synopsis of the regional and local geological setting and characteristic features of all known uranium deposits.

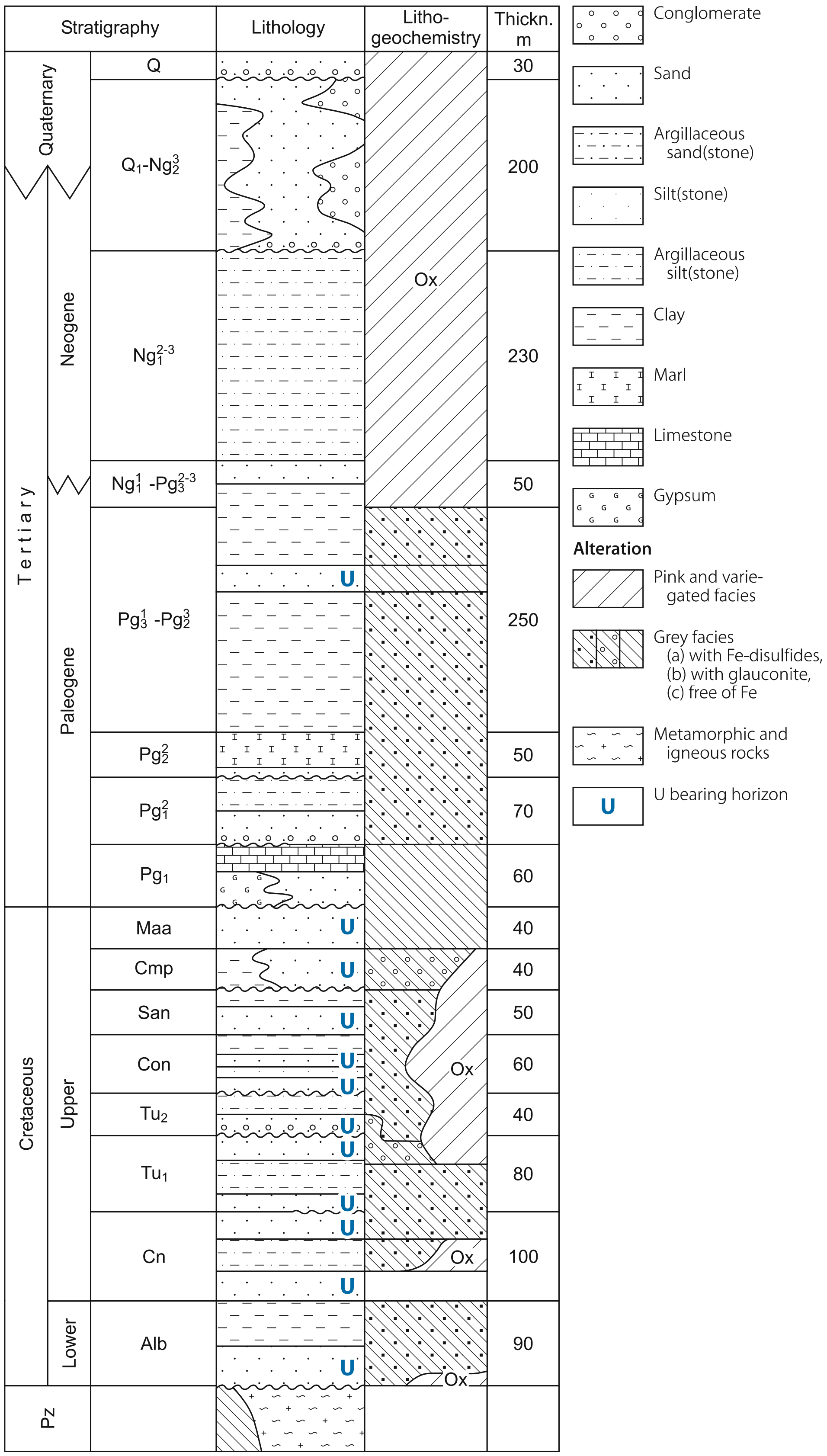
## Regional Geological Setting of Mineralization

The Kyzylkum uranium region occupies the Central Kyzylkum Uplift, an arch-shaped structure raised by Hercynian and Alpine tectogenesis within the SE section of the post-Hercynian Turan Platform. Several large and deep Cenozoic-Mesozoic basins border the Kyzylkum Uplift: the Northern Kyzylkum Basin to the N, the Syr-Darya Basin (see Chap. 6: *Kazakhstan*) to the N, NE and E, and the oil- and gas-bearing Bukhara-Khivin and Bukhara-Karsha Basins to the W and SW.

Block faulting during the Paleozoic and Mesozoic-Quaternary related to the Hercynian and Alpine orogenies, respectively, generated a horst and graben structure in the Kyzylkum Uplift. Folded Proterozoic-Paleozoic rocks are exposed in uplifted blocks while subhorizontally bedded continental clastic sediments of Cretaceous and Cenozoic age fill the basins.

Two stratigraphic-structural units are distinguished in the Kyzylkum Uplift. The *upper unit* (Fig. 15.2) consists of a Paleogene-Cretaceous sequence, from less than 100 m to about 1 000 m thick, of un- to slightly-lithified platform sediments covered by Miocene to Quaternary pink and tan molasse-type deposits, 0 to about 500 m thick. The latter developed in response to the general rise of the Kyzylkum Uplift. Compared with other sedimentary basins adjacent to the Kyzylkum Uplift, the assemblage of Tertiary-Cretaceous sediments in the Kyzylkum Basins has a reduced thickness and an increased and highly differentiated lithologic variation. This sequence evolved by multiple cycles of

**Fig. 15.2.**
**Kyzylkum Basins, generalized litho-stratigraphic column (thickness figures give order of magnitude, deviations are given in deposit descriptions) (after Shchetchkin and Kislyakov 1993)**



transgression and regression reflected by rhythmic development of alternating beds of grey, pink, or variegated, partly carbonaceous sand or weakly cemented sandstone, minor conglomerate, argillaceous, and/or silty facies. The basal Paleogene sediments also include limestone, marl, and gypsiferous horizons.

The *lower or basement unit* is composed of Proterozoic and Lower Paleozoic geosynclinal facies metamorphosed and folded during the Hercynian Orogeny. It includes Cambrian-Ordovician sandstone/quartzite, schists, siliceous phyllite, carbonaceous chert, carbonaceous black shale/slate and carbonates. Magmatic lithologies include felsic intrusives, and intermediate and mafic effusives. The "black shale" contains markedly elevated U values.

The structural framework of the Kyzylkum Uplift, as it is reflected to day by downfaulted, small artesian basins separated by basement horsts, had its root in Late Paleozoic tectonism associated with the Hercynian Orogeny and in tectonic reactivation during the Late Mesozoic and Quaternary. Orogenic activity from the end of the Oligocene onward caused a general rise to form the arch-like uplift, and a subsequent dissection of the uplift into an intricate block structure with horst and graben development. Major faults trend NW-SE. They cut faults oriented about E-W and are displaced by WNW-ESE structures (Fig. 15.1).

Uranium ore bodies occur in twelve arenaceous horizons embedded within argillaceous, silty beds of Upper Eocene, Maastrichtian, Campanian, Santonian, Coniacian, and Turonian age. Mineralized lithologies are of fluvial or shallow marine origin and consist predominantly of sand, minor conglomerate as in parts of Sabyrsai and Ketmenchi, and sandstone cemented by clay (part of Lyavlyakan) and/or carbonate as in sections of Sugraly and Ketmenchi. Quartz (65–80%), feldspar (6–22%), chlorite, biotite, muscovite, and fragments of siliceous (1–5%) and alumosilicate (5–16%) rock fragments are the dominant detrital constituents of mineralized facies. Clay minerals such as hydromica with admixtures of kaolinite and montmorillonite make up between 1 and 15%. Authigenic minerals are mainly calcite and dolomite (up to 10%), pyrite and marcasite (up to 3.5%) or hematite and limonite, and locally siderite, ankerite, glauconite, and others. The sulfides and glauconite are typical for reduced facies whereas hematite and limonite are characteristic for oxidized facies.

Chemically, host rocks are predominantly silicic as reflected by a content of 63–85% $SiO_2$. Carbonate, sulfide, organic debris, and phosphate contents are quite variable (Table 15.1). Some ore bodies are carbonate free while others may contain substantial amounts of up to 5% carbonate. Sulfur contained in pyrite ranges from 0.05 to 3% with maximum values occurring at some sites in Sugraly and Sabyrsai. Organic carbon commonly amounts to 0.03–0.1% C in alluvial sediments but can be up to 10% locally as in Sabyrsai and Ketmenchi. Shallow marine sediments have lower organic carbon contents, on the order of a few hundredths of a percent. Some uraniferous horizons are barren of carbonaceous debris, e.g. the Kendyktube Horizon at Uchkuduk. Bitumen is a common constituent at Sabyrsai but also occurs at Sugraly and elsewhere. Phosphorous ranges generally from 0.03 to 0.4% but can be up to 6% as at Ketmenchi.

Rock temperatures range from 20 to 40°C. Lowest temperatures occur at Beshkak, Lyavlyakan, and in parts of Bukinai and Ketmenchi. Maximum values are recorded from Kenimekh North and the NE section of Sugraly.

Groundwater flow rate is 1–10 m per year in mineralized beds. The filtration coefficient of sand, which is a critical factor for ISL operations, varies between 2 and 10 m $d^{-1}$ but can locally be as low as between 0.1 and 1 m $d^{-1}$ as, e.g. at Sugraly. Depths to groundwater vary between less than 50 m and 100 m and locally more. Water contained in the ore-bearing strata is artesian and, chemically, mostly slightly saline but locally neutral (Table 15.1).

## Principal Host Rock Alterations

Aquifers around uplifted basement blocks commonly exhibit a bipartitioned oxidation zone generated by differential, oxygenated groundwaters that produced either hematitization or limonitization and, as such, imposed a pink or yellow hue, respectively, on the originally grey strata. The inner oxidation aureole is marked by pink facies and extends from a few to several tens of kilometers from an uplifted core into the basin. It grades into the yellow facies, which persists further downdip for a short distance and terminates at the interface with reduced, grey, pyrite and/or glauconite containing arenites. Locally, the limonitic zones enclose pink, hydro-hematitic alteration intervals that are thought to be the product of thermal solutions.

Reduced sediments are characterized by pyritization, bitumenization, carbonatization, and aureoles of hydrogen and hydrogen-sulfide. At least two modes of reducing media generated the reducing environments. The first is widespread and derived diagenetically from synsedimentary carbonaceous matter. The second is locally restricted (e.g. at Uchkuduk, Sugraly, Bukinai, Sabyrsai) and is the result of extrinsic reducing thermal solutions that percolated along faults and invaded the aquifers. It is reflected by pyritized, bitumenized, carbonatized and silicified complex, column-like segments with tongues and lenses extending tree-like into adjacent permeable horizons (Mashkovtsev et al. 1979) (for more details see Sect. *Sugraly*).

## Principal Characteristics of Mineralization

Venatovsky (1993), amended by data from Shchetochkin and Kislyakov (1993) and Kislyakov and Shchetochkin (2000), provides the following information on ore composition: Pitch-blende, black products (sooty pitchblende) and coffinite are the principal uranium minerals in unoxidized ore, whereas uranophane and rarely U-vanadates are typical for oxidized ore. Associated minerals/elements include pyrite, minor marcasite, carbonates (mainly calcite), hematite, molybdenum in the form of jordisite and minor ilsemannite and femolite, vanadium as V-oxides and, more rarely, as U-vanadates, selenium as native Se and selenides, rhenium in form of $ReS_2$ and $ReO_2$, and scandium as Sc-hydroxide and Sc-bearing apatite. Yttrium and lanthanides (cerium, dysprosium, erbium, thulium, ytterbium, europium, samarium, gadolinium, terbium) contained in detrital accessories of ore-bearing sands are reported from the Bukinai-Kenimeth ore field.

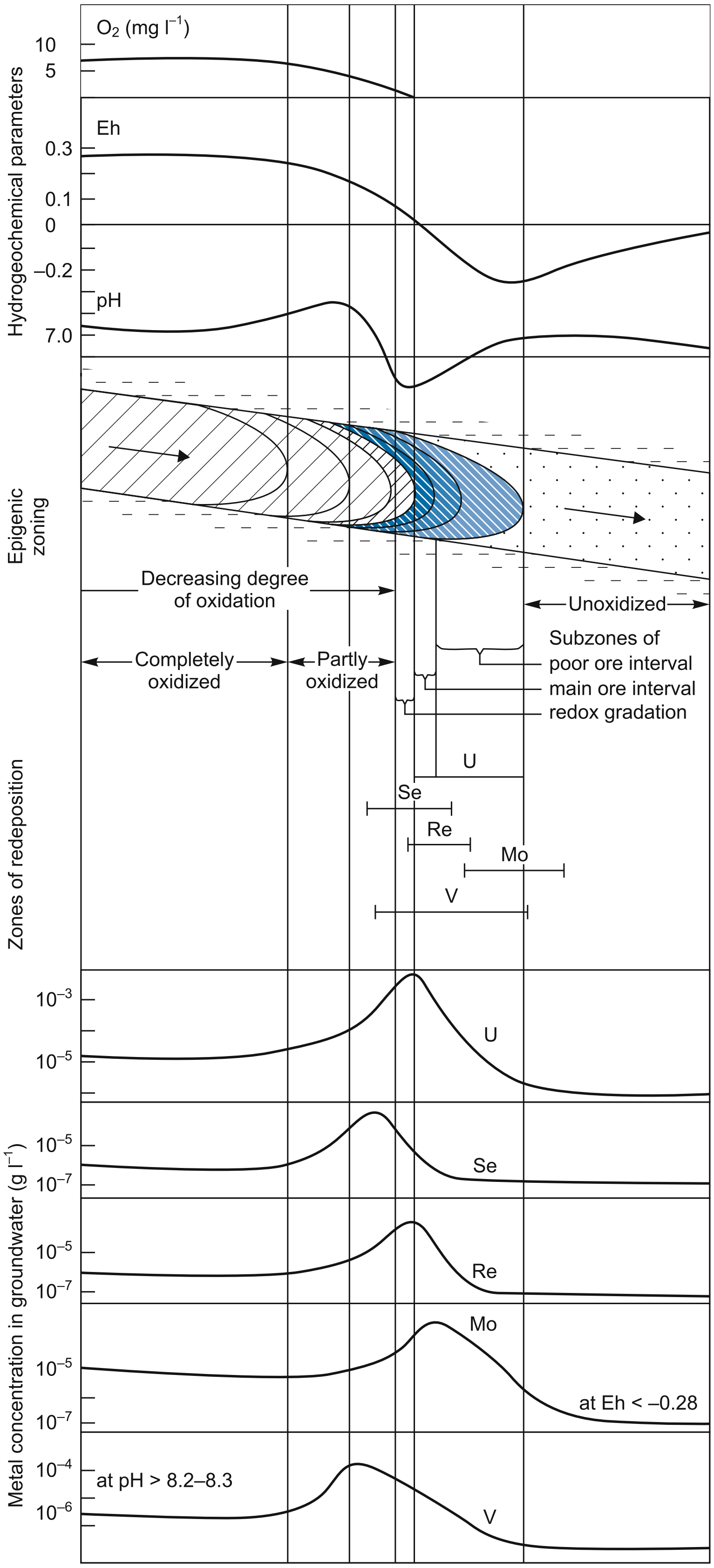
There is a transitional overlapping of elemental assemblages downdip across an ore roll starting on the rear side with native Se or V-Se, followed by Se-Y-lanthanides-U, Sc-Y-lanthanides-U-Re, and Mo-Re on the convex side. Re, V, and locally Mo halos may extend markedly beyond the uraniferous interval (Fig. 15.3).

**Table 15.1.**

**Uzbekistan, Kyzylkum Basins. Geochemical and groundwater characteristics of selected sandstone-type uranium deposits (after Karimov et al. 1996; Kislyakov and Shchetochkin 2000; Kuchersky 1997; Shchetochkin and Kislyakov 1993; Venatovsky 1993) (m b.s.l. = meter below sea level)**

| District/deposit | Ore chemistry | | | | | Groundwater | | | Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|
| | Fe-sulfide S-content (%) | Carbonate $CO_2$ content (%) | Phosphate P-content (%) | Organic carbon (%) | Metallic components | Table (m b.s.) | Flow rate (m $yr^{-1}$) | Chemistry | |
| General | | | | | U, Se, Mo, V:0.x% | | | | |
| • range | 0.05–3 | 0–>5 | 0.03–6 | 0.03–10 | Re, Sc, Y, REE: ppm | <50 –>100 | 1–10 | Neutral or saline | |
| • average | | | 0.03–0.4 | 0.03–0.1 | | >100 | | Slight saline | |
| Uchkuduk Dist | | | | | | | | | |
| • Meylisai | | <5+ | | | | <50 | | | |
| Zarafshan Dist | | | | | | | | | |
| • Sugraly | <3 | <5+ | | | | 100+ | | | <40 |
| Zafarabad Dist | | | | | | | | | |
| • Kenimekh | | <2 | | | | 100+ | | | 40 |
| • Bukinai S | | <2–5 | | | | <50–100 | | | 20 |
| • Bukinai N | | | | | | <50 | | | |
| • Alendy | | | | | | <50 | | | |
| • Beshkak | | <2 | | | | <50 | | | 20+ |
| • Lyavlyakan | | <2 | | | | <50–100 | | | 20 |
| Nurabad Dist | | | | | | | | | |
| • Ketmenchi | | <2–5 | <6 | <10 | | | | | |
| • Tutly | | | | | | | | | 20+ |
| • Sabyrsai | <3 | <5+ | | | | | | | |

**Fig. 15.3.**
**Kyzylkum Basins, schematic section across a redox front documenting typical hydrogeochemical conditions and related differentiated oxidation zones as well as the concentration of U, Se, Re, Mo, and V in groundwater and distribution of these elements across the redox interface (after Karimov et al. 1996)**



Three main ore types and several subtypes are distinguished based on mineralogical composition and U grade:

a **Ordinary, low to medium-grade, unoxidized ore** composed predominantly of black U products (sooty pitchblende). This type is typical for most U deposits in the Kyzylkum region and occurs at a redox front of a stratum oxidized tongue with diagenetically reduced ground derived from intrinsic reducing agents, essentially detrital carbonaceous matter.

b **High in grade, unoxidized (or partially oxidized) ore** consisting of pitchblende-hematite-sulfide or pitchblende-coffinite-sulfide assemblages. This ore variety is related to redox interfaces controlled by locally reduced or re-reduced ground caused by extrinsic reducing thermal solutions that migrated along faults. Ore bodies of this type do not exhibit the mineralogical and elemental features and zoning that are characteristic of normal rollfront deposits (typical ore bodies of this type are identified e.g. in the Sugraly, Bukinai, and Sabyrsai deposits).

c **Oxidized, commonly uranophane dominated ore,** which is rare and commonly positioned updip behind unoxidized lodes and represents relics of former high grade ore bodies.

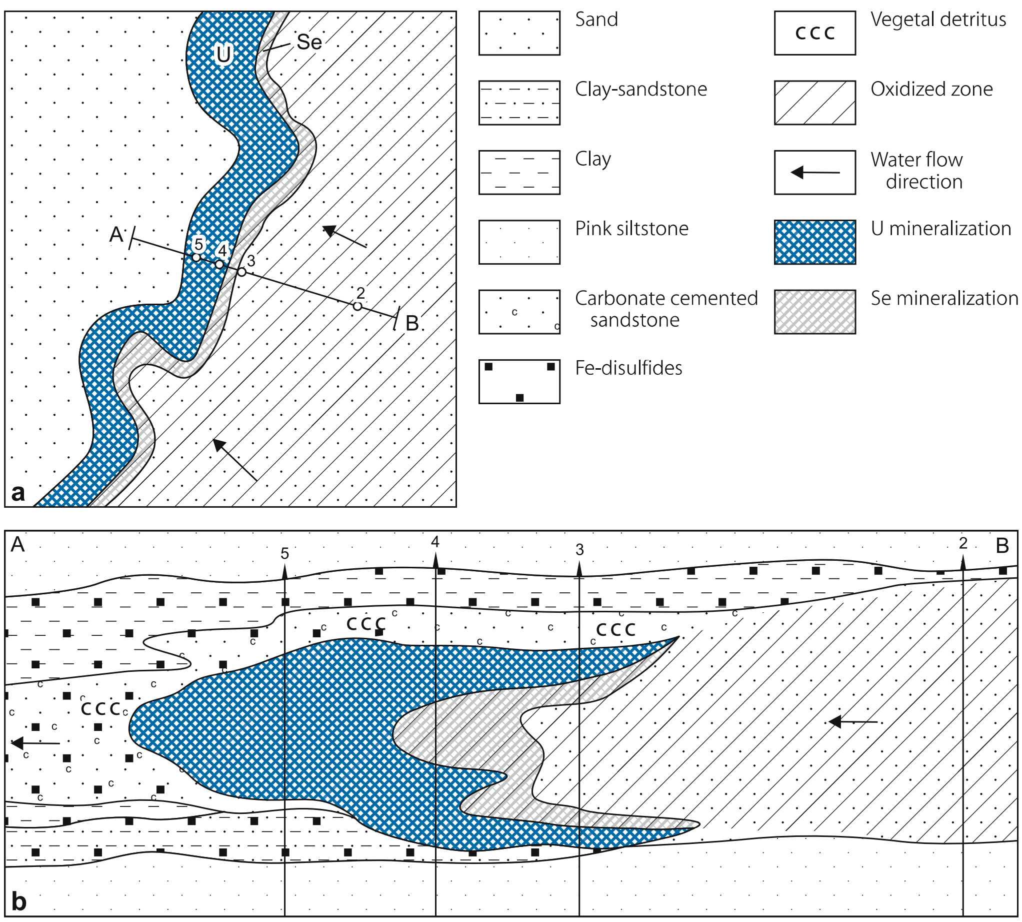
Host rocks, as mentioned earlier (see Regional Geological Setting of Mineralization) are arenaceous, permeable horizons interbedded with impermeable beds. Most deposits are hosted by Upper Cretaceous sediments. A few, like Aktau, Beshkak, and Lyvlyakan, occur in Eocene strata. Mineralization at Bakhaly and Ketmenchi occurs in Tertiary and Lower and Upper Cretaceous sediments as well.

## General Shape and Dimensions of Deposits

Deposits consist, in planview, of a number of discontinuous, elongated ore lodes controlled by highly twisted redox boundaries. These redox fronts can be traced for up to several hundreds of kilometers bending around basement highs. In cross-section, mineralization occurs as simple crescent-shaped (Fig. 15.4) or complex rolls stacked in up to six superjacent horizons; cumulative thicknesses of which range from 8 to 30 m but are generally less than 20 m. Depths vary from less than 50 m to about 700 m. Individual ore bodies are from less than one meter to almost 20 m but mostly between 3 and 5 m thick, from about 50 m to more than 300 m wide perpendicular to the roll, and up to several kilo-meters long. The two thickness parameters give a ratio of ore body thickness to host bed thickness ranging from 1:2 to 1:10 with most common values between 1:3 and 1:7.

Individual deposits have in situ resources from a few 1 000 to more than 50 000 t U and average grades usually of less than 0.1% U.

**Fig. 15.4.**
**Kyzylkum Basins, schematic a map and b section of rollfront-type (Uchkuduk-type) U deposits. (Scale vertical to horizontal 1–10) (after Karimov et al. 1996)**



Grades of ore bodies within a deposit range from 0.01–3% U. Common tenors of associated elements include: 0.001–0.3% Mo; 0.03–0.5% V; 0.05–0.07% Se but with ranges from 0.01 to 0.2% Se; 0.5–2 ppm and occasionally up to 15 ppm Re; 3–20 ppm Sc; and locally, as in the Bukinai-Kenimekh ore field, <120 ppm Y, <150 ppm Ce, and <50 ppm other lanthanides, [dysprosium, erbium, thallium, ytterbium (<10 ppm), europium, samarium (<3 ppm), gadolinium and terbium (<1.5 ppm)]. In terms of a productivity coefficient, values range from 1 to 20 kg U $m^{-2}$ and average between 2 and 6 kg U $m^{-2}$. Respective Mo, Se, and V values range from less than 1 to more than 5 kg $m^{-2}$ while Sc, Re, and REE values vary from less than 1 to more than 5 g $m^{-2}$.

## Stable Isotopes and Fluid Inclusions

Kislyakov and Shchetochkin (2000) report results of stable isotopes and fluid inclusions studies mainly but not exclusively from the Sugraly deposit and arrive at the following conclusions. Decrepitation of inclusions in pitchblende and paragenetic calcite in high-grade ore suggests increased temperatures of 120–200°C for this mineralizing process. Homogenization of gaseous-fluid inclusions in gangue minerals of the various alteration stages indicates a temperature of not less than 120°C during mineral crystallization. Fluid inclusions in vein quartz correspond to gaseous-aqueous brines with very high tenors of (in mol $kg^{-1}$ $H_2O$) 0.3–2.4 total sulfur, 0.9–4.3 Ca and 0.4–1.7 $CO_2$.

Sulfur isotopes in pyrite derived from thermal solutions and associated with pitchblende-hematite-sulfide ore have different ratios than sulfur isotopes of sulfate-ions in present-day groundwater in the Cretaceous aquifers and in near surface deposited gypsum (Table 15.2). This indicates a sulfur source for the pyrite different to that of the groundwater. Otherwise, pyrite in black U ores has a wide range of $\delta^{34}$S‰ values, which may be attributed to the isotopic fractionation during biogenic reduction of sulfate in groundwater and incorporation of sulfur from earlier sulfides including those of thermal fluid origin. The isotopic composition of sulfur in pyrite and baryte in unaltered aquiclude clays, except for diagenetic mineral phases, is thought to be due to early diagenetic fractionation of the sulfur of marine waters.

