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The role of global and local factors in determining the middle to late Holocene environmental history of the South Kurile and Komandar islands, northwestern Pacific

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Abstract

The study of Holocene deposits from northwestern Pacific Islands is very important for understanding the natural development of the area in the context of oceanic climate, strong microclimate variability, and the influence of contrasting marine currents. Holocene sections from Bering Island record the following events: cooling at about 4600–4500 yr BP; warming at about 3500–3400 yr BP; cooling at about 3000 yr BP; sea-level rise (up to 1.5 m) at about 2700 BP; cooling at about 1800–1400 yr BP; and sea-level rise at about 1000 yr BP. On the South Kuriles, a dry and cool climate changed to warm and moist about 7000–6500 yr BP, later than on Hokkaido Island. At this time, the Kuroshio Current system became more active and birch assemblages were replaced by cool–temperate broadleaf forests and mixed coniferous/broadleaf forests. At the Holocene Optimum (about 6000 yr BP), temperate broadleaf forest occupied almost all of Kunashir and the Okhotsk side of Iturup and the climate was warmer than present. The highest sea-level position reached was 2.5–3 m above present level about 6500–6300 yr BP. During the cooling about 4700–4500 yr BP, island vegetation changed slightly due to the influence of warm currents. Major sea-level regression during this period led to the formation of extensive coastal dune fields. The warming at the beginning of the late Holocene was almost as great as that of the Holocene Optimum. Two minor transgressions are recorded. The vegetation changes and climatic deterioration that took place in the second half of the late Holocene resulted in either a disappearance of thermophylous taxa or in a southward shift of their natural habitats. During the cooling from 1700 to 1300 yr BP, the isthmus area increased, coastal wetlands with lakes and coastal dunes with paleosols were formed, and grassland and swamp landscapes developed. Late Holocene warming was not intensive. Volcanic impact on environments led to changes in vegetation assemblage, swamping of the area, and thick soil profile formation.

Keywords: Climatic changes; Paleolandscapes; Sea-level oscillations; Middle–late Holocene

1. Introduction

The Holocene history of the formation and evolution of landscapes of northwestern Pacific islands reflects the environmental reaction to global climatic fluctuations and to the influence of different local factors. This paper focuses on island environmental reconstruction in response to such factors as regional climate, sea-level fluctuations, the migration of warm and cold currents, volcanic impacts, and island isolation. The study area includes islands with an oceanic climate and strong microclimate variability, influenced by different ocean currents: Kunashir and

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Iturup Islands (Kurile Islands) and Bering Island (Komandar Islands; Fig. 1). Within the Kurile Islands, atmospheric circulation is strongly influenced by the Asian Monsoon. During the winter, northwesterly winds from Asia bring cold and snow. During the summer, moist and cool Pacific air masses move south or east across the islands toward the Asian low-pressure area, bringing with them extensive rainfalls, fog, and, in August–September, typhoons. The islands' climate has a small annual temperature range, with relatively warm winters and cool summers. Ocean currents are particularly important in influencing the regional climate of the South Kuriles. The Soya current has a warming effect on the Okhotsk Sea coasts. The Oyashio current brings cold water from the north to the south in the Kurile region. It produces fog, typically on the ocean side of the islands. Marine currents, mountain relief, and hot springs define a wide range of microclimatic conditions on the islands.

The islands have many vegetation zones, whose migration within a limited area is important for understanding paleolandscape development resulting from climatic changes (Fig. 2). The composition, structure, and productivity of the vegetation are primarily controlled by the amount of annual warmth (annual sum of mean daily temperatures above 10 °C, namely, the sum of active temperatures and the period of time with mean daily temperatures ≥ 10 °C; Urusov, 1996). We have used this bio-climatic index because this ecological parameter is usually used by Russian scientists to study the distribution of modern vegetation and for climatic and geobotanic mapping of the region (Urusov and Chipizubova, 2000). This parameter is considered to be a good indicator of the narrow climatic conditions of the area. It characterises the warmth balance of the area, is an indirect indicator of the time interval of the active vegetation period, and it reflects the warmth conditions required for vegetation development. The sum of active temperatures (more than 10 °C) on Iturup Island reaches 1350–1450 °C, on Kunashir, 1590–1700 °C, and the time interval with mean daily temperatures of more

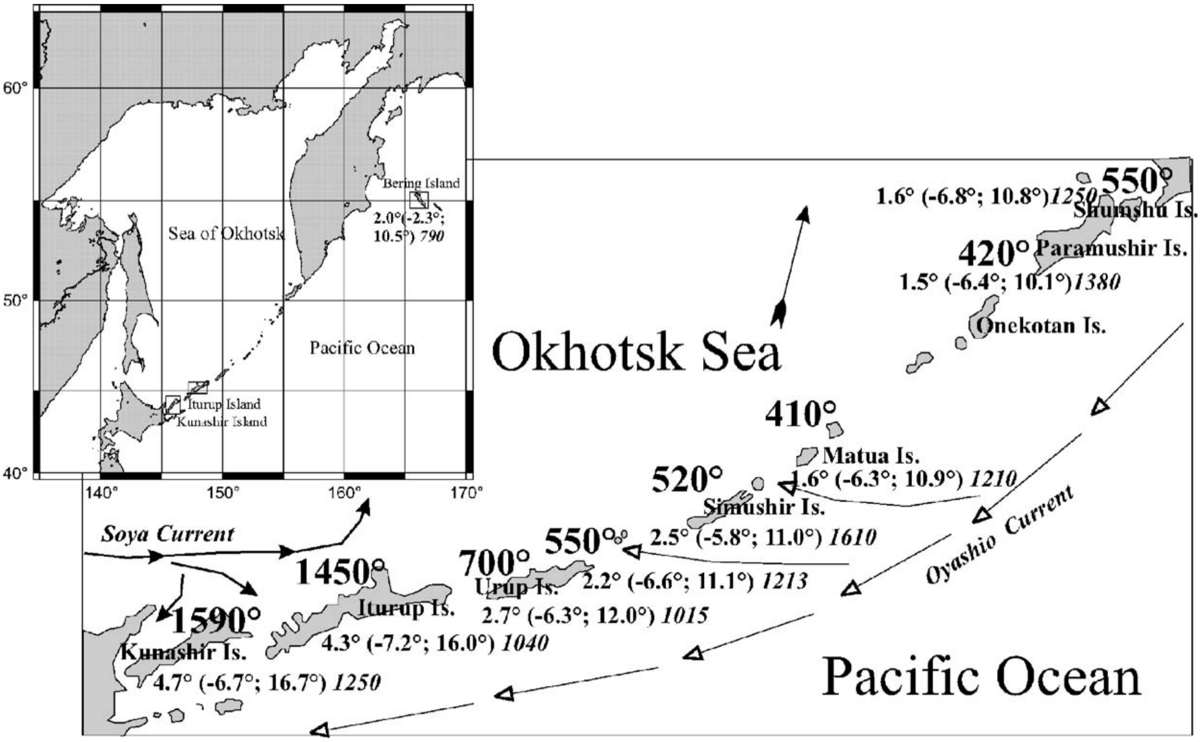

Fig. 1. Location of study area and modern climatic parameters: 1590 °C—sum of active temperatures (>10 °C); 2.2 °C (− 6.6 °C; 11.1 °C); 1230 °C—mean annual *T* °C (*T* °C January; *T* °C August); annual precipitation.

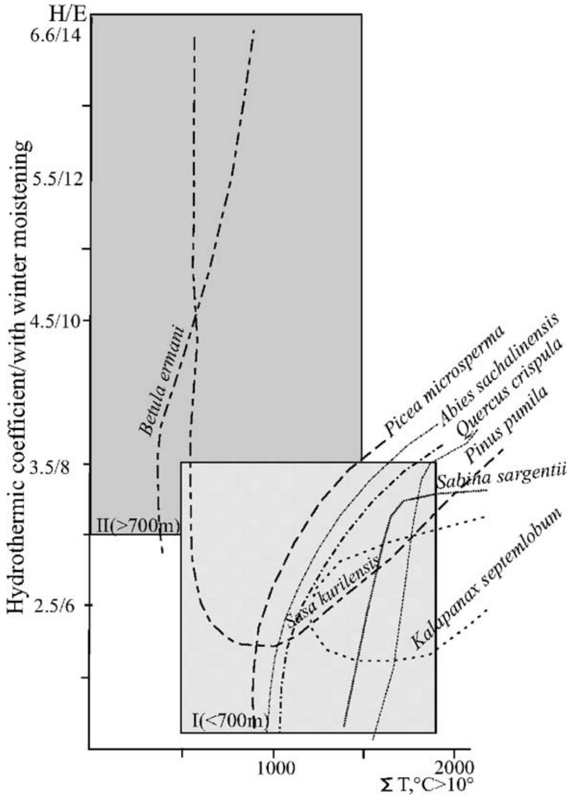

Fig. 2. Ecological area of main forest components and indicators of Kurile Island vegetation (Urusov, 1996).

than 10 °C is 104 days. The vegetation time interval is 166 days (Urusov, 1996).

Kunashir Island supports the largest broadleaf forest massive in the Kurile Islands (Urusov and Chipizubova, 2000). Broad-leaved taxa include *Quercus crispula*, *Kalopanax septemlobus*, *Acer pictum*, *Ulmus laciniata* in association with *Betula ermanii*, and the underwood includes *Taxus cuspidata*, *Ilex rugosa*, *Ilex crenata*, *Rhododendron tschonoskii*, and *Sasa kurilensis* with *Licopodium*, and Polypodiaceae (Vorobiev, 1963; Seledets, 1969; Urusov, 1996). On the Okhotsk side, the forest is considered a relict, existing due to the warming effect of the Soya Current and the barrier role of mountain relief protecting it from fog and cold winds formed by the cold water of the Oyashio current on the other side of the island. The upper boundary of oak–broadleaf forests is located on 300–400 meters above modern sea level (m amsl) (Urusov and Chipizubova, 2000).

