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THE NORTH DVINA RIVER DELTA DEVELOPMENT OVER THE HOLOCENE: GEOCHRONOLOGY AND PALAEOENVIRONMENT

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Abstract: In this paper, a detailed overview of the Holocene evolution of the North Dvina river (ND) delta (southern White Sea) is presented; it is based on radiocarbon dating, geomorphological and other field surveys, and plant macrofossil and palynological data. We have identified three main stages of the delta evolution: estuary erosional (Allerød – 5700 cal BC), lagoon or tidal-marsh (5700 cal BC – 3700 cal BC) and fan-delta accumulative (3700 cal BC – present). These stages are correlated with local climatic curves, sea level changes, glacioisostatic raise curve and Baltic Sea stages. A variety of landforms has been identified and dated within the delta. These results help to explain the spatial and temporal patterns in the prehistoric human occupation of this area.

Keywords: North Dvina River delta, White Sea, Holocene, geochronology, radiocarbon dating, landforms, palaeoenvironmental reconstructions, land evolution.

1. INTRODUCTION

Large deltas entering cold tidal seas provide an opportunity to reconstruct the development of frontier landforms over time. This is an area of fluvial-marine interaction, with mosaic landscape and specific organic-rich sediments and sometimes deltas became inhabited by prehistoric people communities. Therefore deltas provide detailed archives for the studies of chronology of various palaeoenvironmental changes such as sea level oscillations, river dynamics, shoreline evolution, peat bog development, people adaptation etc.

Since 2005, we performed a detailed radiocarbon dating and palaeoenvironmental studies of the North Dvina (ND) river delta and adjacent areas (Zaretskaya, 2006; Zaretskaya *et al.*, 2008; 2009). The main goal of this research was to reconstruct the Holocene chronology and palaeoenvironmental history of the ND delta as a case study of such a landscape evolution, and as an area of ancient people settling.

2. STUDY AREA

The ND delta is located in the northeastern part of Europe where the North Dvina river enters the White Sea (**Fig. 1A**). Nowadays this is a lobe-type fan delta with many river arms and islands. Its surface area is 1100 km^2, the maximum length – 45 km (Lupachev, 1984) and its maximum elevation is 6-7 m a.s.l. Two big cities with well developed transport system – Arkhangelsk in the east and Severodvinsk in the west – make it easier to access the study area by truck, bus or regular boat.

During LGM (18-16 kyr BP) the White Sea was covered by ca. 2 km thick ice (Demidov *et al.*, 2006). There is a hypothesis of an ice-dammed lake affecting this area during the deglaciation period (Bølling-Allerød) (Demi-

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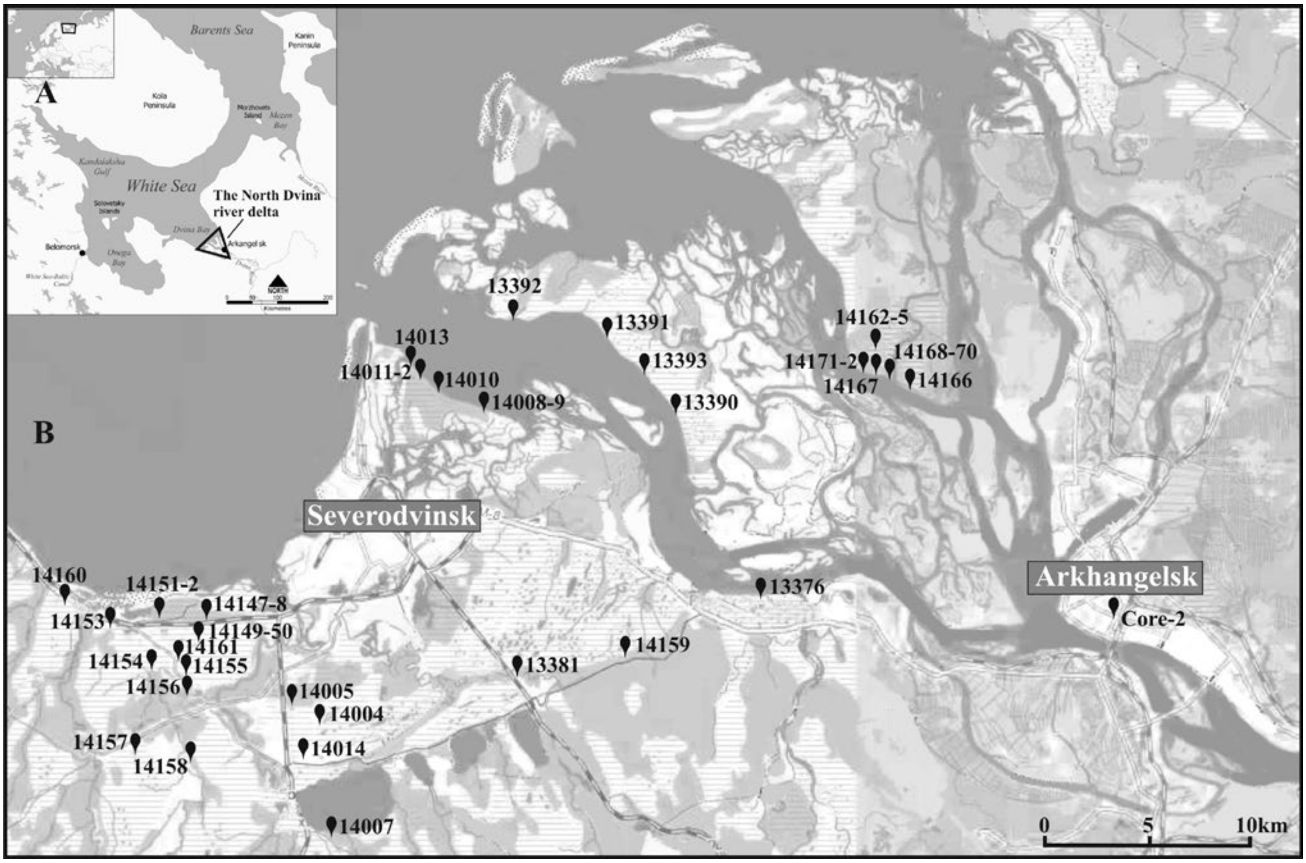

Fig. 1. *Study area: the North Dvina River delta on a map (A) and sampling sites with GIN- laboratory numbers on the ND delta chart (B).*

dov *et al*., 2006; Lavrov and Potapenko, 2005), though in the field we still could not see any traces or deposits of such a lake. The time of complete deglaciation of the White Sea and the opening of the White Sea Gorge (Gorlo in Russian, a strait connecting the White and Barents seas) is still not well known (Demidov *et al*., 2006). Palynological and diatom data obtained in 1960s indicates the presence of marine diatoms in the Allerød sediments within the ND delta (Pleshivtseva, 1977).

A tectonic pattern of the North Dvina delta area is still polemical. There are two controversial theories:

1) The ND delta is located within the southeastern end of the huge Kandalaksha-Dvina rift, which runs in the NW-SE direction from Kandalaksha inlet across the central part of the White Sea to Dvinsky inlet. This rift has been experiencing continuous subsidence during the Holocene (Zhivotovskaya, 1960; Avenarius, 2004). The flanks of this rift are, per contra, rising due to the glacioisostatic uplift. This theory was based on morphostructural data (Avenarius, 2004) and a finding of the Early Holocene buried peat in a borehole in Arkhangelsk city at the depth of 17.5 m (Zhivotovskaya, 1960; Nikonov, 1977; Koshechkin, 1979).
2) This is an area of recent continuous uplift due to the rise of the Arkhangelsk swell of crystalline basement (Zykov *et al*., 2008). Facts which support this theory are 1) pattern of Quaternary deposits in this area; 2) North Dvina river channel pattern (a bend marking a border of the swell).

