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Hazard of Submarine Slides West of the Spitsbergen Archipelago

A. O. Mazarovich[a], *, E. A. Moroz[a], and Yu. A. Zaraiskaya[a]

[a] *Geological Institute, Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 119017 Russia*

**e-mail: amazarovich@yandex.ru*

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Abstract—The paper presents description of the relief, open fracture system, and submarine slides west of the Spitsbergen Archipelago in the Vestnesa Ridge area based on the data collected during cruises of the R/V *Akademik Nikolaj Strakhov.* Data pertaining to seismicity, as well as gas flares, chimneys, and holes are given based on the published sources. Analysis of the full information suggests the development of conditions favorable for large submarine landslides west of the Spitsbergen Archipelago.

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INTRODUCTION

Submarine landslides have been deciphered in many areas of the World Ocean: passive continental margins of North America (McAdoo et al., 2000, Twichell et al., 2009), Africa (Krastel et al., 2006), and Europe (Owen, 2013). In addition, they have been identified on slopes of deep-water trenches (Fryer et al., 2004), island edifices (Masson et al., 2002), and other submarine rises.

Thirty-five landslides have been identified at the passive continental margins of Norway, the Spitsbergen Archipelago included. Their area ranges from 2 to 120 ka km^2; dislocation amplitude, from a few kilometers to 500 km; and slide mass volume, from 1 to 25.5 km^3 (Freire et al., 2014; Hjelstuen et al., 2007). The age of landslide motion is estimated at 400 ka to 2.5 Ma (Hjelstuen et al., 2007). It has been confirmed that at least two (Storegga and Hinlopen) slides triggered large tsunamis (Bryn et al., 2005; Vanneste et al., 2010).

Obviously, submarine slides represent a potential and (or) real geohazard in areas with abrupt seafloor gradients. Their identification, forecast of the landslide timing and site, and modeling of consequences represent an urgent issue because of the tsunami hazard.

In the course of expeditions onboard the R/V *Akademik Nikolaj Strakhov* (Geological Institute, Russian Academy of Sciences, 2006–2010) in the northern Greenland Sea and Fram Strait (Fig. 1), we identified an area favorable for triggering a large submarine slide.

The paper only uses submarine topographical names approved by IOC-IHO/GEBCO SCUFN (*IHO-IOC* ..., 2014).

DEVICES AND METHODS

Studies onboard the R/V *Akademik Nikolaj Strakhov* were accomplished using the multibeam deep-water echosounders Reason Seabat 7150 (acoustic signal of 12 kHz over a 150° sector perpendicular to the vessel movement; effective width of the seafloor sweep >8 km at a depth >2000 m; and acoustic signal power 236 dB). Pickup and transmitter antennas of the hydrolocator from 6 transmitter and receiver modules, which guaranteed the 1.5° beam width, were located in a T-shaped pattern on the gondola welded to the vessel hull. It also included an EdgeTech 3300 nonparametric profilograph for mapping the structure of the upper part (50–100 m) of the sedimentary cover with a resolution ranging from 1 to 0.1 m. The maximum signal penetration depth during Cruise 27 of the R/V *Akademik Nikolaj Strakhov* was provided by the frequency-modulated signal ranging from 2 to 6 kHz with a duration of 40 ms. Such parameters guaranteed the signal penetration to a depth of 50–70 m in unconsolidated sediments. The SPARKER-type SONIK-4M3 electrospark source was used to study the structure of the upper sedimentary cover at a depth of more than 100 m. The main working frequency was 200 Hz at a depth of about 2000 m. Signals were recorded with the 6-channel seismic station (SONIK-4M-6).

During the expedition in 2010, NE-oriented traverses (Fig. 1) were deployed across the Molloy Fracture Zone. The southern spurs of the Vestnesa Ridge, northern Knipovich Ridge, and eastern Molloy Fracture Zone were surveyed in 2006. Bands of the hydroacoustic survey were adjusted for their optimal overlapping by operators with the consideration of depths.