Cool–temperate broadleaf and mixed coniferous–broadleaf forests of the Nemuro–Kunashir Formation occupy the southern and central part of Kunashir. Boreal coniferous forests of the Kunashir Iturup Formation with predominantly *Abies sakhaliensis* and *Picea microsperma* are extensively distributed in northern Kunashir and southern Iturup (Vorobiev, 1963). Six altitudinal vegetation zones are present on the island: broadleaf forest zone (up to 400 m in the southern part and 250 m near Rurui Volcano); boreal coniferous forest zone (up to 700 m in central and northern part); *Betula ermanii* zone (from 400 to 600 m in northern part); *Pinus pumila* zone (up to 1500 m); heath zone–Ericaceae–*Empetrum asiaticum* zone; and alpine zone (Rurui and Tyatya volcanic peaks). Birch forests with *B. ermanii* predominantly occupy 38% of the Iturup Island area and are mainly developed on the Pacific side and on the inner part of the island (Urusov and Chipizubova, 2000). Open forest with *Betula* as the dominant species is typical for the northern part of the island microclimate, which is controlled by the influence of Friz Strait cold water. According to Vorobiev (1963), the line between South Kurile and middle Kurile geobotanic provenances lies on the Vetrovoy Isthmus. Park forest with *Larix kurilensis* developed on the central part of the island from coastal ridges to 400 m amsl. The *P. pumila* zone is located on mountain slopes higher than 400 m. Grasslands are widespread on the northern part of the island. Valley forests are characterised by a predominance of *Alnus*, *Ulmus*, *Salix*, and various herbaceous plants (Vorobiev, 1963). Grassland and grassland with shrubs usually develop on marine terraces and river valleys. Wetland and swamps with small ponds occur on coastal lowlands and on volcano slopes. One of the main landscape plants on the South Kuriles is *Sasa kurilensis* on the lower and middle slopes. Tundra landscape occupies Bering Island.

One problem we will discuss is the role of refugia in influencing vegetation changes during the Pleistocene–Holocene climatic oscillations. Islands such as Iturup and Bering are good examples for the resolution of this problem because these islands are separated from neighbouring areas by deep straits and were isolated during the Last Glacial Maximum.

The islands are situated in active tectonic zones within island arcs of the northwest Pacific. Therefore, tectonic activity has played a major role in environmental evolution. Various studies have examined coastal plain sequences with raised beach ridges and wetlands, with a view to determining the tectonic movements and other characteristics of regional tectonic behaviour. The studies of Holocene sea-level changes have also focused on coastal lowland areas because of the good preservation of geological sea-level records.

2. Material and methods

Holocene environment history in this area is recorded in low marine terrace and lacustrine sequences, soil profiles, dune fields, and peat bogs. Because the terrestrial and coastal records are usually discontinuous, we have studied the stratigraphy of numerous sections, composed of different facies, to derive a reliable palaeogeographical reconstruction. The paleoreconstructions are based on detailed biostratigraphical data including pollen, diatoms, and marine mollusc, and are dated using tephrostratigraphical data and ^{14}C measurements.

Some outcrops were selected for detailed observations and sampling. Diatom and pollen samples were analysed at 5–10-cm intervals from lacustrine, marine, and peat units or at varying intervals depending on the sediment lithology. pH values were measured in the field. Modern pollen spectra from more than 100 sites from surface alluvial and lacustrine silty sands were studied to help in the interpretation of fossil pollen data.

Diatom processing methods follow those of "Diatoms of USSR" (1974, pp. 55–79). The samples were treated by a solution of hydrogen peroxide and washed with distilled water. For certain diatom preparations, a heavy-liquid (mixture of $H_2O/CdJ_2/KI = 1{:}1.5{:}2.25$, density 2.4 g/sm^3) was used. When possible, 200–300 valves were counted per sample. The ecological significance of diatom species was taken from Wolf (1982), Denis (1991), Krammer and Lange-Bertalot (1986, 1988, 1991a,b), Jouse (1962), Davidova (1985), Barinova and Medvedeva (1996).

The material for the pollen analysis was treated with the standard KOH and acetolysis method. Pollen grains were concentrated by means of the heavy-liquid flotation method outlined by Pokrovskaya (1966). More than 300 pollen and spores were counted in rich samples. Three pollen sums were calculated: total arboreal pollen, total non-arboreal pollen, and total spores. The percent of a tree taxon is based on the sum of arboreal taxa only; the percentage of a non-arboreal taxon is based on the sum of non-arboreal taxa only; and the percentage of spores is based on the sum of spores only. Diagrams were divided by visual inspection into pollen zones. Local fossil pollen assemblage zones were established based on the dating and on the occurrences of major arboreal pollen types.

Age was determined by ^{14}C analysis and tephrostratigraphy. ^{14}C dates was obtained on wood and peat in samples 5–10 cm thick. The samples were treated with standard acid and alkali solutions. ^{14}C dates were produced by liquid scintillation counting in the Geological Institute, Russian Academy of Sciences, Moscow. Full ^{14}C age data for deposits of Kunashir and Iturup Islands were reported by Bazarova et al. (1998, in press), and those of Bering Island by Razjigaeva et al. (1994). In paleoreconstructions, we used noncalibrated ^{14}C yr in order to facilitate correlation with available palaeogeographical data collected in surrounding regions, which is primarily in an uncalibrated format.

Tephra layers were identified in the field and later studied in the laboratory under cross-polarised light. For mineral analysis, the 0.05–0.1 and 0.1–0.25 mm fractions were separated from the sediment samples by wet sieving. Heavy minerals were extracted with tribromomethane (density 2.89 g/sm^3). The chemical (wet chemistry) composition of ash layers was also investigated. The correlation of ash layers is based on ^{14}C dates from under- and overlying deposits, on refractive indices and morphology of volcanic glass shards, and on chemical and mineral composition. The sources of ash layers on Kunashir and Iturup, as on Hokkaido, are local volcanoes. The sources of ash layers from Komandar Islands deposits were Kamchatka Volcanoes (Braitseva et al., 1997). Some of these ash layers can be used as markers for the correlation of different facial sections.

3. Results

Holocene deposits comprise coastal lowlands, usually located near river mouths, within the heads of inlets and low isthmuses, and separate volcanic groups (Melekestsev et al., 1974; Korotky et al., 2000; Razjigaeva et al., 2002). Fig. 3 shows examples of Holocene coastal lowland sequences from the areas studied. The sections of Holocene deposits of the islands are characterised by small thickness, sharp

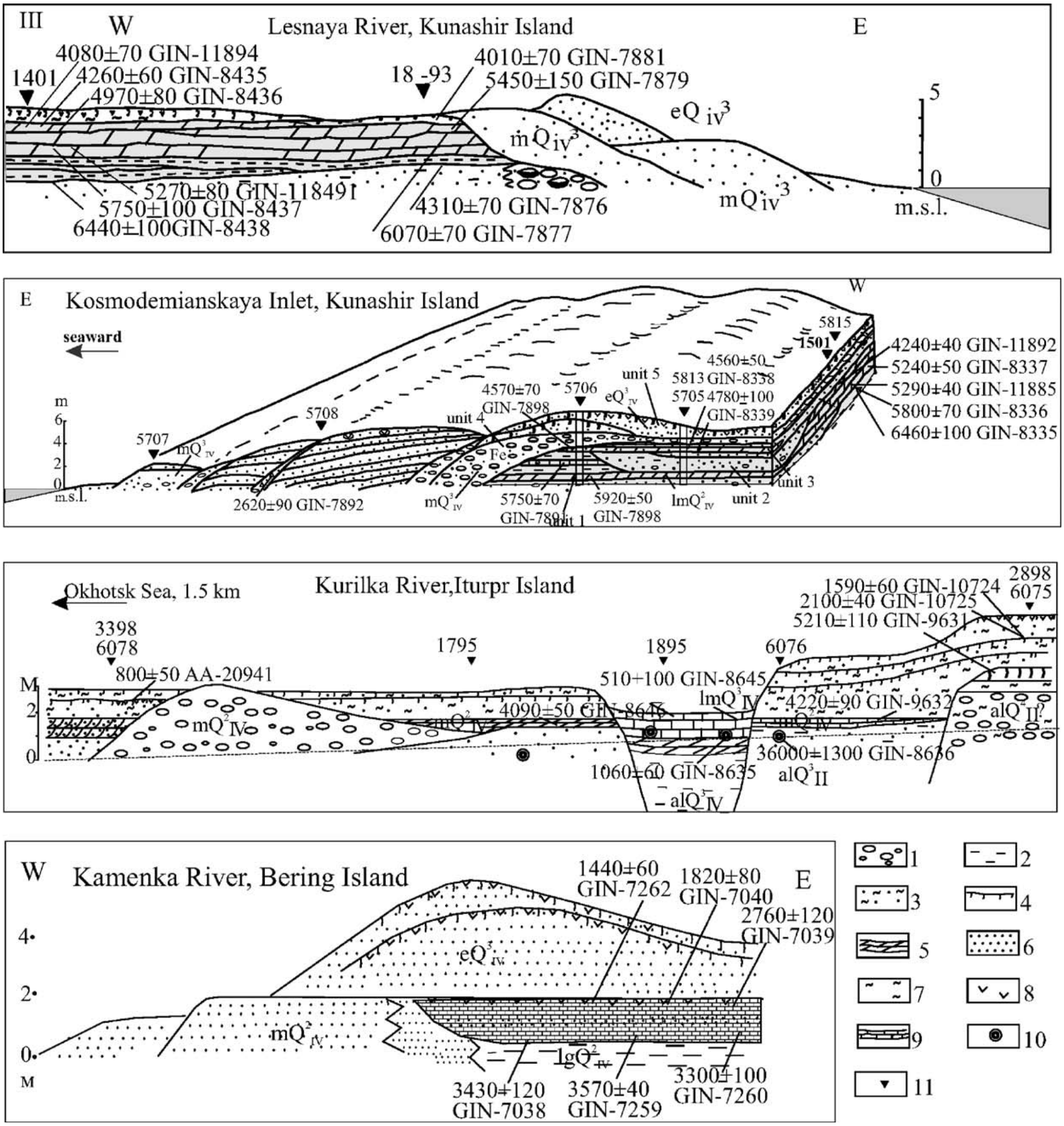

Fig. 3. Cross-sections of late Pleistocene–Holocene deposits of northwestern Pacific Islands; Q^2_{IV}—middle Holocene; Q^3_{IV}—late Holocene facies; m—marine; lm—lacustrine; al—alluvial; 1—pebbles; 2—silt; 3—sandy silt; 4—soils and paleosols; 5—peaty silt; 6—sand; 7—loam; 8—volcanic ash; 9—peat; 10—wood; 11—sections.

facial replacements, nonconsistent layers, and frequent hiatuses. The deposits show that islands are very sensitive and respond not only to large-magnitude climatic changes, but minor ones as well.

