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The Tectonic Conditions of the August 2, 2007, M ~ 6.1 Nevelsk Earthquake

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Abstract—This paper reports the results of field observation and the study of coastal tectonic deformations related to the Nevelsk tsunamigenic earthquake (August 2, 2007, M ~ 6.1) obtained in August–September of 2007. The earthquake caused a 0.5- to 1.5-m rise of and partial desiccation of the southern, central, and northern benches and the formation of longitudinal structural ridges seaward of Lovetskaya Bay. In the framework of the new model of the Kamyshovy (West Sakhalin) Anticlinorum as a structure of the Quaternary and Middle Quaternary crustal detachment, the relationships between the earthquake and the slow gravitational creep of the upper crust on its western slope with local squeezing of the Middle Miocene Nevelsk siltstones are discussed.

Key words: crustal detachment, anticlinorium, earthquake, creep, tectonic pair, shelf, southern Sakhalin.

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INTRODUCTION

The Nevelsk earthquake occurred on the Sakhalin shelf of the Tatar Strait seaward of Nevel'sk harbor in the day time on August 2, 2007 (Figs. 1–9). According to the Sakhalin Branch of the Geophysical Survey of the Russian Academy of Sciences, its magnitude was as high as 6.1 with hypocenter depths of 12 km; i.e., the hypocenter was situated in the upper part of the continental crust, which is 35–40 km thick under Sakhalin [23]. In the displacement type, it was a meridional reversed fault with the eastward plane dipping at an angle of 67°. The earthquake was accompanied by the almost instant rise of the abrasion shelf (likely, by several meters in the epicenter, Fig. 2), a tsunami up to 2–3 m high [9, 13], several notable aftershocks, the mass release of methane in the harbor, and the deformation of buildings in the shore part of the city (over 200 of them were recommended by the special commission for demolition) constructed on irregularly watered landfilling (V.P. Myasnikov, personal communication on August 3, 2007). Numerous rock falls; rock slides; open fractures on roads; significant deformations of railway and highway bridges and timber houses and holiday village houses; and, less commonly, landslides on mountain slopes were observable south of Nevelsk up to the Gornozavodsk and Shebunino settlements [Fig. 5a; [24]). According to witnesses, the damage was partly caused by several strong aftershocks, which occurred during the same day, rather than by the main shock [24]. As was registered, three blocks constituting the monument to lost seamen approximately 3 m high installed on the mountain slope were rotated in the clockwise direction with the amplitude decreasing upward from 4 to 1 cm (Figs. 5b, 7e). At the same time, the monolithic monuments to Lenin and Nevelskii on the main street of the city avoided deformation. Since the Moneron earthquake time (September 6, 1971, M = 7.3), no local tsunamis have been observed in this area [7, 9]. The Nevelsk event makes it possible to decrease the accepted threshold of M = 7 for tsunamigenic earthquakes, because it was accompanied by one to three waves 0.8–3.2 m high that originated at unusually shallow shelf depths.

The study carried out on September 6 was added by the reconnaissance depth measurements from an inflatable boat with the outboard motor provided with continuous GPS control (D.N. Kozlov and R.V. Zharkov, Institute of Marine Geology and Geophysics, Far East Division, Russian Academy of Sciences [9, 13, 24]) and was compared with the model of the Quaternary tectonics and crustal seismicity of Sakhalin [16].

TECTONICS OF THE EARTHQUAKE AREA

On the tectonic map of Sakhalin, the Nevelsk earthquake area is attributed to the southwestern underwater continental margin of Sakhalin formed by the western slope of the Kamyshovy (West Sakhalin) Anticlinorium [5, 6, 14, 17]. This Middle Quaternary [10] inversion uplift (the orogen or the West Sakhalin Mountains) appeared in the depocenter of the Neogene marginal trough between the Sikhote Alin and East Sakhalin mountainous structures during the Sakhalin folding and orogenic epoch [14–16, 25]. In the latitudinal section, the anticlinorium represents a large megahomocline with a relatively steep and narrow eastern slope up to 1 km high. This structure was previously considered as a stamp horst anticlinorium [21] or strike-slip orogen

