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Tectonic Evolution of High Asia in the Paleozoic and Mesozoic

V. S. Burtman and S. G. Samygin

Geological Institute (GIN), Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 109017 Russia

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Abstract—A correlation of the northern Pamir, Kunlun, and northern Tibet structural zones is proposed, and the position of the Paleozoic and Mesozoic sutures in the region is discussed. Analysis of the available data on regional geology and biogeography enabled the reconstruction of the Paleozoic and Mesozoic evolution of the oceanic basins separating the constituent sialic blocks of present-day High Asia. During the Sinian (800–540 Ma), the Tarim–Qaidam block was rifted away from Eastern Gondwana and the Kunlun Ocean opened between them. This basin remained fairly narrow during the Cambrian but expanded considerably in the Ordovician and Silurian. During the Middle Devonian, convergence between Tarim and Gondwana probably led to a short-term amalgamation of these sialic blocks. During the Early Carboniferous, the Kurgovat–Songpan block separated from Eastern Gondwana and the Vanch–Jinsha Ocean opened between them. This basin expanded rapidly and turned into a vast ocean that spread over two climatic belts of the Earth in the Artinskian. The fragmentation of the High Asian terranes peaked in the Permian. During this period, the Vanch–Jinsha Ocean separated Gondwana from the South China continent and the Kurgovat–Songpan island arc off its western promontory. The Kunlun Ocean separated the Kurgovat–Songpan arc from the Tarim continent. The Gondwanan margin was split by the Rushan–Shuanghu rift, which separated the peninsula encompassing the Central Pamir and Qiangtang. Late in the Permian, the Qiangtang–Karakorum sialic block was rifted away from Gondwana and the Bangdong Ocean opened between them. The Triassic was marked by the closure of the Kunlun, Vanch–Jinsha, and Rushan–Shuanghu oceans of the Paleo-Tethys system. As a result, the Pamirs, Karakorum, Kunlun, and much of Tibet to the north of the Bangdong suture were accreted to the Eurasian continent. The Cretaceous witnessed the closure of the Meso-Tethyan Bangdong Ocean and the back-arc Shyok Sea. As a result, the Kohistan and Lhasa blocks were sutured to the Eurasian continent. To summarize, the fragmentation of Gondwana was multistage and stretched from the Sinian to Triassic, whereas the suturing of the High Asian sialic blocks to the Eurasian continent was accomplished in two phases in the Triassic and Cretaceous. The third collision event took place in the Paleogene in response to the closure of the Neo-Tethys Ocean.

INTRODUCTION

High Asia (Fig. 1) encompasses the Pamirs, Karakorum, the Himalayas, Tibet, Kunlun, and the Nanshan (Qilian Shan). Much of the territory lies within the Alpine foldbelt. The correlation of events in the Himalaya, southern Tibet, Kohistan, and Karakorum structural zones has been discussed in numerous publications [87, 98, and others]. Paleozoic and Mesozoic events in northern Tibet, Kunlun, and the Pamirs are much more difficult to correlate. A significant amount of published data is available on each of these regions, but familiarity with these publications is hurdled by a language barrier (the works in Russian are difficult for foreigners, and the works in Chinese are difficult for us) and the scarcity of contacts between the explorers of these regions. We worked in the northern Pamirs, eastern Kunlun, and Altyn Tagh at different times; crossed the Pamirs, Tibet, and northwestern and eastern Kunlun on geologic excursions; and visited the Nanshan, Karakorum, Kohistan, and the Tethys–Himalaya regions. Excursions and discussions with the explorers of these regions provided a better understanding of the published data and enabled us, more or less, to distinguish reality from geologic myths as far as we could. Correlation between the Pamir, Kunlun, and northern Tibet structural zones given with reference to the location of the Paleozoic and Mesozoic oceanic sutures in this region and the reconstructed history of oceanic basins are proposed in this paper.

The Paleozoic Paleo-Tethys Ocean was initiated in the Late Proterozoic after the breakup of Rodinia and existed during the whole Paleozoic. It separated the main continents of future Laurasia from the continents of Gondwana for over 500 Ma. Within this time span, the oceanic space of the Paleo-Tethys changed in configuration, microcontinents drifted across it, and island arcs emerged and disappeared within it. These structures divided the Paleo-Tethys into basins with long or short histories, including the Irtysh–Zaisan, Junggar–Balkhash, Turkestan, and other oceanic, back-arc, and inter-arc basins. Collisions between island arcs, microcontinents, and large continents are recorded in numerous sutures. Various sutures were interpreted by scientists as the main suture of the Paleo-Tethys. Most frequently, it was placed in the Alpine foldbelt, which originated from the Cenozoic Tethys Ocean [3, 5, 61, and others]. The suture of the Mesozoic oceanic basin, which belonged to the Meso-Tethyan system of basins, is also located within this foldbelt.

The history of oceanic basins is discussed below with reference to the above-mentioned indications and approaches to data interpretation.

The geographic names in Russian maps of China are often different from their Chinese equivalents and the Latin transcriptions used in English literature. However, the names of geologic features have a geographic origin. Therefore, we shall use the Latin transcriptions of the Chinese names of geologic and geographic features adopted in Chinese and English literature. Because of the deficiency in paleomagnetic data, all directions are given in modern coordinates.

STRUCTURAL ZONES AND OCEANIC SUTURES

The structural zones and oceanic sutures of High Asia are discussed below in three transects, western (1), central (2), and eastern (3).

1. The Pamirs, Karakorum, and Northwestern Kunlun

1.1. Western margin of Tarim and the Vakhsh–Trans-Alay thrust. The crystalline basement of the Tarim platform is Archean and Proterozoic in age. The Pb–Pb age of the oldest rocks in the Tarim zone is 2.46 Ga [84]. The cover of the platform is composed of Sinian and Phanerozoic shallow marine and continental deposits. The Tarim platform deposits deformed by young movements make up the outer structural zone of Northwestern Kunlun.

The northern boundary of the Pamirs with the Karakum block and the Tien Shan is defined by the Late Cenozoic Vakhsh–Trans-Alay thrust fault (V in Fig. 2). The crust between the Pamirs and Tien Shan was shortened by 300 km during the Late Cenozoic [9, 56]. Evidence of the subduction of the Tien Shan continental crust beneath the Pamirs in the Recent time is given in [57, 67]. The thrust sheet conceals the northwestern termination of the Tarim platform. The Vakhsh–Trans-Alay thrust fault joins the fault separating the Pamirs from the Tarim platform in northwestern Kunlun.

1.2. The Kalayhumb–Oytag suture (KO in Fig. 2) is marked by Carboniferous ophiolites. The hyperbasites in the Kalayhumb ophiolite (Ka in Fig. 2) consist of dunites and peridotites. The stratified sequence begins with a thick pillow basalt member with limestone interbeds bearing Serpukhovian goniotites at the top [41]. The basalts are tholeiitic, and their petrochemical characteristics are similar to those of MORB [35]. The supra-ophiolite part of the sequence is composed of basaltic andesites, andesites, dacites, and rhyolites. The gradually differentiated volcanic suite resting upon the ophiolitic basement is an ensimatic island-arc rock association. The volcanics laterally pass into volcaniclastics and olistostromes with early Serpukhovian goniatites in the olistoliths [41]. The volcanics and their equivalents in different facies are unconformably overlain by limestones with late Moscovian foraminifers. Also, conglomerates and limestones with late Bashkirian foraminifers, resting unconformably upon the volcanics, were reported [37].

The structural zone composed of ophiolites and arc-type volcanics extends from the Tajik Pamir into northwestern Kunlun. The Kungai and Oytag ophiolites (Oy in Fig. 2) are composed of basalts, sometimes pillow basalts, interbedded with cherts [99]. Ultramafics have been reported among these lavas. The Kungai basalts are overlain by contrasting volcanics interbedded with sedimentary rocks carrying Visean corals. Above are intermediate and acid tuffs [97]. The Rb–Sr isochron age of basalts from northwestern Kunlun is about 360 Ma [97]. The ophiolites are intruded by granites with U–Pb zircon datings of 277 and 227 Ma [96].

In the northern Pamirs, the Balyandkiik ophiolites (Bk in Fig. 2) have been mapped to the south of the Kalayhumb–Oytag suture. They compose a large massif of peridotites, pyroxenites, gabbro, diorites, and plagiogranites [34] and a basalt, occasionally pillow-basalt, sequence. The lavas are geochemically similar to MORB-type tholeiitic basalts [35]. They are conformably overlapped by mudstones and limestones with Serpukhovian brachiopods and foraminifers [25]. Above these are Upper Carboniferous clastics and Permian carbonates. The structural position of the Balyandkiik ophiolites is obscure. They may represent a fragment of the Kalayhumb–Oytag suture offset along the Uibulak strike-slip fault (U in Fig. 2) or an allochthon, whose roots occur in the Kalayhumb–Oytag suture to the north.

1.3. Kurgovat–Yarkant (KYa in Fig. 2). The basement of this zone is composed of gneisses and schists. The U–Pb zircon age of granite–gneisses from northwestern Kunlun is 2.26 Ga [96]. The Rb–Sr age of the granites that intrude the metamorphosed basic, intermediate, and acid volcanics in the Yarkant River basin in the same region is 1.5 Ga [84]. The U–Pb datings of metamorphism in the gneisses correspond to the Vendian and Early Jurassic [51, 96].

