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New Data on the Structure of the Sea of Okhotsk Bottom

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Abstract—The reinterpretation of the time and deep sections along CDP Profile 1632 revealed different previously unknown structural features: (1) a buried bar and a Late Pliocene regional unconformity, the Bol'sheretsk and Lebed subaerial shield volcanoes, and the Koni–P'yagina and Magadan megadikes at its level; (2) morphological evidence for the nappe structure of the Okhotsk Arch (homoclinal thrust slices of the acoustic basement with ramp half-grabens in the frontal part and a pull-apart zone with a solitary diapir in the Kol'skii Trough, which divides the arch into two allochthonous megablocks with opposite vergence of their thrusts), which is related to a divergent sheet decollement, probably, at the M discontinuity.

Key words: bar, shield volcano, megadike, homocline, half-graben, decollement, Sea of Okhotsk.

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INTRODUCTION

We present new very significant results derived from the reinterpretation of the time and deep sections along near-meridional CDP Profile 1632 (Figs. 1–6) preformed by the *Dal'morneftegeofizika* trust in 1986 (object 11/86) between the northern Kurile Islands and the Magadan shelf [12–14, 19, 27]. The seismic profiling was accompanied by gravimetric observations. Figures 2–4 and 6 (fragments of the time section interpreted by L.S. Chuiko with the stratigraphy of the Cenozoic cover after V.O. Savitskii) taken from the report on object 11/86 (reference in [14]) illustrate the results of these studies with some constraints for the former. The deep section along this profile was constructed by Patrikeev [27]. The reinterpretation of the materials obtained along Profile 1632 is explained by the necessity of the express evaluation of the young (Late Quaternary) structures recently discovered in the Nagaevo sequence in the southern suburbs of Magadan. These structures presumably resulted from lateral compression from the Sea of Okhotsk [22], which is inconsistent with the classical concepts of the block (graben–horst) riftogenic structure of its bottom related to in situ extension of the rigid continental crust in the Cenozoic [2, 3, 6, 8, 10, 26, 27]. These circumstances and the location of CDP Profile 1632 near Magadan (Fig. 1) determined its selection among the regional CDP profiles performed by the *Dal'morneftegeofizika* trust in the 1970s–1980s (the location of the profiles is in [8, 27]).

REINTERPRETATION RESULTS

The reinterpretation of the time and deep sections along CDP Profile 1632 revealed new objects in the Sea of Okhotsk (except for its southeastern part adjacent to the Kurile Islands [13, 27]).

The Late Pliocene bar and regional unconformity (Figs. 1, 2). These structures are missing from previous interpretations of the seismic records [2, 3, 6, 8, 19, 27]. The buried bar 4 km wide and 20–30 m high is observed at stakes (ST) 528–532 km of the profile near the southern edge of the flat abraded summit of the Central Okhotsk Uplift [16]. In the section, it is located in the middle part of the Pliocene–Quaternary seismic complex at a depth of 360 m (the P wave velocity in the sediments is 1600 m/s). In the time section, the bar is recognizable based on its peculiar convex slightly asymmetrical two-phase reflection [24]. The latter is traced at the same stratigraphic level through the most part of Profile 1632. In our opinion, this reflection characterizes the regional Late Pliocene unconformity, because it is represented by a distinct downlap in the neighboring Lebed Trough (Fig. 2) and a conformity or cryptic angular and, probably, azimuthal unconformity beyond the latter. Inasmuch as the Okhotsk avant shelf in this area is located at 680 m of water depth, we arrive at the conclusion that the Late Pliocene bar and unconformity mark the onset of the last transgression and the Sea of Okhotsk deepening by almost 1 km.

Subaerial shield volcanoes (Figs. 1–3) were also never interpreted in the Sea of Okhotsk seismic records [2, 3, 6, 7, 19, 27].

These unique structures similar to volcanoes are found at the Lebed (ST 462–484 km in Fig. 2) and Bol'sheretsk (ST 178–202 km in Fig. 3) uplifts. The near-summit parts of these structures are complicated by depressions 1–2 km wide resembling volcanic craters. Their slopes are overlain by lenses of sediments up to 150 m thick with bedding, which allows them to be interpreted as volcaniclastic aprons. These features pro-

