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GEOLOGY

Cenozoic Upper Mantle Plumes in East Siberia and Central Mongolia and Subduction of the Pacific Plate

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According to petrological and geochemical data, Cenozoic alkali basalts of East Siberia and Central Mongolia are related to mantle plumes [1, 2]. Analysis of geophysical data made it possible to outline tails of these plumes [3, 4] that are apparently confined to the upper mantle [4]. Calculations show that the upper and lower boundaries of plume tails can be located at 150–200 and 420–660 km, respectively.

In addition, some of the authors suppose that Cenozoic basalts of the southern part of East Siberia, Central Mongolia, and northeastern China are related to a specific type of subduction of the Pacific Plate sector corresponding to the Japanese and Izu–Bonin island arcs [5, 6]. Results of global seismic tomography [7–9] suggest that the subducting Pacific Plate (slab) marked by high seismic velocities acquires a horizontal position in the mantle transition zone (the so-called "stagnation") in this area. The slab is dragged in this position beneath the Asian continent over more than 1500 km (up to the eastern Transbaikal region and eastern Mongolia) and then sinks into the lower mantle. It is supposed that dehydration of hydrosilicates retained in the stagnated slab results in the influx of fluids to the asthenosphere. The fluids induce an ascending convective flow and the consequent uplift (upwelling) of the asthenosphere [5]. The upwelling, in turn, fosters basaltic magmatism and rifting. The center of the giant upwelling is presumably located in northeastern China, whereas basalt fields of East Siberia and Central Mongolia are situated at the northwestern margin of the upwelling [5]. However, the absence of a significant negative long-wave isostatic anomaly in the region indicates that the existence of ascending flow in the asthenosphere beneath northeastern China is doubtful. We believe that domains of such anomalies in the southeastern sector of East Siberia and Central Mongolia correspond to upper mantle plumes [3, 4].

Based on the analysis of spatial relationship between the outlined plumes and the subducting plate, on the one hand, and the available data on processes in the upper mantle, on the other hand, we propose a new interpretation for the nature of upper mantle plumes in the study region.

We can determine the spatial position of the oceanic slab beneath East Asia based on global seismic tomography data [9] (Fig. 1). The figure shows the distribution of relative deviation of the calculated *P*-wave velocity from its IASPI 91 value, $\Delta V_P/V_P$ (%) at a depth of 550 km and along profile *AB* corresponding to the arc of a large circle. Digital data used for the compilation of the map and profile were kindly placed at our disposal by Zhao [9].

Elevated values of seismic velocity at 550–660 km can represent two structures: (i) horizontal portions of the Pacific slab that retain a mechanical link with the present-day subduction zone and continue to sink beneath the continent; (ii) older (immobile at present) fragments of the oceanic lithosphere that have lost the link due to change of the subduction zone position. Retention of the mechanical link of the horizontal portion of the slab with the subduction zone can be indicated by continuation of the high seismic velocity zone from the point of the Wadati–Benioff zone entry into the mantle transition zone to the western margin of the high velocity zone. The slab located northwest of the Japanese and Izu–Bonin island arcs (Fig. 1) satisfies this criterion. This sector is characterized by the maximum subduction rate (~10 cm/yr). At present, the Pacific Plate sectors related to Kuril–Kamchatka, Mariana, and Philippine arcs penetrate the lower mantle and do not stagnate in the transition zone [8].

