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Abstract: The study of Holocene deposits on Iturup Island is very important for understanding palaeolandscape changes on the island. It is separated by deep straits from the neighbouring islands and was isolated during the last glacial maximum. Landscape changes over the last 40000 years and the role of refugia on vegetation development are discussed. Changes in natural processes in this region were controlled both by global climatic changes and by regional factors. Birch forests developed at the warming about 36–37 ka ago, whereas tundra-park landscape developed with the cooling of the last glacial maximum. Holocene environments reflect climatic changes and sea-level oscillations. The fluctuation of warm and cold currents influenced the landscape development. At the Holocene Optimum (about 6 ka) broadleaved forests with *Quercus, Phellodendron, Carpinus, Juglans, Fagus, Fraxinus* and *Syringa* occupied the Okhotsk side of central Iturup. Climate was warmer than present and the sum of active temperatures ($\Sigma t \geq 10$°C) was not less than 1800°C. The warming was coincident with the transgression with the highest sea level up to 3.5 m above present sea level (PSL). Numerous coastal lakes were formed at this time. A shallow strait occurred on the low Vetrovoy isthmus. The sea-level drop at 4700–4500 radiocarbon years BP led to the development of large dunefields only within bays with a flat coast due to the supply of sandy material from the inshore drainage zone. At the beginning of the late Holocene about 4000 BP the vegetation changed very little due to the warm current influence. Cool-temperate forests with dominant *Quercus* had a wide distribution, but the diversity of broadleaved genera decreased. A minor transgression occurred about 4100–4000 BP with a sea-level rise on about 2.5 m above PSL. Active accumulation of deposits took place in the coastal zone at this time. Great vegetation changes and climatic deterioration took place in the last 2000 years BP. Cool-temperate broadleaved forests were confined to the Okhotsk side of the central island. Grasslands and swamps also developed in the coastal lowlands at this time. A minor regression led to the formation of large dunefields. Isthmuses increased and coastal wetlands with lakes formed. The presence of marine diatoms in floodplain lake deposits indicates a sea-level rise at about 1060 ± 60 BP. At this time warming was not intensive, but was well pronounced. The last phase of active aeolian accumulation took place during the 'Little Ice Age' cooling and regression.

Key words: Environmental evolution, palaeoclimate, ancient shoreline, sea-level oscillations, vegetation history, Kurile Islands, Holocene.

Introduction

The study of Holocene deposits on the Kurile Islands in the northwestern Pacific is very important for understanding the natural development of islands with an oceanic climate, strong microclimate variability, and the influence of contrasting marine currents. One problem we discuss is the role of refugia in influencing vegetation changes during the Pleistocene-Holocene climatic oscillations. Do shifts in vegetation zone boundaries or does vegetation distribution from refugia under favourable climatic

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conditions control vegetation changes? An island such as Iturup is a good example for addressing this problem because the area is separated by deep straits from neighbouring islands and was isolated during glacial times. Iturup Island has many vegetation zones (Vorobiev, 1963; Urusov and Chipizubova, 2000), migration of which within a limited area is important for understanding palaeolandscape development on an island under a changing climate.

The Kurile Islands are situated in an active tectonic zone. Therefore, tectonic activity has been a major influence on coastal evolution. Various studies have examined coastal terrace sequences, raised beach ridges, wetlands and lake deposits with a view to determining tectonic movements and other characteristics of regional tectonic behaviour. Studies of Holocene sea-level changes have also focused on coastal lowland areas because of the good preservation of geological sea-level records.

Holocene deposits on the Kurile Islands are widespread within bays and inlets, near river mouths and within low isthmuses (Melekestsev *et al.*, 1974; Korotky *et al.*, 1997; 2000). The stratigraphy, genesis and chronology of Holocene deposits on Iturup Island, the largest island of the Kurile Island Arc, are still poorly studied. Previous studies by Aleksandrova (1971) have provided only general information on the development of the vegetation. Little work has been done to link the Holocene history of the Iturup Island area. Bulgakov (1996) studied the history of the Iturup coastal zone based on ^{14}C dating of terrace sequences and found that the age of the low-level terrace lies in an age range from present to 5000 BP.

This paper presents new stratigraphic data on central Iturup Holocene deposits. The aim of our study is to analyse the sedimentary environment evolution, and the influence of global and regional climate, sea-level fluctuations and marine currents on the natural environment history of the island.

Regional setting

Iturup Island (44.45–45.55°N, 146.80–148.88°E) is the largest island of the Kurile Island Arc and is about 200 km long and from 5.5 to 46 km wide. Ekaterina Strait (23.2 km wide, up to 485 m depth) divides Iturup from Kunashir, and Friz Strait (46.3 km wide, up to 890 m depth) from Urup (Figure 1). The Pacific Ocean with the Oyashio cold current borders the island on the east and the Sea of Okhotsk on the west. The warm Soya current penetrates up to Kurilsky Bay on the Okhotsk side of the island (Fuks *et al.*, 1997). Iturup Island has a mountainous relief (up to 500–1800 m) resulting from some volcanic activity and four low isthmuses (from 3–4 m to 60 m high). Peat bogs are mainly developed on coastal plains around the island.

Iturup Island has an oceanic climate with a small annual temperature amplitude, warm winters and cool summers. Atmosphere circulation is strongly influenced by the Asian monsoon. During the winter the northwest air-masses from Asia produce cold temperatures and snow (in open areas, snow depth may reach 0.68·m). During the summer, moist cool Pacific air-masses move south or east across the Kurile Islands toward the Asian low-pressure area, bringing with them extensive rainfall, fog and typhoons in August–September. The annual mean temperature is about 4.3°C (*Atlas of Sakhalin District*, 1967; *Reference book of USSR climate*, 1970). Mean monthly temperature differs from –5.8°C in January and about 16°C in August, and maximum summer temperatures can reach 32.1°C. Annual rainfall is about 1040 mm and mean humidity is 77–89%. Strong NW winds (winds >15 m/sec) prevail in autumn and winter, shifting to SW and SE in summer. The South Kurile Islands are located in an area with an irregular diurnal tide with a mean range of about 1 m and spring tide of about 1.4 m (Glukhovskoy *et al.*, 1998). The coast of Iturup Island with respect to tidal range is microtidal and is wave-dominated.

Ocean currents are particularly important in influencing the regional climate of the South Kurile Islands. The warm Soya current has a warming effect on the Okhotsk Sea coasts of Iturup. The Oyashio cold current brings cold water from the north to south in the Kurile region. It produces fogs, typical of the ocean side of the island. Fogs decrease in the inner part of the island and usually disappear 3–4 km in land. On the Pacific side of the Kurile Islands, the number of fog-days reaches 160 days per year, whereas on the Okhotsk Sea side (Kurilsk region) there are only 50 days. Marine currents, mountain relief and hot springs define a wide range of microclimatic conditions on the island. The vegetation period on the Okhotsk side is warmer than on the Pacific coast side, and the number of sunny days on the Okhotsk side is more than on the Pacific side.

The composition, structure and productivity of the vegetation on the Kurile Islands are primarily controlled by the amount of annual warmth (period of time with mean daily temperatures ≥10°C and the sum of these temperatures during this period, namely the sum of biological active temperatures) (Urusov and Chipizubova, 2000). The sum of biological active temperatures (Σt ≥10°C) in Iturup reaches 1350–1450°C and time period with mean daily temperatures ≥10°C is 104 days (Urusov and Chipizubova, 2000). The vegetative season attains 166 days (Urusov, 1988).

The main study area is coastal lowland near the mouth of the Kurilka River (Figure 1). Special interest in this area is connected with reconstructing the history of the broadleaved forest, located near Kurilsk-Reidovo. It is the largest broadleaved forest area on the Kurile Islands (Urusov and Chipizubova, 2000). Broadleaved taxa include *Quercus crispula, Kalopanax septemlobum, Acer pictum* and *Ulmus laciniata* in association with *Betula ermanii.* Shrubs include *Taxus cuspidata, Ilex rugosa, I. crenata, Rhododendron tschonoskii* and *Sasa kurilensis* with *Lycopodium* and Polypodiaceae (Vorobiev, 1963; Seledets, 1969; Urusov, 1996). This forest on the Okhotsk side is considered a relict, persisting due to the warming effect of the Soya Current, the barrier created by the mountain relief, and protection from fog and cold winds formed by the cold water of the Oyashio current. The upper boundary of the oak-broadleaved forests is located 300–400 m above mean sea level (amsl) (Urusov and Chipizubova, 2000).

