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Endogenic and Exogenic Hazardous Relief-Forming Processes on Sakhalin Island

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Abstract. Endogenous and exogenous relief-forming processes on Sakhalin Island are very dynamic. This can be due to both geological and tectonic (the position of the island on the border of tectonic plates, the predominance of easily destroyed rocks), and geographic factors (including the active interaction between oceanic and continental air masses and altitude). An active Central Sakhalin fault separating microplates provides primary control over seismicity and can have a noticeable effect on mud volcanism. The activity of a mud volcano, taking into account the impact on adjacent valleys, can affect up to 10 km^2. The most common exogenous processes of the island are landslides, avalanches and mudflows. Up to 70% of Sakhalin's territory is subject to these dangerous processes. They are also often triggered by seismic events. It is extremely difficult to predict the exact location and type of activated processes, as well as the time and frequency of their activation. The proposed map of tension in geomorphic systems makes it possible to conduct a reconnaissance assessment of the region, as well as a comparison between individual zones and determine the most dangerous ones.

1. Introduction

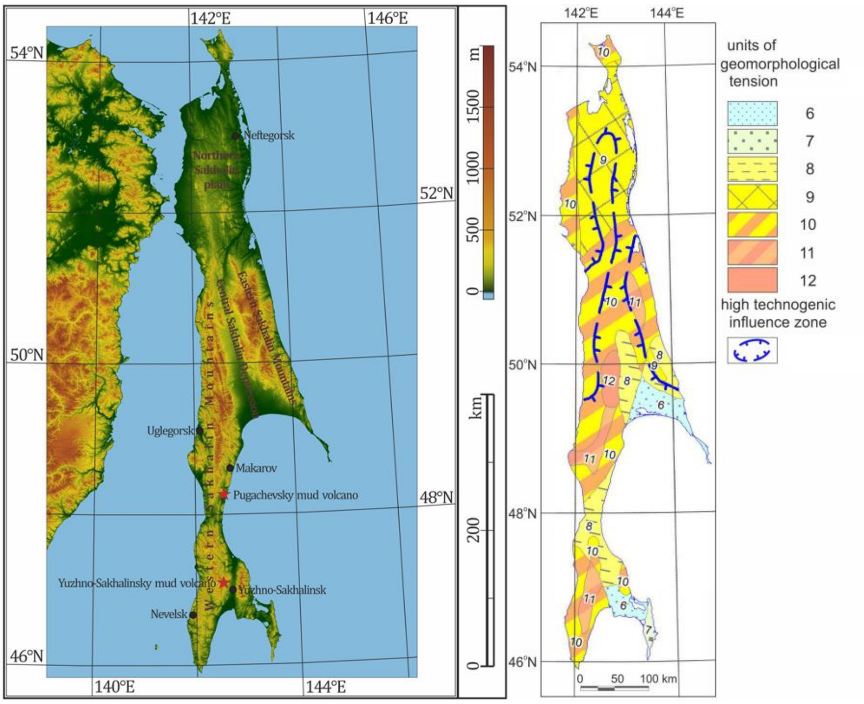
Sakhalin island belongs to a highly dynamic region of NE Asia confined to the boundary between the largest lithospheric plates: Eurasian, North American, and Pacific. Their boundaries are fringed with a large transitional zone consisting of microplates; three of them – Amur, Okhotsk and Kuril ones – are identified within the limits of the studied region. The boundary separating the Amur and Okhotsk micro-plates goes from north to south along the Central Sakhalin fault and divides the island practically in halves [9]. So the island belongs to two micro-plates, and the active fault between them presents the distinctive feature that exerts a control over the principal features of its physiography and relief-forming processes. The relief of the island is modeled both by endogenous and exogenous processes, the assortment and intensity of the latter being controlled by climatic conditions depending on the latitude and altitude of the locality.

2. General features of the relief and seismicity

Sakhalin is confined to the transitional zone from the Eurasian continent to the Pacific Ocean and presents a part of Hokkaido-Sakhalin Rise that corresponds to the Late Mesozoic-Cenozoic fold system. The main orographic units extend approximately along the meridian from north to south and correspond directly to its tectonic structures (Figure, A). Both East Sakhalin and West Sakhalin mountains were subjected to active neotectonic uplifts of the blocks, while the forelands – mostly plains with surface modeled by erosion and denudation – experienced neotectonic uplifts of relatively small amplitude. Typically the mountains are deeply dissected – to a depth of 400–1000 m, which accounts for the steepness and instability of the slopes. The latter develop extremely actively due to gravitational processes. The mountain ridges are separated with a region of tectonic subsidence – a system of intermountain basins belonging to the Central Sakhalin Depression confined to the Central Sakhalin fault and extending from north to south. The amplitude of that overthrust is of an order of many hundreds of meters; the thrust plane dips to the west at an angle of 20 ° to 80°, so that Cretaceous sediments are thrust over the Neogene layers.