From our point of view, this contradiction between these two hypotheses is caused by a lack of geological and geochronological data for this area. Our new data allows us to propose another type of tectonic movements within this area.

3. METHODS

The main method was the radiocarbon dating of peat bogs of different origin, composition, depth and size, widely spread over the delta and adjacent areas. We have dated more than 50 samples of peat, gyttja, loamy peat (lagoon deposits), and wood (**Table 1**) collected from 30 sampling sites all over the area (**Fig. 1B**). The stratigraphy of relatively dry peat bogs was studied in the excavations and outcrops; wet mires were sampled with the help of the Russian corer TBG-1 (**Figs. 4** and **5**).

Radiocarbon dating was performed in the conventional ^{14}C laboratory within the Laboratory of Isotope Geochemistry and Geochronology in the Geological Institute of Russian Academy of Sciences (Moscow), using the standard methods of pretreatment and calculations

Table 1. *Radiocarbon dates obtained within the North Dvina River delta and the adjacent areas, with plant composition of dated samples and calibrated age ranges; Dates Tln-125 and Tln-126 from Koshechkin* et al., *1977.*

No	Field number	Lab (GIN) code	Geographical coordinates (º)	Dated organic matter (with plant composition)	Depth (m)	^{14}C date	Calibrated age range (1σ) (68.2%)	Calibrated age range (2σ) (95.4%)
1	-	Tln-126		buried peat	17.70	9115±100	8470 - 8240BC (68.2%)	8650 - 7950BC (95.4%)
2	SD0933/A1	14158	N64.47188 E39.64941	gyttja	3.30-3.40	9070±60	8320 - 8230BC (68.2%)	8470 - 8200BC (94.1%) 8040 - 8010BC (1.3%)
3	SD0941/A4	14165	N64.64880 E40.32576	loamy peat	4.70-4.80	9030±70	8310 - 8200BC (60.2%) 8110 - 8090BC (2.3%) 8040 - 8010BC (5.8%)	8430 - 8360BC (2.6%) 8350 - 7960BC (92.8%)
4	-	Tln-125		buried peat	17.25	8370±170	7550 - 7310BC (68.2%)	7590 - 7170BC (95.4%)
5	SD0807/A2	14007	N64.44381 E39.78779	peat	2.10-2.25	8610±60	7710 - 7570BC (68.2%)	7760 - 7530BC (95.4%)
6	SD0941/A3	14164	N64.64880 E40.32576	moss-wood peat	4.20-4.30	7950±50	7030 - 6930BC (26.8%) 6920 - 6870BC (12.6%) 6850 - 6750BC (26.9%) 6720 - 6710BC (2.0%)	7050 - 6690BC (95.4%)
7	SD0943/A1	14167	N64.63770 E40.32891	*Phragmites* loamy peat	1.34-1.36	6920±40	5840 - 5745BC (68.2%)	5890 - 5720BC (95.4%)
8	RIKAS3/A14	13376m	N64.54607 E40.22030	*Phragmites*-repleted lagoon deposits with saltish water diatoms	3.50	6400±30	5470 - 5440BC (16.8%) 5430 - 5400BC (9.5%) 5380 - 5320BC (42.0%)	5470 - 5320BC (95.4%)
9	SD0945/A2	14170	N64.63778 E40.33356	*Phragmites*-repleted loam	1.36-1.38	6200±40	5220 - 5200BC (8.8%) 5180 - 5060BC (59.4%)	5300 - 5040BC (95.4%)
10	SD0944/A1	14168	N64.63763 E40.33627	plant detritus	1.48-1.50	6180±40	5210 - 5190BC (6.1%) 5180 - 5060BC (62.1%)	5290 - 5270BC (1.4%) 5230 - 5000BC (94.0%)
11	RIKAS3/A14	13376k	N64.54607 E40.22030	*Phragmites*-repleted lagoon deposits	3.50	5970±40	4910 - 4790BC (68.2%)	4960 - 4720BC (95.4%)
12	SD0941/A2	14163	N64.64880 E40.32576	pine-birch peat	3.20-3.30	5860±40	4785 - 4690BC (68.2%)	4830 - 4610BC (95.4%)
13	SD0945/A1	14169		*Phragmites*-repleted loam	0.60-0.62	5440±40	4340 - 4310BC (26.8%) 4305 - 4255BC (41.4%)	4360 - 4230BC (95.4%)
14	RIKAS3/A13	13375	N64.54607 E40.22030	*Phragmites* loamy peat (lagoon deposits)	3.24	5410±40	4330 - 4245BC (68.2%)	4350 - 4220BC (85.2%) 4210 - 4160BC (6.9%) 4130 - 4110BC (1.0%) 4100 - 4070BC (2.3%)
15	SD0934/A1	14159	N64.51975 E40.07372	birch peat	4.35-4.45	4950±50	3780 - 3660BC (68.2%)	3940 - 3870BC (7.8%) 3810 - 3640BC (87.6%)
16	SD0932/A1	14157	N64.47533 E39.59084	wood peat	2.5-2.6	4870±40	3695 - 3635BC (68.2%)	3760 - 3620BC (86.3%) 3580 - 3530BC (9.1%)
17	KORODA/A5	13381	N64.50906 E39.97263	peat	1.75	4570±30	3370 - 3330BC (42.5%) 3220 - 3180BC (14.8%) 3160 - 3130BC (10.9%)	3500 - 3460BC (6.7%) 3380 - 3310BC (46.2%) 3240 - 3100BC (42.4%)
18	SD0942/A1	14166	N64.63523 E40.35748	loamy peat	3.40-3.50	4430±70	3330 - 3230BC (20.0%) 3170 - 3160BC (1.7%) 3120 - 2920BC (46.5%)	3340 - 2910BC (95.4%)
19	SD0935/A1	14160	N64.54092 E39.53151	loamy peat (lagoon deposits) with *Phragmites* and saltish water diatoms	4.20-4.30	4360±60	3090 - 3060BC (6.5%) 3030 - 2900BC (61.7%)	3330 - 3220BC (7.2%) 3120 - 2880BC (88.2%)
20	LASOM/A9	13390	N64.62278 E40.12851	loamy peat (lagoon deposits) with saltish water diatoms	2.25	4060±50	2840 - 2810BC (6.4%) 2670 - 2490BC (61.8%)	2860 - 2800BC (12.4%) 2760 - 2470BC (83.0%)
21	RIKAS3/A12	13374	N64.54607 E40.22030	*Phragmites*-birch loamy peat with saltish water diatoms	2.57-2.59	3880±40	2460 - 2290BC (68.2%)	2470 - 2270BC (88.2%) 2260 - 2200BC (7.2%)
22	SD0822/A1	14014	N64.47707 E39.77145	loamy peat (lagoon deposits)	2.20-2.30	3530±40	1930 - 1860BC (29.9%) 1850 - 1770BC (38.3%)	1970 - 1740BC (95.4%)
23	SD0932/A1	14156	N64.47533 E39.59084	*Sphagnum* peat	1.55-1.65	3490±40	1880 - 1750BC (68.2%)	1920 - 1730BC (91.5%) 1720 - 1690BC (3.9%)
24	SD0929/A1	14155	N64.50837 E39.62666	*Phragmites* peat	1.95-2.00	3370±40	1740 - 1710BC (12.9%) 1700 - 1610BC (55.3%)	1750 - 1530BC (95.4%)
25	RIKAS3/A10	13372	N64.54607 E40.22030	*Sphagnum* with green mosses peat	2.11-2.12	3200±40	1505 - 1430BC (68.2%)	1610 - 1570BC (2.7%) 1540 - 1390BC (92.7%)
26	SD0946/A2	14172	N64.63838 E40.32116	drift wood (twigs)	1.00-1.17	3030±60	1390 - 1210BC (68.2%)	1430 - 1110BC (95.4%)
27	SD0946/A1	14171	N64.63838 E40.32116	drift wood (twigs)	1.00-1.17	3010±80	1390 - 1120BC (68.2%)	1430 - 1010BC (95.4%)

