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From the strait to the meromictic lake: water bodies of fjard and skerry coasts, their relief, hydrological features, and ecological communities (on the example of Lake Kislo-Sladkoe, Karelian Coast of the White Sea, Russia)

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ABSTRACT. The purpose of the study is to reconstruct the evolution of bodies of water on the fjard and skerrie shores by their uplift. The object of the study is the Lake Kislo-Sladkoe on the Karelian Coast of the White Sea (Russia). It was established that Lake Kislo-Sladkoe was a narrow strait with fast tidal currents up to 600-500 years ago; about 100-150 years ago it became a semi-enclosed lagoon; and since the 1960s the isolation progressed to such a stage that communication with the sea is now limited to monthly reflux of sea water during syzygy tides. Most of the time the lake is stratified, autumn mixing occurs on average once every two years during autumn storms. In the period between these cases the lake stays meromictic with the brackish communities in the upper layer, high amount and biomass of the several eurybiontic species below the halocline, high density of sulfur bacteria on the border of aerobic and anoxic zones, and anaerobic bacterial community in the bottom water. In the previous marine strait the water was totally homogeneous, saturated with the oxygen, and represented typical marine environment. Such dramatic changes occur due to the postglacial uplift of the coast (1-4 mm/year) and closure of bays and straits by coastal accumulative landforms. The emergence of small bars and spits can accelerate the separation of these bodies of water from the sea by 100-150 years.

Keywords: coastal morphodynamics, fireards, skerries, meromictic reservoirs, DEM, White Sea

1. Introduction

The fjaʳd and skerry shores occupy at least 5% of the coastline of the World Ocean. They gravitate toward the outskirts of the Pleistocene ice sheets. The coasts of this type are composed of solid rocks, and glacial forms and sediments occur mainly on the seabed (Kaplin, 1962, Bird, 2008). Erosion of loose sediments in the coastal zone is caused by the action of waves, tides, fast ice and biogenic processes (Romanenko et al., 2012). Due to glacioisostatic adjustment and tectonic movements, the shores now rise with the speed of up to 11 mm / year (e.g., Johansson, et al., 2002). Sea bays and straits rise above sea level, turn into meromictic lakes and lagoons, and then into freshwater lakes and swamps. Isolation basins are the main source of paleogeographic information, including an archive of data on fluctuations in relative sea-level (RSL). Therefore, it is important to know the mechanisms of isolation of water bodies from the sea and the time nesesseary for different marine areas to be isolated. This problem has been resolved for the meromictic Lake Kislo-Sladkoe (66°32′54″ N; 33°08′05″ E, Rugozerskaya Bay, Karelian coast of the White Sea, Russia).

2. Methods

The main method for reconstructing the relief development history is a detailed study of the morphology of the seabed, coastal zone, and elevated terraces. Tacheometric, geomorphological and UAV surveys were carried out on the coasts of the Rugozerskaya Bay. Bathymetric studies were carried out in the bay and the lake Kislo-Sladkoe. The grain

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size analyses of modern sediments obtained from the sea and lake bottoms, tidal flats, beaches, and coastal terraces were also undertaken. A combined digital elevation model (DEM) of the coast and the seabed, geomorphological maps and detailed orthophoto images of the surroundings of Lake Kislo-Sladkoe were compiled.

The lake has been monitored since 2010. Measurement of physicochemical parameters were provided at the point with the maximum depth of 4.5 m. Salinity and temperature at different depths were determined in situ by WTW Cond 197i or YSI Pro probes, or in water samples taken by Whale Premium Submersible Pump GP1352. The hydrogen sulfide boundary was determined by smell in combination with the determination of the redox potential by the portable WaterLiner WMM-73 device. Phytoplankton and other microorganisms were studied at the different depths, the benthos was sampled with the grabber along three radial transects from the deepest point to the shore.

