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GEOLOGY

Origin of the De Long Rise, East Arctic

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The tectonics of the East Siberian Sea shelf remains a matter of debate [1, 4–6, 9, 11, 12] because of its poor geological coverage based on the on-land observations of a small number of islands (Lyakhovsky, New Siberian, and De Long archipelagoes) and scanty geophysical data. The consideration of gravity measurements and aeromagnetic maps [13 among others] in combination with sporadic seismic reflection lines [5] made it possible to delineate the De Long Rise. The results of on-land geological studies primarily concerning magmatism [14] constrained the timing of this rise to the Middle Cretaceous–Pleistocene.

The *tectonic position* of the De Long Rise is related to the Hyperborean continental plate. After detachment from Alaska during opening of the Canada Basin, the De Long Rise adjoined the Verkhoyansk–Kolyma tectonic domain along the South Anyui collisional suture in the Middle Cretaceous [5, 8, 9]. Thereby, the cover of the adjacent Hyperborean Plate was deformed with the formation of the Middle Cretaceous Verkhoyansk–New Siberian–Chukchi Peninsula orogenic system [11]. The unconformably overlapping Aptian–Albian terrigenous coal-bearing sequence and volcanics played the role of neoautochthon in this system. The northeastern sector of this plate, which borders in the east with the Makarov and Canada basins, is overlapped by a slightly disturbed Mesozoic cover. The De Long Rise was regarded previously as a separate uplift of this plate or a terrane with uncertain boundaries [8, 9]. However, many sketch maps exhibit strikingly correct arcuate [1, 6, 13] or even semicircular [12] western and southern boundaries of this rise emphasized by the arcuate (in plan view) New Siberian and Vil'kitsky grabens (Fig. 1). Based on the geophysical data, Gramberg et al. [2] also have shown that the De Long Rise is elliptical in plan view.

The *tectonic structure* of the De Long Rise may be interpreted from geophysical data as a ring system of fault-bounded horsts and grabens ~1000 km in diameter (Fig. 1). The central (highest) sector of this arch (about 400 km across) incorporated a part of the Hyperborean Plate with the slightly deformed Paleozoic–Mesozoic cover. The outer zone of the arch, which embraces the southern shelf, including the New Siberian Islands, is superimposed on the New Siberian–Chukchi fold–nappe system. The De Long Rise is clearly expressed in the gravity field owing to the system of concentric arcuate faults in combination with radial fractures expressed as gradient zones that divide arcuate (in plan view) positive and negative anomalies or positive anomalies of variable intensity. The most intense circular positive gravity anomaly consisting of a number of concentric arcuate anomalies corresponds to the central uplifted sector of the rise (Fig. 1). The core of this circular anomaly with the highest intensity of the gravity field embraces the territory of the Zhokhov, Vil'kitsky, Henrietta, and Jeannette islands (Fig. 1), most of which are covered by within-plate basalts [14]. The mid-Cretaceous basalts of Bennett Island adjoin this basaltic cover in the north [14]. The outer zone of the arch correlates with a system of arcuate (in plan view) positive and negative anomalies that delineate horsts and grabens. The arcuate structures are bounded by arc-shaped normal faults and range from 50 to 150 km in width. This feature is probably typical of the New Siberian and Vil'kitsky grabens (Fig. 1), which are located at the western and southern margins of the De Long Rise, respectively, and are marked by negative gravity anomalies. A similar arcuate anomaly at the eastern periphery of the De Long Rise corresponds to the Eastern Basin (Fig. 1). Outer arcuate faults were traced on the Kotel'ny and Bol'shoi islands as well. The De Long Rise is crosscut by radial faults, and fault-line grabens are recorded in some places (Fig. 1). Based on the interpretation of the seismic reflection profile across the southern sector of the De Long Rise (Fig. 1), one can recognize six seismic complexes (1–6) [4] with ambiguous dates because of the lack of borehole data. However, the spatial distribution of the complexes suggests the succession of their formation. Complexes 1–5 disturbed by normal faults are coeval to gra-