Table 1. *Continuation*

No	Field number	Lab (GIN) code	Geographical coordinates (º)	Dated organic matter (with plant composition)	Depth (m)	^{14}C date	Calibrated age range (1σ) (68.2%)	Calibrated age range (2σ) (95.4%)
28	LASOM4	13393	N64.63567 E40.10415	loamy peat (lagoon deposits) with saltish water diatoms	1.80	2990±40	1310 - 1190BC (55.8%) 1180 - 1130BC (12.4%)	1390 - 1110BC (94.4%) 1100 - 1080BC (1.0%)
29	SD0924/A1	14154	N64.51318 E39.64450	loamy peat (lagoon deposits) with *Phragmites*	1.90-2.00	2900±40	1190 - 1180BC (2.7%) 1160 - 1140BC (3.6%) 1130 - 1010BC (61.9%)	1260 - 1230BC (2.7%) 1220 - 970BC (92.7%)
30	RIKAS3/A7	13369кл	N64.54607 E40.22030	*Sphagnum* peat	1.60	2800±80	1050 - 840BC (68.2%)	1200 - 800BC (95.4%)
31	RIKAS3/A7	13369	N64.54607 E40.22030	*Sphagnum* peat	1.60	2690±80	930 - 790BC (68.2%)	1060 - 740BC (92.1%) 690 - 660BC (1.3%) 650 - 590BC (1.9%)
32	LASOM2	13391	N64.64983 E40.06901	*Phragmites* peat with saltish water diatoms	1.08-1.10	2570±40	810 - 750BC (49.3%) 690 - 660BC (11.4%) 640 - 590BC (7.5%)	820 - 730BC (55.2%) 690 - 660BC (13.8%) 650 - 540BC (26.4%)
33	RIKAS3/A6	13368	N64.54607 E40.22030	*Sphagnum* peat	1.31-1.32	2450±50	750 - 680BC (18.9%) 670 - 640BC (6.3%) 590 - 580BC (1.9%) 560 - 410BC (41.1%)	770 - 680BC (23.0%) 670 - 400BC (72.4%)
34	SD0923/A1	14153	N64.53192 E39.57147	organo-mineral gyttja with saltish water diatoms	2.95-3.05	2370±50	520 - 380BC (68.2%)	750 - 680BC (10.9%) 670 - 630BC (3.1%) 600 - 360BC (81.3%)
35	SD0941/A1	14162	N64.64880 E40.32576	*Sphagnum* peat	1.95-2.05	2200±70	370 - 190BC (68.2%)	400 - 90BC (94.3%) 70 - 50BC (1.1%)
36	SD0809/A2	14012	N64.63898 E39.87736	loamy peat (lagoon deposits)	0.68-0.70	2200±40	360 - 270BC (42.2%) 260 - 200BC (26.0%)	390 - 170BC (95.4%)
37	SD0922/A1	14151	N64.53582 E39.63453	organo-mineral gyttja (lagoon deposits) with saltish water diatoms	1.10-1.20	2160±50	360 - 280BC (29.1%) 240 - 150BC (32.1%) 140 - 110BC (7.0%)	370 - 50BC (95.4%)
38	LASOM3	13392	N64.66272 E39.97818	loamy peat (lagoon deposits) with *Phragmites* and saltish water diatoms	1.30-1.33	2030±40	100 - 30AD (68.2%)	170BC (95.4%) 60AD
39	SD0817/A1	14008	N64.62661 E39.92014	loamy peat (lagoon deposits)	1.35	2010±30	45 - 25AD (68.2%)	100BC (95.4%) 70AD
40	SD0805/A1	14004	N64.48435 E39.77351	peat	2.10-2.20	1960±50	40 - 90AD (68.2%)	100BC (95.4%) 140AD
41	RIKAS3/A5	13367	N64.54607 E40.22030	*Sphagnum* peat	1.05-1.06	1960±40	20 - 10BC (3.6%) AD - 90AD (64.6%)	50BC (95.4%) 130AD
42	SD0817/A2	14009	N64.62661 E39.92014	loamy peat (lagoon deposits)	1.62-1.65	1860±40	80 - 110AD (68.2%)	60AD (95.4%) 250AD
43	SD0812/A1	14010	N64.63369 E39.89173	peat	1.28-1.30	1820±30	135 - 200AD (46.1%) 205 - 235AD (22.1%)	90AD (1.1%) 100AD 120AD (91.9%) 260AD 300AD (2.5%) 320AD
44	SD0937/A1	14161	N64.51826 E39.64148	loamy peat (lagoon deposits)	1.70-1.80	1760±70	170 - 190AD (3.9%) 210 - 390AD (64.3%)	80AD (1.8%) 110AD 120AD (93.6%) 430AD
45	SD0806/A1	14005	N64.49657 E39.74882	peat with *Phragmites*	0.90-1.00	1310±40	660 - 720AD (48.6%) 740 - 770AD (19.6%)	640AD (95.4%) 780AD
46	SD0809/A1	14011	N64.63898 E39.87736	peat	0.43-0.45	1260±20	690 - 750AD (60.4%) 760 - 775AD (7.8%)	670AD (93.5%) 780AD 790AD (1.9%) 810AD
47	RIKAS3/A4	13366	N64.54607 E40.22030	*Sphagnum* peat	0.52-0.54	1080±60	890 - 1020AD (68.2%)	770AD (95.4%) 1050AD
48	SD0821/A1	14013	N64.64246 E39.86846	loamy peat (lagoon deposits)	0.53-0.55	1080±40	890 - 920AD (17.2%) 940 - 1020AD (51.0%)	880AD (95.4%) 1030AD
49	SD0922/A2	14152	N64.53582 E39.63453	organo-mineral gyttja with saltish water diatoms	0.95-1.00	1050±70	890 - 1040AD (68.2%)	810AD (95.4%) 1160AD
50	SD0918/A1	14149	N64.52633 E39.65280	*Carex* peat	1.00-1.10	1000±60	980 - 1060AD (39.7%) 1080 - 1160AD (28.5%)	890AD (95.4%) 1180AD
51	SD0921/A1	14150	N64.52959 E39.65491	*Carex* peat	1.20-1.30	970±70	1010 - 1160AD (68.2%)	890AD (2.0%) 920AD 950AD (93.4%) 1220AD
52	SD0910/A1	14148	N64.53463 E39.65773	*Carex* peat	0.75-0.85	640±80	1280 - 1330AD (30.5%) 1340 - 1400AD (37.7%)	1220AD (95.4%) 1440AD
53	SD0909/A1	14147	N64.53580 E39.65676	wood peat	0.75-0.85	190±150	1630 - 1960AD (68.2%)	1470AD (95.4%) 1960AD
54	RIKAS3/A1	13364	N64.54607 E40.22030	shrub turf	0.11-0.13	Modern		

(Zaretskaya *et al*., 2001; 2007). For calibration, we used the OxCal program v.3.10 (Bronk Ramsey, 1995; 2000) and calibration curve IntCal04 (Reimer *et al*., 2004).

