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Geothermal regime and genesis of the Ninety-East and Chagos-Laccadive ridges

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Abstract

There are two well-founded hypotheses of the Ninety-East and Chagos-Laccadive Ridges genesis: the hypothesis of the extrusive source disposed at a junction of the spreading axis with transform fault and the hot spot hypothesis. The northward increasing trend of volcanism age and the average formation rate of the ridges calculated from the present deep sea drilling data (9 cm/a) shows their common genesis. Their origin is related to a northward migration of the Indian plate during the Late Cretaceous and Paleogene, with an average rate of 9 cm/a. The features of the age variations along the axes of the Ninety-East and Chagos-Laccadive ridges prove the relation of basement subsidence to the cooling model of the oceanic lithospheric evolution. Heat flow distribution in the vicinity of the ridges fits the same model of their oceanic origin and affiliation to the Indian plate. Assessment of the geothermal data and the basaltic age relate the origin of the Ninety-East and Chagos-Laccadive ridges to the hot spots hypothesis.

1. Introduction

The Ninety-East and Chagos-Laccadive aseismic ridges are the largest tectonic structures of the Indian Ocean (Fig. 1) . The Ninety-East Ridge separates the Central Indian Basin from the Cocos and West Australian Basins. The ridge has a S–N (slightly to the East) orientation and extends along 90° E more than 4500 km from 32° S to 10° N. The height of the ridge above adjacent deep Basins amounts, on the average, to 2000 m and its summit depth changes from 2000 m in the south to 3000 m in the north. The ridge is connected at an approximate right angle by the Broken Ridge at about 30° S.

The shallowest part of the Ninety-East Ridge is located near 25° S. The Osborn rise is situated at the west side of the ridge near 14° S. It has a roundish shape of ~200 km in diameter. In the north from 10° N the ridge is buried under the Bengal Fan sediments. The Ninety-East Ridge basement is revealed by seismic investigations up to 12° N (Sclater and Fisher, 1974; Luyendyk, 1977; Peirce et al., 1989).

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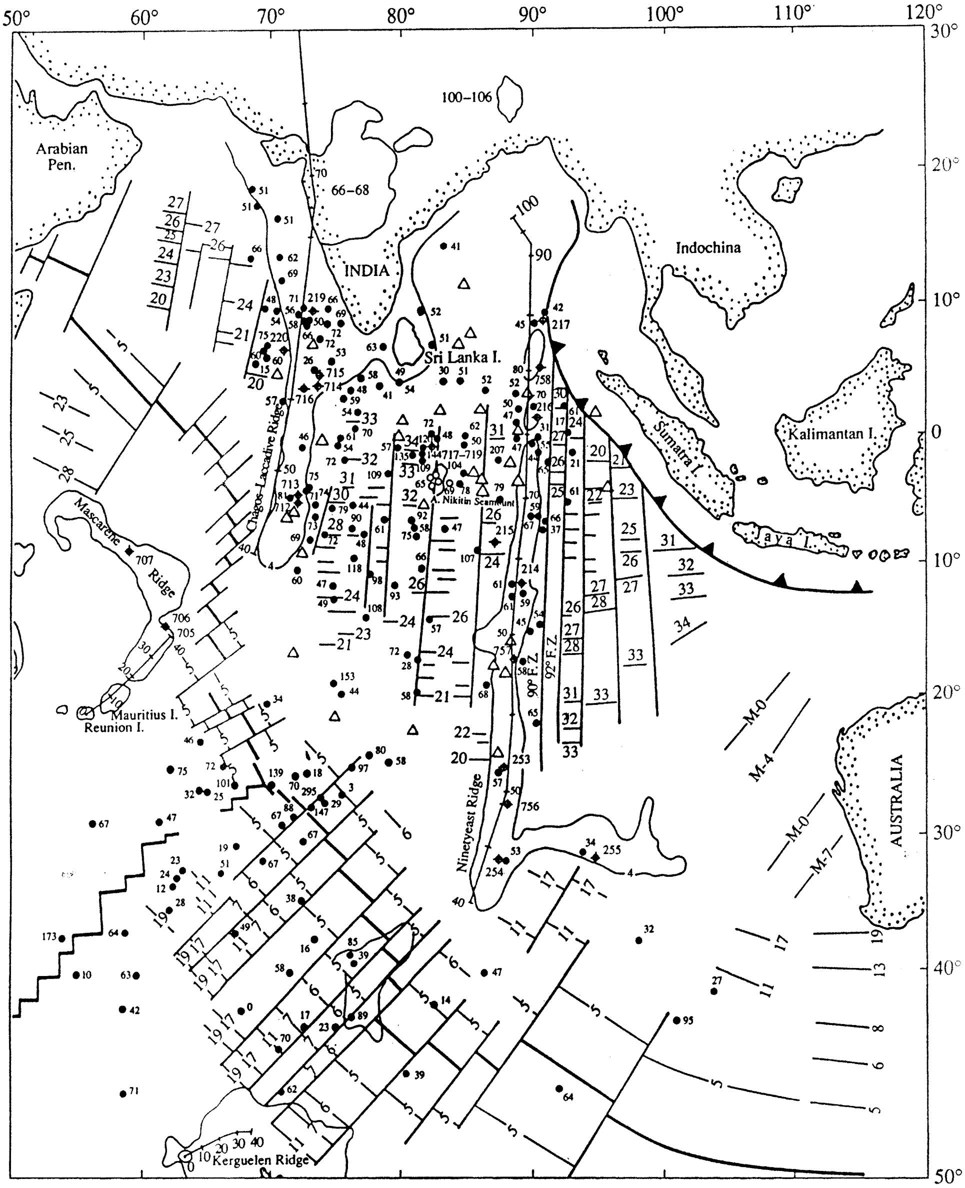

