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CRYOGENIC PROCESSES AND FORMS

GENESIS AND MECHANISM OF FORMATION OF REPEATED-INTRUSIVE MASSIVE ICE LAYERS

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The typical features of massive ice layers occurring *in situ* in the full sections of marine sediments have been specified. The comparison of the total ionic concentration and the chemical composition of ice, lacustrine and marine waters have proven massive ice layers to have been systematically fed by lake waters. It was determined that massive ice layers began forming only after the regression and considerably later than the perennial freezing of the surrounding deposits. It has been ascertained that thick massive ice layers cannot be formed during the process of ice segregation. The leading role of the process of intrusive ice accumulation during the formation of thick layers of ultrafresh ice inside the strata of the frozen deposits have been substantiated. The source "nourishing" massive ice layer occurred to be not inside but outside the surrounding deposits. The conditions of lacustrine waters penetration into the strata of frozen deposits and the layerwise formation of intrusive ice have been examined. It was revealed that the delivery of water from the lake to massive ice layer and its transportation to enormous distances was driven by the huge cryogenic pressure occurring during the freezing of ice within the closed lake depression.

Repeated-intrusive massive ice layers, segregation and intrusive ice accumulation, cryogenic pressure

INTRODUCTION

The abundance of polygonal wedge and massive ground ice in the form of ice beds, lenses, veins and mounds typify the Arctic plains, prone to repeated seawater flooding in the Quaternary. This specificity of the Yamal Peninsula was noted by geological expeditions as long as sixty years ago. However, extensive scientific research and studies of ground ice were initiated later, in the period of 1960–1964 [*Dubikov and Koreysha, 1964; Baulin et al., 1967*]. Since neither origin, nor mechanisms of the formation of polygonal-wedge ice called in for questions, the geocryologists focused their efforts on studying massive ground ice occurrences[1].

Massive ground ice phenomenon has also been studied fairly well. Massive ice beds were encountered in Quaternary sediments of various age (from the Middle Neopleistocene to Holocene) and genesis (marine, littoral-marine, glacial, and less frequently, lacustrine and alluvial). Given that massive ground ice is present in several forms (lenses, layers, veins, etc.), their thickness and observable extent are also diverse. The term "massive ground ice" in recent understanding, as *G.I. Dubikov* emphasized it correctly, "is of collective nature that, however, fails to reflect not only genetic aspects of the phenomenon, but morphological features of ice bodies, either" [*2002, p. 166*]. In most researchers' understanding, almost all ground ice occurrences are commonly assigned to massive ice beds, including those having nothing to do with these. Such are, for instance, ice lenses formed during the freezing of shallow thermokarst lakes, or buried sea-ice cakes [*Vasil'chuk, 2010*]. This might be the reason why geocryologists still have not come to consensus regarding inception conditions of massive ground ice (on the surface or beneath, intrasedimentally), and about origins of "parent" water that formed massive ice bed. It is also obvious that both genesis and formation mechanism of massive ice layers have still been debatable. Among all the diversity of large and small bodies of ground ice, massive ice layer holds a special place. A massive ice layer should be defined as monolith ice body "controlled by two more or less parallel bedding planes of similar thickness and occupying large area" [*Glossary..., 1955, p. 147*]. These

[1] The collective term "massive ice bed" (or "massive ground ice") is not used deliberately in the author's reasoning so far as it doesn't refer to ice bodies with single mechanism of ice formation or with similar morphology. Further in the text, the term "massive ice layer" is used to refer to the studied phenomenon, while separate horizons of ice comprising this massive ice layer are called "ice layers", or "layers of ice".

appear to be the largest accumulations of ground ice masses with the greatest thickness (up to 30–40 m) and sizeable extent (up to 1–3 km) [*Dubikov, 2002*], with ice volumes in some massive ice layers reaching several million cubic meters[2]. It stands to reason that to date most of the parameters of massive ice layers have been studied in detail: their morphological features, composition, and cryogenic structure, as well as chemical composition of discrete ice layers *in situ* and of structure-forming ice and pore solutions in the host rocks. The paper focuses primarily on determining origins and processes of formation of layers of ultrafresh ice within the frozen, marine, and saline deposits.

MASSIVE ICE LAYERS

Massive ice layers in the marine sediments of the Salekhard, Kazantsevo, and Zyriansk-Kargin plains are identical in terms of morphology, cryogenic structure and chemical composition of ice. This attests to the fact that the specific combination of natural factors and conditions, providing for the formation of thick layers of fresh ice in the saline marine sequence were recurrent at various geological periods.

The marine plain sediments comprising thick ice wedges and massive ice layers were subjected to erosional, thermokarst and thermoplanation processes and actively degraded under the submarine and subaeral conditions. Full sections of frozen sediments with massive ice layers formed *in situ* preserved only in the outliers of ancient plains, which is supported by a significant (up to 1–2 %) salinity throughout all the sequence of marine sediments. That is why these sections are used by the author as reference. Relying on earlier predications by [*Dubikov and Koreysha, 1964; Baulin et al., 1967; Baulin and Dubikov, 1970; Dubikov, 1982, 1983, 2002; Koreysha et al., 1982; Parmuzin and Sukhodolskii, 1982; Streletskaya and Leibman, 2002; Kanevskii et al., 2005; Streletskaya et al., 2006; Kritsuk, 2010; Vasil'chuk, 2010, 2012; Slagoda et al., 2012*], the following characteristic features of massive ice layers have been inferred:

Ice thickness: up to 30–40 m.

Areal extent: up to 1–3 km.

Ice volume: several million cubic meters.

Not expressed in the present-day relief, despite the great thickness and considerable extent of massive ice layers, and huge volume of ground ice masses.

Confined to the interface of sands and clays of marine origin. Typically (83 %), massive ice layers are overlain by a clay unit [*Dubikov, 2002*].