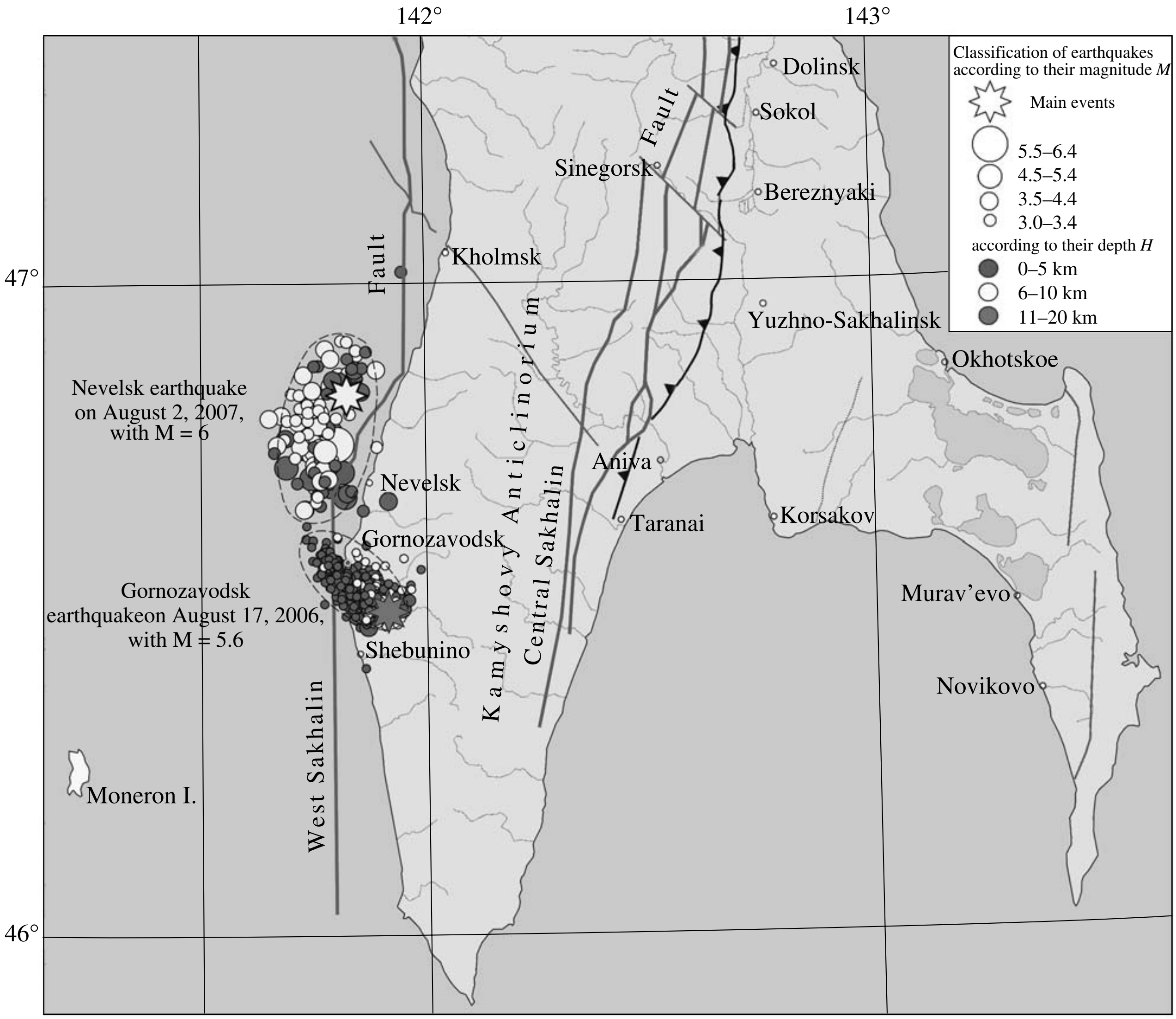

Fig. 1. Position of the epicenters of the Gornozavodsk and Nevelsk earthquakes and their aftershocks (according to data by the Sakhalin Branch of the Geophysical Survey of the Russian Academy of Sciences) and the principal faults in southern Sakhalin (after A.N. Kozhurin).

