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GEOLOGY

Multistage Dynamics of the Upper Mantle in Eastern Asia: Relationships between Wandering Volcanism and Low-Velocity Anomalies

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The nature of vigorous Cenozoic tectonomagmatic reactivation of the lithosphere in central and eastern Asia has been discussed in numerous works. Early publications were focused on the crucial role of the Indo-Asian collision [1] and hot spots [2]. Later the intraplate volcanic activity was taken into account for the large-scale mantle convection starting from the core–mantle boundary [3], various versions of hot spot localization [4 and others], and long-term Late Mesozoic and Cenozoic activity of Amur and other megastructures [5]. Geochronological investigations suggested that the spatiotemporal distribution of volcanism in the southwestern Eurasian Plate was controlled by interplate (collision and subduction) and intraplate processes [6]. It was also suggested that some special conditions existing within the continental lithosphere hamper direct volcanic manifestation of mantle plumes. According to [7], the plumes provide general heating of the sublithospheric mantle, whereas the spatiotemporal distribution of volcanic activity is regulated by weakened zones in the lithosphere.

Classical plumes are considered to be hypothetical columns, up to 200 km in diameter, that ascend from the thermal boundary layer of the convecting system, which is commonly identified with core–mantle boundary [8]. The tomography results have shown that a dense and high-velocity lower mantle exists beneath central and eastern Asia [8, 9]. These data contradict hypotheses on large-scale convection starting from the core–mantle boundary or plume columns related to this boundary.

Hot spots in oceanic lithospheric plates are deduced from migration of volcanic activity as a result of plate motion above the immobile mantle plumes. The velocity of plate motions was calculated from the hot spots. The geophysical models based on reproduced plate motions driven by mantle density and viscosity heterogeneities assumed that the Eurasian Plate was immobile in the Cenozoic or slowly moved eastward [10 and others].

The sequential westward shift of late Cenozoic volcanic activity with an average velocity of 0.8 cm/yr in the Eastern Sayan was interpreted as a result of slow eastward plate motion above a thermal anomaly [11]. Subsequently, the southeastern motion of a stable part of the Asian continent (Siberian Platform) with a high velocity of ~3 cm/yr was supported by GPS geodetic data [12]. The slow eastward motion of Asia inferred from geophysical modeling and the volcanism wandering rate in the Eastern Sayan is not consistent with GPS geodetic data. The northwestward migration of Neogene and Quaternary volcanic fields over a distance of 525–660 km relative to Paleogene counterparts was suggested for eastern China [13]. However, this model was not supported by any geophysical evidence for the existence of a low-density mantle material beneath Neogene and Quaternary volcanic fields.

Yanovskaya and Kozhevnikov [14] constructed a 3D model of *S* wave distribution in the crust and upper mantle of Asia down to a depth of 400 km based on surface-wave tomography. Local low-velocity anomalies (probable fragments of mantle plume-like channels) were detected in the upper mantle at a depth of 50–350 km. Their spatial correlation with wandering Cenozoic volcanism allowed us to develop a hypothesis on the multistage mantle dynamics discussed in this communication.

Low-velocity anomalies. Two stages of low-velocity mantle anomalies (200–350 and 50–200 km) are shown in Fig. 1.

The large Transbaikal low-velocity lens is recognized at the lower stage within a depth interval of 250–350 km. Its western part is continuous, whereas the eastern part is split into three branches that extend from the Transbaikal region to the eastern continental margin. These branches are separated by the Hokkaido–

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Amur and Honshu–Khingan high-velocity bridges. The upper stage includes three low-velocity lenses (Sea of Okhotsk, Philippine Sea, and Sayan-Mongolian) at a depth of ~150 km. The lens of the lower stage occupies a transitional position between three lenses of the upper stage.

In addition to the Transbaikal lens, local anomalies at depths of 300–350 and 200–250 km occur within the lower stage. The Lena and North Sakhalin anomalies accentuate the abrupt northeastern termination of the lens. Two other lenses at the same depth (South China and Tarim) are spatially separated. The local anomalies at a depth of 200–250 km make up projections above the Transbaikal lens. The North Korean, Amur, and Sovgavan–Uda anomalies occur at its eastern margin, while the North Baikal and South Mongolian anomalies occur on the western margin.