Subhorizontal lamination of ice is distinctly consistent with horizontal bedding of the marine sediments, acting as an overburden to the massive ice layers (Fig. 1).

Transparent ice layers are interbedded with ice layers containing mineral inclusions and air bubbles. The inclusions are clay, sand, gravel and pebbles. Layers of ice-soil where content of mineral particles reaches 50 % are less common. The thickness of ice layers varies from 2 to 10 cm, and more.

The chemical composition of ice: calcium (sometimes sodium) hydrocarbonate ice ultrafresh with total ionic concentration ranging from 20 to 120 mg/l [*Fotiev, 2003, 2012*][3].

Total ionic concentration *in structure-forming* ice *in the clay member decreases with proximity to massive ice layer, while the chemical composition of ice becomes enriched with* HCO_3^- *and* Ca^{2+} *ions.* This indicates that ultrafresh water incorporated into the frozen clays affect greatly both the chemical composition and salinity of saline structure-forming ice of marine origin [*Fotiev, 2003, 2012, 2014*][4].

The presence of 10–12 m wide zone of shattered, very ice-rich (up to 60–80 %) frozen clays with large-scale reticulate cryostructure, where thicker (10–20 cm) subvertical schlieren reach 6 cm in height. The zone occurring as an overburden on the layer of ice bears the evidence of water input from beneath, and is indicative of the *in situ* occurrence of marine

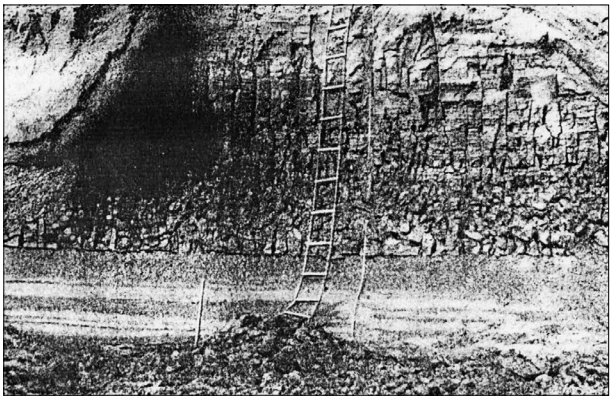

Fig. 1. Massive ice layer in the low reaches of the Seyakha river [*Baulin et al., 1967*].

[2] We should bear it in mind that dimensions of ice layers and volumes of freshwater ice may have been times higher in the eras of their formation.

[3] Nevertheless, quite a number of geocryologists believe massive ice layer to have been formed due to seawater contributions, which is why its composition features high sodium chloride and salinity (up to 350 mg/l) [*Slagoda et al., 2012, p. 17*]. Below, the "marine" hypothesis is discussed in detail.

[4] According to *G.I. Dubikov*: "The exceeding (several times greater) reduction of the pore waters concentration at the interface with layers of ice attests to a significant leaching of rocks due to the induced splitting of sediments into rock mass and free water as the freezing front advances and forces water out into the buffer zone" [*2002, p. 199*].

sediments, comprising massive ice layer [*Dubikov and Koreysha, 1964; Baulin et al., 1967*][5].

Till the present day, discrete ice bodies of small size, sometimes with very fancy configuration, have remained in the extensive marine plains, as a result of selective melting of formerly thick massive ice layers with large volumetric ice content. Such bodies of ice can be classified as massive ice layers only in case if at least part of the representative features of a massive ice layer have remained in them. Both the formation and preserving conditions have never been the same for massive ice layers due to various, yet not fully clear reasons, even within the Yamal Peninsula alone. Suffice it to compare the abundance of thick (30–40 m) massive ice layers in the area of the Bovanenkovo natural gas field and thin (2–4 m) layers in the areas of Kharasavey natural gas field and the Marre-Sale weather station. However, prior to considering the mechanism of water transport to massive ice layers, it is necessary to solve two intermingling tasks: to locate the source of water capable of systematic conveyance of huge volumes of fresh water into the marine sediments during a long period of time; and to determine the timing of the formation of massive ice layers and their host sediments. These problems have been disputable so far, nevertheless, they will not be discussed in detail here due to the fact that earlier, when determining the chemical composition and origin of the "parent" water that formed massive ice layers within the areas of Neito Lake, Bovanenkovo natural gas field and Marre-Sale weather station, they were thoroughly analyzed by the author [*Fotiev, 2003, 2012, 2014*].

THE CHEMICAL COMPOSITION AND ORIGIN OF WATER THAT FORMED MASSIVE ICE LAYERS

Many geocryologists (V.V. Baulin, G.I. Dubikov, M.M. Koreysha, M.O. Leibman, E.A. Slagoda, I.D. Streletskaya, Yu.K. Vasil'chuk et al.) have been studying the chemical composition and salinity of massive ice beds since 1964. The research results and findings allowed the author to infer that the assumed substantial influences of seawater on the chemical composition during the formation of ice has been over-estimated by some researchers, relying on few chemical analyses of ice cores and marine genesis of the saline sediments. In this context, the author, relying further on a detailed study of total ionic concentration and ion-salt composition of precipitates, lake-, sea- and groundwaters, has inferred that the "parent" water that formed massive ice layers injected from thermokarst lakes into the frozen marine sediments [*Fotiev, 2003, 2012, 2014*].

Thus, currently there are two points of view on the genesis of water that formed massive ice layers, one advocating lake water, and the other opting for seawater. Making the right choice is possible only by a thorough comparison of total ionic concentration and ion-salt composition of massive ice layers, and that of lake- and seawaters.

Lake waters, as suggested by the author, is the only ultrafresh source that can provide regular influx of huge amounts of water into the frozen saline marine sediments to form thick (30–40 m), persistent along the strike, laminated massive ice layers. This inference is supported by hydrochemical affinity of ion-salt composition of massive ice layers and lake waters. The chemical composition of ice and lake water are shown as dots, literally intermixed with each other, on the diagrams by *S.A. Durov* [*1961*] (Fig. 2) [*Fotiev, 2012, 2014*].