The solid line with triangles designates the accretion front at the base of the eastern slope of the Kamyshovy Anticlinorium.

that formed under near-latitudinal compression [20 and others]. According to [16], the Kamshovy Anticlinorium forms a front of the large West Sakhalin crustal tectonic slice detached easterly along the Moho boundary décollement and bordered by the westward-dipping Central Sakhalin (Tym–Poronai) updip–thrust (Figs. 1, 3). Smekhov [22] considered it to be one of two principal longitudinal thrusts in Sakhalin. According to [7], the Central Sakhalin Fault penetrates into the asthenosphere and separates the Okhotsk (Sea of Okhotsk) and Amur lithospheric plates. The recent shallow-focus (crustal) seismicity of the Kamyshovy Anticlinorium and the aseismicity of the underlying upper mantle [19] show that the Central Sakhalin Fault and the above-mentioned plates represent crustal structures. The horizontal displacement along this fault is insignificant, no more than 5–10 km [17, 18]. The displacement of the roof of the Cretaceous relative to the adjacent troughs is up to 3–5 km [4, 5, 8, 18]. The hanging wall of the Central Sakhalin Fault is composed of compact Cretaceous sedimentary rocks; therefore, its thrusting is accompanied by accretion of Cenozoic sediments and the formation of a narrow (several kilometers) accretionary prism at the base of the eastern slope [10, 18].

The western gentle slope of the anticlinorium and the adjacent shelf are composed of Paleogene and Neogene sedimentary rocks 2–5 km thick, which are deformed in numerous folds frequently associated with

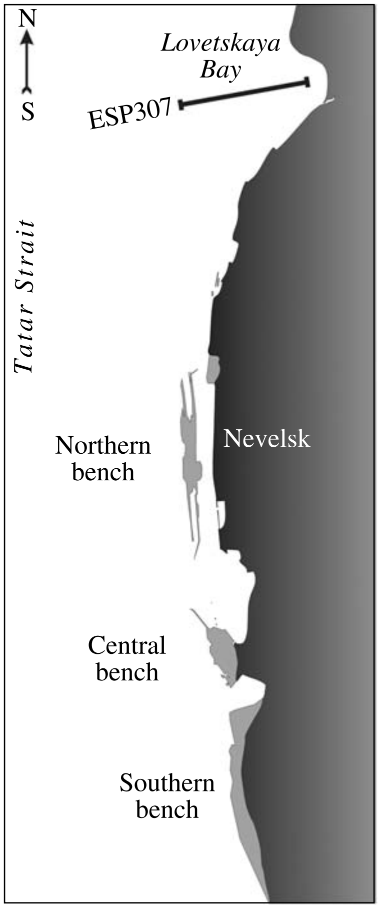

Fig. 2. The schematic map of the newly formed Nevelsk benches (gray-colored) on a scale of 1 : 87000 with echo-sounding profile 307 in Lovetskaya Bay.

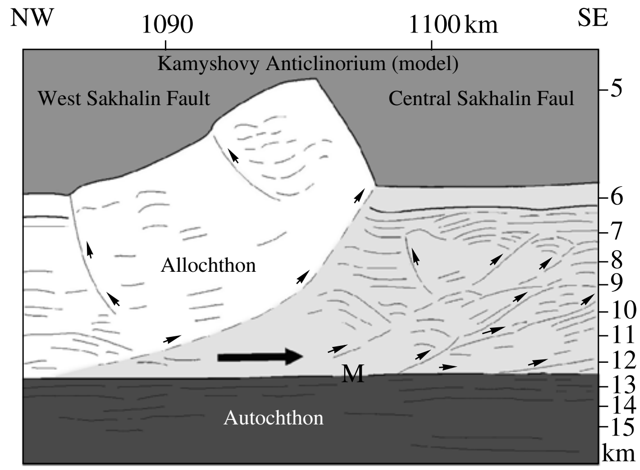

Fig. 3. The deep CMP section across the divergent intracrustal detachment zone in the Northwest Pacific with the thrust homoclinal ridge as a model of the Kamyshovy Anticlinorium of Sakhalin (after V.L. Lomtev and V.N. Patrikeev, Institute of Marine Geology and Geophysics).

