Geodynamic zonation of the Atlantic Ocean lithosphere: Application of cluster analysis procedure and zoning inferred from geophysical data

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[1] Ten geological-geophysical parameters used in geodynamics directly or indirectly reflecting geometry of the Atlantic lithosphere inner boundaries, mass distribution within the lithosphere, and energy release made it possible to calculate 15 stable combinations of parameters whose manifestation areas are interpreted as geodynamically different districts. The Atlantic lithosphere zonation allows a new segmentation of a mid-oceanic ridge zone presenting the alternation of "cold" and "hot" blocks, marked by discrete conditions of basalt melts formation. Additional phenomena superimposed on the standard oceanic lithosphere are discussed. The phenomena present zones pseudosymmetric with respect to a mid-oceanic ridge marked by highly productive plume magmatism, these zones are more extensive than it has been considered earlier, and sublatitudinal zones exhibiting some features of fore-arc zones. *INDEX TERMS:* 3235 Mathematical Geophysics: Persistence, memory, correlations, clustering; 8120 Tectonophysics: Dynamics of lithosphere and mantle: general; 8130 Tectonophysics: Heat generation and transport; 9325 Geographic Location: Atlantic Ocean; *KEYWORDS:* Geodynamic zonation, cluster analysis, mid-oceanic ridge zone.

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1. Introduction. Status and Approach to Solution of the Problem

[2] Progress in accumulation of geological-geophysical information on the structure of the Atlantic Ocean floor (Figure 1) gave rise to persistent recognition of facts poorly explicable in terms of classical geodynamical model of the ocean. Those factors are:

- convergence of passive parts of transform faults east of the Mid-Atlantic Ridge (MAR) easily discernible from satellite altimetry [*Sandwell and Smith,* 1997];
- presence of sublatitudinal seismofocal zones of the Puerto Rico and Scotia Sea zones;
- discreteness of petrologic parameters of basalt magmatism along the axis of the Mid-Atlantic Ridge composed of two radically different basalt associations – spreading and plume – showing marked distinctions in operation of geodynamic processes of different rank as evidenced of the formation of specific ridge structures, and its segmentation that affects geophysical fields [*Dmitriev et al.,* 1999];
- presence of the Atlantic fault zones – obliquely oriented to major structural elements of the ocean floor and intraplate earthquakes related to these zones [*Mazarovich and Sokolov,* 2002];
- existence of anisotropy of basin sedimentary cover deformation being most intense, at northward direction.

[3] The list is far from being complete but the above facts imply a gap between facts and working geodynamic model meant to explain them. The latter is based on the mantle convection when ridge push by extension along its axis, slab pull and dredging of the lithosphere by astenospheric current resulted from convection are considered to be the main forces responsible for surface dynamics of the lithosphere masses. The forces mentioned and mechanism of their energy supply cannot explain their and other factors appearance by deficiency of motion horizontal component nonorthogonally to

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the MAR and because a discrete pattern of parameters of magmatic processes operating along the MAR do not agree with the notion of continuous ascending substance flow along the divergent zone of the convective cell. In other words: lithospheric masses move over the Earth's surface in a more complex way than that stipulated by the geodynamic model.

[4] Noteworthy, that discrete conditions of basalt magma formation also poorly correlate with the usual notion of the convective cell system. This contradiction cannot be resolved even when we proceed from the assumption of a possible southward migration of the Atlantic superplumes along the Mid-Atlantic Ridge axis [*Dmitriev et al.,* 2001].

[5] The questions stated cannot be resolved in the context of a single paper. The authors only generalize new covering original data equally cover the offshore area with the classification of geodynamic environments. Our investigation will make possible the solution of fact – theory discrepancy by compilation of geodynamical maps and better understanding of physical meaning of types recognized.

[6] Thus, problems are the following:

- definition of such notions as "geodynamics" and "geodynamic environment";
- selection of geological-geophysical parameters adequately and spatially regularly describing "geodynamic environments";
- selection of calculation procedure to recognize types of geodynamic environments;
- implementation of computational algorithm and description of its work;
- construction of maps for distribution of geodynamic types and initial interpretation of physical and geodynamic meaning of the results.

2. Statement and Formalization of a Problem

2.1. Problem of Geodynamic Zonation and Previous Studies

[7] Qualitative approach to the solution of geodynamic problem can be based only on coherent definition of "geodynamics". Comparison of experts' views with those of their opponents [*Belousov,* 1975; *Pavlenkova,* 1987; *Zonenshein and Kuzmin,* l993] shows the presence of a common pivot proceeds from the definition of dynamics used in physics. "Mechanics studies the simplest form of matter motion i.e. mechanical movement to change mutual arrangement of bodies and their parts in space and time. Bodies are macroscopic systems consisting of a very large number of molecules and atoms, so sizes of the systems many times higher than intermolecular distances. Kinematics studies mechanical motion of bodies without the connection defining the interaction between bodies. Dynamics studies the way in which force produces motion [*Yavorsky and Detlaf,* 1974]. Interaction means the analysis of forces and energy sources. Therefore, "geodynamics" is considered as science that studies the interaction between geological object with time. The development of approaches to parametrization of complex properties of geological bodies to further use them in the quantative analysis is important for solution of geodynamic problems. A very similar to the above definition of "geodynamics" was given in the work by *Khain and Lomize* [1995]. Objects in terms of geodynamic turn to be much more complicated than those in classical physics which makes this subject quite unique. Complexity of objects affects greatly the presence of adequate and efficient quantitative models describing processes of geodynamics.

[8] The above definition assumes that parameters describing a geodynamic object are to be delivered into three main groups:

[9] 1. Description of geometry and physical properties of the object.

[10] 2. Description of forces and energy release within the object.

[11] 3. Description of object motion behavior resulted from the action of forces on the object and energy release in it.

[12] Thus, the objective of the geodynamic zonation is a search for different stable combinations of parameters describing a geodynamic object and analysis of their distribution in space.

[13] The first works concerning the qualitative approach to solution of geodynamical problems using several parameters are those by *Reisner and Reisner* [1987, 1990]. They made the analysis of endogenous regimes for most of Europe, Caucasus, and the Carpathians. Calculations using the cluster analysis algorithm as a version of popular multidimensional statistic classification of objects. This method is of practical importance because a man cannot make a reliable visual correlation of parameters if their number is above four. Such parameters as thickness and average seismic velocity of the Earth's crust, elevation, depth to the consolidated basement were discussed in the works mentioned. Heat flow is taken as a parameter describing energy release. Isostatic gravity anomalies and velocity of recent vertical movements were used to describe the resultant motion of geomedia. A complete set of parameters was presented for the land and grouped into average values $20' \times 30'$ cell of arc minutes defining stable combinations, i.e. clusters of geodynamic parameters. The latter allowed to find a new type of endogenous regime.

[14] The paper by *Ioganson and Boltyshev* [2000] presented the cluster analysis for the eastern Eurasia. This study differs from the previous works by showing changes in cluster classification as the number of clusters increases and in revealing of stable (homogenous) areas. This does not result in differentiation of a separate region into subclasses of smaller area. Qualitatively, they used linear and dispersed heterogeneity of territories. The former assumes division of territory into contrasting classes much smaller in area (size) than homogeneous areas. At the same time, it made possible to retain a stable mosaic pattern as the classification number increases. Dispersed heterogeneity was meant as "comminution" of territory into small and comparable with size of a zone cell with different combination of main parameters

chaotically covering territory. Prior to the processing stage the study area was homogeneous (linearly heterogeneous) on steps having small classification number.

[15] This paper discusses the Atlantic ocean structure in terms of linear heterogeneity. However, situation will be considered to be optimal when the number of classes allowing to divide the study territory (see Section 5) does not result in critical comminution of the recognized stable zones into much smaller zones whose size is comparable with that of a cell. The authors believe that dispersed (scattered) heterogeneity mentioned in the paper by *Ioganson and Boltyshev* [2000] is directly associated with the scatter of parameters used for their analysis. Its qualitative measure is the scatter of parameters values within a zone of one or another cluster.

2.2. Approach to Selection of Parameters and Their Coordinates

[16] The parameters selected for the analysis should be homogeneously defined within the study area and should have similar detailness. Similar detailness is necessary for adequately assess different parts of the territory because the detail level incorporated into a general data set of low density will make algorithm respond to a difference thus affecting classification results due to detection of false differences. A similar detail level will allow assign to each cell (into which territory is divided) a full vector of parameters used in the analysis. Noteworthy, that the rule can be broken in some cases if parameter should be added to the calculation. Heat flow is such a parameter. It is not equally known in the Atlantic area, so sites lacking interpolation measurement should be covered by calculation of grid (parameter values regularly spaced) and only then fit a high frequency grid component to the level of other parameters.

[17] Parameters to be selected must describe three groups of properties mentioned in Section 2.1. Parameters describing structural features of the lithosphere (group 1) are very easy to select (see Section 3).

[18] Parameters defining energy release (group 2) can be easily selected except for problems related to irregular heat flow measurements.

[19] Most difficult is to describe the resultant motion (group 3). Vertical movements inferred from repeated geodetic measurements from GPS data can be used for the land. There is no such measurements for the sea floor and a regular observation network (measurement grid) can hardly be obtained in future. Therefore, to include data of 3-type group into calculations one should use the so-called “surrogate” parameters reflecting indirectly values no measured or partially measured in the ocean or they present a combination of many effects including those to be processed. In this case, such an approach is the only way to show the necessary information in absence of detailed data.

[20] All the parameters used in this paper are values inferred from instrumental measurements reflecting only the present state of all three groups of parameters. Paleogeodynamic reconstructions of the Atlantic ocean are always based on incomplete information with many assumptions for values remaining unknown. In paleogeodynamics not measurements but interpretations of geological-geophysical data that should reflect paleostate of the lithosphere become important. The ambiguity of interpretation will always make the result debatable.

[21] The paper discusses only the recent state of the lithosphere. Besides, the authors do not use the age of the oceanic lithosphere inferred from magnetometric data as a parameter for calculation [*Mueller et al.,* 1993] because the authors of a data source do not define general linear anomaly position in most complex and important parts of the Atlantic (transition from northern to southern segment), important for geodynamic. The latter follows from the data [*Cande et al.,* 1993] used for the construction of the known age map. Nevertheless, the map in fact completely covers the Atlantic. It means that all the estimates for which we use it in most important areas will reflect the pecularities of interpolation algorithms and not value a parameter. Therefore, the information on the age of the lithosphere can at best be used as a coordinate parameter to present the analysis results along with latitude and longitude.

[22] In this study one arc degree is proposed as the best size for a cell within which the parameters used show similar detail level. In other words, the latter of all the parameters is not worse than this value. The dimensions of the cell are comparable with an average thickness of the lithosphere. The more detailed parameters are to be fit to a chosen threshold by frequency filtration or by moving average. The real size of an area created by a chosen cell decreases at high latitudes which creates less statistical importance of parameters. Nonetheless, as this concerns all the parameters at once the authors do not use estimates in the projection space having equal size. However, the average value of parameters within cell is evaluated well enough.

2.3. Approach to Selection of Data Processing Methods

[23] Three methods of large data sets multivariant statistical classification could be pointed out – discriminant, factor, and cluster analysis. They efficiently use geological-geophysical data and differ in specific features.

[24] The discriminant analysis is aimed at classification of objects by selection of its parameters and comparing their values with “learning” standards. Requiring the presence of known a priori stable type, this method is not applicable because prior to the analysis we can not be sure in the result.

[25] The factor analysis assumes that the available object data set consists of combination of two or more processes actions, each of them contributing to values of all parameters. In other words, there are independent geodynamic phenomena that form superposition of measurement values (we subdivide them by means of factor analysis). At present, it is fairly difficult to construct a model for operation of two or more global processes whose contribution to all the parameters will be of statistical importance, however, this can be done in future.

[26] The cluster analysis assumes recognition of stable combinations of parameters not discernible by visual analy-

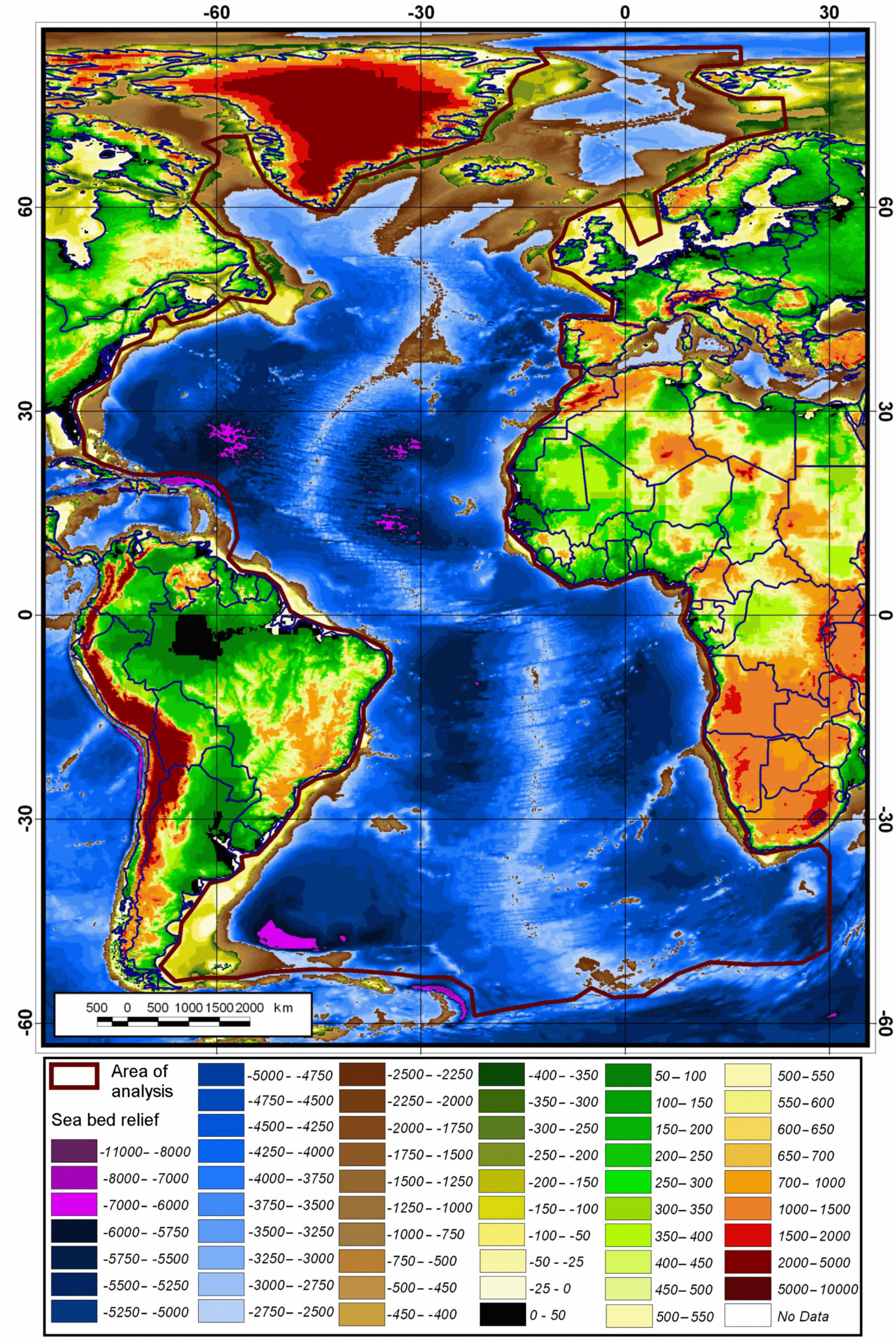

Figure 1. Bottom topography of the Atlantic ocean and adjacent land from ETOPO5 (1993). Hereafter the area used in analysis is outlined.

sis of maps and seems to be the most adequate at this stage of the study as has been shown earlier for other regions (see Section 2.1.). The factor analysis might be used in case of geodynamic model construction exhibiting one (or more) mechanisms affecting surface tectogenesis.

3. Data Applied

[27] Geodynamic zonation of the Atlantic Ocean lithosphere encloses deep-water areas, the Mid-Atlantic Ridge area, passive continental margins, and offshore area (Figure 1). The analysis does not include arc and backarc zones of the Caribbean and Scotia, seas different in geodynamics in environments characteristic of the entire Atlantic. Thus, the class of phenomena studied does not contain collision zones. It is the 82°N at the transition of the Mid-Atlantic Ridge zone to Gakkel Ridge. To the south, it is confined to Bouvet triple junction where a drastic change in the structural pattern of most geophysical anomalies takes place farther south. Analysis area is shown on Figure 1. The brief description of chosen parameters for each $1^\circ \times 1^\circ$ cell multivariant vector will be presented.