Local anomaly of the East China Sea is situated within the upper stage beneath the inner part of the Philippine Sea low-velocity lens. The North Mongolian anomaly stands out against the central Sayan–Mongolian lens. A narrow low-velocity ridge extending from Yuzhno-Salkalinsk to Magadan in the NNE direction projects above the Sea of Okhotsk lens. The local South Primorye and Zeya low-velocity anomalies adjoin the Hokkaido–Amur high-velocity bridge at a depth of ~100 km.

Relationships between volcanism and mantle anomalies. The coherent spatial position of local mantle anomalies in eastern Asia and associated volcanic eruptions wandering in the northwestern direction is demonstrated in Fig. 1. The mantle anomalies formed beneath the incipient Tatar Strait, Sea of Japan, and East China Sea were localized beneath the Eurasian Plate margin owing to its southeastward motion.

The Amur anomaly center was situated beneath the Sea of Japan basin about 21 Ma ago and beneath the vast volcanic fields of southern Primorye 15–8 Ma ago. At present, the anomaly occurs at a distance of 675 km from the volcanic track origin of the South Primorye anomaly. Quaternary volcanic activity of the Udalianchi and other volcanic fields in northeastern China is spatially related to the Amur anomaly. The average rate of plate margin drift above the Amur anomaly center was 3.2 cm/yr. The North Sakhalin anomaly is located at the beginning of the volcanic track produced by the Lena anomaly.

The volcanic track of the Lena mantle anomaly extends over 1370 km. The initial activity of this anomaly was expressed in the middle Cenozoic volcanism 37–35 Ma ago. Lavas of this age occur in the central and northern parts of the eastern Sikhote Alin. The plate margin moved above the anomaly at an average rate of 3.8 cm/yr.

The volcanic track of the Sovgavan–Uda anomaly extends south of the volcanic track of the Lena anomaly. In contrast to the Lena anomaly, which was active beginning from 36 Ma ago, the Sovgavan–Uda anomaly characterizes the plate motion over the last 21 Ma. Lavas related to the initial volcanism are known in southern Sakhalin. Volcanic activity of the intermediate interval (15–8 Ma ago) was developed in central Sikhote Alin. Quaternary eruptions are known in the Toka district of the Stanovoi Range.

The middle Cenozoic mantle anomaly was active beneath the Korean Peninsula. Lavas were erupted in the Khasan district of southwestern Primorye 36–32 Ma ago. The present-day location of this anomaly beneath eastern Mongolia was provided by the southeastward motion of the plate margin at an average rate of 4 cm/yr. The anomaly currently situated beneath North Korea originated 21 Ma ago. The Quaternary volcanic field of Shangbashan is related to this anomaly.

Small dimensions of the North Baikal anomaly suggest its origination in the Pliocene or Quaternary without a substantial change of plate location with respect to the anomaly. Another interpretation supposes the southeastward drift of the plate above this anomaly and the respective migration of volcanic activity at an average rate of 1.5 cm/yr from the Telemba field (volcanism onset 21 Ma ago) to the Vitim field (strong eruptions started 12 Ma ago), and the northern Baikal region. This estimate of migration velocity is lower than those reported for the migration of volcanic activity at the eastern margin of Asia.

The track of wandering volcanism in the Eastern Sayan extends to the northern periphery of the Sayan–Mongolian low-velocity lens. The average westward migration rate of 0.8 cm/yr was estimated from spatial relationships of the early Miocene Urik and Quaternary East Tuva volcanic fields. Taking into account eruptions west of the East Tuva field, the migration rate could be somewhat higher, but in any case it did not exceed 1.5 cm/yr.

Origin of anomalies. The Late Mesozoic and Cenozoic volcanic activity in southern Mongolia, the Transbaikal region, and eastern China testifies to a partial inheritance of Cenozoic thermal history of the upper mantle from the Mesozoic Era. A special study of the spatiotemporal relationships between Mesozoic and Cenozoic volcanic activities is required to clarify relations of older and younger anomalies. In this communication, we focus attention on possible mechanisms driving the Cenozoic anomalies.