## Principal Ore Control or Recognition Criteria

### Host Environment

- Horst and graben structural pattern
- Relatively small artesian basins separated by uplifted basement ranges
- Basins are filled with
  - Quaternary and Upper Tertiary molasse-type sediments, 0–500 m thick resting upon
  - Lower Tertiary to Cretaceous clastic sediments, from less than 100 m to about 1 000 m thick, of fluvial, deltaic, and shallow marine provenance
- Alternating sedimentary cycles are reflected by permeable arenaceous horizons intercalated with impermeable argillaceous or silty beds
- Subhorizontal dip of strata except for flexures along faults
- Widespread faulting by repeated tectonism
- Potential source rocks for U and other metals are provided by basement lithologies particularly black slate

### Alteration

- Principal pre-ore alteration includes oxidation and reduction
- Oxidation is reflected by hematitization and limonitization
- Oxidation zones often occur as relatively narrow aureoles around basement uplifts
- Reduction is documented by sulfidization (mainly pyritization) and bitumenization

**Table 15.2.**
**Kyzylkum Basins. Sulfur isotope composition of sulfide and sulfate minerals and sulfate in present-day groundwater (Shchetchkin and Kislyakov 1993 including data from other authors)**

| Specimen | Sampling site/ deposit | $\delta^{34}$S‰; Fe-disulfide (pyrite) | | | $\delta^{34}$S‰; sulfates | | |
|---|---|---|---|---|---|---|---|
| | | Range | Average | No. of samples | Range | Average | No. of samples |
| Thermal veins in ore bearing beds | Uchkuduk | −33.7 to −37.1 | −35.4 | 3 | +50.4 to +24.0 (baryte) | +37.2 | 12 |
| Pitchblende-hematite-sulfide ore | Sugraly, Sabyrsai | −28.2 to −46.2 | −37.2 | 25 | | | |
| Black U products ore | Uchkuduk, Sugraly, Lyavlyakan | +17.9 to −46.2 | −14.0 | 40 | | | |
| Surficial oxidation zone | Uchkuduk | | | | +9.1 to +4.1 (gypsum) | +6.6 | 12 |
| Groundwater | Uchkuduk, Sabyrsai | | | | +8.2 to +1.4 (sulfate-ion) | +4.8 | 11 |
| Unaltered aquiclude clays of U-hosting strata with diagenetic minerals | Uchkuduk | −13.2 to −40.3 | −26.7 | 10 | +28.8 to +27.0 (baryte) | +27.9 | 3 |

- Reducing agents are of twofold origin
  - Synsedimentary carbonaceous matter and/or epigenetic sulfides and bitumens, and
  - Extrinsic reducing thermal solutions ascending along faults
- Syn-ore alteration includes sulfidization, locally hematitization, carbonatization, silicification, and argillization

**Mineralization**

- Ore bodies are predominantly of rollfront type
- Mineralization is polymetallic and may include U, Mo, Se, V, Re, Sc, Y, and/or REE
- Various ore types exist due to redox fronts of different origin and
- Repeated reworking of older mineralization
- High-grade pitchblende-hematite-sulfide and pitchblende-sulfide ores are associated with redox fronts generated by extrinsic reducing thermal solutions
- Low-grade (ordinary) black U ore is related to redox fronts generated by diagenetically reduced environments based on carbonaceous matter and/or sulfides
- Uranophane mineralization is locally developed due to oxidative replacement of high-grade U-oxide ore
- Zoning of ore-related elements across roll-shaped ore bodies
- Simple and multiply stacked ore rolls in superjacent aquifers
- Relatively close position of most deposits to basement uplifts
- Favorable host rocks include un- to weakly-lithified sands, clay- or carbonate-cemented sandstone, and minor conglomerate with or without organic debris and with Fe-sulfides, -oxides, -hydroxides, phosphates, and carbonates as minor constituents

### Principal Aspects of Metallogenesis

In conclusion from descriptions of the various researchers, uranium deposits in the Kyzylkum Basins were formed and are still in the process of modification by epigenetic hydrodynamic processes, which dominated the hydrodynamic regime in the Kyzylkum Basins from the Pliocene onward. Oxygenated groundwater and intrinsic reductants such as organic matter and diagenetically derived sulfides and bitumens as well as locally active extrinsic reducing thermal solutions ascending along faults are the salient ingredients in the metallogenesis. The hydrodynamic regime is the result of local recharge of oxygenated waters from basement uplifts and their down-gradient migration in permeable strata. U and other ore-forming metals were supposedly leached by meteoric waters from fertile source rocks in the basement complex such as black slates and then incorporated into the groundwater. The basinward migrating oxygenated waters generated an aureole of oxidized aquifers up to few tens of kilometers wide around basement highs. These solutions also transported the ore-forming elements downdip the hydrogenic gradient to redox interfaces where chemical reactions caused their deposition in roll-shaped ore lodes.

Redox interfaces were generated at sites where the oxygenated waters encountered reduced ground. Reducing conditions were provided by two principal sources of reductants. The first was provided by synsedimentary carbonaceous matter and/or diagenetically derived sulfides, and the second by locally upwelling, extrinsic thermal fluids. These reducing thermal solutions percolated along faults, invaded adjacent aquifers and generated locally-restricted reducing environments (Mashkovtsev et al. 1979). Perevozchikov (2000) identified liquid hydrocarbons and hydrogen in the reducing thermal solutions that control the uranium in the glauconite sands of the Kendyktube Horizon of the Uchkuduk deposit (these sands are barren of carbonaceous debris); and he could trace the migration paths of hydrocarbons concentrations in groundwater from the discharge area back to the oil-bearing Amudarya Basin.

Consequently, two varieties of redox fronts were formed. Strata inherent reductants commonly produced only a weak redox front along which only low-grade, ordinary black U mineralization developed. The magnitude or intensity of this type of mineralization is inversely proportional to the width of "young" limonitic subzones in aquifers and in the zone of oxidized strata in general. Extrinsic reducing thermal fluids provided a more powerful reductant. Where they intervened with oxygenated groundwater, a geochemical interface was established that provided the required geochemical conditions for deposition of relatively high-grade U mineralization.

Periodically repeated tectonic activity from the Late Pliocene into Quaternary exerted a strong influence on the metallogenetic evolution by triggering multiple alternations and variably intense processes of oxidation and reduction. During more quiet interludes, ore deposition accelerated. In contrast, periods of increased tectonism were accompanied by not only a rapid advance of oxygenated waters but also by a renewed influx of reducing thermal solutions, which resulted in redistribution of U and other metals. During these processes older mineralization was repeatedly reworked and high-grade pitchblende-hematite-sulfide and pitchblende-sulfide ores were transformed into ordinary black U ores and locally, in zones of oxidation, into uranophane mineralization.

A more detailed metallogenetic model for an individual deposit, namely Sugraly, is forwarded by Shchetochkin and Kislyakov (1993) for which the reader is referred to Sect. *Sugraly*.

## 15.1.1 Uchkuduk or Bukantau District

Four U deposits are reported from the Uchkuduk District; *Bakhaly* is situated to the north and *Uchkuduk, Meilysai,* and *Kendyktyube* to the south of the Bukantau Range. A mining town, Uchkuduk, was established 250 km NNW of Navoi to serve the district. Remaining in situ resources amount to 17 900 t U RAR + EAR-I and 21 200 t U EAR-II + SR (OECD-NEA/IAEA 2005).

Conventional mining produced on the order of 30 000 t U between 1958 and 1994 when conventional mining was terminated. An estimated additional quantity of about 15 000 t U was recovered by ISL operations between 1964 and 2001, all from the Uchkuduk deposit. In 2005 production was restricted to ISL operations at the Kendyktube deposit. The Northern Mining Division, a subsidiary of NMMIW, is the mining operator.

**Source of information.** Karimov et al. 1996; unless otherwise cited.

#### 15.1.1.1 Bakhaly

Bakhaly is an explored deposit located ca. 65 km N of the town of Uchkuduk. It contains in situ resources of some 3 000 t U. Three horizons of Albian, Turonian, and Cenomanian age are mineralized and contain several ore bodies, 0.1–1.5 m thick, of roll and lenticular shape. Ore occurs at depths from 160 to 430 m. Ore grades vary between 0.03 and 0.5% U. Ore body # 3 is the largest. It is 2 700 m long, 200 m wide, and hosted by an Albian carbonaceous sand and clay sequence with lignite intercalations.

#### 15.1.1.2 Meilysai

This explored deposit was discovered 30 km SW of the town of Uchkuduk in 1959. Lenticular U mineralization occurs in three Upper Cretaceous arenaceous beds at depths from 160 to 350 m. Paleogene clay and marl overly the ore-bearing unit, while siltstone of the Taikarshin horizon forms the footwall. Some U mineralization is also found in the latter. A stratum of sand with argillaceous intercalations, 10–30 m thick, within the lower section of the 130 m thick Aitymsky Horizon is the principal ore-bearing unit. Four ore bodies are identified in this unit. Ore bodies consist of 3–10 ore lenses separated by barren ground. Ore body # 1 is the largest; it measures 6 km long, from 50 to 1 300 m wide, from 3 to 4 m thick, and accounts for 60% of the resources of Meilysai. Grades range from 0.01 to 0.05% U and average 0.026% U. The ore contains from 2 to 4% $CO_2$ contained in carbonate.

#### 15.1.1.3 Uchkuduk

Uchkuduk is located 25 km E of the same named town. Discovered in 1952, it was exploited by open pit mining from 1958 to 1994. ISL tests started in 1961 and lasted until 2001/2002. Original total resources amounted to more than 50 000 t U at grades averaging about 0.04% U except for some higher grade ore bodies. Remaining resources (RAR + EAR-I high cost category) are about 12 000 t U.

##### Geology and Mineralization

Bedrock geology consists of a slightly SE dipping Upper Cretaceous-Paleogene sequence covered by an up to some 10 m thick veneer of Quaternary alluvium. The sediments rest on Upper Carboniferous siliceous schists intruded by granite. The basement crops out to the north and plunges to 400 m deep to the south of the deposit. Major faults trend curvilinear NNW-SSE, NE-SW, and E-W (Fig. 15.5). The Cretaceous-Tertiary litho-stratigraphic column includes from top to bottom:

**Lower Oligocene-Upper Eocene:** 0 to >20 m thick, clay

**Middle Eocene:** <40 m thick, marl

**Lower Eocene:** 2–8 m thick, calcareous clay.

**>Unconformity<**

**Senonian, Aitymsky Horizon:** 20–60 m thick, alluvial fine-grained grey sand and carbonatic sandstone

**Upper Turonian, Taikazshinsky Horizon:** 90–105 m thick, separated into

- upper unit: proluvial pink siltstone with interbedded pink sandstone
- lower unit: alluvial carbonate cemented sand

**Lower Turonian**

- Kendyktube Horizon (U): 20–25 m thick, marine green-grey glauconite sand and muddy sand (barren of organic debris)
- Dzheirantyi Horizon: 40 m thick, blue-grey mudstone and montmorillonite-hydromica-bearing clay
- Uchkuduk Horizon (U): 10–35 m thick, alternating fine-grained sandstone and clay

**Cenomanian:** <30 m thick, variegated kaolinitic clay.

U minerals are mainly pitchblende and coffinite with minor uranophane, β-uranotile, and uraniferous phosphatic fish detritus. Associated elements include small concentrations of Se, Mo, and others.

Uchkuduk encompasses 93 roll-type ore bodies within a triangular area with a NNE-SSW-oriented base line, about 30 km long, that forms the SE boundary, and slightly shorter southwestern and northwestern limbs. These ore bodies are distributed over five Senonian, Turonian and Cenomanian aquifers with an aggregate thickness of 150–160 m. Fifty percent of Uchkuduk's resources, however, are contained in the two Lower Turonian Uchkuduk and Kendyktube Horizons; the former contains major lodes. A clay and silty clay aquiclude up to 40 m thick of the Dzheirantyi Horizon separates both horizons. Ore lodes have lengths from 100 to 6 000 m, widths from 25 to 2 000 m and occur at depths from 10 to 110 m in the north and as much as 280 m in the southern Aitinski sector of the deposit. Ore grades average 0.03% U but can be as much 0.4% U. Se and Mo values are commonly on the order of 0.01%.

#### 15.1.1.4 Kendyktyube

This deposit is located ca. 40 km E of the town of Uchkuduk and contains about 1 000 t U RAR + EAR-I in three horizons of Santonian, Turonian, and Coniacian strata; about half of which is contained in the central sector and the rest in the eastern and western segments of the deposit.

### 15.1.2 Zarafshan or Auminza-Beltau District

This district contains the *Aktau* and *Sugraly* deposits on the northern side and the *Amantei* occurrence on the southern side

**Fig. 15.5.**
**Uchkuduk District, Uchkuduk deposit, a geological map with surface projected ore bodies in the Turonian Kendyktube and Uchkuduk Horizons, and b NNW-SSE section (explanations and legend see below) (after Karimov et al. 1996)**

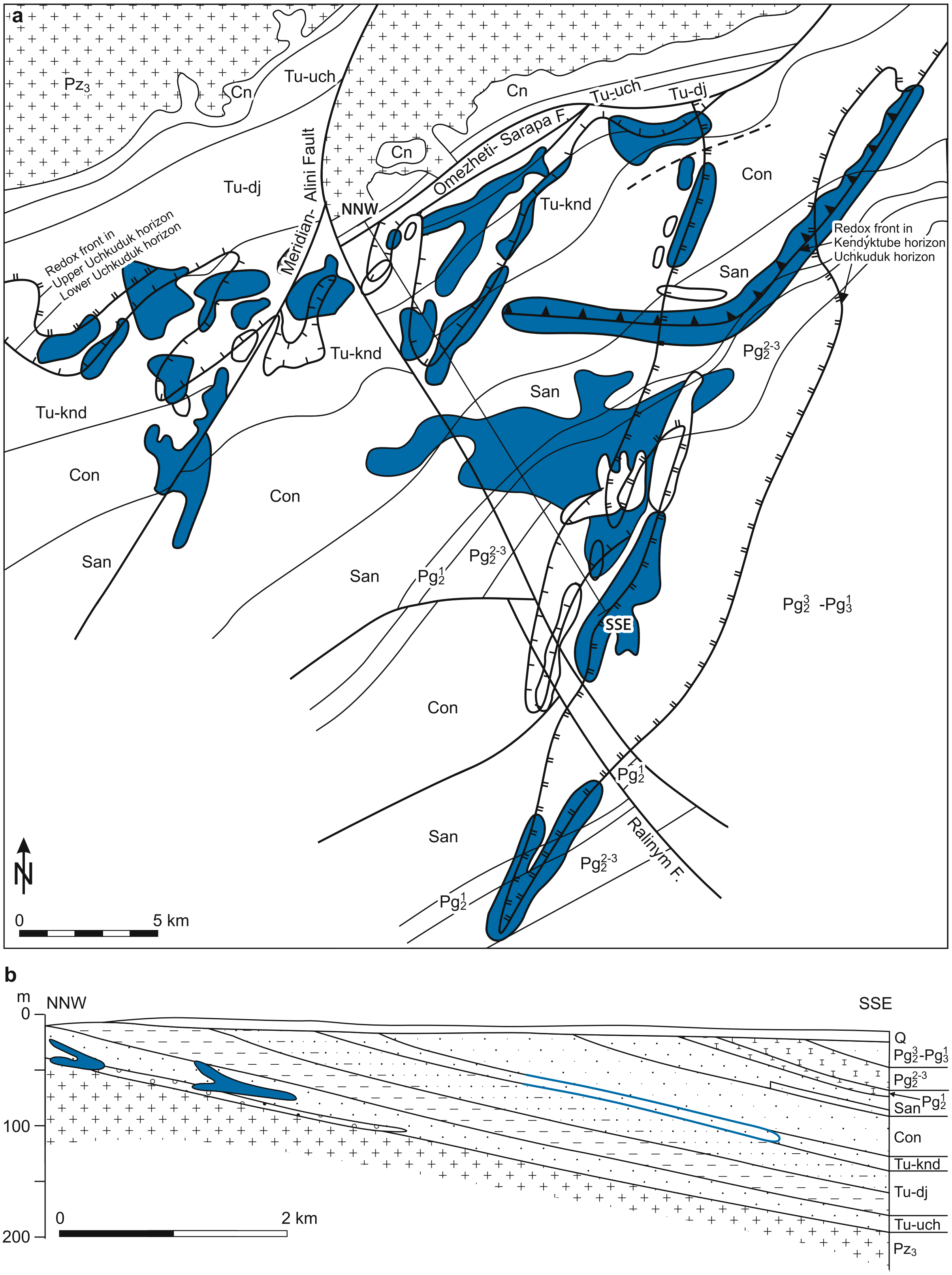
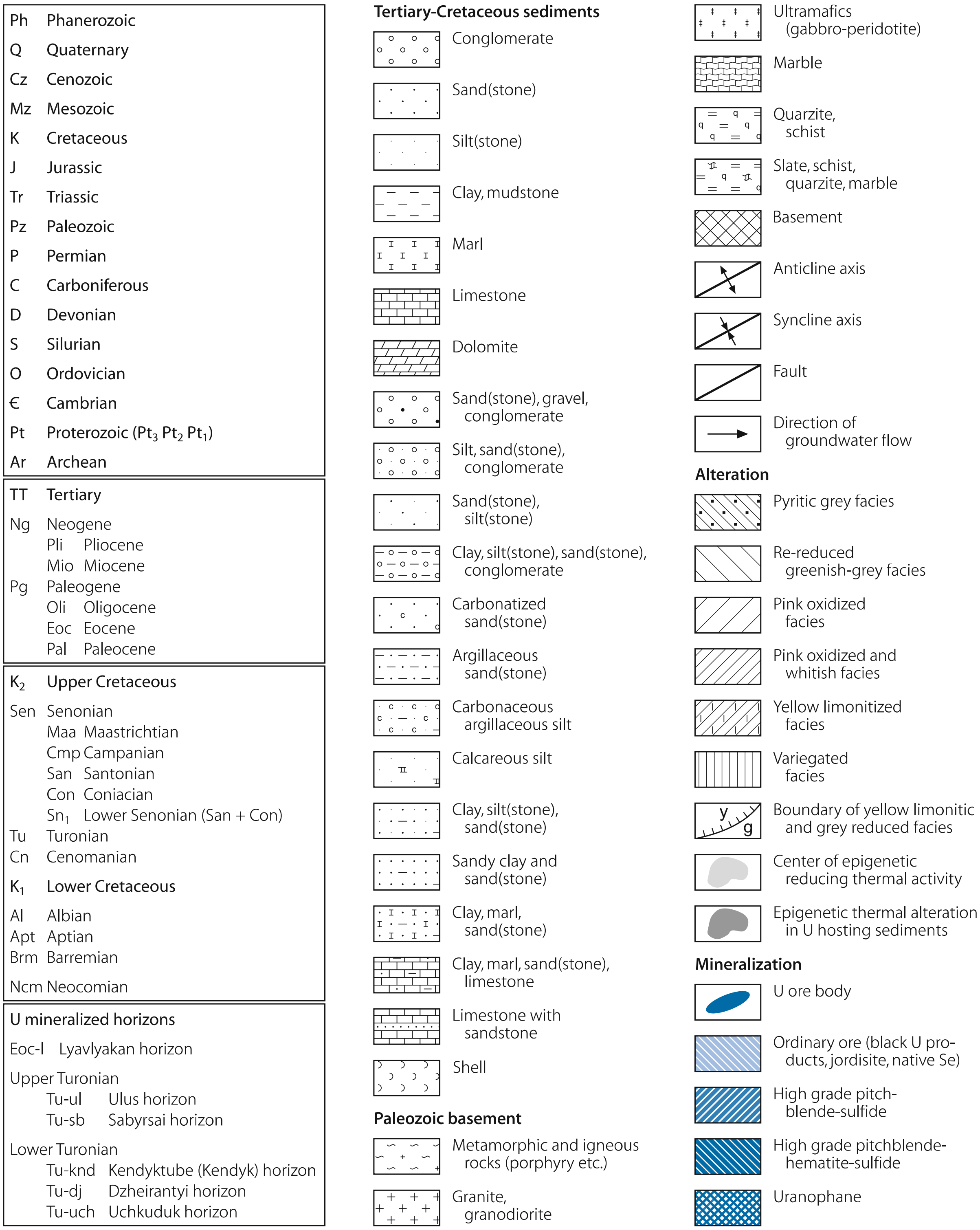


**Fig. 15.5. (Continued)**

**Explanations and legend for figures of Kyzylkum sandstone-type U deposits (Figs. 15.5 to 15.8 and 15.10 to 15.15)**




of the Tamdytau Range. A mining town, Zarafshan, was established about 170 km NNW of Navoi to serve the district. Remaining in situ resources are 36 000 t U RAR + EAR-I and 48 000 t U EAR-II + SR. Sugraly was the only deposit exploited to date. The Eastern Mining Division (also referred to as Central Ore Division), a subsidiary of NMMIW, is in charge of mining operations (OECD-NEA/IAEA 2005).

### 15.1.2.1 Sugraly

Sugraly was discovered to the north of the Tamdytau Range, ca. 30 km NNE of the town of Zarafshan in 1961. Underground mining started in 1977 but was suspended in 1994, as was the ISL operation. Two mines were active, the *Kyzylkumskaya* (lodes 1 and 7?), and the *Oktyabriskaya mine* (lode 8). With an average mining grade in excess of 0.2% U, Sugraly belongs to the better grade U deposits of the Kyzylkum Basins. Original resources amounted reportedly to almost 60 000 t U.

**Source of information:** Shchetochkin and Kislyakov (1993) provide well-documented geological coverage of the Sugraly deposit which is largely used for the following presentation amended by data from Karimov et al. (1996), Kislyakov and Shchetochkin (2000) and other sources.

## Geological Setting of Mineralization

Sugraly is situated on the southern limb of the large artesian Beshbulak Basin. Quaternary, Tertiary, and Upper Cretaceous sediments fill the basin and rest unconformably on a basement of Paleozoic metamorphics (± metamorphosed limestone, dolomite, sandstone, mudstone; porphyry, granite,) and Hercynian felsic and ultramafic (gabbro, peridotite) igneous rocks of the northern slope of the Tamdytau Uplift (Figs. 15.6, 15.7).

The Cenozoic-Cretaceous litho-stratigraphic column includes the following units:

**Cenozoic (total thickness 400–600 m)**

- *Quaternary*: 1–50 m thick, alluvium (sandy rubble)
- *Quaternary-Pliocene*: 10–150 m thick, pink, coarse-fragmented proluvium and yellowish-tan argillaceous-arenaceous alluvium
- *Upper-Middle Miocene*: 80–320 m thick, monotonous pink calcareous siltstone
- *Lower Miocene-Middle Oligocene*: 40–50 m thick, pink arenite of marine and continental origin
- *Lower Oligocene–Eocene*: 140–150 m thick, grey marly-argillaceous sediments

**Upper Cretaceous (total thickness 100–120 m)**

- *Maastrichtian* (main U-bearing unit): 10–25 m thick, micaceous-quartzose sand, calcareous sandstone, conglomerate, and shell beds of shallow marine-lagoonal origin. Carbonaceous matter is absent. The Maastrichtian is continuous over the entire area. It rests upon Campanian in the E, Lower Senonian in the W, and on Turonian sediments elsewhere.
- *Campanian*: 0–30 m thick, variegated clay, argillaceous and calcareous sandstone, with fragments of pelecypod shells, quartz gravel, and phosphorite of marine origin. Campanian strata are only present in the eastern section of the deposit where the Campanian unconformably transgressed upon Lower Senonian, Turonian, and Cenomanian sediments, and further eastward upon the crystalline basement.
- *Lower Senonian* (Santonian-Coniacian) (minor U-bearing unit with few U lodes in grey facies): up to 40 m thick, pink, light grey and grey crossbedded sands alternating with clay, silt, and variegated argillaceous sandstone beds of proluvial, fluvial, and flood plain provenance. The sequence pinches out in the central part of the deposit and increases to the west and south where it rests on Turonian sediments and attains its greatest thickness.
- *Turonian* (some U): 10–45 m thick, argillaceous-arenaceous sediments of marine origin, variegated in upper section and grey in lower section. The Turonian overlies Cenomanian strata in the western, and transgressed over basement in the eastern area.
- *Cenomanian*: 2–12 m thick, pink conglomerate and gritstone, variegated clay, silt, argillaceous sandstone, and sand of proluvial, fluvial, and flood plain provenance forming the basal unit of the Mesozoic sediments resting on Paleozoic basement rocks.

The Mesozoic and Tertiary strata have a monoclinal dip of 1–3° N to NW. Low-angle drag folds occur along faults. Faults are of normal and reverse nature and trend about NE-SW, NW-SE, and E-W. Inclination is commonly steep. The first two fault systems generated three major blocks in the area of the Sugraly deposit: *(a)* a NE-SW-elongated graben structure along the northwestern slope of the Tamdytau Uplift, *(b)* a horst structure (later referred to as "SW block or sector" containing ore lodes # 1–6 and others) situated to the SW of the Charyktin fault and subparalleling to the NW the afore mentioned graben, and *(c)* a downfaulted block ("NE block/sector" with ore lodes # 7, 8, 9, 15 and others) located to the NE of the two aforementioned blocks *(a)* and *(b)* but separated from them by the NW-SE-trending Charyktin fault.

The Charyktin fault also constitutes the boundary between two independent groundwater regimes. The first is contained in the NE block where it is restricted to the Maastrichtian aquifer and the second in the SW blocks in form of a hydraulically integrated water regime in Lower Senonian to Maastrichtian aquifers.

Groundwaters in the Cretaceous and Tertiary aquifers are artesian and flow toward the N and NW. Local recharge is from fracture and karst waters in the Tamdytau Uplift. Discharge of stratum water manifested by springs, lakes, and salt marshes occurs along faults on the N flank of the Beshbulak Basin. Chemically, the groundwater is slightly saline and has a pH value of 7.1–7.8. Constituents include Na and Ca sulfate-hydrocarbonates, Na sulfate-chloride, and 0.7–2.5 g $l^{-1}$ solid resiues. The content of dissolved U, Se, and V varies between 2 and 30 ppb in oxygenated waters. These elements decrease markedly to 0.n ppb in non-oxygenated waters associated with an Eh drop from +140 mV in oxygenated to −180 mV in non-oxygenated waters.

A hydrogeochemical anomaly is noted at the NE margin of the deposit near ore lode 8. Here, present-day groundwater contained in stratum-oxidized rocks is non-oxygenated, has negative Eh values and contains up to 4 mg $l^{-1}$ $H_2S$ and up to 2.8 mg $l^{-1}$ hydrocarbons.

Temperatures in the deposit range from 50°C in the NE to 40°C in the SW part. The high temperatures result from a large geothermal anomaly with a 6.5°C per 100 m gradient centered to the NE of the deposit.