The solid arrow shows the direction of the allochthon detachment.

steeply dipping faults [2, 5, 17, 20, 21, 25]. There are also differences. For example, the shelf anticlines are up to several kilometers high, their arches are abraded (bench or, more exactly, shelf abrasion plateaus, Fig. 4), and their axes are unobservable in the coastal shoal with reefs, which allows them to be considered as half-folds. The structural features are established by the areal CMP survey in the Gavrilovskaya and other anticlines drilled by 11 DVMURBA boreholes during hydrocarbon prospecting [5, 25]. The formation of folds was believed to be related to young right-lateral displacements along the West Sakhalin deep-seated fault [15]. The lack of a similar (echelon) system of NW-trending half-folds on the eastern slope of the Kamyshovy Anticlinorium and the almost ideal stratification of the Cenozoic sediments on the limbs of these folds observed in the CMP records indicate the slow gravitational creep of these sediments on the western slope of the anticlinorium. The shelf faults associate with half-folds and belong to the back or so-called compression-related retrofaults with steep eastward-dipping planes (Fig. 4). Therefore, the West Sakhalin coastal deep-seated fault [6, 17] likely represents a duplex or system of conjugate faults where the back fault (reversed fault) is steeper as compared with the frontal (thrust) one (Fig. 4). Thus, the Nevelsk earthquake and the meridional swarm of its aftershocks were related to the upper crust movements precisely in the zone of this duplex (Fig. 1).

It is established that the young and seismoactive Kamyshovy Anticlinorium of Sakhalin is characterized by thrust and gravitational styles in the structure of the eastern and western slopes, respectively. The opposite dips of the Central Sakhalin and West Sakhalin faults indicate the divergent structure characteristic of orogens in crustal compression zones (after V.E. Khain [26]). Inasmuch as the Kamyshovy Anticlinorium marks the detachment front of a large crustal slice [16], the homoclinal trust nappe 1 km high from the zone of divergent intracrustal detachment in the Northwest Pacific was accepted as its natural model (Fig. 3). The Gornozavodsk earthquake (M = 5.6) on August 17, 2006, which occurred at depth of 18 km with reversed faulting along the plane confined to the Central Sakhalin frontal fault zone [11], may likely be considered as a particular seismotectonic trigger for the Nevelsk earthquake in the zone of the West Sakhalin back fault (Fig. 1). If this assumption is correct, it is reasonable to unite these main faults of the Kamyshovy Anticlinorium into a tectonic pair, where the back fault is related, contrary to the frontal one, to the creep of the Cenozoic sedimentary cover and the underlying upper crust composed evidently of Mesozoic and Paleozoic rocks. It should also be noted that, unlike the West Sakhalin Fault, the Central Sakhalin one crosses the entire crust reaching the Moho boundary décollement. It remains unclear whether their planes are intersected at depths

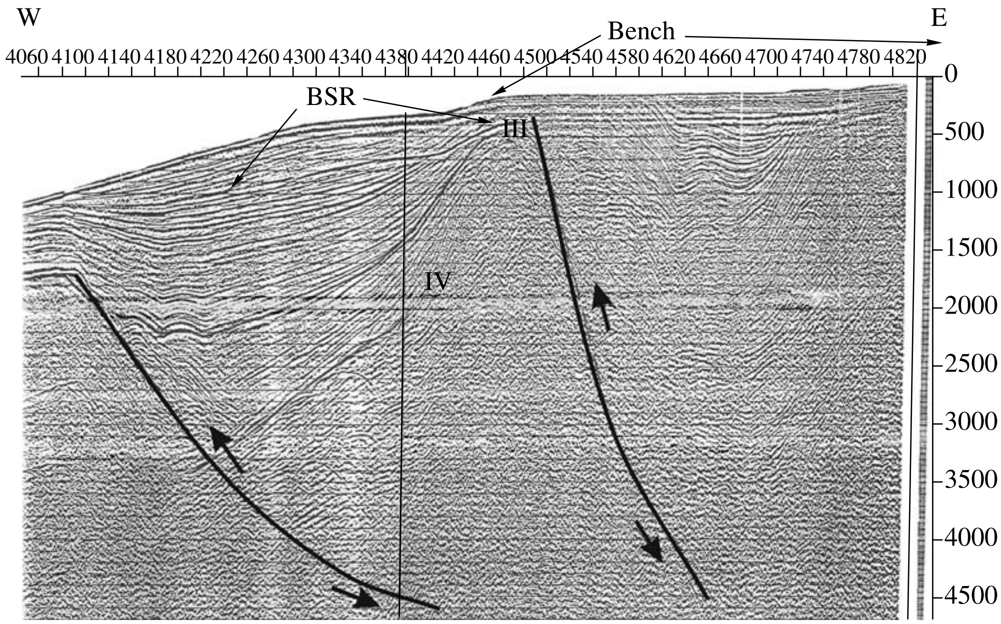

Fig. 4. Fragment of latitudinal CMP time section no. 11 across the southwestern underwater margin of Sakhalin Island [2]. (BSR) The bottom-stimulating reflector at the base of the gas hydrate layer; (III, IV) the seismocomplexes of the Neogene sediments; the lines with arrows designate the updip–thrust planes and the displacement along them. The train of flat reflections crossing folds is formed by noise waves, except for the upper (bench). The vertical axis shows the seconds of the two-way travel time with a step of 0.1 s, and the horizontal axis shows the CMP stakes with a step of 40 stakes/km.

