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SHORT COMMUNICATIONS

Slumping Processes on the Caucasian Continental Slope of the Black Sea

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Abstract—New results of geomorphological, seismoacoustic, and lithological investigations on the upper continental slope off the Arkhipo-Osipovka Settlement are presented. Here, a large submarine slump was discovered by seismic survey in 1998. The assumed slump body, up to 200 m thick, rises 50–60 m above the valley floor that cuts the slope. Recent semiliquid mud that overlies laminated slope sediments with possible slump deformations flows down in the valley thalweg. Radiocarbon age inversion recorded in a Holocene sediment section of shelf facies recovered from the upper slope points to the gravity dislocation of sediments.

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This paper was just under revision when grievous news came about the tragic death of its first author, V.N. Moskalenko, who was among pioneers of the Russian seismic profiling. We acknowledge our debt of gratitude to complete the work, preserving his ideas as much as possible. However, new materials appeared which forced us to revise some earlier theses of Moskalenko. We believe that our changes do not detract his merit as the principal author of the work.

High-frequency seismic profiling carried out by the Shirshov Institute of Oceanology and its Southern Division on the Caucasian continental slope in the area extending from the Arkhipo-Osipovka Settlement to the Dzhubga Settlement revealed an abundance of submarine slumps and gravity flow deposits (Moskalenko and Shimkus, 1976; Moskalenko, 2000; Shimkus *et al.,* 2002). The slumps occur in the entire study area of the continental slope except for minor spaces (Fig. 1).

A considerable proportion of topographic rises on the continental slope represents slump blocks of complex structure. Most of the blocks are located on the steepest upper slope. The floor of submarine canyons is commonly covered with gravity flow deposits. Powerful high-energy gravity flows moving down the slope along the canyons can not only transport huge sediment masses, but also erode older sediments (Esin *et al.,* 1991). Erosion and reworking of sediments by gravity flows are widespread on continental slopes of the World Ocean, and these processes play a significant role in the formation of slopes of the Black Sea basin (Esin *et al.,* 1987). Sections of Pleistocene-Holocene sediments recovered from valleys and canyons provide evidence of repeated erosional events alternating with sediment accumulation (Shimkus *et al.,* 2002). Young sediment bodies in valleys and canyons are characterized by variable thickness that increases toward the continental slope base and locally reaches 300 m.

The lithological study of sediment cores retrieved from the continental slope and its foot in the area extending from the town of Gelendzhik to the Dzhubga Settlement confirms the development of submarine slumps and turbidites in the Pleistocene–Holocene section. Outcrops of bedrocks and ancient sediments related to slumping of young sediments are also found. Apparent slumping structures occur in some cores (Shimkus *et al.,* 1999). The data obtained indicate that the gravity displacement of sediments occurred on the Caucasian continental slope in the Late Pleistocene–Holocene, and this process continues today.

Geological and geomorphological investigations show that throughout the continental margin from Novorossiisk to Tuapse, sedimentation rates drastically increase (up to 90 cm/ka) toward the continental slope base, where deep-sea fans composed of gravity flow deposits are developed (Esin *et al.,* 1986; Shimkus *et al.,* 2002).