They are akin to plumes in spatial relations to the wandering volcanism. However, the anomalies arose within the upper mantle rather than at the core–mantle boundary. They were formed beneath the active continental margin of eastern Asia where the subduction of Pacific and Phillipine Sea plates beneath the continent was coupled with large-scale strike-slip displacements along the Sakhalin–Hokkaido–Sea of Japan and Tsusima strike-slip zones in the Sea of Japan mobile belt [6]. The incipient buoyant plumelike domains of partial melting were retained beneath the moving continental plate for a long time (Fig. 2).

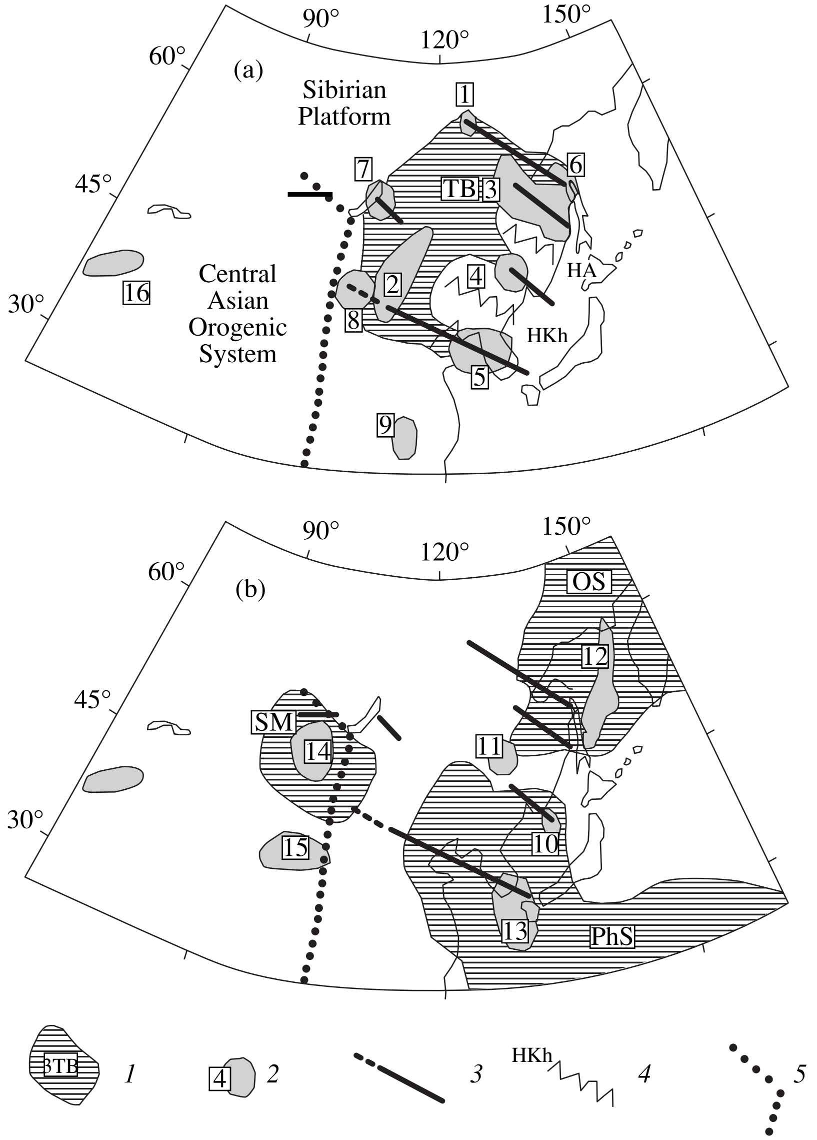

Fig. 1. Spatial relationships between hot spot tracks of Cenozoic wandering volcanism and low-velocity anomalies within mantle stages of (a) 200–350 km and (b) 50–200 km. (*1*) Low-velocity lenses: (TB) deep-seated Transbaikal (250–350 km), shallow-seated (SM) Sayan–Mongolian, (PhS) Phillipine Sea, and (OS) Sea of Okhotsk (150 km); (*2*) low-velocity local anomalies formed in the Sea of Japan mobile system extending from the southern Korean Peninsula to northern Sakhalin [6] (numerals in boxes). *36 Ma ago*: (1) Lena (depth 300–350 km), (2) East Mongolian (250 km); *21 Ma ago*: (3) Sovgavan–Uda (200–250 km); (4) Amur (200–250 km), (5) North Korean (200–250 km); *<4 Ma ago*: (6) North Sakhalin (300 km); (10) Southern Primorye (100 km), (13) South Korean (200 km); other anomalies of uncertain age: (7) North Baikal (250 km), (8) South Mongolian (200 km); (9) South China (300–350 km); (11) Zeya (100 km); (12) Sakhalin–Magadan anomalous projection above the Sea of Okhotsk lens; (14) North Mongolian (150 km); (15) Tsaidam (100 km); (16) Tarim (300–350 km); (*3*) lines of the northwestward and westward migration of volcanism spatially related to the mantle anomalies (dashed line is a hypothetical track of the South Mongolian anomaly based on its early Cenozoic age, see text for additional explanation); (*4*) high-velocity bridges between low-velocity anomalies within the Sea of Japan mobile system and adjacent eastern margin of Asia: (HA) Hokkaido–Amur, (HKh) Honshu–Khingan; (5) eastern boundary of the Central Asian orogenic system [6].

The morphogical difference of low-velocity anomalies at depths of 200–350 and 50–200 km reflects an abrupt change in their dynamics. Judging from wandering volcanism, the central and eastern parts of Asia moved southeastward relative to the mantle anomalies of the lower level at an average rate of 3–4 cm/yr. Similar estimates for the stable part of the Eurasian Plate based on GPS geodetic data (3 cm/yr) and wandering volcanism (3–4 cm/yr) show the relative immobility of anomalies in the upper mantle.

The variation of Nd, Sr, and Pb isotopic compositions in volcanic rocks from the Baikal and Sea of Japan mobile systems demonstrates a pulsatory basaltic melt