(in the middle part of the crust section) or not; this problem needs special studies. Another problem is connected with the assessment of the real, likely limited scale of the right-lateral movements along faults of the West Sakhalin shelf duplex.

SEISMOGENIC DEFORMATIONS IN THE COASTAL PART OF THE ISLAND

Of significant interest is the almost instant seismogenic rise of the three coastal areas of the rock bottom (benches), which are made up of steeply westward dipping partly silicified [6] siltstones of the Middle (Lower [5]) Miocene Nevelsk Formation. They notably increased the territory of Nevelsk, which extends as a narrow band for 10 km south of the Lovetskaya River mouth and the synonymous bay. This accretion is an unusual fact in the recent geological evolution of Sakhalin, whose territory is decreasing due to shore abrasion [1, 24]. The witnesses note that the water retreat from the central bench was so rapid that the stokers from the nearest boiler room collected on two sacks of fresh fish. In addition, the stern of a trawler that was moored to another ship at the southern end of the pier was turned approximately 45° by the strong northern current.

The *southern bench* (Figs. 2, 6a, 6b) joins the southern margin of the Nevelsk territory, where it extends as a narrow (200–250 m) band for 2.3 km seaward of the former shore protected almost universally by the sea wall (Fig. 6a). The bench is characterized by its horizontal surface, which cuts outcrops of the Nevelsk Formation siltstones and is bordered on the sea side by a steep scarp. The bench is slightly covered by sediments with abundant shells and rare boulders. During the earthquake on August 2, the southern bench was raised by 0.5–1 m up to the sea level and was partly flooded (Fig. 6b). Under storm surges, it becomes flooded with the water depths reaching ~0.5 m. During its visual examination, we failed to find fresh seismogenic fractures or faults, which indicates the block deformation of the rocky bottom composed of the Nevelsk siltstones. Their beds are oriented northwestward at an acute angle to the shore strike and buried under the present-day beach sands >1 m thick (Fig. 6a).

In the area where they are exposed on the shore, the latter changes its orientation from the near-meridional (in the north) to the southwestern (in the south) one. It is noteworthy that the contact of the southern bench with the former sandy shore and its protecting sea wall was not disturbed by the earthquake.

The *central bench* is located seaward of a small salient of the sandy shore in the southern part of Nevelsk Bay near the Kazachka River mouth.(Figs. 2, 7a–7e). It extends in the northwestern direction for 750 m, being up to 250 m wide. Its end part corresponds to the southern breakwater 300 m long, which was uplifted by 1.0–1.5 m, as is evident from the level grown on by