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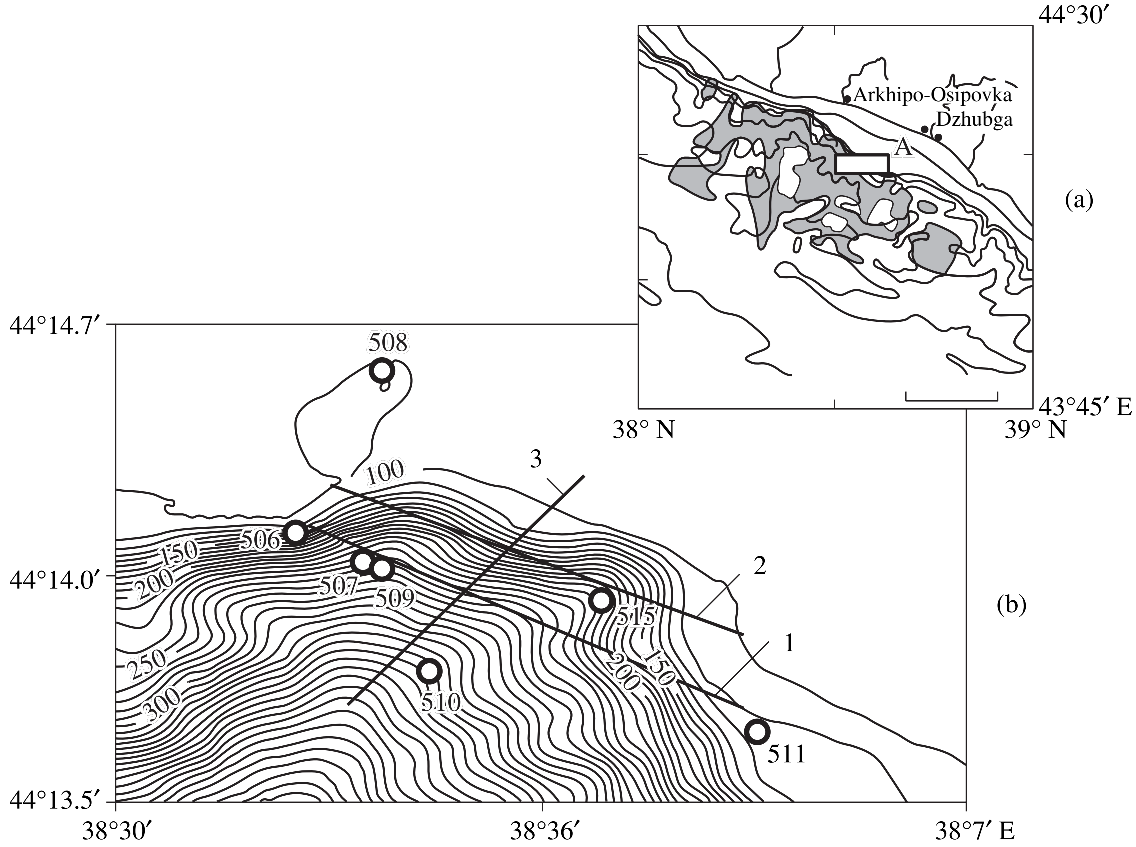

Fig. 1. (a) Schematic map of the northeastern continental margin of the Black Sea showing distribution of slumping processes on the continental slope (shadowed) and location of detailed study area A. (b) Bathymetric map of the study area A with the location of profiles 1–3 and coring stations Ak 506–Ak 515 on the upper continental slope off the Arkhipo-Osipovka Settlement.

NEW GEOLOGICAL AND GEOPHYSICAL DATA

The geological-geophysical expedition on R/V *Aquanavt* was carried out at the Caucasian continental margin from the Arkhipo-Osipovka Settlement to the Dzhubga Settlement in July 2001. This expedition included detailed investigations of the large slump discovered earlier (1998) within a valley on the upper continental slope (Shimkus *et al.*, 2002). Chirp Datasonic profiler (United States) and sparker profiler of the Shirshov Institute of Oceanology were used for the seismic survey. Several gravity cores were collected near the slump (Fig. 1).

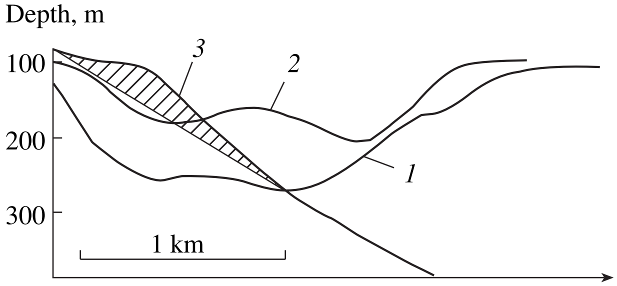

Fig. 2. (*1, 2*) Transverse and (*3*) longitudinal bathymetric profiles across the slump on the valley floor. Hatching beneath profile 3 shows the relative elevation of the slump body over the valley thalweg, Profile 2 corresponds to the seismic profile shown in Fig. 4. See Fig. 1b for location of profiles.

Erosion and accumulation processes (including slumping) developed in submarine valleys and canyons within the depth interval from the middle continental slope (1000–1500 m) to slope base have been previously characterized based on results of the 1998 expedition (Shimkus *et al.,* 2002). Submarine valleys serve as main sediment transport routes to the deep Black Sea basin. The supposed slump body discovered in 1998 is located in one of such valleys. Here, we present results of its study.