3. Results and discussion

Analysis of DEM and modern bottom sediments showed that moraine hills exist at the seabed of the Rugozerskaya Bay. As a result of the continued uplift, hills (bathymetric maxima) gradually elevated to within the wave impact zone. In the coastal zone, hills become small islands and capes. The speed of tidal currents between the islands can be more than 1 m/s. Glacial deposits undergo significant selective erosion (Romanenko et al., 2012). As a result, "boulder coatings" or well-washed coarse-grained sands appear at the bottom of the straits and near the capes. An ancient strait with a "boulder pavement" at the floor adjoins the modern basin of Lake Kislo-Sladkoe from the west. A small sand spit gradually severed the lake from the north. The current height of these landforms and data on the rate of modern uplift 3-4 mm/year (Romanenko, Shilova, 2012), allow us to estimate the time of events as 600-500 and 100-150 years ago. According to the observations of the White Sea Biological Station of Lomonosov Moscow State University employees, the spit finally closed the lake in the 1960s. Reconstruction is confirmed by the results of analytical studies of bottom sediments of Lake Kislo-Sladkoe (see the article by O.S. Shilova et al. in this journal), as well as maps from the 1833 and 1960s.

Currently, the Lake Kislo-Sladkoe has a mark of 0.7 m above the sea level. The waters of spring tides enter it through a narrow rocky barrier on the east of the lake basin. Most of the time water flows from the lake to the sea, and in syzygy at the highest tidal phase, water flows backward. The amount of the entered seawater usually is insufficient to disrupt the stratification. Intrusions drop to the depth with an equal density, which in summer is situated above the chemocline. However, in late autumn and early winter, especially when the sea cools to the freezing temperatures, and salinity increases, incoming sea water sinks to the bottom and can displace bottom water. This happens about once every two years. In ordinary years, ice appears on the lake early and prevents the sea water inflow, in this case the stratification established in the summer stays through the winter. This results in a two-year quasi-cyclical pattern.

In the summer, Lake Kislo-Sladkoe is always stratified. According to the hydrological, hydrochemical and biological properties the vertical structure can be divided to 5 layers. 1) The upper 1 m is the zone of wind mixing (mixolimnion), desalinated by the freshwater income from the catchment, and melting of ice and snow. 2) Halocline is located at the depth of 1 m. 3) Underlying salt water by the depth of 2.5-3.5 m is aerobic, sometimes oversaturated by oxygen up to 300% due to the phytoplankton photosynthesis. 4) Chemocline with the sharp gradient between aerobic and sulfide zones. A layer of red water with the cryptophyte flagellates *Rhodomonas* sp. often occurs here qualified as hyper blooming (Krasnova et al., 2014). Most of the bacterial processes reach here the highest intensity (Lunina et al., 2013; 2016). 5) The lower anoxic layer accumulates organic matter, sulphides, and nutrients, that are stored here inaccessible to aerobic organisms, including phytoplankton, before the sudden cases of autumn mixing.

Communities of different layers differ not only by microorganisms, but also by zoobenthos. The upper shallow layer is inhabited by somewhat depleted fauna of the marine littoral zone, enriched by insect larvae, mainly dipterans (Mardashova et al., 2020). The middle salt aerobic layer of water contacts with deeper areas where two species of marine organisms (gastropods *Hydrobia ulvae* and oligochaetes *Tubificoides benedeni*) and tolerant to salinity larvae *Chironomus* gr. *salinarius* reach a very high biomass exceeding that in neighboring marine areas. In the lower anaerobic layer only single individuals of nematodes resistant to hydrogen sulfide were found.

4. Conclusions

1. On the fjard and skerry coasts, straits and bays are separated from the sea due to glacioisostatic and tectonic rise, as well as the appearance of small accumulative forms; the source of sediments input is the erosion of glacial deposits.
2. At RSL +3-4 mm/year, and the amplitude of tide is ~2 m, plugging with accumulative forms can accelerate the isolation of basins for a period of 100-150 years.
3. The contribution of coastal processes should be taken into account during paleolimnological reconstructions.
4. Current physico-chemical and biological vertical structure differs from the initial marine one by strong vertical stratification, depleted fauna with high quantitative values, and the massive development of microorganisms. Due to insufficient isolation from the sea vertical stratification is periodically violated.

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