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UNDERGROUND GLACIATION OF EURASIA: MACROSTRUCTURE AND HISTORY OF DEVELOPMENT

V.I. Solomatin

Lomonosov Moscow State University, Faculty of Geography,
1, Leninskie Gory, Moscow, 119991, Russia; vi.solomatin@mail.ru

The paper analyzes the most important events of the of underground glaciation development and distribution, comprising the processes of its formation and spatial-temporal changes. The author has provided definition of cryolithogenic formations and formulated a new concept of the macrostructure of syncryogenic ice formation zone. A permafrost-facial analysis of the Ice Complex has revealed the mechanism for replacement and redeposition of the enclosing deposits by the growing syngenetic ice wedges. The principle of the similarity of geographical space and paleogeographic time is formulated.

The space-time structure of underground glaciation, paleogeography, cryolithogenic formations, syngenetic ice wedges, sedimentogenesis, Ice Complex, the similarity principle

INTRODUCTION

The structure and geography of the modern area of underground glaciation of Eurasia began to develop with the onset of the first cooling stage when the base of the cryosphere lowered below earth's surface, and were subject to modification in the aftermath of climate changes and affiliated geological and geomorphological processes and phenomena. The primordial forms and extents of underground glaciation appeared in high latitudes and mountainous regions, and as their temperatures decreased, expanded into the lower-lying areas and latitudes. During the warming episodes, degradation of ground ice proceeded in reverse order. The appearance of primordial permafrost and ground ice is associated either with the initial stages of permafrost zone aggradation, or sediments refreezing after their temporary thawing during episodes of climate warming, and therefore both belong to the epigenetic type. As the climate became colder, the lower limit of permafrost descended, whereas permafrost table has risen, depending on certain lithofacies and zonal-climatic conditions, on account of syncryogenesis of sediments accumulating on the frozen substrate. In the absence of geomorpholithogenic criteria for determining the time of epicryogenesis of deposits, the age of syngenetic ice is determined from the dates of the enclosing deposits. The structural-genetic analysis methods underlie the immanent paleocryogenic reconstructions.

GUIDING PRINCIPLES IN RECONSTRUCTIONS OF UNDERGROUND GLACIATION HISTORY

Various forms of ground ice, their origin, structure, occurrence and distribution patterns thus cumulatively constitute the criterion for paleobiological reconstructions. Specifically, the extensive syngenetic wedge ice aggradation during the formation of the Ice Complex attests to the continental climatic conditions and the absence of terrestrial forms of glaciation at that time and area. Buried fossil glacier ice, on the contrary, is a compelling evidence for the glaciation reconstructions. *E.M. Katasonov* [*1965, 2009*] has developed the basis for the permafrost-facies analysis and reconstructions of conditions of permafrost aggradation. Traces of ground ice within the thawed country deposits can survive in the form of pseudomorphs (soil wedges in place of the thawed wedge ice), comminuted structures of soils resulted from thawing of texture-forming ice schlieren or in the form of cryoturbations (traces of soil deformation caused by uneven stresses and strain of soils during the freeze–thaw processes). Because of complete destruction of both the deposits structure and cryotexture during their thawing, degradation of cryogenetic formations with high content of ground ice, e.g. Ice Complex (where total ice content reach 60–70 %) or massive ice (whose beds are up to tens of meter in thickness and locally have nearly continuous bedding) does not leave geological imprints. Locally, evi-

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dences of permafrost polygonal patterned ground, or bulgunnyakhs persist, although the latter have proven to be most vulnerable to the processes of thermodenudation (erosion). As such, geomorphological traces of ancient glaciers provide proxy evidence to reconstruct the history of underground glaciation. Ground ice largely account for the lower zone of congelation ice aggradation in the cryosphere, gravitating to its sector with a continental type climate, while glacier ice tends to form in a humid marine climate. Terrestrial glaciation in one segment of the cryosphere is accompanied by its underground analog in the other. The areas of terrestrial and ground ice formation appear to be conjugated (not coinciding) in time and space. The traces of glacial activity in the geological sections (moraine, fluvioglacial and other glacial formations) and geomorphological forms of glacial erosion and accumulation can therefore be taken as benchmarks of the areas and patterns of permafrost and underground ice distribution.

