Evolution of a paleolake on Russian Island (Sea of Japan) in middle-late Holocene: record of sea-level oscillations, extreme storms and tsunami

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Abstract. The diatom algae from sediments of a paleolake serve as records of changes to environments over the last 7500 cal yr. The lagoon lake formed when the sea level approximately corresponded to the present-day position. Evolution of the paleolake was controlled by sea-level oscillations and humidity changes. Eight stages have been distinguished. During a dry episode in 7330–7090 cal yr BP the lake size decreased. The salinity reached maximal values at the Holocene transgression peak. Three stages of a higher salinity are recognized (6750–6500, 6080–5830, 5420–5090 cal yr BP). A severe flood occurred in 6080–6000 cal yr BP. The brackish water lake existed in ~5090 cal yr BP and the freshwater lake in ~4090 cal yr BP. A prolonged phase of decreasing humidity, associated with a weakening of summer monsoons, led to a drop in sedimentation rates in ~3510 cal yr BP. Peat accumulation started at the Little Ice Age. The lake was transformed into a swamp during drop in precipitations in ~270 cal yr BP. Presence of marine diatoms typical in bay and deep-water forms are evidence of influence of extreme storms and tsunami. The age of the paleotsunami coincides well with the regional data.

1. Introduction

Small lakes and peatlands located on the seashore are among the most informative of natural archives that record information on climate change, related sea-level fluctuations, and the manifestation of extreme hydrologic events such as severe storms and tsunami [1 – 3]. The study of lake sediments makes it possible to reconstruct changes in the climate and natural environment with high-resolution. The paleolakes occupy a special place among such objects and are widespread on the islands of the Russian Far East. Studying such objects show their high-information content for the study of the climate and the manifestation of tsunami and other anomalous processes [4 – 6]. Shore lakes and lagoons are considered as having favorable conditions for calm sedimentation, where paleo-tsunami deposits are well preserved [7], and sea surges during severe storms caused by strong typhoons are also recorded in detail [3]. The flooding of coastal areas by sea water during extreme storms and tsunamis has a significant effect on the natural course of the development of many landscape components. A comprehensive study of the traces of catastrophic events occurring not only in the
present, but also in the prehistoric past, makes it possible to learn about their recurrence, run-up height, and the range of the penetration of sea water into the land in order establish the degree of influence of sea flooding on natural systems and to estimate the course of their further development.

It is especially important to study paleoclimatic records and natural disasters in the paleo-lake sediments on islands that are actively involved in land use and have great prospects for economic growth. Located in the Russian Far East, Russian Island, which is part of Greater Vladivostok, has such a significance. The island was actively developed in the second half of the 19th century and has been more actively developed since the construction of the Vladivostok fortress in the early 20th century [8]. The 2012 Summit provided a new impetus for the development of this territory. Presently, the island is connected by a bridge to the mainland, making it more accessible. The buildings of the Summit were transferred to the rapidly developing Far Eastern Federal University, and additional infrastructure was built. International economic forums and summits are regularly held there, island is actively used for recreational activities. Prospective economic development of the island will inevitably also lead to further transformation of its landscapes [9].

The aim of this study is to analyze the evolution of the paleolake on the coast of Russian Island and to assess the possible impact of climate changes and sea level fluctuations on the coastal development and reconstruction that has occurred after extreme hydrological events in the middle-late Holocene.

2. Material and methods
Reconstruction of paleolake development was based on studies of the lagoon terrace sequence (42°59.061’ N, 131°47.107’E) on the Krasnaya Bay coast, southwest of Russian Island (figure 1). The lagoon terrace (2 m high) is located behind the storm ridge (~3.5 m high) and is composed of pebbles and boulders. The size of the paleolake was 400 m long and 160 m wide. The section contains light-gray, non-stratified silty clay (2.4 m in thickness), overlying a layer of peaty clay (0.10 m), and peat (0.4 m) at the top. Samples were collected for every 5 cm.