3.1. Bottom Topography

[28] Bottom topography in the first and the major parameter describing the top of the earth's crust and the lithosphere (see Figure 1). It was inferred from ETOPO5 (1995), lowpass filtered frequency filtration and recalculated to one degree cell. Its shape gathers together the effect of many processes: magmatism, ocean floor deformation, sedimentation, etc. In our classification it is assigned to group 1 of parameters describing the object geometry being so a direct measure of the required characteristics. Qualitatively, the bottom topography assumes the result of the crustal block movement under the effect of contacting forces (parameter of group 3). An accurate observation over the movement similar to ground-based GPS measurements for the ocean floor are absent, off processing of the bottom topography data indirectly, though not precisely, is accounting these movements.

3.2. The Thickness of Sedimentary Cover

[29] The thickness of sedimentary cover in the Atlantic ocean was inferred from data of *Laske and Masters* [1997] and is shown in Figure 2. These authors collected information on the sedimentary cover (averaging thickness by 30 arc minutes grid to make corrections to tomographic model. In the present paper the data are arranged to fit its detailed pattern. There are several reasons of sediment thickness usage. The main is that the ocean periphery being a zone of intense sediments deposition delivered from the continents exhibits unbalanced isostatic state between the crustal blocks and viscous mantle substrate caused by the higher load on the latter. This results in processes striving to restore the balance by response vertical movements trying to bring the medium back into isostatic equilibrium and decrease the aquiered disturbance. Another reason why the sedimentary cover should be accounted into estimates is a great difference in density between bottom and crystalline basement. This surface describes properties of group l and is responsible for object geometry – in this case a stratified conformity of the Earth's crust with the upper mantle.

3.3. Tomography Inferred From Surface Love Waves

[30] This parameter is based on the data provided by *Larson et al.* (http://www.seismology.harvard.edu, 1999) and shown on Figure 3. In fact, it is a "surrogate" used to describe object geometry reflecting not directly but indirectly behavior of an efficient base of the lithosphere layer (depth to the lithosphere for the entire Atlantic has not been measured). It shows the dependence of surface wave phase velocities (waves propagating in an efficient surface layer) on the layer thickness. The greater the thickness, the less is wave velocity and, in contrast, velocity increases as thickness decreases. Therefore, phase velocity deviation from average value implies relative variations of the efficient surface layer. They are proportional to the required parameter, i.e. a depth to the lithosphere base. The 35 s period wave (the shortest of published) model was used for calculations, in this case penetrations of displacements along the wave front is not deep and approximately corresponds to the lithospheric layer. Long period waves involve deeper layers into wave motion. Figure 3 clearly shows that continental areas and those with low velocities in regions of intense magmatism can be easily distinguished from the oceanic zones underlain by thin and high velocity lithosphere. It also shows that mountain edifices with deep roots have adequate minima complying with geometry of the surface layer base, it implies that the selected parameter can be used as a "surrogate" in description of the lithosphere base geometry. However, a peculiar linear anomaly zone extending along the azimuth at about 30°N and not orthogonally crossing the Mid-Atlantic Ridge near the equator can be discernible in the Atlantic.

3.4. Bouguer Anomaly

[31] Bouguer anomaly was calculated from EGM97 data [*Hwang et al.,* l997] and from bottom topography data (ETOPO5, 1993) for the average density of the oceanic crust at 2.8 g cm^{-3} and the land density at 2.67 g cm^{-3}, and 166 km in integration radius, shown in Figure 4. EGM97 matrix originally was on the 2-minute grid, therefore this and ETOPO5 matrix were smoothed prior to calculations to the 10-minute grid followed by averaging of the result to 1 arc degree cell. Gravity anomalies of EGM97 are free-air anomalies. In offshore area it means that about 80% of anomalous field variability is proportional to the most distinct density boundary – to the bottom topography inferred

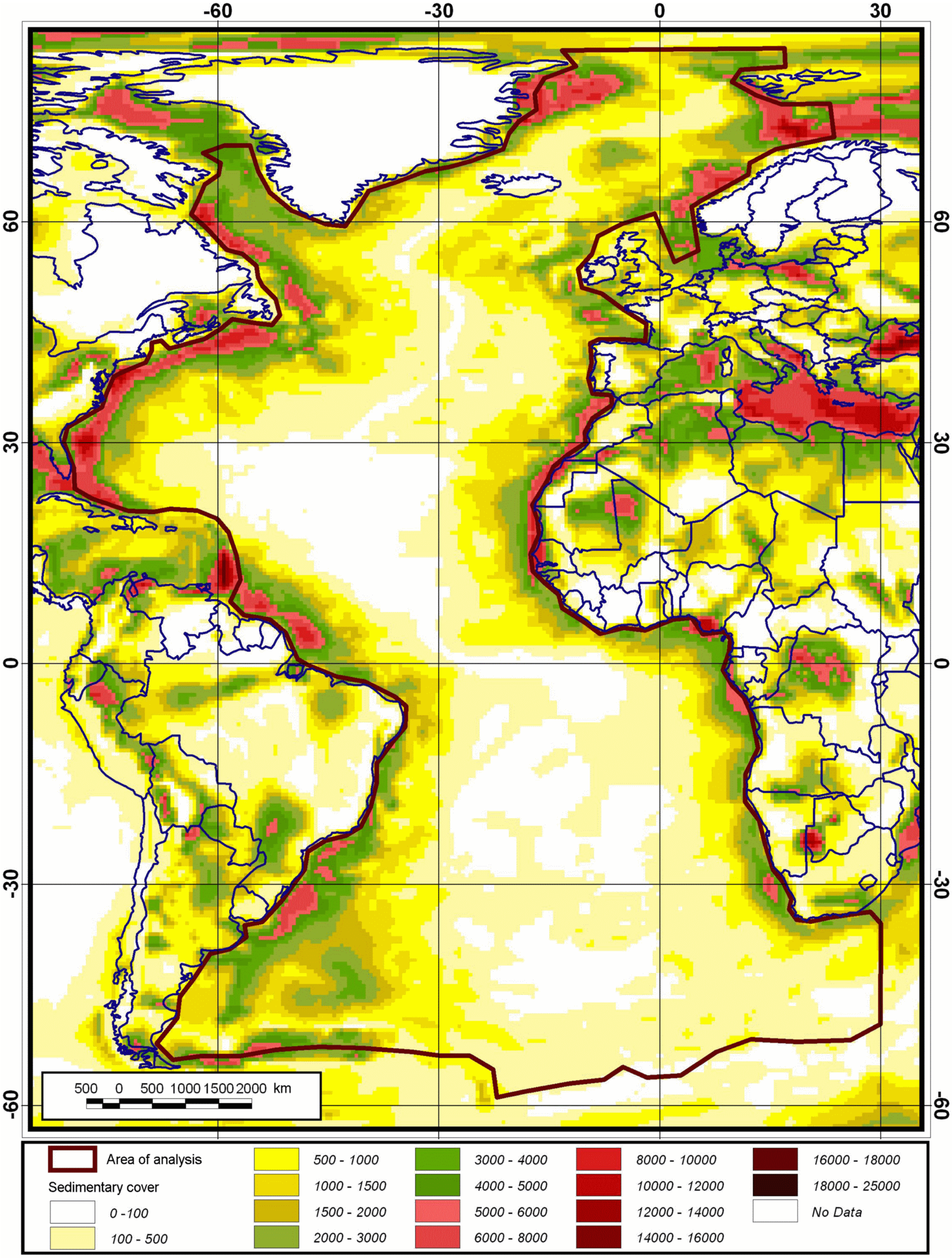

Figure 2. Sediment thickness of the Atlantic Ocean and adjacent land after *Laske and Masters* [1997].

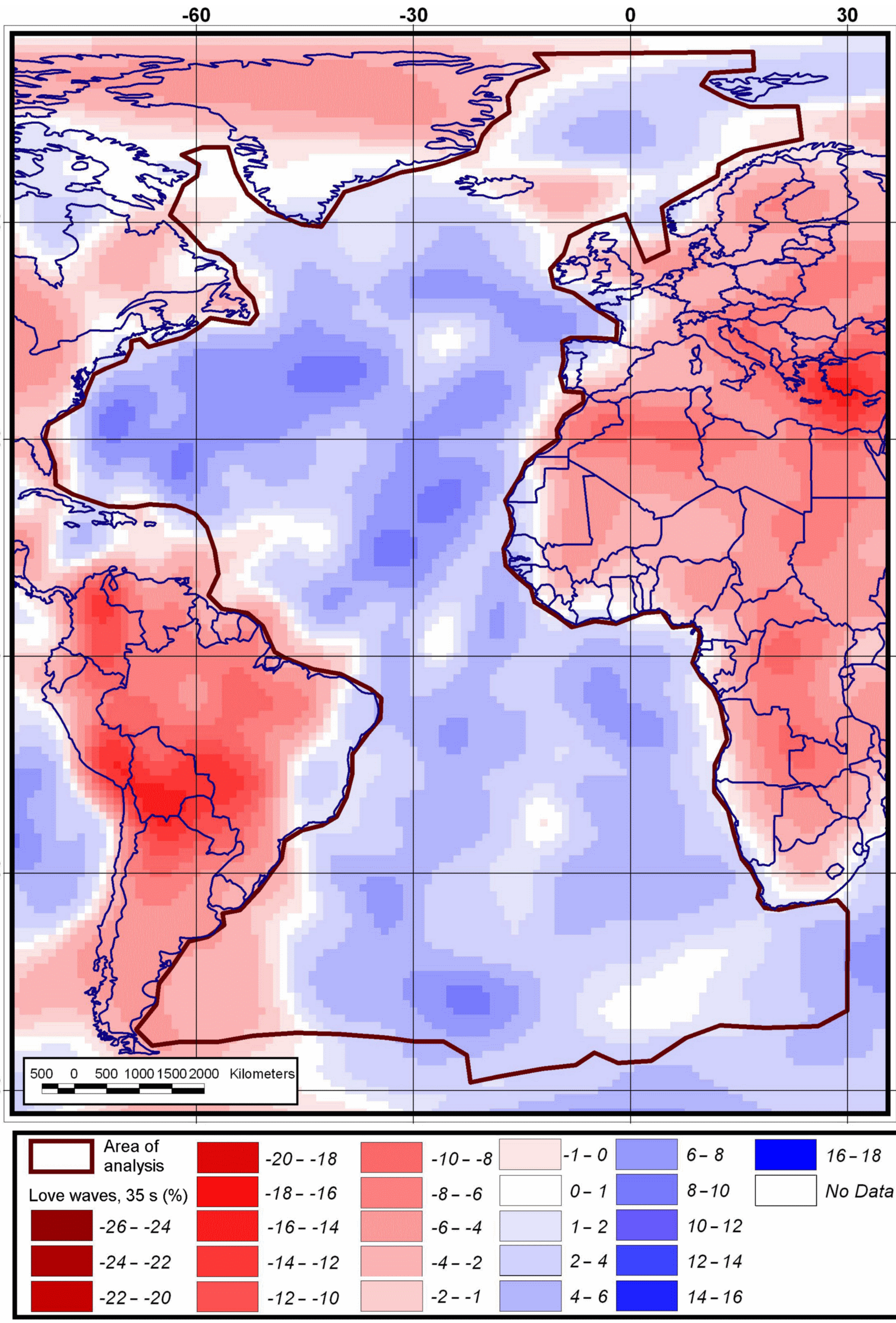

Figure 3. Tomography by surface Love waves (35 sec period) after *Larson et al.* [1999].

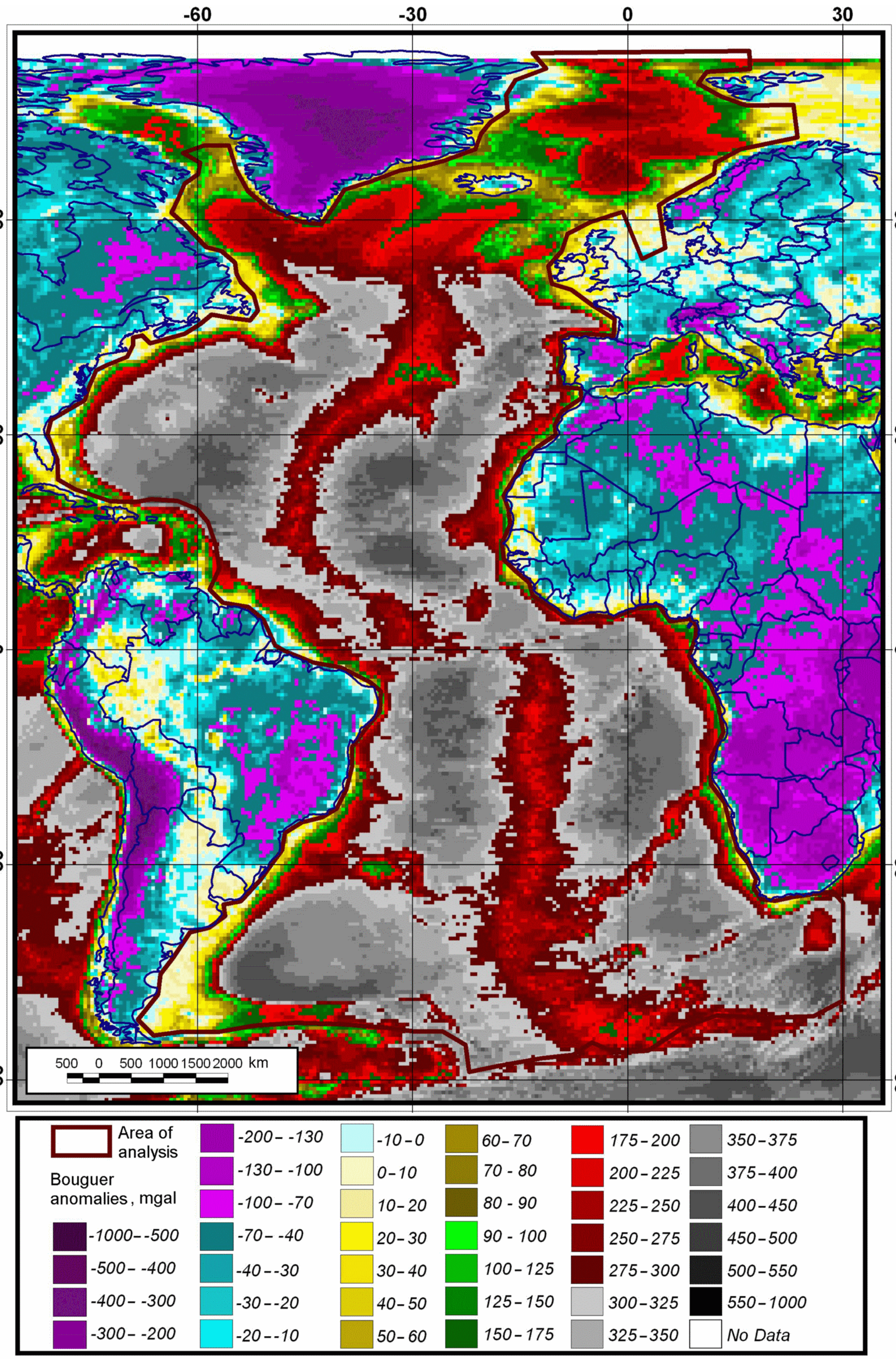

Figure 4. Bouguer anomalies calculated by authors from gravity EGM97 data [*Hwang et al.,* 1997] and relief data (ETOPO5, 1993) for average density of oceanic crust of 2.8 g cm^{-3} and that for continent of 2.67 g cm^{-3} integrated at 166 km in radius.

from echo soundings. Calculation of Bouguer anomaly, i.e. "addition" of the crustal density masses into the water layer (which is less than an average value) that will eliminate the effect of bottom topography on the anomalous field. Hence, variability of residual field will show mainly a depth difference in density at the crust-mantle boundary along with lateral density heterogeneities in the crust and mantle. In deep water basins they can be small or fairly important where serpentization of the upper mantle rocks take place but the absence of deep seismic sounding does not allow to tell reliably their effect from variation in a depth to the crust base. However, lateral heterogeneities in the MAR area can be great and occupy extensive zones of hundreds of kilometers (e.g. Azores and Iceland plume areas). They show heated zones where the lithosphere has magma chambers and areas exhibiting high partial melting. These zones are marked by intense magmatism, and accordingly greater crustal thickness, the latter being the load on the viscous mantle substrate, increases a depth of the M-discontinuity. The above means that Bouguer anomalies are proportional to a depth of the crust-mantle boundary and the less the anomaly value, the greater is the depth. The cases when it is reasonable to introduce a correction into the anomalous field for thermal effect should be accounted for heat flow data or another parameter reflecting the heated state, for example, tomography inferred from S-waves. However, the parameters being independently used in our geodynamic analysis (see below), calculation of Bouguer anomalies accounted for thermal correction makes no sense. Thus Bouguer anomalies belong to the first group parameters defining the lithospheric layer geometry or the inner boundary to distinguish the "dense stages" of the crust and mantle from the variation pattern of masses along the lithosphere. The features of Bouguer anomaly mentioned are the combination of contribution whose reliable separating seems difficult. Bouguer anomalies are "surrogate" parameters for description of geometry and are true for description of mass variation.

