ISSN 0016-8521, Geotectonics, 2011, Vol. 45, No. 6, pp. 415–438. © Pleiades Publishing, Inc., 2011.
Original Russian Text © M.I. Kuz'min, V.V. Yarmolyuk, V.A. Kravchinsky, 2011, published in Geotektonika, 2011, Vol. 45, No. 6, pp. 3–23.

Phanerozoic Within-Plate Magmatism of North Asia: Absolute Paleogeographic Reconstructions of the African Large Low-Shear-Velocity Province

M. I. Kuz'min[a], **V. V. Yarmolyuk**[b], **and V. A. Kravchinsky**[c]

[a] *Vinogradov Institute of Geochemistry, Siberian Branch, Russian Academy of Sciences,*
ul. Favorskogo 1a, Irkutsk, 664033 Russia
[b] *Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences,*
Staromonetnyi per. 35, Moscow, 119017 Russia
e-mail: yarm@igem.ru
[c] *Physics Department, University of Alberta, Edmonton, Alberta, T6G 2G7 Canada*

Received January 20, 2011

Abstract—The phanerozoic within-plate magmatism of Siberia is reviewed. The large igneous provinces (LIPs) consecutively arising in the Siberian Craton are outlined: the Altai–Sayan LIP, which operated most actively 400–375 Ma ago, the Vilyui LIP, which was formed from the Middle Devonian to the Early Carboniferous, included; the Barguzin–Vitim LIP (305–275 Ma); the Late Paleozoic Rift System of Central Asia (318–250 Ma); the Siberian flood basalt (trap) province and the West Siberian rift system (250–247 Ma); and the East Mongolian–West Transbaikal LIP (230–195 Ma), as well as a number of Late–Mesozoic and Cenozoic rift zones and autonomous volcanic fields formed over the last 160 Ma. The trace-element and isotopic characteristics of the igneous rocks of the above provinces are reviewed; their mantle origin is substantiated and the prevalence of PREMA, EM2, and EM1 mantle magma sources are shown. The paleogeographic reconstructions based on paleomagnetic data assume that the Iceland hot spot was situated beneath the Siberian flood basalts 250 Ma ago and that the mantle plumes retained a relatively stable position irrespective of the movements of the lithospheric plates. At present, the Iceland hot spot occurs near the northern boundary of the African large low shear velocity province (LLSVP). It is suggested that the within-plate Phanerozoic magmatism of Siberia was related to the drift of the continent above the hot spots of the African LLSVP.

DOI: 10.1134/S0016852111060045

INTRODUCTION

The principles of plate tectonics hold that the main activity of geological processes is confined to plate boundaries [1, 80]. As early as the 1960s, Wilson [94, 95] and Morgan [76, 77] called attention to manifestations of within-plate magmatism, which they referred to hot spots, or more precisely to the ascent of deep mantle plumes. Such hot spots, for example the Hawaiian hot spot, remain at the same place for a long time, and their traces in the lithosphere make it possible to restore the absolute motions of the lithospheric plates [77, 57]. Zonenshain and Kuz'min [9] were the first to show that present-day hot spots are grouped in certain regions rather than distributed chaotically on the Earth's surface. These regions were called hot fields of the mantle.

The seismic tomographic data display the arrangement of low-velocity (hot) and high-velocity (cold) mantle domains, which are traced from the lithosphere bottom to the core [58–60, 74]. The large low-velocity provinces localized beneath Africa and the adjacent territories and the Pacific Ocean coincide with the hot mantle fields outlined by Zonenshain and Kuz'min. These large low-velocity mantle provinces are commonly termed the African and Pacific large low-shear-velocity provinces (LLVSP), or superplumes [84, 97], which correspond to rises, or superswells of the geoid surface [56, 62, 71, 78]. As was mentioned above, the present-day volcanic activity in hot spots is conjugated to them [55] (Fig. 1), as is the formation of the Mesozoic and Cenozoic large igneous provinces (LIPs) [51, 52].

It is suggested that mantle plumes originate at the upper–lower mantle interface, where most subducted lithospheric material accumulates, and in the layer D" at the interface between the solid silicate mantle and the liquid iron–nickel core. Seismic tomographic data have shown that after the first stagnation in the transitional zone (400–600 km) the subducted plates sink to the mantle–core interface [61, 97, 98]. This process corresponds to general mantle convection: the cold subducted material descends into the Earth's mantle, whereas the hot mantle material ascends as mantle plumes.

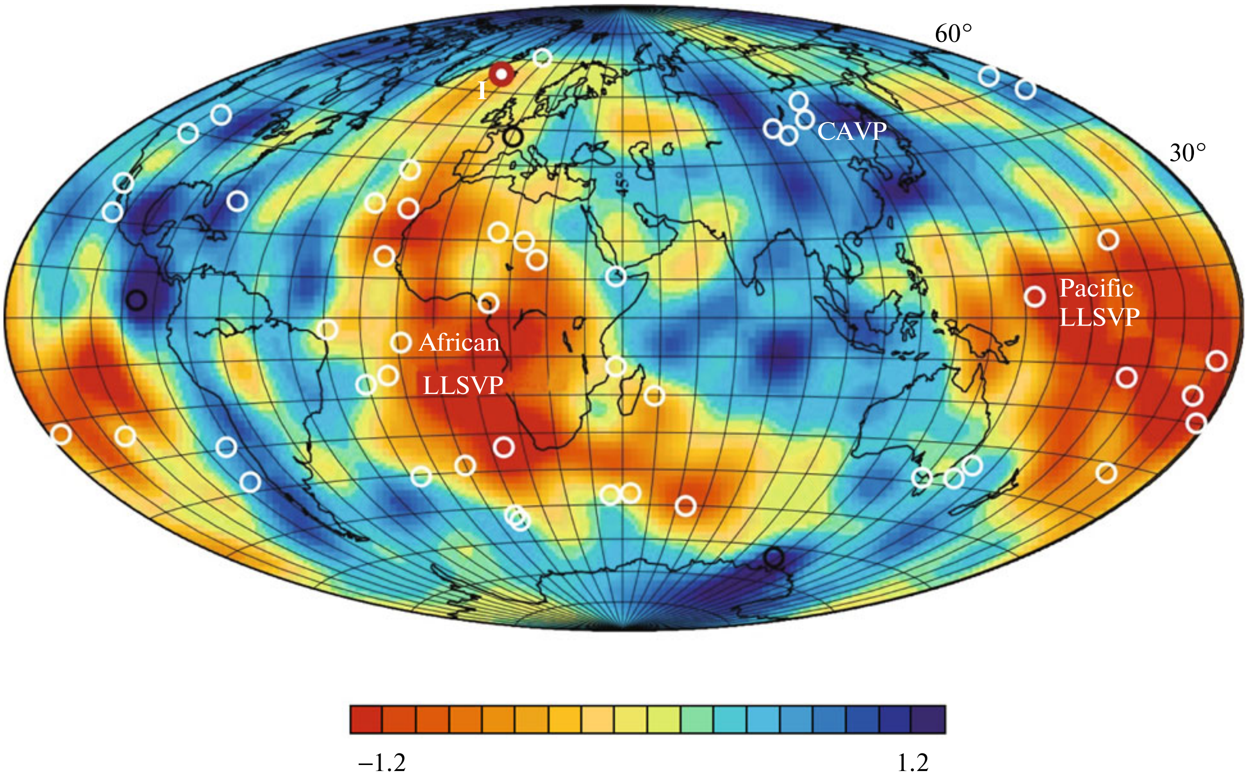


Fig. 1. Arrangement of hot spots (white circles) relative to hot fields of the mantle at a depth of 2800 km, after [55]. I, Iceland hot spot; CAVP, Central Asian within-plate volcanic province [42]. Low and high velocities of seismic waves with maximal amplitudes of anomalies up to 1.2% are shown in red and blue, respectively.

The hot mantle of the superplumes ascends through the lower mantle, breaking down into a series of isolated plumes manifested at the Earth’s surface as clusters of hot spots [60, 75]. The conjugation of ascending and descending flows in the mantle leads to the idea of close relationships between deep geodynamics (mantle plumes) and plate tectonics [52, 55, 57, 66, 85]. This idea was stated in contrast to the early concept assuming that mantle plumes act independently of plate-tectonic processes [63].

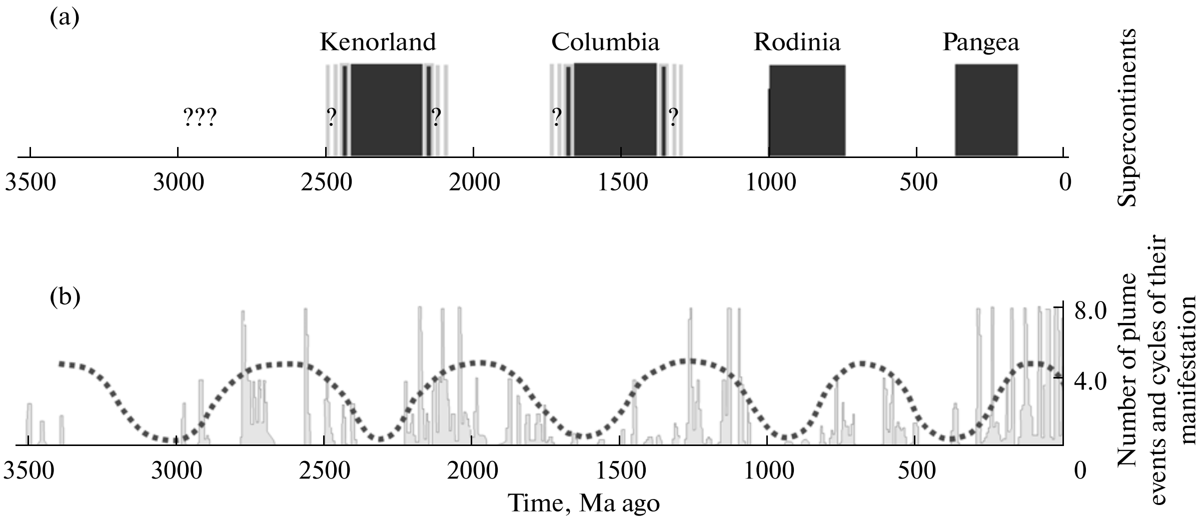


Fig. 2. Graphs illustrating (a) the time of supercontinent origination and (b) the distribution of large igneous provinces in the Earth’s history. The sinusoid curve displays probable cycles of superplume activity destroying supercontinents, after [70].

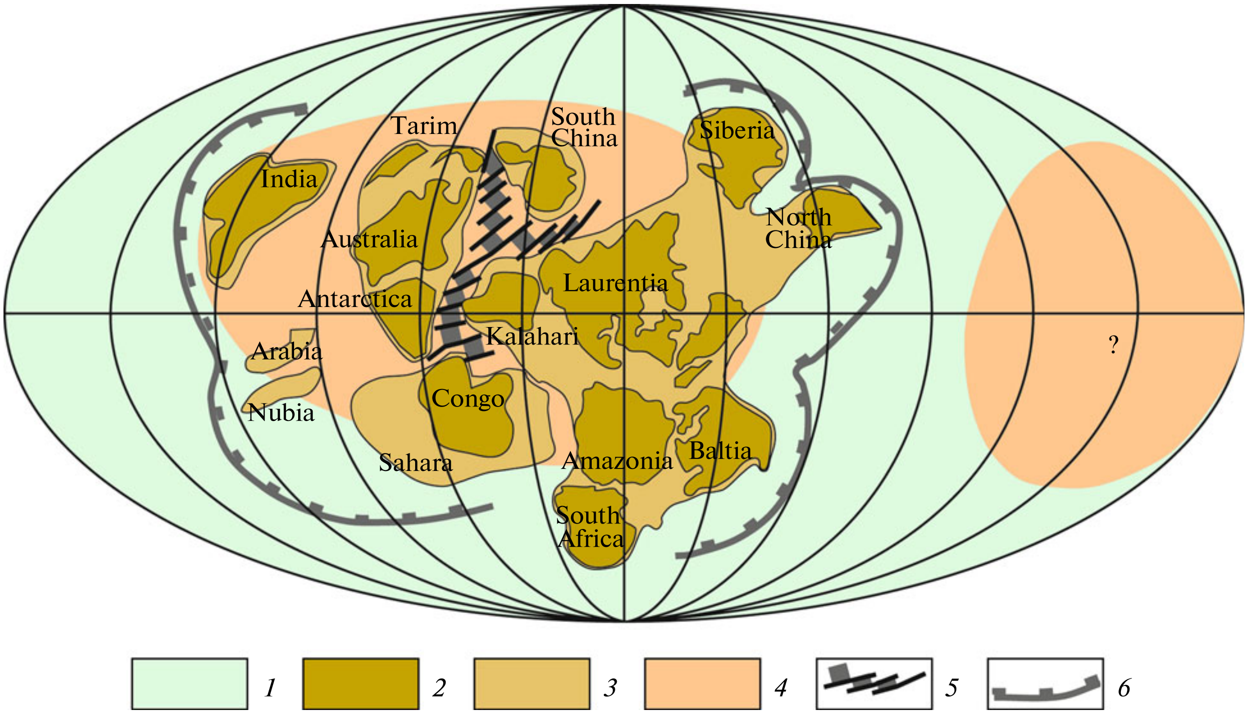


Fig. 3. Breakdown of Rodinia under the effect of the Rodinian superplume and location of the antipodal superplume, after [70]. (*1*) Ocean, (*2*) continent, (*3*) craton, (*4*) fold region, (*5*) breakup zones in the continental lithosphere, (*6*) convergent boundary.

The most convincing argument for the relationship between plate and plume tectonics is the coordination of the formation of supercontinents and superplumes in supercontinental cycles [19, 20, 51, 52, 66, 70, 75]. At present, it is established that the supercontinents, which combine almost all of the continental masses of the Earth into a single whole, arose during the evolution of the planet. The cycles of origination of supercontinents and their breakup under the effect of superplumes into separate continental blocks are shown in Fig. 2.

To date, the formation history of the Rodinia and Pangea supercontinents have been studied in most detail [64, 69, 70, 87]. Rodinia was formed about 1 Ga ago and broke down about 700 Ma ago under effect of the Rodinian superplume situated beneath it [75, 96]. It is suggested that an antipodal superplume existed simultaneously with the Rodinian Superplume [70] (Fig. 3). After the breakdown of Rodinia, the continents that made it up, including Siberia, could have been displaced into the Late Riphean Ocean. In this case, the products of within-plate oceanic magmatism which mark the activity of the antipodal superplume should be manifested in the Late Riphean and Early Paleozoic structural elements of Siberia and its fold framework. Indeed, rocks corresponding to fragments of oceanic islands and lava plateaus of this age are widespread in the orogenic belts surrounding the Siberian Platform [39, 40]. Furthermore, a number of Phanerozoic LIPs formed in the Siberian continent as products of interaction of continents with mantle hot spots [38, 39, 96].

In this paper, we show that Siberia drifted over most of the Phanerozoic in the zone affected by the superplume antipodal to Rodinia and comparable with the present-day Pacific superplume [75, 96]. Thus, the plume antipodal to the latter can be compared with the present-day African superplume, which was denoted as the pra-African superplume for that time interval.

