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Coastal dunes of Urup Island (Kuril Islands, North-Western Pacific): palaeoclimatic and environmental archive

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Abstract. The Late Holocene phases of aeolian processes have been reconstructed on the basis of dune fields construction. The palaeoenvironmental studies were targeted to following problems: 1) to determine the periods of higher and lower activity of aeolian processes; 2) to establish the age of aeolian deposits and buried soils; 3) to retrace the development of coastal landscapes. The age was determined by radiocarbon dating of paleosols and tephrostratigraphy. The correlation of tephra was performed using data on the volcanic glass chemical composition. The dunes formed during the cooling accompanied by a minor regression. Six buried soils found in the dunes reflect stabilization and overgrowing of dune fields. The longest period of dune stabilization began after a cold event 2800–2600 cal yr BP and lasted until the Little Ice Age. Paleosols contain the tephra of large volcanic eruptions on Urup (Kolokol volcano), Simushir (Zavaritsky volcano) and Iturup (tephra). Pollen analysis allows us to retrace the development of coastal landscapes. Thickets of dwarf pine developed during cooling, birch forests spread in the Medieval Warm Period, and herb meadows were widely represented on the dunes. Human impact on the coastal palaeovegetation was found. Aeolian sedimentation was high during the Little Ice Age. One of the factors of dune reactivation during the Little Ice Age was increased winter storminess associated with the East Asian winter monsoon. Evidence of active cyclogenesis is the increasing proportion of allochthonous pollen. The modern reactivation of aeolian processes is associated with human activity and storm erosion of dunes.

Keywords: aeolian deposits, paleosol, minor regressions, tephra, coastal landscape, human impact

Береговые дюны острова Уруп (Курильские острова, северо-западная Пацифика): архив изменений палеоклимата и природной среды

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Реферат. На основе изучения строения дюнных полей восстановлены фазы активизации эоловых процессов в позднем голоцене. Изучение природной среды в прошлом сфокусировано на следующих проблемах: 1) определить периоды активизации и затухания эоловых процессов; 2) выделить возраст генераций эоловых отложений и погребенных почв; 3) проследить развитие береговых ландшафтов. Возраст определялся на основе радиоуглеродного датирования погребенных почв и тефростратиграфии. Корреляция прослоев тефры выполнена с использованием данных по химическому составу вулканического стекла. Дюны формировались при похолоданиях, сопровождавшихся малоамплитудными регрессиями. Шесть погребенных почв, обнаруженных в дюнах, отражают периоды стабилизации и зарастания дюнных полей. Наиболее длительный период стабилизации дюн начался после холодного события 2800–2600 кал. л.н. и продолжался до малого ледникового периода. Палеопочвы включают тефру крупных извержений вулканов на островах Уруп (влк. Колокол), Симушир (влк. Заварицкого – Zav-1) и Итуруп (тефра CKr). Развитие береговых ландшафтов восстановлено на основе данных спорово-пыльцевого анализа. Заросли кедрового стланика на побережье

Статья представлена в редакцию на английском языке.

получали широкое распространение при похолоданиях, березовые леса – в малый оптимум голоцена, на дюнах были развиты разнотравные луга. Установлено влияние древнего человека на развитие палеорастительности. Эоловая седиментация происходила и в малом ледниковом периоде. Одним из факторов активизации эоловых процессов в малый ледниковый период были сильные штормовые ветра, связанные с более интенсивным восточноазиатским зимним муссоном. Увеличение пропорции аллохтонной пыльцы является подтверждением активного циклогенеза. Современная активизация эоловых процессов связана с воздействием человека и размывом дюн в сильные штормы.

Ключевые слова: эоловые отложения, палеопочвы, малоамплитудные регрессии, тефра, береговые ландшафты, воздействие человека

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Introduction

Coastal dunes can be considered a natural archive that reflects the history of coastal development during climatic changes in the Holocene and associated sea level fluctuations. The development of aeolian processes on sea coasts in temperate latitudes results from a combination of several factors, the main ones being a strong wind regime and the presence of rich sources of sand [1–4]. Dune fields, which have been forming for a long time, include several generations corresponding to the phases of aeolian processes activation, and buried soils that correspond to the stabilization of dunes with attenuation of aeolian accumulation and vegetation development. Paleosols provide important information about the development of coastal landscapes. Dunes are widespread on the coast of the Kuril Islands, with particularly large dune fields confined to the shores where sand is abundant: the mouths of large rivers, areas of active sand accumulation and rapid shoreline progradation, areas near active cliffs composed of poorly consolidated rocks or pumice.

The formation of coastal dunes is associated with minor regressions caused by short-term coolings in the Middle-Late Holocene [5–7]. On volcanic islands, aeolian processes develop on the shores near large calderas, where large volumes of loose pyroclastics are processed [8]. Some researchers associate the formation of coastal dunes with the intensification of the winter monsoon and the intensity of winter winds [3]. There are especially many dune fields in the south of the Great Kuril Ridge. The dunes of Kunashir and Iturup islands are well studied [5, 6]. The purpose of this article is (1) to determine the periods of activation and attenuation of aeolian processes on Urup Island based on the large dune fields stratigraphy, (2) to determine the age of buried soils and phases of dune stabilization, (3) to find out the relationship with climatic changes and minor sea-level fluctuations, (4) to retrace the development of coastal landscapes in the Late Holocene, (5) to determine the role of volcanic ashfalls in the development of geocomplexes.

Materials and methods

The work was carried out on the dune fields in the Novokurilskaya Bay (5 sections), the Okhotsk Sea side of northern Urup Island, and the Osma Bay (1 section), Pacific side, southern Urup (Fig. 1). The sections of aeolian deposits with buried soils in the back part of the dune fields are described in detail – section 7508 (46°12.652′ N, 150°19.118′ E) and 7608 (46°12.640′ N, 150°19.146′ E). In the Novokurilskaya Bay, we also described the section 8108 (46°12.649′ N, 150°19.221′ E) of the aeolian cover on the soil-pyroclastic unit on a high marine terrace (at an altitude of 38–40 m a.s.l.). The paleosols were sampled for pollen analyses at 5 cm intervals; besides, samples were taken from tephra layers. The genetic horizons in the soil profiles were distinguished based on the classification of the volcanic soils of Kamchatka [9] adapted to the classification and diagnostics of soils in Russia [10].