3.5. Isostatic Anomalies

[32] The authors calculated isostatic anomalies by means of the Bouguer anomaly data and topography (ETOPO5) for the average density of the oceanic crust, continent density, and the mantle density of 2.8 g cm^{-3}, 2.67 g cm^{-3}, and 3.3 g cm^{-3}, respectively, with radius of 166 km integrating by the Airy model and the surface reduction depth of 33 km (Figure 5). The long-wave components of above 900 km were eliminated from the anomalous field because they reflect sublithospheric heterogeneities and their effect obscures the processes operating in the upper shell of the Earth. On elimination of the anomalous field variability related to the upper boundary of the crustal masses and determination of Bouguer anomaly, the estimate of isostatic anomalies controls the hypothetic field variability caused by the change of the compensation surface topography due to the difference in thickness of the crustal blocks drifting upon the viscous mantle surface. The authors proceed from the fact that in case of isostatic equilibrium the position of the compensational surface and topography can be expressed by a simple equation:

$$H = T + h^{*}(\sigma_{\mathrm{c}} - \sigma_{\mathrm{w}})/(\sigma_{\mathrm{m}} + \sigma_{\mathrm{c}})$$

where H is a depth of the compensational surface, T – level of reduction, σ_{c} – crustal density, σ_{w} – water density, σ_{m} – mantle density; this will allow us to calculate correction for Bouguer anomaly. They eliminate the effect of a hypothetical surface topography obtained as in the case of bottom topography. The residual field represents isostatic anomalies when their positive values imply an excess of masses above the compensation surface unlike the negative values pointing to their deficiency. The excess of masses might well result in submergence of the crustal block in a given site, while emergence together with the mantle part owes it to deficiency. If the action (e.g., thrust) is not completed then we'll get both the excess of masses (positive isostatic anomalies) and positive vertical movements of the crust. The interpretation of isostatic anomalies being ambiguous, its resolution calls for further investigation of the general tectonics of the region. In terms of geodynamics this parameter concerns directly the variation of crust density properties intensity of energy release in the crust, and generation of stresses (modulus of isostasy gradient) caused by the transition from disturbed state into equilibrium. This parameter is also a "surrogate" in description of the resultant vertical movement of the crustal blocks subjected to energy release. The isostatic anomaly field presents the above properties as, in fact, an indivisible combination.

3.6. Heat Flow

[33] Heat flow is inferred from the data by *Pollack et al.* [1991], *Podgornykh and Khytorskoy* [1997], see Figure 6. Figure 6b shows it is not equally studied in the Atlantic but we have to use it in our estimates as it has been determined by the authors mentioned. Grid was calculated for each cell degree of the region to use scattered and irregular cloud of values by means of "kriging" technique, followed by reduction of its high frequency component to the level of other parameters to minimize the effect of irregular density of measurements. The obtained map (Figure 6a) differs in data available for the polar areas and for basins. Besides, there is an area on the Mid-Atlantic Ridge (Azores archipelago) also poorly studied. Heat flow being a true parameter of group 2 reflecting energy release, must be included into calculations. It is clear that irregular pattern of knowledge will make this parameter a tool for reliable classification in areas with a dense network of observations, and the opposite will take place in areas with low density of measurements, in such a way the latter will affect the results. In this case, it is the best we have at our disposal.

3.7. Tomography by S-Waves

[34] Tomography by S-waves was inferred from the data by *Grand et al.* [1997], *Becker and Boschi* [2001] and is

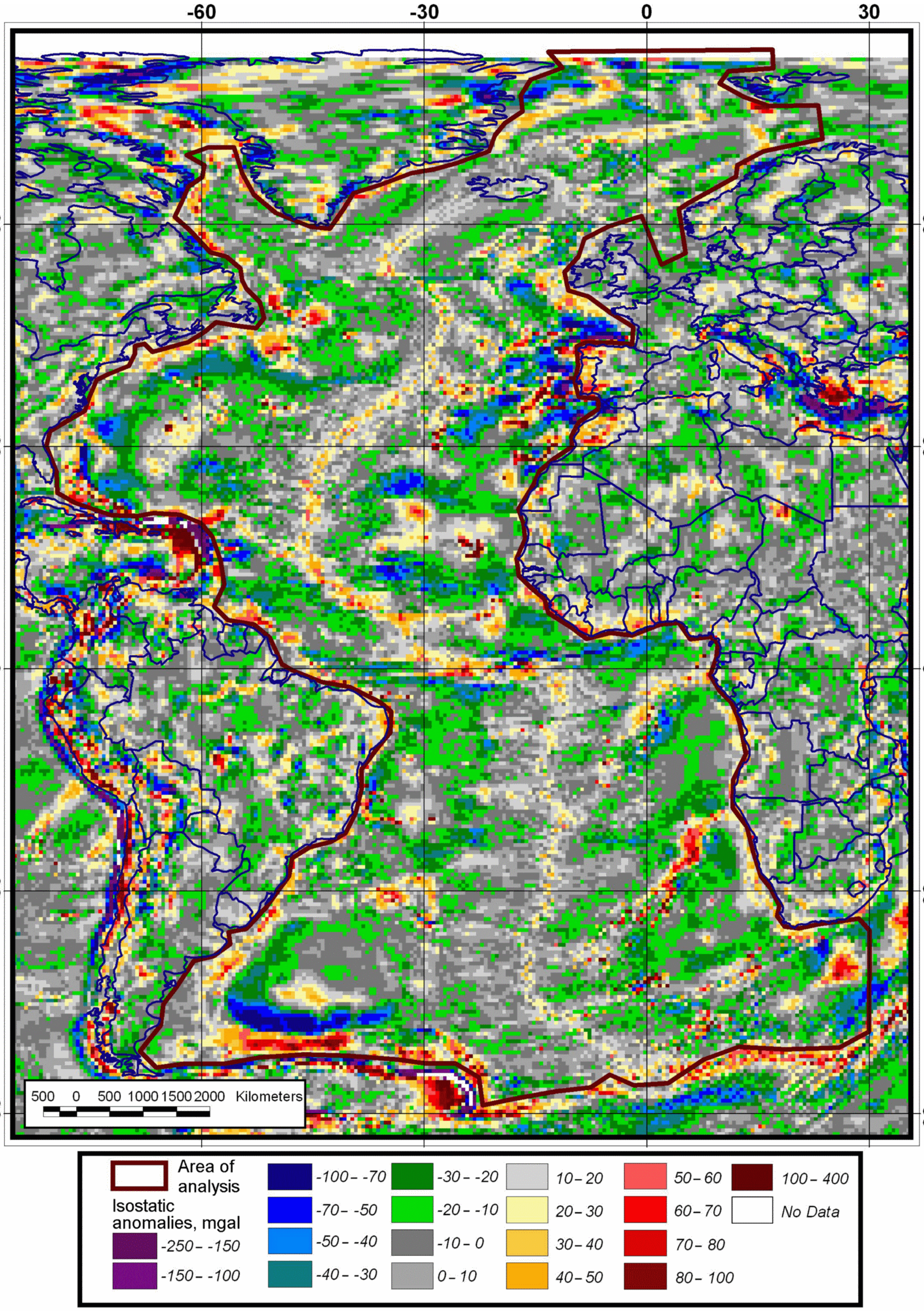

Figure 5. Isostatic anomalies calculated by authors from Bouguer anomaly and from relief (ETOPO5, 1993) for average crustal density for ocean (of 2.8 g cm^{-3}) and that for continent (of 2.67 g cm^{-3}), and that for mantle (of 3.3 g cm^{-3}), respectively integrated at 166 km radius by Airy model and surface reduction depth of 33 km. Long-wave components of above 900 km were removed from anomalous field.

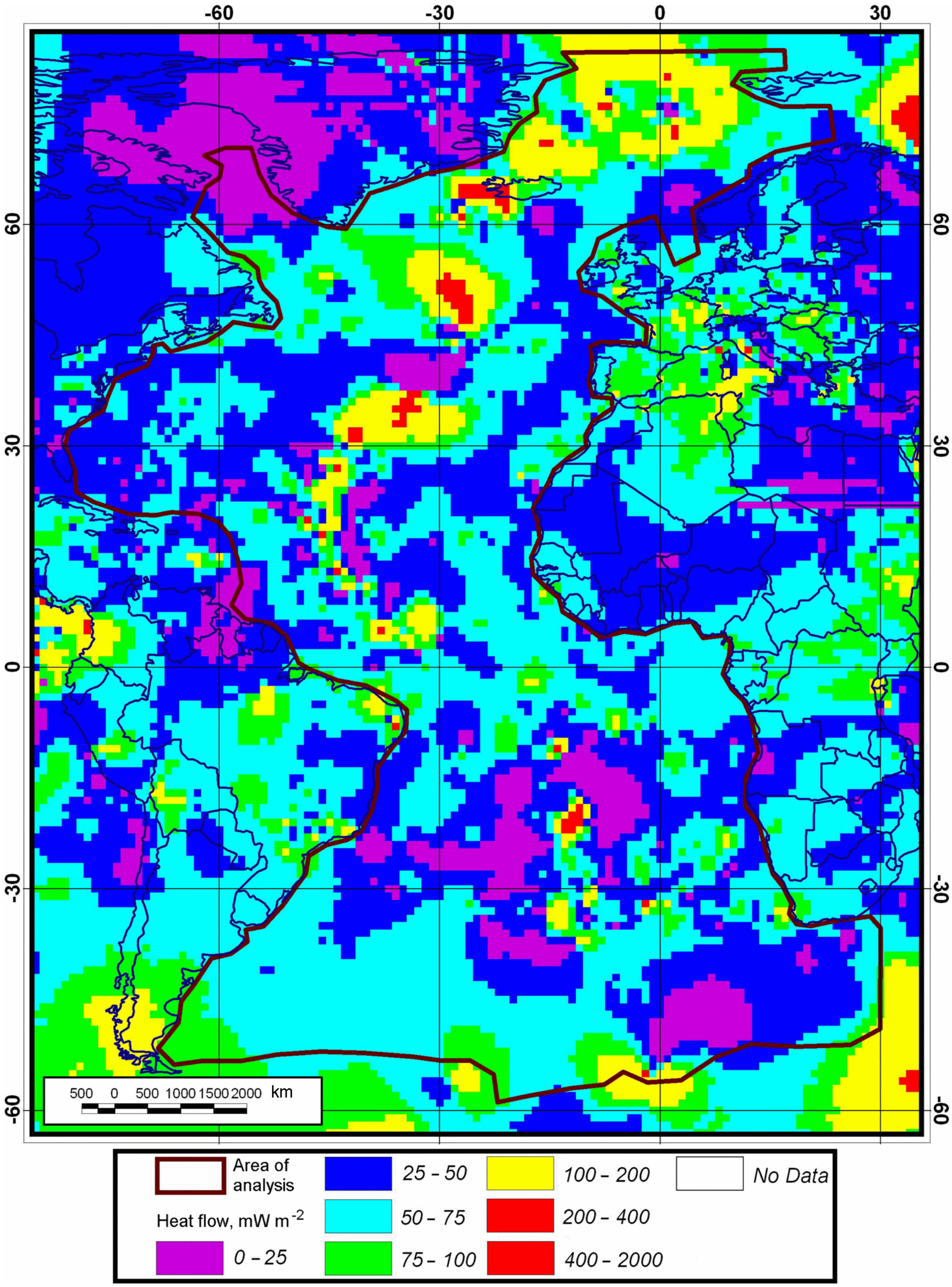

Figure 6a. Heat flow map inferred from data of *Pollack et al.* [1991] and *Podgornykh and Khytorskoy* [1997]

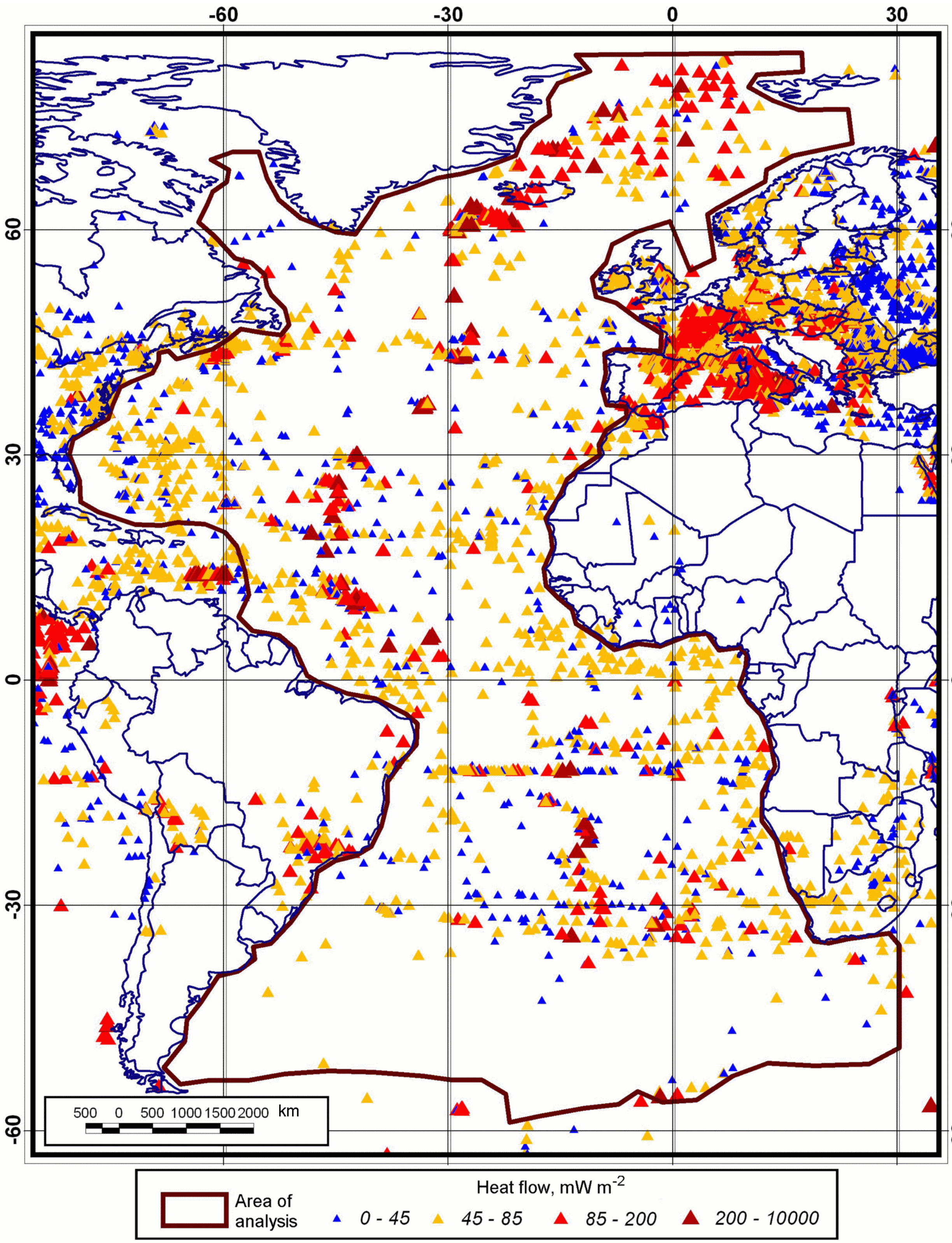

Figure 6b. Heat flow data of *Pollack et al.* [1991] and *Podgornykh and Khytorskoy* [1997].

shown in Figure 7. The uppermost segment of NGRAND model from 0 to 100 km, calculated by its authors for 2° by 2° blocks and represented by spherical harmonics of the 31 order. Matrix of tomographic values was recalculated for 1° × 1° grid. These values show the variation of S-wave propagation velocity from the average within the layer (in %). This parameter responds to heated zones exhibiting high partial melting. It clearly points to the presence of plumes commonly accompanied by magmatism and to zones of mid-oceanic ridges. These zones are characterized by negative, inferred from tomography, values: –3.5% and less because warmed up and viscous medium decreases seismic velocities.

[35] So, this parameter is an almost indivisible combination of effects of energy release (heated state) and medium geometry (zone of prolific magma production and greater thickness of the crust). This parameter is "surrogate" for both groups reflecting indirectly and not directly properties of the groups.

