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RIFT AND WITHIN-PLATE MAGMATISM IN THE CONTEXT OF HOT AND COLD MANTLE FIELDS

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Igneous rocks in oceanic and continental rifts are derived from depleted mantle or from deeper lower mantle. Within-plate magmatism may be related to hot mantle fields. The Phanerozoic history of magmatism in Siberia was to a great extent controlled by the drift of the continent over the Central Asian (Atlantic-African) hot field.
Rift, within-plate magmatism, mantle hot field, plume, plume tectonics

INTRODUCTION

The formation analysis developed by Kuznetsov [1] for igneous rocks is mainly based on their compositions and does not conflict with the plate tectonic theory. On the contrary, it is consistent with the idea originated from plate tectonic and later plume tectonic studies that assemblages or geochemical types of igneous rocks [2, 3] are attributed to specific tectonic settings. We offer a brief account of the geodynamic position of high-alkali rocks, such as alkali basalts, alkali gabbros, phonolites, trachytes, comendites, and tholeiitic basalts in trappean provinces or ocean islands, or basalts of E-MORB affinity, i.e., differing from typical N-MORB in slightly higher LILE contents. These rocks are as a rule of within-plate origin and occur in continental rifts or are associated with mantle hotspots.

We classified rifts in terms of magmatism and analyzed their relations with hot and cold mantle fields [4]. Rifts are generally oceanic, which produce juvenile oceanic crust and lithosphere, or continental which control continent breakup and large-scale deposition and, on the other hand, may provoke flood basalt volcanism.

OCEANIC RIFTING AND RELATED MAGMATISM

Oceanic rifts are associated either with mid-ocean ridges or with back-arc basins. Despite the morphological difference of mid-ocean ridge rifts, especially well evident between the Atlantic and Pacific rift systems, their rocks, primarily basalts, demonstrate stable compositions. N-MORB varieties predominate because of a very shallow position of the asthenospheric top. Geophysical data indicate magma sources immediately beneath many mid-ocean ridges, especially in regions of fast spreading. These source may include two layers, with high-Mg picritic melts at base and tholeiites in the upper part [5].

Rb systematics [6] and Pb and Nd signature in mid-ocean ridge and oceanic island basalts, as well as the evolution modeling of primordial mantle [7], indicate that the asthenospheric layer producing MOR basalts separated from the mantle about 1.8–2.0 byr ago. The formation of the asthenosphere may have been accompanied by partial LILE loss from the upper mantle which resulted in broad development of rapakivi granites on almost all platforms of that time. Production of comatiites ceased at that period and gave way to production of hotspot rocks and ophiolites with sections similar to those of the present-day oceanic crust [8].

Rift basins in back-arc oceanic rifts are often sites of active basaltic volcanism [9]. Mature basins (Mariana, North Fiji, etc.) are marked by prominent magnetic anomalies and may involve hot springs as in mid-ocean rifts.

Basaltic volcanism in back-arc rifts produces MORB and BABB rocks similar to island-arc volcanics. Frequently encountered porous structures of BABB indicate that their parent magmas were rich in volatiles. Therefore, basalts in back-arc rifts are N-MORB, asthensophere-derived, and subduction-related varieties.

CONTINENTAL RIFTING AND RELATED MAGMATISM

Continental rifting may (i) initiate ocean opening, (ii) arise on continental margins overriding mid-ocean ridges, or (iii) be caused by rotation or lateral motion of small plates as a result of collision-induced dispersal of a continental plate.

The first scenario is known in the East African rift system in which the Ethiopian, Red Sea, and Gulf of Aden rifts meet at the triple junction of Afar where voluminous eruptions produce crust of embryonic oceans [10]. The Ethiopian rift occurs within a swell with the basement uplifted to 2500–3000 km above the sea level in the center and in the south. The rift basin itself is 3000 km long by 70–80 km wide. The oldest synrift flood basalts (55 Ma) make up 100–150 m thick lava fields of mostly fissure alkali basalts similar to the Hawaiian alkalic series. Surface bimodal volcanics within the rift basin are melilitites, phonolites, and olivine alkali basalts in association with rhyolites, comendites, and pantellerites. Rifts of this type may also involve ring complexes of alkalic ultramafics and carbonatites. Thus, magmatism in mature continental rifts is marked by bimodal volcanism with alkalic chemistry.