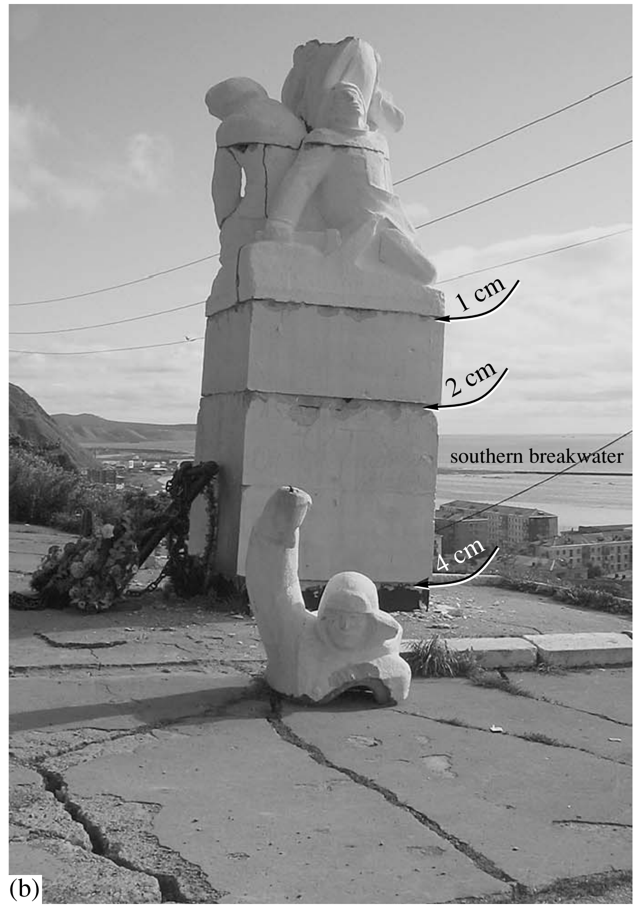

Fig. 5. Landslide on the mountainous forested slope near the Lopatino settlement south of Nevelsk (a) caused by the double impact of the main shock and the strong aftershock (according to the observations of eyewitnesses); the monument to lost seamen (view from the northeast) (b).

The arrows show the direction of the rotation of three of the blocks during the earthquake and their amplitudes in centimeters (for the monument location, see Fig. 7a).

laminarias (Fig. 7a). This breakwater, which was constructed after World War II, now serves as a sea lion rookery. The central bench is characterized by the even surface raised 0.5–0.8 m above the sea level near the outer western edge and by the insignificant landward incline. The surface cuts the steeply westward dipping Nevelsk siltstones and locally is covered by sediments (the near-shore part of the bench) and laminaria mats (Figs. 7b–7d). When the sea is calm, the central bench is entirely desiccated, although, under storm surges, it is partly or completely flooded by a thin water layer. The visual examination of the bench revealed several methane seeps along its northern edge; the skerry to, locally, fjord appearance of the western and northern edges (Figs. 7c, 7e); and the almost perfectly smooth western edge in the band a few tens of meters wide. The smoothness of the latter remains unexplainable (floating ice?) due to the lack of sediments. This area of the bench, including the breakwater, is also lacking large fresh seismogenic ruptures or faults, which implies the block character of its movements. According to local residents, the former depths at the outer edge of the bench were approximately 1 m, which indicates that the amplitude of its seismogenic uplifting exceeded 1.5 m. Similar to the southerly areas, the contact of the central bench with the shore protected by the sea wall is undisturbed (Fig. 7d).

The *northern island bench* (Figs. 2, 8a–8e) appeared after the earthquake on August 2 due to the seismogenic rise of the shore by 1.0–1.5 m, as is evident from the band of laminaria on the lower part of the eastern wall of the half-destroyed northern breakwater, the narrow beach along the eastern wall of the breakwater in its southern part, and the desiccation of a significant area of the adjacent rocky bottom (Figs. 8a, 8b). The bench extends in the meridional direction for 2 km, being 150–210 m wide (Figs. 8c, 8d). On the western side, it is almost inaccessible because of reefs locally with outcrops of silicified siltstones with acute cutting edges of beds (Figs. 8e, 8f). The bench relief is represented by

Fig. 6. The southern flat flooded bench.
(a) The initial part (the southern exit from Nevelsk); (b) the middle part.

ridges and intervenient depressions with two large shallow (up to 1.0–1.5 m) bays. The beds of the Nevelsk siltstones in this bench dip steeply to the west as well and are distinctly distinguished by their relief owing to the lack of sediments. The largest ridges are up to 1 m high and were probably related to interstratal faults and, partly, outcrops of hard silicified siltstones (Figs. 8d, 8e). Boulder–pebble sediments occur only near the western wall of the breakwater, where they constitute a narrow beach (Fig. 8b). In the northern underwater continuation of the island, echo sounding profile 307 registered longitudinal structural ridges that partly block the exit from Lovetskaya Bay and are likely related to creep-induced squeezing of the Nevelsk siltstones (Figs. 2, 9). The ridges are up to 10 m high, which is an order of magnitude higher as compared with the amplitude of the seismogenic rise of the Nevelsk benches (see above). Consequently, they were formed well prior to August 2, 2007. It is of importance to confirm this assumption with diving observations, which should also involve the rock ridge >6–8 m high with numerous underwater and subaerial reefs that dams the adjacent (4 km north) Yasnomorskaya Bay and was discovered during sounding on September 6.