The fragment of detailed bathymetric map (Fig. 1) and profiles of the bottom topography (Fig. 2) outline the general morphology of the valley and the supposed slump. The valley gently widens seaward from less than 2 km in its upper part to 4 km in the lower part. In its uppermost part (at a depth of 100–200 m), the slump is observed as a large positive swell-shaped morphostructure (relative height 50–60 m) elongated along the valley thalweg. The detailed high-frequency seismic profiling did not find any continuation of the valley on the

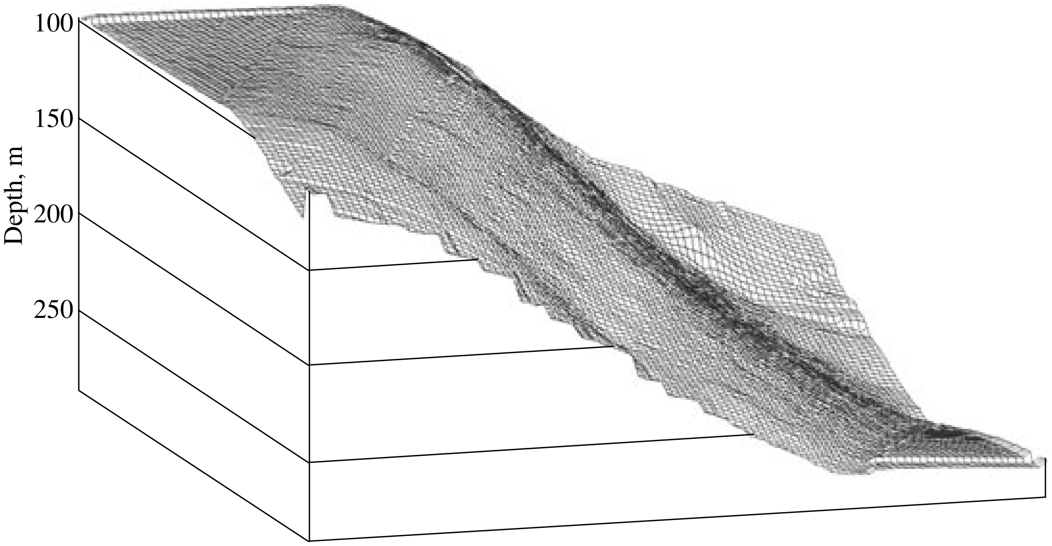

Fig. 3. Block map of the slump in the study area A.

adjacent shelf. Buried ancient channels entering the valley head are also absent here.

The seismic records demonstrate a simple two-layer structure of shelf deposits. Unconsolidated Holocene and Upper Pleistocene sediments, up to 15 m thick, overlie with a sharp angular unconformity strongly dislocated lithified rocks of the Cretaceous–Paleogene carbonate flysch. Elements of relict topography are preserved at the unconformity surface (Torgunakov *et al.,* 2002).

In the transverse profiles (Fig. 2, profiles 1 and 2), the slump is represented by a gentle rise, ~700 m wide in its upper part and ~500 m wide in the lower part. In the longitudinal profile 3 along the slump crest (Fig. 2), one can see a swell extending from the shelf edge (water depth approximately 100 m) down to 250 m. The swell-shaped morphology of the slump is also well seen in the block map (Fig. 3). The swell becomes flatter with increasing depth up to the point of complete disappearance at nearly 300 m (Fig. 1).

The seismic profile across the upper part of the slump shows that the valley is 1.6–1.7 km wide and its relative depth is up to 100 m (Fig. 4). Water depth varies from ~130 m to 225 m and is approximately 200 m over the slump crest. We cannot identify any reflector in this profile that might be interpreted as a bottom surface of the slump. In the axial part of the valley, the slump bottom presumably lies at nearly 350 m below sea level. The maximum thickness of the slump is 200 m.

Judging by the transverse seismic profile across the slump (Fig. 4), its internal structure is typical for such sedimentary bodies of the Caucasian continental slope (Shimkus *et al.,* 2002). The submarine slumps are generally characterized by a chaotic internal structure without continuous regular reflecting surfaces. The slump body may incorporate hyperbolic reflectors and short reflecting areas related both to small bottom topographic irregularities and to internal deformations or heterogeneities of the sedimentary mass. In some places, one can see separate, more continuous reflecting boundaries that possibly correspond to slumping surfaces. The typical chaotic structure is formed owing to destruction of the primary bedding of marine sediments during slumping.

The transverse seismic profile (Fig. 4) shows numerous chaotic reflections in the upper part of the slump, whereas several fragments of strong subhorizontal and gentle reflectors occur in its deeper part. These deeper reflectors are possibly related to cyclic slumping. The formation of a large slump body is often related to several slumping cycles. In this case, each younger slump overlies the older one, and we see the boundary between them in the seismic pattern. We have to note that collapsed blocks of sedimentary rocks with primary stratified flysch structure may also occur within the slump body.

We assume that the slump-hosting valley may also be related to slumping. Complicated structure of the valley slope that is well visible in the transverse seismic profile (Fig. 4) supports this suggestion. Unlike a typical stratified carbonate flysch structure composed of the monoclinal succession of reflectors, the valley slopes accommodate numerous hyperbolic reflections similar to those within the slump body. The hyperbolic reflections may be related to small topographic features of the slope and to slumping or collapse of the slopes.