Birch forests with a predominance of *Betula ermani* occupy 38% of the island area and are mainly developed on the Pacific side and in the inner parts of the island (Urusov and Chipizubova, 2000). Such forests occur on the lower part of the slopes and usually include *Betula platyphila.* Open forests with *Betula* as the dominant and grasslands are typical of the northern part of the island, the microclimate of which is controlled by the influence of cold water in the Friz Strait (Urusov and Chipizubova, 2000). Accordingly, the Vorobiev (1963) line between the South Kurile and the Middle Kurile geobotanical provenances lies on the Vetrovoy Isthmus. Park forest with *Larix kurilensis* occurs on the central part from coastal beach ridges to 400 m amsl. Coniferous forests with *Abies sachalinensis, Picea microsperma, P. glehnii* and *Taxus cuspidata* occupy the southern part of the island. The *Pinus pumila* zone is located on mountain slopes above 400 m. One of the main plants is *Sasa kurilensis* on the lower and middle slopes. Valley forests are characterized by a predominance of *Alnus, Ilmus, Salix* and various herbaceous plants (Vorobiev, 1963). Grassland and grassland with shrubs usually develop on marine terraces and river valleys and occupy mountain heads. Wetlands and swamps with small ponds occur on coastal lowlands and on volcanic slopes.

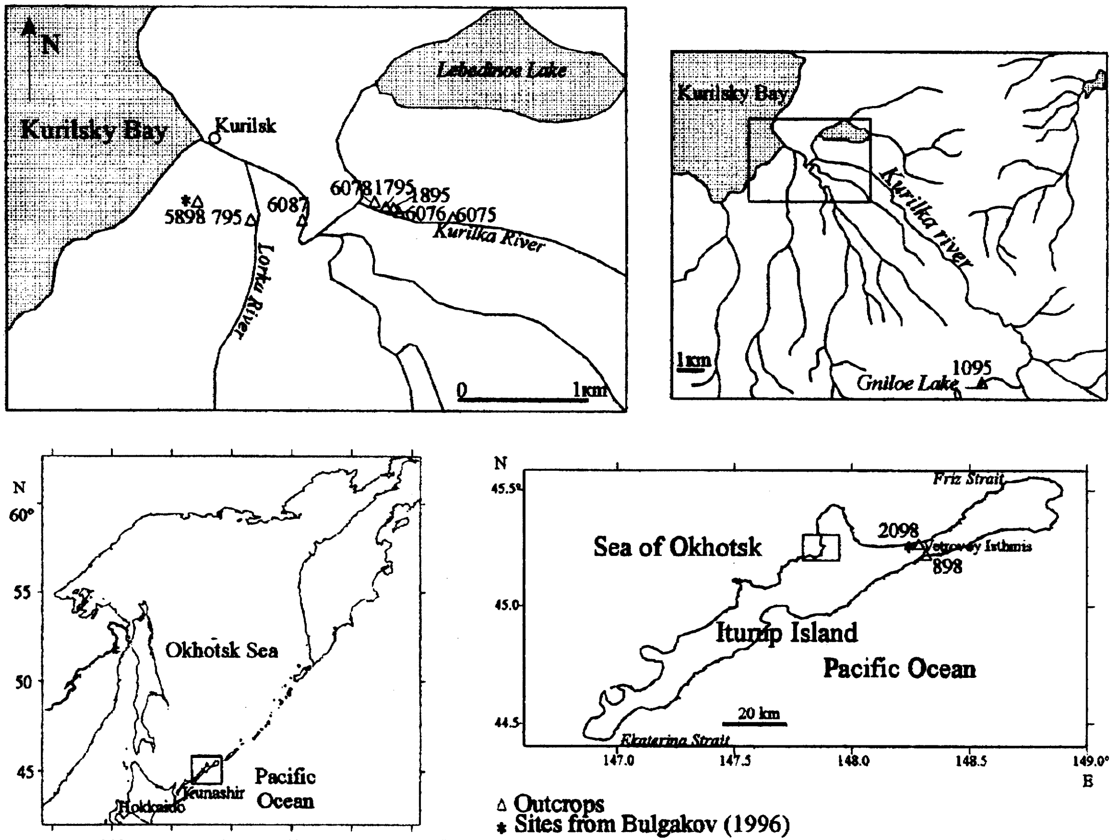

Figure 1 Location of the study area.

Material and methods

The Holocene sections studied in 1995, 1998 and 1999 include low marine and lacustrine terraces, wetlands and dunefields. Some outcrops were selected for detailed observations and sampling. Figure 1 shows the location of the outcrops studied. Most of them are located within the coastal lowlands. For the reconstruction of the vertical migration of vegetation zones, the section of lacustrine deposits from the plateau (400 m elevation) was sampled (site 1095).

Diatom and pollen samples were analysed at 10 cm intervals from lacustrine, marine and peat units, or at varying intervals depending on the sediment lithology. Diatom and pollen methods are described in detail in Korotky *et al.* (2000). Diatom identifications follow Krammer and Lange-Bertalot (1986; 1988; 1991a; 1991b). At least 300 valves were counted per sample. The ecological significance of the diatom species is based on de Wolf (1982), Denis (1991), Krammer and Lange-Bertalot (1986; 1988; 1991a; 1991b), Jouse (1962), Davidova (1985) and Barinova and Medvedeva (1996). The ecological data given by the abovementioned authors have enabled most taxa to be grouped into the categories marine, brackish and freshwater, and then divided into planktonic and benthic species. Only taxa with the highest abundances and important indicator species are graphed.

Material for pollen analysis was treated with the standard KOH and acetolysis method. For identification of pollen types, the key by Pokrovskaya (1966) was used. Pollen identifications were assisted by the regional reference collection held at the Pacific Institute of Geography. Two distinct type of *Picea* and five type of *Betula* are identified following Pokrovskaya (1966). Taxa are grouped into arboreal pollen, non-arboreal pollen and spores and are expressed as percentages of the total pollen sum. Tree and shrub pollen percentages are based on total arboreal pollen, herb pollen on total non-arboreal pollen, and spores on total spores. Diagrams were divided by visual inspection into pollen zones. Local pollen-assemblage zones were established on the basis of the major arboreal pollen types.

Ages were determined by ^{14}C analysis. ^{14}C dating of samples was based on wood, peat and soil samples 10 cm thick (Table 1). The samples were treated with standard acid and alkali solutions. ^{14}C dating was done by liquid scintillation counting at the Geological Institute, Russian Academy of Sciences, Moscow. The full ^{14}C age data for the deposits on Iturup Island are presented by Bazarova *et al.* (2001). Table 1 lists the ^{14}C dates for the sections studied and radiocarbon years BP are used throughout the text.

Ash layers were identified in the field and later studied in the laboratory under cross-polarized light. The correlation of ash layers is based on refractive indices, morphology of volcanic glass shards and chemical (wet chemistry) and mineralogical composition.

Results

Figure 2 shows cross-sections of the coastal lowland located near the mouth of the Kurilka River. The deposits include marine, fluvial, lacustrine, swamp and aeolian facies. Three terrace levels at 5–6, 3–4 and 2–2.5 m are well pronounced. The stratigraphy of some key sites within these levels was studied.

Site 6075

Site 6075 exposes deposits on the 5 m terrace and 1.5 km from the sea (Figure 2). Moderately rounded pebbles within a yellow-brown matrix are exposed at the base of the terrace. Well-pronounced cryogenic structures typical of seasonally frozen

Table 1 ^{14}C ages of late Pleistocene-Holocene deposits on Iturup Island

Sample no.	Collection site	Position	Depth (m)	Material	^{14}C age (yr BP)	GIN-no.
I/6075	Kurilka River	5 m terrace	1.5–1.65	soil	5210 ± 110	9631
II/2898	Kurilka River	5 m terrace	1.1–1.2	soil	2100 ± 40	10725
I/2898	Kurilka River	5 m terrace	0.95–1.05	soil	1590 ± 60	10724
I/6076	Kurilka River	3–4 m terrace	2.6–2.8	wood	36900 ± 1300	8636
II/6076	Kurilka River	3–4 m terrace	2.3–2.4	peat	4220 ± 90	9632
I/1795	Kurilka River	3–4 m terrace	0.7–0.73	peat	4090 ± 50	8646
I/6087	Kurilka River	3–4 m terrace	2.3–2.7	wood	4000 ± 70	8637
I/1895	Kurilka River	Peat bog from erosion cut within 3–4 m terrace	3.0–3.2	wood	1060 ± 60	8635
Ia/1895	Kurilka River	ditto	0.7–0.85	peat	510 ± 100	8645
I/6078	Kurilka River	ditto	0.9–1.0	coal	Modern	8957
I/9798	Channel from Lebedonoe Lake	3–4 m terrace	0.6–0.7	peat	970 ± 60	10726
I/795	Lorka River	3–4 m terrace	1.3–1.4	wood	3700 ± 110	9633
*	Kurilsk	Dunefield, buried soil	1.1–1.2	soil	800 ± 40	7344
I/1095	Stream in 100 m from Gniloe Lake	Lacustrine terrace (+400 m amsl)	0.22–0.3	peaty silt	2420 ± 70	8946
II/1095	Stream in 100 m from Gniloe Lake	Lacustrine terrace (+400 m amsl)	0.2–0.3	peat	4980 ± 90	8947
Ia/1095	Stream in 100 m from Gniloe Lake	Lacustrine terrace (+400 m amsl)	0.22–0.42	wood	Modern	8633
I/898	Vetrovoi Isthmus, Pacific side	3–4 m terrace	2.2–2.24	soil	1280 ± 110	10494
*	Vetrovoi Isthmus, Okhotsk Sea side	Storm ridge (5–6 m)		shells	5350 ± 50	7094
I/6898	Yankito II	3–4 m lacustrine terrace	0.47–0.5	soil	1190 ± 130	10485
II/6898	Yankito II	3–4 m lacustrine terrace	0.65–0.68	soil	1400 ± 100	10486
III/6898	Yankito II	3–4 m lacustrine terrace	1.55–1.65	peaty silt	3760 ± 110	10487
I/8298	Yankito II	Buried soil under storm ridge	4.9–5.0	soil	6820 ± 100	10488

*Dates from Bulgakov (1996).