Fig. 1. Geothermal structure map of the Ninety-East and Chagos-Laccadive Ridges and adjoining areas of the Indian Ocean. Bathymetric contours, in km; thick and medium lines, axes of mid-ocean ridges and transform faults; thin lines, magnetic linear anomalies (Sclater and Fisher, 1974; Anderson et al., 1977; Shreider et al., 1989; Royer et al., 1991); thin long lines, theoretical tracks of hot spots with age intervals, Ma (Shipboard Scientific Party, 1988a,b); black circles, heat flow points, mW/m^2: on the World Ocean (Anderson et al., 1977; Sychev et al., 1987; Cochran et al.,1988), open circles, the same of the 20-th cruise of R/V Academik M. Keldysh (Verzhbitsky, 1996); circles with cross, deep-sea drilling sites (Whitmarsh et al., 1974a, 1974b; Weissel et al., 1991; Shipboard Scientific Party, 1988a, b; Fisk and Howard, 1990; Davies et al., 1974; Peirce et al., 1989; Von der Borch et al., 1974; Cochran et al., 1988); number on Indian continent, age of the Raj Mahal and Decan trapp basalts, Ma (Duncan, 1978); triangles, epicenters of earthquakes; thick line with black triangles, Sunda subduction zone.

The Ninety-East Ridge is morphologically divided into three provinces (first—to the north of 7.5° S, second—between 7° S and the Osborn Rise, third to the south of the Osborn Rise). In the first province, the ridge consists of a series of blocks with north-northeast strike, showing en echelon structures similar to those of the Pacific seamount chains. In the second province, it is of straight-line configuration and has steep symmetrical slopes; the width of the ridge here is about 100 km. In the third province, the ridge is characterized by widening to 200 km and it becomes shallower. Its section is asymmetrical with the east flank steeper. The geological–geophysical investigations during the 58th cruise of R/V "Vityaz" revealed a block structure of the central Ninety-East Ridge. The blocks of the ridge are shifted northeast along faults, which have a prolongation in the Central Indian Basin (Bezrukov and Neprochnov, 1981). From 7° S up to 31° S, the eastern part of the ridge is bounded by subparallel narrow ridges and depressions (Fig. 2). A trench extends along the eastern flank of the Ridge, which is interpreted as a transform fault zone between the Indian and Australian plates.

The average thickness of carbonate sediments on the crest and the slopes of the Ninety-East ridge is 500 m by seismic data (P-wave velocities assumed $V_p = 2.0 \div 2.7$ km/s). Under the sediments, rocks, occur with velocities $V_p = 3.9 \div 4.7$ km/s and thickness $2.0 \div 4.7$ km. A layer with $V_p = 6.7$ km/s and thickness $3.0 \div 5.5$ km is lying below. A boundary with $V_p = 7.7$ km/s is at 8.5 km depth below sea-level (Bezrukov and Neprochnov, 1981).

The Ninety-East Ridge is characterized by a quiet sign-variable magnetic field with anomalies, which do not exceed, on the average, 100–200 nT. The magnetic anomaly 32 was identified in the lower part of the ridge north of the equator and traced in the Central Indian Basin (Shreider and Vorob'ev, 1988).

The Ninety-East Ridge is weakly expressed in the gravity field. The free-air anomalies over the ridge crest amount to 40–60 mGal, and are about zero at the equator (Kanaev, 1979).

The Chagos-Laccadive Ridge separates the Central Indian Basin and the Arabian Basin. It extends approximately for 3000 km from 12° S to the western Indian coast at 15° N (Fig. 1). The summit of the ridge rises above the sea level as the Chagos, Maldive and Laccadive coral islands.

The height of the Chagos-Laccadive Ridge relative to the adjacent deep basins, near the Maldive Islands, is up to 2 km and its width in the upper part is 75–150 km. Along the northern part of the eastern coast there is a steep trench with a depth of 2.5–3 km. The ridge is bounded by broad accumulative plains that suggest efficient sedimentary supply from coral shallows and ridge slopes.

In the south, the ridge has an asymmetrical structure (Fig. 3). Its east slope is steeper, up to 10°, as compared with the western slope (0.5°). In the Chagos archipelago area, near the eastern ridge

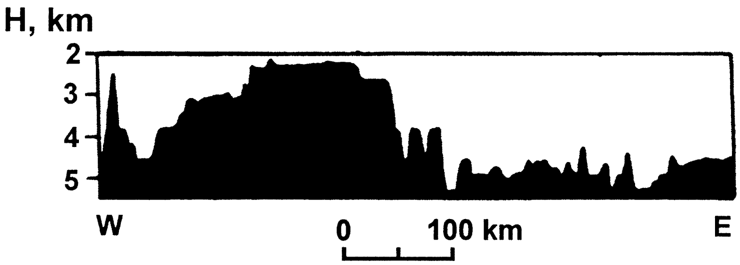

Fig. 2. Bathymetric profile crossing the Ninety-East Ridge at 22° S (Kanaev, 1979).