## Host Rock Alteration

Repeated oxidation and reduction related to diagenetic events and multiple epigenetic hydrogeochemical processes of extrinsic and intrinsic provenance generated the alteration features in

**Fig. 15.6.**
**Zarafshan District, Sugraly deposit. a Geological map with surface projection of ore bodies in Maastrichtian and Senonian strata; b NW-SE section with intersection of ore body #1 (explanations and legend see Fig. 15.5) (after Shchetchkin and Kislyakov 1993, amended by data from Sikorskii, Kazarinov, and Ponomarev)**

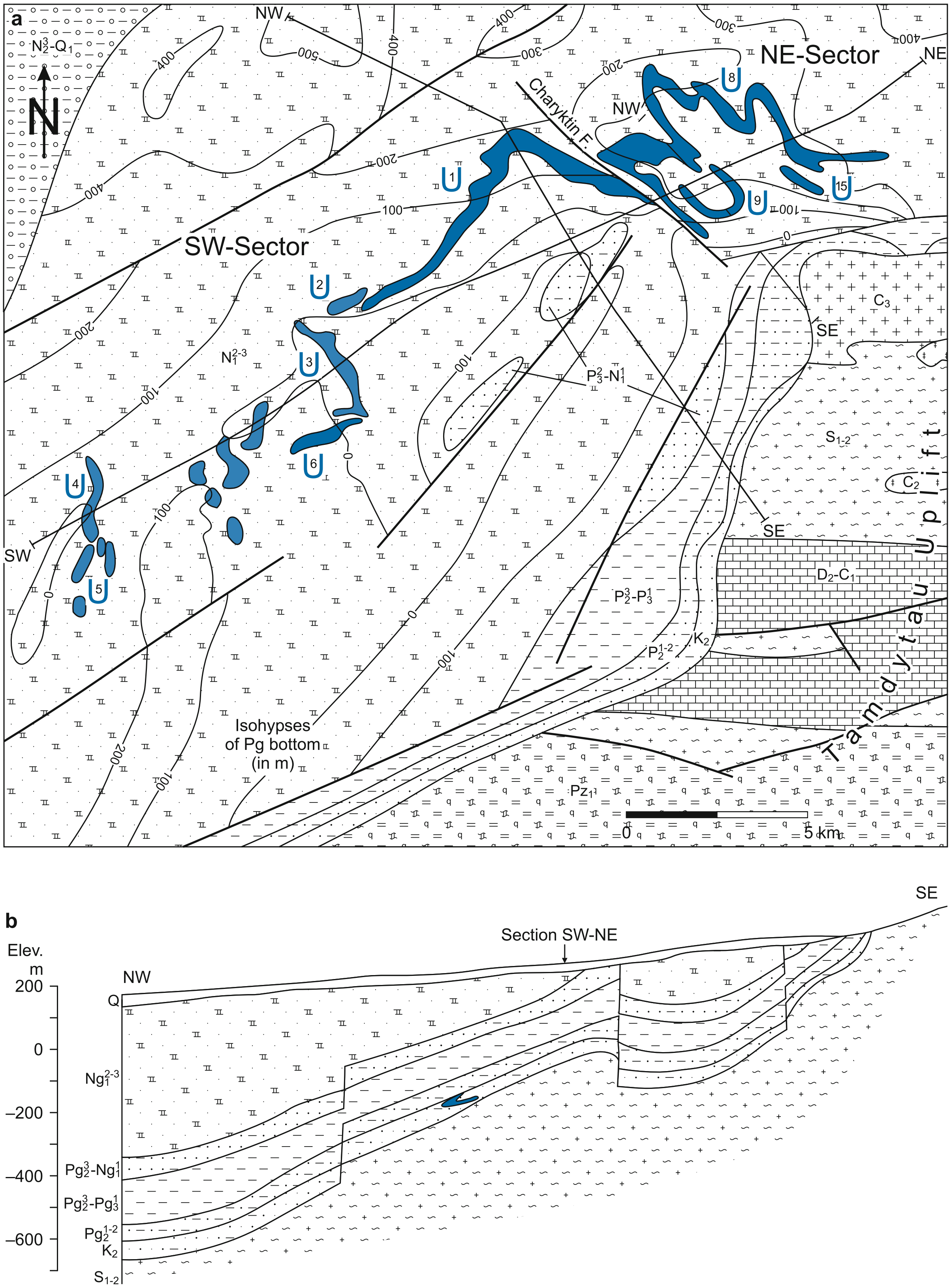
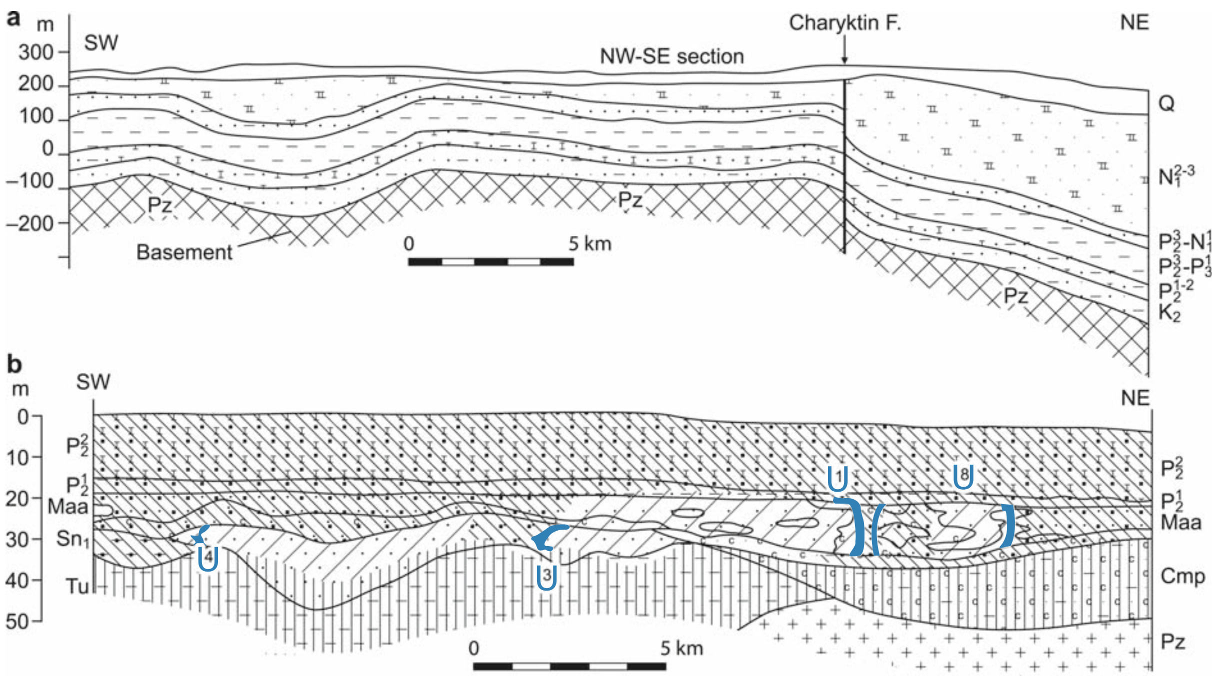


**Fig. 15.7.**

**Zarafshan District, Sugraly deposit, SW-NE longitudinal sections (for location see Fig. 15.6) showing a the geological profile and b the lithologic-geochemical characteristics of the uranium-bearing Maastrichtian and Senonian Horizons (explanations and legend see at Fig. 15.5) (after Shchetchkin and Kislyakov 1993)**




the U-hosting Maastrichtian and Lower Senonian strata. Early stratum alteration by oxygenated groundwaters percolating downdip the hydrological gradient from the Tamdytau Uplift toward N-NW imposed a 3–12 km wide differentiated oxidation tongue on aquifers ending in redox fronts at the interface of diagenetically reduced grey facies in the blocks mentioned earlier.

Subsequent processes, however, as noted by Shchetochkin and Kislyakov (1993), generated different modes of alteration in the two blocks situated to the SW and NE, respectively, of and separated by the Charyktin fault. In the *SW block*, early oxidation imposed a pink hue on the permeable Maastrichtian beds, which was overprinted downdip by a frontal zone of yellow limonitization. The limonitized zone is 25–100 m wide in the NE and increases to 4–6 km in the SW. The limonitic oxidation apparently replaced diagenetically (?) reduced pyritic facies, which prevail further basinward. Underlying Lower Senonian strata are primarily pink but also white colored in an up to about 5 km wide belt adjacent to the Paleozoic basement outcrop of the Tamdytau Range. Limonitization affected the belt to some extent but was strongest further downdip to the N and NW where it generated a yellow limonitic alteration facies. The yellow facies ends basinward at the updip boundary of a narrow, NE-SW-oriented reduced pyritic zone. In contrast to the Maastrichtian sequence, the Lower Senonian sediments are oxidized towards the center of the basin. (Figs. 15.8a,b). In the *NE block*, the U-hosting Maastrichtian aquifer, colored pink or red brown due to traces of finely dispersed hematite, became locally re-reduced to a greenish-grey facies, which was subsequently partially re-oxidized as reflected by neogenic yellowish goethite-hydrogoethite as found at lodes 9 and 15.

Re-reduction is a prominent feature in the NE sector and occurred in response to reducing thermal fluids ascending along faults. These fluids caused alterations proceeding through several stages including:

1. Early acidic alteration associated with argillization and silicification reflected by kaolinite, illite, montmorillonite, quartz, chalcedony, and opal formation;
2. Carbonatization documented by dolomite and calcite associated with pyrite crystallization;
3. Low-grade bitumenization of hydrocarbons resulting in bitumens associated with calcite, pyrite, and marcasite; and finally
4. Sulfidization expressed by pyrite and marcasite associated with calcite derived by secondary reduction of stratum oxidized facies.

Silicic alteration of the first stage is restricted to the immediate vicinity of faults and fractures. Second stage carbonatization persists in a significantly wider aureole (Fig. 15.9) while bitumenization and sulfidization of the last two stages display the widest spreading. The total amount of Fe-sulfides in reduced zones is approximately 1% or more while that of bitumens soluble in chloroform is as much as 0.15%.

Fracture controlled reduced ground within sandy horizons is conspicuous by greenish-grey colored, lenticular, tabular or patchy bodies altered by silicification, argillization, carbonatization, sulfidization, and/or bitumenization. In aquicludes over- and underlying such horizons, reduction-related minerals include disseminated carbonates and sulfides, and veinlets or stringers of quartz-carbonate-sulfide.

Re-reduction in the SW sector of the Sugraly deposit occurred along contact faults of the horst block where primarily pink Lower Senonian sediments were altered to grey pyritic facies.

## Mineralization

Mineralization is polymetallic composed primarily of U, Se, Mo, Re, and traces of other elements. The principal U minerals are pitchblende, black U products (sooty pitchblende?), and locally uranophane. Additional ore constituents include native γ-Se, jordisite, minor ilsemannite and femolite, and rhenium-bearing minerals. Associated minerals are pyrite, minor marcasite, hematite-hydrohematite, carbonates (mainly calcite), and locally zeolites.

Several mineral assemblages are noted: black U products associated with jordisite and native selenium, pitchblende-hematite-sulfide, pitchblende-sulfide, and uranophane. The first assemblage is typical for ordinary ore while the latter three are typical for high-grade ore (for more details see further below).

Ore minerals occur in the matrix of sandy beds as powdery black U products together with jordisite, fine colloform pitchblende, acicular native selenium, and other minerals. Uranophane occurs as cone-shaped and radiated-fibrous particles or spherulites finely disseminated in oxidized, pink and reddish-brown sand and sandstone. It is also present in spheric aggregates up to few millimeters in size that consist of detrital minerals cemented by uranophane and calcite.

In the few cases where pitchblende-sulfide and uranophane mineralizations are overlapping, dark grey sandstone with U-oxides and Fe-sulfides may be dotted with disseminated yellow uranophane spherulites. U-oxides of this assemblage are clearly superimposed on the uranophane as documented by finely dispersed pitchblende coating not only sand grains but also uranophane. Uranophane spherulites as well as massive carbonate intercalations often contain relics of Fe-hydroxides

**Fig. 15.8.**
**Zarafshan District, Sugraly deposit, geological map illustrating the distribution of alteration facies a in Maastrichtian and b in Lower Senonian sediments and the related position of U ore bodies (explanations and legend see at Fig. 15.5) (after Shchetchkin and Kislyakov 1993)**

a

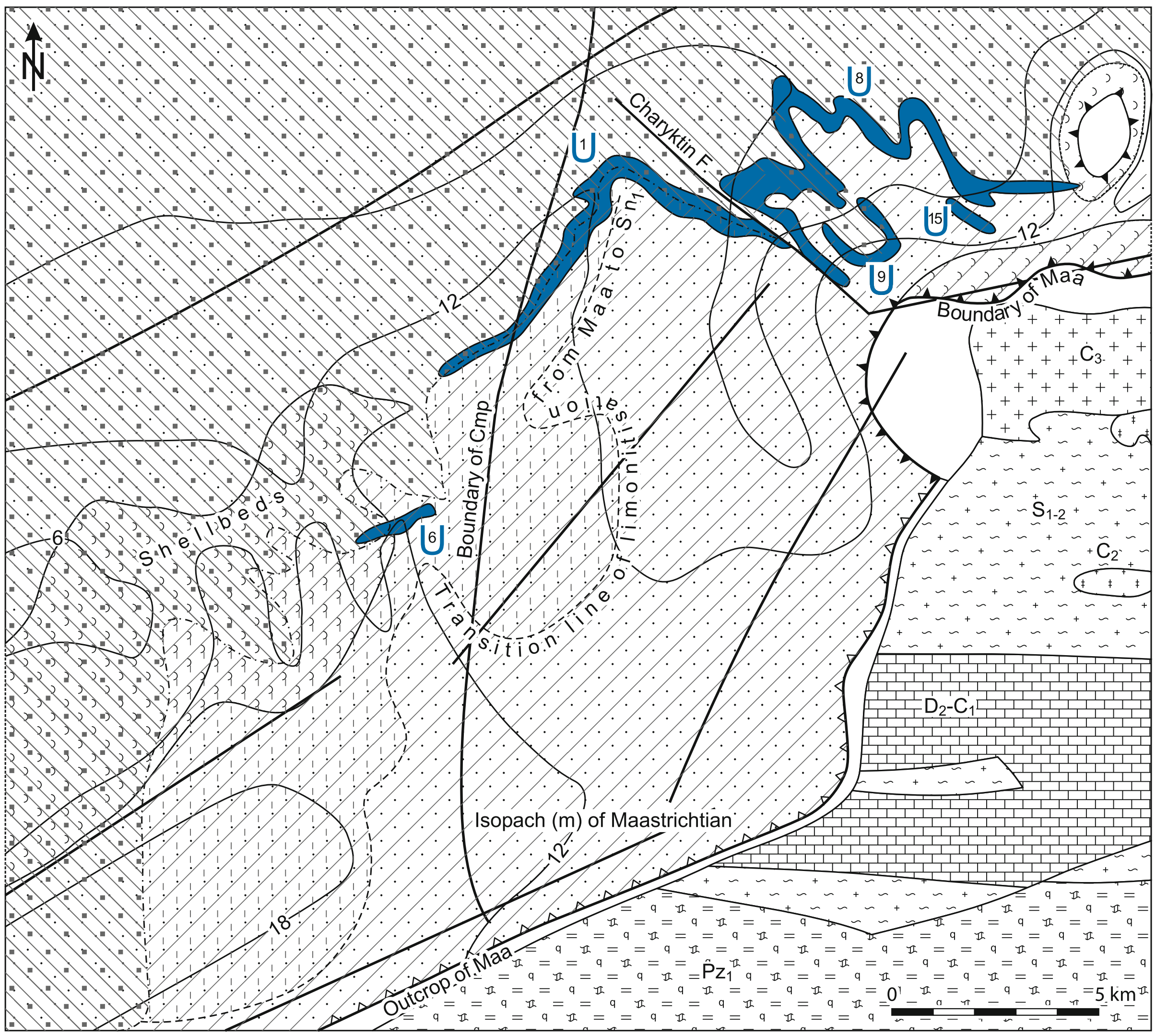
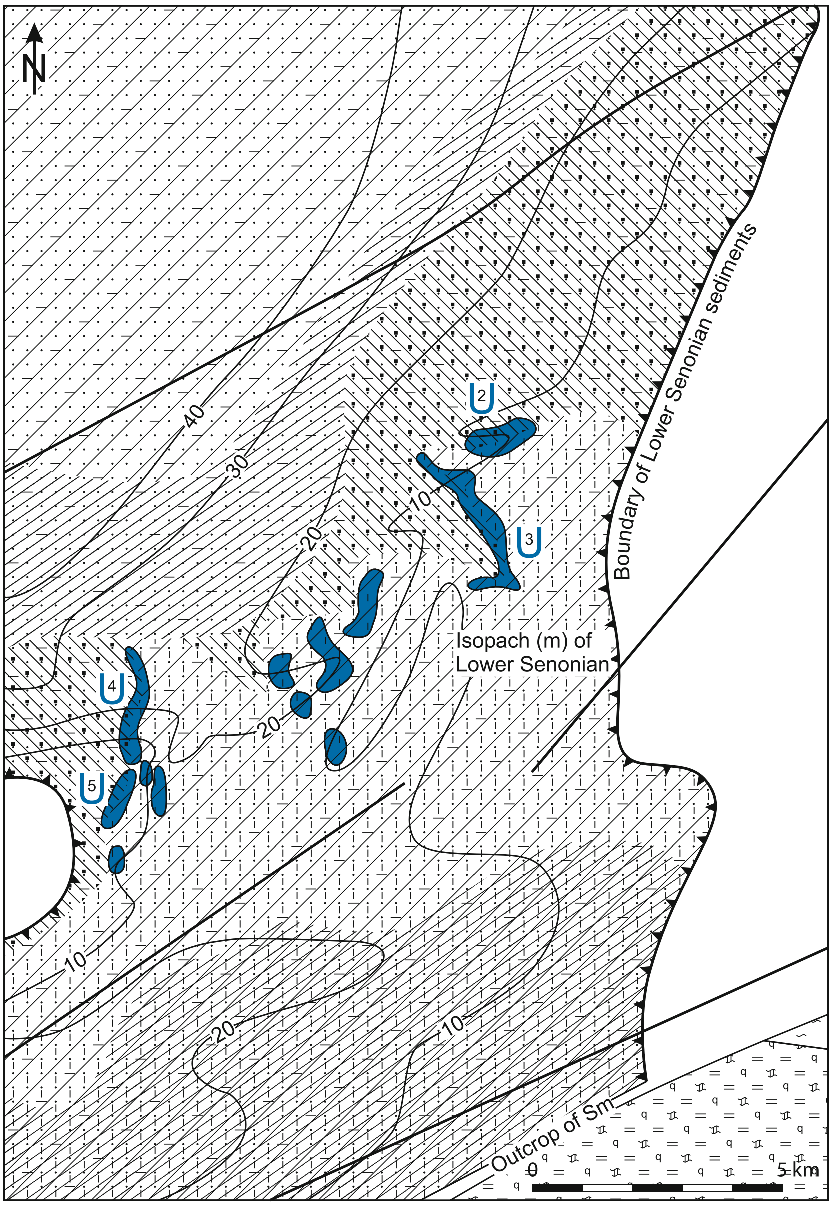


**Fig. 15.8. (Continued)**

b



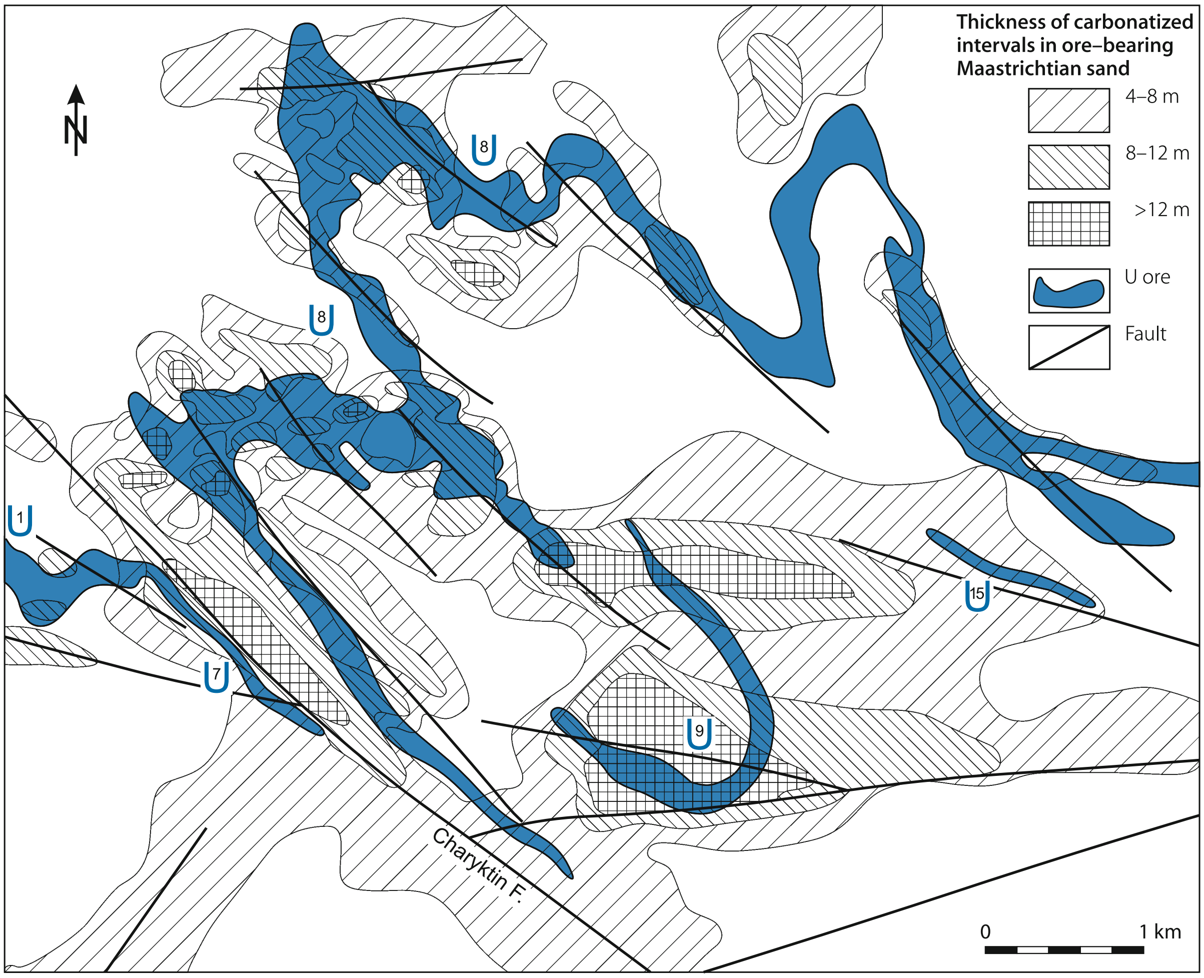

representing traces of an earlier pre-uranophane rock oxidation. In most permeable zones, Fe-hydroxides underwent reduction during the co-precipitation of U-oxides and pyrite. The reduction also affected Fe-hydroxides along the margins of massive aggregates of uranophane spherulites. A younger oxidation effect is reflected by a hematitic aureole occasionally found around uranophane aggregates, and is likewise noted adjacent to pitchblende-sulfide segregations.

Three principal *types of ore* and several subtypes are distinguished based on mineralogical composition and U grade: *(a)* ordinary (unoxidized) low- to medium-grade ore composed predominantly of black U products; *(b)* high-grade (unoxidized or partially oxidized) ore consisting of pitchblende-hematite-sulfide and/or pitchblende-sulfide assemblages; and *(c)* uranophane dominated (oxidized) ore.

***Ordinary U ore,*** the typical ore of most U deposits in the Kyzylkum region, is characteristic at Sugraly for all ore lodes in the block SW of the Charyktin fault and for some lodes to the NE thereof. Ore bodies are roll-shaped and positioned at a redox front at the downdip head of yellow limonitic oxidation zones. Ore constituents are predominantly black U products, jordisite, and native selenium. The NE block contains ordinary ore lodes updip behind the main oxidation front, which is controlled by redox interfaces between locally developed yellow limonitization and greenish-grey reduction intervals as exemplified in lodes 9 and 15 (Figs. 15.10a–c).

***High-grade U ore*** with grades up to 3% U is restricted to the block NE of the Charyktin fault where it is found in lode 8. Three reduced mineral assemblages of high-grade ore are distinguished by mineralogical composition and redox front-related setting: pitchblende-sulfide, pitchblende-hematite-sulfide, and pitchblende-U black products-sulfide. A fourth subtype of uranophane is typical for oxidized ore (see below). The pitchblende-sulfide assemblage typically occurs in grey lithologies at the frontal part of the redox interface. Mineral phases include aggregates of colloform pitchblende (lattice constant ao = 5.370 ±0.007 Å),

**Fig. 15.9.**
**Zarafshan District, Sugraly deposit, planview of distribution and thickness of carbonatization in ore-bearing Maastrichtian sands and its spatial relationship to U ore zones/bodies (after Shchetchkin and Kislyakov 1993)**




pyrite, calcite, and locally zeolites. The pitchblende-hematite-sulfide assemblage is commonly restricted to the rear part of a roll. Mineral phases include pitchblende, pyrite, and calcite associated with neogenic hematite-hydrohematite, and pink color-altered goethite. Ore has a patchy texture and a bright-variegated pinkish-black hue. Occasionally, pitchblende and black products coat or cement Fe-hydroxides in oxidized ores, and fill cracks therein. Dark ore aggregates are up to 1 cm in size and are successively rimmed by bleached and hematitic lamellae superimposed on pink rocks. Locally, hydrohematite replaces completely pink or reddish-brown goethite associated with a marked increase of U to the highest ore grades. The pitchblende-black U products-sulfide assemblage occurs in grey rocks at some distance from oxidized rocks and is controlled by the interface of secondarily reduced greenish-grey with originally grey sands and sandstones.

***Uranophane ore*** of lode 8 occurs in a few, discontinuous bodies on the rear side of the redox front in oxidized ground. Uranophane is thought to be the replacement product derived by secondary oxidation of high-grade pitchblende ores.

The spatial distribution of associated elements in lode 8 corresponds in principle to that in other lodes. An exception is the replacement of Mo- and Fe-sulfides in the rear, updip part of the grey Mo-bearing zone by black, pitchblende-dominated ore. In this case, the pitchblende ore is developed in pink oxidized sand and sandstone that are locally re-reduced by secondary processes. The halo of native selenium is displaced updip and partially overlaps the interval of variegated, pinkish-black U mineralization, and oxidized U poor rocks.

A Maastrichtian arenaceous horizon is the principal U-hosting unit at Sugraly. It contains the largest lodes, # 1 and 8, and likewise all other ore bodies in the NE sector like lodes 9 and 15, and several lodes in the SW sector of the deposit such as lode 6. Lower Senonian sands are mineralized to a minor extent in the SW sector (lodes 2–5) (Figs. 15.6, 15.7).

High-grade lodes to the NE of the Charyktin fault, such as lode 8, are associated with a redox front at the head of a pink, hematitic oxidation tongue while a few small lodes with ordinary mineralization, like lodes 9 and 15, hang isolated behind this redox front and are positioned at the contact of a localized yellowish, limonitic zone with re-reduced facies. In contrast, lodes in the SW sector occur at a redox interface at the front of a yellowish, limonitic zone forming and replacing the frontal part of a pink hematitic tongue in both Maastrichtian and

Lower Senonian aquifers. An exception occurs with a few lodes in the SW sector in which U mineralization, as in lodes 4 and 5, is also found in grey facies several hundreds of meters ahead of the redox boundary of the limonitized tongue as a result of post-ore reduction of originally oxidized strata (Figs. 15.7, 15.8a,b).

