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CRYOSTRATIGRAPHY OF THE FIRST TERRACE IN BELY ISLAND, KARA SEA: PERMAFROST AND CLIMATE HISTORY (Part 3)

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The distribution of lithological and permafrost facies deposited on the first terrace of Bely Island in the Kara Sea record alternated freezing and thawing cycles. The cryostratigraphy of the terrace, with constraints from data on the taxonomic diversity and habitats of microphytes found in the sediments, allows detailed reconstructions of the permafrost and deposition history associated with Late Pleistocene-Holocene climate and sea level changes.

Cryostratigraphy, lithology, cryofacies, microphyte, thermokarst, taberal deposits, sealevel, Kara Sea

INTRODUCTION

The deposition history of frozen coastal and shelf facies and formation of thermokarst in the context of latest Cenozoic sealevel changes in the Arctic Kara Sea area has been much less studied than in the East Arctic shelf. Freezing of shelf sediments in most of the Arctic seas during the Sartan glacial (cryochron) and the subsequent permafrost degradation were associated with climate and sealevel changes: regression during the cold event, with a 100–200 m lower stand than at present [*Grigoriev, 1987; Baulin et al., 2005*], and transgression in the warmer latest Sartan and Holocene time [*Zarkhidze and Musatov, 1989; Levitan et al., 2007*].

In the East Arctic areas, the transgression began about 15,000 years BP upon thermokarst topography. About 5000 years ago, the sealevel had reached its present position and the changing climate and neotectonic activity induced further thermal erosion and thermokarst effects [*Romanovsky et al., 2006; Gavrilov, 2008; Winterfeld et al., 2011*]. Thermokarst of that time formed by thawing of ground ice (a subaerial ice complex) while earlier karst sinkholes became flooded with seawater, marine sediments were deposited, and sediments in taliks became re-salinized [*Romanovsky et al., 1999; Kasymskaya, 2010*]. The Holocene environments of subaerial and marine shelf and beach deposition have been inferred from fossil microphytes (algae) [*Polyakova, 1997*] which record two transgression events ~4000 and ~1200–2000 years ago, when the sea stood 6–10 m and 4–6 m above the present level, respectively [*Bolshiyanov et al., 2013*].

In the West Arctic, however, the late Quaternary climate and sealevel correlations remain more controversial (Fig. 1) being interfered with a warming effect from the Atlantic water penetrated into the Barents-Kara region [*Polyakova, 1997*]. The part of the Kara shelf emerged by regression froze up during the Sartan glacial like in the eastern shelf, and the permafrost degradation began about 12,000 yr BP during transgression [*Kulikov and Martynov, 1961; Grigoriev, 1987; Biryukov and Sovershaev, 1998; Kozlov, 2006*]. The sea reached its present level between 7000 and 5000 yr BP, according to different estimates (Fig. 1), whereas the present shoreline, layda (vegetated saline coastal mud flat), and low terraces rising 1.0–1.5 m or 8–14 m above the present sealevel formed in the earliest Subatlantic period (2500 yr BP). The Holocene transgression of the Kara Sea gave rise to wave erosion of the sea floor, thermal erosion of the coast, and formation of thermokarst in the coastal plain [*Kozlov, 2005; Kamalov et al., 2006; Nikiforov et al., 2007; Badu, 2010*]. The sealevel in the Holocene was estimated to be 5–6 m higher than at present, from the deposition environments and wedge ice in Sibiryakov Island and western Taimyr [*Makarov and Bolshiyanov, 2011; Streletskaya et al., 2012*]. However, the role of thermokarst in the coastal and shelf deposition under transgression remains underexplored.

METHODS OF STUDY

In this study, we reconstruct the genesis and freezing-thawing history of sediments in the area by

This publication continues two previous publications: Slagoda et al., 2013. Cryolithologic structure of the first terrace at Bely Island, Kara Sea. Part 1. *Kriosfera Zemli* XVII (4), 11–21; Slagoda et al., 2014. Cryolithologic structure of the first terrace: microstructure and evidence of cryolithogenesis, Bely Island, Kara Sea. Part 2. *Kriosfera Zemli* XVIII (1), 12–22.

analysis of cryostratigraphy based on microscopic and macroscopic signatures of cryogenesis in rocks and on microphyte data, with a focus on thermokarst effects. Cryostratigraphic changes can result either from global climate and sealevel events or from local processes. Syngenetic freezing of sediments produces different permafrost facies (cryofacies) [*Katasonov, 2009; Popov, 2013*] and changes the composition, structure, and texture of sediments on the macro- and micro-scales [*Konishchev, 1981; Katasonov, 2009; Rogov, 2009*]. Thermokarst erosion implies thawing of ice-rich soil beneath rivers and lakes followed by re-freezing of lacustrine and fluvial sediments and taliks [*Katasonov, 1979; Romanovsky, 1993; Kaplina, 2011a,b*]. Thawing of soil with ice wedges leaves imprints as casts, post-cryogenic textures, cryoturbation, or involution. The soil thaws and subsides *in situ* underneath lakes or rivers and freezes back to form the so-called taberal (thawed and refrozen) deposits. These deposits have low contents of ice as lenses aligned with the freezing fronts of taliks [*Katasonov, 1979; Ivanov, 1984; Romanovsky, 1993; Melnikov and Spesivtsev, 2000*] and bear post-cryogenic macro- and micro-structure signatures [*Zigert and Slagoda, 1990; Slagoda, 2005*].

The reported data were collected in the course of the international project *Greening of the Arctic: Climate Change and Circumpolar Arctic Vegetation* [*Leibman et al., 2011; Walker et al., 2011*].

