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SPECIFIC FEATURES OF THE UPPER SEDIMENTARY COVER AND SLUMP STRUCTURES IN THE NW PACIFIC AND THE BERING SEA BASED ON SEISMOACOUSTIC PROFILING DATA

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The authors studied geology-geophysical data that had been obtained during German RV «Sonne» Cruise in NW Pacific organized in frames of the Russian-German Project KALMAR («Kurile-Kamchatka and Aleutian Marginal sea-island arc systems: geodynamic and climate interaction in space and time»). The profiling was carried out using PARASOUND P70 system, including narrow-beam system and sub-bottom profiler. The study showed that besides undisturbed sedimentation, landside processes are widely spread in open areas of the ocean and the Bering Sea as well as deposits caused by strong submarine currents. Landslides were revealed on the slopes of the Emperor Ridge in the NW Pacific and the Shirshov Ridge submarine mountains, in canyons near Eastern Kamchatka coasts and apparently in many other areas.

Keywords: North-Western Pacific, sedimentary cover, seismoacoustic profiling, landslides.

INTRODUCTION

Geology-geophysical data on the structure of upper sedimentary cover (to a depth of 100 m) that had been obtained during two German RV “Sonne” cruises in NW Pacific organized in frames of Russian-German Project KALMAR (“Kurile-Kamchatka and Aleutian Marginal sea-island arc systems: geodynamic and climate interaction in space and time”) are presented below. We used mainly acoustic profiling data obtained in these cruises; multi-channel seismic profiling records were analyzed for interpretation of separate geologic bodies (Kurile-Kamchatka ..., Leg 1a. 2009¹, Kurile-Kamchatka..., Leg 2. 2009²).

The profiling was carried out with PARASOUND P70 system (Atlas Hydrographic, Bremen), including narrow-beam system (NBS, 20 kHz) for bottom relief study and sub-bottom profiler (SBP, 4 kHz) for

investigation of sub-bottom sediments. Penetration depth reached 200 m (266 ms). Basing on these data specific features of upper sedimentary cover structure were studied in the following areas: Kamchatka Peninsula continental slope, bottom of Komandorskaya Basin in the Bering Sea, Shirshov Ridge, Obruchev Rise, the Emperor Seamounts and Emperor Trough (Fig. 1). The survey carried out using the system PARASOUND P70 in RV “Sonne” cruises showed acoustic complexes with chaotic structure in many areas or the sea floor. On some of the profiles landslide complexes were revealed, that implies development of landslide processes in the studied areas.

It was shown in (Cannals et al., 2004) that main factors that could lead to landsliding are: high sedimentation rates, broken bottom relief, active tectonics, seismic and volcanic activity, presence of gases in sediments and diagenetic fronts. The landslides may cause tsunami waves that constitute a real danger for population and coastal infrastructural objects (Baranov et al., 2013). The areas considered in present work are affected by listed factors and thus investigation of upper sedimentary cover here is a matter of both research interest and practical importance.

¹ Kurile-Kamchatka and Aleutian Marginal Sea — Island Arc Systems: Geodynamic and Climate Interaction. Cruise Report Nr 32, Sonne Cruise SO-201, Leg 1a. 2009. 105 p.

² Kurile-Kamchatka and Aleutian Marginal Sea — Island Arc Systems: Geodynamic and Climate Interaction. FS Sonne Cruise Report SO 201-KALMAR Leg 2. 2009. 125 p.

