Vegetation of the Yuzhno-Sakhalinsky mud volcano as an indicator of activity

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Abstract. In the present paper we have addressed the issue of identification of mud volcanic activity based upon the vegetation, its structure and dynamics, as well as the structural peculiarities of woody plants. The study was conducted using an integrated approach which includes: the description of vegetation and the structural analysis of woody plants that grow at various distances from the eruptive centre of the volcano. The obtained data on the vegetation suggest that the Yuzhno-Sakhalinsky mud volcano is a far more extensive landscape feature that it was considered before, with an eruptive centre which changes its location every 150–300 years.

1. Introduction

The activity of mud volcanoes forms unique natural landscapes, their vegetational constituent being represented by various stages of primary succession. The issues of the formation, development, differentiation, and morphology of mud volcano landscapes remain underexplored. There are publications on the matter devoted to the mud volcanoes of Azerbaijan [1], the Kerch Peninsula [2, 3], Sakhalin Island [4, 5, 6], Borneo Island [7]. The landscapes of active mud volcanoes differ markedly from the landscapes of territories within which they are located. At the same time, the landscape complexes of dormant and extinct volcanoes are very similar to the background setting in their main parameters. An important feature of mud volcanic landscapes is their capacity for quick changes, which is to a great extent determined by the volcanic activity – the intensity and frequency of eruptions. An important and relevant objective nowadays is to study the various aspects of the transformation of vegetation, edificatory and dominant species resulting from mud volcanic activity. The solution to this task also opens possibilities of bioindication for the assessment of the state of the natural environment and mud volcanic activity. Interesting findings in this area of research have been obtained for the magmatic volcanoes of the Kuril Islands [8, 9]. In this respect, the paper [3] is also of great interest, since it contains the results of bioindication studies for the mud volcanoes of Crimea. The main phytoindicational properties of the Crimea mud volcanoes have been studied. These are syntaxons which, according to the authors, serve as credible markers of topographical features and indicators of the surface age.

Studies of the dynamic pattern of the vegetation and the “driving factors” of phytocoenosis succession in the mud volcanic landscapes of Sakhalin are scarce. In the study [4] an assumption was made that in the Yuzhno-Sakhalinsky mud volcano with an increase of the age of the
discharged substrata, the range of species is becoming wider. Besides, an increase in floristic abundance and projective cover degree is reported, which is determined by the changes in the chemical properties of the ejected substrata due to the washing-out of salts and other toxic compounds with rainfall and snow-melt waters. Another example is the study [10], where, for the Yuzhno-Sakhalinsky mud volcano, the last eruption of the extinct eruptive centre of the volcano was detected by means of tree-ring analysis. Taking into account the succession rate on the volcano substrate, as well as the age of the trees, an assumption was made about the time of the mud field formation.

The objective of the present study is to reveal the possible causes of the changes in the phytocoenoses, identify their location in time and space in the landscape of the Yuzhno-Sakhalinsky mud volcano, and ascertain the nature of the impact of the specific geochemical conditions on woody plants.

2. Materials and methods
In the present study we have implemented an integrated approach including the description of the vegetation and the structural analysis of woody plants (trees and shrubs) involved in the formation of the phytocoenoses that can be found at various distances from the current eruptive centre of the Yuzhno-Sakhalinsky mud volcano. The geobotanical description of the plant communities and aggregations was performed on testing sites with areas of 1×1 m, 10×10 m and 20×20 m. Standard procedures of geobotanical studies were applied [11]. For the structural analysis of woody plants, in different years (2014–2018), samples of the stems and stalks of dominant and codominant species of the tree and shrub layers of the birch-alder-willow tallgrass forest were selected at different distances from the current eruptive centre of the volcano. The selection and fixation of the vegetative matter for the anatomical analysis were performed under the background conditions and in the landscapes altered by the volcanic activity. The analytical study of the stalks (stems) of trees and shrubs was conducted using the methods of light microscopy and the standard procedure [12].

3. Results and discussion
The Yuzhno-Sakhalinsky mud volcano is one of the largest, most active and extensively studied mud volcanoes of Sakhalin Island. Powerful eruptions were documented in 1959, 1979, and 2001. One relatively mild eruption occurred between 1994 and 1996, another one – in the winter of 2011. Based on the studies of these eruptions, as well as our observations since 2008, a conclusion can be made that the location of the current eruptive centre of the volcano is relatively stable. In the period of time between the eruptions, relatively mild unloading of subsurface fluids occurred in the volcano through the system of gryphons and salses, the majority of which are concentrated in rather a small area – within the current eruptive centre of the volcano. Some of the gryphons are located beyond it.