The oldest fossiliferous rocks in the northern Pamirs are sandstones with clasts of metamorphic basement rocks and shales that carry Late Ordovician–Early Silurian corals. Above them are limestones and quartz sandstones with Early Silurian corals and carbonates with Early and Middle Devonian corals. Resting upon them with a slight angular unconformity is a thick volcaniclastic sequence with late Tournaisian and Visean brachiopods and corals [7, 37]. The volcanics compose a contrasting differentiated basalt–rhyolite suite. The rocks are calc-alkaline with alkali basalt interbeds. The petrochemistry of the volcanic rocks suggests that they were formed on a continental crust [35]. The Early Carboniferous volcanics are associated with granitoids, whose petrochemical characteristics are identical to those of acid volcanics [34]. Sandstones and limestones with Serpukhovian goniatites interbedded with acid and basic lavas and tuffs are located stratigraphically

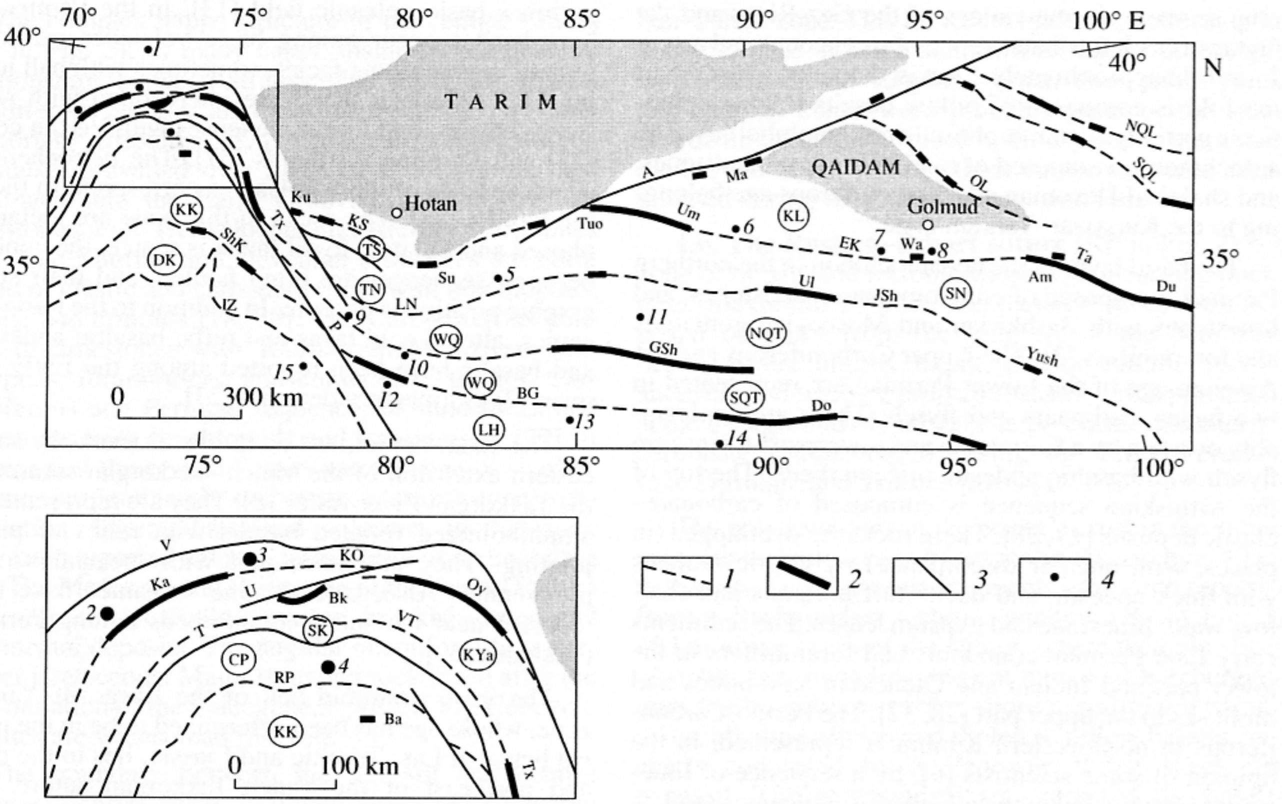

Fig. 2. Structural zones and oceanic sutures of High Asia. (*1*) **Oceanic sutures** (BG—Bangong, EK—Eastern Kunlun, VT—Vanch–Taxkorgan, GSh—Gangmaco–Shuanghu, IZ—Indus–Zangbo, KO—Kalayhumb–Oytag, KS—Kudi–Subashi, LN—Lighten, OL—Olongbruk, RP—Rushan–Pshart, NQL—North Qilian, SQL—South Qilian, JSh—Jinsha, Shk—Shyok); (*2*) **ophiolites** (Am—Anyemaqen, Ba—Bashgumbez, Bk—Balyandkiik, Wa—Wanbaogou, Do—Dongkiao–Amdo, Du—Dur'ngoi, Ka—Kalayhumb, Ku—Kudi, Ma—Mangya, Oy—Oytag, Su—Subashi, Ta—Tatuo, Tx—Taaxi, Tuo—Tuokuzidaban, Ul—Ulan Ula, Um—Ulugh Muztag, Yush—Yushu); (*3*) **faults** (A— Altyn Tagh, V—Vakhsh–Trans-Alay, P—Pamir–Karakorum, T— Tanymas, U—Uibulak); (*4*) **Early Permian fauna and flora sampling sites**: 1—Alay, 2—Darvaz, 3—Trans-Alay Range, 4—Kalaktash, 5—Panshuihe, 6—Aqqikkolhu, 7—Naiji Tal, 8—Golmud, 9—Kongka Pass, 10—Rutog-Gegua, 11—Gangmaco–Xiyargang, 12—Zhiquanghe, 13—Cogen, 14—Xainza, 15—Kashmir. Circled letters indicate structural zones: AT—Alay–Tarim, DK—Dras–Kohistan, WQT—Western Qiangtang, NQT—Northern Qiangtang, SQT—Southern Qiangtang, KL—Eastern Kunlun, KK—Karakorum, KYa—Kurgovat–Yarkant, LH—Lhasa, SK—Sarykol, SN—Songpan, TS—Tisnab, TN—Tianshuihai, QD—Qaidam, CP—Central Pamirs. Shaded areas indicate the extent of Cenozoic deposits in the Tarim and Qaidam massifs.

higher [3]. In addition to the volcaniclastic section, purely carbonate Lower Carboniferous sections were reported from the study area [37]. The Lower Carboniferous volcanic belt extends along the western flank of the Pamirs into the Afghani Badakhshan, Western Hindu Kush, and further west [1].

In the Yarkant River basin in Northwestern Kunlun, the Proterozoic basement is unconformably overlain by shallow-marine deposits with Ordovician fossils [79]. The Lower Paleozoic and Middle Paleozoic deposits were laid down in shallow marine and partially (during the Devonian) continental environments [17, 69]. The principal difference from the northern Pamirs is the Middle Devonian unconformity and the presence of Late Devonian molasse. The Late Devonian in the northern Pamirs is marked by a hiatus with an unconformity at the base of the Carboniferous sequence.

To summarize, the Kurgovat–Yarkant zone is underlain by a metamorphic basement, which was covered by shallow marine sediments during the Ordovician, Silurian, and Devonian and by a contrasting volcanic suite in the Early Carboniferous. Volcanic activity took place on a continental margin. It was caused by subduction or rifting. During the Serpukhovian, an island arc was formed on the oceanic crust to the north of this sialic block [31, 35]. The Kalayhumb basin that separated this island arc and the Kurgovat–Yarkant sialic block closed during the late Bashkirian or early Moscovian time. Collision between the sialic block and the island arc was accompanied by folding and thrusting [41]. Another major folding event in northwestern Kunlun took place during the Late Carboniferous. Thrust sheets composed of Paleozoic and Proterozoic rocks were reported from this region [51, 52, 73]. Some French scientists [51, 52] interpret them as Jurassic based on the isotopic ages of biotites from the thrust zone. These datings, however, may correspond to the age of the latest movements rather than to that of the initial thrust emplacement. In the valleys of the Gez River and the Oytagsu (its left tributary) one of us encountered a synform fold approximately 3 km in diameter. The core of the fold is composed of pillow basalts (Oytag ophiolites) partially metamorphosed into amphibolites. The autochthon is composed of marbles, quartz sandstones, and shales of Devonian and Carboniferous age belonging to the Kurgovat–Yarkant zone.

The basal layer of the neoautochthon in the northern Pamirs is composed of conglomerates, sandstones, and limestones with Bashkirian and Moscovian goniatites and foraminifers [3]. The Upper Carboniferous and the Asselian age of the Lower Permian are represented in two facies, carbonate and flysch. These are conformably overlain by a Sakmarian and lowermost Artinskian flysch with basaltic andesite tuff interbeds. The top of the Artinskian sequence is composed of carbonate–clastic deposits [27, 28]. These rocks are overlapped (in places, with angular discordance) by clastic redbeds with thick andesite and dacite tuff horizons and shallow-water limestone and gypsum lenses. The sediments carry Late Permian conodonts and foraminifers in the lower part and Induan and Olenekian ammonites and mollusks in the upper part [28, 37]. The Permo-Carboniferous in northwestern Kunlun is represented, in the opinion of some scientists [6], by a sequence of limestones interbedded with calc-alkaline volcanics (andesites and basaltic andesites) without any definite indications of the age.

The Permian sequence in the northern Pamirs is unconformably overlapped by conglomerates and tuffstones interbedded with basalts, basaltic andesites, andesites, tuffs, and coal seams with Late Triassic flora [37]. The belt of Triassic volcanics extends from the northern Pamirs into western Hindu Kush and further west [1, 44]. The Triassic in the Pamirs is unconformably overlain by Liassic, Aalenian, and Bajocian coal-bearing strata. The Upper Jurassic, Cretaceous, and Cenozoic continental and shallow marine sediments complete the stratigraphic sequences of the northern Pamirs and northwestern Kunlun.

The area under consideration is pierced by granites, which occur in two belts, northern (outer) and southern (inner). The granites of the outer belt are associated with the Early Carboniferous volcanics and are probably Early Carboniferous in age. The granites of the inner belt cut through the Permian strata. The K–Ar datings of granites from the Pamir yield 200–230 Ma [33, 34], and the U–Pb age of granites from the Kunlun is 204 Ma [69].

