Earth-Science Reviews 102 (2010) 29–59

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Phanerozoic hot spot traces and paleogeographic reconstructions of the Siberian continent based on interaction with the African large low shear velocity province

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ARTICLE INFO

Article history:
Received 20 April 2009
Accepted 16 June 2010
Available online 23 June 2010

Keywords:
Icelandic hot spot
intraplate magmatism
isotopic composition
paleomagnetism
mantle plume
rare element
reconstructions
Siberia
Siberian traps

ABSTRACT

We review intraplate magmatism in Siberia and its folded surroundings from 480 Ma to the present. We describe several large igneous provinces (LIPs) and the intervals in which they were continuously formed within the limits of the Siberian continent: the Altay–Sayan Early Paleozoic magmatic area (598–446 Ma), the Altay–Sayan LIP (408–393 Ma), the Viluy LIP (380–350 Ma), the Barguzin–Vitim LIP (310–275 Ma), the Late Paleozoic rift system of Central Asia (318–242 Ma), the Siberian traps and West Siberian rift system (250–249 Ma), the East-Mongolian and West-Trans-Baikalian LIP (228–195 Ma), and a number of various aged Late Mesozoic and Cenozoic rift zones and magmatic areas (from 160 Ma to the present day).

Following Lawver and Muller (1994), Kharin (2000), Lawver et al. (2002) and Chernysheva et al. (2005), we accept the position of the Icelandic hot spot under the Siberian trap area at the Permo-Triassic boundary. That enables us to estimate the geographic coordinates of the Siberian trap location at 250 Ma (they are the same as Iceland today). Presently the Icelandic hot spot is situated above the African large low shear velocity province (LLSVP) that indicates a hot mantle plume. We suggest a set of paleogeographic reconstructions of the Siberian continent for which we evaluate the paleolatitude based on the paleomagnetic data and estimate the paleolongitude position by placing Siberia above the African LLSVP. Furthermore, we estimate the geographic coordinates for other ancient hot spots in the framework of the African LLSVP that we consider to be responsible for the intraplate magmatism during different time periods in the Phanerozoic eon.

Available rare element and isotopic characteristics of the intraplate magmatic rocks of Siberia enable us to determine three primary sources – moderately depleted mantle (PREMA), enriched mantle (EM-I and EM-II) – of the mantle origin magma. We propose that the model explains the interaction of the hot mantle plume including hot spots (plume tails) with the Siberian intraplate magmatism areas throughout the Phanerozoic eon.

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doi:10.1016/j.earscirev.2010.06.004

1. Introduction

Plume tectonics, a relatively new field in the Earth Sciences, studies the movements of mantle plumes and the interactions of mantle plumes with tectonic plates. Beginning with the pioneering works of Wilson (1963, 1965, 1973) and Morgan (1971, 1972), many authors have related intraplate events to hot spot activities induced by hot upwelling mantle plumes. Zonenshain and Kuzmin (1983, published in Russian) and then Zonenshain et al. (1991a) suggested that the hot spots on the Earth's surface do not have a random distribution and can be reliably grouped into regions they called hot mantle fields (presently called hot plumes) with cold mantle fields (presently subducting zones) in between. They proposed that hot plumes are surficial expressions of hot upwelling deep mantle flows, and that cold plumes correspond to downgoing branches that reflect convective cells in the lower mantle.

Seismotomography demonstrated the different natures of hot and cold mantle plumes and defined their distinct locations in the Earth's interior. Dziewonski et al. (1977, 1984), Fukao et al. (1994), and Maruyama (1994) reported higher and lower shear velocity zones in the mantle, and traced them from the lithospheric base to the core. Two of the largest low shear velocity zones or provinces (LLSVP) correspond to the excess temperature mantle located under Africa and the surrounding area and under the Pacific Ocean (Fig. 1) (Zonenshain and Kuzmin, 1983; Dziewonski, 1984; Zonenshain et al., 1991a; Zhao, 2001; Romanowicz and Gung, 2002; Romanowicz, 2008). These LLSVPs are usually called the African and Pacific superplumes. Superplume locations are characterized by positive anomalies of the geoid (McNutt and Judge, 1990; Davies and Pribac, 1993; Lithgow-Bertelloni and Silver, 1998), clusters of hot spots mostly along their peripheries (Anderson, 1982; Courtillot et al., 2003; Jellinek and Manga, 2004), and large igneous provinces (Burke and Torsvik, 2004; Burke et al., 2008).

Davies and Richards (1992) proposed co-existence of plate tectonics and plume tectonics. A number of recent studies show that mantle plumes (hot spots) are most likely produced by instability in the D″ layer at the core–mantle boundary (CMB) that lies between the Earth's solid silicate mantle and its liquid iron–nickel outer core (Davaille, 1999; Campbell and Kerr, 2007). Such plumes separate into a distinct head and tail and carry only about 10% of the Earth's heat to the surface today. In contrast, hot mantle material upwellings or superplumes that rise in response to radiogenic heating of the mantle account for at least 60% of the heat were carried to the surface. Many plumes may be contained within a single mantle upwelling. Mantle plumes are commonly used to estimate plate movements (Besse and Courtillot, 2002; Steinberger and Torsvik, 2008) as it is assumed that they are relatively stable in relation to the mantle and the lithosphere. It is largely accepted that an array of hot spots may produce upper mantle material displacement in the asthenosphere leading to continental breakup (Morgan, 1971; Storey 1995; Condie, 2002; Li and Zhong, 2009). Such phenomena indicate that mantle plumes can drive lithospheric plate dynamics. At the same time it is suggested that plate tectonics effectively control the location and growth of mantle plumes (Steinberger and O'Connell, 1998; Zhong et al., 2000; Gonnermann et al., 2004; Li and Zhong, 2009). Seismotomography also demonstrates that subducting slabs experience significant flattening and stagnation in the lower mantle and can sink to the CMB (Zhao, 2007; Fukao et al., 2009), participating in whole-mantle convection. Such convective movement in the mantle interacts with the hot mantle plume columns rising from the CMB and may aggravate the rise of the hot material. The upwelling rises through the lower mantle in the form of a huge mushroom, breaking into a number of isolated plumes in the upper mantle and a chain of hot spots in the lithosphere (Fukao et al., 1994; Maruyama, 1994; Maruyama et al., 2007).

Present day hot spots, superficial indicators of mantle plumes like the African and Pacific plumes, and large igneous provinces (LIPs) are located in two areas away from subduction slabs (Anderson, 1982; Hager et al., 1985; Weinstein and Olson, 1989; Duncan and Richards, 1991; Romanowicz and Gung, 2002; Courtillot et al., 2003; Burke and Torsvik, 2004; Burke et al., 2008). This suggests a close association between mantle plumes and plate tectonics as opposed to the earlier

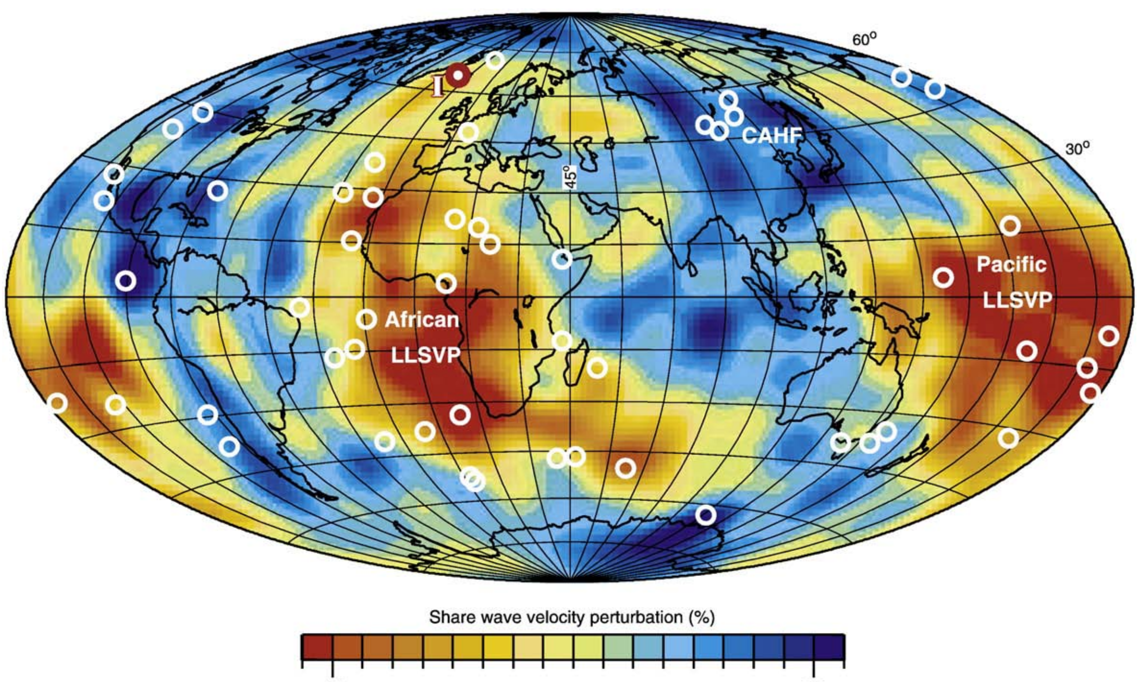

Fig. 1. Distribution of the 49 hotspots (white circles) from Courtillot et al. (2003) superimposed on a section at 2800 km depth through tomographic model S20RTS for shear wave velocity (Ritsema et al., 1999). Color code from −1.2% (red hues) to +1.2% (blue hues) shows the share wave velocity perturbation in %. Letter I corresponds to Icelandic hot spot. Central Asia Hot Field (CAHF) represents the recent occurrences of the intraplate volcanism in Southern Siberia and Mongolia (Zonenshain et al., 1991b). Hammer–Aitoff projection of the Earth is used.

point of view that mantle plumes operate irrespective of plate tectonic processes (Hill et al., 1992). McNamara and Zhong (2005) and Trønnes (2009) discuss in details that lithospheric subduction leads to the creation of both African and Pacific LLSVPs by convective sweeping of chemically denser material in the lowermost mantle and thus provoke the upwelling of the mantle matter from the CMB always along the edges of the LLSVPs. The LLVSPs are roughly 180° apart and both centered near the equator. The spatial relationships between the LLSVPs as well as recent subduction zones and the geoid highs seem to be a natural consequence of global mantle dynamics. The hotter/colder mantle material distribution associated with the LLSVPs and subduction zones must be linked to the orientation of the Earth rotation axis and continuously adjusted via true polar wander (Richards et al., 1997; Steinberger and Torsvik, 2008).

One of the most convincing arguments for plume and plate tectonics interaction is supercontinent and superplume evolution in uniform supercontinental cycles (Burke and Torsvik, 2004; Maruyama et al., 2007; Burke et al., 2008; Li and Zhong, 2009). The formation and breakup of two supercontinents – Rodinia (Hoffman, 1991; Pisarevsky et al., 2003; Torsvik, 2003; Li et al., 2008; Ernst et al., 2008; Li and Zhong, 2009) and Pangea (Anderson, 1982; Burke and Torsvik, 2004; Scotese, 2004; Torsvik and Cocks, 2004) – are well explained. Rodinia was formed nearly one billion years ago and it broke up about 750 Ma. Pangea was formed in the beginning of the Permian era, about 300 Ma, as a result of collisions among Laurussia, Gondwana, Siberia, and some Central Asian terranes. Its breakup began ~200 Ma. In both cases the supercontinental breakup occurred because of the underlying superplume upwelling. Seismotomography demonstrates that the superplume LLSVPs could be more than 6000 km in diameter. Each superplume survived longer than a hundred million years with a maximum activity of about 100 Myr. The superplume underneath Rodinia was active from at least 825 Ma to ~750 Ma and the superplume underneath Pangea was active from ~200 Ma to ~80 Ma. The present day African plume is considered to be a prolongation of the Pangea superplume (Li and Zhong, 2009).

The Pacific plume is another huge mantle structure and there are various points of view about its origin. Maruyama et al. (2007) and Utsunomiya et al. (2007) consider that the plume was formed under Rodinia and led to Rodinia's breakup. Larson (1991) and Li and Zhong (2009) argue that there is not enough evidence for this theory and these authors consider the Pacific plume to be antipodal to the African superplume that caused Pangea's fragmentation. The surface expression of the Pacific plume is a widely known system of hot spots (Hawaii, the Marshall Islands, Louisville, and others) and LIPs (the Cretaceous Ontong Java Plateau and the Magellan Rise). In addition, Li and Li (2007) associated the subduction 250 Ma of an oceanic plateau along south-eastern Asia with the Pacific hot mantle plume.

Following Li and Zhong (2009) we assume that an antipodal plume, similar to the present day Pacific plume, led to the breakup of Rodinia. Possibly the magmatic rocks generated by the plume were subducted or in part may be preserved in the late Proterozoic–early Paleozoic orogenic metamorphosed zones and therefore cannot be easily identified today. After Rodinia's breakup the continents began moving in different directions and Siberia moved into the area of the antipodal, future Pangean plume. Intraplate magmatism related to plume activity occurred within central parts of the Siberian continent and in the future orogenic belts that were not a part of Siberia in the earliest stages of the Phanerozoic migration. The plume generated intracontinental magmatic activity as witnessed by Siberian volcanic rock sequences. Associations of alkaline basalts, alkaline gabbros, phonolites, trachytes, comendites, pantellerites, etc., denote distinctive intraplate magmatism sequences (Kuzmin, 1985; Condie, 2001; Kuzmin et al., 2003a,b). These rocks are typical of flood basalt provinces, continental rifts, and hot spot locations. Enriched Mid-Oceanic Ridge Basalt (E-MORB) type basalts characterize the oceanic island magmatic sequences and the oceanic basalts. Intraplate magmatism from depleted mantle sources is distinguishably different from the 'Normal' Mid-Oceanic Ridge Basalt (N-MORB) type basalts which are more common type of basalts in the Mid-Oceanic Ridges and are strongly depleted in the light elements, such as Cs, Rb, Ba, Th, U, and formed by a relatively high degree of melt of the uprising mantle.

Yarmolyuk et al. (2000) demonstrated that intensive intraplate magmatic activity existed throughout the Phanerozoic eon in Siberia. Maximum intraplate magmatic activity took place in the Late Paleozoic and Early Mesozoic eras. For example, Siberian flood basalts and gigantic rift systems around Western Siberia and Central Asia were formed during the Permo-Trassic period (Dobretsov, 1997; Yarmolyuk et al., 2000). Extensive granitic magmatism is described in Altay, Kazakhstan, Trans-Baikalia, Mongolia, and North China during the same time period. Granitic magmatism is connected to the polygenesis process influenced by large-scale mantle fluids (Yarmolyuk et al., 1997b, 2003a). Interaction of the superplume with the Northern Asia lithosphere led to the uplifting of a large territory and a system of sedimentary basins appeared around the uplift (Dobretsov, 1997). Intensive magmatic activity persisted through the Phanerozoic eon and continues presently in the Siberian continent.

We use available information on volcanic rocks in Siberia to explain the long-term intraplate magmatic activity that took place in Siberia and its adjunct folded areas. We propose that the Siberian continent moved above a hot mantle plume during most of the Phanerozoic eon and that intraplate magmatism was a result of interactions between hot spots in the African LLSVP. We reconstruct the paleoposition of the Siberian continent using paleomagnetic data and assuming long-term relative immobility of the African mantle plume. Knowing the stationary position of the mantle plume enables us to perform the approximate paleolatitude reconstructions for the Siberian continent.

2. Siberian intraplate magmatism during Phanerozoic era

Multiple grabens and horsts of different ages and the alkali magmatic rocks connected with them indicate intensive intraplate magmatic activity all over Siberia and surrounding areas (Fig. 2). Table 1 contains parameters of magmatic rocks within the Siberian platform and surrounding folded areas throughout the Phanerozoic eon.

The Early–Middle Paleozoic phase of intraplate magmatic activity occurred in the Altay–Sayan and Viluy areas and, possibly, in the territory of the former oceans around Siberia as indicated by high-Ti volcanics (volcanic material with a higher content of titanium) in Late Riphean ophiolites (Terenteva et al., 2008) and Vendian–Early and Middle Cambrian hot spots (Almukhamedov et al., 1996; Kovalenko et al., 1996; Vrublevskii et al., 2009; Safonova, 2009) in the southern margin (in present day coordinates) of the Siberian platform. The oldest intraplate magmatic occurrences within Central Asian folded belt were related to the evolution of tectonic units of the Paleoasian Ocean described in (Zonenshain et al., 1991b) (island arcs, back-arc basins, lava plateau and oceanic islands, and small Precambrian terranes accreted in the early Paleozoic). The magmatic complexes in which geochemical composition corresponds to the oceanic islands and lava plateau were produced in the time interval 600–510 Ma in the Altay–Sayan area and adjacent territory of the northwest Mongolia (Kovalenko et al., 1996; Yarmolyuk et al., 2003c; Safonova, 2008) (Fig. 3). They correspond to sequences of high-Ti OIB basalts occurring in the Ozerny zone ophiolites (>530 Ma, Kovalenko et al., 1996; Yarmolyuk et al., 2002b), Kuznetsky Alatau (544 Ma, Plotnikov et al., 2000), Dzhida zone (>506 Ma, Almukhamedov et al., 1996; Medvedev et al., 2008), Kurai (598 Ma) and Katun (550–530 Ma) complexes of the Gorny Altay (Safonova, 2008). The effusive volcanic complexes were formed simultaneously with their intrusive equivalents: high-Ti layered gabbro, dunite–pyroxenite–gabbro and gabbro–

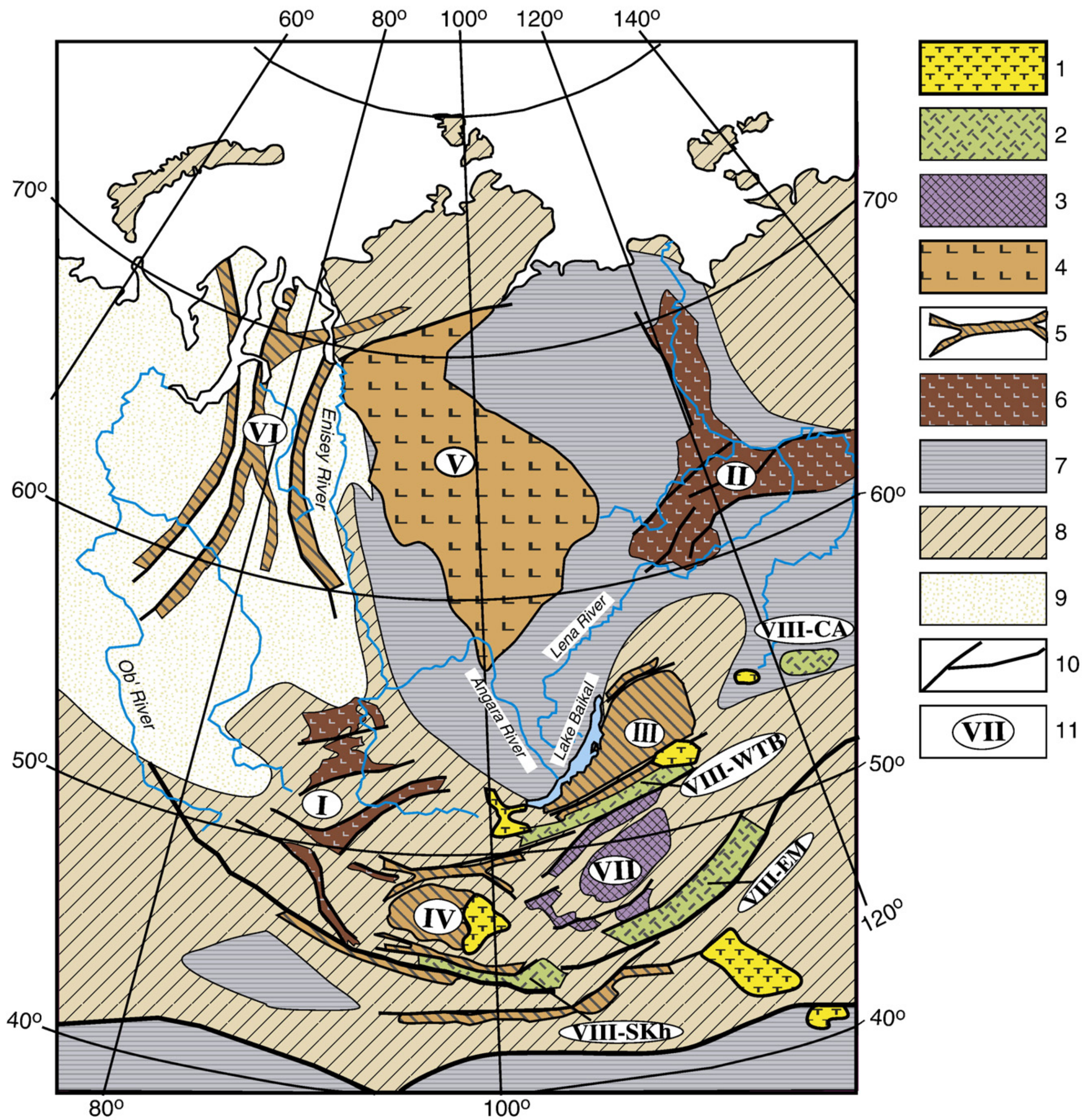

Fig. 2. Location of the intraplate magmatism areas within the Siberian platform and its folded surrounding (modified after Yarmoluk et al., 2000). 1–7 — intraplate magmatic associations: 1 — Cenozoic, 2 — Late Mesozoic, 3 — Early Mesozoic, 4 — Late Permian–Early Triassic, 5 — Late Paleozoic–Early Triassic riftogenic magmatism zones, 6 — Late Paleozoic, 7 — Precambrian platforms, 8 — folded belts, 9 — sedimentary basins, 10 — faults, 11 — numbers that correspond to different large igneous provinces (also see Table 1). Large igneous provinces (LIPs) (numbers in circles): I–II — Early–Middle Paleozoic: I — Altay–Sayan, II — Viluy, III–VII — Late Paleozoic–Early Triassic: III — Barguzin–Vitim, IV — Central Asian, V — Permo-Triassic Siberian traps, VI — Western-Siberian Rift System, VII — East Mongolia and Trans-Baikalia LIP, VIII — Late Mesozoic Rift Systems: VIII-CA — Central Aldan, VIII-EM — East-Mongolian, VIII-WTB Western Trans-Baikalian, VIII-S-Kh — Southern Khangay (Gobi–Altay).

monzonite associations as well as subalkaline gabbroids (Izokh et al., 2001; Vrublevskii et al., 2009). It includes several intrusions of gabbroids (Bayantsagan massif; 531 ± 25 Ma; Khain et al., 1995), high-Ti gabbroids (527 ± 43 Ma; Kovalenko et al., 1996), dunite–troctolite–gabbro intrusives (Khaerkhan massif, 513 ± 18 Ma; Rudnev et al., 2009). In addition to ultrabasic–basic magmatic rocks the island arc complexes contained intraplate ultrabasic alkaline complexes with carbonatites in the Kuznetsky Alatau (510 Ma, Vrublevskii et al., 2009) and in the Gorniy Altay (Edelweiss complex, 507 Ma, Vrublevskii et al., 2009), as well as peralkaline (agpaitic) granites in the Ozerny zone (510 Ma, Yarmolyuk, personal communication).

Ophiolite and island arc complexes of the Paleoasian Ocean accreted between each other in the end of Cambrian — beginning of Ordovician (between 510 and 480 Ma) forming Altay–Sayan composite terrane (Yarmolyuk et al., 2003c, 2006). The process was accompanied by the folding, metamorphism and intense, primarily granitoid, magmatism, resulting in numerous large plutons with a total area of 200,000 km^2 (Fig. 3). The late-accretion and post-accretion stages in the evolution of the terrane were manifested by abundant intraplate magmatism (Fig. 3). Numerous alkaline areas include massifs of the nepheline syenites (Dzhargalantsky — 487 Ma; Kozakov et al., 2003; Tazheransky — 470 Ma; Sklyarov, et al. 2009,

Table 1
Phases, provinces and areas of the intraplate Phanerozoic magmatism within the Siberian Platform and its folded surrounding (the number in brackets is the age of the rocks in Ma).

Phases and stages of activity	Large igneous provinces and areas of intraplate activity and character of magmatic events	
Early Paleozoic	I. Altay–Sayan area intraplate magmatism	
Cambrian–Ordovician	Origin of oceanic island basalts (high-Ti basalts, layered olivine gabbro, and high-Ti gabbro) [598, 544, 530, 531, 527, 513], complexes of alkaline granites with carbonatites [510], alkaline granites [510]. Formation of the oceanic island type basalt dyke swarms [510–480] in syn-accretional granitouds. Formation of the late- and post-accretional alkaline and nepheline syenites [494, 490, 470], alkaline granites [495, 490, 480, 450], subalkaline and alkaline gabbro [464, 446].	
Middle Paleozoic	II. Altay–Sayan LIP	
Early Devonian	Origin of grabens and depressions with trachybasalts, trachytes, trachyrhyolites, ultramafic and alkaline rocks [408–389, 402].	
Middle Devonian	Origin of associations: phonolite–trachybasalt, trachybasalt–trachyte–pantellerite, nepheline–syenite peralkaline and Li–F granite [393].	III. Viluy LIP Arc uplift, eruption of trachybasalts, trachytes, phonolites. Origin of rift zones, belts of basite dikes, flood basalt eruptions.
Late Devonian–Early Carbonaceous		Eruption of trachytes, subalkaline and alkaline basaltoids, intrusion of dikes pf shonkinites and teshenites, formation of massifs of alkaline–ultramafic rocks with carbonatites [380–350].
Late Paleozoic–Early Mesozoic	IV. Barguzin–Vitim LIP	V. Late Paleozoic Rift systems of the Central Asia
Late Carboniferous–Early Permian	Synnyr rift belt — massifs of alkaline, nepheline and pseudoleucite syenites [310, 290, 285]. Udin–Vitim rift belt — peralkaline granites, bimodal volcanic associations [305–275] Saizhen rift belt — ultramafic alkaline rocks, alkaline gabbroids, nepheline syenites, carbonatites [290–285]. East-Sayan rift belt — gabbroids, nepheline syenites, peralkaline granites [302–298] Generation of granitoids of the Angaro–Vitim batholith with syn-plutonic dikes of alkaline basites [305–275].	Gobi–TianShan rift zone with bimodal basalt–comendite, peralkaline–granite magmatism [318–285] and Li–F granites [285]. Gobi–Altay rift zone with bimodal basalt–pantellerite and alkaline–granite magmatism [275].
Late Permian–Early Triassic	VI. Siberian trap LIP Origin of the Siberian trap volcanic complexes. [250–249]. VI. Western-Siberian rift system Basalt and bimodal basalt–trachyrhyolite associations [250–249].	North Mongolian rift zone [265–249] with bimodal basalt–pantellerite and peralkaline–granite magmatism. Origin of zonal-symmetric Khangai magmatic area with Khangai granitoid batholith [266–242] in the center.
Triassic–Early Jurassic	VIII. East Mongolia and Trans-Baikalia LIP Origin of zonal-symmetric magmatic area in the East Mongolia and Western Transbaikalia. Center of the area – Khentei granitoid batholith [225–195], surrounding – Western Trans-Baikalia and Northen Gobi Rift zones with peralkaline and Li–F granites, basalt and bimodal basalt–comendite associations [228–195].	
Late Mesozoic–Early Cenozoic	IX. Central Asian intracontinental rifts	
Late Jurassic	Origin of systems of hot spots: South-Khangai, East-Mongolian, West Transbaikal and Central Aldan. Generation of separate grabens with basalts, trachytes, trachyrhyolites, in places with carbonatites, pantellerites and massifs of peralkaline and Li–F granites [160–140].	
Early Cretaceous	Origin of systems of grabens in South-Khangai, East-Mongolian and Western Transbaikal areas with flood basalts eruptions and occurrences of tephrites, phonolites, nepheline syenites, shonkinites, carbonatites, ongonites and Li–F-granites [140–110].	
Late Cretaceous–Early Cenozoic	Separate fields of basalts, melanephelenites, tephrites, basanites in the volcanic areas of South-Khangai, West Transbaikal and Central Aldan [100–25].	
Late Cenozoic	X. Central and Eastern-Asian intracontinental areas Activization of magmatic activity in South-Khangai, West Transbaikalia areas; origin of a new system of hot spots (South-Baikal, Darihanga), eruptions of flood basalts, tephrites, basanites [<25], origin of the Baikal Rift System.	

