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GEOPHYSICS

Mantle Plumes beneath the Baikal Rift Zone and Adjacent Areas: Geophysical Evidence

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Late Cenozoic alkaline basic volcanics in the Baikal Rift Zone and adjacent territories of eastern Siberia and central Mongolia are relatively small in volume. However, the geochemical and isotopic signatures indicate that these volcanics could be related to mantle plumes [1–3]. At the same time, some researchers deem that the geochemical signature does not serve as critical evidence for the existence of plumes [4]. Geophysical methods may substantially help in the identification and localization of mantle plumes. The gravity and seismic evidence in favor of mantle plume development in the study region is discussed in this communication.

A heated material of mantle plume should have lowered density and seismic velocity. Gravity measurements may be helpful in plume recognition. It is commonly noticed in the literature on plumes [2, 5, and others] that ascending material flows in plume conduits exert dynamic influence upon lithosphere, giving rise to positive gravity anomalies combined with topographic uplifts. The associated positive anomalies in free air are attributed to the domination of topographic masses influence. Moreover, theoretical estimates show that the influence of ascending flows on lithosphere is significant only for mantle models with uniform viscosity [6]. The models taking into account the existence of asthenosphere having a viscosity two orders of magnitude lower than the viscosity in a deeper mantle assume a marked weakening of the dynamic influence of an ascending flow on lithosphere [6]. Due to the damping effect of asthenosphere, the anomalous masses of plume conduit virtually do not participate in either dynamic or static equilibria. Since density is decreased, the above phenomenon should create a negative isostatic anomaly that should be rather wide (i.e., regional) owing to the deep localization of the attracting object. The relative gravity minimum above Iceland and the absolute minimum above the Galapagos Islands [7] are examples of such anomalies.

Calculating the isostatic anomalies as guides for gravity effect of plume conduits, one should keep in mind that topographic uplifts above the plume may be equilibrated both by crust thickening caused by its magmatic underplating and by lithosphere thinning as a result of its replacement with a plume head [5].

In this work, we have calculated the isostatic anomalies taking into account that only 40% of topographic masses are compensated by variation of the Moho depth and the remainder (60%) is compensated by variation of lithosphere thickness. These relationships are based on the previously established correlation of topography and gravity field with seismic data on the crustal structure of eastern Siberia and central Mongolia [8, 9]. Gravity effects of isostatic compensation in plane zones with a radius of 222 km were attributed to the influence of deep-seated thin layers formed as a result of the condensation of topographic masses with opposite sign. The compensation masses related to variations of the Moho depth were condensed into a thin layer localized at the mean depth of this discontinuity (45 km), whereas the compensation masses related to the mantle were condensed into a thin layer at an average depth of the lithosphere–asthenosphere boundary (120 km). The depths of these layers were estimated from seismic data on crust and lithosphere thickness in this region [8, 9]. The gravity compensation effects within the plane zones, 222 km in radius, were subtracted from the Bouguer anomalies. Topographic isostatic corrections for spherical zones (beyond the radius of 222 km) were determined using the correction map compiled by Artem'ev [10].

Isostatic anomalies thus calculated were averaged by sliding window with a radius of 200 km. This allowed us to practically eliminate the gravity effects of density inhomogeneities in the upper crust and their assumed local compensation [9]. The regional isostatic gravity anomalies were obtained as a result of averaging. Gravity minimums (Fig. 1a, *I–V*) are crucial in the field of these anomalies.

