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Seismic stratigraphy and sedimentary processes on the Kurile Basin northern slope (Okhotsk Sea)

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Abstract

The Kurile Basin in the Okhotsk Sea, northwestern Pacific, is a back-arc basin located west of the Kurile Island Arc. Cenozoic sedimentation on the Kurile Basin northern slope and on the Academy of Science Rise was studied using 2420 km of high-resolution air gun profiles. Late Oligocene–Quaternary sedimentary history of the northern slope and of the Academy of Science Rise includes three major phases. They are characterized by (1) mass wasting during the rift stage of the Kurile Basin, in Late Oligocene–Middle Miocene; (2) bottom current-controlled sedimentation, which led to widespread occurrence of contourite deposits during the second phase in Early Pliocene–Pleistocene; (3) turbidite and hemipelagic sedimentation on the upper slope and drift sedimentation on the Academy of Science Rise during the third phase in Pleistocene–Holocene. Downslope processes predominate on the lower slope. They include large-scale slumping and sliding of sediments. Mass wasting events are possibly triggered by earthquakes or/and gas hydrate decomposition during sea-level lowstands.

Keywords: Okhotsk Sea; Kurile Basin; contourite drift; mass wasting

1. Introduction

The Okhotsk Sea is a large marginal sea at the northwestern rim of the Pacific and its southern part consists of the Kurile Basin. The Kurile Basin represents a back-arc basin located behind the Kurile Island Arc. It has a triangular shape and strikes in the NE–SW direction. This triangular outline is defined by Sakhalin–Hokkaido Islands to the west, the Academy of Sciences Rise to the north and the Kurile Island Arc to the southeast (Fig. 1).

It is suggested that the Kurile Basin was originated from back-arc spreading and several models for its evolution have been proposed recently (Savostin et al., 1983; Niitsuma and Akiba, 1985; Kimura and Tamaki, 1986; Jolivet, 1987; Maeda, 1990). However, the age of the basin is poorly constrained because its basement has not been drilled and its magnetic anomalies are poorly delineated. It is little known about its stratigraphy as well, although a number of single and multichannel seismic reflection profiles have been obtained. This is also true for the Kurile Basin northern slope bounded by the Academy of Sciences Rise, where the sedimentary stratigraphy is practically unknown.

In this paper, we report on new data obtained within the framework of the German–Russian cooperative Project KOMEX I (Kurile–Okhotsk Marine EXperiment)

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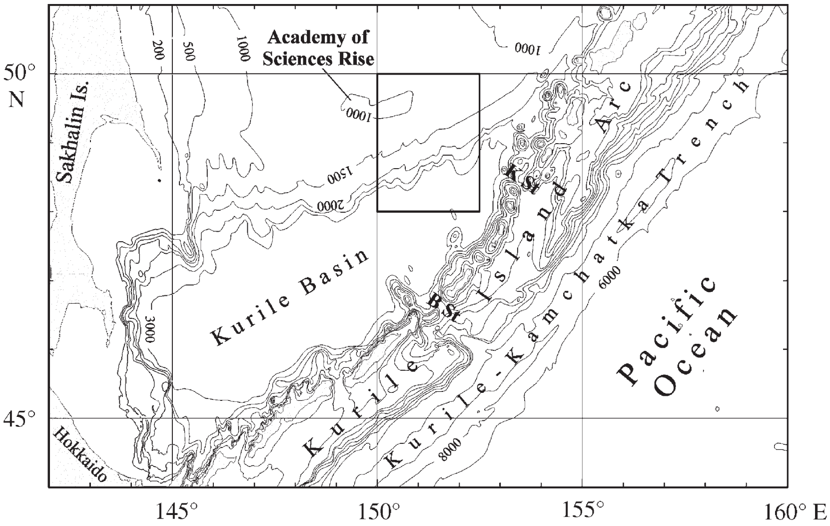


Fig. 1. Bathymetry of the Kurile Basin and location of the study area (rectangle). B St = Bussol Strait, K St = Kruzenshterna Strait. Contours in meters.

and discuss the seismic stratigraphy framework of the Kurile Basin northern slope and controlling factors of sedimentation on its northern slope and on the Academy of Sciences Rise.

2. Tectonic and geological background

The Kurile Basin is about 200 km wide at its southwest end and narrows towards the Kamchatka. The nearly horizontal floor of the Kurile Basin lies mainly a depth of 3200–3300 m. Seismic refraction study (Galperin and Kosminskaya, 1964; Bikkenina et al., 1987) indicates that the Kurile Basin is underlain by oceanic crust, the top of which is 7–8 km deep, and it contains 4 to 5 km of undeformed sedimentary fill. Data on crustal structure in the northeastern part of the basin are absent; recently an existence of thinned continental crust has been shown by geochemistry of the volcanic rocks dredged from the Geophysicist seamount (Tararin et al., 2003).

The northern slope of the Kurile Basin ascends to the Academy of Sciences Rise (ASR), the top of which is located at water depths of about 1000 m, elevated 2300 m above the abyssal plain of the Kurile Basin (Fig. 1). The rise forms an E–W-trending structure with a flat top. The length of the rise is about 400 km. The flat summit of the Academy of Sciences Rise is interpreted as an erosional surface formed when the upper parts of the rise were near the sea level. This feature suggests that the tectonic subsidence of the rise occurred in association with the subsidence of the central part of the Okhotsk Sea to about 1000 m (Gnibidenko and Svarichevsky, 1984).

The Academy of Sciences Rise is draped by sediments with thickness of 0.2 to 2.0 km (Tuezov, 1979; Belousov and Udintsev, 1981). Therefore, the morphology of the northern slope is very smooth because the sedimentary cover masks the rugged basement relief. Only on the lower slope have canyons, slumps, slides and basement outcrops been observed (Gnibidenko et al., 1995).

Dredge data show that the basement of both the Academy of Sciences Rise and the northern slope of the Kurile Basin are composed of extrusive, intrusive and metamorphic rocks. The chemical composition of the igneous rocks indicates that they belong to the calc-alkali island arc series. The majority of these rocks dated by the K–Ar method are Cretaceous in age (Gnibidenko et al., 1995). Recently Pliocene–Pleistocene volcanic activity has been found on the Academy of Sciences Rise (Lelikov et al., 2001).

Seismic refraction data show that the northern slope is underlain by stretched continental crust with a thickness of about 20 km. It represents the region of transition to the oceanic crust of the Kurile Basin (with a thickness of about 10 km) (Galperin and Kosminskaya, 1964).

On the northern slope of the Kurile Basin is a system of NE-trending regional faults, which are intersected by NW-striking faults (Tuezov et al., 1978; Gnibidenko et al., 1995; Kharakhinov, 1996). These faults represent the structural pattern at the time of initial lithospheric break-up before the beginning of the spreading process in the Kurile Basin. Recent investigations have shown that NE-trending regional faults represent are strike slips and NW-striking faults are normal ones (Baranov et al., 2002b).