1.4. The Vanch-Taxkorgan suture (VT in Fig. 2) is marked in the Pamir by a belt of serpentinized hyperbasite protrusions and lenticular amphibolized gabbro and diorite bodies. The serpentinized rocks have been identified as dunites, peridotites, and pyroxenites; they are low-Ti, high-Mg rocks geochemically similar to alpinotype hyperbasites [12]. The belt extends into northeastern Afghanistan, where the hyperbasites occur within a basic volcanic field [13]. In the Pamirs, the hyperbasites occur among basic volcanics metamorphosed in greenstone facies, sometimes with ball jointing [34]. The lava sheets are interbedded with sandstones, shales, and limestone lenses with Visean corals [23] and Permian fusulinids [37]. The petrochemical characteristics of these volcanics correspond to tholeiitic basalts [88]. The rocks in this zone are metamorphosed and foliated, fossil fauna is scarce, the contacts between sequences are often faulted, and their stratigraphic position is obscure. In addition to the basic volcanics, altered acid lavas and tuffs, basaltic andesites, and basalts have been reported among the Early Permian (?) sedimentary deposits [23].

The Taaxi ophiolites (Tx in Fig. 2) mark the southeastern extension of the Vanch–Taxkorgan suture into the Taxkorgan River valley [8]. They are represented by amphibolitized foliated basalts with relics of pillow jointing. They are associated with metagabbro and pyroxenites. Also, calc-alkaline volcanics have been reported near the suture as interbeds among Permian (?) shales [69].

The inner granitoid belt of the Kurgovat–Yarkant zone, whose age has been determined to be in the interval between Late Triassic and Liassic, lies to the north and northeast of the Vanch–Taxkorgan suture. The granitoids consist of potassium granites, granodiorites, and monzonites, including both high-temperature subduction-related granitoids and low-temperature granites. The latter are probably confined to collisional stress zones [12]. The granitoid belt extends into northwestern Kunlun. Geochemical data on these rocks indicate their formation during or after oceanic crust subduction [102]. It seems reasonable to suggest that the emplacement of these granitoids was related to the subduction of the oceanic crust of the Vanch–Taxkorgan oceanic basin beneath the Kurgovat–Yarkant microcontinent.

1.5. The Sarykol zone and the central Pamirs. The basement of the Sarykol zone (SK in Fig. 2) is composed of metamorphic rocks of unknown age, which do not exhibit any stratigraphic contacts with the Paleozoic rocks. The contacts between the other members of the stratigraphic sequence of the zone are also faulted. The oldest fossiliferous deposits are Ordovician. The lower part of the thick sequence is composed of interbedded trachyrhyolites, keratophyres, basalts, and albitophyres overlain by sandstones, shales, and limestones with Early, Middle, and Late Ordovician trilobites and crinoids [29]. Above these are limestones with Late Ordovician–Silurian corals, limestones, and sandstones with Wenlockian–Ludlowian, Early Devonian, and Eifelian corals and crinoids and late Tournaisian and Visean foraminifers and crinoids. The Paleozoic sequence is crowned by a thick sequence of shales, siltstones, and sandstones with Serpukhovian ammonoids and Late Carboniferous and Early Permian foraminifers and crinoids [4].

The complex nappe structure of the central Pamirs (CP in Fig. 2), in many cases, disguises the primary relationships between stratigraphic units. The oldest fossiliferous deposits are limestones with Lenan (Early Cambrian) trilobites [37]. Carbonate sedimentation obviously prevailed over much of the Cambrian and continued into the Early Ordovician, giving rise to limestones with Tremadocian and Arenigian trilobites [37]. The Silurian and Devonian sequences are composed of clastic and carbonate rocks with brachiopods, corals, and crinoids [18, 30]. The Carboniferous consists of limestones with Tournaisian–Moscovian brachiopods, foraminifers, and corals [19]; the top Carboniferous and Permian sequence, of sandstones and limestones with brachiopods and foraminifers [22]. It follows that the central Pamirs were a zone of shallow marine, predominantly carbonate, platform-type sedimentation. Intermediate–acid volcanics in this zone have been reported among clastic strata of an uncertain age. The Mesozoic and Paleogene in the central Pamirs are composed of shallow marine, brackish-water, and continental deposits. The angular unconformity is pre-Upper Cretaceous. Major thrusting took place after the accumulation of the Paleogene deposits [40]. Cenozoic granites are widespread [34, 69].

The boundary between the Sarykol and central Pamir structural zones is drawn along the Cenozoic Tanymas fault (T in Fig. 2), on which the Central Pamirs underthrust the northern Pamirs [20]. The extent of thrusting can be estimated based on the magnitude of the late Cenozoic Pamir–Karakorum right-slip fault (P in Fig. 2), whose northern branch is conjugate with the Tanymas thrust fault. The lithotectonic zones recognized in the southern Pamirs are offset over 270–290 km along the Pamir–Karakorum fault relative to the extensions of these zones in western Tibet [10]. All zones exhibit arcuate bending that makes up horizontal folds with vertical axes near the fault. Therefore, actual strike separation is less than the total magnitude of the offset, which is partially due to plastic deformation in the strike-slip zone. Strike separation was estimated in the interval 170–250 km [10, 82]. The latest geologic maps of western Tibet [84, 85] show clearly that the plastic deformation of structures on the eastern side of the Pamir–Karakorum fault is much greater than was previously considered. As a result, much of the total offset of the Pamirs relative to Tibet is due to plastic deformation in a fairly wide strike-slip zone and the strike separation along the fault is shorter by half than previously inferred. This conclusion is supported by data from the southern segment of the Pamir–Karakorum fault: the Indus valley and a Miocene intrusion in the Karakorum Range are offset over 90–120 km along the fault [88].

In the southeastern Pamirs, the Pamir–Karakorum fault joins a system of right-slip faults and thrust faults in the Rushan–Pshart suture zone [32, 39]. These structures compensate much of the offset along the Pamir–Karakorum fault as identified to the south of the Rushan–Pshart zone. This leaves no reason to believe in the disappearance of some unknown terrane or an oceanic suture beneath the Tanymas thrust. The central Pamir and Sarykol zones were probably parts of the same Paleozoic continental block with a passive margin in the Sarykol zone, where a thick clastic sequence accumulated during the Carboniferous and Permian.

1.6. The Rushan–Pshart suture (RP in Fig. 2) is a zone of thrusts and tectonic slices with a varying thickness (maximum 25 km). The tectonic slices are composed of rocks from the margins of the Mesozoic ocean, where high-K basalt, picritic basalt, basaltic andesite, and trachyte erupted (basaltic lavas prevailed) at the background of bathyal cherty–clastic and cherty–carbonate sedimentation during the Early Permian, Late Permian, and Triassic times [16, 32, 72].

The only remnants of the oceanic crust in the suture zone are tectonic lenses of serpentinites and hyaloclastic basalts. Oceanic crust fragments have been reported from a Bashgumbez tectonic window (Ba in Fig. 2) 40 km to the south of the suture, where tectonic slices of ophiolites, including serpentinites and harzburgites intruded by gabbro, gabbro-diorite, and plagiogranite dikes, alkaline olivine and tholeiitic pillow basalts, and cherts concealed by a Cenozoic thrust sheet, are exposed. The geochemical signatures of the basalts indicate an oceanic origin. Siltstone intervals in the lava sheets contain Mesozoic phytoplankton. The basic lavas are overlain by a sequence of acid lavas and pyroclastics and an olistostrome sequence with blocks of limestones containing Permian and Triassic fauna (to the Carnian inclusive). Rocks from the central Pamirs have been recognized among olistoliths [45]. Olistostrome accumulation was probably related to the thrusting of the central Pamirs onto the Karakorum block as a result of collision between them. The time of olistostrome accumulation is unknown. Similar olistostrome overlies the Permo-Triassic volcaniclastics within the suture zone, where limestone interbeds in the olistostrome contain Jurassic crinoids [72].

1.7. Karakorum (KK in Fig. 2). The Karakorum structural zone is bounded by the Rushan–Pshart suture to the north and the Shyok suture to the south. It encompasses the southern Pamirs and the Karakorum Range. The pre-Paleozoic basement of the zone is exposed in the southwestern Pamirs. The Paleozoic sequence of the southeastern Pamirs begins with clastic deposits with Early and Late Carboniferous, Sakmarian, and Artinskian fauna [14, 37, 39]. The rest of the Permian and much of the Triassic sequence are shallow marine carbonates and clastics and carbonate–cherty strata deposited in a pelagic environment. The Early Permian witnessed basalt eruptions, and the latest Permian was marked by the deposition of tuff, tuffite, and volcaniclastic sandstones with clasts of basic and acid volcanics over a part of the territory [39]. The Upper Triassic carbonate sequence laterally passes into and is upbuilt by clastic flysch with Carnian and Rhaetian fauna [2].

The deformed Permian and Triassic strata are unconformably overlain by red sandstones, grading upward into shallow marine, predominantly carbonate deposits with fauna of all Jurassic series. These are unconformably overlain by Tertiary marine and continental clastics and acid and intermediate volcanics. Granite emplacement in the southeastern and southwestern Pamirs took place in the Late Triassic to Early Jurassic, Cretaceous, and Tertiary times [12].

The Upper Paleozoic and Mesozoic sequence of northern Karakorum is similar to that of the southeastern Pamirs [64, 87]. Note the absence of flysch in the Upper Triassic sequence, which is composed of carbonates. Numerous geochemical data and U–Pb, Ar–Ar, and K–Ar datings enabled us to reconstruct the igneous evolution of the Karakorum [87]. The subduction-related granitoids were emplaced in the Late Jurassic and Early Cretaceous. They compose a 600 km long South Karakorum batholith, which characterizes the southern margin of the Karakorum block as an Andean-type margin. Post-collision granites are sometimes Oligocene but mostly Miocene in age.

1.8. The Shyok suture (ShK in Fig. 2) separates the Karakorum block from the Mesozoic Dras–Kohistan arc (DK in Fig. 2). Members of an ophiolitic sequence (peridotites, pyroxenites, gabbro, basalts, and cherts) occur as blocks in the olistostrome, which also contains fragments of Albian–Aptian limestones that are common in Kohistan. Rocks in the suture zone exhibit strong cleavage and folding; the radiometric age of deformations is 100–90 Ma (Cenomanian–Turonian). These deformations probably result from a collision between the island arc and the Karakorum block during the closure of the Shyok marginal sea during the Late Cretaceous [87].