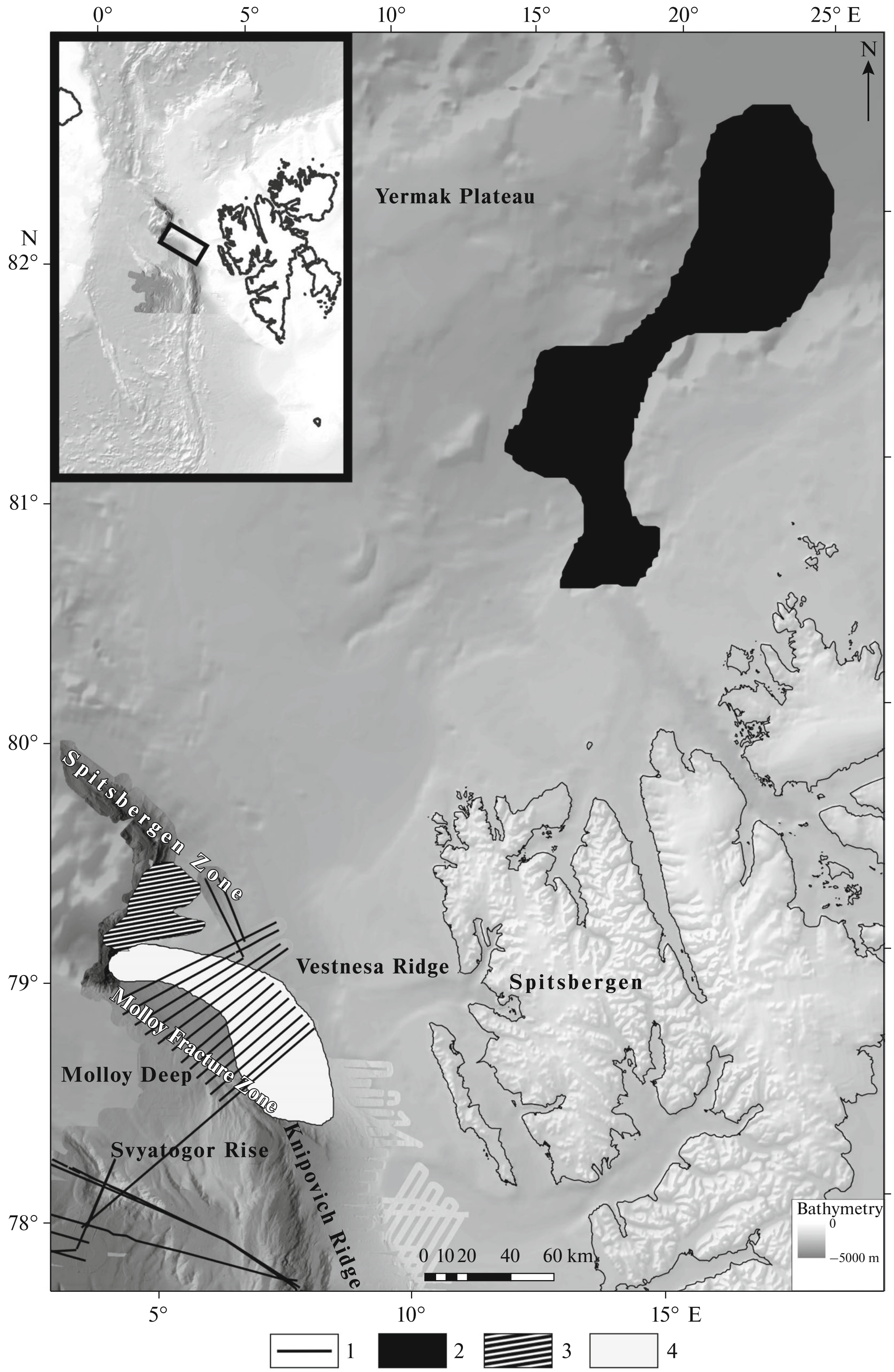

Fig. 1. Topography with the topographic base adopted from (Jakobsson et al., 2012) and positions of submarine slides in the Spitsbergen Archipelago area. (1) Traverses of the R/V *Akademik Nikolaj Strakhov*, (2–4) landslides: (2) Hinlopen, (3) Molloy, (4) inferred. Inset shows the study area.

GEOLOGICAL SETTING WEST OF THE SPITSBERGEN ARCHIPELAGO

The study area is located in the Greenland Sea and Fram Strait (Fig. 1). This area is marked by the transition of structures of the Knipovich Ridge via the Molloy Fracture Zone, Molloy Hole (Deep), Spitsbergen Fracture Zone, and Lena Trough to the Gakkel Ridge in the Arctic Ocean with an ultraslow spreading rate.