Both timing and paleogeographic conditions of the onset of underground glaciation can vary widely. However, there exist general laws and patterns of its formation, which we propose to be considered on the basis of paleogeographic representations and analysis of macro-scale features of the underground glaciation framework. Paleogeographic features of underground glaciation were largely controlled by climatic fluctuations and alternations of warm and cold cycles, as well as were subject to changes not only in time, but also in space, including zonal and regional differentiation, which was discussed previously [*Solomatin, 1981, 1986, 2013*]. In the context of similar geological and geomorphological characteristics, the variations in climatic conditions (and, consequently, their derivative – permafrost conditions) of any area driven by cooling (or warming) episodes reflect the succession of zonal changes.

In other words, **the area-specific climate-driven trending in paleogeographic events should coincide with its zonal changes dynamics, taking into account geological and modulations within the geomorphological framework**.

It can be assumed that the principle of comparability of temporal and zonal transformation of natural environmental complexes is a universal geographical rule. The current latitudinal zonation of natural environments illustrates the trends in its transformations under climate changes in past.

Syngenetic ground ice can be extant in the frozen state primarily in high-latitude and high-altitude areas of the permafrost distribution where negative thermal cycles persist in the upper horizons of the lithosphere even during climate warming. It can be also ascertained a priori that the most ancient frozen (both epi- and syn-cryogenic) deposits also tend to expand into high-latitude and high-altitude permafrost areas with a steadily cold climate. Permafrost deposits and ground ice within cryophilic deposits are known to be highly conservative, which facilitate preservation of permafrost, such as peat and soils of fine grained composition, in contrast to more dispersed deposits with less heat-insulating properties.

We should bear it in mind that besides climate warming, activation of geomorphologic destructive cryogenic processes, which include thermokarst, erosion, slope processes etc., might as well be triggering factors for degradation of ground ice. Areas with flat topography are therefore more favorable for preservation of the ancient (massive) ground ice, than areas with high-energy relief.

The entire complex of spatio-structural features of the area of underground glaciation (starting from ice structure, its occurrence/distribution patterns and interactions with the host sediments, to end with the region-specific geography, macrostructure and relationships between major forms of underground glaciation) developed under specific conditions of climatic cooling and cryolithogenesis, which therefore can be helpful in paleogeographic reconstructions.

Importantly, the above-mentioned cryolithological methods of the investigation of history of underground glaciation are used in complex with the whole spectrum of paleogeographic and Quaternary geology methods.

EVOLUTION OF UNDERGROUND GLACIATION

The onset of glacial epoch (Ice Age) prompted the lowering of temperature range of phase transitions of water and of the cryosphere base. The existing data on ancient glacial-cryolithogenic epochs [*Ershov, 2002*] and geological evidence of their occurrence (moraine-like tillites) revealed by frozen sediments since Early Proterozoic shed little light on the ground ice structure and distribution at that time.

The materials available on the permafrost conditions in the Middle Pleistocene appear more informative because of a maximum expansion of terrestrial glaciation reported in the Atlantic sector of the Arctic and on the Islands of The Canadian Arctic archipelago [*Velichko, 1999*]. In southern European and North Africa regions the traces of permafrost were found to be extant to a height of 1300–1500 m [*Baulin and Danilova, 1998*]. In the north-east of European Russia, the frost penetration depths were reported to be 400–600 m [*Oberman, 1981; Sukhodolskii, 1982*], up to 600–800 m in the lower reaches of the Yenisei in Western Siberia [*Baulin, 1985*], and up to 1500 m in the mountains of Verkhoyansk [*Nekrasov, 1976*]. At this, neither any significant forms, nor occurrences of ground ice confidently dated older than the Pleistocene have hitherto been identified.