1.9. Oceanic basins. Given below is a summarized timing of oceanic basin evolutions.

The Kalayhumb–Oytag basin was located between an ensimatic island arc and the sialic Kurgovat–Yarkant block. There is evidence of its existence during the Early Carboniferous, as indicated by the age of the ophiolites and ensimatic island arc deposits. This island arc existed from the early Serpukhovian to early or late Bashkirian time. The inception of this marginal basin took place in the Tournaisian and was associated with a synrift contrasting volcanic suite of the same age mapped along the margin of the Kurgovat–Yarkant block [23, 35]. During the Bashkirian or early Moscovian time, the Kalayhumb marginal basin closed. This dating is based on the age of the neoautochthon resting upon the slices of rocks from the Kurgovat–Yarkant block overriding the island-arc rock associations [41].

Data are scarce on the oceanic basin to the north of this island arc, which separated it from the Alay–Tarim continent. The Late Carboniferous and Early Permian flysch in the neoautochthonous sequence of the northern Kurgovat–Yarkant block suggests the existence of a deep basin between the Pamirs and Tarim. Possible indications of the Late Paleozoic subduction at the active margin of the basin are the calc-alkaline volcanics of Permian and Carboniferous age in northwestern Kunlun and the tuff and lava beds in the Upper Permian–Triassic sequence of the northern Pamirs. The suture of this Paleozoic oceanic basin is not exposed in the Pamirs.

The Vanch–Taxkorgan basin. The age of ophiolites and flysch attests to the existence of this oceanic basin in the Carboniferous and Early Permian. The basin closed during the Late Permian to Triassic as a result of oceanic crust subduction beneath the Kurgovat–Yarkant block. This fact is supported by subduction-related and collisional granitoids. The inception date is not recorded. The basin presumably opened in the Devonian or Early Carboniferous. It might be older, considering that the Ordovician alkaline lavas known in the Sarykol zone mark a continental rifting event, which might lead to the opening of an oceanic basin.

The Rushan–Pshart basin. The existence of this ocean seems well substantiated. It most probably existed during the Late Triassic, as obvious from the accumulation of turbidites on the margin of the southeastern Pamirs to the south of the suture. The Late Permian–Triassic volcanics are attributed to rifting, which led to the inception of this oceanic basin [32]. However, the Early Permian basaltic volcanism in the suture zone suggests an earlier inception of this basin. Collision between the central Pamirs and the Karakorum block took place late in the Rhaetian to early Lias prior to the formation of the olistostrome and accumulation of clastic redbeds in the southeastern Pamirs.

The Shyok basin was a marginal sea separated from the Tethys Ocean by the Dras–Kohistan island arc. The volcanic activity of the arc occurred in the Jurassic to Early Cretaceous. This marginal sea closed in the mid-Cretaceous. The subduction zone was tilted beneath the Karakorum block.

2. Western Kunlun and Western Tibet

2.1. Southern margin of Tarim. The metamorphic basement of the Tarim platform is exposed on the surface in the western Kunlun foothills. The Rb–Sr zircon age of the gneisses was determined as 1567 and 1764 Ma [84]; the U–Pb age, as 2260 Ma [76]. The metamorphic basement is unconformably overlain by limestones with Sinian microflora. They contain tholeiitic basalt interbeds of presumably synrift origin [77]. The limestones are unconformably overlain by red sandstones with Devonian flora and Carboniferous and Permian limestones [76, 90]. The ancient rocks are intruded by the Early Paleozoic granites [58, 101]. The top of the sequence is composed of Jurassic marine and Cenozoic thick continental strata.

2.2. The Kudi–Subashi suture (KS in Fig. 2) is marked by a chain of ophiolite outcrops. The Kudi ophiolites (Ku in Fig. 2) are exposed near the northwestern and western Kunlun boundaries. They consist of dunites, peridotites, harzburgites, cumulate gabbro, a thick pillow basalt sequence, radiolarites, and deep marine turbidites. Geochemical features suggest that the volcanics were formed in a mid-oceanic ridge and an island arc [79, 97]. The age of the ophiolites is disputable. Some authors consider them ancient on the basis of the following facts [79, 96]. The ophiolitic sediments are interbedded with marble with Sinian stromatolites. The U–Pb isochron age of a dike (metamorphosed into amphibolite) intruding the ultramafics is 816 Ma [69]. The ophiolites are intruded by diorites, granodiorites, and monzogranites. The Rb–Sr isochron age of the diorites is 480 Ma, and their Ar–Ar age was also determined as 480 Ma [69]. The granodiorites yield an Ar–Ar plateau biotite age of 449 Ma and U–Pb isochron hornblende and zircon ages of 474 and 458 Ma, respectively. The monzogranites give a Rb–Sr isochron whole-rock age between 423 and 510 Ma and a biotite age (Ar–Ar plateau) of 384 Ma [96]. Also, flysch with Ordovician radiolarians [101] and Devonian strata [79] resting unconformably upon the ophiolites have been documented. However, some other researchers [58, 77] believe that the ophiolites have tectonic contacts with the granites and other rocks and show the ophiolites as allochthonous. This point of view implies an Early Carboniferous age of the ophiolites. This is supported by the whole-rock Rb–Sr isochron ages of pillow lavas determined as 359 Ma and the Late Paleozoic microphone found in the radiolarites of the ophiolitic sequence [58]. The most probable solution is that the suture zone (as in eastern Kunlun) hosts pre-Paleozoic, Early Paleozoic, and Carboniferous ophiolites.

The Subashi hyperbasites (Su in Fig. 2) occur at the top of the western Kunlun loop. The age of this and other hyperbasite bodies that mark the suture under consideration to the west of Kudi is uncertain [99].

2.3. The Tisnab and Tianshuihai zones. The basement of the Tisnab zone (TS in Fig. 2) is composed of gneisses and intruding granites. The metamorphic Ar–Ar biotite age of the gneisses was determined as 420 Ma; the potassium feldspar age, as 350–380 Ma. The post-kinematic granites yielded an U–Pb zircon age of 377 Ma, a Rb–Sr biotite age of 380 ± 10 Ma, and a whole-rock age of 392 ± 35 Ma (Middle Devonian) [76]. Resting unconformably upon the metamorphic rocks is an Upper Paleozoic sequence composed of carbonates and island-arc volcanics. The latter are probably genetically associated with granodiorites, whose Rb–Sr isochron biotite age is 267 Ma [96]. The gneisses are intruded by granites that yield a Late Triassic Ar–Ar age of 211 ± 8 and 212 ± 11 Ma [76, 96]. Granite chemistry suggests a subduction-related genesis [58]. The whole variety of rocks is unconformably overlain by molassic redbeds with Late Triassic fauna and coal-bearing fossiliferous Jurassic deposits [77]. The Jurassic shales include acid lava interbeds, whose Rb–Sr ages were determined as 163 ± 10 Ma (isochron) and 180 ± 10 Ma [58, 76, 77].

The exposed sequence of the Tianshuihai zone (TN in Fig. 2) begins with a sequence of sandstones, slates, and marbles with Proterozoic stromatolites. These are unconformably overlain by a thick sequence of conglomerates, sandstones, slates, and marbles with Upper Ordovician brachiopods, trilobites, and cephalopods at the top. The Lower Silurian is represented by arkosic sandstones with brachiopods. The unconformably overlying sandstones contain Middle Devonian fauna. The Upper Devonian consists of quartz sandstones and carbonates; the Lower Carboniferous, of sandstones, conglomerates, and limestones with brachiopods and gastropods [58]. These rocks are unconformably overlain by a thick fossil-free, strongly deformed flysch sequence. The megaliths (?) in the flysch carry Paleozoic and Triassic fossil fauna [79]. The flysch is interpreted as Triassic (by analogy with eastern Tibet), but it may well include the Upper Paleozoic. The flysch is cut through by Early Jurassic granites, which yield a U–Pb zircon age of 192 Ma and Ar–Ar (plateau) ages of 190 ± 8 Ma (on muscovite) and 177 ± 3 Ma (on biotite) [76]. The Ar–Ar (plateau) biotite age of the monzogranites is 196 Ma [96]. The flysch is overlain by Jurassic marine sandstones, shales, and limestones. The overlying conglomerates, red sandstones, and limestones with Albian–Aptian rudists rest with a slight angular unconformity upon the flysch and with a pronounced angular unconformity upon older rocks [76].

The boundary between the Tisnab and Tianshuihai zones is defined by a fault zone in which some structural indications of a left slip have been reported [76, 77]. Some researchers interpret this boundary as an oceanic suture [58, 79, and others], but neither ophiolites nor any other indications of the existence of an oceanic basin between these zones were ever reported. We consider both zones parts of a single Paleozoic Tisnab–Tianshuihai sialic block.

2.4. The Lighten suture (LN in Fig. 2). The boundary between the Tisnab–Tianshuihai and the Quiangtang zone in western Tibet is drawn along the Longmuco fault, which accommodated left-lateral movements during the Cenozoic [76]. Ophiolites are unknown in this fault zone. The area immediately to the south of the Longmuco fault exhibits the Late Paleozoic Gondwanan facies with diamictites and Early Permian cryophilic pelecipods and fusulinids, whereas the corals of the same age found in Kunlun to the north of this fault indicate a tropical climate [58, 85]. In all probability, an oceanic suture separating the Tisnab-Tianshuihai and Quiangtang zones was offset along the Longmuco fault. In western Kunlun, it is referred to as the Lighten [90] or the Qiaoertianshan–Hongshanhu [58, 79] suture.

2.5. Western Qiangtang (WQT in Fig. 2). The basement of the Qiangtang zone is composed of metamorphics of uncertain age, including metabasites and andesites. The Paleozoic is represented by two types of sequences, with flysch and with limestones. The oldest fossiliferous rocks in the former are sandstones, shales, basic volcanics, and cherty limestones with Early Carboniferous brachiopods. The lower part of the Upper Carboniferous shows a similar lithology. The top of the Carboniferous and the lowermost Permian are composed of diamictites with signs of glacial abrasion on the boulders [59]. The diamictites are overlain by thick Asselian–Sakmarian flysch with Gondwanan pelecipods, brachiopods, and corals [58]. In places, flysch accumulation continued till the Late Permian. The flysch is underlain and interbedded with basalt sheets and sills [92]. Resting upon it with angular unconformity are the Upper Permian carbonates with a basalt and radiolarite horizon in the middle [58].

