ISSN 0024-4902, Lithology and Mineral Resources, 2009, Vol. 44, No. 5, pp. 441–450. © Pleiades Publishing, Inc., 2009.
Original Russian Text © S.Yu. Sokolov, A.O. Mazarovich, 2009, published in Litologiya i Poleznye Iskopaemye, 2009, No. 5, pp. 483–492.

Gas Hydrates in the Sedimentary Cover of Passive Oceanic Margins: Possibilities of Prediction Based on Satellite Altimetry Data in the Atlantic and Arctic

S. Yu. Sokolov and A. O. Mazarovich

Geological Institute, Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 119017 Russia
e-mail: sysokolov@yandex.ru, amazarovich@yandex.ru

Received December 24, 2008

Abstract—Analysis of factual data on acoustic indicators of fluid occurrences, negative gravity anomalies based on satellite altimetry, tectonic deformations, and findings of ultramafic rocks and serpentinites was carried out. Such data make up stable sublatitudinal groups across the Atlantic Ocean. The image obtained suggests the following cause-and-effect series of processes: (1) tectonic deformations; (2) serpentinization of ultramafic rocks and generation of methane; and (3) accumulation of gas hydrates in the sedimentary cover near the continental margin. The second process is accompanied by the formation of negative gravity anomalies; the third process, by the specific reflection of fluids in the acoustic wave field. These facts provide a basis for forecasting the presence of gas hydrates based on reductions of the satellite altimetry data and regional maps of the sedimentary cover in the Atlantic and Arctic.

DOI: 10.1134/S0024490209050034

PREREQUISITES OF THE PROGNOSTIC METHOD

At the beginning of the 1980s, two types of abiogenic methane sources were investigated at the bottom of the Atlantic Ocean. The first type was associated with high-temperature (up to 400°C) hydrothermal systems confined to the axial segments of mid-oceanic ridges (MOR) that are described in (Rona and Scott, 1993) and other publications. Tectonic settings of such systems suggest their interrelation with regions of intense fracturing of the crust in the MOR zone that fosters the circulation of water (Mazarovich and Sokolov, 1998). This fact is evident, in particular, in zones of low background seismicity with the Richter magnitude of more than 3 (Mazarovich and Sokolov, 2002). According to several geochemical indicators (Charlou et al., 1998), generation of methane of this type is mainly related to the interaction of seawater with basalts.

Methane of the second type and hydrogen are generated during the serpentinization of mantle peridotites (Charlou et al., 1991, 1998; Donval et al., 1997; Simonov et al., 1999). This process is confined to exposures of massive mantle ultramafic rocks near some transform faults in the Mid-Atlantic Ridge (MAR). According to (Charlou et al., 1998), such phenomena are common for the MAR, where low spreading rate and low-productive basaltic magmatism promote the development of a crust with abundant residual mantle ultramafic rocks defined as the Hess-type crust (Cannat et al., 1995).

Dmitriev et al. (1999) reported data on the geochemistry of serpentinization and the quantitative assessment of potential volumes of methane generation: the ultramafic rock volume of 1 km^3 involved in reaction yielded 2.5×10^5 t of methane under the following conditions: the water/rock ratio is 2 and the average carbon dioxide content in seawater is 2.4 mmol/kg. The optimal temperature range for the given process is 150–350°C if permeability of rock is fostered by their tectonic fracturing. The water/rock ratio can vary from $10n$ to $1000n$ depending on the geodynamic setting and related fracturing. A gradual subsidence of the 400°C-isotherm from the MOR to passive margins increases the effective thickness of the layer of potential methane generation. Thus, with increasing distance from the MOR, the process is mainly governed by tectonic deformations, which provoke the fracture system, and accessibility of water with the required amount of dissolved carbon dioxide.

Dmitriev et al. (1999) also estimated the volume of methane that can be generated during the accretion of the Atlantic segment extending from the equator to ~35° N. Effective depth of the serpentinization-prone layer bottom can increase to 10–15 km near the passive oceanic margin with an age of approximately 150–170 Ma. Lithospheric peridotites not subjected to serpentinization beneath the axial MOR zone, where peridotite exposures account for approximately 10% of the area based on dredging data (Dmitriev et al., 1999), cool down beyond its domain to temperatures that are favorable for serpentinization. Given that width of the ocean is approximately 4000 km and length of the ridge along the axis is 3000 km, the Hess-type crust has an area of 12×10^6 km^2. Assuming that the average thickness of a rock pile, where the additional serpentinization is possible, is 5 km and the peridotite content therein is 10%, "the serpentinization-prone layer with a volume of 6×10^6 km^3 will release 3×10^{12} t H_2 and 1.5×10^{12} t CH_4, which are rather close to estimates made for an open rift zone. Hence, the total output of hydrogen and methane during the formation of lithosphere with passive margins can be two times higher than the estimate for the open rift zone" (Dmitriev et al., 1999, p. 515).

Accessibility of the oceanic water to unaltered peridotites is problematic, because they are overlain by serpentinites, metagabbro, metabasalts, and the sedimentary cover. In this case, permeability of the crust depends strongly on the availability of different-scale fractures that are governed by the tectonic setting within oceanic plates (Mazarovich and Sokolov, 1998). Their formation is always accompanied by differently oriented tectonic stresses with intricate relationships owing to periodic manifestations of magmatism.

Sedimentary cover of the magmatic substrate hampers the penetration of water into basement. However, if the sedimentary cover is rapidly formed, the water is buried together with sediments and can be injected into the basement along a fracture system in the substrate. The sedimentary cover commonly plays the role of an impermeable bed (caprock) that hinders the escape of gases (hydrogen and methane) and promotes their accumulation, in particular, as gas hydrates.

"In general, such environment does not promote the development of serpentinization because of a low percolation of water in the basement. However, precisely the shortage of water suggests that serpentinization of peridotites in such an environment should take place at a low water/rock ratio and foster the maximal generation of hydrogen and methane" (Dmitriev et al., 1999, p. 515).