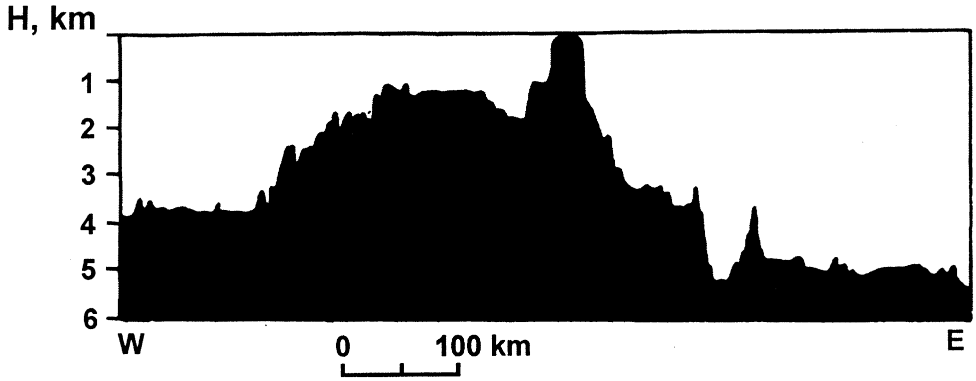

Fig. 3. Bathymetric profile crossing the Chagos-Laccadive Ridge at 7° S (Kanaev, 1979).

foot, there is the Chagos trench. Note that the southern part of the ridge is rotated in the southwest direction. Its relief takes the orientation of the structures of the Central Indian spreading ridge (Kanaev, 1979).

According to seismic data, the thickness of carbonate sediments ($V_p = 3$ km/s) at the Chagos-Laccadive Ridge crest does not exceed 600 m and at the ridge foot 1000 m. The crustal thickness between the Maldive and Laccadive Islands is about 15 km and includes a layer with $V_p = 5$ km/s and a thickness of 3 km, and a layer with $V_p = 6.8$ km/s and a thickness of 12 km. A refractor with $V_p = 8$ km/s lies below. The ridge is characterized by a weak variable magnetic field up to 300 nT. The ridge also is weakly expressed in the gravity field. The free-air anomalies over its foot are −20 to −60 mGal and those in the mountains and islands area amount to 50 mGal (Kanaev, 1979).

A number of hypotheses were suggested regarding the origin of the Ninety-East Ridge. McKenzie and Sclater (1971) suggested that the Ninety-East Ridge was uplifted as a result of the interaction of the Indian and Australian plates during the Late Eocene–Oligocene change from their northward motion to the northeast direction. However, the lack of considerable free-air anomalies over the ridge assumes isostasy. This fact lessens the validity of this hypothesis (Bowin, 1973).

In Luyendyk (1997) it is pointed out that the Ninety-East Ridge was a remnant fragment of the continental crust. Deep-sea drilling data obtained by Glomar Challenger (Davies et al., 1974) showed that the ridge is not composed of continental rocks but of tholeiitic basalts. According to micropaleontological data (Sites 254, 253, 214, 216) basalt ages increase from the south (37 Ma) to the north (75 Ma). These ages are close to the ages obtained by magnetic data for the Central Indian Basin segment to the west. The analysis of the sediment facies and also the bathymetric data showed that the ridge was formed in shallow water. As the first approximation, the ridge basement subsidence follows the theoretical curve of the cooling model (Sclater et al., 1974; Parsons and Sclater, 1977).

Sclater and Fisher (1974) suggested the idea that the Ninety-East Ridge originated at the junction of a "leaky" transform fault with the western part of the ancient spreading axis of the South-East Indian Ridge. According to paleomagnetic and magnetic field data, after the beginning of the Gondwana break-up (~190 Ma ago) India separated from Australia and Antarctica in the

Early Cretaceous and moved to the north from the spreading axis along the transform fault. During about 80–40 Ma basaltic melting occurred at the junction of the spreading ridge with the transform fault ($\sim 50^\circ$ S) that caused the formation of the quasilinear ridge structure. From 32 Ma onward the Indian plate began to move to the northeast together with the Ninety-East Ridge. This was caused by the activity of the eastern part of the South-East Indian Ridge.

The other hypothesis of the Ninety-East Ridge genesis is its formation from a deep mantle source such as a plume—hot spot hypothesis (Morgan, 1972; Peirce, 1978; Duncan, 1978, Morgan, 1981; Curray et al., 1982). The volcanics obtained by deep-sea drilling from the Ninety-East Ridge are not similar to mid-ocean ridge depleted basalts, but are close to tholeiitic basalts of the transitional T–MORB type. Petrochemical analyses of the basalts shows that they are enriched in isotopes of incompatible elements such as Sr, Nb, Rb, Zr, Y, radioactive P and others (Peirce et al., 1989). In particular, for these basalts the $^{87}Sr/^{86}Sr$ ratio varies from 0.7044 to 0.7056, which considerably more than in basalts from spreading ridges (0.7022–0.7029). Such enriched basalts are typical for hot spot oceanic islands, for example, Hawaii, Galapagos.