Gravity cores of soft young sediments collected near the slump (Figs. 5, 6) provide additional data on gravity sediment transport (including slumping) on the upper continental slope.

Core Ak 508 retrieved from a small topographic low at the shelf edge at the water depth of 93 m (Fig. 1)

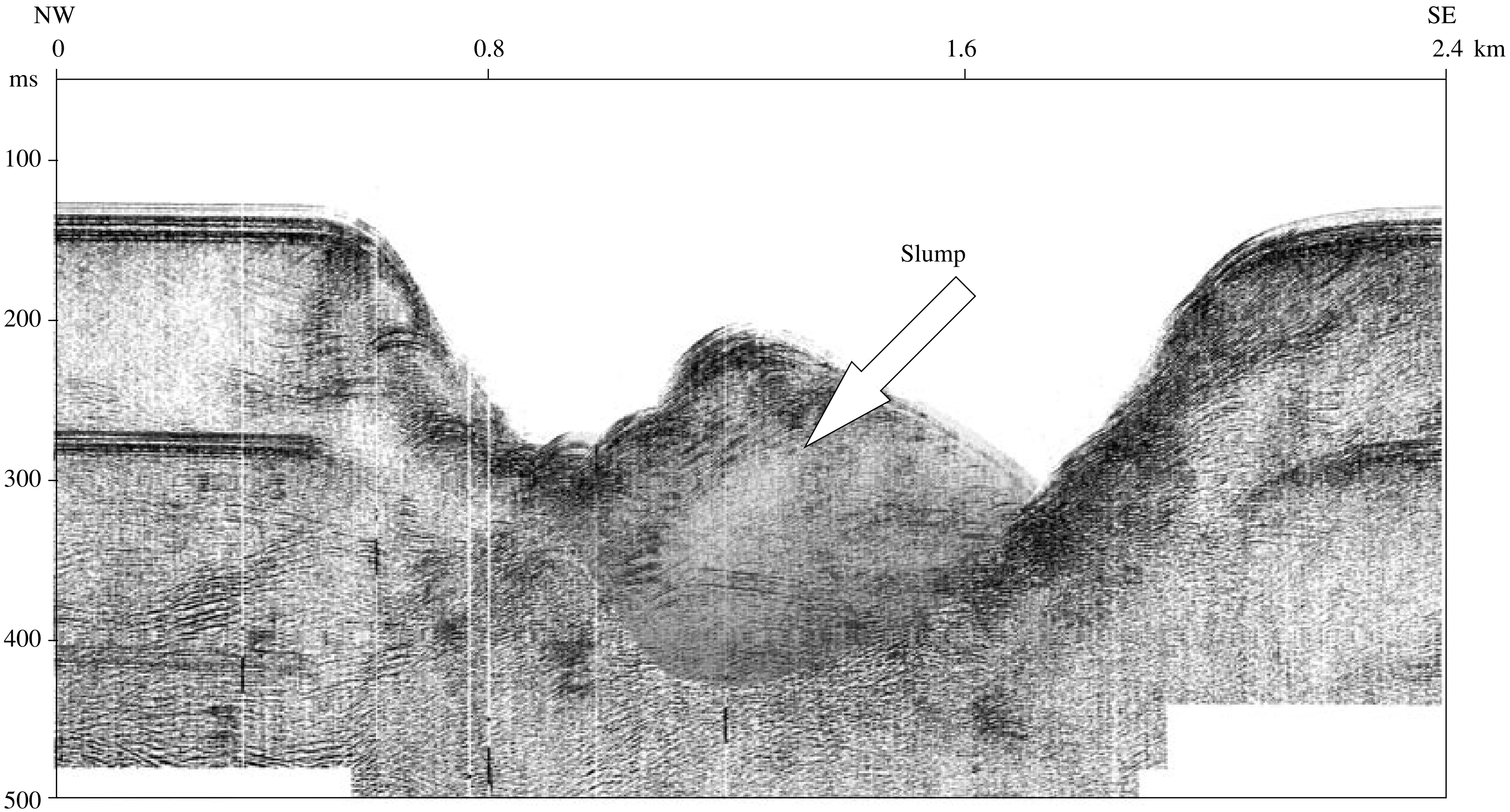

Fig. 4. Seismic profile across the slump within the submarine valley on the upper continental slope. For location, see Fig. 1b, profile 2.