Sand grain size (7 samples) was studied using sieves with γ step and a high-precision Sartorius balance. Samples for pollen analysis (22 samples) were processed by the separation method using a heavy liquid H_2O:CdI_2:KI (2.2 g/cm^3) [11]. Radiocarbon dating (5 samples) was performed in the Institute of Earth Sciences, St. Petersburg State University (Table 1). The samples were pretreated with acid and alkali solutions and then converted to benzole. The ^{14}C-activity of benzole was measured using liquid scintillation counter. The radiocarbon dates were calibrated using OxCal 4.4.1 software and IntCal20 calibration curve [12, 13]. The chemical composition of volcanic glass (5 samples) was analyzed using scanning electron microscopy and micro-analysis by X-ray spectrometry, performed by X-ray spectral microanalysis (EPMA) on a (SEM) MIRA3 FE (TESCAN) using Aztec system (Oxford Inst., UK) at V.G. Khlopin Radium Institute, St. Petersburg. Vegetation on the Novokurilskaya Bay coast was described in detail by N.S. Liksakova with coauthors [14].

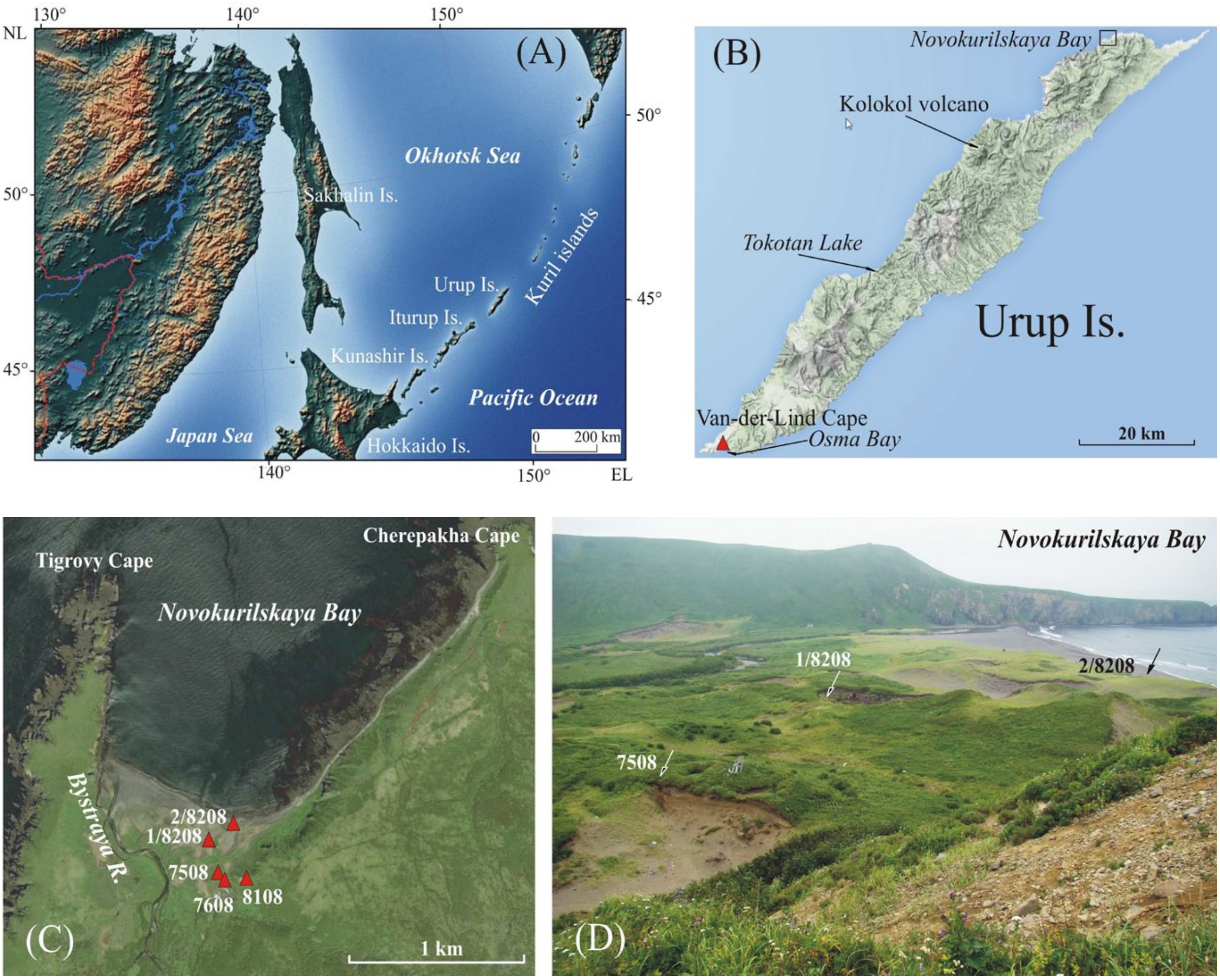

Fig. 1. Location of dune fields of Urup Island. (A) – position of Urup Island in North-Western Pacific region; B – Urup Island with position of study area; C – the Novokurilskaya Bay with dune field and position of studied sections; D – studied dune field with position of key section (7508).

Table 1. Radiocarbon dates obtained for paleosols from the Holocene dune sections, the Novokurilskaya Bay, Urup Island

Sample number	Depth, m	Material dated	^{14}C-age, BP	Calibrated age (2σ)	Laboratory index
1/7508	0.89–0.94	Soil	910 ± 60	820 ± 60	LU-6106
2/7508	1.18–1.23	Soil	2490 ± 70	2560 ± 110	LU-6106
1/8108	1.14–1.17	Charcoal	2590 ± 70	2660 ± 110	LU-6107
2/8108	1.30–1.34	Soil	3230 ± 120	3460 ± 150	LU-6109
3/8108	4.88–4.93	Soil	8170 ± 390	9130 ± 480	LU-6110

Results

Unlike Iturup and Kunashir islands, distribution of coastal dunes on Urup Island is limited due to prevailing abrasion and abrasion-denudation coasts with boulder-pebble beaches, a low-order river network with coarse alluvium, and a deficit of sandy material in the coastal zone. An extensive dune field is located in the Novokurilskaya Bay in the northwest of Urup Island (Fig. 1, 2). The semi-open type bay is open to northerly winds. The inshore zone is shallow, with a wide bench (up to 240 m wide) stretching along the cliff in the eastern part. The coast here is belong to abrasion-denudation type, the beach is composed of blocks and boulders. The Bystraya River (IV order) flows into the bay top, the mouth is pressed against the western side.