Host rocks are fine-grained sand and sandstone with 3–6% silt and 10–15% clay fractions. Allogenic rock constituents comprise 60–80% quartz, 5–15% feldspar, 5–7% muscovite, 10–20% illite, and fragments of basement rocks. Sand grains are predominantly slightly rounded and range in diameter from 0.05 to 0.25 mm. Locally the sands contain biotite, chlorite, ilmenite, leucoxene, and other minerals in accessorial amounts. Carbonaceous plant remains are absent in mineralized strata of the Sugraly deposit. Mineralized and adjacent sands have a filtration coefficient of approximately 1 m $d^{-1}$ and

**Fig. 15.10.**
**Zarafshan District, Sugraly deposit, a planview, b NW-SE section, and c sections across ore bodies illustrating the distribution of U mineralization and adjoining alteration zones as well as morphology and quality of ore lodes in ore body #8 and adjacent ore bodies in Maastrichtian sediments (explanations and legend see at Fig. 15.5) (after Shchetchkin and Kislyakov 1993)**

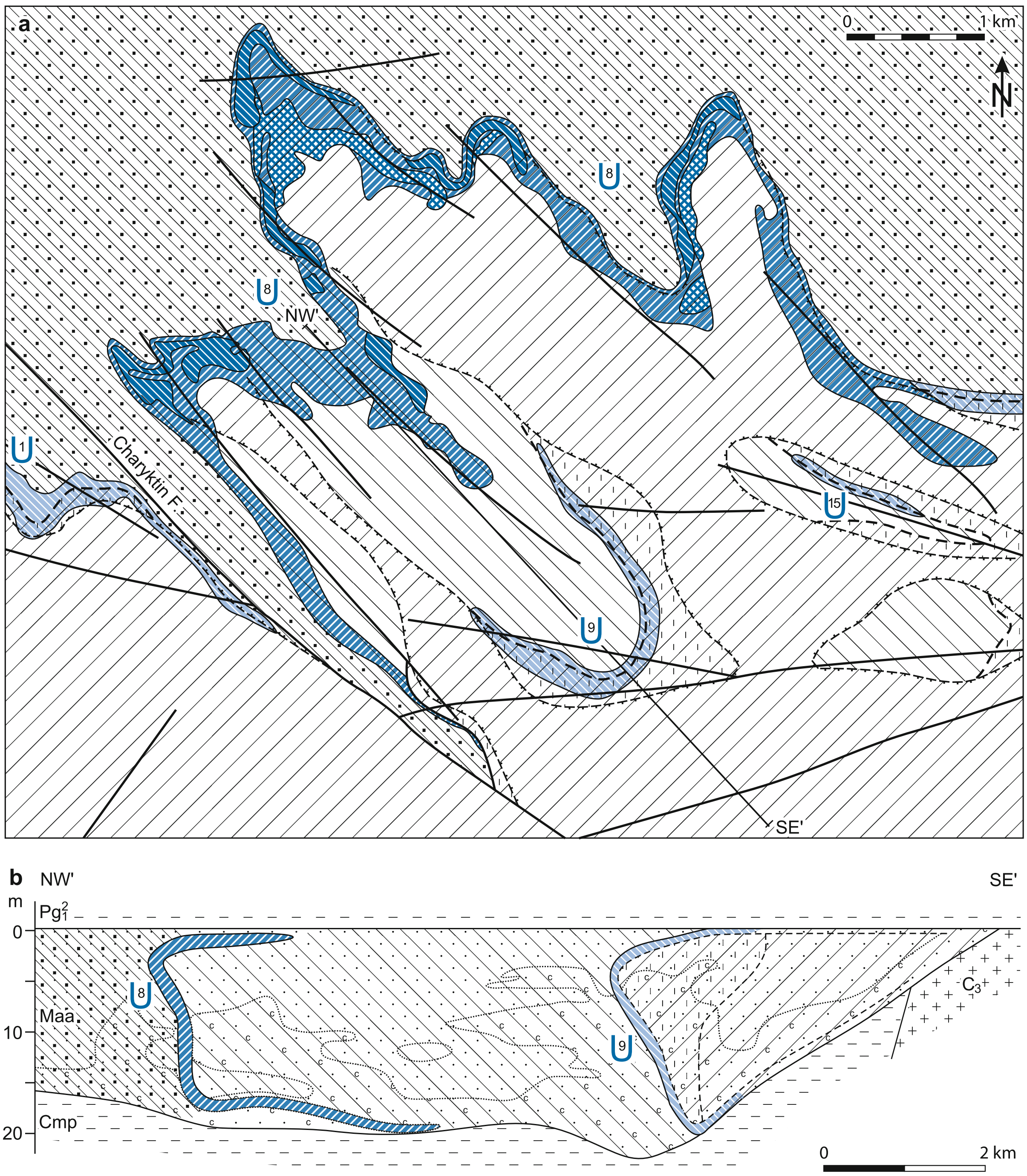
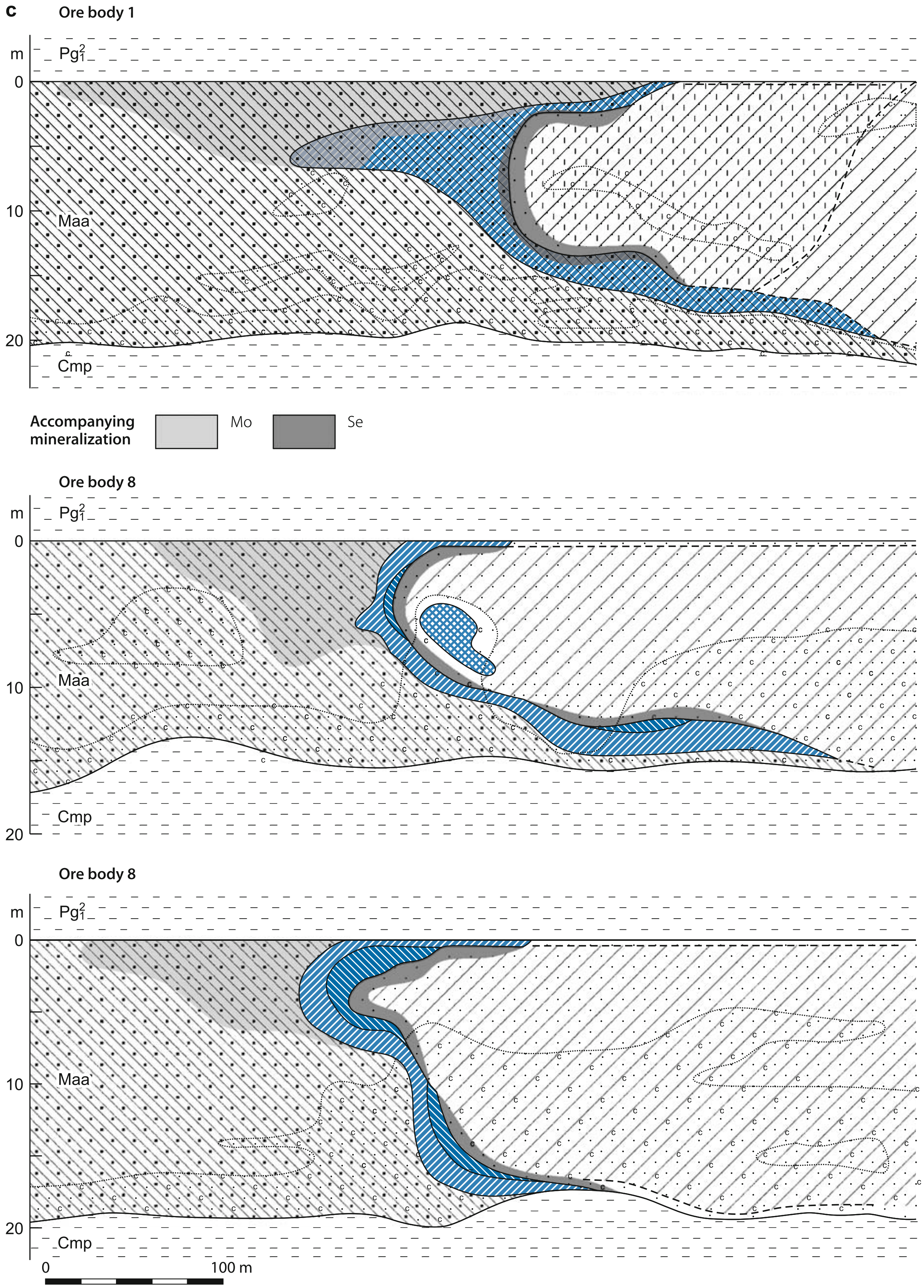


**Fig. 15.10. (Continued)**



more but the permeability is sharply reduced in highly carbonatized sandstone.

## Shape and Dimensions of Deposits

Sugraly consists of a number of ore lodes (Karimov et al. 1996 show 25 lodes on their Fig. 2.2). These ore lodes are distributed over an area in excess of 30 km long in NE-SW direction and few hundred meters to more than 5 km wide in which they occur elongated along partly highly twisted redox fronts. U mineralization occurs at depths from 260 to 580 m but minable ore is confined to depths averaging 450–500 m. Lodes # 1 and 8 are the largest and are separated by the Charyktin fault.

Uranium lodes consist of sinuous bands from several 100 m to 20 km long (Fig. 15.6a). In cross-section, most ore bodies exhibit a crescent-like shape whereas lodes of lenticular configuration are rare. Roll-shaped ore bodies have an elemental zoning, starting with Mo at the downdip head followed by U, and then by Se at the rear of the roll. The Mo interval ranges from 0.03 to 4 m and locally up to 8 m thick and may be as much as 600 m wide (perpendicular to strike) persisting into grey facies. U extends over widths from 100 to 500 m and thicknesses between 0.2 and a few meters, rarely up to almost 20 m. The Se-bearing segment is less than 150 wide and from several tens of centimeters to 4 m thick (Fig. 15.10c).

The in situ U content commonly varies between 0.03 and 0.27% U, but increases to 3% in parts of lode 8. Due to the high-grade sections, the average grade of lode 8 is twice that of lode 1, which contains only ordinary ore. The principal associated elements include: Se (0.06–0.12%), Mo (0.004–0.26%), and Re (10–15 ppm). Increased amounts of carbonates are noticed in some lodes, e.g. in lodes 8 and 9.

Geometric characteristics of the three principal ore types and their distribution in the Sugraly deposit are as follows:

**Ordinary U ore** forms wedge- or C-shaped rolls with tails up to more than 200 m long (Fig. 15.10c). The grade is generally low to medium (0.03–0.3% U). The magnitude or productivity coefficient of the mineralization in the SW sector is inversely proportional to the width of the limonite zone i.e. increasing width of the oxidation zone correlates with a decreasing productivity coefficient.

**High-grade U ore** as found in lode 8 typically exhibits the following characteristics: Mineralization occurs along an up to 400 m wide (perpendicular to the redox front) and almost 20 km long sinuous, highly indented ribbon. In cross-section, the ribbon shows a crescent-shaped roll and mostly a longer and thicker lower tail. The roll has a vertical dimension of 10–20 m, variable widths perpendicular to the strike of a few meters to 60 m or more, and a lower tail from 20 to more than 100 m long and as much as 3 m thick. Grades and reserves of the three mineral assemblages, which constitute the unoxidized high-grade ore of lode 8 are as follows: pitchblende-sulfide ore has a grade of up to few percent U and constitutes the bulk of the U reserves of this lode; pitchblende-hematite-sulfide ore is of higher grade and constitutes about 10–15% of the reserves; while pitchblende-U black products-sulfide ore is commonly of lower grade than the former. The spatial distribution of associated elements in lode 8 corresponds, in principle, to that in lodes of ordinary ore except for differences in the radium distribution.

**Uranophane ore** occurs in a few discontinuous lenses in oxidized Maastrichtian strata on the rear side of lode 8. Ore lenses are from a few tens of meters to 400 m wide, up to 4 m thick, and from less than 100 m to as much as 2 000 m long elongated parallel to the redox front as shown in Figs. 15.10a,c. Grades range from few hundredths to about 2% U.

Radioactive disequilibrium is common for all ores. Ordinary ore has a higher Ra/U ratio at the backside of a roll than at the frontal side. High-grade ore of lode 8 has symmetric and very weak halos of radium on the downdip and updip side of the roll and a radioactive disequilibrium in favor of uranium (av. $K_1$ = 79%). Uranophane ore is in radioactive disequilibrium in favor of radium ($K_1$ = 110–290%).

### Ore Controls and Recognition Criteria

Sugraly is defined as a rollfront sandstone-type U deposit characterized by the following ore controlling or recognition criteria:

#### Host Environment

- Tertiary-Upper Cretaceous artesian basin of relative small size separated by basement uplifts
- 400–600 m thick Quaternary-Tertiary and 100–120 m thick Upper Cretaceous strata
- Alternating permeable and impermeable beds of continental and marginal marine origin
- Widespread block faulting with horst and graben structures along NW-SE-, NE-SW-, and E-W-trending faults
- Separation of the deposit area into two principal blocks by a NW-SE-trending, steep fault
- Separate groundwater regimes in the two main blocks
- Host Rocks consist of
  - two mineralized horizons in Maastrichtian and Lower Senonian aquifers, 10–25 m and <40 m thick, respectively,
  - fine-grained sand and sandstone with minor silt and clay fractions
  - no carbonaceous matter in the Maastrichtian host beds
- A Campanian aquiclude, up to 30 m thick, separates the two host horizons
- Hanging wall and footwall lithologies consist of argillaceous beds
- Potential U and other metal sources exist in basement uplifts

#### Alteration

- Several phases of oxidation and reduction with corresponding redox fronts
- Oxidizing conditions due to differential, repetitive influx of oxygenated groundwaters along aquifers to form
  - hematite altered zones and
  - zones of limonite overprinting the hematite facies

- Early diagenetic stratum reduction reflected by sulfidized grey lithologies
- Epigenetic (re-)reduction by extrinsic reducing thermal solutions percolating along faults
- Reduction-related alterations include sulfidization (pyrite, marcasite), and bitumenization of hydrocarbons
- Carbonatization (calcite, dolomite), silicification, and argillization

**Mineralization**

- Polymetallic U, Mo, Se, Re mineralization present in several generations
- Three varieties of ore, unoxidized ordinary (low-grade) and high-grade ore, and oxidized ore
- Both unoxidized ore types form roll-shaped ore bodies
- Ordinary ore is composed of black U products associated with jordisite and native Se
- Ordinary ore associates with redox fronts at the front end of yellow limonitized rocks
- High-grade ore associates with redox fronts of pink hematitized rocks
- High-grade unoxidized ore includes three parageneses/assemblages
  - Pitchblende-sulfide assemblage occurs in grey lithologies at the frontal part of a rollfront
  - Pitchblende-hematite-sulfide assemblage is mainly distributed on the updip side of a rollfront
  - Pitchblende-U black products-sulfide assemblage is positioned in grey rocks distant from oxidized rocks and controlled by an interface of secondarily reduced greenish-grey sands and sandstones
- Oxidized ore consists of uranophane and occurs as lenses on the rear side of a redox front in oxidized ground
- Spatial distribution of associated elements corresponds to the standard pattern of rollfront-type mineralization
- Radioactive disequilibrium is common for all ore but of different nature in ordinary and high-grade ores

## Metallogenetic Aspects

Rollfront-type U lodes at Sugraly have evolved in a complex manner. Critical ingredients are various and episodically repeated oxidizing events and reducing processes of two different modes. The principal hydrogeochemical activities involved are diagenetic stratum reduction, near surface oxidative leaching of ore-forming elements from basement rocks, low temperature stratum oxidation of different kinds and intervening reducing processes by extrinsic thermal solutions.

Shchetochkin and Kislyakov (1993) elaborate on the genetic implications of the various processes and suggest a metallogenetic model, which may be summarized as follows. Two principal reducing environments and associated processes were involved in the metallogenetic system at Sugraly and originated from diagenetic and extrinsic epigenetic actions, respectively. These two modes are documented by reducing barriers caused by *(a)* rock constituents with reducing potential of supposedly diagenetic origin (see below) and *(b)* upwelling extrinsic reducing thermal solutions. The latter are reflected by a remarkable spatial relationship of ore lodes with sites of authigenic minerals generated by such fluids, in spite of the fact that the fluids by themselves are free of U, Mo, and Se.

Sulfur isotopes provide a clue to the origin of the different reducing sources. Diagenesis-related reduction of Upper Cretaceous sediments is deduced from the isotopic composition of sulfur in pyrite and baryte in diagenetically altered but otherwise unaltered aquiclude clays. The present isotope values are thought to be the product of early diagenetic fractionation of the sulfur of marine waters. The existence of an additional reducing source is supported by different groups of sulfur isotopes in pyrites in high-grade ore versus those in ordinary ore (Table 15.2). These isotopes indicate different sulfur sources and, as such, a distinct contrast in origin between the extrinsic thermal solutions involved as reductants in the formation of the high-grade pitchblende(-hematite)-sulfide ores and reductants involved in the formation of ordinary ore.

A sequence of ore-forming events may read as follows. After the early diagenetic reduction stage, block faulting exposed Cretaceous strata heads on surface at uplifted blocks permitting oxygenated meteoric waters to enter into the aquifers. Permeable horizons were oxidized as reflected by hematite development associated with pink coloration. The oxygenated, fertile groundwaters descended basinward until they encountered reducing barriers of either mineralogical or fluidal nature as outlined further below. Interaction of the oxygenated waters with the reducing media produced favorable redox prerequisites for deposition of uranium and other ore constituents.

Downflow of oxygenated groundwater was not everywhere a simple process. It was repeatedly interrupted not only by tectonic activity but also by locally restricted re-reducing interventions of fault ascending thermal reducing solutions. Consequently, new redox fronts were successively established at variable fault-controlled places and governed the formation of high-grade ore lodes.

Tectonic reactivation apparently played a significant role in the metallogenesis by episodic initiation or reactivation of thermal processes. Each such event presumably promoted the percolation of extrinsic reducing thermal fluids and likewise that of near-surface hot solutions. When the latter contained carbonic acid and were incorporated into meteoric groundwater, the oxidative leaching potential of these waters was notably boosted to liberate ore-forming elements from source rocks in basement uplifts. Favorable source rocks were provided by Paleozoic lithologies such as black slates.

The bulk of the high-grade ore was presumably deposited during relatively short periods of tectonic activity that triggered the postulated thermal reducing processes. These intervals of intense ore formation alternated with calm periods associated with remodification and minor dilution of mineralization formed earlier.

Studies of fluid inclusions in gangue minerals of the various alteration stages indicate a temperature of at least 120°C during alteration processes and an involvement of brines with very high tenors of total sulfur, Ca, and $CO_2$.

Redox processes related to diagenetically derived reducing conditions produced ordinary, low to medium-grade mineralization dominated by black U products along a simple redox boundary at the interface between a reducing environment characterized by Fe-sulfides and bitumens, and basinward migrating oxygenated groundwater. Pyrite in these black U ores displays a wide range of $\delta^{34}S$‰. Isotopic fractionation during biogenic reduction of sulfate in groundwater and incorporation of sulfur from earlier sulfides, locally including those of thermal fluid origin, are considered the reason for this variation.

The inverse proportionality of the concentration of mineralization in ordinary ore to the width of the younger limonitic oxidation zones suggests that under a weak reducing potential a redistribution of ore constituents takes place along the flow path. If this assumption is correct, present-day ordinary mineralization can hardly be considered a product of an independent metallogenetic event but instead it resulted from continuous or repetitive events that presumably reworked and incorporated constituents of preexisting mineralization.

Metallogenesis-related criteria or actions associated with the reducing process(es), which produced high-grade ore in lode 8 of the Sugraly deposit are reported by Shchetochkin and Kislyakov (1993) as follows:

- Pre-ore pink recoloration of yellow limonitized arenite
- Close paragenetic relationship of pitchblende and black U products with neogenic Fe-sulfides, calcite, hematite, and locally zeolites derived from extrinsic thermal solutions
- Partial superposition of U-oxides upon oxidized rocks contradicting any link between the geochemical nature of the host rock and the cause for the precipitation of uranium
- Deposition of U-oxide ore in pink oxidized rocks suggests an involvement of a reductant of fluid nature
- Oxidized ore phases are enveloped in a reduced halo, which became concentrically pyritized, bleached, and hematitized
- Decrepitation of inclusions in calcite paragenetic with pitchblende suggests increased temperatures of 120–200°C for this mineralizing process
- Pitchblende-sulfide mineralization was repeatedly reworked and transformed into ordinary black ore or, at some sites, into uranophane ore, the latter marks the original position of sulfidic high-grade ore
- Post-ore reducing activity caused an isolation of ore zones from the oxidation tongue

Given evidence suggests that the high-grade ore is related to the redox interface that evolved at sites of interaction of oxygenated, fertile groundwater with extrinsic reducing thermal solutions ascending along faults and spreading into aquifers. These solutions consequently generated a mobile hydraulic screen that complicated the general hydrodynamics and produced a highly effective hydrogeochemical barrier.

Mineral relationships suggest a formation of the ordinary ore and ore-controlling limonitization zones postdating that of mineral phases such as Fe-sulfides and bitumens derived from extrinsic reducing solutions. Also, ordinary ore is in radioactive disequilibrium with a higher Ra/U ratio at the rear side of a roll than on the frontal side suggesting a relatively recent if not ongoing formation by redistribution of uranium and other metals.

With respect to processes prior to or following the uranophane formation, relics of Fe-hydroxides often found in uranophane spherulites and massive carbonate inclusions as well document an earlier rock oxidation that was superimposed by reduction. The reducing event is attributed to the contemporaneous precipitation of U-oxides and pyrite in most permeable zones. Reduction of Fe-hydroxides is also noted along the margins of massive uranophane spherulites. These relationships attest to a uranophane formation during an oxidation stage that remodified earlier pitchblende-hematite-sulfide mineralization, which existed slightly updip of the present ore site. On the other hand, uranophane coated by finely dispersed pitchblende documents a post-uranophane generation of U-oxide.

The existence of at least two generations of U-oxides is furthermore supported by rare cases of their telescoping in which an early, finely dispersed pitchblende is restricted to the inner zone of low-permeable intercalations of carbonatized lithologies while the margins of the intercalations are oxidized and colored pink by Fe-hydroxides. The carbonatic intercalations occur in loose, dark grey sands that contain younger U-oxides and pyrite. A bleached rim has formed along the contact of the intercalations attesting to a complete or partial reduction of pink Fe-hydroxides.

A late stage in the evolution of the Sugraly deposit is documented at the far eastern margin of lode 8 where the yellow limonitization zone reappears and oxygenated groundwater remodified high-grade pitchblende ore to ordinary black U ore. Apparently, the same process also generated the small roll-shaped ore bodies of ordinary black U ores of lodes 9 and 15 situated as much as several thousands meters updip behind lode 8. These lodes are controlled by a secondary redox front at the contact between re-reduced ground and confined younger, narrow intercalations of yellow limonitization, which were overprinted upon pink stratum oxidation (Figs. 15.10a,b).

### 15.1.2.2 Aktau

This explored deposit is situated ca. 60 km NE of the town of Zarafshan and 20 km E of Sugraly. It was discovered in 1967. U occurs in Tertiary arenites. The Tertiary stratigraphic column at Aktau includes, from top to bottom: Miocene gravel, Oligocene pink sediments, and the Upper Eocene Lyavlyakan Horizon. This lower horizon is subdivided into three units: an upper unit, 0.2–0.5 m thick, of silty sandstone with pyrite and phosphate nodules; a middle unit, 10–15 m thick, of unconsolidated quartz sand with U mineralization; and a lower unit, up to 15 m thick, of silty sandstone with clay intercalations. U mineralization of rollfront-type occurs in sands of the middle unit for a length of 13 km in a N-S direction and at depths from 400 to 500 m. The main part of a roll is 1–4.2 m (av. 2.8 m) thick and 25 to 100 m wide while tails are from some ten meters to 250 m long. About 50% of Aktau's resources are in the lower tail, which is 0.2–1.0 m thick and 50–250 m long. Resources are estimated at 5 000 t U at an average grade of 0.08% U calculated on average thickness of 1.56 m. U is associated with Se and Mo (Karimov et al. 1996).

### 15.1.3 Zafarabad or West-Nuratau District

This district includes ten deposits (Fig. 15.1): *Kenimekh* and *Bukinai South* (also referred to as Kenimekh-Bukinai South ore field) are located to the southwest of the Nuratau Range, while *Bukinai (North), Alendy, Terekuduk, Varadzhan,* and *Tokhumbet,* which form the Bukinai ore field (Fig. 15.11a), are situated to the north of the range, and *Beshkak, Lyavlyakan,* and *Aulbek* to the north of this ore field. U mineralization occurs in six horizons within Upper Turonian to Maastrichtian strata. A mining town for the district, Zafarabad, was established by the Soviet government about 40 km NNW of Navoi. Remaining in situ sources amount to 51 500 t U RAR + EAR-I and 46 800 t U EAR-II + SR. Four deposits, Bukinai (North) and South, Beshkak, and Lyavlyakan were being exploited by ISL techniques in 2005 and Tokumbet was in ISL testing stage. Mining Division # 5, a subsidiary of NMMIW, is the mining operator (OECD-NEA/IAEA 2005).

**Source of information:** The subsequent descriptions are largely derived from Karimov et al. (1996) unless otherwise noted.

#### 15.1.3.1 Kenimekh

Kenimekh is located in the southwestern foothills of the Nuratau Range, ca. 5 km S of Zafarabad and about 20 km N of Navoi. Kenimekh includes the adjacent ore zones *Kenimekh North* and *South*, which occur in the southern part of the Kenimekh-Bukinai South ore field. (see also Bukinai South). Resources at Kenimekh North (RAR + EAR-I) amount to about 2 000 t U RAR in the <40$/kg U cost category. Grades are about 0.07%U.

**Sources of information.** Laverov et al. 1992b; Venatovsky 1993.

##### Geology and Mineralization

The Kenimekh-Bukinai South ore field occurs in the artesian Kuldzhyktau Subbasin of the Kenimekh Basin. The latter is bounded to the NE by the Nuratau Range and the regional Kokcha fault, and to the SW by a Paleozoic basement uplift. Upper Cretaceous-Tertiary sediments covered by 0–30 m thick Quaternary alluvium fill the basin.

Ore zones at Kenimekh South are hosted by Cretaceous strata, which are overlain by Tertiary sediments and rest unconformably on Devonian-Carboniferous bituminous limestone. The Tertiary-Cretaceous stratigraphic column is over 800 m thick and includes from top to bottom:

**Tertiary**

- *Neogene*: up to 300 m thick, sediments with intercalated, 15–20 m thick, quartz sand beds
- *Paleogene*: 80–200 m thick, argillaceous sediments

**Cretaceous**

- *Upper Cretaceous* (U): more than 300 m thick, alluvial and marine sand, and clay
- *Lower Cretaceous* (some U): 20–70 m thick, sand, conglomerate, and clay

Six ore-bearing horizons, 8–22 m thick, occur within a 130–190 m thick section of Upper Cretaceous sediments. Invariably, there is 1 horizon each in Maastrichtian, Campanian, and Coniacian aquifers, and 3 horizons in Santonian aquifers. Some uranium also occurs in Turonian, Cenomanian, and Lower Cretaceous strata. Permeable sand beds altered by carbonatization, kaolinitization, and pyritization host the ore.

The ore-bearing zone is 15 km long and 3–7 km wide but its southeastern margin is not yet delineated due to an increased depth of the ore horizons to 900–1 000 m. Explored ore bodies occur at depths from 400 to 680 m. Ore bodies are curvilinear ribbon-like in planview and roll- or lenticular-shaped in section. They are from 25 to 150 wide and from 0.5 to 7 m thick. Ore grades range from 0.01 to 0.5% U, 0.01–0.1% Se, 0.005–0.05% Mo, and up to 15 ppm Re. Scandium (<30 ppm) occurs locally. Carbonate content averages 1.54% $CO_2$, but in excess of 30% of the resources average over 2% $CO_2$.

At Kenimekh North, rollfront-type ore lodes occur stacked in five arenaceous horizons of Upper Turonian age. They are distributed along highly twisted redox fronts along the foothills of the Karatau Range. Lode depth is in excess of 300 m.

#### 15.1.3.2 Bukinai South

This deposit was discovered 30 km N of Navoi in 1961. The deposit was being mined by ISL techniques in 2005 and had remaining resources (RAR + EAR-I) of some 7 000 t U at a grade of ca. 0.06%U.

##### Geology and Mineralization

At Bukinai South (Fig. 15.12), Tertiary-Upper Cretaceous strata are covered by up to 30 m thick Quaternary alluvium. The sediments dip slightly NE and rest on Silurian metamorphic rocks. The Tertiary-Cretaceous profile includes from top to bottom:

**Tertiary**

- *Pliocene*: 120 m thick, reddish-brown sand, silt, marl
- *Miocene*, 2–140 m thick, tan silt, and at the base, 80 m thick, greenish-grey sand and pink silt
- *Eocene-Oligocene*, 150 m thick, greenish-grey clay-marl and silt with calcareous intercalations
- *Lower Eocene*, 80 m thick, marl with interbedded clay

**Cretaceous**

- *Maastrichtian* (U): up to 25 m thick, sand with dolomitic intercalations
- *Campanian* (U): up to 35 m thick, sand with intercalations of shell beds
- *Santonian* (3 U horizons): up to 90 m thick, yellow-green sand

- *Coniacian* (U): <70 m thick, green, grey and pink sand
- *Turonian*: 10–90 m thick, clay
- *Cenomanian*: 5–12 m thick, silt

Ore is polymetallic composed of U, Mo, and Se and consists of finely dispersed aggregates of U oxides (pitchblende, sooty pitchblende). Jordisite, pyrite, and native selenium are the principal associated minerals. Uranium grades can be as high as 0.5% U. Carbonate content is commonly less than 2.5% $CO_2$ but can locally be as high as 5% $CO_2$. In addition to authigenic mineralization, uraniferous sands also contain yttrium and lanthanides in detrital heavy minerals. Tenors of these trace elements are <120 ppm Y, <150 ppm Ce, <50 ppm other lanthanides, [dysprosium, erbium, thulium, ytterbium (<10 ppm), europium, samarium (<3 ppm), gadolinium and terbium (<1.5 ppm)].