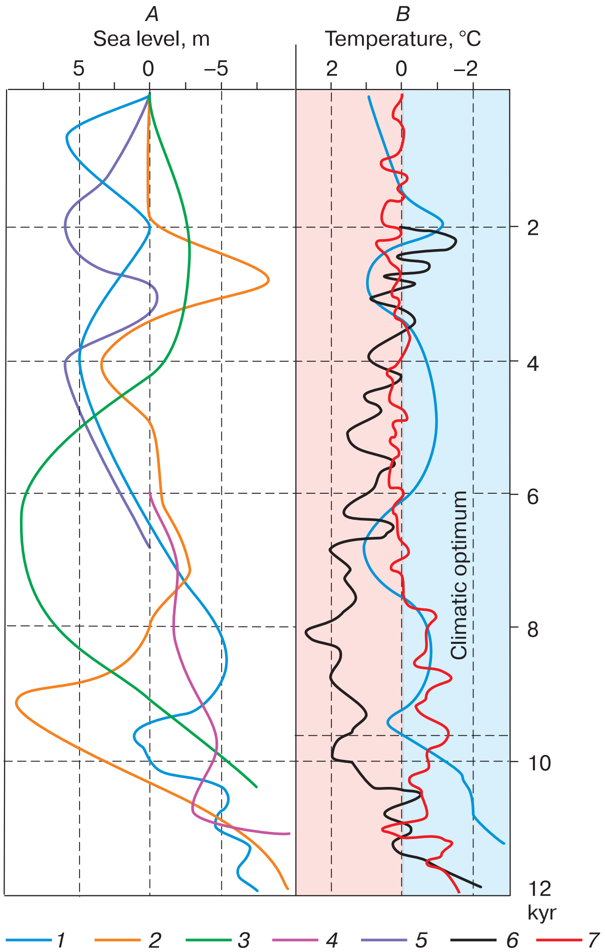

Fig. 1. Holocene sealevel (*A*) and air temperature (*B*) variations in the West Arctic, according to [*Levitan et al., 2000, 2007*] (*1*); [*Kaplin and Selivanov, 1999*] (*2*); [*Svitoch, 2003*] (*3*); [*Biryukov and Sovershaev, 1998*] (*4*); [*Bolshiyanov, 2006*] (*5*); [*Kind, 1976; Shpolyanskaya, 2008*] (*6*); [*Davis et al., 2003*] (*7*).

STUDY AREA AND RESULTS

Bely Island located north of the Yamal Peninsula in the Kara Sea (Fig. 2) is a terraced coastal plain rising in steps from the beach and layda level at 0–3 m a.s.l. to terraces I (3–7 m a.s.l.) and II (6–12 m a.s.l.) composed of Holocene and Late Pleistocene deposits [*Ershov, 1991*].

Comprehensive studies of core samples from four 3 to 10 m deep boreholes drilled in 2010 in the northwestern part of the island reveal several lithological and permafrost facies. The cryostratigraphy was reconstructed with reference to (i) taxonomy and habitats of diatoms, silicoflagellates, and stomatocysts of chrysophyte algae, (ii) signatures of freezing and thawing, including cryogenic and post-cryogenic structure, salinity, and composition of dissolved salts,

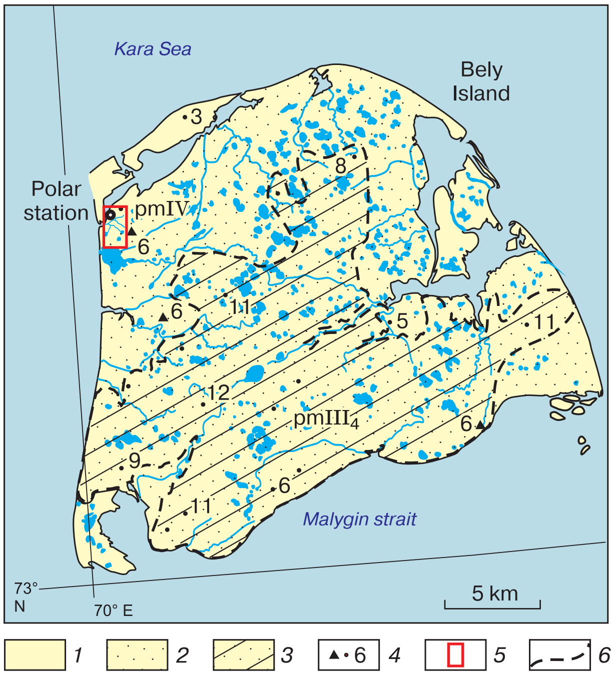

Fig. 2. Study area: location map and geomorphology of Bely Island.

Symbols stand for: beach and layda (*1*), terrace I (*2*), terrace II, according to [*Ershov, 1991*] and satellite image (©Google, 2010; Image©TerraMetrics, 2011) (*3*), elevations above sea level (*4*), borehole site (*5*), inferred limits of terrace II (*6*).

as well as (iii) grain size, texture, and mineralogy of sediments.

Microphytes (algae) were found in clay-rich samples from the lower unit of the terrace section (4.5–10 m core depths) and in sands from the upper unit (boreholes OB1, OB2 at 1.0–4.9 m; OB3, OB4 at 1.0–3.5 m).

Silicoflagellates have been identified in ten out of seventeen samples and include marine *Chrysophyta* (Fig. 3) that commonly live in saline water above 20 pt [*Tsoi, 2011*]. Silicoflagellates are sensitive to temperature change and are especially abundant in littoral, estuary, or lagoonal eutrophic waters rich in nutrients. Other taxa are *Naviculopsis constricta* (Fig. 3, *a*, OB3, h = 2.87 m) tolerable to relatively cold water and warm-water *Corbisema triacantha* (Erenberg) Hanna and *Dictyocha* cf. *medusa* Haeckel (Fig. 3, *b*, OB2, h = 4.6 m), dominant in the sandy base of the upper unit.

Chrysophyte stomatocysts (7 morphological types) are plankton forms common to cold oligotrophic environments [*Duff et al., 1995; Pla, 1999; Voloshko, 2012*]. Sporadic stomatocysts coexist with silicoflagellates mainly at the terrace base. They are more diverse in clay at OB4 (h = 7.06 m) where abundant Stomatocysts 1 occur together with Stomatocysts 31. The former belong to *Paraphysomonas* chrysophytes (epiphytes) or aerophilic species tolerant to cold water, which live in humid air or wetting conditions of Arctic bogs, lakes, and littoral, most often in alkaline environments. Stomatocysts 31 Duff & Smol (Fig. 3, *i*) are typically planktonic species of *Uroglena* (Fig. 3, *e*, *k*) [*Duff et al., 1995; Pla, 1999*].