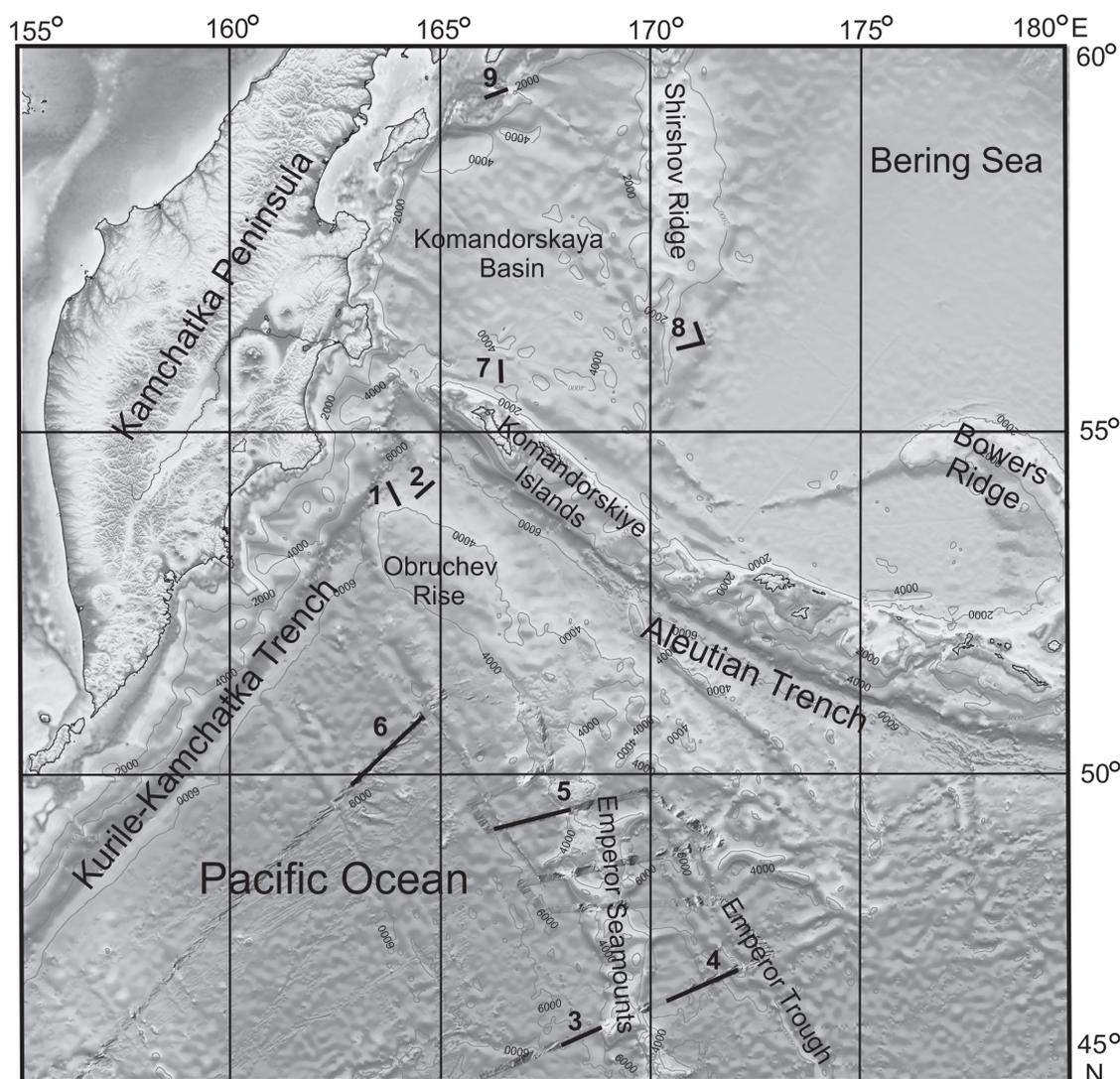


Fig.1. Map of North-Western Pacific and Western Bering Sea, SRTM30PLUS data, Mercator projection, contour interval 1000 m (Kurile-Kamchatka ..., Leg 1a. 2009).

DESCRIPTION OF SEISMOACOUSTIC PROFILES

Seismoacoustic survey of RV «Sonne» provided big amount of data on upper sedimentary cover in the NW Pacific and Komandorskaya Basin of the Bering Sea. Primary records were processed by Reinhardt Lutz from Federal Institute for Geosciences and Natural Resources (BGR, Hannover) using REFLEX W Software (Kurile-Kamchatka ..., Leg 1a. 2009¹, Leg 2. 2009²).

Obruchev Rise, Emperor Seamounts and Emperor Trough. Upper sedimentary cover of the Obruchev Rise was studied on base of several profiles (Fig. 1): in the upper part of north-western rise slope, in the central part and on north-eastern slope towards Aleutian Trench (Fig. 2). On the first profile bottom surface ascends from depth of 4850 m up to depth of 4450 m (Fig. 2a). Observed thickness of the sediments on the profile is 30–35 m. Bottom relief is slightly wavy. Visible part of the sedimentary cover is characterized

by distinct parallel reflectors extended along the strike. In most cases they are conformal to bottom surface and may be traced along the whole profile. Stratified character of sediments is conditioned by alternation of thin acoustically inhomogeneous layers with thickness of 1–2 m. Sedimentary cover on steeper parts of the slope is disturbed by normal faults with displacement amplitude up to 1–3 m (Fig. 2a).

On the profile's fragment located on north-eastern slope of the rise towards the Aleutian Trench (Fig. 2b) the observed thickness of sediments is 35–45 m. The depth on this portion changes from 5000 m to 5400 m. Visible part of the sedimentary cover contains distinct parallel reflectors only within depth interval 5050–5058 m having minimum slope angle. Within the other parts of the slope where slope angle is about 4–6° distinct stratification disappears; it appears in deposits again in depth interval 5220–5300 m. Sedimentary complexes composing upper part of the Obruchev Rise sedimentary cover accumulated in pelagic depositional conditions. Absence of sediments