Main ore bodies occur discontinuously along sinuous redox fronts contained in a zone that varies from a few hundred meters to more than 1 000 m wide. It extends in a linear NNE-SSW direction for about 25 km bordered to the south by the steeply dipping WNW-ESE-oriented Kokzhin fault zone and dissected in the northern part by the likewise oriented North and South Muyunkum faults. Other faults in the area trend NE-SW.

Roll-shaped ore lodes occur in six arenaceous horizons within Maastrichtian, Campanian, Upper Santonian (e.g. ore zone 4), Lower Santonian (ore zones 3, 5, and 6), and Coniacian strata. Depths vary from less than 150 m to 200 m in the southern part to 450 m in the northern segment.

Fazlullin et al. (2002) provide some details on an ore body – lode 10 – that was exploited by ISL from 1968 to 1975. The lode had a lateral extension of 70 000 $m^2$, occurred in a 15.5 m thick aquifer at depths from 150 to 165 m, and contained 1 733 000 t of ore at a grade of 0.024% U. Total in situ U reserves were 500 t U, 420 t U were recovered corresponding to a recovery rate of 84%.

### 15.1.3.3 Bukinai North

Bukinai North (Fig. 15.11a,b) was discovered some 10 km W of Zafarabad in 1959 and has been mined by Mining Division # 5 using ISL techniques since 1969. Remaining resources (RAR + EAR-I) amount to about 5 000 t U. grading about 0.06% U. Selenium resources were on the order of 20% of the U resources.

#### Geology and Mineralization

U is hosted in a Cretaceous sequence, 170–320 m thick, composed of – from top to bottom:

- *Maastrichtian* (U): 25 m thick, marine quartz sand
- *Campanian* (U): 15–35 m thick, marine sand
- *Santonian* Karasazyg Horizon (U): 160 m thick, alluvial sand and clay
- *Upper Turonian* Tokumbet Horizon: 35–40 m thick, sand and silt
- >*Unconformity*<
- *Lower Turonian*
  - Kendyktyubinsky Horizon: 3–8 m thick, sand and clay
  - Dzheyrantuysky Horizon: 20–30 m thick, grey marine clay
  - Uchkuduk Horizon: 5–12 m thick, marine sand and clay
- *Cenomanian*: up to 12 m thick, conglomerate, sand, and silt

The Cenomanian sediments rest unconformably upon weathered Paleozoic basement rocks composed of sediments and metamorphics intruded by Late Paleozoic granite, granodiorite, and diorite.

Pitchblende and sooty pitchblende are the principal U minerals, with minor coffinite. Associated elements include Se (<0.1%), Mo (<0.1%), and Re (<5.5 ppm).

The Bukinai North ore zone is up to 400–500 m wide and extends for a length of some 20 km in a submeridian direction. It contains ore lodes in four Upper Cretaceous arenaceous horizons. The Karasazyg Horizon is the principal ore host: 87% of Bukinai's resources are contained in its lower section, positioned at depths from 150 to 200 m. Ore bodies are of a roll shape, which exhibits a complex configuration at sites where the oxidation zone is split by argillaceous intercalations. Ore bodies have a length from 0.5 to 7.8 km along NW-SE-oriented redox fronts, a thickness from 1.05 to 3.22 m, and grades from 0.028 to 0.09% U. The ore is in radioactive disequilibrium with a Ueq to Uchem coefficient of 53%.

### 15.1.3.4 Alendy

This explored deposit is situated at the northern extension of the Bukinai North ore zone and ca. 10 km NW of Zafarabad and contains estimated in situ resources of 14 000 t U at an average grade of ca. 0.05% U. U is hosted by Lower Senonian continental sands and by Campanian and Maastrichtian marine sandy horizons and occurs at depths from 300 to 600 m. Total thickness of the mineralized strata is 80–90 m. Alendy occupies a 20 km long stretch that encompasses – in planview – discontinuous, ribbon-like ore bodies, 50–100 m wide and up to several kilometers long along sinuous redox fronts. In cross-section – ore bodies are of lenticular or roll shape, ranging in thickness from 0.5 to 3 m. Mineralized zones occur in close proximity, arranged in en echelon fashion. The ore is of low grade, generally less than 0.04% U. Ore lodes in the lower horizon of the Lower Senonian strata contain up to 3 ppm Re. Some mineralization contained in oxidized sediments has tenors of as much as 0.2% Se.

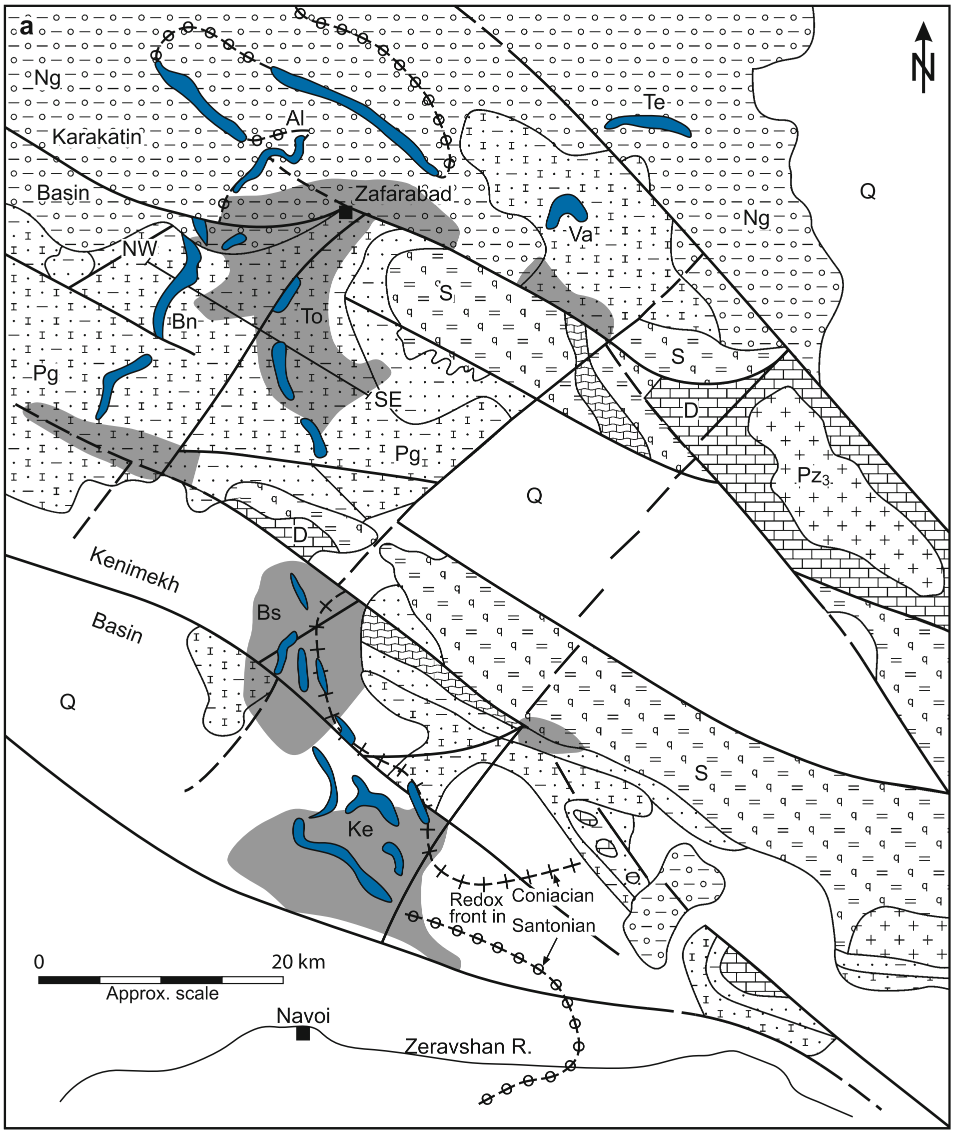
### 15.1.3.5 Terekuduk

This explored deposit is located ca. 25 km NE of Zafarabad, a few kilometers to the south of the Aulbek deposit. U is hosted in two arenaceous horizons of Senonian age and occurs at depths of 135–340 m. Resources amount to some 2 000 t U at grades of 0.02–0.03% U.

### 15.1.3.6 Varadzhan

This explored deposit is located ca. 20 km E of Zafarabad, about 10 km S of Terekuduk. U mineralization is found over a length of

**Fig. 15.11.**
**Zafarabad District/Bukinai ore field, a generalized geological map with location of U deposits; b NW-SE section showing the litho-stratigraphic sequence and alteration zones at the Bukinai (North) and Tokhumbet deposits (explanations and legend see at Fig. 15.5). (Courtesy of Boitsov A.V. based on Russian literature). U deposits in a: *Al* Alendy, *Bn* Bukinai (North), *Bs* Bukinai South, *Ke* Kenimekh, *Te* Terekuduk, *To* Tokhumbet, *Va* Varadzhan**




15 km along the front of a gulf-like tongue of limonitized strata within Upper Cretaceous marine sediments. Explored resources are estimated at 500 t U. Individual ore bodies are up to 5 km long and consist of rolls or lenses, a few meters thick, and occur at depths from 160 to 200 m. Ore bodies have low U grades, commonly less than 0.04% U and contain in sections, up to 1 m thick, as much as 0.1% Mo.

### 15.1.3.7 Tokhumbet

Tokhumbet is an explored deposit located ca. 10 km SW of Zafarabad, 8 km E of Bukinai North. It contains about 700 t U in Upper Cretaceous strata.

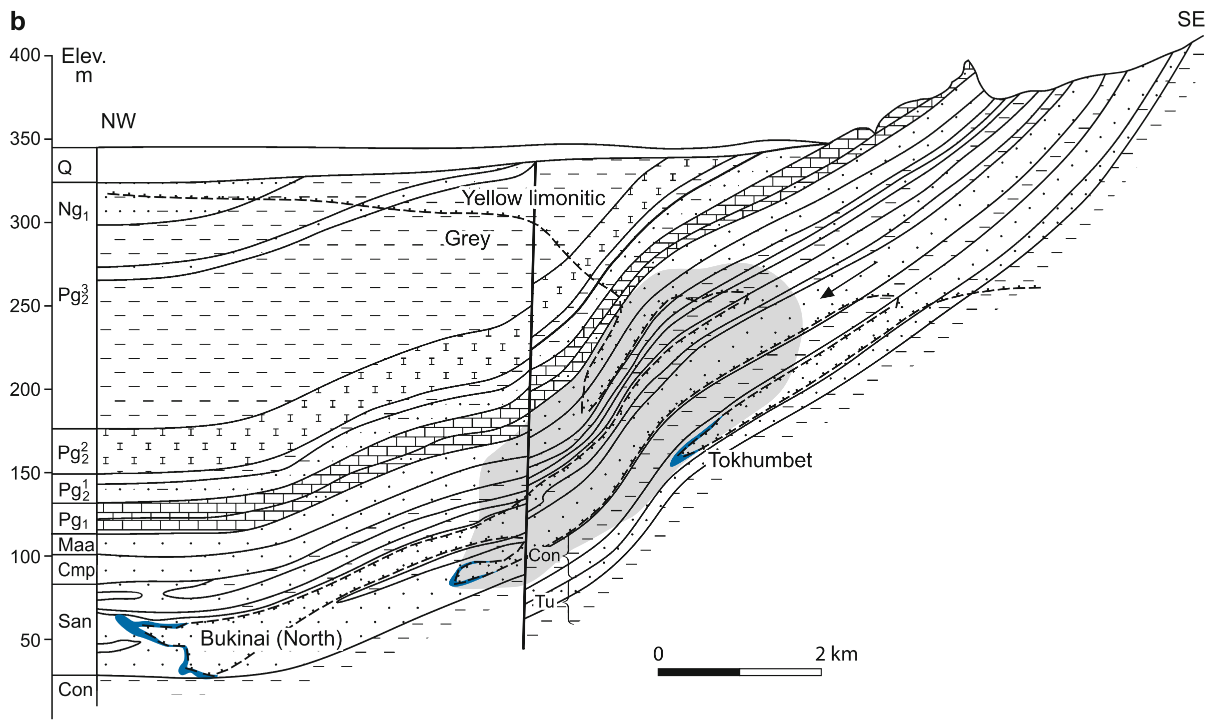
### 15.1.3.8 Beshkak

Discovered in 1969, Beshkak is situated about 40 km NNE of Zafarabad. Exploitation by ISL started in 1978 and was on going in 2005 operated by Mining Division # 5. Remaining resources (RAR + EAR-I) amount to about 5 000 t U including almost 3 000 t U of high cost resources.

#### Geology and Mineralization

Bedrock consists of a slightly SW dipping Tertiary-Upper Cretaceous sequence covered by a 0–50 m thick sheet of

**Fig. 15.11. (Continued)**




Quaternary alluvium and resting on Paleozoic schists (Fig. 15.13a,b). The Tertiary-Cretaceous litho-stratigraphic column includes – from top to bottom:

### Tertiary

- *Pliocene-Miocene*($Ng_2^3$): 0–90 m thick, gypsiferous, carbonatic sandstone and marly clay
- *Miocene*
  - upper unit: ($Ng_1^{2\text{-}3}$) 0–200 m thick, brown-red clay and silt
  - lower unit ($Ng_1^1$) 40 m thick, grey and tan sand and argillaceous sandstone
- *Eocene*($Pg_2^3$):
  - 0–65 m thick, greenish-grey silty clay
  - 30 m thick, sand, clayey sandstone, Lyavlyakan Horizon (U)
  - 100–120 m thick, greenish-grey clay, silt
  - 40 m thick, marl
  - 30 m thick, sand
- *Paleocene*($Pg_1$): 20 m thick, limestone

### >Unconformity<

### Upper Cretaceous

- *Maastrichtian-Campanian*: 30 m thick, sand containing shells
- *Coniacian-Santonian*: 80 m thick, sand
- *Turonian*
  - upper unit: 30 m thick, clay, sand, sandstone
  - lower unit: 60 m thick, silty clay
- *Cenomanian*: 5 m thick, silt and intercalated gritstone

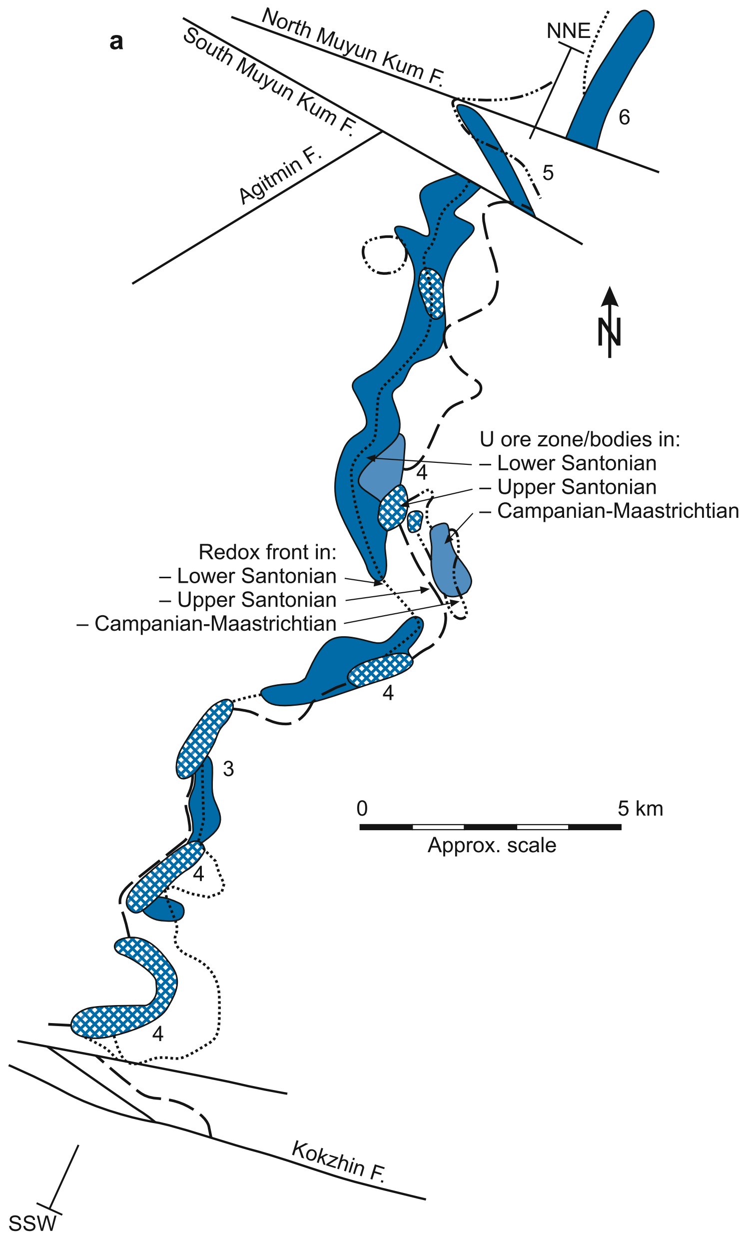
Major faults trend about NNW-SSE, the Aktau fault for example, and NW-SE, as the Lyavlyakan fault. The sediments are bent into wide-amplitude folds along E-W-trending axes to the W of the Aktau fault where the Beshkak deposit is located. These axes turn NW-SE in the area to the NE of that fault.

Mineralization consists of U oxides associated with Se. U grades are low. Carbonate content is up to 2.5% $CO_2$. Ore lodes are of roll shape hosted in the Upper Eocene, ca. 30 m thick, Lyavlyakan Horizon. Host rocks are partly clay-cemented sands sandwiched between clayey-silty aquicludes. The strata have a slight southerly dip. Two ore zones occur in a NE-SW-trending zone, some 20 km long, and join in the southern part of the deposit. Ore depths range from about 50 m in the north to almost 400 m below surface in the southwest (Fig. 15.13b). *Ore zone 1*, located in the SW segment of the deposit, has a length of more than 6 km along a redox front in the lower Lyavlyakan Horizon, and occurs at depths from 250 m in the NE part to more than 350 m in the SW part. *Ore zone 2* forms the eastern part of the deposit and accounts for 87% of Beshkak's resources. Ore in this zone is up to 500 m wide, 6 km long, and occurs at depths from 30 m in the north to 250 m in the south. In planview, it shows a crescent-shaped configuration open to the east. The northern two thirds of the lode contains U mineralization along a redox front in the upper Lyavlyakan Horizon while mineralization in the southern third is contained in both the upper and lower Lyavlyakan Horizon. Ore grades range from 0.015 to 0.2% U (av. 0.045% U) and up to 0.03% Se.

#### 15.1.3.9 Lyavlyakan

This deposit is located about 20 km to the east of Beshkak. It was being mined by ISL techniques in 2005 and had remaining resources (RAR + EAR-I) of some 7 000 t U (including ca. 5 000 t U low cost resources) contained in three ore lodes in Eocene strata. The litho-stratigraphic setting of the Lyavlyakan deposit

**Fig. 15.12.**
**Zafarabad District, Bukinai (South) deposit, a schematic plan and b SSW-NNE section showing the distribution of ore bodies hosted in Senonian sediments; c simplified profile across a rollfront ore body in Santonian-Coniacian sands with grade-thickness values of ore intervals (explanations and legend see at Fig. 15.5) (after a, b Karimov et al. 1996; c Laverov et al. 1992b)**




corresponds largely to that of the westerly located Beshkak deposit (see previous chapter, Fig. 15.13a,c). The two deposits are separated by the NNW-SSE oriented Aktau fault. This fault coincides with the SW boundary, and the NW-SE-trending Lyavlyakan fault with the N boundary, of the Lyavlyakan deposit. Sediments in the Lyavlyakan area are folded along NW-SE-trending axes into wide-amplitude folds.

Three roll-type ore zones occur along a slightly sinuous section, about 25 km long, of an approximately N-S-oriented redox front at depths from 50 to 200 m. The northern # 1 ore zone is 6.5 km long, the central # 2 ore zone 1.5 km, and the southern # 3 ore zone 4 km long. The ore has grades of about 0.06 U and contains as much as 2.5% $CO_2$.

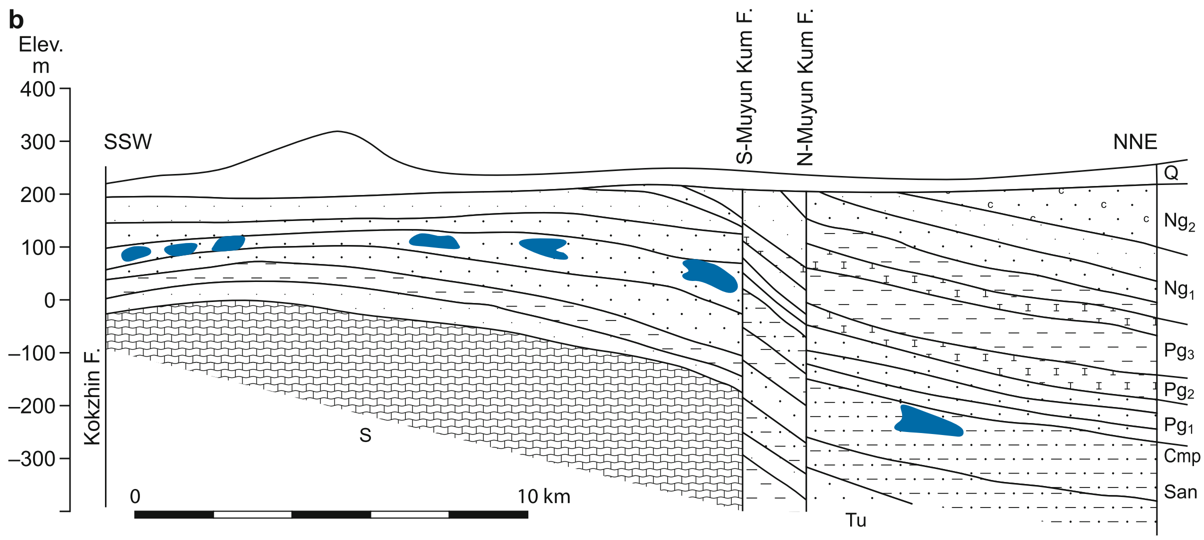
### 15.1.3.10 Aulbek

Aulbek is located a few kilometers from Lyavlyakan. The deposit is only partly explored since exploration was interrupted in 1995. U is hosted in five arenaceous strata of Maastrichtian to Upper Turonian age and occurs at depths from 60 to 520 m. Resources are speculated at 2 000 t U at grade averaging ca. 0.035% U.

## 15.1.4 Nurabad or Zirabulak-Ziaetdin District

Seven U deposits occur in the Nurabad District. *Maizak North* is situated to the northwest, *Ketmenchi* to the central west, and *Agron, Sabyrsai, Shark, Tutly,* and *Nagornoye* to the south and

**Fig. 15.12. (Continued)**



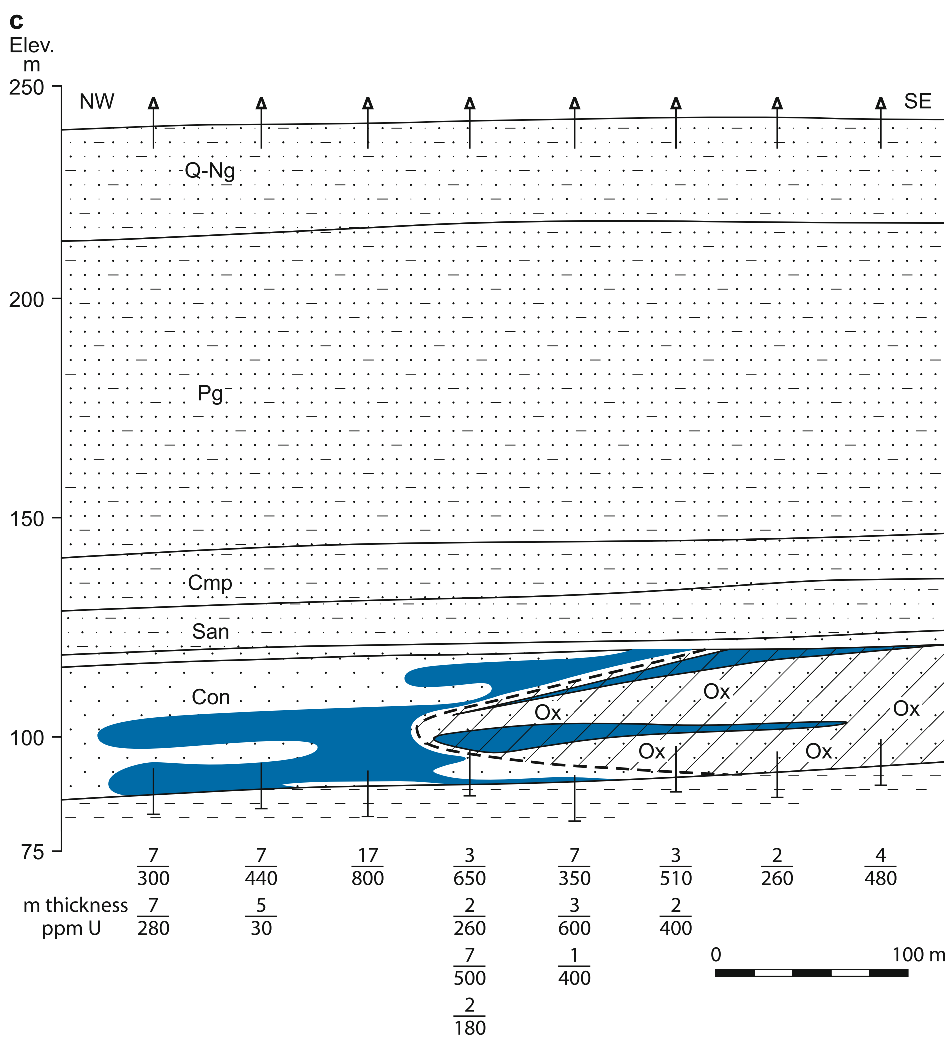
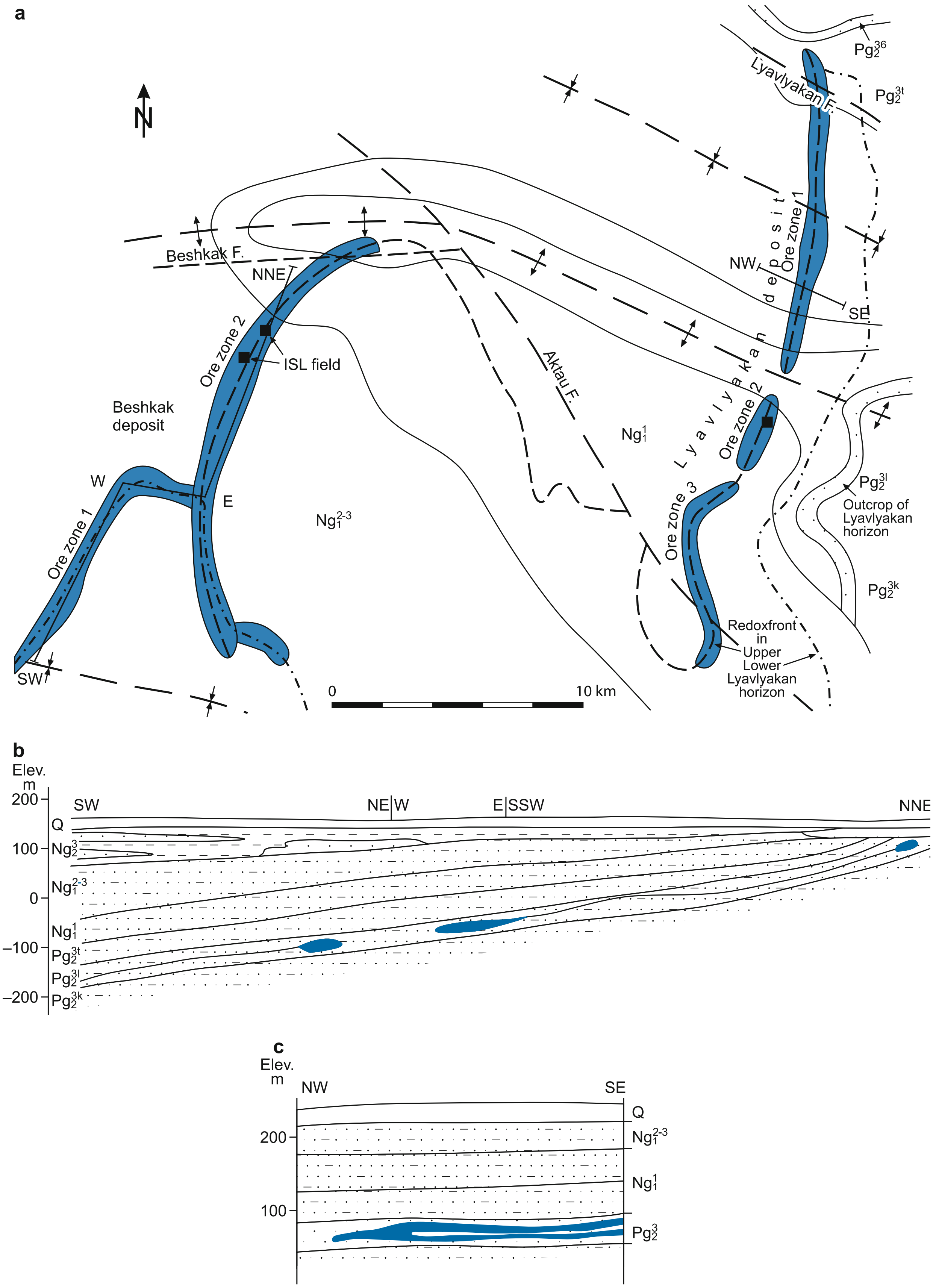



**Fig. 15.13.**
**Zafarabad District, Beshkak and Lyavlyakan deposits, a schematic plan of the ore field, b SW-NNE section along the Beshkak and c across the Lyavlyakan deposit. Ore bodies are controlled by two redox fronts in the upper and lower Lyavlyakan Horizon, Eocene (explanations and legend see at Fig. 15.5) (after Karimov et al. 1996)**



southeast of the Zirabulak Range. A mining town, Nurabad, was established about 70 km SE of Navoi to serve the district (Fig. 15.1). Remaining in situ sources amount to 12 600 t U RAR + EAR-I and 50 100 t U EAR-II + SR. Operating ISL facilities are located at Ketmenchi and Sabyrsai; they are under the direction of the Southern Mining Division, a subsidiary of NMMIW (OECD-NEA/IAEA 2005).