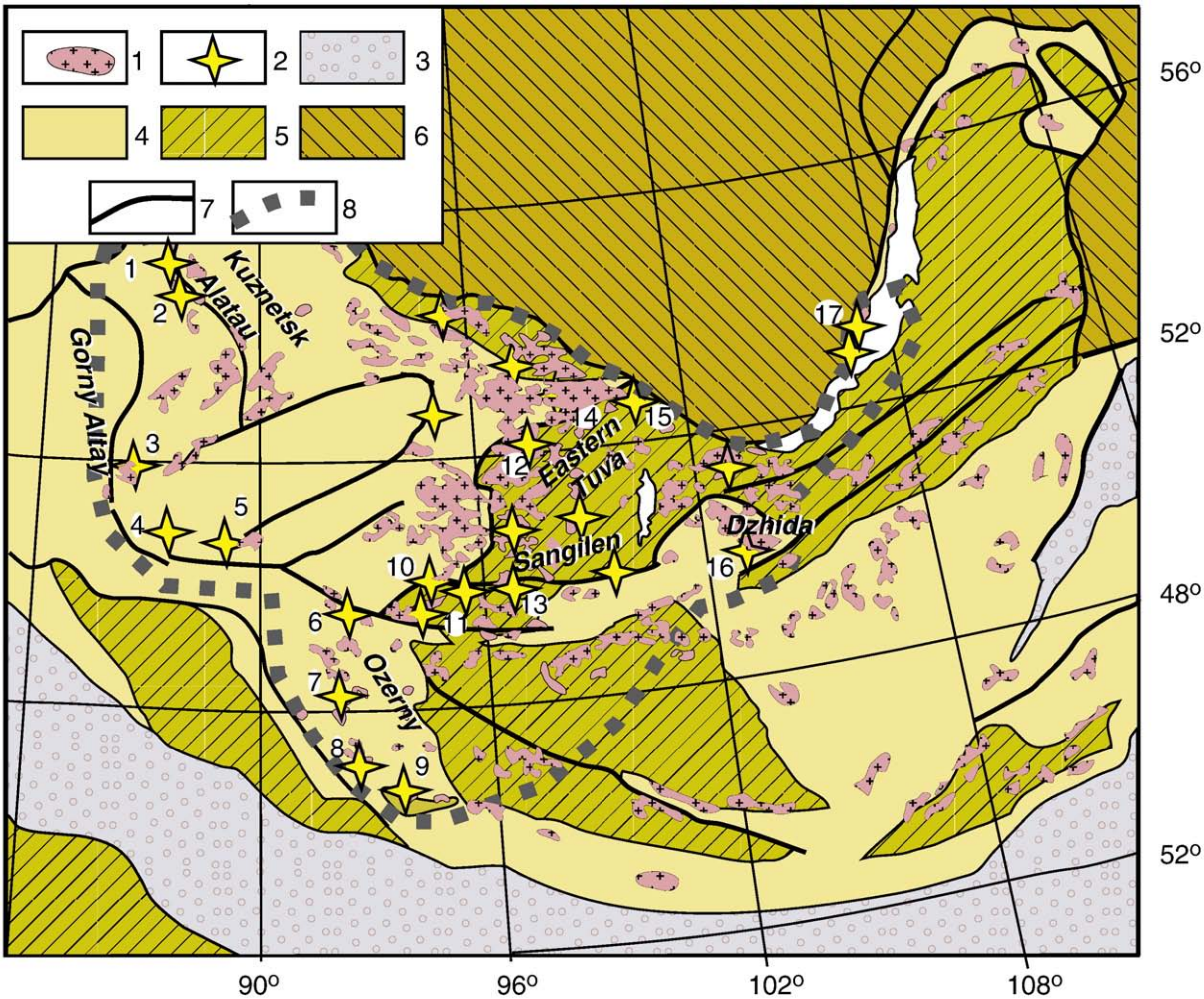

Fig. 3. Locations of the Late Riphean–Early Paleozoic magmatic areas in the Central Asian Folded Area. 1 — granitoids, 2 — key sections and exposures of the oceanic island basalts and complexes of alkaline rocks, 3 — Mesozoic sedimentary cover, 4 — Caledonian orogenic belt, 5 — Precambrian terranes, 6 — Siberian platform, 7 — major faults, 8 — boundary of the Early Paleozoic intraplate magmatism activity indications. Numbers in the small circles correspond to Ultrabasic alkaline complexes with carbonatites: 1 — upper Petropavlovsk, 4 — complex Edelweiss; the ophilite complexes with inclusions of the oceanic island basalt massifs: 2 — Kuznetsk Alatau, 3 — Katun′, 5 — Kurgay; Massifs of high-Ti layered gabbro and subalkaline gabbro, dunite–pyroxenite–gabbro and gabbro–monzonite associations: 7 — Seinur, 8 — Khaerkhan, 9 — Baiatsagan, 10 — Bashkymurgur; Peralkaline (agpaitic) granite massifs: 6 — Bominkharin, 11 — Sangilen, 12 — Khaylamin, 14 — Aryskan; Nepheline syenites massifs: 13 — Dzhargalantsky, 15 — Botogolsky, 17 — Tazheransky.

Botogolsky — 494 Ma, Yarmolyuk et al., 2006), subalkaline gabbroids (Bashkymugur — 464 Ma, Kozakov, et al., 2003) alkaline granites of the Sangilen complex (495, 480 Ma, Kozakov, et al., 2003), alkaline (agpaitic) granites of the Khaylamin and Aryskan area and a number of other massifs in Eastern Tuva (450 Ma, Kostitsyn et al., 1998) were formed during this time interval.

Geochemical and absolute age data confirm that intraplate magmatism occurred during pre-, syn- and post-accretion stages of the Altay–Sayan composite terrane formation. The terrane was formed as a result of collision of smaller terranes with the system of oceanic islands formed by the mantle plume(s) (Yarmolyuk et al., 2003c). Collision of the Altay–Sayan terrane(s) with the Siberian platform occurred progressively between Late Ordovician and Devonian based on dating of collisional complexes and paleomagnetic data (Buslov et al., 2001).

The intraplate magmatism continued after the Altay–Sayan terrane accreted with the Siberian platform. Massifs of alkaline gabbroids, agpaitic granites and syenites, dykes of camptonites, rifting bimodal volcanic associations containing rocks of the increased alkalinity and alkaline rocks, were formed in the area in the Late Ordovician and the beginning of Silurian period at 465–440 Ma (Yarmolyuk et al., 2000; Safonova, 2009).

We consider that during this time Altay–Sayan was situated above one or a few hot spots after breakup of Rodinia. At the same time there is no data available on any intraplate magmatic activity during almost whole Silurian period. The beginning of the Silurian period was probably a period when intraplate magmatic activity in Siberia and surrounding areas was terminated until it started again in Early Devonian.

The Altay–Sayan composite terrane and Siberian continent final amalgamation occurred by the end of the Devonian period (Zonenshain et al., 1991b; Buslov et al., 2001). Starting from the Early Devonian there is a new stage of intraplate magmtism in the Siberian continent and two large igneous provinces, Altay–Sayan and Viluy, were formed.

The Altay–Sayan LIP is located in the south-western folded area of Siberia (Fig. 2, Table 1). The region envelops the Minusinsk basin, Tuva, Eastern and Western Sayan, and north-western Mongolia, a total area of 500×700 km. Zonenshain et al. (1991b) considered that both igneous rocks and sedimentary depressions in the region were formed in the Early–Middle Devonian period. Intrusive rocks continued to form in the Altay–Sayan area until the beginning of the Devonian period. Intrusions of ultra–basic alkali rocks, nepheline syenites, and alkali and lithium–fluorine granites (Ognitsk, Okunev, and Brensk complexes) were formed at this time. These intrusions have Rb–Sr and K–Ar ages of 450–400 Ma (Yarmolyuk and Kovalenko, 2003b). Maximum magmatic activity occurred in the Early Devonian period. The Minusa depressions have as age ranging from 380 to 408 Ma (Fedoseev, 2008). The bimodal volcanic associations in the eastern part of the Tuva depression are dated as 402 Ma (Vorontsov et al., 2008), the age of the rifting magmatism of the Delyuno–Yustyd depression is estimated from alkaline granites as 393 Ma (Kovalenko et al., 2004). Thus, magmatism on different sites of the igneous province was occurring more or less simultaneously and the peak of its activity was reached during a relatively narrow time span from 408 to 393 Ma. A triple-junction graben system formed in this region (Fig. 4). Two branches of the system joined each other at an angle of ~100°. One of the branches, the Tuva Depression, strikes toward the northeast for 500 km and was formed as a volcanic rift with an extended basaltic dyke system. The Delyuno–Yustyd black shale Depression contains basic lavas at the bottom of a stratigraphic sequence and formed a second branch that extends toward the northwest for 600 km. Volcanic grabens enclosed the depression. The third branch most likely was extended toward the ocean between the Siberian platform and the Altay–Sayan block (northwest about 50°N, 88°E in present day coordinates).

Enormous lava eruptions of basic composition (basalts, tephrites, and trachybasalts) and phonolites, trachytes, and comendites accompanied the rifting. Intrusives of teschenites, alkali granites, and syenites were formed at the same time. Magmatic activity was abruptly reduced

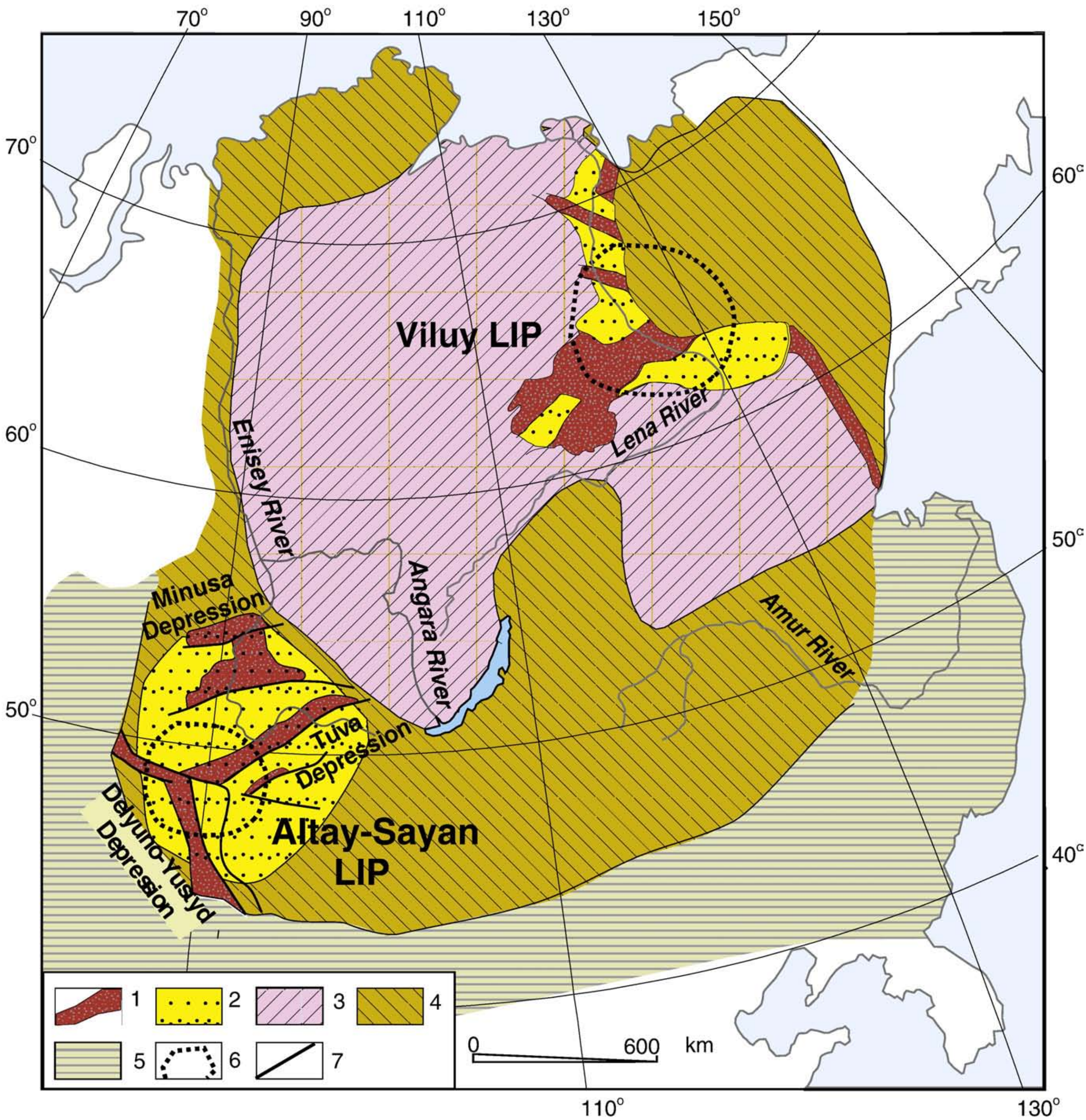

Fig. 4. Locations of the Middle Paleozoic LIPs within the Siberian paleocontinent. 1 — volcanic depressions and grabens, 2 — uplifts (shoulders of rift depressions and grabens), 3 — Siberian platform, 4 — folded surrounding zones of the Siberian continent, 5 — other folded zones, 6 — projections of the mantle plumes, 7 — major faults.

in the Middle Devonian. More than 50,000 km^3 of lava erupted in the Early Devonian only in the Minusa Depression (Luchitsky, 1966), another magmatic center in the Altay–Sayan. Based on this, we estimate vast magmatic activity in the Altay–Sayan area during this time (more than 100,000 km^3 of magmatic rocks were formed from 408 to 393 Ma) and consider the area to be an ancient LIP.

The Viluy LIP covers most of the present day north-eastern margin of the Siberian platform (Fig. 4, Table 1). The triple-junction rift system was formed during the Middle Paleozoic era; the Viluy rift is one branch of the system and two other branches form the modern margin of the Siberian platform (Zonenshain et al., 1991b; Kiselev et al., 2006). The Viluy rift expands to a length of 800 km and has a width of 450 km (Gaiduk, 1987; Kiselev et al., 2006). Diamondiferous kimberlite pipes and an extended dyke set are associated with the rift. The system of sedimentary depressions were filled in with volcanic and clastic rocks with a major eruption event taking place during the Late Devonian–Early Carboniferous reflected in the paleomagnetic data of Kravchinsky et al. (2002b). Volcanic rocks divide the depressions determining the internal structure of the rift. Scarce Ar–Ar data indicate that the magmatism age ranges within 380–350 Ma (Kiselev et al., 2006). Zonenshain et al. (1991b) reviewed multiple fossil descriptions that denote a Devonian–Early Carboniferous age for the sedimentary sequence that contains the volcanic rock sequence. The volcanic rocks, large dyke belts, and multiple thick sills that cover a large area (more than 320×10^3 km^2) establish the Viluy rift area as a region connected to superplume activity following the criteria of Condie (2001).

The earliest magmatic rocks in the Viluy rift (tephrites, trachybasalts, trachytes, phonolites, and ultrabasic alkali rocks with carbonatites) erupted in the Silurian period (Gaiduk, 1987). The rocks accumulated during the earliest stage of rifting (uplift of the arch). A gently sloping depression filled with carbonate–clay sediments was formed in the Middle Devonian period along the axis of the forthcoming Viluy rift. A system of grabens and minor depressions developed in the Viluy rift structure during the Frasnian age accompanied by a large volume of basalt intrusions (sills and dykes) (Kiselev et al., 2006). A reduction in basalt eruptions and an increase in vertical movement amplitude took place at the end of that period corresponding to the final stage of rift formation. A magmatic Kempendyay Depression with a sediment thickness of 3–7 km formed in the western section of the rift at the same time. The intensity of tectonic movements and volcanic activity gradually declined during the Early Carboniferous period. A gigantic amount of magmatic material (more than 300×10^3 km^3) formed in the Viluy branch only of the triple-junction system preserved on the Siberian platform (Gaiduk, 1987; Kiselev et al., 2006). By extending this amount of magmatism to all three branches of the rift we may assign $\sim1000\times10^3$ km^3 for the Viluy rift; that makes it one of the largest magmatic provinces in the world.

The Late Paleozoic–Early Mesozoic stage of magmatism corresponds to another period of great intraplate magmatic activity in Siberia occurring from 320 to 190 Ma. The Permo-Triassic traps are the largest igneous province on the Siberian platform (Fig. 5) and enclose a volume of $\sim1.5\times10^6$ km^3 (Kuzmin et al., 2003a). The traps erupted during a very narrow time interval between 251 and 248 Ma. New Ar–Ar dating of the Kuznetsk Basin traps (Dobretsov et al., 2005) and volcanic rocks of the West Siberian rift system (Almukhamedov et al., 2004; Reichow et al., 2005) corresponds to 249 Ma. Bimodal volcanic associations (alkali basalts and rhyolites) are found in the West Siberian rift system (Almukhamedov et al., 2004; Reichow et al., 2009). The volcanism is connected with grabens which extend through Western Siberia to the Arctic Ocean (about 1500 km) (Fig. 5).

The Late Carboniferous–Early Permian Barguzin–Vitim LIP demonstrates a zonal structure and covers an area of over 150,000 km^2 (Fig. 6, Table 1). The central part of the province is occupied by the largest Angara–Vitim batholith (Litvinovsky et al., 1992) composed of granitoids of different composition (from monzodiorite to granites, granosyenites, and leucogranites). Two stages of granite formation, Early Carboniferous (340–320 Ma) and Late Carboniferous–Early Permian (305–275 Ma), were identified (Yarmolyuk et al., 1997a,b; Tsygankov et al., 2007). Primarily medium acid granites of the Barguzin complex, including autochthonous varieties generated early stage (340–320 Ma). The later stage (305–275 Ma) was more productive and more diverse in magmatic rocks and is represented by the low-silica granitoids — primarily monzonites, quartz monzonites and quartz syenites; leucocratic medium alkali granites; syenites and alkali (agpaitic) granites. Central parts of the Angara–Vitim batholith contain numerous intrusions of rocks with alkaline–basaltoid compositions (Litvinovsky et al., 1992; Yarmolyuk et al., 1997b). A diverse composition of granitoids from this stage is due to different sources responsible for their origin. The crustal metaterrigenous protolith served as a source for medium acid granites (Tsygankov et al., 2007). Basalt magma was responsible for the origin of granitoids of the increased alkalinity and alkali granitoids (Litvinovsky et al., 1992; Yarmolyuk et al., 2001). The mixing of basalt magma with acid crustal melt gave rise to hybrid monzonitoid melts. The significance of basic magmas for the origin of the Late Carboniferous–Early Permian granitoids was confirmed by numerous syn-plutonic intrusions of basalts, which are characterized by mingling structure along the contacts with granitoids suggesting that acid and basic melts intruded simultaneously (Litvinovsky et al., 1992).

The rift zones containing alkaline rocks are found at the batholith's periphery: Uda–Vitim, Synnyr, and Eastern Sayan. One more zone, Saizhen, is situated along the axial part of the batholith. The rift zones are characterized by chains of alkaline ultrabasic and basic rocks, alkaline granites and syenites including leucite and nepheline syenites, and a few volcanic fields (only in the Uda–Vitim zone) composed of rocks with bimodal basalt–alkaline–rhyolite associations. The U–Pb, Rb–Sr, and Ar–Ar ages of the rifting magmatism are slightly different in different zones (Fig. 6). The Synnyr zone has an age of 310–285 Ma (Pokrovsky and Zhidkov, 1993; Yarmolyuk et al., 1997a,b), the Saizhen zone has an age of 294–288 Ma (Pokrovsky and Zhidkov, 1993; Yarmolyuk, personal communication), and the Uda–Vitim zone has an age of 290–275 Ma for syenite–alkali–granite volcanic–plutonic complexes (Yarmolyuk et al., 2001; Litvinovsky et al., 2002; Shadaev and Khubanov 2004; Tsygankov et al., 2007) and 285–303 Ma for bimodal trachybasalt–trachyte–trachyrhyolite dike belts (Rb–Sr age is 285–303 Ma) (Khubanov and Shadaev, 2004; Shadaev et al., 2005). The East-Sayan zone formed at 304–296 Ma (Yarmolyuk et al., 2010).

We identify two distinctive magmatic complexes in the Barguzin–Vitim LIP. The Early Carboniferous complex is composed mainly of granitoids. It was formed due to the subduction related collision of the volcanic arc terranes bordering the Siberian platform and orogeny (Mazukabzov et al., 2010), the evidence of which are folded deformations and thrust faults in the central part of the igneous province formed prior to granites (Ruzhentsev et al., 2005, 2007). The magmatic activity reappeared after a break lasting about 20 Ma forming the Late Carboniferous–Early Permian complex of igneous rocks of the intraplate magmatism type. The alkali-basaltoid intrusions occupy up to 10% of the Angara–Vitim batholith (Litvinovsky et al., 1992). We advocate that the Late Carboniferous–Early Permian Barguzin–Vitim LIP originated as a result of the Siberian continent displacement over the mantle hot spot (Yarmolyuk and Kovalenko, 2003a; Nenakhov and Nikitin, 2007; Tsygankov et al., 2007).

Another rift system in Central Asia was formed during the Late Paleozoic–Early Mesozoic phase (Fig. 7, Table 1) (Yarmolyuk and Kovalenko, 1991). The Central Asian rift system is represented by a set of sub-parallel rifts filled with bimodal basaltic comendite and basalt–pantellerite associations. Rifts determine the positions of multiple alkali granite and syenite intrusives. The set was developed in the

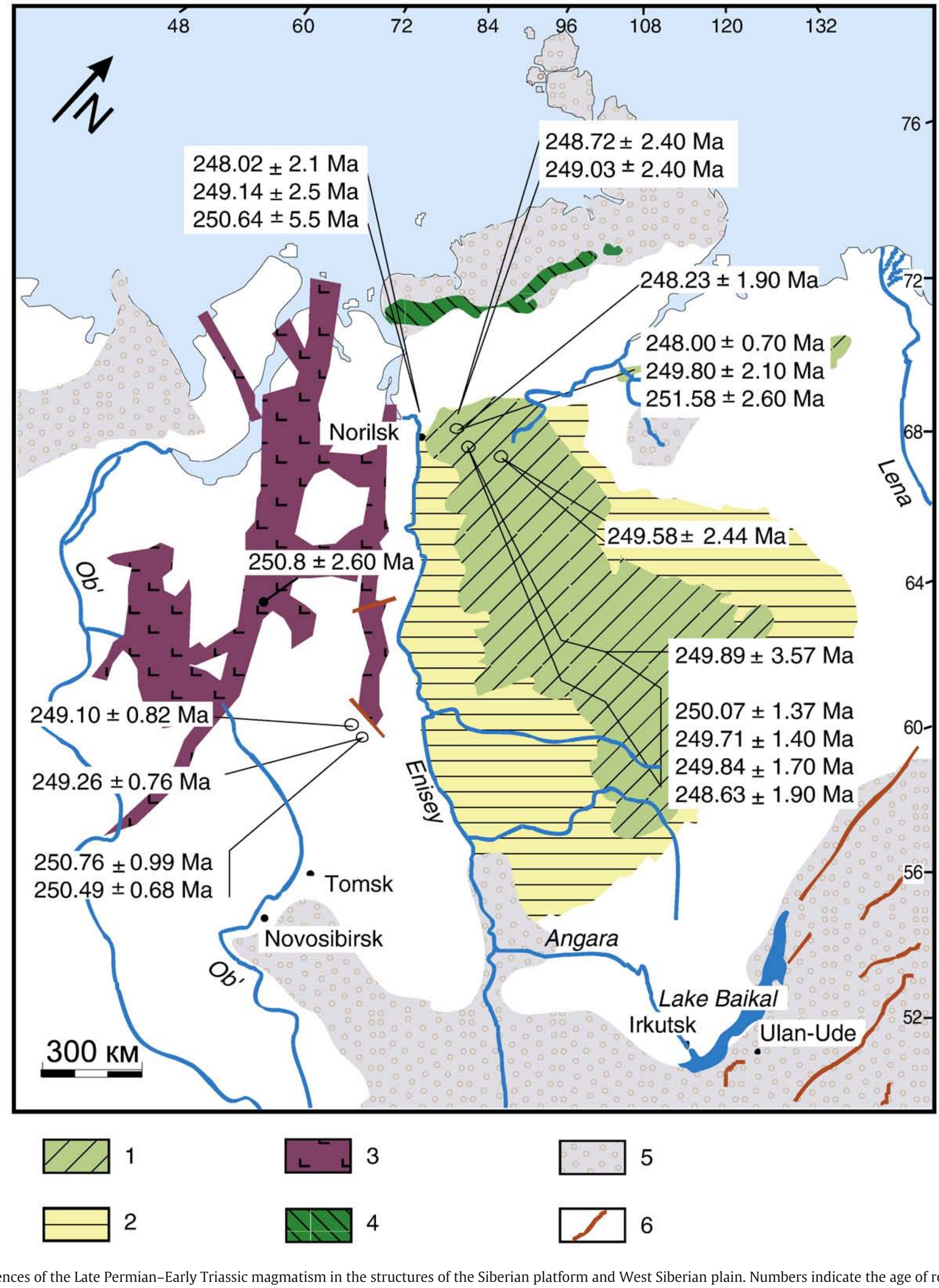

Fig. 5. Occurrences of the Late Permian–Early Triassic magmatism in the structures of the Siberian platform and West Siberian plain. Numbers indicate the age of rocks of different formations from different sites of volcanic areas (in Ma). 1 — extrusive volcanic rock exposure; 2 — intrusive volcanic rock exposure; 3 — West Siberian Rift basalts, tuffs, and tuffites; 4 — Taimyr Early Triassic traps; 5 — folded surrounding; 6 — major tectonic dislocations.

southern active margin of the Siberian continent (in present day coordinates) during the Late Paleozoic era can be traced for more than 300 km with a width of up to 600 km throughout Western Trans-Baikalia, Mongolia, North-Western China, Tarim, and Eastern Kazakhstan. Rift ages vary from the continental margin (318–285 Ma) to the center of the Siberian continent (266–242 Ma) all the way through ~600 km (Wang and Han, 1994; Yarmolyuk et al., 2008b).

