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# The principles of cryostratigraphy

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ABSTRACT

Cryostratigraphy adopts concepts from both Russian geocryology and modern sedimentology. Structures formed by the amount and distribution of ice within sediment and rock are termed *cryostructures*. Typically, layered cryostructures are indicative of syngenetic permafrost while reticulate and irregular cryostructures are indicative of epigenetic permafrost. 'Cryofacies' can be defined according to patterns of sediment characterized by distinct ice lenses and layers, volumetric ice content and ice-crystal size. Cryofacies can be subdivided according to cryostructure. Where a number of cryofacies form a distinctive cryostratigraphic unit, these are termed a 'cryofacies assemblage'. The recognition, if present, of (i) thaw unconformities, (ii) other ice bodies such as vein ice (ice wedges), aggradational ice and thermokarst-cave ('pool') ice, and (iii) ice, sand and gravelly pseudomorphs is also important in determining the nature of the freezing process, the conditions under which frozen sediment accumulates, and the history of permafrost.


**Contents**



## 1. Introduction

Cryostratigraphy is the study of frozen layers in the Earth's crust. It is a branch of geocryology. It first developed in Russia where the study of ground ice gained early attention (Shumskii, 1959; Katasonov, 1962, 1969) and subsequently led to highly-detailed studies (e.g., Vtyurin, 1975; Popov, 1973; Gasanov, 1963; Gravis, 1969; Rozenbaum, 1981; Zhestkova, 1982; Shur, 1988; Romanovskii, 1993; Dubikov, 2002; Seigert et al., 2002; Schirrmeister et al., 2008) that are unparalleled in North America. Cryostratigraphy differs from traditional stratigraphy by explicitly recognizing that perennially-frozen sediment and rock (permafrost) contain structures that are different from those found in unfrozen sediment and rock.

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Cryolithology is a related branch of geocryology and refers to the relationship between the lithological characteristics of rocks and their ground-ice amounts and distribution.

The principal aim of cryostratigraphy is to identify the genesis of perennially frozen sediments and to infer the frozen history of earth material. Today, the permafrost region currently occupies approximately 23% of the earth's land surface. During the cold periods of the Pleistocene it is generally accepted that an additional 20% or more experienced permafrost conditions. Accordingly, knowledge of cryostratigraphy is essential for Quaternary scientists working in the northern latitudes. A second aim of cryostratigraphy is to document the ground-ice conditions in different types of perennially-frozen rock and soil. The latter has significant geotechnical importance in Russia, Canada, Alaska, Svalbard, Greenland and Tibet. A third objective is to correlate sequences of ground ice in contemporary permafrost regions with horizons of former ground ice in past permafrost regions.

## 2. Frozen ground

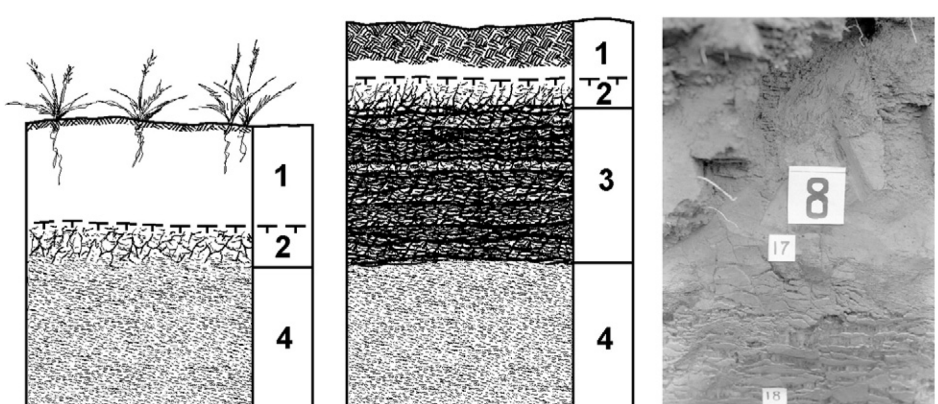
Frozen ground may be *diurnal*, *seasonal* or *perennial* in nature. The latter is termed *permafrost*, namely, earth material that remains below 0 °C for at least two years (Sumgin, 1927; Muller, 1943). In general, the mean annual temperature of permafrost in its stable thermal state is lowest at the permafrost table and increases with depth in accordance with the geothermal gradient. In all types of frost, the physics underlying the freezing process are the same. The major difference between seasonal and perennial frost is that seasonal frost disappears in summer. Seasonal freezing in areas without permafrost involves one-sided freezing (i.e., from the surface downward) whereas seasonal freezing in the permafrost region is often two-sided (i.e., both downwards from the surface and upwards from the underlying perennially-frozen material). Diurnal frost, a relatively well known phenomenon, is not considered in this paper.

