RUSSIAN JOURNAL OF EARTH SCIENCES, VOL. 5, NO. 3, PAGES 165–184, JUNE 2003

The Vendian-Early Paleozoic History of the Continental Margin of Eastern Paleogondwana, Paleoasian Ocean, and Central Asian Foldbelt

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Abstract. This paper is based on the results of the work done during a long period of time in the framework of the International Project "Atlas of Lithopaleographic, Structural and Geoecological Maps of Central Eurasia". Having generalized the original and published data available for the geologic structure and paleomagnetism of the Altai-Sayan and Ural regions, the Siberian Craton, the East-European Platform, Mongolia, Kazakhstan, and Tien Shan, palinspastic maps have been compiled for the Vendian, Early Cambrian, and Early and Late Ordovician (600, 525, 500, and 450 Ma). The maps depict the composition of the rocks and the environments of their origin. The structure, evolution, and geological history of the Paleoasian Ocean is described as a system of marginal basins and island arcs belonging to the continental margin of the East Paleogondwana (a fragment of the Rodinia Supercontinent), including the early stages of the transformation of the Paleoasian Ocean into a fold-and-nappe structure. The maps are accompanied by numerous cross sections, palinspastic profiles, and maps of some areas, showing the details of individual structural features.

Introduction

The vast territories included between the East European Platform and the Siberian Craton, on the one side, and the Chinese (Tarim) Platform, on the other, have been interpreted as the Ural-Mongolia fold-and-nappe belt [*Muratov,* 1965, 1974; *Zonenshain et al.,* 1990]. This belt is known to be one of the Earth's most complex structural ensembles with a history of a few hundreds of million years, which seems to have begun during the breakup of the Rodinia Supercontinent and ended by the end of the Paleozoic.

This paper is based on the results of the long investigations done in the framework of the international project "Atlas of Lithological, Paleogeographic, Structural, Palinspastic, and Geoecological Maps of Central Eurasia" in 1997–2001 by the geological surveys of Azerbaidzhan, Kazakhstan, Kirgizia, China, Russia, Tadjikistan, Turkmenia, and Uzbekistan in the areas of South Siberia, Mongolia, North China, Kazakhstan, Tien Shan, and Ural [*Fedorenko et al.,* 2000; *Miletenko et al.,* 2001].

A model for the Middle and Late Paleozoic history of the region developed in the framework of this project was published in this journal at the end of 2001 [*Filippova et al.,* 2001]. The authors of this paper also traced the history of the destruction of the northern margin of Rodinia and also of its large fragment, namely, the Eastern Paleogondwana. The latter had obviously included the continental blocks of East Africa, Arabian, Iran, India, Tarim, and North and South China, and also some microcontinents, such as, Syrdariya-Ulutau-North Tien Shan, Aktau-Mointa, Dzhungar, Tuva-Mongolia, South Gobi, and Dzabkhan. The palinspastic reconstructions of these authors show the destruction pattern of East Paleogondwana during the Vendian-Early Paleozoic time and also the formation of structural features of dif-

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Paper number TJE03123.
ISSN: 1681–1208 (online)

The online version of this paper was published 31 July 2003.
URL: http://rjes.wdcb.ru/v05/tje03123/tje03123.htm

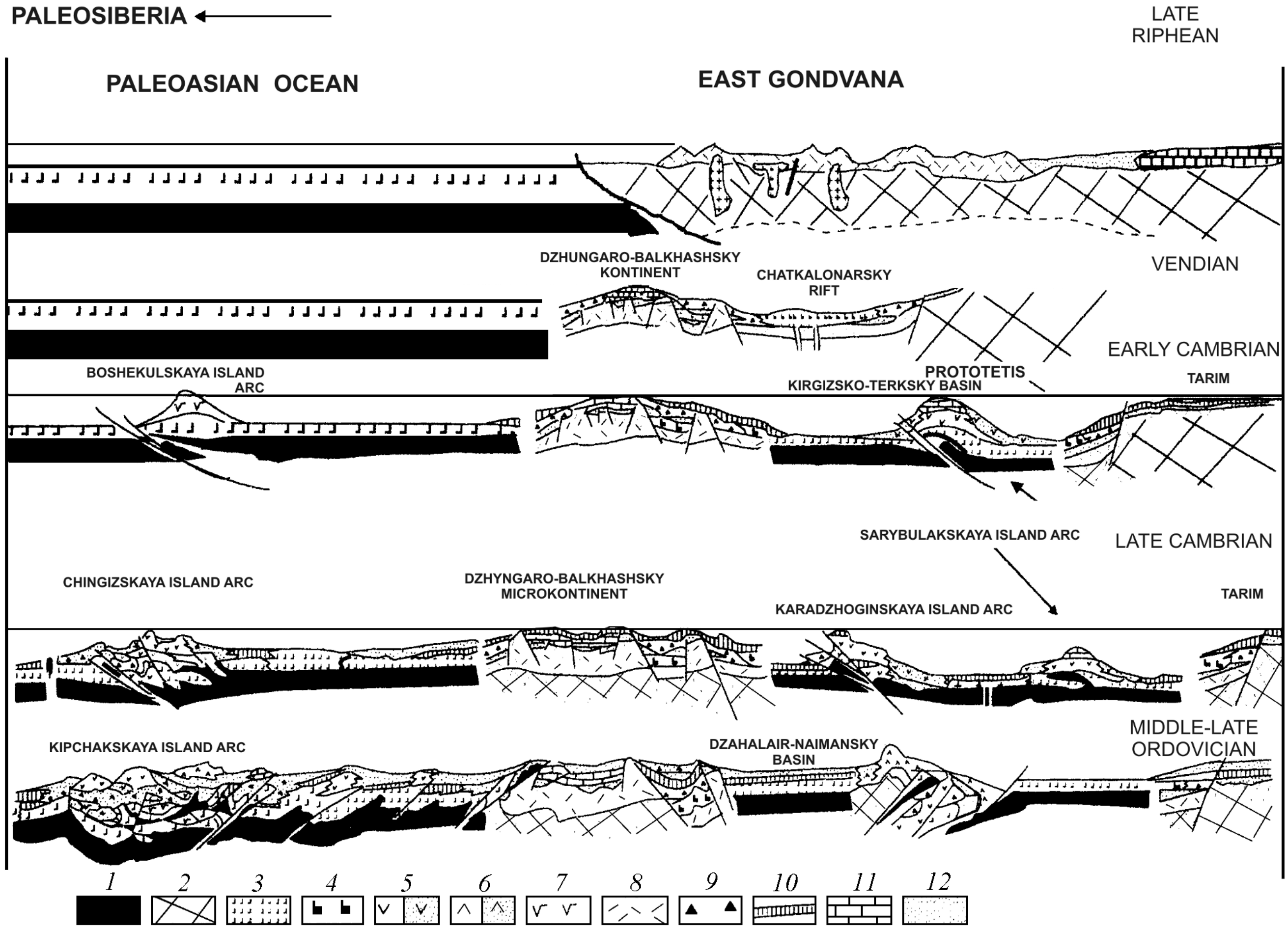


Figure 1. Schematic map of the Late Riphean-Ordovician tectonic evolution of Kazakhstan and northern Tien-Shan.
1 – Oceanic crust, 2 – continental crust, 3 – oceanic crust basalts, 4 – suboceanic basalts of continental rifts, 5 – ensimatic island arc rocks: (a) volcanic rocks, (b) tephroturbidite; (6–7) island arcs with transitional and continental crust; (6) differentiated volcanics (a) and tephroturbidites (b); (7) contrastingly differentiated volcanics and their tuffs; (8) continental, mainly acid, volcanics; (9) olistostroms; (10) siliceous and clayey-siliceous rocks; (11) limestones, (12) terrigenous, mainly quartzose, deposits.

ferent ages in the Paleoasian Ocean, which later composed the Ural-Mongolian fold-and-nappe belt, which had broken off from East Paleogondwana. We interpret the Paleoasian Ocean as a system of marginal basins and island arcs of different ages with a microplate tectonics, which had belonged to the active continental margin of East Paleogondwana. As a starting point, we used a model for the epi-Grenville Rodinia Supercontinent assuming that the structural elements of Central Asia, Baltia, and Siberia had occupied a marginal position relative to Pantalassa [*Khain et al.,* 1993; *Kheraskova,* 1999].

We developed four reconstructions for the Vendian-Ordovician time (600, 525, 500, and 450 Ma). The methods we used were reported earlier [*Filippova et al.,* 2001]. While compiling our maps we used the earlier reconstructions available for the largest structural element of the region, namely, for the Paleoasian Ocean, which were developed with the participation of some authors of this paper [*Didenko et al.,* 1994; *Kheraskova,* 1997; *Mossakovskii et al.,* 1992, 1996; *Pecherskii and Didenko,* 1996; *Zonenshain et al.,* 1990]. In addition, to reconstruct the Ordovician time, we used the idea of the existence of one island-arc system offered by A. M. C. Sengör and coauthors [*Sengör et al.,* 1994, 1996]. Of great importance for this work were new paleomagnetic data and also a great number of geological and geochronological data obtained during the previous years for the territories of Siberia, Ural, Tien Shan, and Kazakhstan, including the data reported by the participants of the project for compiling the Atlas of Electronic Maps [*Belichenko et al.,* 1994; *Berzin et al.,* 1994; *Bukharin et al.,* 1985, 1996; *Didenko et al.,* 2001; *Gruschka et al.,* 1997; *Khain et al.,* 2001; *Kiselev,* 2001; *Koronovskii,* 2001; *Kurenkov et al.,* 2002; *Maksumova et al.,* 2001; *Mossakovskii et al.,* 1996; *Puchkov,* 2000]. The positions of the Siberian and East European continents were reconstructed using the paleomagnetic poles of the respective ages [*Smethurst et al.,* 1998; *Torsvik et al.,* 1996]. The positions of the Gondwana continental blocks were taken to be after [*Li and Powell,* 2001].

In addition to geodynamic and palinspastic reconstructions, the study described included the generalization of the data available for the structure and specific accumulation of Vendian and Early Paleozoic sediments and volcanic rocks, and also for the geodynamics of major fracture zones. It should be noted that compared to the previous reconstructions, mainly based on the structure of the foldbelts, while continental blocks were assumed to serve as a frame, our reconstruction includes the specifics of the geodynamic evolution and sedimentation in the inner parts of the continents, mainly in the Siberian and East European platforms.

As reported by many investigators [*Pickering and Smith,* 1995; *Rogers,* 1996; *Smethurst et al.,* 1998; *Torsvik et al.,* 1996], a huge supercontinent, Rodinia, originated in Late Riphean time (1000–1100 Ma) as a result of the Grenville orogeny, which included all preexisting Precambrian continental massifs. The continental blocks of Kazakhstan, Northern Tien-Shan, and Southern Siberia were obviously located at the margins of this supercontinent, in its so-called East Gondwana part and belonged to a continental margin at the contact with Pantalassa. This follows from the fact that the Grenville orogeny resulted in the obduction of the passive margin rocks and ophiolites over the rocks of the continental shelf [*Khain et al.,* 1993; *Kheraskova et al.,* 1995]. The process of that obduction was completed by the intrusion of granites and granitization dated 1050–1100 Ma. As follows from our investigations [*Kheraskova et al.,* 1995], after the Grenville orogeny, which resulted in the formation of the Rodinia Supercontinent, an Andean-type continental margin was formed along its NNW edge, or a marginal volcanic belt (Figure 1) originated with its terrestrial volcanic rocks, mainly rhyolites and some ignimbrites, dated 900–800 Ma. Epi-Grenville platform sediments accumulated in the more central parts of the continent, represented by mainly terrigenous, often quartzitic rock sequences with acid tuff interlayers. Later, the volcanic belt and partially the edge of the continent with its epi-Grenville sediments were destroyed during rifting and spreading events, yet, some of their fragments were preserved in the continental blocks (microcontinents) of modern southern Siberia, Kazakhstan, northern Tien Shan, and also in Iran, northwest India, and northeast Africa.