The rift system was formed in a number of stages. The earliest stage corresponded to the formation of the first grabens of the Gobi–Tian-Shan rift at the edge of the Siberian continent in the present day folded surrounding area. The rift was stratigraphically dated as Late

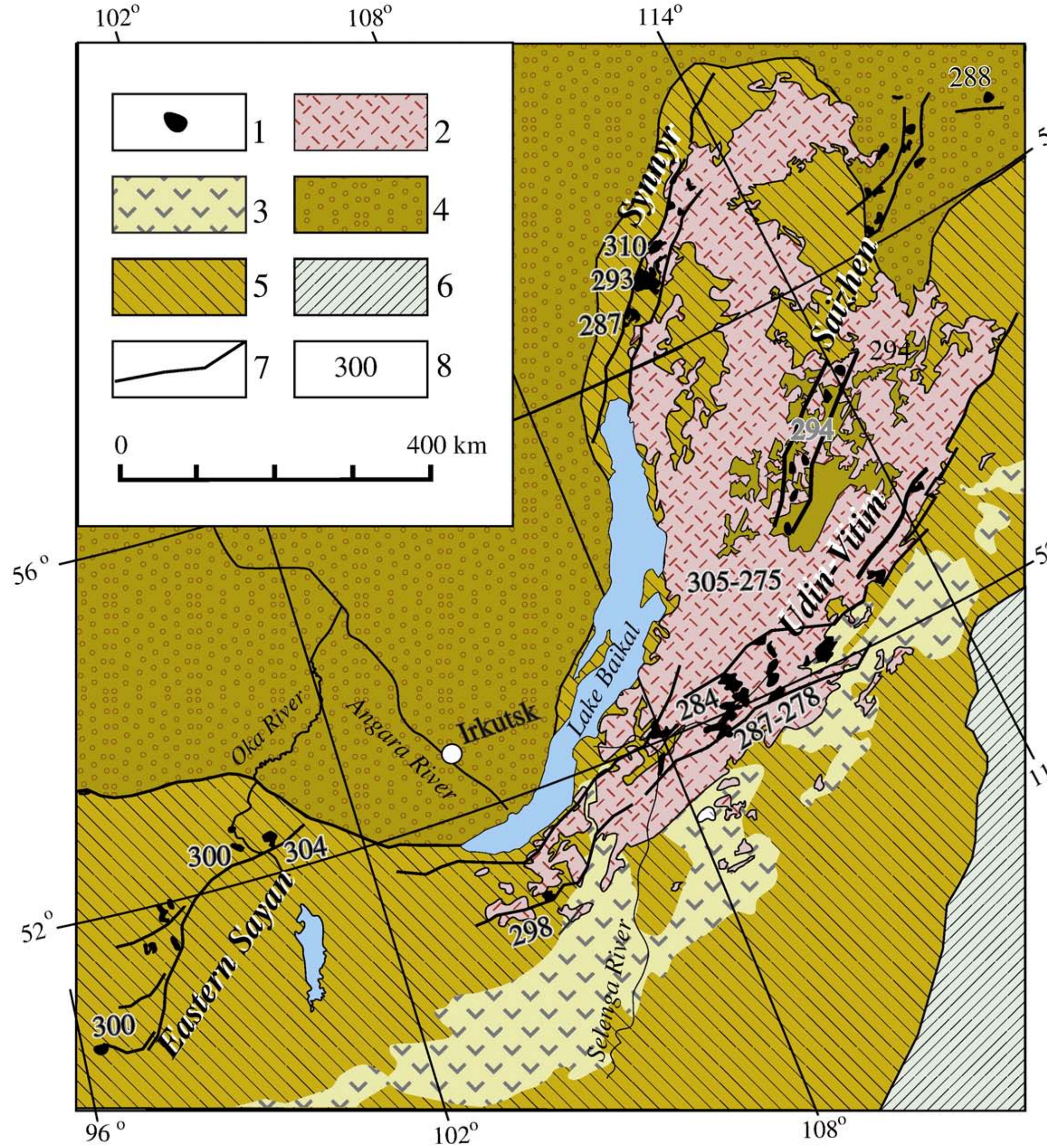

Fig. 6. Simplified geological structure of the Late Paleozoic Barguzin LIP. 1 — alkaline magmatic complexes, 2 — granitoids of Angara–Vitim batholith, 3 — volcanic complexes of active Late Paleozoic continental margin, 4 — Siberian platform, 5 — Phanerozoic folded areas, 6 — Mongol–Okhotsk suture zone, 7 — major faults along alkaline magmatic complexes, 8 — age of the corresponding geological structures in Ma.

Carboniferous–Early Permian (Yarmolyuk and Kovalenko, 1991). A Rb–Sr dating of the alkali granites and effusives match to 318–285 Ma (Wang and Han, 1994; Yarmolyuk et al., 2008b).

Two other rift zones of the Central Asian rift system, Gobi–Altay and North Mongolian, were formed at the end of the Early Permian — the beginning of the Late Permian and at the Late Permian periods, respectively, as a result of the progressive propagation of the rift into the folded margin of the Siberian platform. The North Mongolian rift zone extended into the Siberian continent, 600 km further than the Gobi–Tian-Shan region, was formed during the Permian–Early Triassic stage of magmatism and has symmetrical elongated structures. The Rb–Sr age of the North Mongolian basalt (pantellerite associations and alkali granites) is 265–249 Ma (Yarmolyuk et al., 2000; Yarmolyuk et al., 2003a). The Khangai granitic batholith was formed simultaneously with the Gobi–Altay and North Mongolian rift systems and was located between them (Yarmolyuk and Kovalenko, 1991, 2003a,b, Yarmolyuk et al., 2008a). The batholith was formed similarly to the Angaro–Vitim batholith during an intraplate heating and an anatexis of the continental crust. Granitoids of the Khangai batholith have a U–Pb (zircon) age of 266–242 Ma (Yarmolyuk et al., 2008a).

Magmatic activity continued during the Early Mesozoic stage (Middle–Late Triassic to Early Jurassic; 230–185 Ma) further toward the east and similar types of symmetrical structures were formed (Fig. 7, Table 1). The East-Mongolian–Trans-Baikalian LIP was formed in the Central Asian folded zone during this stage. The area is similar to the Permian–Early Triassic Khangai region and has a symmetric structure with the Khangai batholith in the center. The Khentey batholith formed the inner part of the Mongol–Trans-Baikalian area and was located about 800 km toward the east relative to the Khangai batholith (Fig. 7). The Khentey batholith was formed during the Mongol–Okhotsk ocean closure and is composed of large massifs of granodiorites associations that cover 150,000 km^2. The stratigraphic, U–Pb and Rb–Sr ages of the batholith are between 225 and 195 Ma

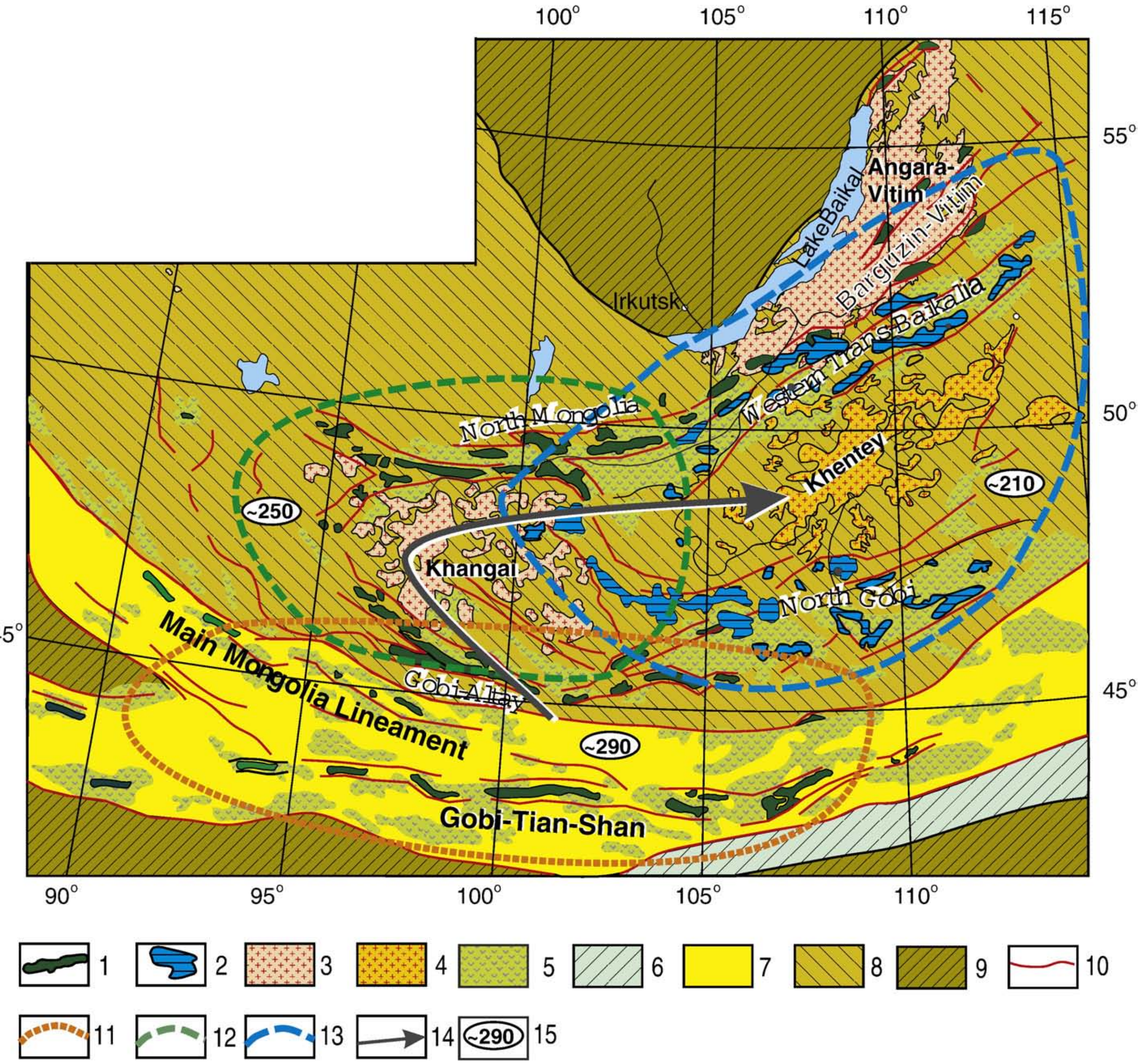

Fig. 7. Location of the Late Paleozoic–Early Mesozoic magmatic associations within the Central Asian rift system. 1–2 — rifting basalt–comndite–pantellerite with alkaline granites: 1 — Late Paleozoic, 2 — Early Mesozoic; 3 — Late Paleozoic granitoid batholith (Angara–Vitim and Khangai) 4 — Early Mesozoic Khentey ganitoid batholoth, 5 — volcanic rocks of active continental margin, 6–8 — folded structures 6 — Early Mesozoic folding zone, 7 — Hercynian folding zone, 8 — Caledonian folding zone, 9 — platforms, 10 — rupture dislocations, 11–13 — location of the magmatic associations associated with the mantle plume for 11 — Late Carboniferous–Early Permian, 12 — Late Permian, 13 — Late Triassic–Early Jurassic, 14 — relocation of the mantle plume projection to the lithosphere for different time intervals, 15 — mean age of the intraplate volcanic activity.

(Yarmolyuk et al., 2002a). The system of grabens accompanied by basalts, alkali basalts, phonolites, trachytes, pantellerites, comendites, lithium–fluorite granites, alkali granites, and syenites frames the batholith (Zanvilevich et al., 1985; Yarmolyuk et al., 2002a). Alkali rocks of the Western Trans-Baikalia rift zone (northern edge of the Khentey region) have U–Pb and Rb–Sr ages of 220–200 Ma. Analogue alkali rocks in eastern Mongolia (Northern Gobi rift zone) have ages of 228–195 Ma (Yarmolyuk et al., 2002a). The intraplate magmatic activity throughout Northern Asia decayed abruptly at ~190 Ma and the Late Paleozoic–Early Mesozoic stage of magmatism terminated.

The Late Mesozoic–Early Cenozoic stage of magmatic activity took place during 140 Myr from the end of the Middle Jurassic (~160 Ma) to the beginning of the Miocene (~25 Ma) periods. The composition of the magmatic rocks changed during this period; thus we divided the period into two phases as described below.

East-Mongolian, West-Trans-Baikalian, and South-Khangai volcanic regions were created during the Late Jurassic–Early Cretaceous phase of magmatism (160–110 Ma) (Fig. 8). The formation of intracontinental rifts in the regions was accompanied by intensive magmatic activity along the periphery of the Mongol–Trans-Baikalian magmatic area indicating that intraplate magmatism was sustained in the Early–Late Mesozoic era. Volcanic associations with trachytes, alkaline rhyolites, pantellerites, phonolites, and tephrites were formed along with the flood basalts and minor massifs of nepheline and leucite syenites, peralkaline syenites, granites, lithium–fluorite granites, and ongonites, shonkinites, and carbonatites. The peak of

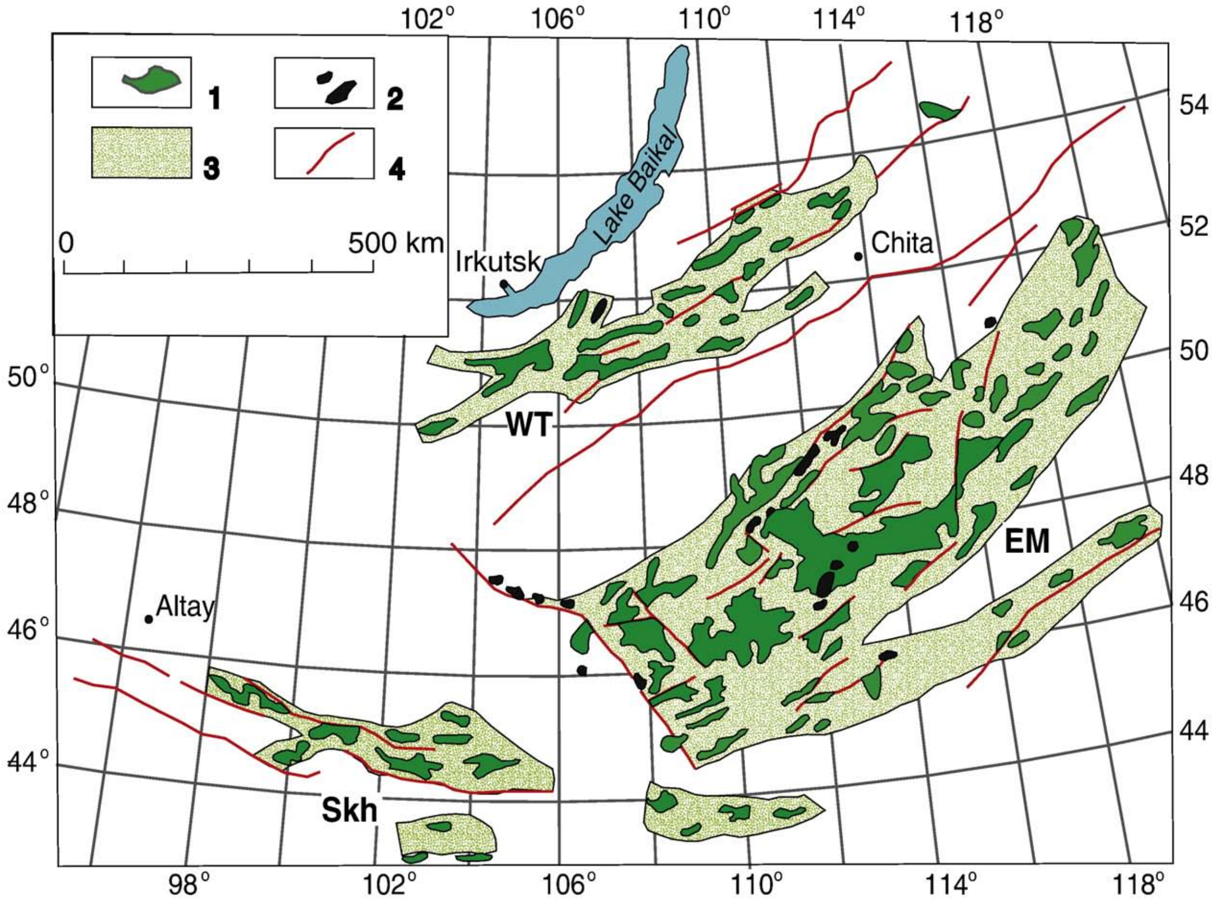

Fig. 8. Schematic location of the Late Jurassic–Early Cretaceous volcanic areas within the Central Asia. 1 — outcrops of rocks of trachybasalt and bimodal basalt–trachyrhyolite associations, 2 — granitoids, 3 — outlines of volcanic areas, 4 — major faults. Late Jurassic–Early Cretaceous rift systems: Western Trans-Baikalian (WT), Eastern Mongolian (EM), South-Khangay (S-Kh).

magmatism corresponded to the beginning of the Cretaceous era (140–130 Ma) when a system of grabens was formed in the area and enormous eruptions (more than 15×10^3 km^3) of plateau basalts occurred during a relatively short time period (Yarmolyuk et al., 1995a; Yarmolyuk et al., 2000).

Only meager magmatic activity took place during the Late Mesozoic–Early Cenozoic stage (100–25 Ma). Small lava fields and shield volcanoes were formed in western Trans-Baikalia, South-Khangai, and eastern Mongolia. The volcanic structures and lava fields were composed of basic alkali rocks (tephrites, basanites, nephelinites, and, rarely, subalkaline basalts) (Yarmolyuk et al., 1995a).

New intraplate volcanic activity occurred in Central and Eastern Asia during the Late Cenozoic stage (<25 Ma) (Fig. 9). Peak magmatic activity took place in Trans-Baikalia, southern Khangai, and other volcanic regions of Central Asia (Yarmolyuk et al., 1995a). Novel hot spots were responsible for a new large volcanic plateau formation in Vitim, South-Khangai, and Udokan and new south Baikal and Dariganga volcanic regions were formed during this phase.

Our review of magmatic aerials in Siberia and their ages demonstrates that intraplate magmatic activity took place in the territory of the Siberian platform and surrounding folded areas throughout most of the Phanerozoic eon with two relatively brief interruptions. The first interruption occurred during the Silurian period, then at 350–310 Ma following the final stage of magmatic activity in the Viluy rift area and continued until the beginning of magmatic activity in the Barguzin–Vitim area. The second interruption occurred 195–160 Ma after termination of the intraplate magmatic activity of the Late Paleozoic–Early Mesozoic period. This second interruption ended in the Late Jurassic period when a new phase of intraplate magmatism began in Central Asia. This enables us to conclude that:

(1) Each magmatic area was formed during tens of millions of years;
(2) Intraplate magmatism migrated in space and time and could correspond to hot spot traces.

Table 2 shows the volumes of magmatism approximately equivalent in different phases of the Paleozoic and Mesozoic eras. There was only one exception, Siberian trap and West Siberian Rift eruption, that produces more than 3.7×10^6 km^3 of volcanic rocks, emplaced during ~1 Ma (Kuzmin et al., 2003a,b; Courtillot and Renne, 2003; Reichow et al., 2009). The volume of intraplate magmatism abruptly decreased to 100 km^3 in the Late Cretaceous. Feeble magmatic activity persisted until the end of the Oligocene epoch. Magmatic productivity reached the level of the Late Mesozoic era again in the Late Cenozoic era (<25 Ma) (Yarmolyuk et al., 2000).

3. Composition of intraplate magmatic rocks from Siberia and Central Asia

During the last decade, geochemical and isotopic studies to evaluate the composition of intraplate volcanic rocks in Siberia and Central Asia indicate that the intraplate basalts in Asia can be split into three different age phases. Compositions of basalts, rocks typical of mantle genesis, are shown in Table 3.

Basalts of the Viluy palaeorift and south of the Altay–Sayan area represent Early–Middle Paleozoic igneous activity. Vorontsov et al. (1997) and Kiselev et al. (2006, 2007) studied the compositions of

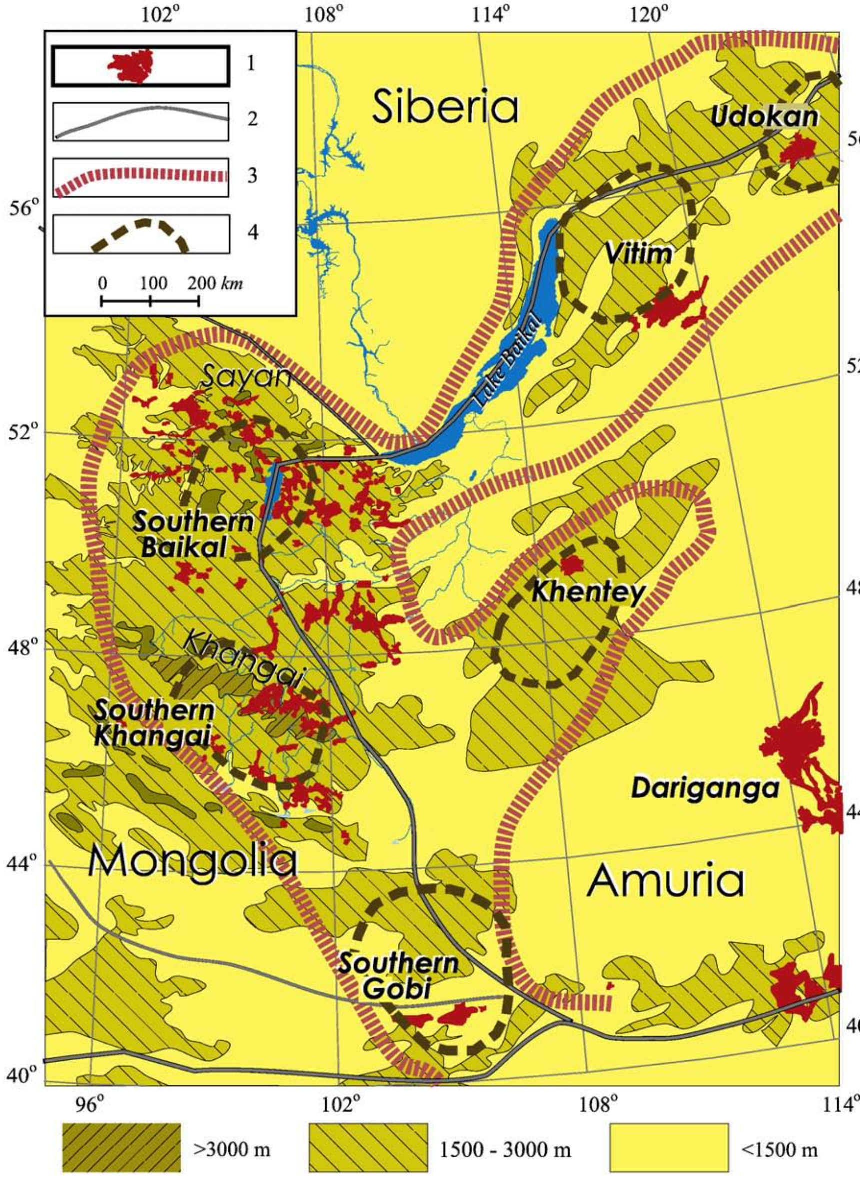

Fig. 9. Distribution of the Late Cenozoic volcanic areas in the Central Asia. 1 — basalt fields, 2 — boundaries of the continental blocks. 3 — boundary of the asthenosphere roof with the depth of occurrences lower than 100 km (Zorin et al., 1989), 4 — asthenosphere protuberances with the depth of occurrence lower than 50 km (projections of the mantle plumes) (modified from Zorin et al., 1989).

bimodal and alkali-basaltoid associations in the Tuva depression, north-western Mongolia, and the Viluy rift. Figs. 10A and 11A summarize the results of rare element and isotopic analysis. The rare Earth element composition of Viluy rift basalts corresponds to the Oceanic Island Basalt (OIB) type, while Altay–Sayan basalt rare element composition is compatible with the E-MORB type. The basalts contain increased amounts of rare Earth elements, as well as potassium, and relatively low amounts of Sr, Nb, and Ti, when compared to the reference element compositions of OIB and E-MORB types (Zindler and Hart, 1986). The isotopic compositions of both areas have positive values of ε_{Nd}^{T}; rocks of the Viluy palaeorift have relatively lower values of ε_{Nd}^{T} and large scatter from +2 to +30. Values of ε_{Nd}^{T} vary from −15 to +40 for basalts of the Altay–Sayan area (Fig. 11). Vorontsov et al. (1997) and Kiselev et al. (2006, 2008) suggested that variations in the isotopic composition correspond to two different sources during the formation of the primary magma. The first source had MORB type basalts of the Altay–Sayan area and moderately depleted mantle (PREMA) for the Viluy rift. The second source was the subducted oceanic lithosphere that had carbonates with isotopic characteristics of Middle Paleozoic marine water (Vorontsov et al., 1997; Yarmolyuk et al., 2000). The Middle Paleozoic oceanic lithosphere was subducted beneath the Devonian active margin of the Siberian paleocontinent in the Altay–Sayan area.

Late Paleozoic–Mesozoic intraplate basalts erupted between 320 and 190 Ma. The rock assemblage includes Siberian traps, Barguzin–Vitim area basalts, basalts of Western Siberia, and Central Asian rift systems. Fig. 10B represents spider diagrams of the average composition for these basalts. The diagrams illustrate analogous compositions for all intraplate Late Paleozoic–Mesozoic basalts from the studied areas. The similarity in basalt compositions of the continental blocks with Precambrian, Caledonian, and Hercynian basement rock indicates a common mantle genesis, i.e., crustal contamination did not take place during basalt formation. The basalts are enriched with Ba, K, Pb, Rb, and Sr and depleted of large ionic radius elements such as Ta, Nb, and Ti. Rocks of this age group have a high ratio of Zr/Y (4.5–12) and Zr/Sm (25–40) and are considerably different from the volcanic arc basalts (Zr/Y<3.5 and Zr/Sm<20) (Wilson, 1989). The isotopic composition of the Late Paleozoic–

Table 2
Intraplate magmatism in the Siberian platform and surrounding areas.

Magmatic phases	Stages	Magmatic areas and provinces	Age boundaries Ma	Size, $\times 10^3$ km^2	Volume of igneous rocks, $\times 10^3$ km^3
Early Paleozoic		Altay–Sayan area of intaplate magmatism	598–446	>25	>50
Middle Paleozoic		Altay–Sayan LIP	408–393	350	>100
		Viluy LIP	380–350	>320 (Viluy branch of the LIP)	~1000
Late Paleozoic–Early Mesozoic	Late Carboniferous–Early Permian	Barguzin–Vitim	310–275	~150	~300
		Gobi–Tian-Shan rift zone	318–285	>25	>50
	Permian–Early Triassic	Gobi–Altay rift zone	~275–255	~15	~30
		North Mongolian rift zone	265–249	~25	~50
		Khangai batholith	266–242	>100	>200
		Siberian trap LIP	250–249	>1200	>1500
		West Siberian rift system	250–249	~2500	>1500
	Triassic–Early Jurassic	Central Asian rift system	228–195	>20	>30
		including: rifting zones and independent occurrences of the Khentei batholith	225–195	>100	>200
Late Mesozoic–Early Cenozoic	Late Jurassic–Early Cretaceous	Central Asian intraplate magmatism including South-Khangai	160–110	~30	7
		Western Trans-Baikalia	160–110	~100	15
		Eastern Mongolia	160–110	~150	70
	Late Cretaceous–Early Cenozoic	South-Khangai	100–25	~30	~0.1
		Western Trans-Baikalia	100–25	~5	<0.1
Late Cenozoic		South-Khangai	<25	~60	~1.3
		Western Trans-Baikalia	<25	~7	~2
		South-Baikal occurrences	<25	~50	>3
		Other minor areas of southern Siberia, Mongolia and Northern China	<25	~100	~10

Mesozoic basalts resembles a normalized distribution of the rare elements indicating a mantle melt source (Fig. 11B) (Yarmolyuk et al., 1995b, 2000). The quantity of radiogenic strontium is higher ($+1<\varepsilon^T_{Sr}<+25$) and the quantity of radiogenic neodymium is lower ($-3<\varepsilon^T_{Nd}<4$) in the rocks. The late Carboniferous–Early Permian basalts of the Gobi–Tian-Shan rifting zone that were formed in the active margin of the paleocontinent are an exception. The basalts are characterized by higher values of ε^T_{Nd} and reduced ratios of $^{87}Sr/^{86}Sr$ (<0.7043) ($\varepsilon^T_{Sr}<+2$). Yarmolyuk et al. (1997a) explained the described quantities as a contribution from the subduction zone material. The isotopic compositions of the Siberian trap and the Central Asian rift system basalts are comparable and are elongated in Fig. 11B toward higher values of ε^T_{Sr} and reduced values of ε^T_{Nd}. Such isotopic characteristics indicate a magma source from an EM-II type enriched mantle and from products of its interaction with a PREMA type mantle.

Fig. 10C indicates characteristics of the final intraplate basaltoid magmatic stage in Siberia (Late Jurassic–Cenozoic). The values of rock composition change from Late Paleozoic–Early Mesozoic basalts to OIB type quantities (Yarmolyuk et al., 1998). The figure illustrates that normalized rare element variations are smoother for younger basalts (Cenozoic) compared to the older ones (from Late Jurassic–Early Cretaceous). Isotopic characteristics of the basalts also changed.