Our geomorphological studies were based on the analysis of the 1:100,000 topographic maps (Aerogeodezia, 2002), the 1:1,000,000 map of Quaternary deposits compiled by Lavrov and Potapenko (Lavrov and Potapenko, 2005) and space images (from Google Earth site). In the field, we mapped various landforms that have allowed us to compile a sketch-map of the North Dvina delta and adjacent areas (**Fig. 2A**). We studied spatial distribution, morphometry and deposits of these landforms. Our conclusions on the origin, age, peculiarities of evolution of various types of landforms and character of landscape-forming processes are based on the field data, GPS navigation results (World Geodetic System 1984) and stratigraphy and ^{14}C ages of deposits composing the ND delta and the adjacent areas.

For reconstructions of palaeoenvironment, we used the results of both plant macrofossil and spore-pollen analyses. Plant macrofossil analysis of all the dated samples was performed by Olga N. Uspenskaya from the Institute of Horticulture at the Russian Academy of Agricultural Sciences, and provided not only the plant composition data of peat and gyttja samples, but also diatom species showing salt- or freshwater conditions, and the organic/mineral ratio of the sample (**Table 1**). This allowed us to reconstruct the scenario of sedimentation, plant assemblages and ecology, and salinity for lagoon deposits.

Spore-pollen analysis of two sections (Rikasiha – 3.5 m depth, and Krugly mokh – 5 m depth) has been performed by Alexandra N. Simakova in the Geological Institute of Russian Academy of Sciences, using the standard methods of analysis and diagram construction (**Fig. 3**) (Bohncke and Simakova, 2008).

4. RESULTS

Actually, the North Dvina delta is heterogeneous in landforms and their age, including such a various types as moraine remains on the Nikolsky Island, Liasomin-Uglomin Island system composed of beach ridges and palaeolagoons between them, and lowland flat sandy islands of modern age and fluvial origin.

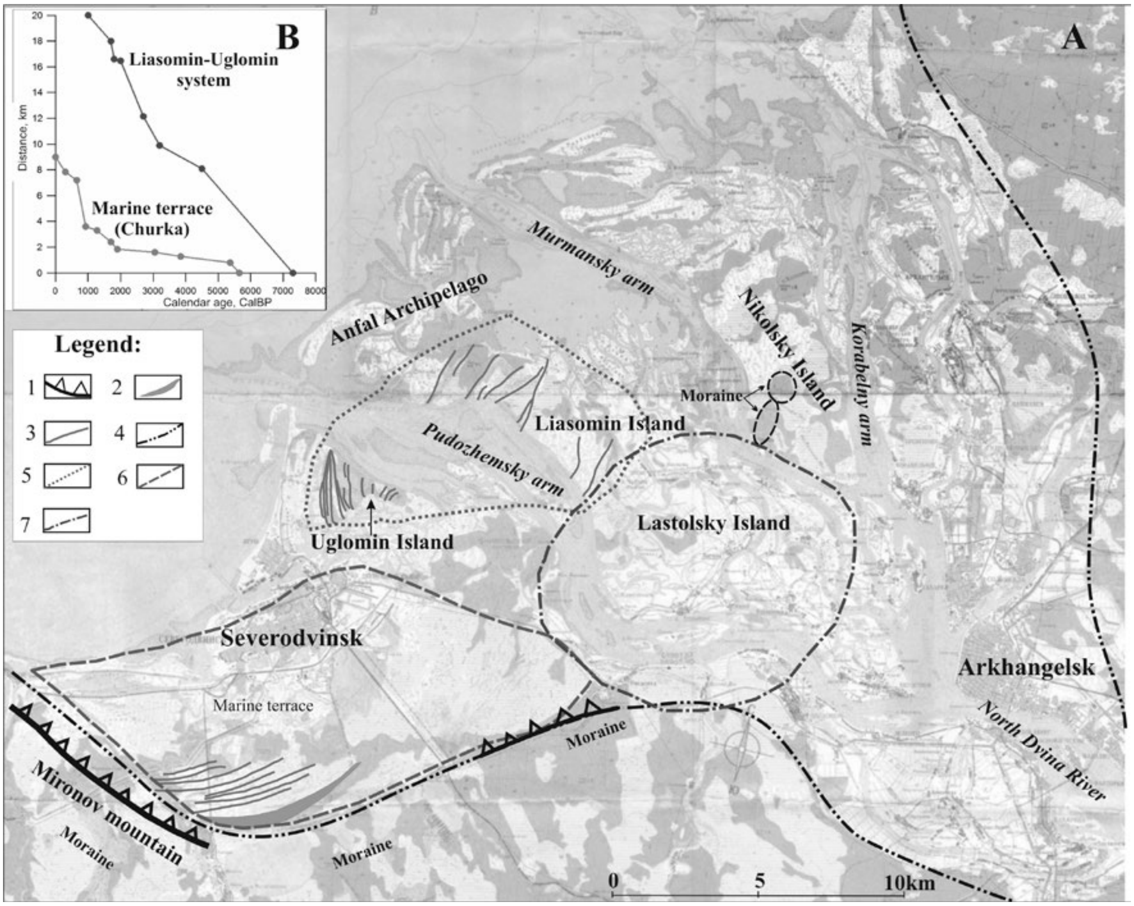

Fig. 2. *(A) A sketch geomorphological map of the North Dvina River delta: 1 – Mironov mountain palaeocliff; 2 – accumulative sand body (the oldest beach ridge) in the inner part of marine terrace; 3 – beach ridges forming the terrace and islands; 4 – borders of the delta; 5 – Liasomin-Uglomin system; 6 – marine terrace (Churka site); 7 – proposed area of lagoon extension. (B) – rates of prograding of ND delta into the White Sea.*

