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OCEANOLOGY

New Geological–Geophysical Data on the Structure of the Ninetyeast Ridge

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The Ninetyeast (or East Indian) Ridge is one of the longest aseismic volcanic ridges in the World Ocean and one of the longest linear structures of the Earth. It is 200 km wide on average, and it extends in the meridional direction via the entire eastern part of the Indian Ocean for almost 5000 km (Fig. 1). The ridge is distinctly expressed in the bottom topography from its intersection with the West Australian Ridge (Broken) in the 31° S area to 10° N, where it disappears under sediments of the Bengal fan. Farther up to 17° N, the Ninetyeast Ridge is traceable in the form of a buried anticlinal uplift of the oceanic basaltic basement. There are many hypotheses proposed for explaining the origin of this enigmatic structure, of which two are most popular at present. Many Russian and some foreign scientists believe that the Ninetyeast Ridge resulted from magmatic activity along a giant transform fault [1, 2]. The overwhelming majority of foreign scientists and some Russian scientists consider the formation of the ridge to have resulted from hot spot magmatism in the course of the Indian–Australian lithospheric plate movement above the ascending mantle plume [3, 4] similar to the classical Hawaiian–Emperor volcanic chain. The main argument in favor of the last hypothesis is provided by the regular successive increase in basalt ages along the ridge from 43 Ma in the south (DSDP Hole 254) to 77 Ma in the north (ODP Hole 758). Despite the fact that ages of basalts from drilled holes form a linear succession, the available seven points are insufficient for discovery of the assumed reverse age trends in its southern part, which follow from the analysis of the anomalous magnetic field [5]. New geological–geophysical data were obtained during Cruise KNOX06RR of the R/V *Roger Revelle* (United States) carried out in the Ninetyeast Ridge area in 2007 [6]. Prior to this cruise, it was assumed that dredging along the ridge should yield samples for representative radiometric dating and geochemical analysis of basalts, which is necessary for testing the "hot spot" hypothesis. The second task of the cruise was a detailed geophysical site survey in areas of planned drilling on the ridge with deep (up to 200–300 m) penetration into basalts (IODP Proposal 620).

Geophysical studies. During the KNOX06RR cruise, a continuous geophysical survey (3500 km in total) was continuously carried out along the arch part of the Ninetyeast Ridge between 5.5° N and 26° S. The survey included bathymetric, seismoacoustic (at 3.5 kHz), magnetometric, and gravimetric profiling (Fig. 1). The detailed geophysical survey using all these methods and additionally multichannel seismic profiling was also performed at six sites of the planned drilling and along the latitudinal profile in the 19° S area [6]. In total, 10 500 km of geophysical records were obtained, 5 500 km of records from planned drilling sites included, of which 3900 km were obtained by multichannel seismic profiling. The bathymetric survey was conducted using the multibeam Konsberg Simrad EM120, which offers the opportunity to compile a large-scale map of the bottom relief for a band of 10–20 km in the online regime. All the data obtained during the cruise were edited and processed on board during the cruise. For multicahannel seismic profiling, a 48-channel Geometrics GeoEel streamer, 600 m in length, was used to record data. Two GI air guns were