The available biostratigraphical data and ^{14}C dates allow us to reconstruct a detailed history of middle–late Holocene palaeogeographical events. Modern pollen spectra were used to help interpret paleolandscape reconstruction (Mokhova and Eremenko, 2001; Mokhova, 2002). On the South Kuriles, arboreal pollen dominates within and near forests (up to 94%); non-arboreal pollen (up to 64%) and its diversity increase within grassland and peatland areas. Small-leaf taxa prevail on central Iturup pollen spectra. Coniferous pollen dominate in spectra from the central and northern part of Kunashir Island. Towards the southern part of the island, broad-leaved pollen increase in spectra. More thermophylous taxa were found only in the southern part of Kunashir. A high content of *Alnus* and *Alnaster* occurs near swamps and reflects river valley forests. Although the entrance of allochthonous pollen did not change the spectrum structure, rare pollen grains from trees whose habitat is limited to Japan were often found.

The results of biostratigraphical, tephrostratigraphical study and ^{14}C dating of some island areas have already been published (Korotky et al., 1995, 2000; Razjigaeva et al., 2002). Diatom data from low marine terrace sequences are summarized in Fig. 5, and are the basis for sea-level curve reconstruction. New results and synthesis of earlier data enabled us to improve extant reconstructions of the development of the island environments. Here, we briefly describe the new results.

Site 5495 is located in the southern part of Golovnin Cliff, in southeastern Kunashir at an elevation about 30 m, and it exposes lacustrine peaty silts with volcanic ashes, diatomit layers, and lenses of fine coals (Fig. 4). The lower part of the section includes dacite volcanic ash. The chemical and mineralogical composition of the ash corresponds to Golovnin Volcano tephra (Razjigaeva et al., 1998).

The deposits contain rich freshwater diatom flora, indicating a swamp environment. Two diatom assemblages are delimited. Assemblage I (0.60–1.65 m) includes epiphytes (up to 62%) with a predominance of *Eunotia bilunaris* var. *bilunaris* (up to 9.1%), *Eunotia implicata* (up to 6.3%), *Eunotia monodon*

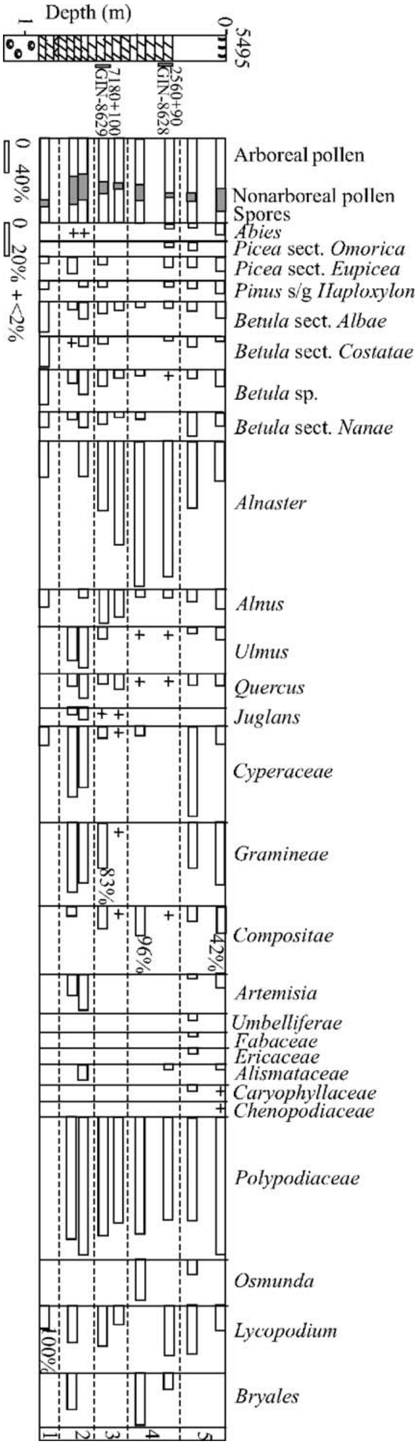

Fig. 4. Percentage pollen diagram for the lacustrine deposits of southeastern Kunashir, site 5495.

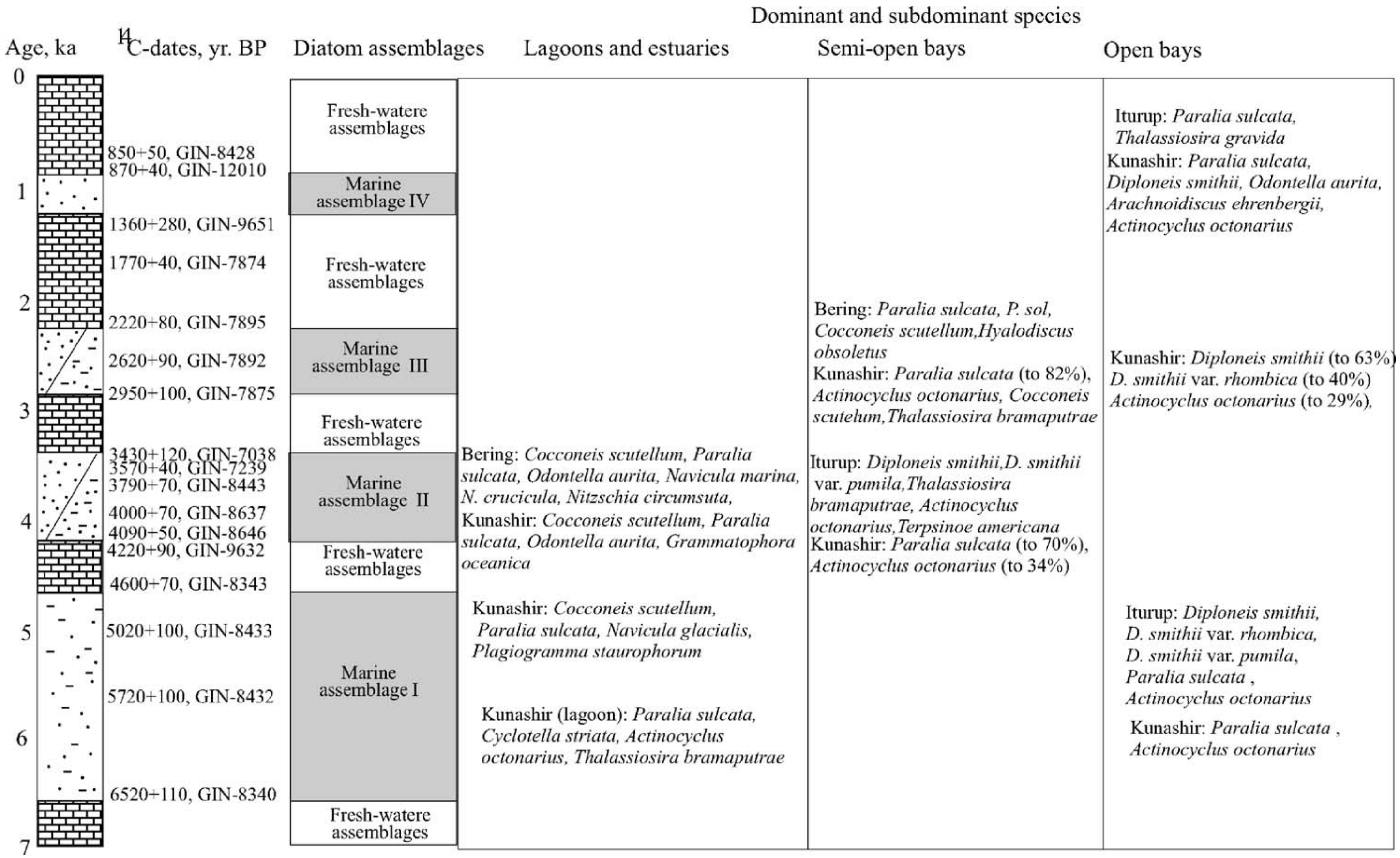

Fig. 5. Diatom assemblages from transgressive units from low marine terrace sequences, South Kuriles and Bering Islands.

var. *monodon* (up to 7.8%), *Eunotia praerupta* var. *bidens* (up to 6%), *E. praerupta* var. *praerupta* (up to 9%), *Eunotia subarcuatoides* (up to 10%), *Eunotia glacialis* (up to 5.2%), *Rhopalodia gibberula* var. *gibberula* (up to 29%) and high contents of benthic species (up to 40%) such as *Diploneis oblongella* (up to 7.6%), *Pinnularia viridis* var. *sudetica* (up to 5.7%), *Pinnularia brevicostata* (up to 5.9%), *Pinnularia borealis* (up to 5.1%), *Nitzschia nana* (up to 5.5%), *Navicula placenta* (up to 5.2%). The presence of rhyophiles such as *Meridion circulare*, *Diatoma elongatum*, *Diatoma vulgaris* var. *vulgaris*, *Fragilaria ulna* indicates some stream influence. Assemblage II (0–0.60 m) includes diverse bottom forms (up to 69%) with predominance of *P. borealis* var. *borealis* (up to 55%) and epiphytes (up to 59%) such as *Eunotia pectinalis* var. *pectinalis* (up to 6%), *E. praerupta* var. *praerupta* (up to 5%), *E. praerupta* var. *muscicola* (up to 3%), *E. glacialis* (up to 5%), *Cymbella ventricosa* (up to 4.6%), *C. cymbiformis* (up to 6%), *C. cistula* (up to 2%), *C. naviculiformis* (up to 2%), *Gomphonema parvulum* var. *parvulum* (up to 4%). Contents of rhyophiles such as *M. circulare* (up to 3%), *D. vulgaris* var. *vulgaris* (up to 14%), *Diatoma hiemalis* var. *hiemalis* (up to 8%) increase. The assemblages indicate small pool environments.