During the Holocene numerous seismogenic shifts occurred on the fault [19], including the seismic catastrophe of Neftegorsk in 1995. That earthquake of 7.6 magnitude on the Richter scale completely devastated the oil-producing town on the plain in the north of Sakhalin where more than 2000 people were killed. The catastrophe was quite unexpected, as the region was considered to be of low seismicity. The 1995 Neftegorsk earthquake turned out to be the strongest for all the history of the geophysical observations on the island (since 1909). At present the seismicity hazard was re-estimated, and the island is classed as a region of 6 to 9 points earthquake intensity. An active mud volcanism suggests the fault is living inconspicuously until the time comes.

A



B

Figure 1. Location map (A) and the map of the tension in geomorphic systems (B) on Sakhalin Island. Detail corresponds to a scale of 1: 5,000,000.

3. Mud volcanism

In the Russian Far East, the Sakhalin Island is the only region known to have terrestrial mud volcanoes. It is customary to identify four regions with mud volcanoes on the island [16]. Three of them - the group of Pugachevsky mud volcanoes, Vostochny and South Sakhalin mud volcanoes - are located closely to the Central Sakhalin fault, and are confined to the area of thick (up to 3 km) highly plastic aleurolite-argillaceous series of the Upper Cretaceous system – Bykov suite.

South Sakhalin mud volcano is in the southern part of the West Sakhalin Mountains. Morphologically, it is a gently sloping hill, oval as viewed from above, extended from north to south. It is slightly more than 300 m a.s.l., its long axis being no less than 2 km long. The most important characteristics of the mud volcano activities are the volume of emitted material and the periodicity of eruptions. To take one example, strong eruptions of South Sakhalin mud volcano (with the ejecta volume of the order of 100 000 m^3) occur every 20 years though weaker events may happen in the intermediate period. When moving downslope, the mudflow breaks tree trunks, and having reached the valley floor it can dam a small river for a while, as was the case of eruption in 2001 [14]. The activity of a mud volcano, taking into account the impact on adjacent valleys, can affect up to 10 km^2. South Sakhalin mud volcano is noted for violent gryphon activities; it exudes the gas and the water-mud mixture from the gryphons and salses (usually 10-100 cm in diameter). They are confined to a zone ~300 m long and ~50 m wide which extends along the Central Sakhalin Fault and passes across the volcano. Such a regular distribution of those features suggests a genetic connection of South Sakhalin mud volcano with the fault. GPS data permitted to recognize horizontal and vertical displacements of the Earth's surface during the volcano eruption in 2011 [18].

The Pugachevsky mud volcano group is confined to a gentle-sloped bowl-shaped depression with convex bottom, elliptic in outlines, with axes ~ 2 and 2.5 km [15]. The bottom of the basin is gently convex, the altitudes are 57 m above sea level at the center and about 50 m a.s.l. at the periphery. Glavny (Major) Pugachevsky mud volcano is at the center of the basin, Maly Severny (Small Northern) Pugachevsky volcano is 600 m north of it, and Maly Yuzhny (Small Southern) volcano is 500 m to southeast. The basin is framed with ridges 60-100 m a.s.l. falling steeply down to arcuate valleys encircling that peculiar structure. Such a river network pattern suggests a considerable age of the structure. Quite possibly, it was dome-like initially and looked like a hill. The fact that all the three centers are confined to a single line of ENE direction strongly suggests them to be related to the zone of the Central Sakhalin fault.

The composition of ejected material and intensity of the mud eruption are in a close correlation with seismic-tectonic processes in the Earth's crust [1, 12, 13]. The information on the interrelation between the mud volcanic activity and the regional seismicity has been obtained for South Sakhalin mud volcano. In the period between July 22 and September 30, 2001, a heightened seismic danger was recorded in the south of Sakhalin in a form of an earthquake swarm of magnitude between 1.5 and 4.7 [8]. At the same time the water and mud mixture in the gryphons showed a tendency towards rise of temperature along with an increase in gas discharge. Noticeable changes were also recorded in the topography of the mud field, where a dome developed ~2 m high and about 30 m in diameter. A strong eruption of the mud volcano occurred at the end of December 2001. The monitoring performed in 2005-2007 permitted to identify statistically significant seismic events in the southern part of Sakhalin reflected in the gryphon activities of South Sakhalin mud volcano [2,3]. The first 24 hours after the Gornozavodsk and Nevelsk earthquakes were marked by certain changes in the gryphon and salse behavior.