The second type of continental rifting is prominent in the western USA and is associated with opening of a spreading-type gulf in California where the East Pacific rise occurs immediately beneath the continental margin. Volcanism in the Basin and Range Province is bimodal with felsic varieties represented by rhyolites, ignimbrites, tuffs (often Be-rich), and peralkaline volcanics; the cycle is as a rule terminated by alkali basalts with OIB trace-element and isotopic signature [3].

Collision-related rifting is observed in the Baikal rift which originated under the effect of the India/Eurasia collision and interaction of several small plates [11]. The evolution of the Baikal basin is controlled by counterclockwise rotation of the Amur plate relative to Eurasia. Unlike the Ethiopian rift, the Baikal rift is almost amagmatic with few off-rift fields of alkalic and tholeiitic basalts, generally of OIB affinity.

WITHIN-PLATE MAGMATISM IN THE CONTEXT OF HOT AND COLD MANTLE FIELDS

The idea of mantle hot fields was first formulated by Zonenshain and Kuz'min in 1983 [12] when they distinguished two large (Pacific and African, 10,000–12,000 km) and two small (2000–3000 km, Central Asian and Tasmanian, or Australia-Antarctic) fields. The fields are marked by clusters of mantle hotspots and by geoid anomalies, positive in large fields (up to +80 m) and negative (–20 to –80 m) in small fields [9].

The within-plate magmatism of mantle hotspots produces strongly alkaline alkali basalts, alkali gabbros, phonolites, trachytes, comendites, pantellerites, etc. Within-plate volcanics in oceans are most often tholeiitic and alkalic OIB varieties which, however, show at least 1.5–2 times MORB enrichment in LILE [3]. Basalts in trappean provinces are also of OIB affinity, such as in the case of Siberian traps [13]. Mid-ocean ridges over hotspots are composed of E-MORB, i.e., basalts with slight incompatible element enrichment relative to N-MORB. Therefore, within-plate magmatism may be fed from mantle sources other than depleted mantle which is the source for N-MORB.

The origin and composition of within-plate magmatism obviously depend on the Earth's deep structure. Teleseismic tomography (3D velocity images) [14, 15] revealed high- and low-velocity zones traceable from the lithospheric base as deep as the core. These zones were reasonably correlated with cold and hot — even partially molten — mantle. Note that this interpretation implies hot mantle beneath the African and Pacific hot fields and the projection of cold, high-velocity, zones should correspond to the small fields of Central Asia and Tasmania.

On this basis, Fukao et al. and Maruyama [14, 15] suggested a model of mantle circulation with cold subducting mantle in cold plumes sinking as deep as the layer D. In response to pressure from the heavy colder plumes, hot material becomes squeezed out elsewhere, rises into the lower mantle, and splits into several isolated plumes in the upper mantle and a chain of hotspots in the lithosphere.

Detailed trace-element studies, especially Rb-Sr, Sm-Nd, and other isotope data, indicate that within-plate rocks may be derived from the originally undepleted or weakly depleted PREMA sources which predominate in the lower mantle or from enriched EM1 and EM2 sources, which most likely correspond to fragments of ancient lithosphere buried in the mantle [16]. These ideas are consistent with models of primitive mantle compositions of hotspot rocks and recycling, and with results of three-dimensional velocity imaging.

PHANEROZOIC HISTORY OF WITHIN-PLATE MAGMATISM IN NORTH ASIA

We analyzed the evolution of within-plate magmatism in the Phanerozoic history of North Asia in the context of hot and cold mantle fields [4, 17].

Table 1 represents Late Paleozoic through present within-plate igneous rocks in Asia and Fig. 1 shows their geographic distribution. More details can be found in [4, 17], and this study is limited to the following brief account.