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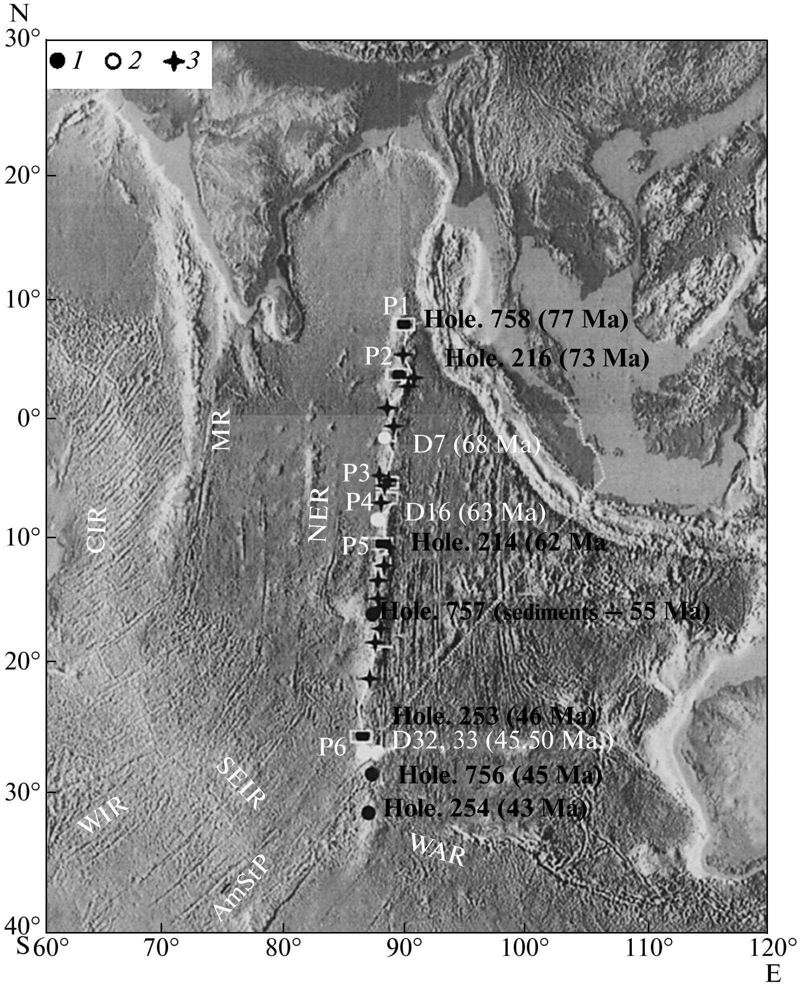

Fig. 1. The schematic map of the study area in the KNOX06RR cruise; the route of the ship is shown by a white line. Main ridges: (NER) Ninetyeast, (WAR) West Australian (Broken), (MR) Maldives (Chagos–Laccadive), (SEIR) Southeast Indian, (WIR) West Indian, (AmStP) Amsterdam–Saint Paul islands. Sampling sites at the Ninetyeast Ridge: (*1*) DSDP and ODP holes with ages (in brackets), (*2, 3*) dredging stations where basalts were obtained during the cruise: (*2*) preliminarily dated, (*3*) the study is in progress.

used for source, with working volumes of 0.9 and 1.7 l. The digital processing of seismic data after the cruise was performed at Texas A&M University using the ProMax processing software suite. Processing steps included band-pass filtering, geometric corrections, normal moveout corrections, stacking, and time-migration. The advanced technique made it possible to study with high resolution the structure of the sedimentary cover constituting the upper part of the basaltic basement. Processing of magnetometric and gravimetric data is still in progress.

The multibeam echo sounder survey revealed substantial variations in the Ninetyeast Ridge morphology along its strike. Its northern part includes separate large isometric rises [7]. Southward, they gradually join each other and the ridge becomes narrower. The middle segment of the ridge comprises numerous linear local uplifts and depressions resembling horsts and grabens, respectively. Its southern part represents a single spacious high mountainous massif approximately 2000 km long. Its gentle western slope is characterized morphological features typical of volcanic rises. The eastern slope of this segment is formed by a steep scarp 1–2 km high, which is undoubtedly formed by fault tectonics. Development of giant meridional faults in this region is established by previous geophysical studies [5, 8]. In addition to these longitudinal faults, the Ninetyeast Ridge exhibits large transverse structures represented by deep graben-shaped depressions of the near-latitudinal–northeastern strike (Fig. 2a), which were probably formed in response to reorganization in the kinematics of lithospheric plates during the Eocene [3, 8]. The seismic records obtained in the KNOX06RR cruise also demonstrate numerous smaller tectonic structures. Large grabens bounded by older faults and likely formed at early stages of the ridge development are filled with deformed sediments (Fig. 2b). Many faults crossing