There are five pollen zones in these deposits corresponding to paleolandscape changes (Fig. 4). Pollen zone 1 (0.9–0.8 m) reflects the development of birch forests with some groups of firs. The upper parts of the slopes were occupied by *Pinus pumila* terraces, and by alder and *Alnaster* groves. The climate was colder and drier than the present. Pollen zone 2 (0.8–0.65 m) reflects the development of oak groves on the coast and on the upper part of Golovnin Volcano slopes, which was replaced by park birch forests with some conifers. The climate was similar to, or warmer than, the present. Pollen zone 3 (0.65–0.4 m) is characterised by a high content of small-leaved taxa, especially *Alnaster* (up to 65%), and by a decrease in broad-leaved taxa. Climate was cooler than the present. These deposits were formed about 7180 ± 100 yr BP. Pollen zone 4 (0.4–0.2 m), with a background predominance of *Alnaster* (up to 87%) and with the presence of shrub birches, reflects climatic cooling, and is ^{14}C dated to 2560 ± 90 yr BP. Pollen zone 5 (0.2–0 m) reflects vegetation and climate similar to the present.

Site 4196 exposes polygenetic soil profiles on a terrace at 2 m elevation on southeastern Kunashir. There are six pollen zones in these deposits, corresponding to major paleolandscape changes (Fig. 7). The lower part of the site exposes a mid-Holocene paleosol (^{14}C date 5630 ± 50 yr BP) with pollen spectra consisting mainly of non-arboreal pollen, which reflects the development of grasslands with cereal (Poaceae) assemblages (pollen zone 1, 0.82–1.05 m), although there may be a problem with tree pollen preservation in Kurile Island soils (Razjigaeva and Mokhova, 2000). Pollen zone 2 (0.82–0.57 m), with a high content of broad-leaved taxa, indicates the development of motley grassland on the coast, cool–temperate broad-leaved forests on the upper slopes, and birch and conifers in the upper relief level. Shrub and liana pollen such as *Rhus*, *Viburnum*, *Lonicera*, and *Araliacea* and arboreal pollen are very diverse. The climate was warmer than at present and similar to the climatic Holocene climatic optimum on Kunashir (Korotky et al., 2000). Pollen zone 3 (0.57–0.47 m) includes shrub birches (up to 31%) and *Alnaster* (up to 28%). Broad-leaved taxa are represented only by oak (14%), and there is a decrease in coniferous and birch pollen. The high content of non-arboreal pollen (31%) suggests the development of grassland with shrub and oak groves. The climate was cold. Pollen zone 4 (0.47–0.29 m) is characterised by an increase in tree and shrub pollen (up to 52%) with birch pollen predominating. The diversity of broad-leaved taxa (*Carpinus*, *Corylus*, *Phellodendron*, *Fagus*, *Juglans*, *Ulmus*, *Zelkova*, *Fraxinus*) reflects climatic warming. Abundant herb pollen reflects grassland vegetation. Pollen zone 5 (0.25–0.15 m) is characterised by predominantly coniferous and small-leaved plant pollen. The content and diversity of broad-leaved taxa is low. High herb pollen content indicates the development of grassland. The climate was similar to, or warmer than, the present. Pollen zone 6 (0–0.15 m) from the upper part of the soil reflects the modern landscape with abundant herb pollen (74%) reflecting grassland vegetation.

Site 2396 is an exposed soil profile located on the Okhotsk Sea side of the South Kurile Isthmus (Fig. 8). Modern vegetation is motley herb grassland. A paleosol from the lower part of the profile was formed about 4090 ± 70 yr BP. The paleosol includes rare coniferous and herb pollen and spores. Pollen assem-

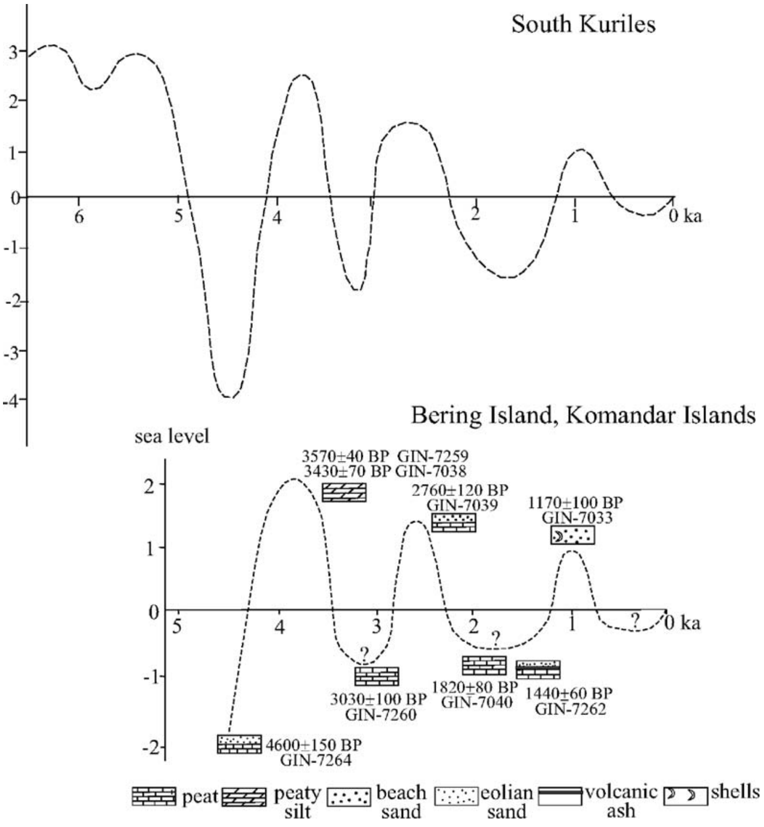

Fig. 6. Sea-level curves for northwestern Pacific Islands.

blage 1 (0.45–0.95 m) reflects the development of grassland with a high diversity of herbs. Dark-coniferous forests occupied the slopes of Fregat and Otdelnaya Mountains. The upper part of the soil contains eolian sands that led to the development of dry herb assemblages such as Poaceae, Compositae, *Artemisia*, Cichoriaceae, Caryophyllaceae (pollen assemblage 2, 0.45–0 m).

Site 3895 is an exposed soil profile from the Pacific side of South Kurile Isthmus (Fig. 9). The lower part of the profile includes mainly spores of *Lycopodium* (pollen zone 1). A paleosol that formed during the mid-Holocene (^{14}C date 6590 ± 50 yr BP) contained no pollen or spores. Pollen zone 2 (0.38–0.47 m) reflects the development of dark-coniferous fir–abies forests with fern about 1090 ± 40 yr BP. A fir forest occupied the dune field of Golovnin Inlet where a dune paleosol includes fir roots in situ (Razjigaeva et al., 1996). Pollen zone 3 (0.38–0.1 m) is characterised by an increase in *Picea* pollen content, indicating cooling. Abundant herb pollen from the upper surface soil (pollen zone 4, 0.1–0 m) reflects the development of grassland.

4. Discussion

4.1. Holocene optimum

Kunashir Island was a peninsula of Hokkaido before the middle Holocene. The sea-level was 25 m lower than its present position at 8000 yr BP[1] (Maeda et al., 1994). The vegetation development and environmental evolution of these areas have many common features. Table 1 shows major Holocene events

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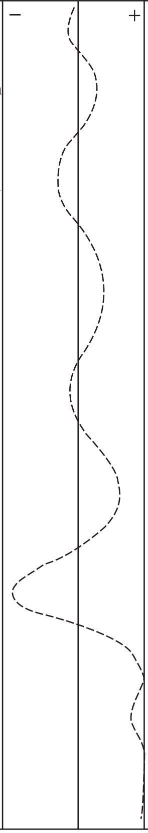
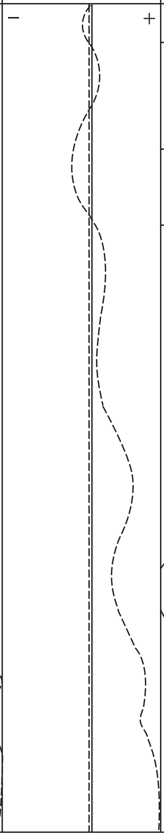
[1] Noncalibrated.