Basalts of the Late Cretaceous–Early Cenozoic eras with reduced amounts of radiogenic strontium ($\varepsilon^T_{Sr}<+5$) and enriched in radiogenic neodymium replaced basalts of the Late Jurassic–Early Cretaceous eras that are enriched with radiogenic strontium (ε^T_{Sr} up to $+20$) (Yarmolyuk et al., 1995b, 2000). This confirms that the magma of the PREMA type mantle of the Early Cenozoic basalts replaced the EM-II type material of the Late Paleozoic–Mesozoic basalts (Fig. 11C).

The Late Cenozoic (<25 Ma) basalts are widespread over Siberia and the adjunct areas. The basalts from different localities have similar rare element compositions and correspond to OIB type basalts (Yarmolyuk et al., 1995b, 2003a,b). The spectrum of rare element normalized quantities demonstrates that the Cenozoic basalts are enriched with the rare light elements. The isotopic composition of the majority of basalts varies largely in radiogenic neodymium (ε^T_{Nd} $+7$ to -11) and feebly in radiogenic strontium (ε^T_{Sr} -9 to $+5$). This confirms that the basalts correspond to a PREMA type mantle source. Basalts with lower values of ε^T_{Nd} correspond to EM-I type mantle sources (Yarmolyuk and Kovalenko, 2003b; Yarmolyuk et al., 1995b, 2003a,b; Kuzmin et al., 2003a,b).

The rare Earth element isotopic composition of the intraplate basalts indicates a gradual change in mantle sources of primary magma during the Phanerozoic eon; this allows us to conclude that:

(1) Devonian magmatic rocks correspond to a depleted mantle source ($\varepsilon^T_{Nd}>4$) and are characterized by broad variations in ε^T_{Sr}. Rocks of basaltic magma were produced from MORB or PREMA mantle sources, supplemented, in some cases, with subducted lithosphere containing marine carbonates.
(2) Although they are located in various geological structures, the similar composition of all Late Paleozoic–Mesozoic basalts indicates that they originated from the same mantle sources — PREMA and EM-II. The EM-II mantle source dominated during the early stages of magma formation. The geochemical characteristics of the mantle sources of the Late Paleozoic and Mesozoic magmatic associations do not depend on the geological age or the geographical or geological positions of the rocks. As indicated by the OIB composition of the mantle source in Late Cretaceous basalts, changes of the mantle source composition began in the second half of the Late Mesozoic era when the PREMA input increased moderately.
(3) Cenozoic basalts vary broadly in radiogenic neodymium (ε^T_{Nd} $+5$ to -11) and slightly in radiogenic strontium (ε^T_{Sr} -9 to $+5$). Isotopic diagrams (Fig. 11C) confirm that a majority of the basalts correspond to a PREMA mantle source. Early Cenozoic and Late Cretaceous basalts have similar isotopic and rare element characteristics. Evidently, basalts of these age groups were generated from the same mantle source. Nevertheless, some Cenozoic basalts are reduced in radiogenic neodymium (ε^T_{Nd} -11) and there are slight variations in the amounts of radiogenic strontium (ε^T_{Sr} $+1$ to $+5$) indicating an EM-I mantle source. The EM-I source was also involved in parental

Table 3
Mean compositions of the basic rocks from the different age intraplate magmatism areas of Siberia, its adjacent regions and Central Asian Rift System.

Phases and areas of intraplate magmatism														
Phases	Cenozoic		Late Mesozoic			Late Paleozoic–Early Mesozoic						Early–Middle Paleozoic		
Elements	KZ_2[a]	KZ_2	K_2	K_1	J_3-K_1	MZ_1	P_2	P_{1-2}	C_3-P_1	PZ_3	P_2-T_1	D_1	PZ_1	PZ_2
	T-B[b]	S-Kh					N-M	G–A	G–T	CARS	traps	A–S	A–S	V
Li	8.1	9.5	14.6	32.4	23.5	20.6	27	17.2	16.3	20.2	9	27	22.6	29.19
Be	2.2	2.1	3.3	3.7	3.5	2.6	2.1	1.2	1.5	1.6	1.3	1.4	3	1.5
Sc	16	16	17	14	16	18	5	7	11	8	34	39	26	30
Ti	13928	12913	10137	9532	9835	11552	10966	9816	7795	9526	9712	15386	16533	17238
P	2663	3012	4169	5589	4879	3515	3197	2471	2333	2667	1300	1855	2381	2395
Cr	150	171	103	74	88	78	107	115	96	106	150	58	48	97
Co	45	40	33	29	31	29	34	32	24	30	40	43	38	40
Ni	119	92	67	50	58	44	59	69	60	63	100	40	51	51
Cu	37	31	43	37	40	25	30			30	85	55	62	176
Zn	121	122	133	139	136	111	91			91	100	377	311	38
Ga	22	22	20	29	25	20	19	15	15	16		23	27	22
Rb	21	30	34	55	44	36	41	29	23	31	28	14	23	33
Sr	731	857	1106	1415	1260	762	859	660	612	710	360	304	518	476
Y	20	18	25	24	25	33	29	25	20	24	27	54	41	34
Zr	201	218	228	299	263	246	236	235	160	210	205	271	303	273
Nb	45	45	37	30	33	15	15	17	9	14	16	8	24	40
Cs	0.2	0.5	1.1	1.7	1.4	1.4	3.9	2.2	1.5	2.5		5.5	0.3	0.4
K	15600	22487	17679	27134	22407	17959	15525	14364	14719	14869	11954	6353	11827	25596
Ba	354	593	1034	1360	1197	769	958	694	491	715	455	197	531	691
La	26.3	30.9	55.7	68.1	61.9	35.7	29.9	20.8	18.9	23.2	22	13.8	30.6	50.2
Ce	54.3	63.5	110.2	134.2	122.2	81.1	67.5	43	42.9	51.1	49	36.7	70.4	99.9
Pr	6.8	7.8	14.3	16.2	15.2	10.4	8.7	4.8	4.9	6.1	6.5	5.3	9.4	11.6
Nd	28.6	34.6	50.2	60.9	55.5	42.6	38.1	23.8	24.2	28.7	25.1	26.5	39.3	45.4
Sm	6.3	8	9.2	10.2	9.7	8.5	7.9	5.8	5.3	6.3	5.8	7.3	9.7	9.1
Eu	2	2.2	2.7	2.8	2.7	2.3	2.4	1.7	1.6	1.9	1.7	2.5	2.9	2.8
Gd	6	6.1	7.5	8	7.8	7.8	6.2	5.4	4.1	5.2	5.7	9.1	9.1	8.4
Tb	0.9	0.8	1	1	1	1.2	1	0.9	0.7	0.9	0.9	1.6 9.1 2.1 5.7 0.9	1.4	1.3
Dv	4.4	3.8	5.1	4.8	5	6.4	5.2	4.8	3.6	4.5^	6.1	9.1	7.5 1.5 3.9 0.6	6.6
Ho	0.8	0.7	0.9	0.8	0.9	1.3	1	0.9	0.7	0.9	1.1	2.1	1.5	1.3
Er	1.9	1.7	2A r	2.2	2.3	3.4	2.9	2.6	2	2.5	3.2	5.7 0.9	3.9	3.3
Tm	0.3	0.2	0.3	0.3	0.3	0.5	0.4	0.4	0.3	0.4	0.4	0.9	0.6	0.5
Yb	1.3	1.2	2	1.8	1.9	3	2.5	2.7	2.2	2.5	2.8	5	3.8	2.9
Lu	0.2	0.2	0.3	0.3	0.3	0.5	0.4	0.4	0.3	0.4	0.4	0.8	0.5	0.4
Hf	4.4	4.6	5.7	7.1	6.4	5.9	4.3	4.9	3.8	4.3	4	5.8	6.9	6.5
Ta	2.4	2.4	1.9	1.3	1.6	од	0.5	0.6^	0.5	0.5		0.5	1.5	2
Pb	2.5	4.2	10.3	15.8	13	10.3	8.9	9.7	6.1	8.2	6.4	8.8	37.7	4.4
Th	2.6	4.3	3.5	4.31	3.9	3.1	1.7	2	1.9	1.9	2.8	1.2	4.6	5.1 1.1
U	0.7	1.2	1.3	1.2	1.3	1	0.7	0.6	0.7	0.7	0.8	0.6	1.2	1.1
La/Yb	1.1	1.51	1.62	2.2	1.89	0.7	0.7	0.44	0.5	0.55	0.46	0.16	0.47	1

[a] Age groups.
[b] Magmatic areas and zones: S-B — Trans-Baikal, S-Kh — South-Khangai, N-M — North Mongolian, G–A — Gobi-Altay, G–T — Gobi–Tien-Shan, CARS — Central Asian Rift System as a whole, traps — Siberian trap province, A–S — Altay–Sayan, V — Viluy.

magma formation (Zindler and Hart, 1986). A model of interactions between the hot mantle plume and different sources of magma is illustrated in Fig. 12.

4. Paleogeographic reconstructions of the Siberian continent in the Phanerozoic eon using paleomagnetic data and hot spot traces

After Rodinia's breakup the Siberian continent moved within the perimeter of the Pan-Rodinian Ocean. A new supercontinent Pangea began to form. Formation of a new so-called Pangean superplume under the future supercontinent led to the formation of an antipodal Paleo-Pacific plume in the open oceanic area (Larson, 1991; Li and Zhong, 2009). We suggest that the Siberian continent moved above the future Pangean (present day African) superplume in the Phanerozoic eon. In Li and Zhong (2009) it is estimated that the Pangean superplume started to interact with the lithosphere 250 Ma and lasted at least to 200 Ma, and the Rodinian superplume started around 850 Ma and lasted at least until 600 Ma. Maruyama (1994) and Torsvik et al. (2008b) speculated that the superplume lifetime could be longer. Continuing intraplate magmatic activity registered in Siberian LIPs demonstrates that Siberia was situated in the boundaries of the LLSVP at least since the Ordovician to Cretaceous eras. It suggests that hot spots related to the hot mantle material upwelling under Siberia are linked to the future Pangean land mass and that the later African superplume existed at least 490–470 Ma.

We chose Iceland as a reference point to define a modern position of the African LLSVP northern border. It has been demonstrated that hot spots do not occupy stable positions relative to each other during long time intervals (Norton, 2000; Koppers et al., 2001; Tarduno et al., 2003; Tarduno, 2008). Other reports indicate that the Icelandic hot

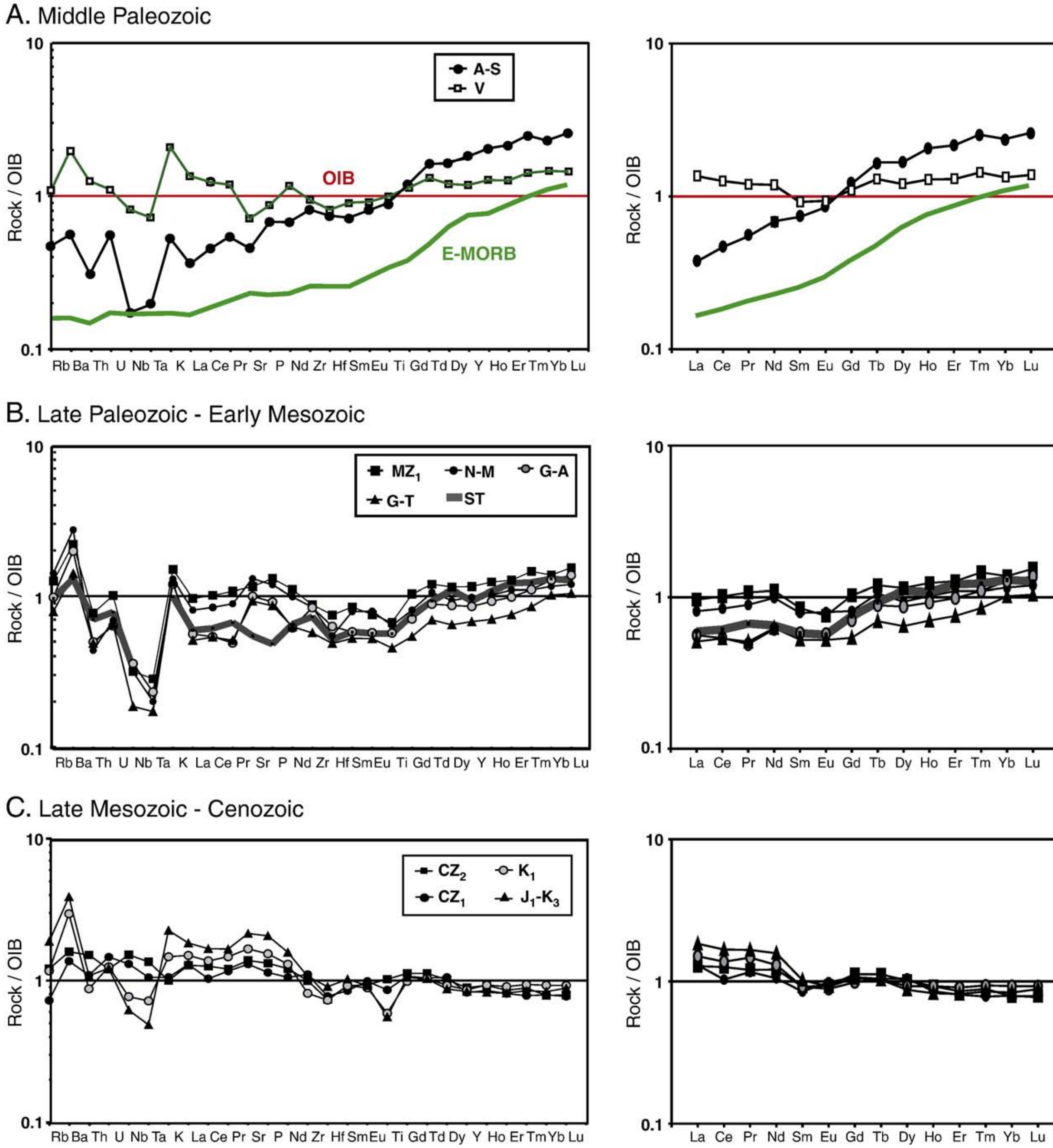

Fig. 10. Spidergrams of distribution of incompatible and rare-earth elements in average compositions of basic rocks of different age occurring within the intraplate areas of the North Asia (modified from Yarmolyuk et al., 2000, 2003a). A — Middle Paleozoic: A–S — Altay–Sayan area, V — Viluy area; E-MORB — enriched basalt of the middle-oceanic ridges. B — Late Paleozoic–Early Mesozoic: MZ_1 — Early Mesozoic Associations of Central Asia, N-M — North Mongolian area, G–A — Gobi–Altay Area, G–T — Gobi–Tyan-Shan area, ST — Late Permian–Early Triassic traps of the Siberian platform (Medvedev et al., 2003; Almukhamedov et al., 2004). C — Late Mesozoic–Cenozoic: J_3-K_1 — Late Jurassic-early Cretaceous, K_2 — Late Cretaceous, CZ_1 — Early Cenozoic, CZ_2 — Late Cenozoic.

spot could have been relatively fixed for at least 150 Myr (Forsyth et al., 1986; Lawver and Müller, 1994; Lundin and Doré 2005) or even 250 Myr (Lawver et al., 2002). Other investigators have proposed a connection between the continuing Icelandic magmatic activity and Siberian trap formation (Kharin, 2000; Lawver et al., 2002; Chernysheva et al., 2005) and this connection is a starting point for our paleogeographic reconstructions. We suggest a relative longevity of the African LLSVP considering that (1) the Skagerrak-centered LIP has been a stable source of magmatism since 300 Ma (Torsvik et al., 2008b) and (2) our review demonstrates that the intraplate magmatism under Siberia has persisted at least since the Ordovician era.

4.1. Siberian continent paleoposition above the Icelandic hot spot 250 Ma

Reconstructions of the Siberian continent during the Phanerozoic era can help us evaluate the nature of intraplate magmatism. Paleomagnetic reconstructions provide only paleolatitude and relative rotation information. Morgan (1972) demonstrated that the steadiness of hot spots could persist during one hundred million years. Courtillot et al. (2003) and Tarduno (2008) argued about different aspects of the relative mobility of hot spots. Davaille et al. (2005) showed that the African superplume initiated 10 trap events, 7 of them related to continental breakup in the last 260 Myr. Several of

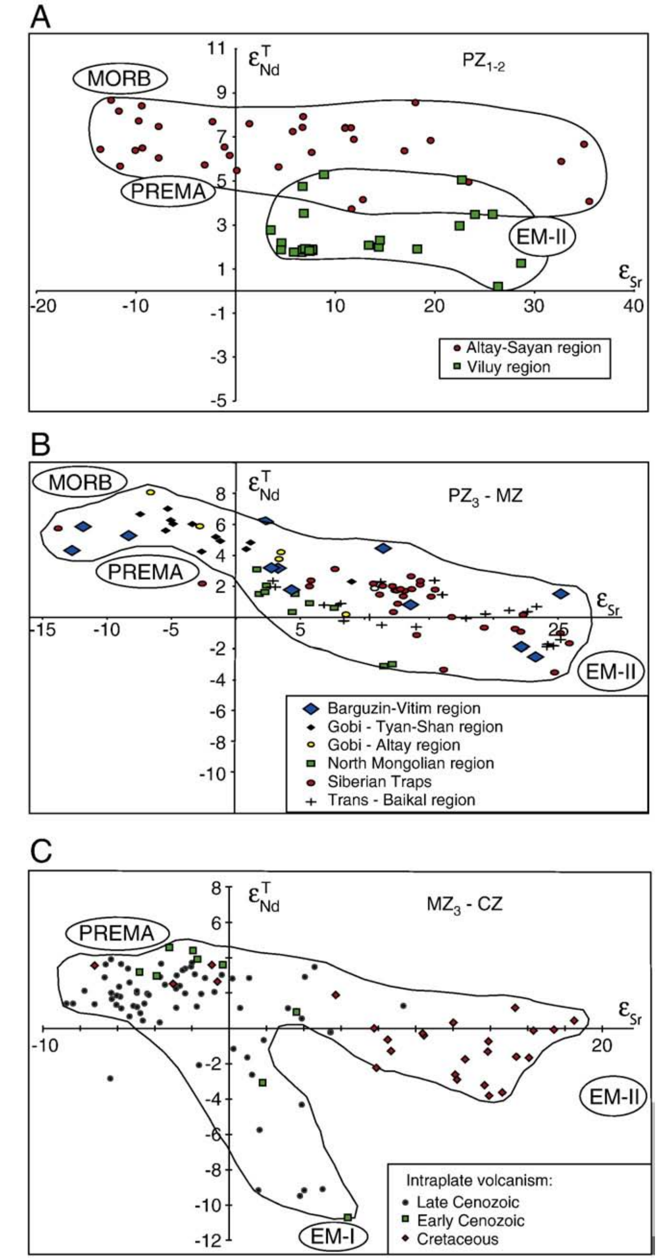

Fig. 11. Variations of Nd (ε^{T}_{Nd}) and Sr (ε^{T}_{Sr}) isotope compositions in basic rocks of intraplate areas of Northern Eurasia (modified from Yarmolyuk et al., 2000, 2003a,b).

these past events are spatially correlated with present day seismic anomalies and/or upwellings with the superswell centered on the western edge of present day South Africa. Tarduno (2008) reviewed the available data that demonstrate that hot spot mobility is affected by convection within the mantle. The hot spots are, however, still attached to the same plume base at the core–mantle boundary.

Torsvik et al. (2008b) demonstrated that the African LLSVP existed at the same spot for at least 300 Myr with the plumes/hot spots always being generated from its margins and almost never from the center. Some hot spots can change the position of their tails while the tails are attached to the same steady base; they also may appear and disappear during long time intervals. The position of plumes that feed large igneous provinces could be sometimes described as instabilities that grow and vanish with time constants of a couple of hundred million years and a critical size of some thousand kilometers. It poses some uncertainties into our attempt to estimate absolute position of Siberia in Paleozoic. Following these findings we further rely on the virtual steadiness of the African LLSVP during the extended geological time interval to perform absolute reconstructions of the Siberian continent paleoposition. The geological data reviewed in Section 2 support our assumption that Siberia moved above a number of hot spots of the African LLSVP during the Phanerozoic eon.

The key point in our paleoreconstructions is the Permo-Triassic magmatism (~250 Ma). The Siberian traps and West Siberian rift system volcanites were formed during this time period. Most likely the same gigantic plume, the so-called superplume, was responsible for both magmatic events. This huge plume stimulated incredible volcanic eruptions during a relatively short geological time period. Initially, Dobretsov (1997) and Yarmolyuk et al. (2000) suggested that two independent plumes were responsible for the Siberian traps and the West Siberian rift volcanites. Recent studies demonstrated that these traps and volcanites have the same age and composition (Almukhamedov et al., 2004; Reichow et al., 2005; Reichow et al., 2009); therefore, we consider that it was a single superplume. The superplume likely formed two large branches on the top of the plume head that were responsible for the simultaneous magmatic events. The superplume existed before and after 250 Ma and was responsible for a set of other Late Paleozoic–Early Mesozoic volcanic events on the Siberian continent and in adjacent areas.

To match the Icelandic superplume with Siberian magmatisms of different ages we assessed the paleogeographic position of the Siberian continent during the Phanerozoic eon. Czamanske et al. (1998) argued that for the Siberian traps there is no obvious succeeding plume track leading to a presently active hot spot, unlike many other flood basalt provinces. Kharin (2000) and Lawver et al. (2002) proposed that Siberian trap formation at 250 Ma was connected to the Iceland hot spot. They summarized absolute ages for various volcanic areas between present day Siberian traps and Iceland. Based on migration of magmatism and changes of the magmatic locality ages the locus of Permo-Triassic trap magmatism migrated northward to what is now the Taimyr Peninsula, and thence onto areas adjacent to Siberia and the Barents and Karsk seas in the Early Triassic period following the main period of continental flood basalt eruption (Saunders et al., 2005). Volcanic rocks of the Franz Josef Islands indicate enduring magmatic activity in the Late Triassic–Early Jurassic period. The Icelandic hot plume trace is observed in the North Atlantic plateaus and islands as well as in Greenland during the Late Mesozoic and Cenozoic eras and was responsible for the North Atlantic opening (Torsvik et al., 2001; Lundin and Doré, 2005). The Icelandic hot plume drastically shrunk in the Cenozoic era and at the present time it operates as a primary hot spot under Iceland. Chernysheva et al. (2005) summarized geochemical data from Mesozoic basalts were studied in an area stretching from eastern Siberia and the south-eastern part of the Kara Sea to Franz Josef Islands and the Svalbald Archipelago in the Barents Sea and the Canadian Arctic Archipelago. They demonstrated that geochemical composition of the basalts is related between different areas and the genesis of these basalts is more likely linked to the activity of the current Icelandic mantle plume. Fig. 13 summarizes the published data reviewed in this study on Icelandic hot spot migration during the last 250 Myr.

Fig. 14 illustrates variations in isotopic composition in the Icelandic volcanites (Condomines et al., 1983; Mertz et al., 1991), the West Siberian rift volcanites (Dril et al., 2004), and the Siberian traps (Sharma et al., 1992; Lightfoot et al., 1993; Wooden et al., 1993). The depleted mantle and EM-II mantle served as a source for both the West Siberian rift volcanites and Siberian traps. That suggests that mantle depletion played a progressively increasing role during evolution of the Icelandic plume located under the Central Asian part of the Siberian continent (i.e., the southern part of the present day coordinates). Composition of the mantle source basalts of Central Asia shifted toward the depleted mantle from Late Paleozoic–Mesozoic to Cenozoic eras. High Nb/Sr ratio basalts from south-

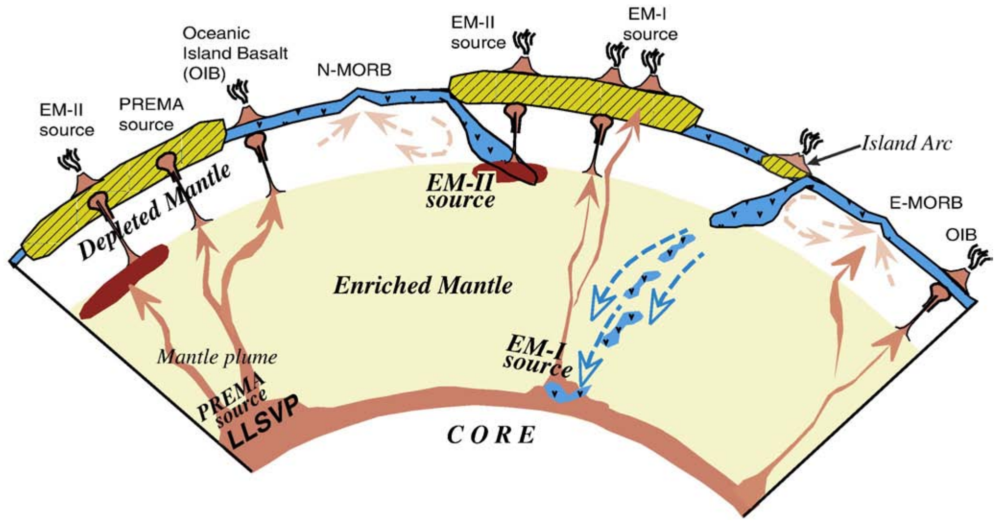

Fig. 12. Characteristic model of interaction of a hot mantle plume and a continent. Different sources of the mantle magma are indicated.

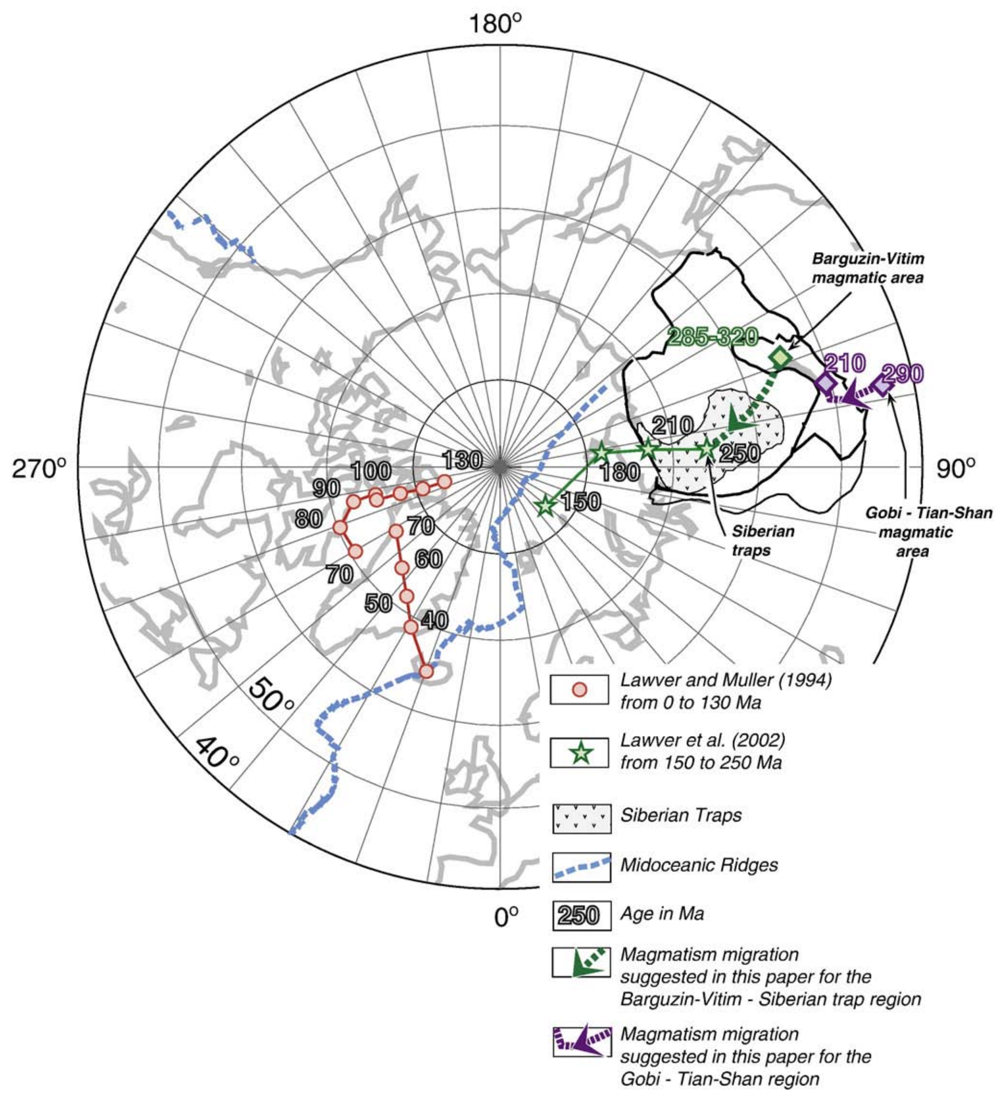

Fig. 13. Scheme of tracing of the Iceland hot spot in the Arctic basin (data from Lawver and Muller, 1994; Lawver et al., 2002). Numbers mean age of the magmatism in Ma. Barguzin–Vitim magmatism (280–310 Ma) is interpreted in this paper as the first indication of the Icelandic hot spot on Siberian platform. Geochemical data and absolute dating enabled us to suggest another Altay–Sayan hot spot which existed at the southern border of the Siberian continent from 290 to 210 Ma.