End of the Riphean and the Vendian (650–540 Ma)

The end of the Riphean and the beginning of the Vendian (700–600 Ma) witnessed the beginning of the Rodinia breakup [*Hogan and Gilbert,* 1998; *Pickering and Smith,* 1995]. The northern margin of breaking Rodinia, corresponding to the Baltic and East Paleogondwana cratons, was active along its boundary with Pantalassa during a time interval of 650–600 Ma (Figure 2). It included a system of island arcs, which separated a large marginal basin from Pantalassa, which has been referred to by *Zonenshain et al.,* [1990] as Paleoasian Ocean.

The island-arc uplifts of that time are traced by the occurrences of differentiated basalt-rhyolite and basaltic andesite volcanism and also by frontal accretionary prisms. The latter include ophiolite slabs of Late Riphean (1010–1035 and 790 Ma) and Neoproterozoic (570 Ma) ages [*Gusev and Khain,* 1995; *Khain et al.,* 1999], as well as sequences of tuffaceous turbidite. The subduction processes that operated in this continental margin seem to have induced the rifting and breakup of Rodinia. For example, an extensive rift system arose at the NW margin of East Paleogondwana. Only fragments of these paleorifts can be observed in the present-day structure, which are best preserved in the west of Central Kazakhstan. More often merely one side of a paleorift can be observed, because the subsequent spreading that operated at the end of the Vendian-Cambrian separated and removed its opposite edge to a great distance. Examples are the fragments observed in the marginal parts of the Tuva-Mongolia and Dzabkhan continental massifs and in the north of Tarim.

Rifting also operated in the Baltia Continent, where the Central Russian system of aulacogens originated (Figure 3) [*Kheraskova et al.,* 2001b]. It is possible that rifting was initiated in this region by the origin of a shear zone between transform faults (Rybinsk and Vologda transform faults). The formation of a shear zone resulted in the right-lateral motion and clockwise rotation of Baltiya, which is proved by paleomagnetic data [*Didenko et al.,* 2000].

Variegated terrigenous rocks of arcose, polymictic, and less common quartz composition accumulated in all rifts (Figure 4), amounting to 1500 m in thickness, and drastically pinch out beyond the grabens. They are combined with basic and acid volcanic rocks. The basalts are distinguished by the high contents of K, Ti, and P. Underwater landslide accumulations are often observed at the foot of tectonic scarps, the rock debris often including the material of glacial origin [*Chumakov,* 1978; *Osokin and Tyzhinov,* 1998]. The above evidence suggests the horst-graben topography. The presence of glacial material confirms the paleomagnetic data suggesting that the Laurentian-Amazonian-African margin of the Rodinia residual continent was in the close vicinity of the South Pole (see Figure 2), although the glacial deposits of that time locally extend as far as the equator (Tarim). The deposits include 2 or 3 members of tillite. The oldest of them has been dated 600 Ma [*Karpukhina et al.,* 1999]. The youngest Baikonur member is restricted to a boundary between the Neoproterozoic and Cambrian rocks. The inferred areas of continental and mountain glaciation, where fragments of the glacier base are preserved, are believed to have been located in Tarim, North Tien Shan, and Fennoscandia [*Chumakov,* 1978; *Zubtsov,* 1972]. The Vendian rift systems had separated and isolated a number of continental blocks at the northwestern margin of Rodinia, which are now known as the Tarim, Syrdariya-Ulutau-North Tien Shan, Aktau-Mointa, and Tuva-Mongolia terrains.

The rocks of the continental shelf have been preserved in all continental blocks that border the northern active continental margin of the dismembered Rodinia. They vary in

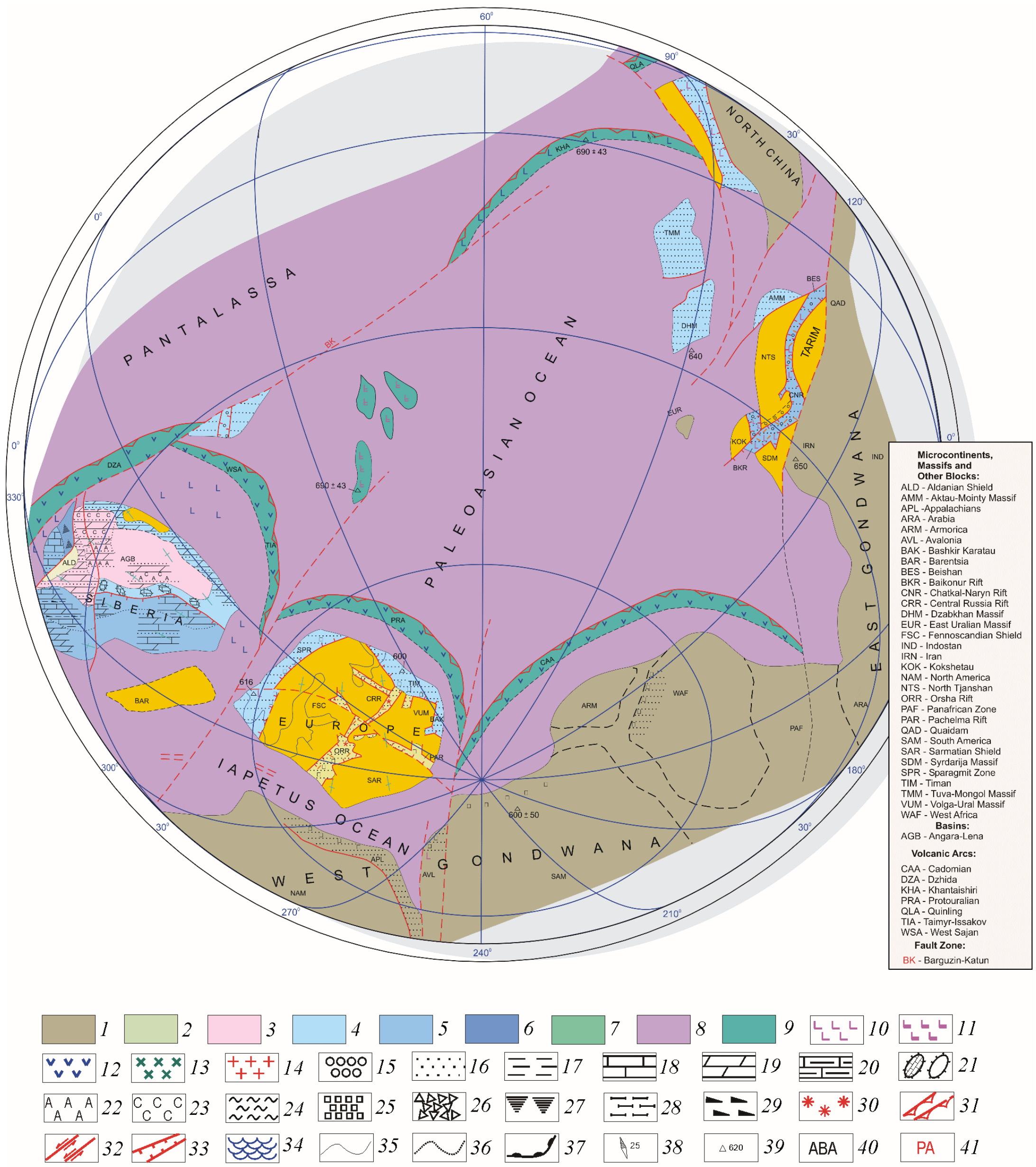


Figure 2. Palinspastic map of Central Eurasia for the beginning of the Vendian (600 million years). The legend for Figures 2, 6, 9, and 10: (1–9) paleogeographic conditions: (1) land devoid of sediments, (2) lowland, (3) lagoons and closed salt-bearing basins, (4) inner and coastal shallow-sea shelf, (5) outer open shelf, (6) bathial slopes and foothills of continents and island arcs, (7) dissected island arcs, (8) oceanic and marginal-sea abyssal plains, (9) sea-floor mounts (intraoceanic heights); (10–14) igneous rocks (indicators): (10) oceanic tholeitic basalts, (11) subalkalic basalts of oceanic islands, (12) calc-alkalic volcanics of island arcs, (13) island-arc granites, (14) granites of collision origin; (15–31) sedimentary complexes: (15) coarse-clastic sandstones and conglomerates, (16) argillaceous siltstones and