Late-Middle Paleozoic within-plate igneous rocks occur in the Altai-Sayan and Vilyui provinces and, possibly, also in the territory of former oceans around Siberia, as indicated by high-Ti volcanics in Early Paleozoic and Late Cambrian ophiolites from the craton border [18].

The **Late Paleozoic-Early Mesozoic** period between 330 and 185 Ma [17] was the time of large-scale within-plate magmatism almost throughout North Asia.

Early stage (310–285 Ma) corresponds to initiation of rifting, when the oldest grabens of the Gobi—Tien Shan rift system formed along the southern margin of Siberia. At the same time voluminous Barguzin-Vitim plutonism in Transbaikalia was marked by the emplacement of the 500 by 300 km^2 Angara-Vitim batholith [19] in which the within-plate origin of granitoids is indicated by their alkalic compositions. Alkaline rocks occur in plutonic belts along the Synnyr and Uda-Vitim rift faults that border the batholith on two sides.

Permian—Early Triassic stage spanned the interval between 280–240 Ma and completed the structural framework of the Central Asian rift system. Propagation of rifting inward the continent produced the Gobi-Altai rift in the latest Early-earliest Late Permian and rifts in North Mongolia in the Late Permian. Rifting was coeval with the emplacement of the Hangayn batholith between the two rift systems which, like the Angara-Vitim batholith, developed under the effect of within-plate heat sources.

Latest Permian—earliest Triassic rifting in Central Asia was accompanied by eruptions of flood basalts which produced a large trappean province in the Siberian craton and the neighboring rift system of West Siberia [20] over an area in excess of $1.5 \cdot 10^6$ km^2. The trappean province apparently originated in the northwest in the Maimecha-Kotui and Noril'sk regions where alkalic and subalkalic differentiated basalts erupted between 253 and 246 Ma.

Early Mesozoic stage (230–185 Ma) likewise produced a symmetrical magmatic province with the Hentiyn batholith in the center bordered by small leucogranite, Li-F granite, alkali granite and syenite bodies, and basalt-pantellerite, basalt-trachyte, and alkali-basalt associations.

Early Mesozoic within-plate rocks encountered likewise in the west far off the province's batholithic core, in Altai, Tuva, and Northwestern Mongolia [21, 22], are belts of basaltic and alkali basaltic dikes, nepheline syentite complexes, rare-metal Li-F and spodumene granites, ongonite dikes and elvans with U-Pb ages of 230 to 205 Ma [21].

Within-plate magmatic activity had reduced abruptly 190 myr ago throughout North Asia, which marked the end of the Late Paleozoic—Early Mesozoic stage.

Late Jurassic—Early Cretaceous stage (170–100 Ma) corresponds to the time when the East Mongolian, West Transbaikalian, South Hangayn, and Central Asian volcanic provinces formed in the conditions of rifting and large-scale magmatic activity.

Magmatic activity during the *Late Cretaceous—Early Cenozoic stage* (100–25 Ma) was weak but regular and produced small isolated lava fields and shield volcanoes in Western Transbaikalia, South Hangayn, and Eastern Mongolia.

Late Cenozoic stage (<25 Ma) of volcanic and tectonic activity covered the territory of Central and East Asia and formed the South Baikal and Dariganga provinces.

Thus within-plate activity lasted throughout the Phanerozoic within the Siberian craton and in the surrounding mountains in the south and in the west. The volume of magmatism was more or less similar in the Paleozoic and Mesozoic, except for the interval between 253–246 Ma when over $1.5 \cdot 10^6$ km^3 of flood basalts erupted during a short period of trappean activity [11, 23].

In the Late Cretaceous, the volume of within-plate magmatism reduced to about 100 km^3 and remained minor as far as the latest Oligocene; after that the level of the first half of the Late Mesozoic ($\sim n \cdot 10^4$ km^3) was reached only in the Late Cenozoic (<25 Ma).

The sources of within-plate magmatism were investigated using Sr and Nd systematic isotope data for mafic rocks from different provinces [17, 24] and published results (see the summary in Fig. 2). Note that these data are for mantle-derived mafic rocks and represent the compositions of mantle plumes responsible for within-plate activity. Classification of mantle sources follows [25].