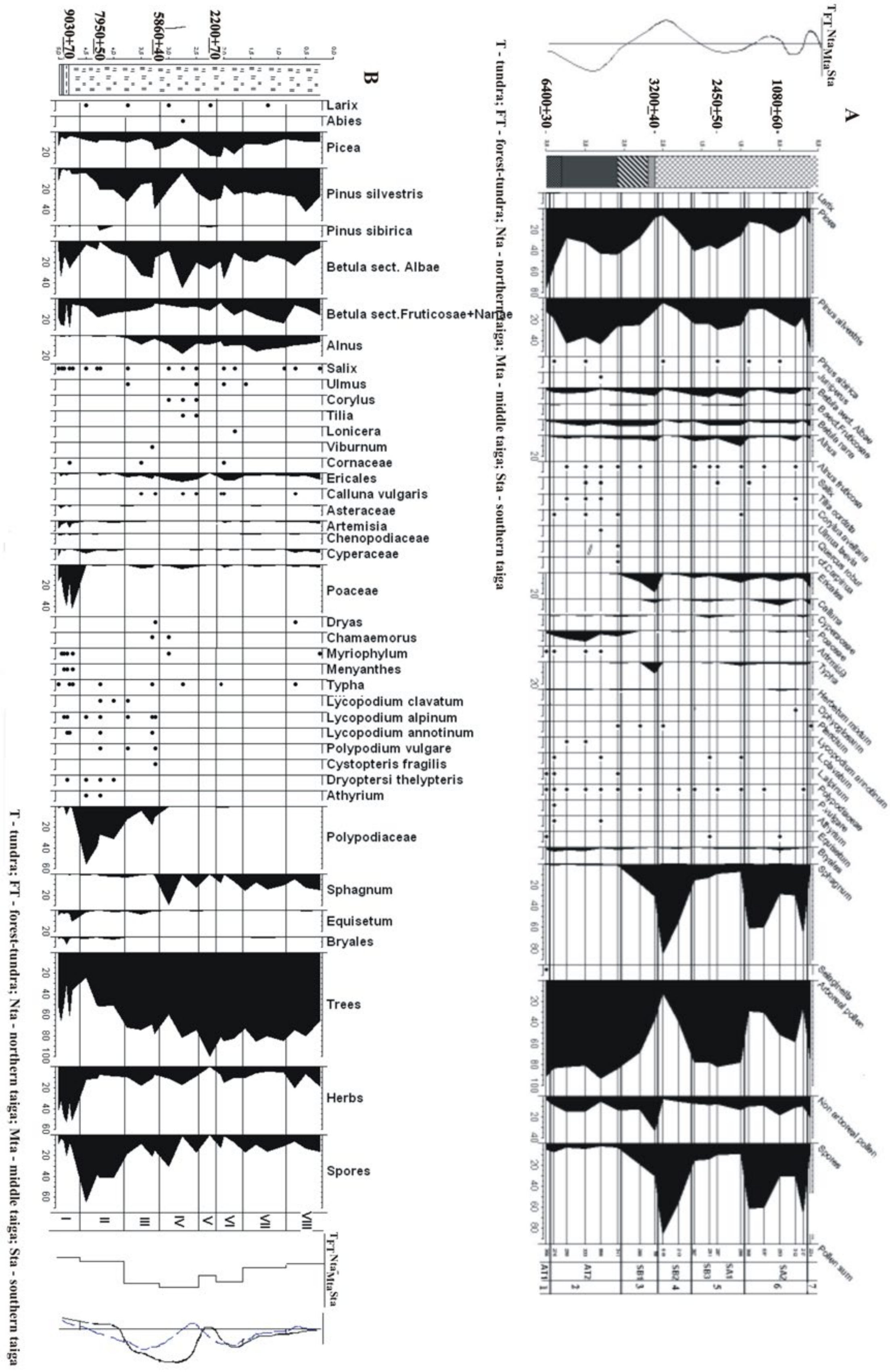

Fig. 3. *Spore-pollen diagrams of the Rikasiha (A) and Krugly Mokh (B) peat sections (analysed by A.N. Simakova).*

Landform types

Within the ND delta and adjacent areas, three main types of Late Pleistocene-Holocene landforms were distinguished: Late Pleistocene moraine, Holocene marine and fan-delta landforms.

Late Pleistocene landforms are presented mostly by moraine - hummocky uplands alternating with depressions, partially flattened by sea activity, with a 20-m high scarp steeply dropping to the White Sea shore (**Fig. 2B**). The moraine is widespread over the delta surroundings (50-60 m a.s.l.) and sometimes within it ("inselberg" moraine 8-9 m a.s.l. on the Nikolsky Island). Depressions on the moraine surface are mostly occupied by Holocene peat bogs of varying thickness (**Fig. 4**), and are submeridionally elongated. Moraine is composed of diamicton – hard clay-loam with gravel and boulders.

Other landforms and deposits are of the Holocene age. Landforms are presented mostly by series of sandy beach ridges within the western part of the delta, and by a 20 m high palaeocliff (**Fig. 2A**). This palaeocliff bordering the

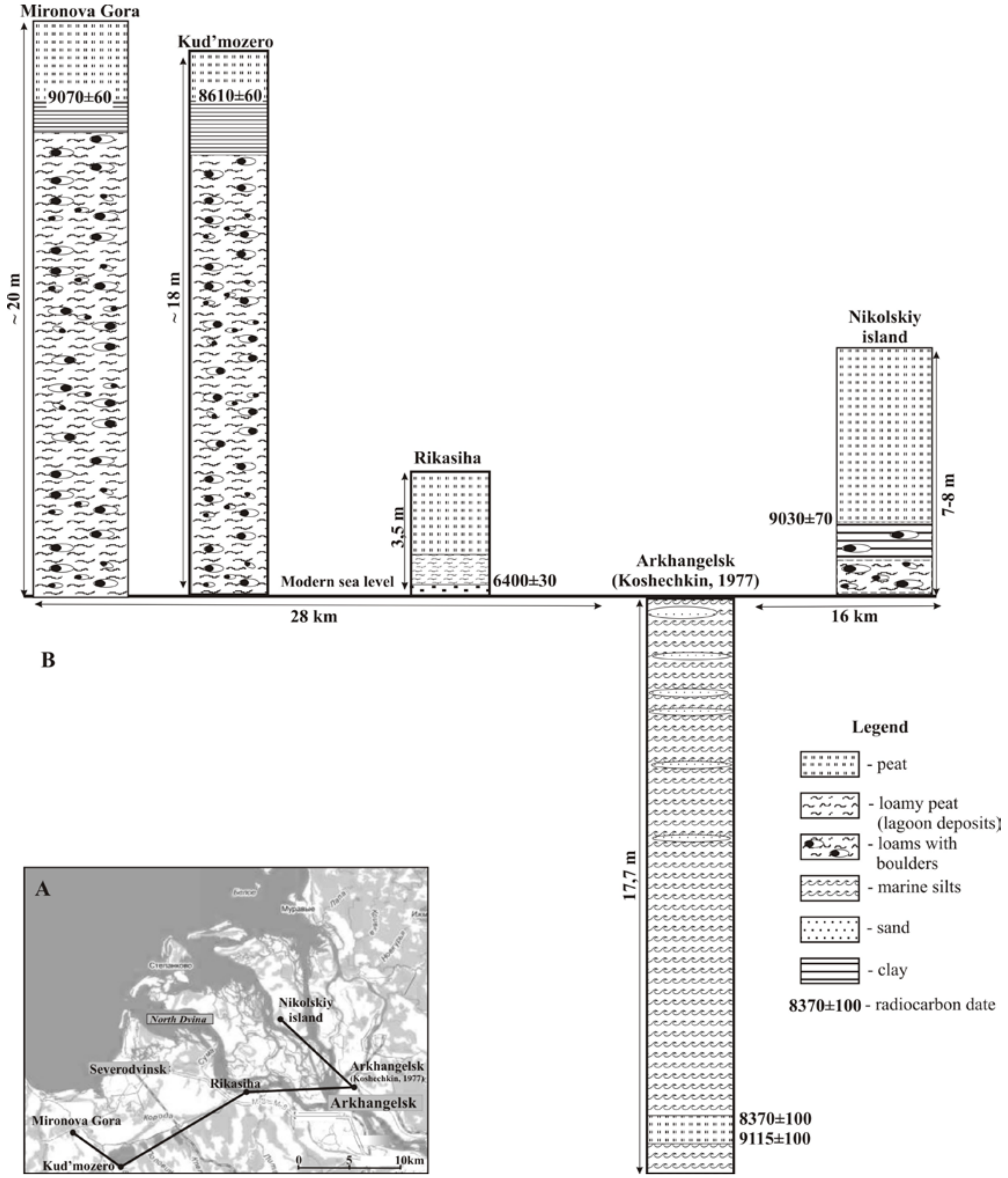

Fig. 4. *A site profile illustrating location of synchronous early Holocene dates at different depths and topographic levels: A - on the map; B - on the sections (with depths and distances).*

delta in the south, and the biggest beach ridge are the oldest Holocene landforms within the study area. Seawards there is a marine terrace (20-25 km long, 10-12 km wide and 5-8 m a.s.l.) composed of a series of younger sub-parallel beach ridges (**Fig. 2A**) alternating with narrow and shallow bogs. Prograding of this terrace into the White Sea occurred in the NW direction.