Diatoms are of 43 species and subspecies [*Skabichevskaya, 1984; Proshkina-Lavrenko et al., 1988; Loseva, 2000; Makarova, 2002; Genkal and Vekhov, 2007; Genkal and Trifonova, 2009; Kharitonov and Genkal, 2012*]. Marine species are most abundant, especially *Aulacoseira distans*, *A. islandica*, *A. granulata, Chaetoceros* sp., *Stephanodiscus minutulus, Paralia sulcata, Paralia crenulata, Pyxidicula arctica, Thalossiosira* sp. (Fig. 4).

According to the ecological and geographic analysis of the identified diatoms, they are cosmopolitan (7), boreal (5), or arctic-alpine (3) taxa. In terms of habitats, they are planktonic (7), plankton-benthic (7), and benthic (8) taxa. On the basis of pH sensitivity, four taxa are alkaliphilic that live at pH = 7 or more, five acidophilic taxa (pH < 7), and 4 indifferent species. Most taxa (9) are indifferent to salinity, two taxa represent freshwater environments, one taxon prefers saline water, and one lives in water of medium salinity. The saprobity of diatoms (sensitivity to dissolved organic matter) is highly variable [*Krammer and Lange-Bertalot, 1986; Likhoshway, 1996; Round, 1999; Krammer, 2002; Edgar et al., 2004; Lange-Bertalot et al., 2011; Tanaka and Nagumo, 2012*].

The identified microalgae, sea urchin spines, and mosses are well preserved and cannot be redeposited. Stomatocysts of aerophilic microalgae bear a record of habitats with frequently changing wetting/drying and freezing/thawing conditions. Relatively thermophilic species of silicoflagellates found at the base of sands in the upper unit indicate deposition at normal seawater salinity.

The taxonomic composition and preservation of the microphytes provide explicit evidence of shelf environments.

The division into ***lithological facies*** is according to high- or low-energy deposition environments, with reference to the composition, salinity, structure and texture of sediments and to the habitats of mycrophytes [*Slagoda et al., 2014*]. All sediments are laminated and belong to three main facies: (1) clays deposited in low-energy shoal and lagoonal conditions, with closely spaced subaerial erosion levels; (2) sands deposited in high-energy conditions of beach and submarine sand bars; (3) peat-rich sand and silt deposited in high-energy conditions of high and low laydas.

Permafrost facies (cryofacies) have been distinguished according to cryogenic and post-cryogenic microscopic and macroscopic sedimentary structures and textures [*Slagoda et al., 2013, 2014*]. They are (1) syngenetic permafrost with freezing-thawing cycles formed during beach and layda deposition; (2) taberal (thawed and refrozen) deposits with post-cryogenic signatures of beach and layda sediments coexisting with cryogenic features produced by refreezing of more or less saline (diluted or re-salinized) sediments confined in taliks underneath shallow brackish lakes and streams; (3) epigenetic permafrost composed of syngenetically frozen lagoonal deposits, which thawed and subsided *in situ*, became unevenly diluted and fully salinized, and then epigenetically froze back from above.

The lithological and permafrost facies in Bely Island make different combinations in borehole sections. Their lateral (geographic) and vertical (stratigraphic) distribution is shown in the map of Fig. 5 and in the cross section of Fig. 6. The lower unit of taberal deposits and epigenetic permafrost composed mainly of evenly salinized clays (Fig. 6, *A*, *B*, V) is spread throughout the island and makes the base of marine terrace I around outliers of terrace II (Fig. 2). The eroded top of the terrace base (lower unit of taberal deposits) lies at the depth 3.2–5.0 m below the surface and is deformed by heaves with contorted vertical wavy bedding over ice wedge casts and small sand injections into the overlying sediments (Fig. 7). Similar heaves, with numerous small lenses and large wedges of ice typically occur at the base of the low terrace at Sibiryakov Island [*Slagoda et al., 2010*].

The sandy upper unit of terrace I is differentiated according to the contents and compositions of dissolved salts and permafrost facies deposited on different landforms (Fig. 5; Fig. 6, *A*, *B*, I–IV).