Table 1

Phanerozoic History of Within-plate Magmatism in Siberian Craton and its Surroundings in Central Asia

Time and *stages* of activity	Provinces and events (figures in parentheses are ages in Ma)	
Early-Middle Paleozoic *Ordovician—Silurian*	**I. Altai-Sayan** Intrusion of alkali granites and syenites, layered olivine gabbro, alkalic ultramafics, and nepheline syenites (490, 460, 450–410)	
Late Silurian—Early Devonian	Rifting and eruptions of trachybasalts, trachytes, and trachyrhyolites, intrusion of alkalic and Li-F granites, ultramafic alkalic rocks (390)	**II. Vilyui** Swelling and eruptions of trachybasalts, trachytes, and phonolites
Middle Devonian	Intrusion of phonolite-trachybasalt, trachybasalt-trachyte-pantellerite, nepheline-syenite, and alkali-granite associations (375)	Rifting and intrusion of mafic dike belts, eruptions of flood basalts
Late Devonian—Early Carboniferous		Eruptions of trachytes, subalkalic and alkalic basalts and intrusion of shonkinite and teschenite dikes, alkalic ultramafics with carbonatites
Late Paleozoic—Early Mesozoic *Late Carboniferous—Early Permian*	**III. Barguzin-Vitim (330–390)** Rifting (*Synnyr* rift, with alkalic, nepheline, and pseudoleucite syenites (295, 285) and *Uda-Vitim* rift, with alkalic ultramafics, alkali gabbros, nepheline syenites, alkalic syenites and granites, carbonatites); eruption of alkali basalts and ensuing palingenetic melting with emplacement of Angara-Vitim batholith	**Rift systems in Central Asia** **IV. Late Paleozoic** *Gobi-Tien Shan* rifting with bimodal basalt-comendite and alkali granite (310–285) and Li-F leucogranite (285) magmatism
Middle Permian		*Gobi-Altai* rifting with bimodal basalt-pantellerite and alkali granite magmatism
Late Permian—Early Triassic	**V. Siberian traps** Eruptions of flood basalts (255–235)	*North Mongolian* rifting (265–250) with bimodal basalt-pantellerite and alkali granite magmatism. Formation of a symmetrical magmatic field with North Mongolian and Gobi-Altai rifts on its periphery and Hangayn granodiorite-granite and granosyenite batholith in its core (255–250)
Triassic—Early Jurassic	**VI. West Siberian rift** Rifting and basaltic eruptions (235–218)	**VII. Early Mesozoic** Formation of a symmetrical magmatic field in East Mongolia and West Transbaikalia with Hentiyn batholith in its core and zones of bimodal basalt-trachyte-pantellerite, basalt, and alkali granite magmatism on its periphery. Local eruptions of tephrites and phonolites, isolated intrusions of alkali and Li-F granites, nepheline and leucite syenites in Central and Western Mongolia, Tuva, and Altai
Late Mesozoic—Early Cenozoic *Late Jurassic*	**Continental Central Asian** Initiation of *South Hangayn* (SH), *East Mongolian* (EM), *West Transbaikalian* (WT), and *Central Asian* (CA) hotspot systems. Formation of isolated grabens with basalts, trachytes, trachyrhyolites, locally with carbonatites, pantellerites, and Li-F alkali granites (170–140)	
Early Cretaceous	Rifting in South Hangayn, East Mongolia, and Western Transbaikalia, with eruptions of flood basalts and intrusion of tephrites, phonolites, nepheline syenites, shonkinites, carbonatites, ongonites, and Li-F granites (140–100)	
Late Cretaceous—Early Cenozoic	Small isolated eruptions of basalts, melanephelinites, tephrites, and basanites in South Hangayn, West Transbaikalian, and Central Asian volcanic fields (100–30)	
Late Cenozoic	**Continental Central and East Asian** Reactivation of magmatism in South Hangayn, West Transbaikalia, and Central Asia; initiation of new systems of rifts (*Baikal* and *Shanxi*) and hotspots (*South Baikal*, *Dariganga*, etc.), eruptions of flood basalts, tephrites, and basanites (<25)	