The findings of the fieldwork conducted in 2017–2018 show that in the direction from the eruptive centre of the volcano the mud field starts to grow over concentrically, and plant aggregations and communities change over time. On the mud volcanic breccias, the age of which is several years, herbaceous non-perennial plants dominate, and later they are superseded by herbaceous perennial plants, the communities of which border on forest vegetation (figure 1). At a distance of about 20–30 m from the active gryphons one can find individual plants Triglochin palustre. This pioneer species of the mud volcano appears 2–3 after a slight eruption, when the ejected substrata cover a relatively small area. In this case the seed sources are located quite close. The colonization of vast mud fields by Triglochin palustre (which was the case after the 2001 eruption) can only be observed no sooner than 5 years later.

Further, at a distance of 60–100 m, free-growing aggregations of this species can be found, evolving into a pioneer mono-community with a projective cover degree of 5–10 %. The species
Figure 1. Drone image (DJI Phantom 4 PRO), taken in September 2018 by R.V. Zharkov (Laboratory of Volcanology and Volcanic Hazards, Institute of Marine Geology and Geophysics FEB RAS). In the central part of the shot: the current eruptive centre and breccias flowing in NW direction after 2001 eruption.

Triglochin palustre in the community grow in small shrubs (grass sod), colonized by green mosses. Further away from the eruptive centre, at a distance of 120–150 m, they are superseded by the communities of Phragmites australis. At a distance of 180 m and further away these phytocoenoses come close to the boundary of small-leaved mixed wood – birch-alder-willow composition, with some species of Picea ajanensis, Abies sachalinensis and Larix cajanderi. At the present time, the phytocoenoses Phragmites australis containing mixed herbs (with perennial short- and long-rooted grasses) populate the substrata ejected by the volcano in 2001. There are herbaceous perennial and non-perennial species: Plantago major, Tussilago farfara, Sonchus arvensis, Anaphalis margaritacea, Taraxacum officinale, Aster glehni, etc. There are also elements of tall herbaceous vegetation: Senecio cannabifolius, Petasites amplus, Cirsium kamtschaticum. In the area of contact between the grassy and forest communities, the 2001 substrate is being colonized by small-leaved trees. In this zone, including a massive flow of ejected breccias in the N-W direction, sporadical seedlings and small-sized new growth (understory of up to 1.5 m) of woody plants can be observed. These trees include such species as Betula ermanii and Betula platyphylla, Salix caprea, the shrub Rubus sachalinensis. 17 years after the eruption, Triglochin palustre still grows predominantly in the centre of the flow formed by the 2001 breccias, whereas Phragmites australis dominates throughout most of the flow with a projective cover degree of 30–60 %. Here, on relatively flat microlrelief, negative in form, green moss synusias are abundant. They serve as a favourable environment for the germination of woody plant seeds. The emergence of the first seedlings of woody plants on the breccias occurs
as early as 10 years after the eruption, but in this setting the survival rate is quite low, so the average age of the undergrowth in 2018 was only 2–4 years. It is worth noting that there are no lichens in the pioneer herbaceous phytocoenoses within the current eruptive centre. They are also not to be observed on the overgrown breccias 17 years after the eruption. Lichens typical of secondary mixed woods of Sakhalin already occur on tree trunks in forest communities at the boundary of the current eruptive centre of the volcano. 

It is to be supposed than in the context of the long (over 20 years) absence of a powerful eruption within the current eruptive centre of a mud volcano, the phytocoenosis Phragmites australis will be present. We believe that after 50–70 years, due to the joint activities of abiotic factors and biota, old mud fields become suitable for forest vegetation. 

Mixed small-leaved wood occupies vast areas around the eruptive centre of the volcano and is represented by different varieties: with a predominance of the willow, Alnus hirsuta or Betula platyphylla, as well as certain variations of herbaceous and fruticulose layer. For instance, birch-and-alder tall-grass aggregations include single-species synusias of tall grass consisting of Cacalia robusta, Filipendula camtschatica, Petasites amplus, occupying an area from 100 m² to 500 m², as well as fruticose synusias consisting of Eunynmus sachalinenis. In birch-alder bamboo aggregations, synusias Sasa kurilensis interchange with tallgrass woodreed. The presence of Picea ajanensis and Abies sachalinenis in the forests is fragmentary and sporadic. On very small plots, abies-spruce and spruce-abies communities feature small-leaved tree species, tall shrubs in the understory, with a predominance of woodreed, ferns and Sasa kurilensis in the herbaceous and fruticulose layer. According to our data, the phytocoenoses (including forest communities) that have been formed at the boundary of the current eruptive centre, grow in the setting of sodium carbonate salinization. 

At the boundaries of forest communities, new gryphons and salses can be formed and dormant ones can get activated (after a quiescent period of 15 years or more). Depending on their activity rates, this can lead to the loss of specific trees: first of all coniferous species – such as spruce and abies, later – deciduous ones, in particular, birch and rowan (or mountain ash). The best survivability in this respect is demonstrated by Alnus hirsuta. However, in the setting of the long-term and sufficiently regular activity of a new gryphon or salse, individual trees can die in this zone, and later so does the overall forest community. On the ejected breccias of the new gryphon or salse, primary succession begins, where herbaceous communities will be superseded first by small-leaved forest, and then by abies-spruce forest. 