3. Data sets

The new data reported here consist of 2420 line-km of air gun seismic reflection profiles from two cruises: cruise 27 of the R/V *Akademik Lavrentiev* of 1996 (1850 line-km of single-channel digital data), and the cruise 26 of the R/V *Professor Gagarinsky* of 1999 (570 line-km of eight-channel digital data) (insert on Fig. 3). For the former cruise the seismic system used consisted of a single air gun (3.0 l) and single-channel streamer with active length of 100 m. For latter cruise, the seismic system used consisted of an air gun array and eight-channel Geco-Prakla mini-streamer with total active length of 100 m. A mini-GI gun (1.44 l) and standard GI-gun (3.36 l), both configured in the harmonic mode were used. In addition, data from the single channel seismic survey carried out with the R/V *Pegas* (Gnibidenko and Svarichevsky, 1984) have been used. New bathymetric data were also collected with an echo sounder operating at a frequency of 12.4 kHz.

The seismic data have been interpreted according to the concepts of seismic facies analysis and seismic sequence stratigraphy (Mitchum et al., 1977; Van Wagoner et al., 1988; Posamentier and Vail, 1988).

4. Result

4.1. Bathymetry

Echo-sounding and seismic lines obtained during geophysical cruises, were analyzed in the study area. The Academy of Sciences Rise, the Kurile Basin slope and the Kurile Basin (Fig. 2) are prominent bathymetric features of the study area. The Academy of Sciences Rise is a plateau-like structure at a water depth of ca. 1200 m and has a block structure clearly recognizable in the bottom relief. Blocks are separated by narrow troughs with NW and NS trends. The Kurile Basin slope can be divided into an upper slope and a lower slope separated by the slope break that lies at the water depth

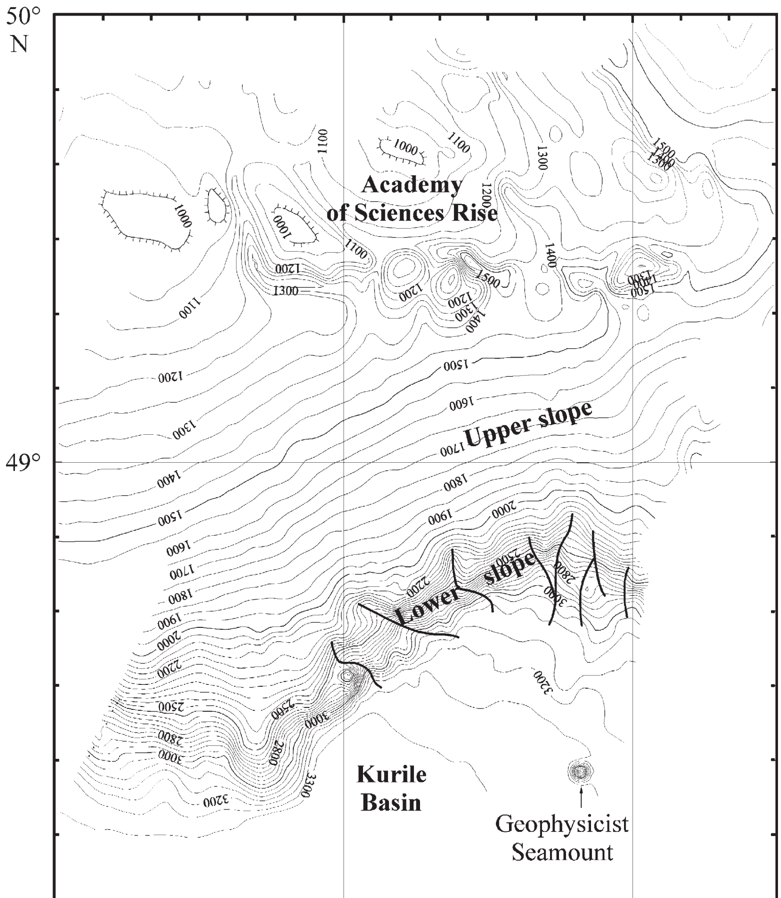


Fig. 2. Bathymetry of the study area. Contours in meters. Heavy lines indicate channels.

of about 2200 m. Seaward of this break, the slope becomes steeper and more complicated. The upper slope strikes NE–SW and has simple relief. The lower slope lies within the depth interval of 2200–3100 m. The most prominent features of the lower slope are channels with a general NW–SE or N–S trend. The Kurile Basin floor within the study area has a water depth of 3100–3300 m, the maximum being 3330 m. The seafloor is smooth and gentle deepens in a SW direction. There is an isolated seamount (Geophysicist seamount) at the southern end of the study area in the Kurile Basin abyssal plain that rises to a depth of 2370 m below sea level. The height of the seamount above seafloor is about 800 m.

4.2. Acoustic basement structure

Acoustic basement is characterized by either an opaque reflection (lack of internal reflectors) or is marked by an envelope of diffraction hyperbolas. The acoustic basement map constructed from seismic data is given in Fig. 3. In general, the seafloor morphology is reflected by the acoustic basement map. The Academy of Sciences Rise, the Kurile Basin slope and the Kurile Basin proper are recognizable in the acoustic basement relief. The basement is characterized by a complex series of elongated ridges, troughs, and domes. The Academy of Sciences Rise has a block structure. The blocks are tilted, their steeper sides are represented by normal fault scarps. These scarps strike generally N15–300 W. The scarps form half-grabens and show an en-echelon pattern. The blocks are separated by several narrow troughs with N–S and NW–SE strike. The upper Kurile Basin slope comprises several small basement ridges and depressions. The ridges generally trend northeast–southwest. The basement depressions are generally obliquely to the trend of the slope. The transition between the upper and the lower Kurile basin slope is marked by a narrow basement ridge, termed the "outer ridge." Some blocks constituents of the outer ridge are tilted and are bounded by near-vertical faults. The outer ridge strikes in the west–southwest direction parallel to general slope trend and is interpreted as a