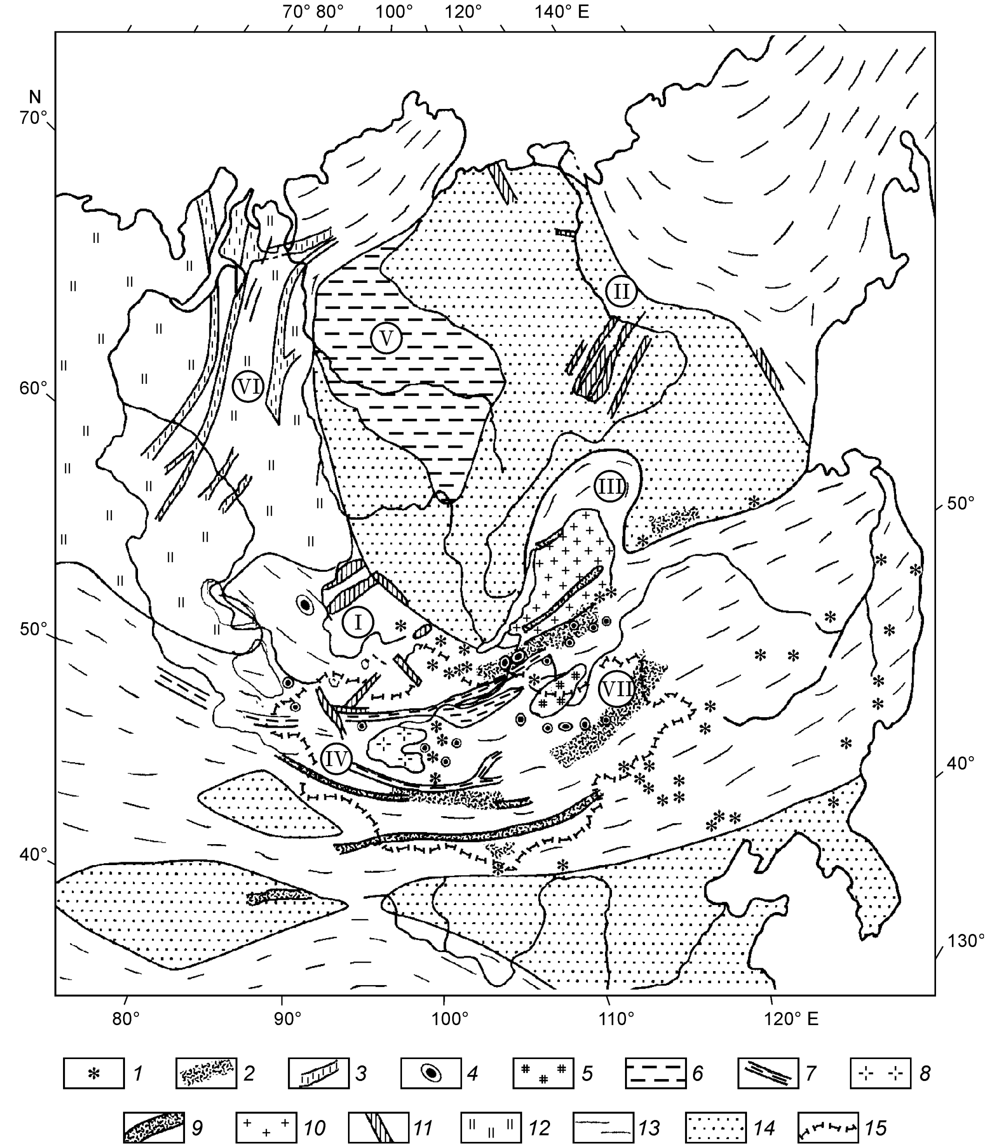

Fig. 1. Geographic distribution of within-plate magmatism in Siberian craton and its surroundings. *1–11* — Igneous rocks of different ages: *1* — Cenozoic, *2* — Late Mesozoic, *3–5* — Early Mesozoic: in West Siberian rift system (*3*), in Central Asian rift system (*4*), in Hentiyn batholith (*5*), *6–8* — Permian-Early Triassic: in Siberian trappean province (*6*), in Central Asian rift system (*7*), Hangayn batholith (*8*), *9*, *10* — Late Carboniferous-Early Permian: in Central Asian rift system (*9*), Angara-Vitim batholith (*10*), *11* — Devonian; *12* — West Siberian Plate; *13* — orogens; *14* — platforms; *15* — national frontier of Mongolia. Roman numerals denote provinces of within-plate magmatism: I — Altai-Sayan, II — Vilyui, III — Barguzin-Vitim, IV — Late Paleozoic Central Asian rift system, V — Siberian traps, VI — West Siberian rift system, VII — Early Mesozoic Central Asian rift system.

Devonian mafic rocks in northwestern Mongolia and Altai-Sayan region differ considerably from later rocks [17, 24]. According to their compositions, they may have been derived from a REE-depleted source ($\varepsilon_{Nd} > 4$) with broad ε_{Sr} variations, and an EM2 source (mantle enriched with Rb and, hence, radiogenic Sr) may have been involved along with the PREMA moderately depleted mantle (prevailing mantle source of OIB).

Rocks produced by the Late Paleozoic-Early Mesozoic and Late Mesozoic within-plate magmatic activity