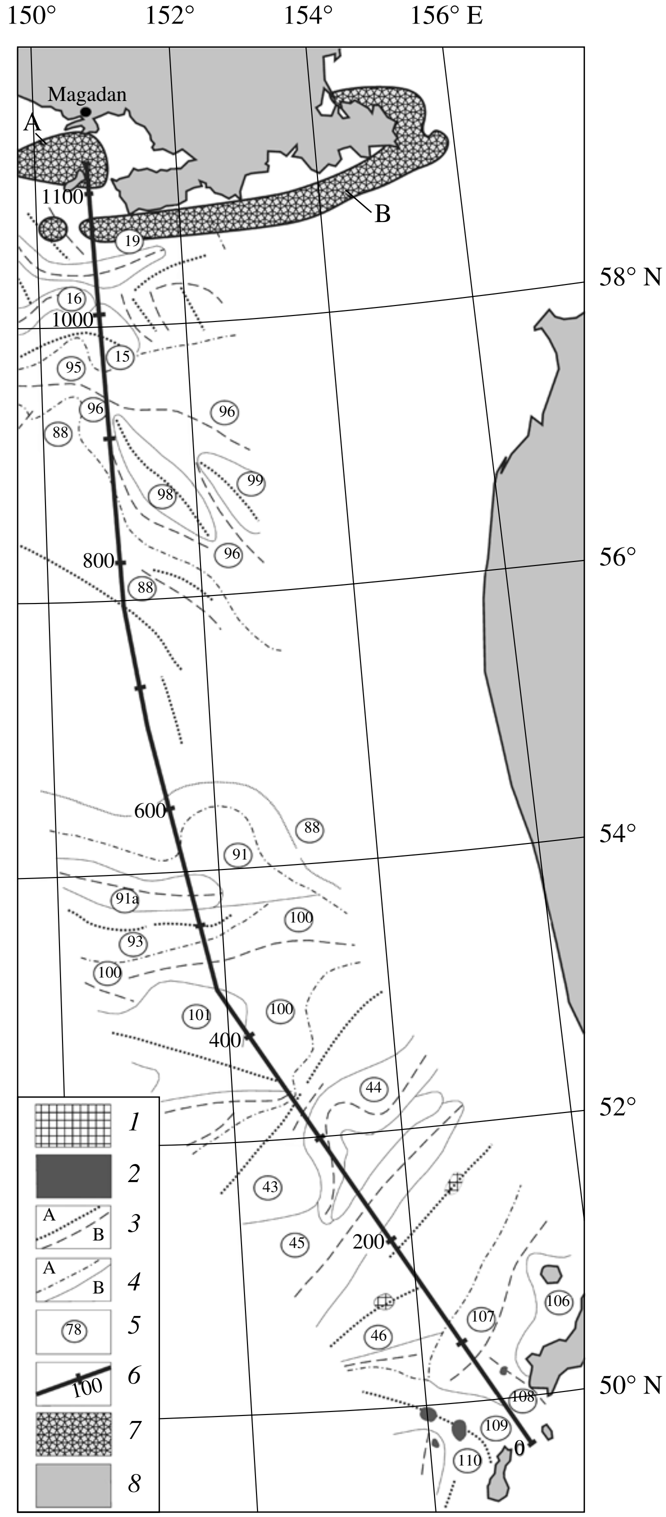

Fig. 1. The structural map (fragment) of the Sea of Okhotsk sedimentary cover with the location of CDP Profile 1632 [27].

(*1*) outcrops of the acoustic basement at the bottom; (*2*) Pliocene–Quaternary volcanoes; (*3*) axes of the relative uplift (A) and troughs (B); (*4*) boundaries of tectonic elements (zones (A) and their structures (B)); (*5*) numbers of structural elements; (*6*) position of CDP Profile 1632 with the stack numbers. CDP Profile 1632 changes its direction for the near-meridional one toward Magadan at the stack of 445 km; (*7*) positive magnetic anomalies (after [26]) above the Koni–P'yagina (B) and Magadan (A) megadikes; (*8*) shoreline of the Sea of Okhotsk.

Numbers in Figs. 1 and 5: uplifts: (15) North Okhotsk, (98) West TINRO, (99) East TINRO, (88) Central Okhotsk, (93) Lebed, (101) Atlasov, (43) Sobolev, (46) Bol'sheretsk, (106) Alaid–Paramushir, (109) Onekotan, (110) Ekarma–Simushir; troughs: (19) Koni, (16) Motyklei, (95) Northwest TINRO, (96) Central TINRO, (91) Lebed, (91a) Lineinyi, (100) Central Okhotsk, (44) Kol'skii, (45) Bol'sheretsk, (107) Golygin, (108) Chetvertogo Kuril'skogo Proliva, (15, 19, 96) North Okhotsk.