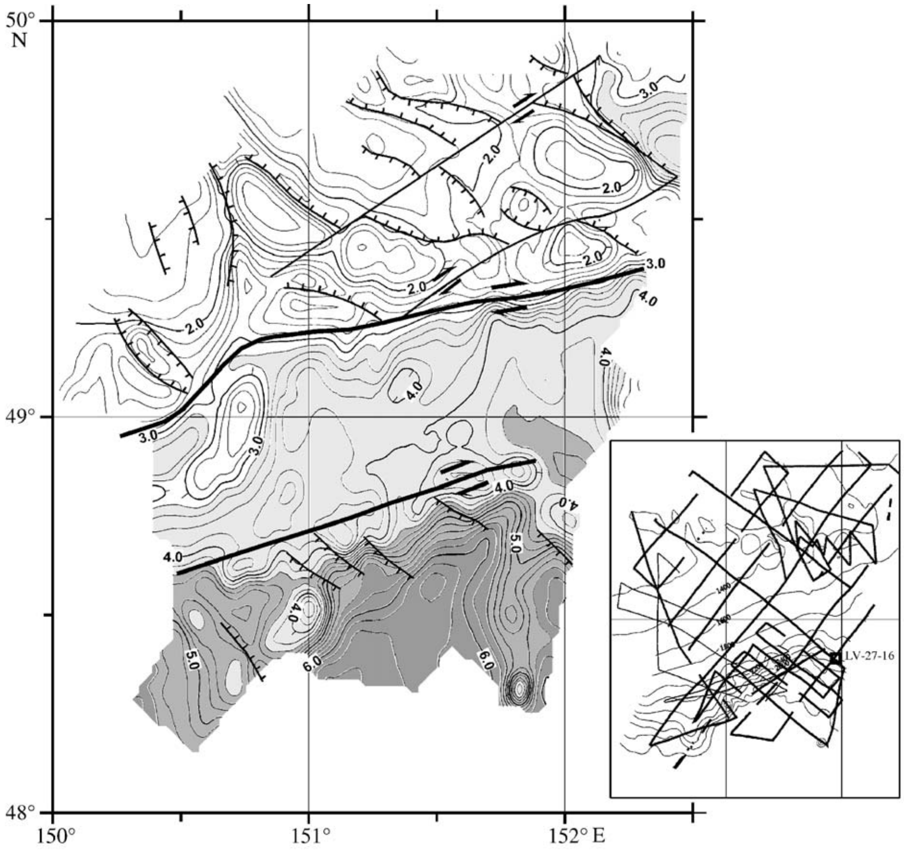


Fig. 3. Map of basement depth below sea level (TWT in s) and main tectonic features of the study area; contour interval is 0.2 s (TWT). Thick lines with arrows indicate master faults (suggested dextral strike-slips). Minor strike-slips are shown by thin line with arrows. Barbed lines mark scarps of normal faults. Inset shows survey tracks of KOMEX expeditions and *Pegas* cruise. Small rectangle is dredge station.

fault (Fig. 3). The basement of the lower Kurile Basin slope is comprised of complex blocks. The blocks are generally tilted; their steeper sides correspond to normal faults with a northerly to northwesterly strike at the angles of 50–70° to the northeasterly strike of slope. However, in comparison of the Academy of Sciences Rise, these blocks are smaller and less pronounced. The basement depression, which corresponds to the Kurile Basin proper deepens in a southwesterly direction towards the basin center. The basement depth exceeds 6.0 s (TWT). There is a narrow basement ridge with SW strike within the basin. The altitude of the ridge above the surrounding basement exceeds 0.4 s. The Geophysicist seamount is located on the southern end of the ridge. Baranov et al. (2002b) suggested the existence of two master faults on the upper slope that separates the Academy of Sciences Rise from the lower slope. These master faults are conjugate to both the normal faults of the Academy of Sciences Rise and the normal faults on the lower slope that strike mainly in the northwest direction. Such a structural pattern permits an interpretation of these master faults as dextral strike-slips.

4.3. Seismic stratigraphy of sedimentary layer

The major part of the study area is blanketed by sediments (Fig. 4). The main depocenters include the Kurile Basin, the upper slope and the southwest end of the lower slope. The sedimentary thickness exceeds 2.2 s (TWT) in the Kurile Basin, and is up to 1.8 s in the upper and lower slope. Acoustic basement is generally exposed on block tops on the Academy of Sciences Rise. The sedimentary layers in the Kurile Basin are generally horizontal. Seismic reflectors within section cannot be followed onto the continental slope because they terminate abrupt against the elevated acoustic basement. The sedimentary layer on

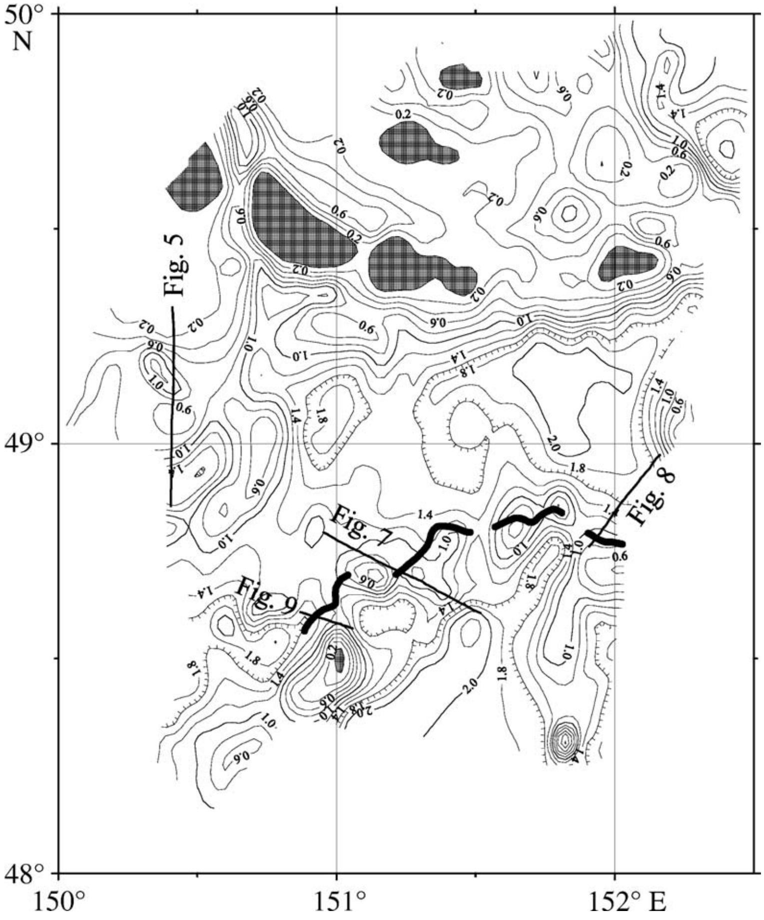


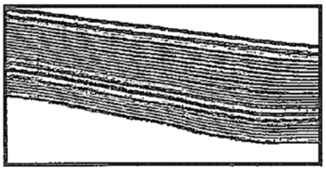
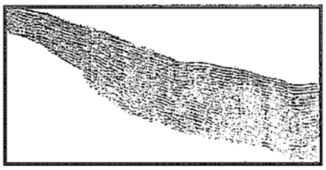
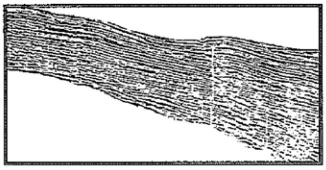
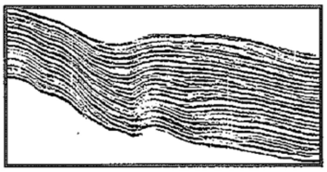
Fig. 4. Total sediment thickness (isopach) between the top of the acoustic basement and the seafloor. Contour interval is 0.2 s (TWT). Sedimentless areas are crosshatched. Heavy curved lines are main scarp (see explanation in text). The thick lines mark location of profiles shown in Figs. 5, 7, 8 and 9.