Ultramafic rocks composed of minerals with a density of approximately 3.25 g/cm^3 are replaced by rocks with a density of 2.55 g/cm^3 in the course of serpentinization; i.e., the process is accompanied by reduction of the density of rocks by 20% and their consequent expansion (*Fizicheskie…*, 1984). This factor can serve as a prospecting guide for methane pools in waters confined to the sedimentary cover. Given that the density of a serpentinite layer decreases by 0.7 g/cm^3 and its thickness reduces to 5 km, the maximal value of gravity anomalies associated with serpentinization zones can increase appreciably (relative to zones with unaltered ultramafic rocks) and reach 140 mGal. Let us note that the estimate is an upper limit pertaining to Bouguer anomalies and their recalculation to residual anomalies rather than anomalies in the free atmosphere, where the gravitational effect of relief is still uncompensated. The value mentioned above is an order of magnitude higher than the accuracy of gravity anomalies (7–10 mGal) recorded in the World Ocean based on satellite altimetry (Sandwell and Smith, 1997). Study of gravity field at the ocean bottom based on satellite data will make it possible to elucidate promising areas, where zones of serpentinization and methane generation may be discovered. The present investigation was carried out in water areas of the well-studied Atlantic Ocean with the confirmed presence of gas hydrates, dredged serpentinites, and methane anomalies that correlate with gravity anomalies. Therefore, data on analogous anomalies will make it possible to predict the potential of the Arctic Ocean.

METHOD OF THE PROCESSING OF GRAVITATIONAL DATA

The altimetry data (Sandwell and Smith, 1997) represent ocean level altitudes recalculated to gravity anomalies in the free atmosphere. The main contribution to variability of these anomalies is made by the bottom relief, while the contribution of density heterogeneities is approximately 35%. The first step of data processing is calculation of Bouguer anomalies, the physical sense of which lies in remoteness of the gravitational influence of relief based on altimetry data. Relief measured by the depth sounding is an independent parameter (*ETOPO5*, 1995), which is in no way related to altimetry. Therefore, the calculation is unbiased. Variability of Bouguer anomalies is primarily related to density heterogeneities of the crust and mantle. Of interest for the majority of geological problems are crustal heterogeneities that create anomalies with the transverse dimension up to 30–35 km. Based on approximate bur highly effective estimates, the transverse dimension/depth ratio for the anomaly source is 3: 1. We obtain precisely this ratio for an average ocean depth of 4 km and crust thickness of 5–7 km. Dimensions of anomalies created by temperature heterogeneities in the mantle are considerably higher than the values given above. Gravitational effect of the crust in the undifferentiated form is masked to a high extent by influence of the mantle that can be eliminated by the compensation for thermal effects. The remaining portion of anomalies (residual Bouguer anomalies) represents the effect of crustal heterogeneities that are "purified" to the maximal extent from the influence of other processes (Fig. 1).

The anomalies obtained reflect the influence of variables of the crustal thickness and density that are not differentiated in the general form by reductions of the gravity field applied in the calculations. We propose a method for the calculation of anomalies, in which the effect of density variations would be expressed to the maximal extent. Essence of the method lies in the execution of a variational fitting of density that yields the best compensation of relief at some neighborhood during the calculation of Bouguer anomalies. In the case under consideration, we accomplished calculation for each point of water area overlapping over a radius of 35 km. Scanning was executed for density values rang-

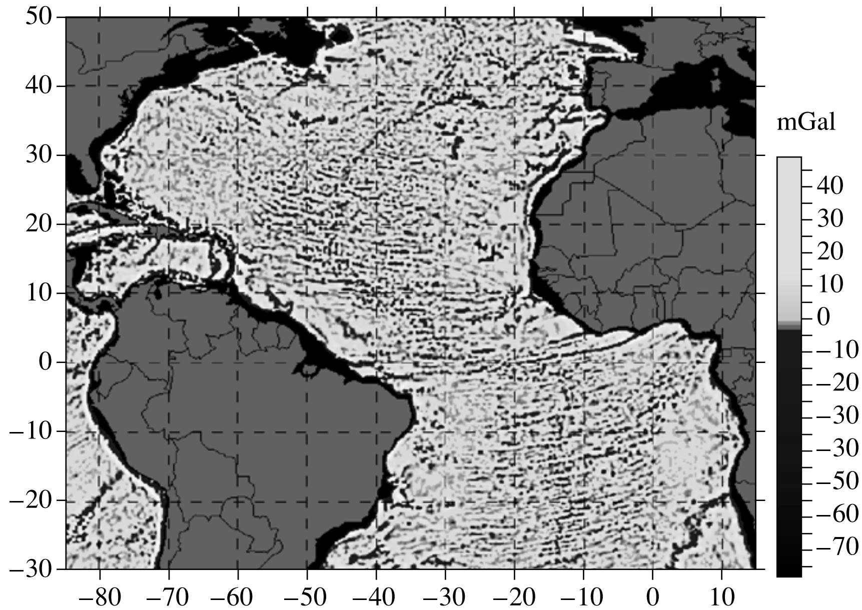

Fig. 1. Residual Bouguer anomalies in the Atlantic Ocean.