Seawaters. The views of the geocryologists advocating the "marine" hypothesis, can be illustrated by the following quotes. During the 40 years' time of investigation of massive ice layers and their host sediments G.I. Dubikov wholeheartedly insisted on the correctness of the standpoint, shared also by M.M. Koreysha in 1964, consisting in "a close hydrochemical relationship of pore water with ground ice, which attests to their paragenesis[6] and to the fact that structure-forming ice and massive ice beds formed from water contained in the freezing precipitates at early stages of diagenesis" [*Dubikov, 2002, p. 224*]. "Saturated sands underlain by the marine clays are most likely to have been the source of water forming massive ice beds" [*Streletskaya and Leibman, 2002, p. 21*]. The formation of massive ice bed "may have taken place during the freezing of freshened aquifer confined in the marine clays in the shallow water environment, or immediately after its release from under the sea level" [*Kanevskii et al., 2005, p. 23*]. E.A. Slagoda et al. believe that "ice melts (i.e. ice in the lower ice bed in the Marre-Sale area. – **S.F.**) are characterized by relatively high total ionic concentration (up to 350 mg/l) due to NaCl concentrations (>50 % of TDS), and low content of calcium-magnesium bicarbonates (<10 %), which may be indicative of pore solutions from marine sediments actively participating in the formation of ice" [*Slagoda et al., 2012, p. 17*].

The main disadvantages of the "marine" hypothesis consist in the fact that it fails to explain, firstly, how seawater being of sodium chloride type with salinity exceeding 20,000 mg/l in pore-space solutes of

[5] The absence of zone of shattered frozen clays on the top of massive ice layer is indicative of complete destruction of a member, formerly acting as an overburden.

[6] Their paragenesis was contested by the author upon the detailed analyses of the chemical composition and total ionic concentration of structure-forming and massive ice beds, sampled at the coastal bluffs of lake Neito by *G.I. Dubikov* [*1982*], since structure-forming ice is largely a product of seawater, while massive ice layer formed by lake water. That said, they evolved 'out of sync', with quite lengthy time interval between them [*Fotiev, 2003*].

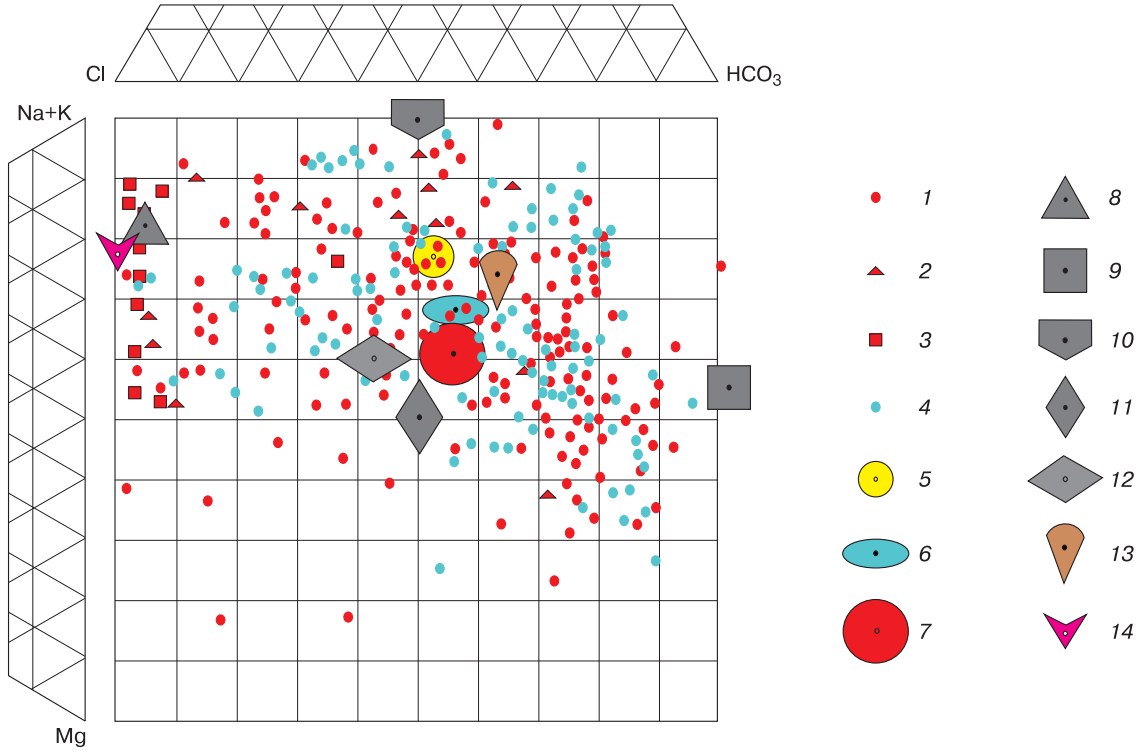

Fig. 2. Compared chemical composition (%-equivalent) of massive ground ice vs. lake waters of the Yamal Peninsula [*Fotiev, 2012, Fig. 3*].

1–3 – dots for ion composition of ground ice with total ionic concentration: *1* – less than 300 mg/l (168 samples); *2* – from 300 to 1000 mg/l (15 samples); *3* – from 1000 to 10 000 mg/l (10 samples); *4* – dots for ion composition of lake water (107 samples); *5–7* – dots for mean ion composition of: *5* – precipitates (43 samples), *6* – lake waters (107 samples), *7* – massive ground ice with total ionic concentration less than 300 mg/l (168 samples); *8–12* – dots for major types of natural waters: *8* – seawater in the present-day ocean, *9* – bicarbonate waters, *10–12* – sulphate waters (*10* – zones of dissolution of mirabilite, *11* – zones of dissolution of gypsum, *12* – zones of sulphides oxidation); *13* – cryometamorphic lake water [*Anisimova, 1981*]; *14* – cryometamorphic seawater, cooled down to –15 °C.