the upper slope is generally characterized by subparallel reflectors. They can be traced on the Academy Sciences Rise where they pinch out against the gentle slope of the tilted blocks. The subparallel reflectors become disrupted on the lower slope where sediment sliding and slumping caused by mass movements occur. Thus, we interpreted seismic profiles separately for three areas: the upper slope and the Academy Sciences Rise, the lower slope, and the Kurile Basin floor.

4.3.1. Seismic facies on the Academy Sciences Rise and on the upper slope

Four seismic facies are recognized on the basis of reflector character and geometry on the Academy Sciences Rise and the upper slope (Table 1 and Fig. 5). A well-stratified facies (facies 1) is interpreted to be turbidites with interbedded hemipelagic sediments because of its widespread, continuous reflectors of uniform seismic character that fill irregular topography. A weakly to moderately stratified facies (facies 2) is characterized by low-to-moderate amplitude, short reflectors as well as nearly transparent zones. The upper surface of this facies has a lens-shaped external form. Seismic facies 2 is interpreted as mass-transport deposits or complexes (Weimer, 1990) formed by various mechanisms (i. e. slides, debris flows, unchannelized high-density turbidity currents, etc.). The internal configuration of facies 2 on the upper part of slope is characterized by subparallel reflections (Fig. 5). They grade into a pattern of chaotic, low-energy reflections from further downslope (Fig. 5). The pattern is interpreted to be caused by mass movement. A moderately stratified facies (facies 3) is characterized by variable-amplitude, low frequency continuous reflectors and locally contains transparent seismic zones. The upper surface of this facies is generally hummocky and locally irregular. We interpret facies 3 to be mixed hemipelagic/turbidites sediments and gravity flow and mass-transport complexes.

Table 1
Seismic facies recognized in this study and their geological interpretation

Facies	Characteristics	Seismic appearance	Geological interpretation
Facies 1	Well-stratified, continuous reflectors with uniform seismic character, fill irregular topography		Turbidites and hemipelagic sediments
Facies 2	Weakly to moderately stratified, low-to-moderate amplitude reflectors, sporadic occurence of transparent zone,with lens-shaped external form		Mass-transport complexes formed by various mechanisms (slides/slump, debris flows, tubidity current)
Facies 3	Moderately stratified, variableamplitude, low frequency continuous reflectors, sporadic occurence of transparent zone, generally hummocky and locally irregular upper surface		Mixed hemipelagic/turbidites sediments and gravity flow and mass-transport complexes
Facies 4	Well-stratified with distinct, hummocky external form, overall internal form, overall internal seismic characteristics intermediate between facies 1 and facis 3, the base is a regional unconformity (generally erosional surface), reflectors termination along this surface frequently show down-and-upslope migration		Bottom-current deposits or tubidites/hemipelagic sediments moulded by bottom currents

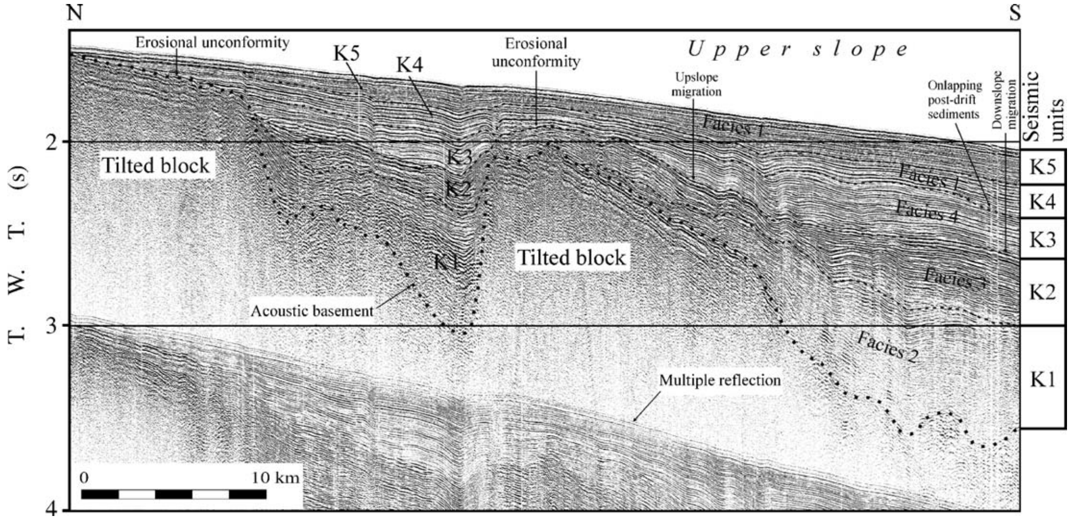


Fig. 5. Seismic profile showing seismic facies and seismic units. See Fig. 4 for location.

A well-stratified facies with distinct, hummocky external form (facies 4) has internal seismic characteristic intermediate between facies 1 and facies 3. The base of this facies is a regional unconformity (generally erosional surface). Reflector termination along this surface frequently shows down-and-upslope migration patterns (Fig. 5). We interpret facies 4 to be reworked and transported bottom-current deposits (contourite drifts) (Faugeres et al., 1999).

4.3.2. Seismic units

We divide sedimentary section of both the Academy of Science Rise and the Kurile Basin upper slope into seismic units K1 to K5 from the oldest to the youngest. The unit boundaries are relatively continuous reflectors and are marked by unconformities (Fig. 5).

4.3.2.1. Unit K1. The base of unit K1 represents the acoustic basement which is recognized on most of seismic profiles. The unit K1 deposits occur in the Academy of Science Rise and the upper Kurile Basin slope (Fig. 6) and fill irregularities of the acoustic basement. The depocenters of unit K1 are located generally on the upper slope and coincide with the basement depressions. The thickness of deposits increases to the east and exceeds 1.1 s (TWT) in some depocenters. The acoustic basement outcrops on the most part of the Academy of Sciences Rise. The unit K1 deposits have accumulated only in two narrow troughs here which intersect the rise in N–S direction.