3.8. Tomography by P-Waves

[36] Tomography by P-waves is inferred from data by *Van der Hilst et al.* [1997], *Becker and Boschi* [2001] (see Figure 8). The uppermost section HWE97p from 0 to 100 km calculated by the above authors for 2° × 2° blocks and represented by spherical harmonics to the 31 order was used to study geodynamics of the lithosphere. Matrix for the tomographic part of values was recalculatad to 1° × 1° grid. Like in the case of S-waves, P-waves should be accounted for thermal state of the subsurface. So, tomography by these waves must be similar to that by S-waves. However, in practice such is not the case. According to *Becker and Boschi* [2001] the S- and P-models correlate better toward the middle part of the mantle (above l000 km) implying a similarity in cases responsible for variability of parameters. The behavior of the S- and P-models differs greatly in the mantle from that on the surface. If pattern by S-model is easily to explain, then distribution of values by P-model should be accounted for sources that caused velocity variation. The authors consider the presence of the stressed condition of the lithosphere and (or) related fracturing system as a possible cause. The system is responsible for a peculiar pattern of highs and lows distribution on the map (Figure 8). Low velocities are seen to be concentrated along the collision zones of the Earth whereas high velocities occur in the rear part. These zones are marked by large-scale fractures, their disposition in plan is not aligned with direction of forces generating collision area. These fractures might well "slow down" the velocity of the P-waves. The parameter points to a stressed state of the medium and relates systems of faults with relieving of stress along them. Thus, it combines parameters of group 2 and group 3 showing both energy release in the medium and the resultant action of forces. The absence of an accepted regional geodynamic interpretation of this parameter makes its discussion in context of remaining parameters more stimulating.

3.9. Total Seismic Moment

[37] This parameter is used for calculation of the total energy released during earthquakes. It was a global query (ANSS,February 2004, http://quake.geo.berkeley.edu/anss/) for events with a Richter magnitude of above 4.5 for a layer of 0 to 100 km. The approach published by *Boldyrev* [1998] was used in our estimates. Summation of released energy for events within a degree cell was calculated from the formula

$$M = (10^{(17.1+1.3\cdot(\mathrm{Mag}-5))})/10^{+13}\ [J \cdot 10^{+13}]\ ,$$

where M is total moment, Mag – magnitude on the Richter scale. The estimate of total moment was followed by calculation of density moment for sq. km accounted for changes in area of call degree at high latitudes. The resultant value shown on the map (see Figure 9) is $[J\ \mathrm{km}^{-2}]\cdot 10^{+13}$. This parameter is marked by an extremely irregular distribution in the study area. Besides, no more than 5% of the entire seismic energy of the planet is released along the Mid-Atlantic Ridge. Therefore, variably of the parameter is mainly out of the region unlike other parameters having within the region values close to minimal and maximal. A given magnitude of scale not imposing limits on record of seismic events along the distance, the entire region is regularly crated by values of the parameter, however, for most of the area it equals zero. Seismic moment belongs to group 2 showing energy release.

3.10. Lithospheric Component of the Earth's Magnetic Field

[38] This parameter was found by processing of satellite CHAMP data [*Maus et al.,* 2002]. At the orbit altitude of about 450 km and trajectory crossing the earth poles this satellite made possible to register the lithospheric component of the anomalous magnetic field or the entire area of the Earth. The authors constructed magnetic anomaly map of full vector, vertical component, and gradient modulus of the full vector. Our study uses the last parameter and Figure 10 shows the map for recalculation to the altitude of 100 km. This altitude is approximately equal to the thickness of the lithosphere and provides a proper averaging. The gradient modulus of full vector has an advantage because the field lacks alternating signs due to changing direction of the magnetized field, i.e. the cause related to the features of the lithosphere which greatly simplifies an interpretation. This parameter is proportional to concentration of magnetically active minerals in the lithosphere and points to reasons responsible for variability of their concentration. Among them are: a depth of the Curie isotherm, the presence of serpentinization zones, zones of intense magmatism differing in composition from that of the adjacent territories, etc. In other words, this parameter is a "surrogate" as concerns properties of group 2, namely, in energy release, and partly those of group 1 – geometry of deep-seated boundaries.

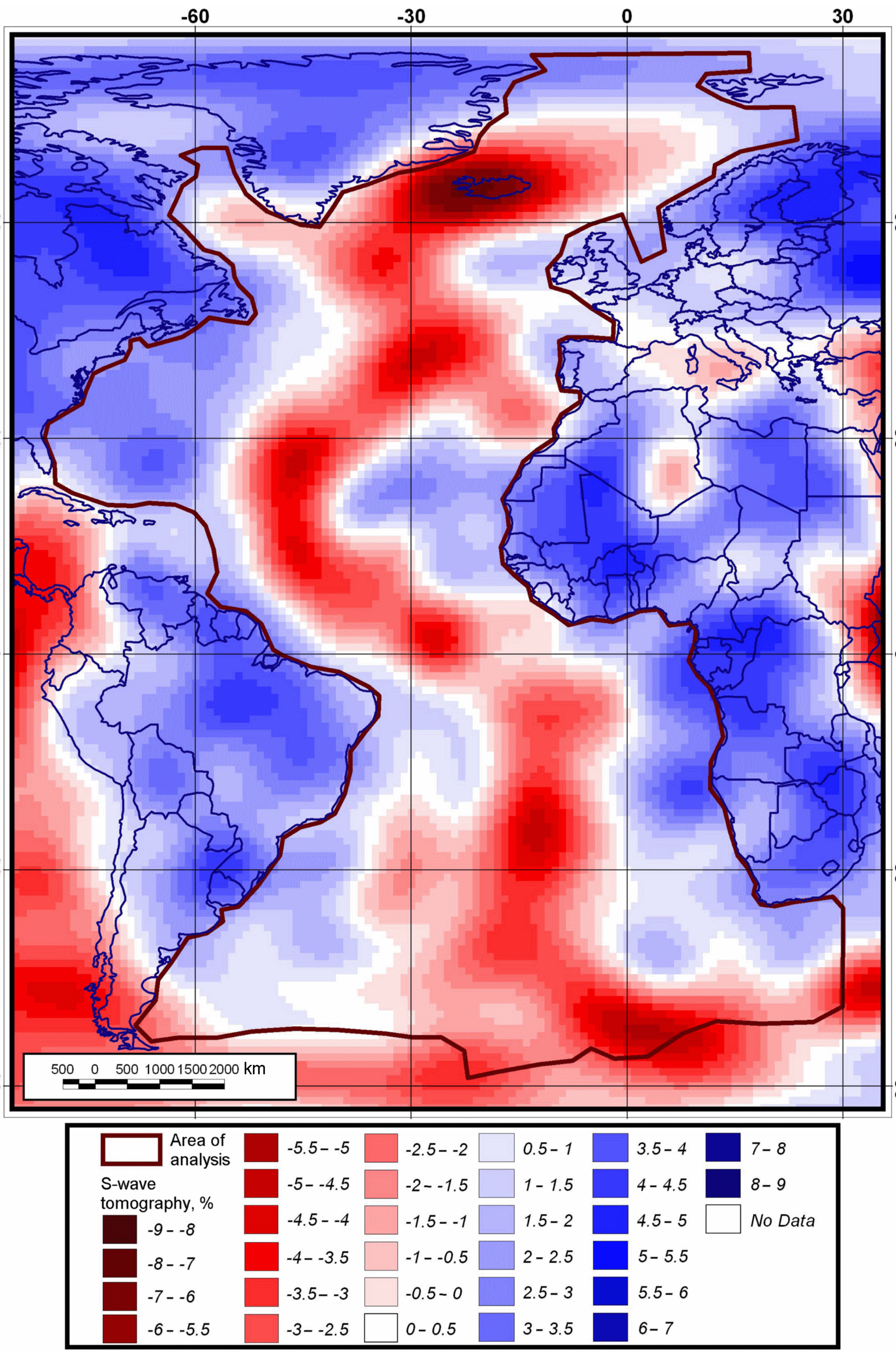

Figure 7. S-wave tomography for 0 to 100 km layer after *Grand et al.* [1997], *Becker and Boschi* [2001].

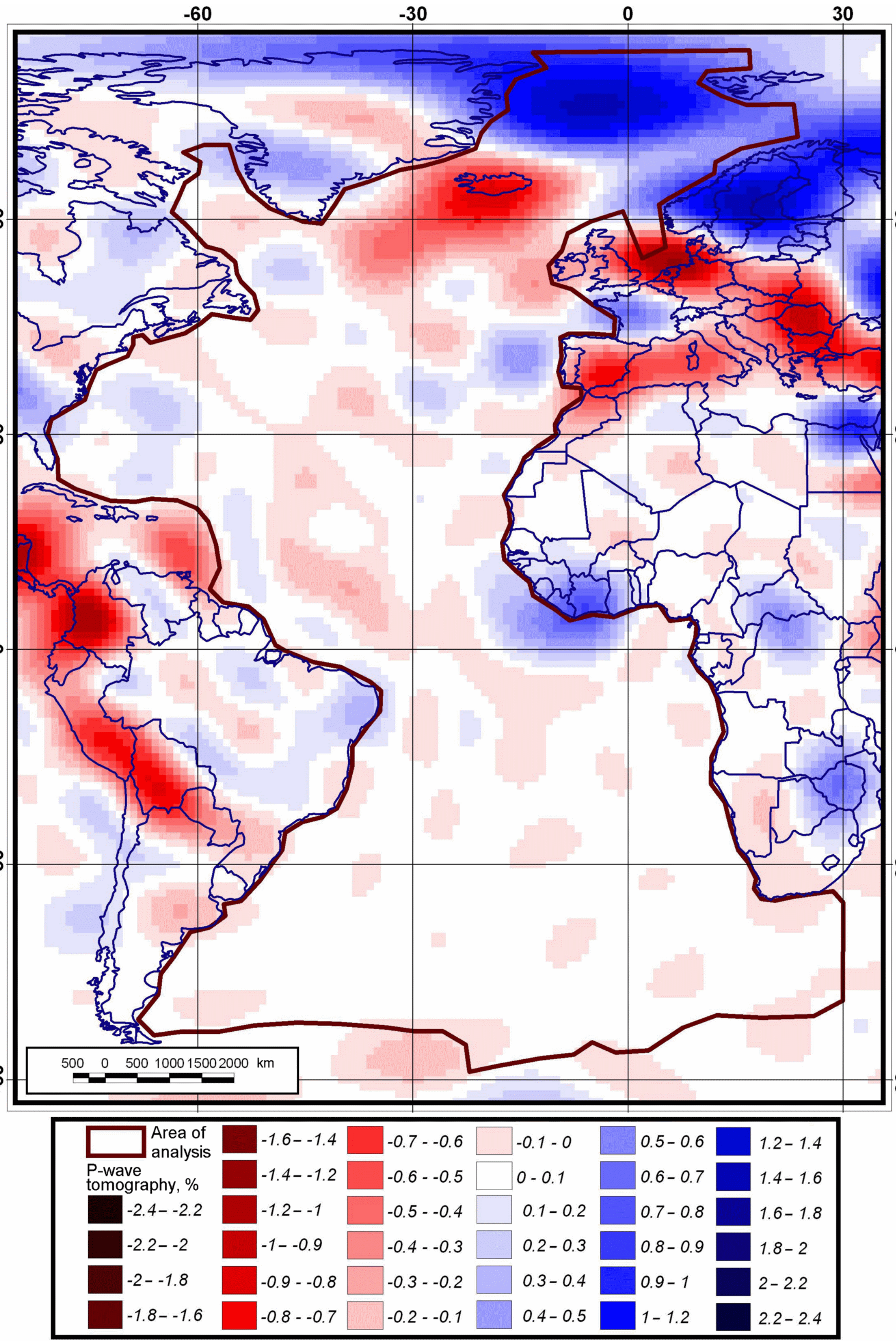

Figure 8. P-wave tomography for 0 to 100 km layer after *Van der Hilst et al.* [1997], *Becker and Boschi* [2001].

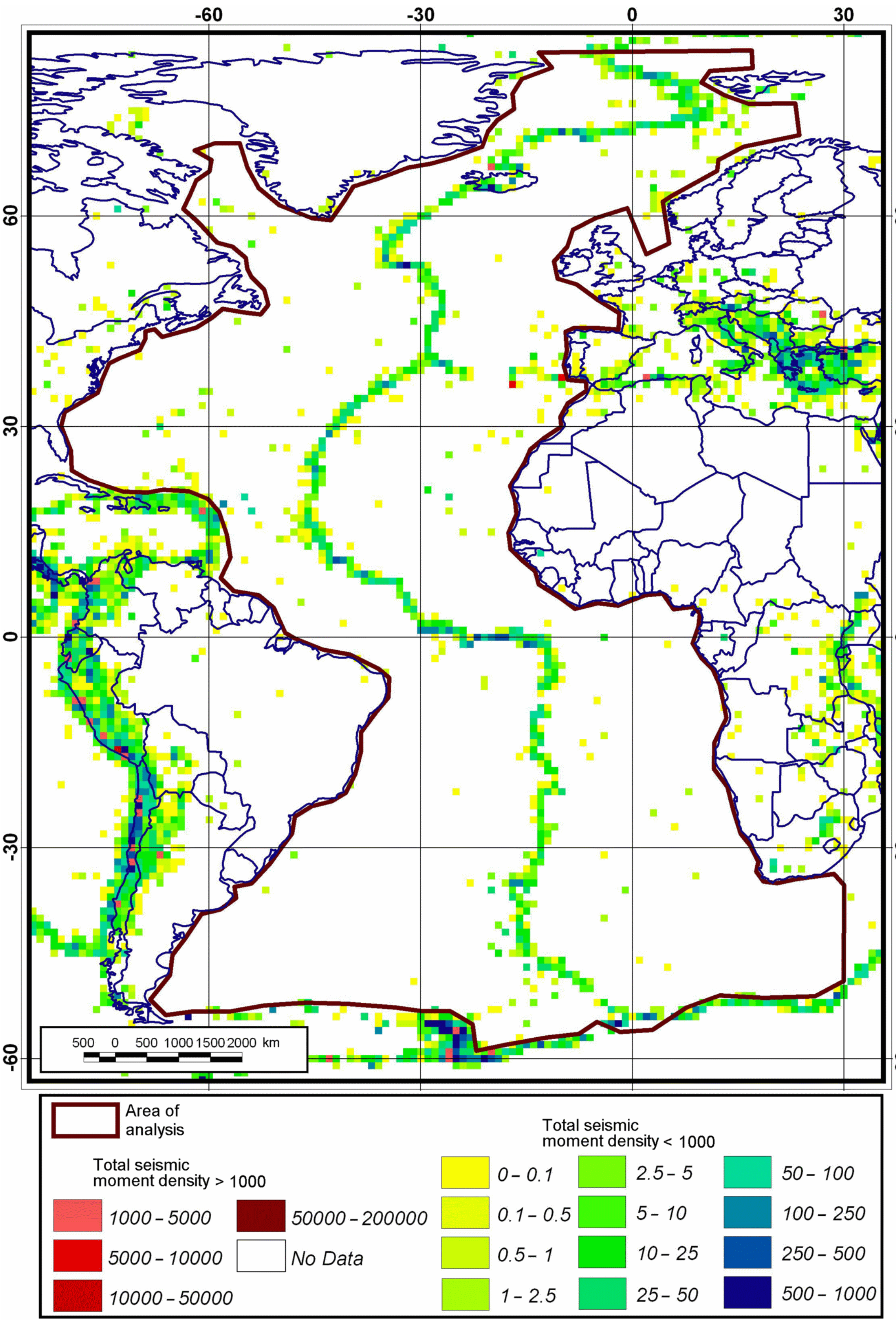

Figure 9. Total seismic moment density $[J\ \mathrm{km}^{-2}] \times 10^{-13}$ for events in 0 to 100 km layer from data of (ANSS Earthquake Composite Catalog, 2004, http://quake.geo.berkeley.edu/anss/, sample 11 02.2004.

