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## *CRYOGENIC PROCESSES AND FORMATIONS*

# CLIMATIC AND GEOCRYOLOGICAL CONDITIONS OF FORMATION OF MASSIVE LAYERS OF ULTRA-FRESH ICE, YAMAL PENINSULA

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The conditions of formation of massive layers of ultra-fresh ice inside the marine saline sediment strata have been studied by geocryologists for several decades. Numerous hypotheses provided different interpretations of their origin and formation mechanisms. Based on the analysis of works of his predecessors, the author has depicted the natural conditions ensuring formation of massive layers of ultra-fresh ice and substantiated possibility of massive ice layers formation under specific climatic and permafrost conditions of different periods during the Middle and Late Neopleistocene.

*Ultra-fresh massive ice layer, climatic and geocryological conditions, Middle and Late Neopleistocene*

## INTRODUCTION

Massive ice layers in the marine sediments of the Yamal Peninsula have been studied for over 40 years. Analysis of their distribution in different areas of the peninsula showed that repeated-intrusive massive ice layers (RIMIL) with thickness up to 20–40 m and spatial extent up to 2–3 km, and volumetric ice content reaching locally 4–5 mln $m^3$ of ultra-fresh ice, were formed in the sediments of the Salekhard ($\mathrm{PS}_{\mathrm{II}}^{2-4}$), Kazantsevo ($\mathrm{PS}_{\mathrm{III}}^{1}$) and Zyryanka-Karginsky ($\mathrm{PS}_{\mathrm{III}}^{3-4}$) marine plains[1], i.e. during the time span of the last 400 thousand years (ka) [*Dubikov and Koreysha, 1964; Baulin et al., 1967; Baulin and Dubikov, 1970; Badu et al., 1982; Dubikov, 1982; Koreysha et al., 1982; Parmuzin and Sukhodolskii, 1982; Baulin, 1985; Dubikov, 2002; Streletskay and Leibman, 2002; Kritsuk, 2010; Vasil'chuk, 2010; Vasil'chuk et al., 2015*].

While studying massive ice layers in different parts of the Yamal Peninsula, researchers have long paid attention to two remarkable characteristics of the deposits of all the marine plains of different ages. *The first peculiarity* is implied by the massive ice layers emplacement along the interface of contact zone between two sediment units of different facies (lithological composition)[2]. By this boundary, the transgressive and regressive cycles of sediment deposition on the seafloor are differentiated.

*The second peculiarity* consists in the fact that subhorizontal layers of massive ultra-fresh ice of calcium bicarbonate (sodium) chemical composition, are over- and underlain by the saline marine sediments with chloride type of structure-forming ice. For over than 40 years researchers have been attempting to unravel these riddles. Many of the hypotheses were suggested, and all the matters lying at the heart of the discussions have been carefully considered by the author [*Fotiev, 2012, 2014, 2015*]. As it turns out, geocryologists have still been in the toils of the view of the marine origin of water that formed massive ice layer, whereas both salinity and ion-salt composition of ice clearly indicate the continental origin of the "parent" water, nourishing the layer of massive ice [*Fotiev, 2003, 2012, 2015*].

It is evident that paleoclimatic and paleogeocryological conditions of the Middle and Late Neopleistocene of Western Siberia have been understudied this far, and massive ice layers investigated in detail only on very few sites (Fig. 1). Relying on works of his predecessors, the author has attempted to highlight the specific combinations of natural conditions controlling the formation of massive ice layers and to compare formation conditions for RIMIL evolved in sediments of the variously aged marine plains on the Yamal Peninsula.

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[1] Significantly less frequently, massive ice layers are found in the deposits of the 1st Marine Terrace (1st MT) and 2nd Marine Terrace (2nd MT) [*Vasil'chuk et al., 2015*]; however, they differ both in origin and morphology from RIMIL occurring in the sediments of the marine plains.

[2] It has been established that in 80 % of cases, RIMIL occur on the sand unit and are overlain by clays [*Dubikov, 2002*].