Unit K1 is dominated by facies 2 and facies 3 (Fig. 6). Facies 2 occupies mainly the western part of the slope and facies 3 occurs mainly in the half-grabens. The lower part of unit K1 comprised of facies 3 which is characterized by divergent reflections in the half-grabens. Thickness variations and seismic facies distribution of unit K1 suggest that sediments, derived mainly from the highstanding the Academy of Sciences Rise, were deposited on the upper slope as mass-transport complexes. Turbidites were transported through two passages by turbidity currents and deposited on the upper slope forming tongue-like sedimentary bodies. The lower unit K1 deposits accumulated in the rift stage of the Kurile Basin development when the motion of tilted block hanging walls was rotational.

4.3.2.2. Unit K2. The base of unit K2 is generally recognized on seismic profiles by a relatively continuous reflector and/or erosion surface. The unit K2 deposits occupy the Academy of Sciences Rise and the Kurile Basin upper slope (Fig. 6). The unit depocenters are located in the middle part of the upper slope. The maximum thickness is over 0.4 s in the depocenters. The unit deposits did not accumulate on the greater part of the rise and on the outer ridge.

Unit K2 is composed of facies of 1 to 4 (Fig. 6). Facies 1 occupies mainly a trough with a north–south trend that intersects the rise. Facies 1 grades westward and southeastward into facies 3 that occurs in a wide area of the lower part of the slope. Facies 2 occurs in restricted areas on the rise and on the slope. Current-controlled deposits (facies 4) have accumulated near the eastern blocks of the rise and in the southeastern corner of the upper slope, implying that a new passage through the rise was developed at this time. It is probably

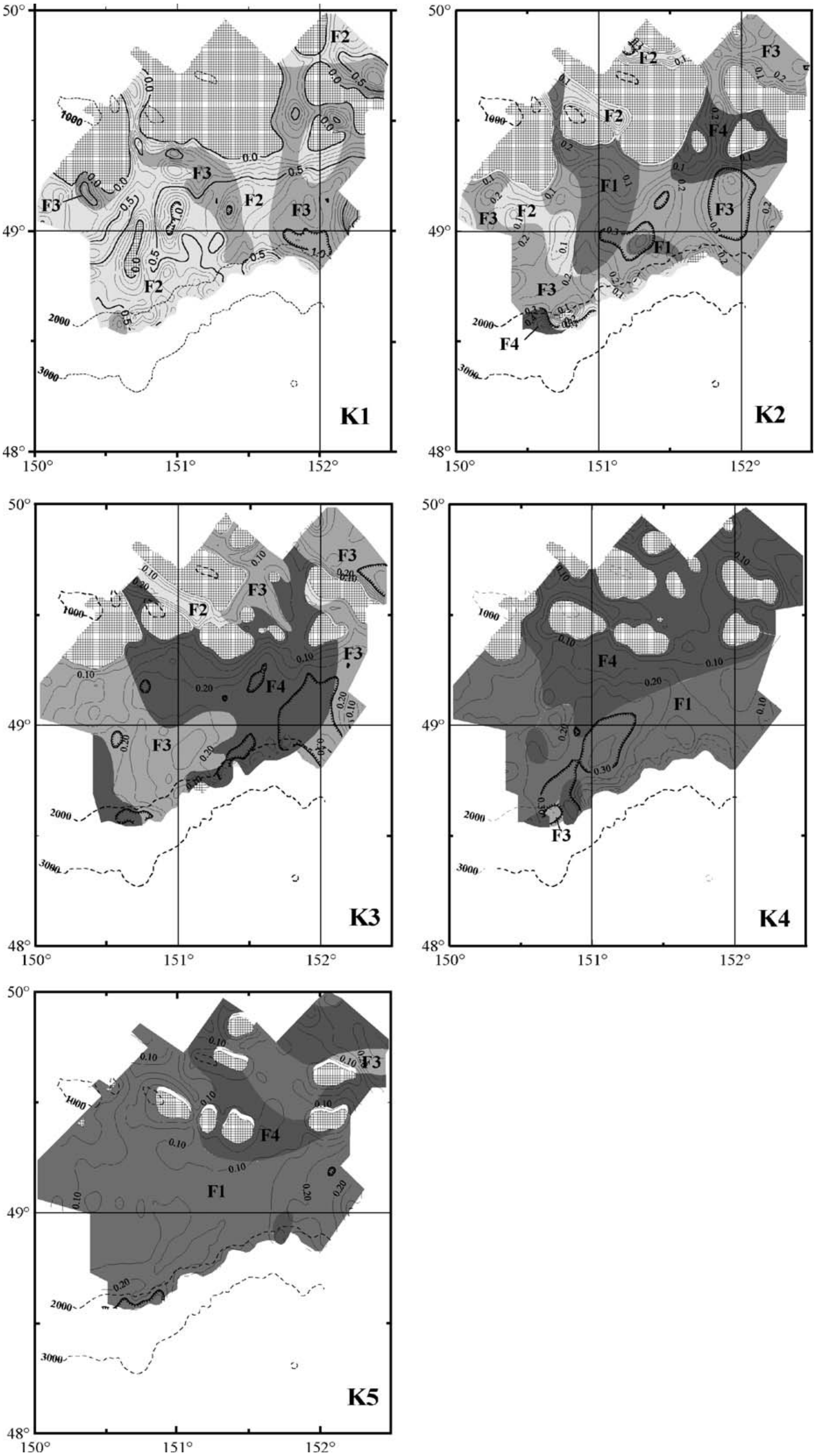


Fig. 6. Isopach maps of seismic units (K1–K5) and distribution of the seismic facies (F1–F4) for each unit. See Table 1 for seismic facies description. Thin lines indicate isopach contours in seconds (TWT). Sedimentless areas are crosshatched. Barbed lines mark depocenters. Dotted lines mark bathymetry contours in meters.

resulted from of the continued rift stage development and subsidence of some blocks.

4.3.2.3. Unit K3. The base of unit K3 is generally marked by boundaries between distinct facies throughout much of the upper slope. The boundaries are onlapped locally by overlying layers. In the transition zone between the upper slope and the lower slope the K3 base is an erosion surface. Unit K3 deposits occur in the Academy of Sciences Rise and the upper basin slope (Fig. 6). Unit K3 does not have a well-defined depocenters. It is thickest locally in the several depressions of the top of unit K2 and thins away from the rise blocks. However, moderately thick deposition occurred in the southwestern corner of the upper slope, suggesting that the depocenters shifted toward the Kurile Basin compared to unit K2. The unit deposits did not accumulate on the greater part of the Academy of Sciences Rise.