Note. More detailed information on the chemical composition of ground ice and natural waters of the Yamal Peninsula are provided in [*Fotiev, 1999*].

the clay unit or in the pore spaces of saline sands could possibly have morphed into ultrafresh water (20–140 mg/l) to be of calcium (sodium) bicarbonate type; secondly, how pores in the sand unit as thick as 20–30 m can be holding huge (several million cubic meters) volumes of ultrafresh water, exceedingly necessary for a thick massive ice layer and a huge underground hydrolaccolith to develop; thirdly, how clay, pebbles, gravel, and even algae, being signatures of the tundra-specific sub-lake taliks could have incorporated into some individual massive ice layers [*Vasil'chuk, 2010*]. Lastly, the hydrochemical affinity of seawater and ice in thick massive ice layers has still not been corroborated.

In the author's opinion, that is exactly why seawater could not participate in the formation of massive ice layers, as they began to form in subaerial conditions only after complete freezing of both clay and sand members.

TIME OF FORMATION OF MASSIVE ICE LAYER AND THE HOST SEDIMENTS

Until present, the timing of formation of massive ice layers still remains a disputable topic. None of the geocryologists (V.V. Baulin, G.I. Dubikov, A.N. Khimenkov, M.M. Koreysha, M.O. Leibman, E.A. Slagoda, I.D. Streletskaya, Yu.K. Vasil'chuk et al.) did ever try to answer the question of when the formation of massive ice layers commenced, prior to the complete regression of the sea, or much later. Most geocryologists share G.I. Dubikov's viewpoint on massive ice beds to have formed in early stages of diagenetic transformation of saturated marine sediments.

There are other quotes to illustrate this: "The age of intrusive ice (i.e. layers of ice. – **S.F.**) is consistent with the age of the frozen sequence" [*Dubikov and Koreysha, 1964, p. 65*]. This view was supported by *V.V. Baulin*: "their age (i.e. massive ice beds. – **S.F.**)

is determined by the epigenetic freezing of sediments" [*1985, p. 36*].

I.D. Streletskaya and co-authors write: "Freshwater massive ice layers may have formed during the freezing of sands saturated with desalinated water at the clay-sand interface in the shallow water environment, or immediately after elevation above the sea level" [*2005, p. 258*]. *Yu.K. Vasil'chuk* contested that "massive ice beds are syngenetic and heterogeneous" [*2010, p. 66*]. And further he writes: "relatively thin layers of segregated ice may have formed in the foreshores, sand spits and shallow beaches where either syngenetic or diagenetic ice segregation was taking place" [*ib., p. 66*]. *E.A. Slagoda* and co-authors believe that the lower body of massive ice bed within Marre-Sale Cape "is likely to have formed as segregated ice during the epigenetic downward freezing in the open system, with salts subjected to expulsion in the course of water migrating to the freezing front" [*2012, p. 21*]. Judging from these, it is evident that geocryologists have not come to consensus regarding the time of the formation of massive ice layers: whether it occurred prior to the complete regression of the sea or much later, already in the subaerial conditions.

According to the author, this problem can be practically solved solely by the right answer to the question: which type of water, from sea or lake, fed the massive ice layer. As it was convincingly demonstrated earlier, the massive ice layer had been fed by water from the lake located in the thermokarst depression[7], thus unambiguously answering the question of the time when layers of ice and host deposits were formed. Massive ice layers began to form during the onset of subaeral conditions, which followed the complete marine regression, and considerably later than perennial freezing of the marine sediments comprising massive ice layers commenced[8].

MECHANISM OF WATER TRANSPORT TO MASSIVE ICE LAYER

The formation of massive ice beds proceeded within the frozen marine sediments on the Yamal Peninsula have long been discussed by many geocryologists. The two most likely types of ice formation are considered here: segregation and intrusion. Their differences are determined by origin of water involved in the formation of ice, by location of water source (within or outside the enclosing sediments), and mechanism of water transport from the source to massive ice layer[9].

Ice segregation. The author suggests the following diagnostic benchmaks of segregation ice formation:

The source of water is located inside the disperse enclosing sediments.

Slightly bound, or capillary water is the main "nourishing" source.

Pressure-free migration is the major mechanism of water influx to the body of ice in the course of the enclosing sediments freezing.

Ice body forms syngenetically during ice segregation, which takes place in the coarse of the enclosing sediments freezing.

The volume of an ice body formed intrasedimentally in the host sediments, is typically small. It should not exceed (over 9 %) the amount of free, slightly bound and capillary water contained in the frozen sediments. Schlieren ice or thin ice lenses and interlayers, normally, form during the episodes of dispersed deposits freezing.

Hydrochemical unity of the chemical composition and total ionic concentration in segregation ice and all types of water contained in the freezing deposits appears an important criterion of the formation of segregation ice.

However, the proponents of the approach of massive ice layers formation in the process of ice segregation (V.V. Baulin, G.I. Dubikov, M.M. Koreysha, Yu.K. Vasil'chuk, B.I. Vtyurin et al.) have highlighted different characteristic features.