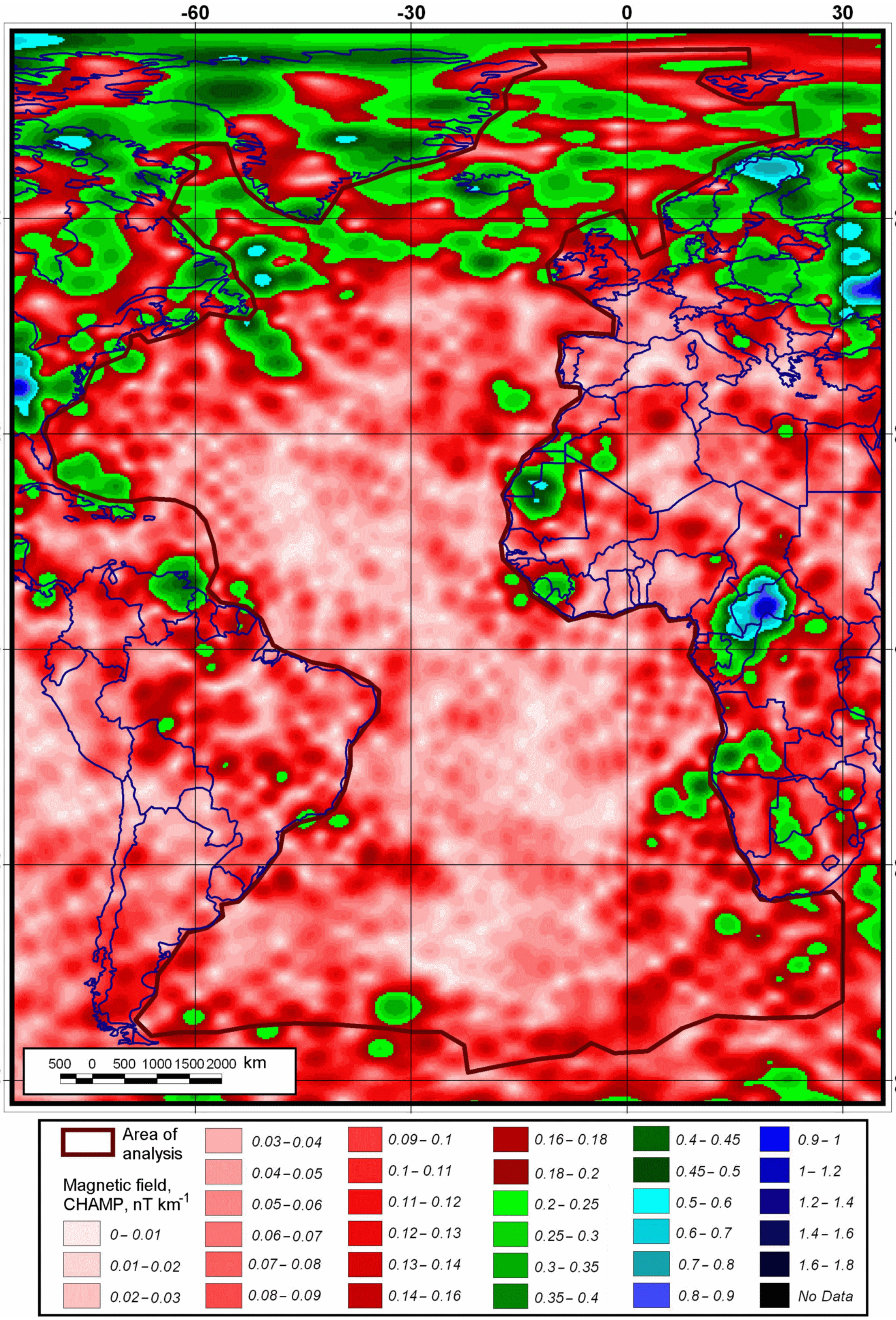

Figure 10. Complete vector gradient module of lithospheric component of anomalous magnetic field from CHAMP satellite data [*Maus et al.,* 2002].

4. Method Description

4.1. Cluster Analysis

[39] Cluster analysis is a method of multi-dimensional statistic classification, based on a compact measurement groups selection (stable parameters composition in multi-dimensional space) and outlining geometry of the groups to access distances between their centers and showing the limit dividing the space according to the assignment to one or another group. As the result of analysis the original points aggregate in multi-dimensional space (which depends on the number of parameters, applied for the classification – 10-dimensional in our case) is divided into clusters or groups of similar objects. The object is meant as elementary $1^\circ \times 1^\circ$ lithospheric cell that was given a 10-parameter value. The cluster is usually defined as a group of objects (here it is a lithospheric area) with a density i.e. compact concentration of applied parameters for the above mentioned area. In this case the object density or similarity of properties is assumed to be higher within the cluster, than out of it. It means that cluster may be defined as a center, variance (efficient radius) within the outlines in shape of hypersphere and separation from other clusters. This definition is far from being absolute.

[40] But it clearly defines its properties and tasks being in fact comprehensive.

[41] In current study calculations were performed in STATISTICA after the loading of the prepared data. It means the authors didn't go into detail of the algorithms, implemented in STATISTICA. The authors knew only a general procedure of classification, confined to parameters available in the user's menu of the program. The number of clusters N into which all the objects are to be divided presents the main parameter. The selection of an optimal number of clusters will be discussed below in Section 4.2.

[42] Standardized parameters (see Section 3) for each lithospheric cell (see Section 6.1.), represented in form of the table, where columns show values of one of 10 parameters for each line, corresponded with cells, are the original data for the calculations. Then the matrix of distances between each pair of objects is calculated within the multi-dimensional space. Algorithm at a given number of required clusters N divides the entire set of objects into N clusters. The general idea of the procedure is the following. At first it is given such a measure (radius), which is greater than total space objects occupation, and using this radius any object could be reached from any of her object. Then the algorithm decreases it until the appearance of separation dense groups from the general "cloud", when the mutual access between groups at the current radius becomes impossible. The method of groups densities and areas weights estimation won't be discussed here. Such procedure could also be carried out in opposite direction: minimum measure (the shortest distance between objects) increases until the aggregation of objects from given number of clusters (equal to number of objects) into N groups.

[43] The above presents the main idea of clusterization using the physically simplest k-means clustering method. This method, realized in STATISTICA, fits our problem the best. STATISTICA suggests a variety of parameters and clusterization algorithms details, but their description is not essential for our work.

4.2. Approach to Criteria Identification for Attainment of Results

[44] A brief description of the method showed that our task is aimed at breaking all the objects into stable and distinctly isolated N-number statistic groups with N number as large as possible. Each group contains a certain combination of all the parameters. Apparently, groups with distinct extreme for any parameter are the first to be singled out. Division using least pronounced variations starts only after the appearance of groups formed due to maximum values or values spanning the main variability range of each parameter. At this stage it is essential to find a moment when separation by statistically different mean values in areas outlined is replaced by "forced" separation, i.e. extraction of clusters slightly differing in value, comparable to dispersion or parameter instrumental error within zone selected. This moment corresponds to the condition when the analysis procedure terminates estimation of environment linear heterogeneity (see Section 2.1.) and starts to analyze scattered heterogeneity. In this case, geodynamical interpretation of separate clusters seems to be useless and the analysis should be stopped at the current N value. A diversity assigned to scattered heterogeneity should be statistically estimated using characteristics of high-order moment type uniform for the entire area. The availability of physical validity and geological meaning for different parameters of each cluster will also be a criterion of the result accessibility. A set of values for characteristics given for each parameter for each of clusters is the solution of the stated geodynamical zonation problem.

5. Algorithm of Geodynamical Classification

[45] Data preparation for cluster classification includes the formation of spatially identical matrixes for all the parameters used (see Section 3) and their values standardization required for this algorithm accounted for calculation of distances (required uniform parameter dimension). Then the tabulated data is loaded into program environment.

[46] The next step should be the classification test by minor N values. Here algorithm should step by step accomplish the classification of space analyzed into clusters, geologically valid. Starting with N=2 algorithm divides the area analyzed into oceanic and continental (shelf areas). At the next step (N=3) the oceanic area is divided into basins and most elevated parts of MAR. During the following steps (up to N=5) successive isolation of MAR zone, including flanks and division into "cold" and "hot" parts takes place.

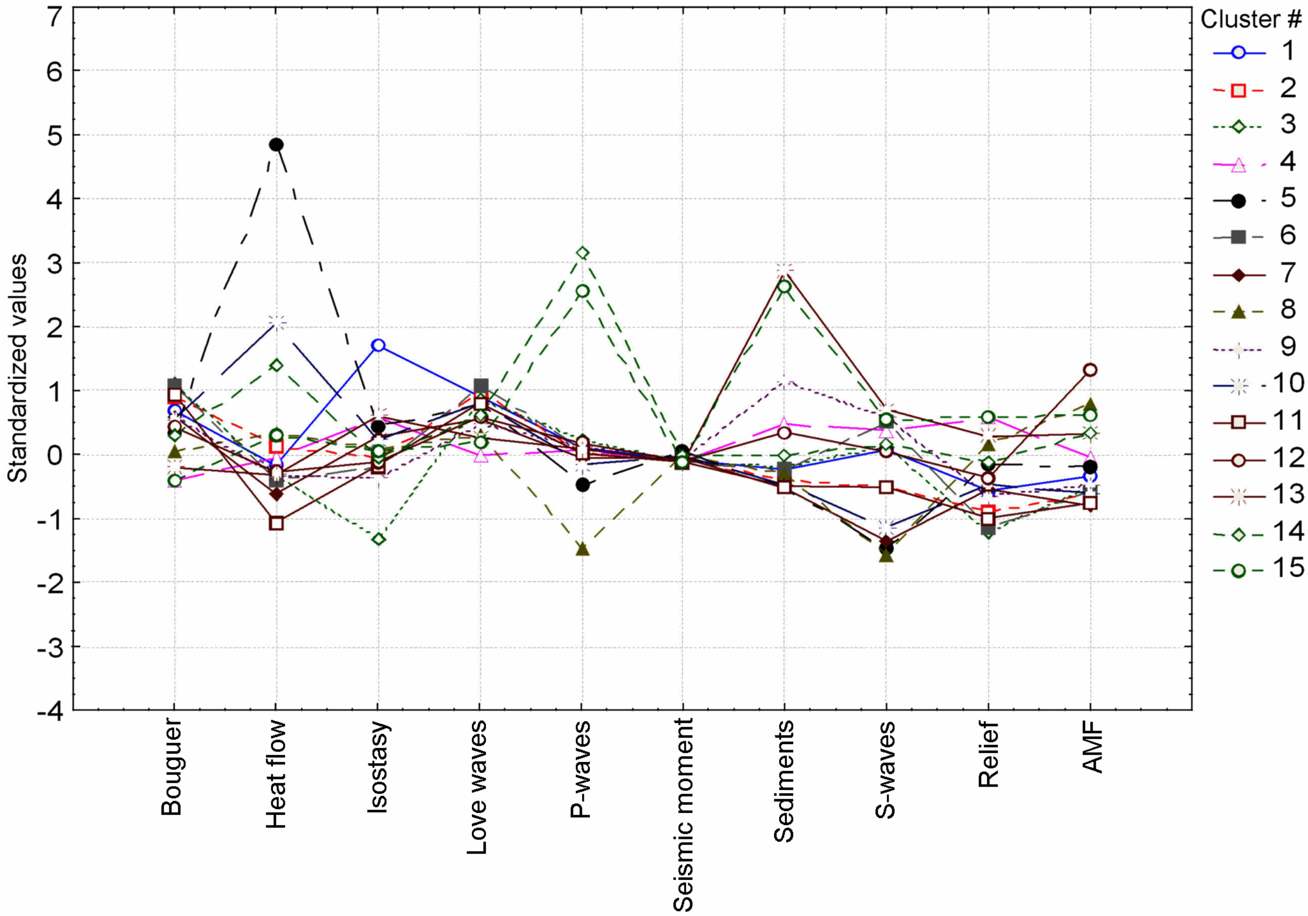

Figure 11. Cluster profiles of parameter central values in dimensionless standardized coordinates.

[47] Starting from step $N > 5$ trivial solutions are followed by situations not visually discernible. For example, differentiation of basins, MAR flanks and continent-ocean transition zones appears. At steps from N=8 to N=10 flank MAR zones obliquely oriented and locally deeply incised into basins along with isolation of MAR zone north of Iceland and pseudosymmetric superimposed effects start to appear. Final stable differentiation of MAR zone as well as most of basins and continental margins into clusters with physically clearly specification takes place on steps N=11 to N=13. Steps from N=14 to N=15 show final extraction of nontrivial clusters superimposed on main oceanic structural elements. The parameters of these elements differ by a value above parameter scatter within isolated zones belonging to one of the clusters.

[48] From the steps $N > 15$ a sudden "scattering" of the largest cluster occurs. It "scatters" to small cell groups chaotically distributed in the space of deep ocean basins. Difference between these groups is comparable to mean dispersion of parameters in standardized space values. At steps from 16 up to 100 avalanche increase in cluster number for all areas of the Atlantic whose profiles are concentrated in zero variation area and do not bounce significantly from zero like at step N=15 (see Figure 11) is observed. It means that the physically valid limit for cluster classification with the available data set has been attained. Further N increase with its asymptotic approximation to the number of objects (or to infinity, depending on degree of detail of area analyzed) won't result in solution of classification problem.

6. Geodynamic Interpretation of Results

6.1. Clusters of Geophysical Parameters

[49] A model of statistic cluster zoning for the Atlantic consisting of 15 stable combinations of parameters used (see Table 1) resulted from calculations using the procedure (see Section 4) and solution selection algorithm (see Section 5) based on parameters (see Section 3). The procedure being based on distance assessment in multi-dimensional space, calculations were made for standardized parameter (parameters of identical dimension with zero mean and unit variation). It is not quite clear if normalizing statistic moments should be calculated only for the study area or for the Earth as a whole. The authors preferred the latter version, because

Table 1. Absolute values of cluster centers and their standard deviations in multidimensional parameter space

	Bouguer anomaly, mgal		Heat flow, mW M^{-2}		Isostasy, mgal		Love waves tomography, %		P-waves tomography, %		Seismic moment, $[J\ km^{-2}] \times 10^{+13}$		Sediments, m		S-waves tomography, %		Relief, m		AMP, nT km^{-1}	
Cluster	Center	σ	Center	σ	Center	σ	Center	σ	Center	σ	Center	σ	Center	σ	Center	σ	Center	σ	Center	σ
No. 1	283	70	57	16	53	29	4.28	2.10	0.05	0.09	2.91	20.23	699	773	0.35	1.41	–3493	985	0.099	0.053
No. 2	323	36	67	12	–2	13	4.67	1.67	0.03	0.08	1.35	15.18	392	381	–1.18	0.93	–4336	541	0.068	0.039
No. 3	367	42	52	13	-41	18	4.10	2.70	0.10	0.15	0.05	0.69	788	733	0.47	1.20	–5190	534	0.082	0.045
No. 4	56	49	61	20	18	20	-0.35	2.58	0.04	0.19	0.86	17.18	2041	1164	1.13	1.31	–561	640	0.129	0.063
No. 5	210	73	222	36	13	18	3.67	2.11	-0.14	0.36	19.41	73.27	204	263	–3.62	1.83	–2457	1104	0.114	0.127
No. 6	363	32	50	11	-6	13	5.15	1.88	0.05	0.07	0.18	3.68	685	574	1.44	0.91	–5012	476	0.074	0.039
No. 7	264	39	43	19	8	14	2.51	1.39	0.00	0.07	6.26	27.79	153	174	–3.35	0.80	–3426	632	0.049	0.034
No. 8	152	75	74	28	3	14	1.29	1.98	-0.48	0.19	10.15	75.77	568	523	–3.90	1.51	-1643	1049	0.218	0.068
No. 9	261	66	51	14	-12	19	2.03	2.48	0.06	0.15	1.06	22.93	3273	1079	1.60	1.09	–3747	909	0.083	0.041
No. 10	255	56	130	24	7	16	3.73	1.85	-0.03	0.14	9.62	49.12	251	309	–2.78	1.10	-3226	850	0.071	0.047
No. 11	336	37	52	12	–6	12	3.77	1.82	0.03	0.06	0.04	0.44	203	287	–1.18	1.00	–4595	521	0.054	0.033
No. 12	229	89	54	21	–3	19	2.69	2.04	0.08	0.17	1.24	24.41	1780	1056	0.25	1.44	–2984	1250	0.272	0.074
No. 13	99	65	52	17	19	25	1.07	2.43	0.05	0.13	0.08	0.56	6491	1605	1.93	0.96	–1317	990	0.167	0.092
No. 14	202	56	108	33	–2	22	2.89	1.42	1.09	0.25	9.96	31.59	1084	865	0.59	1.31	–2349	782	0.168	0.072
No. 15	57	54	73	29	2	27	0.74	1.05	0.90	0.29	0.27	1.12	6040	1888	1.54	0.73	–542	518	0.198	0.058

