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Spatiotemporal Pulsations of Plume Activity and Magmatism Overprinted on the Oceanic Lithosphere

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Abstract—The interaction of mobile lithospheric plates and mantle plumes approaching the surface, which have a periodic supply of magmatic material, leads to changes in geological and geophysical characteristics and the appearance of chains and compact groups of volcanoes of different ages in oceans. Data on the relief, Bouguer anomalies, and dating of seamount rocks along hot spot tracks in the Atlantic, Pacific, and Indian oceans show the presence of stable temporal—~1.5, ~3.7, ~4.5–7.5, and 10–12 Ma—periods of magmatism powered by different superplumes. These values correspond to the periods of maxima of the spectral density of sea level fluctuations. The same frequency set of these phenomena indicates a single mechanism and time modulation of activity in magma-conveying conduits. Analysis of the times of extrema in the tracks also indicates the compatibility of the periodicity of magmatism in phase. Groups of underwater igneous structures without plate movement tracks in the coordinates of the age of the basement and the analytical age of the rocks form compact but geographically separated groups in this reference system, in the range of all ages of the basement of the Atlantic Ocean, and have a duration of pulses of magmatism overprinted on the basement from 20 to 60 Ma. This and other facts indicate a fixed position of the supply conduits relative to the African Plate on the eastern flank of the Mid-Atlantic Ridge during the Cenozoic. They substantiate the assumption of the general western drift of the lithospheric plates and their displacement from the feeder plume. The pulses of magmatism that are currently continuing in different parts of the Atlantic were preceded by a pause in magmatism from 20 to 60 Ma. Analysis of seismic tomography data allows us to explain the discrete spatiotemporal distribution of magmatic pulses by a combination of a variable regime of vertical supply of heated material with simultaneous horizontal movement of plates.

Keywords: mantle, plumes, lithosphere, igneous structures, age of the basement, magmatism pulses, Mid-Atlantic Ridge, large igneous provinces, East Pacific Rise

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INTRODUCTION

One of the main discoveries in global geodynamics, made based on seismic tomography data, are mantle plumes: subvertical areas of low seismic wave velocities, ascending from the core–mantle boundary or from intermediate mantle regions, above which igneous structures are established on the surface of the lithosphere, indicating their relationship with heated and partially molten material [35].

Low-velocity anomalies along the Mid-Atlantic Ridge (MAR) axis do not have deep roots in the lower mantle. According to [32], they have a base no deeper than 120 km.

In 1980–1990, seismic tomography data were obtained and analyzed, which showed that two different types of mantle upwelling occur under the MAR axis and in plumes: active plume upwelling and passive axial upwelling, which occurs as a decompression response to the formation of space for crustal accretion during the divergence of lithospheric plates from the spreading axis [35]. These facts about upwelling led geologists to study plate movement mechanisms. This topic is again being discussed by researchers, reflected in the modern literature [13], and remains unresolved due to the unexplored features of the geodynamic impact of plumes on triggering plate tectonics processes and the formation of tectonic structures on the surface of the mobile lithosphere.

The study of lithospheric plate movement mechanism, in addition to tectonic processes, also affects the physical aspects of planetary processes and energy balance of the Earth, which must contain the energy necessary to trigger movement [4, 5].

The action of plume structures at the prerift, rift and post-rift stages continues with variable intensity, regardless of the structural type of lithosphere overlying the mantle [29].

After the onset of spreading segment formation in oceans, tracks of plume action are localized superposition of deep thermal anomalies on the surface of the oceanic crust in the form of groups of igneous structures called hotspots [14].

They clearly show projections of deep plumes onto the surface, vectors of movement of the lithospheric shell and variations in the intensity of the impact of melts entering through deep conduits.

Age analysis of Cenozoic igneous rocks structures located discretely in space along the tracks of plate movement show the presence of characteristic spectral maxima for periods of magmatic activity of ~20, ~10, and ~5 Ma [29].

The reason for the occurrence of harmonics with these periods, common to all plates, comprises processes at the core–mantle boundary, from which two antipodal superplumes rise: the African and Pacific, along the periphery of which a system of hot spots has formed on the surface [29, 33].

According to [14], there are three types of hotspots:

— deep (with roots near the core–mantle boundary);

— intermediate (with roots in the transition layer 670 km);

— upper mantle.

In addition, it is noted that the most important property for geodynamics of some hot spots is a track of ancient igneous structures, but there are points without a track with igneous structures compactly located above the plume outlets to the surface. Tracks of structures allow us to estimate the temporal variations of magmatic pulses over hot spots in various modern oceans and the planetary regime of pulsations of deep melt supply [29].

It is difficult to detect the long-period component of variation if the main sequence in the seamount chain is filled with pulses in several million years, and intervals in several tens of millions of years are masked by shorter components of variations. The solution to this problem is to analyze not only the age and relief of the seamounts, but also Bouguer anomalies, the minima of which, together with the smoothed relief, indicate a general increase in magmatic flow.

The age of seamount magmatism in compact intraplate groups without tracks of lithosphere movement above deep plumes prevent direct estimation of the periodicity of magmatic processes.

The objective of this paper is to compare seamount data with the age of the spreading basement based on anomalous magnetic field data, makes it possible to assess the geodynamic evolution over time for isolated magmatic pulses overprinted on an older basement and separated in space by thousands of kilometers, while it is assumed that within these groups there may be there may be small, short-term sequences of migrating igneous structures without any connection to the movement of the lithosphere.

SPATIOTEMPORAL VARIATIONS OF PLUME MAGMATISM

Before and after the breakup of supercontinents, as well as during the onset of spreading processes of oceanic spatial formation, a plume system acts on the lithosphere, regardless of its structural type and nature of movement, forming overprinted igneous structures on the surface of the lithosphere. In the case of Pangea, the breakup with subsequent formation of a rift system occurred in places where deep plumes projected onto the surface and it was accompanied by the formation of large igneous provinces (LIPs) [15, 25].

This was the trigger for the Pangea breakup, which continued outside the zones of influence of the LIPs on amagmatic segments of the rift system. In our opinion, this is possible only in the presence of additional mechanisms that, within plates before the point trigger is activated, create tensile stresses that lead to breakup after the triggering effect of plumes [4]. Plumes are characterized by periodic magmatic activity, which can be traced both in temporally and spatially [20, 29].

Analysis of the cyclicity of Late Mesozoic plume magmatism without signs of tracks in the Arctic on its island and continental frame shows the presence of pulsations in the intensity of magmatic processes with an interval of, on average, 20 to 30 Ma and a maximum at ~130 Ma [8]. A similar age maximum of magmatic activity of ~132 Ma is noted in the Southern Hemisphere for the Paraná and Etendeka LIPs [23]. This once again indicates the synchronization of geodynamic activity on a planetary scale, as well as the presence of plume pulsation harmonics with periods longer than ~20, ~10, and ~5 Ma [29].

In [9], harmonics of ~2 and ~16 Ma were determined, which in general indicates the similarity of the spectral maxima of the periodicity of magmatism. The superposition of different harmonics complicates their analysis and search for the causes of periodicity.