A different Paleozoic sequence is represented by carbonates with a thickness of 1500 km with Devonian, Carboniferous, and Permian fauna [59]. The spatial distribution of the Paleozoic facies types over the Qiangtang block has not been established thus far. The flysch sequence occurs in the southwestern part of the zone [92]. The Permian strata in the Aghil Range are probably of the same time [65].

The Paleozoic is overlain by the Triassic composed of reefal and pelagic limestones. The contact between the Paleozoic and Triassic has been reported both as conformable [65, 92] and unconformable [58]. Shallow marine limestone accumulation persisted during the Early–Middle Jurassic (probably Bathonian inclusive). The lower part of the Middle–Upper Jurassic sequence is composed of thick, unconformably bedded flysch; the upper part, by reefal limestones [58]. In some sections, the flysch is reportedly underlain by red sandstones [65]. The Middle Jurassic sequence contains basalts. Fossil-free red conglomerates and sandstones interbedded with acid lavas rest unconformably upon the underlying strata and are conformably overlain by limestones with Eocene microfauna [58]. Granites with Ar–Ar biotite and muscovite ages of 87–91 Ma cut through the Paleozoic and Cretaceous rocks [76].

2.6. The Bangong suture (BG in Fig. 2) is marked by a wildflysch or tectonic melange zone with harzburgite, serpentinized peridotite, gabbro, basalt, radiolarite, and limestone blocks in the flysch matrix. The age of limestones in the block ranges from Permo-Carboniferous to Aptian. Also, a complete set of an ophiolitic suite from peridotites through cumulates and a dike complex to pillow lavas and radiolarites with Middle–Late Jurassic fauna has been reported. The Rb–Sr age of the basalt clusters is between 182–207 Ma. The intensely folded flysch and mélange are unconformably overlain by limestones with latest Early or earliest Late Cretaceous endemic fauna [75, 76, 85].

2.7. Oceanic basins. The available data (from ophiolites and island-arc volcanics) suggest that the **Kudi–Subashi** Ocean existed during the Sinian–Early Paleozoic, Carboniferous, and probably Permian times. The Triassic subduction-related granites in the Tisnab zone suggest its existence during the Triassic. The Devonian metamorphism and deformations in the Tisnab zone and coeval granitoids are considered evidence in support of collision between this and the Tarim block associated with the closure of the Kudi–Subashi basin during the Devonian [76]. All subduction-related igneous rocks of Late Paleozoic and Triassic age occur to the south of the suture.

Lighten basin. The indications of the existence of an oceanic basin (paleogeographic and biogeographic data, Early Permian flysch) are Late Paleozoic, and the indications of the opening and closure of this basin are unknown. Probably the Early Jurassic granites in the Tianshuihai zone are the aftermath of the closure of this basin.

The age of blocks in the wildflysch and the overlying limestones establish the Early Cretaceous closure time of the **Bangong basin**. The Jurassic and Permian flysch are evidence of the probable existence of this basin during this time span.

3. Eastern Kunlun and Eastern Tibet

3.1. Qaidam and Eastern Kunlun. Two structural zones separated by a fault have been recognized in eastern Kunlun. The basement of the northern zone is composed of ancient rocks of the Qaidam massif, gneisses, schists, amphibolites, and marbles with a Rb–Sr age of 1990 and 1846 Ma [60, 65]. The overlying strata are composed of quartzites and metamorphosed carbonates with Middle Riphean stromatolites unconformably overlain by graywacke and dolomites with Late Riphean stromatolites [60, 83]. In the western part of the zone, the Proterozoic is unconformably overlain by various sediments and calc-alkaline differentiated volcanics with Middle–Late Ordovician corals and cephalopods [83]. The lavas and pyroclastics, often metamorphosed into greenschists, are predominantly intermediate. One of us observed small mafic–ultramafic layered bodies among them. These rocks previously composed an ensialic submarine volcanic arc. A fragment of a fore-arc accretionary prism with tectonic lenses of serpentinites, including cataclastic diabase, basalt, chert, and greenschist blocks, has been identified on its southern margin in the Qimantag Mountains.

The Precambrian metamorphites in the Golmud River basin are covered by conglomerates and sandstones grading upward into terrestrial basalts, andesites, and rhyolites interbedded with sediments containing Late Devonian flora [60]. The volcanics were formed on an active continental margin [81]. They are overlain by upper Visean–early Serpukhovian conglomerates and arkosic sandstones [63]. In places, limestones with Early Carboniferous brachiopods and Late Carboniferous foraminifers are found [62]. A discontinuous belt of Late Triassic continental intermediate and acid lavas interbedded with pyroclastic and clastic deposits occurs in the northern zone. The K–Ar age of these rocks is 222–235 Ma. Petrochemical features suggest that these volcanics are suprasubduction [60, 63, 83]. Jurassic continental coal-bearing molasse and Cretaceous redbeds crown the Mesozoic sequence.

A belt of granitoid rocks ranging from granites to diorites extends along the northern slope of eastern Kunlun. Geochemical signatures suggest that these rocks were formed on an active oceanic margin or are post-collisional [69]. The granodiorites from this belt yield a Rb–Sr age of 257 ± 26 Ma and an U–Pb age of 240 ± 6 Ma (Late Permian–Early Triassic) [68]. Among them are intrusions with a Rb–Sr age of 394 ± 13 Ma [94] and a K–Ar age of 417 and 386 Ma (Late Silurian and Early Devonian) and granites and monzogranites that cut through the Upper Triassic rocks with a K–Ar age of 219–191 Ma (Late Triassic–Early Jurassic) [83].

The sequence of the southern zone of eastern Kunlun in the Golmud River basin begins with basal graywacke, quartz sandstones, phyllites, and a sequence of metamorphosed basalts, andesites, tuffs, and tuffites, conformably overlain by marbles with late Precambrian stromatolites [58, 63]. The basalts yield an Ar–Ar age of 660 Ma and K–Ar datings of 718 and 1057 Ma [60, 83]. The basalts are transitional between alkaline and tholeiitic. Stratigraphic and geochemical features of the volcanic sequence suggest a continental rift-related origin [81]. The Lower Paleozoic is composed of graywacke and polymictic sandstones, phyllites, calcarenites, and limestones with a fragment of Early (?) Ordovician trilobite and numerous Middle–Late Ordovician corals. Various parts of the sequence are composed of turbidites and fluxoturbidites [63]. Limestones with Middle Devonian corals occur in the western part of the zone to the south of the Qimantag Mountains [62].

A higher stratigraphic position in the southern zone is occupied by a thick sequence of calc-alkaline basalts, andesites, rhyolites, and continental clastic redbeds. These are overlain by carbonate-clastic sediments with Early Carboniferous corals and foraminifers [58, 83]. The Upper Carboniferous is composed of acid and intermediate volcanics and sedimentary rocks with brachiopods and foraminifers at the top of the sequence [60]. The Permian rests unconformably upon older rocks. The sequence consists of clastics and limestones with acid volcanic horizons. The fusulinids, brachiopods, and cephalopods are Late Permian (Maokou–Changxing ages) [83]. The Triassic deposits rest unconformably upon the Paleozoic and pre-Paleozoic rocks. The sequence begins with conglomerates overlain by sandstones interbedded with andesites, rhyolite tuffs, and limestones with Early and Middle Triassic fauna. These are unconformably overlain by coal-bearing deposits with Late Triassic flora and continental calc-alkaline intermediate and acid volcanics [83, 100]. The Early Jurassic granites with Rb–Sr isochron ages of 189 ± 7, 194 ± 17, and 198 ± 56 Ma cut through the rocks of the southern zone of eastern Kunlun [68], but the relationship between the granites and continental volcanics is obscure. Also, granites with a U–Pb age of 413 ± 5 Ma and diorites with a Rb–Sr isochron age of 426 ± 3 Ma are known [48].

3.2. East Kunlun sutures (EK in Fig. 2). More than 100 ophiolite outcrops have been mapped in the Anyemaqen Range in eastern Kunlun within a 400-km-long zone (Am, Du in Fig. 2). Ophiolite bodies and other rocks occur as blocks and tectonic slices among flysch. Basalt and gabbro geochemistry suggest a mid-oceanic ridge origin. Gabbro yields Rb–Sr isochron ages of 495 ± 81 and 518 ± 102 Ma; a U–Pb zircon age of 467 ± 1 Ma. The Rb–Sr isochron age of the basalts was determined as 480 ± 21 and 340 ± 12 Ma, and the Pb–Pb isochron age, as 491 ± 44 Ma [11, 48, 49]. Amphibolites with a metamorphic age of 579 Ma were also reported from this zone [96]. Chert fragments from the ophiolite mélange contain Early Carboniferous radiolarians [11, 48]. Also, the mélange reportedly contains Early Permian basalts with a Rb–Sr age of 260 Ma [91]. The Late Permian molasse seals the Anyemaqen ophiolitic mélange [48]. The Tatuo ophiolites (Ta in Fig. 2) have been mapped to the north of the main suture. They consist of peridotites, troctolites, gabbro, parallel dikes, and a thick basalt sequence [58]. The age of the Tatuo ophiolites is uncertain.

The Anyemaqen suture zone contains ophiolites and island-arc volcanics, whose geochemical signatures correspond to an intraoceanic island arc [80]. The volcanics are basic and intermediate. They are conformably overlain by calcarenites with Asselian conodonts [36]. Island-arc rock associations also occur in the eastern part of the zone. The Dur'ngoi ophiolites (Du in Fig. 2), reported from this zone, consist of cumulate gabbro, diabase dikes, and IAT-type pillow basalts. The rocks are metamorphosed into amphibolites, whose U–Pb metamorphic age is 417–421 Ma [91]. The suture zone also exhibits island arc-type granitoids with an U–Pb age of 402 ± 24 Ma [47].