Below are some quotes elucidating on their insights. "To date, most of the geocryologists, engaged in the study of massive ice beds of Western Siberia, share the views on their intrasedimental origin, corroborated by factual data" [*Dubikov, 2002, p. 216*]. "The predominance of segregation ice in the formation of ice bodies (i.e. massive ice layers. – **S.F.**) is supported by their characteristic structural features, such as parallel lamination and consistency of elementary layers of pure ice and ice with admixture of soil over a large extent, lying conformably with the overlying sediments" [*Baulin and Dubikov, 1970, p. 186–187*]. "When freezing , the clayey deposits underlain by water-bearing sands at a depth interval 10–30 m provided for the formation of parallel-layered portion of massive ice bed in the first stage, owing to water migration" [*ib., p. 189*]. The presence of "coarse-grained matter (in the sediments. – **S.F.**) containing free water is a key prerequisite for the formation of thick massive ice layers" [*Dubikov, 2002, p. 209*]. "The

[7] Quite a long time period is necessary for the formation of thermokarst lakes and large sub-lake taliks in the frozen marine deposits.

[8] That was why the inferences that "massive ice beds are syngenetic" made by *Yu.K. Vasil'chuk* [*2010, p. 66*] and by *V.V. Baulin* that "the age of layers of ice correlates with epigenetic freezing of the host rocks" [*1985, p. 36*] can't be accepted.

[9] According to *G.I. Dubikov*, their differentiating criterion consists in the mechanism of transport of water to the freezing front described as " pressurized migration and the freezing of free water and floating layer (injection type), or pressure-free migration and freezing of bound and capillary water (segregation type)" [*2002, p. 216*].

most favorable conditions for the growth of large masses of segregation ice account for closely adjacent contact with water-bearing coarse-grained sediments (aquifer) at the base of massive ice with large reserves of free water capable of transforming into slightly bound water" [*Vtyurin, 1985, p. 61*]. "Layers of ice (i.e. segregation ice. – **S.F.**) with different thickness tend to be confined to the contact boundary of clay, either with underlying sands or with fractured bedrocks containing large pool of water, however, such layers are also encountered in the section of clayey rocks" [*Dubikov, 2002, p. 217*]. And further: "The thickness of layers reaches 20–40 m, their observable extent is 200–600 m" [*ib., p. 222*]. *Yu.K. Vasil'chuk* viewed massive ice beds as intrasedimental ice bodies "formed syngenetically owing to segregation, segregation-infiltration or segregation-congelation ice accumulation, while water-saturated unconsolidated rock masses were freezing through" [*2010, p. 66*]. Later, *Yu.K. Vasil'chuk* wrote: "ice segregation in the context of largely excessive wetting or in the presence of thick aquifers, located near the freezing front, resulted in the formation of thick lenses and layers of segregation ice" [*2012, p. 129*]. The papers authored by the geocryologists thinking that the ice segregation is a key process in their formation, have prompted an unambiguous inference to the author: thick (up to 30–40 m) layers of ultrafresh ice of sizeable extent (up to 1–3 km) and sitting within the frozen saline sediments could not be aggrating during segregated ice formation, all the more so in parallel with the enclosing sediments changing into the permafrost state.

The inference has been justified by: the genetic difference in total ionic concentration and chemical composition of ice and all types of water in the freezing marine sediments; the presence of clay, sand, gravel and pebbles in the ice layers, which could not incorporate into the layer under conditions of pressure-free migration; an inconspicuous amount of all types of water in the freezing marine sediments, being hundreds and thousands times smaller than the volume required for the formation of thick massive ice layers.

Intrusive ice formation. The diagnostic features of intrusive ice formation, suggested by the author, are as follows:

Enormous pressures of water is a necessary condition for formation of layer of intrusive ice.

Lake water is the main source "nourishing" the massive ice layer.

Source of water is located beyond the enclosing sediments, with massive ice layer being an extraneous body therein.

Pressurized fluation is a major mechanism of water delivery to the massive ice layer.

A huge cryogenic pressure created during the freezing of lake water in a closed-system thermokarst basin, is the only force that can drive large volumes of water over long distances from the source.

Lake water incorporated into the strata of frozen saline deposits at the clay – sand interface in the thermokarst basin walls. The intrusions of water were recurrent, which is evidenced by a clear stratification of massive ice layer.

The volume of massive ice layer can be many times higher than cumulative volume of all categories of water contained in the enclosing sediments prior to their freezing.

A hydrochemical distinction of intrusive ice in massive ice layer versus all types of water contained in the freezing host sediments, presents an important criterion for the formation of layers of intrusive ice.

However, many geocryologists (V.V. Baulin, G.I. Dubikov, M.M. Koreysha, Yu.K. Vasil'chuk, B.I. Vtyurin et al.), supporting the viewpoint on intrusive ice playing a key role in the formation of massive ice layers, prioritize other features.

Some quotes can illustrate this. *G.I. Dubikov* and *M.M. Koreysha* write: "massive ice beds formed as a result of water intrusion and freezing during the all-out freezing of areas risen above the sea-level" [*1964, p. 15*]. *V.V. Baulin* and his co-authors have inferred that "large masses of ice aggraded during the freeze-up of water-bearing rocks and lenses" [*Baulin et al., 1967, p. 142*]. The main condition for inception of an ice lens or a layer of intrusive ice in the freezing sediments, according to *V.V. Baulin* and *G.I. Dubikov* should be considered "the formation of closed-type talik, where a huge cryogenic pressure develops as it freezes through, forcing the water or running soil incorporate into the freezing rocks" [*1970, p. 182*]. *B.I. Vtyurin* believes that "massive intrusive ice bed is formed as a result of complete freezing of a limited amount of trapped free water injected into the freezing or frozen rocks, either from aside or from beneath during the epigenetic perennial freezing" [*1985, p. 62*]. Later *V.V. Baulin* wrote: "...intrusive ice beds formed as a result of the newly deposited sediments freezing, provided that they comprised aquifers" [*1985, p. 140*]. Further, he goes on: "We have identified two main types (i.e. of massive intrusive ice bed. – **S.F.**): 1) massive ice beds without appreciably disturbed stratification of rocks, however, inclusive of a zone of shattered overburden composed of ice-rich sediments; 2) laccolith-type massive ice, intrusive stocks with observable evidences of intrusions of water masses ... and deformations of the overburden with subsequent folding" [*ib., p. 142*]. *G.I. Dubikov* assumes: "The intrusive type of massive ice develops as a result of water or flow rock masses incorporating into the freezing clayey rocks" [*2002, p. 217*]. He considers it essential that "the presence of sand horizons susceptive to freezing within the clayey rock mass and containing pressurized water, capable of deforming the overburden and disturbing the initial occurrence of clayey rocks" [*ib., p. 217*]. *Yu.K. Vasil'chuk* wrote that within the foreshore areas and sand spits "the sediments freezing was differentiated along the