Seismic tomography data for the basin west of the East Pacific Rise (EPR), which have a spatial resolution of ~100 km, show spatial periodicity of negative velocity variation anomalies at depth in the asthenosphere [20], which has to do with pulsations of the flow of heated material under the EPR and the divergence of the asthenospheric flow orthogonal to the rise.

Taking the average spreading half-velocity in the region as ~8–10 cm/year, we obtain an estimate of the plume activity pulsation period of ~20–25 Ma. If we accept the assumption that horizontal spreading rates determined by sublithospheric flow in the asthenosphere should agree with the rates of material ascent in heated volumes of the mantle, then the content of heated material should also be modulated with similar spatiotemporal periodicity [7].

The seismic tomographic section showed that the effective width of vertical branches of superplumes, determined by the level of velocity deviations of 0.5%, has a variation consisting of four cycles from the core–mantle boundary to the surface [6].

Taking an upwelling rate of ~8 cm/year, we obtain a time period of ~9 Ma. The configuration of the vertical branches indicates a variable width and amplitude of velocity variations in them not only on the branches of the African, but also the Pacific superplume, which supports the idea of the variable nature of material fed through plume conduits throughout the entire mantle and explains the appearance of hiatuses in magmatic activity. Intermittent manifestations of ascending mantle flow may be due to the self-oscillating mode of the rise of hypogene material, which ensured the impulsive nature of its arrival at the surface in intervals of millions of years [34].

Periodicity of melt supply during the formation of the oceanic basement in the absence of hot spots also occurs; for example, for the southern transverse ridge of the Vema Fracture Zone in recent times, periods of 3–4 Ma have been observed [11]. This result was obtained during a detailed bathymetric and magnetometric survey of the object and a dense network of dredging stations for rocks of the crystalline part of the crust and upper mantle, absent for most ocean regions without evidence of hot spots. An interval of several million years was obtained in the range of magmatic activity periodicity [11, 29].

The given values of the periods of pulsations in the intensity of magmatism show the existence of a stable set of harmonics characteristic of the Earth on a planetary scale, but an additional direction of research is the search for the presence (or absence) of synchronization of the phases of individual cycles.

INITIAL DATA

To analyze tracks and compact groups of igneous structures, we used GEBCO bottom relief data on a 30″ grid [21]. They were smoothed and rescaled to a 1′ grid due to the appearance in versions of this coverage since 2014 of a mosaic of multibeam bathymetric observations, which creates artifacts at the boundary with interpolated areas [21].

The bottom relief was compared with gravimetry data on Bouguer anomalies on a 2′ grid [10]. This type of data was used to reliably characterize the minimum anomalies of igneous structures as objects with increased crustal thickness due to more intense magmatism in the local area of these structures [4]. Seamounts and ridges in Atlantic waters were identified by outlining them according to the level of their elevation above the abyssal basement of 1000 m (Fig. 1).

First, the smoothed relief in a 75 km window was calculated and on its basis the residual relief was obtained, the positive anomalies of which are indicated by the isobath (Fig. 1). The resulting compact groups of seamounts and ridges are concentrated along the MAR, the sides of transform faults and in abyssal basins. In this paper we consider only intraplate abyssal seamounts associated with LIPs in the segments where they were identified and began to function before the breakup of the supercontinent. The topographic basis for displaying seamounts and LIPs is the age of the oceanic basement, obtained from data [30].

Data from sampling bedrock in the intraplate space with age determination by geochronological methods were taken from the international GEOROC database [22]. Data for the seamounts of the South and Equatorial Atlantic are taken from [3]. Data for the Cape Verde Islands are taken from [2]. It is assumed that all age determinations cannot be older than the age of the oceanic basement on which the intraplate igneous structures are formed. The position of the points with definitions is given, calibrated by the difference between the age of the basement according to the data of the anomalous magnetic field and the age obtained from geochronological studies of the samples (Fig. 2).

Hot spots according to data [14] are also shown there. Almost all of them have been confirmed by testing and age determination, includingvolcanic structures within their tracks. The topographic basis used was the variations in seismic velocities of S-waves at a depth of 100 km according to the SL2013sv model [32], which show the presence or absence of heated upper mantle beneath compact clusters of igneous structures.

Field dV_s has negative anomalies in heated and partially melted zones—the axial zone of the MAR and at the intersections with the branches of the African superplume. In the case of Iceland and the Azores, the plume branches intersect with the MAR. The structures in the Brazil Basin (partially), on the Walvis Ridge, and in the North American, Iberian, and Guinea basins are located above cold mantle zones (Fig. 2).

They have a small age difference with the spreading basement, which indicates their subsynchronous formation with respect to the onset of spreading. Magmatism above the heated zones is shown in Fig. 2 by larger symbols, indicating the large difference between the age of the basement located near the margins and modern volcanism (Fig. 2).

DATA ANALYSIS

Data along Hotspot Tracks

To identify similarities in the periods and phases of magmatic pulsations in the Earth's oceanic segments, we compared hot spot tracks in the Pacific, Indian, and Atlantic Oceans. Hot spots are spatially represented by linear chains of igneous seamounts, which are formed when a lithospheric plate moves over the outlet of a mantle plume to the surface. The Emperor Seamounts have constant depths below sea level from the Hawaiian Islands to the turning point, gradually increasing to the north to ~2500 m as isostatic and thermal processes develop; the seamounts have an average step of 150 km (Figs. 3a, 3b).