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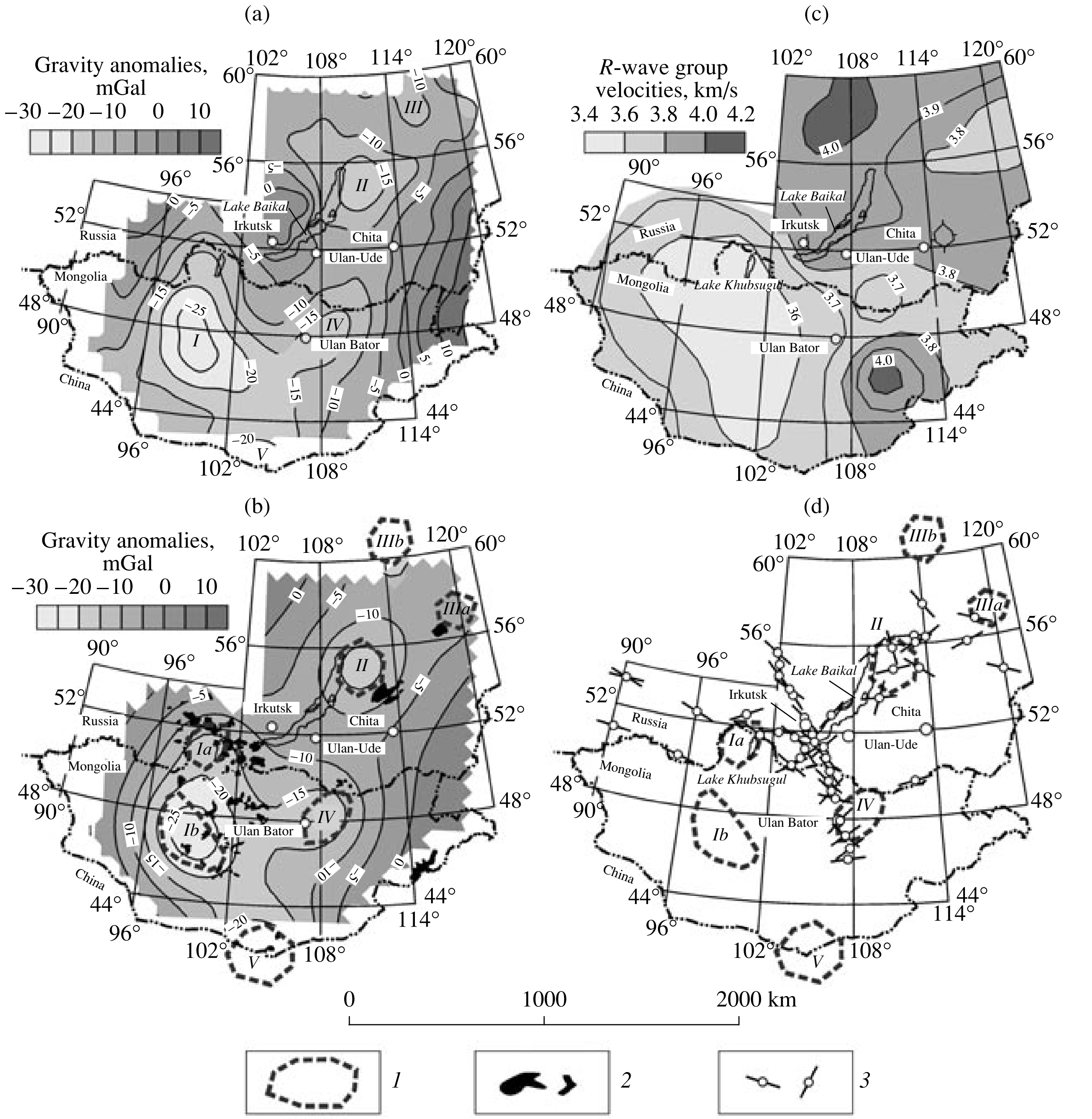

Fig. 1. Geophysical evidence for plumes. (a) Regional isostatic gravity anomalies; (b) theoretical anomalies from vertical polygonal prisms modeling the plume conduits; attracting bodies are localized in a depth interval of 200–670 km; their anomalous density is accepted as –20 kg/m^3; 10 mGal of the constant background were added to the values of theoretical anomalies; (c) *R*-wave group velocities for a period of 100 s; (d) seismic azimuthal anisotropy in the upper 200 km of mantle. Legend: (*1*) projections of the plume conduits on the Earth's surface (Figs. 1b, 1d); (*2*) fields of Late cenozoic volcanics (Fig. 1b, after [1, 3]); (*3*) seismic stations and fast directions of anisotropy (Fig. 1d, after [13, 14]). Gravity minimums (Fig. 1a) and the respective plumes (Figs. 1b, 1c) are denoted by Roman numerals.