There is a sandy beach here (width from 30 to 180 m near the river mouth), with a dune field behind (up to 350 m wide), the dune height is up to 12 m. Beach sand is characterized by single-modal curve (0.315–0.4 mm), medium sand fractions prevail (78.7 %), contain high content of coarse sand (up to 20.1 %) and an admixture of fine sand (1.3 %) (Fig. 3 A). From the sea side, erosion scarps are observed in the foredunes. Composition of modern aeolian sand, that accumulated near the escarp base, is similar to beach sand. The grain-size curves are single-modal (mode 0.315–0.4 mm), proportion of fine sand fractions become higher (6.3 %), gravel appears (0.5 %) (Fig. 3 B). Several deep modern deflation basins (up to 6 m deep) with erosion scarps are located on the seaward part; human activity (removal of sand, etc.) could have stimulated their formation (Fig. 1). Aeolian deflation is active along the site of sand excavation. At deflation basin bottoms, surface of a low marine terrace composed of sandy-pebble material is exposed. There are no regular ridges, perhaps due to active destruction, separate large dunes stand out, which are the remnants of ridges separated by vegetated deflation basins. Modern dunes are composed of well sorted medium-grained sands (mode 0.315–0.4 mm), compared to the beach content of coarse sand fraction decreases (5.7 %), fine sand fraction reaches 12.3 %, and silt appears (<0.1 %) (Fig. 3 C). The surface of the dunes near the sea is covered with monodominant communities of *Carex macrocephala* or *C. pumila* (160 m), vegetated dune ridges in the rear are covered with forb meadows and thickets of *Rosa rugosa* [14]. On the high marine terrace, aeolian deposits are represented by sandy loams with numerous layers of pumice and volcanic ashes.

The dunes located in the seaward part of the field do not have buried soils. The dunes in the rear include up to 6 buried soil profiles. The sections contain 5 tephra interlayers, which correlate well with the tephra layers of the soil-pyroclastic cover on the western side of the bay [15]. In the lower part of the dune section, a pumice layer (pumice size up to 1.5 cm) is exposed in yellow fine-grained sand. Tephra consists of medium-K rhyolite glass (Table 2). It is assumed that this is the tephra of Kolokol volcano, which erupted in the middle of the Late Holocene. The volcanic ash lying above is composed of yellow silt with fine sand. The volcanic glass is rhyolitic with medium proportion of K_2O. The ^{14}C date of 2490 ± 70 yr BP, 2560 ± 110 cal yr BP, LU-6106 was obtained from the soil under the tephra. This volcanic ash is comparable to the CKr tephra, which is widespread on Urup Island and the Middle Kuriles [15–17], the source was located in the north of Iturup Island. In the south of Urup Island (Fig. 2) ^{14}C dates of 2280 ± 90 yr BP, 2300 ± 140 cal yr BP, LU-5947; 2140 ± 110 yr BP, 2130 ± 140 cal yr BP, LU-6257 were obtained from the peat under the ash located on the Osma Bay coast and the peat bog section located on the Van-der-Lind Cape [18]. Above, there is a volcanic ash interlayer composed of coarse pumice sand with pumice (up to 1 cm) with medium-K rhyolitic volcanic glass, which is Kolokol volcano tephra.