In the case of permafrost, the near-surface layer that thaws and freezes annually is termed the *active layer*. Burn (1998) has discussed the terminology and definition of the active layer. In general, active-layer thickness may vary from less than 15–30 cm in peaty terrain and Quaternary-age sediments to over 5.0 m in many igneous and metamorphic rocks exposed to the surface. Thickness also varies from year to year and from locality to locality, depending on controls such as ambient air temperature, slope orientation and angle, vegetation, drainage, snow cover, soil and/or rock type, and water content. In field probing, the active-layer thickness includes the uppermost part of the permafrost wherever either the salinity or clay content of the permafrost allows it to remain unfrozen even though the material remains 'cryotic' (i.e., below 0 °C). The base of the active layer (i.e., the depth of annual thaw) may also vary on annual, decadal and millennia time scales. Accordingly, the *transient layer* includes the typically ice-rich layer marking the long-term position of the contact between the active layer, as defined above, and the upper part of permafrost (Shur et al., 2005). As a result, it is necessarily to recognize a four-layer system of the active layer that incorporates a transient layer at the interface between the active layer and underlying permafrost. These concepts are illustrated in Fig. 1.

Most of the permafrost that occurs in the high northern latitudes today is termed *present permafrost*. It is either in equilibrium with current climate or either aggrading or degrading under prevailing cold-climate conditions. Permafrost may also be *relict*, or ancient, having formed under conditions that no longer exist and which is now preserved under present environmental conditions. Most is usually Late-Pleistocene in age. It can be argued that nearly all present permafrost is relict because climate has warmed in the last 150 years following the Little Ice Age. Permafrost that does not exist today is referred to as *past permafrost* (French, 2008). Its previous existence in now-unfrozen rock and sediment is commonly inferred from disrupted bedrock and the presence of frost- or thaw-related structures. Most past permafrost is of Late-Pleistocene age although permafrost is known to have occurred in earlier geological times.

## 3. Epigenetic, syngenetic and polygenetic permafrost

Permafrost that forms after deposition of the host sediment or rock is termed *epigenetic*. The time lag between accumulation and perennially freezing of epigenetic permafrost reaches thousands and millions of years. By contrast, permafrost that forms at the same time as continued cold-climate sedimentation and causes the base of the active layer to aggrade upwards is termed *syngenetic*. This sedimentation may be alluvial, colluvial (i.e. slump or gravity-induced), aeolian, or lacustrine in nature. By definition, syngenetic permafrost is of the same age (approximately) as the sediment in which it is formed. It means that transformation of sediments at the bottom of the active layer into a perennially-frozen state occurs simultaneously with sedimentation on the soil surface. The concepts of epigenetic and syngenetic permafrost growth are illustrated in Fig. 2. However, many thick permafrost bodies are best regarded as *polygenetic,* in which one part is syngenetic and




A B C

**Fig. 1.** The nature of the active layer and the upper permafrost. (A). The three-layer model (Shur et al., 2005). Legend: 1 — active layer, 2 — transient layer, 3 — permafrost. (B). The four-layer model of the active layer-permafrost interface with two layers in the transition zone originally proposed by Shur (1988). Legend: (1) — *Active layer* (seasonal freezing and thawing); 2 — *Transient layer* (due to variations during about 30 years (the period defining the contemporary climate); 3 — *Intermediate layer* formed from part of the original active layer due to environmental changes, primarily organic accumulation, containing aggradational ice. Together, the transient layer and intermediate layer comprise the Transition Layer (4) *Permafrost* (freezing and thawing at century to millennial scales). (C). A photo showing the active layer (friable, at top, above large marker), the transient layer (compact, ice poor, below large marker) and the intermediate layer (ice-rich with crustal (ataxitic) cryostructure, near bottom, small markers). The sediments are Yedoma series, Kular, Northern Yakutia, Russia. Large marker is 5 × 5 cm, smaller markers are 2 × 2 cm. Photo: Y. Shur.