In our concept, we assign the leading role to the Iceland hot spot, which marks the northern boundary of the LLVSP. The time of existence of this province is traced at least back to 300 Ma [89, 90]. Many authors point out the uniqueness of the Iceland hot spot, assuming that this hot spot has retained its position in the system of absolute geographic coordinates for a long time. The history of this hot spot is traced reliably back to 150 Ma [68, 73]; some researchers refer the formation of the Siberian flood basalts to this hot spot. Proceeding from the suggestion that the Siberian flood basalt province was localized 250 Ma ago above the Iceland plume, we made an attempt to perform absolute reconstruction of Siberia over a wider time interval. Our reconstruction covers a time interval of more than 500 Ma and is based on the arrangement of hot spots of various ages throughout the continent. Unfortunately, the earlier reconstructions carried out together with Zonenshain [10] covered rather short and separate time intervals of the Phanerozoic history

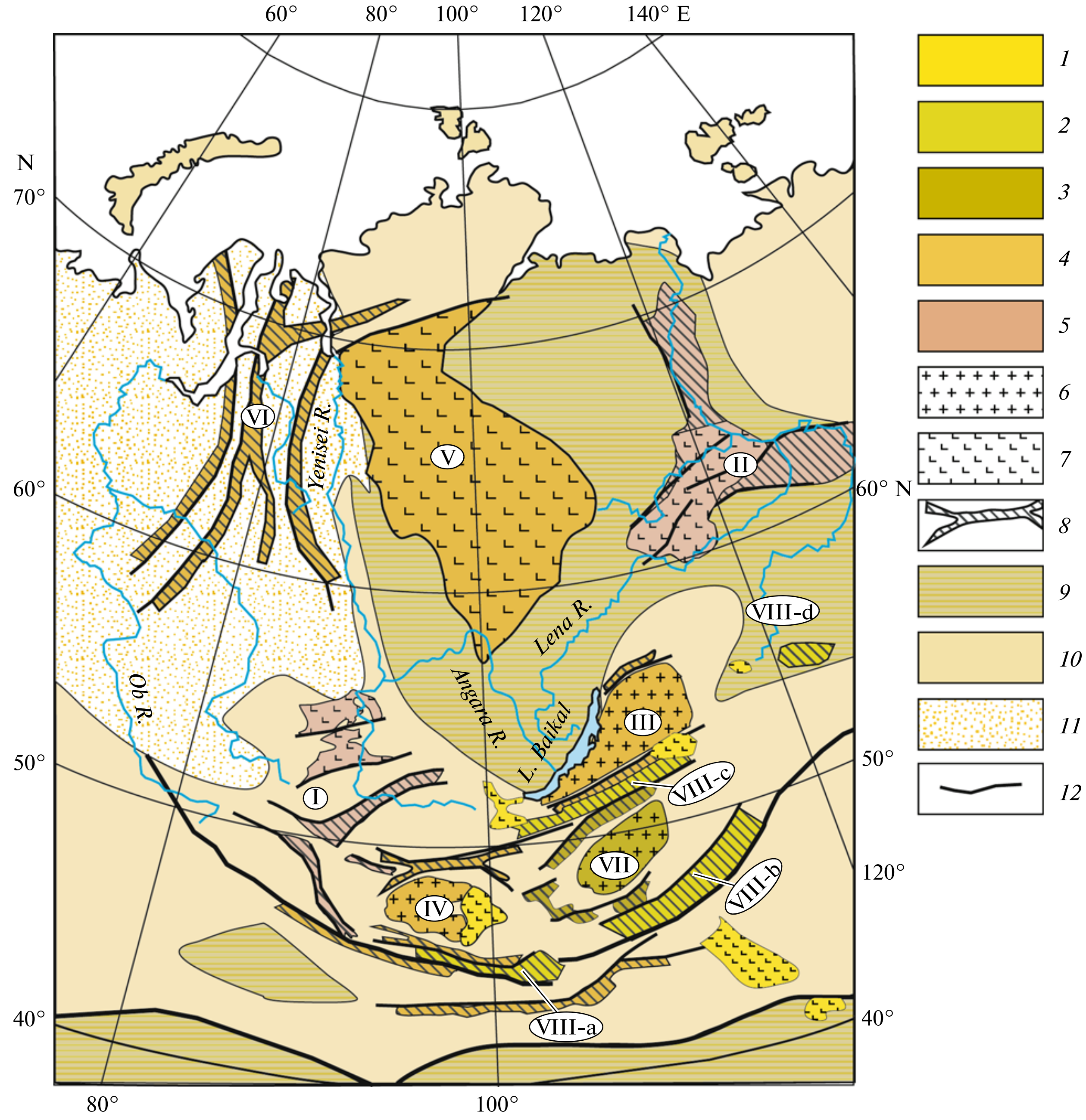


Fig. 4. Area of within-plate magmatism in the Siberian Platform and its fold framework. (*1*–*5*) Age groups of within-plate igneous associations: (*1*) Cenozoic, (*2*) Late Mesozoic, (*3*) Early Mesozoic, (*4*) Late Permian–Early Triassic, (*5*) Devonian; (*6*) granitic batholith, (*7*) flood basalts (traps), (*8*) rift zone, (*9*) platform; (*10*) Phanerozoic foldbelts, (*11*) West Siberian Plate, (*12*) fault. Within-plate igneous domains and provinces (numerals in circles): I, Altai–Sayan; II, Vilyui; III, Barguzin–Vitim; IV, Khangai; V, Siberian flood-basalt (trap); VI, West Siberian Rift System; VII, East Mongolian–Transbaikal; VIII-a, Gobi–Altai; VIII-b, East Mongolian; VIII-c, West Transbaikal; and VIII-d, Aldan.

of North Asia and did not give an integral coherent pattern.

The Siberian continent is understood in this paper as a continental block, which was limited after breakdown of Rodinia by the Siberian Platform and grew out during the subsequent geological history through the accretion of terranes with a younger crust: Caledonian, Hercynian, and Indosinian. The autonomous development of the continent was completed by collision with the North China Craton.

WITHIN-PLATE MAGMATISM IN THE PHANEROZOIC HISTORY OF SIBERIA AND ITS FOLD FRAMEWORK

As is known [22–24, 54], the products of within-plate magmatism are characterized by rock associations of elevated alkalinity, including alkali basalt, alkali gabbroic rocks, phonolite, trachyte, comendite, pantellerite, alkali granite, etc. They are typical of continental rifts and intracontinental domains. The intensity of the within-plate endogenic activity of the Siberian continent is emphasized by numerous graben systems differing in age, as well as horsts and arches, with occurrences of igneous rocks typical of within-plate magmatism. Their spatial distribution is shown in Fig. 4, and their integrated attributes are given in the Table. The geology of the within-plate provinces and the rocks occurring therein are considered in many publications [2, 3, 23, 24, 37–39, 41, 43]; therefore, only a brief overview is given below. The Early–Middle Paleozoic, Late Paleozoic–Early Mesozoic, and the Late Mesozoic–Cenozoic epochs of within-plate magmatism are distinguished in the Phanerozoic history of the Siberian continent.

The earlier manifestations (Late Riphean and Vendian–Early Cambrian) were related to the oceanic framework of the Siberian continent, where complexes of high-Ti mafic rocks of the OIB type corresponding to fragments of oceanic islands and lava plateaus are documented in the ophiolitic zones of the Central Asian Foldbelt [2, 18, 31, 39, 40, 44]; numerous occurrences of alkaline intrusive magmatism are shown in Fig. 5.

The Early–Middle Paleozoic epoch is characteristic of the Altai–Sayan and Vilyui domains of within-plate magmatism corresponding to LIPs in dimensions.

The Altai–Sayan domain of within-plate magmatism is related to the southwestern framework of Siberia and covers the territories of the Minusa basins, Tuva, the Sayan Mountains, and Northwest Mongolia about 500 × 700 km in area [39, 46, 67].

The earliest occurrences of igneous rocks revealing within-plate characteristics are dated at 490–450 Ma. These are layered gabbroic plutons and numerous intrusions of alkali granite and alkali syenite of the Sangilen Complex widespread in the Eastern Sayan. Since that time and until Early Devonian, intrusive activity proceeded almost continuously and resulted in the formation of intrusions of ultrabasic alkaline rocks, nepheline syenite, and alkaline and Li–F granites combined in numerous intrusive complexes (Ognit, Okunevka, Buren, etc.) [39, 46, 67]. The K–Ar and Rb–Sr ages of these rocks vary from 450 to 400 Ma. The peak of within-plate magmatic activity fell on the Early Devonian and was related to the formation of a triple graben system (Fig. 6) coeval with the active continental margin corresponding to the zone of interaction between the Siberian continent and lithosphere of the Paleoasian Ocean. The triple graben system turned out to be partly superimposed on the active continental margin, and this affected the composition of the within-plate igneous associations [4]. The Tuva Graben, which is a branch of this system, is traced inland for more than 500 km. The second branch corresponds to the Devonian Delyun–Yustyd black-shale trough, the section of which begins with mafic and felsic lavas. This trough is traced in the northwestern direction for more than 600 km. The third branch opened in the west-northwest toward the paleoocean and crossed the structural elements of the Mongolian Altai. Rifting was accompanied by eruptions of mainly mafic lavas. The intensity of magmatic activity of this time in the Altai–Sayan region can be determined from the fact that more than 50000 km^3 of lavas were erupted in the Early Devonian in the Minusa Basin alone [26]. It is suggested that no less than 100000 km^3 of igneous rocks formed in the entire region 410–390 Ma ago. Thus, the Altai–Sayan region can be classified as a LIP. In the Middle Devonian, magmatic activity was sharply reduced.

The Vilyui large igneous province covers vast areas of the present-day eastern margin of the Siberian Platform (Fig. 6); a triple system of rift zones arose here in the Middle Devonian. One branch corresponds to the Vilyui Rift and two others to marginal ruptures that determined the present-day eastern boundary of the Siberian paleocontinent [10]. The Vilyui Rift is about 800 km in extent and 450 km in width [5, 15, 16] and characterized by a complex internal structure.

The oldest igneous rocks in the rift system are dated at the Late Silurian [5]. They were formed against the background of a growing arch in the central part of the domain and characterized by high-alkalinity rocks: tephrite, trachybasalt, trachyte, phonolite, and massifs of ultramafic alkaline rocks with carbonatites, which are most abundant close to the eastern margin of the Siberian Platform and to the Sette-Daban. The peak of tectonic and magmatic activity fell on the Middle–Late Devonian [5], when the arch was dissected by the triple rift zone. The breakup was accompanied by eruptions of subalkaline and tholeiitic basalts. The eruptions alternated with sedimentation. As a result, sedimentary–volcanic sequences many kilometers thick filled the rifts. The final stage of rifting (Late Devonian–Early Carboniferous) was characterized by sharply reduced basaltic eruptions against a background of increasing contrast of tectonic movements. A great amount of products of magmatic activity was erupted. In the Vilyui Rift alone their volume is estimated at 100000 km^3 [5, 15, 16].

The Late Paleozoic–Early Mesozoic epoch combines the events that occurred 320–190 Ma ago, when several large igneous provinces were formed.

The Barguzin–Vitim large igneous province was formed in the Late Carboniferous and Early Permian.

Epochs, provinces, and domains of Phanerozoic within-plate magmatism in the Siberian Platform and its Central Asian fold framework

Epoch and *stage* of magmatic activity	Province and domains of within-plate magmatic activity and character of magmatic events (age, Ma is bracketed)	
Late Riphean—Early Paleozoic	**I. Early Paleozoic Altai—Sayan** Rock complexes of oceanic islands (OIB-type high-Ti basalts, layered intrusions of gabbro and high-Ti gabbroic rocks) [598, 544, 530, 531, 527, 513]; complexes of alkaline rocks with carbonatites [510, 510]; peralkaline granite intrusions [510]	
	Synaccretionary granitic rocks [510—480] and OIB-type mafic dikes	
	Postaccretionary intrusions of peralkaline granite and nepheline syenite [494, 490, 470], alkali granite [495, 490, 480, 450], subalkali and alkali gabbroic rocks [464, 446]	
Middle Paleozoic	**I. Middle Paleozoic Altai—Sayan**	**II. Vilyui**
Early Devonian	Formation of grabens and basins and basalt—trachyte, bimodal basalt—trachydacite—trachyrhyolite, nephelinite—phonotephrite volcanic associations; emplacement of dolerite, teshenite, teralite, alkali syenite [408, 402, 400—383], alkali and Li—F granite [390]	Arching, eruption of trachybasalt, trachyte, and phonolite
Middle Devonian		Formation of rift zones and mafic dike belts. Two stages of eruption and accumulation of basaltic flows along with deposition of Devonian terrigenous rocks: Givetian—Frasnian [~375] and Frasnian—Famennian [~365]. Emplacement of dolerite, shonkinite, and teschenite dikes; formation of alkaline ultramafic massifs with carbonatites
Late Devonian—Early Carboniferous		
Late Paleozoic—Early Mesozoic	**III. Barguzin—Vitim [330—280]**	**Central Asian Rift Systems** **IV. Late Paleozoic**
Late Carboniferous—Early Permian	Formation of rift belts: —*Synnyr:* alkali, nepheline, and pseudoleucite syenites [295, 290, 285];	*Gobi—Tien Shan Rift Zone* with bimodal basalt—comendite, alkali granite [318—285] and Li—F leucogranite [285] magmatism
	—*Uda—Vitim*: ultrabasic alkaline rocks, alkaline gabbroic rocks, nepheline syenite, carbonatite [290—285];	
	—*Saizhen Zone:* ultrabasic alkaline rocks, alkaline gabbroic rocks, nepheline syenite, carbonatite [290—285];	*Gobi—Altai Rift Zone* with bimodal basalt—pantellerite and alkali granite magmatism [290—280]
Early and Late Permian	Formation of the Angara—Vitim batholith and synplutonic dikes of alkaline mafic rocks [305—280]	*North Mongolian Rift Zone* with bimodal basalt—pantellerite and alkali granite magmatism [270—250]
		Formation of the Khangai zonal—symmetrical magmatic aureole with the Khangai granitoid batholith in its center [270—250]
Permian—Triassic boundary	**V. Siberian flood-basalt (trap)** Formation of flood-basalt (trap) complex [252—247]	

(Contd.)

Epoch and *stage* of magmatic activity	Province and domains of within-plate magmatic activity and character of magmatic events (age, Ma is bracketed)	
Triassic–Early Jurassic	**VI. West Siberian Rift System** Basaltic and bimodal basalt–trachyrhyolite associations [252–247]	**VII. Early Mesozoic** Zonal–symmetrical magmatic aureole of East Mongolia and West Transbaikal region. The Khentii granitoid batholith [230–195] is its core; the *West Transbaikal* and *North Mongolian* rift zones with alkali and Li–F granites, basaltic, and bimodal basalt–comendite associations [230–195] make up its framework
Late Mesozoic–Early Cenozoic	**Central Asian intracontinental**	
Late Jurassic	Origination of hot spots: South Khangai (SH), East Mongolian (EM), West Transbaikal (WT), and Central Aldan (CA). Formation of separate grabens with basalt, trachyte, trachyrhyolite, locally with carbonatite, pantellerite, and alkali granite and Li–F granite intrusions [170–140]	
Early Cretaceous	Formation of graben systems in SH, EM, WT domains with plateau basalt eruptions and occurrences of tephrite, phonolite, nepheline syenite, shonkinite, carbonatite, ongonite, and Li–F granite [140–100]	
Late Cretaceous–Early Cenozoic	Isolated fields of basalt, melanephelinite, tephrite, and basanite in volcanic domains of SH, WT, and CA [100–30]	
Late Cenozoic	**Central and East Asian intracontinental**	
	Reactivation of magmatic activity in SH, WT, and CA domains; origination of a new system of hot spots (South Baikal, Dariganga, Shanxi, etc.); eruption of plateau basalt, tephrite, basanite [<25]; formation of the Baikal Rift System	

The province covers more than 150 000 km^2 and has a zonal structure (Fig. 7). The central part of the province is occupied by the world's largest Angara–Vitim batholith, composed of various intrusive rocks from monzodiorite to granite, granosyenite, and leucogranite. The time of batholith formation was determined based on numerous U–Pb and Rb–Sr data and is estimated at 320–275 Ma, with the most massive granite formation between 305 and 285 Ma [35, 38, 45]. The Uda–Vitim, Synnyr, and Eastern Sayan rift zones with alkaline rocks are traced at the batholith margins. The Saizhen Rift Zone is traced along the axial zone of the batholith. The rift zones are marked by chains of massifs of ultramafic and mafic rocks; alkali granite and syenite, including leucite and nepheline syenites; and sporadic volcanic fields of bimodal basalt–comendite associations. The age of these igneous rocks was established with the U–Pb, Rb–Sr, and Ar/Ar methods: 200–285 Ma in the Synnyr Zone, 290–288 Ma in the Saizhen Zone, 290–275 Ma in the Uda–Vitim Zone [65, 72], and 302–295 Ma in the Eastern Sayan [49].