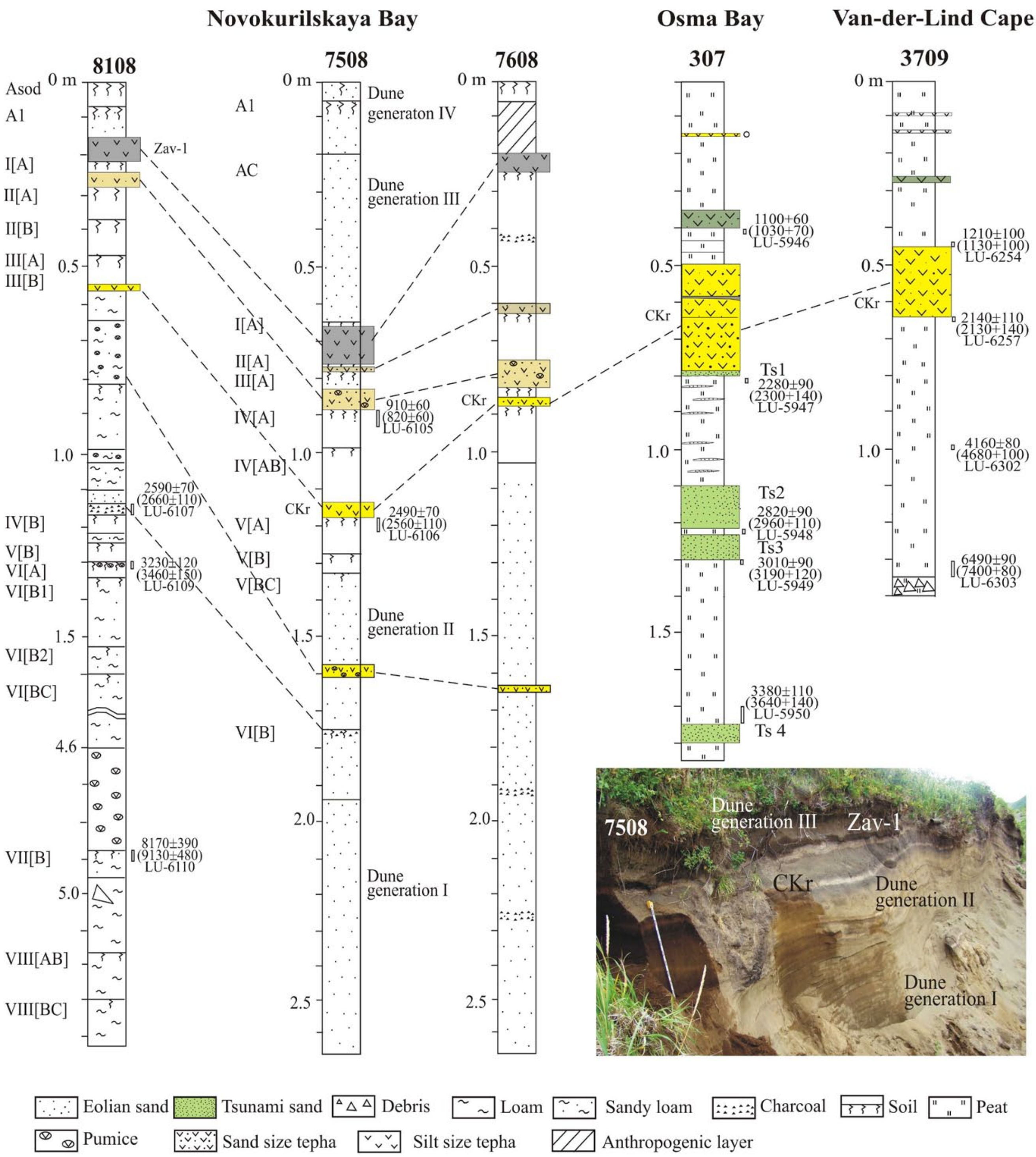

Fig. 2. Lithological columns of aeolian-soil sequences with soil genetic horizons, photo of key section (7508) and sections of peat bogs with tephra layers [18], Urup Island. CKr – marker tephra, Ts – paleotsunami events. We showed the color of tephra.

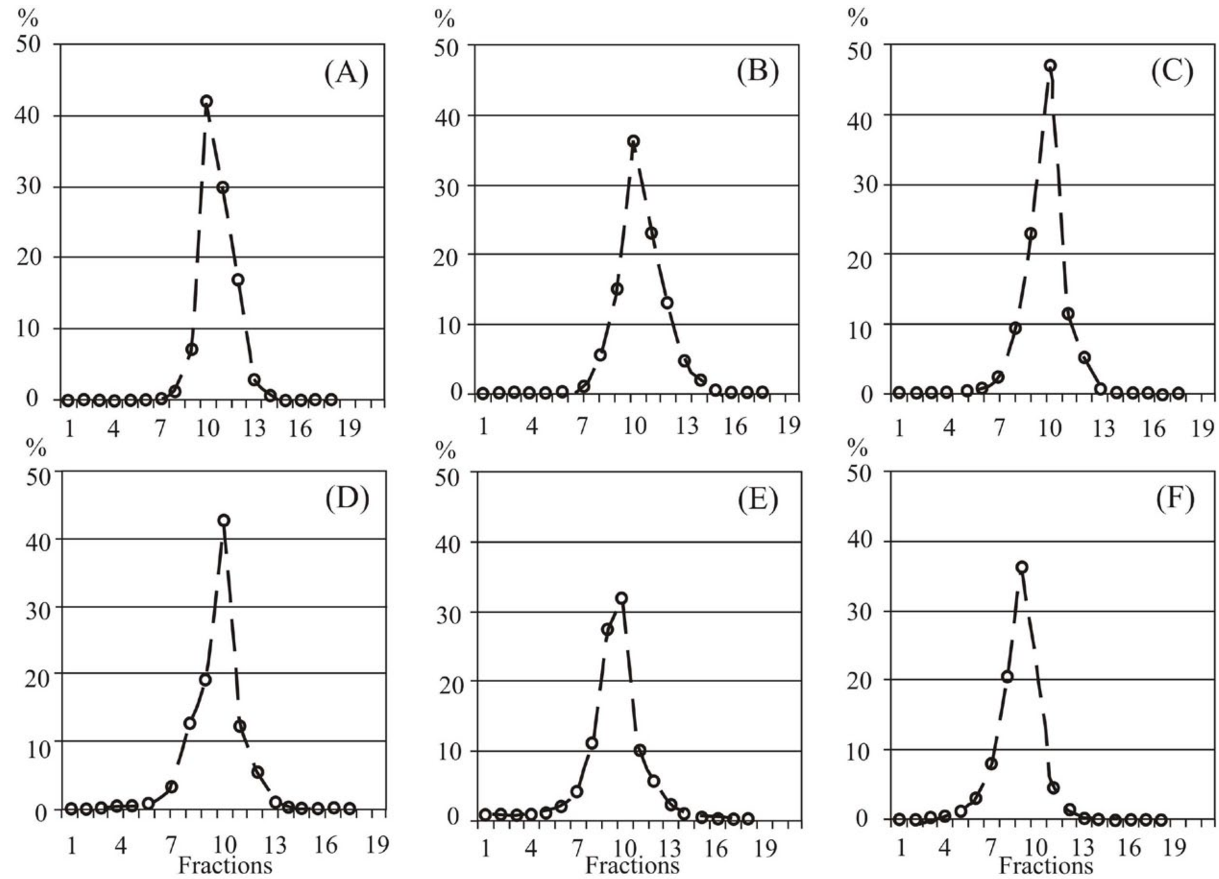

Fig. 3. The grain-size curves of beach and dune sands of the Novokurilskaya Bay.
Fractions (in mm):: 1 – <0.05; 2 – 0.05–0.063; 3 – 0.063–0.08; 4 – 0.08–0.1; 5 – 0.1–0.125; 6 – 0.125–0.16; 7 – 0.16–0.2; 8 – 0.2–0.25; 9 – 0.25–0.315; 10 – 0.315–0.4; 11 – 0.4–0.5; 12 – 0.5–0.63; 13 – 0.63–0.8; 14 – 0.8–1; 15 – 1–1.25; 16 – 1.25–1.6; 17 – 1.6–2; 18 – 2–3; 19 – 3–4. (A) – beach; (B) – modern aeolian sand, accumulated near escarp in foredune, site 2/8208; (C) – modern dune near large deflation basin, site 1/8208; (D) – aeolian sand of generation II, section 7508; (E) – aeolian sand of the Little Ice Age, generation III, section 7508; (F) – modern aeolian sand from the top of the dune located in back part of the dune fields, generation IV, section 7508.