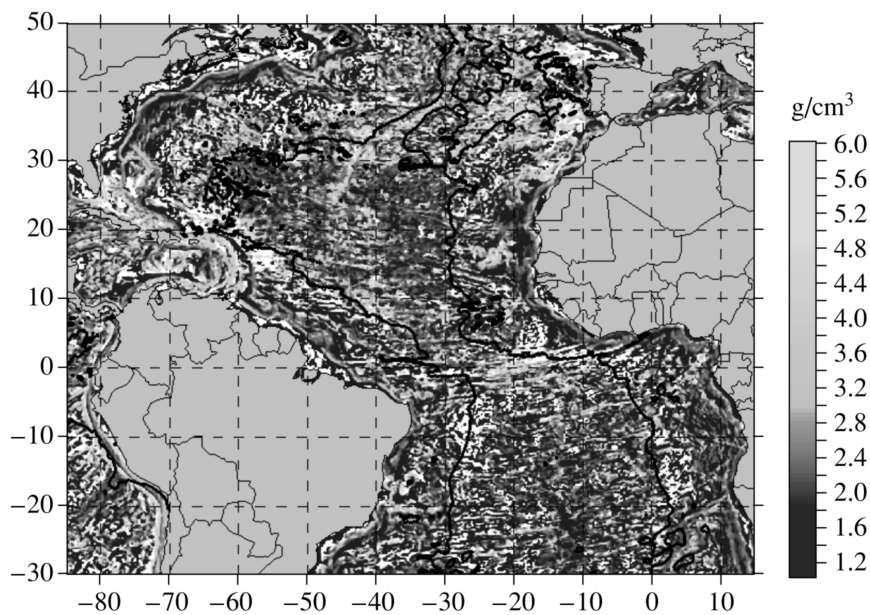

Fig. 2. Density anomalies in the Atlantic Ocean and the 200-m isopach based on (Divins, 2003) showing the applicability boundary of the method for density anomaly calculation.

ing from 1 to 6 g/cm^3 with a step of 0.01 g/cm^3. For a fortiori low density values, the relief compensation is lacking and the correlation coefficient of relief and Bouguer anomalies is close to 1. For a fortiori high density values, we obtain relief overcompensation and the anomaly relief gets inversed with the correlation coefficient close to –1. This implies that we have a zero crossing that allows the determination of optimal density at the neighborhood of the target point. This method is inapplicable if a large segment of the area is underlain by sedimentary cover more than 200 km thick. In this case, correlation between relief and the major gravitat-

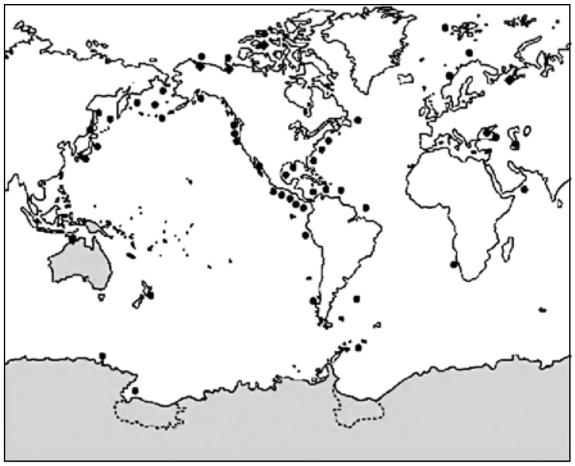

Fig. 3. Setting of gas hydrate occurrences. Modified after (Downey et al., 2001).

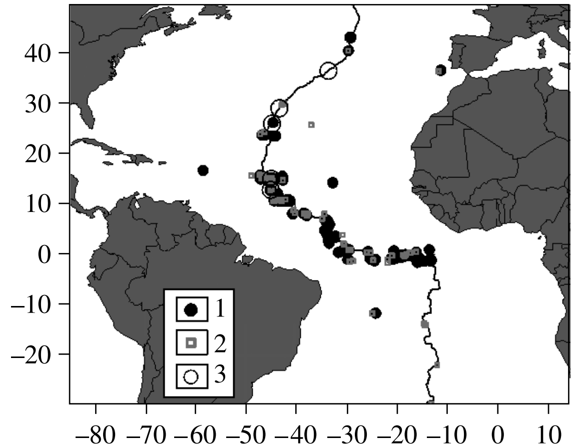

Fig. 4. Settings of manifestations of (1) peridotites, (2) serpentinites, and (3) methane plumes based on literature data.

ing surface (e.g., acoustic basement) is violated. Density anomalies obtained after such calculations are presented in Fig. 2.

The anomalies have a realistic average level of 2.62 g/cm^3. Positive and negative deviations from this level demonstrate the qualitative density distribution in the crust, the quantitative calibration of which is beyond the scope of the present paper. With respect to both residual (Fig. 1) and density (Fig. 2) anomalies, one can clearly discriminate the central Atlantic segment with the Hess-type crust, which incorporates the serpentinized peridotites that was responsible for the negative density background at flanks of the MAR. Let us note that zones of significant negative background exist in the southern Atlantic, which is less investigated by dredging than the northern segment.

COMPARISON OF DENSITY ANOMALIES WITH PERIDOTITE AND GAS HYDRATE OCCURRENCES

Analysis of the spatial distribution of gas hydrate occurrences suggests the following conclusions (Fig. 3). In the Atlantic water area, an ocean with passive margins, the main gas hydrate occurrences occur near the western continental margins in a band extending from the equator to 35–40° N, where data on the study of MAR rocks suggest the development of the Hess-type crust. In addition, negative density anomalies (Fig. 2), which are likely related to serpentinization of rocks in depressions, trace the Hess-type crust from the MAR to continents at the same latitudes. We believe that this coincidence is not accidental.

Gas hydrate occurrences are also recorded in the southern Atlantic, but they are significantly rare, probably, because of a considerably lesser study of the region south of the equator by all methods (bottom dredging, acoustic sounding, hydrochemical survey, and others). However, density and residual anomalies of the gravity field suggest the existence of similar manifestations in this region.

Degree of the region exploration by bottom dredging is reflected in Fig. 4 that shows findings of ultramafic rocks, serpentinites, and methane plumes based on literature data. The material was adopted from the database of the Laboratory of Geomorphology and Ocean Floor Tectonics, Geological Institute, Russian Academy of Sciences (347 records of rock types mentioned above in the oceanic segment under consideration).