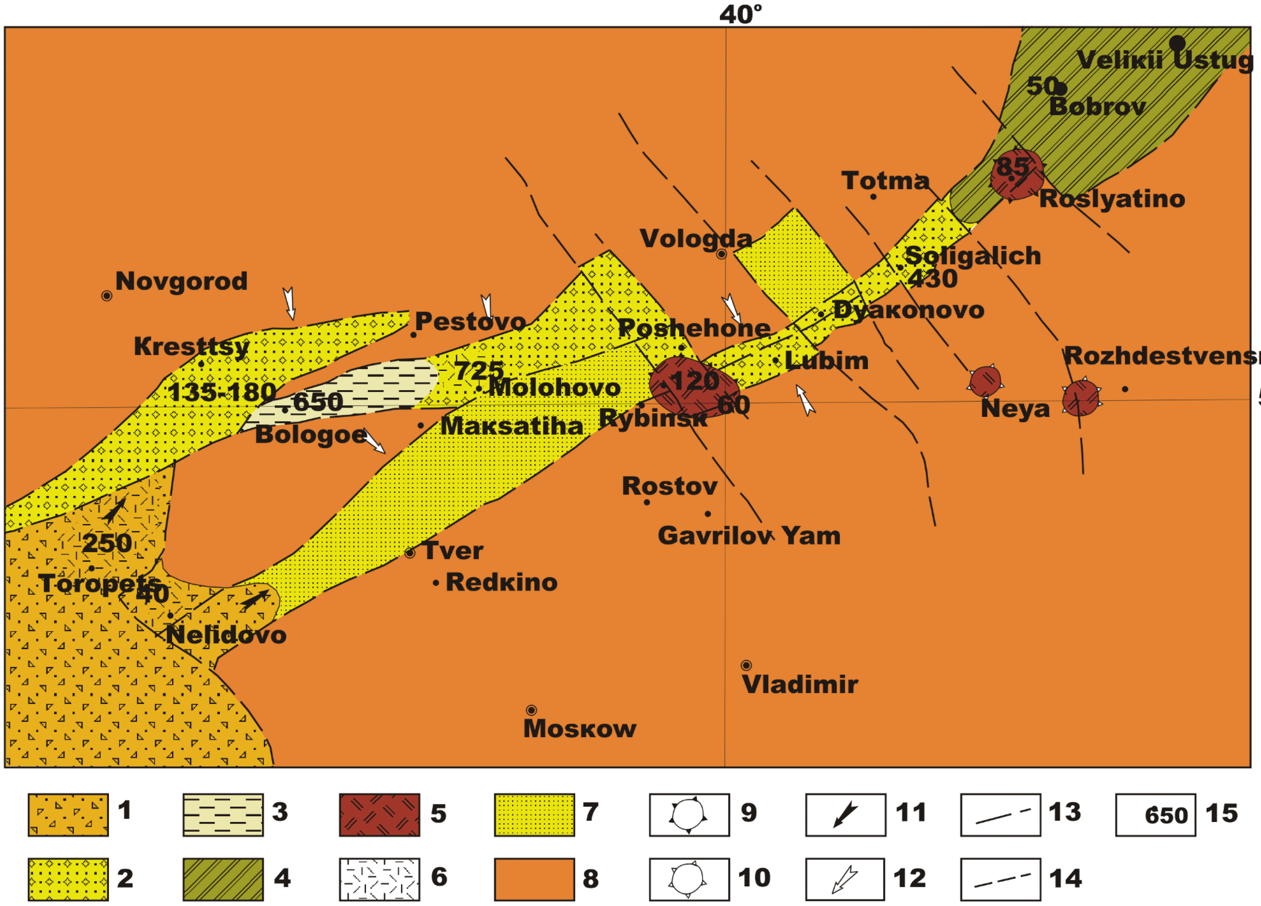
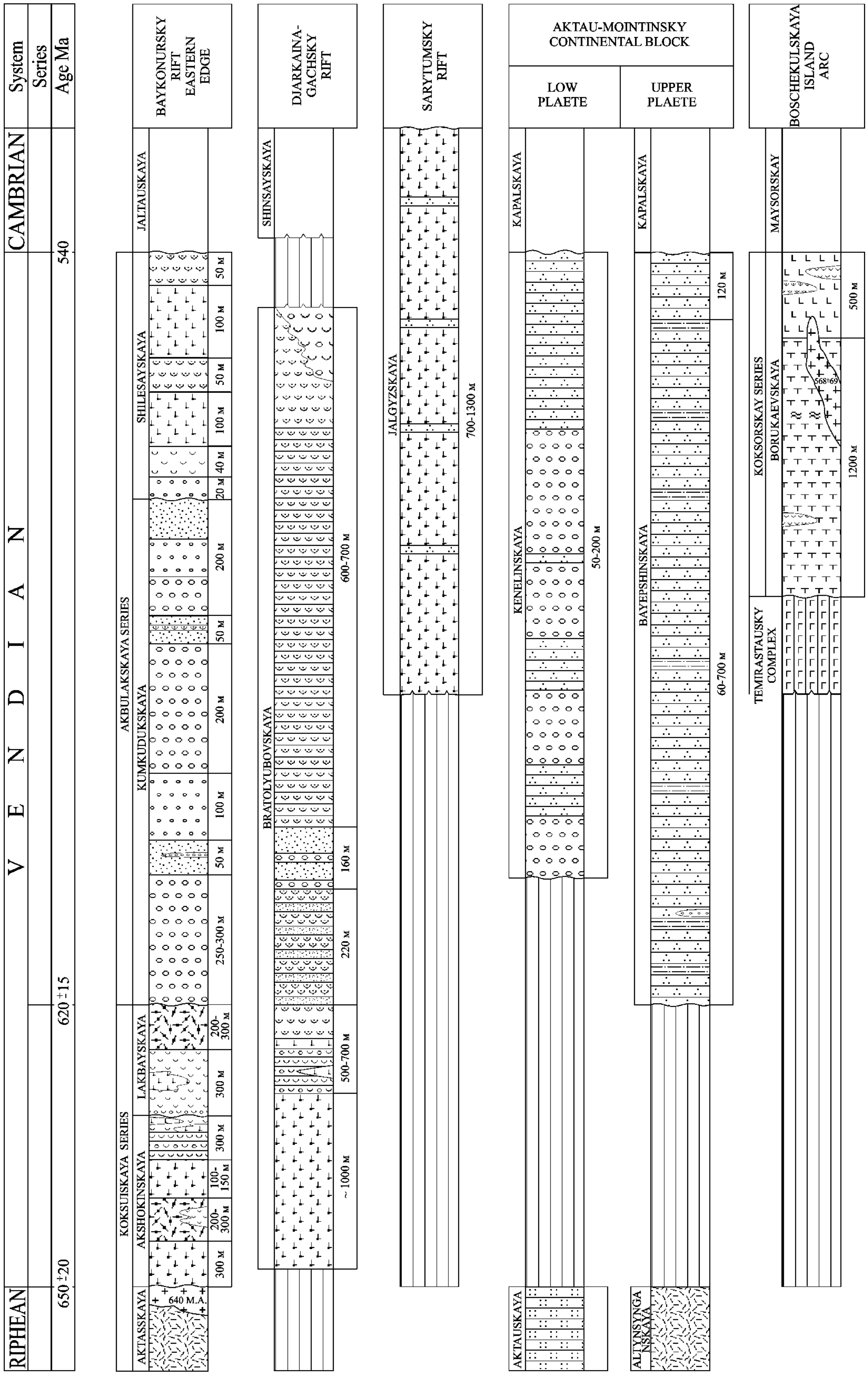


Figure 3. Schematic lithologic and paleogeographic map of the Middle Russian paleorifts for the end of the Late Riphean and Early Vendian.
(1–4) facies: (1) fluvial deposits with glacial materials, (2) alluvial-proluvial red beds, (3) variegated sands and clays of shallow-sea and lake origin, (4) variegated sandy and clayey deposits of shallow-sea origin, (5) crystal-clastic tuff and occasional acid lava, (6) tuffite and pyroclastic sedimentary rocks, (7) undifferentiated deposits mapped from seismic profiling data, (8) areas of eroded or missing deposits of the Late Riphean and Lower Vendian top, (9) inferred volcanic centers, (10) inferred volcanic centers eroded in Late Vendian time, (11) direction of the removal of glacial clastic material, (12) direction of the removal of mature clastic deposits, such as the products of the erosion of the Riphean platform sediments, (13) active faults, (14) facies boundaries, (15) sites of drill holes and rock thickness in meters.

lithology depending on their latitudinal positions (see Figure 4). Terrigenous and carbonate sediments had accumulated in the shelf areas of Paleosiberia located close to the equator. The Angara-Lena evaporite basin had began to form in this area at the end of the Vendian, being shut off from the open shelf by a system of reef massifs [*Astashkin et al.,* 1984].

The Paleoasian Ocean had existed during the Vendian as a relatively simple structure. It is possible that it had been separated into several basins, such as the Sayan, Agardak,

sandstones, (17) fine-clastic (mainly clays), (18) limestones, (19) dolomites, (20) marl and marly dolomite, (21) bioherms (reef masses), (22) gypsum and anhydrite, (23) rock and potassium salts, (24) siliceous rocks (jasper and phthanite), (25) glacial deposits, (26) olistostromes, (27) turbidite and flysch, (28) anaerobic clay and shale, (29) bituminous sediments, (30) red beds, (31) subduction zones(deep sea trench, (32) transform faults and large shear zones, (33) continental rifts, (34) accretionary prisms and forearc terraces; other symbols: (35) outlines of paleogeographic environments; (36) boundaries between facies complexes, (37) outlines of carbonate platforms, (38) paleomagnetic vectors and paleolatitude values, (39) isotopic age, (40) names of structural elements, (41) names of major faults.


System
Series
Age Ma
CAMBRIAN
V E N D I A N
RIPHEAN
540
620 ± 15
650 ± 20
BAYKONURSKY RIFT EASTERN EDGE
DJARKAINA-GACHSKY RIFT
SARYTUMSKY RIFT
AKTAU-MOINTINSKY CONTINENTAL BLOCK
LOW PLAETE
UPPER PLAETE
BOSCHEKULSKAYA ISLAND ARC
JALTAUSKAYA
SHILESAYSKAYA
AKBULAKSKAYA SERIES
KUMKUDUKSKAYA
LAKBAYSKAYA
KOKSUISKAYA SERIES
AKSHOKINSKAYA
AKTASSKAYA
640 M.A.
SHINSAYSKAYA
BRATOLYUBOVSKAYA
JALGYZSKAYA
KAPALSKAYA
KENELINSKAYA
AKTAUSKAYA
BAYEPSHINSKAYA
ALTYNSYNGANSKAYA
MAYSORSKAY
KOKSORSKAY SERIES
BORUKAEVSKAYA
TEMIRASTAUSKY COMPLEX
568±69
50 м
100 м
40 м
20 м
200 м
250-300 м
300 м
100-150 м
200-300 м
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700-1300 м
50-200 м
120 м
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500 м
1200 м