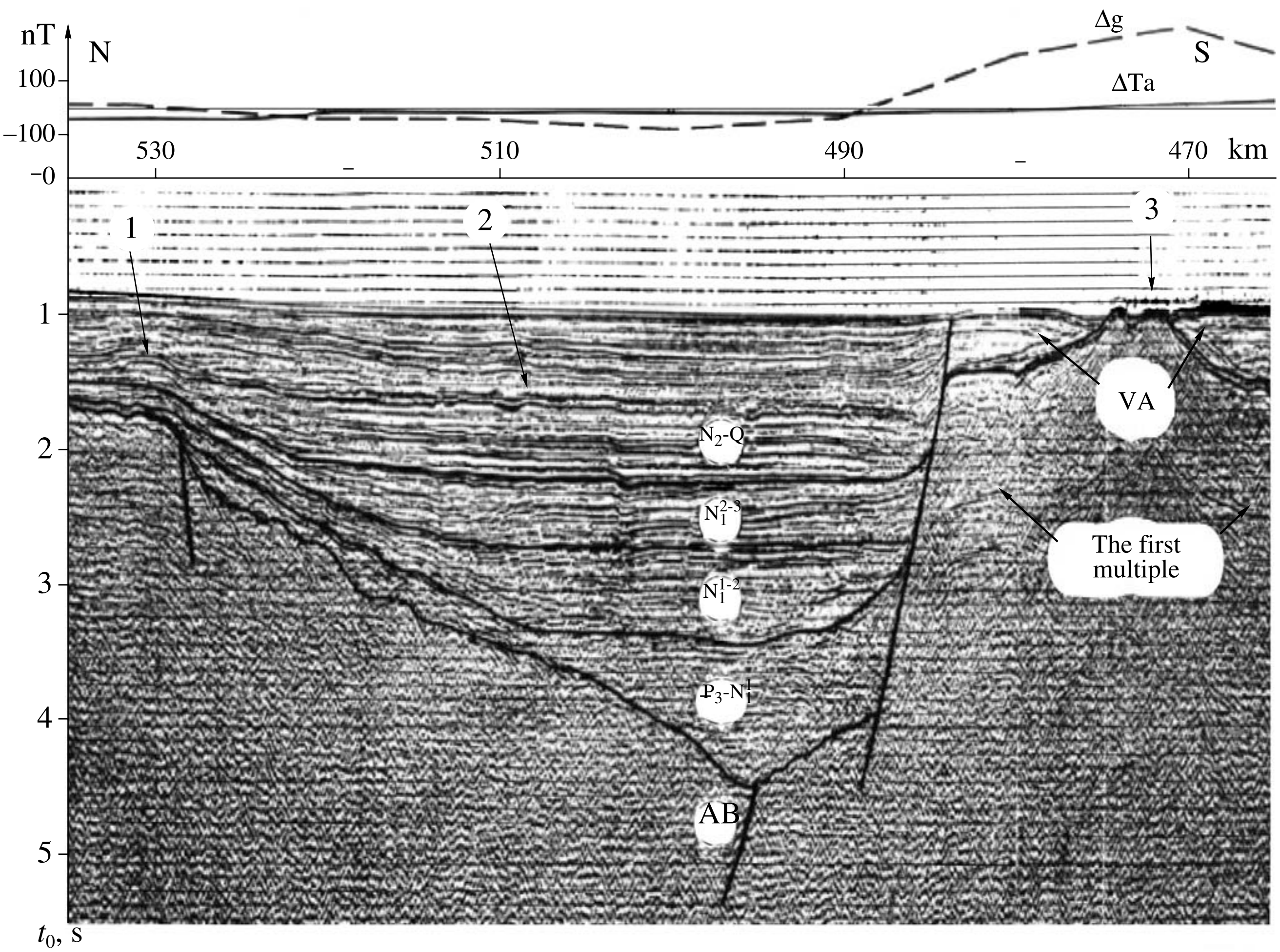

Fig. 2. The time section (fragment) along CDP Profile 1632 across the Lebed Trough and the synonymous uplift with observed values of the anomalous gravitational (dashed line) and magnetic (solid line) fields (here and in Figs. 3, 4, and 6, materials from the report on object 11/86, reference in [14]). The solid near-vertical lines in the sedimentary cover and the underlying acoustic basement designate here and in Figs. 2–6 planes of normal faults interpreted by the authors of the report on object 11/86. Numerical designations: (1) buried bar, (2) Late Pliocene regional unconformity, (3) Lebed shield volcano with volcaniclastic aprons. (VA) volcaniclastic apron here and in Fig. 3; (AB) acoustic basement here and in Fig. 6.

vide grounds for interpreting the structures under consideration as volcanoes even based on a single profile. The first of the volcanoes (Lebed [14]) with a small summit crater is observed at the Lebed Uplift (or ridge) with water depths of 710–750 m (ST 462–484 km in Fig. 2). It is 500 m high and 22 km across at the base. At the bottom, only its cone 30 km high towers above the sediments. The low-angle differently inclined slopes are covered by volcaniclastic aprons up to 100–150 m thick overlain unconformably by Upper Pliocene–Pleistocene marine sediments. Taking into consideration the fact that this structure towers above the buried bar and the Late Pliocene unconformity (Fig. 2), it may be assumed that the latter was formed in subaerial settings (island volcano).

A well-preserved volcano (Bol'sheretsk [14]) 650 m high and 24 km across is recorded at the Bol'sheretsk Uplift of the acoustic basement at water depths of 450–600 m (ST 178–202 km in Fig. 3). In the bottom topography (avant shelf), it represents a low (150 m) solitary cone 5 km across with a summit crater 75 m deep. The cone rests on the base with differently inclined slopes; the northern slope is covered by a thin (up to 100 m) volcaniclastic apron unconformably overlying Upper Pliocene–Pleistocene marine sediments up to 400 m thick. With account for the volcano towering above the Late Pliocene unconformity, this feature indicates its subaerial formation setting (island volcano). In the southern base slope, the volcaniclastic apron is likely abraded and/or is characterized by low (20–30 m) thickness close to the resolution limit of the CDP method in the Cenozoic sedimentary cover. It should be noted that these volcanoes are confined to inliers of Jurassic and Cretaceous compact volcano-sedimentary rocks [2, 3, 6, 7, 27], the roof of which is marked by intense multiple wave reflections in the time section