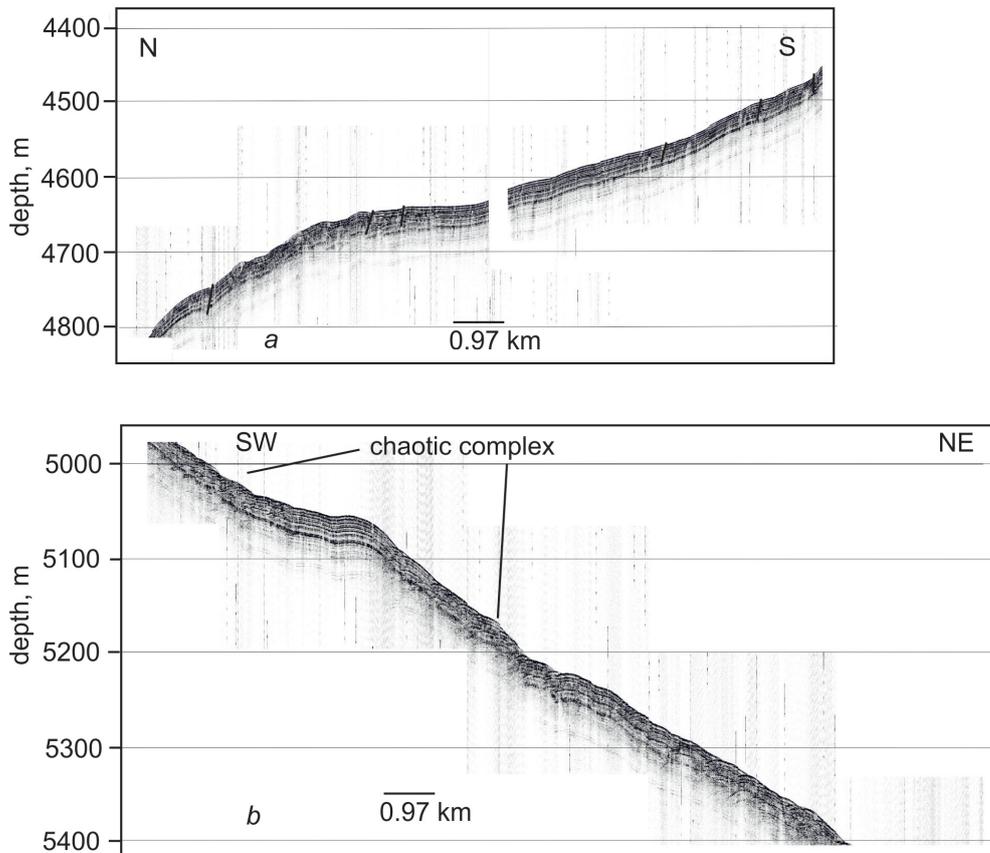


Fig. 2. Fragments of acoustic profiles on the Obruchevev Rise: *a* — western slope, *b* — north-eastern slope (indicated on Fig. 1 by characters 1 and 2, correspondingly). Supposed faults on profile (*a*) are shown by black lines.

stratification on separate fragments of the profiles is apparently conditioned by deformation of deposits on the rise slopes caused by gravitational processes.

Profile BGR09-101 (Kurile-Kamchatka ..., Leg 1a. 20091) (Fig. 1, profiles 3, 4) characterizes the structure of upper sedimentary cover of the oceanic plate in front of Emperor Seamounts (Fig. 3*a*) and to the north-east from them towards the Emperor Trough (Fig. 3*b*). On the profile (Fig. 3*a*) depth to the bottom ascends from 8130 s to 8260 s (thickness on reflection profiles is given in TWT seconds). Sedimentary cover is represented by thin-layered sedimentary unit with visible thickness of about 120 m. This unit is composed by deposits with thin (3–5 m) alternation of acoustically heterogeneous layers that are traced on long distances parallel to the bottom surface (Fig. 3*a*).

To the north-east from Emperor Seamounts towards Emperor Trough (Fig. 3*b*) dissected bottom relief is observed. The depth to the bottom reaches maximum value (8300 s) to the north-east from the Emperor Seamounts; in the Emperor Trough the depth is 8200 s. On the flanks of the Emperor Trough bottom surface rises up to 7450 s. Maximum visible thickness of sediments is observed in the depression in the north-eastern part of the profile

and exceeds 120 m. Sedimentary cover according to multi-channel seismic profiling data reaches 1 s and reduces to 0.5 s on the uplifts (Kurile-Kamchatka ..., Leg 1a. 20091). Tree complexes may be distinguished here according to the acoustic characteristics of the sedimentary cover deposits. They have different internal structure and either alternate in the section or substitute each other along the strike. The first complex includes sedimentary bodies with length from several kilometers to several tens of kilometers and observed thickness from 10 to 40 m. They are formed by acoustically transparent unstratified complexes. As a rule these sedimentary bodies are observed in depressions of the relief (Fig. 3*b*). Such structure is most likely conditioned by disintegration and mixing of sedimentary material. The second complex is formed by deposits with observed thickness varying from 10 to 60 m; on echograms they have distinct stratification. In deposits of the third complex stratified structure is poorly defined or absent. They are developed on the slopes of bottom relief rises and have thickness of about 10 m. Forming of the first complex is apparently conditioned by submarine currents, debris flows and mass wasting processes. It is clearly seen on a profile from the south-western rise between