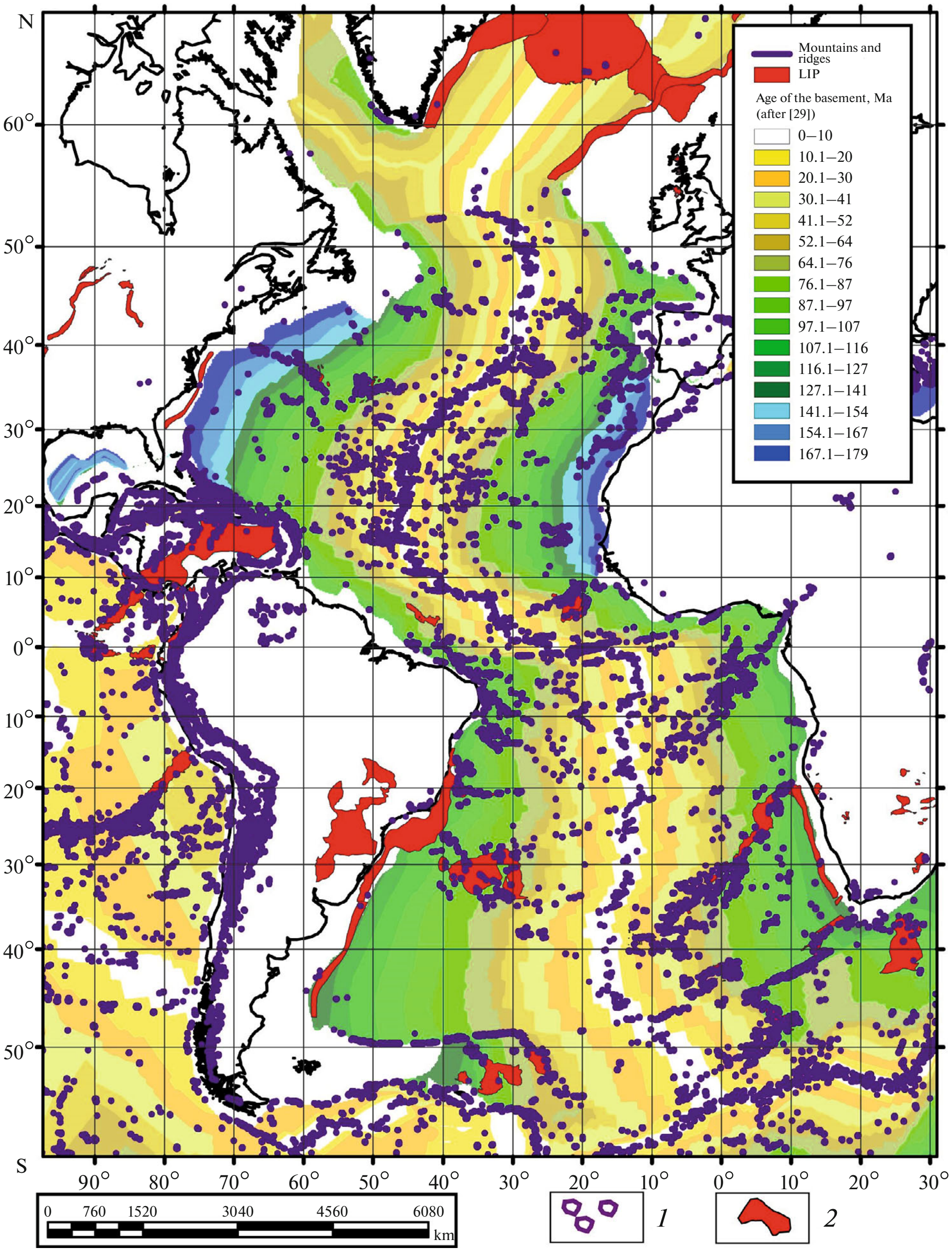

Fig. 1. Seamounts and ridges of Atlantic Ocean with elevation above abyssal base of >1000 m (according to data from [12, 19, 29]): *1*, seamounts and ridges; *2*, large igenous provinces.

With an average plate movement rate above the spot of ~8.8 cm/g, the period of their formation is ~1.7 Ma [9, 18] (Fig. 3c). The relief of the seamounts indicates the action of pseudo-periodic magmatic impulses that are associated with the influx of deep melts, but the spatially consistent high-frequency geometry of the mountainous relief along the track masks longer-period variations in the intensity of magmatism.

These variations along active oceanic magmatic systems typically result in the formation of locally thicker basaltic crust with relief maxima and minima in Bouguer anomalies, which have planar dimensions of tens and several hundreds of kilometers [4].

The relief profile, originally constructed using bathymetric data on a 0.5 arcmin grid, was smoothed in a floating window of 111 km [21] to eliminate high-frequency inhomogeneities (Fig. 3a).

This led to an obvious negative correlation of the relief with Bouguer anomalies; this correlation has a geophysically sound interpretation (Fig. 3a).

A quantitative assessment of the age intervals between the manifested relief maxima shows their dense distribution with average values of ~5–7 Ma (Fig. 3d).

Thus, along the track of the Emperor Seamounts, the periods of magmatic activity and times of their maxima have been identified, similarly to the previously identified values for other magmatic systems.

The data for the Ninetyeast Ridge were processed and displayed in a manner similar to that for the Emperor Seamount track (Fig. 4b).

Primary and smoothed profiles of the bottom relief, Bouguer anomalies and reference ages of igneous rocks with plate displacement rates above the hot spot were constructed based on data from [16, 17, 31] (Fig. 4a).

The negative correlation of the smoothed relief and Bouguer anomalies showing density variations in the crust and upper mantle, and the buildup of the relief due to highly productive magmatism on this track from the Kerguelen hotspot clearly shows variations in the intensity of plume magmatism and sharp drift of the Indo-Australian {late north of the hotspot ~40 Ma ago, which ceased the formation of igneous structures in the intraplate space (Fig. 4a).

Another feature of the variations in magmatic relief along the Ninetyeast Ridge is a slight shift in its high-frequency period to values of 1.4 Ma compared to 1.7 Ma on the Emperor Seamounts (Figs. 3c, 4c).

The main feature is preservation of a smoothed period of intensity ~4.5 Ma with a value close to the broad maximum of 5–7 Ma on the Pacific track (Fig. 3g; Fig. 4g).

Almost identical ages are shown with an average deviation of 1.3 Ma, which confirms the phase compatibility of magmatic processes in geological time with the same prevailing periods (Figs. 3a, 4a).

However, note that the track of the Emperor Seamounts between the reference maxima that coincide with the Ninetyeast Ridge contains intermediate maxima with shorter periods (Fig. 3d).

The data for the Walvis Ridge were also processed and shown in the manner similar to other tracks (Fig. 5b).

The primary and smoothed profiles of the bottom relief and Bouguer anomalies were compared with data on the age of igneous rocks taking into account plate displacement rates over the hot spot of Tristan da Cunha and Gough Island [28] (Fig. 5a).

A particular feature of the Walvis Ridge track is its disintegration into several branches after 70 Ma and a sharp increase in the intensity of magmatism starting from 40 Ma. The profile line in our study was chosen so that its trajectory passed through the densest location of age determinations (Fig. 5).

The negative correlation of the smooth relief and Bouguer anomalies on the track from the hot spot in a pair of Tristan da Cunha and Gough Island in the South Atlantic is clearly expressed. It illustrates the obvious variations in the intensity of plume magmatism of the southwestern branch of the African superplume, of which the Kerguelen hotspot is also a part. A feature of the variations in magmatic relief along the Walvis Ridge is the bimodal distribution of high-frequency unfiltered periods with values of 1.4 and 3.6 Ma and their overlap with filtered data with values of 3.8 and 7.4 Ma (Figs. 5c, 5d).