Deposits composing these landforms are of different origin and structure. Marine transgression sediments are represented by blue-gray solid wet clays and loams, sometimes with sand, sometimes with pebbles and boulders (when coastal erosion had been reworking moraine in the course of transgressions). They occur both inside and outside the delta, overlying moraines in former White Sea ingressive inlets, and underlying lagoon deposits within the ND river mouth. Lagoon deposits are represented by stinking grayish or brownish loams or gyttja with organic matter (remnants of *Phragmites* roots etc.), usually underlying mire sediments (**Fig. 5**). Mires and composing deposits (peat of various composition and preservation rate) are particularly widespread over the delta and adjacent areas. These are continuous vast and deep swamps overlying moraines and marine clays, or long, tight and shallow bogs between beach ridges, sometimes overlying lagoon deposits on the Liasomin and Uglomin islands, and directly lying on the marine sands on the terrace. Beach ridges and dunes which sometimes formed upon them are composed of fine to coarse beach sand.

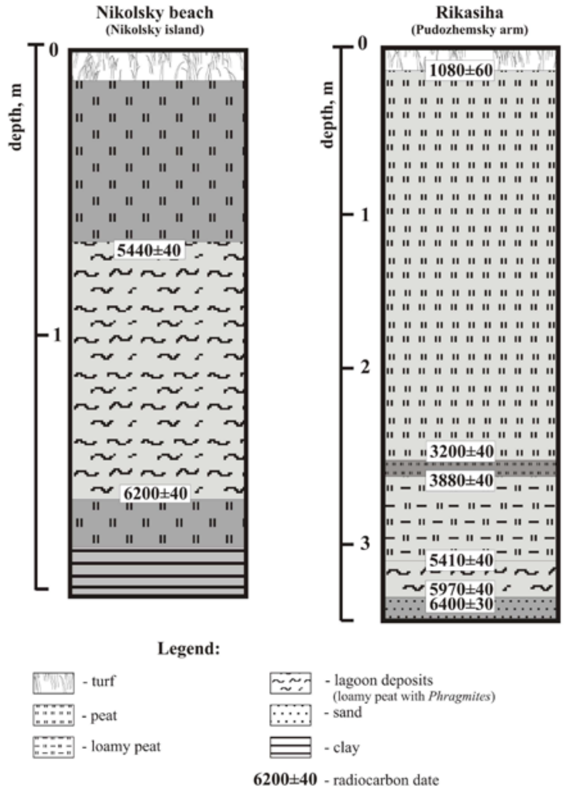

Fig. 5. *Examples illustrating the lagoon deposits (loamy peat with* Phragmites communis*) presence in the sections within the North Dvina delta.*

All these landforms are influenced by modern erosional processes, incised by plenty of rills, temporal streams and arms. The eastern part of the marine terrace was strongly modified by human activity in 1930s while construction of the Severodvinsk (Molotovsk) city and special channels for submarine exit from the docks.

Radiocarbon dates

To reconstruct a time record and sequences of processes forming the ND delta we used radiocarbon dates obtained on samples related to all types of analyzed landforms and deposits. All dates with sample composition and calibrated age ranges are presented in the **Table 1**. To work with such a huge radiocarbon data set, we used “Sum probability distribution” operation from OxCal 3.10 program (Bronk Ramsey, 1995; 2000; Reimer *et al.*, 2004); we consider that the obtained diagram can reflect the stages of the ND delta development, separating various chronological phases and periods. In the analysis, we did not include dates obtained from continuous core profiles because they do not reflect real stages of the whole area development (**Fig. 6B**).

Palynological data

Spore-pollen analysis of two peat cores (Rikasiha and Krugly moh) resulted in the reconstruction of consecutive transition of plant communities over the Holocene within the North Dvina delta (**Fig. 3**).

In the early Holocene (ca. 9000 ^{14}C BP, 8300-8200 cal BC), forest-tundra swampy landscapes predominated over this area, with relatively dry and cool climate.

At the end of Boreal period, sparse coniferous-birch forests and eutrophic bogs formed the landscapes, which is characteristic for the first postglacial transgression time in this area (Pleshivtseva, 1977).

At the beginning of the Atlantic period (ca. 7950 ^{14}C BP, 7000-6700 cal BC), forest landscapes expanded. Spruce-pine communities predominated, and they had been transforming into pine-spruce-birch complexes with rare broadleaf species and alder during the Holocene climatic optimum. In the late Atlantic optimum (ca. 5860 ^{14}C BP, 4800-4700 cal BC), a maximum of broadleaf pollen is fixed, which is well correlated with spore-pollen data from South Scandinavia (Bradshaw *et al.*, 2000), Kola Peninsula (Lebedeva, 1977; Kremenetsky *et al*, 1998), Pechora lowland (Bratuschak, 2005), Onega inlet shore (Koshechkin *et al.*, 1977) and North Dvina depression (Pleshivtseva, 1977; Baranovskaya *et al.*, 1977).

At the beginning of Subboreal (ca. 3200 ^{14}C BP, 1500-1400 cal BC), forest-tundra landscapes (sparse pine-spruce-birch forests with tundra communities) began to predominate. At ca. 3000 ^{14}C BP (1300-1200 cal BC)

Sphagnum peat bogs expanded over the area, adjacent areas and Kola Peninsula (Lebedeva, 1977; Kremenetsky *et al*, 1998; Velichko *et al*., 1994). In the late Subboreal (ca. 2200 ^{14}C BP, 400-200 cal BC), north taiga vegetation replaced forest-tundra landscapes. Peaks of *Sphagnum* bogs and *Ericaceae* occurred within the middle subboreal and in the second half of Subatlantic time.

At the beginning of the Subatlantic time, north-taiga spruce-pine forest communities began to predominate, with some broad-leaf species. At the second half of the Subatlantic, they transformed into pine-larch and pine-spruce forests alternating with tundra communities, and at the end of Subatlantic time – into pine forests.

5. DISCUSSION: RECONSTRUCTION

According to our data, we can distinguish three stages of the North Dvina river mouth development over the Holocene: 1) “estuary” stage (Late Glacial age – early Holocene), 2) “lagoon” stage (middle Holocene), and 3) “fan delta” stage (second half of the Holocene – till now). For more convenient presentation of our reconstruction, we used the Baltic Sea Holocene stages adapted to Barents and White Seas (Koshechkin, 1979; Kaplin and Selivanov, 1999) (**Fig. 6A**). In the following text, we mostly cite calibrated ages; for correlation of radiocarbon dates and calibrated ages please see **Table 1** and **Fig. 6**.