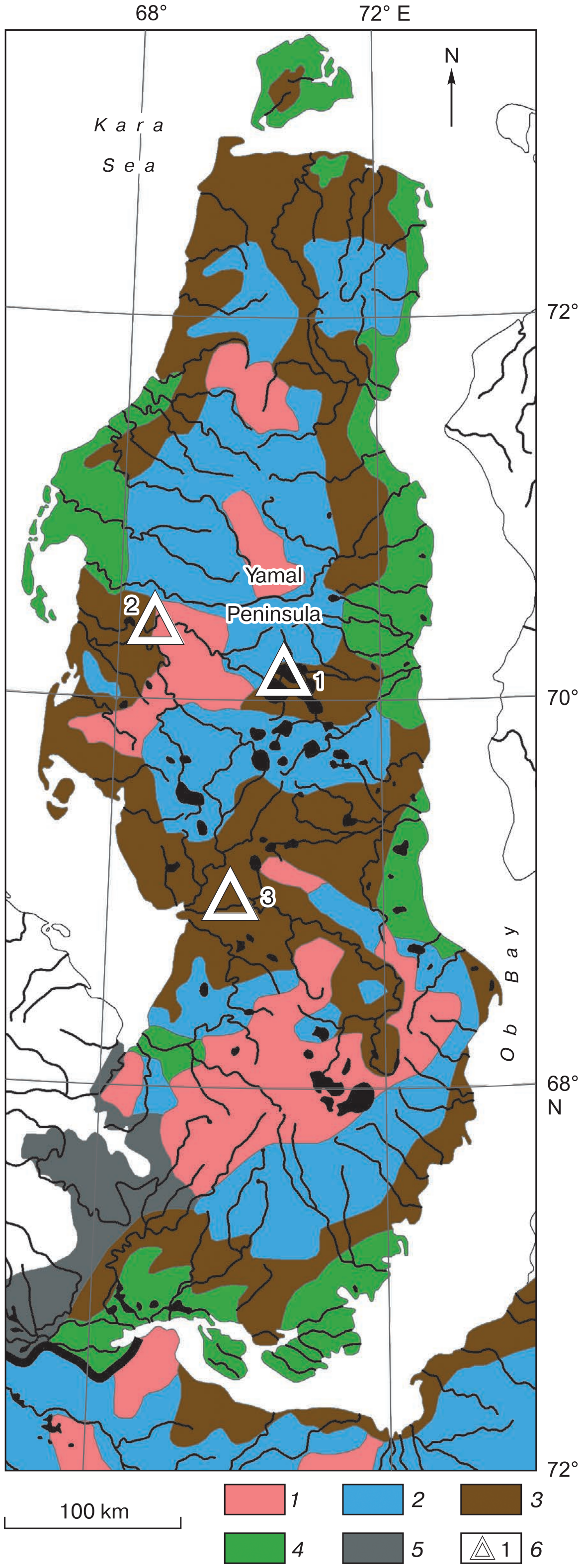

**Fig. 1. Geomorphological levels of the Yamal Peninsula:**

I–III marine plains: *1* – Salekhard ($Q_{II}^{2-4}$); *2* – Kazantsevo ($Q_{III}^{1}$); *3* – Zyryanka-Karginsky ($Q_{III}^{2-3}$); *4* – glacial and glaciofluvial non-dissected plains ($gfQ_{II}^{2-4}$, $gfQ_{III}^{2}$); *5* – marine, lagoonal-marine and alluvial terraces (non-dissected); *6* – test sites for detailed study of massive layers of ultra-fresh ice: 1 – Lake Neyto area, 2 – Bovanenkovo GCF, 3 – Yuribey River valley.

Note. The schematics is compiled after the “Map of geological zoning of the West-Siberian plain for the upper horizon of the permafrost strata” [*1982*].

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## NATURAL CONDITIONS NECESSARY FOR FORMATION OF MASSIVE ICE LAYERS

While studying the conditions for the formation of massive layers of ultra-fresh ice inside the stratum of saline marine sediments the author had to deal with numerous interconnected tasks and associated problems, which have been solved consistently since 2003 [*Fotiev, 2003*]. The formation of the same (or similar) type of layers in variously aged sediments of the marine plains, understandably, required a combination of systematically recurring natural conditions in the Middle and Late Neopleistocene paleogeography, whereas periods of their formation are separated from one another by tens and hundreds of thousands of years.

The question of natural conditions that predetermined the formation of massive ice layers suggested that they were responsible for the following processes: 1) accumulation of thick sandy and clayey strata with a substantial areal extent; 2) continuous preservation of layers of ice and, consequently, of the enclosing sediments in a frozen state, which lasted many tens or hundreds of thousands of years; 3) existence of huge volumes of ultra-fresh water; 4) water transport to considerably long distances from the source to massive ice layer; 5) layer-wise aggradation of massive ice layer from the bottom up and a clear horizontal stratification parallel to the intrastratum layering, traceable at a considerable distance; 6) occurrence of the uppermost horizontally stratified layers of massive ice at a depth of 10–15 m (and, occasionally, deeper) with undisturbed horizontal surfaces of the sea plains; 7) a distinct differentiation between total ion concentration and ion-salt composition of ice in the adjacent ice layers.

Periodic transgressions and regressions that changed the Arctic Sea level in the Middle and Late Neopleistocene now is considered to be a proven fact [*Lazukov, 1972; Gudina, 1976; Bryzgalova and Bidzhiev, 1986; Pavlidis, 1992; Pavlidis et al., 1998*][3]. The transgression and regression phases were responsible for the accumulation of saline deposits – sand, silt, clayey silt and clays – with their layers alternating in

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[3] Some researchers, nevertheless, still argue that “there was not any appreciable transgressions of the sea in the Neopleistocene in the northern West Siberia” [*Kritsuk, 2010, p. 120*].

the section. After a complete regression of the sea, the long-term freezing of the sediment and the formation of marine terraces (plains) commenced.

When did the formation of massive ice layers actually begin – before the complete regression of the sea, or much later? This problem appeared of little interest to geocryologists, as many of them believed that massive ice layers formed during the early stages of diagenesis occurring in water-saturated marine sediments [*Fotiev, 2015*].

After careful weighing all existing viewpoints of the leading geocryologists, the author has concluded that a real solution to this problem consists solely in finding out the answer to the question: which water – from sea or lake – "fed" the massive ice layer? To this end, the author has studied and compared the total ion concentration and ion-salt composition of RIMIL and those of precipitations, as well as lacustrine and marine waters.

The results allowed the author to ascertain that lake water was the only source capable of providing regular entries of huge volumes of ultra-fresh water into the strata of frozen deposits, which is vital for the formation of massive ice layers, persistent along the strike. This inference is confidently supported by the hydrochemical affinity of ion-salt composition of RIMIL and lake waters [*Fotiev, 2012*]. The presence of $NO_4^+$ and $Fe_2^{2+}$ ions in the chemical composition of ice, and even algae typical for lakes of the tundra zone bear essential evidence of the "parent" water to have derived from lake [*Vasil'chuk, 2010*], providing thus the proof that the layer of ice was "fed" with water from thermokarst lakes, which offered an unambiguous answer to the question of time of the massive ice layer formation and deposition of the enclosing sediments. Massive ice layers formed under subaerial conditions established in the wake of complete marine regression, and far later than the freezing of the enclosing marine sediments [*Fotiev, 2015*]. Given that it takes a long time for the saline marine sediments to become perennially frozen from the surface downward and for deep thermokarst lakes and sub-bottom taliks to form in the permafrost strata, this conclusion appears obvious.

Actually, what climatic conditions could have ensured perennially (lasting many tens and hundreds of thousands of years) frozen state of the saline rocks and promoted the formation of deep thermokarst basins? On the one hand, climate must be very cold and persistent in time, to provide for both perennial freezing of the saline deposits after each marine regression and deep seasonal freezing of water in the lakes. On