Table 1
The middle–late Holocene environments of Kunashir Island and correlation with Holocene events in the Japanese Islands

	Kunashir Island					Japanese Islands				
yr, BP	^{14}C-dates, BP	Market tephra layers	Landforms	Sea-level curve	Paleo-climatic curve	Sea-level position	Climate (Sakaguchi, 1983)	Vegetation (Tsukada, 1988)	Zones (Igarashi and Kumano, 1974)	Dune generations (Taira, 1980)
0	290±60 510±70	Ma-a, Ma-b	3rd Dune Generation			Edo Regression	Little Ice Age	P-3b	Abies-Picea-Betula	Kurosuna K4
	820±80		Marine terrace 2.5 m			Heian Transgression	Nara-Heian-Kamakura warm stage		Abies-Quercus	
1000										
	1310±80 1770±40		2nd Dune Generation			Nakayama Regression	Kofun cold stage	P-3a		Kurosuna K3
2000		Ma-d				Late Jomon transgression (Funabashi Transgression)	Yayoi warm stage Latest Jomon cold stage			
			Marine terrace 3-4 m				Late Jomon warm stage		Abies, Picea	
3000	2620±90 2950±100	Ko-f								Kurosuna K2
4000	4010±70								Quercus-Juglans	
	4570±70 4600±70		1st Dune Generation			Middle Jomon Regression (Kemigawa Regression	Middle Jomon cold stage	P-2		Kurosuna K1
5000										
	5450±150 5750±70 5890±130 5920±50		Marine and lacustrine terraces 5-6m			Early Jomon Transgression	Early Jomon warm stage			
6000	6070±70 6440±100 6520±110	Ma-f								

on the South Kuriles and Japanese Islands. On Hokkaido, the dry and cool climate changed to warm and moist about 8000 yr BP, when the Tsushima Current reached the coast of northern Japan along with a general background of global warming (Igarashi, 1994). This paleogeographical event resulted in a sharp transformation of vegetation with birch and coniferous forests being replaced by cool–temperate broad-leaved forests and mixed coniferous–broadleaf forests, a main component of which was *Quercus*. On Kunashir Island, birch forests were replaced by broad-leaved forests about 7000–6500 yr BP. Evidence of this vegetation shift is seen in the pollen data, collected from lacustrine peaty silt deposits from the southeastern part of the Kunashir Islands (Fig. 4).

Maximum warming on Kunashir Island is dated to about 6000–5000 yr BP. Optimum Holocene vegetation changes were recorded in detail in some barrier–lake sequences. At this time, *Quercus* expanded across Kunashir and became the main component of the broadleaf forests that occupied much of the island. Mixed coniferous/broad-leaved forests occupied northern Kunashir. We suggest that the mid-Holocene vegetation of Kunashir was similar to southern Hokkaido's modern landscape. At the Holocene Optimum, temperate broad-leaved forests also occupied central Iturup. The main components of the forests were *Quercus* (up to 56%) and birches (up to 32%) (Korotky et al., 2000; Razjigaeva et al., 2002). Other broad-leaved trees included *Juglans* (up to 10%), *Ulmus* (up to 6%), *Phellodendron*, *Carpinus*, *Fagus*, *Tilia*, *Fraxinus*, *Aralia*, and *Syringa*. The modern distributions of these taxa are limited to Kunashir and Hokkaido, excluding *Phellodendron*, which is also found on southern Iturup. The presence of these indicator taxa suggests that the mean annual temperature was 2–3 °C higher than the present level. The presence of these taxa allows us to infer not only increased annual temperature but also higher summer temperature (up to 20 °C) and a total sum of active temperatures up to 1800 °C. Rare *Costanea*, *Pterocarya*, and *Acanthopanax* were found only in Kunashir pollen spectra and could have been wind-blown from Japan. The modern forest on the Okhotsk side of Iturup Island near Kurilsk is considered a relict of the Holocene Optimum forest, existing due to the warming effect of the Soya Current and the mountain barrier, which protects the forest from fog and cold winds formed by the cold water of the Oyashio current. At the Holocene Optimum, the timber-line rose more than 200 m, and oak–birch forests developed in the area of the modern *Pinus pumila* zone (Razjigaeva et al., 2002).

This warm phase is correlated with the Early Jomon warming of the Japanese Islands and the Holocene Optimum of Sakhalin, Primorye, and China (Sakaguchi, 1983; Igarashi, 1994; Korotky et al., 1996). The northward migration of vegetation zones on the South Kuriles, Hokkaido, and Sakhalin reflects climate warming intensified by the influence of warm currents. The Tsushima current reached northern Hokkaido at this time (Taira and Lutaenko, 1993). We suppose that the Soya Current was more active, too. The activity of the Kuroshio system currents is confirmed by fossil littoral mollusc assemblages, which are shifted 5–6° latitude north of their modern range. In this area, the minimum temperature of the surface water at the climatic optimum is estimated to have been about 5 °C higher than at present (Matsushima and Ohshima, 1974).

The maximum sea-level rise at the Holocene transgression coincided with the climatic optimum (Figs. 5 and 6). The sea-level curves are based on stratigraphy of low marine sequences (Korotky et al., 1995, 2000; Razjigaeva et al., 1997). During the mid-Holocene, the coastline of the islands was more irregular, and the sea reached its most landward position on the island coasts. Shallow straits developed within the low isthmuses. One typical feature of the Holocene Optimum shoreline is the abundance of marine molluscs. For example, beach deposits, located on the Okhotsk side of Vetrovoy Isthmus, Iturup Island, include rich mollusc assemblages: *Astarte borealis*, *Crenomytilus grayanus*, *Callista brevisipkonata*, *Clinocardium californiense*, *Mya* sp., *Mezcenariaa stimpsoni*, *Serripes groenlandis*, *Nucella* sp., *Buccinidae* sp., and *Chlamys swifti* (the ^{14}C date for shells 5350 ± 50 yr BP, GIN-7094; Bulgakov, 1996). Usually, evidence of this coastline is preserved only on the backside of modern lowlands and it was strongly eroded during later sea-level oscillations. There are elevated benches (up to 2–2.5 m above present sea level) dating to this age located on abrasion coasts. The altitude of the upper limit of marine facies, which provides direct evidence for sea-level position, was recognised by the horizon where sediment sequences changed abruptly from a marine unit to a peat layer. Marine species are replaced by freshwater diatoms in a diatom assemblage from this boundary (Fig. 5). The elevation of the coastline can be estimated by lagoon deposits positioned on the east coast of Lagunnoe Lake. These data are well correlated with the maximum amplitude of the Holocene transgression of the Japanese Islands (Maeda et al., 1994), as well as Sakhalin and Primorye (Korotky et al., 1996). The correlation of marine deposits in the studied sections shows that the terraces correspond to small magnitude fluctuations of the Holocene sea level and indicate weak tectonic deformation. We suggest that the magnitude of Holocene tectonic changes on the northwestern Pacific Islands was much less than that of contemporary sea-level changes.

During this Holocene stage, the sea-level rise led to active erosion, causing a large volume of detrital material to enter the coastal zone. The active formation of barrier forms led to the separation of numerous coastal lakes. For example, a cross-section of the terrace sequence of Kosmodemyanskaya Inlet shows barrier–lake deposits formed at the Holocene Optimum recovered by storm ridge deposits (Fig. 3). In some cases, the deposits have well-pronounced seasonal lamination. The lakes have passed through hydrological ‘open’ and ‘closed’ stages, caused not so much by climatic changes but by geological processes in a coastal zone. Development of epiphytes and benthic forms from the genus *Eunotia*, *Cocconeis*, and *Pinnularia* are connected with an increase in the shallowness of and in the swamping of the paleolake. The predominance of planktonic diatoms (mainly from the genus *Aulacoseira*) reflects pluvial phases. Marine diatom species typical for coastal regions (*Odontella aurita*, *Trachyneis aspera*, *Paralia sulcata*, *Thalassiosira gravida*) arrived in the lake with storm waves or tsunami impact, showing that sea level was higher than at present (Iliev et al., 2002). The growth of barrier forms at this time may have led to an increase in the depths of coastal lakes. The barrier–lake deposits record weak cooling about 5700 yr BP resulting in a slight regression and development of alder forests on the coasts and within river valleys. The same slight regression has also been established on Japanese islands (6100–5900 yr BP). Some coastal lakes in the Kuriles and in Japan were formed from embayments as a result of barrier development at the final stage of the transgression maximum.

On Bering Island, the Holocene Optimum deposits were not reliably distinguished, but we could not exclude that the marine unit from the Kamenka River (Fig. 3) sequence belonged to this age (Razjigaeva et al., 1997) because it is characterised by pollen spectra with a high content of tree birch pollen (more than 50%, mainly *Betula* sect. *Costatae*) and by warm diatom assemblages with species typical of modern flora of the Japan Sea (the favourable temperature for this vegetation is about 12–15 °C). The assemblages include exotics for this latitude such as south-boreal *Coscinodiscus perforatus* and moderately warm water *Stephanopyxis nipponica*. Other marine species are represented by moderately cold water sublittoral species, typical for the Bering and Okhotsk Sea regions (*Diploneis smithii*, *Cocconeis scutellum*, *Paralia sulcata*, *Hyalodiscus obsoletus*, rare *Odontella aurita*, *Trachyneis aspera*, *Arachnoidiscus ehrenbergii*, *Diploneis subcincta*).

The cooling at the middle–late Holocene boundary is dated about 4600–4500 yr BP. Pollen assemblages show that the South Kurile island vegetation changed slightly. Pollen assemblages from south Kunashir include *Quercus* (up to 54%) (Korotky et al., 2000) and a high content of birch pollen (up to 17%) and coniferous taxa (*Picea* sect. *Eupicea*, *Picea* sect. *Omorica*, *Abies*, *Pinus* s/g *Haploxylon* total—up to 17%), reflecting the development of oak forests in the coastal area, and birch and coniferous forests on the slopes. Because the content of broadleaf pollen is higher than in modern pollen spectra (33%), we infer that the climate was warmer than the modern day. Perhaps this resulted from the effect of warm ocean currents. The diversity of broad-leaved forests decreased, but oak forests were widely distributed on south Kunashir and central Iturup. The Hokkaido vegetation at this time did not change much (Igarashi, 1994).