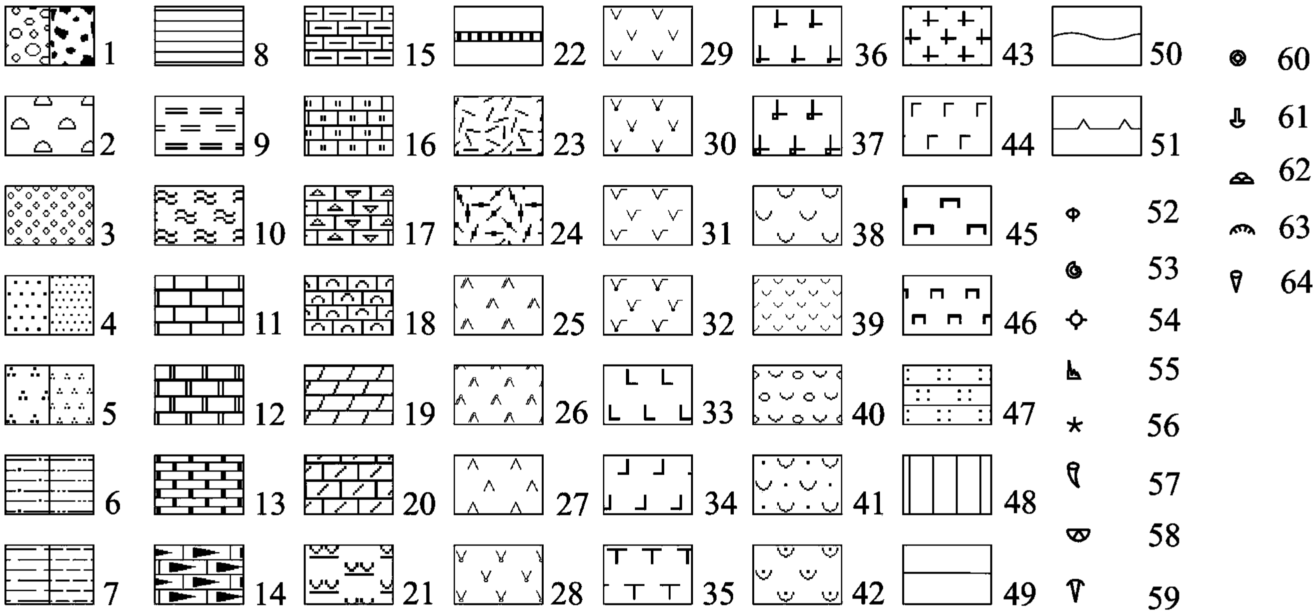


Figure 4. Correlation of the Vendian rock sequences in Central Kazakhstan.
(1) Polymictic conglomerates and olistostromes, (2) tillite-like conglomerates, (3) gravelstone, (4) polymictic sandstone (sand), (5) quartz and quartz-feldspar sandstones (sands), (6) siltstone, (7) argillite and phyllite (clay), (8) black and dark gray carbonaceous siltstone and argillite (black shale), (9) phthanite and dark gray chert, (10) jasper and various kinds of chert, (11) undifferentiated limestones, (12) thick bedded and massive limestone, (13) dark thin-bedded limestone, (14) bituminous limestone, (15) argillaceous limestone and marl, (16) siliceous limestone, (17) stratified carbonate breccia with fragments of irregular forms, (18) clastic organic limestone, (19) dolomite, (20) dolomitized limestone, (21) tuff and tuffite turbidite, (22) phosphorite, (23) rhyolite, (24) trachyrhyolite, (25) rhyodacite, (26) trachyrhyodacite, (27) dacite, (28) trachydacite, (29) andesite, (30) trachyandesite, (31) basaltic andesite, (32) trachybasaltic andesite, (33) basalt, (34) picritic basalt, (35) tholeitic basalt, (36) trachybasalt, (37) alkali basaltic rocks, (38) tuff, (39) fine ash tuff, (40) tuff conglomerate, (41) tuffaceous sandstone, (42) sedimentary pyroclastic rock (tuffite), (43) plagiogranite, (44) gabbro, (45) pyroxenite and hornblende, (46) peridotite, (47) orthoquartzite after sedimentary rocks, (48) break in sedimentation, sediments unknown, (49) stratigraphic conformity, (50) erosion, unconformity, (51) tectonic contact, (52) phosphate, (53) marine microfauna (shells), (54) radiolarias, (55) conodonts, (56) sponges, (57) archaeothyathids, (58) brachiopods, (59) trilobites, (60) corals, (61) micro problems, (62) algae, (63) stromatolites, (64) chiolite.

and Kazakhstan basins, by the Siberia-Baltiya [*Mossakovskii et al.,* 1996], Barguzin-Katun, and other fracture zones.

Information for the composition and structure of the oceanic crust in the Vendian Paleoasian Ocean can be derived from the composition of the ophiolites that had been preserved mainly in the accretionary prisms of the Vendian and Cambrian island arcs [*Dergunov,* 1989; *Dergunov and Kheraskov,* 1985; *Kepezhinskas et al.,* 1991; *Kheraskov,* 1979; *Kurenkov et al.,* 2002; *Kheraskova et al.,* 1985].

The most northern Sayan Basin had been partially inherited from the Riphean Ocean. The basalts of its oceanic crust are highly alkaline and have high Ti contents, this making them similar to continental basalts. Mainly black shales and phthanite had been deposited in this basin. The exception is the near-equator zone of high biological activity on some intraoceanic mounts (Batenevo, Gornaya Shora, Baratal, et al.), where the Riphean oceanic crust had been crowded. The end of the Vendian had been marked by mostly carbonate accumulation (Figure 5). In some areas the growth of intraoceanic mounts had been accompanied by intraplate subalkalic basalt flows, dated 690±43 Ma [*Vladimirov et al.,* 1999].

The most of the Agardak Basin had been subducted. The fragments of its rocks have been preserved in the Kobdo-Darib segment of the Khantaishir Island Arc and in the Agardak suture zone. It appears that this arc had originated in the place of an old fracture zone that had divided the Sayan and Agardak basins. The melanocratic basement of this zone has been dated 695±25 and 570±20 Ma [*Khain et al.,* 2001; *Konnikov et al.,* 1994]. As follows from the data reported by *Gonigberg* [1995], the composition of the Agardak basalts suggests their rift origin. The northeastern side of the Agardak Basin had been in contact with the Eastern Paleogondwana protocontinent and had a well developed terrigenous shelf. It appears that there had been a continental slope with terrigenous turbidite sedimentation.

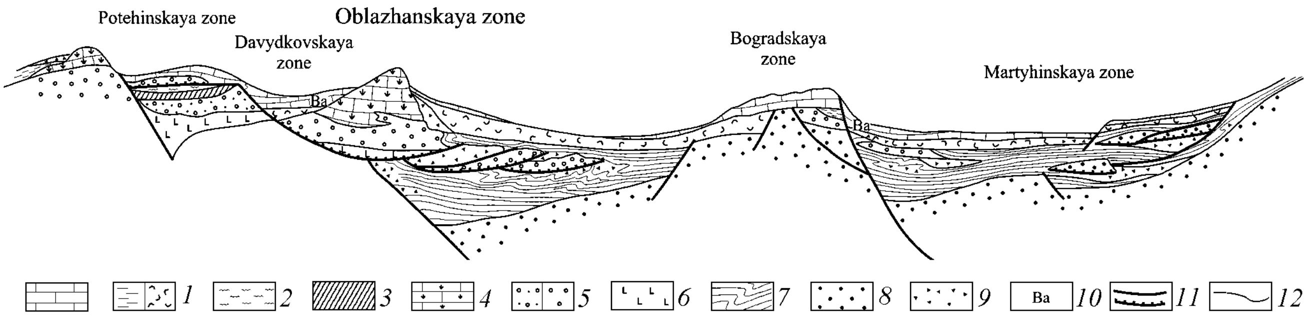


Figure 5. Inferred structure of the Batenev intraoceanic mount of Vendian-Middle Cambrian age. (1) Varved limestone with a high Ba content in the lower rocks of the Middle Cambrian; (2) tuffite, ash-bearing limestone, and carbonaceous-siliceous shale (a); same in shallow-sea rocks (b); (3) ash limestone of conglomerate and breccia structure in the upper interval of the Lower Cambrian; (4) carbonaceous limestone in the upper part of the Lower Cambrian; (5) bioclastic and reef limestone at the base of the Lower Cambrian; (6) dolomitized calcarenite and calcilutite with interlayers of oncolite and fenestrate varieties (a) and interlayers of organoclastic varieties of Vendian-Early Cambrian rocks (b); (7) Vendian subalkalic basalt; (8) Vendian-Early Cambrian carbonaceous carbonate turbidite; (9) Vendian dolomitized calcarenite and calcilutite; (10) carbonate breccias of underwater slumping origin; (11) barite mineralization; (12) geologic boundaries and contacts between landslide slabs; (13) normal faults.

This is indicated by the great thickness of graben rock facies (up to 5–6 km) in the perioceanic rift system in the area of the Kuruk-Tag Ridge in the Tarim outskirts. It appears that one of the preserved fragments of the continental slope material is the oligomictic flysch now occurring as an allochthone over the rocks of the Tuva-Mongolia Massif [*Kheraskova et al.,* 1987].

The most southern Kazakhstan Basin had also bordered the passive margin of the East Paleogondwana. In the present-day structure the rocks of the latter compose the basement of the Boshchekul ensimatic island arc (see Figure 4). An ophiolite belt has been mapped there. Its melanocratic basement has been dated 560±59 Ma [*Khromykh,* 1986].

At the end of the Vendian, along with destructive activity, the Protoural and Kadoma island arcs collided with the continental blocks. The collision was most extensive along the eastern periphery of the Baltia (in the modern coordinates). For instance, in the Timan Ridge the collision of the continent with the island arc resulted in the addition of clastic materials from the island arc to the edge of Baltia, which resulted in the accumulation of conglomerates consisting of andesite fragments [*Olovyanishnikov,* 1998]. It appears that a collision with the Protoural island arc and the formation of a deformation front were responsible for the formation of a basement in the southern segment of the Caspian Basin (Astrakhan-Aktyubinsk or East Caspian block) [*Volozh et al.,* 1993].

A shallow fresh-water basin was formed at the end of the Vendian in the central part of the Baltiya continent. Clastic material was transported to this basin not only from the Volga-Ural uplift, like in the earlier time, but also from the side of the Pechora segment of the proto-Ural Island Arc [*Andreeva et al.,* 2001].

Early Cambrian (540–520 Ma)

This period of time witnessed the continuing destruction of the eastern edge of Paleogondwana and the partial destruction of the Vendian rift systems caused by the intensive formation of new oceanic crust (Figure 6). This activity resulted in the detachment of the Syrdariya-Ulutau-North Tienshan, Dzhungar-Balkhash-North Tarim-Tsaidam, and Kokchetav microcontinents from the East Paleogondwana [*Kheraskova,* 1999; *Kheraskova,* 1997; *Lomize et al.,* 1997]. This resulted in the formation of the Protothetis marginal basins (see Figure 1). This seems to have been associated with the subduction under East Paleogondwana and with movements along the fracture zones. The detachment of the continental blocks and their drifting into the equatorial regions of the Paleoasian Ocean were recorded by the onset of their transgression and by the replacement of the terrigenous sedimentation by the accumulation of carbonates (see the Aktau-Monta continental block in Figure 1), similar to the sediments of the Vendian intraoceanic mounts. At the beginning of the Cambrian phosphorite deposits accumulated as a result of high biological productivity on some detached blocks and on intraoceanic rises in the equatorial zone. Archaecyathid-algal bioherms, as well as small reef massifs, arose during the later half of the Early Cambrian on intraoceanic highs, on some island-arc hills, and on some detached rock masses. These highs and massifs were distinguished by their horst-and-graben topography (see Figure 5). Carbonate and clastic-carbonate flysch, as well as landslide breccias including blocks of collapsed bioherms, accumulated in the grabens between the elevated blocks and also on the slopes.