Table 1. **Principal distinctions in the conditions of the formation of massive ice layers in the course of accumulation of intrusive ice**

No.	Description of the distinction	According to S.M. Fotiev	According to V.V. Baulin et al.
1	Location of water source, "nourishing" massive ice layer	Outside the deposits, enclosing massive ice layer	Within the deposits, enclosing massive ice layer
2	Origin of water, "nourishing" massive ice layer	Lake waters or water from sub-lake talik	Pore, bound and capillary waters of marine origin
3	The chemical composition of and total ionic concentration in water	M – 20–120 mg/l; $HCO_3 \geq Cl \geq SO_4$, $Ca \geq Na + K \geq Mg$	M – 1000–15 000 mg/l; $Cl \geq HCO_3 \geq SO_4$, $Na + K \geq Ca \geq Mg$
4	Circumstances and localization of cryogenic pressure growth	Freezing of water within the closed-system lake depression	Freezing of water in closed-system talik within the frozen sand unit
5	Timing of the formation of massive ice layer	Much later than the host sediments have frozen through	Concurrently with the host sediments freezing

coast, with some portions of their masses subject to more intense and extensive freezing, while the other remained for a long time saturated with water in the subfreezing state. This eventually led to the formation of closed-system water-saturated talik zones, where the prerequisites for intrusive ice accumulation... and intrusive massive ice beds formation were created" [*2010, p. 66*].

The bottom line is that V.V. Baulin, G.I. Dubikov, M.M. Koreysha, Yu.K. Vasil'chuk, B.I. Vtyurin and other geocryologists share the view that it is possible for thick (up to 30–40 m) largely extending (as far as 1–3 km) layers of ultrafresh intrusive ice to form under the conditions that: 1) concurrently, the enclosing marine sediments are subject to perennial freesing; 2) there exist significant genetic differences in the chemical composition of intrusive ice and all categories of water present in the surrounding sediments; 3) the freezing sediments contain exceedingly small cumulative volume of all categories of water, which is hundreds and thousands times less than the volume of water required for the formation of massive ice layer; 4) cryogenic pressure was created in the course of water freezing in the closed taliks formed in the sand horizons. With these conditions applied, the author thinks, that thick layers of ultrafresh intrusive ice could never have incepted within the marine saline sedimentary sequence.

However, the author suggests that the formation of intrusive ice has proven to be a critical process, controlling the formation of thick ultrafresh laminated massive ice layers in the frozen saline marine sediments. The formation of intrusive ice occurred under the following conditions: 1) lake waters "nourished" the massive ice layers, which hydrochemical affinity has been ascertained; 2) water was supplied to the massive ice layer under enormous cryogenic pressure, generated by the freezing of water in a closed lake depression, or (more rarely) when water freezes in closed sub-lake taliks. A distinct stratification of massive ice layer signify repeated (multiple) intrusions of lake waters.

As can be seen from the above, we are dealing currently with two fundamentally different points of view on the prerequisites for ultrafresh massive ice layers to form during the formation of intrusive ice within the marine saline sediments (Table 1).

DEVELOPMENT STAGES OF THE MARINE PLAIN AND FORMATION OF MASSIVE ICE LAYER

Stage I. *Marine regression, draining of plain surface, the onset of perennial freezing of sediments.* As is known, marine sediments began to cool and freeze already during the marine regression. Following it, the sediments began their active and progressive freezing downward from the drained surface of the plain (Fig. 3, I).

Stage II. *The formation of thermokarst lakes and sub-lake taliks* are likely to have started in the period of climate warming. The warming, however, was not sufficient for the permafrost degradation from the surface, but it proved fairly potent for thermokarst process to begin and for lakes and sub-lake taliks to start developing. At this stage, sand lenses containing cryopegs tend to differentiate in the frozen sand unit (Fig. 3, II). Relict lake have remained within the marine plains in the form of vast hasyreys.

Stage III. *Penetration of lake water into the frozen sediments* became possible only when absolute marks of the freezing lake bottom dropped lower than absolute marks of the clay-sand contact zone in the walls of the thermokarst pit (Fig. 3, III). Continuous ice cover establishing onto the lake was followed by developing of a closed system within the lake basin. Lake water freezing in the closed-system basin has gained enormous cryogenic pressure, allowing it to make way through the contact zone along the cryogenic aquiclude into the frozen sediments. An aquiclude was presented by the top of frozen sands unit[10].

[10] Had the sands been not frozen, then pressurized water would have percolated into the sand member; on the contrary, it penetrated into the sub-bottom layer of the frozen saline clays, causing the deformation of the unit. A large-scale reticulate cryostructure has developed there, with vertical schlieren of ultrafresh ice being much thicker than horizontal (Fig. 3, III).