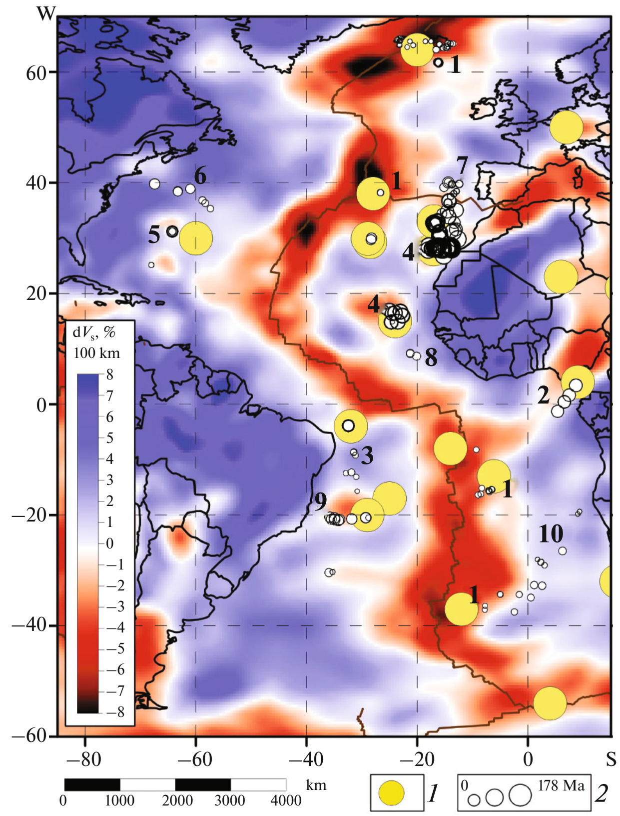

Fig. 2. Variations in seismic *S*-wave velocities at depth of 100 km (according to SL2013sv model [31]), hot spots (according to [13]), and points with obtained data sampling of bedrock in intraplate space, calibrated by difference between age of basement according to anomalous magnetic field data and age obtained from geochemical studies of samples. Bold Arabic numerals denote groups of intraplate igneous seamounts with age determination (Atlantic Ocean): 1, islands of Iceland, Azores, St. Helena, Gough Island, and Tristan da Cunha; 2, Cameroon Line; 3, Brazil Basin (cold mantle); 4, Cape Verde Islands (West Africa) and Canary Islands (northwest coast of Africa); 5, Bermuda Islands; 6, New England Seamounts; 7, Iberian Basin; 8, Bathymetric Seamounts (eastern edge of Equatorial Atlantic); 9, Brazil Basin (hot mantle); 10, Walvis Ridge. *1*, Hot spots; *2*, analytical age of rocks from seamounts outside MAR axis, graded from 0 to 178 Ma.

In our opinion, this indicates increased an intensity of magmatism during the period 3.6–3.8 Ma, which is comparable to processes of longer periods. Comparison of the smoothed intensity maxima with the maxima on the Indian Ocean track and the Pacific track shows good agreement with maxima in the ~2 Ma range (Figs. 3a, 4a, 5a).

The track of the Emperor Seamounts, when compared to the Ninetyeast Ridge and Walvis Ridge, contains similar intermediate maxima (Fig. 3d).

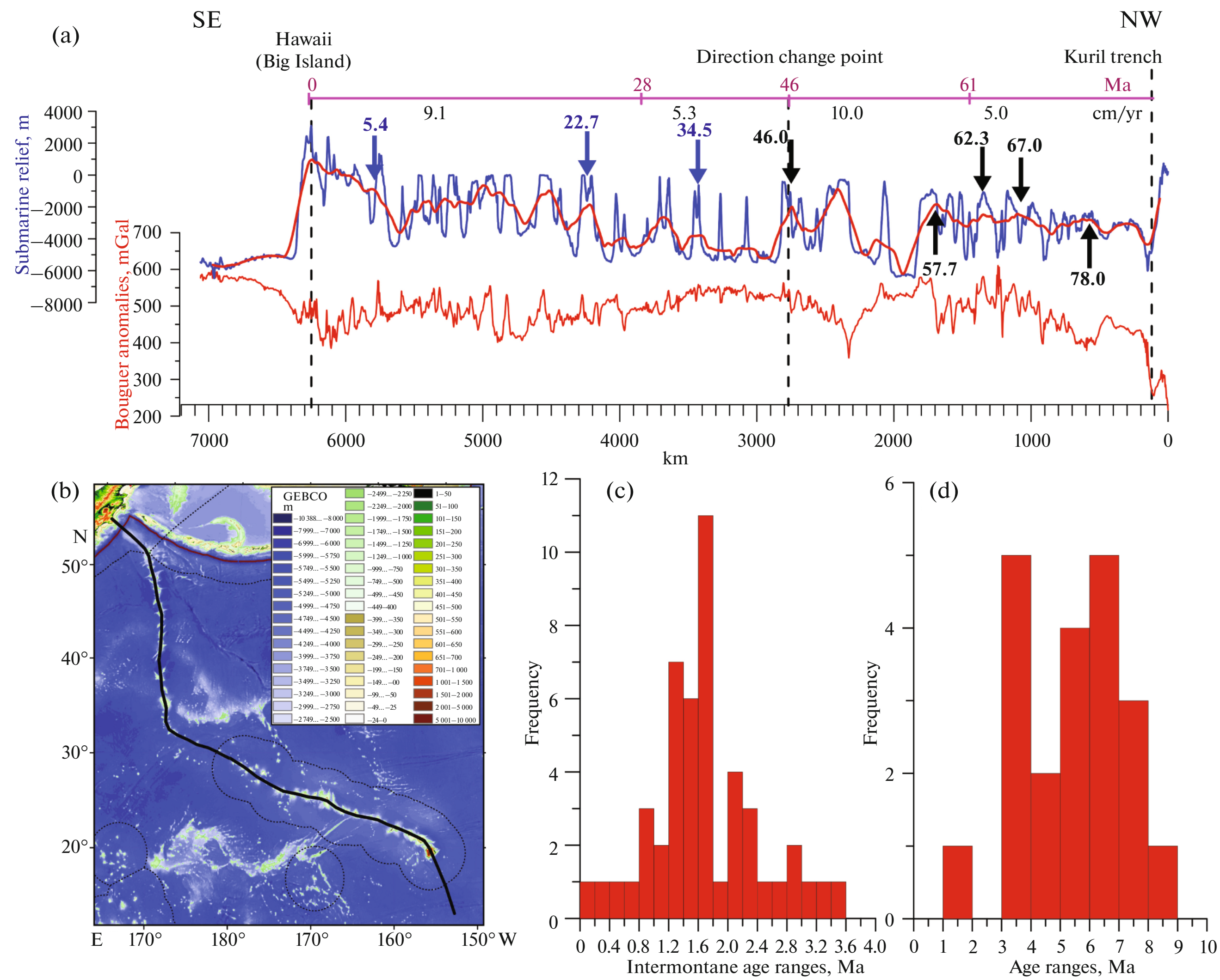

Fig. 3. Comparison of geological and geophysical parameters along track of Emperor Seamounts from hot spot of Hawaiian islands in Northwest Pacific Ocean (according to data from [10, 18, 21]). (a) Profile bottom relief with smoothed profile in 111 km floating window (line blue); anomalies (line in red); age (Ma) of coincidence maxima: with Ninetyeast Ridge (black arrows); with Walvis Ridge in South Atlantic (blue arrows); (b) bottom reliefof Northwest Pacific Ocean and position of profile of Emperor Seamounts track; (c) histogram age intervals between seamounts obtained by referencing linearly interpolated values between reference dates in segments with different rates; (d) histogram age intervals between maxima of smoothed relief, obtained by referencing to linearly interpolated values between reference dates.

Seamount Data without Plate Motion Tracks

The seamounts in the Atlantic, except for the ridge with zero age along the MAR axis and rises along the sides of transform faults, are represented by compact intraplate groups (Fig. 1).

They generally do not form long linear tracks of lithospheric movement above deep plumes, with the exception of the Walvis Ridge and the Cameroon Line, located east of the MAR axis.

However, individual linear groups are located symmetrically in the West Atlantic Ocean, the attribution of which to movement tracks is questionable [14] (Fig. 1).

We consider only groups of igneous structures for which analytical determinations of the age of rocks have been obtained and which are located within the oceanic lithosphere with dating of the age of the basement based on magnetometry data [2, 3, 22, 30].