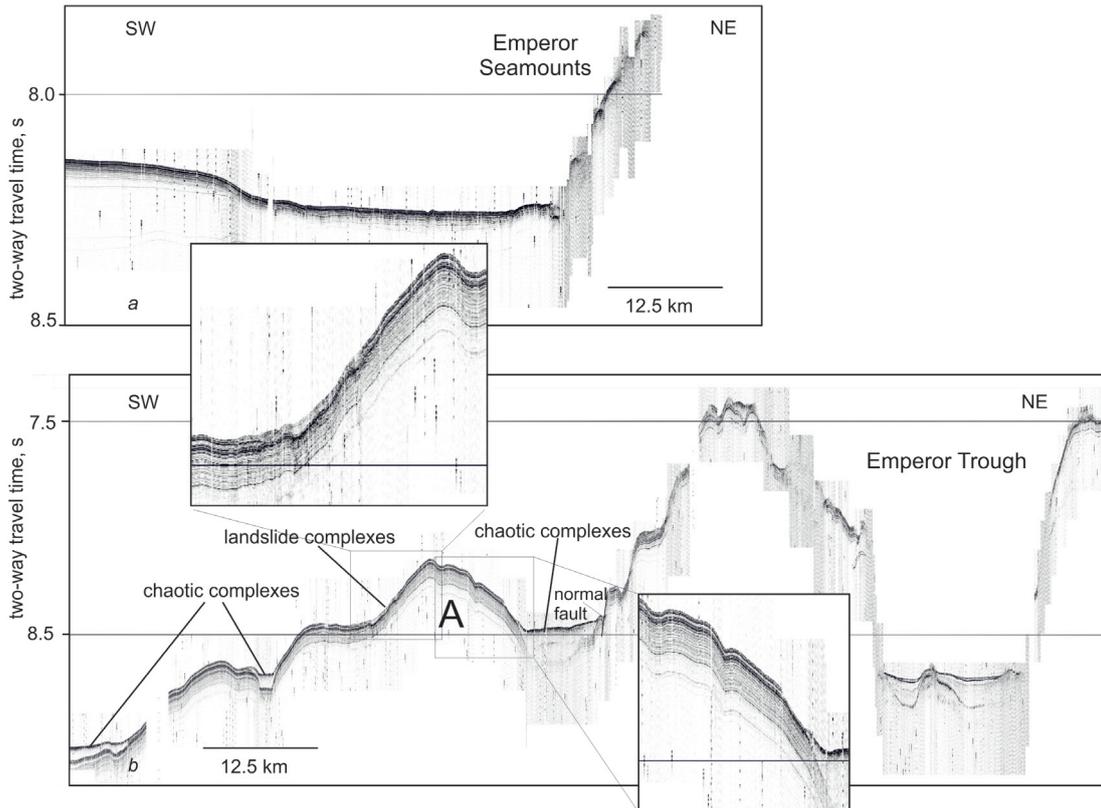


Fig. 3. Fragments of profile BGR09_101: *a* — to the south-west from the Emperor Seamount Chain, *b* — across Emperor Trough (indicated on Fig. 1 by characters 3 and 4, correspondingly). Insets show extended parts of profile (b).

the Emperor Seamounts and the flank of Emperor Trough (Fig. 3*b*, rise “A”). On this profile the upper 10-meter well-stratified sedimentary unit abruptly ends, formations of the first complex are traced throughout 2 km and sedimentary lens composed by acoustically transparent unstratified deposits is observed downward the slope. The lower boundary of this sedimentary body runs along 3–5-meter interlayer; below it the deposits have distinct stratification (Fig. 3*b*). An “erosion window” is observed on the north-eastern slope of this rise at the same depth (7.9 s). Upper 10-meter layer with stratification abruptly terminates here and sedimentary lens composed by acoustically transparent unstratified complexes forms near the slope foot. It can be supposed that such peculiarities of uppermost sedimentary cover structure are resulting from slumping of unconsolidated deposits. A normal fault is observed in the lower part of the south-western slope of the south-western Emperor Trough’s flank (Fig. 3*b*). Here the thin-layered sedimentary unit with thickness of about 60 m is dislocated on nearly 80–85 m.

Sedimentary complex with stratified structure and thickness of about 270 m overlying Emperor Seamounts slope is observed on seismic profile BGR09-107 (Kurile-Kamchatka ..., Leg 1a, 2009¹), on the south-western slope of the seamounts. North-eastern limitation of this complex is distinctly manifested in the relief and has V-shaped form

(Fig. 4*a*). It may be supposed that this negative relief form has erosion nature conditioned by near-bottom current. From the south-west the complex is limited by a scarp with amplitude of about 180 m. Below the scarp the seismic record changes and reflectors become more deformed. One can clearly see it on profiler record (Fig. 4*b*). Downwards the slope this sedimentary thickness continues up to more gently sloping scarp exposed to the north-east. To the south-east from this scarp sediments again become less deformed.

The sedimentary body has deformed structure and is well-manifested in the bottom relief (Figs. 4*a*, 4*c*). A winding-shaped scarp serves as the north-eastern limitation of the body (Fig. 4*c*). Sedimentary bodies with similar seismoacoustic properties and manifestation in the relief usually are interpreted as submarine landslides (Ormen ..., 2005; Submarine ..., 2012; Cannals et al., 2004).

Bottom relief on the fragment of BGR09_m03 profile crossing the Pacific Plate southward of the Obruchev Rise (Kurile-Kamchatka ..., Leg 2, 2009²) represents relatively flat surface with separate uplifts up to 1 s (Fig. 5). Observed thickness of the sedimentary cover exceeds 100 m; it is characterized by development of acoustic complexes typical for pelagic and hemipelagic deposition (well-expressed stratification, extension of the interlayers on big distances, absence of deformations).