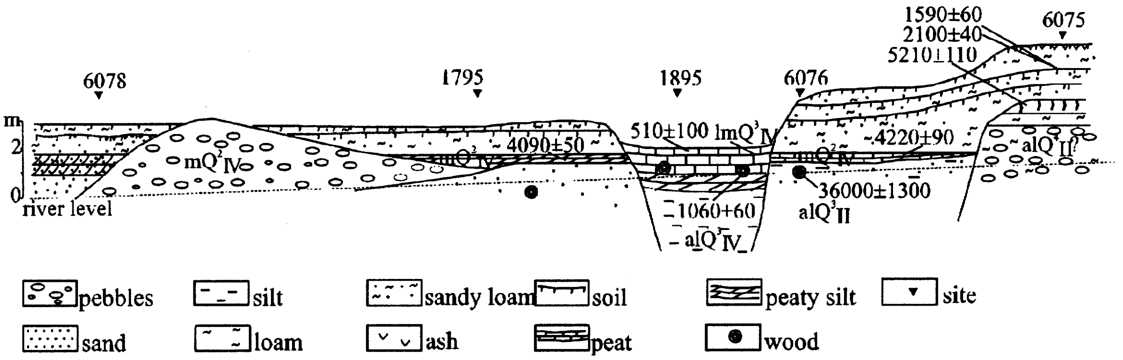

Figure 2 Cross-section of Holocene deposits in the low current of the Kurilka River. Q^2_{IV} = middle Holocene; Q^3_{IV} = late Holocene. Facies: m = marine; lm = lacustrine; al = alluvial.

layers (Vtyurina, 1966) occur at the top of this unit. The upper part of the site is composed of yellow-brown loams and sandy loams with some buried soils. The deposits from the base of the site (1.4–4.0 m) contain rare freshwater diatoms and redeposited marine species from the Pliocene Ribakovskaya Formation (Vitukhin *et al.*, 1996). A rich freshwater diatom assemblage was found in the upper sandy loams unit (0.15–1.4 m). An abundance of *Cymbella, Diatoma, Rhoicosphenia abbreviata* and *Didymosphenia geminata* indicates that the unit was deposited in a floodplain environment.

There are six pollen zones in these deposits, corresponding to major palaeolandscape changes (Figure 3).

Pollen zone 1 (1.85–3.5 m) reflects the development of shrub birch and *Alnaster* with abundant Gramineae and various herbaceous plants. The presence of Ericaceae, *Polygonum* and *Potamogeton* indicates the development of wet areas with small ponds. Climate was cold. These deposits could be correlated with the last glacial maximum, because tundra and park-tundra were typical landscapes on Northeastern Hokkaido and South Kurile at this time (Tsukada, 1986).

Pollen zone 2 (1.4–1.85 m) corresponds to the second buried soil. Spores, dominant at the base of the soil are mainly represented by *Sphagnum* and *Adiantum*. Among the arboreal pollen, the predominance of *Alnaster* (up to 60%) and shrub birch suggests a cold wet climate. The ^{14}C date of 5210 ± 110 BP obtained from the soil is considered too young, because the time interval 7000–4000 BP was the warmest period during the last 20000 years on South Kurile (Korotky *et al.*, 2000) and the Japanese Islands (Tsukada, 1986; 1988; Igarashi, 1994).

Pollen zone 3 (1.08–1.4 m) with a background predominance of shrub birch (26%) and *Alnaster* (18%). Tree birch pollen increases (up to 18%), reflecting the development of open birch forests. The soil was formed about 2100 ± 40 BP.

Pollen zone 4 (0.95–1.08 m) from the first buried soil is characterized by the appearance of rare broadleaved taxa (*Quercus, Fraxinus, Phellodendron,* Vitaceae, *Euonymus*). Shrub birches and *Alnaster*, pollen of which dominate the pollen spectra, developed on the coastal lowland. The soil was formed about 1590 ± 60 BP.

Pollen zone 5 (0.03–0.95 m) from the sandy loam and the lower part of the surface soil mainly includes *Alnaster* (up to 47%) and shrub birch with some tree birch, *Alnus*, coniferous and broad-

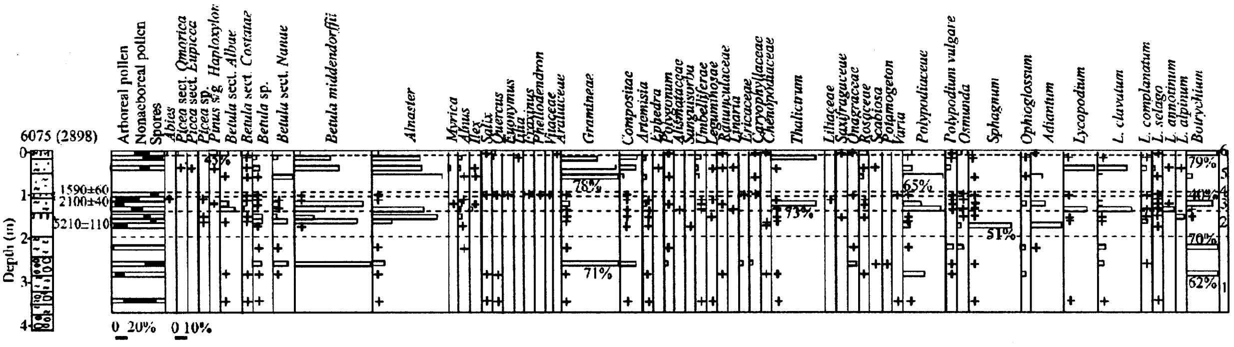

Figure 3 Percentage pollen diagram for the 5–6 m terrace in the Kurilka River valley, site 6075 (2898).

Table 2 Chemical composition of volcanic ash layers from Holocene deposits on Iturup Island

Sample no.	Position	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
1a/2898	Soil on 5 m terrace	70.02	0.49	14.80	3.91	1.55	0.11	1.27	3.75	2.45	1.38	0.24
1/5898	First buried soil from dunes	70.80	0.38	14.15	2.18	1.63	0.09	1.11	4.35	3.35	1.85	0.11

leaved taxa. The high content of non-arboreal pollen suggests the development of grassland.

Pollen zone 6 (0–0.03 m) from the upper part of the surface soil above the volcanic ash layer reflects the modern landscape. Abundant herb pollen (38%) and spores (22%) reflect grassland vegetation. *Pinus pumila* (45%) and tree birch pollen dominate. Broadleaved taxa are represented by *Quercus* (8%). Valley and swamp assemblages are recorded by the presence of *Alnus, Alnaster* and *Salix*. The top soil includes rhyolithic volcanic ash (Table 2), correlated to the ash layer from the first buried soil in the dunefield near Kurilsk (^{14}C date 880 ± 40 BP) (Bulgakov, 1996).

Site 6076

Site 6076 exposes deposits of the 3–4 m terrace about 0.6 km from the sea. The sandy unit at the base of the site (2.7–3.0 m) contains rare freshwater diatoms such as *Melosira undulata* and *Diploneis elliptica*. The deposits were formed about 36900 ± 1300 BP. Overlying Holocene deposits include two diatom assemblages (Figure 4).

Assemblage 1 (2.05–2.7 m) from the peat unit is characterized by a high content (up to 76%) of marine species, such as sublittoral north-boreal *Diploneis smithii*, *D. smithii* var. *pumila*, *Thalassiosira bramaputrae*, south-boreal *Actinocyclus octonarius* and *Terpsinoe americana*, indicating a semi-open bay environment. In the interval 2.05–2.6 m the content of marine diatoms sharply decreases (0.4–6%) and freshwater species such as *Fragilaria construens* var. *subsalina*, *F. construens* var. *venter* and *F. brevistriata* dominate (up to 95%). The presence of *Anomoeoneis sphaerophora*, *Mastogloia smithii* and *Navicula peregrina* indicates a brackish environment. At 2.2–2.3 m the assemblage includes only freshwater taxa from the genera *Eunotia* and *Pinnularia*. This may indicate the input of river-derived diatoms caused by strong rainfall and floods. A coarser grain-size composition of this layer supports this hypothesis. The peat was formed about 4220 ± 90 BP.