According to the bathymetric survey on September 6 and incidental measurements from trawlers (private communication by the harbor captain), the maximal (up to 7.3 m) bottom depths in the eastern part of Nevelsk harbor remained unchanged after the earthquake, although mass methane seeps on August 3 occurred precisely in this area. At the same time, during the bathymetric survey, only single jets were registered there and the maximal gas release was observed near the exit from the harbor (the fairwater between the northern and southern breakwaters limited by leading beacons). The methane likely associates with coal seams and/or petroliferous formations, which are penetrated by the Lovetskaya prospecting hole in the Lovetskaya River valley 4 km away from its mouth. The presence of gas in the near-surface sedimentary section near the edge of the southwestern Sakhalin shelf composed largely of its abrasion products is reflected in the development of the bottom-simulating reflector (BSR) recognizable in the CMP records [23 and others] at the base of the gas hydrate layer (CMP Profile 11) (Fig. 4). Gas hydrates were first discovered in the near-surface sediments of the Tatar Strait by the shallow DVMIGE borehole in the Izyl'met'evskaya gas area of the Sakhalin shelf near the Lamanon Peninsula [12].

CONCLUSIONS

The above-mentioned deformations related to the Nevelsk tsunamigenic earthquake on August 2, 2007, involved the southwestern shelf of Sakhalin and the coastal shoal, where three areas of the rocky bottom (the southern, central, and northern benches near Nevelsk harbor) were raised by 0.5–1.5 m and almost entirely desiccated. In the context of the new tectonic model of the Kamyshovy Anticlinorium [16], the earthquake was likely connected with the slow gravitational creep of the Cenozoic sedimentary cover and the underlying upper crust on its western slope. The creep was locally accompanied by squeezing of the Nevelsk Formation siltstones forming meridional underwater ridges seaward of Lovetskaya and Yasnomorskaya bays. The comparison of the aerial photographs obtained before and after the earthquake shows that the benches repeat the contours of formerly elevated shoal areas (the so-called banks). Consequently, the movements of the upper crust caused by the Nevelsk earthquake were controlled by the former tectonic structure, i.e., occurred in an inherited manner. Also noteworthy is the resistance of the benches to abrasions, which is caused by the lack of sediments, particularly the boulder–pebble varieties; the lithology of the sedimentary

Fig. 7. The central bench.

(a) The southern breakwater with laminarias in the lower part of the west wall; (b) the steeply westward-dipping siltstone beds of the Nevelsk Formation slightly covered by sediments; (c) the high western edge of the bench with minifjords (shallow narrow bays) and laminaria mats smoothed-out by the rapidly flowing water; (d) the back part of the bench with the breakwater wall; (e) the smooth edge of the bench (the light circle on the mountainous slope adjacent to the city center is the monument to lost seamen, see Fig. 5b).

rocks of the Nevelsk Formation (hard frequently silicified siltstones), and the steep scarp along the outer edge of the southern and central benches. The tectonic scenario of the Nevelsk earthquake is evident from the data obtained by the network of bottom and land-based seismographs on the swarms of aftershocks produced by the upper crust earthquake of 2007 ($M = 6.9$) under the back, Sea of Japan shelf of central Honshu Island. In this area, the main seismic rupture was represented by the eastward-dipping reverse fault [27].