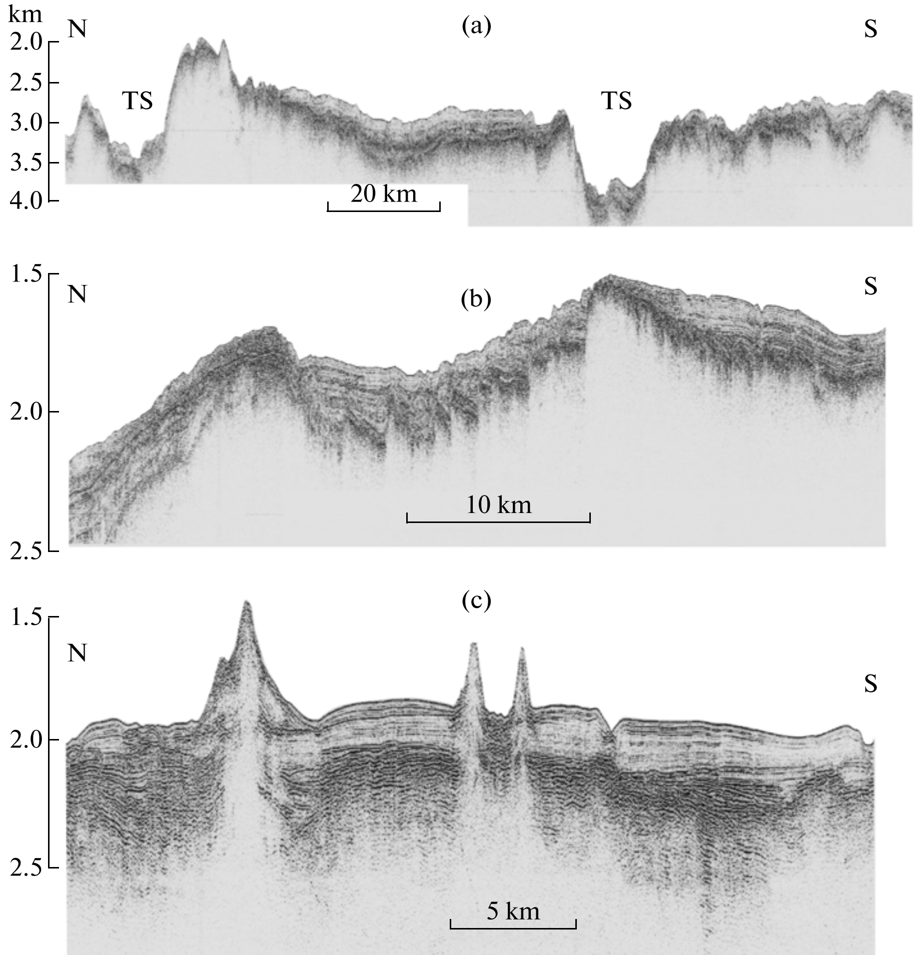

Fig. 2. Multichannel seismic profiling sections obtained in the KNOX06RR cruise. (a, b) Tectonic structure in the central part of the Ninetyeast Ridge: (a) deep transverse fault-line depressions of the northeastern strike or transverse structure (TS), areas P3 and P4; (b) two types of different-age deformations: old graben bounded by normal faults and young faults and folds in its sedimentary infill, Area P5; (c) solitary seamounts (young volcanoes ?), Area 6. The position of areas is shown in Fig 1.

the basement continue upward into overlying sediments of the lower stratified shallow-water complex with numerous folds. These data imply several stages in the tectonic development history of the Ninetyeast Ridge. Similar fold–fault deformations in the upper acoustically transparent complex of pelagic sediments are less distinguishable. It is conceivable that they are locally developed up to the floor; i.e., they are young. The neotectonic activity of the ridge is evident from the high level of registered seismicity [9]. Young deformations defined in its sedimentary cover resulted probably from intraplate tectonic activity and intraplate deformations in the adjacent Central Basin [10]. The general block morphology of the ridge and fault–fold deformations in its crust imply the significant role of tectonic processes in its formation, although final conclusions may be drawn only after complex interpretation of the obtained geophysical materials.