Unit K3 is dominated by facies 3 and 4 (Fig. 6). The facies 3 occupies mainly the western part of the upper slope and its eastern marginal area, the facies 4 occurs on the rise, in the central part of the upper slope and in the southwestern corner of the lower slope. Unit K3 is composed of facies 2 in the depressions that intersect the high-stand blocks of the rise. Seismic facies distribution of unit K3 suggests that sediments were derived from the tilted blocks of the rise persisted to accumulate on the rise summit. Current-controlled deposits are widespread on the rise and the upper slope suggesting the availability of bottom currents in this time there. The deposits of unit K3 have built up the upper slope in the southwestern corner of the study area.

4.3.2.4. Unit K4. The base of unit K4 is generally recognized on seismic profiles by the presence of relatively continuous reflector. The top of unit K4 is an onlap surface in places. Unit K4 has one depocenter in the southwestern part of the study area where it forms an oval-shaped body oblique to the strike of the slope (Fig. 6). Unit K4 is over 0.25 s thick in the depocenters, but thins to 0.1 s on the Academy of Science Rise. Unit K4 deposits have also built up the upper slope in the southwestern corner. Unit K4 is generally composed of facies 1 and 4 (Fig. 6). Current-controlled deposits (facies 4) extend farther to the north of the rise and to the south of the upper slope as compared to these of unit K3, indicating enhanced bottom currents. Facies 1 occurs in the lower part of the upper slope and on the northeastern part of the rise that is evidence of a quiet tectonic environment during K4 accumulation.

4.3.2.5. Unit K5. The base of unit K5 is generally a surface separating the high-frequency well-stratified unit K5 from low-frequency well-stratified facies below. It is an onlap and downlap surface in places. Unit K5 deposits occurs on the Academy of Science Rise, excluding its several small high-standing blocks, and in the upper slope. Unit K5, similar to unit K4, includes a major depocenter in the southwestern part of study area. A secondary depocenter occupies the northeastern margin of the area (Fig. 6). Unit is over 0.2 s thick in the major depocenters and exceeds 0.4 s thick in the secondary depocenters, but thins to 0.1–0.15 s on the Academy of Science Rise. Unit K5 is composed of facies 1 and 4 (Fig. 6). Most part of the upper slope is occupied by facies 1. Facies 4 occurs on the Academy of Science Rise and in the southwestern upper slope. Restricted occurrence of current-controlled deposits (facies 4) is suggestive of a marked decrease in bottom-current activity compared to unit K3 and K4.

4.4. Lower slope

Mass-movement is the dominant process controlling the morphology and sedimentary structure of the lower slope during recent times (Fig. 7). Relatively underformed, well-stratified sediments of the upper slope are truncated by erosive processes and in places by tectonics. The instability features comprise erosive surface associated with submarine channels and gullies, small and large-scale slides, small and large-scale slide scars. The main slide scarp is at about 2200 m water depth and extends along the north and northwest part of the lower slope (Fig. 4). The mass wasting deposits overlie at the base of the lower slope lens-shaped drift bodies with strong continuous and parallel reflectors (Fig. 7). Data are not sufficient to map the drift bodies along the base of the lower slope.

4.5. The Kurile Basin

The sedimentary cover in the Kurile Basin proper can be divided in two main seismic units: an upper, well-stratified unit and a lower, relatively transparent unit. The transparent unit overlies the basement and comprises only occasional, low-amplitude, continuous reflectors that drape the basement. The well-stratified unit consists of a series of sub-parallel and sub-horizontal reflectors. It has been proposed that the lower unit was deposited in the Oligocene and Early Miocene and the upper unit between the Middle Miocene and Quaternary (Kharakhinov, 1996).

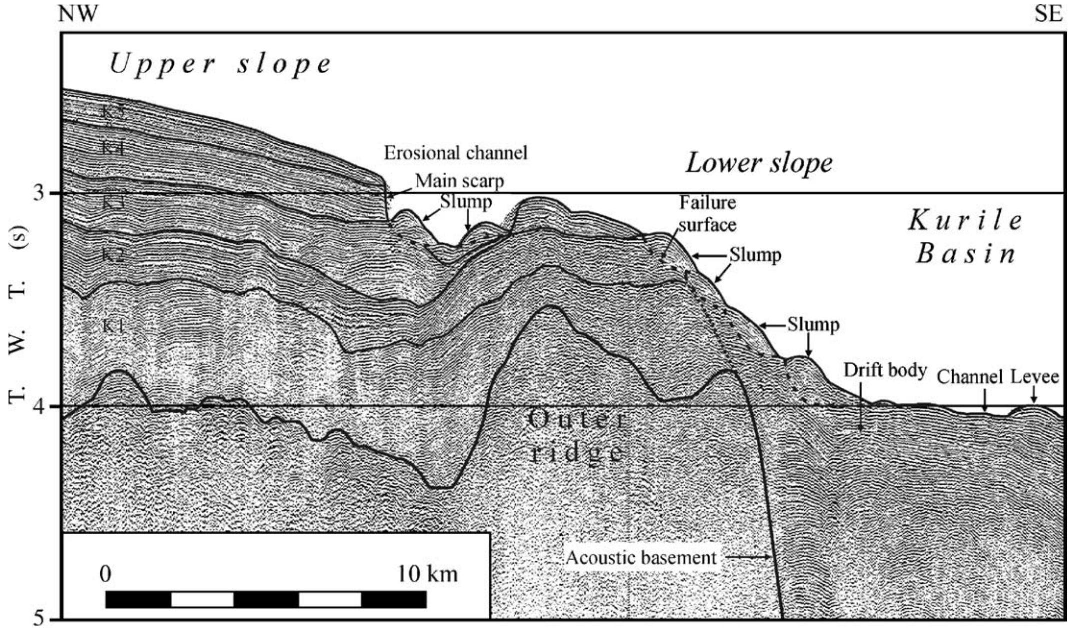


Fig. 7. Seismic profile showing mass waste deposits on the lower slope. Mass waste deposits overlie lens-shaped drift body. See Fig. 4 for location.

4.6. Age of seismic units

Piston core samples show that the upper part of seismic unit K5 corresponds to Quaternary deposits (Nurenberg et al., 1997). We suggest that the unit K5 have accumulated in Pleistocene–Holocene time. The geological age of units K3 and K4 are inferred from the biosratigraphic data (Baranov et al., 2002b; Tsoy, 2004; Tsoy and Shastina, 2005) in dredge samples from a scarp in the eastern part of study area, where this sedimentary sequence outcrops (Fig. 8). The unit K3 is composed to Early Pliocene silt, deposited at a depth of 300–700 m. There is some evidence that sedimentation occurred in a vicinity of a shoreline and/or a narrow shelf zone. The top of the unit K3 approximately coincides with Early–Late Pliocene boundary. The unit K4 is composed to Late Pliocene silty clays and diatomaceous oozes. In the Late Pliocene, the sedimentation occurred in a near basin environment at a depth of 1000–3000 m (Baranov et al., 2002a). The top of unit K4 approximately coincides with the Plio–Pleistocene boundary. Deposits below the base of the unit K3 have accumulated in pre-Pliocene time and their age is poorly known. The biostratigraphic data (Tsoy, 2004; Tsoy and Shastina, 2005) in dredge samples from the northern Kurile basin slope show that the lower part of the sedimentary section is Late Oligocene–Early Miocene in age. This sedimentation occurred in outer shelf and/or slope environment. The upper part of the sedimentary section sampled by dredging is Middle Miocene in age and was deposited in a slope environment. We suggest that units K1 and K2 have accumulated in Late Oligocene–Middle Miocene time.