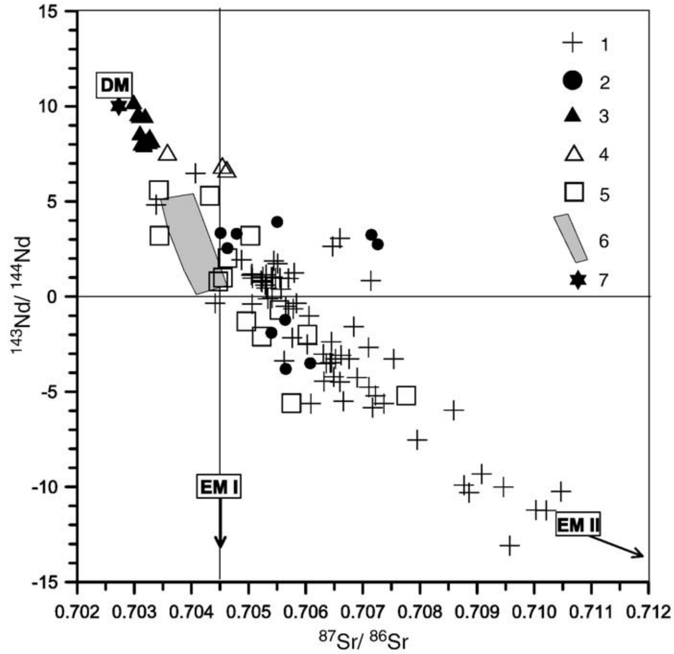

Fig. 14. Change of the isotope composition of volcanic products of the Icelandic plume trace in Siberia for the last 300 Ma. 1 — Eastern Siberian traps, 2 — Western Siberia basalts, 3 — Arctic Ocean basalts, 4 — Eastern Greenland basalts, 5 — basalts of the Vitim plateau, 6 — South-East Greenland basalts, 7 — Icelandic hot spot at present time.

eastern Greenland (upper left part of Fig. 14) are connected to the Icelandic plume (Saunders et al., 1998) and have compositions close to that of the depleted mantle. Basalts of the eastern part of Greenland that erupted around 60–54 Ma (Price et al., 1997) appear in the same upper left section of the graph. Steinberger (2000) invokes plume drift models for a number of hot spots including Iceland because the paleomagnetic data from both Greenland and Britain dictate notably lower paleolatitude than what is expected if the Iceland hot spot magmatism occurred at exactly the same location as it is observed today. Analysis of geochemical data does not contradict the theory that the Icelandic plume was responsible for Siberian trap eruptions if we postulate that the Siberian trap province is located above this plume and accept that the locus of the plume was not exactly at its present day location. Steinberger (2000) demonstrates a continuous westward motion of the Iceland surface projected hot spot for the last 40 Myr. The rate of this hot spot migration is debated. The wander of the Icelandic plume tail on the Earth's surface does not mean that the base of the plume at the CMB migrated considerably. We assume that the base of the Iceland hot plume did not drift much since the Permo-Triassic period and that the Siberian trap region was located above the Icelandic hot spot 250 Ma.

The present day coordinates of the Icelandic hot spot are 65°N and 342°E. Using the paleomagnetic data in Kravchinsky et al. (2002b) we estimate the Permo-Triassic paleolatitude for the Siberian trap location to be 62° ± 7° which is in agreement with Pavlov et al. (2007). This paleolatitude matches the present day position of the Icelandic hot spot (Fig. 15). Torsvik et al. (2008a) analyzed the true polar wonder, which signifies the rotation of the entire Earth with respect to the spin axis, and demonstrated that the African LSSVP appears not to have moved by much over the past 300 Ma. Therefore we consider that Siberia was situated in the framework of the long-term steady African LLSVP because Iceland has been located above the northern edge of the LLSVP at least since the Permo-Triassic period. Signs of extensive intraplate magmatic activity in Siberia are evidence that the Siberian continent has drifted over the hot plume at least from the Early Paleozoic era to the Permo-Triassic period. That allows us to postulate that the paleolongitude position of Siberia has not varied radically although its paleolatitude position has changed considerably. According to Fig. 1, the African LLSVP is located roughly between 330°E and 70°E, putting a limit on the longitudinal displacement of the Siberian longitudinal position prior to the Permo-Triassic period. In our reconstructions we evaluate the paleolatitude and paleolongitude of the point under the Siberian trap province where there was an ancient approximate projection of the Icelandic hot spot ~250 Ma (65°N, 342°E). We refer to this point as the "Siberian trap point" (STP).

In order to constrain the paleoposition of the Siberian platform, we used the apparent polar wander path (APWP) of Siberia from Cocks and Torsvik (2007) for the Paleozoic era, the poles of Kravchinsky et al. (2002b) and Pavlov et al. (2007) at, respectively, ~360 Ma and ~250 Ma, and the APWP of Europe from 240 Ma to the present (Torsvik et al., 2001; Besse and Courtillot, 2002).

We used the Mongol–Okhotsk suture as the south-eastern boundary of the Siberian continent in our reconstructions. It is now

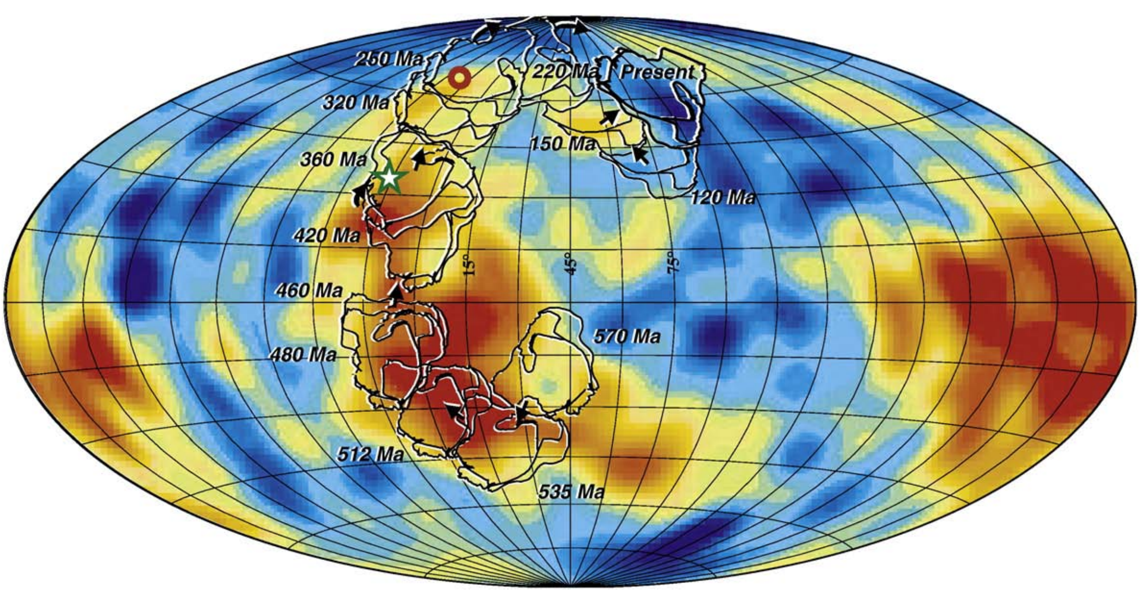

Fig. 15. Reconstruction of the Siberian platform paleoposition from 570 Ma (Hammer–Aitoff projection). The reconstruction assumes that Siberia was above the African LLSVP during the whole Paleozoic.

generally accepted that the Mongol–Okhotsk Ocean, lying between Siberia to the north (in present day coordinates) and Amuria/North China to the south, was closed between the Early Permian period in Eastern Mongolia and the Jurassic period in Trans-Baikalia and the Cretaceous period in the Pacific part of Russia (Kuzmin and Fillipova, 1979; Zonenshain et al., 1991b; Enkin et al., 1992; Kravchinsky et al., 2002c). Following Zonenshain et al. (1991b), the Siberian continent includes Altay–Sayan and Central Asian regions along the south-western border and Taimyr in the north in all Phanerozoic reconstructions (see Figs. 2 and 15).

We start from the Permo-Triassic position of Siberia above the Icelandic mantle plume and analyze the Siberian displacement from ~250 Ma to the present. The absolute dating of Montero et al. (2000) indicates that the closure of the Uralian Ocean started in the south and migrated progressively northwards, between 320 and 250 Ma. After the Uralian Ocean closure we can consider North Eurasia as a single continent; that allows us to use paleomagnetic data from Europe to reconstruct Siberia after 250 Ma. North Eurasia was incorporated into Pangea during that time (Van der Voo, 1993; Torsvik et al., 1996; Smethurst et al., 1998).

The paleomagnetic poles for Laurussia and Gondwana, however, do not agree with the continental reconstruction of Pangea A for the Permian period. A number of explanations are presented in Van der Voo (1993), Rochette and Vandamme (2001); Muttoni et al. (2003), Irving (2004), Van der Voo and Torsvik (2004) and references therein. The largest misfit is observed for 250 Ma. Torsvik et al. (2008a) pointed to uncertainties in the Siberian paleolongitude position and suggested that Siberia 250 Ma was probably not yet fully attached to Europe. In order to resolve the paleomagnetic misfit, Torsvik et al. (2008a) proposed the following options: (1) modify the Pangea A reconstruction, (2) reevaluate the available paleomagnetic poles and erase overprinted directions, (3) eliminate sediment because of an inclination shallowing problem, and (4) allow a significant octupole field contribution in the Permian geomagnetic field. The fourth option could work if the Pangea misfit is caused by inferring a too far northerly position of Gondwana from the geocentric axial dipole hypothesis, and a too far south position for Laurussia (Van der Voo and Torsvik, 2001, 2004). Since the debate about the Pangea reconstructions continues and the nondipole contribution in the Permian period is still controversial, Torsvik et al. (2008a) applied the configuration of Pangea that incorporated only geocentric axial dipole-based APWPs. This configuration allowed the authors to suggest that an independent small size mantle plume was responsible for Siberian trap eruptions (Fig. 16A). The positions of the major mantle plume features were considered to be reasonably steady with time. Such positioning of Siberia contradicts the geochemical and absolute data discussed in previous sections of our manuscript. Our data provides evidence for Icelandic hot spot migration, tracing it to Siberian traps, and is the basis of our hypothesis that Icelandic hot spot migration was responsible for trap eruptions 250 Ma.

Fig. 16B shows a reconstruction of the Siberian platform and other major continents as they might have existed 250 Ma. The figure incorporates both Pangea A reconstruction and shows the Siberian location above the present day Icelandic hot spot utilizing the paleomagnetic latitude and paleomeridian orientation of Pavlov et al. (2007). Kazakhstan, Tarim and Asian terranes situated south of the Mongol–Okhotsk Ocean (Amuria, North China, Indonesia, and South China) are reconstructed after Kravchinsky et al. (2002c), Van der Voo et al. (2006) and references therein. This reconstruction assumes that, although the Uralian Ocean between the Russian platform and Kazakhstan was already at the final stage of closing, North Eurasia was not a consolidated rigid block. The Late Permian final closing of the Uralian Ocean permits a further folding and shortening of Western Siberia as well as its relative rotations. For this option we need to assume that the right-lateral strike–slip fault existed in the Late Permian–Early Triassic period that is presently covered by the West Siberian Sedimentary Basin (proposed dashed line in Fig. 16B). Such a fault, or more likely a set of faults, could correspond to the well documented seismic, magnetic, and gravimetric anomalies of the West Siberian basement under the sediments (Zonenshain et al., 1991b; Aplonov, 1995; Allen et al., 2006). The ages of some of these faults have been estimated as post Early Triassic. The Ural–Altaid right-lateral strike–slip fault system is the largest set of faults. The collision of the Siberian platform and Kazakhstan/Europe was incomplete in the Early Triassic period, and in the central part of West Siberia, small relict basins containing Paleozoic ocean crust were preserved. For a limited period during the Early Mesozoic era the newly formed West Siberian basement began to disintegrate as a result of Permo-Triassic LIP formation and intensive rifting that accelerated spreading of the sea-floor (Aplonov, 1995). The structures generated under these earlier regimes controlled the subsequent passive evolution of West Siberia during Mesozoic and even Cenozoic eras.

In order to incorporate Siberia into a single rigid post-Triassic North Eurasian block, we need to admit a large strike–slip displacement from west to east in the Triassic period (Fig. 16B). The fast uplift of hot magma pushed Siberia from the west and the strike–slip displacement led Siberia to drift away from Icelandic plume upwelling and subsequently to a wider opening of the Arctic Ocean. The size of strike–slip displacement along the strike–slip fault would vary depending on the configuration of West Siberian and Kazakhstan smaller terranes that compose two composite blocks today. Such a configuration cannot be precisely investigated yet because of the insufficient paleomagnetic database from the composite Kazakhstan block for Triassic period. The strike–slip displacement of Siberia would have to lead to Triassic deformations of the basement under the Mesozoic and Cenozoic West Siberian Sedimentary Basin. Other scenarios are possible alternatively or additionally to explain longitudinal difference between Siberia and Kazakhstan. Natal'in and Şengör (2005) suggested that ~2000 km shortening (right-lateral and then left-lateral shearing) occurred in Central Asia when Tarim had been already attached to the Altaids. A large right-lateral strike–slip fault occurred in the West Siberian Sedimentary Basin additionally to the Central Asian shortening, our reconstruction presumes such shortening as a result of a clockwise rotation of Siberia relatively to Laurussia. Such a scenario agrees with the suggestions in Torsvik and Andersen (2002) and Cocks and Torsvik (2007) that substantial Mid- and Late Triassic shortening is required to take place in Western Siberia to adjust available paleomagnetic data from the Taimyr fold and thrust belt as well as to accommodate the westward thrusting of Novaya Zemlya. Such a reconstruction places the Mongolian hot spot (Gobi–Tian-San magmatism) and the Tarim trap Early Permian formation (Li et al., 2008) above the hot mantle plume. We show Tarim attached to Kazakhstan following Gilder et al. (1996) and Van der Voo et al. (2006).

In Fig. 16 we also show Tarim, Amuria, North China, Indonesia, and South China terranes after Enkin et al. (1992), Gilder et al. (1996), Kravchinsky et al. (2002c), Davaille et al. (2005) and Van der Voo et al. (2006) and references therein. South China is placed toward the east to North China in order to match the Pacific hot mantle plume which was most likely responsible for the Emeishan trap eruption. This reconstruction agrees with the commonly accepted model of Enkin et al. (1992). Tarim is placed close to Kazakhastan and Siberia above the hot spot that was responsible for the Early Permian basalt volcanism (Li et al., 2008) which is allowed due to poor paleomagnetic data for this time period (Gilder et al., 1996).

In the Triassic period, the clockwise rotation of Eurasia occurred (Besse and Courtillot, 2002) with the rapid west to east displacement of Siberia if we accept the model in Fig. 16B. A lack of reliable paleomagnetic data from Siberia prevents reconstruction of the exact position of Siberia in Triassic times (Cocks and Torsvik, 2007). The continent was gradually leaving the Icelandic hot spot but remained

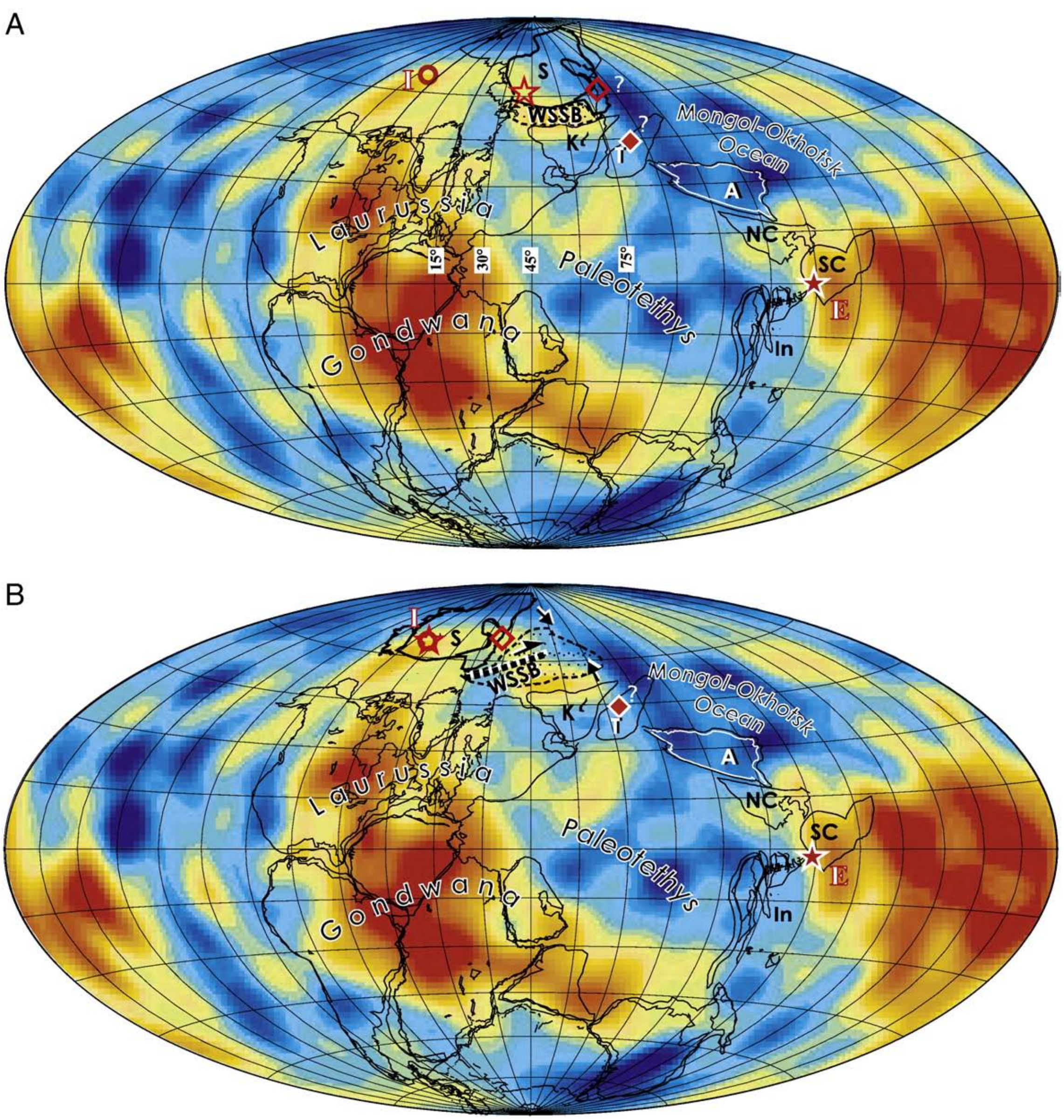

Fig. 16. The reconstruction of the Siberian platform and other major continents for 250 Ma. The continents contours are illustrated with the present day shear wave velocity anomalies near the core–mantle boundary for comparison (see Fig. 1 for explanations and the legend). The position of the major LLSVP features is considered reasonably steady with time (Kuzmin et al., 2003a,b; Burke and Torsvik, 2004; Torsvik et al., 2008c). Circle, open star and open diamond denote present day Icelandic hot spot position, the Siberian trap eruption location, and the Mongolian hot spot (Gobi–Tian-Shan magmatism) correspondently. Three different scenarios for the Siberia are illustrated: A — following the Pangea A reconstruction and placing Siberia above most north-eastern limb of the African hot plume (Torsvik et al., 2008a). B — following the Pangea A reconstruction and placing Siberia above the present day Icelandic hot spot. White arrow illustrates hypothetic clockwise rotation of Siberia (see discussion in the text). Dashed lines indicate the border of North Eurasian continent (Russian platform and Baltic shield, Kazakhstan and Siberia). Letters I, T and E correspond to the Icelandic (open circle), Early Permian Tarim (filled diamond) and Emeishan trap (filled star) hot spots. Emeishan trap is 260 Ma and shown at 250 Ma reconstruction to illustrate it's different mantle plume origin from the Siberian traps. We show the Siberian (S), Kazakhstan (K), Tarim (T), Amuria (A), North China (NC), Indonesia (In) and South China (SC) blocks after Kravchinsky et al. (2002a,b,c) and the references therein. WSSB — West Siberian Sedimentary Basin is shown with the dashed line. The basin was in the initial stage of formation and had different from present day contours. Dashed line indicates the right-lateral strike–slip fault that could exist in the Late Permian–Early Triassic period and covered by the present day West Siberian Sedimentary Basin.

in the hot mantle plume framework until ~220 Ma. The later reconstructions are based on the paleomagnetic data of Besse and Courtillot (2002). These reconstructions assume that Siberia essentially became a part of the rigid North Eurasian continent and that the paleomagnetic data from Europe could be transferred to Siberia for the period from 220 Ma to the present.

The generally eastward movement of Europe during the northern Atlantic Ocean opening determined the course of the Siberian drift. Some time in the Triassic period the Siberian platform passed over the North Pole, continuing to rotate clockwise. The eastward displacement of Siberia was transferred into a northward movement after the Miocene accretion of India and Asia, and Siberia reached its present day position.

4.2. Siberian continent paleoposition during the Paleozoic eon

We reconstruct the Siberian continent paleoposition from the Late Vendian to Permo-Triassic period considering that Siberia was always located in the framework of the African LLSVP between 330°–70°E (see Fig. 1); this allows us to suggest an approximate longitudinal paleoposition of Siberia in our reconstructions (Fig. 15). We show the STP location in all reconstructions and estimate the Siberian paleolatitudes in the Paleozoic eon on the basis of paleomagnetic data. There is no consensus on data for different regions during the Vendian–Early Cambrian period (Kirschvink and Rozanov, 1984; Pisarevsky et al., 1997, 2000, 2001; Kravchinsky et al., 2001; Meert and Van der Voo, 2001; Metelkin et al., 2007), but all authors agree about the nearly equatorial position of the Siberian platform; its modern southern or south-eastern border faces northward (Fig. 15). We performed the Vendian–Early Cambrian reconstruction using data from Kravchinsky et al. (2001) that were validated recently by Metelkin et al. (2007). We chose a paleolongitude of 30°E in order to preserve the relatively short displacement distances of the platform in the framework of the African LLSVP although we recognize that the Paleo-African LLSVP could have different from today geometry and the edge's hot spot positions could fluctuate with time.

The position of Siberia in the southern hemisphere (about 30°S) during the Early Cambrian period (~535 Ma) is accepted following Pisarevsky et al. (1997). Holding the continent inside the African LLSVP we allow a longitude of ~20°E for Siberia. Starting from the Middle Cambrian (505–520 Ma), Siberia moved northward from ~20° in the southern hemisphere to near equatorial latitudes in the Early–Middle Ordovician era (460–480 Ma) (Fig. 15). The velocity of the paleolatitudinal displacement from 512 to 480 Ma reaches 5 cm/year; this agrees with the estimation of Cocks and Torsvik (2007). With possible longitude displacements the velocity would be even higher. A speed of 5 cm/year is relatively high compared with today's continental drift; therefore, we consider that the paleolongitude displacement should be held minimal. For that reason we propose the paleolongitude of Siberia 480 Ma to be similar to the paleolongitude 512 Ma, between ~20°W and 10°E. Thus, the STP 480 Ma would have approximate coordinates of 10°S and 30°E.

Fig. 17 illustrates details of the Siberian drift from Middle–Late Cambrian (510 Ma) to Permo-Triassic (250 Ma). Most of the intraplate magmatic events discussed in this study (Altay–Sayan, Viluy, and Siberian trap) are connected with hot spots that operated during this time interval. According to the paleomagnetic data, Siberia continued a northward displacement between 510 Ma (Middle–Late Cambrian) and 435 Ma (Early Silurian), a time period for which there are reliable paleomagnetic data. The continent moved from 30°S to 10°S between 510 and 480 Ma and from 10°S to 20°N between 480 and 435 Ma with an average latitudinal velocity of ~7.3 cm/year. Cocks and Torsvik (2007) discussed a gradual increase in latitudinal velocity from 1 to 13 cm/year for the same time period which agrees with our average estimation. The average velocity is relatively high, therefore, we assume that the displacement of Siberia was mainly along the meridian. We showed the Early Paleozoic hot spot under the Altay–Sayan terrane that was responsible for intaplate magmatism in the blue color. This hot spot was likely different from the Devonian Altay–Sayan hot spot (red color) that formed Altay–Sayan large igneous province. Intraplate magmatic activity for almost whole Silurian period is not known in Siberia and its surrounding. Most likely such activity was temporary terminated or the Altay–Sayan terrane left the Early Palozoic hot spot. There are only two reliable paleomagnetic poles for the Early Silurian period (Rodionov et al., 1982; Torsvik et al., 1995), then a large data gap endures until the Late Devonian where only one set of poles satisfies the present day quality requirements (Kravchinsky et al., 2002b). We construct two intermediate positions at 400 and 380 Ma assuming that the Viluy rift opening and magmatism must be associated with the same hot spot throughout 400–340 Ma. That means the latitude and longitude of the hot spot was a fixed point situated beneath the Viluy rift system. According to paleomagnetic data, Siberia rotated clockwise between the Early Silurian and Late Devonian periods (the angle of rotation was about 30°). Following Kuzmin et al. (2003a,b), we propose that Siberia preserved both latitude and longitude paleopositions above the Viluy hot spot during this time (Fig. 17). We also follow Torsvik et al. (2008c) who placed Siberia over present day Morocco, above the African LLSVP 360 Ma (Fig. 18). This places the Altay–Sayan rift above the hot mantle plume. In our reconstruction, the close proximity of Laurussia allows the Uralian Ocean to exist between two continents, and the position of the Russian platform above the African LLSVP allocates the Pripyat–Dniepr–Donets and Kontogero rifts described in Kusznir et al. (1996) and Wilson and Lyashkevich (1996). We follow published global reconstructions (McElhinny et al., 2003; Scotese, 2004; Torsvik et al., 2008c) to determine the positions of Laurussia and Gondwana. Unfortunately, the Late Devonian palaeomagnetic record is poor for both of these large terranes. For example, there are no reliable palaeomagnetic data for Laurussia between 396 and 337 Ma. Our 360 Ma reconstruction of Laurussia is thus based on

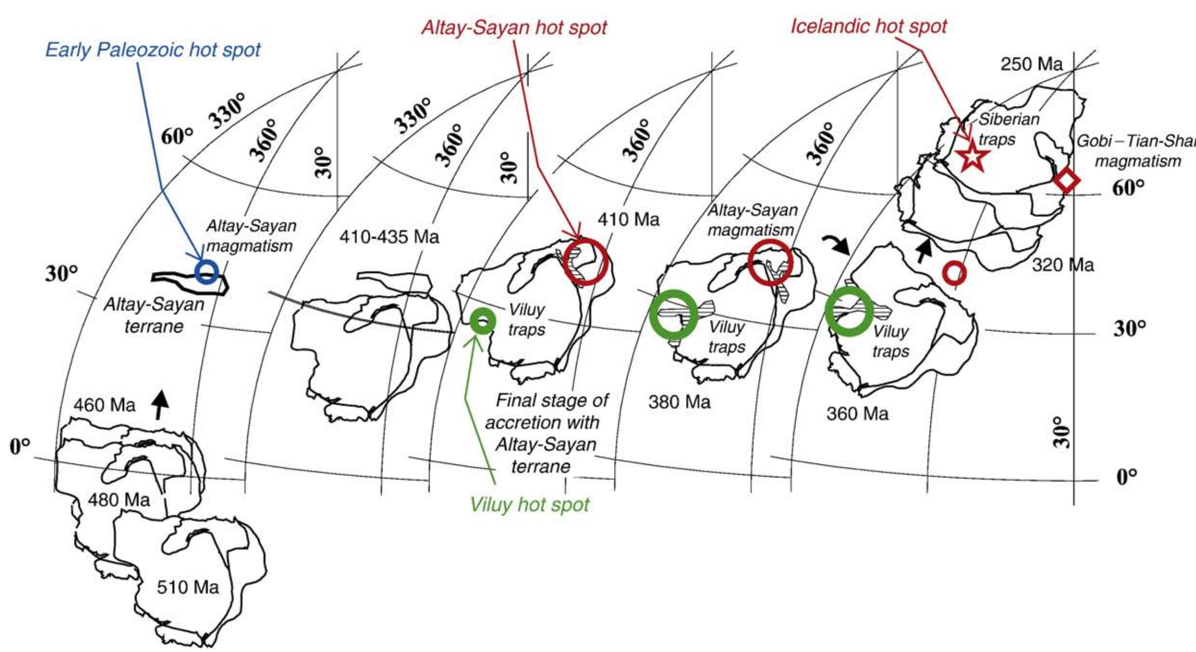

Fig. 17. Details of the reconstruction of the Siberian platform paleoposition in Paleozoic when Siberian platform drifted over the Altay–Sayan and Viluy hot spots which were situated in the framework of the African hot mantle plume. See discussion in the text. Siberia reached the Icelandic and Mongolian hot spots by Late Carboniferous–Early Permian.