In addition, rocks revealing within-plate geochemical and isotopic specialization occur in the central part of the batholith as numerous minor intrusions, dikes, and sills of alkaline basaltoids [25, 38, 45] emplaced contemporaneously with granites forming contact zones of mingling. Thus, the mafic intrusions have the same age as the granites (305–285 Ma). It is suggested that the thermal effect of basaltic magma gave rise to large-scale crustal anatexis and the formation of a granitic batholith [38, 45]. In this regard, the Angara–Vitim batholith is an example of within-plate granitoid rocks that originated under the effect of typical within-plate mantle rocks.

The most attractive within-plate magmatic event in the formation history of the Late Paleozoic North Asian continent was the formation of the giant igneous province, which combines the flood-basalt domain of the Siberian Platform and the rift system of West Siberia (Fig. 8). Flood basalts (traps) cover more than 1 500 000 km^2 and their volume is approximately equal to 1.5×10^6 km^3 [23, 24]. The time of their formation is estimated at a narrow interval of 251–248 Ma ago. According to numerous Ar/Ar data, the traps of the Kuznetsk Basin and volcanic rocks of the West Siberian Rift System were formed at the Early Triassic (~249 Ma) [3, 23, 24, 82, 83]. The volcanism of West Siberia is characterized by development of bimodal volcanic associations with participation of basalts, including alkaline varieties, and rhyolites. Volcanic activity was related to the grabens which are traced through the entire West Siberian Lowland from its southern boundary to the Arctic Ocean for 1500 km and more (Fig. 8).

At the same time, within-plate volcanism developed in the fold framework of Siberia, where the Late Paleozoic–Early Mesozoic rift system of Central Asia

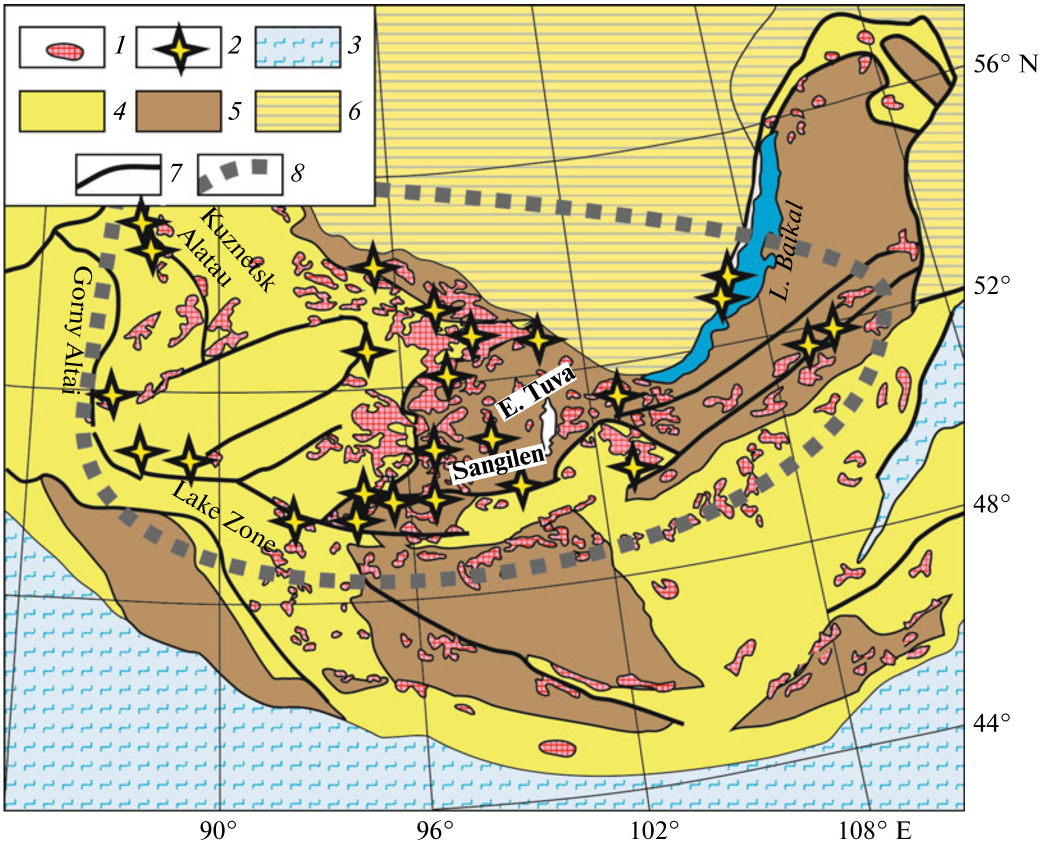


Fig. 5. Late Riphean–Early Paleozoic rock complexes with within-plate characteristics in the Caledonides of the Central Asian Foldbelt. (*1*) Tonalite, granodiorite, granite; (*2*) rock complexes with within-plate characteristics (OIB-type basalts in ophiolites, alkali granite and syenite, nepheline syenite, alkali gabbroic rocks, and carbonatite); (*3*) Paleozoic marine trough; (*4*) Caledonian fold zone; (*5*) Precambrian terrane; (*6*) platform; (*7*) fault; (*8*) boundary of the domain with rocks of within-plate type (projection of mantle plume).

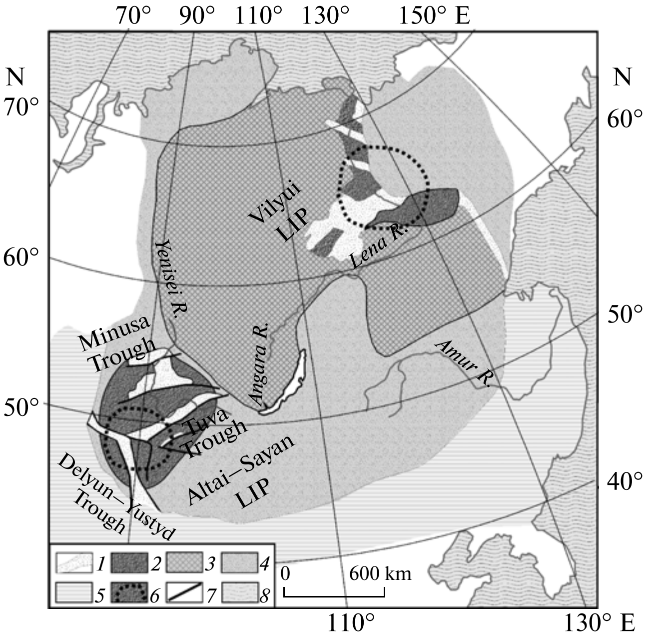


Fig. 6. Localization of the Middle Paleozoic LIPs in the Siberian continent. (*1*) Volcanic troughs and grabens, (*2*) area of arching (shoulders of rifts and troughs), (*3*) Siberian Platform, (*4*) Caledonian fold framework of the platform, (*5*) Paleoasian Ocean, (*6*) projection of mantle plume, (*7*) fault, (*8*) present-day marine basin.

was formed (table) as a belt of nearly parallel rift zones (Fig. 7) accompanied by bimodal basalt–comendite and basalt–pantellerite associations and numerous alkali granite and syenite intrusions [41, 65].

The rift system was formed in several stages. The *early stage* corresponds to the origination of the rift system and formation of the earliest grabens of the Gobi–Tien Shan Rift Zone and the Main Mongolian Lineament. These zones arose at the outer margin of the continents in the Hercynian fold framework of the Siberian Platform. The geological age of this zone is Late Carboniferous–Early Permian. The U–Pb and Rb–Sr datings of alkali granites and volcanic rocks range from 318 to 285 Ma [48, 93].

The Gobi–Altai and North Mongolian rift systems were formed 290–270 and 270–250 Ma ago, respectively, as a result of progressive propagation of the center of rifting toward the fold framework of the Siberian Platform [41]. The Khangai granitoid batholith was emplaced between these rift systems simultaneously with their development [38, 41, 47]. Like the Angara–Vitim batholith, this batholith is a product of crustal anatexis under the effect of within-plate heat sources. The U–Pb age of the batholith is 269–242 Ma [47]. As

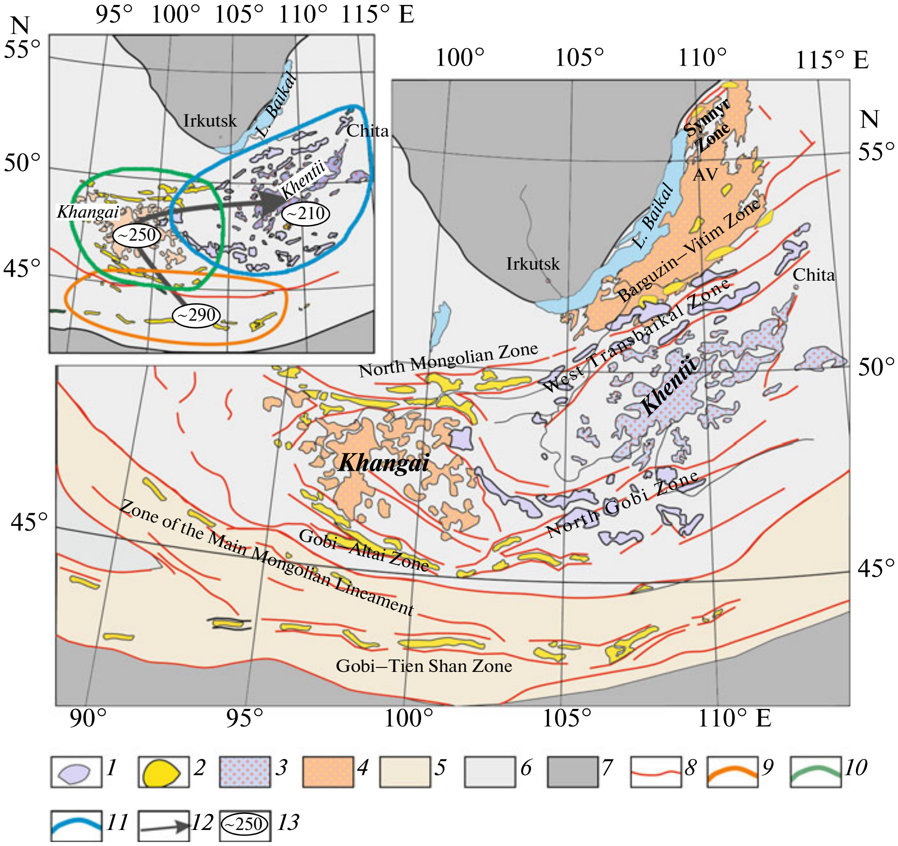


Fig. 7. Localization of the Late Paleozoic–Early Mesozoic LIPs in the Central Asian Foldbelt. (*1, 2*) Bimodal basalt–comendite associations of rift zones: (*1*) Early Mesozoic and (*2*) Permian; (*3*, *4*) batholiths: (*3*) Early Mesozoic Khentii–Daur and (*4*) Late Paleozoic Khangai and Angara–Vitim (AV); (*5*–*7*) geoblocks: (*5*) Hercynian and Indosinian, (*6*) Caledonian, (*7*) craton; (*8*) fault; (*9*–*11*) areas of within-plate igneous associations related to the Mongolian mantle plume: (*9*) Late Carboniferous–Early Permian, (*10*) Permian, (*11*) Late Triassic–Early Jurassic; (*12*) direction of shift of the mantle plume projection with time; (*13*) average age of within-plate magmatic activity.

Inset: migration of aureoles of within-plate magmatism related to the Mongolian hot spot. The shift of the aureoles was caused by movement of the continental lithospheric plate above the mantle plume in the directions opposite to those indicated by the arrows.

a result, the Khangai magmatic aureole of this age acquainted elements of a zonal symmetric structure. The Khangai batholith occupies the central part and the periphery is made up of the Gobi–Altai and North Mongolian rift zones.

The formation of the Late Paleozoic rift system was completed by the development of the Early Mesozoic Mongolian–Transbaikal magmatic aureole, which resembles the Permian Khangai aureole. The core of this aureole (Khentii batholith) is shifted 800 km to the east from the core of the Permian aureole (Khangai batholith) (Fig. 7), The Khentii batholith was formed near the western closure of the Mongolia–Okhotsk oceanic basin and comprises large granodiorite–granite plutons ~150000 km^2 in area. The Late Triassic–Early Jurassic age of this batholith is based on the U–Pb and Rb–Sr isotopic dates of its main intrusive phases (225–195 Ma) [43]. The batholith is surrounded by rift zones which are accompanied by igneous associations with participations of basalt, phonolite, trachyte, pantellerite, comendite, Li–F granite, alkali granite, and syenite. Their U–Pb, Ar/Ar, and Rb–Sr ages are estimated at 220–200 Ma. The age of 228–195 Ma was established for similar rocks in East Mongolia in the southern periphery of the aureole.

By 190 Ma ago, the within-plate activity was abruptly reduced throughout North Asia, which denotes the termination of the Late Paleozoic–Early Mesozoic epoch.

The Late Mesozoic–Cenozoic epoch of within-plate magmatism covered about 140 Ma of geological history from the Middle Jurassic (~160 Ma) to the Holocene inclusive. Over this epoch, the character of magmatic activity progressively changed, and three stages are distinguished in line with these changes.

The Late Jurassic–Early Cretaceous stage (160–100 Ma) corresponds to the formation of East Mongolia, West Mongolia, South Khangai, and the Central Aldan rift systems (Fig. 9), which arose in the frame-

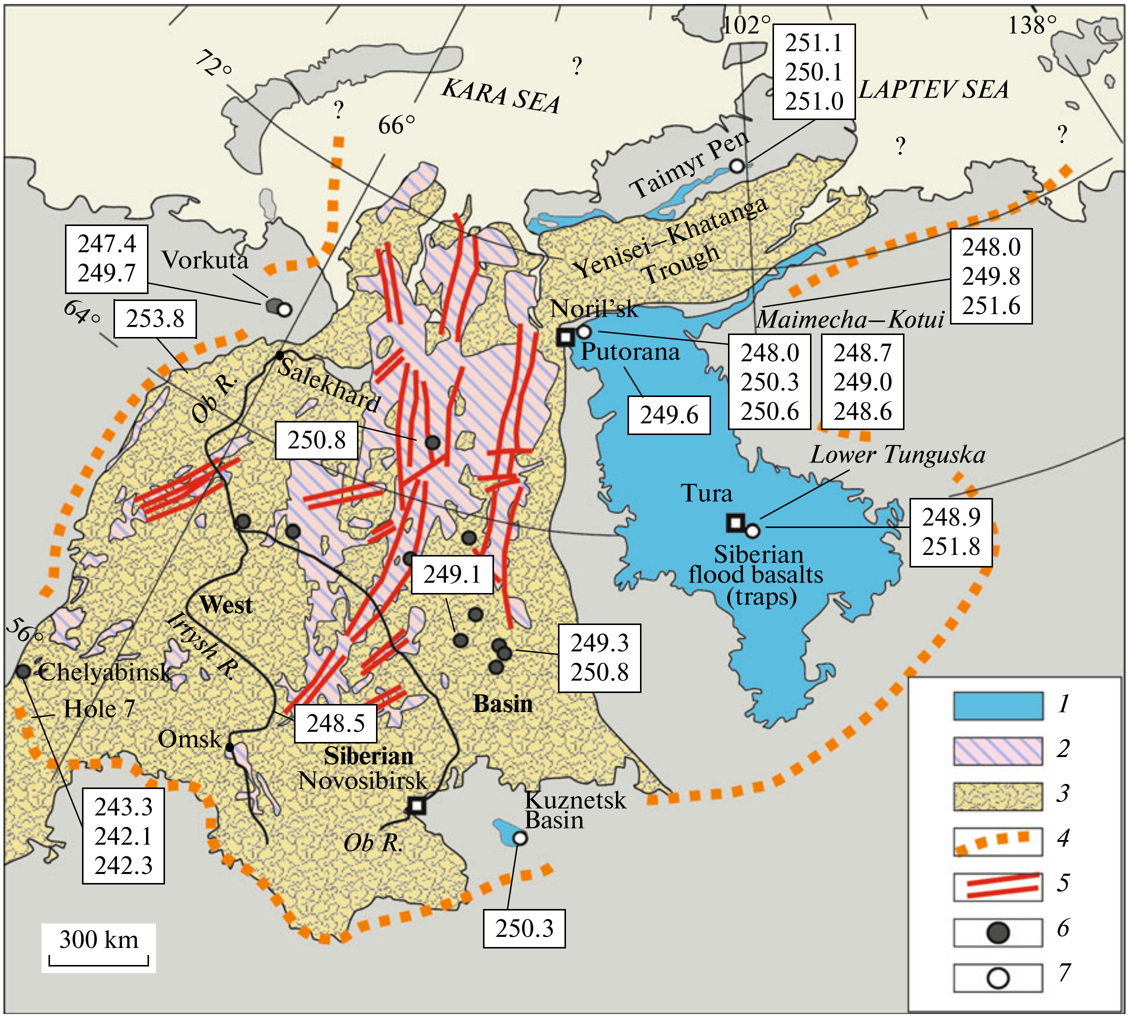


Fig. 8. The Late Permian–Early Triassic magmatic occurrences in the Siberian Platform and the West Siberian Plate, after [83]. (*1*) Exposed flood basalts (traps), (*2*) buried basalts and tuffs, (*3*) cover of the West Siberian Plate, (*4*) boundary of volcanic province, (*5*) rift, (*6, 7*) sample location: (*6*) borehole core and (*7*) outcrop. Age, Ma is shown in boxes.