The most significant regression of sea level in the middle–late Holocene is connected with this cooling, which caused the formation of extensive dune fields on the coast due to the supply of sandy material from the near-shore zone. This regression is correlated with the middle Jomon regression or Kemigawa regression of the Japan Islands (Sakaguchi, 1983). On Bering Island, the cooling and slight regression about 4500 yr BP was characterised by intensive accumulation of eolian material. A marker ash layer, KMPZ-1 of the Karimskiy Volcano (Kamchatka), is present at the base of the dunes (^{14}C date from underlying peat 4660 ± 150 yr BP, GIN-7264).

4.2. Late Holocene

The conditions at about 4000 yr BP were almost as warm as the Holocene Optimum. Mixed coniferous–broadleaf forests, with predominantly *Abies* among the conifers, occupied the central part of Kunashir Island. Cool–temperate broad-leaved forests were developed in the south (Fig. 7). It is possible that rare pollen grains of *Carpinus*, *Corylus*, *Fraxinus*, *Pterocarya*, and *Podocarpus* were wind-blown from the Japan islands. The mass development of warm water diatom species (*Actinocyclus octonarius*—up to 85%, *Terpsinoe americana*—up to 9%, *Navicula marina*, *Achnanthes brevipes*, and *Odontella laevis*) in the coastal waters of Kunashir and Iturup Islands indicates a warm water environment. Warm currents reached northern Hokkaido at this time (Taira and Lutaenko, 1993). This warming is also recorded in paleolandscapes of the Japanese Islands (Tsukada, 1986). Two high sea-level positions observed on the South Kuriles (Fig. 5) are correlated with the Late Jomon transgression of the Japan Islands (Sakaguchi, 1983). We think that the magnitude of the first phase was of a short-time duration and similar to the Holocene Optimum sea-level rise. The transgression led to erosion of the dune fields and abrasion of the weakly lithified rocks. The supply of a great amount of terrigenous material to the coastal zone during this transgression resulted in rapid accumulation of sediments, progradation of the coasts, and filling of inlets. The position of the units with marine diatoms indicate a transgression with sea-level rise of up to 1.5 m above modern sea-level position during the second phase.

On Bering Island, diatom data allow us to reconstruct two warming stages (Table 2), accompanied by small magnitude transgressions (Fig. 6). Sea-level rise about 3500 yr BP resulted in the development of small estuary lagoons. Diatom assemblages include mainly brackish species such as *Nitzschia circumsuta*, *Nitzschia acuminata*, *Navicula crucicula*, *Navicula peregrina*, and *Diploneis interrupta* and marine north-boreal (*Cocconeis scutellum*, *Paralia sulcata*, etc.) and moderate warm water species (*Navicula marina*, *Hyalodiscus obsoletus*, and *Actinoptychus senarius*). Ocean water influence in these lagoons fell to 500 m from the modern coastline, indicated by the presence of the marine diatoms *D. smithii* and *C. scutellum*. The lagoon existed up until the cooling about 3000 yr BP. Later sea-level rise (up to 1.5 m above modern sea-level position) took place about 2700 yr BP. The deposits of this transgressive phase are characterised by interbedding of beach sands and peat. Pollen spectra reflect the development of tundra landscapes, which perhaps existed during the entire Holocene period. Spores (up to 50%) prevalent in total pollen spectra, and *Betula* sect. *Nanae* (up to 49%) dominate among arboreal pollen. A small amount of tree birch pollen (up to 11%), and coniferous pollen (*Picea* up to 2%, and *Pinus pumila* up to 9%) were wind-blown from Kamchatka.

The period of comparative sea-level stability at the beginning of the late Holocene on the islands studied caused lateral shoreline erosion, amplified relative to present rates in many places on abrasion coasts. This resulted in the cutting of extensive low-tidal benches, which became exposed as sea level began falling 2000 years ago. These benches became covered with younger marine terrace deposits, aeolian deposits, and colluvium in many places (Fig. 3). All tropical Pacific Islands are now known to have experienced a sea-level fall during the late Holocene (last 3000 yr BP); the fall was possibly oscillatory (Nunn, 1997).

Significant changes in vegetation took place on the South Kuriles after 3000–2500 yr BP, with climatic deterioration indicated by pollen results. The northern boundary of mixed coniferous–broadleaf forests shifted southward and boreal coniferous forests with predominantly *Picea* occupied a large part of the Kunashir. Small-leaved forests became dominant in central Iturup. On the Japanese Islands, a general cooling trend began after 4000 yr BP. The summer temperature was lower during the late Holocene, while the winter temperature did not change appreciably, and precipitation increased (Tsukada, 1986).

Pronounced cooling coincident with a slight sea-level regression on the South Kurile and Japan Islands was established about 1700–1300 yr BP. This cooling is correlated with the Kofun cold stage of the Japan Islands (Sakaguchi, 1983). The beginning of this cooling is recorded by sharp increase of small-leaved genera and decrease of *Quercus* pollen. Shrub birches

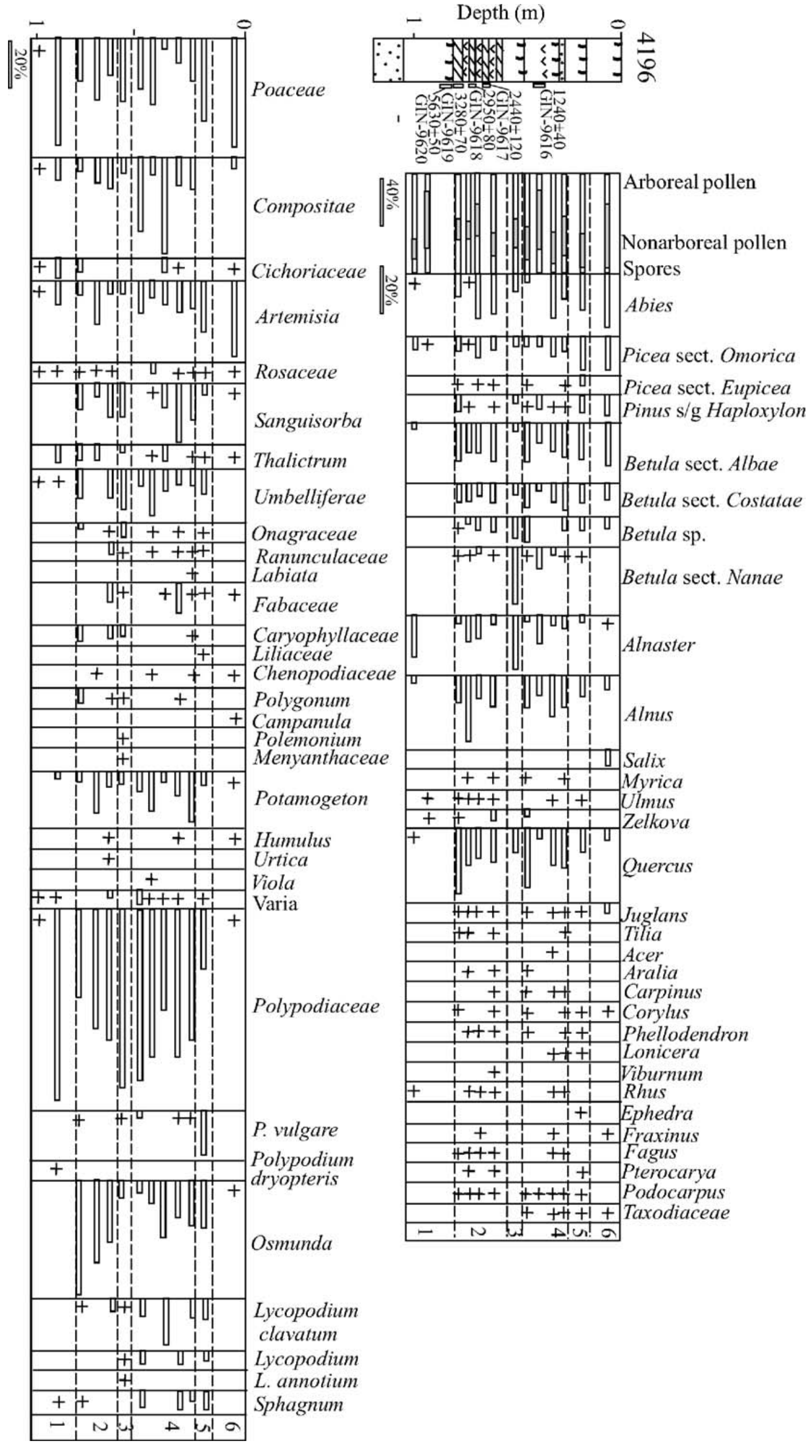
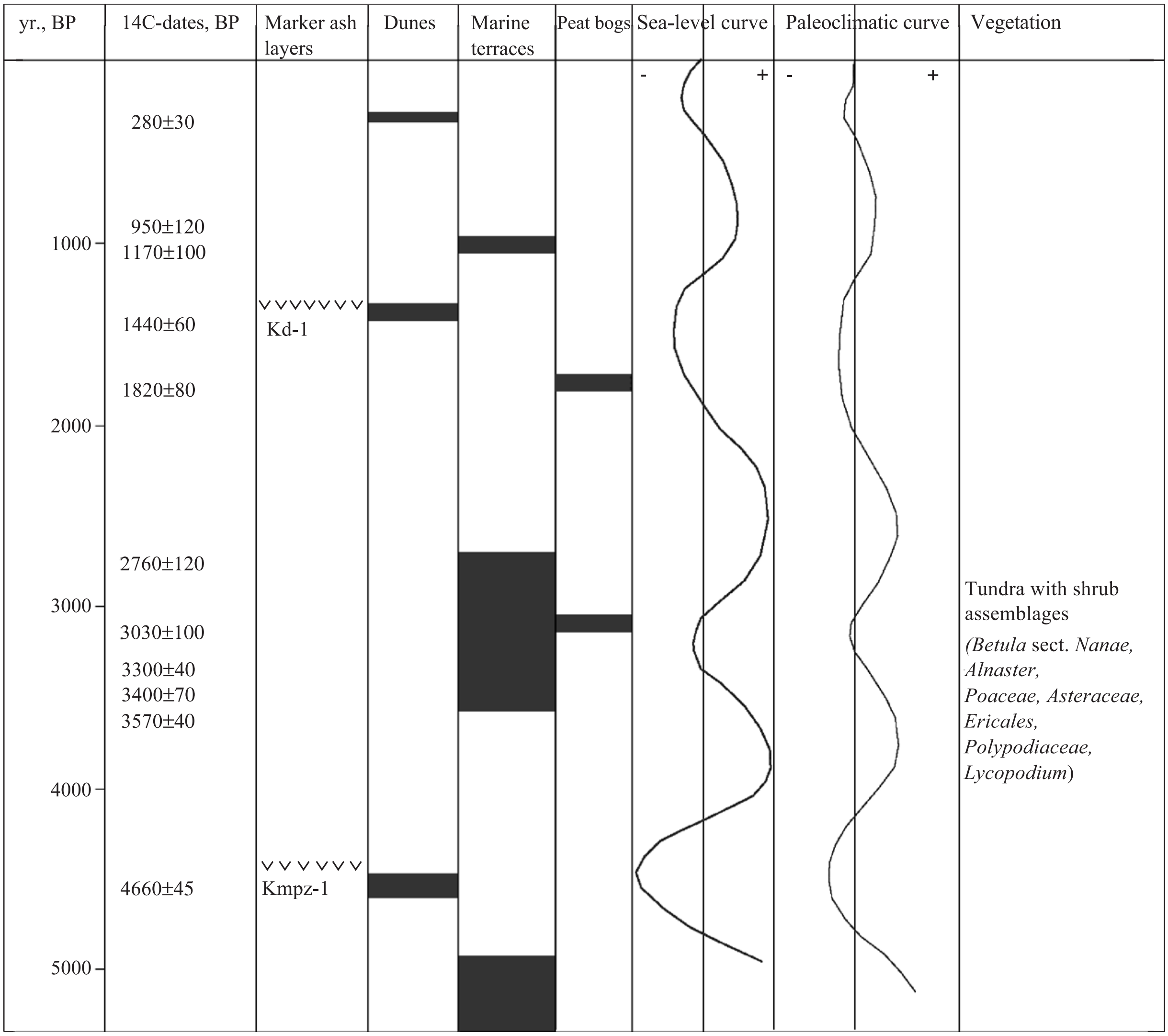