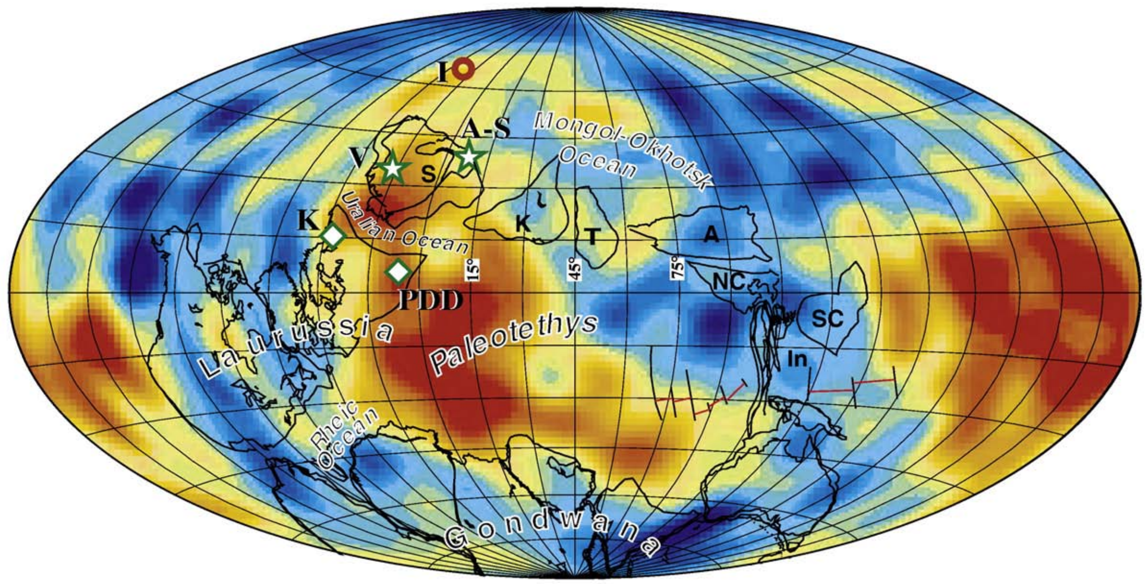

Fig. 18. The reconstruction of the Siberian platform and other major continents for 360 Ma. The continent contours are illustrated with the present day shear wave velocity anomalies near the core–mantle boundary (see Fig. 1 for explanations and the legend). The position of the major mantle plume features is considered reasonably steady with time (Kuzmin et al., 2003a,b; Burke and Torsvik, 2004; Torsvik et al., 2008c). Letter I corresponds to the Icelandic (open circle) hot spot. Stars indicate other hotspots responsible for the intraplate magmatism on Siberian platform in the Viluy (V) and Altay–Sayan (A–S) rift; diamonds indicate the intraplate magmatism on Russian platform in the Pripyat–Dniepr–Donets (PDD) and Kontogero (K) rifts (see Kravchinsky et al. (2002b,c) for some discussion and references). We show the Siberian (S), Kazakhstan (K), Tarim (T), Amuria (A), North China (NC), Indonesia (In) and South China (SC) blocks after Huang et al. (2001), Kravchinsky et al. (2002b,c) and the references therein.

profound interpolation and we have placed Laurussia west of Siberia and far away from the African LLSVP in order to keep the Uralian Ocean open. During Devonian times, Laurussia moved northward and we placed Laurussia at slightly more eastern longitudes at 360 Ma compared to Torsvik et al. (2008c). Gondwana was moved eastward to avoid overlap with southwest Laurussia. Laurussia was placed closer to the African LLSVP to slightly reduce the distance to the future location of the Skagerrak Centered LIP described by Torsvik et al. (2008b) and to decrease the speed of continental drift toward the LIP.

Another gap in reliable paleomagnetic data for Siberia exists between 360 and 275 Ma. There is only one pole for the Early Permian era (275 Ma) (Pisarevsky et al., 2006); nevertheless the paleomagnetic pole 250 Ma is determined very precisely on the basis of a number of reliable poles (Pavlov et al., 2007). Based on available paleomagnetic data, the rapid northern migration of Siberia (40° of south-north displacement over 110 Myr) was associated with an ~60° clockwise rotation between 360 and 250 Ma (Fig. 17). The average velocity of latitudinal displacement for this time period was about 4 cm/year which approaches present day continental drift velocities and agrees in general with the estimate of Cocks and Torsvik (2007). Since a velocity higher than 4 cm/year is not typical of present day continental drift, we consider a large longitudinal displacement that could augment the velocity as doubtful. Siberia moved mostly along the meridian with a simultaneous clockwise rotation to its Permo-Triassic position above the Icelandic hot spot. If the Icelandic hot spot was situated under Siberia 320–285 Ma as we suggest, i.e., before the Siberian trap eruptions, we need to accept that Siberia was at high latitudes (~60°) at the time of the Barguzin–Vitim magmatic event (see the reconstruction for 320 Ma in Fig. 17).

4.3. Hot spots and paleoreconstructions of the Siberian continent

Locating the STP above the Icelandic hot spot at 250 Ma enabled us to determine geographic coordinates of other hot spots that were responsible for intraplate magmatism in Siberia from the Late Vendian period to the present time. We have discussed the stable position of the Viluy rift ~400–340 Ma (Fig. 17). The paleogeographic position of the Viluy hot spot was evaluated using the reference position of the Icelandic hot spot applying a paleomagnetically determined latitude and holding Siberia in the African LLSVP in terms of longitude (see the discussion above). The Viluy hot spot may have existed before 400 Ma, but it was not overlapped by the Siberian continent until ~400 Ma. According to the paleomagnetic data, the Siberian latitude position did not change much from 435 to 360 Ma (~6° ± 15°), however, the clockwise rotation was notable (30° ± 15°) (Fig. 17).

The Altay–Sayan magmatic area is another hot spot that was active during approximately the same time as the Viluy hot spot (from 408 to 390 Ma). Zonenshain et al. (1991a,b) indicated that this area could have been separate from the Siberian terrane during Ordovician and Silurian periods, and its accretion to Siberia occurred only in Late Silurian–Early Devonian times. The magma formation in the Altay–Sayan area began in the Ordovician–Silurian period in the ocean above the hot spot, some distance from Siberia (Fig. 17).

Maximum eruptions occurred 430–390 Ma when Altay–Sayan accreted to Siberia (Zonenshain et al., 1991a,b). The terrane was located in the margin of Siberia, still holding its position above the hot spot (Fig. 17). In the Late Silurian–Early Devonian period, Siberia started its clockwise rotation without considerable latitudinal displacement and moved onto the Viluy hot spot. The Altay–Sayan area was still located above the Altay–Sayan hot spot, but followed the rotations of the Siberian continent (Fig. 17). Considering the Viluy hot spot as a stable permanent point, we estimate the coordinates of Viluy and Altay–Sayan hot spots (Viluy: ~35° ± 15°N and ~340°E; Altay–Sayan: ~40° ± 15°N and ~360°E).

Siberia continued a clockwise rotation in the Late Devonian–Early Carboniferous period holding the same stable position above the Viluy hot spot. We do not have magmatic event evidence for younger traces of Altay–Sayan hot spot magmatism in the Siberian continent;

therefore we consider that the Altay–Sayan area, being a margin of the Siberian continent, drifted away from the Altay–Sayan hot spot as the result of the continuous rotation (Fig. 17).

In the Early Permian period (275 Ma), Siberia was possibly situated at almost the same latitude as in the Permo-Triassic (Pisarevsky et al., 2006). Such a high latitude position means that Siberia moved northward and left the Viluy hot spot in the Early Carboniferous period. A sharp reduction of magmatism in the Viluy area at the end of the Frasnian–Famennian period supports this conclusion. At the same time, the age of Barguzin–Vitim magmatism (320–285 Ma) suggests that the Siberian continent moved onto the Icelandic hot spot by the Late Carboniferous period. In this case Siberia would have had to displace from ~30° to ~60°N during 40 Myr at an average velocity of ~11 cm/yr. This velocity is very high, but possible if the continent moved along the meridian only. The similarity of basalt composition and isotopic data from Barguzin–Vitim basalts and Permo-Triassic traps (see Fig. 11) allows us to locate the Barguzin–Vitim area above the Icelandic hot spot prior to Siberian trap eruption. Numerous paleomagnetic data for Permo-Triassic and Viluy traps (Kravchinsky et al., 2002b; Pavlov et al., 2007) suggest a ~60° clockwise rotation between Late Devonian–Early Carboniferous and Permo-Triassic periods. The main rotation most likely occurred in the interval between Barguzin–Vitim magmatic activity and the Siberian trap eruption because in order to place the Barguzin–Vitim area on the Icelandic hot spot we are required to move the continent with negligible rotation from Late Devonian–Early Carboniferous to Late Carboniferous periods (Fig. 17, reconstruction for ~320 Ma). Therefore, most of the rotation had to occur later, ~300 to 250 Ma. The intraplate magmatism trace migrated from the Barguzin–Vitim area to the Siberian trap area as a result of this rotation, with a slight paleolatitude displacement toward the north (Figs. 13 and 17). The Siberian trap area was located above the hot spot 250 Ma.

Another large magmatic event along the southern border of the present day Siberian platform in Gobi–Tian-Shan (310–285 Ma) that occurred simultaneously with the Barguzin–Vitim magmatism enables us to propose the existence of another hot spot (Mongolian hot spot) during the same time (see Figs. 16 and 17). Ruzhentsev et al. (1989) suggested that the Gobi–Tian-Shan area could be a separate terrane during this time. Later, 265–240 Ma, Siberia accreted with the Gobi–Tian-Shan terrane and overlapped the Mongolian hot spot (Fig. 7). Continued displacement and clockwise rotation of Siberia in the Late Mesozoic era led to the migration of magmatism above the Mongolian hot spot toward the east-northeast in present day coordinates (see Fig. 13). Yarmolyuk et al. (2000) suggested that magmatism migrated from Gobi–Tian-Shan (290 ± 10 Ma) through Mongolia (255 ± 10 Ma) to Trans-Baikalia (210 ± 15 Ma). Fig. 13 illustrates the positions of the Barguzin–Vitim magmatic area above the Icelandic hot spot 285–320 Ma and the Gobi–Tian-Shan magmatic area above the Mongolian hot spot 290–210 Ma. Gobi–Tian-Shan and surrounding areas shown in the Fig. 7 were later folded during closure of the Mongol–Okhotsk Ocean. Other local tectonic rotations and shortening of the Earth's crust took place in the Mesozoic era. Fig. 13 illustrates that Siberia experienced continued anticlockwise rotation above the Icelandic hot spot 320–285 to 180 Ma; our estimates agree with paleomagnetic data for Siberia and Europe (Torsvik et al., 2001; Cocks and Torsvik, 2007).

Kharin (2000) and Lawver et al. (2002) proposed that Siberia moved away from the Icelandic hot spot and the intracontinental magmatism related to the hot spot migrated to the shelf of the north-western margin of Siberia (in present day coordinates) 250 to ~200 Ma. The average latitudinal velocity over the last 250 Myr, as Siberia moved from the Icelandic hot spot to its present day position, is ~1.7 cm/yr which is comparable to the mean present day velocity of tectonic plates in the north Atlantic Ocean (~2.0 cm/yr). Yarmolyuk et al. (2000) concluded that intraplate magmatic activity came to an end 185–160 Ma because intraplate magnatic rocks of this time interval have not been found in Siberia. We consider that the Siberian continent moved away from the Icelandic hot spot rapidly during the initial opening of the Atlantic Ocean.

Late Mesozoic intraplate activity took place in Central Asia and was located at the periphery of the Mongol–Trans-Baikal area that was formed in the Early Mesozoic era. By the end of the Cretaceous era magmatic and tectonic activity was considerably reduced (Table 2) and intraplate magmatic activity appeared again only at the end of the Cenozoic era (younger than 25 Ma).

5. Discussion

We reconstruct the paleogeographic positions during the Phanerozoic eon of Siberia and estimate the latitude and longitude of four hot spots – Icelandic, Altay–Sayan, Viluy, and Mongolian – based on geochemical and paleomagnetic data. We propose that intraplate magmatism in Siberia, documented by magmatic rocks of Mesozoic–Cenozoic age, was caused by other hot spots.

Siberia was likely attached to Laurentia as a part of the supercontinent Rodinia 700 Ma (Meert and Torsvik, 2003). After Rodinia's break up, Siberia was displaced into the hot spot cluster that associates with the African LLSVP. The first sign of mantle plume action near the Siberian continent was observed in the Altay–Sayan area in the Ordovician–Silurian period, but the Altay–Sayan terrane itself accreted to Siberia only in Early Devonian times (Zonenshain et al., 1991b). Volcanic complexes with basalts of the OIB type from oceanic plateaus and mountains indicate hot spot activity in the ocean surrounding Siberia, in Late Riphean ophiolites (Terenteva et al., 2008), and in the Vendian–Early Cambrian hot spots (Almukhamedov et al., 1996; Kovalenko et al., 1996). OIB type basalts from the Dzhida ophiolite zone were situated at 15–20°S according to the paleomagnetic data of Gordienko and Mikhal'tsov (2001). These results confirm the existence of a hot spot near Siberia in the Vendian–Cambrian period. Thus we place the Siberian continent in the African LLSVP frame starting 570 Ma (see Fig. 15).

By the Middle Devonian, Siberia rotated and overlapped the Viluy hot spot, at the same time holding its position above the Altay–Sayan hot spot (Fig. 17). The displacement of Siberia toward the north at the beginning of the Carboniferous age led to collisions with a number of small terranes, volcanic arcs, and islands situated in the Paleoasian Ocean (Zonenshain et al., 1991b). These terranes together formed the South-Mongolian zone of Hercynides in the Siberian margin foldbelt (Mossakovsky et al., 1993). The terranes and oceanic islands of the Hercynides are indicators of hot spot activity above the LLSVP. The Gobi–Tian-Shan magmatic area (herein called the Mongolian hot spot) was formed when the South-Mongolian margin of the Siberian continent overlapped one such hot spot in the Late Carboniferous–Early Permian period. A northward displacement of Siberia led to overlapping of the Icelandic hot spot 320–285 Ma and the formation of the Barguzin–Vitim magmatic area. The Angaro–Vitim batholith in the center of the area is the largest geological feature in the region. Formation of the granitoid batholith occurred when the uplifting magma from the hot spot mixed with material in the Earth's crust. The heat and basaltic melt formed the granitoid batholith. The Early Permian dykes in the area were recently dated and described by Pisarevsky et al. (2006), extending the magmatic duration to ~275 Ma. Shortening took place in the area after accretion of the terranes of the Paleoasian Ocean that formed the South-Mongolian folded zone (Zonenshain et al., 1991b; Mossakovsky et al., 1993). The thickness of the Earth's crust increased as a result of the shortening.

An analogous process of shortening played a key role in formation of the Khangai batholith 265–240 Ma when the Central Asian rifting area moved over the Mongolian hot spot. Coincident closing of the Mongol–Okhotsk Ocean provoked shortening and thickening of the Earth's crust causing formation of a batholith in the center, with rifting structures framing the batholith (Zonenshain et al., 1991b; Yarmolyuk and Kovalenko, 1991, 2003a; Yarmolyuk et al., 2000).

During the Permian period the Siberian continent changed its latitudinal position slightly and continued a clockwise rotation that led to migration of magmatism from the Barguzin–Vitim area to the Siberian trap province. The trace of the hot spot can be monitored by paleomagnetic data from the polymetal ore deposit Ozernoe found in dolerite sills and dykes situated near Ozernoe, a town in the Barguzin–Vitim area (east of Lake Baikal; geographic coordinates 53°N and 112°E) (Kravchinsky, 1989) and from the gold ore deposit Sukhoy Log located between the Barguzin–Vitim area and the Siberian trap province (Bodaibo administrative region; geographic coordinates 58°N and 115°E) (Zhitkov and Kravchinsky, 1982). In both deposits, the Permo-Triassic strong overprint was observed in the Precambrian rocks and Ordovician sediments. The Sukhoy Log deposit is situated between the Barguzin–Vitim area and the Siberian trap province and could indicate the trace of the hot spot's migration.

An incredibly large amount of mantle plume material erupted on the Earth's surface during the Permo-Triassic Siberian trap formation. This suggests that a superplume was responsible for intraplate magmatism in the present day Icelandic hot spot. Siberia moved from the Icelandic hot spot, continuing a clockwise rotation and latitudinal displacement, in the Late Triassic–Early Jurassic period while the magmatism migrated to the Siberian margin shelf toward the northwest in present day coordinates. During the same time, another hot spot magmatic activity (the Mongolian hot spot) migrated from the Khangai area heading for the east-northeast of present day Siberia (in the Khentey area). The area was folded in the Mesozoic era during closing of the Mongol–Okhotsk Ocean, and shortening of the southern margin of the continent during the Amuria–Siberia collision permitted the penetration of India into Asia.

We suppose that the discontinuation of intraplate magmatic activity between 185 and 165 Ma signifies the departure of Siberia from the African LLSVP. In the Late Mesozoic–Early Cenozoic period, intraplate magmatism reappeared in Siberia but was considerably less in volume than before. Magmatic activity increased again during the last 25 Myr, almost to the Early Mesozoic volume (Table 2), although the mantle material composition changed in type from EM-II to EM-I.

Our reconstructions indicate that Siberia interacted with mantle hot spots almost continuously during the Phanerozoic eon. Isotopic and rare element compositions and absolute age data demonstrate that a few hot spots acted simultaneously under Siberia. Timing and space migration of the magmatism suggest that Siberia moved over hot spots associated with the African LLSVP. Courtillot et al. (2003) pointed out that such hot spots could be tails of a large plume containing molten hot material upraised from the core–mantle boundary to the LLSVP. The mantle superplume stems from the CMB, thus the plume's tails are connected with the core–mantle boundary. The plume tails drift at the Earth's surface with velocities ranging from 1 to 6 cm/year (Courtillot et al., 2003) and can endure at least 100 Myr (Campbell, 2007). Zonenshain et al. (1991b) proposed that the hot mantle plume could persist much longer than a single hot spot (at least 200 Myr). Torsvik et al. (2008b) demonstrated that the deep-sourced African LLSVP at the CMB has not moved significantly with respect to the spin axis of the Earth during the past 300 Myr. Siberian long-term intraplate magmatic activity supports the latter idea and allows us to suggest that the African LLSVP could have existed at approximately the same location 500 Ma. We consider that although hot spots and mantle tails migrate and appear on or disappear from the Earth's surface, they reside in the framework of the same LLSVP for very long time. We use the present day location of the African LLSVP as a reference frame to attempt paleogeographic reconstructions of the Siberian continent through the Phanerozoic eon.

The composition of magmatic rocks in the studied areas indicates that three mantle sources participated in formation of the primary mantle melts: moderately depleted mantle (PREMA) and enriched mantle of types EM-I and EM-II (Zindler and Hart, 1986). Mantle melts from EM-I and EM-II mantle types are enriched with the rare elements Sr and Nd. Mixtures of these two magmatic sources determine the geochemical signatures of relicts of the Earth's crust and lithosphere. Evaluation of the isotope composition of Nd and Sm/Nd in intraplate magmatism basalts assists in determining the time span required for the depleted mantle to penetrate and erupt at the Earth's surface. The Sm/Nd ratio in the partially melted magma that infiltrates to the Earth's surface is ~30% less than in the original source. Yarmolyuk et al. (2000) estimated the age of initial formation for EM-II and EM-I mantle magmatic sources to be 1.1–1.5 and 2.3–2.5 Ga, respectively.

Most of the matter in the Earth's lower mantle is of the PREMA type. We demonstrate that the PREMA type was the key source of magmatic material in the Early–Middle Paleozoic era (see Fig. 10) and was the main source of material in the oceanic islands (Fig. 11). Under Siberia, EM-II was mixed with PREMA material in different proportions starting from the Late Paleozoic to the beginning of the Late Cretaceous periods. A sharp reduction in magmatic activity occurred during a shift from EM-II to EM-I material types in the Late Cenozoic era when the Siberian continent moved away from the African LLSVP and toward the colder region located under Eastern Asia today. The EM-I type of material became the primary mantle material in the Late Cenozoic era. The volume of magmatic material sharply increased during this period (Table 2). Courtillot et al. (2003) reported that the cold mantle material of the subduction zones often sank to the core–mantle boundary. We propose that interactions between down-welling cold material and hot materials at the core–mantle boundary provoked an upwelling of mantle material in the Late Cenozoic era (see Fig. 12). EM-I material, common at the core–mantle boundary and in volcanic rocks of the Late Cenozoic era, probably originated from this mantle source.

Hot spot magmatism is responsible for the formation of LIPs in Siberia. The continuous magmatic activity allows us to assume that Siberia was situated in the framework of the African LLSVP at least since the Ordovician period. As discussed above, superplumes could be active for at least 100 Myr. A number of hot spots and plumes corresponding to the African LLSVP started to function about 200 Ma and caused the breakup of Pangea and formation of the Central Atlantic Magmatic Province.

Li and Zhong (2009) discussed the cyclic activity of superplumes. Siberian intracontinental magmatism data allow us to propose the existence of the African LLSVP in the time interval essentially exceeding the periods of superplume hyperactivity exposed in the supercontinental breakup. Possible migration of mantle plume locations at the Earth's surface could cause some imprecision in our reconstructions but overall we consider that the African LLSVP was positioned approximately at the same place as today. Otherwise it is necessary to assume a much larger longitudinal migration of the Siberian continent in the Paleozoic eon, and that would lead to substantial time intervals of migration velocity higher than any known continental drift which we consider unlikely.

Our model illustrates interaction of the African LLSVP with the intraplate magmatism of the Siberian continent. Fig. 19A illustrates the interaction between the Siberian continent and the African LLSVP from Ordovician to Early Carboniferous ages. The Altay–Sayan and Viluy magmatic areas occurred as a result of hot spot activities during this time interval. The plume originated from a PREMA mantle source. Most likely the plume tail was responsible for the volcanic activity in the areas. Subduction slabs were located somewhere aside from the plume and carried the cold material downward. The sinking material formed EM-II type mantle sources at the lower–upper mantle boundary.

Fig. 19B corresponds to the Late Carboniferous–Permian period when the Barguzin–Vitim magmatic area was formed above the Icelandic hot spot. Upwelling hot material from the hot plume

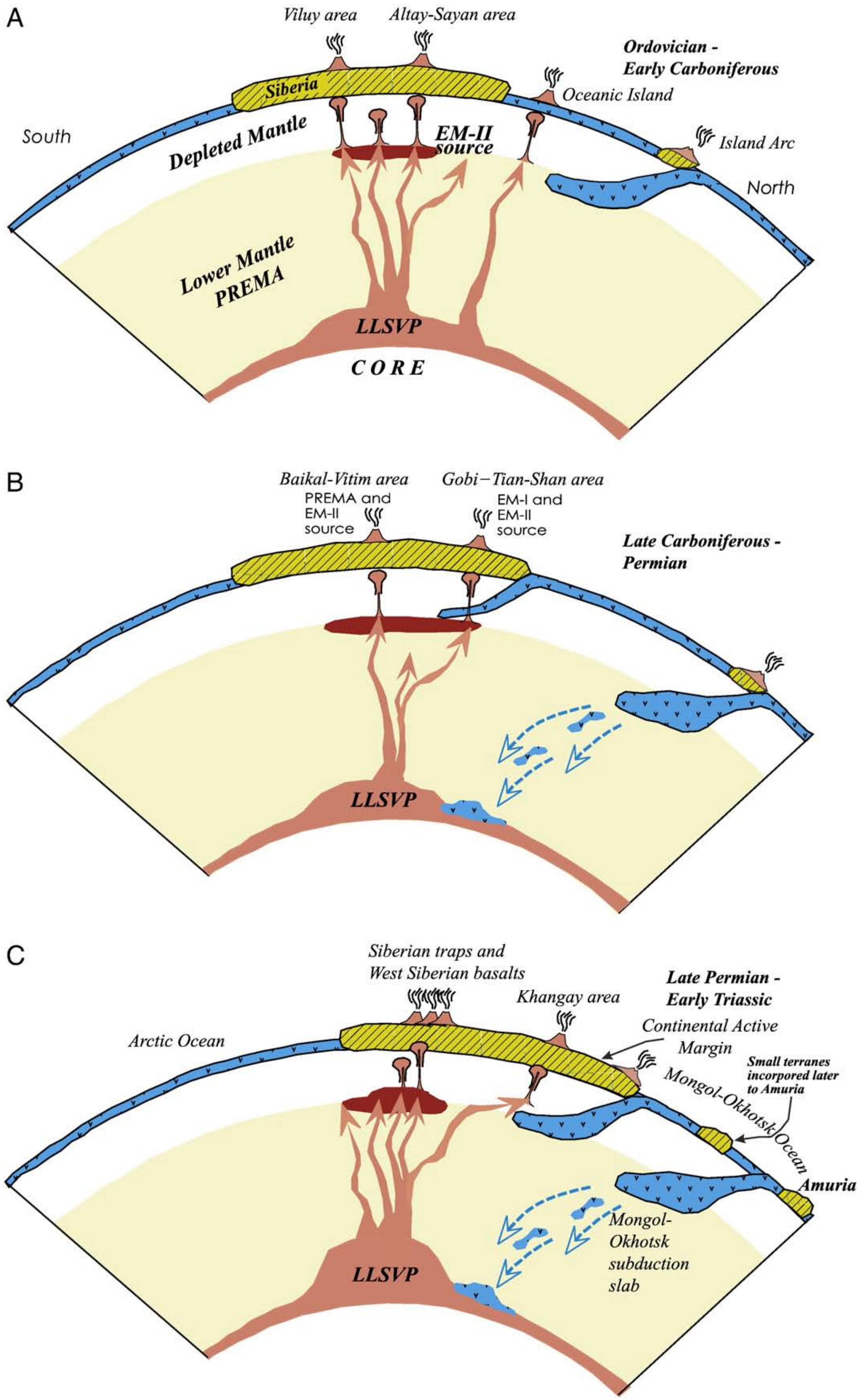

Fig. 19. A model that illustrates the interaction of the African hot mantle plume and the drifting Siberian continent during Phanerozoic. The representation of the hot magma upwelling and downwelling follows Courtillot et al. (2003), Li and Zhong (2009), and Trønnes (2009).