The soil under the ash was dated by radiocarbon at 910 ± 60 yr BP, 820 ± 60 cal yr BP, LU-6105. The source of the thin layer of tephra composed of silt with fine sand has not been identified. The upper layer of volcanic ash, represented by green-gray silt, including andesite low-K volcanic glass, is the Zav-1 tephra of the last major eruption of Zavaritsky volcano [15]. On Simushir Island, this eruption age is estimated as ca. 600 ± 50 yr BP, 610 ± 40 cal yr BP, LU-6111; 660 ± 50 yr BP, 630 ± 50 cal yr BP, LU-5912 [17].

In the lower part of the section, on a thick unit of aeolian sands (generation I), only soil horizon VI[B] with small charcoal inclusions has been preserved. Paleosol horizon VI[A] may have burned out. Pollen spectra (pollen zone 1), obtained from the sand lying immediately under the buried soil, have approximately equal proportions of tree and shrub pollen (AP), grass pollen (NAP), and spores, which correlates well with the widespread development of dwarf pine with a fern cover in the dune framing (Fig. 4). Open birch forests occupied a limited area on the slopes. Alder grew along the valley. On the dunes, forb meadows with abundant Asteraceae, Apiaceae, Caryophillaceae, *Geranium* were developed. In the section of aeolian sandy loam on the surface of the high marine terrace, a charcoal layer was found, from which the ^{14}C-date 2590 ± 70 yr BP, 2660 ± 110 cal yr BP, LU-6107 was obtained. These may be the traces of a large fire that engulfed the bay coast with the dune field and the surrounding slopes.

Aeolian sand in the middle part of the section was formed during a short-term phase of aeolian processes activation (generation II). The grain-size curves are similar to sand of generation I (Fig. 3 D). Proportion of medium sand fractions reaches to 74.4 %, but dune sand contains more fine sand (up to 17.5 %). Kolokol volcano eruption producing loose material occurred during this phase, possibly stimulating the development of aeolian processes, especially on high surfaces. On the dunes and on the sea terrace, forb meadows were developed with a wide participation of ferns (pollen zone 2), mainly *Botrychium lunaria, B. robustum*, common for forb meadows and shrub communities [14, 19]. The wide development of Asteraceae and the ferns among the pioneer vegetation was noted on Simushir Island [17]. Spores of *Lycopodium* and *Hupersia* appeared. *Duschekia* pollen began to occur.

Higher in the section, there are a series of paleosols V–II buried by tephra layers and paleosols I[A] overlain by aeolian sand. A well-preserved complete paleosol profile V underlies the CKr volcanic ash. The pollen spectra (pollen zone 2) include a large amount of AP, represented mainly by dwarf pine (*Pinus pumila*), which probably grew on the dunes. In horizon V[A], the proportion of AP decreased sharply, and the content of *Botrychium* spores increased.

Well-developed paleosol profile IV was formed after the fallout of CKr tephra. On the dune field, motley grass meadows with ferns and club mosses (pollen zone 3) were widely developed. The dwarf pine was probably being suppressed, since it was constantly used by ancient people. The clearings were likely overgrown with club moss *Lycopodium clavatum*, characteristic of such habitats [19]. The species is also included in forb meadow communities [14]. Allochthonous *Picea* pollen was found, brought in from the south.

Kolokol volcano erupted about 910 ± 60 yr BP, 820 ± 60 cal yr BP, LU-6205. A thin paleosol profile III[A] was formed on tephra. Subsequent volcanic ashfalls led to the burial of both paleosol horizons III and II, which were being formed for only a short period. On the volcanic ash interlayer Zav-1, a thin buried soil I[A] was formed, which was then overlain by aeolian sands (generation III) of the Little Ice Age. The sand is poorly sorted, and contains more gravel (1.2 %) and silt admix (2.9 %) (Fig. 3 E). Pollen spectra from buried soils III–I and tephra interlayers have similar compositions (pollen zone 4). Pollen AP, NAP and spores are represented in equal proportions. The AP group is dominated by birch pollen and dwarf pine. *Duschekia* pollen increased in the upper part of the pollen zone, and *Myrica* pollen appeared. Allochthonous pollen of *Picea, Quercus* was found. In the NAP group, a large amount of *Artemisia* pollen was found in the coarse tephra. Just as under modern conditions [14], monodominant communities with sedges (Cyperaceae – up to 53 %) were developed on the dunes. There was a lot of pollen from hygrophilous plants (Ranunculaceae, Iridaceae, Apiaceae), especially in the Zav-1 ash. Club mosses began to dominate among the spores. Single spores of *Sphagnum* and green mosses *Bryales* were found. Paleosols III–I were formed at the Medieval Warm Period.

Pollen zone 5 from the sands of the Little Ice Age and soil A1, reflects widespread development of dwarf pine paralleled with the gradual decrease of birch forests.

Table 2. Chemical composition of volcanic glass from tephra layers of section 7509, the dune field of the Novokurilskaya Bay, Urup Island

№ sample	Depth, m	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Tephra index or volcano
5/7508 (15)	0.66–0.76	63.58	0.95	15.11	8.24	0.28	1.79	5.62	3.57	0.64	Zav-1
7/7508 (4)	0.77–0.78	76.35	0.34	12.95	2.10	0.02	0.37	2.34	3.08	2.33	Kolokol
9/7508 (14)	0.83–0.89	76.24	0.47	12.68	2.25	0.07	0.49	2.28	3.12	2.28	Kolokol
15/7508 (15)	1.14–1.18	77.86	0.36	11.81	1.86	0.04	0.29	1.69	4.13	1.70	CKr
20/7508 (11)	1.58–1.61	77.53	0.44	12.03	1.89	0.03	0.28	1.78	3.07	2.77	Kolokol

Notes. All components are in wt %. Total Fe expressed as FeO. Number of analysis of glass shards in round brackets.