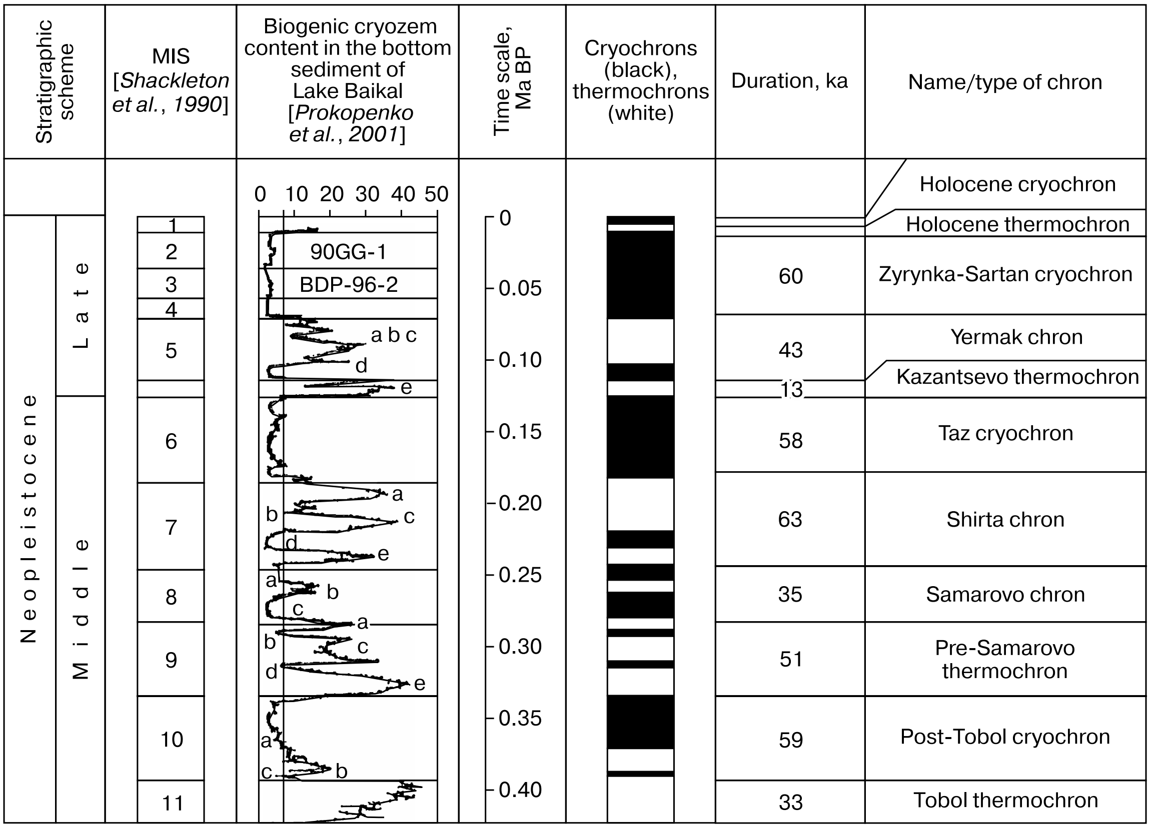

**Fig. 2. Cryochrons and thermochrons of the Middle and Late Neopleistocene on the Yamal Peninsula (426–11 ka BP) [*Fotiev, 2009*].**

Table 1. **Characteristic features of climates during cryochrons and thermochrons of the Middle and Late Neopleistocene (426–11 ka BP)**

| Stage | Index | Time, thou. years | MIS | Cryochrons (index) | Thermochrons (index) | Time, thou. years | Durationь, thou. years | $T_a$, °C |
|---|---|---|---|---|---|---|---|---|
| Sartan | $Q_{III}^4$ | 37–11 | 2 | Zyryanka-Sartan | – | 71–11 | 60 | Lower, by 8–12 |
| Karginsky | $Q_{III}^3$ | 57–37 | 3 | | | | | |
| Zyryanka | $Q_{III}^2$ | 71–57 | 4 | | | | | |
| Kazantsevo | $Q_{III}^1$ | 127–71 | 5 | – | Yermak MIS 5a, b, c | 103–71 | 32 | Higher, by 1–3 |
| | | | | Yermak MIS 5d | – | 114–103 | 11 | Lower, by 8–12 |
| | | | | – | Kazantsevo MIS 5e | 127–114 | 13 | Higher, by 2–4 |
| Taz | $Q_{II}^4$ | 185–127 | 6 | Taz MIS 6 | – | 185–127 | 58 | Lower, by 8–12 |
| Shirta | $Q_{II}^3$ | 248–185 | 7 | – | Shirta MIS 7a, b, c | 223–185 | 38 | Higher, by 3–5 |
| | | | | Shirta MIS 7d | – | 238–223 | 15 | Lower, by 8–12 |
| | | | | – | Shirta MIS 7e | 248–238 | 10 | Higher, by 3–5 |
| Samarovo | $Q_{II}^2$ | 248–334 | 8 | Samarovo MIS 8a | – | 259–248 | 11 | Lower, by 1–3 |
| | | | | – | Samarovo MIS 8b | 268–259 | 9 | Higher, by 1–3 |
| | | | | Samarovo MIS 8c | – | 283–268 | 15 | Lower, by 8–12 |
| | | | 9 | – | Pre-Samarovo MIS 9a | 287–283 | 4 | Higher, by 1–3 |
| | | | | Pre-Samarovo MIS 9b | – | 290–287 | 3 | Lower, by 3–5 |
| | | | | – | Pre-Samarovo MIS 9c | 312–290 | 22 | Higher, by 1–3 |
| | | | | Pre-Samarovo MIS 9d | – | 314–312 | 2 | Lower, by 1–3 |
| | | | | – | Pre-Samarovo MIS 9e | 334–314 | 20 | Higher, by 3–5 |
| Tobol | $Q_{II}^1$ | 426–334 | 10 | Post-Tobol MIS 10a | – | 369–334 | 35 | Lower, by 8–12 |
| | | | | – | Post-Tobol MIS 10b | 389–369 | 20 | Higher, by 1–3 |
| | | | | Post-Tobol MIS 10c | – | 393–389 | 4 | Lower, by 1–3 |
| | | | 11 | – | Tobol | 426–393 | 33 | Higher, by 3–5 |

Note. MIS – Marine Isotope Stages [*Shackleton et al., 1990*]; $T_a$ – mean annual temperature, lower/ higher versus modern *T*, °C.

the other hand, climatic conditions "must preclude" progressive advancement of permafrost thawing (degradation) from the surface downward, but "ensure" the active layer (AL) deepening in some locations, providing for thermokarst process development and formation of thermokarst lakes.