![Figure 1. Study area and position of the studied section. A – the north-western part of the Sea of Japan showing the location of some bays mentioned in text. B – the location of the Peter the Great Bay and Russian Island. C – the location of the Krasnaya Bay and position of the studied section. C – the location of the swamp, developed on the place of paleolake, and position of the studied section. 1 – state boundaries, 2 – studied section.](image)

Diatom samples were prepared using the standard procedures [10]. The species composition of diatoms was determined in permanent slides using an Axioscop microscope at 1000x magnification.
More than 250–300 frustules were counted in each slide. The number of diatom frustules per 1 g of air-dried sediment was counted. Diatom species were identified using atlases [11 – 13]. The data from studies by Tsoy and Obrezkova [14] were used. The main taxa indicative of environmental changes are shown in the figure 2.

The sediment age was determined by radiocarbon dating of peat and peaty clay samples performed at the Institute of Earth Sciences, St.-Petersburg State University. The radiocarbon dates were converted into calibrated ages, using OxCal 4.3 software, with a calibration curve IntCal 13 [15]. The age of the deposits exposed at the base of the section is estimated to be 7500 cal yr BP, which corresponds to the Holocene transgression, during a period of time the sea level was approximate to the present-day sea level [5, 16]. The age-depth model of the section is based on linearly interpolated ages that are between the calibrated radiocarbon ages and an estimated date from base.

3. Results and interpretation

A total of 259 taxa of freshwater and 90 marine, brackish-water, brackish-water and brackish-water-freshwater diatoms were identified in the sediments of the studied section. Among the freshwater diatoms, bottom species predominate (146), epiphytes are represented by 99 species, and planktonic and temporarily planktonic are represented by 14 species. Salinity data are known for 227 species; oligogalobes predominate, among which species of indifferent dominate (151), followed by halophobes – (44), and halophiles (32). With regards to the pH, information is available for 236 taxa, among which circumneutral species (96) and alkaliphiles (84) were found in approximately equal amounts, and 56 species are acidophiles. Within the relationship to the geographic distribution, cosmopolitans dominate. Among marine and coastal-marine diatoms, benthic species predominate (80), and plankton species are represented by 10 forms.

Changes in the diatom composition allowed us to distinguish eight assemblages corresponding to the following stages in the development of the paleolake (figures 2, 3).

Figure 2. The stages in the development of the paleolake, distribution of different groups of diatoms within relationship to salinity and key species.
7500–6750 cal yr BP: A lake of the lagoon type had formed at mouth of the stream on the Krasnaya Bay coast when the sea level was approximately similar to present-day sea level [16]. The lake was separated from the sea by a barrier bar. It was inhabited by a mixed diatom flora dominated by freshwater epiphytes (77%–95%). The dominant species (Staurosira venter, up to 52.4%; Pseudostaurosira brevistriata, up to 41.5%; P. elliptica, up to 22.2%; and Staurosira subsalina, up to 11.9%) are typically present in shallow lakes and rivers that are overgrown with aquatic plants and are also quite common in lagoons [17]. The littoral diatoms are dominated by benthic, brackish-water species. A lower content of diatom frustules in the middle part of the interval suggests that, the size of the water body probably decreased in 7090–7330 cal yr BP. Coastal-marine diatoms include 32 taxa, and benthic, brackish-water species prevail (17 taxa). The content of coastal-marine diatoms at the base of the section is less than 7.3%. Navicula peregrina, Campylodiscus echeneis, Gyrosigma strigilis, and Diploneis pseudovalis are common. Significant fluctuations in the content of coastal-marine diatoms (7.2%–18.6%), due to an increase in the content of Navicula peregrina (18.6%) are characteristic of estuaries and are often observed at the top layer. Such changes are indicative of more active hydrological conditions and suggest a transition from lake to lagoon in the evolution of a water body in ~ 6840 cal yr BP under conditions where the sea level was rising. This is confirmed by the presence of benthic Tryblionella granulata, which is typically found in bays. The largest number of marine and brackish species are found at a depth of 2.50-2.55 m, where Amphora proteus, Diploneis smithii, Pinnunavis yarrensis, Caloneis westii, Halamphora coffeiformis, and spores of Chaetoceros, which typically live in bays, are found. Neritic Thalassionema nitzschioides is also found here. Such changes indicate seawater inflow that can be associated with a severe storm.

![Figure 3](image-url)  
**Figure 3.** The stages in the development of the paleolake, distribution of different groups of diatoms with regards to habitat, biogeography, mineralization and the pH.