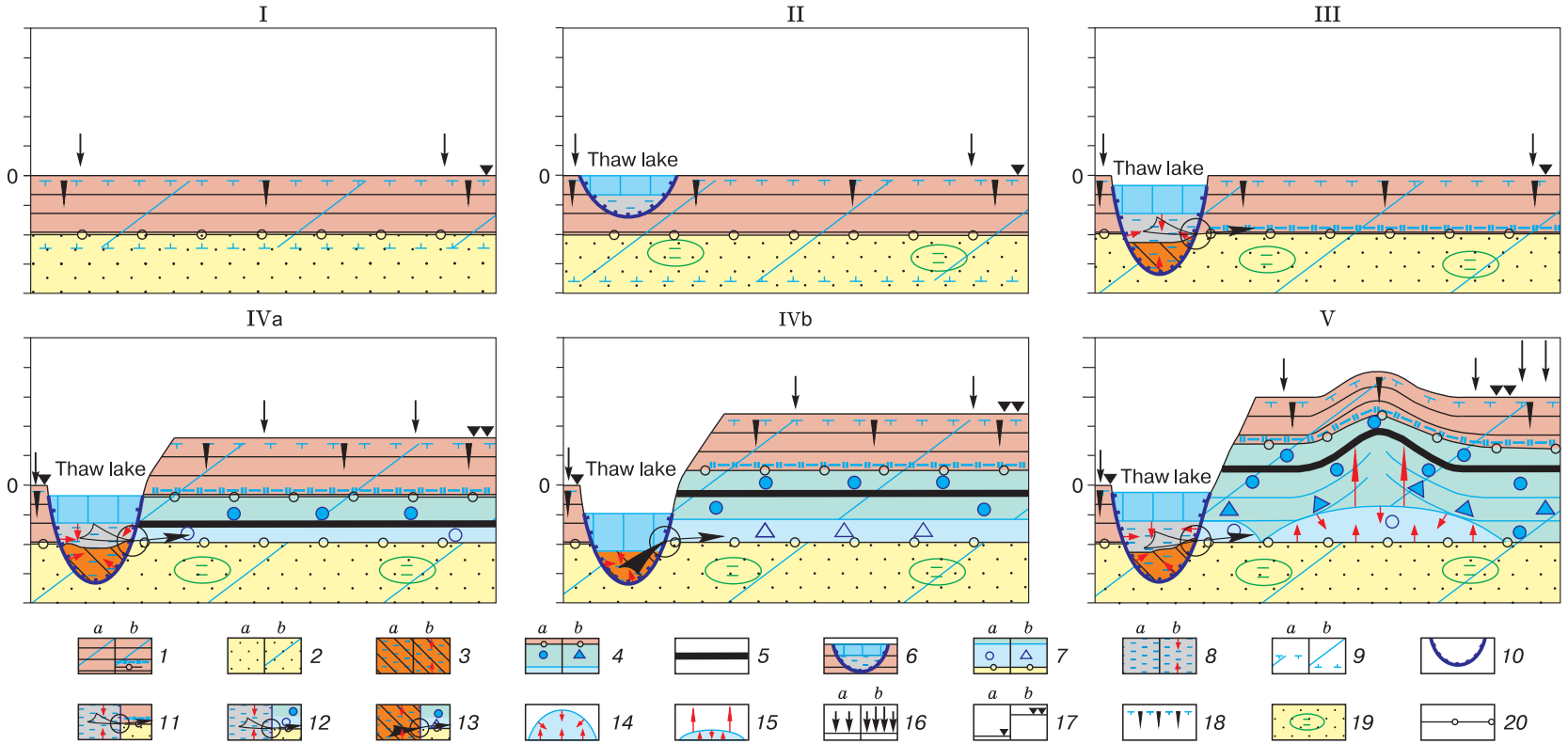

Fig. 3. Stages of development of the marine plain and formation of massive ice layer.

I – marine regression, draining of the plain surface, commencement of perennial freezing of deposits; II – formation of thermokarst lakes and sub-lake taliks; III – penetration of water into the strata of frozen lacustrine deposits; IV – layerwise upward aggradation of ice: IVa – formation of transparent ice layer, IVb – formation of ice layer enriched with mineral inclusions; V – formation of underground hydrolaccoliths. *1* – saline clay: *a* – frozen, *b* – frozen, shattered, strongly ice-rich with thick subvertical schlieren; *2* – saline sand: *a* – non-frozen, *b* – frozen; *3* – taberal water-bearing strata: *a* – non-frozen, *b* – within freezing closed-system talik with progressively growing cryogenic pressure; *4* – ice layers inside the massive ice layer: *a* – transparent, *b* – non-transparent with mineral inclusions; *5* – ice-soil layer; *6* – lake ice; *7* – layers of water: *a* – pure, from lake, *b* – muddy, from sub-lake talik; *8* – lake water: *a* – pressure-free, *b* – freezing, with growing cryogenic pressure; *9* – cryogenic strata: *a* – top, *b* – base; *10* – sub-lake talik boundary; *11–13* – zones of water inflow into frozen sediments: *11* – lake water, along the frozen sand – frozen clay units contact boundary (III), *12*, *13* – along the contact boundary: top of frozen sands–bottom of massive ice layer: *12* – lake water (IVa, V), *13* – waters or liquefied sand loam derived from talik (IVb); *14* – layer of water, freezing within the closed system with growing cryogenic pressure; *15* – cryogenic pressure causing deformation in massive ice layer and clay unit; *16* – top down cooling of the frozen rock mass: *a* – uniform, *b* – non-uniform; *17* – elevation of the marine plain surface: *a* – after the marine regression, *b* – after the formation of massive ice layers; *18* – polygonal wedge ice; *19* – sand lenses with cryopegs; *20* – lithologic boundary.

Stage IV. *Layerwise upward aggradation of ice*. Given the thickness of ice on the lake was less than its depth, highly pressurized pure lake water migrated to the base layer of ice from the closed-system lake basin (Fig. 3, IVa). In contrast, when lake ice thickness was greater than the depth, then muddy water or liquefied sediments from water-bearing taberal deposits were contributed from the sub-lake talik (Fig. 3, IVb). In the first case, the freezing lake water produced a layer of glassy ice, whereas impurity- and mineral inclusion-rich massive ice layer, i.e. ice-soil, was formed, in the latter case[11].