Estuary stage

Based on published data (Demidov *et al*., 2006; Pleshivtseva, 1977) and our field observations we suppose that the start of estuary stage took place during the deglaciation in Allerød. At that time, the North Dvina river mouth and adjacent areas represented a moraine flatplain; we did not find any evidence indicating the existence of an ice-dammed lake within this area 13-11 kyr BP (Demidov *et al*., 2006; Lavrov and Potapenko, 2005).

Late Glacial age

When the White Sea Gorge (Gorlo straight) became free of ice and the water exchange between Barents and White Seas established, the White Sea level became equal with the level of the World Ocean ca. 120 m below the modern shoreline (Koshechkin, 1979). Hence, the erosion base level of the North Dvina River was ca. 100-120 m lower than the modern one and glacioisostatic rise of Scandinavian shield started, so we suppose a huge and deep (even catastrophic) incision of the North Dvina into the moraines, and after the early Holocene White Sea transgression and regression – into the marine deposits. The depth of this incision could exceed 50 m (according to the difference in absolute heights between moraine surface and bottom of Holocene deposits in the core #2 (Koshechkin, 1979) in Arkhangelsk (**Fig. 4**).

Portlandia-Littorina transgression (Younger Dryas – Preboreal)

We have no dates for this period, and our conclusions are based on morphostratigraphy, lithological data and image analysis.

When the Portlandia transgression started ca. 11,000 ^{14}C BP (Kaplin and Selivanov, 1999; **Fig. 6A**), the primary glacial landscape of the North Dvina river mouth and adjacent areas got drowned. Ingression inlets formed along, and marine deposits (blue-gray clays) accumulated in moraine depressions, and the heights (uplands) had been smoothing: we usually found marine blue-gray clays underlying peat deposits when drilling bogs southwards of the modern ND delta (**Fig. 4B**), and there is evidence of marine clays and loams with special fauna under the buried peat in the Arkhangelsk core (Koshechkin, 1979). A huge estuary-type inlet existed at the place of the modern delta, with dissected shoreline and numerous islands.

Littorina regression (Boreal): 8470-7310 cal BC

For this period, we have radiocarbon dates, and spore-pollen and palaeobotanic data (**Table 1**; **Figs. 4B** and **6**).

Two radiocarbon dates have been earlier obtained on buried peat from the Arkhangelsk core (Koshechkin *et al*., 1977): 9115±100 (Tln-126, 8240-8470 cal BC) and 8370±170 (Tln-125, 7310-7550 cal BC) at the depth of 17.5 m. Other three dates: 9070±60 (GIN-14158, 8230-8320 cal BC) 9030±70 (GIN-14165, 8010-8040, 8090-8110, 8200-8310 cal BC), 8610±60 (GIN-14007, 7500-7710 cal BC) have been received for our samples originating from core bottoms in the mires westwards and southwards from the modern delta (Mironov mountain and Kud’mozero), and on the Nikolsky Island within it (**Table 1** and **Fig. 4A**). All the dated mires are located within the LGM moraine depressions – palaeoinlets of the Portlandia-Littorina Sea.

As it is well seen in the profile (**Fig. 4B**), the subsynchronous dates are located at different depths, and, consequently, at different levels relative to the modern sea level. We have the following explanation of this phenomenon: as it was considered above, before the first Holocene White Sea transgression, a deep North Dvina river incision took place. After the start of Portlandia transgression, this part of the river bed was being filled by marine deposits, and synchronously marine clays deposited within the ingression inlets. During the Littorina regressive stage, the North Dvina river was incising again, and we suppose that overgrowing oxbow lakes in abandoned palaeochannels could have formed within its valley, and on the moraines the palaeoinlets were synchronously overgrown by mires. These processes could be strengthened (or intensified) by tectonic processes: glacioisostatic rise of river flanks, and a “tool bend” along a line “Mironov Mountain – Kud’mozero – Nikolsky Island” (**Fig. 4B**).

After that, in the depressions of the hummocky moraines peat accumulation have been continuing on the marine clays and oxbow peat layer within the ND river valley had been buried by marine deposits during the further Folas and other transgressions.

Folas transgressive – regressive phase (Boreal/Atlantic): 7710-5745 cal BC

We have no chronological data for this period, only boundary dates 8610±60 BP (7710-7570 BC) and 6920±40 BP (5840-5745 BC) bracketing its lower and upper chronological limits (**Fig. 6**, **Table 1**).

Morphological data can tell us that during the transgressive period a palaeocliff had been forming in the moraines of Mironov Mountain and southwards the modern terrace, and on the Nikolskiy Island, while peat accumulation had been proceeding in the mires on their surfaces. We suppose that these cliffs could start forming during the Portlandia-Littorina phases, and during the Folas they almost reached their modern pattern.

Lagoon stage

Tapes-Trivia phase (middle – late Atlantic): 5745-2490 cal BC

This was a long (ca. 6900-4000 ^{14}C BP) period of higher water stand and/or weak oscillation of sea level.

Since ca. 6900 BP, between Rikasiha site and Nikolskiy Island (**Fig. 2A**), a series of shallow lagoons with saltish water existed within the area of the modern ND mouth. This is confirmed by dates and composition of deposits in appropriate sections (**Fig. 5**). Probably, a