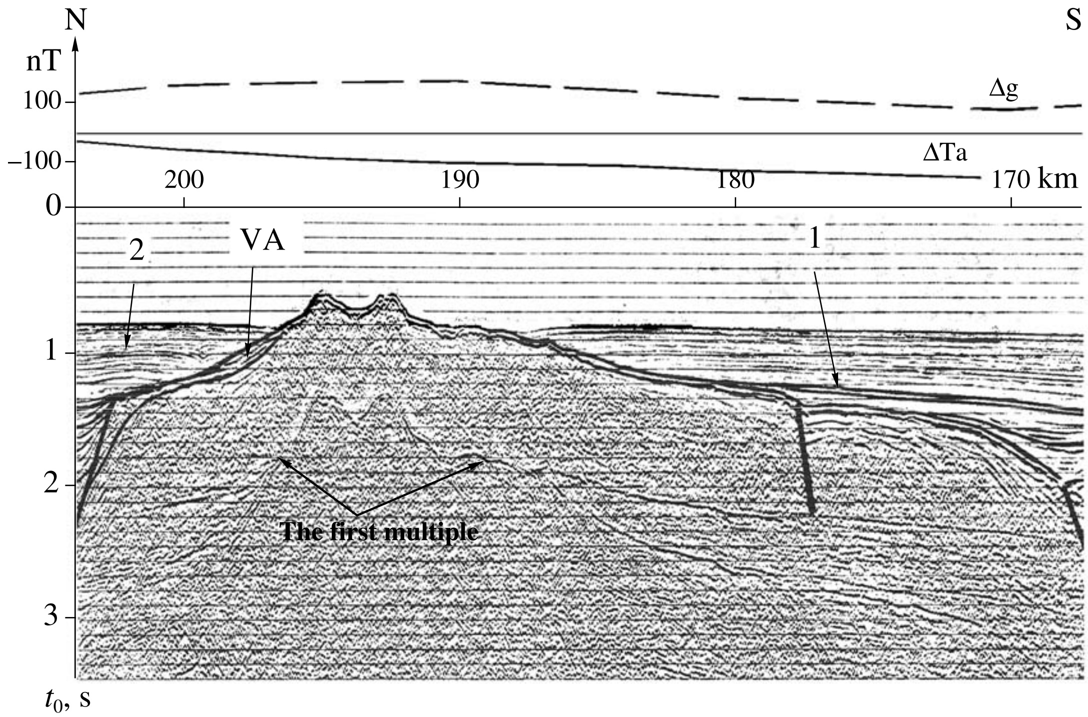

Fig. 3. The time section (fragment) along CDP Profile 1632 across the Bol'sheretsk Uplift and shield volcano. Number designations: (1) base of the Pliocene–Quaternary seismic complex, (2) Late Pliocene unconformity.

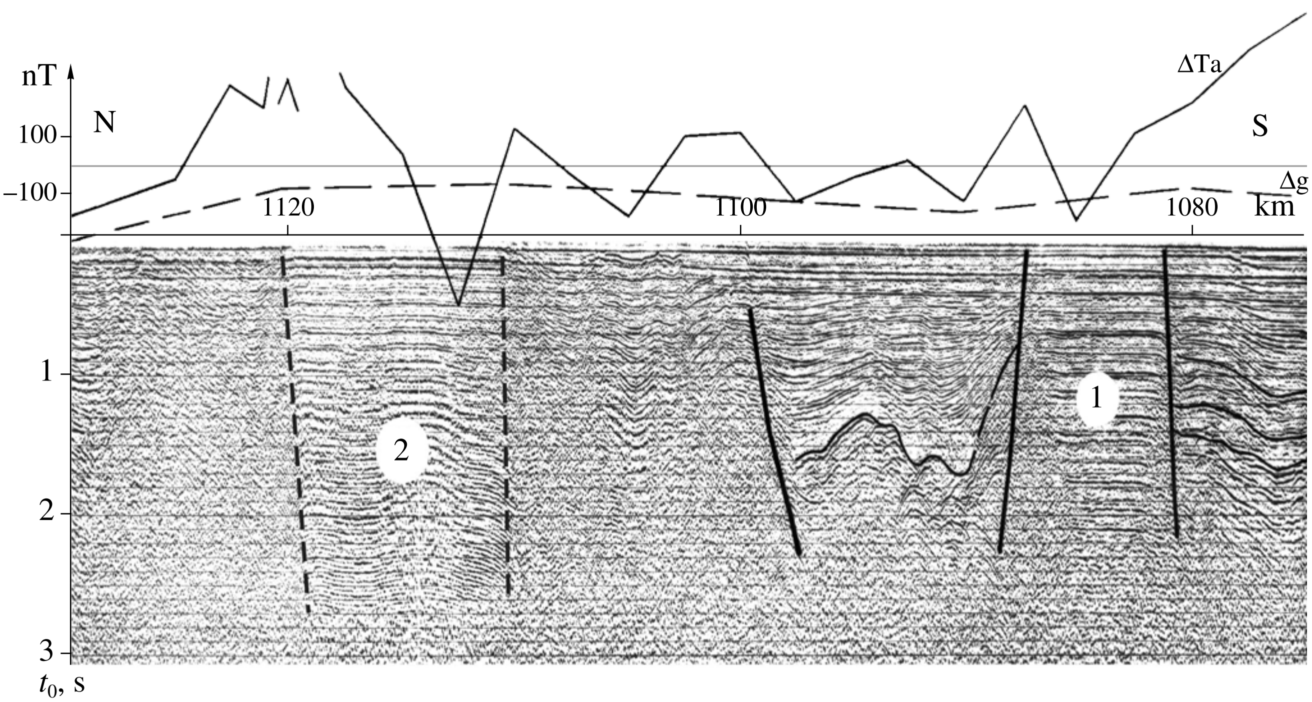

Fig. 4. The time section (fragment) along CDP Profile 1632 across the Koni–P'yagina (1) and Magadan (2) megadikes. The lateral walls of the latter are outlined by the near-vertical dashed lines.