To the northeast from Reunion Island at the eastern slope of the Mascarene Ridge (Nazareth Bank) JOIDES Resolution has drilled two Sites (705 and 706; Fig. 1). At Site 706 plagioclase basalts were recovered. Their age by paleontological data is 36 Ma. Directly at the Maldive Ridge five Sites (712, 713, 714, 716 and 716) were drilled. Besides, one more hole (Site 219) is located in the eastern part of this ridge (Whitmarsh et al., 1974). However, the basement was reached only at Sites 713 and 715, where olivine tholeiites (Site 713) and subalkaline olivine basalts (Site 715) were collected with isotopic ages of 49.6 and 57.5 Ma, respectively (Fisk and Howard, 1990). Hence, the lava age also increases to the North. It should be noted, that volcanics collected at the Mascarene and Maldive Ridges are enriched in isotopes of incompatible elements, Nb and Zr in particular (Duncan, 1991).

We have performed an analysis of the available geological–geophysical data and first of all, recent deep-sea drilling and geothermal data to make a choice between "leaky" transform fault and hot spot hypotheses of the origin of both ridges, to determine the rate of their growth and the applicability of the cooling model (Parsons and Sclater, 1977), their relationship to respective lithospheric plates. All the data from deep-sea drilling sites in the ridge area, heat flow data obtained by R/V Akademik Mstislav Keldysh, R/V Pegas, magnetic data by R/V Morskoi Geophysik, (Russian Academy of Sciences) and Indian Ocean heat flow data were used in the present study (Anderson et al., 1977; Sychev et al., 1987; Cochran et al., 1988; Verzhbitsky, 1996).

2. The analysis of geological—geophysical data in the area of the Ninety-East and Chagos-Laccadive Ridges

The sublongitudinal profile through the Ninety-East Ridge, with the locations of the deep-sea drilling sites is shown in Fig. 4. The absolute age of the basalts obtained during deep-sea drilling was measured by the K-Ar and $^{40}Ar/^{39}Ar$ methods (Duncan, 1978, 1991).

Paleomagnetic data show that from Cretaceous till Early Oligocene the Indian plate moved to the north at about 8–10 cm/a (Duncan, 1978). In order to find the age changing along the Ninety-East Ridge we carried out model calculations for the average rate of the displacement of India to North using basaltic age in drilling cores. The difference in the real age of the ridge basalts

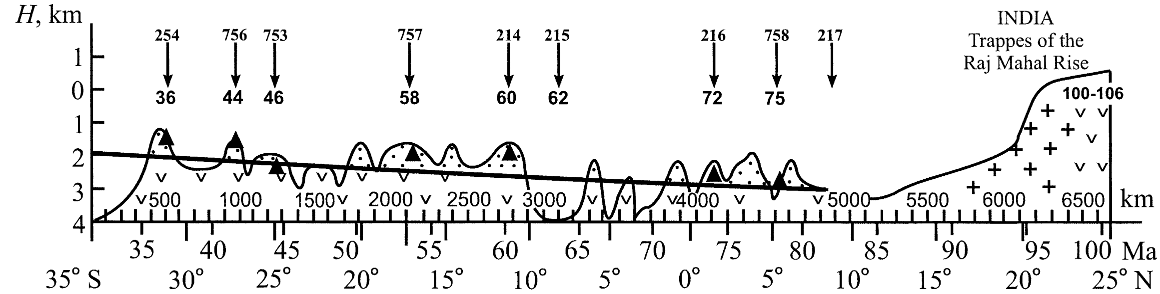

Fig. 4. Basement depth and the Ninety-East Ridge age. Arrows, number of deep-sea drilling sites (top) and basaltic age, Ma (bottom); dots, sediments; angles, basalts; black triangles, basaltic depth in sites; long line, theoretical curve of basement subsidence with age; crosses, granites of the Indian continent; numbers (100–106), basaltic age of the Raj Mahal trappes, Ma. Bathymetry by (Udintsev, 1979).

(including the Raj Mahal trapps) and the theoretical age estimated for 9 cm/a rate does not exceed 10% that shows at the optimal choice of the average rate. Note that the average rate of 9.4 cm/a (Duncan, 1978) found by the paleontological data (Sites 217 and 253) and by absolute chronology of the basalts (Sites 214, 216, 254 and the Raj Mahal basalts) is also close to 9 cm/a obtained from modeling. The satisfactory coincidence (with 15% discrepancy) of the age of the Central Indian Basin segment combined with the Ninety-East Ridge based on magnetic data and the calculated ages for the 9 cm/a rate (Fig. 1) shows that they evolved together. The absolute age of the basalts (62 Ma) at Site 215 differ by only 3.5% at the latitude of the site obtained by the 9 cm/a (64 Ma). Therefore it is concluded that the Ninety-East Ridge belongs to the Indian plate.

Sediments of the Ninety-East Ridge deep-sea drilling sites contain macro and microfossils: carbonate plankton, benthic and planktonic foraminiferas, ostracods, pelecypods, gastropods and others. Besides, in the sediments pollen assemblages, glauconites and volcanic material were found. The detailed study of sediment facies shows that the ridge formation took place in Cretaceous-Paleogene and suggests subaerial, lagoonal and shallow conditions in subtropical, tropical and temperate zones (Luyendyk, 1977; Royer et al., 1991). Thus, the paleontological data show that the Ninety-East Ridge, when formed, was shallow and then subsided and moved northward.