The accumulation of carbonaceous-argillaceous sediments

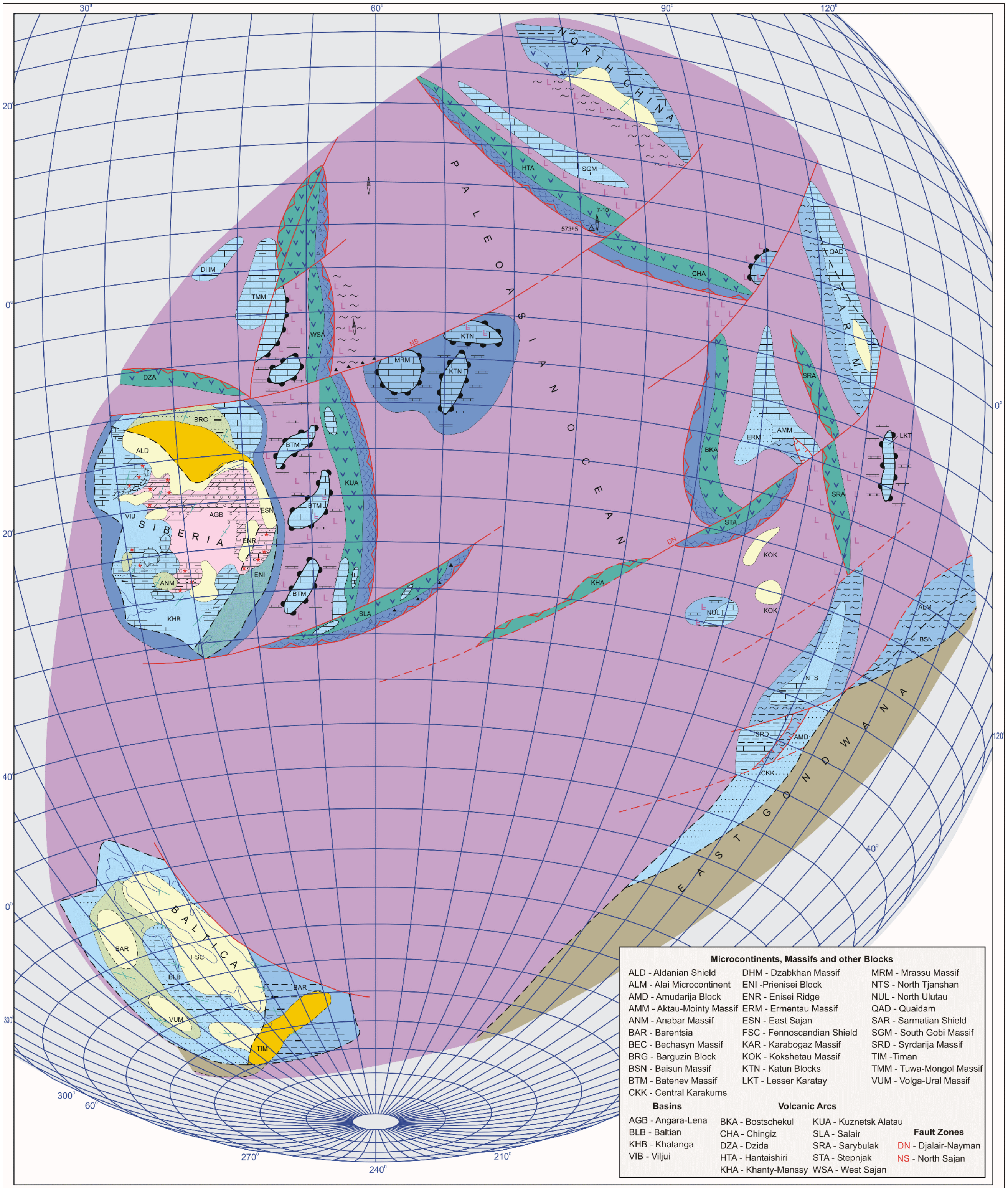
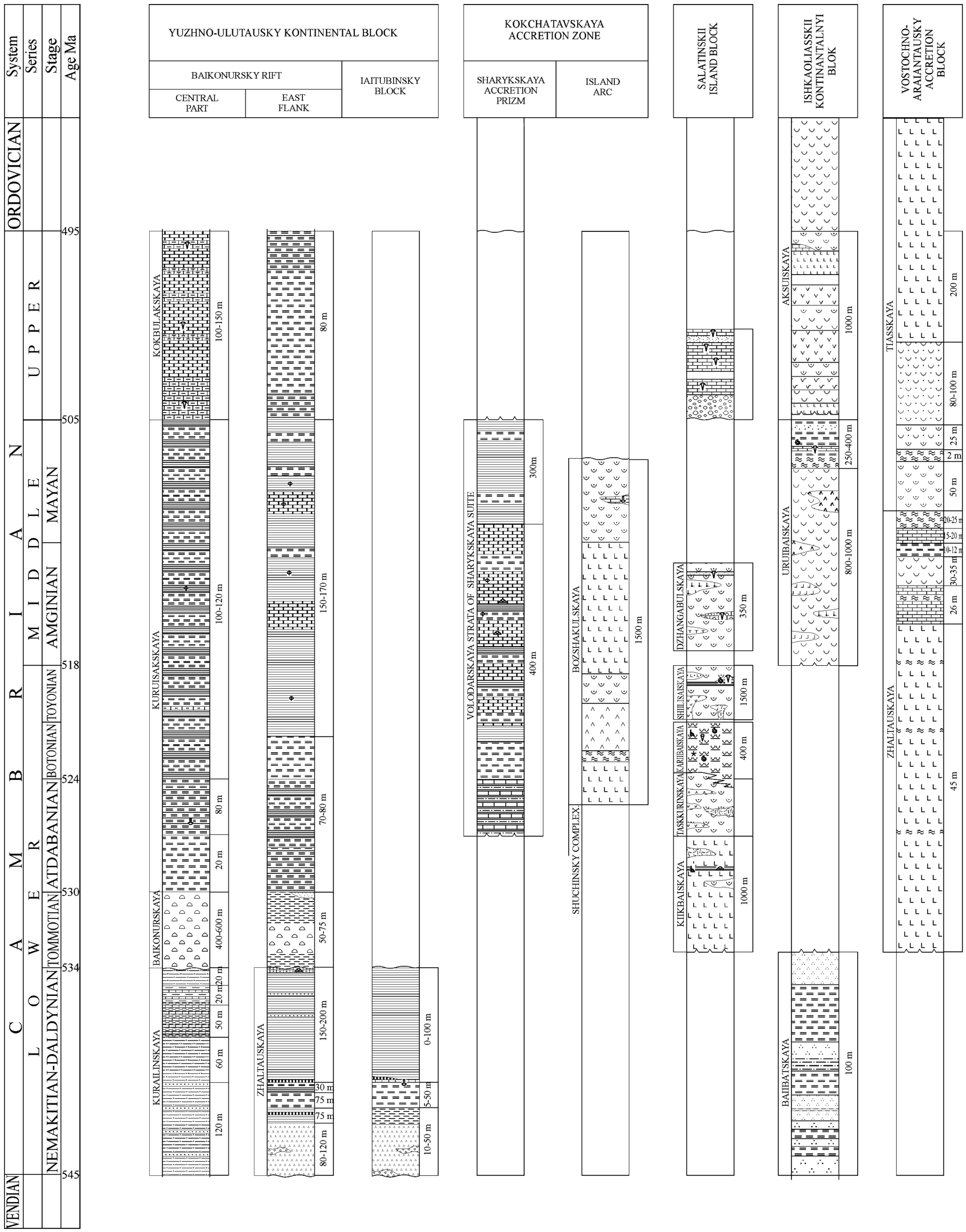


Figure 6. Palinspastic map of Central Eurasia for the Early Cambrian (520 Ma). See Figure 2 for the legend.


System
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LOWER
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AMGINIAN
TOYONIAN
BOTONIAN
ATDABANIAN
TOMMOTIAN
NEMAKITIAN-DALDYNIAN
VENDIAN
495
505
518
524
530
534
545
YUZHNO-ULUTAUSKY KONTINENTAL BLOCK
BAIKONURSKY RIFT
CENTRAL PART
EAST FLANK
IAITUBINSKY BLOCK
KOKCHATAVSKAYA ACCRETION ZONE
SHARYKSKAYA ACCRETION PRIZM
ISLAND ARC
SALATINSKII ISLAND BLOCK
ISHKAOLIASSKII KONTINANTALNYI BLOK
VOSTOCHNO-ARAIANTAUSKY ACCRETION BLOCK
KOKBULAKSKAYA
KURUISAKSKAYA
BAIKONURSKAYA
KURAILINSKAYA
ZHALTAUSKAYA
VOLODARSKAYA STRATA OF SHARYKSKAYA SUITE
BOZSHAKULSKAYA
SHUCHINSKY COMPLEX
DZHANGABULSKAYA
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TASSKURINSKAYA
KIIKBAISKAYA
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100-150 m
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20 m
50 m
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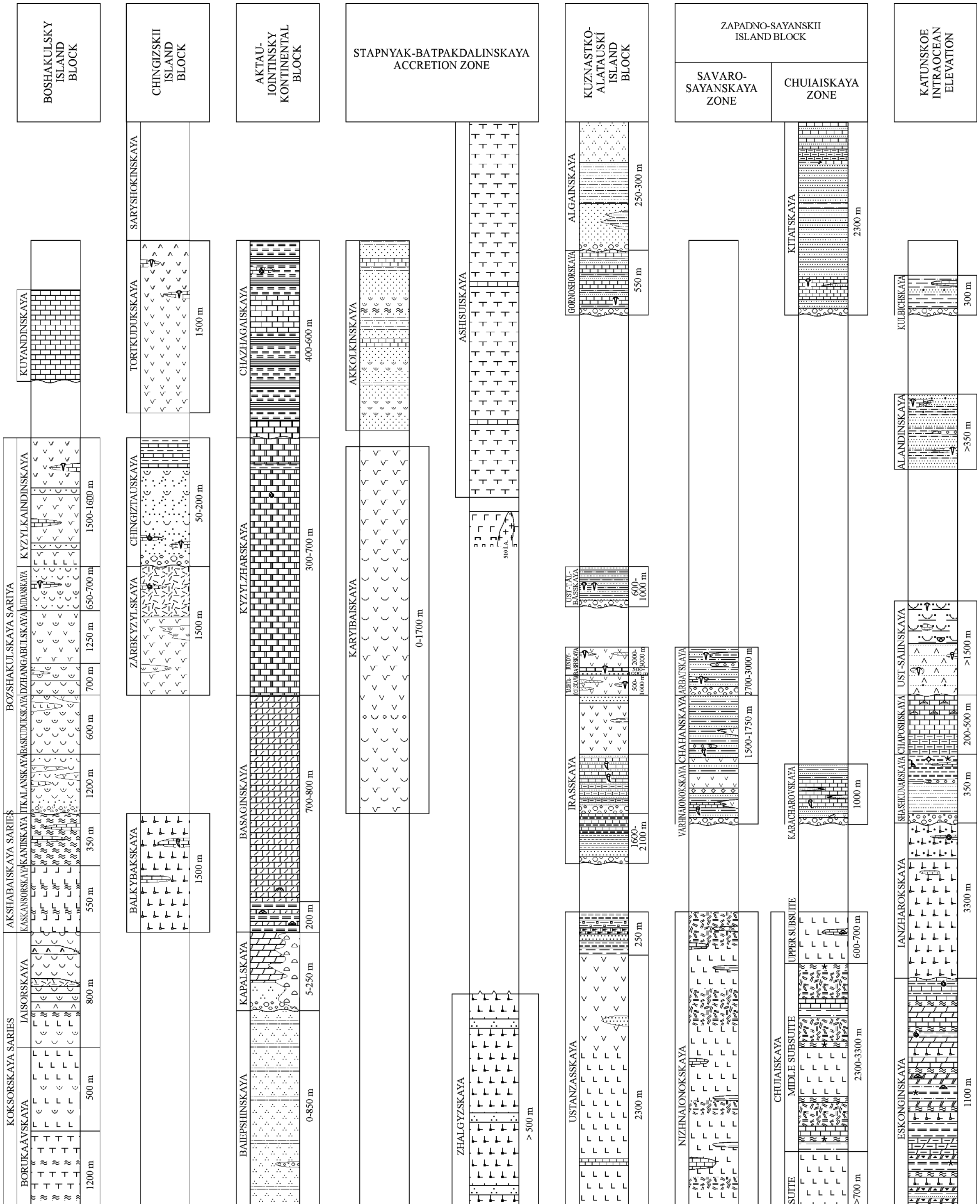

Figure 7. Correlation of the sections of the Vendian-Cambrian rocks of Kazakhstan and South Siberia, based on the data of N. A. Gerasimova, M. Z. Novikova, N. N. Kheraskov, B. F. Khromykh, and C. P. Shokalskii. See Figure 4 for the legend.

dominated also in the North-China and North-Tarim blocks, in the Baltia Continent, and on the shelf and slope of East Paleogondwana. Carbonaceous sediments prevailed in the Baikonur-Major Karatau rift basin, inherited from the Vendian epoch (see Figure 1). Stagnation and condensed sedimentation were predominant there. The Lower Cambrian rocks are represented by relatively deep-sea carbonaceous-argillaceous-siliceous and carbonaceous-siliceous sediments. The sediments are enriched in heavy metals (V, Ag, Pb, Zn, U, Ba, P, and others), this suggesting the effects of hydrothermal activity. It is possible that the phosphatization and carbonization of the Early Cambrian deposits was facilitated by the mantle degassing during the formation of the oceanic crust and by intraplate basalt volcanism.