The geophysical survey during the cruise revealed that the arched part of the Ninetyeast Ridge hosts along its entire strike small solitary volcanic edifices (Fig. 2c), the age of which is of particular interest. Previously, several such edifices were established by a bathymetric multibeam survey in the central part of the ridge [11]. As is shown by seismic profiling in Area P1 (ODP 758 Hole area), the thickness of sediments overlying the seamount in the northern part of the ridge amounts to 15–20 m. The downlap patterns of reflectors inside sediments and preliminary paleomagnetic analysis of modeled anomalous magnetic field allow a young age for this volcano to be assumed [7]. Dredging at this seamount yielded only lithified carbonate sedimentary rocks, which cover the volcanic cone. In the south, the thickness of sediments overlying seamounts is reduced to minimal values. In southernmost Area P6 (DSDP Hole 253 area), the volcanic edifice protrudes the sedimentary cover almost up to the floor or is probably exposed (Fig. 2c). Such relationships likely indicate the relatively young age of volcanism. The multibeam survey also revealed numerous

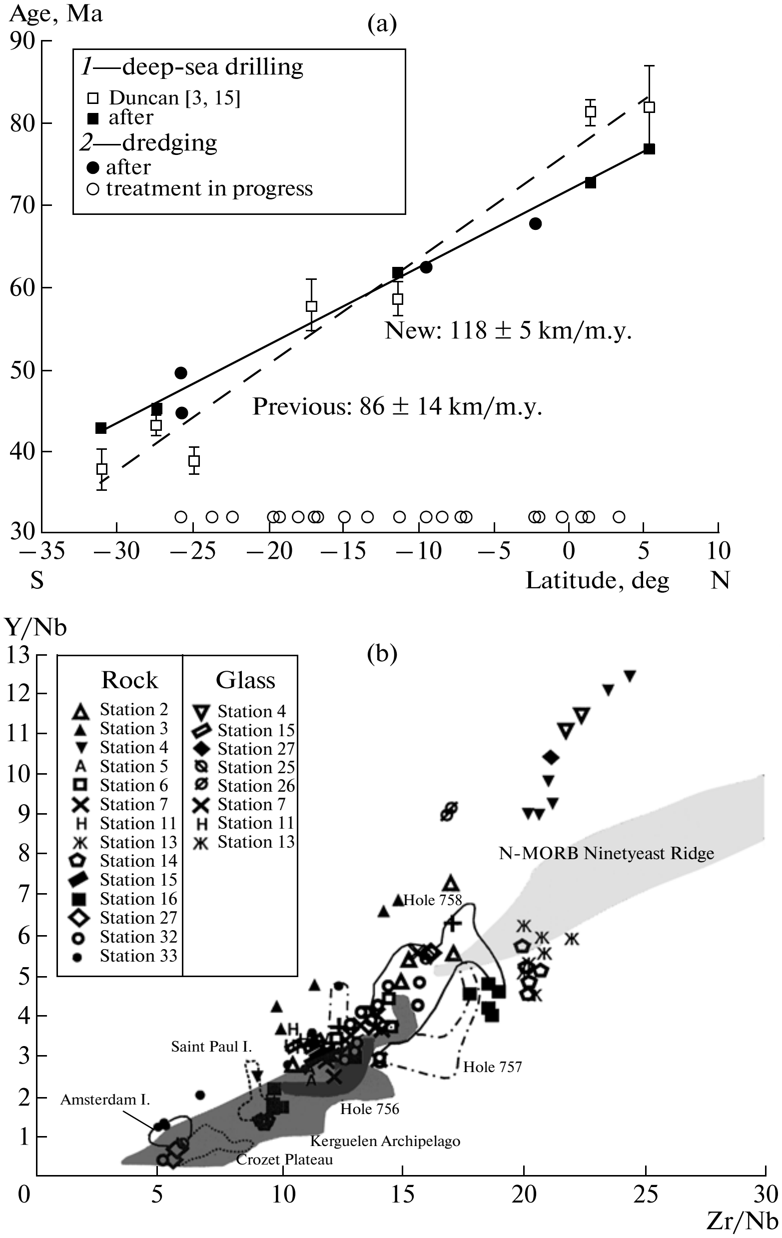

Fig. 3. Geochemical characteristics of basalts from Ninetyeast Ridge. (a) Plot illustrating changes in the Ar^{40}/Ar^{39} age of basalts along the Ninetyeast Ridge: (*1*) deep-sea holes, (*2*) dredging stations in the KNOX06RR cruise. In both selections, ages become older in the northern direction; new data demonstrate the linear correlation between increasing ages from 77 to 43 Ma and substantially higher and well-expressed motion velocity (118 ± 5 versus 86 ± 14 km/m.y.). The spatial positions of basalts dredged in the KNOX06RR cruise are shown along the *X* axis by open circles; (b) plot demonstrating Y/Nb and Zr/Nb values in basalts of the Ninetyeast Ridge. By these parameters, basalts fall into the range between basalts of oceanic islands (Kerguelen Archipelago, Crozet Island, and Amsterdam–Saint Paul islands are two potential hot spots, which are responsible for the formation of the Ninetyeast Ridge) to enriched MORB varieties from the Southeast Indian Ridge (the lower part of the MORB field), to unusual samples from Stations 4 and 26, where the Zr/Nb values are overlapped with MORB rocks from the Southeast Indian Ridge, but they have higher Y/Nb values than N-MORB at a given Zr/Nb value).