According to the cooling model (Parsons and Sclater, 1977) the thickness of the oceanic lithosphere increases and its surface subsidences. The basement depth can be given by the equation (Carlson and Johnson, 1994).

$$H = 0.345\ t^{1/2}, \tag{1}$$

where H is the basement depth of the ridge, in km, t is age, in Ma. The parameters used here in the half-space model are temperature of asthenosphere, $T_a = 1350$ °C; temperature of basalt $T_s = 1200$ °C; the coefficient of the thermal conductivity: $\lambda_l = 3.1$ Wm^{-1}K^{-1} ; the coefficient of the thermal diffusivity, $a = 7.810^{-7}$ m^2 s^{-1}.

The average rate of 9 cm/a of the Indian plate displacement to the north was used to estimate t and to plot (Fig. 4) the subsidence curve for the Ninety-East Ridge given by Eq. (1).

The typical deviation of the oceanic basement from the theoretical curve of Parsons and Sclater (1977) is usually ±15% (Backman et al., 1988). Fig. 4 shows that the maximum deviation of the basaltic basement from the curve does not exceed this value. It implies that the Ninety-East Ridge is close to isostasy and its formation took place in the accordance with the oceanic cooling model. The free-air gravity anomalies on the Ninety East Ridge do not exceed 100 mGal confirming its proximity to isostasy.

To obtain additional arguments on the Ninety-East Ridge origin in view of the cooling half-space model (Parsons and Sclater, 1977), we analyzed the heat flow data in the ridge area. The theoretical curve of heat flow with age can be estimated as (Carlson and Johnson, 1994).

$$q = 480\ t^{-1/2}, \quad (2)$$

where q is heat flow, in mWm^{-2}; t is age, in Ma.

Fig. 5a shows the heat flow distribution along the Ninety-East ridge and the theoretical geothermal curve based on Eq. (2) for plate velocity of 9 cm/a. Deviations of the measured heat flow values from the theoretical curve are on the average ± 20 mW m^{-2} for the sea-floor age greater than ~ 55 Ma (Stein and Stein, 1993, 1994). For the sea-floor with age less than ~ 55 Ma heat flows are mainly distorted by hydrothermal convection and they do not reflected the cooling half-space model (Carlson and Johnson, 1994).

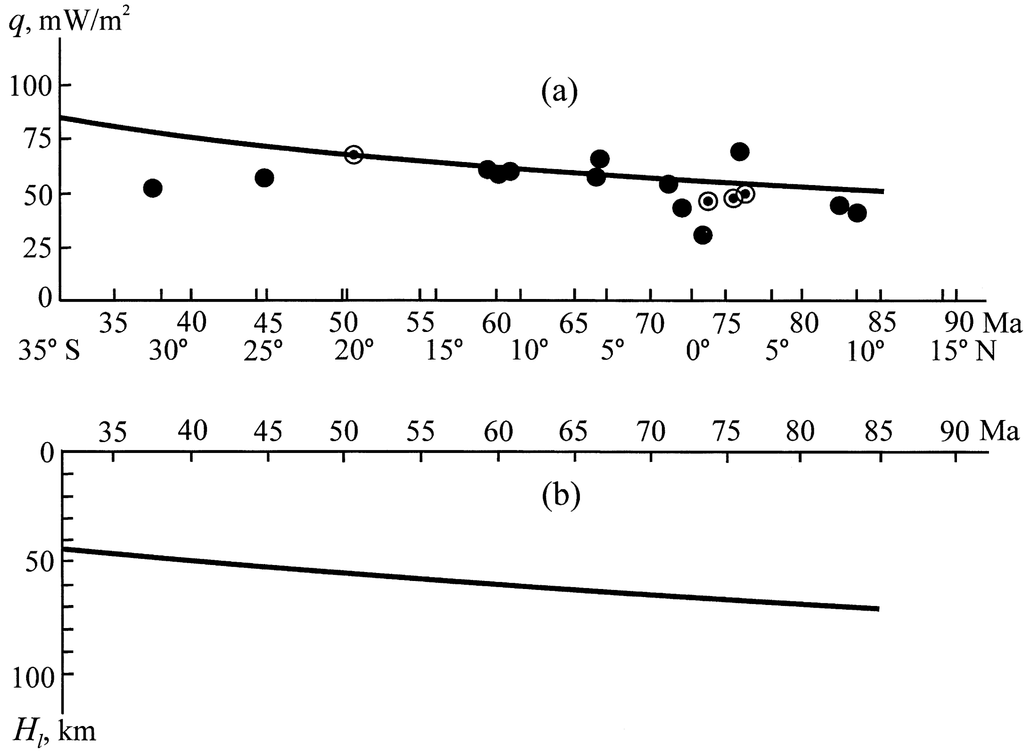

Fig. 5. (a) Heat flow distribution in area of the Ninety East Ridge and (b) variation of the ridge lithospheric thickness with age. Black circles, heat flow values over the ridge; circles with dot, the same—over the Central Indian Basin segment joined from the West to the ridge; long upper line, theoretical geothermal curve.

Measured values of heat flow are distorted by the bottom topography, sedimentation, contrast of thermal conductivity, refraction and so on. Therefore deviation of measured values of heat flow from theoretical geothermal curve (Parsons and Sclater, 1977) is in main features in accordance with Fig. 5 for sea-floor greater than ~55 Ma.