Assemblage 2 (1.15–2.05 m) from the upper sandy loam unit includes freshwater taxa such as benthic *Epithemia adnata*, boreal *E. turgida*, *E. sorex*, *Cymbella cymbiformis*, *C. cistula* and plank-

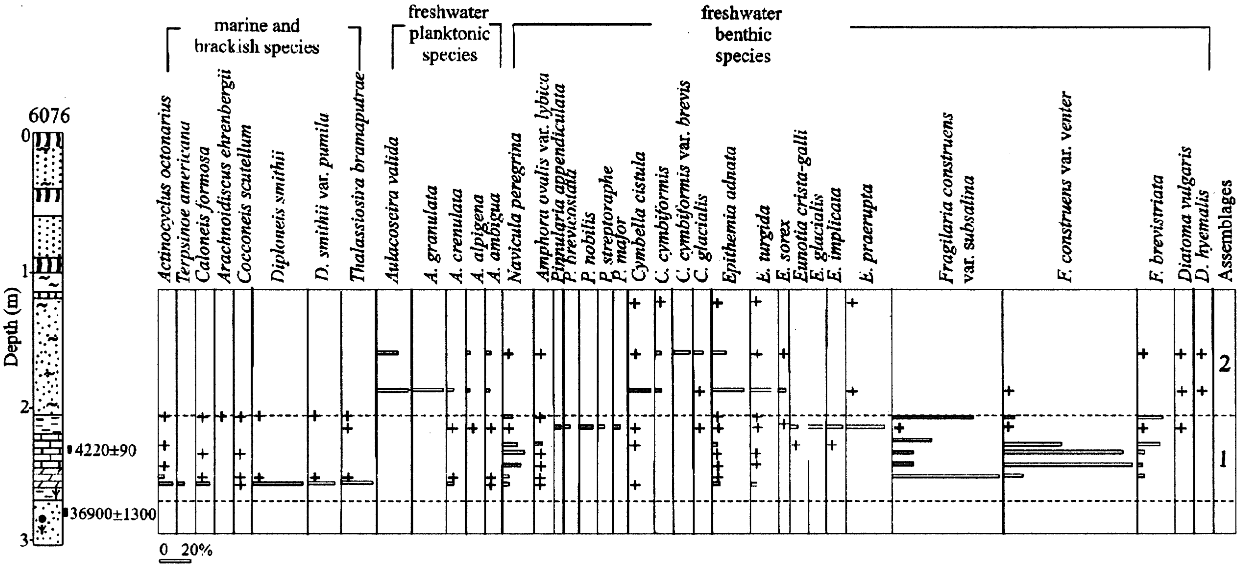

Figure 4 Percentage diatom diagram for the 3–4 m marine terrace in the Kurilka River valley, site 6076.

tonic *Aulacoseira*. An abundance of species from the genus *Cymbella* and the presence of *Meridion circulare* and *Diatoma vulgaris* indicate a floodplain environment with lakes.

The pollen diagram has three pollen zones (Figure 5).

Pollen zone 1 (2.7–3.0 m) reflects the development of birch forest with a predominance of *Betula ermanii*. An abundance of *Alnaster*, *Alnus* and *Betula* sect. *Nanae* records the development of wet open areas. The low values of the broadleaved taxa *Quercus*, *Ulmus* and *Juglans* indicate that the climate was similar or somewhat cooler than present.

Pollen zone 2 (2.05–2.70 m) with abundant non-arboreal pollen (up to 44%) reflects the widespread development of grasslands with a predominance of Gramineae. Swamp vegetation is represented by Cyperaceae and Ranunculaceae. Arboreal pollen (up to 62%) corresponds to birch forests with nemoral elements. The low content of conifer pollen suggests that pollen of these taxa were probably derived from other parts of the island. The high content of *Betula* sect. *Albae* (up to 48%) and broadleaved taxa (more than 20%) suggest that climate was warmer than at present. The appearance of shrub birch pollen (up to 14%) and the peak of *Alnaster* at 2.2–2.3 m possibly reflect pollen input from the upper mountain slopes during strong rainfall or floods corresponding to the diatom data.

Pollen zone 3 (0.4–2.05 m) reflects the coexistence of tree and shrub taxa with different ecological characteristics. We suppose that the combination of *Alnaster*, shrub birch and *Alnus* in the pollen spectra reflects local vegetation of the coastal lowlands. The high content of tree birch (up to 21 %) and *Quercus* pollen reflects the development of birch forests with broadleaved taxa on the surrounding slopes, distant from any sea influence. The herb assemblage was mainly composed of Gramineae, Polypodiaceae and *Lycopodium*, and in swampy areas Cyperaceae.

Site 1795

Located near site 6076, site 1795 exposes the same units (Figure 2). The peaty silts were formed about 4090 ± 50 BP. The pollen assemblages indicate the development of birch forests with *Quercus*, *Juglans*, *Fagus*, *Fraxinus*, *Phellodendron*, *Tilia*, *Corylus* and *Ilex* that corresponds to pollen zone 2 of site 6076 (Figure 6).

Site 1895

Site 1895 is a peaty-bog exposure (Figure 2). Two diatom assemblages are delimited.

Assemblage 1 (2.2–3.0 m) from the green-grey and peaty silts includes epiphytes (up to 76%), benthic species (22–41%) and planktonic taxa (less than 5%). The high content of *Cymbella tumidula* (up to 10%), *C. naviculiformis* (up to 11%), *Diatoma mesodon* (up to 11%), *Fragilaria arcus* (up to 8%), *F. arcus* var. *recta* (up to 5%), *Meridion circulare* (up to 2%), *Didymosphenia geminata* and *Rhoicosphenia abbreviata* indicates a floodplain lake or river-channel environment.

Assemblage 2 (0–2.2 m) from the peat contains planktonic (up to 30%) (*Aulacoseira granulata*, *A. ambigua*, *A. alpigena* and *A. crenulata*), benthic (up to 89%) (*Eunotia bilunaris*, *E. flexuosa*, *E. praerupta*, *Pinnularia appendiculata*, *P. braunii* var. *amphicephala*, *P. stomatophora*) and rhyophilous (genus *Diatoma*, and *Meridion*) taxa which may indicate a flooded lake environment. The presence of the marine *Thalassiosira gravida* and *Paralia sulcata* in peaty silts formed about 1060 ± 60 BP indicates that the lake was located near the sea.

The pollen diagram is divided into two zones (Figure 7).

Pollen zone 1 (1.5–3.0 m) includes mainly arboreal pollen (up to 96%) and reflects the development of birch forests with broadleaved taxa, and alder forests. Increasing *Alnaster* and shrub birch pollen at the base of the peaty silt may indicate some short-time cooling.

Pollen zone 2 (0.3–1.5 m) was formed during the last millennium (1060 ± 60 BP; 510 ± 100 BP). There is a prevailing background birch pollen content (up to 77%) and the diversity of broadleaved taxa sharply increases (*Quercus* up to 30%; *Acer* up to 4%; *Ulmus* 1.5%; *Juglans* 0.4%; *Tilia* 0.3%). Rare conifer pollen was possibly supplied by far-distance transport. Swamp vegetation is represented by *Myrica*, Cyperaceae, Ranunculaceae and *Sphagnum*. The zone indicates the development of birch-oak forest similar to the modern forests near Kurilsk.

Site 6087

Site 6087 is located about 1 km from the sea. The rich diatom assemblage from 2.7–2.9 m has a prevalence of marine species (70%) such as benthic south-boreal *Actinocyclus octonarius* (31%), *Terpsinoe americana* (9%), *Navicula marina* (3%), *Achnanthes brevipes* (2%), *Odontella laevis* (4%), north-boreal *Diploneis smithii* (12%), *Paralia sulcata* (4%) and brackish *Diploneis interrupta* (12%), indicating a warm, brackish environment. The presence of rhyophiles such as *Diatoma hyemalis*, *Fragilaria leptostauron* var. *martyi* and *F. arcus* indicates some river influence. The unit was deposited about 4000 ± 70 BP. The pol-