Analysis of the distribution of ultramafic rocks and their transformation products (hereafter, specific complex) and their comparison with gravity anomalies suggest conclusions that are essential for the prediction of gas hydrates in the Arctic, the water area of which is virtually unsurveyed by bottom dredging, in contrast to the Atlantic Ocean. Large-scale occurrences of the specific complex are confined to the ridge segment with the maximal curvature radius and increased ratio of the length of offset zones to separate segments of the MAR. Tectonic deformations of the MAR and its flanks are best expressed precisely in such zones. As was noted in several works based on the geological dredging data, for example (Raznitsyn, 2004), many exposures of the specific complex could be formed due to horizontal tectonic displacements of crustal blocks along a nearly meridional direction and their partial overthrusting along the transform fracture line. In addition, precisely this segment is marked by the maximal density of multitransform systems with duplex (Marathon and Mercury), triplex (Arkhangel'sky, Doldrums, and Vernadsky), and even quadruplex (San Paulo) trough systems. Hence, this region can be marked by much more extensive crustal microfracturing (relative to other regions of the water area) and, consequently, more intense serpentinization along the fracture system, including flanks of the ridge. Anomalous fields (Figs. 1, 2) in this zone enclose large negative zones, the origin of which is logically attributed to tectonic constraints of the region with the specific complex. Thus, geodynamic setting of the region reflects its fragmented pattern and fosters intensification of serpentinization of the mantle substrate. Prospecting guide for methane is represented by large negative fields in the density and residual anomalies based on the satellite altimetry data.

Spatial distribution of the specific complex makes it possible to identify four separate groups located in the following areas: from the equator to 6° N (the most numerous group), from 10° N to 16° N (association of 15°20′ Fracture Zone), from 24° N to 30° N, and from 35° N to 45° N near the Azores–Gibraltar Sill area. Based on the cluster analysis of ten geophysical parameters, Sokolov et al. (2008) divided the Atlantic water area into several nearly latitudinal zones with a stable contrast combination of high Bouguer anomalies and low isostatic anomalies. Such combinations are encountered in pre-arc zones of the Pacific Ocean. The sublatitudinal pattern of these zones and the presence of thrusts therein suggested by the meridional seismic profiles (Sokolov, 2007), which encompass the entire sedimentary complex, indicate the presence of recent tectonic activation related to the nearly meridional movement of blocks of the oceanic crust. These spatial groups of the specific complex fall precisely into the separate zones outlined during an independent investigation of the oceanic lithosphere. Hence, the new displacement vector of lithospheric blocks is activated along older fracture zones and new exposures of the specific complex can be discovered along the old lineaments.

INDICATIONS OF THE PRESENCE OF FLUIDS IN SEISMIC AND ACOUSTIC WAVE FIELDS

The sedimentary cover formed at remote flanks of the MAR and its continental margin can accumulate gaseous products serpentinization and retain them as gas hydrates at certain *PT* conditions. If serpentinization zones are exposed on the seafloor, methane is released to the marine water, resulting in the formation of methane plumes and accumulation of gas bubbles. Such objects are recorded well in the acoustic field of echosounders and high-frequency profilographs as typical images of wave diffraction.

Figure 5 presents some examples of the acoustic record of fluid discharge into the water column. The objects are located in a nearly latitudinal zone identified by cluster analysis in the southern Atlantic. They are also confined to the negative residual and density anomalies (Figs. 1, 2). This is a sufficiently convincing illustration of the fact that degassing can take place in the depression located 1150 km east of the MAR. Since water and gas samples were not taken during the cruise, we cannot affirm that the emission observed during the cruise comprises precisely products of serpentinization.

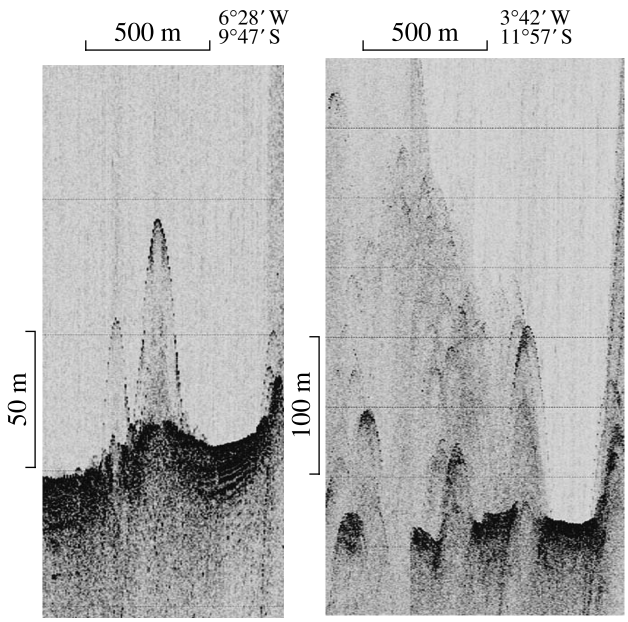

Fig. 5. Acoustic images of fluid discharge into the water column. Recorded by an EdgeTech 3300 profilograph (frequency 3.5 kHz). Cruise 23 of the R/V *Akademik Nikolai Strakhov* (2006).

However, the process is evidently related to the spatially correlated tectonic and fluid (and, possibly, magmatic) activity in depressions. A target-oriented study of these data is also essential, because the modern tectonic theory lacks a consistent explanation of such phenomena at a great distance from the marginal parts of plates. It should be noted that the cause-and-effect series discussed in this paper is a special case in general degassing of the Earth and acoustic records with signs of the existence of gases in water can also be related theoretically to another factor, which is beyond the scope of the present paper.