In the absence of a long series of age datings along the track and a compact distribution of ages within groups of seamounts, the pulses of overprinted magmatic activity over time were analyzed in intraplate oceanic regions in X (age of the basement) and Y (age of rocks) coordinates, which were proposed in [1] for this type of age analysis (Fig. 6).

Examination of the data in the specified coordinate space also makes it possible to visually assess the difference between the time of formation of the basement and the later overprinting of an intraplate magmatism

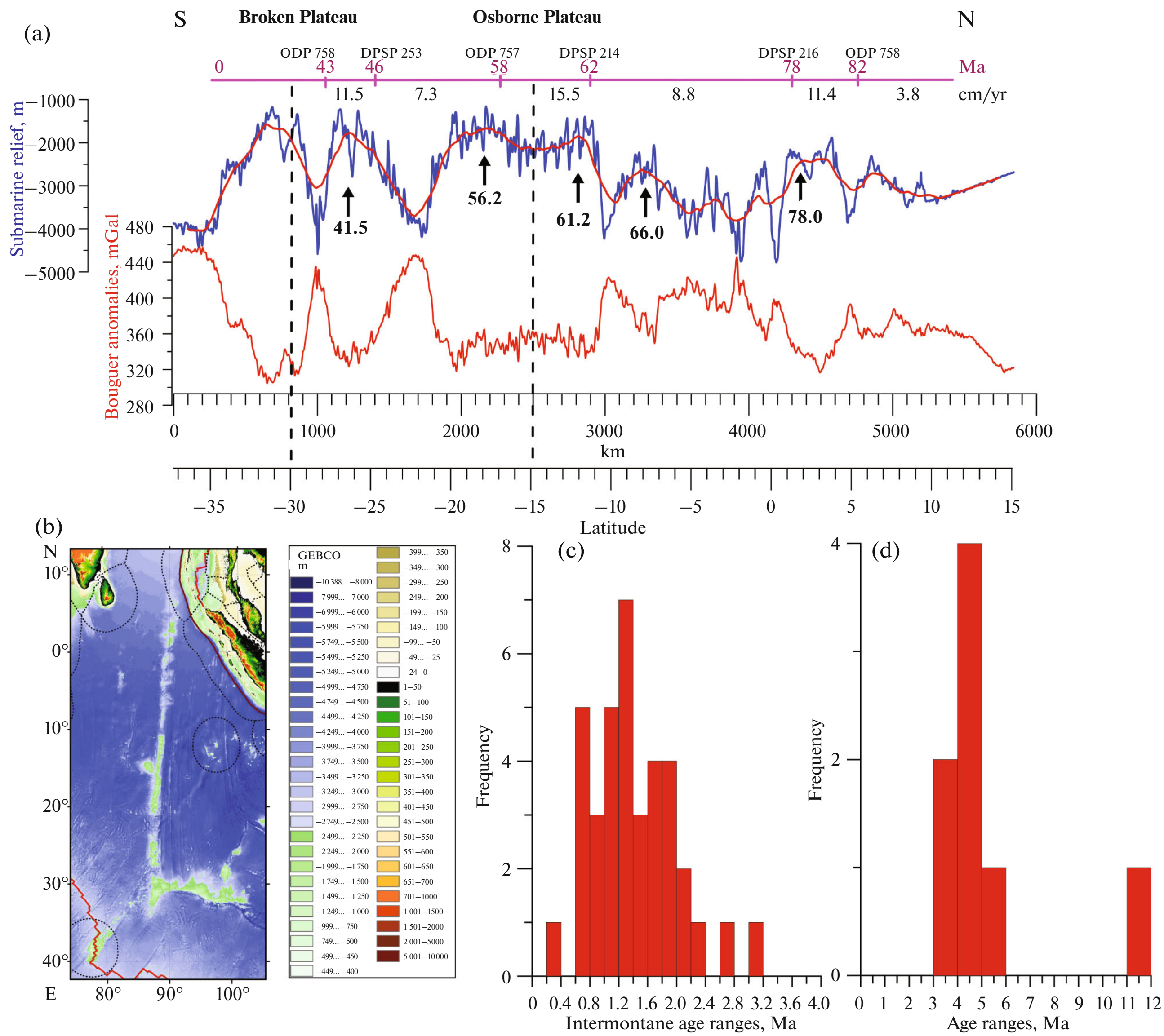

Fig. 4. Comparison of geological and geophysical parameters along Ninetyeast Ridge track from hot spot Kerguelen from age of 40 Ma (according to data from [16, 17, 21, 31]). (a) Bottom relief profile (blue line) with 111 km smoothed profile in floating window (red line), age (Ma) of coincidence maxima with Emperor Ridge (black arrows); (b) relief of bottom of Eastern Indian Ocean and position of Ninetyeast Ridge track; (c) histogram of age intervals between seamounts obtained by referencing linearly interpolated values between reference dates in segments with different rates; (d) a histogram of age intervals between maxima of smoothed relief, obtained by referencing to linearly interpolated values between reference dates.

pulse on it (Fig. 2, symbol graduation). Since we have characterized the age of ten compact groups located in different parts of the Atlantic, a spatiotemporal comparison of the coordinate space is carried out in terms of the group numbers and their geographic reference (Fig. 2).

Groups of igneous structures are concentrated in the lower part of the plane under the diagonal horizon of magmatic events (Fig. 6). This is explained by the impossibility of the formation of intraplate igneous structures before formation of the spreading basement on which they were discovered.

Directly below the horizon are groups of igneous structures that formed during the several tens of millions of years after formation of the basement (Fig. 6):

— the Brazil Basin with cold mantle (group 3);

— the New England Seamounts (group 6);

— the Iberian Basin (group 7);

— the Bathymetrists Seamounts (group 8);

— Whale Ridge (group 10).

By now, the upper mantle space beneath these groups of igneous structures is cold, indicating that the absence of hot mantle volumes producing melts for