Climatic conditions of the Middle and Late Neopleistocene were characterized by the author on the basis of the paleoclimate record compiled by a large team of scientists from their study of $SiO_{2biog}$ (%) content in the bottom sediment of Lake Baikal (Fig. 2)[4] [*Bezrukova et al., 1999; Karabanov et al.,*

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[4] During very cold cryochrons, at $SiO_{2biog}$ content being ca. 3 %, the mean annual air temperature ($T_a$) decreased by 8–12 °C versus the present-day temperature, whereas during the contiguous thermochrons it would rise in leaps by 10–15 °C, remaining generally negative, though. At $SiO_{2biog}$ content equaled 39–49 %, $T_a$ was found to be by 3–5 °C higher than the modern-day. Further details from the Lake Baikal paleoclimatic record are given in [*Fotiev, 2009*].

*2001; Kuzmin et al., 2001; Prokopenko et al., 2001*]. The curve configuration distinctly indicates: 1) the stability of harsh climate both in the Middle and Late Neopleistocene; 2) significant and saltatory variations in the climate severity; 3) repeated and rhythmic alternations of cold to very cold epochs (cryochrons) with warm periods (thermochrons). A significant increase in negative air temperature ($T_a$) features thermochrons of northern-most Arctic regions. "High-resolution of the Lake Baikal paleoclimatic record allowed to reveal additional short-term climate changes" [*Karabanov, 2001, p. 59*]. These include the cooling event during isotope sub-stages 5d, 7d, 9d, and the warming event during isotope substage 8b (Fig. 2, Table 1).

Based on $SiO_{2biog}$ content in the bottom sediment of Lake Baikal, the paleoclimatic record allowed to reconstruct air paleotemperature and estimate the magnitude of its increase during thermochrons or decrease during cryochrons versus modern values of $T_a$, and to assess permafrost conditions in each chron (Table 1). Total ionic concentration and ion-salt composition of cryopeg lenses in the sand unit attest to low (down to −20 °C and lower) temperature of rocks ($T_r$) [*Fotiev, 2012*].

*Balobaev* [*1997*] has convincingly proved that the development of thermokarst process does not necessarily imply increased $T_r$, to the extent of positive values in the upper layers of permafrost. He linked the inception of thermokarst process with increasing AL thickness[5] under $T_r$ taking negative values. Probably, this was the true pattern of the onset of thermokarst processes and thermokarst lakes formation, under essentially harsh climatic conditions of Yamal.

Determining the mechanism of water delivery from the lake to massive ice layer appeared an equally important problem. It has been long known that when freezing in winter, lake water forms a closed system, creating thereby a huge cryogenic pressure in the lake basin. Under the developed cryogenic pressure, expelled lake water flowed out on the surface of lake ice, forming either icing ("naled" in Russian) (Fig. 3, *A*) or hydrolaccolith (Fig. 3, *B*). However, lake water could possibly penetrate into the frozen sediment strata only when the contact zone between clay and sand units cropped out (exposed) in the lake basin sides. Only when absolute level of the lake-bed dropped below the absolute elevations of the contact zone (Fig. 3, *C*) lake water intruded into the contact zone driven by the created thereby enormous cryogenic pressure, without filtering through the sand layers, though. The water flow penetrated into the sediment strata along the top of the frozen sands[6], and at times migrated to a considerable distance from the lake. The flow of water would evenly spread along the base of the massive ice layer, with sand, coarse clay aggregates and algae readily transported along the top of the cryogenic aquiclude. However, the water could possibly do so only provided there was a crack between the top of cryogenic aquiclude and the base of massive ice layer. The author thinks the crack is produced by the uniform uplifting of both the massive ice layer and clay unit as a result of the vast area

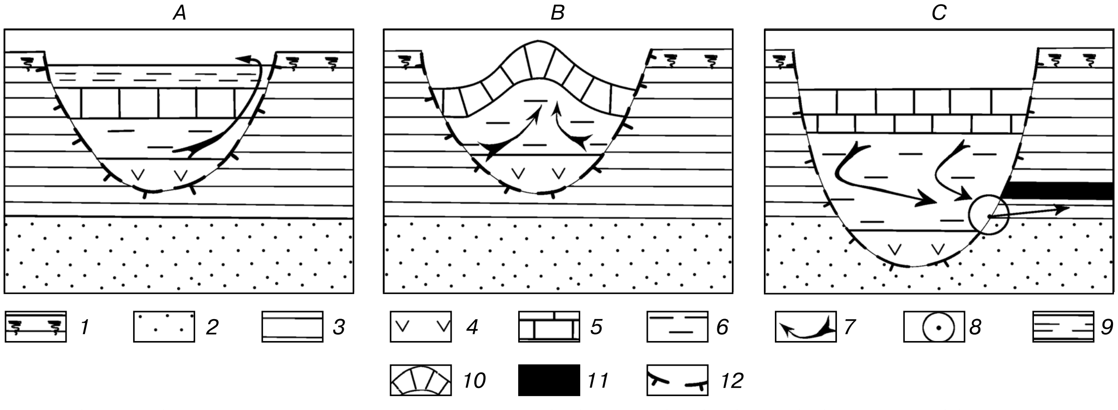

**Fig. 3. Conditions benefiting formation of icing (naled) (*A*), hydrolaccoliths (*B*) and layers of ice during the water freezing in the lake (*C*).**

*1* – marine plain surface; *2* – ice-rich sand, frozen; *3* – ice-rich clay, frozen; *4* – non-frozen taberal deposits; *5* – ice; *6* – lake water, freezing from top to bottom; *7* – cryogenic pressure; *8* – contact zone between frozen clays and frozen sand units; *9* – icing (naled); *10* – hydrolaccolith; *11* – layer of ice; *12* – delineation of sub-bottom talik.

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[5] The calculations showed that as $T_a$ warmed by 2–4 °C on the northern coast of the Kara Sea, $T_r$ responded by 1.8 and 3.3 °C. Thus, increased $T_r$ in the range of Tambey settlement resulted in a greater seasonal thaw depth, with the top of permafrost strata lowered by 0.56 and 0.37 m, respectively [*Vyalov et al., 1997*].

[6] Had the sand been not frozen, then the highly pressurized lake water, no doubt, would infiltrate into the sand unit rather than making its way into the frozen clay unit from beneath, along the existing vertical ice schlieren. This processes has been studied in detail by [*Koreysha et al., 1982*].

of frost heaving, which occurs annually during the freezing of subsequently discharged layer of water. It's true only under the assumptions that: 1) sand, large clay aggregates and algae could be found inside discrete layers of ice; 2) layer-wise aggradation of ice may have occurred from the massive layer base; 3) horizontality of the marine plain surface could persist, even in the areas where RIMIL thickness reaches 30–40 m [*Fotiev, 2015*].