(Figs. 2, 3). This feature, combined with the distinct differences in the morphology of the Lebed and Bol'sheretsk structures as compared with the Kurile volcanoes [5, 11], provides grounds for the preliminary assumption that they represent shield edifices composed largely of basalts [14]. According to [27], no

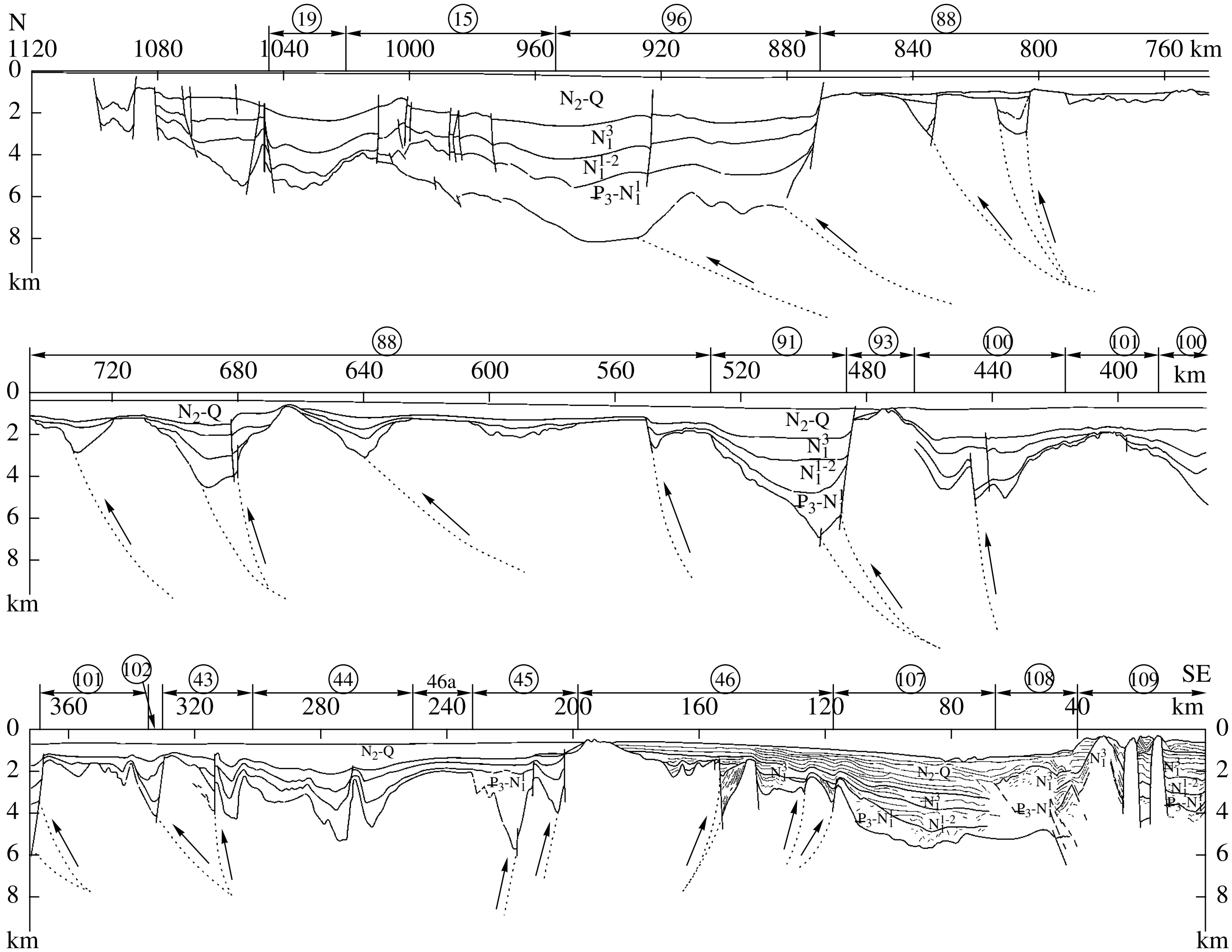

Fig. 5. The deep section along CDP Profile 1632 from [27] with the new tectonic interpretation of the basement scarps (compression faults, the assumed planes of which are shown by dotted lines with arrows [13]).
For the numerical designations of the uplifts and troughs, see Fig. 1.

dredging was carried out in this area. It should be emphasized that both volcanoes are almost indistinguishable in the anomalous gravimetric and magnetic fields. This may be indicative of a significant weathering degree of the constituting volcanics. Taking into consideration the fact that the conical shape of the volcanoes is determined by their composition of noncoherent, lava, and lava–cinder materials [5, 11, 15, 18, 19, and others], the diagnostics of these structures based on single CDP and continuous seismic profiles is quite possible.