The Knipovich Ridge extends in a nearly meridional direction (approximately along 7°30′ E) over more than 500 km from the Mohns Ridge to the transform Molloy Fracture Zone. Its topography, architecture, and deep structure are described in many works (Avetisov and Verba, 1999; Chamov et al., 2010; Crane et al., 2001; Dobrolyubova, 2009; Gusev and Shkarubo, 2001; Kokhan et al., 2010; Peive and Chamov, 2008; Peive et al., 2009; Shkarubo, 1999; Sokolov, 2011; Sokolov et al., 2014; Sushchevskaya et al., 2000; Zayonchek et al., 2010a, 2010b; and others). Spreading rate of the Knipovich Ridge is estimated at 1.5 cm/yr, which matches the ultraslow spreading rate. Its eastern slope is buried beneath a thick sequence of sedimentary material transported from the Spitsbergen Archipelago.

At 78°30′ N, the Knipovich rift valley is united with the Molloy Fracture Zone (Fig. 1). This ridge–transform intersection differs significantly from analogous areas in the Atlantic Ocean. The nodal basin, an anomalously subsided part of the seafloor, is lacking. As seen in (Fig. 1), the western part of the rift-transform junction accommodates the Svyatogor Rise (size 60 × 38 km, minimum depth 1498 m). The northern side of the Knipovich rift valley accommodates depressions (up to 3400 m deep) separated by the NE-striking volcanic rises with peaks at a depth of 2800 to 3000 m. The relative depth gradient is as much as 1 km. The western side of the northernmost depression in the Knipovich rift valley hosts the Greenland–Spitsbergen Sill (about 70 km wide) bordered by the Molloy Fracture Zone and Hovgaard Ridge in the north and south, respectively.

The SE- to NW-striking (123°–125°) Molloy Fracture Zone (Fig. 1) displaces axes of the mid-ocean ridges over more than 120 km and is expressed in the seafloor topography as trench with an asymmetric transverse profile and maximum depth of 2950 m in the axial part. Its southwestern flank hosts a scarp with steepness up to 15° (Fig. 2) and depth gradient up to 500 m. The fracture width is as much as 12 km near the northern termination of the Knipovich rift zone and varies from 3.5 to 4.5 km in the central and northwestern parts. The northeastern wall of the trench lacks clear boundaries and coincides with the gentle slope of the Vestnesa Ridge that extends over 115 km from the northern Knipovich Ridge to the eastern Molloy Hole (Fig. 2).

DISCUSSION

Submarine slides are formed owing to the combination of several factors: steepness and unstable state of slopes, seismicity, and others. Let us examine prerequisites for the motion of landslide masses west of the Spitsbergen Archipelago.

The deepest areas in the Fram Strait are detected in the Molloy Hole (Fig. 1) located 160 km away from the Spitsbergen shelf edge (about 200 m deep). Such areas occur at a depth of more than 5600 m: 5607 m (Thiede et al., 1990); 5669 m (http://en.geomapedia.org/information/molloy-deep.html). The hole has an equant shape and trough-shaped profile. Its diameter is about 35 km in the upper part at a depth of about 2700 m. The hole is bordered from the south, east, and north by straight steep (up to 35°) slopes. The western slope is gentler and terraced.

The Vestnesa Ridge (Fig. 1) represents an accumulative ridge (drift), with the peak located at depth of 1200 to 2100 m. Its width varies from 15 to 30 km. According to (Petersen et al., 2010), the ridge was formed by the northward contour currents in the late Miocene and Pliocene. Deposits are represented by the middle Weichselian and Holocene silty turbidites and clayey–silty contourites up to 2000 m.

Surveys during Cruise 27 of the R/V *Akademik Nikolaj Strakhov* on the southwestern slope of the Vestnesa Ridge made it possible to outline a zone of narrow, en-echelon (sickle-shaped in plan view), seafloor depressions. Steepness of the Vestnesa Ridge slope does not exceed 4° in the zone of depressions that represent a system of NW-striking (335°–345°) subsidence fractures in the upper and middle parts of the slope at a depth ranging from 1100 to 2000 m. Their parameters are as follows: maximum length 30–35 km (width 700–800 m), average length 20–25 km, minimum length 5–7 km, and depth from 15–20 to 40–50 m. Acoustic sections show that the majority of fractures are underlain by dip-slip faults with amplitude up to 300–400 m downward the section (Fig. 3). Their genesis is attributed to the northward displacement of the Knipovich Ridge (Crane et al., 2001).

Landslides and cirques are located on the western side of the southern Vestnesa Ridge slope (Fig. 2). Area of the landslide blocks varies from 8.5–10 to 23 km^2. In total, landslides are observed over an area of more than 500 km^2. Signs of slow slope slide (creep) are recorded east of the Vestnesa Ridge up to the shelf edge.