SPECIFIC FEATURES

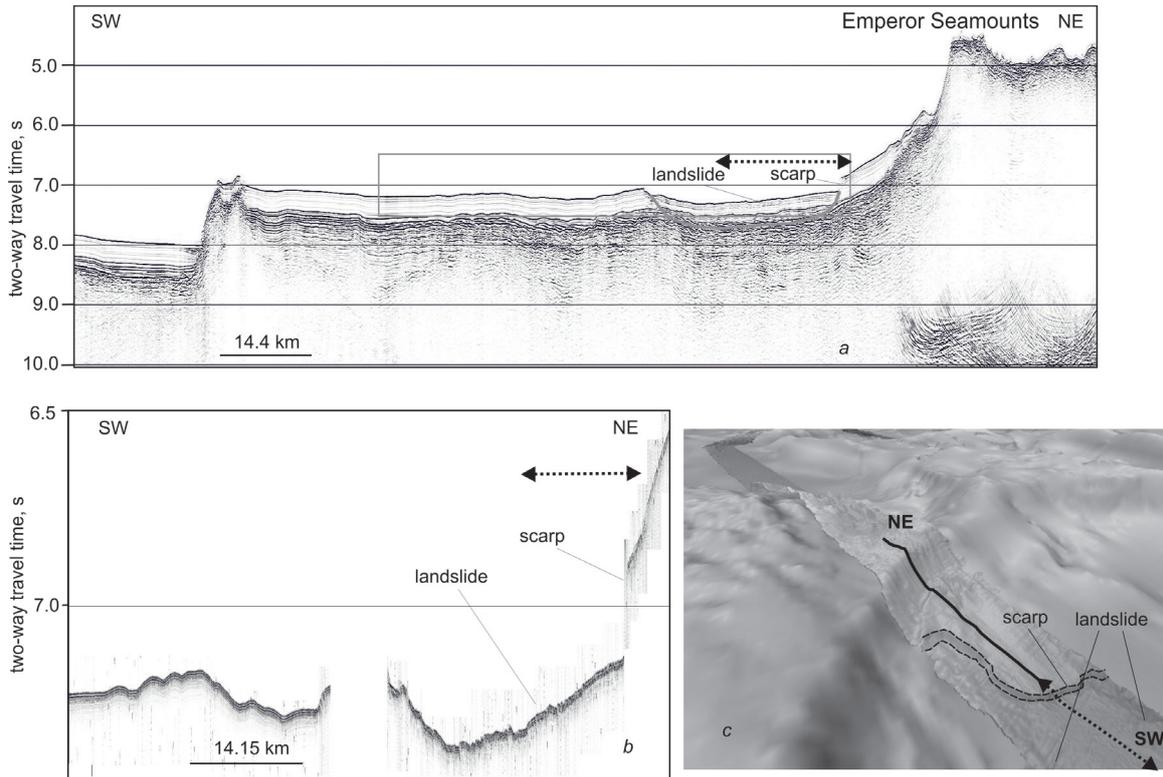


Fig. 4. Fragments of profile BGR09_107 (indicated on Fig. 1 by character 5): *a* — seismic, *b* — acoustic (western slope of the Emperor Seamount Chain), *c* — 3D-view of the western slope of the seamount and the supposed landslide (Kurile-Kamchatka and Aleutian ..., Leg 1a). Rectangular on the seismic profile (*a*) shows location of acoustic profile (*b*). Grey line marks bottom of supposed landslide body. Line on 3D image (*c*) marks location of fragments of profiles *a* and *b*; dotted line with arrows shows a portion, correspondingly marked on profiles *a* and *b*. Dotted lines on 3D image show top and base of the scarp.

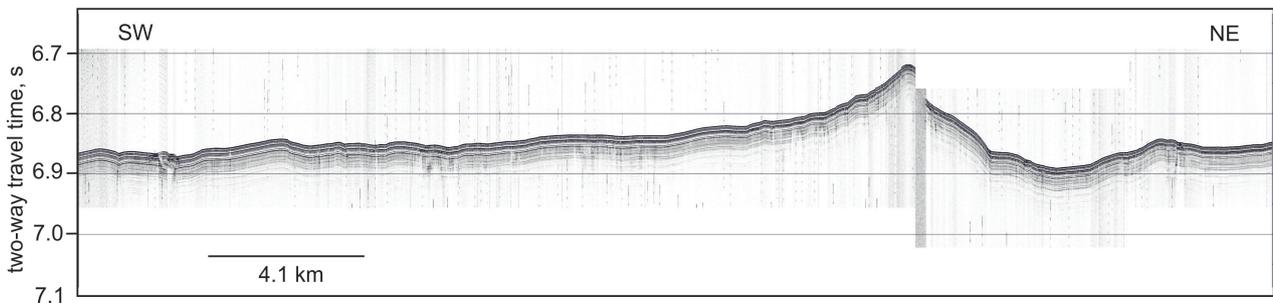


Fig. 5. Fragment of acoustic profile BGR09_m03 on the Pacific Plate (indicated on Fig. 1 by character 6).

The Bering Sea. High-quality acoustic records were obtained in the Komandorskaya Basin of the Bering Sea. Profile fragment on Fig. 6 demonstrates the structure of sedimentary sequence in the southern part of the Komandorskaya Basin. Observed thickness of sedimentary cover on the profile exceeds 60 m. Depth to the bottom varies in the interval of 5050–5150 m. Sedimentary cover is characterized by distinct parallel thin reflectors traceable over big distances. At the same time some changes in sedimentary cover structure are observed along the profile. On its northern intersect an acoustically transparent horizon with thickness of about 5–7 m is traced in the upper part of the section; it decreases in thickness and pinches out in southern

direction. Below this horizon well-stratified sequence with thickness of about 25 m is observed. Under it there is an acoustically transparent layer (7–10 m) that also pinches out in direction to the slope break and bottom relief subsidence. Lens-shaped interlayer of acoustically transparent sediments appears here in the stratified unit. In the basin the character of sedimentary cover structure changes after slope becomes on 50 m deeper. Lens-shaped layer with thickness of 21 m bended in the central part and composed by acoustically transparent deposits is observed in the upper section. Below this lens sedimentary sequence has well-manifested thin stratification. Basing on the character of acoustic record we can suppose that the sedimentary section is

formed by pelagic and hemipelagic deposits and that lens-shaped bodies appearing in its southern part are formed by deposits of submarine currents.