**Source of information:** Karimov et al. (1996) amended by data from other sources.

#### 15.1.4.1 Maizak North

This explored deposit is situated ca. 110 km NW of Nurabad and about 8 km W of Navoi. Resources (RAR + EAR-I) amount to some 2 500 t U. Stacked U mineralization occurs at depths from 250 to 500 m and locally down to 600 m in a 5 km long and 50–150 m wide, sinuous string. U hosts are four sand horizons, 20–38 m thick, of Maastrichtian, Campanian, and Santonian age. Grades are on the order of 0.03–0.04% U. Carbonate content is less than 2% $CO_2$.

#### 15.1.4.2 Ketmenchi

Ketmenchi is situated ca. 60 km NW of Nurabad and about 40 km SE of Navoi (Fig. 15.1). The deposit was discovered in 1967, ISL tested between 1973 and 1977. Zone II of this deposit was subsequently exploited by ISL methods (Fig. 15.14). Remaining in situ resources (RAR + EAR-I) amount to about 12 000 t U at about 0.07% U.

### Geology and Mineralization

Bedrock consists of a Tertiary-Cretaceous sequence covered by 2–200 m thick Quaternary alluvium (loam, conglomerate). These sediments rest unconformably upon a Paleozoic basement composed of Ordovician to Carboniferous metamorphic rocks intruded by Upper Carboniferous-Permian granite. The Tertiary-Cretaceous litho-stratigraphic profile includes – from top to bottom:

**Neogene:** 20–40 m, thick proluvial sand-silt.

**Paleogene:** marine carbonate-clay facies including

- *Oligocene*: 5–15 m thick, sand-mudstone
- *Upper Eocene*: up to 80 m thick, clay
- *Middle Eocene*: 10–15 m thick, marl
- *Lower Eocene*: 15–20 m thick, clay with shale beds
- *Paleocene*: 10–15 m thick, limestone

**>Unconformity<**

**Upper Cretaceous**

- *Maastrichtian-Campanian* (U): 40–80 m thick, marine sand underlain by alternating sand and mud beds,
- *Santonian-Coniacian* Tepalik Horizon: 40–50 m thick, alluvial-lacustrine clay, silt, and sand
- Upper Turonian
  - Ulus Horizon: 25–45 m thick, marine clay and mudstone
  - Sabyrsai Horizon (U): 5–15 m thick, alluvial sand and grit
- Lower Turonian
  - Kendyktube Horizon (U): 25–40 m thick, marine clay-carbonate interbedded with dolomitic sandstone
  - Dzheizantyi Horizon: 30–50 m thick, marine clay
  - Uchkuduk Horizon (U): 5–15 m thick, marine sand, clay, basal conglomerate (U at base extending into Cenomanian)
- *Cenomanian* (U): 50–70 m thick, silt, gravel, conglomerate, basal claystone

**Lower Cretaceous**

- *Albian* (U): 5–50 m thick, upper clay with intercalated lignite seams underlain by sand, grit, and basal silt
- *Aptian-Neocomian* (two U horizons): 15–20 m thick, continental proluvial conglomerate, sandstone with intercalated carbonaceous clay, and basal gritstone

The Tertiary-Cretaceous beds exhibit a shallow monoclinal dip to the SW from basement outcrops situated in the E-NE. Faults trend NNW-SSE, NW-SE, and curvilinear ENE-WSW to E-W. The latter offset the two former systems.

Ore is polymetallic essentially composed of U, Mo, and Se. U occurs primarily as U-oxides (pitchblende, sooty pitchblende) and to a minor degree adsorbed on phosphate and vegetal matter. Mineralization occurs in eight Cretaceous horizons but minable ore bodies are confined to two horizons in Cenomanian and three horizons in Lower Cretaceous strata. Mineralized horizons consist mainly of sand and some of gravel or gritstone facies (see above), which are partly cemented by carbonate with $CO_2$ contents commonly less than 2.5% but locally up to 5%. Some 40 ore lodes have been identified. They are essentially of roll shape and occur at depths from less than 100 m to as much as 500 m discontinuously distributed along sinuous redox fronts within a NW-SE-elongated zone, about 35 km long and as much as 10 km wide.

#### 15.1.4.3 Tutly

This deposit is located ca. 50 km WNW of Nurabad. In situ resources amount to some 3 000 t U at ca. 0.1% U, hosted in Campanian-Maastrichtian strata at depths from 220 to 700 m.

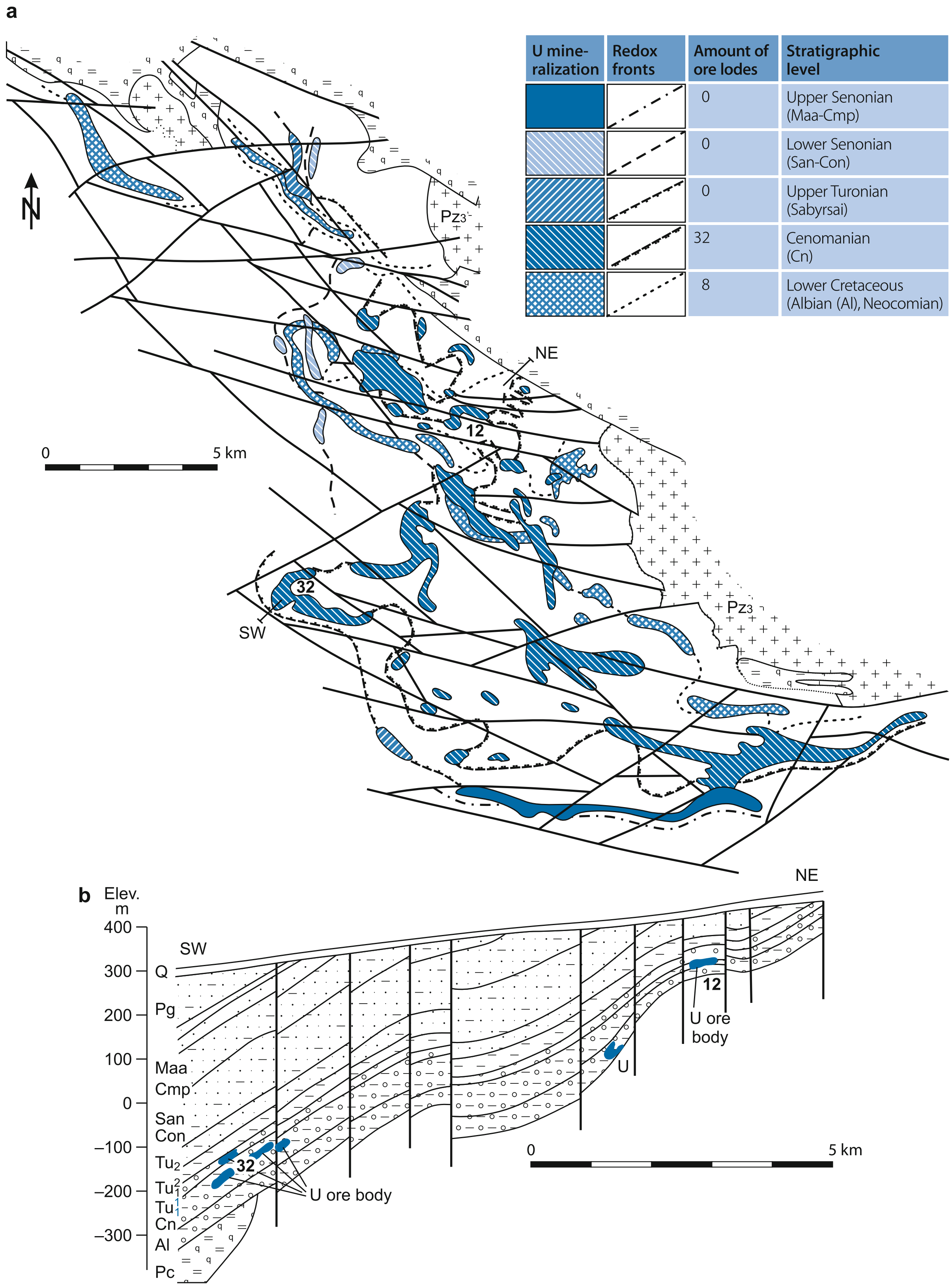
#### 15.1.4.4 Agron

This deposit was discovered ca. 20 km SSW of Nurabad and 20–30 km W of Sabyrsai in 1980 (Fig. 15.1). In situ resources are estimated at some 5 000 t U at a grade of about 0.1% U.

U mineralization occurs in a N-NE to S-SW-oriented trend some 15–25 km long, at depths from 220 to 700 m in Upper Cretaceous arenaceous horizons intercalated with argillaceous beds. Tertiary sediments achieve a cover thickness from 700

**Fig. 15.14.**

**Nurabad District, Ketmenchi deposit, a schematic plan and b SW-NE-NNE section showing the distribution of ore bodies in Upper and Lower Cretaceous sediments (explanations and legend see at Fig. 15.5) (after Karimov et al. 1996)**



to 900 m to the S and SW of the deposit. Maastrichtian and Campanian sand beds with an aggregate thickness of 100–140 m provide the main ore hosts. Six ore-bearing horizons, 4–40 m thick, are identified. Ore bodies are from 0.3 to 2.8 m thick, up to 100 m wide, and have grades between 0.01 and, 0.1% U.

#### 15.1.4.5 Sabyrsai

Sabyrsai was discovered 8 km SE of Nurabad in 1960. U was extracted by underground mining between 1977 and 1983 and by ISL techniques since 1975. The latter was active in 2005 and was operated by the Southern Mining Division. Remaining resources (RAR + EAR-I, status 1999) amount to about 2 300 t U.

##### Geology and Mineralization

Paleogene-Cretaceous sediments are covered by Quaternary-Neogene sediments up to 200 m thick. The sediments rest on Silurian schist and marble intruded by Upper Paleozoic granite (Fig. 15.15). The Paleogene-Cretaceous stratigraphic column includes – from top to bottom:

**Paleogene:** 140–230 m thick, limestone intercalated with dolomitic sandstone layers

**Maastrichtian:** 3–10 m thick, calcareous sandstone

**Campanian:** 20–40 m thick, calcareous sandstone on top, underlain by sorted sand with rare clay lenses

**Coniacian-Santonian Telalik Horizon:** 25–40 m thick, silt, silty clay with interbeds of calcareous sandstone

**Upper Turonian**

- Ulus Horizon: 25–40 m thick, silty clay with interbedded silt and sand
- Sabyrsai Horizon (U): 5–20 m thick, sand, silt, basal conglomerate

**Lower Turonian**

- Kendik Horizon: 30–35 m thick, sand, silt, with basal dolomite
- Azhenrantui Horizon: 22–44 m thick, finely laminated clay
- Upper Uchkuduk Horizon: 4–9 m thick, sandstone, gritstone, and conglomerate
- Basal Uchkuduk Horizon: 0–1.2 m thick, sandstone and siltstone

**Albian:** 5–13 m thick, carbonaceous sand and clay.

In the deposit area, strata are downwarped to form the Ulus-Dzhamoky Depression between two basement outcrops situated to the east and west within a distance of approximately 20 km from each other. The depression is bordered or transected, from N to S, by the curvilinear WNW-ESE-trending and steeply inclined Borikly, Khodzhalyk, Bakalysay, and South Bakalysay faults. Other major faults such as the Uikir trend E-W.

Some 15 ore lodes are delineated within a WNW-ESE-elongated area, about 13 km long and 8 km wide, which covers part of the Ulus-Dzhamoky Depression. Most of the lodes are controlled by a redox front on the northern and southern flank of the depression. The basal Upper Turonian Sabyrsai Horizon, from 5 to 20 m thick, and composed of alternating lenses of sand, conglomerate, and silt is the principal ore-hosting unit. Parts of the host lithologies are cemented by carbonate in amounts up to as much as 5% $CO_2$. Argillaceous-silty aquicludes several meters thick of the Upper Turonian Ulus and Lower Turonian Kendik Horizons overly and underlay, respectively, the mineralized horizon.

U mineralization consists predominantly of sooty pitchblende and minor pitchblende and coffinite that form roll- and tabular-shaped ore lodes. Roll-shaped ore bodies extend ribbonlike from 400 to 3 000 m long, are from 100 to 350 m wide, and up to 8 m thick. Tabular ore bodies range in length from 1 000 to 3 000 m and in width from 450 to 700 m. Ore lodes occur at depths from 50 to 150 m in the western part, and from 200 to 250 m in the eastern part of the deposit. Ore grades vary between 0.03 and 0.2% U.

#### 15.1.4.6 Shark

Shark is located about 5 km E of Sabyrsai and ca. 15 km ESE of Nurabad. It was discovered in 1978 and contains resources of about 1 500 t U grading ca. 0.08% U. Three ore bodies, from 2.5 to 8 km long, are delineated in two Upper Cretaceous horizons within a zone up to 250 m wide. The bulk of resources occurs in sand and gravel beds of the 10–17 m thick upper Cenomanian horizon. One ore body is in gravel-sand intercalated with sandstone, siltstone, and clay beds of the Turonian, 10–15 m thick Sabyrsai Horizon. Ore bodies are 0.2–4 m thick, 25–250 m wide, grade up to 0.1% U and occur at depths from 150 to 300 m except at the S and SE margin where ore is as much as 500 m deep.

#### 15.1.4.7 Nagornoye

Nagornoye is located ca. 20 km NE of Nurabad (Fig. 15.1). In situ resources are estimated at to some 3 000 t U, hosted in Senonian strata at depths from 550 to 700 m.

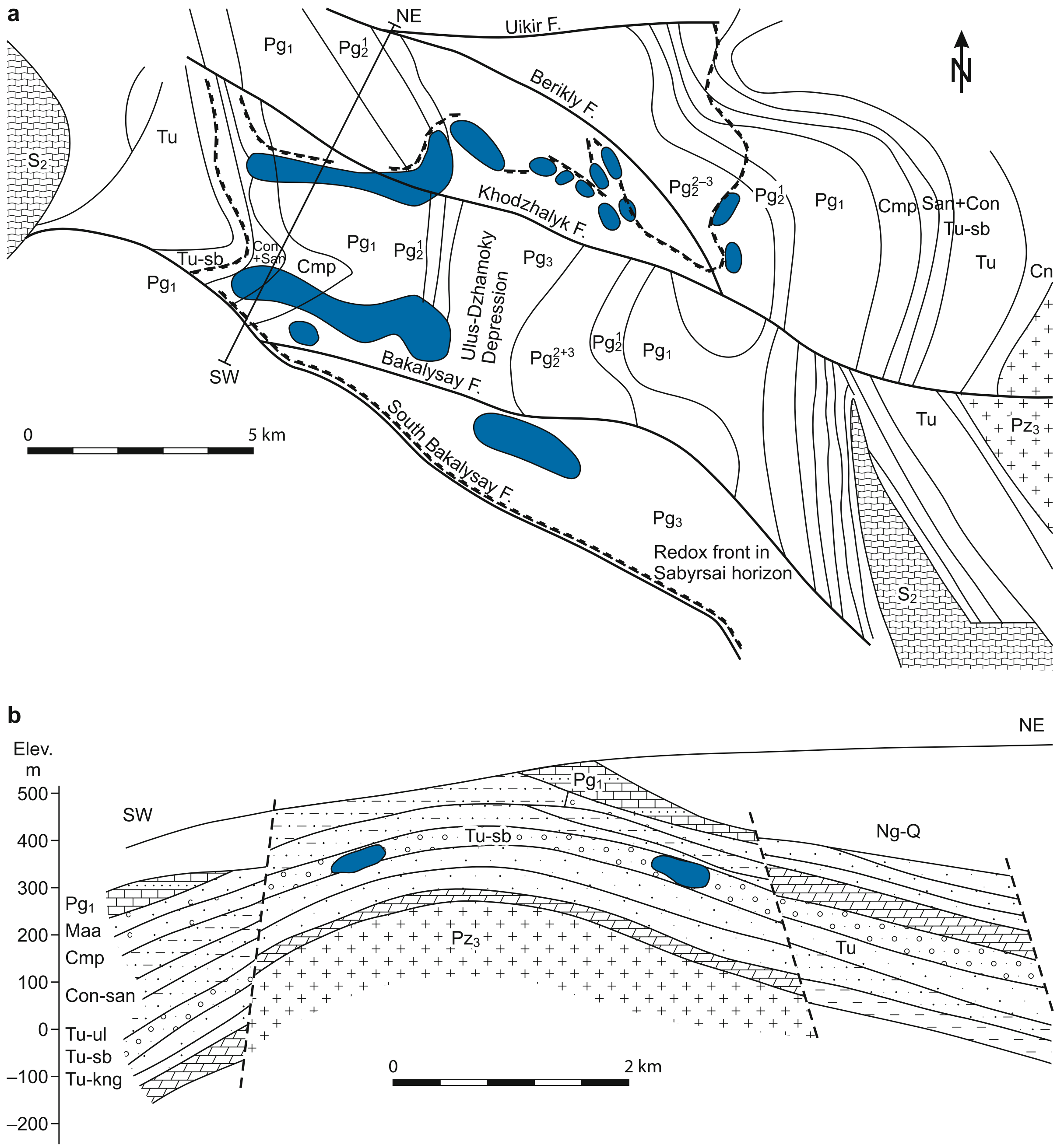
#### 15.1.4.8 Ulus

Discovered in the late 1990s, a first drilling phase identified some 800 t U in Coniacian and Santonian strata at depths from 170 m to 220 m.

## 15.2 Kyzylkum Basement Areas

Geologic data is available for two ore fields, *Altyntau* and *Auminza-Beltau,* in Precambrian-Paleozoic basement ranges of the Kyzylkum region (Fig. 15.1). Resources for these fields total 47 000 t U in the RAR + EAR-I and 54 000 t U in the EAR-II + SR categories (OECD-NEA/IAEA 2005). Deposits/ore bodies

**Fig. 15.15.**
**Nurabad District, Sabyrsai deposit, a schematic plan and b SW-NE section showing the distribution of ore bodies hosted in Upper Turonian Sabyrsai Horizon (explanations and legend see at Fig. 15.5) (after Karimov et al. 1996)**




consist of stratiform and/or complex stockwork mineralization contained in graphitic slate and phyllite (siliceous and carbonaceous shale metamorphosed to greenschist grade facies). Both deposit configurations are strata-controlled, structure-bound and therefore tentatively assigned to the carbonaceous shale-related stockwork deposit type (locally referred to as "black shale type").

Ore bodies occur at depths from 20 to 600 m and consist of uranium oxides (pitchblende, black U products) and/or uranium-vanadium/uranium-phosphate minerals, which may be accompanied by appreciable tenors of other elements such as Au, Mo, and Y. Uranium grades range from 0.02 to 0.132%.

*Metallogenetic considerations* favor a multistage evolution with roots in the Hercynian Orogeny. Hydrothermal ore-forming processes continued periodically through the Alpine Tectogenesis. Present-day deposits/ore bodies are thought to have derived by redistribution of uranium and other ore components from older mineralization during the Neogene-Quaternary as suggested by ages ranging from 400 Ma to Recent. Extrinsic hydrocarbons provided the reducing conditions required for ore mineral precipitation (see Dzhantuar). Final activities were of supergene nature and resulted in the formation of $U^{6+}$ minerals down to considerable depths.

**Sources of information.** Gorlov et al. 2005; Laverov et al. 1992a,b; OECD-NEA/IAEA 1995, 1999, 2005.

### 15.2.1 Altyntau or Bukantau Ore Field

The Altyntau (also referred to as Bukantau) ore field is located in the Bukantau Range, about 30 km NE of the town of Uchkuduk (Fig. 15.1). In situ resources are 33 100 t U RAR + EAR-I and 11 200 t U EAR-II + SR. Several deposits including *Khodzhyakhmet* and *Novoye* were explored to the development stage. Underground mining associated with heap leaching is considered to be the potential extraction method. Estimated resources of Khodzhyakhmet are between 500 and 1 500 t U at grades ranging from 0.02 to 0.1% U.

The ore field occupies the northern flank of the Altyntau anticline and is bordered by the approximately N-S-trending Altym and Taikarshi fault zones. Country rocks are folded Proterozoic (Vendian-Riphean) black slate and phyllite. Mineralization consists of uranium and vanadium associated with yttrium and REE, and occurs in stockwork ore bodies within brecciated black slate.

### 15.2.2 Auminza-Beltau or Auminzatau Ore Field

This ore field is located in the Auminzatau Range, centered about 50 km SW of Zarafshan (Fig. 15.1). In situ resources are 13 900 t U RAR + EAR-I and 42 700 t U EAR-II + SR (OECD-NEA/IAEA 2005). Reported U deposits include *Dzhantuar, Dzitym, Kostcheka, Rudnoye,* and *Voskhod*. Grades range from 0.02 to 0.13% U and average about 0.05% U.

#### Regional Characteristics of Mineralization

Country rocks consist of metamorphosed and tectonically deformed black carbonaceous and siliceous slates/schists, phyllite, quartzite, and diabase dikes of the Proterozoic Taskazgan and Auminza Formations. Increased tenors of U, V, Mo, Zn, and other elements are typical accessories of the carbonaceous black slate. The metasediments were intruded by granite during the Carboniferous. Regional weathering imprinted a kaolinite-type crust on the rocks during Triassic-Jurassic time. Numerous faults transect the crystalline complex and were repeatedly reactivated until the Quaternary.

Structurally controlled U deposits occur in the exocontact zone of granite plutons. These deposits consist of discontinuous ore bodies of complex stockwork or lensoid/stratiform configuration. Primary mineralization is represented by pitchblende and coffinite associated with several generations of sulfides. Unoxidized ore minerals are restricted to lower levels of the deposits, downward from 250–300 m below present-day surface. Mineralization above the 300 m level consists exclusively of uranyl vanadates and phosphates. Some deposits, like Rudnoye, contain appreciable amounts of vanadium while vanadium tenors in other deposits are low.

Wall rock alteration includes an early quartz, chlorite, and sericite stage that accompanies early pitchblende while later pitchblende generations are associated with argillization. Uranyl-type mineralization may, in addition, be accompanied by limonitization.

#### 15.2.2.1 Dzhantuar

Dzhantuar is located ca. 60 km SW of Zarafshan and has been investigated by an exploratory mine. Mineralization is of stockwork and stratiform type hosted by graphitic slate and phyllite of Proterozoic age. Rocks are folded into an about NW-SE oriented syncline, which is complicated by faults oriented about NW-SE and steeply inclined to the SW and NE (Fig. 15.16). Wall rocks are altered by silicification and kaolinitization.

Uranyl vanadates and uranyl phosphates are typical for upper levels, to depths of about 250 m. Pitchblende and sooty pitchblende occur in the southern part of the deposit, but only at depths from 250 to 600 m.

The deposit is NE-SW elongated and almost 600 m wide. Most ore bodies occur intermittently over depth intervals from 60 to 300 m. In the southern part of the deposit, some ore persists to 600 m deep. Ore bodies are placed at or near faults but in unpredictable distribution. The preferential position is in black slate at the fault contact with siliceous phyllite. Ore lodes commonly have an irregular strata-peneconcordant to -discordant configuration. Better grade lodes (>0.03% U) are a few meters to about 30 m thick and extend from a few meters to approximately 200 m downdip. Lower grade mineralization (<0.03% U) forms semi-continuous haloes around and interconnects better-grade lodes.