The layer-wise aggradation of ice from the bottom upwards continued as long as the following three natural conditions were maintained *in loco*: 1) availability of a deep, seasonally freezing lake; 2) the contact zone in the basin's sides and its positioning in waters of the freezing lake; 3) uniform cooling (freezing) from the surface of rocks overlying massive ice layer. The latter is known to occur only provided the uniform composition of the freezing rocks and equal depth of the snow cover on the barren subhorizontal surface of the plain. The thick, persistent along the strike beds holding huge volumes (several millions cubic meters) of ice could have formed only under these conditions which continued for many years [*Fotiev, 2012*]. If at least one of these components became non-existent, the growth of RIMIL would be immediately arrested. Equally, uneven freezing of rocks from the surface precludes the spreading of discharged water over the top of the cryogenic aquiclude, whence either a lens of ice varying in thickness and extent, or massive ground ice of arbitrary, sometimes bizarre, shape formed in the plain's subsurface.

Analysis of layer-by-layer changes in total ionic concentration and ion-salt composition of RIMIL revealed the following regularities [*Fotiev, 2012*]: given thickness of lake ice was less than the lake's depth, then lake water approaching the base of massive ice layer was calcium bicarbonate (sodium) in composition, and another layer of transparent, ultra-fresh ice was produced; given water in the lake froze through from top to bottom, then water entering the RIMIL base derived from talik and was either turbid, with high total ionic concentration (300 mg/L and greater), or (less frequently) aqueous, highly mineralized sediments, with mineral particles reaching 40–60 % in their composition. In this case, the *in-situ* formation of a highly saline (up to 1200–8500 mg/L) layer of ice-rich sediments of dark color was taking place, with chemical composition containing cryo-metamorphosed seawater [*Fotiev, 2012*]. This is the only explanation, in the author's opinion, of the distinct alternation of layers that differ in color, mineralization and ion-salt composition, which is characteristic of RIMIL, and can not be attributed to segregation/intrusive mechanisms of ice formation, at the expense of water amount in the marine sediments, as many geocryologists believe (V.V. Baulin and others) [*Fotiev, 2015*]. The clear boundaries between individual layers of ice bear a distinct indication to the alternative source of water.

After identifying natural conditions potential for formation of layers of massive intrasedimental ultra-fresh ice in the marine saline deposits, it is important to analyze the possibility of RIMIL to form in the specific depositional environments of different stages in the Middle and Late Neopleistocene.

## FORMATION CONDITIONS FOR LAYERS OF ICE IN THE DEPOSITS OF THE VARIOUSLY AGED MARINE PLAINS

The three hypsometric levels with the corresponding surfaces of the marine terraces and marine plains confined to them – the Salekhard, Kazantsevo, and Zyryankian-Karginsky Plains – are fairly distinctly differentiated on the Yamal Peninsula.

### The Salekhard Plain

The Salekhard Plain is located within the watershed area of the Yamal Peninsula (Fig. 1) (absolute elevations: 75–95 m). The deposits composing it accumulated during the Arctic Sea transgressions and regressions, beginning from the second half of the Middle Neopleistocene, in the Samarovo, Shirta and Taz time (314–127 ka BP; $Q_{II}^{2-4}$ ).

**Paleoclimate.** Paleoclimate of the Middle Neopleistocene was extremely unstable. As is known, six marine isotope stages (MIS) are identified on the marine oxygen isotope curve (MOIC) within this age interval [*Shackleton et al., 1990*], which, according to the geocryological records, match with 18 chrons are matched in Siberia: 9 cryochrons and 9 thermochrons [*Fotiev, 2009*]. In each MIS, very cold and cold cryochrons are distinguished, when the $T_a$ dropped 8–12 °C lower than modern, along with the prominent thermochrons when $T_a$ increased dramatically by 10–15 °C (within a span of just 1–2 thousand years), remaining in negative values range, though (Fig. 2, Table 1). The Taz cryochron (MIS 6) was the coldest (with $T_a$ 8–12 °C lower than modern $T_a$) and longest (lasted ca. 60 thousand years), whereas the Samarovo (MIS 8c) and post-Tobol (MIS 10a) cryochrons appeared shorter (spanning 15 thousand years), but equally cold (Fig. 2, Table 1)[7].

The warmest ($T_a$ was 3–5 °C warmer than modern $T_a$) and longest (20–38 ka) were the Tobol (MIS 11), pre-Samarovo (MIS 9e) and Shirta (MIS 7a, b, c) thermochrons (Fig. 2, table 1). The pre-Samarovo (MIS 9) and Shirta (MIS 7) chrons were characterized by abrupt drops in $T_a$. Longer (10–22 ka) thermochrons with $T_a$ 1–3 °C higher than modern $T_a$ were abruptly succeeded by short-term

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[7] According to *N.V. Kind* [*1974*] and *C. Emiliani* [*1970*], during the cold maximum (150 ka BP), long-term (for a hundred years) average annual $T_a$ was 5–6 °C lower than modern.

(2–4 ka), but very cold (with $T_a$ 8–12 °C lower than modern) cryochrons (Fig. 2, Table 1).

**The marine transgression** onset is associated with the Tobol period. The Yamal transgression of cold Arctic waters started in the second half of the Middle Neopleistocene. The water depth reached 150–200 meters, with its salinity 34 g/L. The water temperature was negative or close to 0 °C. The peak of transgression event coincided with the time of maximum glaciation of the mountainous periphery along the sea coast. The regression event of the Arctic Sea began in the late Middle Neopleistocene. By the beginning of the Kazantsevo period, the sea coastline position had been more northerly versus its present-day delineation [*Bryzgalova and Bidzhiev, 1986; Pavlidis, 1992; Pavlidis et al., 1998*].

**Marine sediments.** Marine sediments exhibited lithological and facies diversity. The deep basin accommodated 150–200 m thick strata of marine, coastal-marine and glacial-marine sediments. The transgressive sequence of marine sediments comprises homogeneous clays and clayey silts and is characterized by a high degree of sediment sorting and maximum content of soluble salts. “The accumulation of the Salekhard Formation and its regressive sequence of clayey silts and sands composing the surface of the plain subjected to draining, ceased at the end of the Middle Neopleistocene” [*Badu, 2011, p. 52*].