Fragment of the profile in south-eastern part of the Shirshov Ridge with length of 12.5 km characterizes the eastern ridge slope where the bottom depth varies from 2750 to 3132 m (Fig. 1, 7a, 7b). Observed thickness of upper sedimentary cover is about 80 m. It is represented by two sedimentary complexes. Upper part with thickness of about 50 m is characterized by absence of stratification and is formed by structureless (chaotic) acoustically transparent unit. In the lower part of the profile this unit changes for indistinctly-stratified unit where separate reflectors can be detected. The second complex occurs below the upper unit and demonstrates signs of stratification. Apparently the upper complex may be regarded as a landslide body.

On Fig. 7b one can see substitution of well-stratified heavy unit by structureless complex. A scarp apparently corresponding to normal fault is clearly seen on the profile. Observed thickness of sedimentary cover here is about 140 m and is represented by well-stratified unit of deposits. The profile is oriented in the north-western direction. Stratified unit stretches on 6 km and chaotic unit has extension 3.7 km.

Investigation of sedimentary cover on the north-western slope of Komandorsakaya Basin has shown that its upper part (with thickness 68–80 m) is represented on the echogram by indistinctly-stratified unit; thickness of interlayers in it changes along the strike. Interlayers with thickness from 3–5 m to 10–15 m are divided by separate distinct reflectors (Fig. 8). Internal structure of the interlayers is characterized by lens-like structure and absence of stratification.

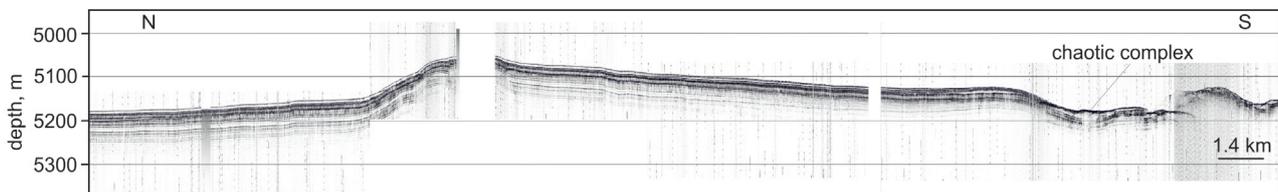


Fig. 6. Fragment of acoustic profile in Komandorskaya Basin of the Bering Sea (indicated on Fig. 1 by character 7).