6750–5090 cal yr BP: The lake converts into a lagoon distinctive for its high species diversity (66 taxa) and has a considerable proportion of littoral diatoms (up to 68%). Thermophilic diatoms become more important, which confirms the attribution of the deposits to the Holocene optimum. An alternation of dominant species likely occurs due to the changes in the lagoon water salinity. A conspicuous increase in the number of planktonic Aulacoseira granulata, along with Staurosira
construens, and Cymbella aspera might be related to a severe flood at 6080–6000 cal yr BP. Relative changes in the abundance of freshwater and coastal-marine species allowed us to distinguish between several phases in the development of the lagoon: three phases with a higher water salinity (6750–6500, 6080–5830, and 5420–5090 cal yr BP) and two phases corresponding to a freshened and more isolated water body (6500–6080, and 5830–5420 cal yr BP). We noted a trend towards a lower proportion of littoral diatoms in the deposits from the “marine” phases, ranging from 68% during the first phase, to 30% and 20% in the subsequent phases, respectively. The two earlier phases approximately have of the same duration and coincide well with minor transgressions of the middle Holocene [16]. The sediments include neritic Thalassionema nitzschioides; its fragments were likely brought into the lagoon by strong storms (6750–6650, and 6580–6500 cal yr BP). The greatest influx of marine water into the lagoon occurred at the beginning of the third short-term “marine” phase. The deposits from that interval show an increase in the proportion of littoral species, along with occasional fragments of deep-sea Thalassiosira sp. and planktonic Paralia sulcata, that is typical of bays. The recorded changes in the composition of the diatom species are indicative of an active water exchange between the lagoon and the sea. The sea level was seen to be lower during that period [5, 16]. The salinity is likely to have increased as the barrier bar was partially destroyed by an extremely strong storm or a tsunami.

Some intervals marked by a stronger marine influence on the freshened lake, such as ~6500–6330, and 6250–6080 cal yr BP. The deposits from those intervals yielded Tryblionella granulata and T. lanceola, which could have been brought into the lagoon only by extremely strong storms or tsunamis. The amount of diatom frustules present in those sediments is lower (2–9 million/g), probably due to a considerable admixture of terrigenous material. Changes in the composition of diatom species suggest a decrease in salinity in ~5830–5420 cal yr BP, which occurred as the sea level dropped.

5090–4840 cal yr BP: The lagoon became a semi-closed body of water, containing slightly brackish water. The list of coastal-marine diatoms is reduced to 50 taxa; all taxa are few, and their total content decreases (to 6.6%–7.3%). The content of frustules in sediments exceeds 1183 million/g. The marine littoral diatom proportion increases up to 14.1% in the sand lenses (depth 2.51–2.55 m). The interval is noted for the greatest number of marine species (13), their proportion (6.2%) is much greater than in the enclosing silts (<2%). Fragments of oceanic and neritic Coscinodiscus marginatus, Thalassiosira eccentrica, and Thalassionema nitzschioides are observed. The low quantity of frustules in the deposits (9.4 million/g) is connected to terrigenous dilution and a coarser composition of grain size. We proposed that this material was presumably deposited by a paleo-tsunami in ~5000–4920 cal yr BP.

4840–4340 cal yr BP: The lagoon becomes increasingly freshened. Among freshwater diatoms, the content of indifferents reaches 84.1%, and the proportion of halophiles decreases to 12%. Among the dominant are Pseudostaurosira brevistriata and P. elliptica, which are both tolerant of a wide range of electrolytes in water [13], prevail. The proportion of the bottom species of the genera Navicula and Nitzschia, which are widely distributed in lakes, has increases. A diversity of rheophilic diatoms of Achnanthes, Cymbella, Encyonema, and Gomphonema genera suggests an increase in river discharge. An appearance of Eunotia and Pinnularia genera indicates that of the lake waters are waterlogged. The list of coastal-marine diatoms includes 47 species, and their content is stable (6.2%–9.7%). The composition of these diatoms is changing in this stage. The brackish-water species are the most diverse (22), fresh-brackish-water diatoms include 12 species, such as Ctenophora pulchella, Gyrosigma peisonis, Fallacia pygmaea, Bacillaria paxillifera, and Mastogloia smithii. Among marine (7) and brackish-water (7) taxa, benthic Tryblionella acuminata, and Mastogloia pumila are most noticeable. A strong input of marine water, presumably as a result of an extreme storm or tsunami (~4590–4510 cal yr BP) is recorded in the 1.10–1.15 m interval, where marine planktonic diatoms, Odontella aurita, and Paralia sulcata are observed.