small-scale morphological structures of different geneses in the bottom topography, which are missed during the survey with a single-channel echo sounder. Thus, this area is characterized by a wide spectrum of accumulative–erosional sedimentary bodies likely related to intense bottom currents and slumping. Small isometric depressions could be formed due to migration of fluids toward the floor, which may also be caused by tectonic activity.

Geological studies. During the KNOX06RR cruise, basalts were obtained at 23 (of 33 total) dredging stations: in the area from Station 2 in the north (03°15′N) to Station 33 in the south (25°40′ S) (Fig. 1) [6]. This substantially increased the density of rock sampling at the Ninetyeast Ridge. The total weight of dredged rocks is 3135 kg, 2238 kg of basalts included. They are accompanied by lithified carbonate rocks, phosphorite, chert, ferromanganese crusts, and volcaniclastic varieties. Most basalts were obtained from steep slopes of the ridge at depths exceeding 3500 m, where tholeiitic or alkali basalts erupted in underwater conditions, i.e., pillow lavas, were usually found. On the contrary, in deep-sea holes, which recovered the volcanic basement at the arch of the Ninetyeast Ridge, samples are represented by tholeiitic basalts that erupted in subaerial settings [3, 12, 13].

New Ar^{39}/Ar^{40} geochronological data obtained for basalts from five holes and several samples dredged during the cruise [14] served as a basis for new kinematic interpretations (Fig. 3a). The results of the geochronological analysis performed at the Massachusetts Institute of Technology (MIT) with application of advanced technologies confirm the linear trend of the age increase towards the north. They are at variance with models of the collision between India and Eurasia, according to which the motion of the Indian litrhospheric block that drifted with a velocity of at least 200 km/myr started decelerating 55 Ma ago. At the same time, these results are consistent with the hot spot model, although conceding that data in the southern Ninetyeast ridge are insufficient to rule out a complex evolution. The date of 50 Ma determined for basalts from Station 32, which is located above the linear trend for changes in volcanism age, could indicate that this area formerly belonged to the Antarctic Plate and later was amalgamated by the Indian Plate due to the southward jumps of Wharton spreading centers closer to the hot spot that was responsible for the Ninetyeast Ridge formation.