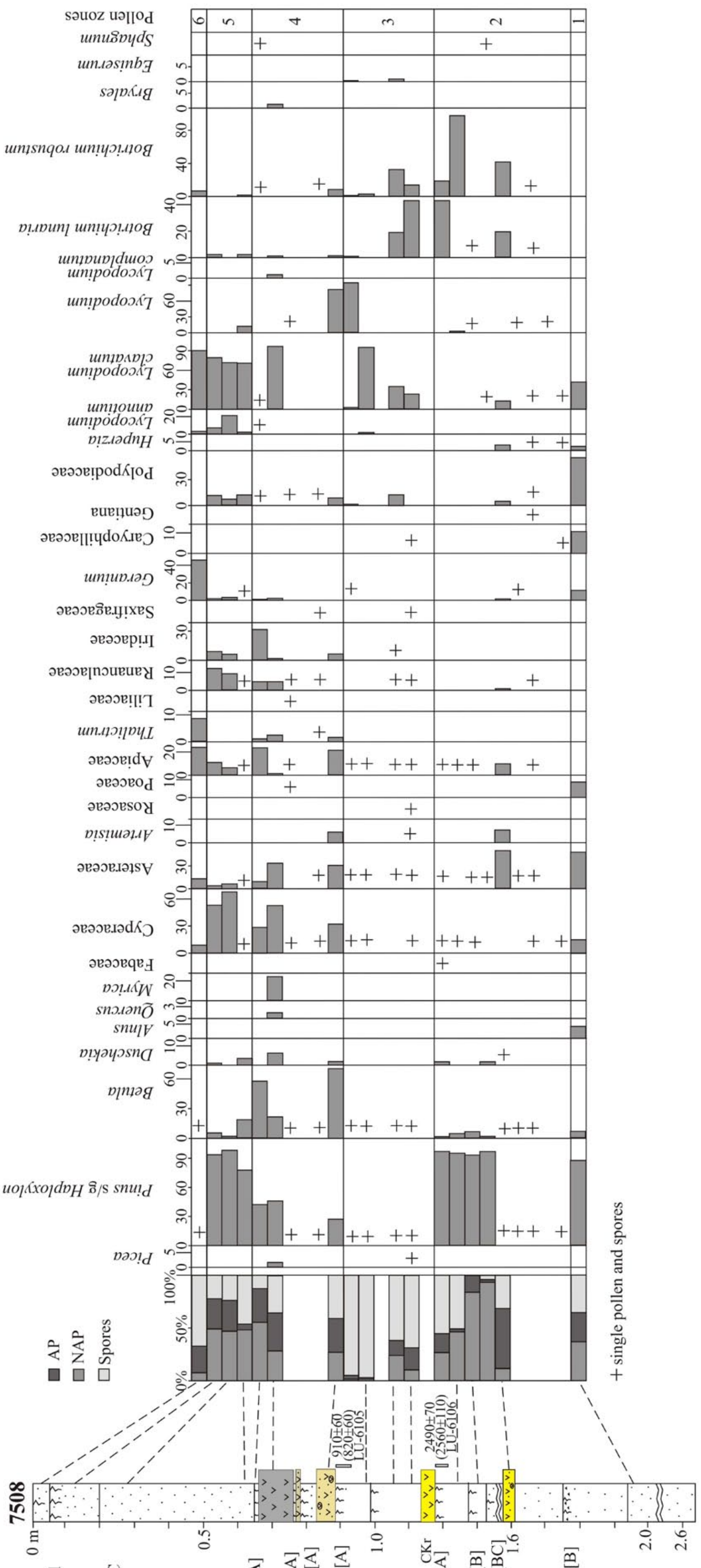

Fig. 4. Pollen percentage diagram of the section 7508, dune field of the Novokurilskaya Bay, Urup Island.

The dunes were occupied by forb meadows and sedge communities, which were pioneers in new dune ridges. Among the ferns, the Polypodiacea had become more widely represented. On wetlands and in dwarf pine thickets, the club moss *L. annotinum* was widely developed.

The surface layer of lightly turfed sand (generation IV) reflects modern situation. Proportion of fine sand fractions increase up to 32.8 %. Modal fraction become 0.25–0.315. The sands contain small silt admix (up to 1.3 %) (Fig. 3 F). Spores and NAP prevail in pollen spectra (pollen zone 6). The proportion of moisture-loving plant pollen decreased, and plenty of *Geranium*, *Thalictrum*, and Apiaceae pollen was registered, typical for ancient dune communities with *Rosa rugosa* [14].

The soil-pyroclastic cover with aeolian deposits on the 40 m marine terrace includes 8 paleosols buried by interlayers of tephra and aeolian sandy loams and sands. The most pronounced soil profile is VI with 4 genetic horizons, formed under warm conditions of the beginning of the Late Holocene [18, 20]. From horizon VI[A], the ^{14}C-date was obtained 3230 ± 120 yr BP, 3460 ± 150 cal yr BP, LU-6109. The upper part of the section reveals a series of buried soils III–I, including tephra of Kolokol volcano, CKr and Zav-1.

Discussion

Two phases of intensive accumulation of aeolian deposits are recorded in the studied sections. The age of these phases of aeolian accumulation is estimated by the age of the buried soils (Fig. 2, 3). The first phase combines generations 1 and 2 of aeolian sands, separated by a weakly expressed soil profile with charcoals. The age of generation 1 is estimated by the age of the buried soil VI[A], which lies at the base of aeolian sandy loams on a high marine terrace (^{14}C-date 3230 ± 120 yr BP, 3460 ± 150 cal yr BP, LU-6109) and the overlying charcoal layer (^{14}C-date 2590 ± 70 yr BP, 2660 ± 110 cal yr BP, LU-6107). The upper age limit of generation 2 is estimated by the age of the buried soil V (^{14}C-date 2490 ± 70 yr BP, 2560 ± 110 cal yr BP, LU-6101), topped by CKr ash. Generation 2 of aeolian deposits is well expressed in the section on the high marine terrace. Buried soils of this age were found in the dune massifs of Kunashir Island, including the Ta-c marker volcanic ash (2400 cal yr BP) of Tarumai volcano, located on Hokkaido [6].