work and at the periphery of the Early Mesozoic Mongolian–Transbaikal zonal magmatic aureole, thus displaying a certain inheritance in the evolution of the Early and the Late Mesozoic magmatism. The evolution of these domains was related to the formation of graben systems and accompanied by intense magmatic activity. Volcanic associations with trachyte, trachyrhyolite, pantellerite, phonolite, and tephrite along with prevalent plateau basalts arose in these systems. Sporadic minor intrusions of nepheline and leucite syenites, alkali syenite and granite, Li–F granite and ongonite, shonkinite, and carbonatite were formed as well. The peak of tectonic and magmatic activity fell on the onset of Early Cretaceous (130–140 Ma), when a system of grabens was formed and large volume of plateau basalts (>15000 km^3) erupted [42, 46].

The Late Cretaceous–Early Cenozoic stage (100–25 Ma) was characterized by suppressed magmatic activity [42]. In the West Transbaikal, South Khangai, and East Mongolian volcanic domains, isolated and small in size lava fields and shield volcanoes were formed at that time. Tephrite, basanite, nephelinite, and to a lesser extent, subalkali basalt are typical. The volume of volcanic products of that time did not exceed 200 km^3.

The Late Cenozoic stage (<25 Ma) is expressed in recent within-plate volcanic and tectonic reactivation of Central and East Asia (Fig. 10). The magmatic activity proceeded in the West Transbaikal, South Khangai, and Central Aldan volcanic domains [42], where a large lava plateau (Vitim, Central Khangai, and Udokan) grew at that time up. New volcanic regions, e.g., South Baikal, Dariganga, etc., scattered throughout Central and East Asia arose as well.

It should be noted that despite the stadial character of the Late Mesozoic–Cenozoic magmatism, the for-

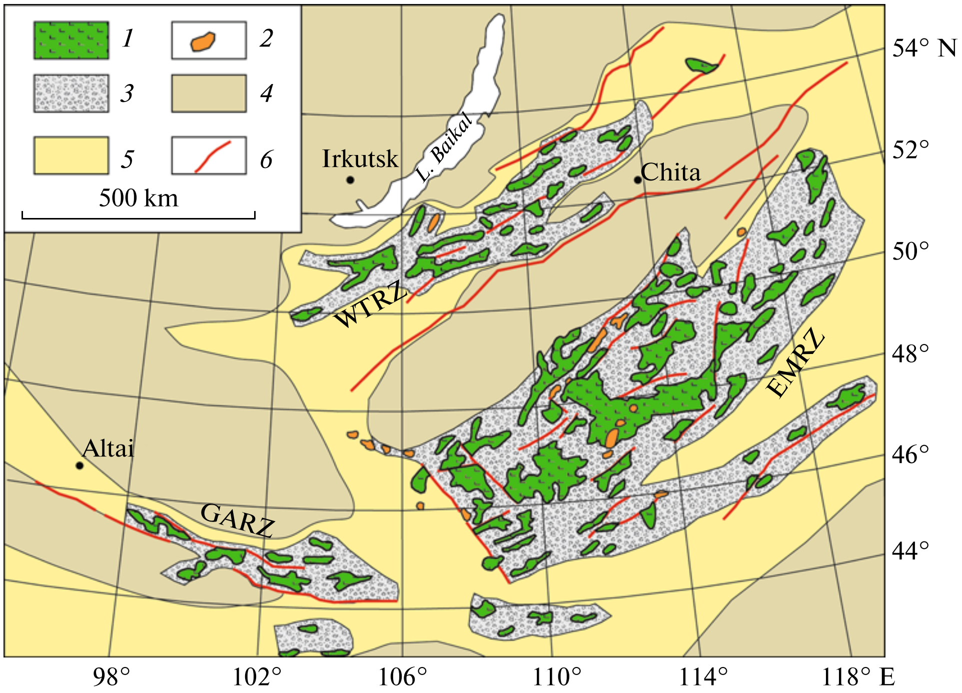


Fig. 9. Late Mesozoic volcanic zones in Central Asia. (*1*) Fields of trachybasalt, trachyte–phonolite, trachyte–trachyrhyolite, and basalt–trachyrhyolite volcanic associations; (*2*) intrusions of alkali and Li–F granites; (*3*) contour of volcanic zones; (*4, 5*) areas of denudation, after [36]: (*4*) low mountains, (*5*) elevated plains; (*6*) fault. Volcanic (rift) zones (abbreviations in figure): WTRZ, West Transbaikal; EMRZ, East Mongolian; GARZ, Gobi–Altai.

mation of some igneous domains could have been related to long-functioning mantle hot spots. For example, at least two hot spots (South Khangai, West Transbaikal) developed over the last 160 Ma [42]. This is indicated by inheritance in the localization of volcanic centers differing in age, the similar compositions of igneous rocks that erupted at different times, and the constant paleogeographic coordinates of active volcanic zones.

The data discussed above show that from the Riphean and then during the entire Phanerozoic, the Siberian Craton and the fold regions surrounding it (in the south in present-day coordinates) were a field of within-plate magmatism. Two short breaks in magmatic activity are noted. One pause between 350 and 320 Ma followed the completion of magmatic activity in the Vilyui LIP and continued up to the onset of magmatic activity in the Barguzin–Vitim LIP. The second pause embraced the interval of ~190 to 160 Ma due to the termination of activity in the Late Paleozoic–Early Mesozoic within-plate domains of North Asia and continued to the Late Jurassic, when a new generation of within-plate domains was formed in Central Asia. After the Early Cretaceous active phase, the productivity of volcanic activity fell sharply to less than 200 km^3 in the Late Cretaceous–Early Cenozoic. In the Late Cenozoic volcanism reactivated again.

INTERACTION OF SIBERIA WITH THE LARGE LOW-SHEAR-VELOCITY PROVINCE (LLSVP) IN THE PHANEROZOIC

The available data on within-plate magmatism of Siberia allows us to state that after breakdown of Rodinia the Siberian continent started to wander in the Riphean Ocean, called the Paleoasian Ocean in the Russian literature. As a result of this travel and according to the data on the interaction between the supercontinents and superplumes, the Siberian continent reached the area affected by the pra-African superplume antipodal with respect to the Rodinian superplume. We suppose that over most of the Phanerozoic, the Siberian continent interacted with the LLSVP corresponding to this superplume. Various plumes formed within this LLSVP were active during different time intervals.

As was mentioned above, the unique Iceland hot spot retained its relative position in geographic coordinates for a long time. Some authors believe that the Iceland hot spot was situated 250 Ma ago beneath the Siberian flood-basalt (trap) province and determined the formation of this large igneous province [34, 68, 73]. Since the Early Triassic, the trap magmatism propagated to the adjacent area of the Barents and Kara Seas (Fig. 11). The Franz Josef Archipelago marks the propagation of magmatic activity in the Early Jurassic and Cretaceous. The High Arctic large

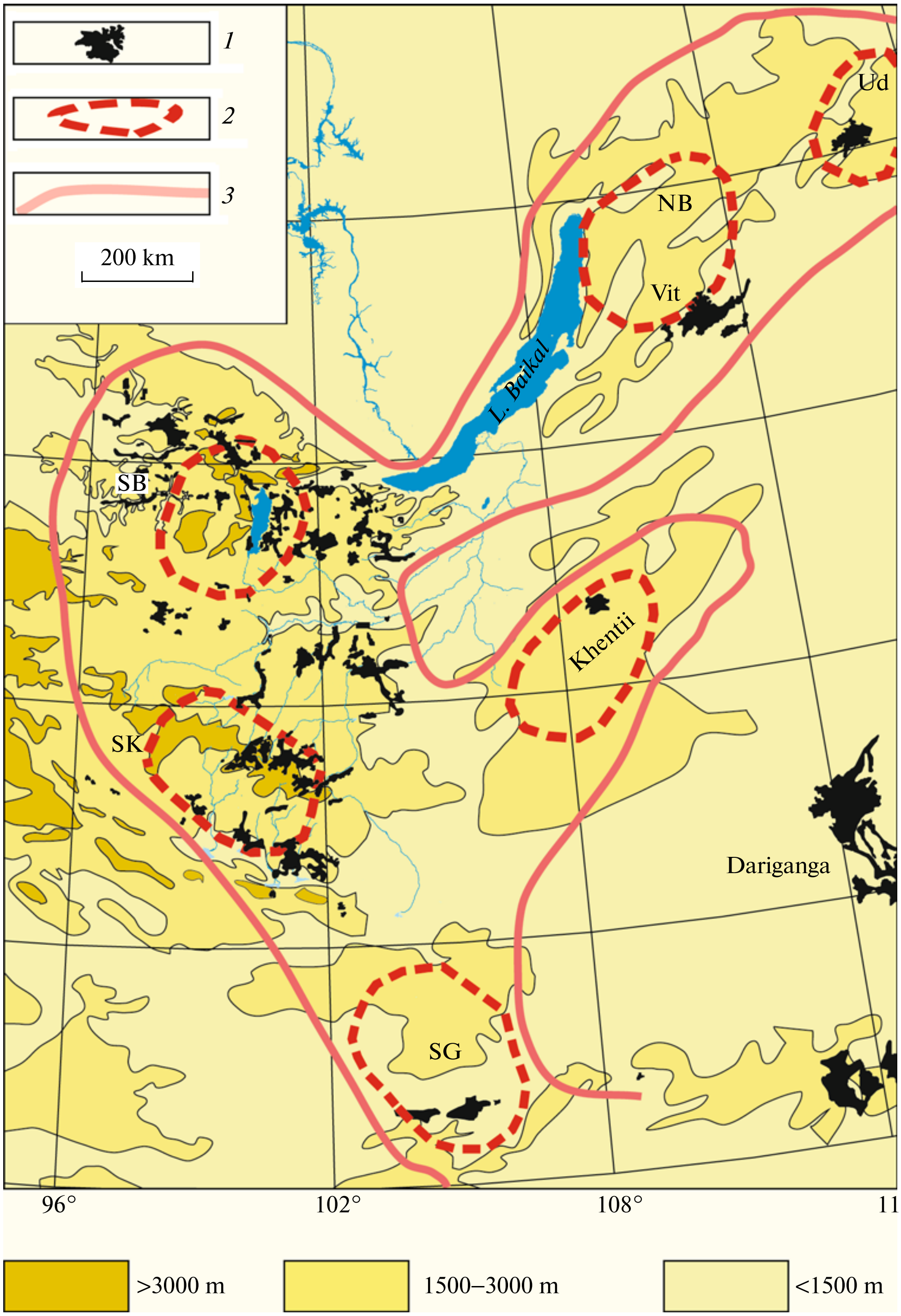


Fig. 10. Areas of recent volcanism and mountain systems in the Central Asian subprovince and location of asthenospheric uplifts, after [11]. (*1*) Lava field, (*2*) areas of ascent of the asthenosphere to a depth of <50 km, (*3*) asthenospheric uplifts (mantle plumes) ascending to a depth of 50–100 km. Asthenospheric uplifts (mantle hot spots): SK, South Khangai; SG, South Gobi; SB, South Baikal; NB, North Baikal; Ud, Udokan; KT, Khentii; lava plateaus: Vit, Vitim; Dar, Daringanga.

igneous province (HALIP), whose fragments are retained in various parts of the present-day Arctic Basin, was probably related to this hot spot in the Early Jurassic and Cretaceous [50]. About 50 Ma ago, the Iceland plume was responsible for opening of the North Atlantic [73, 92], from where its trace is tracked via Greenland up to the present-day location of Iceland. The data on migration of the Iceland hot spot over the last

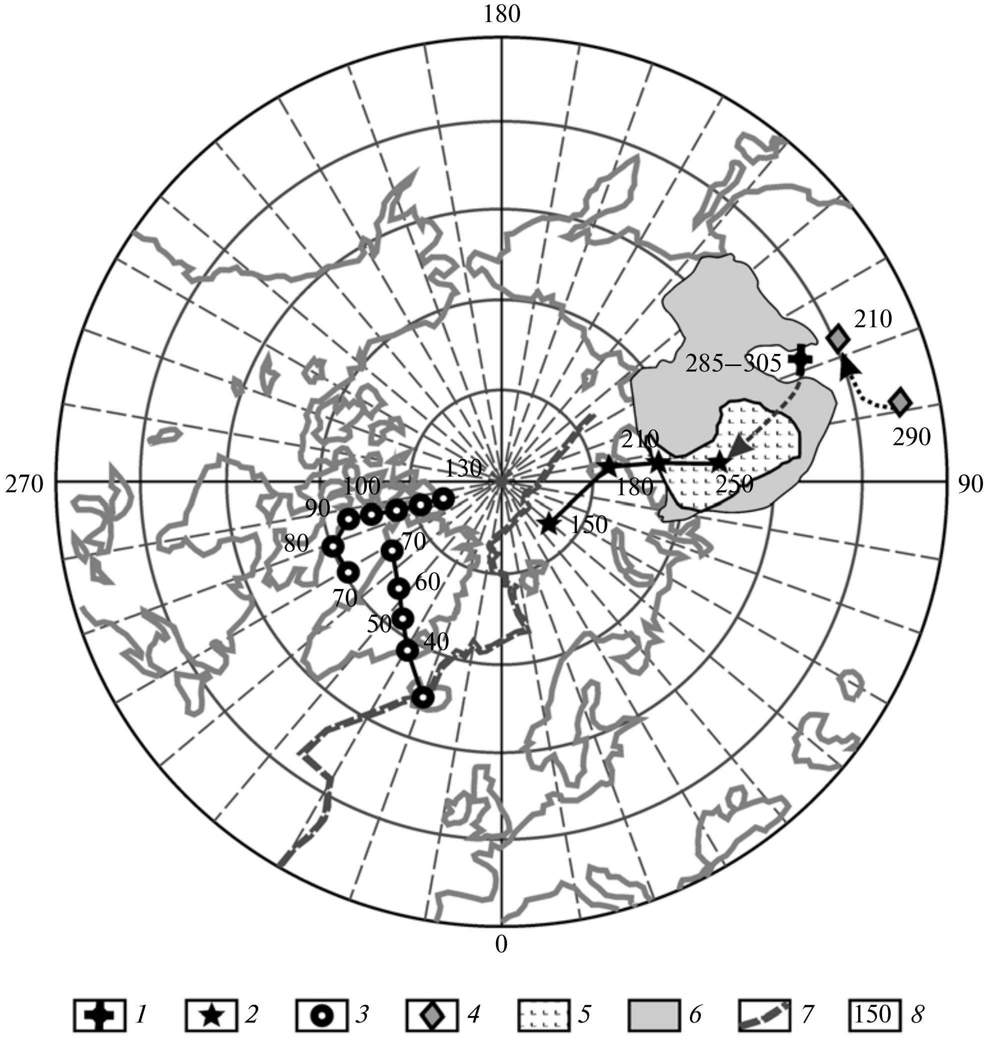


Fig. 11. Trace of the Iceland hot spot in the Arctic Basin. (*1–3*) Trace of the Iceland hot spot in (*1*) Barguzin–Vitim province, after [67]; (*2*) after formation of the Siberian flood basalts (traps), after [32, 73]; (*3*) after formation of mid-ocean ridge, after [68]; (*4*) trace of the Mongolian hot spot; (*5*) flood basalts (traps); (*6*) Siberian Platform; (*7*) mid-ocean ridge; (*8*) age, Ma, after [69, 73].