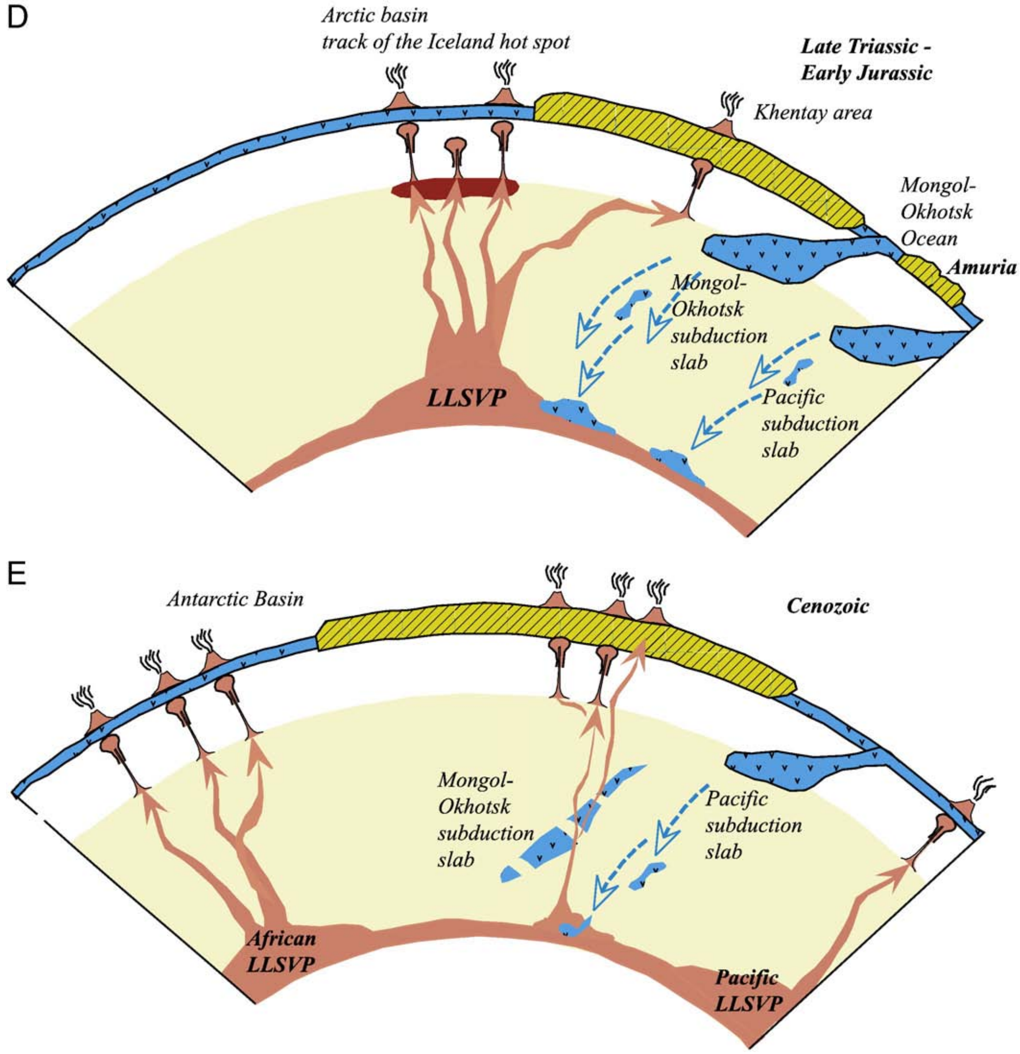

Fig. 19 (*continued*).

captured remains of the cold mantle from the EM-II type source. The mixture of PREMA and EM-II material was the source of material for the primary magma of the Barguzin–Vitim area. Gobi–Tian-Shan magmatism occurred at the northern margin of the Siberian continent (the southern margin in present day coordinates) at about the same time interval. A mixture of EM-I and EM-II materials was the primary source of the volcanic material.

During the Permo-Triassic period, Siberia rotated clockwise and moved over the Icelandic hot spot; magmatic activity migrated to the Siberian trap location. Two gigantic plume tails were responsible for trap eruption and the formation of volcanic rocks in Western Siberia (Fig. 19C). Basaltic material of PREMA and EM-II composition increased dramatically and erupted in the Siberian trap area. We propose that the mantle plume approached the lithosphere capturing the upper mantle. The Central Asian intraplate magmatic area only is shown in the model in Fig. 19C, although the other hot spots could have existed at this time. The Khangai batholith occupied the central part of this area.

Siberia moved away from the plume during the Late Mesozoic era. Magmatic activity migrated from the Khangai area toward the east-northeast (in present day coordinates) into the Khentey batholith area. We consider that the movement of Siberia away from the hot plume was accompanied by capture of material from the upper part of the lower mantle; Siberia “dragged” the plume's tail as the continent moved away from the plume (Fig. 19D). The similarity of basaltic magma composition of the Early Mesozoic era (PREMA and EM-II) and the Late Mesozoic era (dominantly PREMA) confirms that the material originated from the hot plume; i.e., the plume was likely elongated in the direction of Siberian drift. The volume of eruptive material decreased considerably in Cretaceous and Early Cenozoic eras (Table 2). Material from the plume likely diminished as the Siberian continent moved further away from the plume. Van der Voo et al. (1999) demonstrated that the Mesozoic Mongol–Okhotsk subduction plate co-exists with the present day Pacific plate in the mantle underneath Siberia. Therefore we consider that the Mongol–Okhotsk oceanic slab was in charge of the intraplate magmatism in the Late Paleozoic–Mesozoic period. The proposed position of the Mongol–Okhotsk subduction agrees with the reconstruction in Van der Voo et al. (1999).

The present day interaction between Siberia and the cold mantle began in the Late Cenozoic era (Fig. 19E). Downwelling of the cold material penetrated to the core–mantle boundary and initiated the rise of minor columns from the EM-I source. Late Cenozoic intraplate basalts were formed as a result of the upwelling of such material.

6. Conclusions

(1) 1 We review intraplate magmatism features that indicate the Siberian continent was situated in the framework of the African

LLSVP from at least the Early Paleozoic era until the end of the Late Jurassic period.

(2) Volcanic rocks of intraplate magmatic origin observed and dated in Siberia and in subsequently accreted terranes indicate that Siberia was above the African LLSVP from at least 570 Ma. The largest magmatic activity occurred at the Permo-Triassic boundary (~250 Ma). A gigantic volume of basaltic magma (1.5×10^6 km^3) erupted during ~1 Myr indicating superplume upwelling to the lithosphere in the area of the present day Icelandic hot spot.

(3) The location of Siberia in the African LLSVP and long-term interactions of Siberia with persistent hot spots enable us to estimate the paleolatitude and paleolongitude of Siberia during the Paleozoic and Mesozoic eras. Using the long-standing position of the Icelandic hot spot (from at least 250 Ma), we reconstruct the paleopositions of three other hot spots – Altay–Sayan, Viluy, and Mongolian – that played critical roles in the intraplate magmatism in Siberia. Paleomagnetic data were used to reconstruct a Siberian paleolatitude while the Icelandic hot spot's considerably stable position was used to reconstruct an approximate Siberian paleolongitude. The African LLSVP expansion between 330°E and 70°E limits the accuracy of the estimated paleolongitude of Siberia.

(4) Prime magmas from the mantle formed intraplate magmatism areas in different time periods. The magmas originated from three types of the mantle sources: PREMA, EM-II, and EM-I. Magma from the PREMA source formed magmatic areas in Siberia from the Ordovician to the Early Carboniferous period. Magmatic areas from the Late Carboniferous to Early Jurassic times were combinations of EM-II and PREMA materials. The EM-II material type played a larger role during formation of Permo-Triassic traps and West Siberian rift basalts. From the Late Jurassic period to the Early Cenozoic era, PREMA type materials became predominant again. In the Late Cenozoic era, EM-I and PREMA sources dominated in forming magmatic areas in Siberia.

Acknowledgments

The paper benefitted considerably from the comments and suggestions of R. Van der Voo, T.H. Torsvik, and two anonymous reviewers. We thank J.-P. Cogné for supplying the paleomagnetic software PaleoMac-6.2 (Cogné, 2003) that was used to perform the continental paleoreconstructions and Y.J. Gu for helping us to illustrate the deep mantle structure on the basis of the seismic tomography data sets. The work was supported by the Natural Sciences and Engineering Research Council of Canada for V.A.K. and Russian funds for M.I.K. and V.V.Ya. (Russian Fund for Basic Research grants # 08-05-00660 and 09-05-00772, the Scientific School # 3047.2008.5, the Project of the Presidium of Russian Academy of Sciences 16.11, and the Integration Projects of the Presidium of Siberian Branch of Russian Academy of Sciences #13, 37 and 142).

References

Allen, M.B., Anderson, L., Searle, R.C., Buslov, M., 2006. Oblique rift geometry of the West Siberian Basin: tectonic setting for the Siberian flood basalts. Journal of the Geological Society, London 163, 901–904.

Almukhamedov, A.I., Gordienko, I.V., Kuzmin, M.I., Tomurtogoo, O., Tomurhuu, O., 1996. Dzhida zone — fragment of Paleoasian ocean. Geotectonics 30 (4), 25–42 in Russian.

Almukhamedov, A.I., Medvedev, A.Ya., Zolotukhin, V.V., 2004. Compositional evolution of the Permian–Triassic basalts of the Siberian Platform in time and space. Petrology 2 (4), 339–353 in Russian.

Anderson, D.L., 1982. Hotspots, polar wander. Mesozoic convection and the geoid. Nature 297, 391–393.

Aplonov, S.V., 1995. The tectonic evolution of West Siberia: an attempt at a geophysical analysis. Tectonophysics 245, 61–84.

Besse, J., Courtillot, V., 2002. Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr. Journal of Geophysical Research (B) 107 (B11), 1–31. doi:10.1029/2000JB000050.

Burke, K., Torsvik, T.H., 2004. Derivation of large igneous provinces of the past 200 million years from long-term heterogeneities in the deep mantle. Earth and Planetary Science Letters 227, 531–538. doi:10.1016/j.epsl.2004.09.015.

Burke, K., Steinberger, B., Torsvik, T.H., Smethurst, M.A., 2008. Plume generation zones at the margins of large low shear velocity provinces on the core–mantle boundary. Earth and Planetary Science Letters 265 (1–2), 49–60.

Buslov, M.M., Safonova, I.Yu., Watanabe, T., Obut, O., Fujiwara, Y., Iwata, K., Semakov, N.N., Sugai, Y., Smirnova, L.V., Kazansky, A.Yu., 2001. Evolution of the Paleo-Asian Ocean (Altai–Sayan region, Central Asia) and collision of possible Gondwana-derived terranes with the southern marginal part of the Siberian continent. Geosciences Journal 5, 203–224.

Campbell, I.H., 2007. Testing the plume theory. Chemical Geology 241, 153–176.

Campbell, I.H., Kerr, A.C., 2007. The great plume debate: testing the plume theory. Chemical Geology 241 (3–4), 149–152.

Chernysheva, E.A., Kharin, G.S., Stolbov, N.M., 2005. Basaltic magmatism in Arctic seas related to the Mesozoic activity of the Iceland Plume. Petrology 13 (3), 289–304.

Cocks, L.R.M., Torsvik, T.H., 2007. Siberia, the wandering northern terrane, and its changing geography through the Palaeozoic. Earth-Science Reviews 82, 29–74.

Cogné, J.-P., 2003. PaleoMac: a MacintoshTM application for treating paleomagnetic data and making plate reconstructions. Geochem. Geophys. Geosyst. 4 (1), 1007. doi:10.1029/2001GC000227.

Condie, K.C., 2001. Mantle Plumes and their Record in Earth History. Cambridge University Press. 305 pp.

Condie, K.C., 2002. The supercontinent cycle: are there two patterns of cyclicity? Journal of African Earth Sciences 35, 179–183.

Condomines, M., Gronvold, K., Hooker, P.J., Muehlenbachs, K., O'Nions, R.K., Oskarsson, N., Oxburgh, E.R., 1983. Helium, oxygen, strontium and neodymium isotopic relationships in Icelandic volcanics. Earth and Planetary Science Letters 66, 125–136.

Courtillot, V.E., Renne, P.R., 2003. On the ages of flood basalt events. Comptes Rendus Geosciences 335 (1), 113–140.

Courtillot, V., Davaille, A., Besse, J., Stock, J., 2003. Three distinct types of hotspots in the Earth's mantle. Earth and Planetary Science Letters 205 (3–4), 295–308.

Czamanske, G.K., Gurevitch, V., Fedorenko, V., Simonov, O., 1998. Demise of the Siberian plume: palaeogeographic and palaeotectonic reconstruction from the prevolcanic and volcanic record, north-central Siberia. International Geology Review 40, 95–115.

Davaille, A., 1999. Simultaneous generation of hotspots and superswells by convection in a heterogenous planetary mantle. Nature 402 (6763), 756–760.

Davaille, A., Stutzmann, E., Silveira, G., Besse, J., Courtillot, V., 2005. Convective patterns under the Indo-Atlantic "box". Earth and Planetary Science Letters 239, 233–252.

Davies, G.F., Richards, M.A., 1992. Mantle convection. Journal of Geology 100, 151–206.

Davies, G.F., Pribac, F., 1993. Mesozoic seafloor subsidence and the Darwin rise, past and present. In: Pingle, S., et al. (Ed.), The Mesozoic Pacific: Geology, Tectonics, and Volcanism. : Geophys. Mono, 77. AGU, Washington, DC, pp. 39–52.

Dobretsov, N.L., 1997. Permian–Triassic magmatism and sedimentation in Eurasia as a superplume reflection. Doklady Earth Sciences 354 (2), 220–223 in Russian.

Dobretsov, N.L., Vladimirov, A.G., Kruk, N.N., 2005. Permian–triassic magmatism in the Altai–Sayan Fold System as a reflection of the Siberian superplume. Doklady Earth Sciences 400 (1), 40–43.

Dril, S.I., Medvedev, A.Ya., Almukhamedov, A.I., Sandimirova, G.P., Elizarova, M.V., Ronkin, Yu.L., 2004. Sr–Nd isotope systematic of the Permian–Triassic volcanics of the Western Siberia. Geodynamic evolution of the lithosphere of the Central-Asian orogenic belt (from the ocean towards the continent). Proceedings of the Scientific Conference Devoted to the Program of Fundamental Investigations. Institute of the Earth's Crust. SB RAS, Irkutsk, pp. 126–129. in Russian.

Duncan, R.A., Richards, M.A., 1991. Hotspots, mantle plumes, flood basalts, and true polar wander. Review of Geophysics 29 (1), 31–50.

Dziewonski, A.M., 1984. Mapping the lower mantle, determination of lateral heterogeneity up to degree and order 6. Journal of Geophysical Research 89, 5929–5952.

Dziewonski, A.M., Hager, B., O'Connell, R.J., 1977. Large scale heterogeneities in the lower mantle. Journal of Geophysical Research 82, 239–255.

Enkin, R.J., Yang, Z., Chen, Y., Courtillot, V., 1992. Paleomagnetic constraints on the geodynamic history of the major blocks of China from the Permian to the Present. Journal of Geophysical Research 97, 13,953–13,989.

Ernst, R.E., Wingate, M.T.D., Buchan, K.L., Li, Z.X., 2008. Global record of 1600–700Ma Large Igneous Provinces (LIPs): implications for the reconstruction of the proposed Nuna (Columbia) and Rodinia supercontinents. Precambrian Research 160 (1–2), 159–178.

Fedoseev, G.S., 2008. The role of magmatism in age specification of Devonian continental trough deposits: evidence from the Minusa Basin, western Siberia, Russia. Bulletin of Geosciences 83 (4), 473–480.

Forsyth, D.A., Morel, A.L., Huissier, P., Asudeh, I., Green, A.G., 1986. Alpha Ridge and Iceland: products of the same plume. Journal of Geodynamics 6, 196–214.

Fukao, Y., Maruyama, S., Obayashi, M., Inoue, H., 1994. Geological implication of the whole mantle P-wave tomography. The Journal of the Geological Society of Japan 100, 4–23.

Fukao, Y., Obayashi, M., Nakakuki, T., the Deep Slab Project Group, 2009. Stagnant Slab: A Review. Annual Review of Earth and Planetary Sciences 37, 19–46.

Gaiduk, V.V., 1987. Viluy Middle Paleozoic Rift System. Geotectonics 3, 66–76 (in Russian).

Gilder, S., Zhao, X., Coe, R., Meng, Z., Courtillot, V., Besse, J., 1996. Paleomagnetism and tectonics of the southern Tarim basin, northwestern China. Journal of Geophysical Research 101, 22,015–22,031.

Gonnermann, H.M., Jellinek, A.M., Richards, M.A., Manga, M., 2004. Modulation of mantle plumes and heat flow at the core mantle boundary by plate-scale flow: results from laboratory experiments. Earth and Planetary Science Letters 226 (1–2), 53–67.
Gordienko, I.V., Mikhal'tsov, N.E., 2001. Position of Vendian–Early Cambrian ophiolitic and island arc complexes in the Dzhida zone of Caledonides in Paleoasian oceanic structures: interpretation of paleomagnetic data. Doklady Earth Sciences 379A (6), 622–626.
Hager, B.H., Clayton, R.W., Richards, M.A., Comer, A.M., Dziewonski, A.M., 1985. Lower mantle heterogeneity, dynamic topography and the geoid. Nature 313, 541–545 (in Russian).
Hill, R.I., Campbell, I.H., Davies, G.F., Griffiths, R.W., 1992. Mantle plumes and continental tectonics. Science 256 (5054), 186–193.
Hoffman, P.F., 1991. Did the breakout of Laurentia turn Gondwanaland inside-out? Science 252, 1409–1412.
Huang, B.C., Otofuji, Y., Zhu, R.X., Shi, R.P., Wang, Y.C., 2001. Paleomagnetism, of Carboniferous sediments in the Hexi corridor: its origin and tectonic implications. Earth and Planetary Science Letters 194 (1–2), 135–149.
Irving, E., 2004. The case for Pangea B, and the intra-Pangean megashear. In: Channell, J.E.T., et al. (Ed.), Timescales of the Paleomagnetic Field. : Geophys. Monogr., 145. AGU, Washington, D.C., pp. 13–27.
Izokh, A.E., Polyakov, G.V., Mal'kovets, V.G., Shelepaev, R.A., Travin, A.V., Litasov, Y.D., Gibsher, A.A., 2001. The Late Ordovician age of camptonites from the Agardag Complex of southeastern Tuva as an indicator of the plume-related magmatism during collision processes. Doklady Earth Sciences 379 (5), 511–514.
Jellinek, A.M., Manga, M., 2004. Links between long-lived hot spots, mantle plumes, D″, and plate tectonics. Reviews of Geophysics 42 (3).
Kharin, G.S., 2000. Impulses of magmatism of the Icelandic plume. Petrology 8 (2), 115–130 in Russian.
Khain, E.V., Amelin, Yu.V., Izoh, A.E., 1995. Sm–Nd age of the ultrabasic–basic complexes in the subduction zone of the Western Mongolia. Doklady Earth Sciences 341 (6), 791–796 In Russian.
Kirschvink, J.L., Rozanov, A.Yu., 1984. Magnetostratigraphy of lower Cambrian strata from the Siberian Platform: a palaeomagnetic pole and a preliminary polarity time-scale. Geological Magazine 121, 189–203.
Kiselev, A.I., Yarmolyuk, V.V., Nikiphorov, A.V., Egorov, K.N., 2007. Composition and sources of Devonian volcanism in the Vilyui Rift. Doklady Earth Sciences 415 (5), 744–750.
Kiselev, A.I., Yarmolyuk, V.V., Egorov, K.N., Chernyushov, R.A., Nikiphorov, A.V., 2006. Middle Paleozoic basite magmatism of the north-west part of the Viluy Rift: composition, sources, geodynamics. Petrology 6, 660–682.
Koppers, A.A.P., Phipps, M.J., Morgan, J.W., Staudigel, H., 2001. Testing the fixed hot spot hypothesis using $^{40}Al/^{39}Ar$ age progressions along seamount trail. Earth and Planetary Science Letters 185, 237–252.
Kostitsyn, Yu.A., Altukhov, E.N., Filina, N.P., 1998. Rb–Sr dating of the North-East Tuva alkaline granites. Russian Geology and Geophysics 39 (7), 917–923 In Russian.
Kovalenko, V.I., Yarmolyuk, V.V., Kovach, V.P., Kotov, A.B., Kozakov, I.K., Sal'nikova, E.B., 1996. Sources of phanerozoic granitoids in Central Asia: Sm–Nd isotope data. Geochemistry International 34 (8), 628–640.
Kovalenko, V.I., Yarmolyuk, V.V., Sal'nikova, E.B., Kartashov, P.M., Kovach, V.P., Kozakov, I.K., Kozlovskii, A.M., Kotov, A.B., Ponomarchuk, V.A., Listratova, E.N., Yakovleva, S.Z., 2004. The Khaldzan–Buregtei Massif of peralkaline rare-metal igneous rocks: structure, geochronology, and geodynamic setting in the caledonides of Western Mongolia. Petrology 12 (5), 412–436.
Kozakov, I.K., Kovach, V.P., Yarmolyuk, V.V., Kotov, A.B., Salnikova, E.B., Zagornaya, N. Yu., 2003. Crust-forming processes in the geologic development of the Tuva–Mongolia Massif: Sm–Nd isotopic and geochemical data for granitoids. Petrology 11 (5), 444–463.
Kravchinsky, V.A., 1989. Application of paleomagnetic method when studying the problems of genesis and age of rocks and ores of the Ozeyrney polymetallic deposit. In: Mikhalevsky, V.I. (Ed.), Acceleration of a Scientific and Technical Progress in Geophysical Investigations in Eastern Siberia. Publ. House “East Siberian Pravda”, Irkutsk, pp. 103–108. in Russian.
Kravchinsky, V.A., Konstantinov, K.M., Cogné, J.-P., 2001. Palaeomagnetic study of Vendian and Early Cambrian rocks of South Siberia and Central Mongolia: was the Siberian platform assembled at this time? Precambrian Research 110 (1–4), 61–92.
Kravchinsky, V.A., Cogné, J.-P., Harbert, W., Kuzmin, M.I., 2002a. Evolution of the Mongol–Okhotsk Ocean with paleomagnetic data from the suture zone. Geophysical Journal International 148, 34–57.
Kravchinsky, V.A., Konstantinov, K.M., Courtillot, V., Valet, J.-P., Savrasov, J.I., Cherniy, S.D., Mishenin, S.G., Parasotka, B.S., 2002b. Palaeomagnetism of East Siberian traps and kimberlites: two new poles and palaeogeographic reconstructions at about 360 and 250 Ma. Geophysical Journal International 148, 1–33.
Kravchinsky, V.A., Sorokin, A.A., Courtillot, V., 2002c. Paleomagnetism of Paleozoic and Mesozoic sediments of southern margin of Mongol–Okhotsk ocean, far east of Russia. J. Geophys. Res. 107 (B10), 2253 EPM 10-1–10-15.
Khubanov, V.B., Shadaev, M.G., 2004. Late Paleozoic dyke belts: geology, geochemistry and isotope records (Transbaikalia), in: metallogeny of the Pacific northwest: tectonics, magmatism and metallogeny of active continental margins. Proc. Interim IAGOD Conference, Dalnauka, Vladivostok. 218–219.
Kusznir, N.J., Kokhuto, A., Stephenson, R.A., 1996. Synrift evolution of the Pripyat Trough: constraints from structural and stratigraphic modeling. Tectonophysics 268, 221–236.
Kuzmin, M.I., 1985. Geochemistry of igneous rocks in Phanerozoic mobile belts. Nauka, Moscow. 200 pp. (In Russian).
Kuzmin, M.I., Fillipova, I.B., 1979. The history of the Mongol–Okhotsk belt in the Middle–Late Paleozoic and Mesozoic. In: Zonenshain, L.P. (Ed.), Lithospheric Plate Structure. Institute of Oceanography, the USSR Acad. Sci., Moscow, pp. 189–226. in Russian.
Kuzmin, M.I., Al'mukhamedov, A.I., Yarmoltyuk, V.V., Kravchinsky, V.A., 2003a. Rift and with-in plate magmatism in the context of hot and cold mantle fields. Russian Geology and Geophysics 44 (12), 1270–1279.
Kuzmin, M.I., Almukhamedov, A.I., Yarmolyuk, V.V., Kravchinsky, V.A., 2003b. Rifting and rifting magmatism — features of spreading zones and areas over “hot” and “cold” mantle fields. In: Runkvist, D.V. (Ed.), Problems of Global Geodynamics. Issue 2, Publishing House of the United Institute of Geology and Geophysics of Siberian Branch of the Russian Academy of Sciences, pp. 7–31. in Russian.
Larson, R.L., 1991. Geological consequences of superplumes. Geology 19 (10), 963–966.
Lawver, L.A., Grantz, A., Gahagan, L.M., 2002. Plate kinematic evolution of the present Arctic region since the Ordovician. In: Miller, E.L., Grantz, A., Klemperer, S.L. (Eds.), Tectonic Evolution of the Bering Shelf-Chukchi Sea-Arctic Margin and Adjacent Landmasses, Special Paper. Geological Society of America, Boulder, CO, pp. 333–358.
Lawver, L.A., Muller, R.D., 1994. Iceland hotspot track. Geology 22 (4), 311–314.
Li, Z.X., Li, X.H., 2007. Formation of the 1300-km-wide intracontinental orogen and postorogenic magmatic province in Mesozoic South China: a flat-slab subduction model. Geology 35 (2), 179–182. doi:10.1130/G23193A.1.
Li, Z.X., Zhong, S., 2009. Supercontinent–superplume coupling, true polar wander and plume mobility: plate dominance in whole-mantle tectonics. Physics of the Earth and Planetary Interiors 176, 143–156.
Li, Z.L., Yang, S.F., Li, Z.L., Yang, S.F., Chen, H.L., Langmuir, C.H., Yu, X., Lin, X.B., Li, Y.Q., 2008. Chronology and geochemistry of Taxinan basalts from the Tarim basin: evidence for Permian plume magmatism. Acta Petrologica Sinica 24 (5), 959–970.
Lightfoot, P.C., Hawkesworth, C.J., Hergt, J., Naldrett, A.J., Gorbachev, N.S., Fedorenko, V.A., Doherty, W., 1993. Remobilisation of the continental lithosphere by a mantle plum: major-, trace-, and Sr-, Nd-. And Pb-isotope evidence from picritic and tholeiitic lavas o Noril'sk District, Siberian Trap, Russia. Contribution to Mineralogy and Petrology 114, 171–188.
Lithgow-Bertelloni, C., Silver, P.G., 1998. Dynamic topography, plate driving forces and the African superswell. Nature 395, 269–272.
Litvinovsky, B.A., Zanvilevich, A.N., Alakshin, A.M., Podladchikov, Yu.Yu., 1992. Angaro–Vitim Batholith — Largest Granitoid Pluton. Nauka, Novosibirsk, p. 141. in Russian.
Litvinovsky, B.A., Jahn, B.M., Zanvilevich, A.N., Saunders, A., Poulain, S., Kuzmin, D.V., Perchov, K., Titov, A.V., 2002. Petrogenesis of syenite–granite suit from Bryansky Complex (Transbaikalia, Russia): implications for the origin of *A*-type granitoid magmas. Chemical Geology 189 (1), 105–133 in Russian.
Luchitsky, I.V., 1966. Paleovolcanic reconstructions and some aspects of paleoenergy. In: Luchitsky, I.V. (Ed.), Comparative Paleovolcanology of the Middle and Upper Paleozoic of the South Siberia and Eastern Kazakhstan. Nauka, Novosibirsk, pp. 263–281.
Lundin, E.R., Doré, A.G., 2005. The fixity of the Iceland “hot spot” on the Mid-Atlantic Ridge: observational evidence, mechanism and implications for Atlantic volcanic margins. Geological Society of America 388, 627–651 Special Paper.
Maruyama, S., 1994. Plume tectonics. Journal of Geological Society of Japan 100 (1), 24–49.
Maruyama, S., Santosh, M., Zhao, D., 2007. Superplume, supercontinent, and postperovskite: mantle dynamics and anti-plate tectonics on the core–mantle boundary. Gondwana Research 11 (1–2), 7–37.
Mazukabzov, A.M., Donskaya, T.V., Gladkochub, D.P., Paderin, I.P., 2010. The Late Paleozoic geodynamics of the West Transbaikalian segment of the Central Asian fold belt. Russian Geology and Geophysics 51, 482–491.
McElhinny, M.W., Powell, C.M., Pisarevsky, S.A., 2003. Paleozoic terranes of eastern Australia and the drift history of Gondwana. Tectonophysics 362, 41–65.
McNamara, A.K., Zhong, S., 2005. Thermochemical structures beneath Africa and the Pacific Ocean. Nature 437, 1136–1139.
McNutt, M.K., Judge, A.V., 1990. The superswell and mantle dynamics beneath the South Pacific. Science 248 (4958), 969–975.
Medvedev, A.Ya., Al'mukhamedov, A.I., Reichow, M.K., Sounders, A.D., White, R.V., Kirda, N.P., 2003. The absolute age of basalts from the pre-Jurassic basement of the West Siberian Plate (from Ar40/Ar39 data), 2003. Russian Geology and Geophysics 44 (6), 617–620.
Medvedev, A.Ya., Gordienko, I.V., Gornova, M.A., Almukhamedov, A.I., 2008. Geochemistry of metavolcanics in the southern Hövsgöl area (northern Mongolia): geodynamic implications. Russian Geology and Geophysics 49 (4), 245–254.
Meert, J.G., Van der Voo, R., 2001. Comment on New palaeomagnetic result from Vendian red sediments in Cisbaikalia and the problem of the relationship of Siberia and Laurentia in the Vendian by Pisarevsky et al. Geophysical Journal International 146 (3), 867–870.
Meert, J.G., Torsvik, T.H., 2003. The making and unmaking of a supercontinent: Rodinia revisited. Tectonophysics 375, 261–288.
Mertz, D.F., Devey, C.W., Todt, W., Stoffers, P., Hoffman, A.W., 1991. Sr–Nd–Pb isotope evidence against plum–asthenosphere mixing north of Iceland. Earth and Planetary Science Letters 107, 243–255.
Metelkin, D.V., Vernikovsky, V.A., Kazansky, A.Yu., 2007. Neoproterozoic evolution of Rodinia: constraints from new paleomagnetic data on the western margin of the Siberian craton. Russian Geology and Geophysics 48, 32–45 (in Russian).
Montero, P., Bea, F., Gerdes, A., Fershtater, G., Zin'kova, E., Borodina, N., Osipova, T., Smirnov, V., 2000. Single-zircon evaporation ages and Rb–Sr dating of four major Variscan batholiths of the Urals. A perspective on the timing of deformation and granite generation. Tectonophysics 317, 93–108.
Morgan, W.J., 1971. Convective plumes in the lower mantle. Nature 230, 42–43.
Morgan, W.J., 1972. Deep mantle convection plumes and plate motions. Bulletin American Association of Petroleum Geologists 56, 202–213.