The dredged rocks are variably altered by postmagmatic processes (L.O.I.s range from 0.3 to 10.4%), although glassy crusts of pillow basalts in some samples remained unaltered. For the characteristics of the bulk rock composition, samples from 14 dredging stations were analyzed at MIT by the X-ray fluorescence method to determine concentrations of major and minor elements and five glass samples in the electron microprobe for major elements; minor elements were studied by the laser spectroscopy method. Stable elements Y, Zr, and Nb were used during the analysis to eliminate the effects of postmagmatic alteration. The conclusions on the geochemical characteristics of mantle sources responsible for the formation of volcanics from the Ninetyeast Ridge were derived from the analysis of Y/Nb and Zr/Nb values (Fig. 3b). The depleted MORB mantle source of the Indian Ocean and hot spots that formed the Kerguelen Plateau and Amsterdam–Saint Paul islands represented probable sources for basalts of the Ninetyeast Ridge. Basalts from ODP Holes 756–758 fill the gap between the field of MORB varieties that erupted in the Southeast Indian Ridge and the field of basalts that formed the Kerguelen Plateau and Amsterdam–Saint Paul islands. The wide range of Y/Nb and Zr/Nb values in dredged rocks and glasses is remarkable. In the southern part of the ridge (stations 25, 27, 32, and 33), the ratios between these elements are characterized by high Nb contents, which imply the origin of basalts from hot spots. In its central segment (stations 13, 14, and 16), the Zr/Nb value is typical of the marginal part of the MORB field characterizing the Southeast Indian Ridge, and that obtained for the northern segment (Station 4) falls into the field per se. In samples from Station 4, the Y/Nb value is substantially higher against the background of the same Zr/Nb value. Similarly remarkable is the scatter of Zr/Nb values in rocks originating from the same dredge, for example, in basalts from stations 4, 16, 27, 32, and 33 (Fig. 3b). As a whole, the preliminary geological results confirm the conclusion that basalts dredged from the Ninetyeast Ridge originate from the Kerguelen hot spot. At the same time, they are geochemically heterogeneous and include untypical elements of depleted components that make them different from MORB varieties of the Southeast Indian Ridge, in addition to "Kerguelen" components, while the formation of the southern part of the ridge is related to the Kerguelen and Amsterdam–Saint Paul hot spots [14].

The geological–geophysical data obtained in the KNOX06RR cruise indicate the complex tectonomagmatic evolution of the ridge, which is likely far from being just a simple linear volcanic trace of the hot spot. This is evident from preliminary geochronological and geochemical data on basalts with "anomalous" characteristics from several dredges, although as a whole they confirm the "hot spot" hypothesis. The morphologically massive Ninetyeast Ridge is different from the classical Hawaiian–Emperor chain of solitary strato-volcanoes as well. New geophysical data demonstrate also that the Ninetyeast Ridge is tectonically more active than was thought previously. The observable different-scale tectonic deformations are evidently related to jumps of spreading centers of the Wharton Ridge and other later episodes in reorganization of kinematics of lithospheric plates in the region under consideration [3, 5, 8]. The defined young fold–fault deformations in the sedimentary cover of the ridge and young volcanic edifices at its arch appeared, probably, in response to such an episode in the Miocene, which was accompanied by intraplate tectonic deformations in the neighboring Central Basin.

Further progress in geological studies of the Ninetyeast Ridge, which are necessary for solving the problem of its origin and evolution, may be achieved using the *Mir* submersibles for detailed observations and targeted sampling of volcanic rocks.

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