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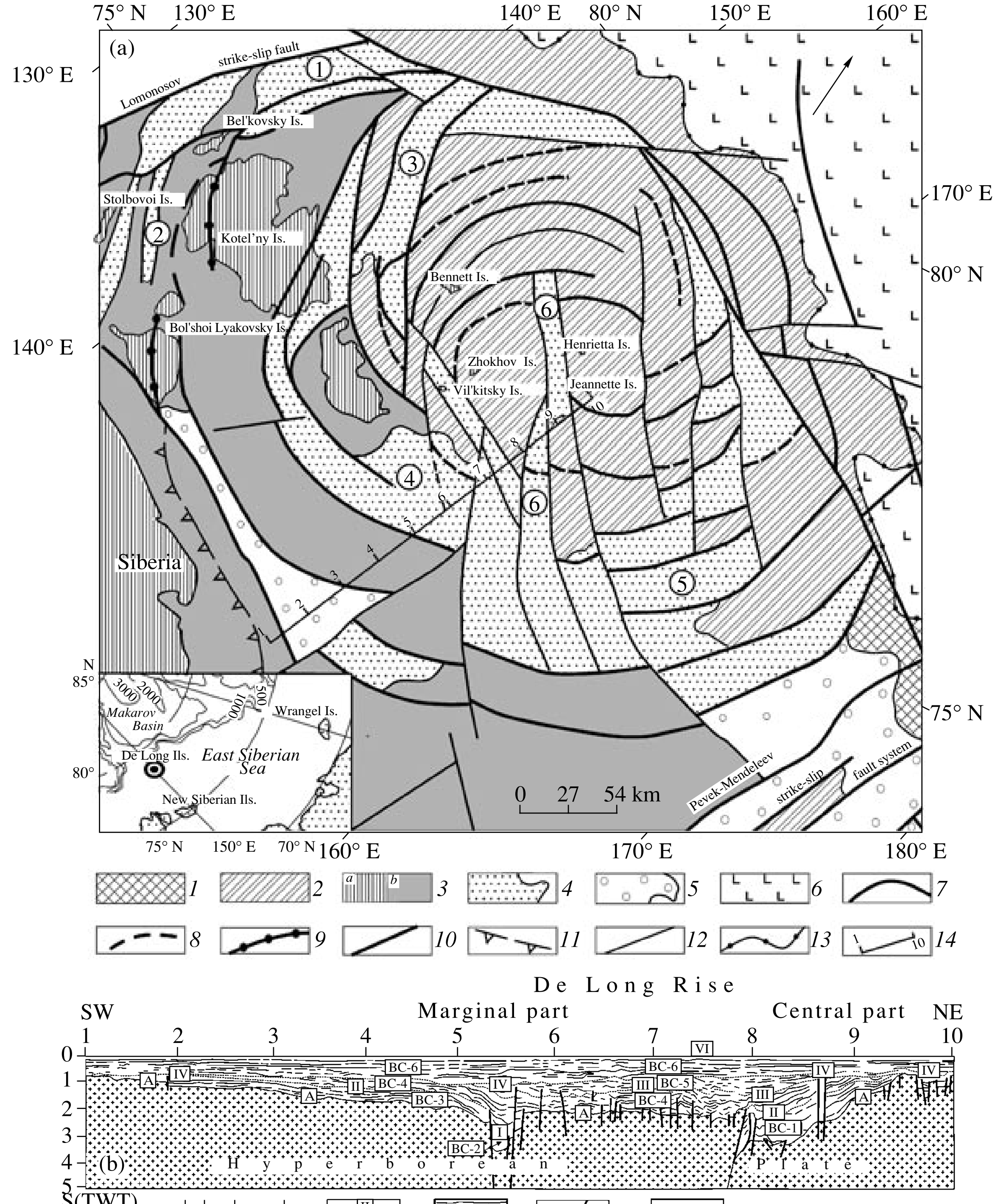