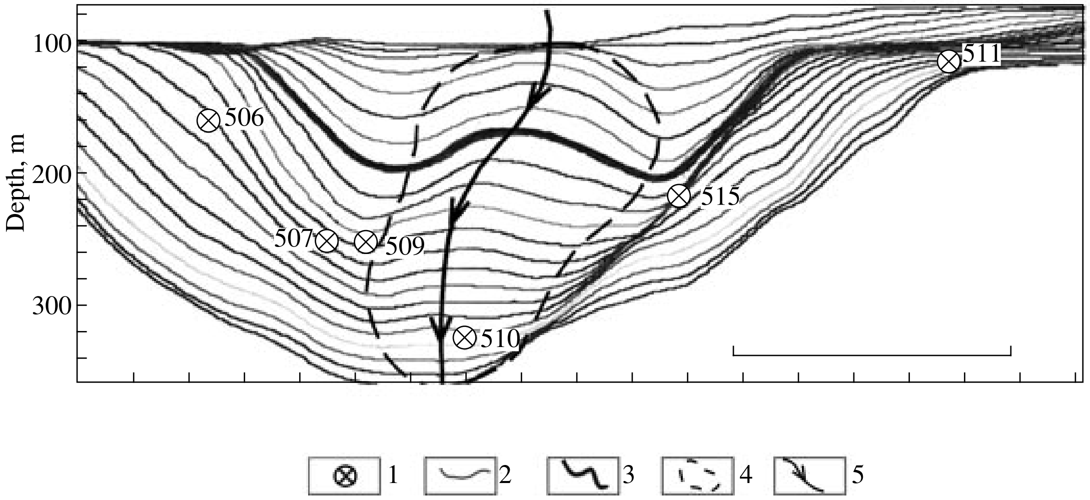

Fig. 5. Series of transverse bathymetric profiles across the valley and slump on the upper continental slope (study area A) with location of coring stations. (1) Coring stations and their numbers; (2) parallel bathymetric profiles; (3) seismic profile shown in Fig. 4; (4) contour of the slump body; (5) assumed direction of the slump movement.

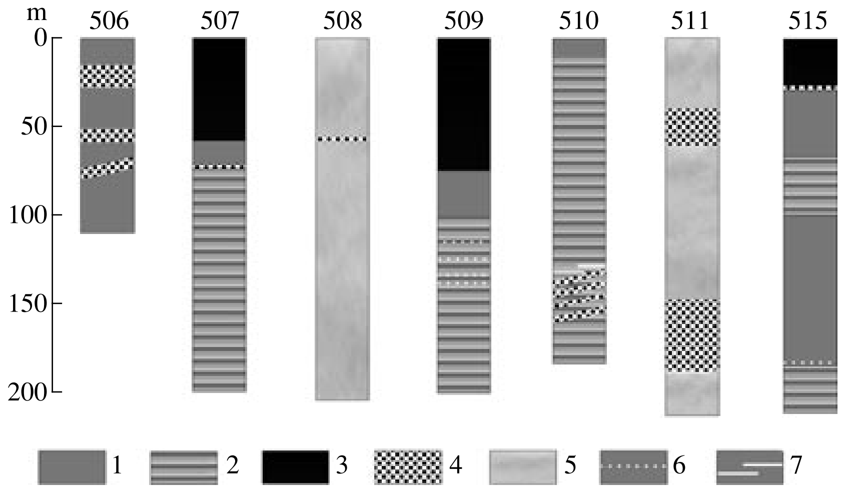

Fig. 6. Sediment cores collected from the slump area. For location of cores, see Figs. 1 and 5. (1) Aleuritic-pelitic mud, greenish gray, with scattered mollusk shells; (2) aleuritic-pelitic mud, parallel laminated (alternating dark and light laminae); (3) aleuritic-pelitic mud, black, semiliquid; (4) mollusk shells mixed with sandy aleuritic-pelitic mud; (5) aleuritic-pelitic mud with abundant mollusk shells; (6) thin sandy interbed; (7) microfault with displacement of layers.

recovered terrigenous sandy silty mud with abundant but unevenly distributed bivalve shells. An indistinct layering related to muddy shell layers is noted.

Core Ak 506 (water depth 160 m) characterizes sediments from the upper northwestern slope of the valley (Figs. 1, 5) with clear signs of reworking by gravity processes. At 15–28 cm, the core recovered an interbed enriched in shallow-water bivalve shells that are atypical for such water depth. Graded bedding is noted below this interbed at 28–59 cm. Muddy sand layer with reworked mussel shells occurs at the base of the graded bed. Angular unconformity is observed at 74–80 cm between the inclined shell layer and the overlying horizontally bedded clayey mud (Fig. 6).