Seismic record presents several possibilities for the detection of anomalous fluid regime in the oceanic sediments. According to (Panaev and Mitulov, 1993, p. 85), the presence of fluids can be suggested by three signs: (1) the appearance of acoustic transparency of layers; (2) the "sagging" of cophased axes due to the local attenuation of sound velocity in sediments; and (3) the appearance of narrow vertical zones acoustic brightening related to the injection of fluids. Let us also note the acoustic brightening of sediments across various seismoacoustic complexes of the sedimentary cover near the basement. The first sign mentioned above resembles a facies replacement along reflections from the well-stratified and contrasting beds (up to the clarified and chaotic ones). According to (Panaev and Mitulov, 1993, p. 102), such signs can be attributed to the saturation of sediments with free ("not crystal-confined") gases related to the decomposition of gas hydrates under the influence of high thermal flux and

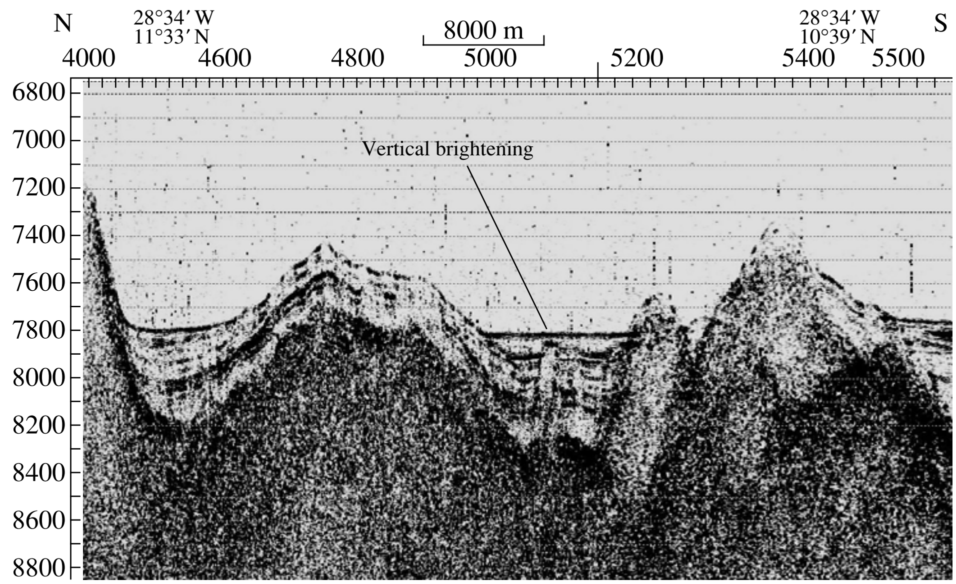

Fig. 6. Submeridional seismoacoustic record with the vertical acoustic brightening in the sedimentary pile due to the discharge of fluids and tectonic folding. Cruise 22 of the R/V *Akademik Nikolai Strakhov* (2000).

hydrothermal reworking of the sedimentary cover; anomalous seismic records are also attributed to the presence of sills, dikes, and basalt sheets. The latter formations, however, lead to chaotization and "darkening" of the record rather than its brightening. In addition, plug structures usually push upward the margin of cophased axes. Thus, complications of seismic record can be divided into two different types: (i) complication related to fluid regime in sediments; (ii) complication related to the appearance of alien magmatic bodies. We should discriminate these types. We should also note that both types of complication can coexist in nature. Based on the historical review of this phenomenon, V.A. Panaev and S.N. Mitulov noted that the fluid-mediated "brightening" of sedimentary rocks near the acoustic basement is a reliably established fact recorded over large areas in all oceans. We believe that this phenomenon is primarily related to the serpentinization of igneous rocks of the basement and their chemical reaction with water. Let us emphasize that the effect of methane generation during the reworking of ultramafic rocks is only two times less prominent for the basalts (Dmitriev et al., 1999).

Figure 6 demonstrates an example of the nearly meridional seismoacoustic record of the Cabo Verde Ridge area that reflects deformation of the sedimentary cover and the vertical penetration of fluids expressed as brightening of the record and formation of a flat acoustic contrasting profile at the penetration site approximately 40 m downward from the seafloor. It is interesting that both deformation and vertical brightening of the record are confined to negative density anomalies (Fig. 2) that coincide with the nearly latitudinal anomaly zone identified by the cluster analysis (Sokolov et al., 2008).

Reason for the coincidence of such data—small-scale anomalous zones in depressions and acoustic records with fluid and deformation attributes—is unknown so far. However, comparisons accomplished in our work have revealed a clear series of cause-and-effect relations: (1) tectonic deformations; (2) serpentinization of ultramafic rocks (with the formation of negative anomalies in the gravity field) and generation of methane; and (3) accumulation of methane as gas hydrates in the sedimentary cover (with the formation of specific forms of the acoustic wave field). Processes of the second and third types are responsible for the above-mentioned signs that can be used as guides for the remote detection of target zones. Tectonic deformations are also expressed well in the acoustic image. This is evident from data on the Cape Verde Basin (Fig. 6). Matching of anomalous gravitational zones with the results of geodynamic regionalization based on cluster analysis (Sokolov et al., 2008) can provide insight into causes of the origination of deformations that are beyond the scope of this paper.

Figure 7 presents an example of the seismoacoustic record with both deformations and associated brightening of the record owing to fluid regime in sediments. The recorded region is located at the junction of the Arkhangel'sky, Doldrums, and Vernadsky faults (Mazarovich and Sokolov, 1997) with a "lense" of negative density anomalies in the adjacent area (Fig. 2).