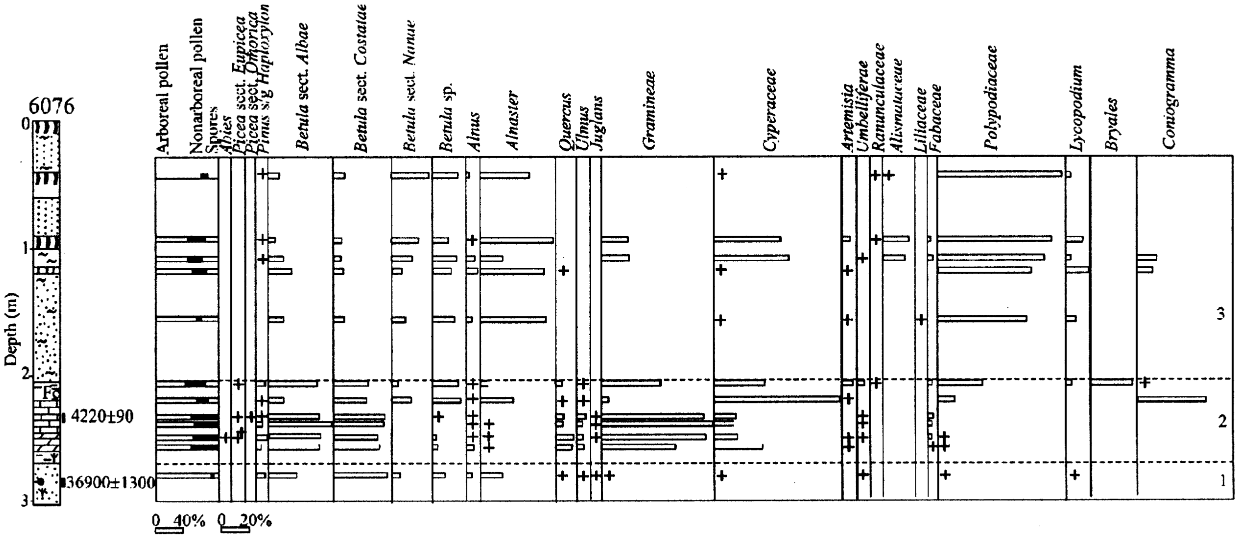

Figure 5 Percentage pollen diagram for the 3–4 m marine terrace in the Kurilka River valley, site 6076.

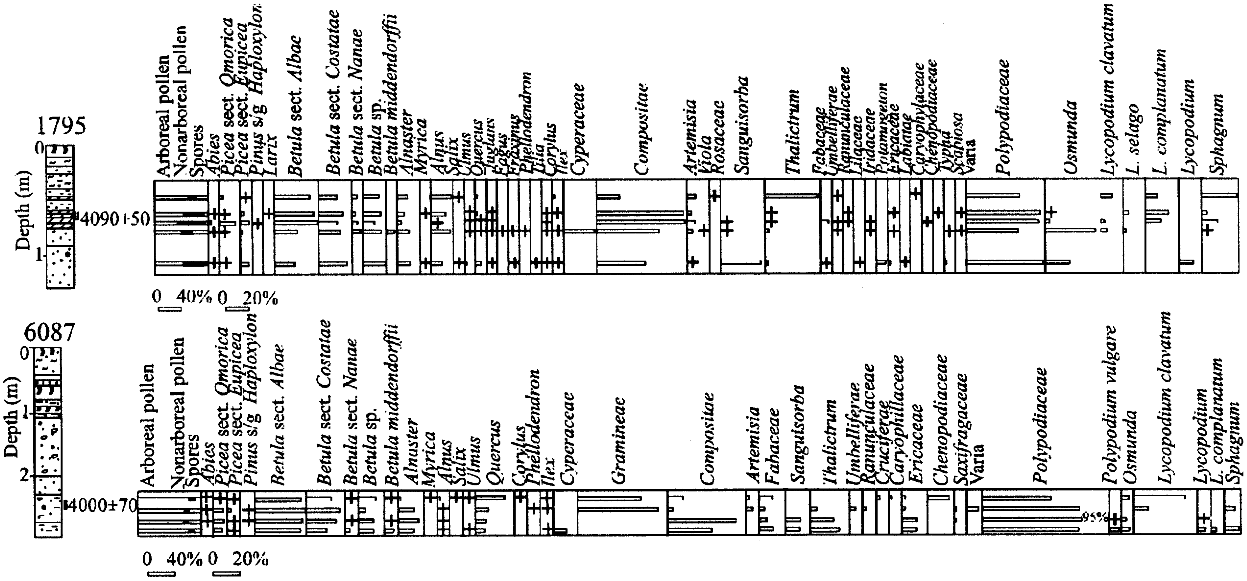

Figure 6 Percentage pollen diagram for the 3–4 m marine terrace in the Kurilka River valley, sites 1795 and 6087.

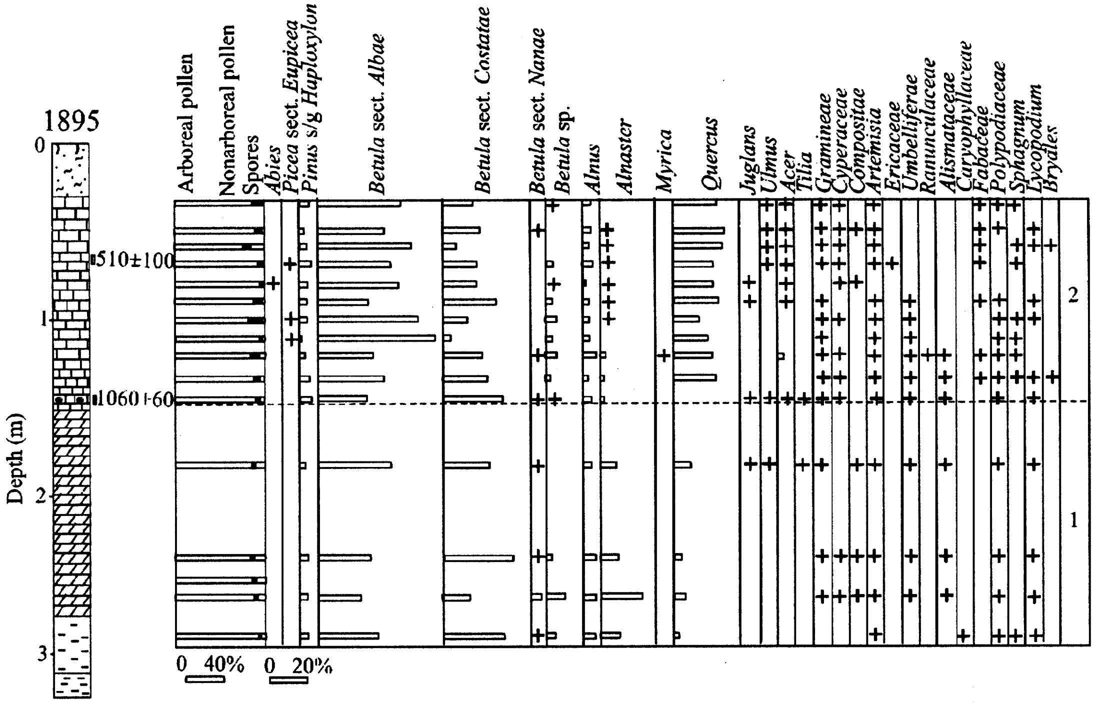

Figure 7 Percentage pollen diagram for floodplain lake deposits in the Kurilka River valley, site 1895.

len assemblages reflect the development of birch forests with broadleaved taxa and a swamp landscape with *Alnaster* and *Myrica*, corresponding to pollen zone 2 at site 6076 (Figure 6).

Site 795

Site 795 is exposure of deposits on the 3–4 m terrace, located in the low current zone of the Lorka River (Figure 1). The deposits from the terrace base are represented by blue-grey silts with aquatic plant remains. The upper part consists of blue-grey and yellow-grey sands and sandy loam. Two diatom assemblages are delimited (Figure 8).

Assemblage 1 (0.5–2.0 m) includes marine taxa such as benthic north-boreal *Diploneis smithii*, *D. smithii* var. *rhombica*, *D. smithii* var. *pumila*, *Paralia sulcata*, *Cocconeis scutellum*, *Odontella aurita*, *Thalassiosira bramaputrae*, south-boreal *Actinocyclus octonarius*, *Hyalodiscus obsoletus* and brackish *Navicula peregrina*, *N. oblonga* and *Nitzschia tryblionella*, indicating a shallow bay environment. The presence of freshwater species such as *Fragilaria construens* var. *subsalina*, *F. construens* var. *venter* and *F. leptostauron* var. *martyi* reflects some river influence.

Assemblage 2 (0.05–0.5 m) includes benthic *Navicula pussila*, *Pinnularia borealis* var. *brevicostata*, *P. borealis*, *P. brevicostata*, *P. viridis* var. *leptogongyla*, *Pinnularia lata*, *Hantzschia amphioxys* var. *capitata* and *Eunotia praerupta*, which indicates a swamp environment (Davidova, 1985; Barinova and Medvedeva, 1996).

There are two pollen zones within these deposits (Figure 9).