4340–4090 cal yr BP: A decrease in the mineralization of the lake water occurs at this stage. Among freshwater diatoms, dominants change. The indifferent Staurosira venter predominates, followed by Pseudostaurosira brevistriata, and P. elliptica. Such changes indicate a progressive
decrease in the degree of the mineralization of the lake water. An increase in the content, *Stauroforma exiguaformis*, a typical oligotrophic species, confirms the supposition that the waters are weakly mineralized. The list of coastal-marine diatoms is reduced to 38 taxa, but their content increases to 16%. Brackish-water species (21) and freshwater-brackish-water species (10) prevail. Among this group are *Gyrosigma strigilis*, which typically lives in estuaries, *Navicula peregrina*, and *Gyrosigma wormleyi* (up to 3%) are also common there. Marine and brackish-marine species include 7 taxa, *Arachnoidiscus ehrenbergii* and *Pinnunavis yarrensis* are found regularly. The presence of marine diatoms suggests an active periodic input of marine water into the lake. The intensified water exchange could be due to an increase in storm activity that corresponds to a rising sea level. The deposition occurs during a minor transgression during the late Holocene warming [16]. Silts that are attributed to the transgression peak (4340–4260 cal yr BP) appear to contain neritic *Chaetoceros* sp.

4090–700 cal yr BP: A coastal lake exists in place of the lagoon. The ecological situation transforms due to a gradual change in water pH–changing, from slightly alkaline to neutral. Among dominant alkaliophitic species, *Pseudoaustrionensus brevistriata* disappears; it is replaced by the circumneutral *Stauroforma exiguaformis*. The diversity of the species that are typical in stagnant and flowing water increases. The lake gradually turns into a swamp; the process becomes particularly active after 3510 cal yr BP. This transition is made evident by the richness of the genera *Pinnularia* (34) and *Eunotia* (13). By the end of the stage, the deposition rate drops, probably due to the drying of the lake. The list of coastal-marine species include 28 taxa. Marine and brackish-water species are commonly found, and notable species include *Trybionella plana*, *Cocconeis scutellum*, *Gyrosigma strigilis*, and *Campylodiscus echeneis*, that may have entered the lake during a strong storm. Another neritic form, *Chaetoceros* sp., was recovered from the silts in the 0.50–0.55 m depth interval and dated to 3270 ± 150 yr BP, 3510 ± 90 cal yr BP, LU–8851. Its presence quite possibly indicate a tsunami. The most considerable uprush of the marine water is documented at the top of the peaty clay layer. Numerous frustules (17 taxa) of marine and brackish-water diatoms (8.7%) are recovered, including deep-sea *Coscinodiscus* sp., *Thalassiosira* sp., benthic *Rhabdonema arcuatum*, and colonies of *Rhabdonema adriaticum*, the latter species is widespread within warm seas. Because of the presence of thermophilic species, a strong tsunami is presumed to have occurred in AD 1026 [18].

700–360 cal yr BP: The organic matter accumulation in the lake begins at the Little Ice Age (750 ± 90 yr BP, 700 ± 80 cal yr BP, LU–8850). Epiphytes prevail (up to 73%), and alkaliophile *Stauroforma exiguaformis* remain among the dominants, which may indicate an even greater decrease in the degree of mineralization of the water. A conspicuous increase in species richness is recorded in *Eunotia* (from 9 to 19) and *Pinnularia* (from 24 to 35) genera, which suggests that the lake and its surroundings are turning into wetlands, with both pH and mineralization decreasing. The contents of acidophiles (up to 10%) and halophobes (up to 11.4%) increase. In the list of marine and brackish diatoms, 30 taxa are found. Fragments of *Arachnoidiscus ehrenbergii*, *Trybionella plana*, brackish water *Cocconeis scutellum*, *Campylodiscus echeneis*, *Trybionella victoriae*, *T. littoralis*, and *Navicula peregrina* are constantly present in sediments. Marine and brackish-water diatoms seem to have been brought in by storms. The most conspicuous input of seawater happens in ~560 cal yr BP. The proportion of marine and brackish-water diatoms rises to 8.5% (from ≤5% in underlying and overlying layers). Among the identified remains, there are fragments of deep-sea *Coscinodiscus marginals*, *Thalassiosira* sp., benthic *Rhabdonema adriaticum* colonies, and planktonic *Odontella aurita*.