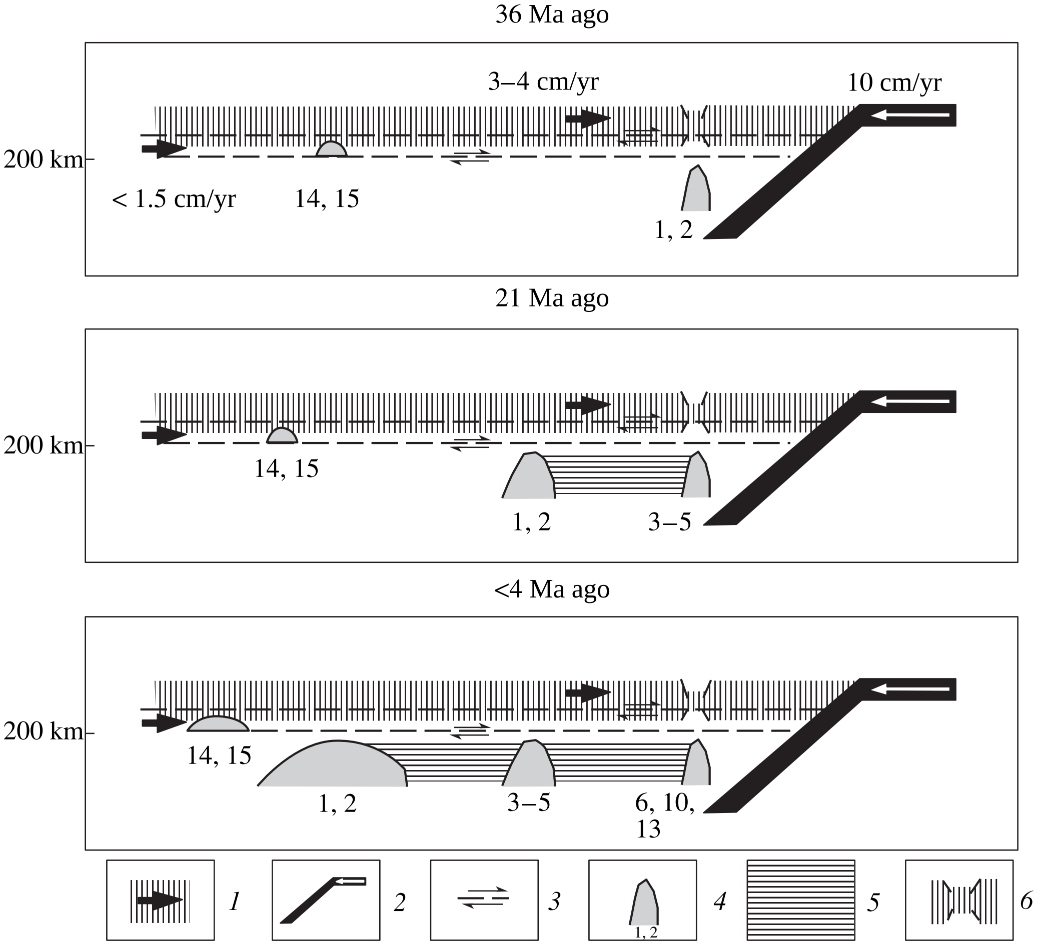

Fig. 2. Scheme of multistage dynamics of the upper mantle in eastern Asia. (*1*) Eurasian Plate and velocity of the southeastward motion of its upper and lower parts; (*2*) Pacific Plate and velocity of its northwestward motion; (*3*) zones of change in plate motion velocity; (*4*) plumelike mantle anomalies (numbers as in Fig. 1); (*5*) fragments of the low-velocity mantle lens formed between pulses of local plumelike anomalies of the lower stage; (*6*) Sea of Japan (strike-slip and pull-apart) mobile system.

supply from the sublithospheric mantle. Two large middle and late Cenozoic cycles of magmatic pulses are recognized. The delivery of the sublithospheric material was enhanced 37–35 and 24–21 Ma ago. This process is also observed over the recent 4 Ma [15]. The pulsatory character of deep processes apparently resulted in episodic formation of plumelike fragments.

The age of local anomalies at the eastern margin of Asia depends on their distance from the Sea of Japan mobile system. The North Sakhalin and South Primorye anomalies localized within this system were likely formed during the last 4 Ma. The late Cenozoic (Amur, Sovgavan–Uda, and North Korean) anomalies existed beneath the continental margin over a relatively short time. The lateral redistribution of their materials was insignificant. Therefore, the Hokkaido–Amur and Honshu–Khingan high-velocity bridges between the anomalies were retained. On the contrary, the middle Cenozoic Lena and East Mongolian anomalies partly disintegrated to merge into a continuous Transbaikal low-velocity lens as a result of their long-term existence.

The southeastern propagation of the western Transbaikal territory above the mantle anomaly of the eastern plate margin at a rate of 4.0 cm/yr required no less than 60 Ma. The early activity of the plumelike anomaly should cause a breakup of the eastern continental margin already in the early Cenozoic. The South Mongolian anomaly was active in the Eocene beneath the northern Circum-Ordos rift system where volcanic activity started 36 Ma ago [6]. It remains ambiguous whether this anomaly formed immediately in the Eocene beneath this rift system or somewhat earlier beneath the eastern continental margin.