In the studied forest communities formed in the northern, north-western and western parts of the mud volcano, the age of deciduous trees (alder, birch and willow) is much greater (up to 180 years), than that of coniferous trees (abies, spruce, larch), the average age of the latter being only 60–75 years. Coniferous trees participate in the formation of the forest stand of these communities, serving as “foreign” inclusions. Of all woody vegetation, the first plants to colonize the sediments of a mud volcano are small-leaved trees, and coniferous trees will be emerging in such communities much later. Thus, at the present time, on the plots located at a distance of 250–1000 m from the current eruptive centre of the volcano, we can observe one of the stages of succession on mud volcanic sediments, which will later develop into a zoned abies-spruce forest. The correlation between the age of coniferous and small-leaved trees, as we believe, is crucial for assessing the age of the phytocoenosis and the breccias discharged by the mud volcano, as well as for detecting mud volcanic activity.

The structural macro analysis of tree trunks at a height of 50 cm from the soil level, which we performed in different parts of the mixed small-leaved forest surrounding the current eruptive centre of the volcano, proved that trees growing on the sediments of mud volcanic breccias possess a number of structural peculiarities. With commeasurable trunk diameters (Alnus hirsuta, Betula ermanii, Betula platyphylla, Sorbus commixta, Larix cajanderi), their age in the setting of a mud volcano is 1.5–2 times greater; there are also irregularities and non-uniformity in
the formation of annual increments of wood. This indicates that these plants grow under the conditions of abiotic stress, which results in the formation of structural anomalies in the stem (trunk), as opposed to the the regular development of bark and wood tissues.

The structure and composition of vegetational forest communities, the age structure of the tree layer, the presence of mud volcanic clays (shales) in the pedologic horizons under these communities – all this suggests that the Yuzhno-Sakhalinsky mud volcano is an extensive territory represented in the landscape by low irregular hills colonized by various types of mixed small-leaved or dark coniferous forest communities, which represent different stages of the regeneration of climax abies-spruce forests. The presumed boundaries of the mud volcano encompass a territory extending for 1 km from W (the river Alat) to E and several km from N to S, and for their specification and correction further research is required.

4. Conclusion
The vegetation of the Yuzhno-Sakhalinsky mud volcano possesses a complex mosaic-like structure and is represented both by grassland in the first stages of primary succession, and woodland – by various mixed small-leaved and dark coniferous communities. Not only does the vegetation here go through the main stages of primary succession, when the ejected mud volcanic breccias start growing over, but it is also prone to transformations as a result of the reactivation of individual gryphons and salses at different development stages of small-leaved and abies-spruce communities.

The distribution of the phytocoenoses in the current centre of the mud volcano demonstrates zonality, which manifests itself in the succession of the plant aggregations and communities – from herbaceous monodominant communities to complex secondary forest communities. Since the 1900’s, the forestland of the Yuzhno-Sakhalinsky mud volcano has been exposed to severe man-caused impact, which contributes to the inhomogeneity of its structure and composition. This impact includes the wood felling during the construction of the railroad, as well as the forest fires and the massive afforestation in the 1950–1970s.

The Yuzhno-Sakhalinsky mud volcano is probably a much more extensive landscape feature, with an eruptive centre that changes its location every 150-300 years.

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References
[1] Kerimova E J 2009 ANAS Transactions. Earth Sciences 3 53–59
[2] Korzhenevsky V V and Klyukin A A 1991 Feddes Repertorium 102 137–150
[3] Korzhenevsky V V and Kvitnytska A A 2009 Natural Almanac. Biological Sciences 12 155–165
[4] Korznikov K A 2014 Tomsk State University Journal of Biology 1 56–65
[5] Korznikov K A 2015 Bulletin of Moscow Society of Naturalists. Biological series 120 61–68
[6] Korznikov K A 2015 Moscow University Biological Sciences Bulletin 70 99–103
[7] Ting T M and Poulson A D 2009 J. Trop. For. Sci. 21 198–209
[8] Kopanina A V 2016 Bulletin of the Botanical Garden Institute of the FEB RAS 15 36–38
[9] Kopanina A V, Vlasova I I and Vacerionova E O 2017 Bulletin of the FEB RAS 1 88–96
[10] Mel'nikov O A and Sabirov R N 1999 Geology of the Pacific Ocean 18 37–46
[11] Ipatov V S and Mirin D M 2008 Phytocenosis description: Methodical recommendations. (St. Petersburg: SPbU Publ.) p 71
[12] Barykina R, Veselova T, Devyatov A, Dzhaliilova K, Iljina G and Chubatova N 2004 Manual on botanical microtechnique. Basic principles and methods. (Moscow: MSU Publ.) p 312