The earliest Late Pleistocene was marked by a significant warming with maximum falling on the period spanning 130–120 ka BP (marine isotope stage MIS 5e) [*Emiliani, 1971*]. This event caused ground ice melting in most of the permafrost area, except for the highest-latitude regions in the northeast of Eurasia and Arctic islands.

Cooling and expansion of the underground glaciation is reported from the late Pleistocene Ice Age [*Velichko, 1999*]. According to the most recent studies [*Hughes et al., 2015*], the glacial shield of Western Eurasia reached its maximum 21 ka BP. The mean annual air temperature (MAAT) was 5–6 °C lower than today's [*Emiliani, 1971*]. Assumingly, conditions for distribution of permafrost, including syngenetic ice developed in the area beyond the ice sheet extent.

At the end of the Late Pleistocene period of the underground glaciation, during the time interval spanning from 14 to 10 ka BP, climatic conditions were characterized as unstable, marked by short-term and sharp (by 2–4 °C) temperature differentials (rises and falls) against the backdrop of the generally warming climate. The so called isotope shift reported at the turn of the Pleistocene–Holocene, according to numerous data, including the oxygen isotope analysis results and stable isotope measurements on ice wedges showing a drastic (by 2–4 ‰) shift towards heavier isotopes, thus implying warmer winter temperatures, i.e. climate warming [*Velichko, 1999*]. The implications are that the permafrost area began to shrink, accompanied by northwardly displacement of its zonal boundaries, as well as by the activation of thermal denudation processes in the low-temperature permafrost regions. The Holocene Climatic Optimum roughly dated 8–5 ka PB is attached a great importance to in terms of the permafrost and underground glaciation development in northeastern Eurasia [*Velichko, 1999*]. The detailed studies of the of Greenland ice cores revealed a sharp increase in methane content which is assumingly associated with the warming events and affiliated vegetation change in the Northern Hemisphere at the turn of the Pleistocene–Holocene (11.6–11.5 ka PB) [*Orombelli et al., 2010*].

A significant sea level rise and transgression event are assigned to that same period. In the Late Atlantic time (ca. 5 ka PB) average annual air temperature has warmed by 3–4 °C in North Yakutia [*Orombelli et al., 2010*]. Supposedly, permafrost deposits locally experienced thawing from the surface to a depth of 50–150 m in the northeast of European Russia and in the north of the West Siberian permafrost zone [*Baulin, 1985*]. The thermoabrasion and thermokarst – induced degradation of ice-bearing permafrost deposits were probably taking place at that time in most of the Laptev and East Siberian seas, while the coastline retreated to its present-day position. Numerous data indicate that in the Pleistocene, land areas composed of the Ice Complex deposits extended as far as the outer edge of the shelf [*Soloviev, 1981; Tumskoy, 2012*]. The air temperature decreased following the Holocene Climatic Optimum, which was associated with the southwardly latitudinal advancement (by 2–5°) of the boundaries of underground glaciation. Many areas are characterized by the regrowth of ice wedges within peatlands and syncryogenic sediments. For the time being, the multidirectional processes of underground glaciation development are primarily observed along with syncryogenesis and wedge ice aggradation; while the Ice Complex remains (yedomas) continue to degrade in the modern high latitude floodplain and lacustrine-boggy deposits.

CRYOLITHOGENIC FORMATIONS

During the cooling eras, beginning from the Middle Pleistocene, aggradation of major ground ice bodies (cryogenic structures) and the most voluminous paleogeographic syncreolithogenic formations preserved till the present time as: a) Ice Complex within the permafrost – underlain areas with a sharply continental climate in the northeast of Eurasia, the New Siberian Islands and Alaska; b) buried glacier ice in the moderately continental climate sector of permafrost distribution in the northeast of European Russia, in the northern West Siberia, in the northern parts of the New Siberian Islands and in the Canadian Arctic.