Cenozoic upper mantle plumes (based on gravimetric data [3, 4]) make up a domain that is located west of the stagnated oceanic slab sector and extends nearly parallel to its margin (Fig. 1). Tails of these plumes

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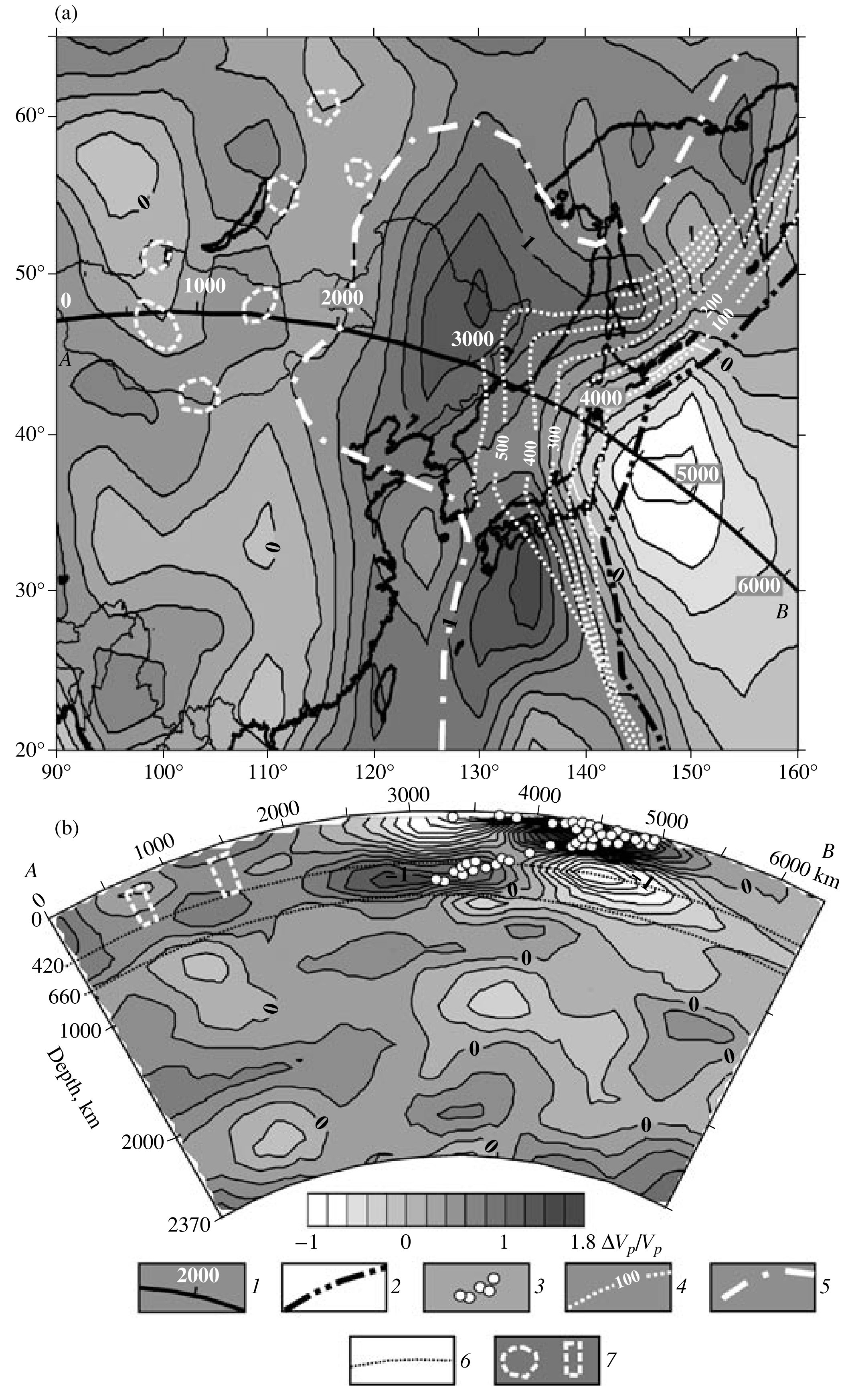
(a)
60°
50°
40°
30°
20°
90°
100°
110°
120°
130°
140°
150°
160°
0
1000
2000
3000
4000
5000
6000
A
B
500
400
300
200
100
(b)
A
B
1000
2000
3000
4000
5000
6000 km
0
420
660
1000
2000
2370
Depth, km
−1
0
1
1.8 ΔVp/Vp
2000
1
2
3
100
4
5
6
7