On the northern slope of the Vestnesa Ridge, a submarine channel (about 60 m deep and 450–500 m wide) was traced from a depth of 1600 m. It downcuts the continental slope and turns along the northwestern direction.

As depicted in (Fig. 4), numerous seismic events were recorded west of the Spitsbergen Archipelago, within the transform Molloy Fracture Zone and hom-

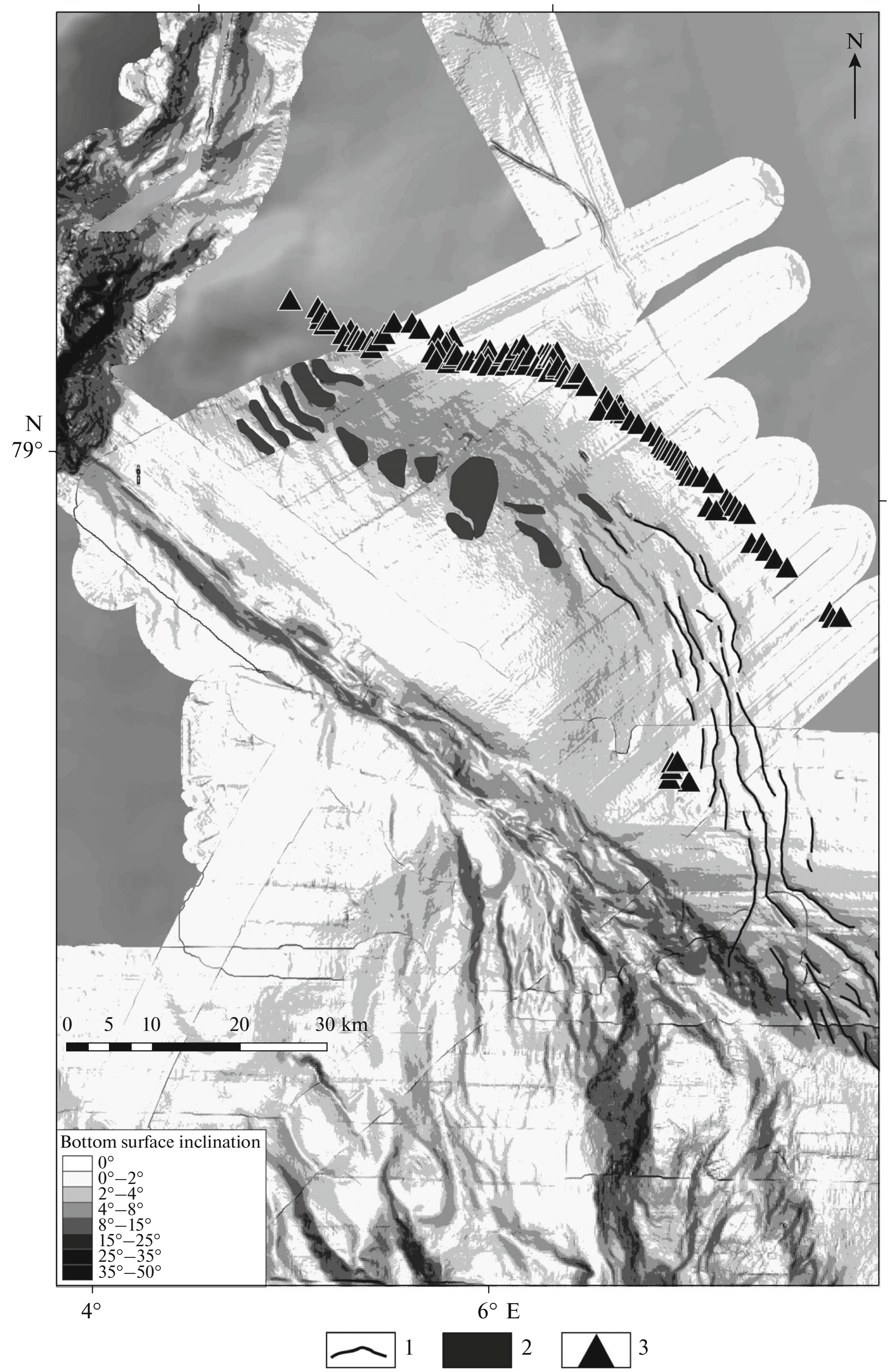

Fig. 2. Map of the seafloor inclination (Moroz, 2017). (1) Shrinkage fractures, (2) landslides, (3) gas flares and holes. Topographic base adopted from the data on Cruise 27 of the R/V *Akademik Nikolaj Strakhov* and (Jakobsson et al., 2012).