Fig. 1. Structure of the Middle Cretaceous–Cenozoic De Long magmatic rise and seismogeological profile LARGE-8900 [4]. (a): (*1–3*) Hyperborean continental plate: (*1*) with undeformed Paleozoic cover, (*2*) involved in the De Long Rise, (*3*) with Paleozoic–Lower Cretaceous cover deformed during mid-Cretaceous orogeny on (*a*) land and (*b*) the bottom of the East Siberian Sea; (*4*) basins related to arcuate and radial faults at the De Long Rise (originated in the Middle Cretaceous and continued to evolve in the Late Cretaceous and Cenozoic); (*5*) Cretaceous–Cenozoic syncollision and fault-line basins (mainly pull-apart); (*6*) Makarov Basin with presumably Late Cretaceous–Early Paleogene crust; (*6–9*) arcuate faults deduced from (*7*) gravity measurements, (*8*) aeromagnetic survey, and (*9*) geological data; (*10*) strike-slip fault system; (*11*) frontal sector of the mid-Cretaceous South Anyui collision suture (inferred from aeromagnetic data); (*12*) other faults; (*13*) foothill of the continental slope; (*14*) seismic profile LARGE-8900. Grabens and basins (numerals in circles): (1) Anisin, (2) Bel'kovsky–Svyatoi Nos, (3) New Siberian, (4) Vil'kitsky, (5) Eastern, (6) Radial. Geographic position of the De Long Archipelago is shown in the inset. (b): (*1a*) seismic boundaries and their indexes, (*1b*) surface of acoustic basement; (*2*) reflectors within seismic complexes; (*3*) faults; (*4*) indexes of seismic complexes. (TWT) two-way travel time, s.

bens [4]. The complexes pinch out at the arch crest, suggesting its uplift during the deposition of sediments. Complexes 1 and 2 are located at stake intervals 5/6 and 8/9. Hence, the initial stage of arching was marked by the appearance of two narrow (10–25 km) grabens. The marginal arcuate graben formed at the initial stage of the Vil'kitsky and probably New Siberian grabens. The Radial graben (Fig. 1) disturbed the arch crest. The maximum thickness of complex 3 is confined to these two grabens as well. The inferred age of complexes 1–3 is Cretaceous [4]. The high contrast of near-horizontal reflectors suggests that they are composed of terrigenous–volcanic rock sequences that are coeval to the Aptian–Albian basalts [14], which occupy the central sector of the arch and erupted at the early stage of its evolution. It is notable that the lowermost seismic complex bears attributes of mid-Cretaceous dislocations [4]. Hence, the onset of the De Long Rise formation was coeval to the mid-Cretaceous orogeny. The terminal Cretaceous–Paleogene boundary was characterized by the subsidence of a wide arcuate block of the Vil'kitsky Graben and the deposition of seismic complexes 4 and 5 in this block and the neighboring grabens [4]. The youngest seismic complex 6 (probably, Late Miocene–Holocene) makes up a continuous but unconformable cover on all older complexes. This complex is present in a reduced form on the arch crest that continued to rise.

Based on the gravity measurements, the De Long Rise is disturbed by variously oriented Late Cretaceous–Cenozoic strike-slip faults. In the east, the structure is bounded by the NE-trending Pevek–Mendeleev strike-slip fault system (Fig. 1), which extends from the coast of Chukchi Peninsula toward the central Arctic arch. The NE-striking Lomonosov strike-slip fault complicates the western sector of the arch. In the north, the De Long Rise is distorted by the NW-trending strike-slip and normal faults that mark the edge of the continental shelf. The strike-slip faults of a similar orientation are located on the southern side of the arch. Many strike-slip faults are accompanied by pull-apart basins, which are younger than the arcuate grabens that appeared in the Middle Cretaceous along normal faults.

The domal structure of the De Long Rise is emphasized by the aeromagnetic data. Its central area is delineated by a number of circular and associated semicircular positive anomalies that likely correspond to the Cretaceous–Cenozoic basaltoid fields and deep-seated magma chambers. The local positive magnetic anomalies clustered along marginal arcuate faults (Fig. 2) most likely fit the fields of similar basalts and their conduits. This assumption is corroborated by exposures of mid-Cretaceous volcanics on Kotel'ny Island, the territory of which is marked by an intense positive magnetic anomaly.

Igneous rocks exposed in the central De Long Rise correspond to alkaline basaltoids in composition and can be divided into two groups. The mid-Cretaceous group is developed on Bennett Island, whereas the Late Miocene–Pleistocene group is found on Zhokhov and Vil'kitsky islands [14]. The first group includes nepheline hawaiite with a K–Ar age of 124–106 Ma [14]. Judging from the high Ti and Fe contents, undersaturation with silica, and enrichment in incompatible elements, these rocks are close to Fe- and Ti-rich within-plate basalts characteristic of continental rifts and oceanic islands. Similar alkaline lavas, which may also be expected in other parts of the De Long Rise, are known elsewhere in the Arctic (in particular, the New Siberian Islands) as elements of the vast Arctic domain of plateau basalts [3, 14].