250 Ma are summed up and illustrated in Fig. 11. At present, the Iceland plume marks the northern boundary of the African LLSVP. It is suggested that the Iceland plume has remained at this position relative to the LLSVP since the moment of its origination [89, 91].

Torsvik et al. [88, 89] have shown that the African LLVCP has not changed its position over the last 300 Ma. This statement is based, in particular, on the data concerning the Skagerrak LIP, which covers Great Britain, Germany, Norway, and Sweden, with its center in the Skagerrak Graben in the North Sea. This province, which arose about 297 Ma ago, is responsible for the eruption of 0.1×10^6 km^3 of basalts and the formation of the Oslo Graben. Paleomagnetic reconstructions have shown that the formation of this LIP fixed the near-equatorial margin of the African low-velocity province. This implies that the African LLSVP has existed at least 300 Ma and has constant absolute geographic coordinates. The stable position of the Iceland hot spot over the last 250–300 Ma in absolute geographic coordinates allows us to consider this hot spot as a longitudinal datum mark of the migration of Siberia within the LLVSP in the Phanerozoic.

ESTIMATED MIGRATION OF SIBERIA ON THE BASIS OF PALEORECONSTRUCTIONS

The positions of Siberia in particular time intervals of the Phanerozoic are reconstructed in [67]. On the basis of these data, the migration of Siberia from the Vendian to the Late Cenozoic is considered below. The main point of this reconstruction is the suggestion that the Siberian flood basalts are related to the Iceland hot spot, which determined the longitudinal position of Siberia within the LLVSP at the Permian–Triassic

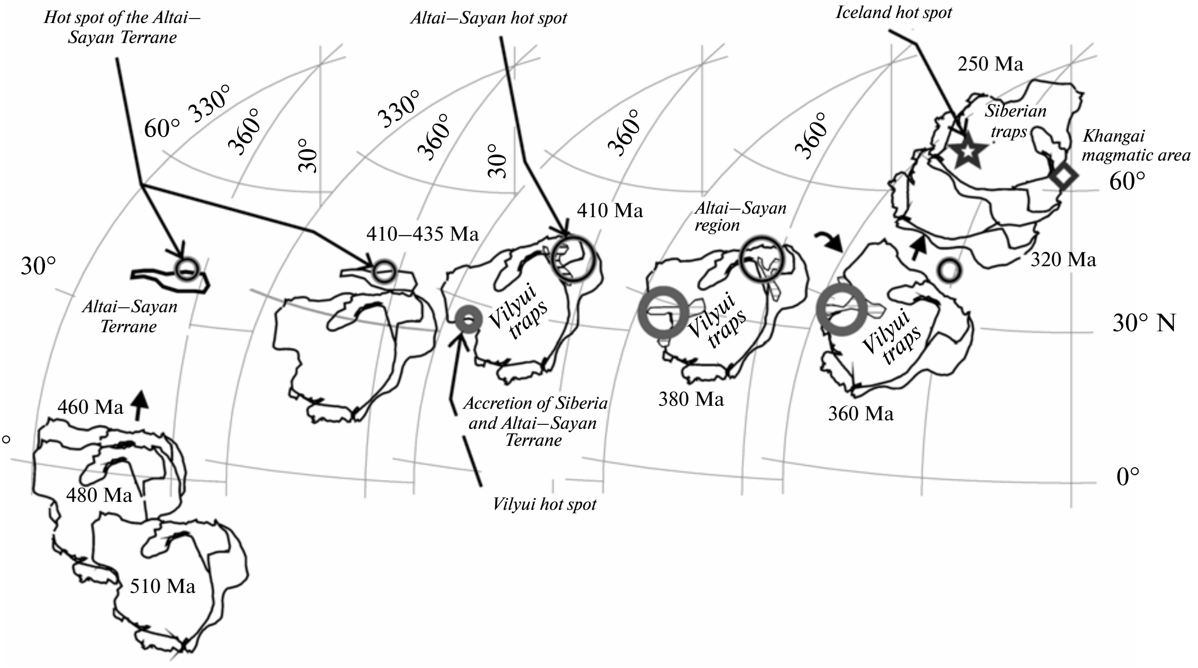


Fig. 12. Detailed reconstruction of paleoposition of the Siberian continent during its migration above the Altai–Sayan and Vilyui hot spots toward the Iceland and the Mongolian hot spots reached at the Carboniferous–Permian boundary.

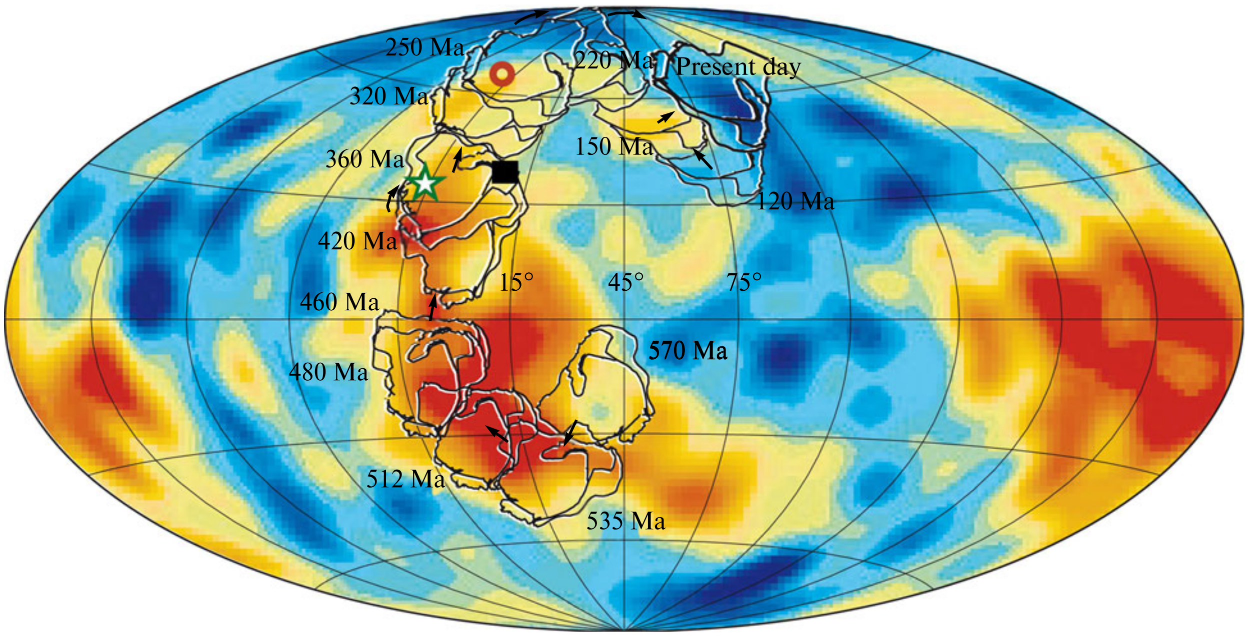


Fig. 13. Paleogeographic position of the Siberian continent back to 570 Ma, after [67] in the course of its migration above the African LLVSP. Mantle plumes: black square, Altai–Sayan; green star, Vilyui; red circle, Iceland (Siberian trap). Arrows indicate the direction of continent wandering; numerals are age, Ma corresponding to the position of the continent.

boundary. This, in turn, made it possible to establish the absolute coordinates of the hot spots marked by within-plate magmatism in the Phanerozoic history of the continents. In doing so, we proceeded from the assumption that the longitudinal arrangement of the hot spots was determined by the coordinates of the African LLVSP between ~330° and 70° E.

First of all, note the stable position of the Vilyui Rift ~400–350 Ma ago (Fig. 12). The corresponding hot spot could have existed before 400 Ma; however, according to paleomagnetic data, the Siberian continent overlapped it only 400 Ma ago. As follows from the paleomagnetic data [67], the latitudinal position of Siberia did not significantly change from 435 to 360 Ma ago (~6° ± 15°), however it rotated clockwise through ~30.0° ± 15.0° (Fig. 13).

The Altai–Sayan magmatic aureole is determined by another hot spot, which corresponded to the Vilyui hot spot in time of activity (490–370 Ma). Zonenshain et al. [10] have determined that during the Ordovician and Silurian this aureole was a separate terrane, which was attached to Siberia only in the Late Silurian–Early Devonian. In the Altai–Sayan magmatic aureole, magmatism began in the Ordovician–Silurian above a hot spot in the ocean at a distance from Siberia [18, 40, 44] (Fig. 12). The maximum of volcanic activity fell on the interval of 410 to 370 Ma, when the Altai–Sayan Terrane joined Siberia, which remained above the hot spot (Fig. 12). In the Late Silurian–Early Devonian, the Siberian continent, having increased in size, rotated above the Altai–Sayan hot spot without significant displacement relative to the meridian and, as a result, overlapped the Vilyui hot spot (Fig. 12). Thus, taking the Vilyui hot spot as constantly immobile, we can estimate the coordinates of the Vilyui hot spot (35° ± 15° N and ~340° E) and the Altai–Sayan hot spot (40° ± 15° N and ~360° E). Siberia continued its clockwise rotation in the Late Devonian–Early Carboniferous, occupying a stable position above the Vilyui hot spot. No data are available on the interaction of the Altai–Sayan hot spot and the Siberian continent in the post-Devonian time. We suggest that the continent shifted apart from this hot spot (Fig. 12).

In the Early Permian (275 Ma ago), Siberia was situated at the same latitude as in the Permian–Triassic [81, 86]. Such a high latitudinal position indicates that, having detached from the Vilyui hot spot, Siberia was displaced from 30° to 60° N over 30–35 Ma. The average velocity of ~11 cm/yr is very high. Therefore, we have to suggest that the continent moved only along the meridian. The subsequent clockwise rotation resulted in the appearance of the Iceland hot spot beneath the Siberian flood basalts. The reconstruction of the probable pathway of Siberia above this hot spot during the Permian allows us to suggest that the first contact of the hot spot with the continent took place close to its Transbaikal active margin. This interaction was fixed 310–280 Ma ago and led to the formation of the Barguzin–Vitim zonal magmatic area with the Angara–Vitim batholith as a core surrounded by marginal rift zones [38, 45].

The trace of the hot spot related to the rotation of Siberia above it during the Permian is traced from paleomagnetic data. For example, the Permian–Triassic magnetic anomalies in the Early Paleozoic base-metal ore and doleritic dikes and sills at the Ozernoe deposit to the east of Lake Baikal (present-day geographic coordinates are 53° N and 112° E) and in the Middle Carboniferous ore at the Sukhoi Log deposit in the Bodaibo district (present-day geographic coordinates 58° N and 115° E) [8, 21, 67] indicate their remagnetization. Both deposits are localized between the Barguzin–Vitim area and the province of Siberian flood basalts. Therefore, remagnetization could have been related to migration of the continent above the hot spot.

Thus, the Barguzin area of the Siberian continent migrated to the vicinity of the Iceland hot spot in the Late Carboniferous (320 Ma ago). At the Permian–Triassic boundary, the Iceland hot spot ejected an enormous amount of plume material, having provided the formation of the Permian–Triassic Siberian flood basalts. In the Late Triassic–Early Jurassic, Siberia continued to move apart from the Iceland hot spot, rotating clockwise and displacing in the latitudinal direction, so that magmatism migrated in the northwestern direction (in present-day coordinates) to the shelf of the Siberian continent.

The Central Asian Rift System composed of igneous rocks typical of within-plate setting was formed approximately 310–285 Ma ago in the Hercynides of South Mongolia simultaneously with the Barguzin–Vitim area. The formation of this province is referred to the Mongolian hot spot [39, 46]. The displacement and clockwise rotation of Siberia in the Late Paleozoic led to the eastward–northeastward (in present-day coordinates) migration of magmatism related to this hot spot (Fig. 7). As was shown in [46], magmatism migrated at that time from South Mongolia (290 ± 10 Ma) to Central Mongolia (255 ± 10 Ma) with the formation of the Khangai zonal magmatic area and then to East Mongolia and Transbaikal region (210 ± 15 Ma), where the Mongolian–Transbaikal zonal magmatic area arose. The coordinates of the Mongolian hot spot are estimated at 65° ± 15° N and ~25°–35° E.

The specificity of within-plate magmatism in the southern fold framework of the Siberian Platform is expressed in the formation of large zonal magmatic area with batholithic cores (Angara–Vitim, Khangai, and Khentii) in the domains affected by mantle plumes. This feature was determined by a special regime of interaction between the mantle plumes and the lithosphere in the setting of active continental margin, when the melts ascending from mantle hot spots apparently did not reach the surface and concentrated in the lower crust, provoking anatexis [39, 41, 46].

The traces of the Iceland and Mongolian hot spots, which are consistent with clockwise rotation of Siberia, are documented by paleomagnetic data on Siberia and Europe [53, 67, 92] (Fig. 11). The average velocity of plate movement from 300–250 to 180 Ma, estimated at ~1.7 cm/yr from the trace of the Iceland hot spot, is comparable with the average velocity of tectonic plate movement in the northern part of the Atlantic Ocean (~2.0 cm/yr).

No within-plate magmatic activity in Siberia was established 185–160 Ma ago. We suppose that this time coincided with the onset of opening of the Atlantic Ocean, and in this connection, Siberia rapidly displaced eastward beyond the African LLSVP.

In the Late Mesozoic, the within-plate activity led to the formation of several rift zones in Central Asia. The peak of magmatism fell on the Early Cretaceous, whereas by the end of the Cretaceous, the intensity of magmatic and tectonic activity was abruptly reduced. A new outburst of within-plate magmatism took place in the Late Cenozoic (<25 Ma). Despite the nonuniform evolution of magmatism in the Late Mesozoic and Cenozoic, it was obviously related to long-living hot spots, which retain their stable geographic position over more than 100 Ma [17]. These hot spots belong to the cluster of mantle plumes recently revealed at the southwestern margin of the Pacific Ocean [99] as a branch of the Pacific superplume. Therefore, it may be inferred that by the beginning of the Late Mesozoic, Siberia substantially displaced to the east and reached the field affected by the Pacific plume, which determined the within-plate activity in East Asia during the Late Mesozoic and Cenozoic.

The data presented above make it possible to reconstruct the paleogeographic position of Siberia in the Paleozoic and Early Mesozoic using the absolute coordinates of the Iceland, Altai–Sayan, Vilyui, and Mongolian hot spots reconstructed on the basis of geological and paleomagnetic data (Fig. 13). The Late Mesozoic and Cenozoic position is reconstructed from the hot spots formed at the corresponding time in Central and East Asia.