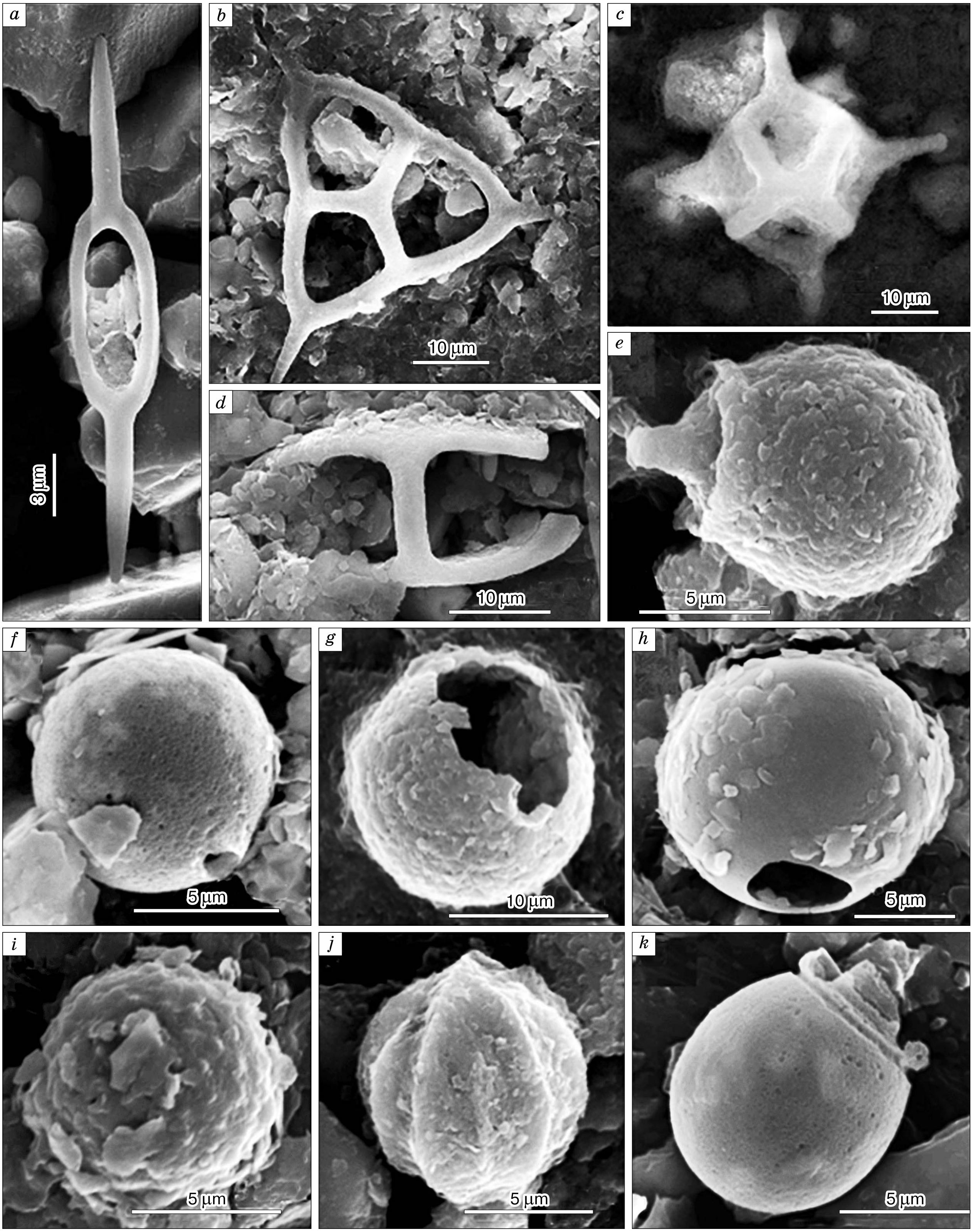

Fig. 3. Silicoflagellates (*a–d*) and chrysophyte stomatocysts (*e–k*).

a: Naviculopsis constricta; *b: Corbisema triacantha*; *c: Dictyocha* cf. *medusa*; *d: Naviculopsis eobiapiculata*.

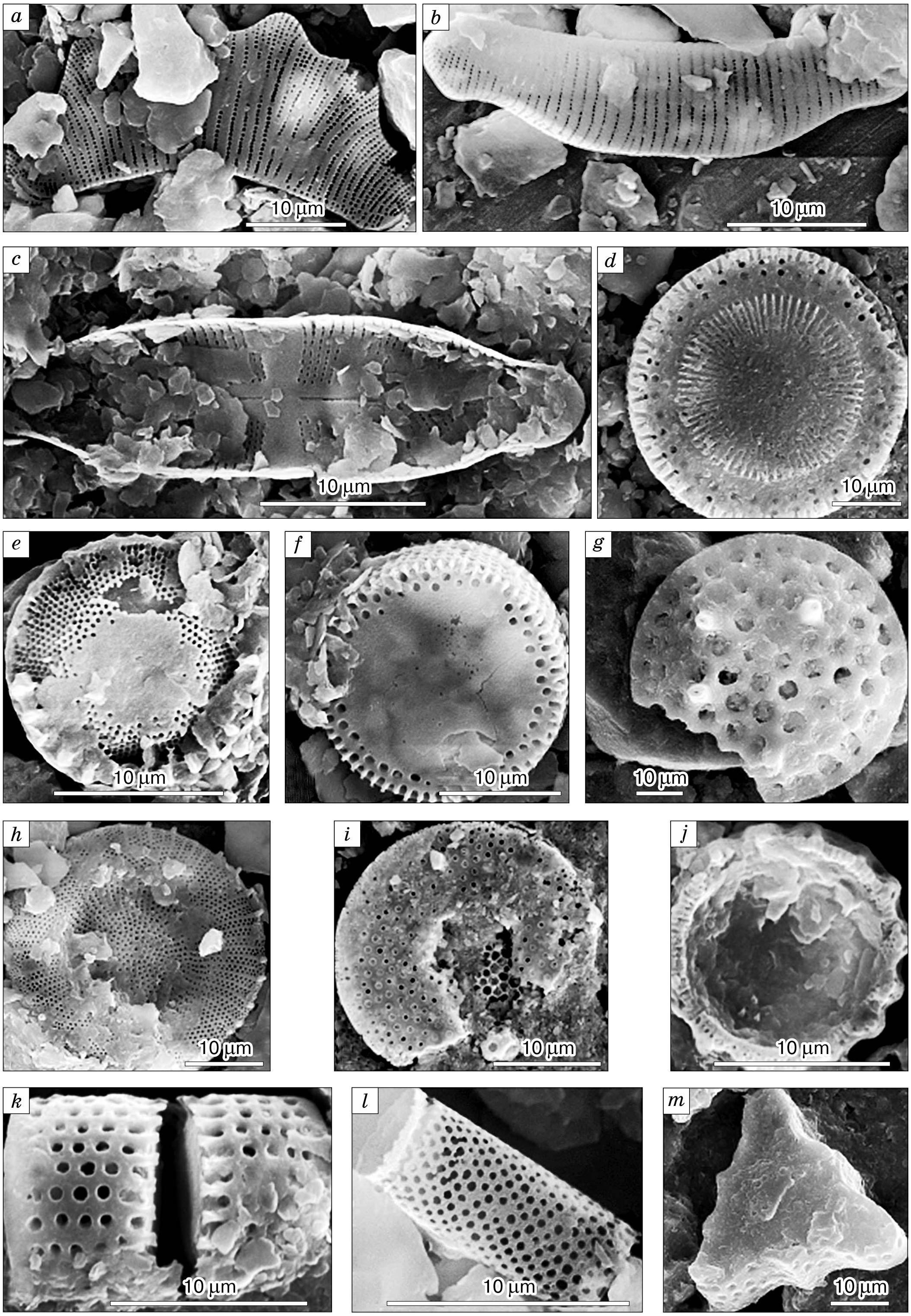

Fig. 4. Diatoms.

