The DUPAL Mantle Anomaly of the Tuva–Mongolian Massif and Its Paleogeodynamic Implication

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The Tuva–Mongolian Massif (paleomicrocontinent) was characterized by domination of subplatformal marine (nearly shelf type) sedimentation conditions in the Vendian and Early–Middle Cambrian [1, 2]. Its basement was assumed to be Early Precambrian [1], Riphean [2, 3], or Early Caledonian [4]. According to the last-mentioned viewpoint, the basement of the Tuva–Mongolian Massif was coeval with the formation of the framing Eastern Tuva and Dzhida–Il’ chir structural zones (Fig. 1). Thus, the existence of the ancient basement of the Tuva–Mongolian Massif was questioned by some researchers.

The boundaries and internal structure of the massif are debatable. The Il’ chir and Khamardaban zones were included but the Oka zone was excluded from the Tuva–Mongolian Massif [5]. The massif basement was considered a heterogeneous structure composed of the Garga Microcontinent (790 Ma) and blocks accreted from the north and west. The blocks are composed of sedimentary and volcanosedimentary rocks of the Oka Group and Kharabera Formation (second half of the Late Riphean) [3]. Some authors emphasized an autonomous significance of the Khamardaban–Garga paleomicrocontinent [6]. Ultrametamorphic blocks (Garga, Sangilen, and others), which are widespread in the Eastern Sayan Range, were considered outliers of the Siberian Platform basement, while the southern Tuva–Mongolian Massif and similar massifs of Central Asia were interpreted as fragments that had detached from eastern Gondwana in the Vendian and drifted over the Paleosasiastic Ocean toward the Siberian Continent until the Late Cambrian [5].

If the Tuva–Mongolian Massif basement did form long before its accretion to the Siberian Paleocontinent, the mantle section of its lithosphere could possess a certain isotope-geochemical feature. Continents that previously comprised eastern Gondwana (Antarctica, Australia, India, and New Zealand) are now situated within the large-scale DUPAL anomaly of the Southern Hemisphere. This anomaly was distinguished in the 1980s in oceanic basalts on the basis of the parameter $\Delta$8/4Pb > 60 and $^{87}\text{Sr}/^{86}\text{Sr} > 0.705$ and is represented by the EM1 and EM2 branches of the enriched mantle [7]. The $\Delta$8/4Pb parameter characterizes the vertical deviation of $^{208}\text{Pb}/^{204}\text{Pb}$ from the trend for oceanic basalts of the Northern Hemisphere in the coordinates $^{208}\text{Pb}/^{204}\text{Pb}$--$^{206}\text{Pb}/^{204}\text{Pb}$ ($\text{Th}/\text{U} = 4$). The high $\Delta$8/4Pb value is evidence for a prolonged and more intense accumulation of the Th-derived isotope $^{208}\text{Pb}$ as compared to that of the U-derived $^{206}\text{Pb}$, due to a relative increase in the Th/U ratio in the mantle of the remote geological past.

After the discovery of the anomaly, researchers demonstrated its discreteness [8] and revealed that mantle rocks with a similar isotopic characteristics are distributed not only in the Southern Hemisphere but in the Northern Hemisphere as well. In the summary work [9], the anomaly of the Northern Hemisphere is represented as the Arctic, Philippine Sea, and Asian domains. The Asian domain extends from the western Pacific to central Asia. In the present work, we confirm the presence of the DUPAL anomaly in Late Cenozoic mantle-derived alkaline basalts in the northwestern segment of the proposed [9] Asian domain; however, we call attention to its discreteness. The Pb isotopes were measured on a VG sector-54 mass spectrometer at the Massachusetts Institute of Technology, United States [14, 15] and on a Finnigan MAT-262 mass-spectrometer at the Irkutsk Center. Variations in the Sr isotopes are generally consistent with the conclusion on the existence of the Pb isotope anomaly and are not considered in this work.

Mantle components. Spatiotemporal variations in Pb, Nd, and Sr isotope ratios in Late Cenozoic alkaline basaltic lavas erupted within the Tuva–Mongolian Massif provided the basis for distinguishing the general sublithospheric component A and the lithospheric admixture components B1, B2, and B3 [10]. Component A is isotopically depleted compared to chondrite and possesses relatively un radiogenic Sr but radiogenic Nd and Pb ($^{87}\text{Sr}/^{86}\text{Sr} \sim 0.7040–0.7041$, $\varepsilon_{\text{Nd}} \sim +3$, $^{206}\text{Pb}/^{204}\text{Pb} \sim 18.1–18.2$, $^{207}\text{Pb}/^{204}\text{Pb} \sim 15.53$). Component B1 is less depleted and differs from component A by more radiogenic Sr but less radiogenic Nd and Pb. Its admixture in component A is expressed as an
Fig. 1. Variations in the $\Delta^{8/4}$Pb value in Late Cenozoic basalts along a profile across the northern Tuva–Mongolian paleomicrocontinent and the adjacent Early Caledonian zones. Sample location along profile I–II on the schematic map (top) and corresponding data points on the diagram (bottom) are shown by the same symbols. Sampling areas: (ET) Eastern Tuva, (B) northwestern boundary of the Tuva–Mongolian Massif, (OP) Oka Plateau (NW, SW, and E are the northwestern, southwestern, and eastern segments of the plateau, respectively), (TN) Tunkin River valley, (D) Dzhida River basin. (1) Cenozoic basalt, (2) Paleozoic, (3) Riphean, (4) Proterozoic, and (5) Archean.
increase in unradiogenic Pb but no substantial varia-
tions in $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}$. Component B2 is isotopically
enriched and identified by relatively high $^{87}\text{Sr}/^{86}\text{Sr}$
($\sim 0.7075$), low $\varepsilon_{\text{Nd}}$ ($\sim -0.75$), and low unradiogenic Pb.
Component B3 is also enriched ($^{87}\text{Sr}/^{86}\text{Sr} \sim 0.705$ and
$\varepsilon_{\text{Nd}}$ is approximately $-1$). According to Pb isotope
ratios, component B3 is close to component B2.