Each of the above mentioned ground ice aggradation phenomena is characterized by its own morphological traits, an array of genetic types of ground ice, a variety of cryolithogenic facies of host sediments and corresponding geographic areas of distribution.

Whereas cryomorpholithogenesis of the Ice Complex has its own specific structural features: enormously voluminous wedge-ice aggradation in the monotonous sediments, silty in composition, locally sandy and admixed with gravel, with characteristic deformation of layers containing sediment on the contacts with ice wedges and abounding with inclusions of slightly decayed plant and fauna residues, the so-called mammoth fauna.

The buried glacier ice, in contrast, is characterized by diverse cryolithogenesis of ice and host deposits. Ice layers largely vary in size, shape and structural features – from massive, relatively homogeneous, to very complicated on account of different types of deformations, as well as numerous inclusions, up to large rock monoliths. Sheet ice deposits are located often discretely, in the form of large, but scattered bodies whose boundaries on the Yamal Peninsula are instrumentally traced over a few kilometers along the strike and tens of meters along the profile. Enormous accumulations of buried massive glacier ice take significant part of shallow occurring sediments, which were also discovered on the Gydan Peninsula, in the lower reaches of the Yenisei, on the New Siberian Islands, in the North of Canada and on the Islands of the Canadian Arctic archipelago. Southwardly, their deposits occur more sparsely, diminishing in size. Although the boundaries of the area of buried glacier ice distribution can not yet be strictly outlined, it stands to reason that, unlike the Ice Complex, they gravitate to the above indicated high-latitude regions with a more moderate climate.

Such major and distinctly pronounced cryolithogenetic complexes, and strikingly differing from any others formations of underground glaciation with specific traits of cryomorpholithogenesis and a characteristic diversity of ground ice and specificity of permafrost-facies structures of the host sediments, with their own areal and geographical distribution, are proposed to be termed *cryolithogenic formations*, or *cryoformations*.

Among the known sections, only few exhibit joint occurrence and direct contact between the considered cryoformations. Thus, the observed frozen siltstones in the Seyakha (Mutnaya) River basin, Yamal Peninsula, comprised large syngenetic ice wedges composing a 20-m alluvial terrace embedded in the outliers of the upland surface with massive occurrences of buried glacier ice [*Solomatin and Konyakhin, 2004*].

In the lower reaches of the Yenisei River, where the coastal bluffs exhibit deposits with massive ice, I.D. Streletskaya and colleagues [*Streletskaya et al., 2013*] documented in the upper part of the section the yedoma-like loamy horizon with reduced thicknesses (7 m), which contained inclusions of clastic material and syngenetic ice wedges. In the Labaz lake sections (North-Siberian lowland), A.Y. Derevyagin and colleagues [*Chizhov et al., 1997*] revealed a horizon of the Ice Complex stratigraphically lying above the sediment with tabular ice. In the northern parts of the New Siberian Islands, the Ice Complex section with reducing thickness underlain by massive ice is described in [*Anisimov et al., 2006*]. Note that investigations of contacts between the cryoformations, as well as patterns and controls of their spatial localization and permafrost-facies conditions of their development are critical for reconstructions of the evolution of syncryolithogenesis.

PERMAFROST-FACIES ANALYSIS OF THE ICE COMPLEX

The cryolithogenetic formation of the Ice Complex (IC) includes the 30–40 m thick relief forming permafrost strata composed by the largest syngenetic ice wedges with host siltstones and a specific permafrost-facies structure. Ice wedges cross-cutting the entire IC thickness with the lower, tapering ends intruding into the underlying sands or basal pebbles which overly the top of the bedrock (along the coastal lowlands in the foothills of Yakutia).