Pollen zone 1 (2.0–0.5 m) reflects the development of cool-

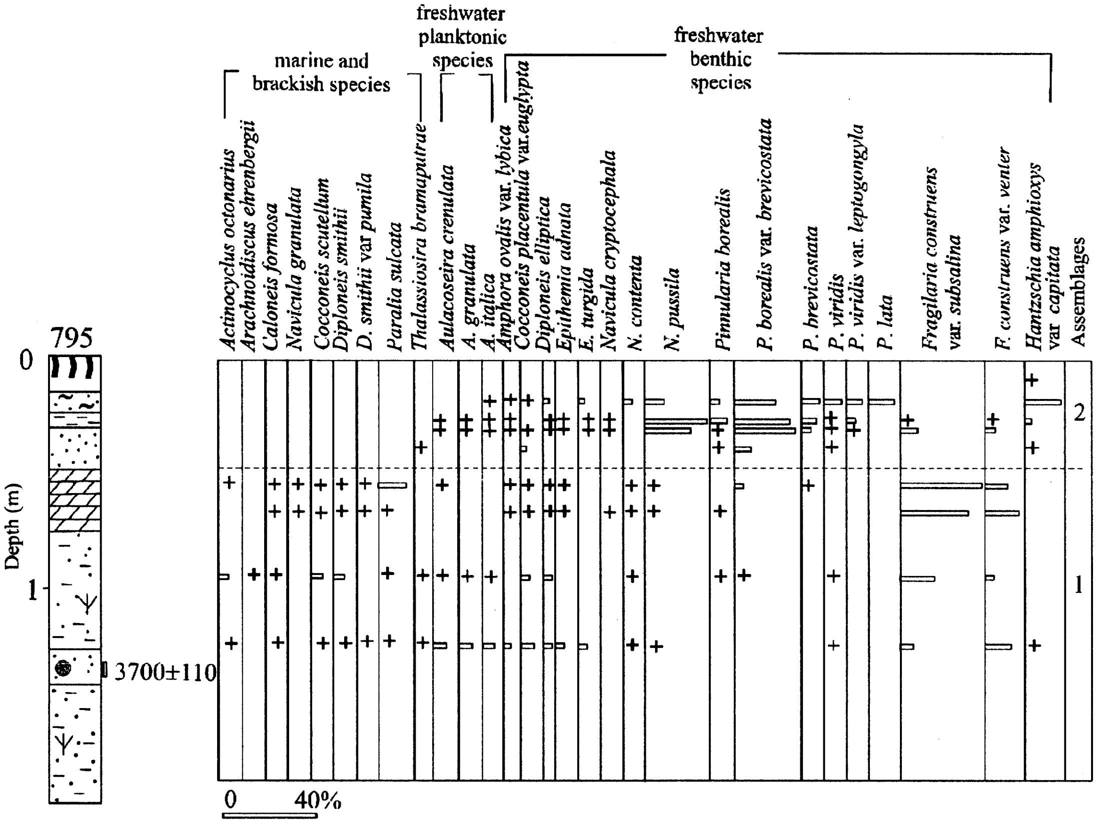

Figure 8 Percentage diatom diagram for the 3–4 m marine terrace in the Lorka River valley, site 795.

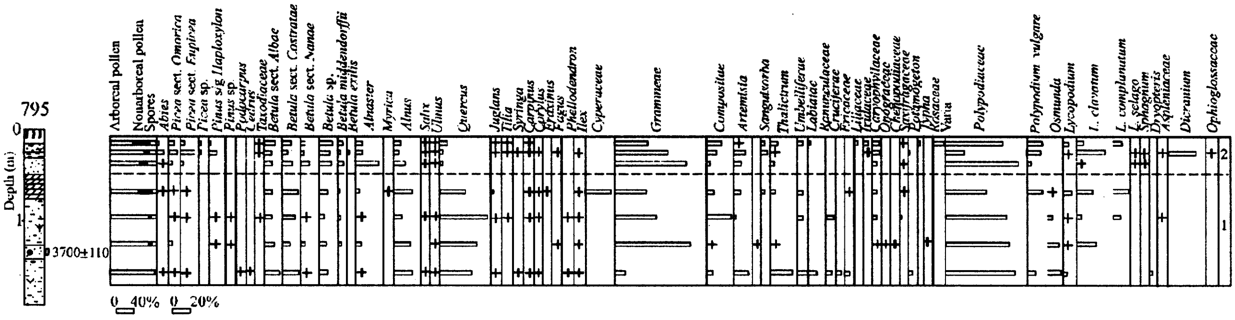

Figure 9 Percentage pollen diagram for the 3–4 m marine terrace in the Lorka River valley, site 795.

temperate broadleaved forests with a dominance of *Quercus* and birch. The understorey was represented by *Ilex* and *Syringa*. Valley forests and swamp assemblages include *Alnus, Salix, Myrica, Alnaster* and *Betula middendorffii*. Rare conifer pollen could be derived from other parts of the island. Non-arboreal pollen reflects assemblages from different environments: *Thalictrum*, Ranunculaceae and Iridaceae are typical of wet areas whereas *Artemisia*, Rosaceae, Caryophyllaceae, Saxifragaceae and Cichorioideae may be derived from drier sites. Cyperaceae appears in the peaty sands. Spores are mainly represented by Polypodiaceae and *Lycopodium*. The presence of pollen of *Juglans, Tilia, Carpinus, Corylus, Fraxinus, Fagus* and *Phellodendron* indicates that the climate was warmer than present. Almost all these taxa are absent in modern Iturup forests. The ^{14}C date 3700 ± 110 BP from these deposits is considered too young because deposits of this age from sites 6076, 1795 and 6087 have different pollen spectra.

Pollen zone 2 (0–0.5 m) reflects the development of birch forests. The sharp decrease in quantity and diversity of broadleaved taxa and the increase in values of shrub birches and *Alnaster* suggest climatic cooling. The high values of conifers (up to 36%) indicate that these taxa developed in the Kurilka River valley. High amounts of *Lycopodium* occur (up to 32%), including *Lycopodium selago*.

Site 1095

Site 1095 is composed of lacustrine silts, peaty silts and peat and was studied on a flat plain at an elevation of 400 m above PSL. The diatom assemblage includes rare diatoms, such as *Eunitia exigua, E. praerupta, Anomoeoneis serians, Pinnularia streptoraphe, P. microstauron* and *P. globiceps*, which indicate lakes with marginal swamps.

The pollen diagram is divided into three pollen zones (Figure 10).

Pollen zone 1 (0.4–0.75 m) reflects the development of a park-tundra landscape with shrub birches, *Alnaster* and *Pinus pumila* and suggests a cold climate. Tree birch pollen (less than 5%) may have come from the lower slopes. Cyperaceae dominates among the herbs.

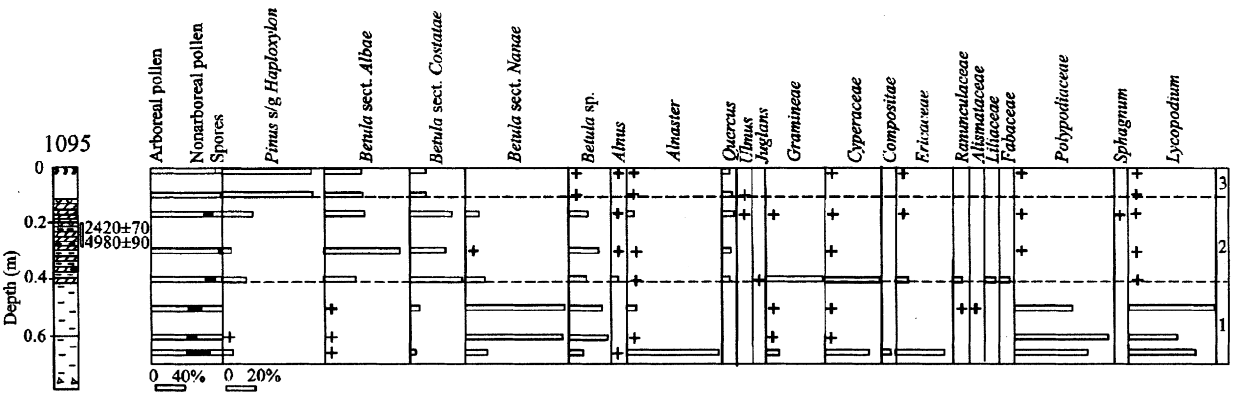

Figure 10 Percentage pollen diagram for lacustrine deposits near Gniloe Lake, site 1095.

Pollen zone 2 (0.12–0.4 m) reflects great landscape changes and a rise of the timber-line. Arboreal pollen dominates (up to 95%). Birch forests prevailed at this level. Broadleaved taxa (*Quercus, Ulmus, Juglans*) appeared. The increase of Gramineae and herb pollen suggests drainage of the plain. We suppose that the peat unit was formed about 4980 ± 90 BP because the pollen spectra reflect climatic conditions considerably warmer than present. The ^{14}C date of 2420 ± 70 BP is probably younger than the real age (Table 1).

Pollen zone 3 (0–0.12 m) reflects a modern landscape in the *Pinus pumila* (up to 61%) zone, located above the timber-line.