Diagrams of the $\Delta^{7/4}\text{Pb}$–$\Delta^{8/4}\text{Pb}$ relationships for
basalts of the northern and southwestern Tuva–Mongolian Massif and adjacent Caledonides are presented in
Fig. 2. Component A is characterized by high $\Delta^{7/4}\text{Pb}$ with
$\Delta^{8/4}\text{Pb}$ within the DUPAL anomaly range (nearly 69). Components B2 and B3 with the high
$\Delta^{8/4}\text{Pb}$ values ($\sim 100$) correspond to the DUPAL anom-
aly, whereas component B1 with the low $\Delta^{8/4}\text{Pb}$ value
($\sim 20$) is assigned to depleted mantle material.

Component A plays a substantial role in basalts of the
northeastern and eastern Oka Plateau and the
Tunka rift valley. On the diagrams in Fig. 2, the data
points of basalts from these areas fall between the fieldsor volcanic rocks of northeastern and southwestern
Japan. Basalts of the southwestern Oka Plateau are
characterized by the widest variations in the $\Delta^{7/4}\text{Pb}$
and $\Delta^{8/4}\text{Pb}$ values. Three rock groups differ from each
other in component variations. In the first group (with a
lava age of about 11 Ma), relationships between com-
ponents A and B3 do not change with varying contents
of component B1. In the second group (with a lava age
of about 9 Ma), component B3 is predominant. In the
third group (with a lava age of about 2 Ma), component
B3 is missing and components A and B1 mix with each
other. Rocks of the second group fall into the basalt lava
field of southwestern Japan. Data points of basalts from
the Dzhida and Eastern Tuva zones fall within the vol-
canic rock field of northeastern Japan. Specimens taken
at the boundary between the Tuva–Mongolian paleomi-
crocontinent and Eastern Tuva zone yield a separate
trend intermediate between isotopic compositions of
these areas.

Anomaly origin. The Garga Block of metamorphic
rocks is situated in the northeastern Tuva–Mongolian
Massif. The model Pb isotope age of galena from gold
ore deposits in the Garga Block demonstrates that the
principal ore material source was the Late Archean con-
tenental crust remobilized during the Early Paleozoic
metamorphism and granite formation about 450 Ma
ago, while the homogeneous, relatively radiogenic
composition of Pb in galena from the Butugol Block is
interpreted as evidence for its formation during the
Early Paleozoic metamorphism and granite magmatism
[13]. The data points of unmetamorphosed cenotypal
tholeiitic, alkaline basaltic, tephritic, and lamprophyric
dikes from the Garga and Oka zones, along with the
Sharyzhalgai Uplift of the Siberian Platform basement,
are confined to a common line corresponding to an iso-
chron age of about 500 Ma on the $^{207}\text{Pb}/^{204}\text{Pb}$–
$^{206}\text{Pb}/^{204}\text{Pb}$ diagram [14]. Proterozoic volcanic rocks
from the southeastern and southwestern framings of the
Siberian Platform basement with a Rb–Sr isochron age
of about 1700 Ma also correspond to the line with an
age of about 1700 Ma on the Pb isotope ratio diagram.
It should be noted that this linearity does not necessar-
ily reflect radiogenic Pb accumulation after the isotope
homogenization, but may represent a result of the mix-
ing of materials with low and high $\mu$. In other words,
evolution of the U–Th–Pb isotope system as a closed
system could follow two alternative scenarios: homo-
genization and differentiation in terms of U/Pb and
Th/Pb ratios or development with the incorporation of
a new (subducted, for instance) material having a high

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Fig. 2. Diagram $\Delta^{7/4}\text{Pb}$ vs. $\Delta^{8/4}\text{Pb}$ for the Late Cenozoic basalt. Symbols are the same as in Fig. 1. The diagram shows mantle
components A, B1, B2, and B3 of the Tuva–Mongolian Massif [10], directions of the DUPAL enriched components (EM1 and EM2)
and HIMU component [7], and Late Cenozoic basalt fields of northeastern and southwestern Japan [12].
U/Pb ratio. These trends correspond to lithospheric blocks with different isotope-geochemical characteristics, namely Proterozoic accreted complexes of the Siberian Platform basement and the younger Tuva–Mongolian Massif basement.