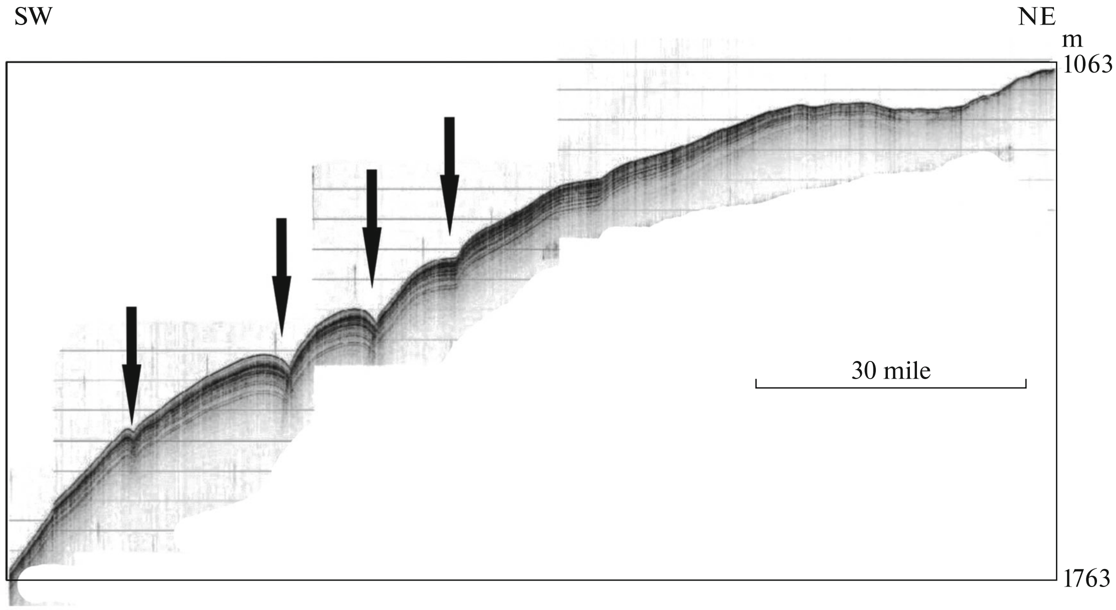

Fig. 3. Shrinkage fractures (arrows) on the southern slope of the Vestnesa Ridge (fragment of profile s27-p3-3, Cruise 27 of the R/V *Akademik Nikolaj Strakhov*).

onymous depression, and on the Knipovich Ridge (Avetisov, 1996; Zaraiskaya, 2016). In 1978–2012, 32 events (M = 3.3–5.7, peak at Mb = 4.6) were recorded in the Molloy Fracture Zone. In the Molloy Ridge area, this period was marked by 36 events (M = 3.4–4.8). Events with Mb = 4.3, 4.4, and 4.7 were most widespread.

A large gas venting province (16000 km^2) was recorded west of the Spitsbergen Archipelago (Vanneste et al., 2005), with the main zone extending along the Vestnesa Ridge summit. Origination of this province is attributed to the destruction of a gas hydrate bed recorded on the basis of seismic data and traced at a depth of about 200 mbsf, where a bottom-simulated reflector was deployed. Gas flares (gas bubble columns) were recorded by direct observations (Bünz et al., 2012). Their position, amount, and gas volume are variable, with the gas flare height reaching 800 m (https://cage.uit.no/news/). Numerous gas hole (pockmark) fields (up to 400 m across) and vertical systems of conduits (chimneys), which crosscut the sedimentary sequences, serve as additional evidence in favor of active degassing in the region. These processes can influence the decompaction of sediments and the formation of spacious areas of the destabilized sedimentary material located on slopes with steepness varying from 4° to 8°–10°, which is sufficient for displacement of the friable material.

CONCLUSIONS

Conditions on the continental slope west of the Spitsbergen are favorable for the motion of a large submarine landslide that can trigger tsunamis. The development of such events can be provoked by the following circumstances:

(i) topographic gradient more than 5 km over a distance of about 160 km;

(ii) sickle-shaped (in plan view) open fracture system;

(iii) slope steepness ranging from 4° to 35° in some sectors;

(iv) seismicity in the Molloy Fracture Zone, homonymous depression, and northern Knipovich Ridge;

(v) active landslides along southern slopes of the Vestnesa Ridge; and

(vi) numerous gas flares, chimneys, and holes that destabilize southern slopes of the Vestnesa Ridge.