a: Eunotia tetraodon; *b: Eunotia ernestii*; *c: Stauroneis phoenicenteron*; *d: Paralia sulcata*; *e: Stephanodiscus* sp.; *f: Aulacoseira distans*; *g: Pyxidicula arctica*; *h: Stephanodiscus minutulus*; *i: Stephanodiscus* aff. *Khurseviczae*; *j: Paralia crenulata*; *k: Aulacoseira islandica*; *l: Aulacoseira granulata*; *m: Sheshukovia* sp.

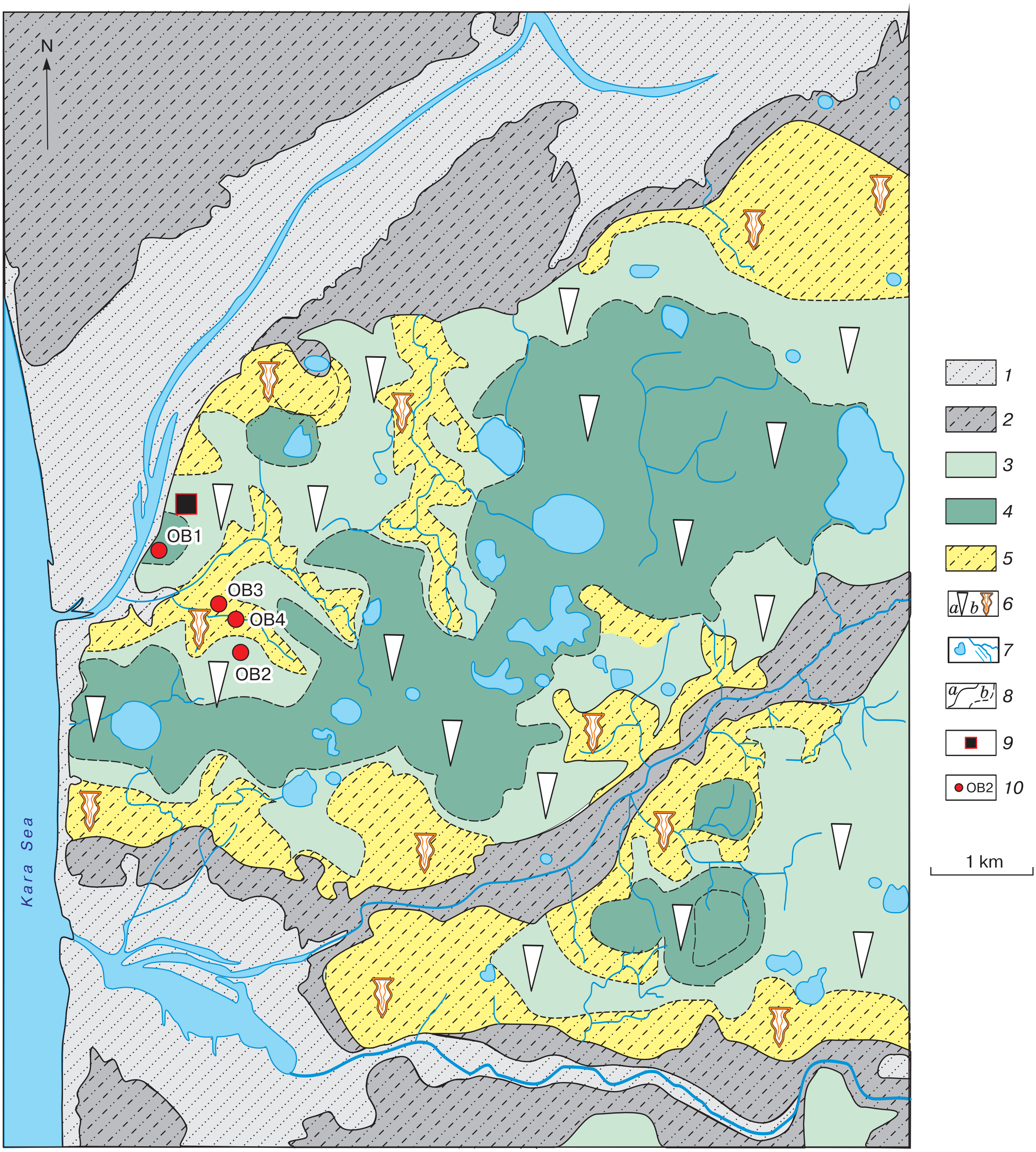

Fig. 5. Surface topography of test site.

1 – sand spit, beach, flood delta; *2* – layda, bottom of stream valley; *3–6* – terrace I: elevated parts (*3*), swampy lows (*4*), drained lows (*5*), polygons (*6*): ice wedges (*a*), ice wedge casts (*b*); *7* – drainage network; *8* – observed (*a*) and inferred (*b*) boundaries; *9* – weather station; *10* – borehole number.