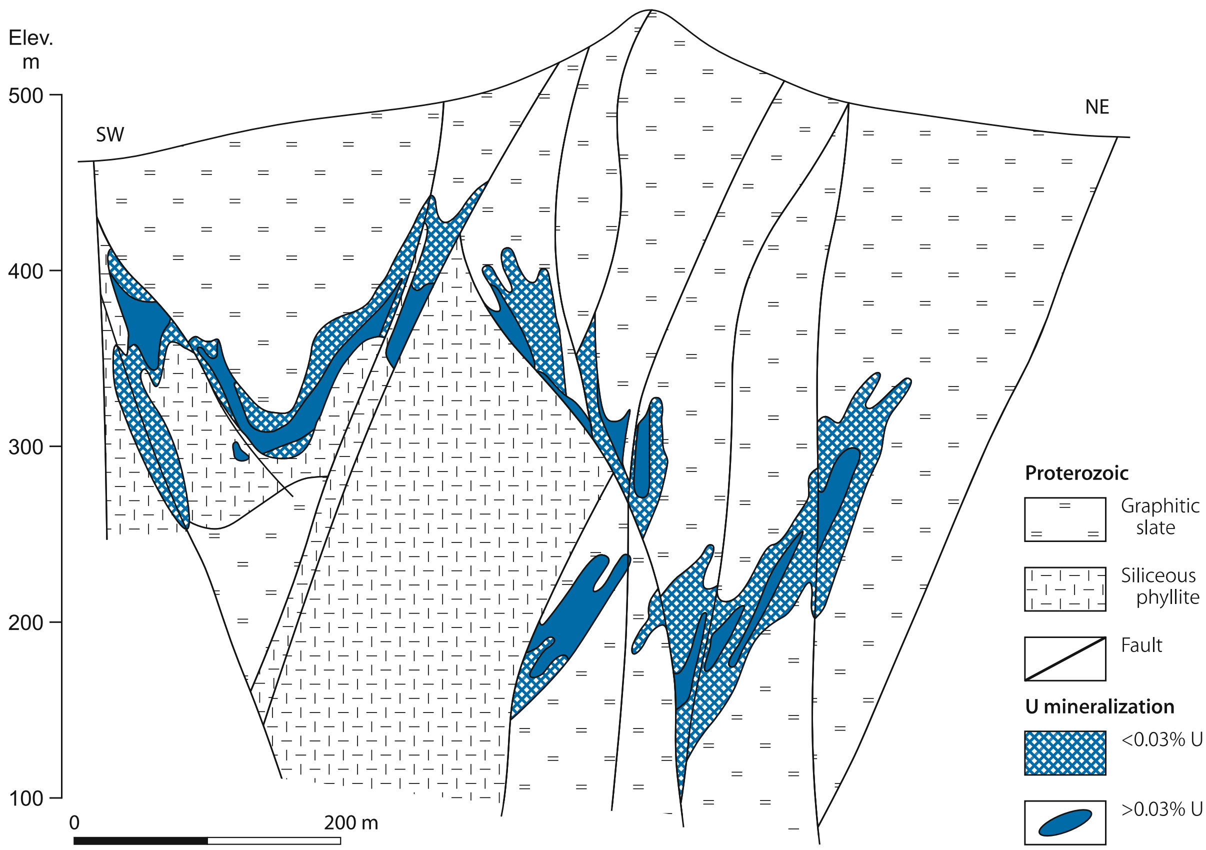
Perevozchikov (2000) documents the presence of extrinsic gaseous and liquid hydrocarbons and hydrogen that form geochemical haloes around ore-controlling structures. These geochemical haloes show a close spatial relationship to the uranium ore bodies; consequently, the author postulates the involvement of hydrocarbons and hydrogen in the formation of ore. Liquid hydrocarbons and hydrogen provided a reducing environment and, as such, were instrumental in the concentration of uranium and in the preservation of ores.

#### 15.2.2.2 Rudnoye

Rudnoye was discovered ca. 50 km SW of Zarafshan in the early 1960s. The deposit is of polymetallic U-V-Mo stockwork-type mineralization. Grades range from 0.06 to 0.132% U, 0.1–0.8% $V_2O_5$, up to 0.024% Mo, 6–8 ppm Y, and 0.1–0.2 ppm Au (OECD-NEA/IAEA 1995, 1997). In situ resources amount to 2 900 t U (RAR + EAR-I).

U occurs in the oxidation zone of weathered Proterozoic carbonaceous, siliceous slate, quartzite, and microquartzite. The metasediments are folded into a NW-SE-oriented syncline and are transected by faults in 40–50 m intervals. Ore lodes are of stratiform shape controlled by interformational fracture zones that follow lithology contacts. Wall rocks are altered by kaolinitization and montmorillonitization. Ore lodes are composed of minute veinlets, specks, and disseminations of autunite, carnotite, torbernite, tyuyamunite, and zeunerite. Associated gangue

**Fig. 15.16.**
**Kyzylkum basement area, Auminza-Beltau ore field, Dzhantuar deposit, geological SW-NE section illustrating the setting of stockwork and stratiform U mineralization controlled by faults in Proterozoic graphitic slate and siliceous phyllite (after Laverov et al. 1992b)**




minerals include alunite, baryte, calcite, gypsum, kaolinite, and montmorillonite. A lithologic affinity of various mineral parageneses is noticed. Uranium-vanadium mineralization prevails in siliceous slate and uranium-phosphate-vanadium mineralization prevails in carbonaceous, siliceous slate.

### 15.2.2.3 Kostcheka

Kostcheka was discovered about 40 km SW of Zarafshan in 1973. Mineralization is of polymetallic U-V-Mo lenticular stockwork type. Grades are from 0.03 to 0.224% U, up to 0.3% V, and up to 0.012% Mo (OECD-NEA/IAEA 1995, 1997). In situ resources are reportedly almost 2 000 t U averaging a grade of 0.07-0.08% U.

Two horizons of black slate intercalated with phyllite of the Riphean-Vendian Taskazgan and Auminza Formations are mineralized and are cut by NW-SE-trending faults. Wall rock alteration includes silicification, montmorillonitization, and limonitization. Ore bodies consist of structurally controlled lenses and saddle-back lodes intermittently distributed over a depth interval of 50–200 m below surface. U minerals include carnotite, tyuyamunite, autunite, torbernite, saleite, minor pitchblende, coffinite, and ningyoite. A vertical zoning of ore minerals is noticed. Uranyl vanadates prevail at depths from 50 to 80 m; uranyl phosphates dominate between 100 and 120 m while uranyl vanadates, uranyl phosphates and minor U silicates and pitchblende are typical for the 150–200 depth interval. Gangue minerals compare largely with those at Rudnoye.

## 15.3 Karamazar Uranium Region, Uzbekistan-Tajikistan-Kyrgyzstan

The Karamazar U region (also referred to as Chatkal-Kuramin region or district) is located to the north and northeast of the town of Khudzhand, Tajikistan (formerly Leninabad). It covers parts of the Chatkal and Kuramin Ranges of the western Tien Shan mountains in eastern Uzbekistan and northwestern Tajikistan, respectively, as well as an adjoining area in western Kyrgyzstan, to the NW of the Fergana Valley (see Chap. 7: *Kyrgyzstan*, 12: *Tajikistan* and Fig. 7.1). The region is known for uranium as well as for gold, silver, base metals, and fluorite deposits. Laverov et al. (1992a,b) report original resources of 20 000 t U for the entire Karamazar region.

U deposits in the Uzbekistan part of the Karamazar region occur in the Chatkal mountains. Deposits are of volcanic vein-stockwork type [in Russian literature termed deposits of "uranium-molybdenum", "uranium-fluorite", or "deposits in volcanic depressions": Vlasov et al. (1966), Volfson (1978), Kazansky and Laverov (1977)]. Mineralization is polymetallic and classified either as U-Mo, U-Bi, or U-Cu-Pb-Zn mineral assemblages. The principal deposits are *Adrasman* (U-Bi), *Chauli, Alatanga,* *Kattasay, Dzhekindek* (U-Mo), and *Maylikatan* (U-Cu-Pb-Zn). Resources of these deposits were on the order of a few hundred to a few thousand tonnes U except for the two largest deposits Alatanga and Chauli, which contained 4 500 t U each. Additional, but small, deposits are *Aksay, Dzheekamae, Kazakhat,* and *Tary-Ekan* in the vicinity of Adrasman, and *Rizak* (Rezak). A small sandstone-type deposit, *Uigar Sai*, is known from the Papsk region in the northern Fergana area. Ore grades averaged 0.1–0.3% U. All known deposits are depleted. Mining was by underground means and lasted from the late 1940s to the early 1960s. Ore processing was at the Chkalovsk mill near Khudzhand, the former Leninabad.

**Source of information:** Kazansky and Laverov (1977); Laverov et al. (1992a,b, 1993); Melnikov et al. (1996) unless otherwise cited.

## Regional Geological Setting of Mineralization

The Karamazar uranium region is within the Chatkal-Kuramin metallogenetic zone located in the Chatkal-Kuramin Uplift, a section of the Ural-Mongolian Hercynian orogenic belt in central Asia. Precambrian to Early Paleozoic metasediments intruded by Early Paleozoic granite (with xenoliths of schists and marble), Early to Middle Paleozoic continental carbonates, and Ordovician-Silurian schists constitute the basement. Early orogenic mafic to intermediate and late orogenic intermediate to felsic volcanics of the Beltau-Kuramin volcanic-structural belt were intruded and extruded during the Hercynian Orogeny. The Carboniferous and Permian volcanic suite consists of alternating rhyolite to dacite and andesite lava sheets intercalated with pyroclastic and clastic rocks. Multiphase subvolcanic stocks and dikes of rhyolitic to andesitic composition and various types of granitic, syenitic, and silicic porphyries were intruded into this suite and the older basement. The volcanics occupy structural depressions represented by calderas and linear troughs. Deep-seated lineaments control the position of volcanic structures. Mesozoic-Paleogene continental- to shallow-marine sediments overlain by Neogene-Quaternary coarse-grained clastics fill the adjacent intermontane Fergana Basin.

## Principal Host Rock Alteration

Beresitization is ubiquitous in all lithologies but is more pronounced at depth. Felsic host rocks are altered on upper levels by albitization and carbonatization, and on lower levels by quartzitization and sericitization. Other types of alteration include argillization, chloritization, and fluoritization. More details are given below and in Sect. *Alatanga-Kattasay OF*.

## Principal Characteristics of Mineralization

Pitchblende is the principal U mineral while coffinite and/or U-Ti-phases occur locally. Associated metallic minerals may include Bi, Cu, Mo, Pb, and Zn-phases giving rise to three ore mineral parageneses: U-Mo (Alatanga, Kattasai, Dzhekindek, and Chauli), U-Cu-Pb-Zn (Maylikatan), and U-Bi (Adrasman). Gangue minerals include quartz, sericite, carbonates, and some minor minerals as listed below. Pitchblende is present in three generations. Major quantities formed together with galena, molybdenite, and calcite. Molybdenite and jordisite occur in some deposits in considerable amounts. Ore exhibits a disseminated, stringer or veinlet, and locally a massive texture.

Kazansky and Laverov (1977) distinguish four stages of mineralization and alteration:

- Pre-uranium stage 1: Beresitization
- Pre-uranium stage 2: Predominantly ankerite and dark sphalerite veinlets and veins, associated with arsenopyrite, chalcopyrite, fahlore, galena, hematite, magnetite, pyrite, pyrrhotite, chlorite, dolomite, and sericite
- Uranium stage: Pitchblende, carbonate, chlorite, jordisite, molybdenite, quartz, sericite, as well as bournonite, chalcopyrite, cleiophane (= white sphalerite), fahlore, and galena
- Post-uranium stage: Calcite, baryte, fluorite, and quartz veins and veinlets that may contain cleiophane, cinnabar, galena, hematite, magnetite, marcasite, pyrite, pyrargyrite, chlorite, and dickite

[A more differentiated mineral suite is provided by Melnikov et al. (1996) for the Alatanga-Kattasay deposits mentioned further below]

Deposits exhibit a distinct vertical and lateral mineral zoning. Phases of the earlier stages and a wider aureole of beresitization are typical for lower levels but gradually decrease upwards. On upper levels of stockworks and on their flanks, specimens of the post-uranium stage and late pitchblende prevail.

Ore lodes are controlled by steeply to gently dipping faults and highly fractured zones. Particularly favored sites of ore concentrations are cataclastic zones at the contact of intrusions and at the paleounconformity of the basement. Favorable host rocks include leucocratic, mainly rhyolitic volcanics, preferentially in form of subvolcanic bodies and, to a lesser extent, pyroclastic and clastic sheets, and locally basement rocks.

## General Shape and Dimensions of Deposits

Deposits are highly variable in magnitude and grade. Original reserves range from a few hundred to 4 500 t U and grades from 0.03 (= cutoff grade) to about 2% U averaging 0.1–0.3% U. Deposits are composed of several ore bodies separated by barren or weakly mineralized ground. Such intermittently mineralized zones may be up to 2 km long, 250 m wide, and in excess of 300 m deep as exemplified by the Alatanga-Kattasay ore field (see later). Ore is rarely exposed at surface.

The shape, dimensions, grade, and internal structure of ore bodies are highly irregular due to heterogeneous systems of interlinked veins, stockworks, and stratiform lenses. Lateral dimensions range from a few meters to about 200 m, while vertical persistence is from a few meters to about 100 m. Reserves vary between a few tonnes and a few hundred tonnes U.

As may be derived from Kazansky and Laverov (1977) (they do not give names and dimensions but the deposits they describe can be tentatively identified as situated in the Karamazar region), ore bodies may simplistically be grouped into two principal geometric-structural types: gently dipping lodes (the most significant variety from an economic point of view) and steeply dipping veins, lenses, and shoots. Gently dipping lodes have a stockwork structure. Their position in multiphase extrusions and intrusions is controlled by lithologic boundaries along which they preferentially occur at those interface sections that vary in attitude and are intersected by major faults. Steeply dipping ore lenses and shoots are composed of interlinked veinlets and disseminated ore minerals. They prevail in latest dike-like bodies of granite porphyry. Locally, the contour of an ore body coincides entirely with that of the host intrusion; but most commonly, the lenses or shoots occupy the intrusive endocontact zone where the rock interface is markedly irregular. In essence, the morphology of ore bodies hosted by intrusive bodies tends to be conditioned, to some extent at least, by the shape and internal structure of the intrusive edifice. The internal structure is reflected by stockworks of complex fracture systems that served as receptacles for ore veinlets. Stockworks are widest in the upper parts while they taper substantially at depth where the host intrusions acquire a narrow stock-like form. In the latter case, mineralization is essentially restricted to complexly arranged, closely spaced, cm to dm thick veins positioned in the contact zone between intrusion and country rocks.

Uranium distribution in lodes is extremely irregular. The largest U accumulations are typical for gently inclined segments of a stockwork. With increasing depth, the quantity and grade of ore decreases gradually.

Deposits hosted in multiphase extrusive domes consist of ore bodies of a particularly complex structure with marked variations in position and configuration due to the irregular shape of the subvolcanic bodies and numerous steeply and gently dipping faults. Ore frequently occurs in these deposits at several vertical levels and concentrates at major tensional faults.

## Regional Geochronology and Fluid Inclusions

Laverov et al. (1993) and Melnikov et al. (1996) report geochronological data from the Chauli deposit in the Karabash Caldera and the Alatanga-Kattasay ore field, respectively, which may also be considered representative for the other uranium deposits in the Karamazar region. Basement granitoids range in age from 410 to 385 Ma; K-Ar dating of rhyolite effusives that fill the Karabash depression yields ages from 305 to 270 Ma, while felsic extrusives and dikes that contain ore bodies date from 279 to 264 Ma. Sericite from the Chauli U deposit and the nearby Chiborgata fluorite deposit give K-Ar ages of 274 ±8 and 278 ±8 Ma, respectively. U-Pb dating yields concordant or close to concordant ages of 275–267 Ma for pitchblende-I (calcite-coffinite-pitchblende association) and strongly discordant ages ranging from 259 to 212 Ma for admixtures of coffinite and pitchblende-II (sulfide-pitchblende associations). Similar ages are obtained for the Alatanga-Kattasay ore field as documented by 280–270 ±10 Ma for third phase granite porphyry and latest dikes, and 270 ±10 Ma for pitchblende and beresite.

Fluid inclusion and stable isotope data are reported from the Alatanga-Kattasay ore field and presented in Sect. *Alatanga-Kattasay*.

## Principal Ore Controls or Recognition Criteria

Ore control is by a combination of structural and lithologic elements. Primary control of deposits is by extrusive and intrusive felsic volcanics of rhyolitic composition with alkaline tendency and major faults. The position and shape of ore lodes tend to be a function of shallow- and steeply-dipping faults with their associated fracture and breccia zones as well as with their intersection with youngest magmatic bodies or with interfaces of different lithologies.

## Principal Aspects of Metallogenesis

Polymetallic uranium deposits of the Karamazar region are of epigenetic hydrothermal origin. Circumstantial evidence suggests a genetic relation to felsic volcanics as indicated by a distinct spatial association of mineralization with near surface emplaced felsic (sub-)volcanic lithologies, which formed during the waning episode of the Hercynian Orogeny. Critical ingredients for deciphering the metallogenesis of the volcanic-type U deposits include the age correlation between volcanism and ore formation, the duration of these processes, the composition and source of mineralizing solutions, and the potential sources of uranium and other ore constituents.

A variety of metallogenetic concepts has been proposed by various geoscientists. Early models on the evolution of the Karamazar U deposits are summarized by Laverov et al. (1993) as follows:

1. The formation of the deposits was related to deep-seated magmatic processes that occurred after volcanic activity ceased, and is chronologically discrete from continental volcanic processes (Smorchkov 1966).
2. The ore deposits were formed as a result of and are genetically linked with hydrothermal activity accompanying volcanic processes (Kotlyar 1968).
3. Ore deposits formed at the final stage of volcanic activity in the anomalous conditions of thermo-artesian depression systems. Metalliferous fluids of magmatic and meteoric origin were involved in ore formation (Barsukov et al. 1972).

Laverov et al. (1993), largely based on their studies of the Chauli deposit, arrive at the following conclusion: The Karamazar U deposits are spatially closely linked to paleovolcanos that extruded a subplatform environment on an ancient, consolidated basement. The position of paleovolcanos, and of volcanic depressions in continental volcanic belts in particular, is controlled by deep fault zones. Uranium mineralization is associated with differentiated intrusive and extrusive volcanic lithologies, for the most part of andesite-rhyolite composition and increased alkalinity. The deposits formed by postvolcanic polyphase hydrothermal activity. Ore minerals were predominantly deposited in form of stringer-disseminations, stringers, and breccia fillings in discharge areas of the hydrothermal systems. These areas are essentially confined to faults and fracture zones in volcanic rocks, necks, deep morphological depressions that existed at the time of ore formation, and most-permeable sections of lithologic horizons. Associated wall rock alterations are dominated by argillization and beresitization.

The principal U mineral, pitchblende, occurs in several generations and various mineral associations, which formed within a fairly wide range of temperature from 200 to 90°C. The most reliable age of the original uranium ore formation, represented by pitchblende I, is 275–267 Ma as established for the Chauli deposit. This age correlates fairly well with the 280–270 Ma value obtained from intrusive dikes of the final magmatic stage, and with the isotopic ages of wall rock alterations (e.g. 270 Ma for beresite of the Alatanga-Kattasay ore field).

According to Kazansky and Laverov (1977) the isotopic composition of lead and sulfur and the geochemical signatures of rocks and mineralization as well indicate a polygenetic origin of the ore-forming elements. Uranium, fluorine, and heavy metals most likely derived from a deep seated, possibly magmatic source while other ore components have a different provenance. Ore-forming hydrothermal fluids had a temperature of about 200–120°C. Mineral deposition occurred at shallow depth, about 500–3 000 m below surface during Permian time.

Melnikov et al. (1996) established four metallogenetic cycles in the Alatanga-Kattasay ore field, and related fluid inclusions data suggest a decrease of solution temperatures from 290°C at the onset to 160°C at the final stage of the metallogenetic evolution. For more details see Sect. *Alatanga-Kattasay Ore Field*.

With the above given time span of primary pitchblende formation in the Karamazar region, this metallogenetic event in the Hercynian Belt of the western Tien Shan correlates well with the period of 280–260 Ma established for the formation of hydrothermal uranium vein deposits in the Hercynian Orogen in central and western Europe.

### 15.3.0.1 Chauli

Chauli is located at the western margin of the Chatkal Range, about 80 km SE of the town of Tashkent (Fig. 7.2). Discovered in 1952, the U-Mo deposit was mined by underground methods and delivered about 4 500 t U. Ore grade was similar to deposits in the Alatanga-Kattasay ore field.

**Sources of information.** Barsukov et al. 1972; Laverov et al. 1972, 1985, 1992b, 1993.

#### Geology and Mineralization

Chauli occurs in the Karabash Caldera (Fig. 15.17). Crystalline schists intruded by granite and granodiorite (410–385 Ma old) with xenoliths of schists and marble constitute the basement. The caldera is filled with a bipartite volcanic-sedimentary complex, 500–1 000 m thick. The upper, rhyolitic *Ravashskaya Formation* consists of three Lower Permian horizons of felsic effusives, quartz porphyry and pyroclastic sheets of tuff, tuffaceous breccia, and ignimbrite, intersected by Upper Permian felsite, granite porphyry and lamprophyre dikes, rhyolite and granite porphyry extrusions, and felsite and quartz porphyry domes. The lower *Akchinskaya Formation* is composed of Middle Carboniferous mafic volcanics, 70–250 m thick, including – from top to bottom – dacitic tuff and tuffite, clastic andesite lava 15–80 m thick, and andesitic lava agglomerate 20–150 m thick. Lower Permian dacite and andesite dikes cut these rocks.

Uranium mineralization is confined to felsic extrusions, domes, and dikes of the youngest volcanic formations. Host rocks are altered by argillization, chloritization, and carbonatization. Ore consists of pitchblende, coffinite, and molybdenite associated with galena, chalcopyrite, and pyrite. Gangue minerals include calcite and chlorite. At least two mineral associations are identified: pitchblende I-coffinite-calcite and pitchblende II-sulfides.

Fourteen ore lodes are identified in a 2 km long and 700 m wide zone controlled by the NW-SE-trending Chaulisai fault and bordered by the Pologi and Sushizotny faults. The position of ore lodes is controlled by cataclastic zones and faults cutting volcanic sheets above felsic intrusions. Four geometric-textural configurations of ore lodes are recognized: steeply dipping veins in pyroclastic rocks, pipe- and lens-shaped stockworks, flat lenses composed of veinlets, stringers and disseminated mineralization, and lensoid and pipelike bodies of disseminated mineralization. Veins prevail on upper levels and stockworks on lower levels. Ore lodes are from 50 to 160 m long and 5–60 m wide or thick, respectively.

### 15.3.0.2 Alatanga-Kattasay Ore Field

This ore field, located in the SW part of the Chatkal Range, 120 km E of Tashkent, is the largest U ore field in the Karamazar region. It includes a number of polymetallic U-Mo deposits and occurrences including *Alatanga*, centered approximately 3 km to the NW and *Dzhekindek* about 3 km to the SE of *Kattasai*, plus several Pb-Zn occurrences (Figs. 15.18, 15.19). Underground mining of the U deposits started shortly after discovery in 1948–1949 and ceased after their depletion in the early 1990s after yielding some 4 500 t U (from 6 000 t U reserves). Mining grades ranged from 0.03 to 2% U and 0.03–0.5% Mo. In addition to uranium and molybdenum, some tin was recovered at Kattasai.

**Source of information:** Melnikov et al. (1996) unless otherwise cited.

#### Geological Setting of Mineralization

The Alatanga-Kattasay ore field is situated at the NW margin of the large mushroom-shaped Babaitaudor intrusive massif composed of Upper Permian, multiphase, felsic subvolcanic

**Fig. 15.17.**
**Karamazar region, Chauli deposit, a geological map of and b sections across the Karabash Caldera showing the lithologic-structural setting of the volcanic-type deposit (see Fig. 7.2 for location) (after Laverov et al. 1993)**

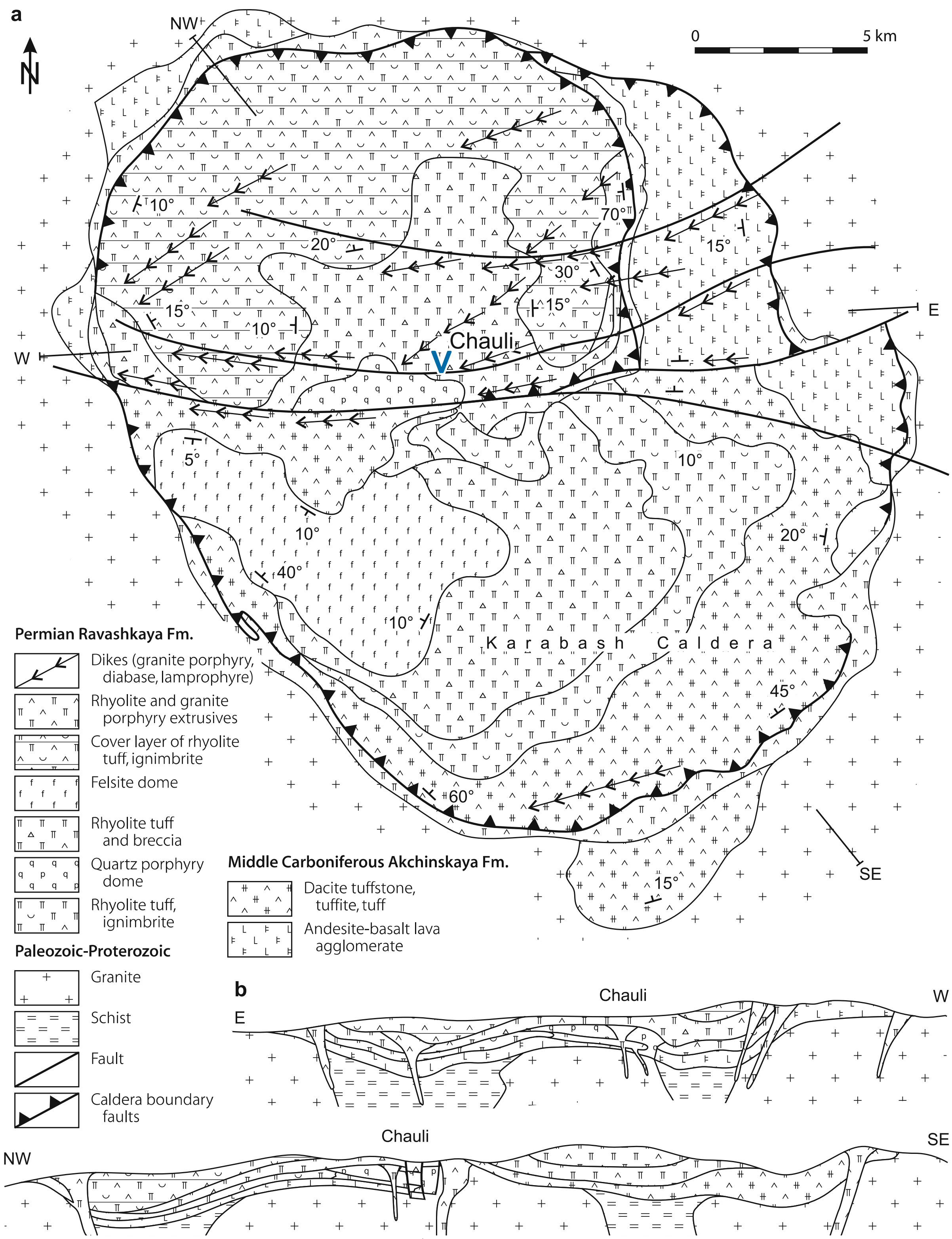


**Fig. 15.18.**
**Karamazar region, Alatanga-Kattasay ore field, geological map with position of volcanic-type U deposits and occurrences (see Fig. 7.2 for location) (after Melnikov et al. 1996 based on Laverov, Rybalov, Korotaev)**