**Geocryological conditions.** Harsh, cold and very cold climate of cryochrons when $T_a$ dropped to –20...–30 °C, favored a rapid and deep multiyear freezing of the deposits within drained areas of the marine terraces. The low-temperature (–15...–20 °C) and continuous permafrost developed on the peninsula, with coastal marine sediments freezing syngenetically along the coastline, and epigenetically – under subaerial conditions in drained areas of the plain. In parallel, ice wedges evolved almost everywhere, which have partially preserved till the present day.

During thermochrons, the AL thickness experienced growth at a significant increase $T_a$ and $T_r$ within the range of negative values, which also promoted thermokarst processes inception, from whence thermokarst lakes emerged, expanded and deepened, with sub-bottom taliks developing underneath.

**Massive ice layers.** Layers of massive ice have been substantially understudied in the Salekhard Plain subsurface. There are many reasons to this: firstly, the Salekhard sediments comprising layers of ice were washed out (redeposited) in the appreciably large area, and to a considerable depth during the Kazantsevo and Zyryanka-Karginsky transgressions of the Arctic Sea (Fig. 1). Secondly, in the absence of gas-bearing structures in the area, the Salekhard Plain subsurface nested in the peninsula’s watershed area with absolute elevations of 75–90 meters has been largely ignored. Nevertheless, the great abundance of large thermokarst lakes and khasyreys on the plain’s surface indicates the presence of massive ice layers deep inside it. Thirdly, large rivers, such as Yuribey, in some areas are structurally controlled by blocks of the Salekhard Plain, which alternate in the coastal cliffs with those of the Kazantsevo and Zyryanka-Karginsky Plains. Given that deposits of the variously aged plains are almost similar in composition, it would be all but impossible to determine the age of sediments comprising layers of ice, particularly under field conditions. Several outcrops of massive ice beds have been discovered and studied in the coastal cliffs of the Yuribey valley, where massive ice layers occur horizontally, have a distinct parallel stratification, and are bicarbonate, calcium (sodium) in composition; their total ionic concentration is low (30–300 mg/L).

### The Kazantsevo interglacial plain

The Kazantsevo Plain (a.s.l. 45–60 m ) stretches vastly along the western, northern and eastern coasts of the Yamal Peninsula (Fig. 1). The deposits composing the plain accumulated during the Arctic Sea transgressions and regressions that took place during the Kasantsevo time of the Late Neopleistocene (127–71 ka BP; $Q^1_{III}$ ).

**Paleoclimate.** Paleoclimate of the Kazantsevo interglacial period identified on the Middle and Late Neopleistocene boundary, was subject to oscillations. To this time interval identified [*Shackleton et al., 1990*] as MIS 5 in the MOIC, correspond two thermochrons – Kazantsevo and Yermak – and one Yermak cryochron in Siberia, according to the geocryological records (Fig. 2, Table 1) [*Fotiev, 2009*].

The Kazantsevo thermochron (MIS 5e) was short-termed (only 13 ka), but “warm”. A very cold Taz cryochron was abruptly succeeded by climate warming. Air temperature sharply increased (over the 1–2 ka time interval) by 11–13 °C and became 2–4 °C higher than the present-day $T_a$, however, still remaining in negative values. The climate was characterized by high moisture and heat capacity, as compared not only with the contemporary status, but also with climate during the Holocene thermal maximum[8]. The Kazantsevo thermochron climate did not last longer than 1–2 ka before it was succeeded by a harsh climate of the Yermak cryochron (MIS 5d) (Fig. 2, Table 1). $T_a$ sharply decreased and within a time spanning 10–11 ka remained to be 8–12 °C lower than modern. The cold climate was also abruptly replaced by the long-term Yermak thermochron (MIS 5a, b, c), with its climatic conditions greatly subject to variability. The periods of warming repeatedly alternated with cooling events. When warmed

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[8] In the Kazantsevo optimum (125 ka BP), $T_a$ was 2–3 °C higher than the present-day [*Emiliani, 1970*].

up, $T_a$ continued to be 1–3 °C higher for almost 25 ka BP than today's, but always remained negative (Fig. 2, Table 1).

**Marine transgression.** Transgression of the sea is attributed to the beginning of the Kazantsevo time. It was of much smaller scale than that of Middle Neopleistocene, however most of the peninsula had been covered by the sea waters to absolute elevations of 50–60 m, which triggered erosion processes in the Salekhard sediments in a large area and to a great extent [*Badu, 2011*]. During maximum phase of the marine transgression the peninsula represented by itself an archipelago consisting of islands, separated by extensive straits (Fig. 1). The Arctic Sea level began to recede in the Late Kazantsevo time. The straits partitioning the islands, gradually drained. When the sea completely receded from the Yamal Peninsula area, there developed a vast marine plain, with the remnants of older Salekhard plain hanging out over it in the most elevated axial part and in the south of the peninsula (Fig. 1). The surface of the Kazantsevo plain was exposed to deep erosional dissection early in the Zyryanka period, when the sea level decreased by 70–80 m [*Gudina, 1976; Bryzgalova and Bidzhiev, 1986; Pavlidis, 1992; Pavlidis et al., 1998*].

**Marine sediments.** The marine sediments accumulated in the environment of a shallow marine basin with numerous islands. The transgressive sequence features coarse cross-bedded sands with pebbles, nested in the Salekhard plain. "They are commonly overlain by sandy-silty ( less frequently, clayey-silty) deposits of coastal-marine and marine facies, concealed under the 10–15 m thick cross-bedded sands deposited in the regressive phase of the sea basin development" [*Badu, 2011, p. 52*]. The content of clayey silt and clays in the marine sediments tends to grow with greater distances from the coastline. A strata of interbedded saline marine sands, silts and clayey silts with high content of vegetable detritus and alluvial peat was thus found onshore at the decline of the Kazantsevo period.

**Geocryological conditions.** The cold to very cold climate of the Yermak cryochron with the $T_a$ ranging between –25 and –30 °C, triggered a quick and deep perennial freezing of deposits and almost ubiquitous formation of ice wedges. The low-temperature (–15...–25 °C) continuous permafrost strata developed thereby in the drained areas of a young marine plain. In parallel, sands with cryopeg lenses were distinguished in the context of saline frozen deposits and some of them preserved till the present day. Given that negative $T_r$ experienced a significant warming during the thermochrons, the AL thickness also had grown, giving rise to thermokarst processes, formation of thermokarst lakes and sub-bottom taliks.