The emergence of continental blocks (terrains) in the internal areas of the Paleoasian Ocean resulted in the complication of its internal structure and in the formation of stacking zones in the oceanic lithosphere and to their transformation, beginning from the Atdabanian time, to island arcs which concentrated around the detached continental blocks and intraoceanic uplifts (see Figures 1, 6, 7).

The most characteristic feature of the Early Cambrian epoch was the formation of the extensive system of the Kazakhstan and Tien-Shan island arcs. The Early Cambrian island arcs are distinguished by a variety of volcanic events. The Boshchekul ensimatic arc was dominated by contrasting basalt and rhyolite volcanism of low explosivity [*Geology of North Kazakhstan,* 1987; *Samygin and Kheraskova,* 1994]. The volcanic activity of the Darib-Dzhida island arc was distinguished by high differentiation with the predominance of andesites and basaltic andesites and their tuffs. As a result, the sediments in the adjacent basin contain significant amounts of a fine-grained pyroclastic material.

Preserved in the present-day structure are the fragments of the accretionary prisms of Early Cambrian island arcs, represented by black-shale and tephroturbidite sequences including blocks of Precambrian rocks, olistostrome horizons, and Riphean, Vendian, and Early Cambrian ophiolite sheets. A typical example is the Boshchekul island arc, the subduction of which had been responsible for the formation of Middle Cambrian eclogite in its frontal part [*Shatagin et al.,* 2001; *Shatskii et al.,* 1993]. An accretionary prism of the Early-Middle Cambrian fragment of the Boshchekul Island Arc, preserved in the structure of the Kokchetav Massif in the north of Central Kazakhstan [*Kheraskova,* 1999] (Figure 8, see also Figure 7), includes a complex collage of allochthonous blocks in carbonaceous fillite. The blocks vary in structure. Some of them consist of crystalline schist and gneiss (Zerenda Group), overlain unconformably by late Riphean rhyolite (Kuuspek Group, 850 Ma old after *Rozen* [1971]). There are outliers of tectonic nappes composed of basalt and iron quartzite, also of Riphean age. These blocks are believed to have been fragments of the Andian margin of the Late Riphean East Paleogondwana. The Precambrian blocks of the other type are also composed of schist and gneiss. However the basement of this type is overlain by the sedimentary rocks of an epicontinental basin, mainly by quartzitic sandstone (Late Riphean Kokchetav Series). It is believed that the Precambrian blocks of the second type are the fragments of the internal parts of the East Paleogondwana Continent. The Cambrian olistostromes are cut by the gabbroids of the Zlatogorsk (530 Ma) and Krasnomaisk (510 Ma) complexes [*Noth Kazakhstan magmatism,* 1988].

At the end of the Early Cambrian some fragments of the Paleosiberian Continent (Barguzin and Gargan-Sangilen blocks) collided with some continental masses that had separated in Tommotian time from East Paleogondwana. Their accretion to the Paleosiberian Continent is proved by the abundance of Early Cambrian olistostromes [*Bersin,* 1995; *Dergunov,* 1989]. Besides, the western edge of the Tuva-Mongolian Massif had been combined tectonically with the Dzhida Island Arc [*Belichenko et al.,* 2000]. Accretion also occurred in the northeast of the Baltia Continent, where the Timan nappes produced by a collision with the Kadoma island arc continued to move. These processes manifested themselves as rises and sea regressions in the internal areas of the continent.

The island arcs were obviously separated by strike-slip faults. The largest of them were the North Sayan Fault separating the Kuznetsk Alatau and West Sayan arcs [*Berzin,* 1995; *Kheraskov,* 1979] and a fault between the Dzabkhan and Tuva-Mongolia massifs [*Dergunov,* 1989].

Beginning from the Tommotian time, the Paleo-Asian Ocean experienced microplate tectonics and was divided by island arcs and continental massifs into several independent basins. During the later half of the Early Cambrian, the newly formed island arcs and their highly explosive volcanism changed radically the type of sedimentation in the Paleoasian Ocean. The condensed argillaceous-siliceous sedimentation remained only in the linear basins that had opened along the destructed edge of East Paleogondwana. Elsewhere, the sediments were enriched in pyroclastic material. Widely developed are thick tephroturbidites. Somewhat different are the basins that arose in the Early Cambrian as a result of the destruction of the East Paleogondwana edge. Examples are the Neimongolian and Beishan basins [*Zuo Guochao et al.,* 1991]. Their distinctive features are their linear form, the not ubiquitous development of the oceanic crust, and the compositional variability of the basalts. In addition to extrusive volcanic rocks, there are numerous diabase sills and abundant tuff. The sedimentary materials are thick quartz turbidites, whose clastic material was derived from the passive margins of these basins.

The above features of the Early Cambrian East Paleogondwana continental margin suggest that the typical mechanisms of the period discussed were the continuing destruction of the East Paleogondwana margin, the formation of new island arcs, and the associated accretion events. Destruction predominated along the edge of East Paleogondwana, and accretion, in the vicinity of the Paleosiberian Continent. It appears that the nappe-accretion and mosaic structural style of the Paleoasian oceanic region began to form during that time.

Middle Cambrian (520–510 Ma)

At the boundary between the Early and Middle Cambrian the active continental margin of East Paleogondwana experi-

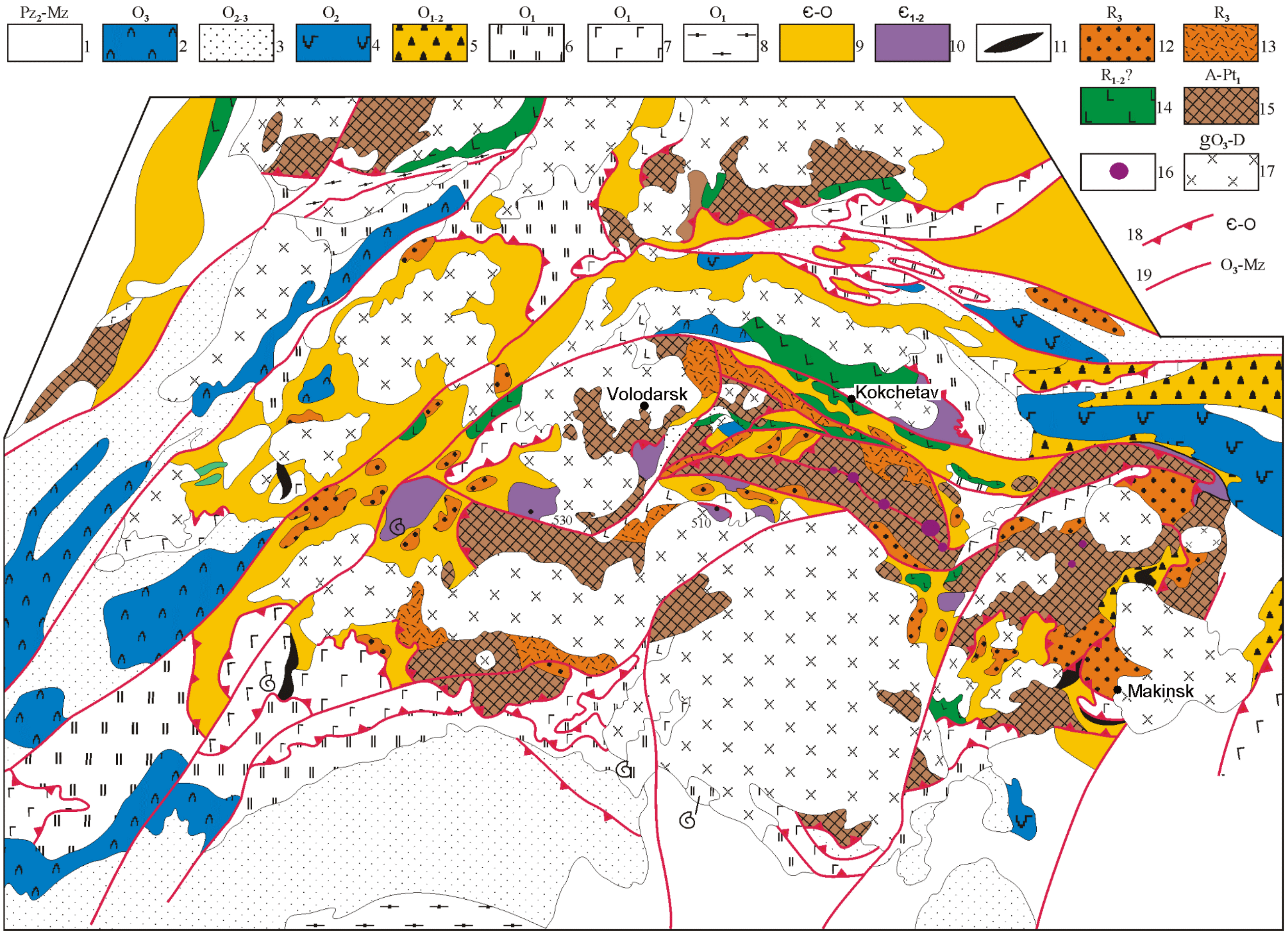

Figure 8. Geological map of the Kokchetav Massif compiled using the data reported in the [*Geology of Northern Kazakhstan...,* 1987].
(1) Cenozoic-Middle Paleozoic, (2) volcanic rocks of the Kipchak Middle-Late Ordovician ensialic island arc, (3) terrigenous rocks from the forearc basin and accretionary prism of the Middle-Late Ordovician Kipchak island arc, (4) volcanic rocks of the Stepnyak Early-Middle Ordovician mature island arc, (5) volcanogenic sedimentary and olistostrome rocks of the Stepnyak island arc, (6) Early-Middle Ordovician jaspers, (7) Early-Middle Ordovician oceanic basalts, (8) Cambrian-Early Ordovician black shale and phthanite (the shelf rocks of the Ulutau-North Tien Shan Massif), (9) undifferentiated shale and olistostrome rocks of the accretionary prisms of the Early-Middle Cambrian and Early Ordovician island arcs, (10) volcanic rocks of the Boshchekul Early-Middle Cambrian ensimatic island arc, (11) ophiolite sheets, (12–16) olistoliths and olistoplacks in olistostromes of different ages: (12) clastic quartzite of the Late Riphean Epi-Grenville sedimentary cover, (13) acid volcanics of the Late Riphean marginal volcanic belt, (14) Riphean basalt and jaspilite, (15) Proterozoic granitized metamorphic rocks, (16) eclogite, (17) Late Ordovician and Devonian granitoids, (18) basements of tectonic nappes and slabs, (19) other faults.

enced a significant rearrangement. The Siberian Continent changed the direction of its rotation and began to rotate clockwise simultaneously with its movement to the north [*Pecherskii and Didenko,* 1995]. This resulted in the intensification of the accretion at the edge of the Siberian Paleocontinent. As a result, beginning from the Middle Cambrian, the island arcs moved closer to the continent and collided with it, and the Siberian Continent grew larger (Salair tectogenesis). The environment of compression and stacking in this region was recorded by the origin, during the Mayan time, of nappes and associated olistostromes [*Melyakhovskii and Sklyarov,* 1985]. Island-arc volcanism attenuated, and a passive margin was formed in this region as stacking developed further.