360–0 cal yr BP: The diatom species composition suggests an active paludification process. The acidity of the swamp water increases while the mineralization decreases. Bottom diatoms prevail (up to 83.5%). The content of acidophiles (up to 41%) and halophobes (up to 47.8%) sharply increases. The content of diatoms in the sediments gradually decreases from 18 to 13 million/g, *Eunotia bidens*, *E. glacialis*, *E. groenlandica*, *Pinnularia eifelana*, *P. viridis*, *Neidium bisulcatum*, and *Nitzschia nana*, typical in oligotrophic-dystrophic water bodies, reaching their highest values. The growth of the soil-inhabiting diatom proportion (*Hantzschia amphioxys*, *Luticola mutica*, *Humidophila contenta*, and *Pinnularia borealis*) indicates a more arid climate in 200–170 cal yr BP. After that the species...
inhabiting wet moss (*Eunotia nymanniana*, 3.5%; *Cavinula lapidosa*, 2.6%) grow in number, along rheophiles that are indicative of the influence of river water. The appearance of *Navicula festiva*, and *Chamaepinularia hassiaca*, which are characteristic of acidic peat bogs, indicates an increase in the acidity of the water in the swamp. A shallow-water lake can exist on the terrace surface. Marine and brackish-water diatoms (a total of 23 taxa) are mainly brought in by storms. Fragments of neritic and oceanic species *Coscinodiscus marginatus*, *Coscinodiscus* sp., and *Thalassiosira leptopus* could be thrown onto the terrace by tsunami that have reached Russian Island.

### 4. Discussion

Barrier lakes of the lagoon type are quite common on the islands in Peter the Great Gulf. Their deposits are successfully used to reconstruct the evolution of the island environment [19, 20]. The lakes present the final stage of the development of lagoons that had formed at different phases of the Holocene transgression. Together with bodies of water that still exist, there are paleo-lakes, which are easily recognizable by their topography and are now occupied by swamps. A paleo-lake of this kind was also found on the isthmus of the Kondratenko Peninsula, near the Krasnaya Bay coast.

#### 4.1. Minor transgression-regressive cycles and evolution of the paleo-lake

The lagoon formed when the sea level was similar to the present-day sea level, and the evolution up to the present-day state is extensive, having eight recognized stages (figures 2–4).

![Evolution of paleolake, Russian Island](image)

*Figure 4.* Evolution of a paleolake on Russian Island, sea-level oscillation curve [16], dry event on the Shufan Plateau and summer monsoon intensity [21–26].
The body of water decreased in area during 7090–7330 cal yr BP, probably due to a decrease in the annual rainfall. This event was synchronous with the end of a shallowing phase of the lake on the Shufan Plateau (7490–6930 cal yr BP) (unpublished data of the authors). The size of the lagoon was at its maximum during the peak of the Holocene transgression (6750–5090 cal yr BP), coinciding with the Holocene optimum [16]. Both the water inflow into the lagoon and the increase in salinity corresponded with the peaks of the transgression (6750–6500, 6080–5830, and 5420–5090 cal yr BP). The traces of a severe flood dated to ~6080–6000 cal yr BP, are roughly synchronous to the end of the flooding phase (6210–5980 cal yr BP) identified in the paleolake of Shufan Plateau. The first “closed” phase of the lagoon’s evolution (6500–6080 cal yr BP) was roughly simultaneous with the short-term lowering of the sea level [16], which also chronologically coincide with a global cooling event during 6400–6200 cal yr BP [21]. The second phase of the shallowing in ~5830–5420 cal yr BP was also simultaneous with the sea level lowering [16]. The “closed” phases in the lagoon’s evolution were noted for their higher diatom productivity.