A rich diatom assemblage was found in the peat bog about 5 m from site 1095. Dominants are periphyton taxa such as *Eunotia praerupta* (18%), *Frustulia rhomboides* (18%), *Cymbella gracilis* (5%), *Anomoeoneis exilis* (3%) and *A. serians* (8%). Planktonic species with a prevalence of *Aulacoseira valida* and *A. crenulata* reach only 15%. An interesting find is the planktonic *Melosira arentii* (Kolbe) Nugano et Kobayasi. This rare species grows in dystrophic and mesotrophic lakes of Sweden, Ireland, Scotland and Japan (Krammer and Lange-Bertalot, 1991a). *Melosira arentii* has a pH optimum of about 4.8–5.5 and can be influenced by acid hydrothermal springs. The pollen stratigraphy corresponds to pollen zone 3 at site 1095.

Discussion

The available biostratigraphical data and ^{14}C dates allow a reconstruction of some features of late-Pleistocene environments and the elucidation of a more detailed history of mid- to late-Holocene palaeogeographical events on Iturup Island. Changes of natural processes in this region were controlled by both global climatic changes and regional factors. Sharp changes in facies in the late-Pleistocene/Holocene deposits resulted from global climatic changes and sea-level oscillations and local factors such as fluctuations of warm and cold marine currents, Kurilka River dynamics and the development of swamp-lacustrine environments. In contrast to deep-sea cores, terrestrial and shelf records are usually discontinuous, and it is important to study the stratigraphy of several sections, composed of different facies, to derive a reliable palaeogeographical reconstruction.

The sections of the 5–6 and 3–4 m terraces include fluvial deposits and record the natural environmental evolution of the late Pleistocene. Two phases of vegetation development connected to large-magnitude climatic changes can be detected. The first phase, recorded at the base of the 3–4 m terrace, is correlated with warming at about 36900 ± 1300 BP. Birch forests with *Quercus, Juglans* and *Ulmus* occupied central Iturup. Climate was somewhat cooler than present. This warm phase is correlated with the Chernoruchinsky time in Primorye (Korotky *et al.*, 1985) and the Karga warming in Siberia (42–33 ka) (Arkhipov, 1997). The second stage, recorded at the base of the 5–6 m terrace section is characterized by the development of a park-tundra landscape with shrub birches and *Alnaster.* Pollen spectra from these deposits do not include arboreal pollen. The deposits could be correlated with the last glacial stage. Climate was very cold with some permafrost development. On the Japanese Islands and on Sakhalin, annual temperatures at the last glacial maximum were estimated to be about 7–9°C lower than present (Korotky *et al.*, 1996a; Tsukada, 1986; 1988). The lowest sea level (up to 100–120 m below mean sea level) is thought to have occurred at this time (Korotky *et al.*, 1996a; 1997). Iturup was not connected to the neighbouring islands and to the continent during last glacial times, because the straits dividing the island are 480–890 m deep.

At the Holocene Optimum cool-temperate broadleaved forests occupied much of the island. The main components of the forests were *Quercus* and birches. Other broadleaved trees included *Phellodendron, Carpinus, Fagus, Fraxinus, Juglans* and *Syringa.* The modern distributions of these taxa are limited only to Kunashir and Hokkaido (Vorobiev, 1963; Igarashi, 1994; Tsukada, 1988), excluding *Phellodendron*, which is also found on southern Iturup. At the Holocene Optimum (4980 ± 90 BP) timber-line rose more than 200 m, and oak-birch forests developed in the area of the modern *Pinus pumila* zone at elevations more than 400 m. The presence of indicators such as *Fraxinus, Phellodendron, Carpinus* and *Juglans* suggests that the mean annual temperature was 2–3°C higher than present. Mean August temperature reaches +20°C and the total sum of biologically active temperatures ($\Sigma t \geq 10°C$) attains 1800°C at the northern modern boundaries of these taxa on Far East continental coasts (Korotky *et al.*, 1985).

Pollen assemblages of mid-Holocene deposits on Iturup Island are correlated with Holocene Optimum pollen zones in Kunashir, dating from 6500–5000 BP (Korotky *et al.*, 2000) and pollen zone RII of the Japanese Islands, dating from 7000–4000 BP (Tsukada, 1986). This warm phase is correlated with the Early Jomon warming on the Japanese Islands and the Holocene Optimum in Sakhalin and Primorye (Sakaguchi, 1983; Korotky *et al.*, 1996a; 1997). Migration of vegetational zones to the north on South Kurile, northern Japan and Sakhalin reflects climate warming which was intensified by the influence of warm currents (Matsushima and Ohshima, 1974; Sakaguchi, 1983; Taira and Lutaenko, 1993; Korotky *et al.*, 1996a; 1997).

The Holocene Optimum sea-level rise can be estimated from the top of marine deposits. The elevation of the deposits allows us to establish that sea level reached 3.5 m above PSL. At that time the sea reached its most landward position on the island coasts and coastal inlets or embayments were most extensive. A large semi-open bay developed in the lowland in the Kurilka River low-current zone and Lebedinoe Lake. A shallow strait developed within the Vetrovoy Isthmus. In North Hokkaido the temperature of the surface water at the Climatic Optimum was estimated to about 5°C higher than present and was compared with the water temperature of northern Honshu (Matsushima and Ohshima, 1974). At this time the Kuroshio Current system became more active (Taira and Lutaenko, 1993). We suppose that the Soya Current was more active too (Korotky *et al.*, 2000).

One typical feature of the Holocene Optimum shoreline is the abundance of marine molluscs. Similar beach deposits, located on the Okhotsk side of the Vetrovoy Isthmus (Figure 11), include rich mollusc assemblages, with *Astarte borealis*, *Crenomytilus grayanus*, *Callista brevisipkonata*, *Clinocardium californiense*, *Mya* sp., *Mezcenariaa stimpsoni*, *Serripes groenlandis*, *Nucella* sp., *Buccinidae* sp., *Chlamys swifti* and *Crenomytilus grayanus*. The ^{14}C date for these shells is 5350 ± 50 BP (Bulgakov, 1996).

During this Holocene stage, active formation of barrier forms led to the separation of numerous coastal lakes. Most coastal lakes in Kurile and Japan are considered to originate from coastal embayments prevalent at the culmination of the Holocene transgression and to have been formed as a result of barrier development initially related to relative sea-level changes during the Holocene (Sakaguchi, 1983; Koroky *et al.*, 2000). The ^{14}C date obtained from the buried soil under the mid-Holocene barrier at Yankito II is 6820 ± 100 BP (Figure 11). Diatomite accumulated in the palaeolakes. A high supply of nutrients was possibly associated with hydrothermal activity (Grebennikova, 2000). This could explain the long-term accumulation of diatom deposits from the Holocene Optimum to 3760 ± 110 BP.

Studies of Holocene deposits in Kunashir (Korotky *et al.*, 2000) and on the Japanese Islands (Sakaguchi, 1983) suggest cooling and a sea-level drop at about 4500–4600 BP. Possibly this cooling is recorded in the lower buried soil from the 5–6 m terrace section (site 6075), reflecting the development of shrubs on the coastal plain. The sea level is estimated to be 4–5 m below PSL during this regression (Korotky *et al.*, 1996a). Dunes of this age are absent near Kurilsk because the drainage of the open bay floor with a steep inshore did not cause the formation of extensive dunes. On flat coasts a minor regression led to the development of a dune environment within bays with such as the Prostor, Kasatka and Kuibishevsky Bays. Dunes of this age are stable landforms with some pronounced buried soils and a well-developed vegetation. Usually generations of these dunes are located within the back side of the coastal plains.

In spite of the climatic deterioration at about 4000 BP, compared to Kunashir Island where vegetation changed very little due to the warm currents, the central part of Iturup was occupied by birch-oak forests with dominant *Quercus*. Other thermophilous broadleaved taxa were represented by rare *Juglans*, *Phellodendron* and *Carpinus* compared to the forests at the Holocene Optimum. Swamp assemblages were represented by shrub birch, *Myrica*, *Salix* and *Alnaster*. The top elevation of the marine deposit allows us to establish that sea level reached more than 2 m above PSL at about 4000 BP (4090 ± 50 BP, 4000 ± 70 BP), possibly similar to the Holocene Optimum. According to Bulgakov (1996), the peak of the Holocene transgression on South Kurile occurred at about 4000 BP and sea level did not exceed the present level. The supply of terrigenous material in the coastal zone during these transgressions resulted in the rapid progradation of sediments at the coasts, filling of inlets and the formation of a series of storm ridges, small lagoons and marshes. Sharp changes in diatom assemblages and pollen spectra from coarser deposits record traces of large floods.