West of the Anyemaqen sutures, the East Kunlun suture runs along the Cenozoic South Kunlun strike-slip fault. Outcrops of the Wanbaogou gabbro and island-arc basalts (Wa in Fig. 2) with a Rb–Sr isochron age of 684 Ma [97] have been reported near it. Another outcrop of the ophiolites occurs on the northern slope of the Ulugh Muztag Mountains, where mélange with serpentinized peridotites and cumulate gabbro have been documented [78]. This ophiolitic zone (Um in Fig. 2) extends westward to the Altyn Tagh fault (A in Fig. 2). Here, a thick sequence of basalts and basaltic andesites interbedded with sedimentary rocks containing Visean brachiopods and corals has been mapped in the Tuokuzidaban Mountains (Tuo in Fig. 2). In the same region and farther south, flysch with Late Carboniferous fauna has been mapped [99].

3.3. The Songpan zone (SN in Fig. 2). The Songpan zone in eastern Tibet exhibits a thick (10 km) flysch sequence of distal turbidites with chert and pelagic limestone interbeds. The rocks carry fossil fauna from all Triassic series [83, 98]. Reportedly, the flysch rests unconformably upon the Permian [83]. The flysch is strongly deformed. It is intruded by postorogenic tonalites with a Late Triassic K–Ar age of 213 ± 6 Ma [61]. Above are Jurassic marine and continental and Cretaceous–Paleogene continental deposits [60]. The Paleozoic and pre-Paleozoic basement of the block is exposed in the Tisnab–Tianshuihai zone in western Tibet, which lies on the extension of the Songpan zone.

3.4. The Jinsha suture (JN in Fig. 2) is marked by a wide (50 km) Ulan Ula ophiolitic zone (Ul in Fig. 2) located to the north and east of the lake of the same name. It exhibits ophiolitic mélange, hyperbasites, gabbro, pillow basalts, picrites, and cherts with Tournaisian radiolarians. The petrochemical signatures of the basalts correspond to OIB. The gabbros show an Early Permian Rb–Sr age of 266 ± 41 Ma. The ophiolitic mélange is unconformably overlain by Upper Permian–Lower Triassic deposits [58]. Farther southeast, the suture under consideration is marked by Yushu ophiolites (Yush in Fig. 2). They compose tectonic blocks among the Upper Triassic rocks and consist of peridotites, gabbro, pillow basalts, picrites, and siliciliths. Geochemical signatures of the lavas suggest eruption in a mid-oceanic ridge [80]. Some blocks in the mélange of the Jinsha zone are composed of cherts with Early Triassic fauna. There is evidence of ophiolite obduction from the Jinsha onto the Qiangtang zone [61].

3.5. Northern Qiangtang (NQT in Fig. 2). The Qiangtang zone in western Tibet is split by an oceanic suture into the northern and southern sectors in eastern Tibet. The sequence of northern Qiangtang rests upon crystalline rocks overlain by Sinian carbonates [60]. Above them are the Upper Ordovician and Lower Silurian quartz sandstones, phyllites, and limestones. These are unconformably overlain by Middle–Upper Devonian carbonate–clastic sediments. The Carboniferous and Early Permian are represented in two facies (one coal-bearing with intermediate volcanics and a thick flysch with diamictites), basic lava interbeds, and Gondwanan fauna [58, 10]. Geochemical signatures suggest that the lavas interbedded with coal-bearing deposits are related to rifting [81]. The top of the Lower Permian is composed of reefal limestones. They are unconformably overlain by Upper Permian sandstones and limestones. The Triassic sequence begins with basalts and radiolarites overlain by Triassic and Lower Jurassic shallow-marine limestones. The Middle Jurassic is composed of carbonate flysch with subalkaline andesite interbeds [81], and the Upper Jurassic consists of shallow marine limestones. Resting unconformably upon the folded underlying strata are Upper Cretaceous–Eocene shallow marine and continental deposits. All systems and series of this sequence are fossiliferous [58, 85].

3.6. The Gangmaco–Shuanghu suture (GSh in Fig. 2). This structural zone is abundant in ophiolite outcrops. The zone is lens-shaped in plan view with a width of about 100 km and a length of more than 500 km. The lavas range in composition from alkaline basalts in the lower part of the sequence to MORB-type tholeiitic basalts in the upper. The basalts contain Early Permian limestone blocks. The cherts in the ophiolitic mélange contain Triassic radiolarians. The ophiolites occur among the Upper Carboniferous–Lower Permian diamictites; the latter are foliated and partially metamorphosed into glaucophane schists. The Ar–Ar crossite age is 223 ± 4 Ma (Late Triassic). The zone immediately to the north of the Gangmaco–Shuanghu suture exhibits calc-alkaline volcanics and molasse of Early Jurassic age [58, 70].

The eastern extension of the Gangmaco–Shuanghu zone is marked by outcrops of rocks with Late Permian fusulinids and brachiopods. The lower part of this sequence is composed of limestones and intermediate and basic lavas grading upward into sandstones and shales interbedded with basalts. Geochemical signatures suggest that the basalts are intracontinental. The upper part of the Upper Permian sequence is composed of clastics interbedded with limestones and coals [58, 63, 100].

3.7. Southern Qiangtang (SQT in Fig. 2). The southern Qiangtang zone exhibits Mesozoic rocks composing the Tanggula synclinorium. The Upper Triassic rests unconformably upon rocks of various ages. The lower part of the Upper Triassic sequence is composed of shallow marine and continental deposits, and upper, of basalts, andesites, and rhyolites interbedded with limestones and clastic flysch. The lavas are calc-alkaline and correspond to arc-type volcanics. Alkaline basalts have been reported. The Jurassic consists of thick alluvial redbeds and shallow-marine deposits, and the Cretaceous and Paleogene sequence is continental [58, 63].

3.8. The Bangong suture (BG in Fig. 2) is marked by the Dongkiao–Amdo ophiolites (Do in Fig. 2). As a result of intense deformations, the ophiolites are disintegrated. Ultramafics, cumulates, sheeted dikes, and pillow basalts are exposed separately. Based on petrochemical and geochemical signatures, oceanic rocks and IA basalts were recognized [80]. The cherts interbedded with and overlying the basalts contain Liassic and Tithonian radiolarians. The gabbros and amphibolites yield a Late Triassic Ar–Ar age of 200–220 Ma [58]. The ophiolites were thrust southward onto the Lhasa block and survived as numerous klippen within a 180-km-wide zone. The ophiolitic allochthon rests upon the Jurassic flysch and is overlain by conglomerates, sandstones, and shallow-marine limestones with Late Jurassic–Early Cretaceous corals [58]. The whole sequence is overlapped by Upper Cretaceous red sandstones and andesites.

3.9. Oceanic basins. The East Kunlun suture zone contains a suture of an oceanic and back-arc (or several back-arc) basins. The isotopic ages of rift-related volcanics and the oldest ophiolites attest to the existence of an oceanic basin in **eastern Kunlun** since the Sinian. For the later epochs, there are data on Cambrian oceanic basalts and gabbroids, Middle–Late Ordovician turbidites and island-arc volcanics, Late Silurian and Early Devonian suprasubduction granitoids, Late Devonian–Early Carboniferous subduction-related volcanics, Early Carboniferous oceanic basalts and cherts, a Late Carboniferous ensimatic island arc, and Late Permian–Triassic collisional or post-collisional magmatism. During the Late Paleozoic, the subduction zone was tilted beneath Qaidam. Angular unconformities in the Upper Permian and Triassic are related to deformations, which probably accompanied the formation of the accretionary prism, including a collision between the Carboniferous island arc with eastern Kunlun. This event probably accounts for the accumulation of the Late Permian molasse. The basin closed completely prior to the accumulation of the Late Triassic continental coal-bearing sediments.

The data on ophiolites in the **Jinsha** suture suggest that this oceanic basin existed in the Carboniferous and Permian. The Late Paleozoic volcanics of northern Qiangtang originate from continental rifting near the margin of this basin. This rifting event was probably associated with the opening of the Jinsha basin. The Early Triassic radiolarites in northern Qiangtang and the cherts of the same age discovered among the mélange were probably deposited in a residual deep-sea basin. The timing of deformations suggests that the collision probably began late in the Permian, but the complete closure of the Jinsha basin took place in the Triassic.

The specific features of volcanism in the **Gangmaco–Shuanghu** suture suggest a rift-related opening of an oceanic basin of the same name during the Permian or later. Collision and the closure of the basin took place late in the Triassic, as is obvious from the Lower Jurassic molasse and the age of high-pressure metamorphism. This suture probably does not extend beyond the Gangmaco–Shunanghu zone. The Upper Permian deposits on the eastern extension of this zone are related to continental rifting that failed to split the sial to the bottom. The Early Jurassic calc-alkaline volcanics, which occur to the north of the Gangmaco–Shuanghu zone, are probably post-collisional and mark the northward dip of the subduction zone. The short distances between the oceanic sutures of Tibet and a poor understanding of the magmatism often disable the establishment of the affinity of igneous rocks to a certain suture bounding the sialic block in which these rocks are presently found. In this case, however, the Early Jurassic volcanics occur to the north of the Gangmaco–Shuanghu ophiolites and are unknown farther east, where this suture is absent.

The **Bangong** oceanic basin undoubtedly existed during the Jurassic. Ophiolites were obducted late in the Jurassic, probably independent of basin closure. No products of Jurassic subduction-related magmatism are known to the south or to the north of the suture. The collision most probably took place prior to the deposition of the Upper Cretaceous red clastics. There are granites emplaced in two phases in the northern Lhasa block to the south of the suture. Geochemical signatures suggest that the early-phase tonalites and granodiorites were emplaced at an active continental margin, whereas the late-phase granitoids are postcollisional [69]. The early-phase granodiorites yield a Rb–Sr whole-rock age of 126 ± 26 Ma and K–Ar biotite ages of 117 and 123 Ma (Early Cretaceous) [68]. The Bangong basin probably opened no later than the Late Permian. This is supported by thick Upper Permian turbidites widespread on the northern margin of the Lhasa block [74]. Triassic basic and intermediate volcanics are preserved in the suture zone [58].