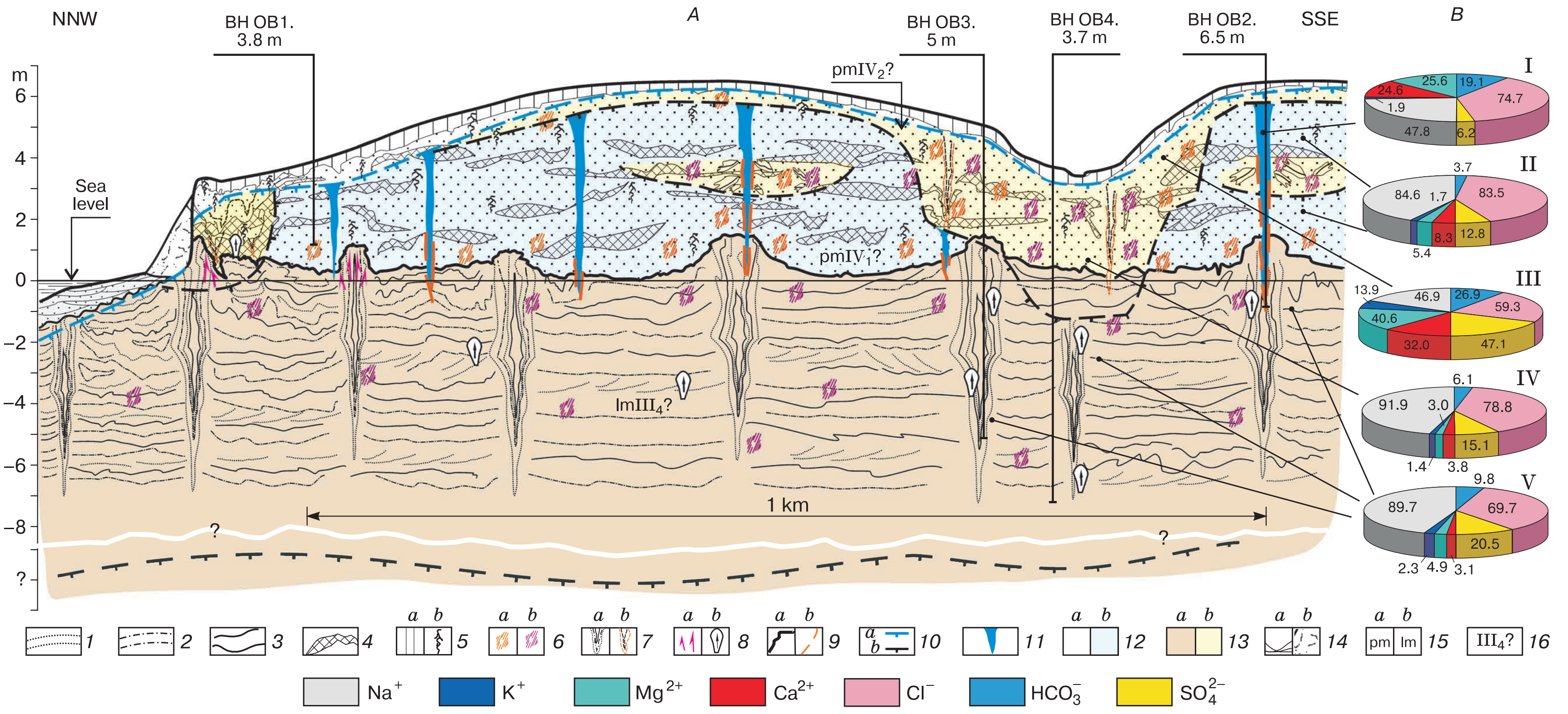

Fig. 6. Cryostratigraphy (*A*) and composition of dissolved salts (*B*).

A: *1* – sand, *2* – silty sand and silt; *3* – clay silt (loam) and clay; *4* – peat and plant detritus; *5* – top soil (*a*) and *in situ* rootlets (*b*); *6* – ochre (*a*) and grayish-black (*b*) iron stains and bands; *7* – ice wedge casts in terrace base (*a*) and in upper unit (*b*); *8* – slip planes (*a*) and sand injections (*b*) identified in sections and thin sections; *9* – lithological (*a*) and iron-stained (*b*) observed and inferred boundaries; *10* – present (*a*) and relict (*b*) permafrost boundary; *11* – wedge ice; *12, 13* – types of permafrost and related deposits: seasonally thaw (*a*) and syngenetic (*b*) permafrost (*12*), epigenetic (*a*) and syngenetic (*b*) taberal deposits; *14* – present beach sediments (*a*) and talus (*b*); *15* – coastal and shelf facies deposited in high-energy environments in the beach and layda (*a*) and shoal and lagoonal facies deposited in low-energy environments (*b*); *16* – inferred age of sediments. *B*: Chemistry diagrams (% equ.): I – wedge ice, II to V – different permafrost facies: syngenetic permafrost (II), fresh taberal deposits (III), re-salinized taberal deposits (IV), epigenetic permafrost in taberal deposits (V). Numbers at boreholes (BH) are asl elevations of their heads.

Syngenetically frozen shelf facies with NaCl salinity and ice wedges enclose thin layers of saline taberal deposits. The latter are ubiquitous upon the terrace base and are preserved intact on less deformed elevated parts of terrace I beneath transitional (active layer) deposits [*Shur, 1988*]. The presence of taberal deposits among syngenetic permafrost records shallow closed taliks that formed beneath ephemeral salt lakes during the terrace deposition [*Vasilchuk, 2006, 2012; Kaplina, 2011b*].

Taberal deposits have been found within drained lowlands in the upper unit of the terrace. They are uneven in terms of salinity: less saline low-ice sands beneath low slopes with remnant patterned ground and re-salinized ice-rich sediments beneath the bottom of thermokarst depressions (Fig. 6, *B*, III, IV). To produce such a structure, syngenetic permafrost must have thawed under thermokarst, the sediments subsided *in situ*, with formation of ice wedge casts, then underwent erosion on slopes and salinization in deeper closed taliks, and finally froze back on all sides.