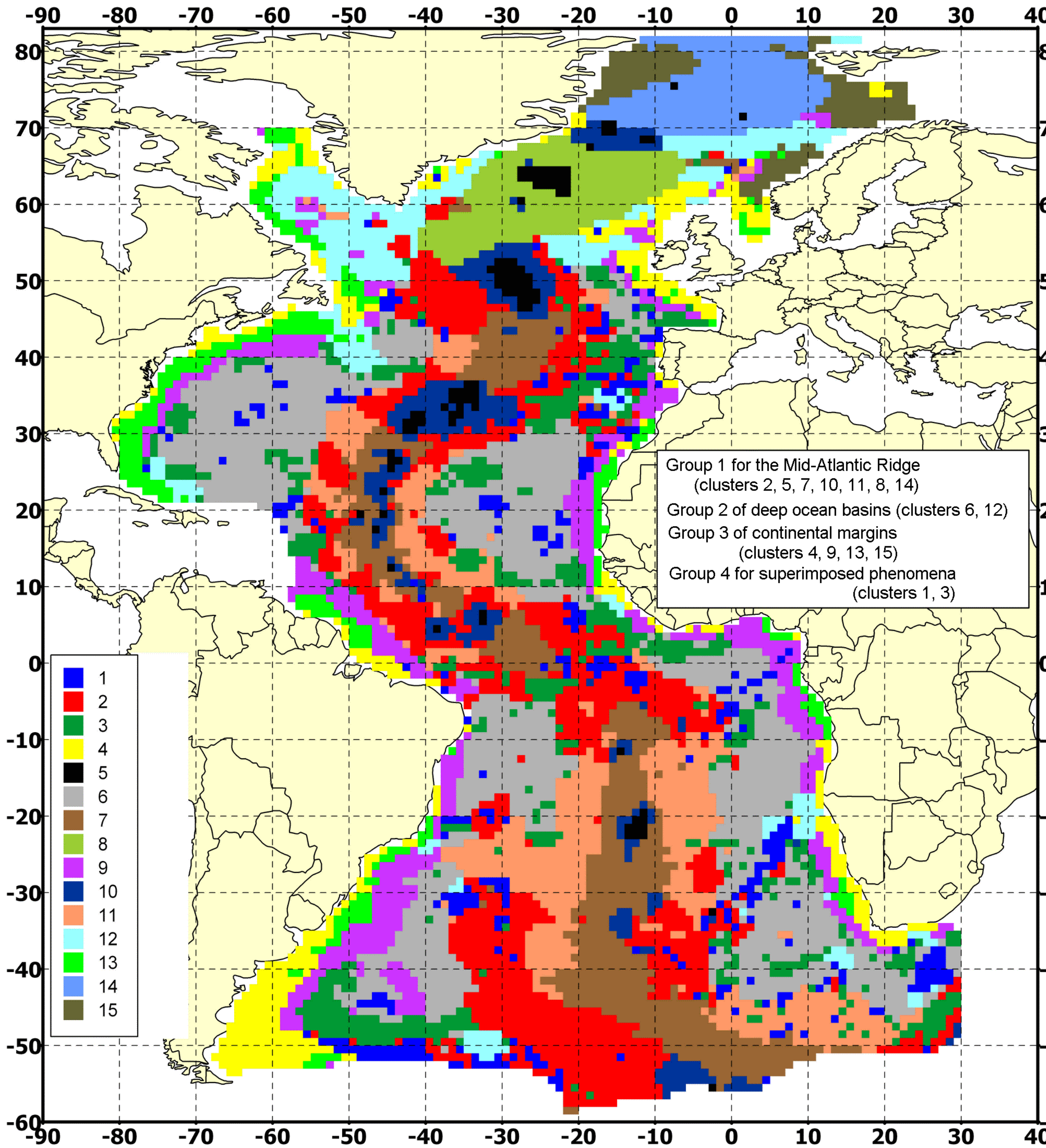

Figure 12. Geodynamic zonation of the Atlantic ocean based on cluster analysis and cluster groups for main structural zones.

otherwise it would be difficult to quantitatively compare the results from different regions as parameter norm vary from area to area. All the data used in the present work are presented in matrixes for the entire Earth and parameter standardization was carried out for the above area. All the parameters in the study area have extreme values close to absolute minima and maxima except total seismic moment. Its mean values obtained from clusters by an order of magnitude 4–5 less maximum reported from the Pacific island arc zones not falling into the region studied. Nevertheless, this parameter has also been normalized by global value. It resulted in higher deviation of the parameter by clusters in the Atlantic (see Table 1). In such a case central values by a given parameter for clusters obtained become informative.

Table 2. Areas, occupied by clusters

Cluster	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Mln km^2	3.64	11.64	6.25	3.67	0.89	16.06	7.25	1.71	5.49	2.82	7.91	3.14	2.79	0.84	0.57
%	4.9	15.6	8.4	4.9	1.2	21.5	9.7	2.3	7.3	3.8	10.6	4.2	3.7	1.1	0.8

[50] Figure 11 shows cluster profiles for parameter central values in dimensionless standardized coordinates according to calculated parameters. These profiles imply that each parameter value is involved in cluster combinations reflecting so nearly all the main $\pm\sigma$ range of values (equal to 1). All principal parameter values are thus incorporated in one or another stable combination i.e. cluster. The exceptions are the seismic moment, as mentioned above and Love wave tomography exhibits only positive values due to oceanic study area (negative values are attributed to continents). The above is due to the fact that values normalization was based on the known information for the entire Earth.

[51] The zoning obtained for distribution of parameters combination selected for geodynamical analysis is represented as a map in the end of calculation. A corresponding number of cluster is assigned to each of the one-degree cell in which it falls due to calculations. This cell gets a unique color. As the result of this procedure the map of geodynamic zonation for the Atlantic lithosphere (see Figure 12) was compiled. The above along with Table 1 represents the main result of analysis made. Later the readers will be mainly referred to this map.

[52] Geodynamical zonation of the Atlantic lithosphere resulted in obtaining of 15 stable clusters that could be conventionally divided into 4 unequal groups according to the main ocean structure zones:

[53] group 1 for mid-oceanic ridge (7 clusters – 2, 5, 7, 10, 11, 8, 14);

[54] group 2 for deep sea depressions (2 clusters – 6, 12);

[55] group 3 for continental margins (4 clusters – 4, 9, 13, 15);

[56] group 4 for superimposed effects (2 clusters – 1, 3).

[57] Table 2 shows calculation for areas, occupied by each cluster, accounted for change in size of degree cell at high latitudes.

[58] 74.75 mln km^2 was totally defined in the region. Cluster 6 (basin group) occupies the largest area of 16.06 mln km^2 (21.5%). These include basins with maximal water depth, sediment thickness, Bougue and Love anomalies, tomography by S-waves. Cluster 5 (ridge group) has a minimal area of 0.89 mln km^2 (1.2%). These are parts of high heat flow along the Mid-Atlantic Ridge; cluster 14 (0.84 mln km^2, 1.1%) and cluster 15 (0.57 mln km^2, 0.8%) present the region north of Iceland with high extreme values of P-waves tomography, superimposed on the ridge zone.

[59] Comparison between the above zonation and segmentation of the Atlantic which can be made separately for each of the parameters (see Sections 3.1.–3.10.) shows that this zonation can't be carried out by means of classification using of or several parameters. Nevertheless there are parameters e.g. bottom topography or heat flow whose effect is stronger than that of the others. However, the visual analysis based only on bottom topography is not sufficient for reliable subdivision of the area analyzed: the ridge will exhibit less distinct structure, if only topography data are used, than if it is statistically compared. This may be attributed to the overloading of the topography as a geometric parameter with other parameters associated with energy release and geometry of the lithosphere inner boundaries. As a result we get a basis for geodynamic classification. Noteworthy that visual correlation leads to comparison of parameters by distinct extreme values of one or another parameter, whereas numerical correlation makes it possible to compare different background (average for separate regions) values in fact not visually discernible, but important in case of parameters to be obtained for extensive areas.

6.2. Description of Groups Obtained in Terms of Geodynamics

[60] Now we turn to description and geodynamic interpretation of obtained cluster groups. For physical meaning of parameters the readers are referred to Section 3.

[61] **6.2.1. Group of mid-oceanic ridges.** Clusters 2, 5, 7, l0, 11, 8 and 14 are assigned to this group (Figure 12, Table 1). To interpret this group together with petrological data by *Dmitriev et al.* [1999] geophysical and petrological parameters were correlated along the Mid-Atlantic Ridge zone (see Figure 13). Discriminant of D1>255.5 and D1<255.5 fit, respectively, to spreading and plume basalt associations in terms of the paper cited. The thickness of the basalt crust is a parameter determined from petrologic parameter Na8 depending on basalt magma production rate.

[62] *Cluster 5.* This cluster is characterized by maximal heat flow, maximal seismic moment, tomography by S-waves close to minimal, and fairly high elevation. This cluster shows up (see Figure 12, Table 1) in areas where deep plumes are in superposition to the Mid-Atlantic Ridge structures (Iceland, Azores archipelago area, isolate shows north of the fault at 15°20′, sublatitudinal forking near Bogdanov and Sierra Leone faults, south of Ascention Islands, and the intersection with the projection of the Cameroon line, Tristan de Cunha, and the Bouve triple junction). It is in these areas, where the above parameters take values close to extreme tomography values (less than –3.5%), whereas high heat flow implies the presence of extensive zones of heated up and partially melted mantle. High density of seismic moments suggests often onset of earthquakes due to magma advance; high average elevation of the Mid-Atlantic Ridge (–2457 m) correlates along the ridge with low value of

Bouguer anomaly which is proportional to the mantle depth (or crustal thickness) confirmed by high calculated values for the crustal thickness by parameter Na8 (see Figure 13) and highly prolific plume magmatism by parameter D1. This cluster has a geodynamic meaning in productive magmatism and energy release resulted in emplacement of the thick crust composed of basalts with high P-T values and depths (400–700 km) for uplift of the enriched mantle matter and formation of parental melts (50–100 km at 1400°C) [*Dmitriev and Sokolov,* 2003]. The lithosphere within this cluster is in the isostatic equilibrium, which was caused by low viscosity of the substrate. Thus, in the Mid-Atlantic area, geophysical and petrologic parameters for this cluster form logically agreeing and physically explicable combination.

[63] *Cluster 10.* This cluster is characterized by high heat flow, high seismic moment, low tomography value by S-waves, and low gradient of the magnetic field. In general, cluster 10 has the same parameters as in cluster 5 but they are less pronounced. They differ in deeper elevation, and magnetic gradient, close to minimal. The cluster (see Figure 12, Table 1) shows itself in the same areas as cluster 5, in plan it "frames" the distribution of extreme values physically and geodynamically characteristic parameters of cluster 10 are the same as those of cluster 5. The low magnetic field suggests, most likely, a low concentration of magnetically susceptible matter in the heated zone and fast disintegration of magnetic properties going from zones occupied by cluster 5. However, main parameters of the cluster correlate well (see Figure 13) with petrologic data.

[64] *Cluster 7.* This cluster is characterized by minimal heat flow, fairly high seismic moment, low tomography value by S-waves, and minimal gradient of the magnetic field. In plan, cluster 7 covers in fact the entire area along the Mid-Atlantic Ridge (see Figure 12, Table 1) not occupied by clusters 5 and 10 (except for the site north of Iceland, occupied by clusters 8 and 14). Minimal heat flow in the Mid-Atlantic Ridge area not intersecting with deep plumes cropping out at the surface is easily explicable. According to the data by *Podgornykh and Khytorskhoy* [1997] heat flow values on the surface reflect in general the geodynamic state of the Earth interior at the measurement site (conductive component correlating with tomography data). However, along the Mid-Atlantic Ridge heat flow varies greatly due to irregular "convective" component whose value is caused by water washing out of heat along the strong fractures in the nearby ridge areas, and due to heat discharge by degassing of the magmatic substrate [*Letyshkov et al.,* 1997]. A high seismic activity occurs along the entire Mid-Atlantic Ridge as a result of processes responsible for emplacement of the young oceanic crust due to accretion of products of magmatic activity. However, in the main part of the Mid-Atlantic Ridge seismic activity is lower than in zones presented in clusters 5 and 10. Seismic events within cluster 7 area are not so often and of higher magnitude [*Dmitriev et al.,* 1999], but in general manifestation the seismic moment is higher. Low value of tomography by S-waves is characteristic of the entire Mid-Atlantic Ridge due to the mantle uprise and formation of melts, but within cluster 7 it is lower than in case of "plume" clusters. Based on the data by *Dmitriev and Sokolov* [2003], this area is marked by low production rate of basalt magmatism of spreading association caused by the adiabatic rise of the depleted mantle from a depth of below 200 km and its weak partial melting at depths of 15–30 km at a temperature of about I200°C. According to the classification of *Wilson* [1989] these basalts are assigned to N-MORB. Weak, in this case, minimal value of the magnetic field gradient is a characteristic feature of areas adjacent to the Mid-Atlantic Ridge (see Figure 10). This can be attributed to the fact that the field reduced to an altitude of 100 km reflects an integral characteristics of the layer commensurable to an altitude of field sources. In this case, a high frequency spatial magnetic field will be strongly smoothed. However, the main factor responsible for low value of this parameter we ascribe to a low total concentration of the matter in the heated zone with high partial melting in the upper mantle.

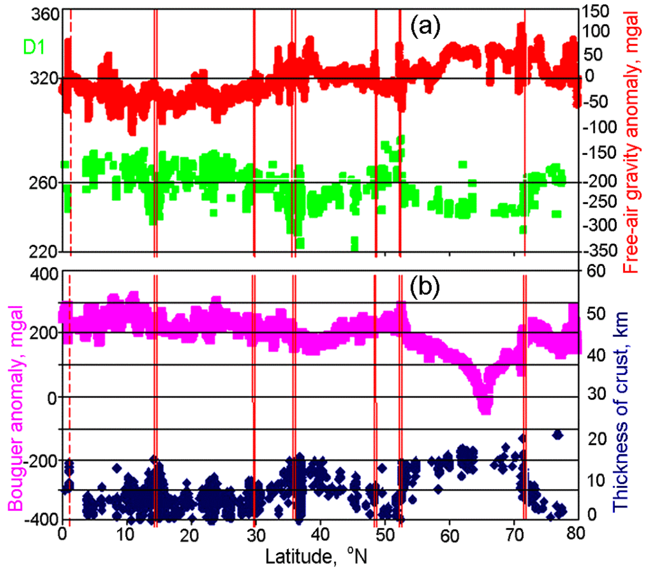

Figure 13. Correlation of geophysical and petrologic data along the Mid-Atlantic Ridge axial zone from equator to 80°N [*Dmitriev et al.,* 1999]; (a) Free-air gravity anomaly (m gal) [*Sandwell and Smith,* 1997]; (b) Bouguer anomaly (m gal) and thickness of basalt crust (km) according to rate of magmatic activity parameter Na8.

[65] Geodynamically, cluster 7 is similar to clusters 5 and 10: environment with high energy capacity along with the rise of the mantle matter, basalt magmatism of different productivity rate, and high seismicity, specific variation of Bouguer anomaly (see Figures 4, 13), and tomography by S-waves. They differ fundamentally in discrete conditions of magma formation and P-T values. In this case change in space from one type to another may take place along the Mid-Atlantic Ridge within the range of 70–100 km. Figure 13 shows a close correlation of zones along the Mid-Atlantic Ridge with D1>255.5 (spreading basalt association) and geophysical parameters reflecting respectively the low crustal thickness, low elevation value, and high Bouguer anomaly.

[66] *Clusters 2 and 11.* These clusters present flanks of the Mid-Atlantic Ridge and differ slightly in heat flow and seismic moment. They show a transitional zone from purely ridge clusters 5, 7 and 10 to the ocean floor clusters inheriting some features of the Mid-Atlantic Ridge clusters. In plan, this clusters (see Figure 12, Table 1) occupy a band of about 500 km on either side of the Mid-Atlantic Ridge, within the equatorial Atlantic they "strangle" the Mid-Atlantic Ridge represented by clusters with high heat flow and form "a cold belt of the equatorial Atlantic" [*Bonatti et al.,* 1993]. The latter in all other parameters analyzed is similar to an intermediate type with respect to that of basins. All the above clusters of the group are, in general terms, isostatically compensated. Clusters 2 and 11 in the southern Atlantic are deeply incised into the area of basins and join clusters of the superimposed events (Martin Vaz, Rio Grande, Walvis Ridge) as will be discussed later. Cluster 2 having higher heat flow, than that of cluster 11, is more close to clusters of these superimposed events. Cluster 2 also has higher (though low in absolute expression) seismic moment, than cluster 11, implying that it encloses zones of intraplate earthquakes. Noteworthy, that zones of cluster 2 in general are oriented northwestwards, this agrees with published data on the intraplate earthquakes and north-western faults [*Mazarovich and Sokolov,* 2002]. Of interest also, that these zones branch off the Mid-Atlantic Ridge on sites of plume clusters 5 and 10. Thus, these clusters having resulted from the action of forces, whose superposition gives rise to a system of north-western spurs, start to show themselves from weakened and energetically active plume zones on the Mid-Atlantic Ridge and involve flanks and partly basins in the field of their activity. Of interest also is projection of zones of these clusters into the north-west striking Labrador Basin.

[67] Based on other parameters, clusters 2 and 11 are presented as follows. Bouguer anomalies acquire values close to maximal of those in basins. Tomography by Love waves shows stable high values characteristic of the oceanic zones. Tomography by P-waves in fact does not differ over most of the region except its northern part. The sedimentary cover within margins (like that on the Mid-Atlantic Ridge) has a minimal thickness of about first hundreds of meters. Tomography by S-waves has low negative values characteristic of marginal zone. Elevation is close to the weighted average for the ocean. Magnetic field gradient is close to minimum.