Cores Ak 507 (water depth 252 m) and Ak 509 (water depth 248 m) recovered valley-floor facies of the northwestern thalweg (Figs. 1, 5). This facies is characterized by the presence of a semiliquid black (sapropelic?) surface mud layer with thickness varying from 58 cm (Ak 507) to 75 cm (Ak 509). Parallel lamination is noted in the lower part of this black layer. A similar 26-cm-thick semiliquid black layer was recovered by core 515 (water depth 229 m) from the southeastern thalweg of the valley (Figs. 1, 5). However, the black layer is absent in core Ak 510 retrieved from the valley thalweg beneath the slump at a water depth of 324 m (Fig. 6).

Grain-size distribution of sediments in core Ak-509

Interval, cm	Water content, %	Content of size fractions (mm), %						Sum of fractions <0.01 mm, %
		0.1	0.1–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	
0–25	58.86	0.16	0.97	30.31	20.91	32.25	15.40	68.56
25–35	52.13	0.27	0.82	33.38	20.11	30.64	14.77	65.53
35–45	56.33	0.15	0.92	34.20	17.10	33.89	13.74	64.73
45–55	55.54	0.45	0.89	30.85	17.29	36.81	13.71	67.81
55–65	54.66	0.29	1.30	32.08	17.05	35.40	13.87	66.33
65–75	54.89	0.14	0.84	27.07	16.83	38.29	16.83	71.95
75–85	52.09	0.27	0.80	29.05	10.98	43.91	14.99	69.88
85–95	45.98	0.36	0.96	34.09	12.72	37.21	14.65	64.59
95–105	37.47	3.11	4.04	30.88	16.68	31.19	14.09	61.97
95–105	37.53	2.14	2.24	28.87	19.69	32.96	14.08	66.73
105–115	38.36	0.31	2.92	40.83	13.02	25.31	17.60	55.94
115–120	34.33	6.70	9.86	32.25	9.18	23.64	18.37	51.20

The layer of recent semiliquid black mud overlies with a sharp contact the greenish gray silty mud layer, 3–25 cm thick, in all three cores (Ak 507, Ak 509, and Ak 515). In two cores, an apparently reworked thin shell layer is recorded at its base. The underlying more or less distinctly laminated denser silty mud contains rare thin sandy laminae. Age of the laminated sediments has not been determined, but a similar laminated sequence from other continental slopes is commonly attributed to the Neoeuxinian horizon of the Upper Pleistocene. The same type of laminated sediments, but without the surface black layer, is described in core Ak 510. In addition, interval 140–160 cm in core Ak 510 contains a series of coarse-grained interbeds with shell debris that is obliquely oriented relative to the lamination (Fig. 6). This is strong evidence in favor of the transport of reworked shallow-water material by gravity flows at the valley floor.

Grain-size distribution analyzed in 10-cm-thick samples from core Ak 509 (table) is rather uniform and probably typical for valley floor sediments near the slump. The content of pelite fraction (<0.01 mm) is high (51–72%). Contents of sand (1–0.1 mm) and coarse aleurite (0.1–0.05 mm) are generally low, but they increase in the interval of 95–120 cm, where thin sand laminae are noted (Fig. 6). The grain-size distribution is bimodal with modes in the medium pelite (0.005–0.001 mm) and fine aleurite (0.05–0.01 mm) regions. However, such bimodality is likely an artifact resulting from the approximation of too thick samples that may include interbeds with different grain sizes.

Evidence for the development of gravity (probably, slumping) processes on the upper continental slope beyond the valley described here is obtained from core Ak 511 (Figs. 1, 5). The core retrieved directly below the shelf break (water depth 116 m) recovered a section of aleuritic-pelitic mud with a variable (generally, high) content of bivalve shells. The section contains two shell layers (with dominant shallow-water species) mixed with muddy sand at 40–60 and 147–187 cm (Fig. 6). A similar section is described in core Ak 521 (water depth 103 m) from the adjacent area, where it represents a typical shelf edge facies (Murdmaa *et al.,* 2003). However, radiocarbon datings of mollusk shells revealed an age inversion in core Ak 511: $\delta^{14}C$ age is 7880 yr BP in the interval of 51–65 cm and 6120 yr BP in the lower interval of 117–125 cm (Murdmaa *et al.*, 2003). This inversion likely indicates slumping of sediments from the shelf edge to the upper slope, resulting in overlapping of younger sediments by older ones.

Strength properties of sediments were measured in several cores from the slump area. Basic sediment strength parameters determined by standard methods included rotation shear force and penetration force. The specific cutting force was measured along cores using a special device practically in a continuous regime (with the frequency of 10 measurements per 1 mm).