The beginning of the dune field formation in the Novokurilskaya Bay corresponds to one of the global cold episodes of 2800–2600 cal yr BP [21], which manifested itself in the South Kuril Islands and the Japanese Islands. The cool conditions in the northern Urup were evidenced by the widespread dwarf pine and the limited distribution of birch forests. The development of dwarf pine was probably facilitated by heavy snowfalls [22]. On the Tokotan Lake, in the center of Urup (on the coast facing the Okhotsk Sea), temperature decrease was recorded ~ 3090–2770 cal yr BP [23]. Cold and dry episodes were revealed in the development of the paleolake in the Osma Bay, southeastern Urup, 3180–2960 cal yr; 2840–2410 cal yr BP [18]. On Iturup Island, a decrease of the Lebedinoe Lake level was noted in 2800–2650 cal yr BP, the areas of broadleaved forests on the coast decreased, and alder thickets began to develop around the lake [24]. In the mountainous part of Iturup, a pronounced cooling occurred about 2870–2570 cal yr BP [25]. In the south of the Okhotsk Sea, the cooling manifested itself about 2800–2400 cal yr BP [26]. The temperature in Japan (Latest Jomon cold stage) decreased by 2 to 3 °C compared to the present, and winter precipitation increased [27, 28]. An increase in the content of allochthonous broad-leaved pollen in the peat bog section in the mountainous part of Iturup Island indicates growing cyclonic activity, and, consequently, points to the activation of the wind regime and strong winds from the sea; the sources of the pollen being the south of the ridge and Japan and the lower landforms [25].

Compared to the transgressive phase in the beginning of the Late Holocene, the sea level decreased about 3000 cal yr BP [20, 29]. During minor regressions an intensive accumulation of material took place in the coastal zone, which led to progradation of coasts and stimulated development of aeolian processes. The sea level drop on the sandy shores led to an increase in beach area and the emergence of additional sources of sand.

The loose material in the Novokurilskaya Bay is likely to have originated from Kolokol volcano ash fall, the ash being found in the section of dunes and aeolian cover on the high marine terrace (Fig. 2). A connection between the activation of aeolian processes and minor regressions was noted for Iturup and Kunashir islands; large dune fields of generation 2 were formed there [5, 6].

In the southeast of Urup Island, a dune field was formed at this time on the coast of the Osma Bay. A well-defined buried soil with CKr ash is found in the upper part of the dune ridges. Behind the dune field, in the peat bog section, a peat unit with numerous interlayers and lenses of well-sorted aeolian sand is found, which makes it possible to date the aeolian activity phase about 2840–2410 cal yr BP (Fig. 2). The paleolake that existed behind the dune ridge grew shallower and smaller at that time, the climatic conditions became colder and drier [18].

In drier conditions of minor coolings, sandy layers or layers enriched by magnetic minerals, formed by incoming aeolian sand, were found in the coastal lake sediments of the Kuril Islands [30]. On Paramushir Island, the sand layer in the sediments of the Pernatoe Lake was formed 3300–3100 cal yr BP [7]. Paleomagnetic data reflect the activity of aeolian processes for the Tokotan Lake area about 3450–2300 cal yr BP [23]. As shown by the study of the Maloye and Kasatka lakes, aeolian activity also increased in the dune fields of Central Iturup [31].

During the long stabilization phase of the dune field in the Novokurilskaya Bay, a series of soil profiles V–I were formed, buried by CKr tephra, Kolokol volcano tephra and volcanic ash Zav-1 Zavaritsky volcano and by aeolian sands. The dunes were stabilized due to the development of meadow vegetation and dwarf pine thickets. At this time, dwarf pine was widespread on Simushir Island, south of Urup Island and in the Iturup mountains [17, 18, 25]. The dwarf pine area decreased on the dune field after CKr ash fall, probably owing to the activity of ancient humans who destroyed most of the dwarf pine thickets. In the central part of the dune field, buried soil IV includes numerous artifacts (archaeological site Kompaneiskoye 1), indicating a long-term human habitation in the dunes [32]. Here, the thickness of the buried soil IV reaches 1.5 m.

The development of soil forming processes was stimulated by climatic conditions, which became slightly warmer and more humid. In the south of Urup Island, slight warming about 2340–2260 years ago is recorded by an increase in the proportion of broadleaf trees in the pollen spectra. About 2340–2250 years ago the paleolake flooded in the Osma Bay [18]. Cool and humid conditions were also recorded on Iturup Island about 2100–2000 cal yr BP and 1900–1200 cal yr BP [24].

In the Novokurilskaya Bay, soil formation in the dunes continued without interruption during the Kofun cold stage (1600–1300 cal BP), which is distinguished in the south of the Kuriles and the Japanese Islands [5, 20, 27]. On Kunashir and Iturup islands, aeolian processes intensified at this time, and dunes of generation 3 were formed [5, 6]. Activation of aeolian processes is also recorded in the south of Paramushir Island 1700–1300 cal yr BP [7]. Weak development of aeolian processes during this cooling in the north of Urup Island can be attributed to local causes. It is possible that a strong tsunamigenic earthquake that occurred before the CKr ash fall [18] was accompanied by coseismic subsidence. The humid conditions (frequent rains, drizzle) could hinder the development of aeolian processes. Moisture increase is indicated by the appearance of grass pollen, typical of moist habitats. High humidity at that time was recorded in the section of lacustrine deposits of the Lebedinoe Lake on Iturup [24]. During the Kofun cold stage [27], the cold Oyashio Current became more active, which contributed to an increase in rains and fogs in the Southern Kuril Islands [29].

The warmest conditions on the Novokurilskaya Bay coast were registered in the Medieval Warm Period, when birch forests were widely developed. Birch occupied large areas during the Medieval Warm Period on Simushir Island. The average annual temperature increased only slightly – by tenths of a degree, but the sum of active temperatures could be 150–180 °C higher than the current one [17]. The warm phase is comparable to the European Medieval Climate Anomaly (MCA) and

Nara-Heian-Kamakura warm stage in Japan 1200–700 cal yr BP [27]. This warming affected all Kuril Islands, including Iturup, Kunashir and Lesser Kurils [20, 24, 29, 33, 34].

At the end of the warming, alder became more common in the north of Urup Island, possibly due to frequent ash falls, and *Myrica* appeared in a swamp in a river valley. Sagebrush spread widely in the grassy communities on coarse tephra of Kolokol volcano. On the Zav-1 tephra, composed of silt with low water permeability, the proportion of moisture-loving plant pollen (Cyperaceae, Ranunculaceae, Iridaceae) increased among grass pollens; spores of *Sphagnum* and green mosses *Bryales* appeared. Transport of allochthonous pollen (*Picea, Quercus*) from the south became more active. Before the Little Ice Age, oak area could extend to the south of Urup Island [18].