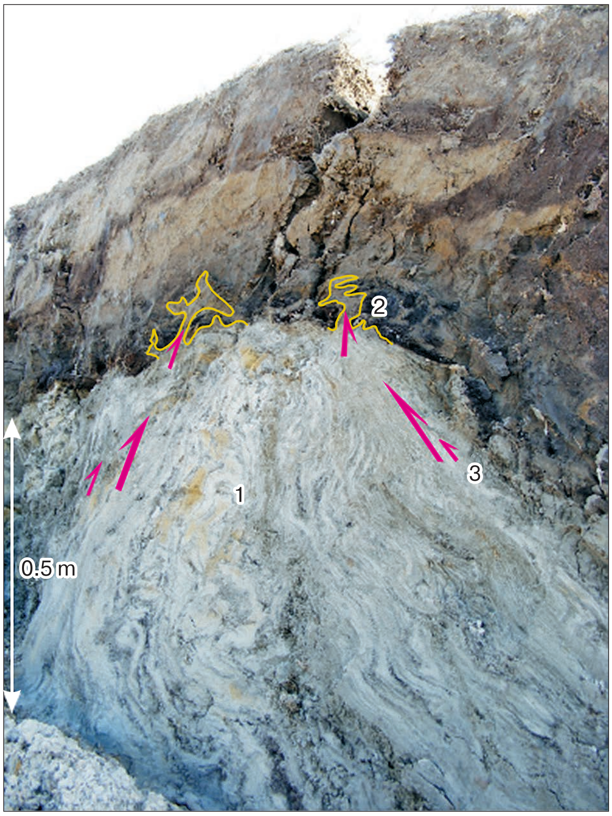

Fig. 7. Surface deformation of clay sediments (see Fig. 6 for cryostratigraphy). Photograph by M.O. Leibman.

1 – heave with vertical wavy bedding; 2 – small sand and silt injections in eroded heave top; 3 – heaving direction.

DISCUSSION

The cryostratigraphy of marine terrace I in Bely Island stores a record of freezing-thawing cycles that correlate with sealevel and climate change in the West Arctic. The Early Holocene age of the terrace was constrained by a radiocarbon date of peat from the terrace top lying over sand with wedge ice (^{14}C age of 8500 ± 120 yr BP, LU-115) and by spore-pollen spectra [*Vasilchuk and Trofimov, 1984*]. Thus, the sediments of terrace I record the history of syngenetic and epigenetic permafrost and taberal deposition and more or less extensive themokarst in the latest Sartan glacial and in the Holocene.

The deposition history of the frozen shallow sediments at Bely Island was as follows.

A. Prior to transgression in Sartan time, Bely Island was part of the Yamal Peninsula (Fig. 8, *A*), with marine terrace II composed of Upper Pleistocene ice-rich sediments enclosing ice wedges [*Ershov, 1989, 1991*]. Satellite imagery shows features of patterned ground, numerous thermokarst lakes, drained depressions, and gullies produced by thermal erosion. Remnants of terrace II remain preserved at the base of terrace I and apparently belong to deposits of shallow brackish lagoons and a large littoral zone, judging by the taxonomy of microphytes, clayey lithology, and primary sediment structures. They froze syngenetically, apparently, during the Sartan cold event, in a coastal and shelf environment, with formation of ice wedges. This inference is consistent with the presence of post-cryogenic features in the taberal deposits of the lower unit of terrace I.

B. Taberal deposits at the base of terrace I were produced by erosion of subaerial sediments and thawing of the terrace II material. Thawing can be inferred from post-cryogenic primary structure elements in rocks and from deformation associated with ice wedge casts. Transgression caused flooding of thermokarst depressions in terrace II and in the coastal plain of the Laptev Sea [*Romanovsky et al., 1999*], as well as flooding of unfrozen saline taberal deposits preserved from erosion and frozen saline deposits with wedge ice. Salinization of permafrost favored rapid progress of thermokarst formation in the seafloor and thermal erosion of the coast. Transgression, which induced erosion of terrace II, had reached Bely Island in the end of the Sartan glacial event and separated it from the Yamal Peninsula. The Kara Sea stood at least 5–6 m kigher than the present level (Fig. 8, *B*); after flooding, the seafloor became covered with sand containing microphytes that typically live in seawater of normal salinity, including relatively thermophilic species.

C. While being deposited on shallow shelf, the sediments of terrace I began freezing up syngenetically as the sea level fell during the Early Holocene regression (Fig. 8, *C*). Shoal deposition involved mainly sand with microphytes typical of saline and