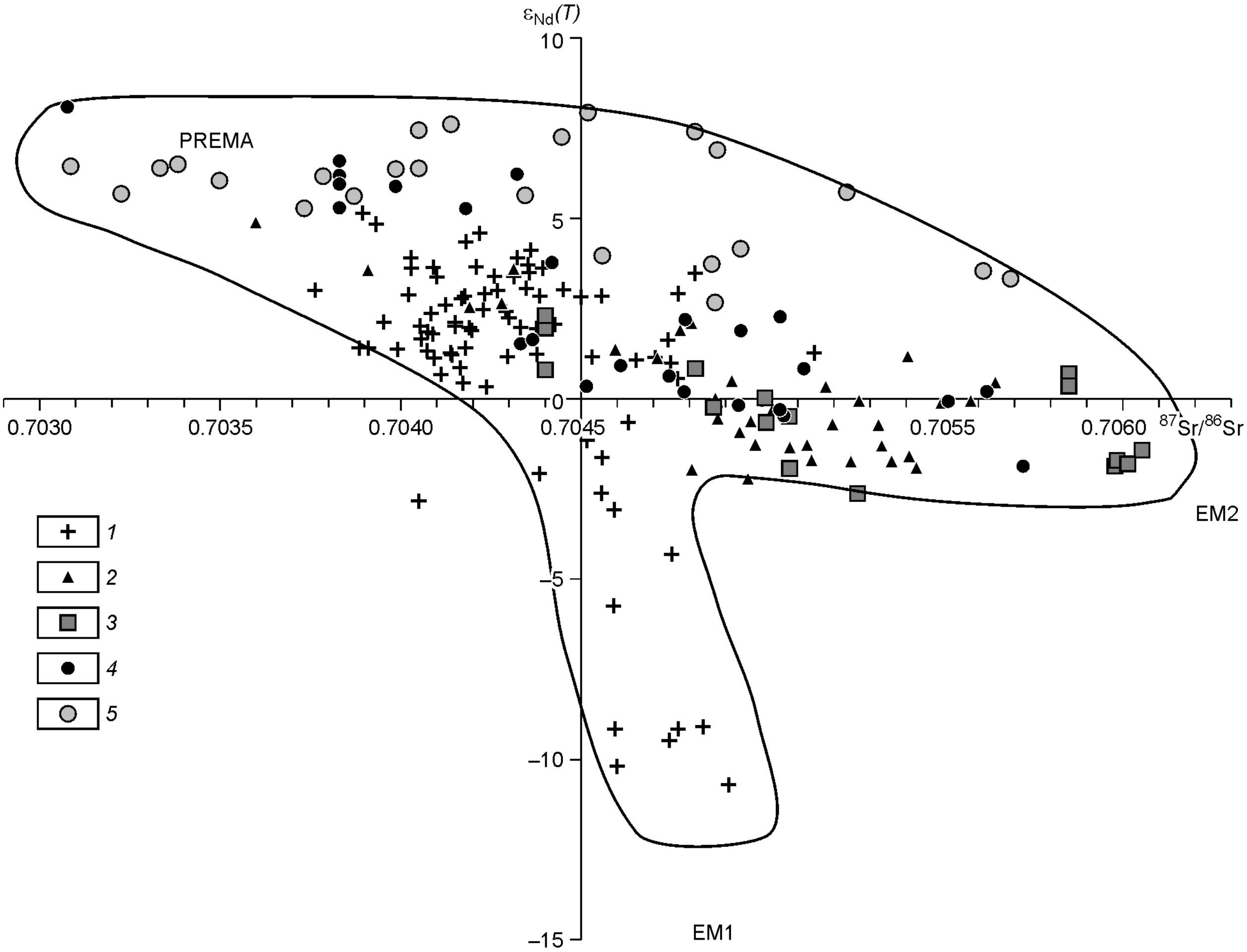

Fig. 2. Isotope compositions of mafic rocks from Phanerozoic provinces of within-plate magmatism in North Asia. ***1*** **— Cenozoic,** ***2*** **— Late Mesozoic,** ***3*** **— Early Mesozoic,** ***4*** **— Late Paleozoic,** ***5*** **— Middle Paleozoic.**

share their source compositions [26] and plot between the EM2 and PREMA fields. EM2 signature ($\varepsilon_{Sr} > 0$, $\varepsilon_{Nd} \sim 0$) in Late Mesozoic rocks occurs in the varieties most strongly enriched in radiogenic Sr ($\varepsilon_{Sr} > 10$–15). A PREMA source apparently played a secondary role and is responsible only for the elongate geometry of the composition field.

Unlike the older rocks, Early and Late Cenozoic mafic rocks (Fig. 2) have either PREMA-type isotope compositions (ε_{Sr} up to –10 and ε_{Nd} up to +7) or show Nd enrichment over Sm (ε_{Nd} up to –10) and slight Sr variations. The latter compositions are typical of EM1-derived melts [25]. Thus within-plate magmatism in Central Asia was associated with PREMA, EM1 and EM2 mantle sources, with the leading role of EM2 mantle and various PREMA contributions. EM2 mantle participated in within-plate activity in different provinces of Central Asia, at least from the Late Paleozoic to the Late Cretaceous, i.e., for over 200 myr.

The transition from EM2 to PREMA mantle sources in the history of within-plate magmatism in Central Asia coincided with abrupt production decrease and decay of tectonic activity, obviously driven by changes in the thermal state and deepening of geotherms to greater mantle depths. As a result, the origin depth of mantle plumes should have deepened correspondingly, and the PREMA sources became deeper than EM2 mantle. Note that PREMA mantle is a source for the greatest portion of OIB volcanism and is usually assumed to be located in the lower mantle.

The next change of source compositions coincided with a Late Cenozoic episode of activity in Central and Eastern Asia which was most likely induced by a thermal pulse at base of a mantle plume, possibly, related to