Thus, the geothermal data show that the Ninety-East Ridge origin is in accordance with the cooling model of the oceanic lithosphere. Besides, the closeness of heat flow values to the theoretical geothermal curve in the eastern segment of the Central Indian Basin (except for the anomalous zone of intraplate deformations) implies no significant transform motion between the ridge and this part of the Central Indian Basin, which belongs to the Indian plate.

The thickness of the oceanic lithosphere for the cooling model (Parsons and Sclater, 1977) of sea-floor formation is given by the equation (Parker and Oldenburg, 1973; Yoshii, 1975; Verzhbitsky and Sborshchikov, 1988).

$$H_l = 7.8\ t^{1/2}, \tag{3}$$

where H is lithospheric thickness, in km and t is age, in Ma. The lithospheric thickness beneath the Ninety-East Ridge (Fig. 5b) was found from Eq. (3) for age calculated for the 9 cm/a rate.

Fig. 6 represents a sublongitudinal profile through the Chagos-Laccadive Ridge showing the location of the deep-sea drilling sites. The absolute age of basalts recovered by deep-sea drilling (Sites 713 and 715) was determined by isotopic chronology (Duncan, 1991). Calculation of the average rate of the Chagos-Laccadive Ridge formation from basaltic age at Sites 713 and 715 gave 9 cm/a, equal to that of the Ninety-East Ridge. The similarity suggests that they have a common origin by northward the displacement of the Indian plate during Late Cretaceous–Cenozoic with the rate of 9 cm/a.

The basaltic age obtained at Site 220 (6°30.97′ N, 70°59.02′ E) in the Arabian Basin (Fig. 1) is estimated by paleontological data to be 51 Ma (Whitmarsh, et al., 1974). The difference of the sea-floor age here and of the Chagos-Laccadive Ridge age calculated for 9 cm/a by the deep-sea drilling data at the latitude of the site (61 Ma) reaches 20%. Besides, the age of the magnetic anomaly 20 in the Arabian Basin near the Chagos-Laccadive Ridge (Fig. 1) corresponds to 45 Ma. It is more than 20% smaller than the ridge age (58 Ma) from deep-sea drilling data. Thus, it

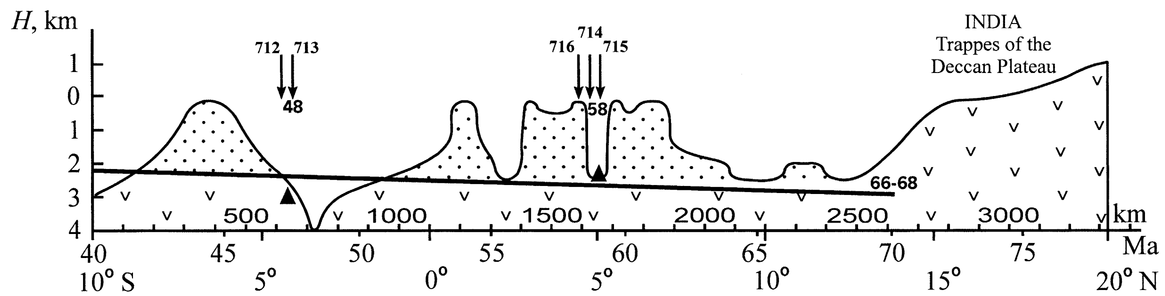

Fig. 6. Basement depth and the Chagos-Laccadive Ridge age. Arrows, number of deep-sea drilling sites (top) and basaltic age, Ma (bottom); dots, sediments; angles, basalts; black triangles, basaltic depth in sites; long line, theoretical curve of basement subsidence with age; numbers (66–68), basaltic age of the Deccan trappes, Ma. Bathymetry by (Udintsev, 1979).

is proposed that the Chagos-Laccadive Ridge origin was connected not with the Arabian Basin, but with the Central Indian Basin. Paleontological data of the sites show that the Chagos-Laccadive Ridge was formed under shallow tropical conditions (Duncan et al., 1990).

To determine the origin of the Chagos-Laccadive Ridge we draw from Eq. (1) the basement depth–age curve for 9 cm/a (Fig. 6). The basaltic depth at Site 715 practically coincides with the depth determined by the theoretical curve. At Site 713 the basaltic depth differs by 20%. As noted earlier, the average deviation of the oceanic basement from the theoretical curve is usually ±15%. As the Chagos-Laccadive Ridge has a great thickness of carbonate sediments (~500 m) it is concluded that the ridge is close to isostasy. Thus, the Chagos-Laccadive Ridge subsidence approximately follows the cooling model of sea-floor formation. The free-air gravity anomalies over the Chagos-Laccadive Ridge are small and do not exceed 60 mGal that suggests isostasy.

To confirm the oceanic model of the Chagos-Laccadive Ridge origin we have analyzed geothermal data in the ridge area. Fig. 7a shows the heat flow distribution versus the ridge age calculated for the rate of formation of 9 cm/a. The theoretical geothermal curve [Eq. (2)], on the whole, describes the average heat flow for both the Chagos-Laccadive Ridge and the adjoining western part of the Central Indian Basin. Deviations of the measured heat flow from the theoretical curve usually do not exceed ±20 mW m^{-2} for the basement ages greater more than ~55 Ma (Stein and Stein, 1994). Hence, geothermal data demonstrate the cooling model (Parsons and