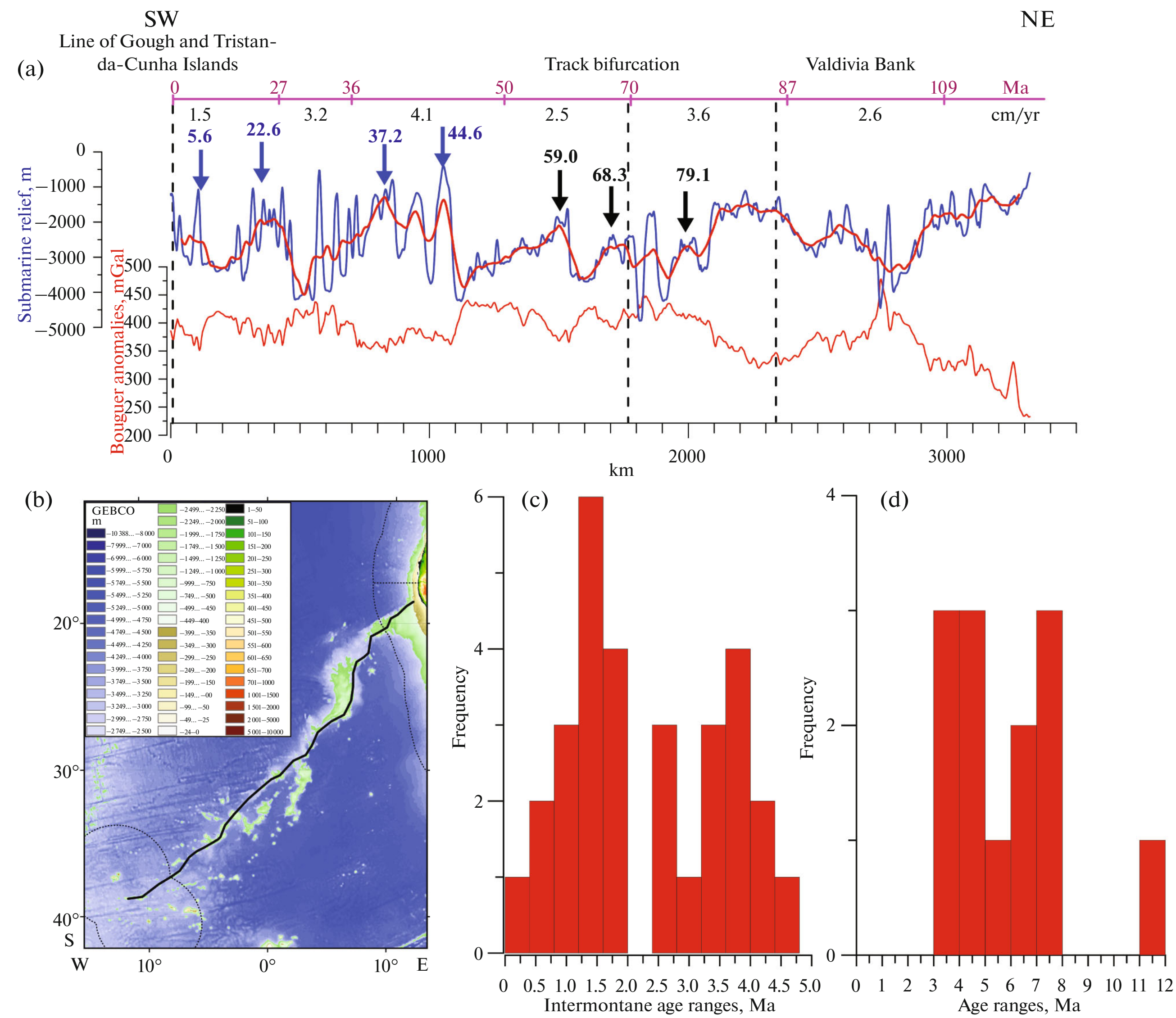

Fig. 5. Comparison of geological and geophysical parameters along Walvis Ridge track from hot spot of Gough Island and Tristan da Cunha Island (based on data from [10, 21, 28]). (a) Bottom relief profile (blue line) with a smoothed 111 km moving profile window (red line); age (Ma) of coincidence maxima with Emperor and East Indian Ranges (arrows in black); (b) relief of bottom of South Atlantic and position of Walvis Ridge track, drawn through areas with maximum density of rock dating; (c) a histogram of age intervals between seamounts obtained by referencing linearly interpolated values between reference dates in segments with different speeds; (d) histogram of age intervals between maxima of smoothed relief, obtained by referencing to linearly interpolated values between reference dates.

seamount formation, and the attenuation of the pulse of intraplate magmatism (Figs. 2, 6, groups 3, 6–8, 10).

Group 10 (Whale Ridge) is elongated along the *X* axis, corresponding to the track of the hot spot currently located beneath Tristan da Cunha and Gough Island (Figs. 2, 6, group 10).

Group 10 (Whale Ridge) is connected to a group of igneous structures (group 1) of the youngest magmatism from plumes of the Icelandic islands approaching the MAR, the Azores, and St. Helena (Fig. 6, groups 1, 10).

All projections of the indicated plumes onto the surface correspond to a hot region of the mantle near the basement with an age less than ~40–45 Ma, after which there is a pause in the presence of the latest igneous structures on the basement up to an age of ~80 Ma (Figs. 2, 6).

Groups of igneous structures with recent or modern activity are adjacent to the horizontal axis throughout the range of basement age data greater than 80 Ma (Fig. 6):

— Cape Verde and Canary Islands (group 4);

— Bermuda (Group 5);

— the New England Seamounts (Group 6);

— the Iberian Basin (group 7);

— Bathymetrists Seamounts (group 8);

— the Brazil Basin with a hot mantle (group 9).

They have a duration in time that increases with the age of the basement. These groups are concentrated above the hot mantle, indicating the presence of plume branches with modern activity (Figs. 2, 6, groups 4–9).

Group 4 (Cape Verde and Canary Islands), as opposed to Group 1 (Iceland), is located on the most ancient basement for the Atlantic, from 120 to 180 Ma (Fig. 6). The basement contains manifestations of a plume magmatism pulse in a stationary position without a track of lithospheric plate movement with a total duration of 20–60 Ma [2]. This indicates the absence of plate drift with respect to the branch of the African superplume projected onto the Cape Verde and Canary Islands.

A chain of igenous structures groups with a cold mantle at the base is separated from a chain of groups with a hot mantle pause area with a width along the Y axis from 20 to 60 Ma, and adjacent to the pause in the newest age values in the basement interval from ~45 to ~80 Ma (Fig. 6, blue rectangle).

The exception is the age interval of the basement from ~80 to ~120 Ma, in which there is no pause in the ages of magmatism (Fig. 6, red rectangle).

The pause along the diagonal of the plane is set both along the Y (age of rocks) and X (age of the basement) axes (Fig. 6).

Groups, pairs 6 and 7, 3 and 10, formed on a relatively ancient and cold basement within no more than 20 Ma after its accretion, when compared with their spatial position, show a symmetrical with respect to the MAR divergence of the active upper fragments of plume branches during plate drift (Figs. 2, 7).

These paired groups to the east and west of the MAR indicate the initial projection of the plume onto the surface near the MAR axis with subsequent movement of magma chambers from the active interplate boundary (Fig. 7, double arrows).

This mechanism explains how, when they are entrained by the diverging lithosphere, magmatism remains active outside plume branches and attenuates after some time [2]. In both presented spatially symmetric paired groups, the western part is located on a more ancient basement, which additionally substantiates the appearance of western drift and movement of plates framing the MAR away from the plume's feeding projection with a subsequent attenuation in intensity.

The plume magmatic systems closest to the MAR form group 1 of igneous structures (Iceland, the Azores, and St. Helena) (Figs. 6, 7). The groups formed after a temporal pause closer to the X axis are located on the hot mantle basement with the most productive manifestation of neotectonic and modern intraplate magmatism (Fig. 6).