The Koni–P'yagina and Magadan megadikes (Figs. 1, 4) represent new geological objects interpreted for the Magadan shelf of the Sea of Okhotsk [14]. They are confined to the southern flank of the Cretaceous Okhotsk–Chukotka volcanic belt [2, 3, 6, 27]. In the time section, these structures are distinguished at ST 1082–1087 and 1111–1119 km, respectively, being recognizable owing to the vertical zone of the reverberation of flat–parallel contrasting reflections 5 and 8 km wide, which are related to the intrusion of presumably compact high-velocity (ultramafics) rocks into the Cenozoic sedimentary cover, including the Pliocene–Quaternary bottom sediments. The reverberation of seismic waves at the Magadan megadikes and, in contrast, the transparent pattern of the Trekhbratka dike at the outer edge of the southeastern Sakhalin shelf interpreted in records along tens of CDP profiles performed by the *Dal'morneftegeofizika* trust [18] are determined by the different (1–2 and 15–20 m, respectively) thicknesses of the boulder–pebble sequences at their summit benches, which provides a sharp or gentler wave velocity jump at the transition from the water column to the ultramafics [18]. Their Quaternary age and intrusive nature assumed by analogy with the Trekhbratka megadike [18] are confirmed by anticlinal (stamp) folds with flat arches abraded at the shelf level and by linear positive magnetic and gravimetric anomalies. According to [20], the shift of anomalies relative to megadikes in Fig. 4 indicates their opposite (toward each other) dip

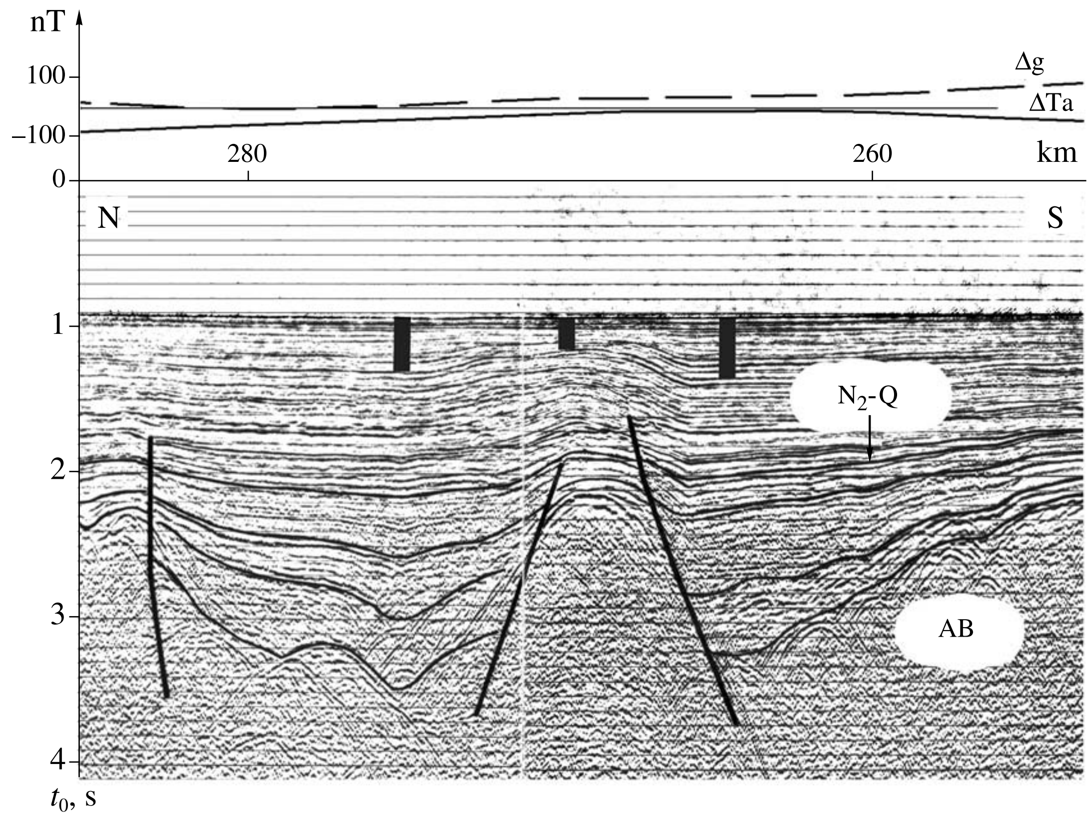

Fig. 6. The time section (fragment) along CDP Profile 1632 across the Kol'skii Trough with the diapir.
The arrow shows the base of the Pliocene–Quaternary seismic complex; the black columns designate the bottom sediments that accumulated synchronously with the diapir intrusion.

in the upper crust, which probably amounts to ~45°, although, at the deep level, they are most likely related to the concealed fault that borders, in the opinion of many researchers, the southern flank of the Okhotsk–Chukotka volcanic belt [2, 3, 6, 7, 19, 27].