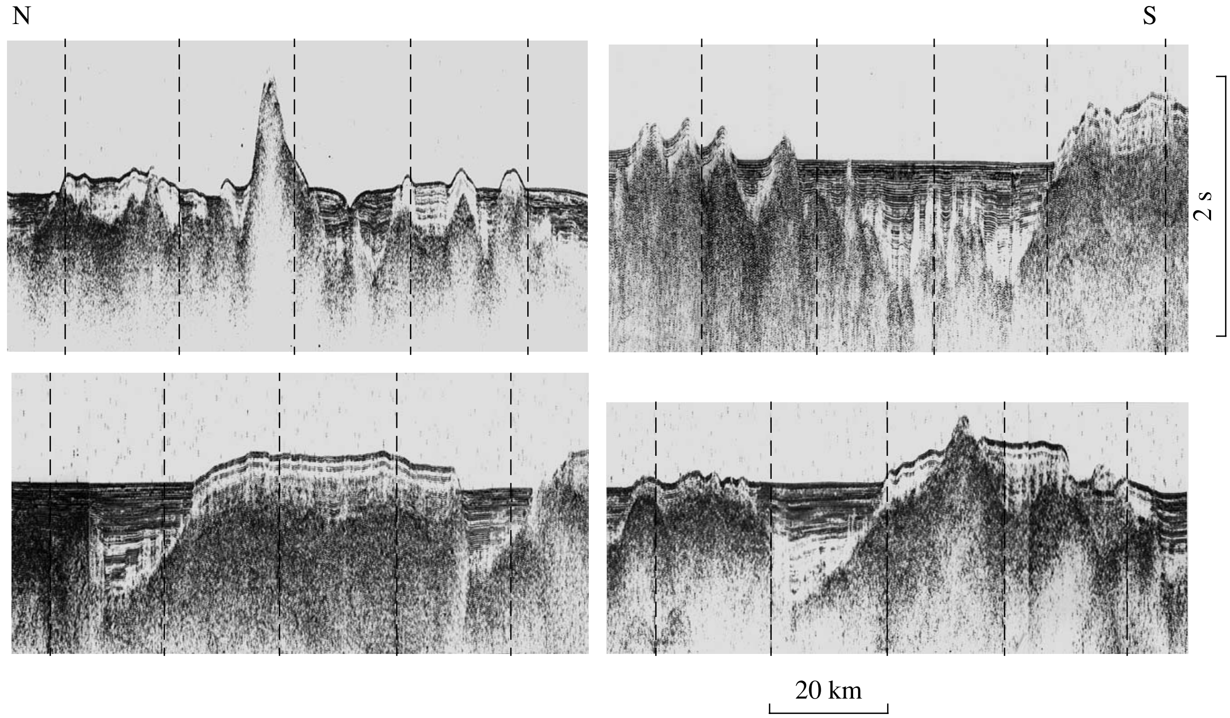

Fig. 7. Submeridional seismoacoustic records illustrating deformations of the sedimentary cover at eastern flanks of the Arkhangel'sky, Doldrums, and Vernadsky faults. The records are related to fluid regime of the acoustic brightening (Cruise 9 of the R/V *Akademik Nikolai Strakhov*, 1989).

PREDICTION OF THE PRESENCE OF GAS HYDRATES IN SEDIMENTS OF THE ARCTIC REGION

Figure 3 shows that gas hydrate occurrences in the Arctic region are known in the Canada Basin near the coasts of Alaska and west of the Spitsbergen Archipelago. In the latter area, Cruise 24 of the R/V *Akademik Nikolai Strakhov* was accomplished in 2006 by the Geological Institute of the Russian Academy of Sciences in cooperation with the Norwegian Petroleum Directorate. Observations carried out during this cruise also included the area with gas hydrate occurrences reported in (Knies et al., 2004). The paper based on the results of these works (Chamov et al., 2008) demonstrated that tectonic dislocations leading to the destabilization of gas hydrate pools and the discharge of fluids are reflected as brightening of the seismic records of various shapes, including the deformations confined to faults. In addition, sonar images of seafloor segments at the sites of fluid discharge include numerous pockmarks, which are related to the sagging of ground, and conical buildups related to degassing and evacuation of the sedimentary material. In the Molloy Fracture Zone located north of the segment mentioned above, we detected a segment with intense tectonic fracturing, brightening of the seismic record, and traces of gas seepage in the water column (Fig. 8).

Thus, the phenomenon of degassing of sediments testifying to their saturation with gases is well known in the Arctic, particularly in the tectonically deformed areas adjacent to the shelf. Considering the cause-and-effect series mentioned above into consideration and its validity for forecasting manifestations of degassing, we calculated analogous density anomalies for the Arctic region. The results are presented in Fig. 9. Calculations were carried out for the gravitational data (Forsberg and Kenyon, 2005) and the relief data (*IBCAO*, 2005). Lack of the detailed information about the sedimentary cover, similar to that for the Atlantic Ocean, does not allow us to draw the 200-m isopach. We used the position of the shelf edge as an intermediate boundary of applicability of the method for density anomaly calculation. In this process, we remembered that the Arctic water region includes large (up to 20 km thick) sedimentary bodies, where this method is inapplicable. Like in Fig. 2, density values given in this case demonstrate the qualitative pattern of their variation rather than their quantitative calibration.

The degassing sector shown in Fig. 8 is located in a negative density anomaly field near the Molloy Fracture Zone. The anomaly field also comprises a degassing site (16°20′ E, 80°46′ N) at the northern edge of the Spitsbergen Archipelago. Relative to the Atlantic Ocean, data on the Arctic region placed at our disposal are less abundant. However, the recent growth of inter-