Fig. 1. Distribution of anomalies of seismic velocities, $\Delta V_P/V_P$ (%) (a) at a depth of 550 km and (b) along profile *AB*. Based on digital data on the global seismic tomography [9]. (*1*) Profile on the map (numerals designate distance from the profile origin, km); (*2*) axes of oceanic trenches; (*3*) hypocenters of earthquakes; (*4*) isolines of the Wadati–Benioff zone depth, km; (*5*) western boundary of the Pacific slab portion that occurs in the mantle transition zone and retains connection with the subduction zone; (*6*) boundaries of the mantle transition zone in the profile; (*7*) upper mantle plumes in the map and profile [3, 4].

(up to 200 km in diameter) cannot be recorded by the global seismic tomography because of its low resolution [9].

Thus, the domain of upper mantle plumes, which are supposed to be responsible for the formation of distal (relative to oceanic trenches) intracontinental basalt fields, is located near the margin of an oceanic plate sector characterized by maximal distance of movement beneath the Asian continent along the mantle transition zone. This fact is probably not accidental.

Stagnation of the slab in the mantle transition zone is attributed to specific features of phase transitions in a relatively thick and cold oceanic plate with a high subduction rate. The internal zone of such a structure is slowly heated. Therefore, this zone can retain metastable olivine, the density of which is significantly lower than that of other spinel-type phases that are typical of the mantle transition zone. Minerals like Mg-wustite and ferromagnesian silicate perovskite, which represent end products of the alteration of olivine in the lower mantle, have an even higher density [10, 11]. Therefore, the lower portion of the subducting slab loses the negative buoyancy due to its low temperature and transformation of olivine into the stable phase. Consequently, the slab acquires a horizontal position and continues to move in this state above the transition zone bottom until the internal zone of the slab is heated up to a certain threshold temperature, at which the metastable olivine is rapidly transformed into the spinel-type phases. Subsequently, the olivine is transformed into other minerals that are typical of the lower mantle. The slab can ultimately sink into the lower mantle. The slowly subducting, relatively thin and moderately cold slabs do not stagnate in the mantle transition zone. Instead, they sink into the lower mantle, because such slabs promote phase transition of olivine in the stable state [10, 11].

Following Ringwood [12], we believe that the former oceanic crust undergoes partial melting at a depth of 200–600 km. Products of this moderate melting are enriched in incompatible elements. The silicate melts penetrate the depleted mantle located above the subducting slab and transform the DM material into the fertilized peridotite, i.e., peridotite enriched in incompatible elements. The fertilized peridotite layer, 10–20 km thick, overlaps the former oceanic crust and participates in the slab descending process [12]. Thus, the peridotite layer is integrated into the slab.

Recent seismic data [7–9] and numerical simulations of subduction [11] revealed that slabs formed as a result of processes described above do not pile up into a giant "megalith," as was supposed in [12], when they reach the bottom of the mantle transition zone. Instead, the slabs either penetrate the lower mantle or stagnate in the transition zone without apparent signs of continuousness distortion. According to this scenario, the stratification of slabs should also be retained; i.e., the former oceanic crust should be underlain by a modified lithospheric mantle and overlain by a fertilized peridotite layer. In principle, olivine of the fertilized peridotite should undergo phase transformations similar to those in olivine of the oceanic plate. If the plate submerges in the lower mantle without stagnation, the fertilized peridotite should also be removed from the transition zone.