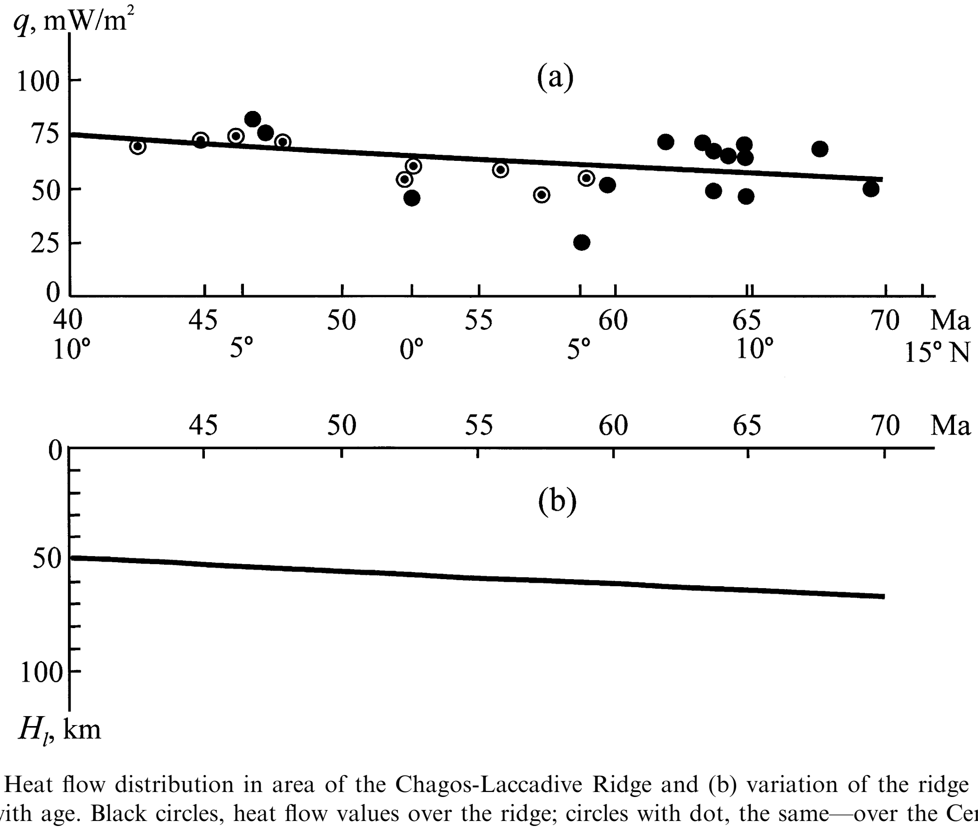

Fig. 7. (a) Heat flow distribution in area of the Chagos-Laccadive Ridge and (b) variation of the ridge lithospheric thickness with age. Black circles, heat flow values over the ridge; circles with dot, the same—over the Central Indian Basin segment joined from the East to the ridge; long upper line, theoretical geothermal curve.

Sclater, 1977) of formation of the Chagos-Laccadive Ridge and its belonging to the Indian Plate. The difference between the ridge age from deep-sea drilling data and of the western part of the Central Indian Basin from magnetic data implies a transform fault between these structures. Fragments of such a fault, including the Chagos trench, draw up from bathymetric data along the ridge east side up to the Indian continent (Kanaev, 1979). Taking into account the oceanic model of the Chagos-Laccadive Ridge origin, the lithospheric thickness against the ridge age was calculated by the formula (3) (Fig. 7b).

3. Discriminating the hypotheses of the Ninety-East and Chagos-Laccadive ridges genesis

As stated earlier, an analysis of the deep-sea drilling, geothermal and other geological-geophysical data demonstrates the oceanic origin of the Ninety-East and Chagos-Laccadive Ridges, id est, in accordance with the cooling model of oceanic lithosphere evolution (Parsons and Sclater, 1977). There are two rather plausible hypotheses of ridge genesis related to the Indian plate displacement to the north from the Late Cretaceous to the Oligocene. The first hypothesis suggests that of a stationary ($\sim$100 Ma) extrusive source at a transform fault related to a spreading axis. The transform fault is a channel of basaltic melt from the asthenosphere. The second hypothesis is a hot spot, implying a stationary ($\sim$150 Ma) mantle plume. A plume melts a moving oceanic plate, forming a volcano, which decays after the plate has drifted away. In the first hypothesis, the oceanic lithosphere and the ridge are formed simultaneously; according to the second hypothesis, the previously formed oceanic lithosphere is partially remelted by the plume (Sager et al., 1995; Zonenshain and Kuzmin, 1997).

According to both hypotheses, the ridge forms approximately in agreement with the cooling half-space model, and the geophysical data do not discriminate between these hypotheses. Tholeiitic basalts of both a transform fault and of a plume are enriched in light lithophile elements (e.g. K, Rb, Sr, Zn, Nb, La, Ce, Sn and other) compared to depleted MORB (Claque and Dalrymple, 1987; Kashintsev, 1991; Hekinian et al., 1992; Melankholina et al., 1994) and the petrogeochemical basalt characteristics also hardly discriminate the hypotheses (Kashintsev and Pushcharovsky, 1995).