Significant changes in vegetation took place on the coastal lowlands formed in the Kurilka River low current zone during the late-Holocene sea-level lowering (at least 2500 BP). Grassland and swamp landscapes developed widely on the island. We suggest that many Iturup grasslands may be climatic in origin rather than anthropogenic. Thick soils began to form on the Kurilka River floodplain. Pedogenic processes were periodically stopped

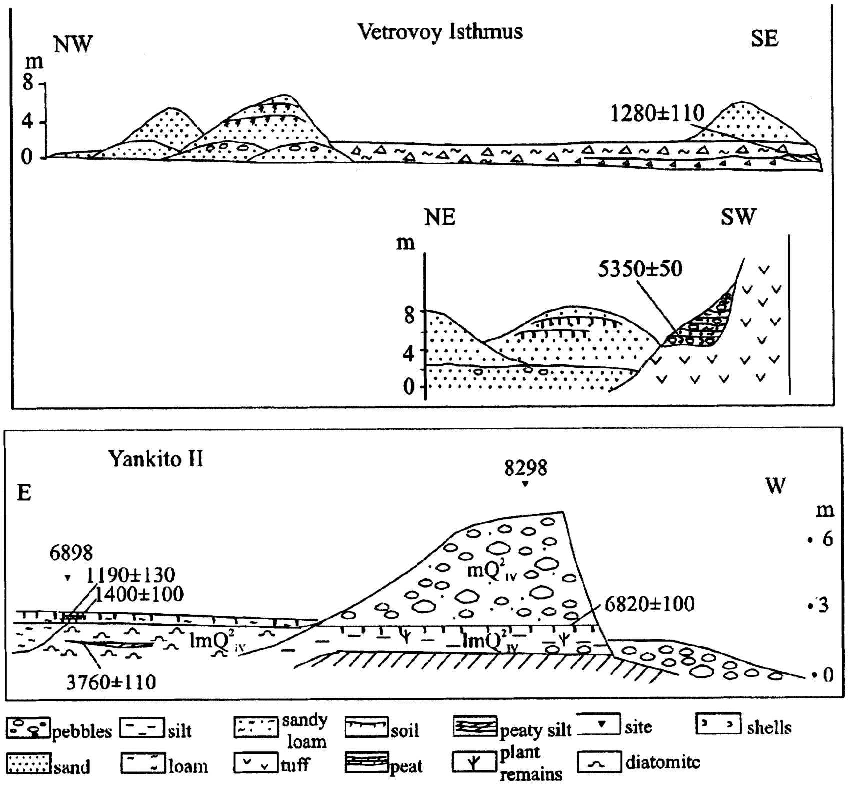

Figure 11 Cross-section of Holocene deposits in the Vetrovoy Isthmus and on the Yankito II lacustrine terrace. Horizontal scale is free.

by the accumulation of floodplain sandy loam. Pronounced cooling on the South Kurile and Japanese Islands was established about 1700–1300 BP (Sakaguchi, 1983; Korotky *et al.*, 2000). Shrub birches and *Alnaster* assemblages developed on coastal lowlands near Kurilsk, to formed a pseudo-forest-tundra zone (Urusov, 1996). There may have been a high productivity of these taxa. Late-Holocene pollen spectra compared to last glacial maximum spectra consistently include tree pollen such as birch, alder and oak, which reflect the development of forests on the lower slopes within the river valleys and other areas protected from any influence of maritime cooling. Evidence for the coexistence of such vegetation groups comes from pollen spectra which contain abundant *Alnaster* and *Betula* sect. *Nanae* and, respectively, high values of tree birch pollen with broadleaved taxa (sites 6075 and 6076). Possibly this cooling led to the disappearance of thermophilous broadleaved taxa such as *Carpinus*, *Fagus* and *Fraxinus* from the vegetation of Iturup. Cool-temperate broadleaved forests developed only on the Okhotsk coast in the central part of the island, protected by a volcanic ridge from fogs and cold winds from the Pacific Ocean. Vegetation changes seem to have been caused by climatic deterioration and marine current influences. At this time warm stream activity in the Sea of Japan and the Okhotsk Sea decreased significantly (Taira and Lutaenko, 1993). It is possible that the Oyashio Current increased, leading to an increase in fogs and drizzle and a more intense wind regime. Modern analogues of these landscapes are typical for North Sakhalin (Tolmachev, 1959), where the annual sum of biologically active temperatures ($\Sigma t \geq 10°C$) is less than 700–1000°C (*Reference book of USSR climate*, 1970; 1971).

A slight regression led to the formation of dunes on the Kurilsky Bay coast and other sandy coasts. These dunes with minimal soil formation and pioneer vegetation are correlated with the second generation of Kunashir dunes (Korotky *et al.*, 1996b). In several coastal regions of Japan, small fluctuations in sea level have also been reported over the past 6000 BP (Sakaguchi, 1983).

Climate changes over the past 1000 years in the Pacific are also believed to have been driven by sea-level changes. The Little Climatic Optimum (about 1000 BP) is believed to have been a time of warmer climate than at present in Japan (Sakaguchi, 1983). On Iturup Island the warming at about 1000 BP was not intensive and led to a decrease in aeolian processes and soil formation. Cool-temperate forests with *Quercus* dominance and birch, maple and elm had a wide distribution on the Kurilsky Bay coast. The presence of marine diatoms in peat bog site 1895, located in a low current area of the Kurilka River, indicates a sea-level rise at this time. At the end of the late Holocene, the *Pinus pumila* zone increased and the forest limit moved 400 m downwards in the Kurilka River basin.

The study of dunefields on Kunashir shows that dune ridges without soils formed during the 'Little Ice Age' minor regression (Korotky *et al.*, 1996b; 2000). Dunes of this age are widespread on Iturup. The Pacific side of the Vetrovoy Isthmus is a good example of the development of this generation of dunes (Figure 11). Within ancient dunefields, this dune generation covers a buried soil formed at about 1000 BP (^{14}C date 880 ± 40 BP). The dunefield construction indicates that the Vetrovoy Isthmus was formed in the late Holocene. Peat accumulation within the coastal lowland near the Kurilka River mouth started at this time (^{14}C dates 1060 ± 60 BP and 970 ± 60 BP).

Under the 'Little Ice Age' dunes the isthmus surface is covered by lahar deposits dated to 1280 ± 110 BP. Effect of the 'Little Ice Age' on tree regeneration are not discernible in the available pollen data because the study area is far from tree-line areas where such climatic changes could be expected to be most detrimental to tree regeneration.

Thus, the presence of thermophilous broadleaved taxa in the Holocene Optimum vegetation and the disappearance of these taxa or shifts in their natural range during late-Holocene minor climatic changes contradict the hypothesis of Urusov (1996) about the origin of Iturup's vegetation. According to Urusov (1996), the modern vegetation of Iturup is a relict from the last glacial maximum with thermophilous taxa surviving within refuges on the drained shelf-area. There was a redistribution of vegetational elements as a result of the climatic changes in the late Pleistocene and Holocene. The main argument for this viewpoint is the impossibility of natural habitat shifts because of the deep straits and island isolation during the last glacial maximum regression with a sea-level lowering about 100 m below PSL. The land bridge in the South Kurile region connected only Kunashir and Little Kurile Ridge and Hokkaido (Tsukada, 1986; Korotky *et al.*, 2000). Modern natural habitats for the majority of these thermophilous taxa are limited to South Hokkaido (Ohwi, 1984). It could be assumed that natural habitat shifts of these taxa at the Holocene Optimum on Hokkaido and Kunashir, and on central Iturup, resulted in their pollen being far transported by wind. According to a study of modern pollen assemblages this is hardly possible. The arguments for this interpretation are also supported by studies on modern pollen rain and subfossil pollen spectra on Kunashir (Mokhova *et al.*, 2000). The pollen rain there includes rare pollen of some thermophilous taxa from the Japanese Islands, but the values of these taxa are very low and pollen spectra from modern lacustrine and alluvial sediments contain only taxa which grow on the island.

Conclusions

The Holocene environmental history of Iturup Island reflects climatic changes and sea-level oscillations. The fluctuations of warm and cold currents actively influenced the landscape development. The present forests are a product of their past history. The Holocene Optimum landscapes on the Okhotsk side of central Iturup were dominated by cool-temperate broadleaved forests. Climate was warmer than present. The warming was coincident with a transgression with the highest sea-level position up to 3.5 m above PSL. Numerous barrier coastal lakes were formed at this time. A shallow strait occurred on the low Vetrovoy isthmus. The sea-level drop at 4700–4500 BP led to the development of large dunefields only within bays with a flat coast due to the supply of sandy material from the inshore drainage zone. In the beginning of the late Holocene about 4000 BP the island vegetation changed little due to the influence of warm current. Cool-temperate forests with dominant *Quercus* dominance had a wide distribution, but the diversity of broadleaved genera decreased. A minor transgression is recorded at about 4100–4000 BP with a sea-level rise of about 2.5 m above PSL. Active accumulation of deposits took place in the coastal zone at this time. Great vegetation changes and climatic deterioration took place in the second half of the late Holocene, and a pronounced cooling was established in the second half of the late Holocene. Cool-temperate broadleaved forests were confined to the Okhotsk side of the central island area. Grasslands and swamps also developed on coastal lowlands at this time. A minor regression led to the formation of large dunefields. Isthmuses increased and coastal wetlands with lakes formed. The presence of marine diatoms in floodplain lake deposits indicates sea-level rise at about 1060 ± 60 BP. At this time warming was not intensive. The last phase of active aeolian accumulation took place during the 'Little Ice Age' cooling and regression.

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