The younger (K–Ar age 6.1–0.4 Ma) alkali olivine basalts are exposed on Zhokhov Island. Together with older volcanics from Bennett Island, the olivine basalts display a common evolutionary picrite–alkali basalt trend typical of within-plate magmatism [14]. The high-alkali limburgite from Zhokhov Island (4.2–1.9 Ma) and Vil'kitsky Island (0.89–0.40 Ma) are the most primitive rocks of this association at the De Long Rise [14]. Basaltic rocks in the central part of the arch contain dolerite xenoliths of probably Early Cretaceous age (100 Ma). They are close to MORB in the REE pattern (Fig. 3) but are markedly enriched in radiogenic Sr and depleted in radiogenic Nd [14]. All basaltic rocks of the arch are enriched in REE (relative to MORB) and Sr isotopes but depleted in Nd isotopes (Fig. 3). In terms of isotopic–geochemical signatures, they are close to the Cretaceous–Cenozoic ocean-island basalts in the Pacific (in particular, volcanic rocks of the Marquesas Islands genetically related to the Pacific lower mantle superplume) [10, 15]. According to [14], a plume source (probably a system of connected magma chambers) was active beneath the De Long Rise during the last 125 Ma. This plume produced alkali basalts and limburgite with different degrees of melting. Olivine basalts of Bennett Island were formed at the initial mid-Cretaceous stage of arching at a relatively high degree of melting. Probably coeval dolerites from xenoliths found on Zhokhov Island are characterized by chemical attributes of E-MORB (Fig. 3). They are apparently related to spreading in the Makarov Basin [4, 5, 11]. The next plume-related magmatism, which was accompanied by the uplift of the De Long Rise, is recorded in the late Miocene after a 100-Ma-long interval. The lavas of this age are similar to the mid-Cretaceous alkali basalts. Limburgites (products of a low degree of partial melting of the plume source) erupted at the same stage. These rocks exposed on Vil'kitsky Island completed the evolution of within-plate magmatism at the De Long Rise 0.89–0.40 Ma ago (Fig. 3).

Magmatic diapirism, which produced the De Long Rise, most likely was related to the lower mantle upwelling. This assumption is consistent with the presence of a plume source beneath the De Long Rise and the absence of genetic links between Meso–Cenozoic basaltic rocks and spinel lherzolite xenoliths in this area. The Late Cretaceous–middle Miocene amagmatic

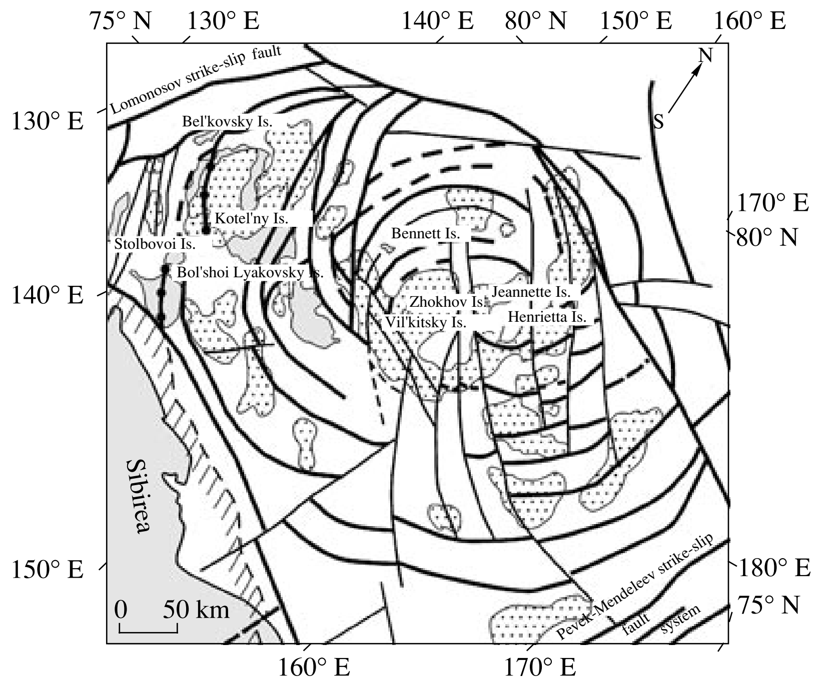

Fig. 2. Location of positive magnetic anomalies (dotted pattern) relative to the arcuate faults in the De Long Rise. Ranks of faults and other structural elements of the De Long Rise are shown in Fig. 1. The positive magnetic anomaly that corresponds to the frontal part of the South Anyui collision suture is hatched.