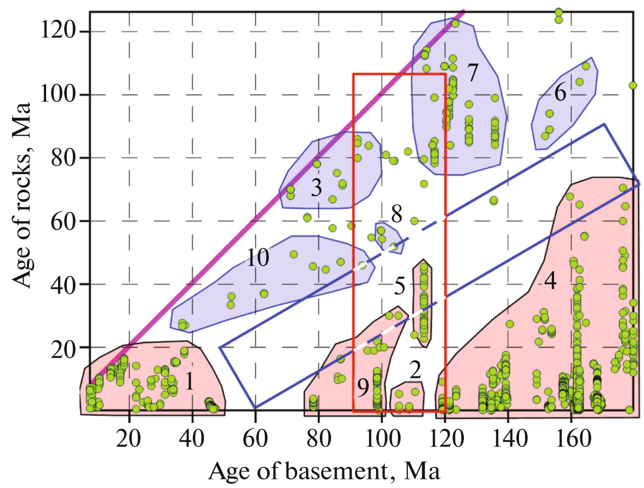

Fig. 6. Diagram of dating of igneous rocks in coordinates of basement age (according to magnetic data [30]) and analytical age values (according to data [2, 3, 22]). The following are shown: datings of igneous rocks (green circles); fields of age clusters correspond to areas with positive (cold) values of seismic velocity variation in layer from 0 to 100 km (blue); areas with negative (hot) values (red); magmatic event horizon (purple diagonal); area of pause in appearance of magmatic impulses (blue rectangle); area without interruptions of magmatism (red rectangle). Bold Arabic numerals denote groups of intraplate igneous seamounts with age determination (Atlantic Ocean): 1, islands of Iceland, Azores, St. Helena, Gough Island, Tristan da Cunha; 2, Cameroon line; 3, Brazil Basin (cold mantle); 4, Cape Verde Islands (West Africa) and Canary Islands (northwest coast of Africa); 5, Bermuda; 6, New England Seamounts; 7, Iberian Basin; 8, Bathymetrists Seamounts (eastern edge of Equatorial Atlantic); 9, Brazil Basin (hot mantle); 10, Walvis Ridge. 1, Hot spots; 2, analytical age of rocks from seamounts outside AR axis, graded from 0 to 178 Ma

On the eastern flank of the Atlantic, group 4 (Cape Verde and Canary Islands) is extended along the vertical axis to the Cretaceous ages [2] (Fig. 6). The symmetrical paired groups 9 and 2, and especially paired groups 5 and 4, which are distant from the MAR, reflect the modern activation of magmatism within the ancient basement along one of the branches of the African superplume east of the MAR, leading to the arrangement of the eastern groups of igneous structures along the ascending X axis (Fig. 6, Fig. 7, Fig. 8).

This also indicates the absence of modern drift the eastern flank of the Atlantic with respect to the branches of the African superplume. The basement age interval of 80–120 Ma does not have a pause (Fig. 6). We can interpret this as the influence of Pacific plume branches on the magmatic system of the Bermuda Islands (Fig. 8a).

DISCUSSION

Analysis of relief data and Bouguer anomalies from tracks referenced to seamount dates in the Atlantic,

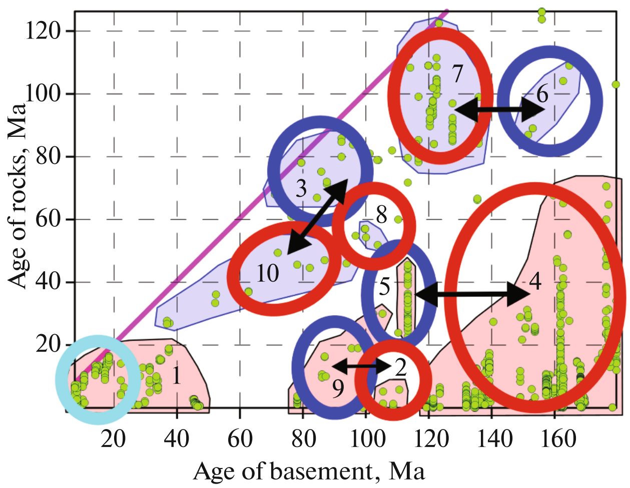

Fig. 7. Diagram of datings of igneous rocks in coordinates of basement age (according to magnetic data [29, 30]) and analytical age values (according to data [2, 3, 22]). The following are shown: datings of igneous rocks (green circles); areas with positive (cold) values of seismic velocity variation in layer from 0 to 100 km (blue); areas with negative (hot) values (red); igneous event horizon (purple diagonal); genetically and spatially related groups of seamounts (black double arrows); MAR region (blue circle); groups of seamounts located west of MAR (blue circles) and east of MAR (red circles). Bold Arabic numerals denote groups of intraplate igneous seamounts with age determination (Atlantic Ocean): 1, islands of Iceland, Azores, St. Helena, Gough Island, Tristan da Cunha; 2 Cameroon Line; 3, Brazil Basin (cold mantle); 4, Cape Verde Islands (West Africa) and Canary Islands (northwest coast of Africa); 5, Bermuda Islands; 6, New England Seamounts; 7, Iberian Basin; 8, Bathymetrists Seamounts (eastern edge of Equatorial Atlantic); 9, Brazil Basin (hot mantle); 10, Walvis Ridge.

Pacific, and Indian oceans has shown the presence of stable time periods in the formation of seamounts (Figs. 3–5):

— ~1.5 Ma and ~4.5–7.5 Ma on all tracks;

— ~3.7 Ma in the South Atlantic.

The main difference between the Atlantic and others between the hotspot and oceans is that the plate moves at lower rates above the hotspot, ~3.7 cm/year, compared to 8–10 cm/year in the Indian and Pacific oceans, which likely influences the nature of melt supply and relief formation.

In the Atlantic and Indian oceans, a period of 10–12 Ma is also distinguished (Figs. 4, 5). Long periods are clearly visible on the smoothed relief profiles, which have a clear inverse correlation with the Bouguer anomalies, indicating an elevated top of basaltic crust and increased thickness of the crustal layer, which is less dense than the upper mantle (Figs. 3–5).

In [6], when assessing the evolution of the volume of water masses in geological history, the relationship between the Earth's tectonomagmatic activity and spreading rates with the curve of eustatic sea level fluctuations in the Phanerozoic was convincingly demonstrated [26]. This gives grounds to compare the obtained periods of magmatism intensity with the spectrum of the sea level fluctuation curve [27]. It was shown that the spectrum, in addition to a clear logarithmic trend over periods from 600 to 1 Ma, has significant extrema above the trend over periods of 10, 7, and 5 Ma and a dense cluster of harmonics from 3 to 1 Ma [27].

These periods at the spectral density maxima were independently obtained by us from an assessment of the relief in combination with datings of rocks on individual seamounts in oceans with different plate movement rates over hot spots and powered by different antipodal superplumes. The intensity of oceanic magmatism has the same frequency set, indicating on a single mechanism and temporal modulation of activity in magma-conducting conduits. The analysis of the times of extrema, in addition to frequency, also indicates phase compatibility in the geological time of magmatic processes with the same prevailing periods (Figs. 3–5).

For spatially compact groups of magmatic intraplate structures in the Atlantic without plate movement tracks show a discrete supply of material over time. For basement areas of the same age and located thousands of kilometers apart, pulses of magmatism are observed with a time pause of 20–60 Ma. This confirms the discrete and periodic nature of the flow of heated material through plume conduits in different parts of the ocean. There is an obvious pause between the groups of igneous structures with the newest and contemporary activity, located above the hot upper mantle, and the inactive groups above cold upper mantle in the range of basement ages from 40 to 160 Ma (Fig. 6).

The maximum duration of pulses of modern magmatism also ranges from 20 to 60 Ma (Fig. 6).