The uniqueness of IC formations consists primarily in their relatedness exclusively to particular areas and time of their development. No analogues of such cryogenic morphogenesis have been reported from any other regions or at any other time of formation of underground glaciation. At this, a paradoxical combination of seemingly inconsistent landscape-facies conditions of sedimentation and freezing is observed in the structure of the IC formations. The most popular concepts of the IC evolution provided in the literature describe its formation in the conditions of syncryogenic floodplain alluvial deposits in extremely harsh and sharply continental climatic conditions of the lowland plains in the North-East of Eurasia and Alaska [*Popov, 1959*]. However, the cross sections with IC formations exhibit no stream-bed facies which might provide for accumulation of exceedingly thick stream sediment [*Shancer, 1966*]. Besides, thick and vertically continuous ice wedges are also inconsistent with the assumption of periodic rewashing of the deposits accumulated as a result of the river channels meandering.

Among the characteristic features of the structure of ice wedges and the host IC deposits, the most prominent is the thick body of ice wedges having a vertically oriented slate bubble cryostructure, which resulted from the metamorphism affected by multiple contraction–expansion cycles. Only a few small fragments of the original structures of water crystallization in frost cracks – elementary veins – are retained in the ice. The contractual mechanism of formation of ice wedges was revealed by *P.A. Shumsky* [*1955*]. In the wake of the heated debates about the role of mechanism of their frontal growth *V.I. Solomatin* [*1986, 2013*] provided a compelling evidence that ice of elementary veins is the only source of ice wedge aggradation. The subsequent cycles of thermal contraction-expansion and extensional displacements of the host sediments rising upward along the lateral contacts lead to metamorphosis of ice and the appearance of slate bubble cryotextures and laminae of pure ice on the lateral contour of ice wedges. The cryolithogenic structure and composition of IC formations attest to: 1) the extremely severe and extreme continental climate conditions; 2) the excessive moisture content for wedge and segregated ice formation. The volume of wedge ice aggradation allows assuming that multiple frost cracking events appear to be multiply recurrent during each spring period (rather than occurring once a year), as intermittent frost-cracking and ice aggradation are caused by frequent and sudden changes in temperature (e.g., diurnal) of the near-surface sedimentary horizons.

The IC section is composed of a series of vertically succeeding identical packages of sediments up to 2 m thick, in varying degrees composed of deformed sedimentary layers impregnated with segregated ice. The contact between the packages is sharp and unconformable: the base of the overlapping packages truncates the deformed layers of the underlying series along the even horizontal contact. Laminae of sediments and segregated ice occur horizontally at the base of each package. Upwards, they are by far more strongly bent at the contact with wedges, to the extent that their position become vertical to the upper contact with the package. At the level of horizontal interlayers of host sediments the contacts of ice wedges are complicated by "shoulders" intruding into the rock as wedge-shaped rims of wedge ice with a horizontal upper contact and adjacent deformed layers parallel-inclined to the lowermost layers. Ice wedge is thinning upward from the broadened part (marked by appearance of the "waist-line"). At the top of each package the bent layers of soil and ice form a "bowl" filled with peat-rich soil. Note that the described sediments are saturated with segregated ice whose content reaches up to 50 % of the total volume. The structure of soil and ice layers indicates that initially their position was horizontal, and then deformed by the developing ice wedges. If, hypothetically, we straightened the layers, their ends in the packages on both sides of the wedges would not close in on, which means that their middle part was squeezed out onto the surface by the growing ice wedge. This phenomenon in the structure of the IC strata consist in the truncation of the enclosing sediments clearly indicating periodic hiatuses in sedimentation and partial erosion of the surface. At this, there are no stream bed facies on the contact between the packages, whereas the growth of ice wedges, as already noted, proceeds continuously, irrespective of the sedimentation dynamics.