A highly productive lake with slightly brackish water developed in ~5090 cal yr BP. The diatom abundance in the sediments is at its maximum at this stage. This stage coincides with an interval of heavy deposition and the development of barrier landforms at the time of a minor regression at the boundary between the middle and late Holocene [16]. The lagoon in the north of Russian Island and the lagoon in Kit Bay turned into lakes during this time [5, 20].

Since 4090 cal yr BP, a gradually degrading freshwater lake has existed. The rate of silt deposition decreased in approximately 3270 ± 150 yr BP, 3510 ±90 cal yr BP, LU–8851. This could be due to a prolonged phase, where a pronounced decrease in the humidity occurred in the continental Primorye. At this time Cherepakha Lake (Murav’ov-Amursky Peninsula), shrank drastically in ~2200–1760 cal yr BP [6]. In the middle portions of the Razdolnaya River, a decrease in the runoff resulted in soil formations that date to 2110 ± 80 yr BP, 2100 ± 110 cal yr BP, LU–8854 and 1610 ± 110 yr BP, 1520 ± 120 cal yr BP, LU–8856. A dry phase in the southern Sikhote-Alin dates to ~3100–2700 cal yr BP, with particularly dry conditions in 2700–2000 cal yr BP [22]. The duration of the dry interval was longest on the Shufan Plateau, where the moisture supply began decreasing since 3740 cal yr BP, and reached its minimum between 3050 and 1080 cal yr BP. Chronologically, this event approximately corresponds to the global cold event in 3300–2500 cal yr BP, which was related to a drop in solar activity. This was recorded in the north of the monsoon regions in Asia that are noted for having arid environments at the time [21]. These observations agree with the data for NE China, obtained by several authors, that suggests that the summer monsoons weakened between ~3740 and 1920 cal yr BP [23, 24]. In the Shihailongwan Lake region the climate became more arid in ~3500 cal yr BP and colder in 2900 cal yr BP [25]. The lower intensity of the summer monsoon was also recorded in the lower reaches of the Amur River [26]. The cold event in Asia in ~1750–1350 cal yr BP was also noted for its drier climate [21].

The accumulation of organic matter in the lake in the south of Russian Island is related to the lake basin filling with water in ~700 cal yr BP, at a time when the mineral material supply was considerably reduced. The lake became overgrown, and only a small shallow lake persisted until 360-270 cal yr BP. Later, during at a short-term dry phase, it disappeared completely.

4.2. Extreme storm surges and tsunami impacts. Marine water occasionally flowed into the lake during extreme storms, primarily typhoons or deep cyclones. At the same time, strong tsunami probably occurred. The presence of marine diatoms that are typical in bays and deep-sea plankton species and can only be brought into a lagoon or lake from the sea is evidence of a sea-water input into a brackish-water lagoon or fresh lake. In the absence of paleotsunami deposits, diatom analysis is a good tool for the reconstruction of the recurrence of severe storms and tsunami. The section is located within the inundation zone of extreme storms, caused by the passage of Goni (August 26, 2015) and Lionrock (August 31, 2016) typhoons. Observations that were conducted immediately after the storms on the coast of Russian Island showed that these two extreme storms were accompanied by surges, but sand sheets did not form in the inundation area [27]. In the surface layer of peat, the sum of marine diatoms
is 1.5%, represented primarily by benthic sublittoral species (*Amphora proteus*, *Arachnoidiscus ehrenbergii* *Rhabdonema adriaticum*, and *R. arcuatum*). Only one planktonic species, *Thalassiosira leptopus* was found. We consider the increase in the number of marine diatoms and the presence of deep-sea species as a sign of the tsunami.

It should be noted that detailed information on paleo-tsunami in Primorye is available only for the last 3500 cal yr [28, 29]. Our data allow us to identify more ancient events. The beginning of the marine phase in 5420–5090 cal yr BP is not related to a minor transgression. This may explain influence of strong storms or tsunami. The peak of marine diatoms is the evidence of a tsunami that occurred in 5340 cal yr BP. A similar event was recorded in the Kit Bay lagoon (Eastern Primorye), where the marine water influx into the lagoon (~5300 cal yr BP) was presumed to be related to a violent tsunami [5]. The presence of sand lenses with deep-sea diatoms provide support for the attribution of the deposit to a paleotsunami in ~5000–4920 cal yr BP. Another considerable inflow of marine water occurred in ~4510–4590 cal yr BP, as suggested by the marine planktonic diatoms found occasionally in freshwater assemblages. There are data from an area south of the Japanese islands that suggest an increased frequency of strong typhoons during this time [3]. An increase in storm activity occurred in ~4340–4090 cal yr BP occurred in a minor transgression during the late Holocene warming that was comparable to the middle Holocene optimum.