We carried out a quantitative interpretation of the regional gravity minimums assuming that all of them correspond to the plume conduits having the form of vertical cylindrical bodies. The theoretical influence of such 3D bodies was calculated using the program for polygonal prisms [11]; i.e., horizontal sections of vertical cylinders were approximated by polygons. The position of polygon vertices was determined by the trial-and-error method.

The following limitations on vertical dimensions of attracting bodies were accepted in the quantitative interpretation. The upper and lower boundaries are situated at depths of 150–200 and of 670 km, respectively. Locations of the upper boundaries were chosen from the estimated lithosphere thickness [8, 9] beneath the Siberian Platform (200 km) and plains of eastern Mongolia (150 km). The estimates above determine the depth of asthenospheric ridge beneath the Baikal Rift Zone and mountains of central Mongolia [8]. We suppose that this ridge is filled with merged heads of several plumes, providing a considerable portion of isostatic compensation of large topographic uplifts [9]. Hence, the ridge should not be reflected in the field of isostatic anomalies. Positions of lower boundaries of bodies were chosen as the minimum possible for plumes originating at thermal boundary layers [5]. The anomalous density of attracting masses was accepted in different variants of the model as –20 and –30 kg/m^3. These values approximately correspond to an increase in temperature by 200 and 300°C, respectively, relative to the background temperature [5].

In all variants of the interpretation, we managed to reconcile the observed and theoretical gravity fields with a standard deviation no higher than ~4.5 mGal under the condition that a constant background of 10 mGal was added to the theoretical anomalies. Figure 1b shows a variant of interpretation with the maximal horizontal sections of bodies. The introduction of two attracting bodies (*Ia, Ib* and *IIIa, IIIb*) was required in all of the interpretation versions in order to explain each of the *I* and *III* minimums. Late Cenozoic volcanic fields are spatially related to most of the selected bodies (Fig. 1b).

The results of the gravity anomaly interpretation do not contradict, in principle, the mantle inhomogeneity deduced from the seismic data. The distribution of *R*-wave group velocities for a period of 100 s, which demonstrates the mantle structure down to 250–300 km, is roughly similar to the gravity anomaly pattern (cf. Figs. 1a, 1b). Such distribution of group velocities in the study region is retained for periods of 150 and 200 s [12] corresponding to a depth of about 500 km. The attracting bodies (except body *IIIb*) fall into regions of relatively low group velocities (Figs. 1b, 1c). The velocity anomalies of separate deep-seated bodies probably merge with one another due to a low resolution of surface wave method.

Compliance of attracting bodies *Ia, II, IIIa*, and *IV* with plumes is confirmed by seismic azimuthal anisotropy revealed in the upper 200 km of mantle from SKS wave analysis [13, 14]. The fast direction of anisotropy (orientation of polarization plane of quasi-*S* wave with elevated velocity) corresponds to the predominant orientation of the crystallographic *a* axis in olivine that indicates the direction of mantle material flow [15]. It turned out that the vicinity of the bodies listed above demonstrates a systematic orientation of fast directions of anisotropy tending to be arranged along radii relative to these bodies (Fig. 1d). The material supplied along the stems to the plume heads likely spreads in radial directions.

Thus, geophysical data indicate the existence of mantle plumes in the study region. Gravity bodies *Ia, Ib II, IIIa, IV* and *V* (Fig. 1b) correspond to the plume conduits. With a lesser certitude, this statement may also be valid for body *IIIb* localized beneath the margin of the Siberian Platform.

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