The significance of the pause in intraplate activity differentiates geographically distinct regions. This allows us to assume that the pulsed mode acts synchronously on different plume conduits not only within the Atlantic, but taking into account the spatial distribution of volcanic groups, on a global scale.

The formation of the observed pattern of intraplate magmatism without plumes with deep roots can be explained by a geodynamic model based on entrainment of a region with heated and partially molten material by a moving lithospheric plate. In particular, this model was proposed in 2000 by A.O. Mazarovich [2] for the magmatic system of the Cape Verde Islands. In particular, we note the temporal pulsed mode of the flow of material up the plume conduit [34], which, taken together, should lead to both the temporal periodicity of groups of igneous structures with deep plume roots, and to the spatial periodicity of magmatism without such roots due to the drift of plates with heated material.

We backed this up with seismic tomography data, which show the deep geodynamic state of the mantle and contain active and symmetrically diverged with respect to the MAR heated areas without deep roots,

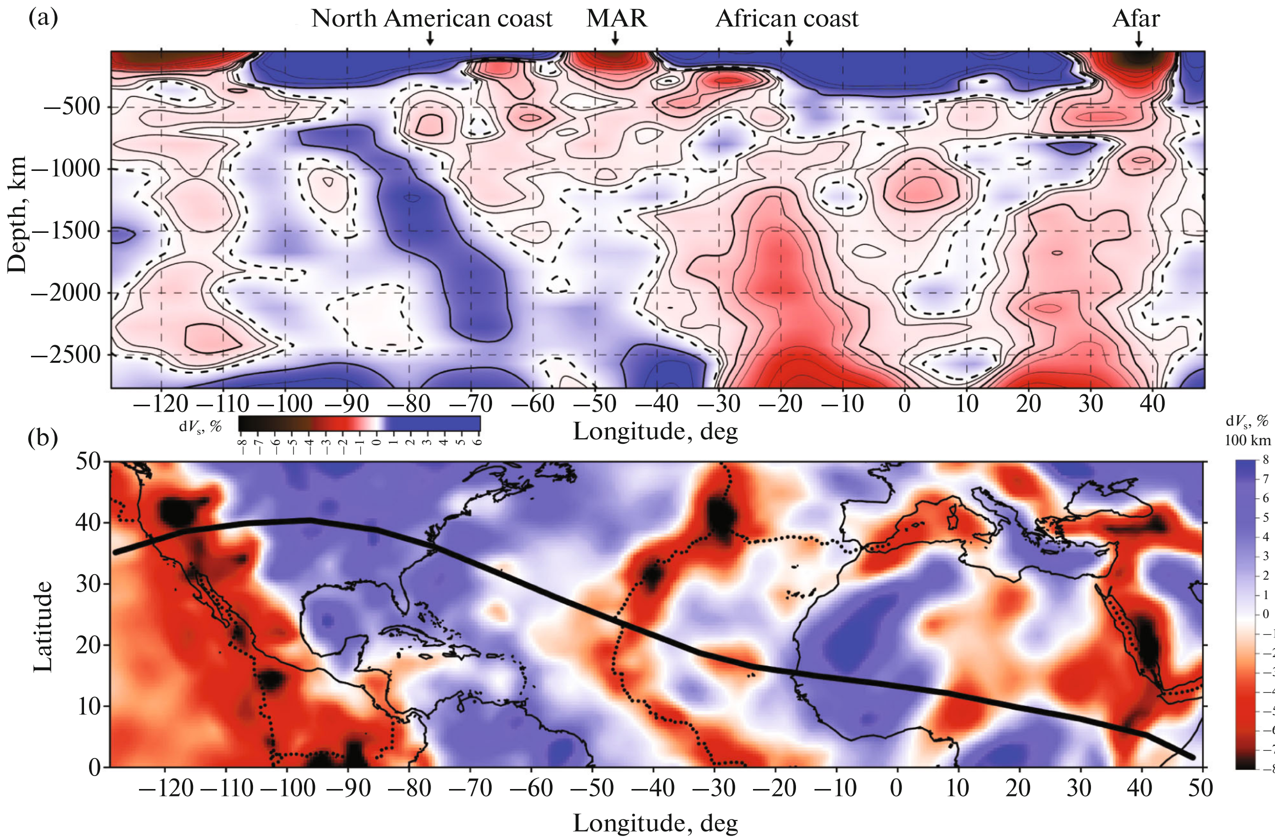

Fig. 8. Section δ*V* of NGRAND seismic tomographic model [24] for *S*-waves from top of mantle to its base (a) and position of its profile on section of this model at depth of 100 km (b). Contours are drawn at 0.5% intervals; zero isoline is shown as dotted line.

torn away from the MAR and from the feeding branch of the African superplume (Fig. 8).

These branches of the African superplume are variable in width, and along them there is an ascent of heated and partially molten material, determining the spatio-temporal periodicity of magmatism on the surface of the lithosphere.

CONCLUSIONS

1. Topography data, Bouguer anomalies, and hotspot track dating of seamount rocks in the Atlantic, Pacific, and Indian Oceans have shown consistent time periods of ~1.5, ~3.7, ~4.5–7.5, and 10–12 Ma of variation in the intensity of magmatism fed by different superplumes. These values correspond to periods of maxima of the spectral density of sea level fluctuations. The identical frequency set of these phenomena indicates a single mechanism and temporal modulation of activity in magma conduits. Analysis of the times of extrema in tracks showed phase compatibility of periodic magmatic processes in geological time with similar periods.

2. Inactive magmatic systems with minimal age difference between rocks and basements are located above the cold mantle regions. Under currently active intraplate magmatic systems with the maximum difference in age between rocks and basement, hot seismic tomography anomalies are observed in the mantle at the same basement ages as in inactive systems, indicating the activation of ancient supply conduits.

3. Underwater igneous structures in the coordinates of the age of the basement (axis *X*) and the analytical age of the rocks (axis *Y*) form compact but geographically separated groups in this reference system in the range of all basement age data, and have a duration of impulses of magmatism overprinted on the basement from 20 to 60 Ma, in particular, in the area of the Cape Verde Islands and Canary Islands. This indicates a fixed position of the feeder conduits with respect to the African Plate on the eastern flank of the MAR during the Cenozoic.

4. Symmetrical with respect to the MAR and paired groups of seamounts located above the cold mantle have a more ancient basement on the western flank of the MAR. We interpret this on the basis of the general westward drift of the lithospheric plates and their displacement from the plume feeding the seamount groups located above the hot mantle. The driftless seamount groups overprinted on the superplume branches have an older basement on the eastern flank of the MAR.

5. The magmatic pulses that are currently ongoing in various parts of the Atlantic were preceded by a magmatic pause of 20 to 60 Ma, common to different parts of the Atlantic, indicating the global nature of the pulsed regime.

6. Impulsive, concentrated in groups, manifestations of intraplate magmatism in the coordinates of the age of the basement and rocks have both a temporal and spatial discrete distribution. Analysis of seismic tomography data allows us to explain this phenomenon by a combination of a pulsed regime of vertical supply of heated material with simultaneous horizontal movement of plates.

7. Intraplate volcanism on the oceanic basement with ages from 80 to 120 Ma had no pauses in development.

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CONFLICT OF INTEREST

The authors of the work declare that they have no conflicts of interest.

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