Thus, 700 Ma ago Siberia entered into Rodinia [79]. After the breakdown of Rodinia, Siberia traveled to the pra-African hot field of the mantle, where a number of hot spots differing in age were localized. The earliest mantle plume that developed in the structure of the Siberian continent affected the evolution of the Altai–Sayan domain as early as the Ordovician and Silurian. Later, in the Early Devonian, after accretion of this domain to Siberia, this plume affected the structure and magmatism of the southwestern margin of the continent. Numerous Late Riphean and Vendian–Cambrian volcanic complexes composed of OIB-type basalts which participated in the structure of the oceanic plateaus or oceanic islands are noted as fragments in the ophiolitic zones of the Central Asian Foldbelt [2, 18, 31, 44], providing evidence for the migration of Siberia trough the domain of mantle plumes. According to paleomagnetic data [6], such complexes of the Dzhida ophiolitic zone were formed at 15°–20° S. These data show that the hot spot existed near Siberia as early as the Vendian and Cambrian. This gives grounds to place the Siberian continent in the field affected by the African LLSVP as early as 570 Ma ago (Fig. 13).

By the Mid-Devonian, Siberia remained above the Altai–Sayan hot spot, and, owing to rotation, overlapped the Vilyui hot spot (Fig. 13). The northward migration of Siberia in the Early Carboniferous resulted in the collision and accretion of volcanic arcs and oceanic islands, which existed in the Paleoasian Ocean [10]. The accreted structural elements made up the South Mongolian Zone of the Hercynides in the Central Asian Foldbelt [29]. The Hercynian terranes and islands were indicators of hot-spot activity within LLSVP beyond the limits of the Siberian continent. In the Late Carboniferous, the South Mongolia margin of Siberia overlapped one such hot spot, called the Mongolian. As a result of its interaction with the continent from the Late Carboniferous to the Early Jurassic, a large rift system with Khangai and Mongolian–Transbaikal zonal magmatic areas was formed. Another hot spot, which determined the formation of the flood-basalt province of Tarim, operated simultaneously with the Mongolian hot spot.

As can be seen from Fig. 13, in the course of migration, the Siberian continent went above the Altai–Sayan and Vilyui hot spots, the traces of which were lost after departure of the continent from them. The Mongolian hot spot affected the Siberian continent for a longer time. Later, it was responsible for a number of magmatic areas in Central Asia. Finally, the Iceland hot spot affected the continent for the longest time. Its trace, documented in the displacements of magmatic centers from the Barguzin–Vitim region to the Siberian flood basalts and farther into the Arctic Basin, stabilized in the Early Cenozoic in the zone of breakup of the North Atlantic.

After 190 Ma ago, Siberia went out from the effect of the African hot field and was displaced to the east, where it overlapped one of the branches of the Pacific superplumes by its southern (in present-day coordinates) fold framework. As a result, several long-living mantle hot spots arose in Central and East Asia. Their paleomagnetic characteristics show that in the Late Mesozoic and Cenozoic, North Asia underwent rotation without significant horizontal displacements.

ISOTOPIC–GEOCHEMICAL CHARACTERISTICS OF SOURCES AND EVOLUTION OF PHANEROZOIC WITHIN-PLATE MAGMATISM OF SIBERIA

The geological and paleomagnetic data on the migration of the Siberian continent above the African LLVSP in the Phanerozoic allow us to estimate the composition of the mantle magma sources operating within the superplume in various time intervals and to consider the compositional evolution of these sources.

In the ***Early–Middle Paleozoic epoch,*** the Siberian continent was situated at the middle latitudes above the central area of the African LLVSP and overlapped the Altai–Sayan and the Vilyui hot spots.

The Altai–Sayan hot spot was overlapped by the active margin of the Siberian continent, and the triple system of grabens of the Altai–Sayan rift domain was formed above this hot spot. The magma sources comprised both plume- and subduction-related components. The basalts and basaltic andesites widespread in this domain are derivatives of magma melts. They are divided into high- and medium-Ti varieties. The high-Ti basalts occur in the areas furthest from the continental margin [4]. In their geochemical characteristics, they are close to the OIB-type basalts and are distinguished by elevated HREE contents (Fig. 14). The medium-Ti basalts reveal Ta–Nb and Ti minimums and somewhat lower contents of other trace elements. This feature is probably caused by the participation of the aqueous fluid taken from zone of melting in the subduction zone [4].

The isotopic composition of the basaltic rocks is shown in Fig. 15. A wide variation in the Sr isotopic composition in combination with persistent positive εNd values is characteristic. The isotopic parameters of the left part of the data point cluster are close to PREMA. The cluster extending along the *x*-axis indicates the participation of the component enriched in radiogenic Sr and depleted in Nd. Marine carbonates satisfy these conditions, so that subducted carbonate material was probably involved in magma generation [4].

Thus, the composition of the mafic rocks from the Altai–Sayan Rift System suggests the participation of a plume mantle source with OIB geochemical and PREMA isotopic characteristics. The appearance of hydrous and carbonate components, which determined variation in the isotopic composition of rocks and the geochemical features of medium-Ti basalts, is a result of the interaction of this source with the subduction zone.

High-Ti basalts are predominant in the *Vilyui rift domain* both as lava flows and subvolcanic eruptions. These OIB-type volcanic rocks (Fig. 14) are close to the high-Ti basalts of the Altai–Sayan rift domain. As in the latter, significant variations in the Sr isotopic composition are noted in the Vilyui rift domain. These variations are especially inherent to dikes and sills that are hosted in the carbonate platform cover and thus contaminated with carbonate rocks. In contrast, the lava flows have a more-or-less stable isotopic composition [16]. Taking into account that εNd of the least contaminated rocks from the Vilyui rift domain is +3 to +6, it may be supposed that the initial composition of mantle-derived magma was close to PREMA.

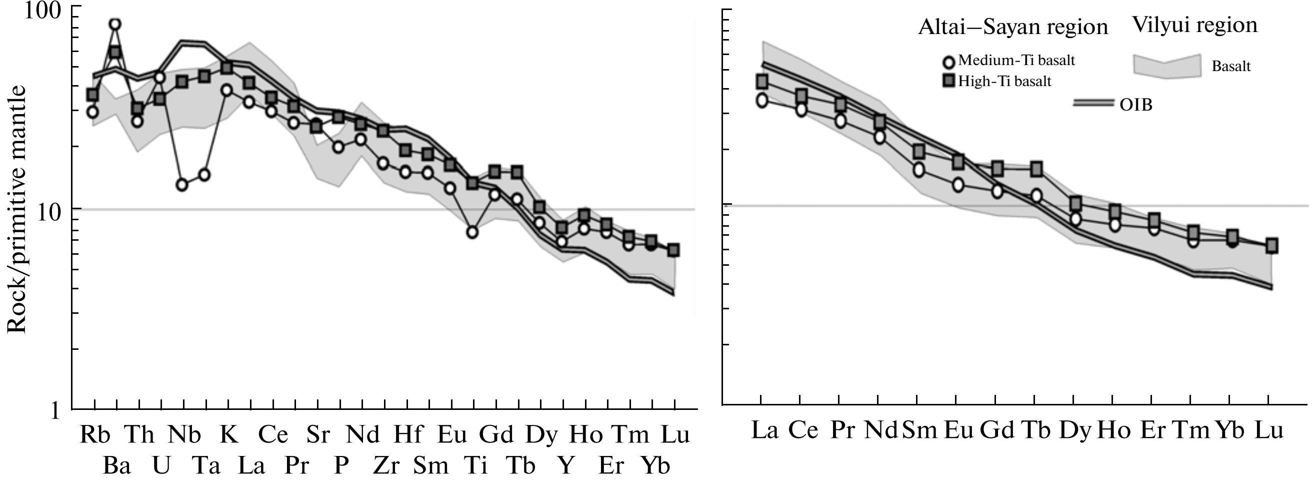
The Late Paleozoic–Early Mesozoic epoch was characterized by the most intense within-plate magmatism and the formation of a number large igneous provinces in a different part of the Siberian continent. These provinces correspond to the traces of two hot spots: the Iceland hot spot, to which the formation of the Barguzin–Vitim zonal magmatic area and the Siberian flood-basalt (trap) province is related, and the Mongolian hot spot, which determined the formation of the Late Paleozoic–Early Mesozoic rift system of Central Asia. The paleogeographic parameters of these hot spots indicate that the Siberian continent occurred at that time at high latitudes and was underlain by the northern part of the African LLVSP.

Irrespective of its location, the within-plate magmatism of this epoch was characterized by uniform elemental and isotopic compositions. In the flood basalts of the Siberian Platform, the basalts of rift-related associations, and the synplutonic mafic dikes in giant granitoid batholiths, medium-Ti basalts (1–2 wt % TiO_2) are predominant. In REE content, they are close to the OIB-type basalts (Fig. 14); however, in contrast to the latter, mafic rocks of the Late Paleozoic and Early Mesozoic associations reveal a Nb–Ta minimum (Fig. 14). This feature is probably related to the elevated water content of the mantle beneath Siberia due to the migration of this continent above the mantle domains, which permanently underwent fluid reworking related to the continuous subduction beneath the continent from the side of the Paleoasian Ocean.

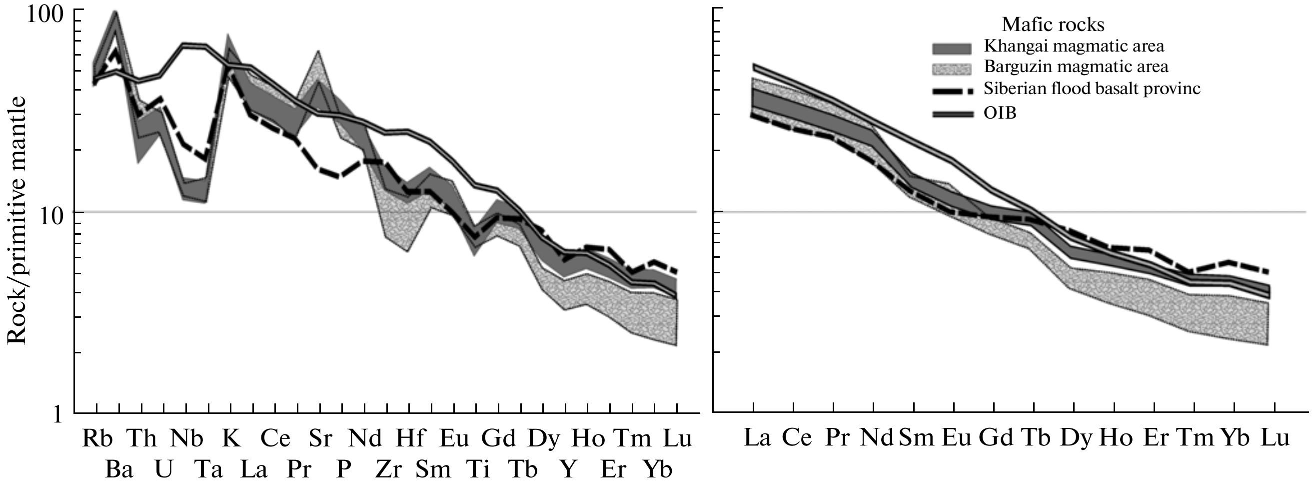
In comparison with the flood basalts of the Siberian Platform, related to the activity of the Iceland plume, the mafic rocks of the Barguzin area are distinguished by higher Ba and Sr contents and are depleted in Ta, Nb, Zr, and Hf. The REE pattern of the mafic rocks from the Barguzin interval corresponds to that of OIB-type basalts and differs from subalkali flood basalts in more pronounced fractionation and enrichment in LREE.

The isotopic compositions of these domains are also almost the same. The data points pertaining to the different regions make up a single trend compatible with the mantle array and displaying insignificant regional deviations (Fig. 15). This trend is traced from the region of moderately depleted mantle of the PREMA type toward sources enriched in radiogenic Sr and, to a lesser extent, in LREE (Nd relative to Sm), which are commonly compared with the enriched mantle reservoir EM2. The available isotopic

Early–Middle Paleozoic epoch



Late Paleozoic epoch



Late Mesozoic–Cenozoic epoch

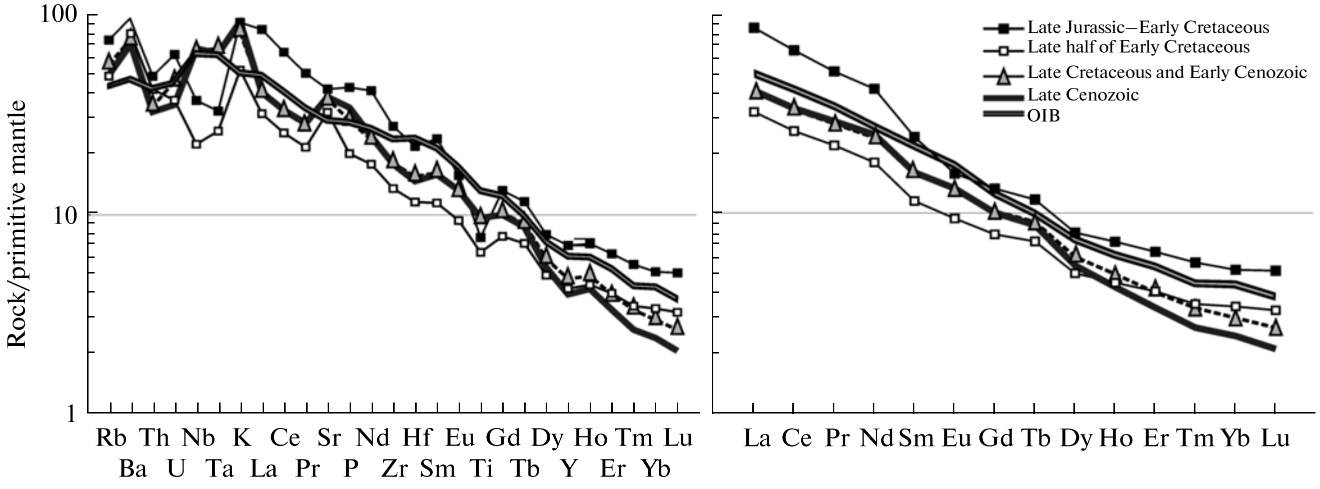


Fig. 14. Distribution of average trace element contents normalized to the primitive mantle composition in mafic rocks of the LIPs different in age in Siberia and its fold framework.

and geochemical data provide evidence for a homogeneous medium of magma generation in the Late Paleozoic and Early Mesozoic beneath the entire Siberian continent.

The Late Mesozoic–Cenozoic epoch. The arguments adduced above indicate that during this epoch the Siberia as a part of the Eurasian continent migrated into the field affected by the Pacific superplume. Indeed, the most appreciable changes in the composition of the within-plate magma sources occurred over the last 150 Ma. As was noted above, a number of long-living hot spots functioned in the mantle at that time in the Central Asian framework of the Siberian Platform [30, 42]. The magma sources were broadly similar to the sources of OIB-type basalts but underwent a certain evolution through this epoch. In geochemical parameters, this evolution is clearly expressed in progressive enrichment in Ta, Nb, and Ti (Fig. 14). While an insignificant negative Ta–Nb anomaly is still discerned in the Early Cretaceous mafic rocks, indicating a certain inheritance in the composition of Late Paleozoic–Early Mesozoic mafic rocks, this anomaly disappears in the Late Cretaceous associations, and the Late Cenozoic igneous rocks are distinguished by a pronounced Ta–Nb maximum. Other geochemical parameters varied insignificantly. In particular, the relatively high K_2O contents remained unchanged, indicating that the igneous rocks of this epoch belong to the high-K petrochemical series.

Some evolutionary tendencies are noted in the variations in the isotopic composition of rocks (Fig. 15c, 15d). At the Early Cretaceous stage, the mantle magma sources were enriched in the EM2 component expressed in Sr and Nd parameters. From the end of the Early Cretaceous and during Early Cenozoic, the PREMA component was predominant. From the Early Cretaceous to the Late Cenozoic, the Sr, Nd, and Pb isotopic compositions of the magmatic melts were determined by combinations of the PEMA and EM1 components [30].