The homoclinal ridges of the acoustic basement (Figs. 1–5) are usually described as inliers, uplifts, or horsts of the acoustic basement bordered by normal faults [2, 3, 6, 8, 10, 27]. CDP Profile 1632 demonstrates, however, their homoclinal structure, which is readily recognizable based on the differently inclined faces (slopes) up to 5–6 km high. For example, in the Central Okhotsk Ridge (megahomocline), which borders the North Okhotsk Trough on the south, the frontal and rear (southern) faces are characterized by incline angles of 45° and 16°, respectively. The width of the ridges exceeds 10–20 km. According to [12, 13, 18, 21], they resulted from the strata decollement, which determines their position between imbricated thrusts (allochthonous slices and nappes). Near the bottom, the thrusts grade into updip–thrusts and reversed faults. In Fig. 5, their planes are shown by analogy with the structural interpretation of the CDP and continuous seismic profiling records in [13, 17]. For example, the frontal (base) thrust of each nappe continues the low-angle outer slope of the neighboring trough downward, where it separates the allochthonous and autochthonous complexes of the basement. The type of faults was determined using the Lagrange principle, and their active limbs were identified similarly to [17]. This procedure resulted in revealing the opposite (toward each other) dip of the thrusts characteristic of the divergent decollement zone [12–14] on both sides of the Kol'skii (Makarov Trench [2]) near-latitudinal trough (pull-apart structure). This pull-apart zone divided the Okhotsk Arch into two allochthonous megablocks slowly diverging in the northern and southern directions. The Central Okhotsk megahomocline 180 km wide consisting of several slices represents the largest nappe of its northern block. Judging from the relief of the basement surface, these nappes may be attributed to either stratal or folded homoclines, although the former show locally small-scale folding as well.

Thus, judging from the deformation mode in Fig. 5, the Okhotsk segment of Profile 1632 is dominated by crustal compression, except for a narrow pull-apart zone. The compression is responsible for the raising of some ridges by 1.0–1.5 km in the Quaternary (for example, the Lebed Uplift; Fig. 2) and the development of thrusts in the northern megablock along the regional rise of the bottom and basement surface north of the Kol'skii Trough, i.e., similar to regional overthrusts in

Pacific trenches [17, 18]. Such kinematics are characteristic of each allochthonous slice or nappe of the acoustic basement.

Ramp half-grabens (Figs. 1–5) have never been described in the Sea of Okhotsk [2, 3, 6, 8, 10, 27]. Nevertheless, the seismic record obtained along CDP Profile 1632 demonstrates that the North Okhotsk and smaller troughs (except for the Kol'skii Trough) compensated for by Cenozoic continental and marine sediments [1, 27] are characterized by an asymmetrical transverse section, which is typical of half-grabens. The depocenters of the troughs are confined to steep (up to 45°) faults. Judging from thrust bordering of contiguous ridges in Fig. 5 and their kinematics, the half-grabens should be considered as belonging to the ramp type, not to riftogenic structures as was previously thought [2, 3, 6, 8, 10, 26, 27]. Moreover, it is reasonable to unite them together with basement ridges into tectonic nappe pairs "thrust homocline–ramp half-graben" characteristic of divergent decollement zones. By analogy with the Pacific trenches [17, 18], the formation of half-grabens was evidently determined by the subsidence of the acoustic basement under the load of conjugate allochthonous slices (such a mechanism was proposed for the Peru–Chile Trench by A. Wegener [17]) and partly by the occurrence of plastic sequences in the underlying continental crust.

Some researchers explain the formation of half-grabens by crustal extension in shear zones in line with the new tectonic concept of pull-apart basins [9]. This standpoint is, however, inconsistent in the studied segment of the Sea of Okhotsk with the areal (not linear as in strike-slip faults) development of nappe tectonic pairs (Fig. 1), the signs of young (Quaternary) uplifting of some homoclinal ridges (Figs. 2, 5), and the lateral compression in the Magadan area [22], as well as with the opposite (toward each other) dip of imbricated thrusts following from the structural interpretation.

The young solitary diapir (Fig. 6) is a unique structure previously unknown for the Okhotsk Arch [2, 3, 6, 8, 19, 27]. It is registered in the Kol'skii Trough (pull-apart zone) at ST 266–274 km, where the diapir intrudes into the basal layers of its Cenozoic sedimentary section, without changing their thickness, to form a low (up to 150 m) anticline up to 6–8 km wide. The young age of the fold is evident from the synsedimentary thinning (from 350 to 170 m) of the bottom presumably Quaternary sediments [1, 2, 6, 27] toward the arch. In the topography of the Okhotsk avant-shelf, the fold is undistinguishable because of its erosion by bottom currents. The diapir is also unrecognizable in the magnetic and gravimetric fields, which indicates its independence from the Late Cenozoic magmatism recorded by the reflection method on the Okhotsk margin of the Kurile island arc and in the North Pacific abyssal plain [15, 18, 21, 27]. Taking into consideration the conical structure of the diapirs regardless of the composition of their intruding cores (salt, clay, or viscous magma), their diagnostics in solitary CDP and continuous seismic profiling records is quite possible [5, 11, 15, 24, 27].

DISCUSSION

The reinterpretation of the time and deep sections along CDP Profile 1632 revealed several additional features in the geological and tectonic structure of the Sea of Okhotsk basin and its development history. For example, the Late Pliocene buried bar and regional unconformity mark the onset of the last large transgression and deepening (approximately by 1 km) of the Sea of Okhotsk. These events are correlative with data obtained from three boreholes drilled in the North Okhotsk Trough, where Cretaceous continental volcanics are overlain by beach conglomerates and Paleocene–Eocene coaliferous sediments [1], boulder–pebble material of local rocks dredged from the Okhotsk avant-shelf [2, 6, 7], the development of spacious benches and abrasion-related plateaus in the Okhotsk region (Late Mesozoic–Early Cenozoic [16]), and the Bol'sheretsk and Lebed subaerial shield volcanoes interpreted in continuous seismic profiling and CDP records [14]. However, the distribution of this unconformity and its age require additional study.