Minimum sediment strength values (1.0–4.5 kPa) characterize recent sediments of the surface layer. Sediment strength increases downward in cores and reaches 7.51-11.0 kPa at a depth of 1.5–2 m below the sea floor (BSF). Sediments from the upper continental slope are characterized by the following values: wet density (ρ) 1.15–1.82 g/cm^3; sediment strength (τ) 1.5–14.0 kPa; plasticity index (M_p) 15–42.

In core Ak 507 (water depth 250 m) recovered from the northwestern valley thalweg, the upper layer is represented by semiliquid black mud with the minimum strength (specific cutting force < 1.0 kPa) (Fig. 7). Below this layer, the specific cutting force gradually increases to 10.0–12.0 kPa. At the depth of 75–80 cm BSF, the specific cutting force abruptly increases to 30.0–40.0 kPa. Such an abrupt increase in sediment strength is likely related to the unconformity created by slipping down of a portion of sediment section. Recent very soft sediments (with water content up to 280% and wet density from 1.12 to 1.28 g/cm^3) were deposited over the unconformity surface of older (Neoeuxinian?)

sediments. Regular changes of sediment strength are not recorded downward the section. This fact is consistent with the visual description of stiff laminated aleuritic-pelitic mud and a rather uniform grain-size distribution of the same mud in adjacent core Ak 509 (table).

For comparison, Fig. 7 shows the distribution of specific cutting force in core Ak 508 from the shelf beyond the slump area (Fig. 1). In general, the specific cutting force gradually increases with depth BSF, suggesting a continuous sedimentation and compaction of Holocene sediments. Peaks of high sediment strength in curve 1 (Fig. 7) are likely related to the presence of large mollusk shells in the shelf sediments.

Comparison of curves 1 and 2 (Fig. 7) reveals higher strength values in shelf sediments (Ak 508), as compared to the semiliquid black mud from core Ak 507 (interval 20–58 cm) and the underlying soft greenish gray mud (interval 58–73 cm). Specific cutting force of laminated (Neoeuxinian?) sediments from core Ak 507 (interval 80–110 cm) is higher than that of Holocene sediments from core Ak 508. However, the curves converge at 110 m BSF and stay at approximately the same level downward the section, regardless of a considerable difference in lithology (and, probably, age) of sediments. Such a similarity in strength properties of the Holocene shelly mud from the shelf edge (core Ak 508) and the Neoeuxinian(?) laminated mud from the valley floor (core Ak 507) may be caused by termination of the early diagenetic unstable stage and transition to the more long-term stable state of sediment layer in both cases.

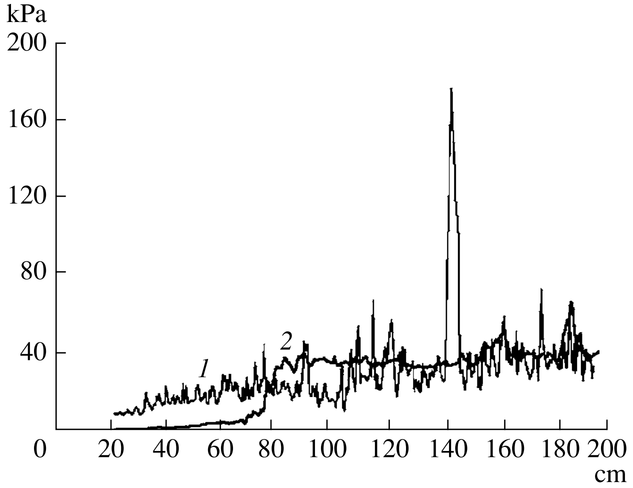

Fig. 7. Examples of specific cutting force variations in sediment cores with depth BSF: (1) Core Ak 508 from a small depression at the shelf edge (depth 93 m) composed of aleuritic-pelitic mud with bivalve shells typical for the outer shelf; (2) core Ak 507 from the thalweg of the northwestern valley branch (depth 252 m), the upper 58 cm thick layer in which is composed of semiliquid black mud (warp) flowing down the thalweg, whereas the lower interval is represented by laminated aleuritic-pelitic mud (see Fig. 6).

DISCUSSION

The above-presented results of geomorphological, seismoacoustic, lithological, and geotechnical investigations support previous ideas (Shimkus *et al.,* 2002) about the virtually ubiquitous development of gravity displacement of the friable Holocene and Upper Pleistocene sediments on the Caucasian continental slope of the Black Sea. Examination of the continental slope off the Arkhipo-Osipovka Settlement provided evidence of various gravity processes, including a large submarine slump filling of valley on the upper continental slope, minor slumps, gravity flow deposits, and mud creep on the valley floor. Although the intense gravity displacement of sediment masses on the continental slope (especially, in submarine valleys) is admitted today, certain mechanisms of these processes are disputable.