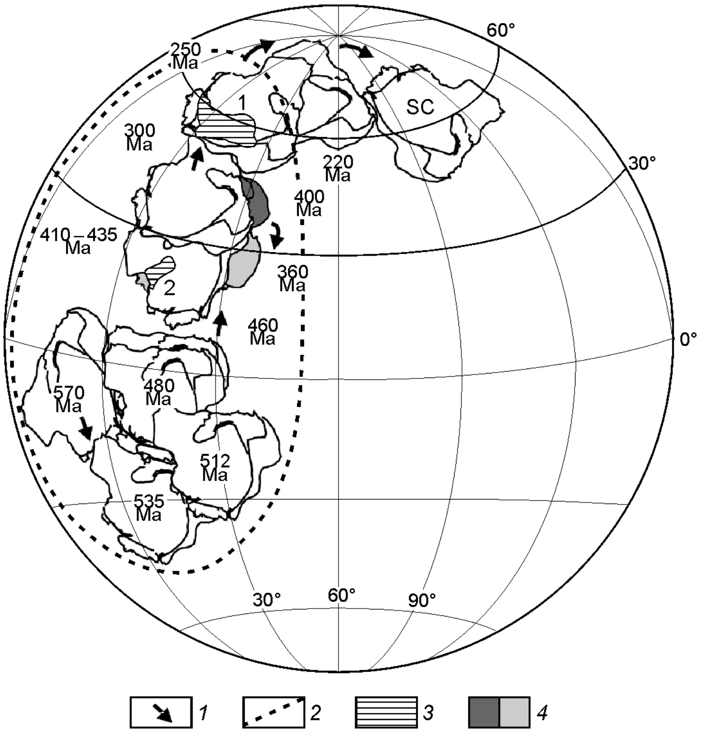

Fig. 3. Paleogeographic reconstructions for Siberian craton through Phanerozoic, based on paleomagnetism and within-plate magmatism. ***1*** **— Horizontal motion and rotation of Siberia;** ***2*** **— limits of Atlantic-African hot mantle field;** ***3*** **— P_2—T_1 traps (1), Vilyui rift (2);** ***4*** **— Altai-Sayan region; SC — present position of Siberian craton.**

EM1 mantle. EM1 products had remained isolated from mantle magma generation as long as the Late Cenozoic and, hence, it may have occurred deeper than other types of mantle sources.

EM2 and EM1 sources, enriched with Sr and Nd, respectively, may be associated with relict crust and lithosphere buried in subduction zones. If it is so, the EM2 and EM1 sources of within-plate volcanics in North Asia have model ages of 1.1–1.5 Ga and 2.3–2.5 Ga, respectively [26, 27]. EM2 sources may be located at the lower/upper mantle boundary, and EM1 may originate at the core/mantle boundary.

The position of Siberia through the Phanerozoic in the absolute frame of reference, was reconstructed using paleomagnetic data, under the assumption based on published results [28, 29] that at the time of trappean activity Siberia was over the Jan-Mayen (Northern Atlantic) hotspot. If this hypothesis proves valid, Siberia should have stayed within the zone of influence of the Africa-Atlantic mantle hot field from the Cambrian through Mesozoic (Fig. 3).

Therefore, almost throughout its Phanerozoic history, the Siberian continent interacted with mantle plumes which evolved following common laws and belonged to the single *North Asian superplume* [17]. This idea is supported by compositional similarity of plume sources.

Therefore, the Central Asian igneous province was apparently detached from the hot field, or from the mantle superplume, and moved to the zone of the cold plume at least since the Late Mesozoic, and then within-plate magmatism was controlled by the cold plume. This should be taken into account in modeling the history of within-plate magmatism.

We suggest the following scenario of the Phanerozoic evolution of Siberia. It moved in the northwestward direction after the dispersal of Rodinia [15] and the ensuing opening of the Pacific and Paleoasian oceans. Since the Cambrian, when it fell under the influence of the Africa-Atlantic hot field, the continent developed under the effect of the Central Asian (Africa-Atlantic, in the present frame of reference) hot superplume. At the same time, the history of the Siberian craton and its folded surroundings may have included motions of lithospheric mantle blocks rooted at different depths. Some blocks, with mantle layers as far as the layer feeding the within-plate activity, encompassed almost the entire upper mantle. This preserved the root system of mantle plumes and maintained the stable position of within-plate magmatism on the surface despite the changes in the geographic position of the continent.

In the course of further plate motion, and, possibly, the dispersal of Pangea, Asia lost its connection with the hot mantle field, moved eastward and fixed its position over the cold superplume. Thereby the Central Asian igneous province detached from its lower mantle roots and the magmatic activity decayed. Nevertheless, relict hot mantle preserved in the upper mantle of the region is detectable by tomographic methods [30]. The Late Cenozoic pulse of within-plate activity may be related with the response of the core/mantle boundary to the effect of the cold superplume. This interaction requires further investigation.

The suggested reconstructions reconcile the existence of hot mantle beneath Siberia through the greatest portion of Phanerozoic time with its present cold state.

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