4. Hazardous exogenous processes

The annual precipitation amount on Sakhalin varies from 500 to 1200 mm on the coasts and from 1500 to 2000 mm in mountains. Typically it increases from north to south (from 500-600 to 800-1200 mm) and is somewhat higher on the eastern slopes of mountain ridges (due to cyclones and typhoons coming from the east and southeast), while in the inner depressions rainfalls are less abundant. On Sakhalin many hazardous exogenous processes are related directly to the abundant, and often heavy, rainfalls. That is true both of fluvial and of slope processes. Among hazardous processes most common are landslides, avalanches, and mudflows. They are constant factors affecting human life and economic activities on the island.

Landslides occur in mountains, on valley slopes, on the river banks and sea coasts; they occur particularly often on the slopes composed of alternating impermeable (water-resistant) layers and aquifers. Up to 70% of Sakhalin area being prone to landslides. More than 50 settlements with more than 150 thousand people and about 1200 km of roads are confined to the endangered areas. The landslide processes are closely related to the geological structure of the region and develop mostly in comparatively young sedimentary rocks. Landslides of Sakhalin may be divided into 4 main types on the basis of the rock lithology, mechanism of development, size and thickness [5, 17]: large block slides and rock slide-falls; landslide of visco-plastic debris flow; slump-debris flow; surface earthflows. There are two periods of the most active development of landslides during the year. The first falls as a rule on the end of May – beginning of June and is due to the soil waterlogging by meltwater. The second period begins in the 2^{nd} half of July and is due primarily to the strong cyclones passing over the island and accompanied usually by abundant and heavy rainfall (more than 50 mm per day). The rainfall is the most significant factor in the landfall occurrence.

The seismic processes can activate land sliding, though no direct correlation between the two phenomena has been recorded. At the time of strong earthquakes (particularly following a long period of rainfalls) block landslides of more than 5×10^6 m^3 volume may develop both in mountains and in the coastal parts of Sakhalin. The sufficient humidity of sediments is an essential condition for landslide activation by earthquakes [5].The analysis of data on precipitations obtained from hydro-meteorological stations with long-term series of observations (80-100 years) reveals a certain periodicity in the onset of conditions for large-scale landslide forming. There are 5 large cycles (with period of 17-21 years) distinguished within a secular cycle of moisture supply on Sakhalin; the large cycles may be subdivided, in turn, into smaller cycles (6-7 years long each, 14 cycles in a century) [4]. The probability of the landslide activation by seismic activities is also higher during those periods.

Sakhalin is one of most *avalanche-prone* regions in Russia. More than 55 settlements and more than 1100 km traffic routes lie within avalanche-hazardous zones. Up to a few thousands of avalanches are recorded yearly in the zones of economic activity and in the settlements during the avalanche season. Accidents with people falling into avalanche occur every year. The amount of precipitation over the winter may exceed 1500 mm. On Sakhalin avalanches develop in mountains at any altitude, from the sea level to the ridge crests, so that about 70% of the area is avalanche-hazardous. Not even forested slopes are avalanche-free: the fir-spruce forest, though somewhat reducing the avalanche frequency, does not prevent their development on the slopes with angles exceeding 35°. Avalanches are known to occur on relatively low slopes – only 10–30 m high. The snow recrystallization is of great importance in the development of large-volume avalanches: in December – May the snow mass slides usually along the layers composed of large ice crystals. The period of avalanche hazard is 5 months long in the coastal part of the Southern Sakhalin to 8 months in the Middle Sakhalin mountains. In most catchments the avalanches form 1 to 5 times during winter. The avalanches are one of the greatest natural hazards. From 1905 to 2018 more than 1365 people were buried under avalanches, 766 of them were killed.

The avalanching is often initiated by seismic shocks, even by weak ones. An analysis of avalanche and earthquake records on Sakhalin over the period of 1945-2018 permitted to find a good agreement between the dates of avalanching and those of seismic events; within the period of mid-December – late March the coincidence is recorded in 85.7% of all the cases. The earthquake intensity in the regions of avalanching rarely exceeded 1–3 units. The distance between the focus of earthquake (of such magnitude) and the region of avalanche development may vary from 20 to 240 km. At 7-8 magnitude and the focus depth up to 30 km, the distance may increase to 350–420 km. A necessary condition for an avalanche initiation by seismic vibrations is a strong recrystallization of the snow mass so that at least one layer in it was metamorphosed to a stage of fiber texture and large crystals. In general, however, probability of avalanching at earthquake of magnitude less than 7 does not exceed 10% [6].