Origin of the above-described large swell-shaped morphostructure in the submarine valley is still insufficiently understood. Following the ideas of V.N. Moskalenko, we attribute this feature to submarine slumps mainly based on the interpretation of the seismic pattern (Fig. 4). However, composition of sediments (rocks) in this prominent morphostructure has not been studied so far. None of the cores collected in the study area recovered the slump body (Fig. 1, 5). Judging by the gentle swell-shaped body elongated along the valley thalweg (Fig. 3) and the chaotic seismic structure (Fig. 4), the slump body is built up of young soft sediments that slipped down the valley thalweg and deformed during the gravity displacement. This does not exclude incorporation of bedrock (flysch) blocks into the slump owing to a collapse of shelf edge or valley slopes, although we have no direct evidence of such collapse.

The question arises about sources of the huge unconsolidated sediment mass necessary for building up the slump body, up to 200 m thick and several millions of cubic meters in volume. The thin Holocene–Upper Pleistocene sedimentary cover (no more than 15 m) on the adjacent shelf can provide with sediments the formation of only small slump bodies similar to that recovered by core Ak 511. Detailed seismic survey has not discovered any channels on the adjacent shelf that might serve as routes for sediment supply. Therefore, we have to assume that near-bottom suspension flows, especially intense over the shelf edge (Aibulatov, 1990), represent the main sediment source maintaining gravity processes on the upper continental slope. Rapid mud accumulation from the near-bottom nepheloid layer just behind the shelf break can not only provide the sedimentary material for gravity (mud) flows, but also create unstable sediment bodies that may slump down from the steep upper slope.

Present-day sedimentation rates were measured on the northeastern Black Sea shelf and continental slope during performance of the international project RER/2/003. Radioactive markers in sediments corresponding to moments of nuclear weapon tests and the Chernobyl catastrophe were used for the estimation.

According to these estimates, present-day sedimentation rates are up to 6 mm/yr on the shelf and up to 1.6 mm/yr at the base of the continental slope. Such enormous values are 5–10 times higher than the average Holocene sedimentation rates determined by stratigraphic methods or inferred from radiocarbon datings. They likely characterize an unstable ephemeral warp, rather than a real increase in thickness of the Holocene sediment layer. However, the rapid warp accumulation points to a potential possibility for sedimentary material to be involved into gravity transport on the continental slope including slumping. Moreover, radiocarbon datings reveal at least one case of 1-m-thick mud layer accumulation at a rate of more than 1 mm/yr on the outer shelf off the Arkhipo-Osipovka Settlement in the middle Holocene (Ivanova *et al.,* in press).

We can evaluate the ability of unconsolidated (semiliquid to soft) recent mud to slumping based on the gravitation shear resistance determined as

$$\tau_g = \rho' g h \sin\alpha,$$

where ρ' is sediment density in water; g is acceleration of gravity; h is depth BSF; and α is bottom slope angle. Quantitative estimates show that, for actual values of the parameters (h = 0.05–075 m; ρ' = 0.12–0.28 g/cm^3; and α = 8–12°), the lower and upper limits of gravitation shear resistance are 0.01 kPa and 0.4 kPa, respectively, i.e., practically equal to shear strength of these sediments (0.02–0.6 kPa) according to (Polyakov, 1997). Therefore, recent sediments on the upper continental slope would slump by their dead weight without any external impact. As a result, many cores from the continental slope manifest characteristic slump deformations in sediments. This process, presumably, functions continuously starting with the formation of the slope and is driven by sediment supply from the shelf.

A slump starts to move if the gravitation stability of the slope is disturbed owing either to sediment accumulation exceeding the critical mass or to seismic impacts, which often occur in the seismically active Caucasian continental margin. The sediment mass loading strongly increases during earthquakes. Seismic impulses of an earthquake destroy internal bonds within sediments, resulting in the appearance of a fluidized layer, in which the plastic strength of sediments (τ) is many times lower. In other favorable conditions, this layer may serve as a slipping surface.

However, it should be considered that seismic patterns fail to provide any evidence of such a surface beneath the slump described here. Along with other reasons noted above, this suggests an alternative hypothesis explaining the origin of the positive morphostructure described above. The positive topographic feature possibly represents a remnant rise between tributaries of the submarine erosion valley rather than a slump. Its young sediment cover might be deformed by slumping similarly as on the adjacent upper continental slope. Further investigations must elucidate which of the suggested hypotheses is true.

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