Evolution of within-plate magmatism. While estimating the composition and evolution of the Phanerozoic within-plate magmatism of the Siberian continent in general, it should be noted that over the Paleozoic and Early Mesozoic, the PREMA reservoir, which is suggested to correspond to the lower mantle, was a constant component of its sources. The Early and Middle Paleozoic mantle-derived magmas interacted very little with the lithospheric mantles, and the variations in their composition were determined either by crustal contamination or interaction with the fluids related to subduction zones. In the Late Paleozoic–Early Mesozoic epoch, the enriched EM2 reservoir participated in the magma sources along with the PREMA component. The EM2 reservoir was enriched in water, and this was the cause of the deficiency in Ti, Ta, Nb, and to a lesser degree, Zr and Hf in the products of mantle melting. The enrichment in water could have been a result of continuous subduction of the Central Asian Ocean under the Siberian continent with the formation of a graveyard of stagnated slab fragments (EM2 reservoir) beneath the continent and saturation with water of the supraslab mantle with a model isotopic age of ~1.2 Ga [37].

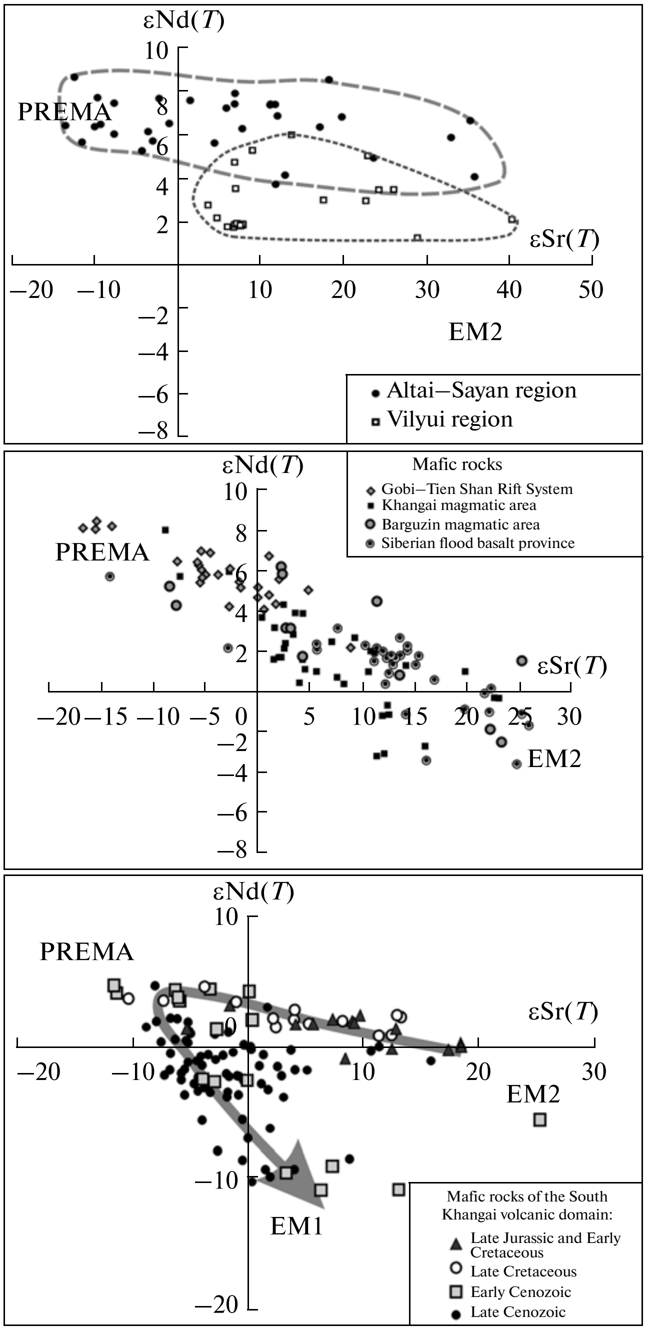


Fig. 15. Isotopic compositions of mafic rocks from the LIPs of various ages of Siberia and its fold framework plotted on the εNd–εSr diagram.

In the Late Mesozoic and Cenozoic, Siberia migrated into the field affected by the Pacific plume. This led to substantial change in the composition of the within-plate magma sources. In addition to PREMA, the enriched magma reservoir EM1 participated in melting. This mantle had the isotopic characteristics of recycled lithosphere about 2.5 Ga in age [30]. The long-term isolation of recycling probably took place only in the very low mantle, in particular, at its boundary with the core. Thus, deep magma sources existed at that time.

The geophysical data can provide evidence for the mechanisms giving rise to the change in composition of magmatic sources in the Cenozoic. As was shown by Zorin et al. [11–14], uplifts of the asthenosphere, ascending to a depth of less than 50 km from the surface, are detected beneath the Cenozoic volcanic regions of Central Asia. According to the data of seismic tomography [27, 28], these uplifts have deep mantle roots in the form of narrow zones of low-velocity mantle, going down to the bottom of the upper mantle. The low-velocity zones are traced to the deeper mantle levels of Central and East Asia [7], reaching the boundary with the core. The sections presented in [7] show that the structure of the zone of convergence of the Asian continent and the Pacific Ocean is determined by substitution of upper mantle convection for whole-mantle convection.

These data in combination with the isotopic and geochemical evidence allow us to propose the following model describing the change of within-plate magma sources in the southern framework of Siberia in the Phanerozoic. After the breakdown of Pangea, Siberia was displaced to the east in the domain affected by the Pacific LLVSP, which dominated by whole-mantle convection. As a result of the convergence of continent and the oceanic lithospehre, the subducted cold slabs sank to the lower mantle and affected layer D" of the Pacific LLVSP. This effect was compensated by the formation of ascending plumes, which corresponded to formerly buried lithospheric material with attributes of EM1. When these plumes ascended to the surface, they passed through the lower mantle characterized by PREMA parameters and involved it in the ascending flow, which ultimately determined the composition of the basalt sources in the Cenozoic within-plate province of Central and East Asia.

CONCLUSIONS

The performed study makes it possible to connect manifestations of Phanerozoic within-plate magmatic activity in the Siberian continent with its migration above the cluster of hot spots related to the African superplumes and corresponding LLVSP.

The within-plate magmatism developed not only in the paleocontinent but also in the terranes that occurred initially at a distance but then accreted to it, indicating that a number of individual hot spots within the LLVSP functioned synchronously. The most intense magmatic activity is noted at the boundary between the Permian and Triassic (~250 Ma). The enormous volumes of basaltic magma (1.5×10^6 km^3) that erupted during 1 Ma were related to the ascent of a large plume in the area of the present-day Iceland hot spot.

The assumption of the long-term existence of the Iceland hot spot has allowed us to reconstruct the position of the Altai–Sayan, Vilyui, and Mongolian hot spots, which were crucial in the evolution of the within-plate magmatism of Siberia. Paleomagnetic data were the basis for reconstruction of the paleolatitude of Siberia and the localization of the hot spot in the longitudinal tract between 330° and 70° E constraining its paleolongitudinal position. The PREMA, EM1, and EM2 mantle reservoirs were sources of within-plate magmatism. The interaction between these reservoirs progressively changed with time. PREMA dominates in the sources of the Early and Middle Paleozoic within-plate magmatism. In the Late Paleozoic and Early Mesozoic magmatic occurrences, including flood basalts of the Siberian Platform, combinations of EM2 and PREMA reservoirs dominated. In the Late Jurassic and Early Cenozoic, PREMA again became crucial. In the Late Cenozoic, EM1 joined PREMA.

The continuity of within-plate magmatic activity related to the superplume indicates the chronological identity of the superplume to the antipodal Rodinian superplume. Thus, the superplume existed for at least one billion years. Taking into account that the Rodinian superplume is compared to the Pacific superplume, the conclusion suggests itself that superplumes are the most long-living deep structural units of the Earth. Their relationships with the formation of the supercontinents probably reflect their counter-phase activity, one of the causes of which could have been the effect of thermostating and the accumulation of energy by superplumes owing to overlapping by supercontinents [70].

It should also be noted that the processes related to the boundaries of the lithospheric plates should be taken into account when the origin and evolution of the contemporary continents are considered, as well as activity of the superplumes controlling the within-plate magmatism in the continents.

ACKNOWLEDGMENTS

This study was supported by the Presidium (program no. 4) and the Division of Earth Sciences (program no. 9) of the Russian Academy of Sciences.

REFERENCES

1. B. Isacks, J. Oliver, and L. R. Sykes, "Seismology and the New Global Tectonics," J. Geophys. Res., No. 18, 5855–5899 (1968).
2. A. I. Al'mukhamedov, I. V. Gordienko, M. I. Kuz'min, et al., "The Dzhida Zone: A Fragment of the Paleoasian Ocean," Geotectonics **30** (4), 279–294 (1996).
3. A. I. Al'mukhamedov, A. Ya. Medvedev, and V. V. Zolotukhin, "Chemical Evolution of the Permian–Triassic Basalts of the Siberian Platform in Space and Time," Petrology **12** (4), 297–311 (2004).
4. A. A. Vorontsov, V. V. Yarmolyuk, G. S. Fedoseev, et al., "Isotopic and Geochemical Zoning of Devonian Magmatism in the Altai–Sayan Rift System: Composition and Geodynamic Nature of Mantle Sources," Petrology **18** (6), 596–609 (2010).
5. V. V. Gaiduk, "The Middle Paleozoic Vilyui Rift System," Geotektonika **21** (3), 66–76 (1987).
6. I. V. Gordienko and N. E. Mikhal'tsov, "Position of Vendian–Early Cambrian Ophiolitic and Island-Arc Complexes of the Dzhida Zone of Caledonides in Paleoasian Oceanic Structures: Interpretation of Paleomagnetic Data," Dokl. Earth Sci. **379A** (5), 622–626 (2001)
7. D. Zhao, F. Piraino, and L. Liu, "Structure and Dynamics of the Mantle beneath East Russia and the Adjacent Regions," Geol. Geofiz. **51** (9), 1188–1203 (2010).
8. A. N. Zhitkov and A. Ya. Kravchinsky, "Paleomagnetic and Metallogenic Studies of Productive Quartz–Pyrite Mineralization in the Lena Region, a Case of the Glavnoe Deposit," in *Geophysical Research of Deposits in East Siberia* (SNIIGiMS, Novosibirsk, 1982), pp. 105–109 [in Russian].
9. L. P. Zonenshain and M. I. Kuz'min, "Within-Plate Volcanism and Its Implications for Understading of the Processes in the Earth's Mantle," Geotektonika **17** (1), 28–45 (1983).
10. L. R. Zonenshain, M. I. Kuz'min, and L. M. Natapov, *Tectonics of Lithospheric Plates in Territory of the USSR: books 1 and 2* (Nedra, Moscow, 1990) [in Russian].
11. Yu. A. Zorin, E. V. Balk, M. R. Novoselova, and E. Kh. Turutanov, "Thickness of the Lithosphere beneath the Mongolian–Siberian Highland and the Adjacent Regions," Fiz. Zemli **24** (7), 32–42 (1988).
12. Yu. A. Zorin and E. Kh. Turutanov, "Plumes and Geodynamics of the Baikal Rift Zone," Geol. Geofiz. **46** (7), 685–699 (2005).
13. Yu. A. Zorin, E. Kh. Turutanov, V. M. Kozhevnikov, et al., "Cenozoic Upper Mantle Plumes in East Siberia and Central Mongolia and Subduction of the Pacific Plate," Dokl. Earth Sci. **409** (5), 723–726 (2006).
14. Yu. A. Zorin, E. Kh. Turutanov, V. M. Kozhevnikov, et al., "Nature of Cenozoic Upper Mantle Plumes in East Siberia (Russia) and Central Mongolia," Geol. Geofiz. **47** (10), 1060–1074 (2006).
15. A. I. Kiselev, V. V. Yarmolyuk, K. N. Egorov, et al., "Middle Paleozoic Basic Magmatism of the Northwestern Vilyui Rift: Composition, Sources, and Geodynamics," Petrology **14** (6), 660–682 (2006).
16. A. I. Kiselev, V. V. Yarmolyuk, A. V. Nikiforov, and K. N. Egorov, "Composition and Sources of Devonian Volcanism in the Vilyui Rift," Dokl. Earth Sci. **415** (5), 744–750 (2007).
17. D. V. Kovalenko, "Correlation of Areas of Late Mesozoic and Cenozoic Within-Plate Magmatism of Central Asia and Paleomagnetic reconstructions of Localization of Anomalous Mantle," Geol. Geofiz. **50** (7), 993–1005 (2009).
18. V. I. Kovalenko, V. V. Yarmolyuk, V. P. Kovach, et al., "Magmatism and Geodynamics of Early Caledonian Structures of the Central Asian Foldbelt," Geol. Geofiz. **44** (12), 1280–1293 (2003).
19. V. I. Kovalenko, V. V. Yarmolyuk, and O. A. Bogatikov, "Geodynamic Setting of Recent Volcanism in North Eurasia," Geotectonics **43** (50), 337–357 (2009).
20. V. I. Kovalenko, V. V. Yarmolyuk, and O. A. Bogatikov, "The Contemporary North Pangea Supercontinent and the Geodynamic Causes of Its Formation," Geotectonics **44** (6), 448–461 (2010).
21. V. A. Kravchinsky, "Application of Paleomagnetic Method to the Study of Genesis and Age of Rocks and Ores at the Ozernoe Base-Metal Deposit," in *Acceleration of Scientific and Technical Progress in Geophysical Research of East Siberia* (Vostochno-Sibirskaya Pravda, Irkutsk, 1989), pp. 103–108 [in Russian].
22. M. I. Kuz'min, *Geochemistry of Igneous Rocks in Phanerozoic Mobile Belts* (Nauka, Novosibirsk, 1985) [in Russian].
23. M. I. Kuz'min, A. I. Al'mukhamedov, V. V. Yarmolyuk, and V. A. Kravchinsky, "Riftogenic and Intraplate Magmatism: Relationships with Hot and Cold Mantle Fields," Geol. Geofiz. **44** (12), 1270–1279 (2003).
24. M. I. Kuz'min, A. I. Al'mukhamedov, V. V. Yarmolyuk, and V. A. Kravchinsky, "Rifting and Riftogenic Magmatism: Manifestations in Spreading Zones and above Hot and Cold Mantle Fields," in Vyp. 2. *Proceedings of Theoretical Seminar on Problems of Global Geodynamics, 1999–2001,* Ed. by D. V. Rundqvist (OGGGGN RAN, Moscow, 2003), issue 2, pp. 7–31 [in Russian].
25. B. A. Litvinovsky, A. N. Zanvilevich, A. M. Alakshin, and Yu. Yu. Podladchikov, *The Angara–Vitim Batholith—the Greatest Granitoid Pluton* (Nauka, Novosibirsk, 1992) [in Russian].
26. I. V. Luchitsky, "Paleovolcanological Reconstructions and Some Questions of Paleoenergetics," in *Comparative Paleovolcanology of the Middle and Late Paleozoic in the South Siberia and East Kazakhstan* (Nauka, Novosibirsk, 1966), pp. 263–281 [in Russian].
27. V. V. Mordvinova, A. Deschamps, T. Dugarmaa, et al., "Velocity Structure of the Lithosphere on the 2003 Mongolian–Baikal Transect from *SV* Waves," Izv. Physics Solid Earth **43** (2), 119–129 (2007).
28. V. V. Mordvinova, A. V. Treusov, E. V. Sharova, and V. I. Grebenshchikova, "Results of Teleseismic Two-Dimensional P-Tomography: Evidence for a Mantle Plume beneath Khangai," in *Proceedings of Scientific*

Conference under the Program of Fundamental Research on Geodynamic Evolution of the Lithosphere in the Central Asian Foldbelt (from Ocean to Continent) (Inst. Earth's Crust, Irkutsk, 2008), Vol. 2, No. 6, pp. 41–43 [in Russian].