As the Siberian Craton migrated northward with its simultaneous anticlockwise rotation, strike-slip faults were formed, which control the present-day structure of South Siberia [*Berzin,* 1995; *Gibsher et al.,* 2000; *Gonikberg,* 1999].

The further destruction of the East Paleogondwana margin manifested itself in the separation of a new large continental fragment including the modern Central Karakum and Amudariya median masses. This is proved by the presence of the Middle-Late Cambrian allochthonous ophiolite slabs in the southern segment of the Amudariya Massif [*Biske,* 1996]. This produced an extensive area with an oceanic crust, which combined the Paleoasian, Prototethys, and Yapetus paleooceanic basins.

During the Middle Cambrian, the spreading still going on in the Prototethys basins caused a further complication of the island-arc system (see Figure 1). In particular, the Chingiz-Tarbagatai island arc grew longer at the expense of the emplacement of calc-alkalic basaltic andesite and rhyolite [*Samygin and Kheraskova,* 1994].

As to the Baltia Continent, the growth of rises and structural rearrangement at the end of the Early Cambrian was followed by a new sea transgression from the west instead of from the northeast, as was the case during the previous epochs. Because of the intensive addition of clastic material from the epi-Cadomian (European synonym of Baikalian) Timan Massif, shallow-sea terrigenous sediments accumulated in the Baltic territory. The clockwise rotation of Baltia, proved by paleomagnetic data, was accompanied by synsedimentation movements along the faults. Some of them precluded the dissemination of clastic material, whereas others favored the formation of basins where thick Middle Cambrian sediments were deposited. The faunal assemblages of the later half of the Cambrian suggest the position of Baltia at relatively high latitudes [*Ushatinskaya and Malakhovskaya,* 2001], which agrees with paleomagnetic data.

Because the Siberian Continent was located close to the equator, carbonate accumulation was predominant there, like during the Early Cambrian, although, locally, it was suppressed by the addition of abundant terrigenous material from the region of the Salair orogeny. Similar to the Early Cambrian, an evaporate basin existed in the central part of the Siberian Continent [*Astashkin et al.,* 1984].

Early Ordovician (500 Ma)

During the latest Cambrian and the Early Ordovician (Figure 9) the continental margin of East Paleogondwana experienced a structural rearrangement, probably, because of the higher subduction rate and the areal shrinking of the Paleoasian Ocean. At the same time the Chingiz island arc in Kazakhstan and the Sarybulak island arc in the Tien-Shan region experienced breakups (see Figure 1) [*Kheraskova,* 1997; *Tectonics of Kazakhstan,* 1982]. More mature island arcs arose in the remaining arc segment located closer to Panthalassa; they were distinguished by their differentiated volcanic rocks of higher alkalinity, as compared to the Early and Middle Cambrian ones. The Late Cambrian-Early Ordovician island arcs, such as the Karadzhorga and Chingiz arcs [*Degtyarev,* 1999; *Samygin and Kheraskova,* 1994] and the Boshekul and Erementau arcs [*Ryazantsev and Rumyantseva,* 1987; *Ryazantsev et al.,* 1987], still contain well preserved fragments of accretionary prisms. For instance, the accretionary prism of the Karadzhorga island arc in the Tien Shan area contains fragments of a basin with the oceanic crust (Baisaba ophiolite [*Mikolaichuk et al.,* 1997]), and also carbonaceous-siliceous shales of the shelf and the Riphean basement of the North Tienshan microcontinent. The fragments of different ages from this accretionary complex include Lower Ordovician olistostromes. Hence, the Karadzhorga island arc collided in Early Ordovician time with the Ulutau-North Tien Shan microcontinent. This collision modified the polarity of the Karadzhorga and Chingiz island arcs.

Simultaneously with the evolution of the island arcs, new oceanic crust was formed intensively in Kazakhstan and Tien-Shan at the beginning of the Ordovician. The plagiogranites from these ophiolites have been dated 510 Ma [*Gruschka et al.,* 1997]. The basalts of the Early Ordovician oceanic crust are distinguished by the high content of potassium and the low content of magnesium [*Gerasimova et al.,* 1992; *Kheraskova,* 1997; *Lomize et al.,* 1997; *Yakubchuk,* 1989, 1990]. An important point is that the black shales and cherts, typical of the Precambrian, were replaced by sealing-wax red jaspers in the basins of the Paleoasian Ocean.

At the end of the Cambrian-Tremadocian, the eastern margin of Baltiya experienced destruction because of its counter-clockwise rotation. That time witnessed the formation of the Lemva and Sakmara rift basins [*Khvorova et al.,* 1978; *Puchkov,* 2000] and the separation of terrains with the Kadomian age of the continental crust (Khanty-Mansi, Kharbei, Ural-Tau, and some blocks in the Turgai Basin). During the Late Cambrian-Early Ordovician the region concerned experienced subsidence and a new transgression impulse from the destructive margin of the Ural [*Dmitrovskaya and Kheraskova,* 1997; *Nikishin et al.,* 1996].

After the Salair folding event the eastern margin of Paleosiberia experienced granite intrusion and the growth of the Siberian Continent at the expense of a complex collage of the fragments of the Vendian-Cambrian island arcs, their accretionary prisms, as well as of ophiolites of various ages, and of the fragments of the East Paleogondwana continental crust. At the end of the Cambrian to the Early Ordovician a thick sequence of feldspar-quartz turbidites accumulated there as a formation typical of the continental slope and the foot of a passive margin [*Dergunov,* 1989; *Voznesenskaya and Dergunov,* 1982].

To sum up, the Early Ordovician time was an important landmark in the history of the East Paleogondwana continental margin. The structural rearrangement that occurred during that time resulted, as will be shown below, in the formation of the new large blocks of the Caledonian continental crust.

Late Ordovician (450 Ma)

A change in the polarity of the island arcs in Kazakhstan and Tien Shan took place at the boundary between the Middle and Late Ordovician. This change was associated with the continuing destruction of the Baltia and East Pa-

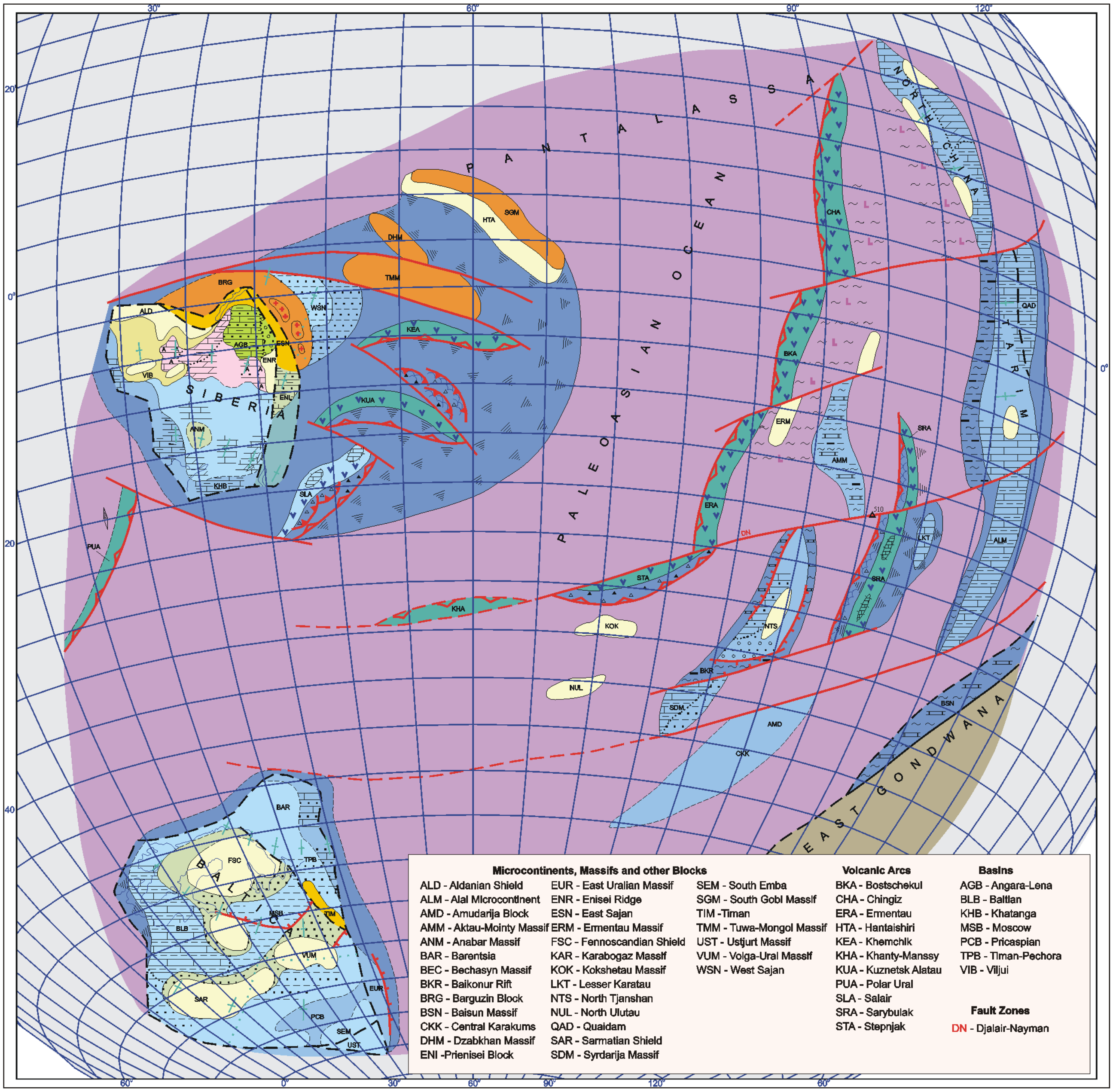

Figure 9. Palinspastic map of Central Eurasia for the Early Ordovician (500 Ma). See Figure 2 for the legend.

leogondwana margins and with the opening of the Ural and Turkestan paleooceans associated with this process. The change of the island arc polarity caused a collision of the Kazakhstan and Tien Shan island arcs with some microcontinents of this region. The process of accretion and collision is best imprinted in the structure of the Kokchetav Massif in Central Kazakhstan (see Figure 8). The modern structure of the Kokchetav Massif was formed mainly during the Middle-Late Ordovician as a result of the accretion in the frontal part first of the Early-Middle Ordovician Stepnyak island arc and then of the Late Ordovician ensialic island arc (of its Kazakhstan segment). Fragments of the island-arc volcanics of that age can be traced along the western, northern, and eastern margins of the Kokchetav Massif. The subduction produced an accretionary prism which includes Precambrian blocks of East Gondwana origin and a fragment of the Early-Middle Cambrian island arc with its accretionary prism (see above). The Early Ordovician segment of the accretionary prism is located closer to the southern segment of the Kokchetav Massif and seems to be structurally lower than the Cambrian accretionary complex. The prism includes an olistostrome and the large tectonic slabs