**Massive ice layers.** Thick layers of ice occurring in the subsurface of the Kazantsevo interglacial plain appear best studied in the vicinity of lake Neyto in the central Yamal [*Dubikov and Koreysha, 1964; Baulin et al., 1967; Baulin and Dubikov, 1970; Koreysha et al., 1982*]. They are exposed in every 100–200 m along a 2–3 km coastal stretch, and are traced to a distance exceeding 100 m deeper into the coast. The thickness of visible parts of massive ice layers is 8–10 m, and their base occurs in the lake, below the water line. It was determined by drilling that the layers thickness is greater than 20 m. "Massive ice layers consist of 0.5–1.5 m thick layers, separated by a thin (3–4 cm) interlayers of ice enriched with soil" [*Baulin and Dubikov, 1970, p. 184*]. The layers of ice occasionally contain sand or clay aggregates with sharp edges. The ice is featured as ultra-fresh (25–130 mg/L), and calcium bicarbonate (sodium) in composition.

"The top of ice layers crop out at a height of 7–8 meters above the water level in the lake. It occurs horizontally, parallel to the rhythmically layered overlying sediments" [*Baulin and Dubikov, 1970, p. 184*]. "Sediments, resting immediately on the massive ice layer, tend to abound with ice schlieren forming reticulate-blocky cryostructure (volumetric ice content: 50–60 %), where thickness of vertical ice schlieren (10–20 cm) is 1.5–2 times greater than that of horizontal ones" [*Dubikov and Koreysha, 1964, p. 59*].

### Marine plain formed during the Zyryanka (glacial)-Karginsky (interglacial) periods

The Zyryanka-Karginsky Plain[9] is located along the western, northern and eastern coasts of the Yamal Peninsula. The absolute elevations of the surface range between 30 and 50 m. The sediments the plain is composed of accumulated during the transgression events of the Arctic Sea in the Zyryanka-Karginsky periods of the Late Neopleistocene (71–37 ka BP; $Q_{III}^{2-3}$ ).

**Paleoclimate.** The latter half of the Late Neopleistocene was marked by a steady global trend to coldest climate conditions, with a maximum in the Sartan. In the MOIC, three marine isotope stages (MIS) account for this time interval [*Shackleton et al., 1990*], which, according to the geocryological records correspond to a single Zyryanka-Sartan cryochron in Siberia [*Fotiev, 2009*], characterized by persistent, very harsh climatic conditions.

A great decline in $T_a$ commenced in the Early Zyryanka (71–57 ka BP), when the $T_a$ was found to be 8–12 °C lower than the present-day $T_a$. Climatic conditions of the Karginsky period are characterized by several alternating phases of warming and cooling

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[9] Some researcher discriminated this geomorphological level as 3rd Marine Terrace (3rd MT) on the western coast, and as lacustrine-alluvial plain on the eastern coast of the Yamal Peninsula.

events. At the beginning and especially at the end of the Karginsky period climate is featured as generally colder and wetter than at present[10]; it proved milder than modern climate only in the climate optimum phase (30–24 ka BP) [*Kind, 1974*].

**Marine transgression.** The transgression event began in the Zyryanka and continued in the Karginsky time. The Arctic Sea waters flooded the coastal area and penetrated far into the interior of the peninsula through the deeply incised river valleys. The ingression basins on the western and eastern coasts would merge during the extreme phase. The growing wider sea straits thereby dismembered the Yamal Peninsula into separate islands. That was a cold-water sea basin, periodically ice-covered. The water started to recede 30 ka BP and by the end of the Karginsky time the basin had approached its modern-day level [*Kind, 1974; Bryzgalova and Bidzhiev, 1986; Pavlidis, 1992; Pavlidis et al., 1998*].

**Marine sediments.** Marine saline deposits accumulated in the water-logged areas of the peninsula. They are overlapped erosively by the deposits of the Kazantsevo transgression. “The sediments are represented by interbedded sands, silt and clayey silt, whereas the share of fine-grained varieties in the section appreciably increases northwards” [*Badu, 2011, p. 53*]. Subsequent to complete regression of the sea, the coastal-marine and the lagoon-marine plains progressively evolved in the Yamal Peninsula area.

**Fig. 4. Zone of shattered ice-saturated clays on the top of horizontally stratified massive layer of ice in the lower reaches of the Seyakha River (Photograph by G.I. Dubikov).**

**Geocryological conditions.** The severe, persistent through many decades subaerial climatic conditions caused the $T_{\mathrm{a}}$ drop to −25...−30 °C, and saline marine sediments were subjected to intense freezing, forming thereby low-temperature (−15...−25 °C), continuous permafrost strata. Ice wedges developed almost ubiquitously. Subsequently, sands with cryopeg lenses became enclosed in the permafrost strata and partially preserved until today. Salinity and ion-salt composition of cryopegs also evidence a low (−15...−17 °C) $T_{\mathrm{r}}$ in the period of perennial freezing of the marine sediments.

In the periods of climate warming, thermokarst processes started, thermokarst lakes and sub-bottom taliks evolved, locally, on the plain’s surface, inasmuch as AL thickness increased.

**Massive ice layers.** Massive ice layers occurring in the subsurface of the Zyryanka-Karginsky plain are best studied in the area of Bovanenkovo gas condensate field (BGCF) in the basins of the Seyakha, Naduiyaha, and Nguriyaha rivers. This area features widely developed, thick layers of ice, persistent along the strike. They have been studied in the coastal out-

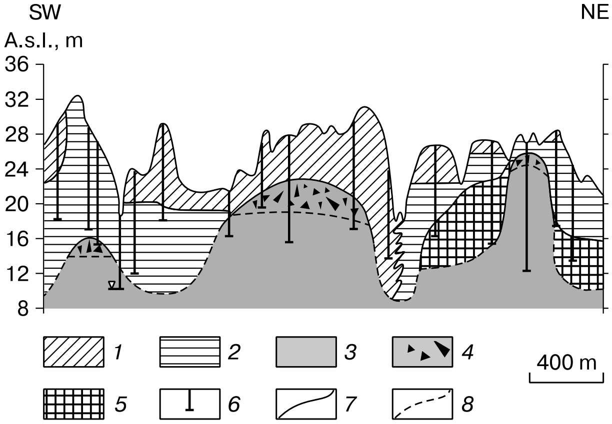

**Fig. 5. “Arete”-shaped top of massive ice layer buried in the outlier of the plain in the Seyakha River valley [*Kritsuk, 2010, рис. 4.9*].**

*1* – clayey silt; *2* – clay; *3* – massive layer of ice; *4* – inclusions of claystone-like clay fragments in ice; *5* – block-textured clayey material; *6* – borehole; *7* – lithologic boundary; *8* – delineation of pure ice (speculative).