Coefficients of U distribution between various mineral phases of mantle rocks and melt are practically identical to those for Th. Therefore, Th/U ratios in the erupted basaltic melts, which are not contaminated by the crust, correspond to those in the melting mantle material. In common mantle mineral paragenesis, Th is not enriched relative to U, but such an enrichment can be achieved during melting of mantle areas with a specific composition (e.g., with Zr). In this case, $1 \leq D^{Th} \leq D^{U}$ [15].

The large DUPAL anomaly of the Southern Hemisphere was interpreted in the following ways: (1) an area of a relative increase in Th/U due to a minor extraction of crustal components from the Earth’s undifferentiated material at the early stage of its development (the value is less relative to the depleted mantle reservoir), or (2) the result of a long-term subduction and recycling of the oceanic crust within small areas, possibly, during the formation of supercontinents.

If we follow the first hypothesis, it should be noted that some mantle xenoliths in basalts of the Tuva–Mongolian Massif chemically correspond to the Earth’s undifferentiated material. However, similar undifferentiated mantle xenoliths have been encountered in alkaline basalts within the Caledonian Dzhida zone and other areas, where the DUPAL anomaly is absent. The sublithospheric depleted component A can be considered as the mantle material having the closest compositional signature of the Earth’s primary substance. The elevated $\Delta^{8/4Pb}$ values (~69) allow us to correlate the general component A of the Tuva–Mongolian Massif with oceanic basalts of the Indian Ocean, presumably contaminated by deep plume material [7]. Component A may correspond to the plume material. In this case, the anomaly could be related to processes in the lower mantle, and enriched components B2 and B3, which correspond to the DUPAL anomaly, should be related to local transformations in the lithosphere. Another explanation of the origination of component A is a convective mixing of the sublithospheric mantle material with that of the lower lithosphere. This possibility is suggested by the sharp shift of isotopic characteristics in basalts during the transition from the microcontinent to the adjacent Caledonian zones (Figs. 1, 2).

The second hypothesis of origination of the DUPAL mantle anomaly beneath the Tuva–Mongolian Massif is supported by the distribution of Late Precambrian and Early Paleozoic suprasubduction igneous rock series. However, the same series occur in the adjacent Caledonian zones where the DUPAL anomaly is missing. Therefore, the subduction process is not the only condition of the anomaly formation.

According to the classification of radiogenic isotopes, the subduction-related component (EM2) is present in back-arc basalts of the Yamato Basin, erupted under spreading and rifting conditions. The DUPAL anomaly is absent in the Late Cenozoic subduction zone of northeastern Japan. It represents a subduction zone of the Pacific Plate and lacks the DUPAL characteristics. In addition, this zone was characterized by a strong additional supply of depleted asthenospheric material with radiogenic Nd, unradiogenic Sr and Pb, and low $\Delta^{7/4Pb}$ and $\Delta^{8/4Pb}$ values [12]. Judging from the variations in the isotopic characteristics (Fig. 2), such a deep dynamics could be manifested in Caledonides of the Eastern Tuva and Dzhida zones. At the same time, the DUPAL anomaly is well expressed in southwestern Japan. It is likely that this isotope-geochemical peculiarity is caused by the episodic subduction of the Philippine Sea Plate (an individual DUPAL anomaly domain [9]) beneath southwestern Japan.

**Conclusions.** Elevated $\Delta^{8/4Pb}$ values, which are typical of the DUPAL anomaly, were determined in Late Cenozoic mantle-derived alkaline basaltic lavas erupted within the area stretching from the Oka zone to the Khamardaban zone. The anomaly domain distinguished here represents the mantle section of the Tuva–Mongolian Massif basement. The anomaly is manifested in the general sublithospheric component A and is substantially intensified due to melting of the enriched lithospheric mantle of the Tuva–Mongolian Massif (components B2 and B3) but smoothed due to melting of depleted lithospheric areas (component B1). Beneath the Early Caledonian Eastern Tuva and Dzhida zones adjacent to the Tuva–Mongolia Massif, the enriched mantle with the DUPAL anomaly characteristics is missing.

The revealed anomaly discreteness has cast some doubt on the origination of the Asian DUPAL domain [9] due to mantle upwelling beneath central Asia and the Asia–Pacific transitional zone. We suppose that the discrete DUPAL anomaly was transported into this lithospheric mantle area with fragments of eastern Gondwana drifting across the Paleoasian Ocean in the Late Precambrian. The anomaly is atypical of Early Caledonian structures adjacent to these fragments. Therefore, the DUPAL characteristics of the mantle lithosphere section can promote the identification of eastern Gondwana blocks and the elucidation of their role in Late Precambrian accretionary processes and similar processes between Gondwana and Asia at the Early–Middle Jurassic boundary.

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