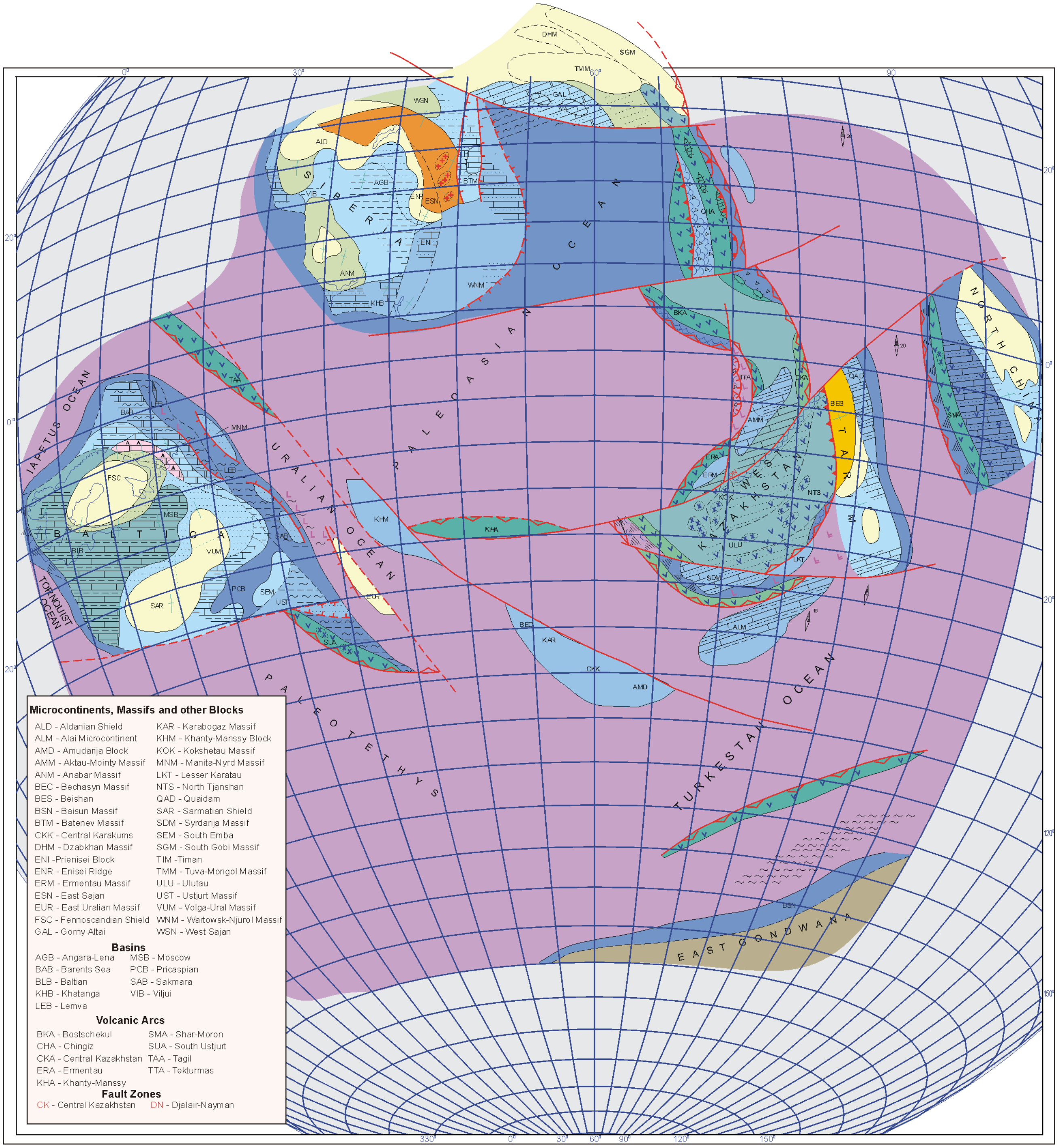

Figure 10. Palinspastic map of Central Eurasia for the Late Ordovician (450 Ma). See Figure 2 for the legend.

of variegated siliceous rocks and basalts, as well as large tectonic slabs of variegated siliceous rocks and basalts, and also of serpentinized ultrabasic rocks, and also the mesolyths of Early Ordovician and Vendian-Cambrian carbonaceous and siliceous schists, and Precambrian granite, gneiss, and schist.

As a result of the accretion, a large ensialic island arc was formed in the Late Ordovician with a subduction in the western and eastern direction (Figure 10; see also Figure 1). This arc connected, via the South Usturt Arc, the Baltia and Siberia continents. By and large, it resembles the Kipchak island arc, as it was reconstructed by *Sengör et al.* [1994].

We were the first to map the South Ust-Urt Arc [*Bakirov,* 1970] as a result of our analysis of the composition and structure of the volcanogenic and sedimentary rock sequences (analogs of the Kokpatas Formation in the Bukuntau area) and granites in the South Ust-Urt and Karabogaz blocks, the volcanic rocks proper occurring only in the Ust-Urt area. The Karabogaz block, dominated by highly deformed clastic and siliceous rocks, including blocks of metamorphic rocks, seems to have belonged to the accretionary prism of the South Ust-Urt island arc.

At the end of the Ordovician the Kazakhstan segment of the Kipchak ensialic arc collided with the Tarim-Tsaidam Microcontinent, and a thick collision zone developed along the Dzhalair-Naiman transform fault. The intrusion of the Late Ordovician granites of the Krykkuduk Complex was associated with the development of the collision zone. The late Ordovician accretion and collision produced a new Caledonian composite continent (Kazakhstan), which was a collage of Rodinia continental fragments, island arcs of different ages, and oceanic crust fragments of different ages.

The Late Ordovician collision and accretion processes (Caledonian orogeny) modified significantly the type of sedimentation in the area of the Siberian Craton and in the Baltia Continent. The uplifts that existed in the area of the Siberian Craton continued to grow, and granites were intruded. Mainly clastic-terrigenous sediments accumulated in the shallow-sea basins of the region. A shallow-sea regressive basin with highly or variably saline water existed at that time in the Baltia Continent.

Conclusion

The specific evolution of the continental margin of Rodinia and East Paleogondwana suggests the following conclusions.

The Rodinia Supercontinent broke up in Vendian time with the separation of several continental blocks from it. At that time a large rift system originated in the East Gondwana part of Rodinia, which extended from Tarim into the Middle Tien Shan and the western part of Central Kazakhstan. In addition, movements renewed along the faults that bounded the Riphean rifts in the Baltia. The Vendian rift systems separated and surrounded a number of terranes at the continental margin of East Paleogondwana (Tarim, Syr Daria-Ulutau-North Tien Shan, Dzhungar-Balkhash, and Tuva-Mongolia).

Collisions occurred along with destructive processes in Vendian time. They were most abundant along the eastern periphery of Baltia (in modern coordinates), where the traces of the Kadomian orogeny have been reconstructed, and where the Baltia area grew larger at the expense of the connection of the Pechora terrain, as well as of the North Ust-Urt and Karabogazgol blocks of the basement of the Scythian-Turanian Plate. As a result of these processes, allochthonous clastic and pyroclastic materials started to be supplied from the island arc.

The processes of rifting and collision were induced by the subduction at the boundary between the Paleopacific and East Paleogondwana, where an extensive island arc system was being formed at that time (Khantaishir, Dariba, and Dzhida island arcs).

A characteristic feature of the Vendian epoch was glaciation development. There are two levels of glacial deposits restricted to the Vendian beginning and end.

During the Early Cambrian the Vendian rift systems were partially destroyed, a new oceanic crust was formed, and a number of microcontinents separated from East Gondwana, including Syrdariya-Ulutau-North Tien Shan, Dzhungar-Balkhash, and North Tarim-Tsaidam.

During the Cambrian the system of island arcs along the boundary between the Paleopacific Ocean and East Paleogondwana grew more complicated compared to the Vendian time. New island arcs originated, such as the Boshchekul, Chingiz-Tarbagatai, Sarybulak, Kuznetsk-Alatau, and West Sayan ones. Some fragments of the accretionary prisms of these island-arc systems can be found in the present-day structure, where they are represented by black shales or turbidite and graywacke sequences including continental blocks of Precambrian rocks, olistostrome layers, and ophiolite sheets of Riphean-Vendian-Early Cambrian age.

Along the periphery of Siberia, the island arcs surrounding it first moved closer to this continent, beginning from the Middle Cambrian, and then collided with it, the island-arc volcanism attenuated slowly, and a passive margin was formed in this region, where thick turbidite sequences of quartz-graywacke composition accumulated.

During the Early Ordovician the island-arc systems that had been formed during the Cambrian continued to develop. In Kazakhstan they grew longer at the expense of the origin of new island arcs. Thick accretionary prisms developed in the frontal parts of the Ordovician island arcs, consisting of turbidites or tephroturbidites including the layers of Early-Middle Ordovician olistostromes, ophiolite blocks of various ages, blocks of intraoceanic mounts, and fragments of microcontinents.

During the Early Ordovician some island arcs in Kazakhstan and Tien Shan (Chingiz and Sarybulak) experienced breakups. New, more mature, island arcs were formed at the arc remnant located closer to Pantalassa. They were distinguished by more differentiated volcanism and somewhat higher alkalinity compared to the Cambrian volcanism, and by thick tephroturbidites. New oceanic crust was formed in the marginal basins.

As to the Tien Shan region, the Karadzhorga island arc collided with the Ulutau-North Tien Shan microcontinent in the Early Ordovician. This collision changed the polarity of this island-arc system.

During the Late Cambrian-Tremadocian time the eastern margin of Baltiya (modern coordinates) was destroyed with the separation of some terranes with the Cadomian age of the continental crust.

At the end of Cambrian-Tremadocian time a major structural readjustment took place, including changes in the polarity of the island arcs in Kazakhstan. This was, apparently, associated with the opening of the Ural and Kazakhstan oceans. These processes resulted in the collision of the Kazakhstan and Tien Shan island arcs with some microcontinents of this region. As a result, the Kipchak large ensialic island-arc uplift was formed, which experienced subduction in the western and eastern directions.

At the end of the Ordovician the Kipchak ensialic arc collided with the Tarim-Tsaidam microcontinent, and a thick collision zone developed along the Dzhalair-Naiman transform fault, accompanied by the intrusion of the Krykkuduk gold-bearing granites.

The Late Ordovician accretion and collision processes resulted in the origin of the new composite Kazakhstan-Tienshan continent, as a collage of the fragments of the Rodinia Continent, island arcs of different ages, and fragments of the varying-age oceanic crust. This continent divided the structural features of the PaleoTethys Ocean and the PaleoPacific Ocean.

During the Late Riphean-Early Paleozoic the Ural-Mongolia Belt existed as a large active continental margin, first of Rodinia and later of its fragment, East Paleogondwana, at the boundary with the Panthalassa Ocean. Apparently, this margin was an analog of the present-day Pacific margin. It experienced microplate tectonics.

During the Vendian-Early Paleozoic, East Paleogondwana served as a source of terranes (microcontinents) which separated from its passive margin during rifting and drifted across the Paleoasian Ocean in the northern direction, where they were accreted to the margin of the Siberian Continent or to one another (in Kazakhstan) producing the Early Paleozoic folds and nappes of the Ural-Mongolia Belt. During the Vendian-Early Paleozoic time East Paleogondwana mainly experienced destruction, which resulted in the formation of marginal rift-type basins (the processes typical of the Atlantic segment of the Earth).

Still debated are the problems of the location and tracing of long-lived faults, including those of the transform type.

Acknowledgments. This work was partially supported by the Russian Foundation for Basic Research, project nos. 01-05-64625, 01-05-64550, and 02-05-64332.

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(Received 16 June 2003)