[68] *Cluster 8.* This cluster is marked by the lowest for the Mid-Atlantic Ridge Bouguer anomaly, heat flow above the average value, low tomography by Love waves implying greater thickness of the crust in the region. Besides, this cluster presents high seismic moment, minimal tomography by S-waves, and high elevation value. The cluster (see Figure 12, Table 1) takes up Iceland area. According to the above set of specific parameters this region should be assigned to cluster of type 5 or 10, but it was defined as a separate type. The thing is, that this region is superimposed by a zone of strong negative values, based on tomography by P-waves characteristic of collision areas of the Earth (see Figure 8). Besides, this cluster has high gradient of the magnetic field. The comparison between the main parameters for the region of this cluster and petrological data for the Mid-Atlantic Ridge (see Figure l3) does not doubt the plume nature of cluster 8. Moreover, a deep-seated nature of the heated zone in the Iceland plume area is well known and was widely discussed. The fundamental interpretation of the region is mainly out of question. Superposition of such a outstanding plume event as that in Iceland area, manifested as a specific extremum according to tomography by S-waves (see Figure 7) with a similar extremum according to tomography by P-waves (see Figure 8) seems quite unique for the Earth. This superposition allows to arrive at two different conclusions. First, due to outstanding nature of the Iceland plume event, this zone is the only place on the Earth's surface showing correlation of strong minima both by P- and S-wave tomography and having similar thermal nature. Second, these extreme still differ in nature. It means that the Eurasian collision zone, singled out by minimum of P-wave tomography, incorporates the Iceland area owing to its extensive front. The following facts favor for the second interpretation. The Azores plume, similar in degree of contrast in tomography, has no analogy to the above one, and two types of tomography show no correlation. The crustal thickness in Iceland area inferred from the DSS data reaches 30 km [*Udintsev,* 1990]; this igneous formation mass is fairly large to affect greatly the tomographic image by the presence of forces responsible for collision of the type existing in Eurasia. At present, the authors cannot give the ultimate answer to this question. A high magnetic field gradient in cluster 8 may be explained in the following way. The integral effect of the field at an altitude of 100 km does not result in complete averaging of the high frequency component because the magnetic anomaly pattern in Iceland area exhibits the presence of extensive zones with a homogeneous field stripped of linear magnetic anomalies [*Udintsev,* 1990]. Besides, an extreme deep type of basalt magmatism (TOP-Fe) was recorded in Iceland area [*Dmitriev et al.,* 1999], which probably contributes to concentration of magnetically active matter, though the other factors within this cluster should decrease the value of the magnetic field.

[69] *Cluster 14.* This cluster is marked by low Bouguer anomaly, high heat flow, maximal values of tomography by P-waves, large seismic moment, great average thickness of the sedimentary cover, positive value of tomography by S-waves, and high gradient of the magnetic field. In plan (see Figure 12, Table 1) this cluster occupies the northern Atlantic north of 71°N and nowhere else. Its main feature is the maximal value of tomography by P-waves occurring north of the minimal value of the same parameters in cluster 8 along with the combination of minima and maxima of P-waves in northern Europe (from the North sea to Scandinavia, see Figure 8). Besides, tomography by S-waves shows for this region a uniform chain of minima, that is in keeping with the Mid-Atlantic Ridge, but here there are positive values characteristic of cold oceanic and continental areas. Even within the cold equatorial segment of the Mid-Atlantic Ridge, tomography by S-waves has not been disturbed in such a way. Bouguer anomaly values are low there approaching to continental ones and extend for the entire width of the northern Atlantic, from Greenland to Scandinavia not showing a distinct minimum of the Mid-Atlantic Ridge (see Figure 4). A high heat flow and marked

increase of seismic moment there, nevertheless point to an active phase of rifting. A great thickness of sediments suggests a proximity and activity of the source areas. A high magnetic field gradient has a pattern similar to that of the adjacent land. Such a set of main parameters in cluster 14 area implies that it is unique. The geodynamic interpretation of the region seems to be fairly difficult, and a possible solution may be an assumption of the original continental nature of this block, going now through the early phase of rifting.

[70] **6.2.2. Group of deep ocean basins.** Clusters 6 and 12 were assigned to this group (see Figure 12, Table 1). The interpretation of clusters is given below.

[71] *Cluster 6.* This cluster is characterized by low Bouguer anomaly, average for the Earth heat flow, isostatic equilibrium, maximal value by Love waves, sediment thickness of about 700 m, positive tomography by S-waves, maximally deep topography, and low magnetic field gradient. In plan (see Figure 12) the cluster takes up areas of ocean basins as reflected in deep and almost flat bottom topography, but cluster occupies less square compared to generally accepted because it does not include basin areas occupied by tails of the Mid-Atlantic Ridge flank clusters, as well as projection of the continental rise, assigned to a different class of clusters. Minimal values of Bouguer anomaly are indicative of cold and dense state of the lithosphere. Besides, along with the minimal seismic moment and average heat flow point to geodynamic “state of rest” in which these areas mainly reside. Maximal and positive values respectively by S-waves and Love waves show that this area is typically oceanic and not affected by deep energy transferred across the plume system. It lies very deep (averaging –5012 m) and is overlain by pelagic sediments averaging 685 m in thickness. Disturbances of “the state of rest”, caused by vertical movements, are isostatic in nature; north-west strike slips; delivery of energy of plumes, and other superimposed events, are formalized in other types of clusters.

[72] *Cluster 12.* This cluster is a modified cluster 6 presenting the transition from ocean basins to superimposed (see 6.2.4.) or plume areas in the absence of clusters 2 and 11 in plan (see Figure 12) essentially represented as a pair symmetrical to the Mid-Atlantic Ridge (see also Figure 10) suggesting an impulse appearance of this part of the lithosphere in the Mid-Atlantic Ridge area and its further division due to spreading. It occurs in symmetrical formations such as the Agulhas plateau: north of South Georgia islands – Walvis Ridge (northern part) – Rio Grande Rise, areas south of the Blake plateau and south of Guinea plateau, parts of Newfoundland and south of Josephine bank, in Labrador basin area and southern spurs of Rockall plateau, Western flanks of Greenland and Norwegian basin. The main features there are a high magnetic field gradient reaching that of the continental field and Iceland area (see Figure 10). In addition to the above pairs, occurring in the study area, there are also pairs covering mainly the continent. It means that the lithosphere may owe its origin to magmatism similar to that of Iceland, i.e. deep ferric varieties of basalts with emplacement of covering sediments exhibiting extensive distribution and similarly magnetically oriented, therefore they haven’t been averaged by the field record from satellite. In this case, products of deep plume magmatism were laying both on the young oceanic lithosphere and on continental lithosphere subjected to rifting. However, magmatism of this type has not “healed” the entire rifting zone. The ascent of deep mantle plumes to the surface was spartially a fairly rare event, nowadays basalts of plume association present an episodic event, whereas spreading association basalts are common all over the Mid-Atlantic Ridge.

[73] The other parameters of cluster 12 are confined to its primary magmatic nature. There were high elevation caused by high rate of magmatic activity, high, as compared to that of basins, seismic activity, because of the proximity of cluster 12 areas of active superimposed events; not very high values by Love waves, low value of Bouguer anomaly, and a greater thickness of sediments because cluster 12 areas are located around the periphery of the ocean. Geodynamically, this cluster presents relict effect of paleoplumes on the Atlantic lithosphere.

[74] **6.2.3. Continental margin group.** This group includes clusters 4, 9, 13, and 15 (see Figure 12, Table 1). The interpretation of these clusters is the least conjectural.

[75] *Cluster 4.* In plan this cluster (see Figure 12) is located on the continental shelf very close to the land or to the source area. The distinctive features of the cluster are: anomaly Bouguer of 56 mgal implying its continental nature, because its value of 175 mgal is the most acceptable value for of separation of the continent from the ocean. Love wave value is below zero and along with positive values by S-waves they argue for continental nature. Heat flow is close to the average. Isostatic anomaly is slightly higher because it reflects loading of sediments on the crustal and mantle substrate not fully compensated in the course of downwarping. The thickness of sediments averages 2041 m at an average water depth of 561 m. The magnetic field gradient is high implying the effect of the continental basement rocks. The geodynamic meaning of the cluster is the operation of the process responsible for isostatic geometric smoothing of the crustal block underlain by viscous substrate resulted from increase of sediment load.

[76] *Cluster 13.* This cluster essentially inherits all the features of cluster 4 except value for elevation and sediments. Sediment thickness averages at maximum 6491 m at an average elevation of –1317 m. It places (see Figure 12) cluster 13 on the shelf edge and into the upper part of the continental slope. Whereas compensation downwarping in the cluster area gave rise to a great submergence of the substrate, the intensity of isostatic process being the same as that of cluster 4.

[77] *Cluster 9.* This cluster inherits features of cluster 13 and is located offshore from cluster 4 and cluster 13, respectively. Main parameter values are as follows there. Bouguer anomaly is high as compared to that of clusters 4 and 13 (26l mgal), it means that sediments rest there on the peripheral oceanic crust which cold and more dense, than the continental crust. These factors do not result in down-warping reflected in isostatic anomaly. The magnetic field gradient also has features similar to those of the ocean basins. The average thickness of sediments equals 3273 m at an average

elevation of –3747 m. So, this cluster in plan (see Figure 12) occupies areas of the continental rise and adjacent part of ocean basins filled in sediments.

[78] *Cluster 15.* This cluster is similar in geodynamics with that of clusters 4 and 13; but based on the following reasons, is set aside as a separate type. In plan (see Figure 12) it occurs only in the northern Atlantic along the periphery of also a unique cluster 14, whose peculiar features affect those of the continental margin cluster showing a great thickness of sediments averaging 6040 m. Bouguer anomaly in cluster 15 is typical of continents and equals 57 mgal. Isostatic anomalies within the cluster area (see Figure 12) are marked by difference in direction resulting in neutral average value for the cluster as a whole. Strong positive anomaly inferred P-wave tomography extends to cluster 15 area as well. Elevation averages 542 m. The magnetic field gradient was found to have high value characteristic of the northern clusters in the Iceland plume area. In terms of geodynamics this cluster is meant to combine features characteristic of the continental margin clusters with those of the anomalous northern block as a substratum for intense sedimentation.

[79] **6.2.4. Group of superimposed events.** The group includes clusters 1 and 3 (see Figure 12, Table 1). Their interpretation seems to be the most nontrivial.

[80] *Cluster 1.* This cluster is marked by low, as compared to those of basins, Bouguer anomaly, maximal isostatic anomaly for the Atlantic, and high seismic moment. The remaining parameters have similar average values. In plan (see Figure 12) this cluster presents areas superposed on the basin and flank zones of the Mid-Atlantic Ridge. Locally, these areas form separate extensive groups (Walvis Ridge, Rio Grande, Cape Verde Islands, Cameroon line), but essentially always they occur as. pairs pseudosymmetrical about the Mid-Atlantic Ridge. They might well be tracks of the plume magmatic events that took place in the Mid-Atlantic Ridge area and occurring in the course of spreading on the opposite sides from the divergent zone of the ocean. Strictly speaking, these formations may be called microscopic "bull's eyes" or be considered as traces hotspots [*Courtillot et al.,* 2002] that functioned over a period of time under the Mid-Atlantic Ridge system, hence their asymmetry on the opposite sides of the ocean. Zones occupied by cluster 1 show up as volcanic edifices, some of them are still active. The edifices have high rate of magmatic activity that gives rise to excessively massive formations above the compensation surface within the ocean floor. This provides an explanation of extreme positive value of isostatic anomaly in the volcanic edifice area, as well as low Bouguer value as compared to background value for basins. High seismic moment may be attributed to the intense recent volcanic activity. The geodynamic meaning of this cluster is interpreted in a way similar to that of clusters 5 and 10 (and to a certain extent cluster 12) as resulted from deep plume energy release. However, in this case it is not aligned with the Mid-Atlantic Ridge system whose heat flow is slightly higher than an average for the Earth and differs in magma composition. Based on the data by *Sobolev and Nikogosyan* [l994], *Sobolev* [l997], parental melts of oceanic intraplate igneous products are resulted from the mantle uprise from a depth of about 1000 km and its melting at depths of 100–130 km, at a temperature of l400–l650°C.

[81] *Cluster 3.* This cluster (see Figure 12) represents mainly a sublatitudinal structure superimposed on ocean basins and the Mid-Atlantic Ridge Zone, it differs in two features from the cluster area on which it is superposed. It has extreme maximal values of Bouguer anomaly and extreme minimal value of isostatic anomaly, such a combination of the above parameters has been recorded only in the fore-arc zones, e.g. of the Pacific Ocean, when extensive thrusting in the island arc area, when ahead of their front there are formed zones with isostatic mass deficit and high Bouguer anomaly. Noteworthy, that based on data of *Silantiev* [2003] igneous rocks, having no equivalents in recent magmatism of the northern Mid-Atlantic Ridge, match these anomalous sublatitudinal zones at 15°N and 25°N. According to this author, products of magmatic activity in these zones might well be formed in the presence of the subcontinental mantle substrate or due to active mixing of melting products and the lithospheric matter as exemplified by the subduction zones. Such a coincidence of geophysical and petrologic characters suggesting not a quite ordinary environment for the Atlantic is hardly to be considered casual. The authors of the present paper think possible to make a tactful statement concerning the change in the Altantic of the horizontal movement vector from sublatitudinal to sublongitudinal during the recent epoch. The GPS and VLBI data reported from the adjacent continents make the above statement more reliable.

6.3. Comparison of the Results Obtained With Main Notions About the Atlantic Ocean Geodynamics

[82] As was mentioned in the introduction, the accumulation of geological-geophysical data on the structure of the Atlantic ocean floor made possible constant recognition of facts not easily explicable in terms of classical geodynamic model for the ocean. The model showing the interaction between the lithosphere formed in the divergent zone and main forces, used in the classical model, which are responsible for the present day tectonics of the ocean. The present paper is not aimed at the discussion of the alternative mechanisms, therefore we have proposed a version to systematize geodynamic environments of the Atlantic with account of new data available. It was done unbiased by means of digital methods and have proposed a geodynamic interpretation of the obtained clusters following the principle of "maximum likelihood" by data interpretation. However, alternative interpretations are not ruled out. First, it should be noted that the authors have obtained a set of clusters reflecting geodynamic features of the ocean structural elements easily explicable in terms of the plate tectonic model. Their description is given in Section 6.2. and presents a small part of the results of the investigation. The authors also obtained a number of clusters that can be explained only by involving geodynamic mechanisms and by means of considerable modification of the existing mechanism. But this goes beyond the scope of this paper. We shall just emphasize the nontrivial results of cluster analysis.

[83] In our opinion, of most interest is the inhomogeneity of geodynamic conditions along the strike of the ridge, which in diversity of clusters recognized in the Mid-Atlantic Ridge zone is not equal to that reflected in any parameters used. The diversity of clusters is shown by alternation of “hot” and “cold” blocks, strongly differing in heat flow, total seismic moment, and Bouguer anomaly evidencing high rate of magmatic activity. It concerns also the thickness of the crust, formed in the rift zone, S-wave tomography characterizing a degree of the mantle partial melting, along with the occurrence of isolated plumes deep in the mantle (up to 700 km). The established zones are compatible well with the published data on variation of P-T conditions during the formation of MORB and also on a depth of magma ascent. Variations in conditions of melt formation result in the presence of two main associations of the basalts. They are [*Dmitriev et al.,* 2006] plume-deep and highly productive – and spreading – less deep and low productive associations. Figure 14 shows their distribution in space. *Dmitriev et al.* [l999, 2003] took into account discrete conditions of melt formation and that they were closely spaced (70–100 km) and the authors cannot state that it was a uniform process operating along the Mid-Atlantic Ridge marked by the ascent of heated up matter subjected to partial melting but having different P-T conditions along the divergent zone. Figure 14 also shows the ubiquitous distribution of the spreading association basalts, whereas those of the plume association are superimposed on spreading ones and were reported from the Mid-Atlantic Ridge only in the presence of deep isolated plume feeders, in other words there is not one but two independent superimposed processes, hence their geodynamic effect should be considered separately, and their superposition is to be calculated in areas of plume associations. However, in this case we need a new separate geodynamic model based on two mechanisms, but this goes beyond the scope of this study. This conclusion will be an assumption about the relation between the basalt associations and related geodynamic mechanisms. It could have remained unchanged during the entire period of the Atlantic opening as follows from the properties of cluster 12 (see 6.2.2.) accounted for the presence of paleoplumes evidence.