5. Discussion

As interpreted from the seismic-reflection data, the Late Oligocene–Quaternary sedimentary history of the Kurile Basin northern slope and the Academy of Science Rise includes three major phases. The first phase, Late Oligocene–Middle Miocene, includes unit K1 and unit K2 consisting largely of facies 2 and 3 interpreted as mass-transport complexes. Sedimentation of the oldest sedimentary sequence on the upper slope and on the Academy of Science Rise was dominated by mass wasting. This sedimentation was controlled by the rift stage of the Kurile Basin development when the motion of tilted block hanging walls was rotational. The ODP drilling in other back-arc basins in the western Pacific revealed that the early phase of back-arc sedimentation is dominated by mass-transport processes (Rangin et al., 1990; Taylor, 1992). The second phase, Early Pliocene–Pleistocene, includes unit K3 and K4 consisting largely of bottom-current deposits and turbidites and hemipelagic sediments. After the end of opening of the Kurile Basin, slope stabilization in the Late Miocene resulted in deposition on the upper slope and on the Academy of Science Rise was under the

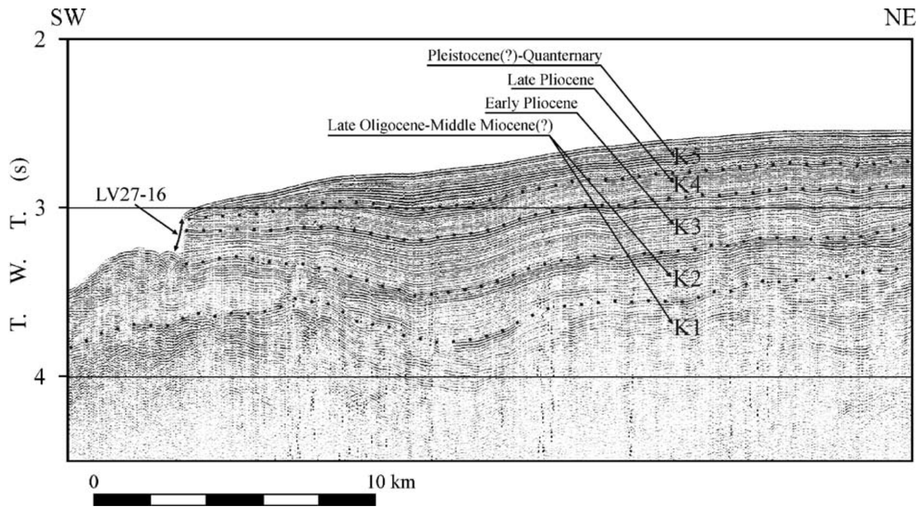


Fig. 8. Seismic profile showing age of seismic units. Seismic units K3 and K4 outcrop on the main scarp. Samples recovered by dredging (dredge station LV27-16 also shown) show that seismic units K3 and K4 have been generated in Early Pliocene (K3) and in Late Pliocene (K4). See Fig. 4 for location.

strong influence of current-induced contoured sedimentation. The third phase, Pleistocene–Quaternary, includes unit K5 consisting largely of well-stratified facies interpreted as turbidites and hemipelagic sediments. Restricted occurrence of the current-controlled deposits indicates decrease of bottom-current activity during this period.

The widespread distribution of mass-transport complexes in unit K1 and unit K2 suggests extensive the Academy of Science Rise blocks failures and mass movements along the margins of the Academy of Science Rise during Late Oligocene–Middle Miocene. This, in turn, may indicate that the Academy of Science Rise and the upper slope were tectonically active during this period. Tectonic activity reduced possible in the end of this period when turbidites and hemipelagic sedimentation and drift deposits developed there. Extension and back-arc spreading of the Kurile Basin began in Early to Late Oligocene and continued until Late Miocene (Takeuchi et al., 1999; Ikeda et al., 2000). The rift stage of basin formation is accompanied by subsidence and facies 1 and facies 4 of the unit K2 formed in a marine basin environment.

The second phase is characterized by the widespread distribution of drift sedimentation on the upper slope and on the Academy of Science Rise. Faugeres et al. (1999) suggest that the onset of contourite drift sedimentation is mainly triggered by global oceanic events accompanied by increased bottom current activity. An example of a global hydrological event is the inception of Quaternary glaciations. In the northern Pacific, it is accompanied by an increase in the vigor of deep-sea circulation and intensification of mixing of the water masses at 2.5 Ma (Rea and Schrader, 1985; Rea et al., 1993). Kwiek and Ravelo (1999) concluded that thermohaline overturning was more rapid, and formation of warmer, saltier intermediate water was more enhanced in the northern Pacific during the warm period of the early Pliocene (2.7 Ma). The Okhotsk Sea participates in the formation North Pacific Intermediate Water (NPIW, Talley, 1991; Freeland et al., 1998). The Okhotsk Sea Intermediate Water (OSIW) flows into the Pacific Ocean and ventilates the Pacific subpolar gyre (Talley, 1991; Freeland et al., 1998). Since the Okhotsk Sea plays an important role in the formation of intermediate and deep water in the North Pacific, similar hydrographic changes must also have occurred there.

During the third phase turbidite and hemipelagic sedimentation predominated on the upper slope. Drift sedimentation occurred only on the Academy of Science Rise. It was demonstrated (Stoker, 1998) that influence of bottom currents on sedimentation and erosion is particularly strong in areas where highly complex bottom morphology leads to a deflection or focusing of these currents and with it an intensification of the flow. This is the case for the Academy of Science Rise where bottom morphology is complex. Water circulation in the Kurile Basin is largely controlled by exchange between the Okhotsk and Pacific waters through the deep Bussol and Kruzenshterna straits. Outflow of the OSIW occurs between the depths of 400–800 m and inflow of the NPIW between 800–1200 m (Talley and Nagata, 1995). From the water depth ranges of these two currents, it is more likely that the NPIW gave rise to the drifts.