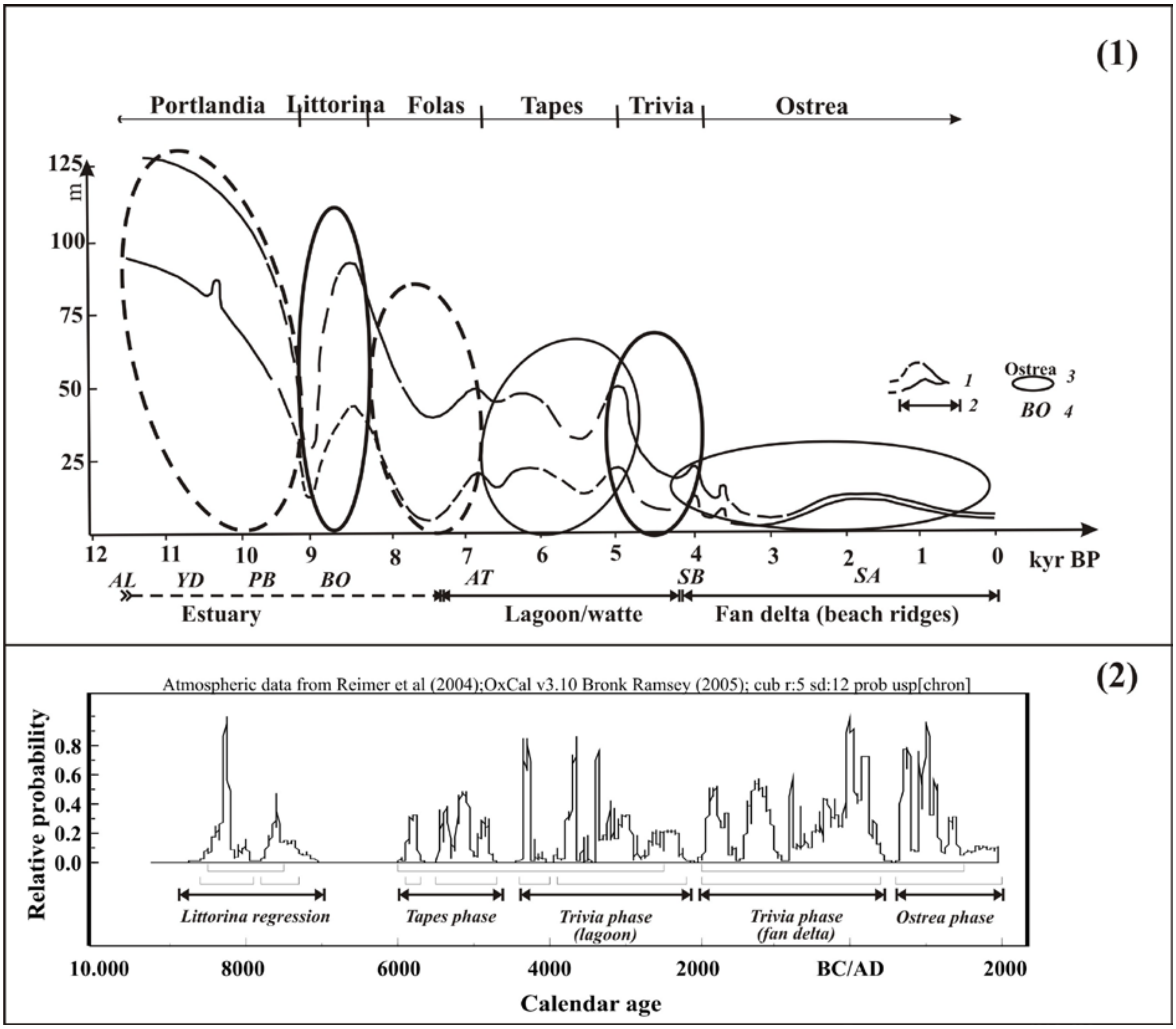

Fig. 6. *(1). Changes of the shoreline level of the Barents and White Seas (Kola peninsula) (after Koshechkin, 1979) during the Last Glacial and the Holocene; completed by N.E. Zaretskaya. 1 – the highest and the lowest positions of ancient shorelines; 2 – stages of ND mouth evolution; 3 – phases of ND mouth evolution; 4 – Holocene climatic phases. (2). Sum probability distribution of calibrated radiocarbon dates, correlated with stages and phases of the ND delta evolution.*

consequent series of subsynchronous lagoons, and then huge tidal marshes existed in this area, with sand bars or islands between them, and the main discharge of the North Dvina passed through the modern Korabelny arm (**Fig. 2A**). Actually, lagoons can "survive" within very limited environmental conditions concerning water depth and salinity and time of their development: the increase of water salinity can cause changes into marine conditions, and the decrease of water level – overgrowing and paludification. That is why the firs "stop" or interruption of lagoon development took place ca. 5400 BP (4330 cal BC), ending the Tapes stage (sedimentary record and dates, **Figs. 5**, **6B**), and the last and final – ca. 4000-3800 BP (2840-2290 cal BC) (Trivia stage), when the first beach ridge formed within the ND mouth and screened off the lagoons from the White sea.

Fan delta stage

Trivia-Ostrea phase (end of Atlantic – Subatlantic): 3780 cal BC – present time

Toward the beginning of Trivia phase (ca. 5000 ^{14}C BP) to the west from the modern ND mouth a vast open marine harbor formed, southerly bounded by Mironov Mountain cliff. This was a time of the ocean level rise stabilization and decrease of the glacioisostatic uplift rate (Koshechkin, 1979; Kaplin and Selivanov, 1999). Within the western part of the study area it manifested in formation of a fan delta (or advanced delta) composed of series of beach ridges (**Fig. 2A**).

Beach ridges are located in the western part of the modern delta and are characterized by different morphology, dimensions and direction, and generally had been forming since ca. 5000 BP till now. The oldest date was obtained within the Churka unit (**Fig. 2A**) on the bottom peat between the moraine scarp (palaeocliff) and the first beach ridge and is 4950±50 (GIN-14159, 3780-3660 cal BC) and seaward the bottom peat date behind it is 4570±30 (GIN-13381, 3370-3330 cal BC), bracketing its age within this short time span (3520-3370 cal BC). This oldest beach ridge is a huge accumulative sand body (width = 100 m, l = 3-4 km), and is strongly modified by human activity since middle Neolithic till now (**Fig. 2A**). A huge and long-term Neolithic settlement has been found on this sand body: our reconstructions show that the shoreline existed here quite a long time (3370-1770 cal BC) allowing ancient people to accustom to living at the sea shore, fishing and hunting marine mammals. Since 3530±40 BP (GIN-14014, 1930-1770 cal BC) further consecutive beach ridges have been forming, breaking off the possibilities of seaside occupation by ancient tribes.

Other beach ridges had been formed further later: the next one is dated back at 3530±40 BP (GIN-14014, 1930-1770 cal BC). That is, at the Churka site a time gap in beach ridge formation took place between 4570±30 (3370-3330 cal BC) and 3530±40 BP (1930-1770 cal BC), probably pointing out the Trivia-Ostrea stages transition (**Fig. 6**).

The next beach ridge series are related to Liasomin-Uglomin Island system which represented earlier a monolithic body. These are sandy sub-parallel ridges alternating with shallow lagoons while advancing into the White Sea (**Fig. 2A**), now overgrown by mires. The height of the ridges is increasing seawards, from older to younger ones. The youngest beach ridge is dated back at 1080±40 BP (GIN-14013, 890-1020 cal AD).

Later on, ca. 3530±40 BP (1930-1770 cal BC), beach ridges continued to form in the Churka site and westwards, and since then went synchronously with Liasomin-Uglomin system. Rates of seaward advance of Churka terrace were lower than those of island system (**Fig. 2B**), and heights and widths of Churka ridges decreased seawards: the most debris that was being discharged by North Dvina river into the White Sea first deposited further west, but later on, while the Liasomin-Uglomin Islands were growing, it was captured by this system.

The advance of the ND delta into the White Sea is still in progress due to the high rate of sediment discharge – 10.1 milion of tons per year (Sokolov, 1952), but its course has been changed by human influence.

6. CONCLUSIONS

1) During the Holocene, the North Dvina river mouth had been transforming from the huge and deep estuary through lagoons and tidal marshes into the lobe-shaped fan delta with many arms and islands.
2) Occurrence of buried organic sediments at the depth of 17.5 m and other facts which earlier were considered as evidence of the tectonic subsidence of the delta, could be explained by deep erosional cut in the early Holocene.
3) Estuary (erosional) stage of the ND river mouth development lasted from the early Holocene till ca. 5745 cal BC, and was interrupted by a short accumulation period (8470-7310 cal BC). This resulted in the development of ingression inlets, huge moraine scarp formation and "canyon-type" deep river bed incision.
4) Lagoon (tidal marsh) stage lasted from ca. 5745 till 2290 cal BC, and resulted in the start of modern delta framework formation and accumulation of tidal-marsh deposits. This stage had been interrupted by beach ridges formation which closed water interaction of lagoons with the White Sea basin.
5) Delta stage started about 3780 cal BC and continues until present times. It resulted in formation of a proper delta (fan delta) and the beach ridges sequence at its western side. On the first western beach ridge, a large Late Neolithic settlement of marine hunter-gatherers existed between ca. 3370 and 1770 cal BC.

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