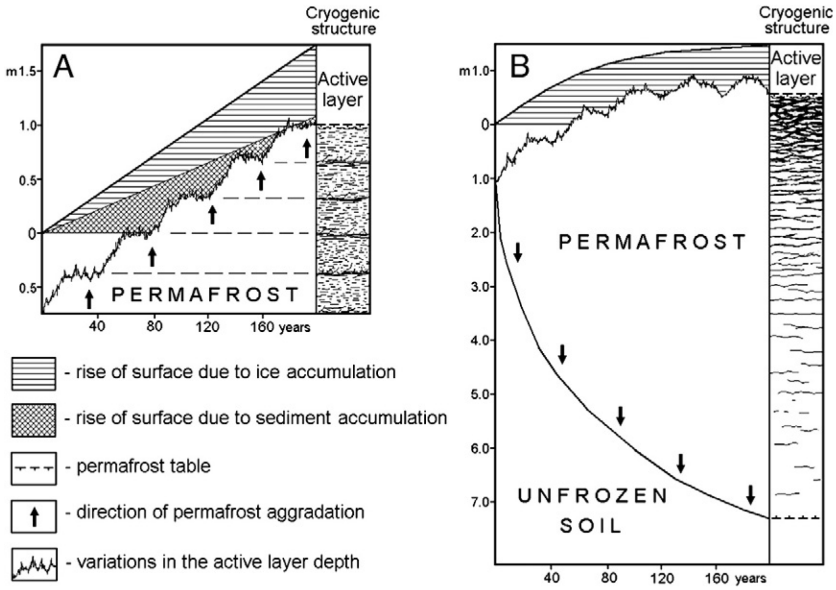



**Fig. 2.** Mechanisms of (A) syngenetic and (B) epigenetic permafrost formation (prepared by M. Kanevskiy (UAlaska-Fairbanks) and based upon Popov et al., 1985).

another is epigenetic. For example, silt in the CRREL permafrost tunnel (Shur et al., 2004) is syngenetically-frozen while bodies of enclosed gravel are epigenetically-frozen.

Typically, syngenetically-frozen sediments are silty, or loess-like (up to 70–80% silt fraction), and ice-rich (the soil gravimetric content may exceed 100–200%). Syngenetic freezing also occurs in aggrading fluvio-eolian sands and in sandy, even gravelly, floodplain deposits. Syngenetically-frozen sediments usually contain rootlets, buried organic-rich horizons, and may exhibit a rhythmically-organized (i.e., layered) appearance. The main locations where syngenetic permafrost is forming today are in the alluvial and deltaic environments of Arctic North America (e.g., Colville and Mackenzie rivers) and in northern Siberia (e.g., Lena, Yenisey, Yana, Indigirka and Kolyma rivers). The thickness of contemporary syngenetic permafrost usually does not exceed a few meters. Pleistocene-age syngenetic permafrost occurs mainly in the continuous permafrost zone of central and northern Siberia and in the valleys and lowlands of the never-glaciated parts of northwestern Arctic North America. In all these regions, uninterrupted periods of long-continued cold-climates, combined with sediment aggradation on lower valley-side slopes and on broad alluvial floodplains, led to the formation of permafrost that is several hundred meters thick. This permafrost is polygenetic in which the upper part is syngenetic and the lower part is epigenetic.

In high-latitude areas that were previously covered by the thick Late-Pleistocene ice sheets, permafrost formation is relatively recent in age and mostly epigenetic, usually being less than 50 m thick. Likewise, much permafrost in the discontinuous permafrost zones in the subarctic of both North America and Eurasia is largely epigenetic.

## 4. Ground ice

Most frozen sediment usually contains ice, especially near the surface. In some circumstances, ice may constitute as much as 30–60% by volume of the upper 5–10 m (e.g., Pollard and French, 1980; Hodgson and Nixon, 1998). Freezing is accompanied by a volume expansion of 9.05%.