Mossakovsky, A.A., Ruzhentsev, S.V., Samygin, S.G., Kheraskova, T.N., 1993. Central-Asian folded belt: geodynamic evolution and history of origin. Geotectonics 6, 3–33 (in Russian).
Muttoni, G., Kent, D.V., Garzanti, E., Brack, P., Abrahamsen, N., Gaertani, M., 2003. Early Permian Pangea 'B' to Late Permian Pangea 'A'. Earth and Planetary Science Letters 215, 379–394. doi:10.1016/S0012-821X(03)00452-7.
Natal'in, B.A., Şengör, A.M.C., 2005. Late Palaeozoic to Triassic evolution of the Turan and Scythian platforms: the pre-history of the palaeo-Tethyan closure. Tectonophysics 404, 175–202.
Nenakhov, V.M., Nikitin, A.V., 2007. Structure, magmatism, and tectonic evolution of the Uakit zone in the Paleozoic in the context of the formation of the Angara–Vitim batholith (western Transbaikalia). Geotectonics 41 (2), 114–129.
Norton, I.O., 2000. Global hot spot reference frames and plate motion, In: Richards, M.A., Gordon, R.G., Van der Hilst, R.D. (Eds.), History and Dynamics of Global Plate Motions, American Geophysical Union, Geophysical Monograph, 121, pp. 339–357.
Pavlov, V.E., Courtillot, V., Bazhenov, M.L., Veselovsky, R.V., 2007. Paleomagnetism of the Siberian traps: new data and a new overall 250 Ma pole for Siberia. Tectonophysics 443, 72–92.
Pisarevsky, S.A., Wingate, M.T.D., Powell, C.M., Johnson, S., Evans, D.A.D., 2003. Models of Rodinia assembly and fragmentation. In: Yoshida, M., Windley Dasgupta, B.F.S. (Eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup: Geological Society London Special Publications, vol. 206, pp. 35–55.
Pisarevsky, S.A., Gurevich, E.L., Khamrov, A.N., 1997. Paleomagnetism of Lower Cambrian sediments from the Olenek River section (Northern Siberia): paleopoles and the problem of magnetic polarity in the early Cambrian. Geophysical Journal International 130, 746–756.
Pisarevsky, S.A., Komissarova, R.A., Khramov, A.N., 2000. New palaeomagnetic result from Vendian red sediments in Cisbaikalia and the problem of the relationship of Siberia and Laurentia in the Vendian. Geophysical Journal International 140 (3), 598–610.
Pisarevsky, S.A., Komissarova, R.A., Khramov, A.N., 2001. Reply to comment by Meert, J.G. and Van der Voo, R., on New palaeomagnetic result from Vendian red sediments in Cisbaikalia and the problem of the relationship of Siberia and Laurentia in the Vendian. Geophysical Journal International 146 (3), 867.
Pisarevsky, S.A., Gladkochub, D.P., Donskaya, T.A., De Waele, B., Mazukagzov, A.M., 2006. Palaeomagnetism and geochronology of mafic dykes in south Siberia, Russia: the first precisely dated Early Permian palaeomagnetic pole from the Siberian craton. Geophysical Journal International 167, 649–658.
Plotnikov, A.V., Stupakov, S.I., Babin, G.A., Vladimirov, A.G., Simonov, V.A., 2000. Age and geodynamic setting of the Kuznetsk alatau ophiolites. Doklady Earth Sciences 372, 608–612.
Pokrovsky, B.G., Zhidkov, A.Ya., 1993. Sources of material for high-K alkaline rocks from the Synnyr and South Sakum massifs in Transbaikalia from the isotopic data. Petrologiya 1 (2), 195–204.
Price, S., Brodie, J., Whitham, A., Kent, R., 1997. Mid-tertiary rifting and magmatism in the Traill O region, East Greenland source. Journal of the Geological Society 154, 419–434.
Reichow, M.K., Saunders, A.D., White, R.V., Almukhamedov, A.I., Medvedev, A.Ya., 2005. Geochemistry and petrogenesis of basalts from the West Siberian Basin: an extension of Permo-Triassic Siberian Traps, Russia. Lithos 79, 425–452.
Reichow, M.K., Pringle, M.S., Al'Mukhamedov, A.I., Allen, M.B., Andreichev, V.L., Buslov, M.M., Davies, C.E., Fedoseev, G.S., Fitton, J.G., Inger, S., Medvedev, A.Ya., Mitchell, C., Puchkov, V.N., Safonova, I.Yu., Scott, R.A., Saunders, A.D., 2009. The timing and extent of the eruption of the Siberian Traps large igneous province: implications for the end-Permian environmental crisis. Earth and Planetary Science Letters 277, 9–20.
Richards, M.A., Ricard, Y., Lithgow-Bertelloni, C., Spada, G., Sabadini, R., 1997. An explanation for Earth long-term rotational stability. Science 275, 372–375.
Ritsema, H.J., vanHeijst, J.H., Woodhouse, J.H., 1999. Complex shear velocity structure beneath Africa and Iceland. Science 286, 1925–1928.
Rochette, P., Vandamme, D., 2001. Pangea B: an artifact of incorrect paleomagnetic assumptions? Annali di Geofisisica 44, 649–658.
Rodionov, V.P., Osipova, E.P., Pogarskaya, I.A., 1982. Pole number 10023. In: Khramov, A. N. (Ed.), Paleomagnetic Directions and Paleomagnetic Poles: Data for USSR, Issue 5, Materials of the WDC-B, Moscow, pp. 14 and 38. (In Russian).
Romanowicz, B., 2008. Using seismic waves to image Earth's internal structure. Nature 451 (7176), 266–268.
Romanowicz, B., Gung, Y.C., 2002. Superplumes from the core–mantle boundary to the lithosphere: implications for heat flux. Science 296 (5567), 513–516.
Rudnev, S.N., Izokh, A.E., Kovach, V.P., Shelepaev, R.A., Terent'eva, L.B., 2009. Age, composition, sources, and geodynamic environments of the origin of granitoids in the northern part of the Ozernaya Zone, Western Mongolia: growth mechanisms of the Paleozoic continental crust. Petrology 17 (5), 439–475.
Ruzhentsev, S.V., Pospelov, I.I., Badarch, G., 1989. Tectonics of the Mongolian indosinides. Geotectonics 23 (6), 476–487.
Ruzhentsev, S.V., Minina, O.R., Aristov, V.A., Katyukha, Yu.P., Golionko, B.G., 2005. Tectonics of the Ikat–Bagdarin and Dzhida zones in western Transbaikalia. The Problems of the Central Asian Tectonics. GEOS, Moscow, pp. 171–196. In Russian.
Ruzhentsev, S.V., Aristov, V.A., Minina, O.R., Golionko, B.G., Nekrasov, G.E., 2007. Hercynides of the Ikat–Bagdarin zone in Transbaikalia. Doklady Earth Sciences 417 (8), 1198–1201.
Saunders, A.D., Larsen, H.C., Fitton, J.G., 1998. Magmatic development of the southeast Greenland Margin and evolution of the Iceland Plume: geochemical constraints from Leg 152. In: Saunders, A.D., Larsen, H.C., Wise Jr., S.W. (Eds.), Proc. ODP, Sci. Results, 152. Ocean Drilling Program, College Station, TX, pp. 479–501.
Safonova, I.Yu., 2008. Geochemical evolution of intraplate magmatism in the Paleo-Asian Ocean from the Late Neoproterozoic to the Early Cambrian. Petrology 16 (5), 492–511.
Safonova, I.Yu., 2009. Intraplate magmatism and oceanic plate stratigraphy of the Paleo-Asian and Paleo-Pacific Oceans from 600 to 140 Ma. Ore Geology Reviews 35, 137–154.
Saunders, A.D., England, R.W., Reichow, M.K., White, R.V., 2005. A mantle plume origin for the Siberian traps: uplift and extension in the West Siberian Basin, Russia. Lithos 79, 407–424.
Scotese, C., 2004. A continental drift flipbook. The Journal of Geology 112 (6), 729–741.
Shadaev, M.G., Khubanov, V.B., 2004. Petrogenesis of the Khorinsky volkano-plutonic structure (Transbaikalia). Geochimica et Cosmochimica Acta 68 (11), 78–81.
Shadaev, M.G., Khubanov, V.B., Posokhov, V.F., 2005. New data on the Rb–Sr age of dike belts in western Transbaikalia. Russian Geology and Geophysics 46 (7), 707–715.
Sharma, M., Basu, A.R., Nesterenko, G.V., 1992. Temporal Sr-, Nd- and Pb-isotopic variations in the Siberian flood basalts: implications for the plume-source characteristics. Earth and Planetary Science Letters 113, 365–381.
Sklyarov, E.V., Fedorovsky, V.S., Kotov, A.B., Lavrenchuk, A.V., Mazukabzov, A.M., Levitsky, V.I., Sal'nikova, E.B., Starikova, A.E., Yakovleva, S.Z., Anisimova, I.V., Fedoseenko, A.M., 2009. Carbonatites in collisional settings and pseudo-carbonatites of the Early Paleozoic Ol'khon collisional system. Russian Geology and Geophysics 50 (12), 1091–1106.
Smethurst, M.A., Khramov, A.N., Torsvik, T.H., 1998. The Neoproterozoic and Palaeozoic palaeomagnetic data for the Siberian Platform: from Rodinia to Pangea. Earth-Science Reviews 43, 1–21.
Steinberger, B., 2000. Plumes in a convecting mantle' Models and observations for individual hotspots. Journal of Geophysical Research 105 (B5), 11,127–11,152.
Steinberger, B., O'Connell, R.J., 1998. Advection of plumes in mantle flow: implications for hotspot motion, mantle viscosity and plume distribution. Geophysical Journal International 132 (2), 412–434.
Steinberger, B., Torsvik, T.H., 2008. Absolute plate motions and true polar wander in the absence of hotspot tracks. Nature 452 (7187), 620–623.
Storey, B.C., 1995. The role of mantle plumes in continental breakup: case histories from Gondwanaland. Nature 377, 301–308.
Tarduno, J.A., 2008. Hotspots unplugged — long considered fixed founts of molten material from deep within the planet, the hotspots that raise islands now join the list of the earth's moving parts. Scientific American 298 (1), 88–93.
Tarduno, J.A., Duncan, R.A., Scholl, D.W., Cottrell, R.D., Steinberger, B., Thordarson, Th., Kerr, B.C., Neal, C.R., Frey, F.A., Torii, M., Carvallo, C., 2003. The Emperor seamounts: southward motion of the Hawaiian hotspot plume in Earth's mantle. Science 301 (5636), 1064–1069.
Terenteva, L.B., Kovach, V.P., Yarmolyuk, V.V., Kovalenko, V.I., Kozlovsky, A.M., 2008. Composition, sources, and geodynamis of rock formationin the Late Riphean Bayankhongor Ophiolite Zone: characteristics of early stages in the evolution of the Paleo-Asian Ocean. Earth Science Section 423, 1462–1467.
Torsvik, T.H., 2003. The Rodinia Jigsaw Puzzle. Science 300, 1379–1381.
Torsvik, T.H., Andersen, T.B., 2002. The Taimyr fold belt, Arctic Siberia: timing of prefold remagnetisation and regional tectonics. Tectonophysics 352, 335–348.
Torsvik, T.H., Cocks, L.R.M., 2004. Earth geography from 400 to 250 Ma: a palaeomagnetic, faunal and facies review. Journal of the Geological Society 161, 555–572.
Torsvik, T.H., Tait, J., Moralev, V.M., McKerrow, W.S., Sturt, B.A., Roberts, D., 1995. Ordovician palaeogeography of Siberia and adjacent continents. Journal Geological Society London 152, 279–287.
Torsvik, T.H., Smethurst, M.A., Meert, J.G., Van der Voo, R., McKerrow, W.S., Brasier, M.D., Sturt, B.A., Walderhaug, H.J., 1996. Continental break-up and collision in the Neoproterozoic and Palaeozoic — a tale of Baltica and Laurentia. Earth-Science Reviews 40, 229–258.
Torsvik, T.H., Muller, R.D., Van der Voo, R., Steinberger, B., Gaina, C., 2008a. Global plate motion frames: toward a unified model. Reviews of geophysics 46 (3), RG3004.
Torsvik, T.H., Smethurst, M.A., Burke, K., Steinberger, B., 2008b. Long term stability in deep mantle structure: Evidence from the 300 Ma Skagerrak-Centered Large Igneous Province (the SCLIP). Earth and Planetary Science Letters 267, 444–452.
Torsvik, T.H., Steinberger, B., Cocks, L.R.M., Burke, K., 2008c. Longitude: linking earth's ancient surface to its deep interior. Earth and Planetary Science Letters 276, 273–282.
Torsvik, T.H., Van der Voo, R., Meert, J.G., Mosar, J., Walderhaug, H.J., 2001. Reconstructions of the continents around the North Atlantic at about the 60th parallel. Earth and Planetary Science Letters 187, 55–69.
Trønnes, R.G., 2009. Structure, mineralogy and dynamics of the lowermost mantle. Mineralogy and Petrology. doi:10.1007/s00710-009-0068-z.
Tsygankov, A.A., Matukov, D.I., Berezhnaya, N.G., Larionov, A.N., Posokhov, V.F., Tsyrenov, B.Ts., Chromov, A.A., Sergeev, S.A., 2007. Late Paleozoic granitoids of western Transbaikalia: magma sources and stages of formation. Russian Geology and Geophysics 48 (1), 156–180.
Utsunomiya, A., Ota, T., Windley, B.F., Suzuki, N., Uchio, Y., Munekata, K., Maruyama, S., 2007. History of the Pacific Superplume: implication for Pacific Paleogeography since the Late Proterozoic. In: Yuen, D.A., Maruyama, S., Karato, S., Windley, B.F. (Eds.), Superplumes: Beyond Plate Tectonics, Springer, Dordrecht, pp. 363–407.
Van der Voo, R., 1993. Paleomagnetism of the Atlantic, Tethys, and Iapetus Oceans. Cambridge University Press. 411 pp.
Van der Voo, R., Torsvik, T.H., 2001. Evidence for late Paleozoic and Mesozoic non-dipole fields provides an explanation for the Pangea reconstruction problems. Earth and Planetary Science Letters 187, 71–81. doi:10.1016/S0012-821X(01)00285-0.
Van der Voo, R., Torsvik, T.H., 2004. The quality of the European Permo-Triassic paleopoles and its impact on Pangea Reconstructions. In (Eds. J.E.T. Channel, D.V. Kent, W. Lowrie & J.G. Meert) Timescales of the Paleomagnetic Field. AGU Geophysical Monograph 145, 29–42.
Van der Voo, R., Spakman, W., Bijwaard, H., 1999. Mesozoic subducted slabs under Siberia. Nature 397, 246–249.

Van der Voo, R., Levashova, N.M., Skrinnik, L.S., Kara, T.V., Bazhenov, M.L., 2006. Late orogenic, large-scale rotations in the Tien Shan and adjacent mobile belts in Kyrgyzstan and Kazakhstan. Tectonophysics 426, 335–360.
Vorontsov, A.A., Yarmolyuk, V.V., Ivanov, V.G., Sandimirova, G.P., Pakholchenko, Y.A., 1997. Sources of basaltic melts for Devonian rift bimodal igneous associations of central Asia: evidence from trace-element and strontium isotopic data on basic rocks from northeastern Mongolia. Petrology 5 (3), 208–222.
Vorontsov, A.A., Yarmolyuk, V.V., Sandimirova, G.P., 2008. Basalt–trachyrhyolite–comendite association of the Kropotkin Range (Eastern Sayany) and problem of Devonian rifting in the southern fringing of the Siberian Platform. Doklady Earth Sciences 423 (8), 1229–1234.
Vrublevskii, V.V., Izokh, A.E., Polyakov, G.V., Gertner, I.F., Yudin, D.S., Krupchatnikov, V.I., 2009. Early Paleozoic Alkaline Magmatism of the Altai Mountains: 40Ar–39Ar Geochronology Data for the Edel'veis Complex. Doklady Earth Sciences 427 (5), 846–850.
Wang, Sh., Han, B., 1994. Geochemistry and tectonic significance of alkali granites along Ulungur River, Xinjang. Scientia Geologica Sinica 29 (4), 373–383.
Weinstein, S.A., Olson, P.L., 1989. The proximity of hotspots to convergent and divergent plate boundaries. Geophysical Research Letters 16 (5), 433–436.
Wilson, J.T., 1963. A possible origin of the Hawaiian Islands. Canadian Journal of Physics 41, 863–866.
Wilson, J.T., 1965. Evidence from ocean islands suggesting movement in the Earth. Philosophical Transactions of the Royal Society of London, Series A-Mathematical and Physical Sciences 258, 145–146.
Wilson, J.T., 1973. Mantle plumes and plate motions. Tectonophysics 19, 149–164.
Wilson, M., 1989. Igneous Petrogenesis. Unwim Hyman, London. 466 pp.
Wilson, M., Lyashkevich, Z.M., 1996. Magmatism and the geodynamics of rifting of the Pripyat–Dnieper rift, East European Platform. Tectonophysics 268, 64–81.
Wooden, J.L., Czamanske, O.K., Fedorenko, V.A., Arndt, N.T., Chauvel, C., Bouse, R.M., King, B.-S.h.W., Knight, R.J., Siems, D.F., 1993. Isotopic and trace-element constraints on mantle and crustal contribution to Siberian continental flood basalts, Noil'sk area. Geochimmica et Cosmochimica Acta 57, 3677–3704.
Yarmolyuk, V.V., Kovalenko, V.I., 1991. Rifting Magmatism of Active Continental Margins and Its Ore Potential. Nauka, Moscow. 263 pp.
Yarmolyuk, V.V., Kovalenko, V.I., 2003a. Batholiths and geodynamics of batholith formation in the Central Asian folded belt. Russian Geology and Geophysics 44 (12), 1260–1274.
Yarmolyuk, V.V., Kovalenko, V.I., 2003b. Deep geodynamics and mantle plumes: role in formation of the Central-Asian folded belt. Petrology 11 (6), 504–531.
Yarmolyuk, V.V., Kovalenko, V.I., Ivanov, V.G., Zhuravlev, D.Z., 1995a. Isotope composition of Sr and Nd of basic volcanics of the South-Khangai hot spot of the Central Asia. Doklady of Russian Academy of Sciences 342 (2), 230–234 in Russian.
Yarmolyuk, V.V., Kovalenko, V.I., Ivanov, V.G., 1995b. Intraplate late Mesozoic–Cenozoic volcanic province in Central East Asia as a projection of mantle hot field. Geotectonics 29 (5), 395–421.
Yarmolyuk, V.V., Vorontsov, A.A., Kovalenko, V.I., Zhuravlev, D.Z., 1997a. Isotope inhomogeneity of sources of Late Paleozoic intraplate magmatism in the Central Asia (based on Sr and Nd isotope data for basalts of bimodal associations). Russian Geology and Geophysics 38 (6), 1178–1183.
Yarmolyuk, V.V., Kovalenko, V.I., Kotov, A.B., Sal'nikova, E.B., 1997b. The Angara–Vitim batholith: on the problem of batholith geodynamics in the Central Asia Foldbelt. Geotectonics 5, 359–373.
Yarmolyuk, V.V., Ivanov, V.G., Kovalenko, V.I., 1998. Sources of intraplate magmatism of western Transbaikalia in the Late Mesozoic–Cenozoic: trace-element and isotope data. Petrology 6 (2), 101–121.
Yarmolyuk, V.V., Kovalenko, V.I., Kuzmin, M.I., 2000. North Asian superplume activity in the Phanerozoic: magmatism and geodynamics. Geotectonics 5, 343–366.
Yarmolyuk, V.V., Litvinovsky, B.A., Kovalenko, V.I., Jahn Bor-Ming, Zanvilevich, A.N., Vorontsov, A.A., Zhuravlev, D.Z., Posokhov, V.F., Kuz'min, D.V., Sandimirova, G.P., 2001. Formation Stages and Sources of the Peralkaline Granitoid Magmatism of the Northern Mongolia–Transbaikalia Rift Belt during the Permian and Triassic. Petrology 9 (4), 302–326.
Yarmolyuk, V.V., Ivanov, V.G., Kovalenko, V.I., Pokrovskii, B.G., 2003a. Magmatism and geodynamics of the Southern Baikal volcanic region (mantle hot spot): results of geochronological, geochemical, and isotopic (Sr, Nd, O) investigations. Petrology 11 (1), 3–31.
Yarmolyuk, V.V., Kovalenko, V.I., Sal'nikova, E.B., Budnikov, C.V., Kovach, V.P., 2002a. Tectono-magmatic zoning, magma sources, and geodynamics of the Early Mesozoic Mongolia–Transbaikal Province. Geotectonics 4, 293–311.
Yarmolyuk, V.V., Kovalenko, V.V., Kovach, V.P., Kozakov, V.P., Kotov, I.K., Sal'nikova, E.B., 2002b. Isotopic composition, sources of crustal magmatism, and crustal structure of Caledonides of the Ozernaya zone, Central Asian foldbelt Source. Doklady Earth Sciences 387A (9), 1043–1047.
Yarmolyuk, V.V., Kovalenko, V.I., Kovach, V.P., Kozakov, I.K., Kotov, A.B., Sal'nikova, E.B., 2003c. Geodynamics of caledonides in the Central Asian foldbelt. Doklady Earth Sciences 389 (3), 311–316.
Yarmolyuk, V.V., Kovalenko, V.I., Kovach, V.P., Rytsk, E.Yu., Kozakov, I.K., Kotov, A.B., Sal'nikova, E.B., 2006. 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. Doklady Earth Sciences 411 (8), 1184–1189.
Yarmolyuk, V.V., Kovalenko, V.I., Kozakov, I.K., Sal'nikova, E.B., Bibikova, E.V., Kovach, V.P., Kozlovsky, A.M., Kotov, A.B., Lebedev, V.I., Eenjin, G., Fugzan, M.M., 2008a. The Age of the Khangai batholith and the problem of batholith formation in Central Asia. Doklady Earth Sciences 423 (8), 1223–1228.
Yarmolyuk, V.V., Kovalenko, V.I., Sal'nikova, E.B., Kovach, V.P., Kozlovsky, A.M., Kotov, A.B., Lebedev, V.I., 2008b. Geochronology of igneous rocks and formation of the Late Paleozoic south Mongolian active margin of the Siberian continent. Stratigraphy and geologic correlation 16 (2), 162–181.
Yarmolyuk, V.V., Nikiforov, A.V., Sal'nikova, E.B., Travin, A.V., Kozlovskiy, A.M., Kotov, A.B., Shuriga, T.N., Lykhin, D.A., Lebedev, V.I., Anisimova, I.V., Plotkina, Yu.V., Yakovleva, S.Z., 2010. Rare-metal granitoids of the Ulug–Tanzek Deposit (Eastern Tyva): age and tectonic setting. Doklady Earth Sciences 430 (1), 95–100.
Zanvilevich, A.N., Litvinovsky, B.A., Andreev, G.V., 1985. Mongol–Transbaikal Alkaline–Granitoid Province. Nauka, Moscow, p. 232. in Russian.
Zhao, D., 2001. Seismic structure and origin of hotspots and mantle plumes. Earth and Planetary Science Letters 192, 251–265.
Zhao, D., 2007. Seismic images under 60 hotspots: Search for mantle plumes. Gondwana Research 12, 335–355.
Zhitkov, A.N., Kravchinsky, A.Ya., 1982. Paleomagnetic-metallogeny investigations of productive quartz-pyrite mineralization in the Lena Region (exemplified by "Glavnoe" deposit). In: Khrenov, P.M. (Ed.), Geophysical Investigations of Deposits in the Eastern Siberia. SNIIGGiMS, Novosibirsk, pp. 105–109. in Russian.
Zhong, S.J., Zuber, M.T., Moresi, L., Gurnis, M., 2000. Role of temperature-dependent viscosity and surface plates in spherical shell models of mantle convection. Journal of Geophysical Research-Solid Earth 105 (B5), 11063–11082.
Zindler, A., Hart, S.R., 1986. Chemical geodynamics. Annual Review of Earth Planetary Sciences 14, 493–571.
Zonenshain, L.P., Kuzmin, M.I., 1983. Intraplate magmatism and its significance for understanding processes in the earth's mantle. Geotectonics 1, 28–45 (in Russian).
Zonenshain, L.P., Kuzmin, M.I., Bocharova, N.Yu., 1991a. Hot-fields tectonics. Tectonophysics 199, 165–192.
Zonenshain, L.P., Kuzmin, M.I., Natapov, L.M., 1991b. Geology of the USSR: a plate-tectonic synthesis. American geophysical Union, Washington. 442 pp.
Zorin, Yu.A., Kozhevnikov, V.M., Novoselova, M.R., Turutanov, E.Kh., 1989. Thickness of the litosphere beneath the Baikal rift zone and adjacent regions. Tectonophysics 168, 327–337.