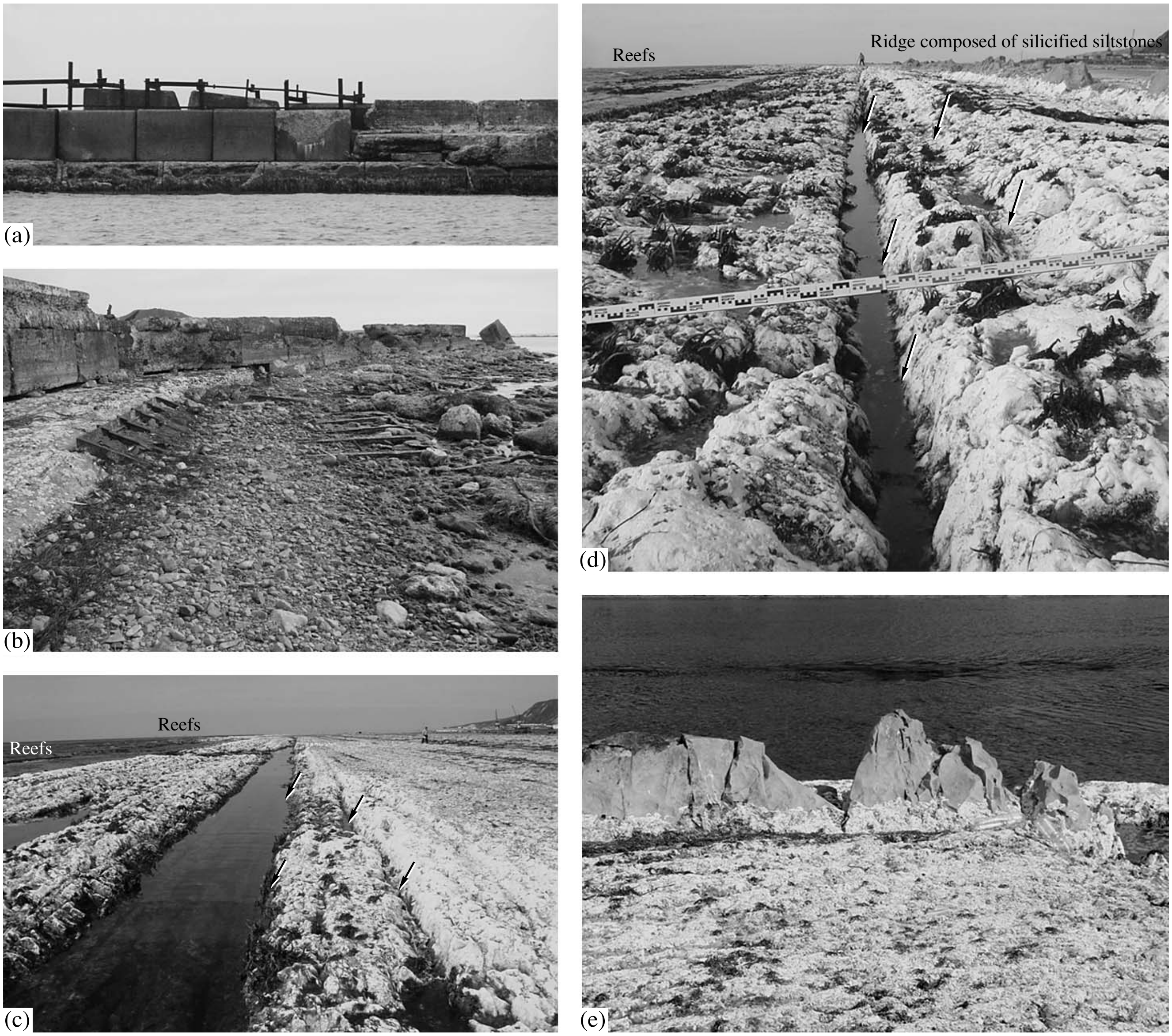

Fig. 8. The northern island bench.

(a) The northern prewar breakwater partly protected by concrete cubes with laminarias on its eastern wall (the photograph was taken at a distance of approximately 20 m from the tugboat kindly provided by the captain of Nevelsk harbor); (b) the narrow beach along the western wall of the breakwater; (c) the depression–ridge microrelief of the bench formed by the steeply dipping Nevelsk siltstones locally displaced for 0.5–1.0 m along the dip of the intrastratal faults (their direction is shown by the arrows here and in Fig. 8d); (d) the north-directed panorama of the bench with the reefs on the left, the ridge of silicified siltstones up to 1 m high on the right, and the longitudinal crack 10 cm wide associated with the intrastratal fault in the center; (e) the detailed structure of the ridge composed of silicified siltstone with an acute fractured crest.

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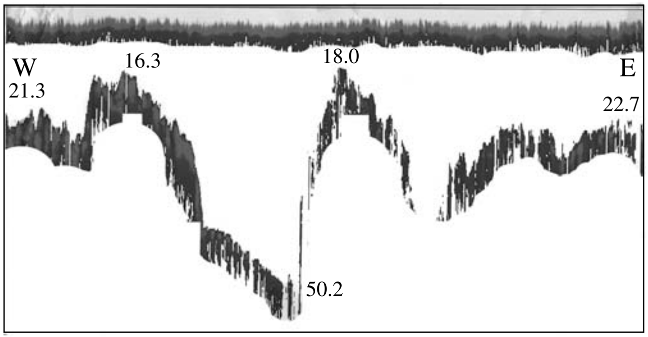

Fig. 9. Echogram 307 of the costal echo sounding on September 6, 2007.
The bottom depths are given in feet. For the echo sounding profile position, see Fig 2.

successful study of this remarkable event in the recent tectonic history of the West Pacific.

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