Arguments for or against the two hypotheses may come from the combined analysis of the geothermal field of the Central Indian Basin, the Ninety-East and the Chagos-Laccadive Ridges and parts of the adjoining West Australian and Arabian Basins. Heat flow of the Central Indian Basin is not homogenous (Fig. 1). The background heat flow of 40 $mW{\cdot}m^{-2}$ typical of the oceanic lithosphere of the Lower Cretaceous age is exceeded by some values of 200 $mW{\cdot}m^{-2}$ and higher In the zone of intraplate deformation especially high values of heat flow were observed. The analysis shows that under the Central Indian Basin an additional heat source ($\sim$20 $mW{\cdot}m^{-2}$) should exist (Verzhbitsky and Lobkovsky, 1993).

In contrast to the Central Indian Basin, the heat flow distribution over the Ninety-East and Chagos-Laccadive Ridges (Figs. 5a and 7a) has no anomalies in the zone of intraplate deformation nor values exceeding the theoretical values. Note, that the Ninety-East and Chagos-Laccadive Ridges are characterized by high recent seismicity, which is not typical for aseismic ridges.

The agreements between the observed heat flow distribution over the Ninety-East and Chagos-Laccadive Ridges and the model of a cooling half-space (Parsons and Sclater, 1977) permit to estimate the expected heat flow at the ridges and parts of the adjoining deep basins on the basis of the assumption that the ridges were formed at a transform fault. Differentiating the relation, which represents the convolution of temperature distribution with the Green's function, we can get the formula for the heat flow distribution across lithospheric blocks divided by transform fault zone within the limits of the cooling model (Karcloy and Eger, 1964; Ushakov, 1979; Dubinin, 1987):

$$q(x,t) = \frac{\lambda_l T_s}{2\sqrt{\pi a}} \left\{ \left[1 - \Phi\left(\frac{x}{2\sqrt{a(t-t_0)}} \right) \right] \frac{1}{\sqrt{t}} + \left[1 + \Phi\left(\frac{x}{2\sqrt{a(t-t_0)}} \right) \right] \frac{1}{\sqrt{t-t_0}} \right\},$$

$$\Phi(\eta) = \frac{2}{\sqrt{\pi}} \int_0^{\eta} \exp\left(-\eta^2\right) d\eta, \tag{4}$$

where $\Phi(\eta)$ is error function; x is the distance from the fault zone axis along the ridge; t is age of the oldest block; t_o is age difference of the lithospheric blocks.

The average age of the Ninety-East Ridge between 25° and 10° S is 50 Ma (Fig. 4) and the age of the West Australian Basin in this area is estimated to be 80 Ma (anomalies 25–33; Royer et al., 1991). Then $t = 80$ Ma, $t_o = 30$ Ma. Substituting these parameters in Eq.(4) we receive the heat flow over the ridge ($x = 0$) to be 59 mW⇕m^{-2} and in the Basin ($x = 200$ km) 46 mW·m^{-2}. The average measured heat flow at the Ninety-East Ridge is 58 mW·m^{-2} in a good agreement with 59 mW·m^{-2}. The average measured heat flow in the adjoining area of the West Australian Basin is 56 mW m^{-2}, which is close to 59 mW·m^{-2}, and exceeds the calculated 46 mW·m^{-2} by ~20%. Thus, the age of the West Australian Basin segment near the Ninety-East Ridge between 25° and 10° S (Fig. 1) is approximately equal to that of the ridge. Similar data of the measured heat flow (60 mWm^{-2}) for these zones show correctness of the calculation by Eq. (4). It follows that the trench along the eastern part of the ridge is not a transform fault zone separating the Indian and Australian plate. Therefore the geothermal data support the hot spot hypothesis. The average age of the Chagos-Laccadive Ridge between 3° and 10° N from deep-sea drilling data is 60 Ma (Fig. 6). The average age of the adjoining Arabian Basin near the ridge from the deep-sea drilling and magnetic data is 50 Ma. The small difference in age of the adjacent blocks of the ridge and the basin (10 Ma) does not allow an accurate comparison of the heat flow calculated by Eq. (4) and measured.

However, the maximal difference of the Ninety-East Ridge age at the calculated track of the hot spot and the basaltic age in drilling cores is 20% (Duncan et al., 1989). The age determined from the average rate of the ridge formation with 9 cm/a and the basalt age in drilling cores do not differ by more than 10%. The good age agreement in of the Chagos-Laccadive and Ninety-East Ridges calculated by the hot spot model and the average rate of the Indian plate drift during Cretaceous-Paleogene of 9 cm/a also suggests that the hypothesis of the ridge genesis by magmatic hot spot activity is valid.

4. Conclusions

The analysis of the deep-sea drilling, geothermal and other geological-geophysical data leads to the following conclusions:

1. The average rate of the Ninety-East and the Chagos-Laccadive Ridges formation calculated by the deep-sea drilling data is 9 cm/a. It shows that the genesis of these ridges is related to the northwards displacement of the Indian Plate in the Cretaceous–Paleogene time with an average velocity of 9 cm/a.
2. The variations of the basaltic ages along the Ninety-East and Chagos-Laccadive Ridges confirm to the basement subsidence with the cooling model of sea-floor spreading.
3. The heat flow distribution along the Ninety-East and Chagos-Laccadive Ridges is in accordance with the same theory of the oceanic lithospheric evolution.
4. Peculiarities of the heat-flow distribution in the area of the Ninety-East and Chagos-Laccadive Ridges demonstrate that the ridges belong to the Indian plate.
5. The analysis of the geothermal regime and of the age of the basalts relates the genesis of the Ninety-East and Chagos-Laccadive Ridges to the hot spot hypothesis.

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