pause may be merely a result of insufficient sampling of the De Long Rise, where the insular land occupies only a negligible part of its total area. The magnetometric data testify to the much greater abundance of volcanic rocks at this arch. The main magma chamber likely was located beneath the central part of the arch and accompanied by smaller chambers localized at the arch periphery, including the area located beneath Kotel'ny Island (Fig. 2).

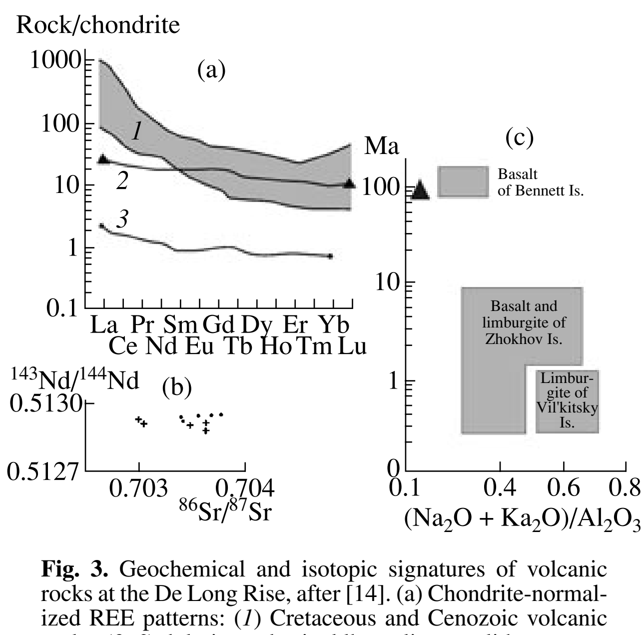

Fig. 3. Geochemical and isotopic signatures of volcanic rocks at the De Long Rise, after [14]. (a) Chondrite-normalized REE patterns: (*1*) Cretaceous and Cenozoic volcanic rocks, (*2, 3*) dolerite and spinel lherzolite xenoliths, respectively; (b) $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ relationship in the Cretaceous (dots) and Cenozoic (crosses) volcanic rocks; (c) compositional evolution of volcanic rocks at the De Long Rise (inferred age of dolerite xenoliths is designated by a triangle).

According to the results of seismic tomography [15], the eastern Arctic is distinguished by lower *P*-wave velocities at several mantle levels. This fact probably corresponds to the lateral flow of the lower mantle material away from the master plume according to the scenario suggested for the Pacific superplume [7, 10]. It is notable that the high-velocity domain of an inferred cemetery of slabs corresponds to the Pacific superplume at the core–mantle boundary (CMB) [7, 10]. This fact implies that the superplume was detached from the root layer D''. In contrast, the Arctic region at the CMB is related to the large low-velocity *P*-wave anomaly [15], which may be interpreted as a still continuing lower mantle upwelling from the layer D''. The Pacific and Arctic superplumes started to act apparently at the same time in the Middle Cretaceous. This period was characterized by a quiet magnetic field without inversions, suggesting a global cause of this phenomenon.

CONCLUSIONS

The joint consideration of geological and geophysical data has shown that the De Long Rise in the eastern Arctic is an arch within the Hyperborean Plate related to the Middle Cretaceous–Cenozoic mantle diapirism. According to gravimetric and seismostratigraphic data, the arch includes a concentric system of arcuate horsts and grabens bounded by arcuate faults combined with radial faults. A reduced Mesozoic–Cenozoic section is typical of the elevated central sector of the arch. The alkaline basaltic rocks responsible for the formation of the De Long Rise erupted in the mid-Cretaceous and Miocene–Pleistocene owing to the mantle plume [14]. The magnetometric data testify to a large magma source. The localization of smaller magma chambers and basaltic volcanic fields is controlled by marginal arcuate faults. Magmatism at the De Long Rise is related to the Arctic lower mantle upwelling that was synchronous with the Pacific superplume.

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