[84] The cluster classification of the Atlantic geodynamic lithosphere resulted also in establishing of zone oblique to major structural elements (flank clusters, see 6.2.1.). These zones have been repeatedly mentioned as inferred from detailed geophysical survey in the Atlantic [*Mazarovich and Sokolov,* 2002]. Their presence have found confirmation in macroscopic description of the lithospheric geodynamic parameters implying fundamental cause-and-effect relationship between parameters of different scale. The northwestern orientation correlates with that of many small structural elements inferred from multi-beam survey of the ocean floor and from seismic profiling of sediment deformations. Geodynamically, it means that the actual tectonosphere has a system of forces tangential to the earth’s surface and not orthogonal to the Mid-Atlantic Ridge, responsible for this phenomenon. The working geodynamic model cannot provide an explanation for this phenomenon.

[85] A combination of cluster 3 parameters (see 6.2.4.) characteristic of the fore-arc zones is considered to be nontrivial. The sublatitudinal orientation of this cluster zones really suggests the presence of the sublongitudinal movement component that is not consistent with the working geodynamic hypothesis. An agreement with exceptional geochemical data ([*Silantiev,* 2003] is hardly to be accidental. Besides, in this cluster area near the fault at $15^{\circ}20'$ N and east of the Mid-Atlantic Ridge a so-called convergence zone of passive parts of transform faults was recorded. This also requires the involvement of the sublongitudinal component of the lithospheric mass movement. There are two subduction zones (Puerto Rico trench and northern margin of the Scotia Sea) in the western Atlantic. The movement along them is also northward and this makes the question, whether its thrusting or subduction, of secondary importance. This cluster forms a latitudinal zone between 22°N and 28°N in the study area along the Canary-Bahama geotraverse [*Mashchenkov and Pogrebitsky,* l998], where there were reported, especially east of the Mid-Atlantic Ridge, deformations and oblique reflectors of sublongitudinal dip in the consolidated crust. These reflectors provide different interpretation in terms of mineralogy to tectonics. The relationship between the crustal structures and sediments allows to conclude that the age of these dislocations may vary from the recent in the Mid-Atlantic Ridge area to Mesozoic in the Canary Basin. Still it should be noted the agreement between the zones established by means of cluster analysis and characteristic features of the fore-arc zones, on the one hand, and, on the other hand, deformation of the consolidated crust along the Canary-Bahamas geotraverse exhibiting thrust features.

[86] Anisotropy of sediments in the Atlantic basins [*Mazarovich and Sokolov,* 2004] represented by foldings, discernible only on sublongitudinal seismic profiles, also implies the presence of the sublongitudinal component of movement. GPS and VLBI data on the adjacent continents support to such pattern of movement. The above-listed set of factors made us possible to speak with confidence about the phenomena whose presence seems imperative in terms of classical plate tectonics theory. The authors are not going to develop in this paper the ideas about a mechanism responsible for their origin, but it should be pointed out, that the classical theory may be applied if it is granted that the crucial changes in all movement components began during the present epoch.

7. Conclusions

[87] 1. Zonation of the Atlantic Ocean lithosphere based on cluster analysis involving 10 geological-geophysical parameters, interpreted geodynamically and classifying the lithospheric structure and energy release allowed us to divide the region into four groups of clusters (all in all 15 cluster combinations of parameters). They cannot be established visually using any parameter or their limited combination. The resultant groups exhibit geologically specified features:

- Group 1 for the Mid-Atlantic Ridge (clusters 2, 5, 7, 10, 11, 8, 14) showing an important inhomogeneity of

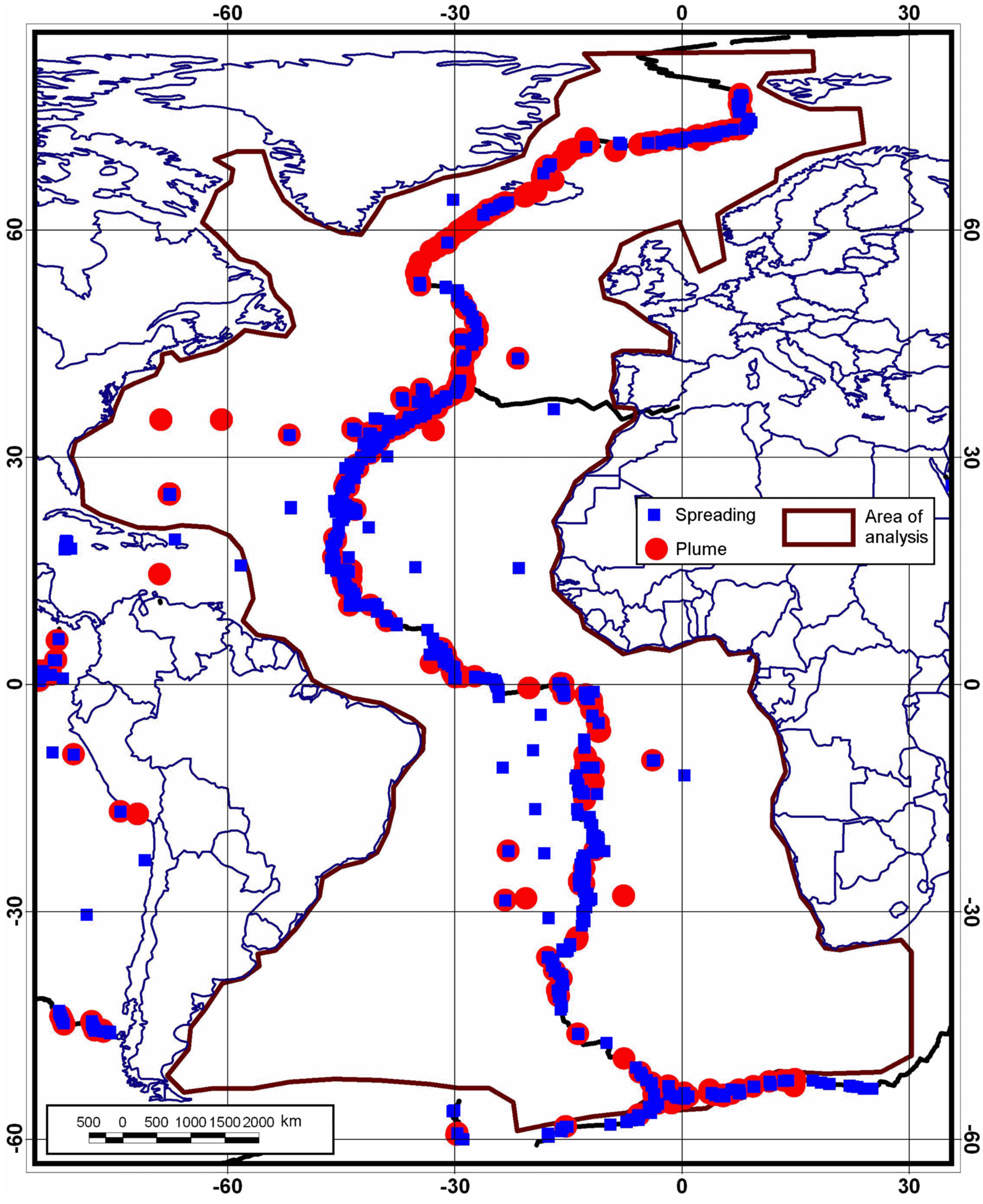

Figure 14. Spatial distribution of two main basalt associations – plume and spreading – calculated from data of glass analyzes [*Dmitriev et al.,* 2006].

geodynamic conditions along the strike of the ridge and its nearby areas;

- Group 2 of deep ocean basins (clusters 6, 12) showing peculiar features of abyssal areas and some transition zones;
- Group 3 of continental margins (clusters 4, 9, 13, 15) showing lithosphere differentiation in the passive margin zone;
- Group 4 for superimposed phenomena (clusters 1, 3) characterizing mainly sublatitudinal zones crossing the above three zones.

[88] 2. Inhomogeneity along the strike of the ridge is an alternation of "hot" and "cold" blocks differing greatly in heat flow, total seismic moment, Bouguer anomaly, as used here, signifies the rate of magmatic activity, and tomography by S-waves, marking a degree of the mantle partial melting along with the presence of isolated plumes going deep into the mantle (up to 700 km). The recognized zones correlates well with published data on discreteness of P-T conditions during the formation of the oceanic ridge basalt melts, whose areas are not widely spaced. The above implies superposition of two independent mechanisms for accretion and further dynamics of the oceanic crust in the Mid-Atlantic Ridge zone.

[89] 3. On the Mid-Atlantic Ridge flanks there were recognized zones north-western oriented to major structural elements of the Atlantic, crossing ocean basins, the Mid-Atlantic Ridge and projecting into the continental margins.

[90] 4. Superimposed sublatitudinal phenomena outside of the Mid-Atlantic Ridge refers to zones resulted from eruptive impulses of high rate magmatic activity (sometimes ongoing); they are similar to the recent manifestation of plumes under the Mid-Atlantic Ridge, caused by spreading of pseudosymmetric structures on either side of the ridge. Vestiges of these phenomena inferred from geophysical parameters imply that frequency rate of such manifestations in the Atlantic lithosphere remained, as a whole, unchangeable since the time of its opening.

[91] 5. Another type of sublatitudinal superimposed phenomena is represented by zones marked by a stable distinct combination of high Bouguer and low isostatic anomalies similar to that of the Pacific fore-arc zones. This cluster type correlates in space with anomalous geochemistry of basalts, convergent zones of passive parts of transform faults, sediment anisotropy of ocean basins, and orientation of the western Atlantic subduction zones.

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References

Becker, T. W., and L. Boschi (2002), A comparison of tomographic and geodynamic mantle models, *Geochemistry Geophysics Geosystems G3,* January 10, *3*(1), 1003, doi:10.1029/2001GC000168.

Belousov, V. V. (1975), *Fundamentals of Geotectonics* (in Russian), 264 pp., Nedra, Moscow.

Boldyrev, S. A. (1998), *Seismodynamics of the Mid-Atlantic Ridge* (in Russian), 124 pp., Nauka, Moscow.

Bonatti, E., M. Seyer, and N. Sushevskaya (1993), A cold suboceanic mantle belt at the Earth's equator, *Science, 261*(5119), 315, doi:10.1126/science.261.5119.315.

Cande, S. C., J. L. LaBrecque, R. L. Larson, W. C. III Pitman, X. Golovchenko, and W. F. Haxby (1993), Magnetic Lineations of World's Ocean Basins (map), Digitized Set by G. Cole, Global Relief Data CD. NOAA Product # G01093-CDR-A0001, Amer. Ass. Petrol. Geol., Tulsa. OK. 1989.

Courtillot, V., A. Davaille, J. Besse, and J. Stock (2002), Three distinct types of hotspots in the Earth's mantle, *Earth Planet. Sci. Lett., 6470,* 1.

Dmitriev, L. V., and S. Yu. Sokolov (2003), Geodynamics of three distinct types of ocean magmatism and their reflection in seismotomography, *Petrologia* (in Russian), *11*(6), 655.

Dmitriev, L. V., S. Yu. Sokolov, and A. A. Plechova (2006), Statistical estimation of variations in composition and P-T conditions of MORB evolution and their regional occurrence, *Petrologia* (in Russian), *14*(3), 227.

Dmitriev, L. V., S. Yu. Sokolov, and N. S. Sokolov (2001), Migration of the Azores superplume: geophysical and petrologic evidence, *Russian Journal of Earth Sciences, 3*(6), 395.

Dmitriev, L. V., S. Yu. Sokolov, V. G. Melson, and T. O'Khirn (1999), Plume and spreading basalt associations reflected in petrologic and geophysical parameters of the northern Mid-Atlantic Ridge, *Russian Journal of Earth sciences, 1*(6), 1.

Grand, S. P., R. D. Van der Hilst, and S. Widiyantoro (1997), Global seismic Tomography: A snapshot of convection in the Earth, *GSA Today, 7,* 1.

Hwang, C., E.-C. Kao, and B. Parsons (1997), *EGM97 – Joint Earth Geopotential Model,* 78 pp., University of Oxford – Department of Earth Sciences, Geodesy and Geodynamics Group, Oxford.

Ioganson, L. I., and G. Yu. Boltyshev (2000), On heterogeneity of Earth' crust in western Eurasia, *Vestnik OGGGN RAN* (in Russian), *4*(14), 1.

Khain, V. E., and M. G. Lomize (1995), *Geotectonics Along With Fundamentals of Geodynamics* (in Russian), 480 pp., MGU, Moscow.

Laske, G., and G. Masters (1997), A global digital map of sediment thickness, *EOS Trans. AGU, 78,* F483.

Letyshkov, F. A., Yu. V. Men'shagin, V. V. Lashkevich, and P. I. Dorogokupets (1997), Comparative energy characteristics of fluid and silicate lithospheric systems, *Petrologia* (in Russian), *5*(6), 247.

Mashchenkov, S. P.,Eds. and Yu. E. Pogrebitsky (1998), *Geological structure and evolution of the central Atlantic lithosphere (surveys along Canary-Bahamas traverse)* (in Russian), 299 pp., VNIIOkeangeologia, St.Petersburg.

Maus, S., M. Rother, R. Holme, H. Luhr, N. Olsen, and V. Haak (2002), First scalar magnetic anomaly map from CHAMP satellite data indicates weak lithospheric field, *Geophys. Res. Lett., 29*(14), 1702, doi:10.1029/2001GL013685.

Mazarovich, A. O., and S. Yu. Sokolov (2002), North-Western Fault Zone in Central Atlantic, *Geotektonika* (in Russian), *36*(3), 87.

Mazarovich, A. O., and S. Yu. Sokolov (2004), Anisotropy of intraplate deformations of the Atlantic Ocean, in *Sovremennye Problemy Geologii* (in Russian), p. 221, Nauka, Moscow.

Mueller, R. D., W. R. Roest, J.-Y. Royer, L. M. Gahagan, and J. G. Sclater (1993), *Digital age map of the ocean floor,* 91 pp., SIO Reference Series 93-30, Moscow.

Pavlenkova, N. I. (1987), Endogeneous regimes and the Earth's crust and upper mantle structure, in *Stroenie i evolyutsiya tektonosfery* (in Russian), p. 253, IFZ AN SSSR, Moscow.

Podgornykh, L. V., and M. D. Khytorskhoy (1997), *Map of global heat flow. 1:30000000,* Explanetary note (in Russian), 55 pp., Nauka, Moscow-St.Petesburg.

Pollack, H. N., S. J. Hurter, and J. R. Johnson (1991), *New Global Heat Flow Compilation,* Univ. of Michigan, Dep. of Geol. Sciences, Ann Arbor. Michigan 48109-1063, USA.

Reisner, G. I., and M. G. Reisner (1987), Technique for establishment of the Recent endogeneous regimes, in *Stroenie i Evolyutsiya Tektonosfery* (in Russian), p. 274, IFZ AN SSSR, Moscow.

Reisner, G. I., and M. G. Reisner (1990), Endogeneous regimes of Europe, in *Sovremennaya Geodinamika i Glubinnoe Stroenie*

Territorii SSSR (in Russian), p. 40, Nauka, Moscow.
Sandwell, D. T., and W. H. F. Smith (1997), Marine Gravity Anomaly from Geosat and ERS-1 Satellite Altymetry, *J. Geophys. Res., 102*(B5), 10,039, doi:10.1029/96JB03223.
Silantiev, S. A. (2003), Variations of geochemical parameters of restite peridotites along the strike of the Mid-Atlantic ridge reflecting the nature of the mantle igneous, *Petrologia* (in Russian), *11*(4), 339.
Sobolev, A. V. (1997), On evolution and formation of mantle magma, Doctoral Thesis, p. 227, GEOKHI RAN, Moscow.
Sobolev, A. V., and I. K. Nikogosian (1994), Petrology of magmatism of long-lived mantle plumes: Hawaii (Pacific ocean) and Reunion island (Indian ocean), *Petrologia* (in Russian), *2*(2), 131.
Udintsev, G. B., Ed. (1990), *Mezhdunarodny Geologo-Gefizichesky Atlas Atlantichaskogo Okeana* (in Russian), 158 pp., IOC(UNESCO), Mingeo SSSR, AN SSSR, GUGK SSSR, Moskva.
Van der Hilst, R. D., S. Widiyantoro, and E. R. Engdahl (1997), Evidence of deep mantle circulation from global tomography, *Nature, 386,* 578, doi:10.1038/386578a0.
Wilson, M. (1989), *Igneous Petrogenesis,* 463 pp., Unwin Hyman Dostal, London-Boston-Sidney-Wellington.
Yavorsky, B. M., and A. A. Detlaf (1974), *Spravochnik po Fizike Dlya Inzhenerov i Studentov Vuzov* (in Russian), 944 pp., Nauka, Moscow.
Zonenshain, L. P., and M. I. Kuzmin (1993), *Paleogeodinamika* (in Russian), 192 pp., Nauka, Moscow.

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