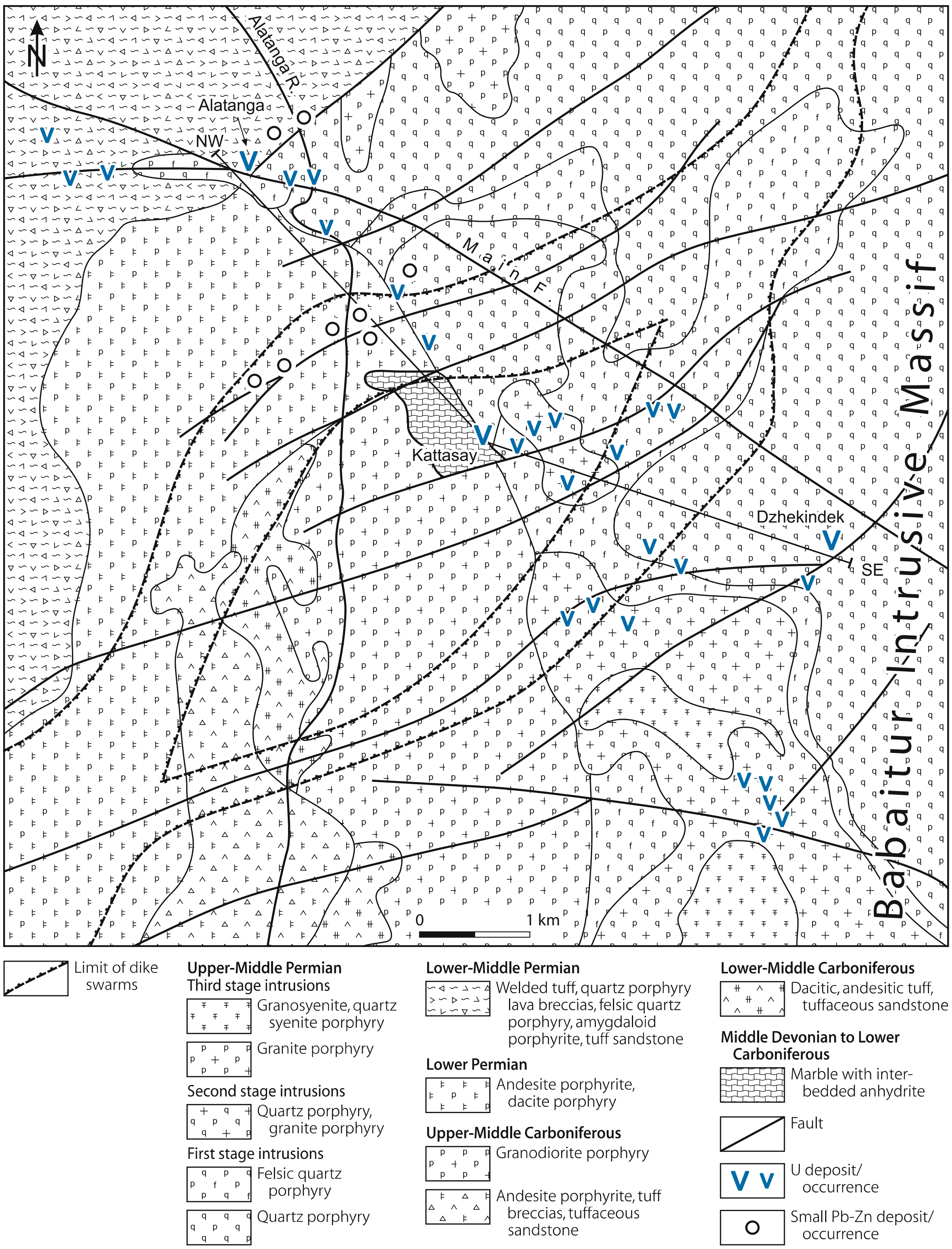
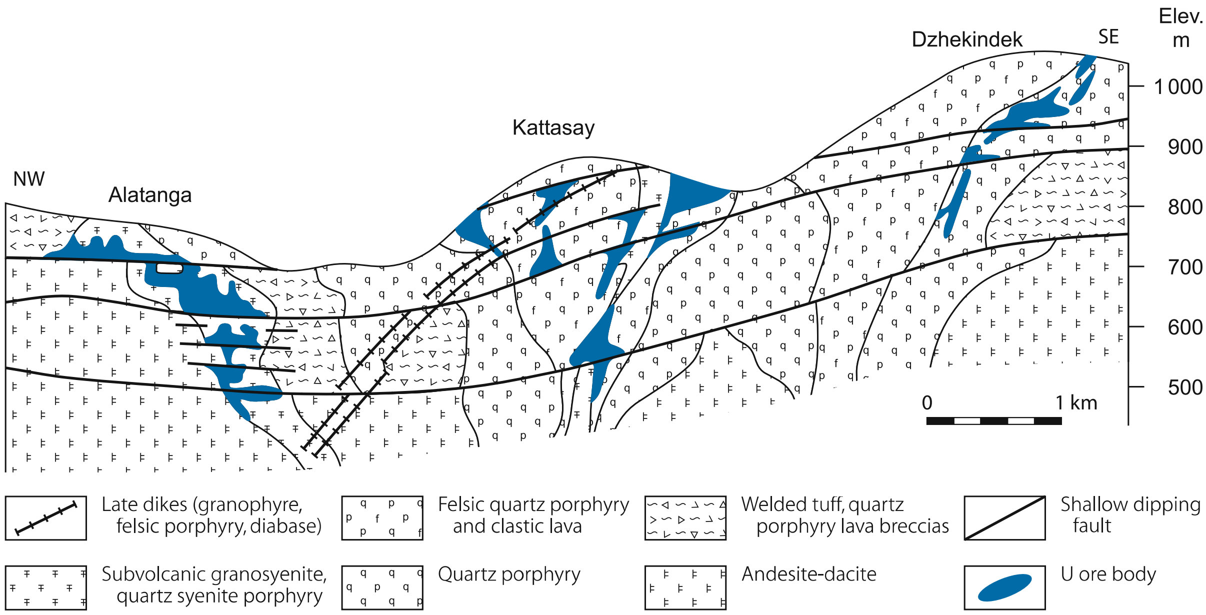


**Fig. 15.19.**
**Karamazar region, Alatanga, Kattasay, and Dzhekindek deposits, geological NW-SE section documenting the irregular shape of stockwork-type U ore lodes and their structurally controlled position in late orogenic felsic volcanic and subvolcanic rocks of Permian age (after Laverov et al. 1992b, Melnikov et al. 1996 based on Tolkunov 1986)**




rocks. The bulk of the massif consists of a first phase core facies of quartz porphyry and a marginal facies of felsite and welded felsitic tuff at the periphery of the massif. In a second phase, quartz porphyry and granite porphyry were intruded along the western fault contact with older volcanics. Granite porphyry, granosyenite, and quartz syenite porphyry constitute the youngest phase of the massif.

The Babaitaudor Massif was emplaced into a variety of older rocks. Xenoliths of Middle Devonian-Lower Carboniferous marble with intercalated anhydrite beds are the oldest. Volcanic lithologies start with a thick sheet of Middle to Upper Carbon-iferous dacitic and andesitic pophyries, tuff breccias, and tuf-faceous sandstone intruded by a N-S-elongated granodiorite porphyry body. Lower Permian andesite porphyry and dacite porphyry rest unconformably upon the Carboniferous rocks, followed by Lower to Middle Permian predominantly felsic pyroclastics and porphyry. Two large, about NE-SW-oriented dike swarms transect the ore field (Fig. 15.18).

The leucocratic magmatites have U and Th background values increasing from 6.4 ppm U and 20.1 ppm Th in older rocks to 13.5 ppm U and 40.5 ppm Th in younger facies but retain the same U/Th ratios. Sn values are commonly 10 ppm in granitoid rocks while the youngest quartz syenite porphyry contains as much as 40 ppm Sn. According to Laverov et al. (1992b) these facies also contain distinctly elevated tenors of syngenetic Be, Y, and REE.

Intense faulting and heavy fracturing deformed the terrane. Major faults trend NW-SE to WNW-ESE and NE-SW and dip steeply. They include the large, NW-SE-oriented "Main Fault". Shallow and steeply dipping secondary faults of variable directions are abundant.

## Host Rock Alterations

Host rock alterations are reflected – in sequential order – by pre-ore albitization, greisenization, and beresitization, followed by widespread, presumably syn-ore, crystallization of phyllosilicates, albite, quartz, Fe-Mg carbonates, calcite, chlorite, and fluorite.

**Albitization** resulted in linear bodies, as much as 15 m thick, of white, massive albitite restricted to faults or tectonic interfaces of intrusive bodies. Albite replaces all pre-existing minerals except quartz. Geochemically, albitization resulted in an increase in the central segments of albitite bodies of the Na2O content of up to 7.8 wt.-% as compared to between 3.8 and 4.2 wt.-% in unaltered felsic precursors, and of FeO from 1.1 to 2.8 wt.-%. Simultaneously K2O was decreased from between 4.9 and 6.1 wt.-% originally to 0.4 wt.-%, Fe2O3 from 1.6 to 0.7 wt.-%, CaO from 1.2 to 0.3 wt.-%, and MgO from 0.25 to 0.08 wt.-%. Tenors of SiO2, Al2O3 TiO2, CO2, and S2− remained practically unchanged.

**Greisenization** was found at Kattasai below a depth of 680 m where it affected not only granite and late dikes but also albitite at some sites. Down to about 720 m, greisen consists of green veins and lenses, 3–5 cm thick, which widen to over 3 m further down. Common greisen constituents are quartz, muscovite, siderophyllite, and cassiterite. With increasing depth, siderophyllite decreases while muscovite and cassiterite increase, and topaz, zircon, and pyrite appear. Sn tenors range from 0.05 to 1 wt.-% but are commonly between 0.1 and 0.5 wt.-%. Other typomorphic phases include Mo, La, Li, and to a lesser extent W and Bi minerals.

**Beresitization** is a widespread phenomenon at all deposits. It overprinted 10–15 m wide zones along steeply inclined major faults, and up to 30 m wide zones above gentle dipping fracture systems. Beresitized bodies display a three-partitioned zoning. The outer zone is characterized by albite and calcite replacement of plagioclase, and by chlorite replacement of mafic minerals. The transition zone is characterized by chlorite, ankerite, and sericite after mafic and intermediate rock constituents, and albite, ankerite, and sericite after felsic rock constituents. Ankerite and sericite also replace remnants of original rock constituents, except quartz, and alteration products of the outer zone. The inner zone exhibits quartz, sericite, and pyrite development in formerly altered felsic and intermediate rocks, and ankerite, pyrite, and sericite in diabase. Downward from a depth of 600 m, quartz and hydromica increase while sericite diminishes. Geochemically, felsic rocks lose – from the outer to the inner zone – alkali and calc-alkali elements and Fe; Si was transferred from the transition to the inner zone whereas Al remained stable.

## Mineralization

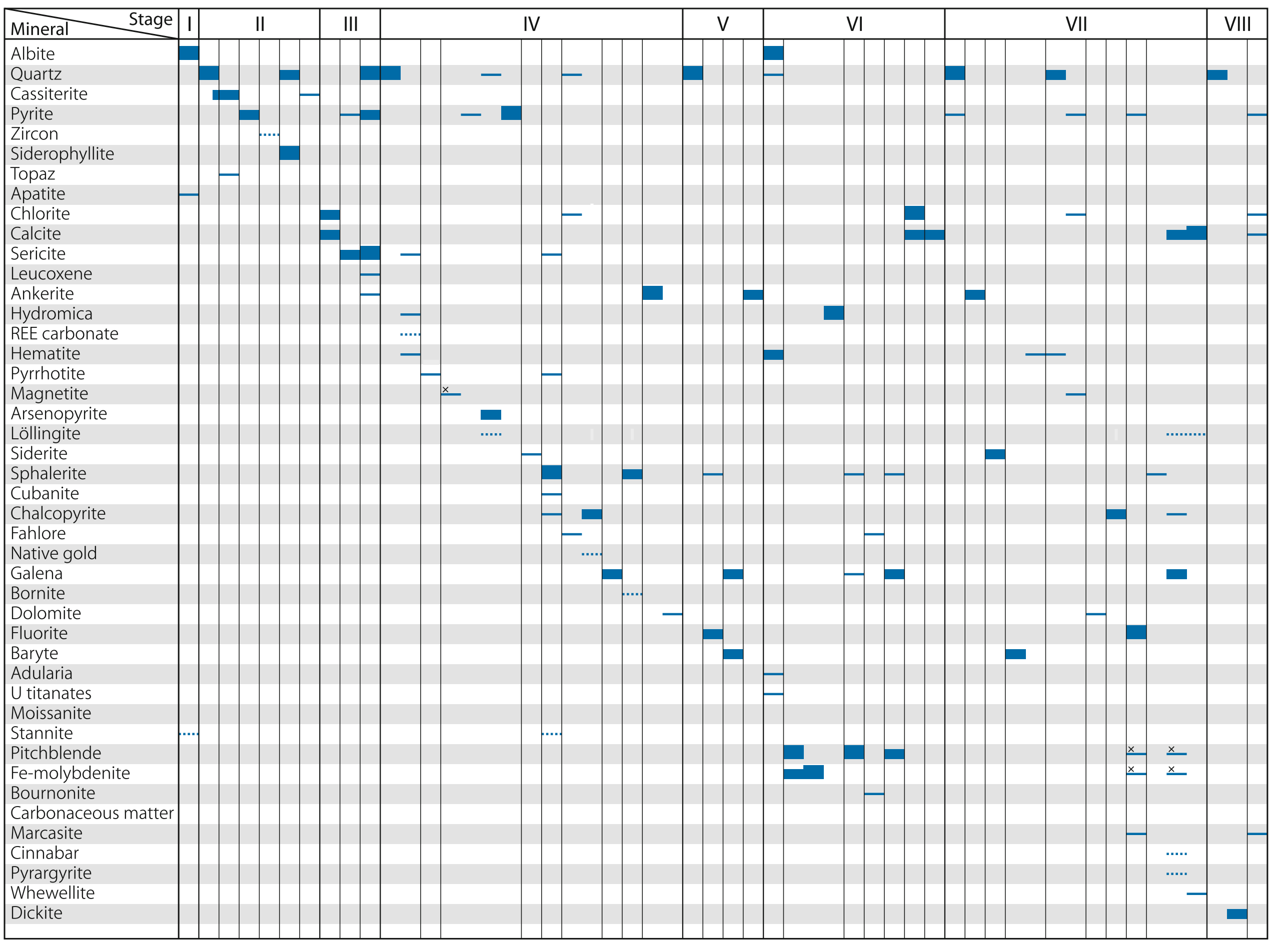
Pitchblende, Fe-molybdenite, cassiterite, and a variety of sulfides and arsenides are the principal ore minerals; calcite, Fe-Mg-carbonates, fluorite, phyllosilicates, and quartz are the prevailing gangue minerals. Ore-forming minerals are present in several generations as illustrated in Fig. 15.20.

Melnikov et al. (1996) identified four metalliferous mineral assemblages that occur spatially separated or telescoped (for specific features of related ore lodes see next section). They exhibit the following features:

1. ***Quartz-sulfide-carbonate assemblage*** forms veins or zones of disseminated mineralization. Sulfides include pyrite, pyrrhotite, arsenopyrite (occasionally with specks of native Au and elektrum), which are partly replaced by chalcopyrite, sphalerite, later galena, and minor cubanite and fahlore. Carbonates are siderite and ankerite. Pb-Zn ore with minor gold was intersected in the Kichgine-Argasan

**Fig. 15.20.**

**Karamazar region, Alatanga-Kattasay ore field, paragenetic scheme of alteration, ore, and gangue minerals (after Melnikov et al. 1996 based on Rekharskii, Kotov, Streltsov, Modnikov, and Sychev). Mineral stages: *I–III* pre-ore alteration: *I* albitization, *II* greisenization, *III* beresitization; *IV* quartz-sulfide-carbonate, *V* quartz-fluorite-baryte, *VI* pitchblende-sulfide, *VII* quartz-baryte-calcite)**



occurrence in the western part of the ore field. Wall rocks are altered by sericitization and/or ankeritization.

2. ***Quartz-fluorite-baryte assemblage*** is present as veins, veinlets, coatings of rock fragments and cement of breccias. Associated minerals include cleiophane, galena, and ankerite. Wall rocks are altered by sericitization and/or carbonatization.
3. ***Pitchblende-sulfide assemblage*** occurs as veinlets and disseminations. The richest ore lodes occur where this assemblage is superimposed on the quartz-sulfide-carbonate assemblage or where it cuts carbonaceous (kerite, anthraxolite) tuffite intercalations. Four parageneses are discerned: *(a)* albite-hematite-U titanates (including brannerite); *(b)* pitchblende I-molybdenite I + II-quartz-hydromica; *(c)* pitchblende II-sulfide (bournonite, fahlore, galena); *(d)* pitchblende III-Fe-chlorite-calcite (with galena and minor cleiophane). The second and third parageneses are most abundant. The three pitchblende varieties have the following lattice constants and impurity contents (in wt.-%). Pitchblende I: $a_o$ = 5.39–5.42 Å; several% Mo and Pb, 0.4–0.5 Mn, 0.05–0.5 Sb and Tl, 0.05–0.1 Zr, 0.005–0.04 Be, and 0.003 Ag. Pitchblende II: $a_o$ = 5.43–5.46 Å; several% Zr, Pb, Zn, and Ca, 0.5–2 Sb, 0.2–0.3 As and Si, 0.02–0.05 Cu, Cd, Ag, and Mn, 0.0003–0.0005 Be. Pitchblende III contains up to 3% Zr. Fe content in ferrous molybdenite is 5.50–6.72 wt.-%. Wall rock alterations relate to the various parageneses. Paragenesis *(a)* is accompanied by albitization and hematitization, *(b)* by hydromicazation and silicification, *(c)* and *(d)* by hematitization, and *(d)* additionally by carbonatization and chloritization. The hematitic halo around pitchblende-bearing veinlets and aggregates is commonly up to 15 cm and locally up to 2 m wide; it contains dispersed fine-grained, reniform pitchblende and galena.
4. ***Post-ore quartz-baryte-fluorite-calcite assemblage*** forms veinlets and up to 10 cm thick and as much as 80 m long veins. Associated minerals are partly present in several generations and include chalcopyrite, cleiophane, galena, hematite, marcasite, pyrite, siderite, ankerite, chlorite, and, rarely, cinnabar, pyrargyrite, and whewellite. Alteration imposed an about 10 cm to a few meters wide aureole on wall rocks by sericitization, silicification, chloritization, and carbonatization. Plagioclase is replaced by sericite, biotite successively by chlorite, sericite and ore minerals, and hornblende by chlorite, quartz, and sericite.

Replacement and recrystallization of various minerals typically occurred where younger assemblages were superimposed on older ones.

Four ore types are distinguished by minero-chemical composition and economic value as outlined further below. *U ores proper* consist essentially of pitchblende. *U-Mo* ore is composed of ferruginous molybdenite and pitchblende associated with hematite, albite, and sericite. *U-Mo-Sn* ore (restricted to Kattasai) has a mineral assemblage of galena, ferruginous molybdenite, pitchblende, and greisen minerals such as cassiterite, fluorite, muscovite, siderophyllite, quartz, topaz, and zircon as a result of superimposition of U-bearing assemblages on greisens. *U-Ti-Na* ores were found only at great depth and consist of U-Ti phases including brannerite, Ti hydroxides, hematite, and albite.

A combination of structural and lithologic elements provided the sites for deposits and ore lodes. Deposit position and extension are primarily controlled by major structures while ore lode position and shape tend to be a function of shallow and steeply dipping faults and their intersection with youngest magmatic facies, or with interfaces of different lithologies. The largest ore bodies and better ore concentrations occur particularly at heavily fractured intervals.

## Shape and Dimensions of Deposits

The Alatanga-Kattasay ore field contains three minable U deposits and some 25 U and almost 10 Pb-Zn occurrences within an area 10 km long in NW-SE direction and up to 2 km wide. Deposits consist of irregularly shaped, variably-sized ore lodes (Fig. 15.19), which may have breccia, stringer, and/or disseminated textures.

The earlier mentioned four ore types differ by economic value. *U ores proper* are of limited distribution and have grades (in wt.-%) from 0.03 to 5% U. *U-Mo* ore is the most extensive type and has grades from 0.03 to 2% U and 0.03–0.5% Mo. *U-Mo-Sn* ore is found at Kattasai at a depth below 680 m; grades range from 0.03 to 5% U, 0.03–0.5% Mo, 0.2–1% Sn and Pb. *U-Ti-Na* ore with grades between 0.03 and 0.08% U were drill intercepted at depths below 1 000 m of present-day surface.

**Alatanga:** The location of this deposit is controlled by the intersection of the "Main Fault" with the northwestern tectonic contact of the Babeitaudor Massif. Ore lodes are controlled by gently dipping faults that transect various volcanics including the youngest facies. U ores have predominantly stringer and disseminated, and minor breccia textures. The quartz-sulfide-carbonate assemblage occurs as disseminations in bodies from 20 to 30 cm thick and 6–8 m long. Minerals of the pitchblende-sulfide assemblage occur predominantly as dispersed grains and aggregates and, rarely, as veinlets.

**Kattasay:** Ore lodes are separated from those of Alatanga by about 1.5 km of barren ground. The deposit is positioned at and controlled by the western tectonic contact of the Babeitaudor Massif. Ore lodes occur in veins, stockworks, and breccias controlled by intersections of shallow and steeply inclined faults within the youngest magmatic facies. Ore textures are dominated by breccia, stringer, and dissemination styles. The quartz-sulfide-carbonate assemblage occurs as veins, from 20–30 cm thick and 6–8 m long, and the quartz-fluorite-baryte assemblage as veinlets and up to 2 m thick veins. Minerals of the pitchblende-sulfide assemblage form veins, 2–3 cm and, locally, up to 15 cm thick.

**Dzhekindek:** This deposit is separated from Kattasay by barren ground about 1.5 km wide. The position of the deposit is controlled by a marked NE-SW fault while the size and configuration of ore lodes tend to be a function of gently and steeply dipping faults, which cut the contact of the youngest subvolcanics with rocks of the core facies of the Babeitaudor Massif. Ore texture is predominantly of stringer and disseminated, and minor breccia nature. The quartz-sulfide-carbonate assemblage is present as disseminations in elongated bands, from 20 to 30 cm thick and 6–8 m long. Veinlets and up to 2 m thick veins are typical for the quartz-fluorite-baryte assemblage whereas minerals of the pitchblende-sulfide assemblage occur predominantly as dispersed grains and aggregates and, rarely, as veinlets.

### Fluid Inclusions, Stable Isotopes, and Geochronology

Primary fluid inclusions in quartz, baryte, fluorite, calcite, and ankerite give homogenization temperatures equivalent to temperatures (after correction for pressure) of ore-forming hydrothermal solutions of 290–230°C for the quartz-sulfide-carbonate stage, 280–210°C for the quartz-fluorite-baryte stage, 215–180°C for the pitchblende-sulfide stage, and 220–160°C for the quartz-baryte-fluorite-calcite stage.

Sulfur isotopes of pyrite, chalcopyrite, galena, and sphalerite of the quartz-ankerite-sulfide stage found at Kattasai and Alatanga yield $\delta^{34}S$ values of +4.5 to +7.4‰ and for Fe-molybdenite $\delta^{34}S$ values of +6.5 to +8.0‰. Pyrite, chalcopyrite, and molybdenite of the post-pitchblende stage at Alatanga have $\delta^{34}S$ values of +3.4 to +5.3.

U-Pb age datings yield 270 ± 10 Ma for beresite and pitchblende. Third phase granite porphyry and latest dikes give ages of 280–270 ± 10 Ma.

### Ore Controls and Metallogenetic Aspects

Ore controls and/or recognition criteria correspond to those mentioned earlier for the other volcanic-type U deposits in the Karamazar region. A metallogenetic model forwarded for the Alatanga-Kattasay ore field by Melnikov et al. (1996) includes the following events and processes. Ore formation was generated by a hydrothermal system related to late volcanism in which hypogene and supergene solutions were involved. Variable fluid inclusion compositions in ore-related mineral assemblages suggest that the ore forming process was not a single event but consisted of periodic pulsations of solutions of variable compositions, which deposited and/or reworked ore minerals in cyclic intervals interrupted or triggered by episodes of intensified tectonic activity.

Melnikov et al. (1996) established four metallogenetic cycles separated from each other by culminating tectonic activity. As deduced from stable isotopes and fluid inclusions, the authors suggest that crystallization of minerals of each stage started at higher temperatures than those at the end of the preceding stage documenting a temperature inversion between stages. A cyclic inversion is also indicated by anion tenors of fluid inclusions. $Cl/CO_2$ ratios in solutions were higher at the beginning than at the termination of each stage. As a result, the initial phases of each stage had higher Cl and lower $CO_2$ contents than the preceding stage. Temperatures of solutions dropped from 290°C at the onset of the metallogenetic evolution to 160°C at its final stage. Minerals of the pitchblende-sulfide stage deposited at 215–180°C.

Ore and associated minerals were deposited predominantly as veins and breccia fillings at Kattasai suggesting the availability of larger open spaces whereas at Alatanga and Dzhekindek, stringer- and dissemination-type ore textures reflect the absence of such openings. Instead, ore deposition was restricted to small pores and fractures.

The time of ore formation was during the Permian, roughly contemporaneous with the intrusion of third phase granite porphyry and the latest dikes as indicated by ages of 270 ± 10 Ma for beresite and pitchblende, which overlaps with the age of 280–270 ± 10 Ma for these intrusions.

Three sources are postulated for components in the mineralizing solutions. Anions, alkali and calc-alkali elements, Sn, REE, Th, U?, and some water are thought to be of magmatic origin. Sulfur isotope ratios of sulfides in various ore-forming mineral assemblages correspond to those of granitoid magma and, as such, they support a derivation from a magmatic source. A non-magmatic source is accepted for the bulk of the solutions. The principal sources for U and Mo as well as for Ca, Mg, and K were presumably felsic volcanics from which these elements were leached by circulating solutions. Leaching of uranium from host rocks is evidenced by a thick zone depleted in uranium at the U-Mo Chauli deposit located some 40 km to the west of the Alatanga-Kattasay ore field.

### 15.3.0.3 Maylikatan

Maylikatan is a U-Cu-Pb-Zn deposit situated at the SW margin of the Chatkal Range (Fig. 7.2). Ore lodes are associated with an 80–400 m wide, 65–70° N dipping granite porphyry dike. The dike occupies the Naugarzan fault zone at the southern exocontact of the Babaytag subvolcanic massif. Middle Carboniferous granodiorite occurs in the footwall and Paleozoic tuff in the hanging wall of the dike. Ore lodes occur at the contact and at flexures in the interior of the dike controlled by NE-SW- and E-W-oriented faults. Ore lodes at the dike contact consist of up to 10 m wide, up to 150 m long, and up to 80 m deep veins and lenses. Dike interior lodes are up to 20 m wide, up to 60 m long, and up to 60 m steeply dipping column-like bodies.

### 15.3.0.4 Rezak

Rezak is located at the southern slope of the Kuramin Range close to the Uzbek-Tadjik borderline. U-Mo mineralization is confined to breccias and fractured intervals at the contact, which separates a Middle Permian rhyolite/felsite porphyry stock from Carboniferous granite and Lower Permian volcanics. Ore lodes consist of columnar stockworks and lenses emplaced in fracture and breccia zones. Linear networks prevail at depth; they bifurcate upwards into fans of radially arranged veins.

### 15.3.0.5 Uigar Sai

The *Uigar Sai* (or Yuigar Sai or Atbash) deposit in the Papsk region in the northern Fergana area, discovered 1923, consists of lenses of carnotite disseminations, cavity linings, and coatings of minor faults in continental Miocene sandstone. U is concentrated near fossil logs and organic trash associated with interbedded mudstone lenses. Some ore lenses have cores of higher-grade material. Mineralization is similar to that in deposits of the Colorado Plateau.

## References and Further Reading for Chapter 15 · Uzbekistan

For details of publications see Bibliography.

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