This situation calls for the modeling of consequences and prognosis of submarine slides west of the Spitsbergen and, if possible, constant geological and geophysical monitoring of the entire region.

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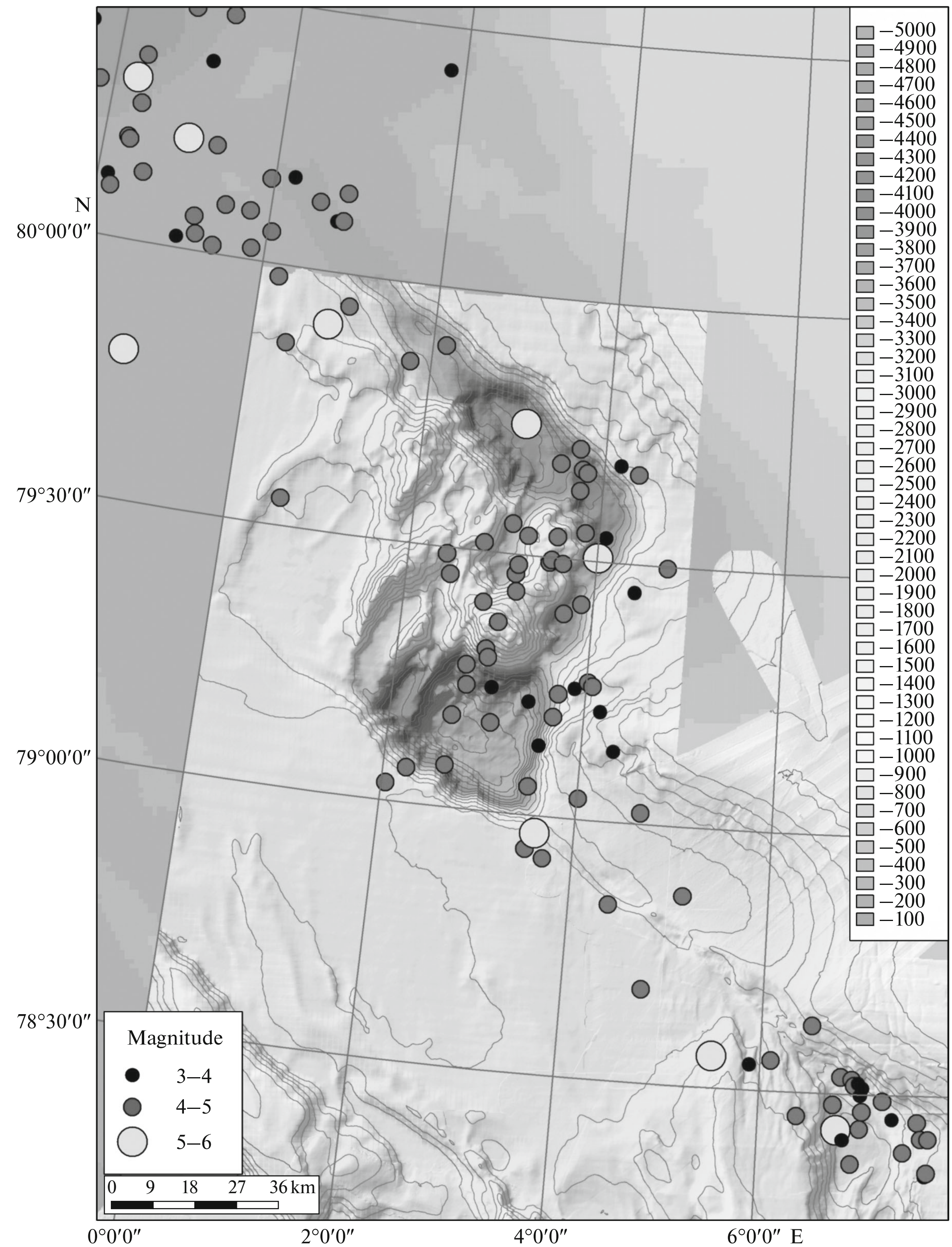

Fig. 4. Earthquake epicenters in the transform fault and Molloy Ridge area (Zaraiskaya, 2016). Topographic base adopted from (Jakobsson et al., 2012; Klenke and Schenke, 2002) and the data on Cruise 27 of the R/V *Akademik Nikolaj Strakhov*.

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