An event dated to ~3270 ± 150 yr BP, 3510 ± 90 cal yr BP, LU–8851 has analogs in the geological record of paleo-tsunami [29]. Strong tsunami occurred on the Eastern Primorye coast (Triozerye Bay) in approximately 3290 ± 70 yr BP, 3520 ± 80 cal yr BP, LU–8033; 3270 ±7 0 yr BP, 3500 ± 80 cal yr BP, LU–8048; and 3320 ± 70 yr BP, 3560 ± 80 cal yr BP, LU–8042 [30]. The greatest inflow of marine water that was recorded at the top of peaty clay was related to the tsunami in 1026 AD [18]. The focus of the tsunami was in the southeastern portion of the Sea of Japan; its initiation was related to a large submarine landslide [31]. The signs of that tsunami were traced to the southern Primorye region (Triozerye Bay) [29, 30].

On the south of Russian Island tsunami repeatedly occurred over the last 700 years. A forceful invasion of seawater into the paleo-lake in ~560 cal yr BP compares well with the data from the Russian Island eastern coast. Traces of a tsunami that dates to ~540 ± 50 yr BP, 570 ± 40 cal yr BP, LU–8037 was found on the eastern coast of the island (Spokoynaya Bay) [27]. Synchronous event (500 ± 80 yr BP, 530 ± 80 cal yr BP, LU–7719 and 540 ± 100 yr BP, 550 ± 80 cal yr BP, LU– 7105) was recorded on the Eastern Primorye coast (Dukhovskie lakes, Rudnaya Bay) [28]. It is difficult to attribute this tsunami on Russian Island to a well-known event. Japanese chronicles include data about intense tsunamiogenic earthquake (M 7), with an epicenter near Sado Island, in 1448 AD [18]. But if the epicenter of the earthquake was near Hokkaido, the information was not recorded in the chronicles. Peak of marine diatoms and presence of deep-sea species probably record the strong tsunami of December 7, 1833, which was caused by the Shonaioki earthquake (7.4–7.8 M). The epicenter was located to the north-east of Sado Island [18]. The deposit of this tsunami was identified on Russian Island (Spokoynaya Bay) [27].

### 5. Conclusion

The paleolake on the Krasnaya Bay shores is sensitive to minor transgressive-regressive cycles and humidity changes. The lagoon was formed in ~7500 cal yr BP, when the sea level was close to the present-day state. The eight stages distinguished in its evolution were primarily controlled by minor sea-level fluctuations. The salinity was at its maximum at the peak of the Holocene transgression; three stages of a higher salinity are recognized (6750–6500, 6080–5830, 5420–5090 cal yr BP) and two of relatively freshened water (6500–6080, 5830–5420 cal yr BP). The brackish-water lake has existed since ~5090 cal yr BP, and, it turned into a freshwater lake in ~4090 cal yr BP. Later, the lake gradually degraded. The rate of the silt deposition decreased in ~3510 cal yr BP, seemingly because of a decreasing amount of rainfall. The terrigenous material deposition gave way to biogenic material at the time of the Little Ice Age (~700 cal yr BP). The lake became actively overgrown and ceased to exist during a short-term drop in precipitations in ~270 cal yr BP.
Marine water occasionally invaded the lagoon and the paleolake during extreme storms and strong tsunami. Diatoms provide evidence for the response of the barrier form to the episodic influx of sea water into the lagoon and paleolake. One such event in ~5340 led to a barrier breach and the beginning of marine stages during a background of a drop in sea level. High storm activity occurred in 4340–4090 cal yr BP during a sea-level rise in the initial warming stage of the late Holocene. Some strong tsunami that had age analogs on the other coasts of Primorye were distinguished on the shore of Krasnaya Bay (paleotsunami, 3510 cal yr BP; historical tsunami, 1026 AD, ~560 cal yr BP and 1833 AD).

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