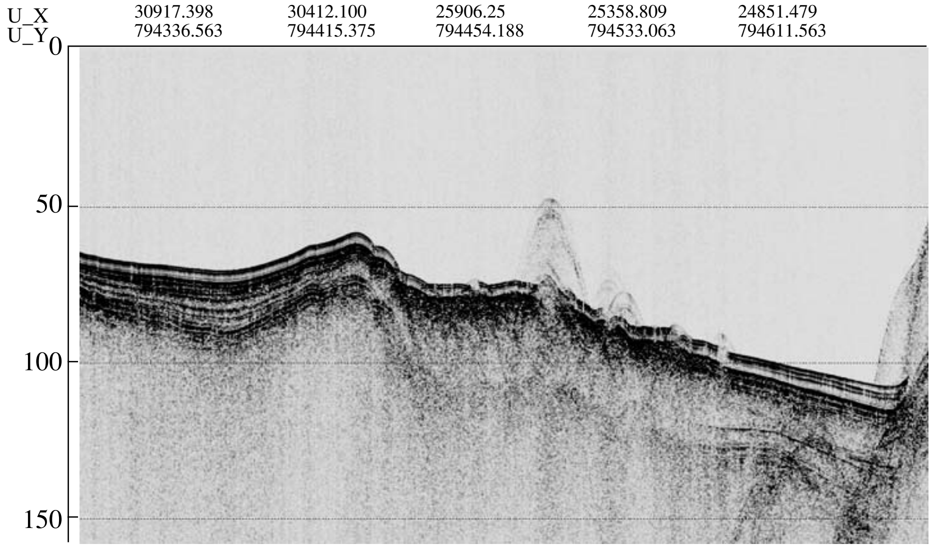

Fig. 8. Acoustic image of fluid discharge into water column in the Molloy Fracture Zone. Recorded by an EdgeTech 3300 profilograph (frequency 3.5 kHz). Cruise 24 of the R/V *Akademik Nikolai Strakhov* accomplished in 2006 by the Geological Institute of the Russian Academy of Sciences in cooperation with the Norwegian Petroleum Directorate.

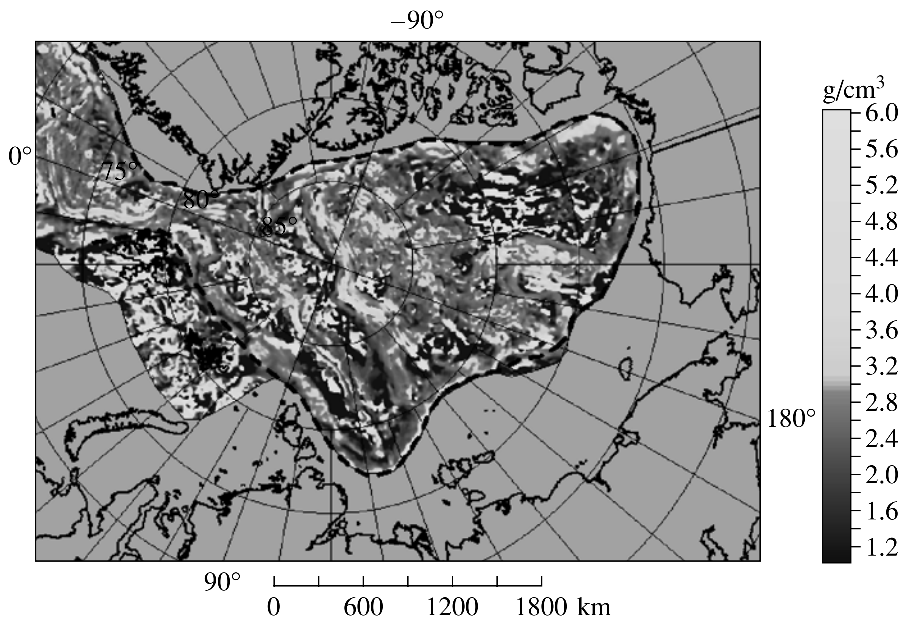

Fig. 9. Density anomalies in the Arctic region and shelf edge. The gray field shows zones where the method of density anomaly calculation in the present form is inapplicable.

est and increase in the number of cruises to this region should put things right and enhance the reliability of prognostic estimates of gas hydrates and other mineral resources in this region.

Highly promising in this respect is an approximately 200-km-wide band extending from the Laptev Sea to the Chukchi Plateau at the continental foothill of Eurasia. This band is confined to the Khatanga–Lomonosov transform zone, implying the presence of deformations and microfracturing in the crust. In addition, this area is crosscut by a series of NE-striking fracture zones (Sokolov, 2009). Given that the Chukchi Plateau and the southern Mendeleev Ridge represent continental outliers, the southern area of these structures should comprise tensile Ones. The northern part of the Laptev Sea and the De Longa Rise are complicated by grabens extending parallel to the Gakkel Ridge near its leaning to the continental slope. Thus, the depression part located near the continental slope is characterized by a set of tectonic deformations that lead to increase in fracturing of the crust. This circumstance should facilitate the percolation of water in ultramafic rocks of the mantle and initiate serpentinization with the subsequent generation of methane and its introduction into the sediments.

CONCLUSIONS

1. The set of factual data on acoustic signs of fluid manifestations, negative gravity anomalies, tectonic deformations, and findings of ultramafic rocks and serpentinites suggest their confinement to nearly latitudinal zones (in the Atlantic Ocean). According to the satellite altimetry data, these zones extend from the continental margins across the ocean.

2. The results obtained revealed the following cause-and-effect series of processes: (1) tectonic deformations; (2) serpentinization of ultramafic rocks and generation of methane; and (3) accumulation of methane as gas hydrates in the sedimentary cover near the continental margin. The second process is accompanied by the formation of negative gravity anomalies. The third process is accompanied by signs of fluid generation reflected in the acoustic wave field. This fact provides a basis for forecasting the presence of gas hydrates in sediments based on the satellite altimetry data and regional maps of the sedimentary cover.

3. In order to predict the development of gas hydrates in deep-water sediments of the Arctic region, we have compiled the map of density anomalies that can allow us to identify the most promising zone extending along the continental slope from the Laptev Sea to the Chukchi Plateau.

REFERENCES

Cannat, M., Mevel, C., Maia, M., et al., Thin Crust, Ultramafic Exposures, and Rugged Faulting Patterns at the Mid-Atlantic Ridge (22°-24° N), *Geology*, 1995, vol. 23, pp. 49–52.

Chamov, N.P., Dobrolyubova, K.O., Peive, A.A., and Sokolov, S.Yu., Presence Indications of Gashydrates in the Upper Parts of Sedimentary Cover on Flanges of the Molloy Fault Zone (Frame Strait, Norwegian–Greenland Basin), *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 2008, vol. 83, no. 2, pp. 51–60.

Charlou, J.L., Bougault, H., Appriou, P., et al., Different TDM/CH_4 Hydrothermal Plume Signatures: TAG Site at 26° N and Serpentinized Ultrabasic Diapir at 15°05' N on the Mid-Atlantic Ridge, *Geochim. Cosmochim. Acta*, 1991, vol. 55, pp. 3209–3222.