29. A. A. Mossakovsky, S. V. Ruzhentsev, S. G. Samygin, and T. N. Kheraskova, "Central Asian Foldbelt: Geodynamic Evolution and Formation History," Geotektonika **27** (6), 3–33 (1993).
30. V. M. Savatenkov, V. V. Yarmolyuk, E. A. Kudryashova, and A. M. Kozlovsky, "Sources and Geodynamics of the Late Cenozoic Volcanism of Central Mongolia: Evidence from Isotope-Geochemical Studies," Petrology **18** (3), 278–307 (2010).
31. L. B. Terent'eva, V. P. Kovach, V. V. Yarmolyuk, et al., "Composition, Sources, and Geodynamis of Rock Formation in the Late Riphean Bayankhongor Ophiolite Zone: Characteristics of Early Stages in the Evolution of the Paleo-Asian Ocean," Dokl. Earth Sci. **423A** (9), 1462–1466 (2008).
32. V. E. Khain, "Basic Principles of the Development of Actual Global Model of the Earth's Dynamic," Geol. Geofiz. **51** (6), 753–760 (2010).
33. V. E. Khain, *Basic Problems of Contemporary Geology* (Nauchnyi Mir, Moscow, 2003) [in Russian].
34. G. S. Kharin, "Magmatic Pulses of the Iceland Plume," Petrology **8** (2), 97–112 (2000).
35. A. A. Tsygankov, D. I. Matukov, N. G. Berezhnaya, et al., "Magma Sources and Stages of Origination of Late Paleozoic Granitoids in the West Transbaikal Region," Geol. Geofiz. **48** (1), 156–180 (2007).
36. V. F. Shuvalov, "Jurassic and Lower Cretaceous Lacustrine Sediments in Eastern Gobi," in *Limnobios of Ancient Lake Basins of Eurasia* (Leningrad, 1980), pp. 91–118 [in Russian].
37. V. V. Yarmolyuk, V. G. Ivanov, and V. I. Kovalenko, "Sources of Intraplate Magmatism of Western Transbaikalia in the Late Mesozoic–Cenozoic: Trace-Element and Isotope Data," Petrology **6** (2), 101–123 (1998).
38. V. V. Yarmolyuk and V. I. Kovalenko, "Batholiths and Geodynamics of Their Formation in the Central Asian Foldbelt," Geol. Geofiz. **44** (12), 1260–1274 (2003).
39. V. V. Yarmolyuk and V. I. Kovalenko, "Deep Geodynamics and Mantle Plumes: Their Role in the Formation of the Central Asian Fold Belt," Petrology **11** (6), 504–531 (2003).
40. V. V. Yarmolyuk, V. I. Kovalenko, V. P. Kovach, et al., "Early Stages of the Paleoasian Ocean Formation: Results of Geochronological, Isotopic, and Geochemical Investigations of Late Riphean and Vendian–Cambrian Complexes in the Central Asian Foldbelt," Dokl. Earth Sci. **411** (8), 1184–1189 (2006).
41. V. V. Yarmolyuk and V. I. Kovalenko, *Riftogenic Magmatism of Active Continental Margins and Its Ore Potential* (Nauka, Moscow, 1991) [in Russian].
42. V. V. Yarmolyuk, V. I. Kovalenko, and V. G. Ivanov, "Late Mesozoic–Cenozoic Within-Plate Volcanic Province of Central and East Asia: Projection of Hot Mantle Field," Geotektonika **29** (5), 395–421 (1995).
43. V. V. Yarmolyuk, V. I. Kovalenko, E. B. Sal'nikova, et al., "Tectono-Magmatic Zoning, Magma Sources, and Geodynamics of the Early Mesozoic Mongolia–Transbaikal Province," Geotectonics **36** (4), 293–311 (2002).
44. V. V. Yarmolyuk, V. I. Kovalenko, V. P. Kovach, et al., "Isotopic Composition, Sources of Crustal Magmatism, and Crustal Structure of Caledonides of the Ozernaya Zone, Central Asian Foldbelt," Dokl. Akad. Nauk **387A** (9), 1043–1047 (2002).
45. V. V. Yarmolyuk, V. I. Kovalenko, A. B. Kotov, and E. B. Sal'nikova, "The Angara–Vitim Batholith: On the Problem of Batholith Geodynamics in the Central Asia Foldbelt," Geotectonics, **31** (5), 359–373 (1997).
46. V. V. Yarmolyuk, V. I. Kovalenko, and M. I. Kuz'min, "North Asian Superplume Activity in the Phanerozoic: Magmatism and Geodynamics," Geotectonics **34** (5), 343–366 (2000).
47. V. V. Yarmolyuk, V. I. Kovalenko, I. K. Kozakov, et al., "The Age of the Khangai Batholith and the Problem of Batholith Formation in Central Asia," Dokl. Earth Sci. **423** (8), 1223–1228 (2008à).
48. V. V. Yarmolyuk, V. I. Kovalenko, E. B. Sal'nikova, et al., "Geochronology of Igneous Rocks and Formation of the Late Paleozoic South Mongolian Active Margin of the Siberian Continent," Stratigr. Geol. Correlation **16** (2), 162–181 (2008b).
49. V. V. Yarmolyuk, A. V. Nikiforov, E. B. Sal'nikova, et al., "Rare-Metal Granitoids of the Ulug-Tanzek Deposit (Eastern Tyva): Age and Tectonic Setting," Dokl. Earth Sci. **430** (1), 95–100 (2010).
50. K. L. Buchan and R. Ernst, "The High Arctic Large Igneous Province (HALIP): Evidence for an Associated Giant Radiating Dyke Swarm," in *Large Igneous Provinces Commission* (2006). http://www.largeigneousprovinces.or/06apr
51. K. Burke, B. Steinberger, T. H. Torsvik, and M. A. Smethurst, "Plume Generation Zones at the Margins of Large Low Shear Velocity Provinces on the Core–Mantle Boundary," Earth Planet. Sci. Lett. **265** (1–2), 49–60 (2008).
52. K. Burke and T. H. Torsvik, "Derivation of Large Igneous Provinces of the Past 200 Million Years from Long-Term Heterogeneities in the Deep Mantle," Earth Planet. Sci. Lett. **227** (1–2), 531–538 (2004).
53. L. R. M. Cocks and T. H. Torsvik, "Siberia, the Wandering Northern Terrane, and Its Changing Geography through the Palaeozoic," Earth-Sci. Rev. **82**, 29–74 (2007).
54. K. C. Condie, *Mantle Plumes and Their Record in Earth History* (Cambridge Univ. Press, Cambridge, 2001).
55. V. E. Courtillot and P. R. Renne, "On the Ages of Flood Basalt Events," Comptes Rendus Geosciences **335** (1), 113–140 (2003).
56. G. F. Davies and F. Pribac, Mesozoic Seafloor Subsidence and the Darwin Rise, Past and Present, in *The Mesozoic Pacific: Geology, Tectonics, and Volcanism*, Ed.

by S. Pingle, et al. (Geophys. Monograph AGU, Washington, DC, 1993), Vol. 77, pp. 39–52.

57. R. A. Duncan and M. A. Richards, "Hotspots, Mantle Plumes, Flood Basalts, and True Polar Wander," Rev. Geophys. **29** (1), 31–50 (1991).
58. A. M. Dziewonski, "Mapping the Lower Mantle, Determination of Lateral Heterogeneity up to Degree and Order 6," J. Geophys. Res. **89**, 5929–5952 (1984).
59. A. M. Dziewonski, B. Hager, and R. J. O'Connell, "Large Scale Heterogeneities in the Lower Mantle," J. Geophys. Res. **82**, 239–255 (1977).
60. Y. Fukao, S. Maruyama, M. Obayashi, and H. Inoue, "Geological Implication of the Whole Mantle P-Wave Tomography," J. Geol. Soc. Japan **100**, 4–23 (1994).
61. Y. Fukao, M. Obayashi, and T. Nakakuki, "The Deep Slab Project Group. Stagnant Slab: a Review," Ann. Rev. Earth Planet. Sci. **37**, 19–46 (2009).
62. B. H. Hager, R. W. Clayton, M. A. Richards, et al., "Lower Mantle Heterogeneity, Dynamic Topography and the Geoid," Nature **313**, 541–545 (1985).
63. R. I. Hill, I. H. Campbell, G. F. Davies, and R. W. Griffiths, "Mantle Plumes and Continental Tectonics," Science **256** (5054), 186–193 (1992).
64. P. F. Hoffman, "Did the Breakout of Laurentia Turn Gondwanaland Inside-Out?," Science **252**, 1409–1412 (1991).
65. B. M. Jahn, B. A. Litvinovsky, A. N. Zanvilevich, and M. Reichow, "Peralkaline Granitoid Magmatism in the Mongolian–Transbaikalian Belt: Evolution, Petrogenesis and Tectonic Significance," Lithos **113**, 521–539 (2009).
66. V. I. Kovalenko, V. V. Yarmolyuk, and O. A. Bogatikov, "Modern Volcanism in the Earth's Northern Hemisphere and Its Relations with the Evolution of the North Pangaea Modern Supercontinent and with the Spatial Distribution of Hotspots on the Earth: the Hypothesis of Relations Between Mantle Plumes and Deep Subduction," Petrology **18** (7), 657–676 (2010).
67. V. I. Kuzmin, V. V. Yarmolyuk, and V. A. Kravchinsky, "Phanerozoic Hot Spot Traces and Paleogeographic Reconstruction of the Siberian Continent Based on Interection with the African Large Low Shear Velocity Province," Earth-Sci. Rev. **102**, 29–59 (2010).
68. L. A. Lawver and R. D. Muller, "Iceland Hotspot Track," Geology **22** (4), 311–314 (1994).
69. Z. L. Li, S. F. Yang, Z. L. Li, et al., "Chronology and Geochemistry of Taxinan Basalts from the Tarim Basin: Evidence for Permian Plume Magmatism," Acta Petrol. Sinica **24** (5), 959–970 (2008).
70. Z. X. Li and S. Zhong, "Supercontinent–Superplume Coupling, True Polar Wander and Plume Mobility: Plate Dominance in Whole-Mantle Tectonics," Phys. Earth Planet. Inter. **176**, 143–156 (2009).
71. C. Lithgow-Bertelloni and P. G. Silver, "Dynamic Topography, Plate Driving Forces and the African Superswell," Nature **395**, 269–272 (1998).
72. B. A. Litvinovsky, B. M. Jahn, A. N. Zanvilevich, et al., "Petrogenesis of Syenite-Granite Suit from Bryansky Complex (Transbaikalia, Russia): Implications for the Origin of A-Type Granitoid Magmas," Chem. Geol. **189** (1), 105–133 (2002).
73. E. R. Lundin and A. G. Dor, "The Fixity of the Iceland "Hot Spot" on the Mid-Atlantic Ridge: Observational Evidence, Mechanism and Implications for Atlantic Volcanic Margins," Geol. Soc. Am. Spec. Paper **388**, 627–651 (2005).
74. S. Maruyama, "Plume Tectonics," J. Geol. Soc. Japan **100** (1), 24–49 (1994).
75. S. Maruyama, M. Santosh, and D. Zhao, "Superplume, Supercontinent, and Postperovskite: Mantle Dynamics and Anti-Plate Tectonics on the Core–Mantle Boundary," Gondwana Res. **11** (1–2), 7–37 (2007).
76. W. J. Morgan, "Convection Plumes in the Lower Mantle," Nature **230**, 42–43 (1971).
77. W. J. Morgan, "Deep Mantle Convection Plumes and Plate Motions," Bull. Am. Assoc. Petrol. Geol. **56**, 203–213 (1972).
78. M. K. McNutt and A. V. Judge, "The Superswell and Mantle Dynamics Beneath the South Pacific," Science **248** (4958), 969–975 (1990).
79. J. G. Meert and T. H. Torsvik, "The Making and Unmaking of a Supercontinent: Rodinia Revisited," Tectonophysics **375**, 261–288 (2003).
80. J. Oliver and B. Isacks, "Deep Earthquake Zones, Anomalous Structures in the Upper Mantle and the Lithosphere," J. Geophys. Res. **72**, 4259–4275 (1967).
81. S. A. Pisarevsky, D. P. Gladkochub, T. A. Donskaya, et al., "Palaeomagnetism and Geochronology of Mafic Dykes in South Siberia, Russia: the First Precisely Dated Early Permian Palaeomagnetic Pole from the Siberian Craton," Geoph. J. Intern. **167**, 649–658 (2006).
82. M. K. Reichow, M. S. Pringle, A. I.Al'Mukhamedov, et al., "The Timing and Extent of the Eruption of the Siberian Traps Large Igneous Province: Implications for the End-Permian Environmental Crisis," Earth Planet. Sci. Lett. **277**, 9–20 (2009).
83. M. K. Reichow, A. D. Saunders, R. V. White, et al., "Geochemistry and Petrogenesis of Basalts from the West Siberian Basin: An Extension of Permo-Triassic Siberian Traps, Russia," Lithos **79**, 425–452 (2005).
84. B. Romanowicz, "Using Seismic Waves to Image Earth's Internal Structure," Nature **451** (7176), 266–268 (2008).
85. B. Romanowicz and Y. C. Gung, "Superplumes from the Core-Mantle Boundary to the Lithosphere: Implications for Heat Flux," Science **296** (5567), 513–516 (2002).
86. C. Scotese, "A Continental Drift Flipbook," J. Geol. **112** (6), 729–741 (2004).
87. T. H. Torsvik, "The Rodinia Jigsaw Puzzle," Science **300**, 1379–1381 (2003).
88. T. H. Torsvik and L. R. M. Cocks, "Earth Geography from 400 to 250 Ma: A Palaeomagnetic, Faunal and

Facies Review," J. Geol. Soc. London **161**, 555–572 (2004).

89. T. H. Torsvik, R. D. Muller, R. Van der Voo, et al., "Global Plate Motion Frames: Toward a Unified Model," Rev. Geophys. **46** (3), RG3004 (2008).
90. T. H. Torsvik, M. A. Smethurst, K. Burke, and B. Steinberger, "Long Term Stability in Deep Mantle Structure: Evidence from the 300 Ma Skagerrak-Centered Large Igneous Province (the SCLIP)," Earth Planet. Sci. Lett. **267**, 444–452.
91. T. H. Torsvik, B. Steinberger, L. R. M. Cocks, and K. Burke, "Longitude: Linking Earth's Ancient Surface to Its Deep Interior," Earth Planet. Sci. Lett. **276**, 273–282 (2008).
92. T. H. Torsvik, R. Van der Voo, J. G. Meert, et al., "Reconstructions of the Continents around the North Atlantic at about the 60th Parallel," Earth Planet. Sci. Lett. **187**, 55–69 (2001).
93. Sh. Wang and B. Han, "Geochemistry and Tectonic Significance of Alkali Granites along Ulungur River, Xinjang," Scientia Geol. Sinica **29** (4), 373–383 (1994).
94. J. T. Wilson, "A Possible Origin of the Hawaiian Islands," Can. J. Phys. **41**, 863–866 (1963).
95. J. T. Wilson, "Evidence from Ocean Islands Suggesting Movement in the Earth," Philos. Trans. Royal Soc. London, Ser. A—Math. Phys. Sci. **258** 145–146 (1965).
96. D. A. Yuen, S. H. Maruyama, S.-I. Karato, and B. F. Windley, *Superplumes: beyond Plate Tectonics* (Springer, Berlin).
97. D. Zhao, "Seismic Structure and Origin of Hotspots and Mantle Plumes," Earth Planet. Sci. Lett. **192**, 251–265 (2001).
98. D. Zhao, "Seismic Images under 60 Hotspots: Search for Mantle Plumes," Gondwana Res. **12**, 335–355 (2007).
99. D. Zhao, "Multiscale Seismic Tomography and Mantle Dynamics," Gondwana Res. **15**, 297–323 (2009).

Reviewers: N.V. Koronovsky, E.V. Sklyarov