The formation of the above-mentioned subaerial volcanoes at summits of homoclinal inliers is likely explained by the defragmentation of rocks constituting the acoustic basement during their decollement and, consequently, higher permeability for basaltic lava as compared with conjugate troughs. This provides conditions favorable for the development of volcanic ridges consisting largely of solitary or merged shield edifices. Taking into consideration the seismostratigraphic correlation of the Cenozoic cover along CDP Profile 1632 with Magadan parametric Borehole 1 drilled in the North Okhotsk Trough (after [14]), the discovered volcanoes can be dated back to the Late Pliocene, which is consistent with the Pliocene age obtained for products of submarine island-arc volcanism at the Akademii Nauk Rise (four dates) [25]. The type of its edifices, however, has not yet been studied by the continuous seismic profiling and CDP methods. Combined with the last summarizing work on the Jurassic–Quaternary continental volcanism in the Sea of Okhotsk [7], the presented CDP data allow the distribution area of Pliocene volcanism, as well as the spectrum of its edifices, products, and eruption settings, to be substantially widened.

When studying the Quaternary Koni–P'yagina and Magadan megadikes, it is necessary to pay attention to their potential ore and oil specialization. The former follows from the metallogeny and long-term mining (chrome, nickel, platinum, and asbestos ores) of the Great Dike (the world's largest dike 2–3 km wide and 500 km long [4]), while the latter from the presumed oil-generating role of the Trekhbratka megadike, west of which all the known hydrocarbon fields of the Cenozoic North Sakhalin petroliferous basin are located [18]. The traditional "horst" interpretation of the Koni–P'yagina megadike in [27] is in discord with the fact that it distinctly truncates the eastern extremity of the P'yagina Peninsula (Fig. 1) and with the opposite dip of the megadikes in the upper crust. In addition, if both "horsts" appeared prior to the Late Pliocene, they should be abraded completely or partly taking into consideration the last sea level rise (see above). This would have resulted in the accumulation of Upper Pliocene–Quaternary sediments approximately 1 km thick in the first case or the formation of a truncated horst with a system of abrasion terraces in the second one. Indeed, following [23], the Magadan megadikes can be considered as ophiolitic belts of the ancient (Mesozoic) subduction zone by analogy with the Trekhbratka structure. Such an interpretation can hardly be harmonized with their intrusion into the bottom Pliocene–Quaternary sediments, which undoubtedly indicates the Quaternary age of the megadikes, as well as with their opposite dip in the upper crust (see above).

The seismic record obtained along CDP Profile 1632 made it possible to define in the structure of the Okhotsk Arch the morphological tectonic pairs "homoclinal ridge–ramp half-graben" and a narrow pull-apart zone in the Kol'skii Trough with a solitary diapir. The zone divides the arch into the southern and northern allochthonous megablocks with thrusts oriented toward each other, which imply divergent decollement at the deep level. The latter is outlined based on the deep seismic sounding materials [27] at the base of the velocity inversion (up to 0.5 km/s) layer 4 km thick (the friction layer at the base of the allochthon [13]) occurring above the M discontinuity. According to [12, 18, 21], the regional incline of this zone under the mountainous structures surrounding the Sea of Okhotsk depression could have stimulated the continental crust decollement in the Cenozoic. The diapirism in the pull-apart zone represents one of its manifestations. The latter is connected with the intrusion of plastic rocks constituting the friction layer similar to numerous diapirs (extrusive domes) developed in the pull-apart zone on the marginal swell and in the Hokkaido Fault area [12, 18, 21]. It is conceivable that the crustal decollement is also responsible for the shallow-focus (crustal) seismicity in the Sea of Okhotsk (according to data by A.A.Poplavskii and A.O. Bobkov from the Sakhalin Branch of the Geophysical Survey of the Russian Academy of Sciences).

In the context of this work, of particular significance is the consistency between the materials obtained along CDP Profile 1632 and inferences in [22] on the Late Quaternary lateral compression of the crust in the southern suburbs of Magadan and its orientation (from the south). In this connection, of importance is the reinterpretation of other records along regional CDP profiles performed by the *Dal'morneftegeofizika* trust in the Sea of Okhotsk as a basis for transition from the classical graben–horst (rift) model of crust extension to the new nappe model connected with its decollement and compression in the allochthonous megablocks of the Okhotsk Arch.

CONCLUSIONS

The reinterpretation of the deep and time sections along CDP Profile 1632 revealed new tectonic features in the bottom structure of the Sea of Okhotsk: the Late Pliocene bar and regional unconformities that mark the onset of the last significant sea-level rise (almost by 1 km) two subaerial shield volcanoes that crown the homoclinal ridge of the basement; two Quaternary megadikes near the southern flank of the Cretaceous Okhotsk–Chukotka volcanic belt; and signs of divergent decollement (nappe tectonic pairs bordered by imbricate compression-related faults, and a young diapir in the pull-apart zone in the Kol'skii Trough that separates the Okhotsk Arch into two allochthonous megablocks with thrusts of opposite (toward each other) dips). This reveals new objects and directions for future studies.

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