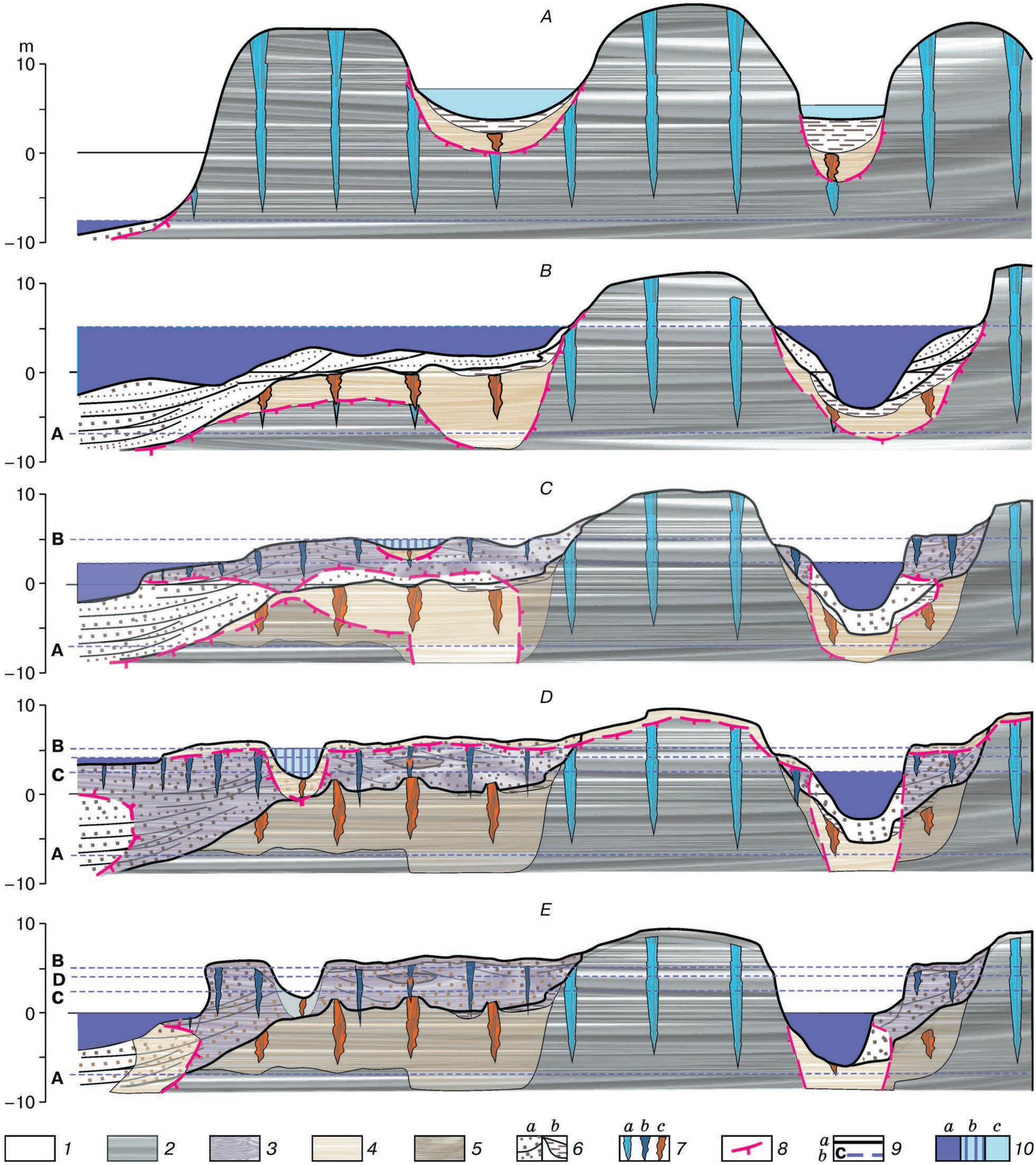

Fig. 8. History of deposition, thawing, and freezing of the Bely Island coastal plain.

A through *E* are different stages (see text for explanation). *1* – unfrozen sediments; *2* – Sartan syngenetic permafrost; *3* – Holocene syngenetic permafrost; *4* – unfrozen taberal deposits; *5* – re-frozen taberal deposits and syngenetic permafrost; *6* – layered sand and silt (*a*) and layers of lacustrine clay silt (*b*); *7* – wedge ice: in Sartan deposits of terrace II (*a*), in Holocene deposits of terrace I (*b*), and ice wedge casts (*c*); *8* – permafrost top; *9* – present (*a*) and past (*b*) sealevel (letters correspond to stages **A–E**); *10* – marine (*a*), diluted (*b*), and limnic (*c*) water.

weakly diluted water habitats. Syngenetic permafrost became cut with ice wedges. Deposition of syngenetically frozen sediments continued on the low layda while the underlying sediments of the terrace base froze up epigenetically. At the same time, the lithologically heterogeneous saline soft sediments at the terrace base experienced viscoplastic deformation [*Khimenkov and Brushkov, 2003; Khimenkov and Vlasov, 2007*], including frost heaving of vertical-layered ice wedge casts with higher water contents (Fig. 8). The epigenetically frozen rocks of the terrace base were injected by ice wedges from the overlying syngenetic permafrost. The sediments and ice thawed to 1 m beneath ephemeral salt lakes on the layda. After the lakes dried out, the taliks froze back and syngenetic permafrost deposition continued, as well as the growth of ice wedges.

D. In the second half of the Holocene, thermokarst was mainly restricted to depressions in terrace I which were connected to the sea (Fig. 5; Fig. 8, *D*): erosion gullies, shallow valleys in the lower reaches of forward and inverted streams, karst sinkholes and lakes. Thawing of Lower Holocene deposits and ice wedges and formation of shallow (2–5 m) taliks indicate that rivers and lakes had longer lifespans than during the previous stage. They were associated with ingression which apparently provided head pressure for meltwater runoff and maintained high stand at 4.5 m above the present sealevel. A remnant transitional active layer of low salinity formed in relatively elevated parts of terrace I [*French and Shur, 2010*]. Its deposition correlates with warming 3300–2400 years ago [*Levitan et al., 2000*] and ingression into topographic lows of islands in the eastern Kara Sea [*Opokina et al., 2014*].

E. The present state of terrace I, including the division of sediments according to salinity and cryostratigraphy, results from several successive events. First, it was a sealevel fall to the present stand, as well as water level fall in rivers and lakes, and draining of unfrozen deposits on slopes and watersheds. Later half-closed taliks froze back beneath the dried depressions: first low-saline taberal deposits under topographic highs and then re-salinized deposits under the lows. Formation of polygonal ice-wedge systems in negative landforms never resumed afterward.

CONCLUSIONS

The cryostratigraphy of terrace I in Bely Island, with syngenetic and epigenetic permafrost facies and taberal deposits bearing signature of thermokarst, records the succession of latest Pleistocene-Holocene deposition, sealevel, and climate events.

Transgression in the latest Pleistocene gave rise to erosion of syngenetic permafrost in terrace II and flooding of its thermokarst depressions filled with taberal deposits and remnant ice wedges. The transgression likely reached its position near the Bely Island shoreline before 10,500 yr BP when the sealevel rose 5–6 m above the present stand.

In the first half of the Holocene, the deposition of terrace I occurred in a relatively low-stand environment, judging by syngenetically frozen shoal and beach sediments and growth of ice wedges. The syngenetic permafrost deposits thawed to shallow depth beneath ephemeral salt lakes that arose during the low layda deposition, and then froze back after the lakes dried out, while ice wedges continued to grow.

In the second half of the Holocene, the active layer on elevated parts of terrace I became thicker as the climate grew warmer. Syngenetic permafrost thawed in topographic lows under the effect of thermokarst, this being evidence of sea ingression.

Terrace I achieved its present permafrost setting after the end of ingression during relative cooling, as the taberal deposits in dried depressions froze back and the active layer thickness reduced.

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