Fig. 7. Percentage pollen diagram for the soil profile of southeastern Kunashir, site 4196.

Table 2
The middle to late Holocene environments of Bering Island



(up to 26%) and *Alnaster* (up to 18%) assemblages developed on coastal lowlands near Kurilsk and formed a pseudo-forest–tundra zone (Razjigaeva et al., 2002). There may have been a high productivity of these taxa. Late Holocene pollen spectra consistently include more tree pollen, such as birch and oak, than are present at the Last Glacial Maximum spectra. This reflects the development of forests on the lower slopes within the river valleys and other areas protected from any influence of maritime cooling. Perhaps this cooling led to the disappearance of thermophylous broad-leaved taxa such as *Carpinus*, *Fagus*, and *Fraxinus* from the vegetation of Iturup. Vegetation changes seem to have been caused by climatic deterioration and marine current influences. At this time, warm stream activity in the Okhotsk Sea decreased significantly (Taira and Lutaenko, 1993). The Oyashio Current was possibly more active, leading to an increase in fog and drizzle and a more intense wind regime. The combination of increased precipitation and falling temperatures on northwestern Pacific Islands during the late Holocene introduced a degree of instability in their environments. A modern analogue of these landscapes is northern Sakhalin, where the annual sum of active temperatures is less than 1000 °C, the annual mean temperature is −2.0 to −2.6 °C, the mean summer temperature is +13 to +15.5 °C, and the mean winter temperature is −20.2 to −21.1 °C. On Bering Island, the cooling at the beginning of the Subatlantic (about 1800–1400 yr BP) is fixed in a peat unit with freshwater diatom assemblages, overlaid with lagoon deposits (Razjigaeva et al., 1994).

The presence of thermophylous broad-leaved taxa in the Holocene Optimum vegetation of Iturup Island and the disappearance of these taxa or shifts in their natural range during late Holocene minor climatic changes indicate that these taxa did not survive in refugia during the Last Glacial Maximum (Urusov, 1996). Modern natural habitats for the majority of these thermophylous taxa are limited to southern Hokkaido. One might be tempted to argue that the habitats of these taxa at the Holocene Optimum were on Hokkaido and Kunashir, and that their appearance in deposits on central Iturup was a result of their pollen being transported far by the wind. However, according to the study of modern pollen assemblages and pollen rain, this is unlikely. Pollen rain on Kunashir Island includes rare pollen of some thermophylous species from the Japan Islands, but the values of these taxa are very low, and pollen spectra from modern lacustrine and alluvial sediments contain only taxa that grow on the island (Mokhova and Eremenko, 2001).

The fall of the sea-level record on the islands during the second half of the late Holocene caused profound changes to their coastlines. On the South Kuriles, the isthmus area increased, and coastal peatlands with small lakes were formed in place of the inlets and lagoons. Dunes were formed at this time. Rare forest in some places and the high humidity caused the activation of slope processes. As a whole, the island vegetation was similar to its current condition (Korotky et al., 2000; Razjigaeva et al., 2002).

The grassland and swamp landscapes spread widely on the southern Kurile Islands. We suggest that most of the grasslands on the islands may be climatic in origin rather than anthropogenic, and this is con-

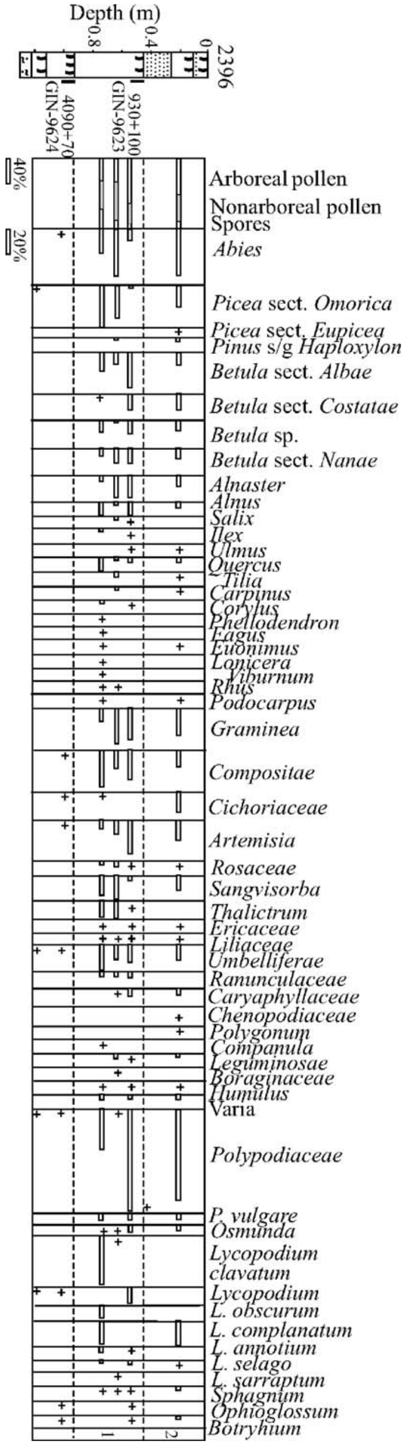


Fig. 8. Percentage pollen diagram for the soil profile of central Kunashir, site 2396.

firmed by pollen data from paleosol sequences (Fig. 8). The settlement of the islands began about 3000–4000 yr BP (Zaitseva et al., 1993) when human impact could not be the cause of vegetation degradation or forest disappearance. The grassland landscape was formed at 2000 yr BP due to a cooling intensified by the influence of cold Oyashio currents, which produced fog and drizzle. This influence mainly occurred within flat surfaces open to Pacific winds. The grasslands are stable landscape elements on island coasts with fog and a strong wind regime. Some grasslands were formed on cleared spaces, which indicates an inability of the forests to regenerate after active anthropogenic impact. The high diversity of herb assemblages in the swamps occurred on coastal plains, which began to form at the Holocene Optimum in central and southern Kunashir, where broad-leaved forests developed. The younger late Holocene accumulative landforms have less diverse grass flora.

Climate changes over the past millennium in the northwestern Pacific are also believed to have been driven by sea-level changes. Warming recorded on the Japan Islands about 1000 yr BP (Nara–Heian–Kamakura warm stage) was small on the South Kuriles (Fig. 9). The tendency to warming is confirmed by increases in broad-leaved pollen genera such as *Quercus* and *Ulmus*. Marine terraces (up to 2.5 m), which correspond to the Heian Transgression of Japan, were formed during a sea-level rise of up to 1 m above the present sea level. At this time, a well-pronounced soil profile was formed. On Bering Island, the ocean-level rise led to the formation of low marine terraces, whose elevations reached 2 m on the Bering Sea coast and up to 5–6 m on the Pacific coast (site near Vhodnoi Mis Cape). The large difference in elevation is explained by more active hydrodynamic activity on the open coast near the cape. The lowering of sea level after the slight transgression is fixed by peat on the bench (dated 850 ± 50 yr BP, GIN-8428), which was found on southern Kunashir. The same data (870 ± 40 yr BP, GIN-12010) was received from peat overlaid with a marine unit (Iliev et al., 2002). The cooling and slight regression of the Little Ice Age was characterised by an intensive accumulation of eolian material and by the input of sand to soil profiles in the coastal area. A typical feature of these dunes is the absence of paleosols.