Accumulation of the enclosing sediment thus proceeded in the following manner/locations: a) in bodies of water in the absence of stream-bed alluvium; b) in water basins shallow enough to preclude thermokarst processes and heads of ice wedges were preserved, along with the conditions favorable for syncryogenic freezing of the sediment accumulating at the bottom and for voluminous formation of segregated and wedge ice; c) water basins were drained at the beginning of the warm season, providing thereby for the tundra biocenoses flourishing and nutrients for the abundant mammoth fauna; d) given that annual sediment transport pattern appeared to be rhythmic, although tending to drastic changes at certain stages of the hydrological regime and causing partial erosion of sediments of the previous series, however, showing no evidence of stream-bed facies, to be overlain by a new series of sediment. The formation of each package of sediment was therefore triggered by the erosion and flattening of the surface of polygonal patterned ground probably along with a periodic increase in the drainage and thaw-penetration to a shallow depth slightly affecting permafrost table, without approaching ice wedge head, though. The horizontally occurring layers in the lower part of the packages are also assigned to this stage. The absence of traces of stream-bed facies remains unfathomable. As a working version, it can be assumed that the surface erosion of the polygonal-rolling tundra microrelief proceeded in the early stormy spring, with the water-flow sourced from snow melting, which is why the water was pure, deprived of suspended ground matter and re-deposited only products of washing of the topmost soil from the surface of thawed layers in early spring, leveling off the surface of the tundra, however, not eroding the tops of ice wedges. The yearly sedimentation probably continued, whereas the ice wedge didn't extend upward owing to the increased depth of water flow and to rising soil temperature, but they continued to rapidly grow in width. At some stage, the accelerated hypsometric rise of the surface due to the growth of ice wedges to the level of spring rise of the water-level arrests sedimentation, prompting thereby partial dehumidification of the surface, lowering soil temperature, and activation of the ice wedge growth upwards. The growing wedge forces the host rock out above its upper contact, deforming thereby its layer structure at the contact, with the amplitude of deformation progressively increasing, as the ice wedge grows in width and upwards. The rolling relief of the tundra has thus developed, while the polygon centers tend to become convex allowing for accumulation of peaty lenses. The dilatation cycles of ice wedges growing predominantly upward tend to be recurrently repeated, in line with the cycles of the formation of the enclosing deposits.

Therefore, growing ice wedges replace and expulse a considerable amount (commensurable to their size) of sediment onto the surface. The expulsed sediment once again is involved in sedimentation, i.e. redeposition on the account of aggradation of syngenetic wedge ice.

The sediment-forming effect of syncryogenic ice formation is manifest not only in the appearance of new deposits within the frozen strata, but also in the volume of ice replacing the host sediments, their squeezing and redeposition in the conditions of polygonal-rolling tundra.

The volume of sediment expulsed and redeposited at the expense of ice wedge aggradation approximately doubles on the account of segregated ice formation. This is augmented by plant residues, and, ultimately, results in the formation of a layer of host sediment commensurate to the vertical build-up of ice wedges, whereas the role of imported sediment becomes minimal.

The proposed scheme however fails to explain the specific features of the structure of the IC deposits, as to: the monotonous pattern of their composition, rhythmic nature and the relationship between the rate of sedimentation and growth of ice wedges, periodic truncation and leveling of the surface of sedimentation, periods of slowed growth of ice wedges in vertical direction and those dominated by their dilatation, succeeded by periods of accelerated upward extension and development of deformations of soil layers on their contacts.

It stands to reason that the issues of hydrological and climatic conditions of the IC development, as well as the determining factors of the unique volume and forms of ice wedge formation within the Ice Complex, its distribution and relationships with other cryolithogenic formations remain to be addressed.

CONCLUSION

The paper has provided a brief overview of the problems of evolution and spatial differentiation of the underground glaciation. The distribution of ground ice masses is governed by the area-specific lithological-facies and zonal conditions and the time of its formation. The concepts of the similarity of the evolution of geographical space and paleogeographic time has been formulated, along with cryolithogenesis of the formation of the Ice Complex and buried glacier ice. The proposed scenario of syncryogenesis of the Ice Complex, explaining its both outstanding and paradoxical permafrost-facies characteristics: unique shape and volumes of ice wedge aggradation and the specific conditions of the enclosing sediment deposition and freezing. The schematics of the sediment-forming effect of ice wedge aggradation has been elaborated.

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