However, if the plate stagnates over a long period and continues to move, the fertilized peridotite layer can be heated by friction at the plate boundary. Quantitative estimates show that, at the constant rate of plate subduction (10 cm/yr) due to the action of mass force (negative buoyancy of the inclined slab portion), which should be compensated by friction forces at two boundaries of the plate), the average temperature of the 10-km-thick fertilized peridotite layer can rise by 270°C (relative to the background temperature at the relevant depth) at the western boundary of the horizontal sector of the slab. In some places, the temperature of the stagnated slab can also increase by 200°C owing to the anomalous heat release in the course of phase transitions of the metastable olivine under nonequilibrium conditions [10]. Heated portions of the fertilized peridotite characterized by lower density should be separated from the slab in the course of its submergence into the lower mantle. Consequently, such peridotite portions can float to the surface of the transition zone and participate in the asthenospheric convection (Fig. 2).

The development of a horizontally extended convective cell in the asthenosphere is related to the cooling influence of the inclined portion of the subducting plate [13, 14]. The ascending branch of such a cell is probably located beneath the Baikal rift zone and mountains of Central Mongolia [13]. In the ascending branch of the convective cell, portions of the floating material should possess the most efficient (from the point of view of energy distribution) drop- or column-shaped configuration; i.e., they should appear as plumes (Fig. 2).

It should be emphasized that the secondary convection described above should appear in the asthenosphere near the subduction zone regardless of the presence or absence of slab stagnation in the mantle transition zone. However, if the convection is confined to the depleted asthenosphere, its decompression can only generate the MORB-type basalt, and its melting is constrained by the asthenospheric material ascent to a

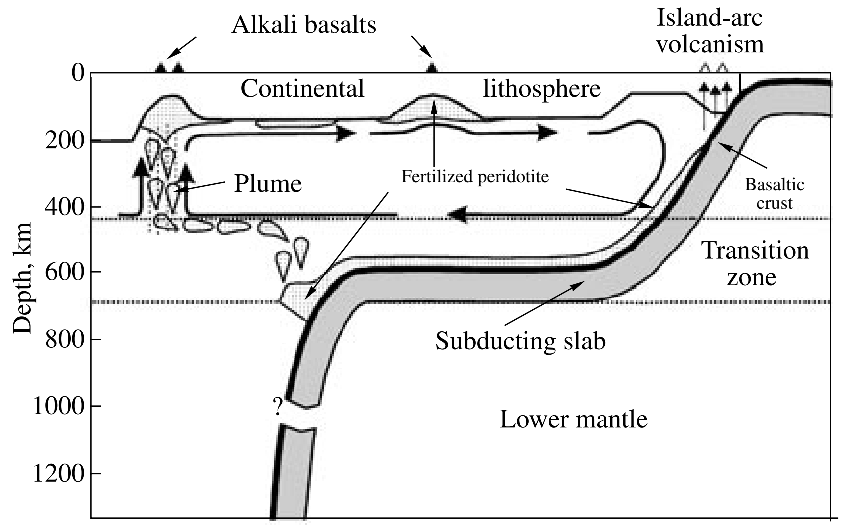

Fig. 2. Proposed model of the formation of upper mantle plumes. Portions of fertilized peridotite break away from the stagnated slab in the course of its submergence into the lower mantle, penetrate the upper part of the transition zone, and participate in the asthenospheric convection. Origination of the elongate branch of the convection is related to asthenosphere cooling by the inclined portion of the subducting plate. The ascending branch of the convective cell is split into separate jets (upper mantle plumes).

depth of 10–30 km [15]. In the study region, however, the continental lithosphere is 50–200 km thick [3]. This is unfavorable for the formation of melts in upper convective zones of a depleted asthenosphere. Doping of the asthenospheric material with the fertilized peridotite is the mechanism that can generate alkali basaltic magmas beneath the continental lithosphere. Preservation of the fertilized peridotite in the upper mantle with heating and subsequent involvement in the asthenospheric convection are provided by stagnation of the oceanic plate.

Thus, we believe that the upper mantle plumes previously identified in East Siberia and Central Mongolia [3, 4] represent jets formed after the splitting of the ascending branch of a secondary convective cell generated by subduction of the Pacific Plate. Stagnation of the plate is responsible for the participation of fertilized peridotite in the convection and the manifestation of alkali basaltic magmatism in the study region.

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