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[10] According to *C. Emeliani* [*1970*] and *N.V. Kind* [*1974*], $T_{\mathrm{a}}$ was 3–5 °C lower than modern in the optimum phase (57–53 ka BP).

crops and in watershed areas. A more detailed descriptions of massive ice layers are provided in numerous papers by Yu.B. Badu, V.V. Baulin, G.I. Dubikov, M.M. Koreysha, L.N. Kritsuk, M.O. Leibman, S.Yu. Parmuzin, I.D. Streletskaya, S.E. Sukhodolskii, Yu.K. Vasil'chuk et al.

The thickness of layers in the coastal outcrops is 5–10 m, rarely up to 20 m, and visible length ranges from 100 to 150 m [*Dubikov, 1982*]. Flat-lying massive layers of ice (Fig. 4) consist of parallel layers of pure ice, alternating with interlayers of ice, with admixture of mineral inclusions (from sandy mud to angular fragments of dense clay) 3–4 mm in size. "The ice is poorly mineralized (0.02–0.06 g/L)[11], with predominance of bicarbonates, magnesium, calcium and sodium chlorides in the ionic composition at elevated levels of chlorides near the contact zones with the host rock" [*Kritsuk, 2010, p. 141*]. The top of massive ice layer occurs horizontally and its layering is parallel to that of clays (Fig. 4). "Clays overlaying massive ice layer in the near-contact zone are characterized by reticulate cryostructure with separate vertical schlieren thickness reaching 10–20 cm (whereas horizontal schlieren are thinner). Volumetric ice content in the zone of shattered icy clay reaches 50–60 %" [*Vasil'chuk, 2010, p. 58*]. Cryogenic structure of this type of rocks is attributed to the primary contacts between the layer of ice and the frozen deposits [*Dubikov, 1982*]. In such areas of the plain, ice layers and the enclosing deposits are not affected by reworking processes (Fig. 4).

Within the interfluve areas, massive ice layers up to 30–40 m thick were found to occur deep in the plain outliers as follows from electric profiling and drilling data [*Kritsuk, 2010, p. 135*]. The layers have length of 1–3 km, and volumetric ice content is estimated to be 4 mln m$^3$ in some areas [*Parmuzin and Sukhodolskii, 1982*]. The top of the layers of ice is "arete"-shaped (Fig. 5). The depth of thermal erosional incisions into the massive ice layers reaches 30 meters. The presence of the incisions attests to complete thermodenudation reworking of the horizontally layered clays, once having been an overburden to the massive ice layer. Whether it is so, remains under wraps with the Bovanenkovo GCF area, and has still not been solved by geocryologists[12].

## CONCLUSIONS

While studying the problem of the conditions favorable for the formation of massive ultra-fresh ice layers in the saline marine sediments strata the author arrived to the following conclusions.

- The revealed natural conditions determining the possibility of the formation of massive layers of ultra-fresh ice of great areal extent inside the strata of saline marine sediments are as given below: 1) the Arctic Sea transgressions and regressions alternating over time periods provided for accumulation of horizontally stratified sandy-clay deposits and formation of the areas of drained extensive marine terraces (plains); 2) both extensive area and horizontal surface of barren plains ensured uniform thickness of the snow cover, and rate and depth of seasonal and perennial freezing (cooling) of rocks from the surface downward; 3) availability of deep-seated thermokarst lakes not subjected to freezing to the bottom, with ultra-fresh waters, bicarbonate-calcium (sodium) in composition; 4) essentially severe, however not persistent in time climatic conditions that dictated the alternation of cryochrons and thermochrons.
- The specific conditions that determine the possibility of penetration of lake water forming massive ice layer into the frozen sediments of marine plains have been defined as: 1) the presence of a lake on the plain, to serve as the main source of "parent" water, forming the layer of ice; 2) formation of a thick seasonal ice cover in the lake basin which will behave as a closed system, with a huge cryogenic pressure progressively building up; 3) the presence of contact zone between lithologically different sand and clay units in the sides of the lake basin (which also reveals a distinction between the marine sediments accumulated in transgression and regression stages); 4) the presence of a contact zone inside the freezing lake water and sub-bottom talik.
- It has been proved that lake water "feeding" the layer of ice, discharged as open flow without filtering through sand beds. The water was flowing along the top of frozen sands and penetrated into the sediment strata evenly spreading along the base of massive ice layer, and thereby easily moving pebbles, sand, coarse aggregates of clay and algae along the uppermost portion of the cryogenic aquiclude. However, such movement of water can only be possible along the crack between the top of the cryogenic aquiclude (the overlying unit of frozen sands) and the base of massive ice layer. This gap recurrently emerged as a result of gradual uplifting of both layer of ice and clay unit (which occurred annually), driven by the freezing of yet another emergent layer of water, and thus producing vast areal heaving.
- It has been established that outward similarity of RIMIL formed in different periods of the Middle and Late Neopleistocene, is a well-grounded fact, indicating that the environmental conditions revealed

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[11] Ice salinity tends to increase up to 0.1–0.2 g/L and greater, while its chemical composition becomes enriched with $Cl^-$, $Mg^{2+}$ and $Na^+$ ions, depending on the amount of mineral inclusions.

[12] Possible causes of development of deep erosional incisions at the top of the massive ice layer are laid down in [*Fotiev, 2012*].

in this study are responsible for potential formation of intrasedimental ultra-fresh RIMIL in the saline marine sediments strata, and when regularly and systematically repeated, provided thereby the mechanism for formation of layers of ice during all stages of development of the variously aged marine plains.

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