Mudflow descent is another dangerous process confined mostly to stream valleys. They are common on Sakhalin; 19 settlements and more than 500 km of roads are within the endangered regions. The high intensity of mudflow processes on the island may be attributed to the following combination of factors: a considerable depth of the surface dissection, steep slopes and river channel gradients in mountains (35°-50°), rainfalls noted for abundance and intensity (up to 1200-1500 mm per year), wide occurrence of easily erodible and soaked sedimentary rocks in combination with hard rocks; the first group fills the stream with clay particles, the second provides the coarse constituent to the mudflows.

The volume, dynamic characteristics, and recurrence period of the largest mudflows are controlled by geological and geomorphological factors, the climatic factors being of secondary importance. A frequency of large-volume mudflows depends on the rate of the weathering product accumulation in mudflow source area. On Sakhalin the zone of mudflow processes spreads from the sea level to the water divides in mountains (that is, from 0 to 1600 m a.s.l.). The mudflow-prone area amounts to ~50% of the total. There are all the types of mudflows on Sakhalin [6], their volumes being 0.5 to 10×10^3 m^3 on average and more than 500×10^3 m^3 at maximum. The mudflow-forming amount of rainfall on Sakhalin exceeds 50 mm at the rain intensity about 30-50 mm per day. In case the rocks are already wet, the mudflow processes develop after 10-20 mm rainfall in a day. In various regions of the island (different in geology and topographic characteristics, as well as in the rainfall regime and intensity) the intervals of intensive mudflow formation occur once in 3-5 years to once in 10-20 years. The periods of numerous mudflow development occur usually from the 2nd half of July to the middle of October.

In some cases the mudflow may be triggered by an earthquake. But a necessary condition of mudflow formation is the accumulation of loose material (at least 70 cm thick) at the place of mudflow origination. Earthquakes with a magnitude of 4-5 may result in water-snow streams and initiate viscous mudflows. If an overwetted layer (layers) is present in the sequence, a seismic shock of 1-2 magnitude would be sufficient for a mudflow activation [7]. On the whole, the activation of slope processes by earthquakes leads to an increased rate of the loose debris accumulation. In spring earthquakes with a magnitude of 4–5 may bring about flows of water mixed with snow (in case of rains and a sharp rise of temperature) and flows of liquid mud and of slurry with debris. In the south of Sakhalin the most dangerous periods are May to mid-June and August to mid-October. Mudflows of $0.1–0.3\times10^3$ m^3 volume may be activated at that time, though the event probability in case of earthquakes of magnitude less than 7 does not exceed 10%.

5. Discussion and conclusion

We can see from the above that catastrophic processes, both endogenic and exogenic ones, are the most characteristic feature of Sakhalin. That may be mostly attributed to the high seismicity of the region, as well as to the intensive and irregular precipitations. An analysis of spatial distribution of the natural catastrophes led us to the conclusion on the existence of regions prone to catastrophic process development to a greater extent than others, and Sakhalin is certainly among them. And it cannot be a coincidence: transitional zones between the continent and ocean are known for considerable topographic contrasts, as well as for a mosaicity well seen both in the land surface and in the Earth's crust structure. Besides, the present-day endogenic processes (including the seismicity and mud volcanism) are particularly well pronounced there. The climatic characteristics of transitional zones are due to an active interaction between the oceanic and continental air masses. All the above accounts for highly diversified relief-forming processes within the territories under consideration, as well as for their high rates and not infrequent catastrophic situations.

To reveal regularities in the spatial distribution of factors accountable for the relief-forming process activation, we attempted to construct a map of tension in geomorphic systems based on the data on the depth of the relief dissection, assortment of dominant processes, seismicity and precipitation amount [10, 11]. The map made possible an identification of the sites marked by maximum values of the listed factors contributing to the processes activation. In that way we could outline the zones of a higher geomorphological tension, with the highest potential for the development of catastrophic processes. On the basis of relationship between the considered factors, the island was divided into 21 regions. In Sakhalin the geomorphological tension due to natural factors varies from 6 to 12 points (Figure, B). Among the areas of higher geomorphological tension there are Schmidt Peninsula, the North-Western Lowland, some regions in West and East Sakhalin Mountains. There are numerous factors in control of the geomorphological tension, including a wide assortment of dangerous geomorphological processes, a high seismicity, abundant precipitations, a considerable depth of the surface dissection in mountains, and the presence of permafrost marked by a high ice content (North-Western lowland).

The forecast of the considered dangerous processes is of particular importance for Sakhalin; as we have seen, the dangerous processes on the island are highly variable in genetic types and are noted for a high intensity. However, it is extremely difficult as yet to predict the precise location and the type of the processes to be activated, as well as the time and periodicity of its activation. The proposed map of tension in geomorphic systems made possible a reconnaissance estimate of the region and it permits also a comparison between individual zones and determine the most dangerous ones.

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