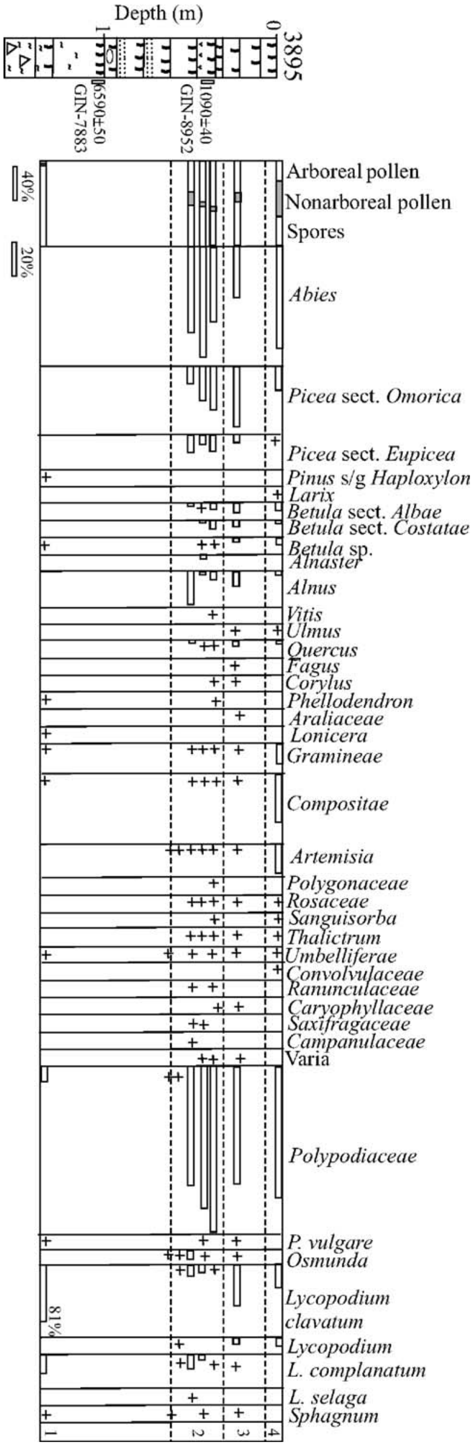


Fig. 9. Percentage pollen diagram for the soil profile of central Kunashir, site 3895.

One of the factors important in influencing the environment of the Pacific islands is volcanic activity. Numerous ash falls, especially during the last 2000 years on the South Kuriles, have resulted in the development of an island environment. Volcanic impact to environments has resulted in the formation of thick soil profiles with a series of buried soils. During eruptions, tephra buried the soil around

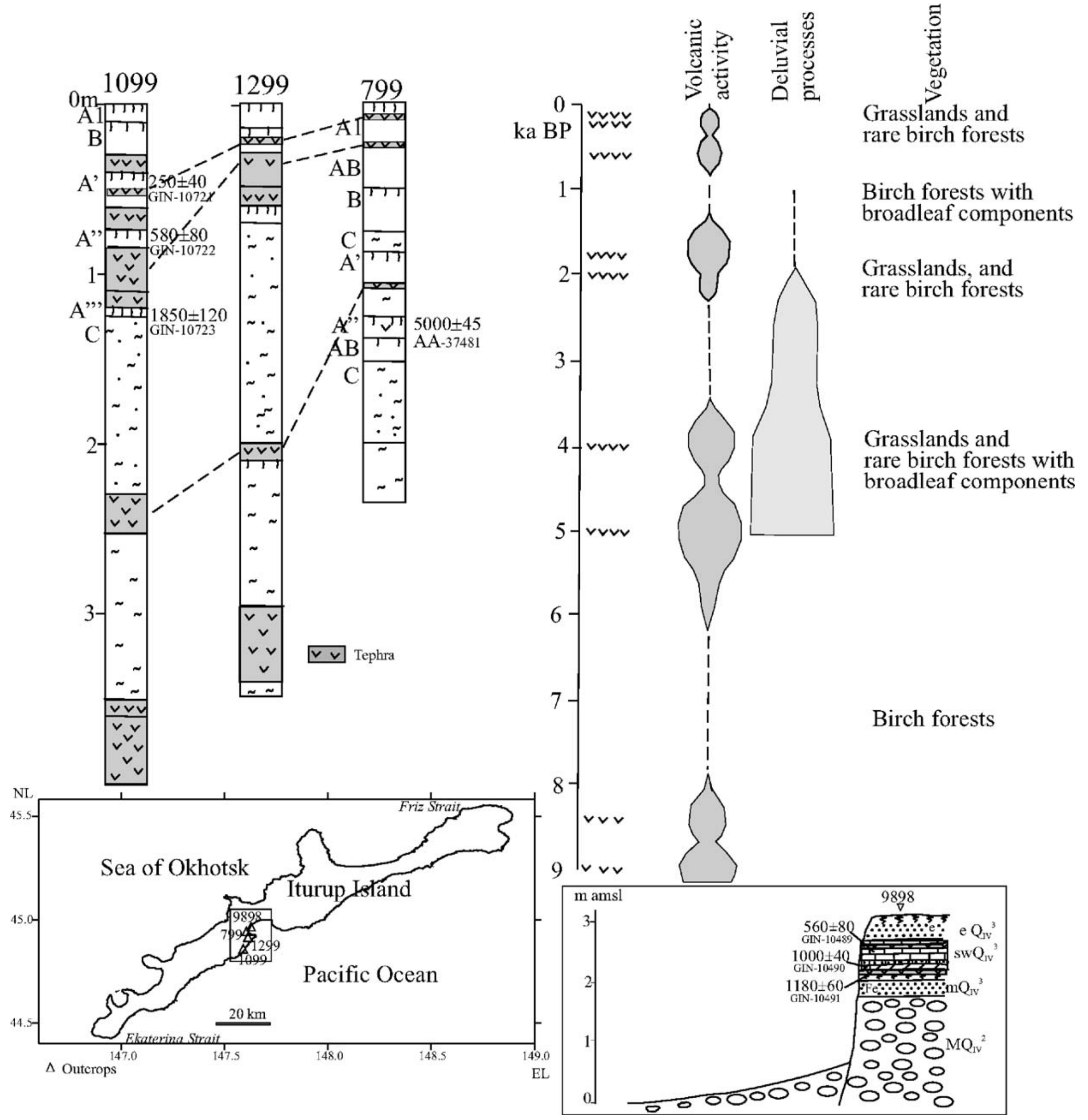


Fig. 10. Volcanic impact on environments, Holocene tephra-soil sections near Burevestnik Volcano, Iturup Island. A, B, C—soil horizons; A′ —paleosol horizons.

volcanoes, and vegetation and soil formation processes repeatedly resumed. After eruptions, large amounts of loose material led to the active development of deluvial processes around volcanic centres. The main landscape elements were herbs and, very rarely, trees and shrubs. One of the pioneer plants on tephra substrate is *Pinus pumila*. The supply of great amounts of nutrients provided by the ashfall promoted the development of vegetation. The andesite–basalt ashfalls, with an abundance of clay and silt fractions, changed the hydrological regime of the area and affected herb assemblages. These ashfalls promoted swamping of some plots (Fig. 10). The supply of a great amount of basalt–andesite ashes promoted the formation of layers with poor drainage. In some cases, this led to the formation of small lakes within interdune depressions or to the development of mires, even on terrace surfaces, composed of coarser pebble material. Environmental changes are in vegetation assemblages. Plants typical for wetter environments became dominant. On the South Kuriles, most peat bogs were formed at the late Holocene, which coincided with volcanic activity increasing at 2000 yr BP.

5. Conclusions

Ocean islands are very sensitive, reacting quickly even to minor climatic changes. Environmental changes on the islands were controlled by global and regional factors, primarily the migration of warm and cold ocean currents. Vegetation distribution from refugia under favourable climatic conditions on a background shift of vegetation zones controlled paleolandscape development, especially on islands separated by deep straits from neighbouring islands. These island areas were isolated during the Pleistocene glacial stages. Extensive landscape changes occurred at the mid-Holocene. The Holocene Optimum on the South Kurile Islands is dated about 6500–5000 yr BP. At this time, the Kuroshio Current system became more active. Birch and coniferous forests were replaced by cool–temperate broadleaf and mixed coniferous–broadleaf forests, a main component of which was *Quercus*. The warming was coincident with transgression to the highest sea-level position about 2.5–3 m amsl. The coastline of the islands was more irregular than today. The sea-level rise led to active abrasion, causing a large volume of detrital material to enter the coastal zone and causing the formation of barrier forms and numerous coastal lakes. The cooling and sea-level drop at 4600–4500 yr BP led to the formation of large dune fields and to the development of a swamp environment in coastal zones instead of shallow lagoons. Despite climatic deterioration, island vegetation changed very little due to the ameliorating influence of warm currents. Two minor transgressions are recorded about 4010–3400 and 2900–2600 yr BP. The warming about 4000 BP was almost as great as that of the Holocene Optimum due to the influence of warm ocean currents. Large vegetation changes and climatic deterioration took place in the second half of the late Holocene. Pronounced cooling was established about 1700–1300 yr BP. A slight regression led to the formation of dunes and coastal wetlands with lakes. Active eolian accumulation took place during the Little Ice Age cooling and regression. Another major factor influencing island environments during the last 2000 years was numerous ashfalls from Hokkaido and local volcanoes on the South Kuriles and from Kamchatka on Bering Island.

Acknowledgements

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