CORRELATION OF STRUCTURAL ZONES AND OCEANIC SUTURES

The Qiangtang zone exhibits two types of Paleozoic sequences. The sequence with Permian flysch is similar to that of the southeastern Pamirs and Karakorum, and the carbonate sequence is similar to that of the central Pamirs. Therefore, Qiangtang corresponds to two zones in the Pamir–Karakorum transect, the central Pamirs and Karakorum.

The southern boundary of the Qiangtang zone is defined by the Bangong suture, which marks an oceanic basin that closed in the mid-Cretaceous time. The southern boundary of the Karakorum zone, the Shyok suture, also traces an oceanic basin that closed in the Mid-Cretaceous. These sutures, offset over some 100 km from each other along the Pamir–Karakorum fault, are probably traces of the same oceanic basin. Subduction in the Shyok basin was directed northward or on both sides, and subduction in the Bangong basin was probably southward. This suggests the existence of a transform fault between them. The Bangong–Shyok basin opened in the Permian or Triassic and existed till the Mid-Cretaceous. The Bangong–Shyok suture is a trace of the Meso-Tethys Ocean. The western extension of the Meso-Tethyan suture probably lies in the Farah Rud zone in southern Afghanistan and Iran [55].

The Gangmaco – Shuanghu basin was initiated in the Permian and existed till the Late Triassic. The northern margin of the basin was active. To the east, the Gangmaco–Shuanghu basin terminated as a continental rift inside the Qiangtang sialic block. This basin is similar in position and evolution to the Rushan–Pshart basin in the Pamirs. Probably, there was a single Rushan–Shuanghu ocean whose suture was offset over some 100 km on the Pamir–Karakorum strike-slip fault (Fig. 2). The opinion generally held that the Rushan–Pshart suture is the extension of the Bangong suture [46, 66, 89, and others] is, in our opinion, incorrect.

The position of the Tisnab–Tianshuihai zone in the Paleozoic structure of the region is similar to that of the

Kurgovat–Yarkant zone in the Pamirs and northwestern Kunlun. These structural zones lie at the extensions of each other. Their sedimentary sequences are largely similar. The Early and Middle Paleozoic in both areas are represented by shallow-water platform-type facies, and the Late Paleozoic is represented by flysch. The direct eastern extension of the Tisnab-Tianshuihai zone is the Songpan zone. It is reasonable to interpret the Kurgovat–Yarkant, Tisnab–Tianshuihai, and Songpan zones as parts of a single Kurgovat–Songpan sialic block.

The southern boundary of the Kurgovat–Songpan block is the Vanch–Taxkorgan suture in the Pamirs and the Lighten and Jinsha sutures in Tibet. They are probably traces of a single Vanch–Jinsha oceanic basin that separated the Kurgovat–Songpan block from the central Pamirs and Qiangtang. There is evidence of the existence of this basin in the Carboniferous and Permian and its closure in the Late Permian to Early Triassic. The northern margin of the oceanic basin was active in the Pamirs and northwestern Kunlun; in Tibet, subduction polarity is uncertain.

In the north, the Kurgovat–Songpan block is bounded by the Kalayhumb–Oytag, Kudi–Subashi, and East Kunlun sutures, which separate this block from the deformed margins of the Tarim and Qaidam platforms. The East Kunlun sutures contain relics of an oceanic basin, whose existence is recorded in the Sinian (?)–Early Paleozoic and from the Late Devonian to Late Permian, and some back-arc basins and island-arc systems that existed in the Silurian–Early Devonian and Carboniferous. The northern margin of the oceanic basin was active. The Kudi–Subashi suture in western Kunlun also contains a record of the existence of an oceanic basin in the Sinian (?)–Early Paleozoic, Late Paleozoic; Triassic. The northern margin was active during the Early Paleozoic; and the southern margin, during the Late Paleozoic. The identical structural positions of the West and East Kunlun oceanic sutures and the similar histories of the basins marked by these sutures suggest that the East and West Kunlun basins were parts of a single Kunlun Ocean and its marginal seas. The Late Paleozoic subduction changed in dip direction on the traverse of the Altyn Tagh.

The Kalayhumb–Oytag suture in the Pamirs is a trace of a back-arc basin that existed in the Carboniferous. This basin is similar to the back-arc basin reconstructed in eastern Kunlun [36]. The main suture of the Kunlun oceanic basin, from which an ensimatic island arc separated the Kalayhumb–Oytag back-arc basin since the Early Carboniferous, is not exposed in the Pamirs. Only the Permian flysch accumulated on the margin of the basin of the Pamirs survived. Probably, this oceanic suture is concealed beneath the Pamirs, which were obducted during the Cenozoic. In this case, the extension of the Kunlun suture with Early Paleozoic ophiolites may extend into Afghanistan. Evidence of the existence of an Early Paleozoic Hindu Kush–Kunlun Ocean is given in [50]. The foothills of the western Hindu Kush only exhibit equivalents of the Carboniferous Kalayhumb ophiolites. However, a thick sequence of metamorphosed basalts associated with greenschists is reported further west in central Afghanistan (Band-i-Baian Mountains) [21]. In western central Afghanistan, these rocks are overlain with angular unconformity by unaltered red sandstones, which grade upward into limestones with Middle-Late Cambrian trilobites [13]. These metabasites are probably fragments of an ancient ophiolitic sequence and trace the extension of the Kunlun suture to the west of the Pamirs.

The Kunlun Ocean separated Tarim and Qaidam from the Pamirs and the Tibet sialic blocks from the Sinian till the Late Paleozoic. The indications of the existence of this oceanic basin are recorded throughout the Paleozoic, except in the Middle Devonian. The Devonian metamorphism, deformations, granites, and Late Devonian molasse reported from Kunlun are interpreted as indicative of a collision between Tibet and Tarim and the closure of an oceanic basin between them during that time [76 and others]. At the same time, these phenomena could be related to accretionary processes on an active continental margin rather than the complete closure of an oceanic basin. No evidence of the repetition of rifting in the latest Devonian to Early Carboniferous has ever been discovered. At the same time, the Kunlun Ocean was again in existence in the Early Carboniferous with a mid-oceanic ridge, ensimatic island arcs, and back-arc basins.

There is an opinion [63, 71, 94] on the existence of a diagonal Paleozoic oceanic suture along the Cenozoic Altyn Tagh strike-slip fault, which separates Tarim from Qaidam and links the Kudi–Subashi suture in western Kunlun with the sutures in the Qilian Shan. This combination seems erroneous. The Early Paleozoic ophiolitic zones to the east of the Altyn Tagh fault, Olongbruk (OL in Fig. 2), South Qilian (SQL), and North Qilian (NQL), which mark sutures of the same names, correlate well with the ophiolitic zones in the Beishan area to the west of the strike-slip fault and 200 km to the north of the Qilian Shan. Oceanic basins in both regions opened in the Cambrian and closed in the Devonian. These basins had a similar structure and similar island arcs and microcontinents [42]. In all probability, the Beishan and Qilian Shan structures are offset relative to each other along a strike-slip [103] or a transform fault [42]. The Beishan–Qilian Shan oceanic basin was separated from the Kunlun Ocean by a continent including the Tarim and Qaidam massifs, whose Proterozoic basements and Sinian cover sequences are composed of similar rock associations.

A belt of ophiolitic mélange with dunite, harzburgite, gabbro, and tholeiitic basalt blocks extends along the Altyn Tagh. The Sm–Nd isochron age of basalts from the Mangya mélange (Ma in Fig. 2) is 481 ± 53 Ma [94]. The basalts include limestone interbeds with Middle Ordovician conodonts (as identified by V.A. Aristov). These are overlain by turbidites consisting of tephroids, intermediate and acid tuffs, and interbedded cherts, hyaloclastites, and calcarenites. Also, finds of Middle and Late Ordovician corals and brachiopods were reported from this sequence [62, 94]. The Altyn Tagh ophiolites mark the suture of an Ordovician oceanic basin. This basin closed during the Silurian. Granitoids with an Ar–Ar age of 432 ± 8 Ma cut through the ophiolites and the margin of the Tarim massif [94]. The Altyn Tagh basin, which separated the Tarim and Qaidam massifs during the Ordovician, probably extended along a transform fault and was fairly narrow [42].

BIOGEOGRAPHY

During the Early Cambrian, High Asia, together with Tarim and the Chinese cratons, was located in the Indo–Australian biogeographic province recognized from trilobites [38, 54]. Common fauna in the territory under consideration probably existed until the Ordovician, when differences in nautiloid and conodont communities arose and marked a weak communication between the North China and South China domains and between them and Australia [54]. Biotic differences between these domains persisted in the Silurian and Early and Middle Devonian and faded away in the Late Devonian [53]. The boundary between these domains in High Asia is the Kunlun Ocean suture.

The data on biotic similarities and differences in East Asia are available for the Carboniferous and Permian. The Visean coral and brachiopod communities in Qiangtang, East Kunlun, and the Qilian Shan do not show any radical differences between them. The Visean coral fauna of the Lhasa and Himalaya blocks is much more sparse, probably due to a different climate or a deeper habitat [93].

During the Early Permian, two biogeographic provinces were distinguished, North Tethyan (Cathaysian and Eurasian Tethys) and South Tethyan (Gondwanan Tethys). The North Tethyan tropical province is characterized by thermophylous fauna of fusulinids, corals, brachiopods, and tropical flora. The South Tethyan nodal nontropical province was an area of glacial and glaciomarine deposits with cryophilic fusulinids, corals, pelecipods, brachiopods, and Glossopteris flora. The contrast between the provinces was particularly striking in the Asselian Age and was smoothed away by the end of the Artinskian. The Early Permian fauna in the Alay (1 in Fig. 2), northern Pamirs (2, 3) and Kunlun (5–8) is North Tethyan [27, 28, 95]. The Sakmarian fauna in the central Pamirs (4 in Fig. 2), Sakmarian and Artinskian faunas in Qiangtang (9–11), the Lhasa zone (12–14), and the Himalayas (15) is South Tethyan [26, 95]. The evidence of a cold climate is provided by glacial and glacial-marine deposits being widespread in most of these zones.