The presence of sand, gravel, pebbles and algae, as well as interlayers of ice soil in discrete layers indicates that the water flowed from the lake or sub-lake talik did not filtrate through the sand strata. The pressurized water flowing through the top of the cryogenic aquiclude migrated to various (sometimes, appreciable) distances along the base of massive ice layer. Relying solely on this assumption, the presence of sand, gravel, pebbles and algae might be found within discrete ice layers. Given the low-temperature permafrost conditions, a thin layer of water is subject to instant and uniform freezing over the entire strata [*Fotiev, 2009*]. The volume of water layer increased by 9 % during its freezing, which caused a uniform areal frost heaving, without damaging the horizontal bedding of individual layers. As a result of the areal heaving both massive ice layer and clay unit were lifted to a height equal to the thickness of the newly formed ice layer. The marine plain surface height has risen, respectively.

Layerwise aggradation onto the bottom of massive ice layer lasted as long as at least three types of natural conditions were persistent. Firstly, the volume of lake water provided a continuous formation of multiple ice layers proceeded throughout the developing massive ice layer. Secondly, absolute mark of the freezing lake bottom (and sometimes that of sublake talik) has always been lower than absolute level of the clay-sand interface zone in the walls of the lake basin. Thirdly, the uniform cooling progressing from the permafrost table provided for uniform freezing (both in terms of depth and rates) of layer of water on the top of the cryogenic aquiclude, and for the formation of another ice layer with stable thickness throughout the extent of massive ice layer. It's only when these conditions combined, horizontally layered massive ice layers up to a 30–40 m thick with length measured in hundreds of meters were able to form within the marine plains. After thick massive ice layers of large extent formed, absolute marks of the marine plain surface in some areas have risen 30–40 m higher[12].

Stage V. *The development of large underground hydrolaccoliths* may have coincided with the final stage of the formation of massive ice layers. Henceforward, the depth and rates of the permafrost rocks downward cooling have failed to be identical. This was largely dictated by the snow cover uneven distribution throughout the area, owing to essential erosion dissection of formerly horizontal surface of the plain and by the erratic pattern of vegetation cover proliferation. Uneven freezing of the succeeding layer of water in the conditions of systematic water influx the base of the massive ice layer have invariably led to the formation of frost-susceptive closed systems with water subject to freezing. When freezing, the water generated huge cryogenic pressure and, in turn, affected the massive ice layers and of clay unit, to the extent that they became arcuate and formed an underground hydrolaccolith, with the size dictated by the amount of the freezing water (Fig. 3, V).

A modern analogue for the above described cryogenic process can be large hydrolaccoliths formation in the bottoms of the drained river valleys owing to the nonuniform freezing of the underflow river waters in the alluvial sediments of underflow taliks.

CONCLUSIONS

Relying on the research results conducted by the geocryologists who studied massive ice beds and the surrounding frozen marine saline deposits on the Yamal Peninsula for more than 40 years, the author has come up with the following conclusions.

- Lake waters is the only source that can provide a regular inflow of huge (several million cubic meters) volumes of ultrafresh water into frozen saline marine deposits, and induce the development of thick massive ice layers, persistent along the strike, and huge underground hydrolaccoliths. The inference is corroborated by hydrochemical affinity of ice and water in thermokarst lakes.
- It has been proved that the formation of massive ice layers occurred in the subaerial environments after the complete marine regression and it took place long after perennial freezing of the sediments enclosing the massive ice layer. The hydrochemical affinity of ice and water in thermokarst lakes served as a substantiation thereof, since a long period of time is required for thermokarst lakes to develop after the complete marine regression.
- Seawaters could not participate in the formation of massive ice layers. This conclusion is ascertained not only by genetic differences in the total ionic concentration and chemical composition of intrusive ice and seawater, but also by the formation of

[11] Distinct parallel boundaries of individual ice layers attest to multiple (probably, seasonal) injections of water, given each subsequent injection occurred only after complete freezing of the water layer from the previous episode.

[12] This fact has so far has failed to be taken into account in the Quaternary paleorelief reconstructions for the Yamal Peninsula.

massive ice layer in subaerial conditions, followed long after the complete marine regression.

• The most likely conditions of inception of massive ice layers during the processes of segregation and intrusive ice formation have been analyzed, which revealed to what extent the conditions differ in: 1) genesis of water involved in the formation of massive ice layers, 2) location of the source of water (inside or outside of the sediments, enclosing massive ice layer), 3) mechanism of water transport from the source to massive ice layer (pressure-free water migration or pressurized water flow).

• It has been ascertained that thick (up to 30–40 m), persistent along the strike, massive ice layers could not form during segregation process and the more so, syngenetically, when the enclosing sediments were changing into the permafrost state.

• It has been proved that the process of intrusive ice accumulation plays a leading role in the formation of essentially thick (up to 30–40 m), persistent along the strike layers of ultrafresh ice within the frozen saline sediments: 1) thick laminated massive ice layers formed by repeated (multiple) influx of ultrafresh lake water into the frozen strata; 2) lake water intrusion, its delivery from the lake to massive ice layer, and progression to appreciable distance along the base of massive ice layer at the top of cryogenic aquiclude proceeded under huge cryogenic pressure created within a closed-system thermokarst depression during the freezing of lake water.

• An ice body occurring in the shape of the layer and formed as a result of repeated (multiple) intrusion of lake water into the frozen deposits, is proposed to be referred to as repeated-intrusive massive ice layer.

• The five stages of the marine plains development in the areas where massive ice layers formed are: Stage I – marine regression; draining of the surface of plains; the onset of perennial freezing of deposits; Stage II – formation of thermokarst lakes and sub-lake taliks; Stage III – penetration of lake water into the interior of the frozen lacustrine deposits; Stage IV – layerwise upward aggradation of massive ice layers; Stage V – formation of underground hydrolaccoliths.

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