A powerful phase of aeolian accumulation took place in the Little Ice Age. At that time, dune ridges were formed in the seaward part of the field which had no buried soils. In the central part of the dune field, the thickness of aeolian sands reached 1.5–3 m. In the field rear part, aeolian sand (up to 0.45 m thick) overlay buried soil I[A]. Sand accumulation also took place on the high marine terrace. There are dunes of the Little Ice Age in the Osma Bay, the thickness of aeolian sand reaches 2.5–3 m. Many studies have examined dune reactivation during the Little Ice Age. Such dunes are widespread on the Kurile Islands [5, 6, 8] and in Japan [1, 3]. On Iturup Island, aeolian processes were actively progressing on the Vetrovoy Isthmus [8], in Prostor, Kurilskiy, and Kuibyshevskiy bays, on Kunashir Island – the Lovtsovskiy Isthmus, near the Saratovka River, in Golovnina and Pervukhin bays, on the Sernovodskiy Isthmus, and in other areas [6]. On the Kuriles, dune fields of this age acquire a maximum thickness in the coastal areas with a gentle underwater coastal slope and extensive benches.

As a rule, dunes of this age have a well-pronounced typical aeolian cross-bedding, emphasized by black layers of heavy minerals, with a wedge-shaped series. Such layering indicates the accumulation of sands due to winds of variable direction. Peaks of magnetic susceptibility and sandy layers formed during the Little Ice Age were found in lacustrine deposits of central Iturup Island [31].

In the south of the Kuriles (Kunashir Island), the average annual temperature was lower than at present by 2 °C [35], in Japan – by 1 to 2 °C, and atmospheric precipitation increased [27, 36]. The cooling led to widespread distribution of dwarf pine in the north of Urup Island. An increase of dwarf pine as also established for central Iturup [24, 31]. At that time, the areas occupied by broadleaved forests decreased on Iturup and Kunashir islands [20].

The cooling was accompanied by a minor regression, which stimulated the formation of dunes. A sea level drop is evidenced by numerous finds of peat on benches found on the Lesser Kuriles, with layers of volcanic ash Ko-c2 (1694 AD) and Ta-a (1739 AD) at bench bases confirming that the regression began at the end of the 16th century [27]. In the South Kuril Islands, the sea level decreased by at least 1 m. Similar estimates were obtained for the Japanese Islands, where the Edo regression occurred 650–50 cal yr BP [27].

One of the factors of aeolian activation in the Little Ice Age was the increased winds, especially winter winds associated with the intensification of the winter monsoon [3]. Strong winds are evidenced by increased storm activity. For example, the raise in salinity of the Tokotan Lake about 615–500 cal yr BP and ~425–385 cal yr BP is attributed to increased storm activity, which is possibly associated with a change in the monsoon [23]. Strong storm surges were also recorded on the Okhotsk Sea coast of Iturup Island, when marine diatoms were carried along the channels into the Lebedinoe Lake [24]. In the south of the Japanese Islands, typhoons intensified from the mid-17th to the end of the 19th centuries [37]. One of the indicators of the increasing wind drift of pollen is the elevated amount of allochthonous pollen of tree species in the sections of the Northern and Central Kuril peatlands: Ketoi, Onekotan, Shiashkotan, and Ekarma islands [16].

Traces of strong storms are observed as large storm bars or accumulative forms at river mouths, which have a height comparable to that of the low marine terraces of the Middle-Late Holocene. The absence of soil cover is typical for such storm bars, formed in historical time. Modern accumulative forms of the same height (up to 4 m) were found in the Pervukhin Bay, Kunashir Island and the Kuibyshevsky Bay, Iturup Island. The formation of such accumulative forms could occur as a result of strong storm surges.

In modern conditions, the dune field of the Novokurilskaya Bay witnesses a reactivation of aeolian processes due to destruction of soil cover and vegetation, and formation of deflation basins with erosion escarps at sand mining sites. Amounts of sand also come from a wide beach, which receives the material due to erosion of the foredunes during strong storms. The thickets of dwarf pine on the dunes and in the framing of the bay are practically destroyed, there are many open spaces. Activation of aeolian processes is observed on Iturup and Kunashir islands in present-day dune fields, where sandy material is actively removed (Prostor Bay – a dune field near the village of Reidovo; a dune field near the Kuibyshevskoye Lake, the Kuybyshevsky Bay, Iturup; a dune field of the Golovnin Bay near the settlement of Yuzhno-Kurilsk, Kunashir).

Conclusions

Cooling and minor regression are the key drivers of the coastal dune development. In the north of Urup Island, four generations of aeolian deposits have been identified corresponding to the phases of aeolian processes reactivation in the coastal zone in the Late Holocene. Extensive development of aeolian processes took place during cooling with an active wind regime and an abundant sand supply in the coastal zone. The aeolian activity was facilitated by the intensive accumulation of material in the coastal zone during minor regressions. An additional source of loose material was the tephra of large eruptions. The formation of large dune fields on Urup Island is found to be synchronous with that of other dune fields in the South Kuriles. Differences in the stratigraphy of the dune field in the north of Urup compared to other islands are attributed to local causes. The East Asian winter monsoon and increased winter storminess were the main factors of the synchronous dune activity in the Little Ice Age.

A hiatus in dune sedimentation, stabilization of coastal dunes and soil formation as a rule took place during warm episodes. A long period of meadow vegetation and dwarf pine thicket development was identified for the dune field of the Novokurilskaya Bay. Meadow-soddy soils were formed there at the time, with a series of profiles buried by tephra during large volcanic eruptions on Urup (Kolokol volcano) and adjacent islands of Simushir (Zavaritsky volcano) and the north of Iturup.

Human impact played an important role in the development of coastal landscapes. Ancient people who lived among the dunes in the Late Holocene are found to have left traces of their impact on the vegetation. Modern human activities still cause environmental changes in the dune fields. At present, active aeolian processes continue on sand mining sites. Aeolian sedimentation also takes in the material from the wide sandy beach that grows larger due to storm erosion of the dunes.

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