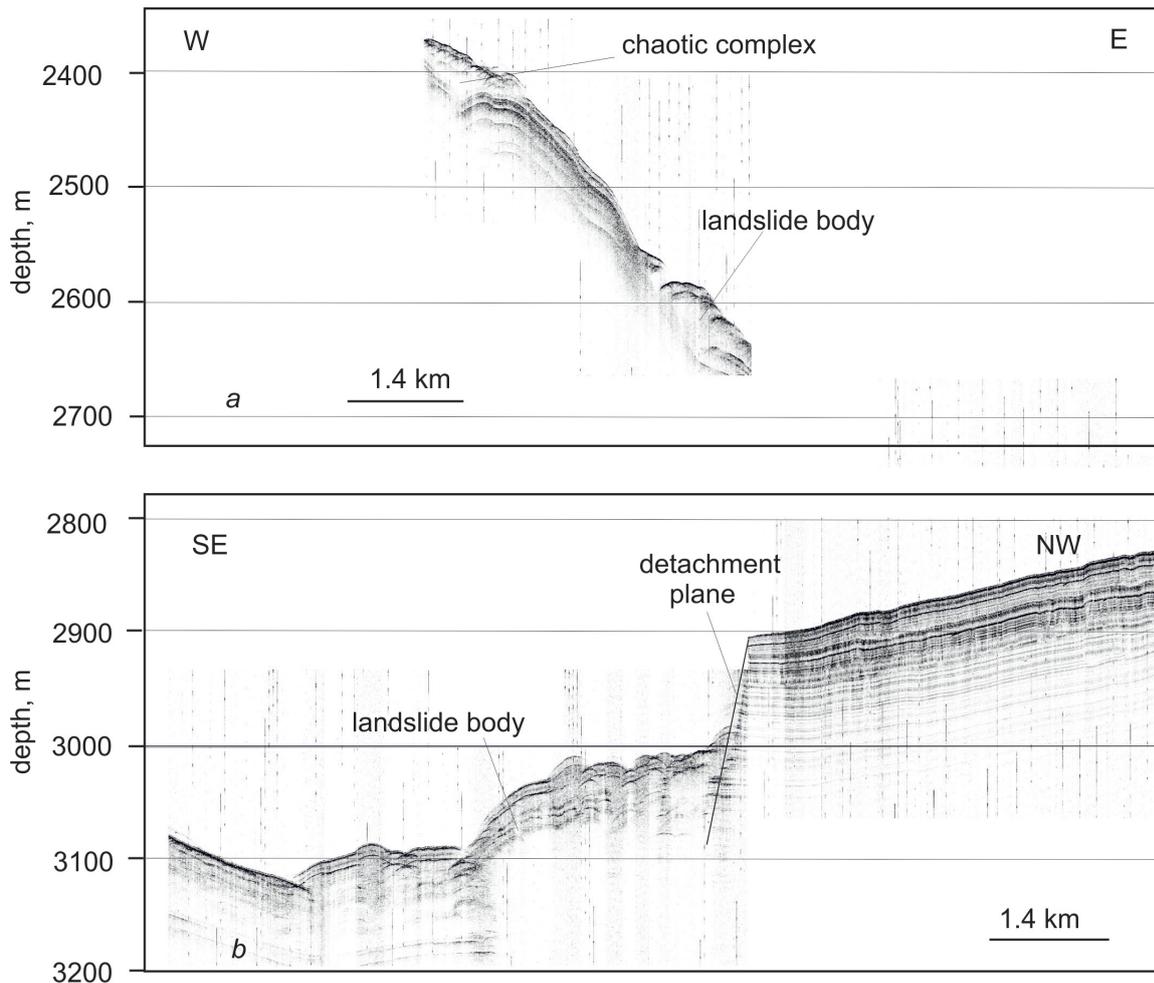


Fig. 7. Fragments of acoustic profiles on the Shirshov Ridge eastern slope: a — latitudinal, b — submeridional (indicated on Fig. 1 by character 8).

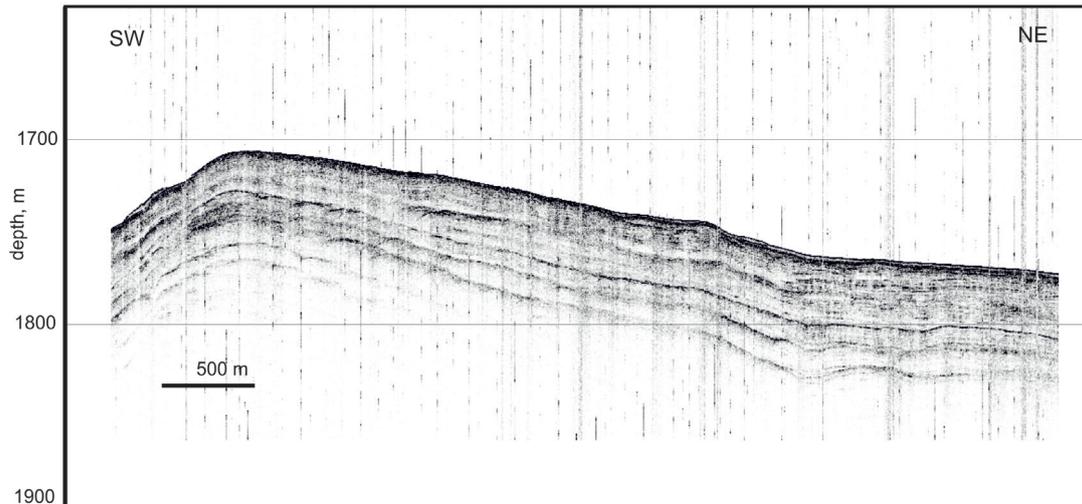


Fig. 8. Fragment of acoustic profile on north-western slope of the Komandorskaya Basin of the Bering Sea (indicated on Fig. 1 by character 9).

The sedimentary cover structure can be observed on profile intersects from the continental slope areas with minimum inclination angle; it seems impossible to decrypt the slope structure on profile fragments from steeper parts of the slope.

DISCUSSION

Our research was devoted to upper (100 m) sedimentary structure (Kurile-Kamchatka ..., Leg 1a. 20091). Presented above description of profiles obtained within different continental slope segments, Obruchev Rise and Pacific Plate show that structure and thicknesses of sedimentary cover are dramatically diverse within different parts of the study area.

Continental slope is characterized by dominating of acoustic complexes including interlayers of relatively coarse psammitic and psephitic sediments, turbidites and slope debris flow deposits; it is supported by data on composition of sedimentary rocks obtained by corer sampling (Kurile-Kamchatka ..., Leg 2. 20092).

Sedimentary cover of the Pacific Plate to the south from the Obruchev Rise, within the Obruchev Rise and the Komandorskaya Basin was formed in pelagic and hemipelagic conditions by well-stratified depositions. Alternation of thin interlayers (3–5 m) with different acoustic characteristics is observed in these depositions.

The structure of sedimentary cover on slopes of the Emperor Seamounts, on flatland between the Emperor Seamounts and the Emperor Through and inside the Emperor Through includes lens-like sedimentary bodies with lengths from several kilometers to several tens of kilometers. They are formed by acoustically transparent unstratified rocks. Usually such deposits are developed in the topographic lows. Observed thickness of the bodies varies from 10 to 40 m. Geometry and internal structure of these sedimentary bodies as well as relatively flat bottom

relief lead to a supposition that they were formed by submarine currents and flows and their internal structure is conditioned by disintegration and mixing of sedimentary material during its transportation.

Intensive reflectors pointing on absence of sedimentary cover or development of coarse igneous rocks are observed on the slope and peak planes of the Emperor Seamounts. Pelagic and hemipelagic sediments occur in the Emperor Trough (Kurile-Kamchatka ..., Leg 1. 20091) along with depositions of submarine flows; the last alternate with pelagic sediments and overlap them. Folds, low-amplitude normal faults, reverse faults and thrusts can be seen on some profiles in the upper sedimentary cover. Relatively large-scale dislocations occur on rare occasions; apparently they are conditioned by gravity processes and associated with origination of landslide bodies or recent movements along old faults (Freitag et al., 2011). Sedimentary bodies that may be interpreted as slump structures were revealed on several acoustic profiling records.