The directions of wandering volcanism related to the anomalies of the upper stage were variable and the velocity did not exceed 1.5 cm/yr. The migration of volcanism in these domains reflected a retarded motion of the boundary layer between the lithosphere and the lower mantle stage. The Sea of Okhotsk and Philippine Sea low-velocity lenses of the upper stage are related to the continent–ocean transitional zone. The Sakhalin–Magadan low-velocity projection characterizes the magmatic evolution in the backarc basin behind the Kuril–Kamchatka island arc. The Sayan–Mongolian low-velocity lens of the upper stage is localized within the Central Asian orogenic system formed at the front of Indo-Asian collision that promoted the development of shallow-seated anomalies due to the decompression melting of lithosphere.

The southward shift of shallower anomalies relative to the deeper counterparts beneath the eastern margin of the Eurasian Plate (Fig. 1) is explained by their adjustment to the paleosubduction zones plunging to the north.

Conclusions. Local low-velocity anomalies formed within the mantle stage of 200–350 km in the process of rifting and spreading in the Sea of Japan mobile system. When the Eurasian Plate moved to the southeast, these anomalies were expressed in the northwestward migration of volcanism from the eastern margin toward Interior Asia at a rate of 3–4 cm/yr. The plumelike activity resulted in sequential volcanic eruptions that started ~36, 21, and 4 Ma ago. Judging by the retarded wandering of volcanism spatially related to the anomalies of the upper mantle stage (50–200 km), the migration rate of volcanism was no higher than 1.5 cm/yr. Anomalies in the Central Asian segment, which were formed independently of the processes that developed beneath the East Asian segment, reflected to a significant extent the intraplate dynamics controlled by the Indo-Asian collision.

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