Charlou, J.L., Fouquet, Y., Bougault, H., et al., Intense CH_4 Plumes Generated by Serpentinization of Ultramafic Rocks at the Intersection of the 15°20' N Fracture Zone and the Mid-Atlantic Ridge, *Geochim. Cosmochim. Acta*, 1998, vol. 62, no. 13, pp. 2323–2333.

Divins, D.L., NGDC Total Sediment Thickness of the World's Oceans and Marginal Seas, 2003 (http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html).

Dmitriev, L.V., Bazylev, B.A., Silant'ev, S.A., et al., Carbon and Methane Genesis by Serpentinization of the Mantle Ultrabasic Rocks of Ocean and Origin of Oil, *Ross. Zh. Nauk Zemle*, 1999, vol. 1, no. 6 (doi: 10.2205/2000ES000030).

Donval, J.P., Charlou, J.L., Douville, E., et al., High H_2 and CH_4 Content in Hydrothermal Fluids from Rainbow Site Newly Sampled at 36°14' N on the Amar Segment, Mid-Atlantic Ridge (Diving FLORES Cruise, July, 1997). Comparison with Other MAR Sites, *Eos Trans.*, 1997, vol. 78.

Downey, M.W., Morgan, W.A., Threet, J.C., *Petroleum Provinces of the Twenty-First Century,* New York: Datapages, 2001.

ETOPO5 Set. Global Relief Data CD. NOAA Product# G01093-CDR-A0001, 1993.

Fizicheskie svoistva gornykh porod i poleznykh iskopaemykh (petrofizika). Spravochnik geofizika (Physical Properties of Rocks and Mineral Resources (Petrophysics): Reference Book of Geophysicist), Dortman, N.B., Ed., Moscow: Nedra, 1984.

Forsberg, R. and Kenyon, S., *Gravity and Geoid in the Arctic Region—The Northern Polar Gap Now Filled*, 2005 (http://earthinfo.nga.mil/GandG/wgs84/agp/readme_new.html).

IBCAO (International Bathymetric Chart of Arctic Ocean), 2005 (http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html).

Knies, J., Damm, E., Gutt, J., et al., Near-Surface Hydrocarbon Anomalies in Shelf Sediments of Spitsbergen: Evidences for Past Seepages, *Geochem. Geophys. Geosyst.*, 2004, vol. 5. Q06003 (doi: 06010.01029/02003 GC000687).

Mazarovich, A.O. and Sokolov, S.Yu., Recent Deformations of the Sedimentary Cover in Passive Parts of the Arkhangel'sky, Doldrums, and Vernadsky Fracture Zones, Atlantic Ocean, *Dokl. Akad. Nauk*, 1997, vol. 357, no. 6, pp. 801–804 [*Dokl. Earth Sci.* (Engl. Transl.), 1997, vol. 357, no. 6, pp. 1320–1323].

Mazarovich, A.O. and Sokolov, S.Yu., The Tectonic Position of Hydrothermal Fields on the Mid-Atlantic Ridge, *Litol. Polezn. Iskop.*, 1998, vol. 33, no. 4, pp. 436–439 [*Lithol. Miner. Resour.* (Engl. Transl.), 1998, vol. 33, no. 4, pp. 361–394].

Mazarovich, A.O. and Sokolov, S.Yu., Hydrothermal Fields in the Mid-Atlantic Ridge: Setting and Prospects for Further Discoveries, *Russ. J. Earth Sci.*, 2002, vol. 4, no. 6, pp. 423-431 (doi 10.2205/2002ES000104).

Panaev, V.A. and Mitulov, S.N., *Seismostratigrafiya osadochnogo chekhla Atlanticheskogo okeana* (Seismostratigraphy of Sedimentary Cover of the Atlantic Ocean), Moscow: Nedra, 1993.

Raznitsin, Yu.N., *Tektonicheskaya rassloennost' litosfery molodykh okeanov i paleobasseinov* (Tectonic Layering of Lithosphere of Yung Oceans and Paleobasins), Moscow: Nauka, 2004.

Rona, P.A. and Scott, S.D., Preface, a Special Issue on Sea-Floor Hydrothermal Mineralization: New Perspectives, *Econ. Geol.*, 1993, vol. 88, no. 5, pp. 1934–1976.

Sandwell, D.T. and Smith, W.H.F., Marine Gravity Anomaly from Geosat and ERS-1 Satellite Altymetry, *J. Geophys. Res.*, 1997, vol. 102, no. B5, pp. 10039-10054 (ftp://topex.ucsd.edu/pub/).

Simonov, V.A., Kolobov, V.Yu., and Peive, A.A., *Petrologiya i geokhimiya geodinamicheskikh protsessov v Tsentral'noi Atlantike* (Petrology and Geochemistry of Geodynamic Processes in the Central Atlantic), Novosibirsk: Sib. Otd. Ross. Akad. Nauk, 1999.

Sokolov N.S. Correlation of the Geological and Geophysical Parameters along the Axis of the Mid-Atlantic Ridge and Pre-Arc Settings on Its Eastern Flank, *Mosc. Univ. Geol. Bull.*, 2007, vol. 62, no. 6, pp. 404–409.

Sokolov, S.Yu., Tectonic Elements of the Arctic Based on Data of Small-Scale Geophysical Fields, *Geotektonika,* 2009, vol. 43, no. 1, pp. 23–38 [*Geotectonics* (Engl. Transl.), 2009, vol. 43, no. 1, pp. 15–28].

Sokolov, S.Yu., Sokolov, N.S., and Dmitriev, L.V., Geodynamic Zonation of the Atlantic Ocean Lithosphere: Application of Cluster Analysis Procedure and Zoning Inferred from Geophysical Data, *Russ. J. Earth Sci.*, 2008, vol. 10, pp. 1–30 (doi: 10.2205/2007ES000218).