The seismic data show that many tilted blocks of the Academy of Sciences Rise have flat tops (Fig. 5), which are typical morphological feature of emerged seamounts resulting from wave abrasion at the sea level, and are covered by only a thin blanket of recent sediments. The present position of these tops is at 1000–1200 m below sea level. These data imply subsidence of the Academy of Sciences Rise at least 1000 m after the end of Kurile Basin opening. The occurrence of an erosional unconformity on the top of the unit K2 (Fig. 5) indicates that some tilted blocks constituting the upper slope were subaerially exposed after the Middle Miocene and that subsidence began in the Early Pliocene. We estimated average subsidence rate of the top of the Academy of Sciences Rise and the upper slope. Estimation of the rate is based on assumption that (1) the entire subsidence occurred since the Early Pliocene and continued to the present and thus covered a time interval of ca. 5 Ma, (2) average velocity of the sediment column above the top of the unit K2 is 2 km/s and the top of the unit K2 is located at depth of 1320 m at the present. This yields a subsidence rate of about 0.2 mm/yr for the Academy of Sciences Rise and of about 0.26 mm/yr for the upper slope. It is suggested that subsidence of the Kurile Basin and its slopes are most likely connected with the plate tectonic situation in which this basin is located (Baranov et al., 2002a). The present distribution of shallow earthquakes defines a separate Okhotsk plate, which is surrounded by the Pacific, North America, Eurasia and Amur plates. As a result of the collision of the major Eurasia and North America plates, the Okhotsk Plate is being extruded to the southeast (Savostin et al., 1983; Riegel et al., 1993). Subduction of the Pacific Plate along the Kurile–Kamchatka Arc induces compression in an opposing northwestern direction, while left-lateral motion along the boundary between the Amur and Eurasian Plates causes right-lateral compressional motion between the Amur and Okhotsk Plate. In summary, the relative motions of the four major plates clearly result in significant interplate stress on the Okhotsk Plate and the Kurile Basin causing them to be squeezed together and their interiors to buckle downwards similar to the model of Cloetingh et al. (1985).

The lower slope has undergone repeated and extensive large-scale slumping and sliding of the presumed pre-Pleistocene sediments. In general, slides are driven by gravity forces. The effective shear strength along potential gliding planes forms the resisting force against sliding. Factors that reduce effective shear strength and promote sliding are earthquakes, under-consolidation due to rapid deposition, gas hydrates which decompose and liberate gas and water that create excess pore pressure (Hampton et al., 1996). Several earthquakes with magnitudes up to 5 have been recorded during the last twenty-five years in our study area (Baranov et al., 2002a). Consequently, instability caused by earthquakes is a very likely mass wasting triggering

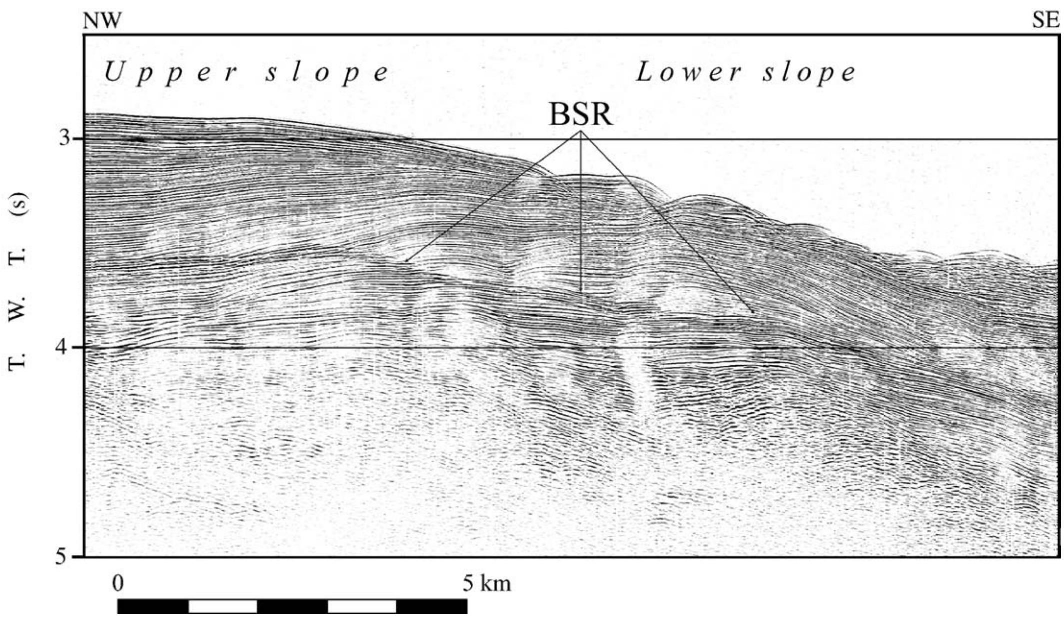


Fig. 9. Seismic profile showing bottom simulating reflector (BSR). See Fig. 4 for location.

mechanism. Gas hydrates in area under investigation are suggested by the existence of a bottom simulating reflectors on the seismic profiles (Fig. 9). Gas releases from the decomposition of hydrates could cause liquefaction of sediments and provide a gliding plane for a slide. The cause of the decomposition could was a sea level fall at the onset of a glacial period. Gas hydrate decomposition can occurred as a result of earthquake agitation of sediments. Earthquakes in combination with gas hydrate decomposition are probably the most likely cause for the mass wasting.

Widespread distribution of drift bodies at the base of the slope suggests the availability of bottom-current activity. We speculate that bottom-current activity existed there in Early Pliocene–Pleistocene when drift sedimentation occurred on the upper slope and on the Academy of Sciences Rise.

6. Conclusion

Our the seismic-reflection data show that Late Oligocene–Quaternary sedimentary history of the Kurile Basin northern slope and the Academy of Science Rise includes three major phases. During the first phase, Late Oligocene–Middle Miocene, sedimentation on the upper slope and on the Academy of Science Rise was dominated by mass wasting and was controlled by the rift stage of the Kurile Basin development. The Academy of Science Rise and the upper slope were tectonically active during this period. Tectonic activity was possibly reduced at the end of this period when turbidites and hemipelagic sedimentation and drift deposits developed there. During the second phase, Early Pliocene–Pleistocene, deposition on the upper slope and on the Academy of Science Rise was under the strong influence of current-induced contoured sedimentation. These bottom currents are controlled by the oceanographic regime in the Okhotsk Sea, which is probably closely linked to intermediate- and deep-water circulation patterns in the northern Pacific. During the third phase, Pleistocene–Holocene, turbidite and hemipelagic sedimentation predominated on the upper slope. Drift sedimentation occurred on the Academy of Science Rise only.

There is evidence that indicates subsidence of the Academy of Science Rise (0.2 mm/yr) and the upper slope (0.26 mm/yr) from the Early Pliocene to the present. Downslope processes are important on the lower slope. They include large-scale slumping and sliding of sediments. Mass wasting events are possibly triggered by earthquakes or/and gas hydrate decomposition during sea-level lowstands.

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