Main properties, triggering mechanisms and tsunami potential of submarine landslides as well as their interrelation with other geological processes are presently an object of prime interest (Ormen ..., 2005; Submarine ..., 2012; Tappin, 2010). Nevertheless not so much information on submarine landslides in NW Pacific and the Bering Sea is available nowadays.

The environments where the submarine landslides are most probable are: the open continental slopes, submarine canyon-fan systems, fjords, active river deltas, oceanic volcanic islands and seamounts, convergent and transform margins (Cannals et al., 2004). Failure of volcanic islands and avalanches in narrow fjords are most dangerous due to their high tsunami potential (Lobkovsky et al, 2013). Detailed review of Pacific submarine landslides and environments of their occurrence can be found for instance in the work (Lee, 2005). Within the

area of present study the submarine landslides had been found earlier in the canyons near eastern coasts of the Kamchatka Peninsula. The submarine canyons represent the ways of terrigenous material transportation and are most widely developed on the Eastern Kamchatka slope. Landslide bodies with volume up to tens of cubic meters and length up to 10–20 km were revealed in this environment. (Yegorov, 2001; Kornev et al., 1981; Lomtev et al., 1980³; Seliverstov et al., 1980; Seliverstov, 2013). As an example, the southern part of Kamchatsky Canyon is separated from the main bed by huge slump with volume over 5 km³, which formed a kind of dam (Kornev et al., 1981). Detailed description of submarine landslides revealed on the submarine Kamchatka margin especially on the upper continental slope, Kamchatsky and Avachinsky canyons, including one potentially tsunamigenic slide, is presented in the work (Lomtev, 2017).

Submarine landslides formed in the environment of submarine canyons were also revealed in the Bering Sea (Carlson, Karl, 1988). In the work (Belous, Svarichevsky, 2007) devoted to the Bering Sea bottom morphology an overview of domestic investigations in this region is presented. In the paper landslides development areas are defined and landslide bodies are allocated mainly on the north-eastern Aleutian Basin slope. Landslide complexes are also observed on several seismic reflection profiles obtained on the Shirshov Ridge (Seliverstov, 2013).

Submarine landslides formed in convergent margins environment within the Aleutian Island Arc area are described in (McAdoo et al., 2000). Large-scale debris avalanches were found on the Hawaii Islands in the volcanic islands environment; giant Nuuuanu submarine landslide occupying an area of 5000 km² occurred here (Lobkovsky et al., 2013, Baranov et al., 2018). Within the area of the Hawaiian Ridge and Emperor Seamounts about 70 large-scale landslides were discovered; some of them reached 200 km in length and had volumes up to 5000 km³ (McMurty et al., 2004; Moore et al., 1989).

Seismoacoustic survey carried out in the NW Pacific in frames of the Russian-German KALMAR Project from board of German RV “Sonne” in 2009 allowed us to find a number of landslide bodies on the slopes of the Emperor Seamounts and Shirshov Ridge in the Bering Sea (Kurile-Kamchatka ..., Leg 1a. 2009). In particular, the upper structure of a landslide body on the south-western Emperor Seamounts slope (Fig. 4) was studied. Multi-channel seismic profiling data allowed us to suppose that volume of dislocated

material may reach here tens of cubic meters. Slide bodies within the Shirshov Ridge are smaller, but supposedly are more frequent. Thickness of the bodies does not exceed 35–40 m and they overlap undisturbed parts of the sedimentary cover sections. Such slump complexes are characterized by chaotic internal structure and presence of low-amplitude (less than several meters) normal faults, thrusts and folded deformations. Besides, bottom above them in most cases has irregular wavy relief. Similar bodies were revealed on the Obruchev Rise slope facing the Aleutian Trench.

It is known that the largest landslides occur in submarine conditions and underwater sliding takes place even at rather small slope angles. Submarine mountains and systems of submarine canyons represent the environments of most probable landslides origination (Lobkovsky et al., 2013, Baranov et al., 2018). Landslide bodies revealed by presented here seismoacoustic investigations are located on the slopes of the Emperor Seamounts, Obruchev Rise and Shirshov Ridge. It may be supposed that steep slopes (more than 6°) and high seismic and volcanic activity are among the factors responsible for their origin. Continuation of upper sedimentary cover investigations in these regions obviously will give evidence for discovering and mapping of many other landslide bodies and slope collapse areas. As far as submarine landslides and associated with them tsunamis relate to the most dangerous natural hazards, such researches represent vital scientific and applicative interest.

CONCLUSIONS

The presented study showed that besides undisturbed (pelagic and hemipelagic) sedimentation, landside processes are widely spread in open areas of the Pacific Ocean and the Bering Sea as well as deposits caused by strong submarine currents. Landslides were revealed on the slopes of the Emperor Ridge in the NW Pacific and the Shirshov Ridge submarine mountains, in canyons near Eastern Kamchatka coasts and apparently in many other areas located in corresponding environments. As far as submarine landslides and associated with them tsunamis relate to the most dangerous natural hazards, the research community should pay close attention to such investigations.

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