To summarize, Gondwana and Cathaysian blocks were separated in the Early Permian by the Vanch–Jinsha Ocean. During the Late Permian, a tropical climate extended over all of High Asia [28, 95].

EVOLUTION OF THE OCEANIC BASINS

Analysis of geological and biogeographic data on the region suggests the following model of evolution of the Paleozoic and Mesozoic oceanic basins that separated the sialic blocks of present-day High Asia (Figs. 3, 4).

During the Sinian, the Tarim-Qaidam block separated from Indo-Australia, giving rise to the Kunlun oceanic basin. The basin remained narrow during the Cambrian. It expanded considerably during the Ordovician and Silurian. The conclusions on the narrowness or width of these basins is based on biogeographic data. Unfortunately, there is no way of giving a quantitative estimate of basin sizes due to the lack of paleomagnetic data on Tibet and the Pamirs.

During the Devonian, the Tarim–Qaidam microcontinent converged with the sialic Tibet massif. The latter is sometimes interpreted as a Paleozoic microcontinent that split off from Indo-Australia late in the Proterozoic [15 and others], but no reliable arguments in support of this model are available. The suture of an Early Paleozoic oceanic basin that separated the Tibetan block from Gondwana according to this model is also unknown. It seems more probable that Tibet was part of eastern Gondwana together with the South China Craton during the Early Paleozoic [86]. The Middle Devonian convergence of Tarim and Gondwana probably led to a short-term suturing of these sialic masses. The contact was probably transpressive. This collision induced the Devonian orogeny in Kunlun. The collision episode was short-term and not ubiquitous.

The Kurgovat-Songpan block was rifted away from eastern Gondwana in the Early Carboniferous, and the Vanch–Jinsha Ocean opened between them. This basin expanded rapidly and turned into a vast ocean encompassing two of the Earth's climatic belts by the Artinskian. The drift of the Kurgovat–Songpan block in the expanding Vanch–Jinsha Ocean initiated accretionary processes on the Kunlun margin of this sialic block, which collided with an ensimatic island arc (or arcs) at the margin of the Kunlun Ocean.

During the Permian, the Gondwanan margin continued to disintegrate. Continental rifting near this margin gave rise to the Rushan–Shuanghu rift underlain by oceanic crust. The rift was blind in the east (in modern coordinates) and opened into the Vanch–Jinsha Ocean in the west. The Bangong rift basin was also initiated in the Permian and later developed into an ocean of the Meso-Tethyan system. The Permian was the period of the utmost fragmentation of the High Asian territory. During this period, the Vanch–Jinsha basin separated the South China continent and the Kurgovat–Songpan island arc from Gondwana. The Kunlun Ocean separated the Kurgovat–Songpan arc and the Tarim continent. The Gondwanan margin was split by the Rushan–

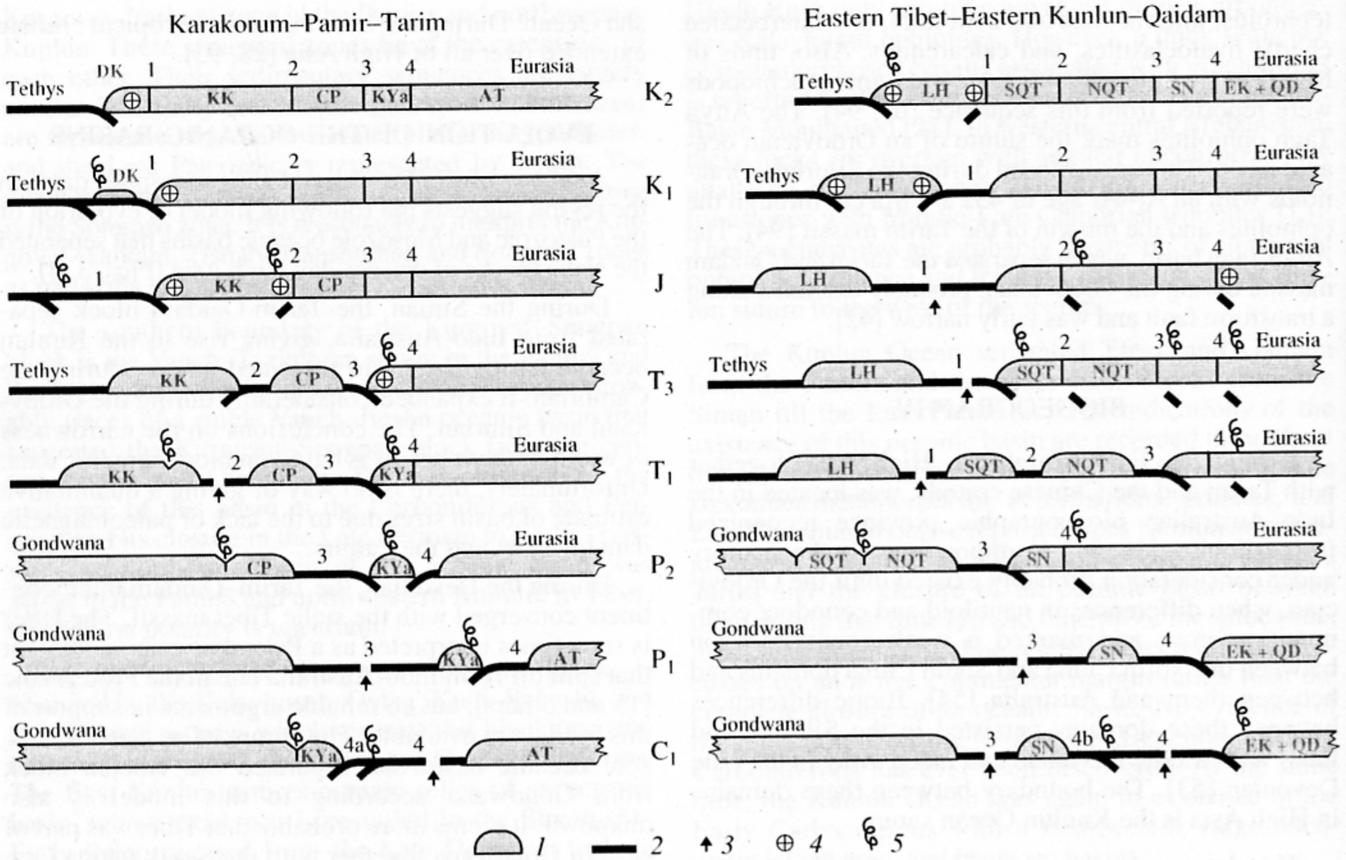

Fig. 3. Geodynamic cross sections. (*1*) Continental crust, (*2*) oceanic crust, (*3*) spreading zones, (*4*) granitic magmatism, (*5*) volcanism. Oceanic basins and their sutures: 1—Bangong and Shyok, 2—Rushan–Shuanghu, 3—Vanch–Jinsha, 4—Kunlun. Back-arc basins of the Kunlun Ocean: 4a—Kalayhumb–Oytag, 4b—East Kunlun. See Fig. 2 for the letter indications.

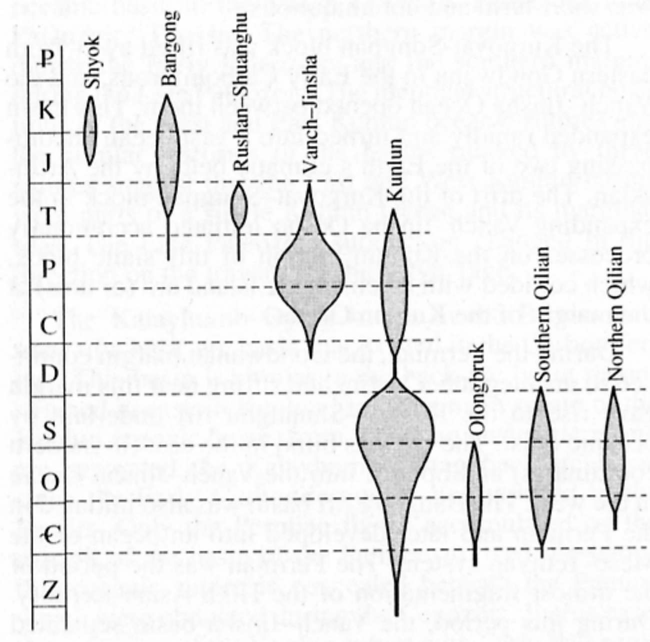

Fig. 4. Diagram of the timing of existence of oceanic basins.

Shuanghu rift, which separated a peninsula encompassing the central Pamirs and Northern Qiangtang. The Bangong continental rift was also located near the edge of Gondwana.

During the Early Permian, the Vanch–Jinsha Ocean separated sialic blocks located in the tropical and nodal non-tropical belts of the Earth. During the Late Permian, all components of future High Asia moved into the tropical belt. This movement was probably accompanied by convergence and shrinking of oceanic space. Collisional processes began in eastern Kunlun, but it is still obscure as to whether they led to the closure of this sector of the Kunlun Ocean or merely to the accretion of an island arc with Qaidam.

During the Late Permian, the sialic Qiangtang–Karakorum block split off Gondwana and the Bangong Ocean opened between them.

The Triassic witnessed the closure of all oceans of the Paleo-Tethys system, Kunlun, Vanch–Jinsha, and Rushan–Shuanghu. As a result, the Pamirs, Karakorum, Kunlun, and much of Tibet to the north of the Bangong suture were welded to the Eurasian continent.

During the Cretaceous, the closure of the oceans of the Meso-Tethys system, the Bangong Ocean and the

Shyok back-arc sea, took place. As a result, Kohistan and the Lhasa block were accreted to the Eurasian continent.

To summarize, the fragmentation of Gondwana was multistage and occupied a time span from the Sinian to Triassic, whereas the suturing of the High Asian sialic blocks to the Eurasian continent took place in two phases in the Triassic and Cretaceous (Indosinian and late Yanshanian orogenic events). The third collision event took place in the Paleogene in response to the closure of the Neo-Tethys Ocean.

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