*Pore ice*, sometimes termed interstitial or 'cement' ice, is the bonding material that holds soil grains together. It forms in capillary spaces by the in-situ freezing of moisture present within the sediment. *Segregated ice* forms lenses, usually visible to the naked eye, that vary in thickness from layers a few mm thick to massive ice bodies several tens of meters thick. It forms when unfrozen water moves towards the freezing plane by cryosuction. Lenses may be inclined to reflect the position of the freezing plane. Fine-grained sediments are especially susceptible to ice segregation and frost heaving of the ground surface. *Vein ice* is formed when thermal-contraction cracks ('frost cracks') become filled with a combination of wind-blown snow and snowmelt-derived water. If repeated cracking occurs in the same place, wedge-shaped bodies of foliated ice develop (ice wedges). Pore ice, segregated ice and vein ice, as described above, are the most widespread forms of ground ice. Structures that reflect the amount and distribution of pore and segregated ice within frozen sediment are termed *cryostructures*.

Ground ice can also be classified as to whether it is either epigenetic (i.e., develops after the enclosing sediment has been deposited) or syngenetic (i.e., forms at, or almost at, the same time as the enclosing sediments are deposited).

Russian scientists (e.g., Shumskii, 1959; Vtyurin, 1975) recognize as many as 20 different types of epigenetic and syngenetic ground ice. They exist in three 'permafrost horizons' that are described (Popov, 1973) as follows: (i) the 'horizon of discontinuous (seasonal) cryohypergenesis' (i.e., the active layer), (ii) the 'horizon of active cryodiagenesis' (i.e., the permafrost that exists above the depth of zero-annual amplitude), and (iii) the 'horizon of passive cryodiagenesis' (i.e., the permafrost below the depth of zero annual amplitude). This three-fold division focuses

**Table 1**
A summary of a descriptive ground ice system commonly used in North America. From Johnston (1981).

| Group symbol | Description | Symbol |
|---|---|---|
| *A. Ice not visible* | | |
| N | Poorly bonded or friable | Nf |
| | No excess ice | Nbn |
| | Well bonded | Nb |
| | Well bonded, excess ice | Nbe |
| *B. Visible ice — less than 1 inch thick* | | |
| V | Individual ice crystals or inclusions | Vx |
| | Ice coatings on particles | Vc |
| | Random or irregularly oriented ice formations | Vr |
| | Stratified or distinctly oriented ice formations | Vs |
| *C. Visible ice — greater than 1 inch thick* | | |
| Ice | Ice with soil inclusions | ICE + soil type |
| | Ice without soil inclusions | ICE |

attention upon the difference in formation of ground ice in the active layer and permafrost, the main accumulation of ice above the depth of zero-annual amplitude and the role of unfrozen moisture movement within frozen ground as one of the principle mechanisms for ground-ice formation. By contrast, the early descriptions of ground ice in North America were simple and largely descriptive (e.g., Linell and Kaplar, 1966; Pihlainen and Johnston, 1963) (Table 1).

Today, following the Russian approach, ground ice is usually classified in North America on the basis of the water source and the principal transfer process at the time of freezing (Mackay. 1972; Johnston, 1981).

## 5. Cryostructures in bedrock

Relatively little information is available about ground ice in bedrock. Theoretically, the amount should vary in accordance with rock open porosity and permeability, and the presence or absence of discontinuities such as faults, joints and bedding planes. The Russian literature recognizes a number of distinct ice-distribution patterns that characterize solid or semi-solid rocks (Fig. 3). Joints in igneous rocks and fractures and bedding planes in fine-grained sedimentary rocks allow bodies of segregated and intrusive ice to form). These cause fracturing, or brecciation, of rock (a cryotexture termed 'basal' in the Russian literature) along the lines of weakness (e.g., Fig. 4A). Brecciated bedrock is also common in weakly consolidated silt, shale and sandstone formations (Fig. 4B), especially in permafrost formed in or above the level of zero annual amplitude. This is because water migrates in response to the temperature gradient to form segregated ice. In Arctic Canada, many fine-grained (disaggregated) siltstones and shales in the near surface have mean ice contents in excess of 40% by volume (e.g., Hodgson and Nixon, 1998) while in Siberia, Yadoma-type deposits may average 60–120% gravimetric ice content (Schirrmeister et al., 2008). On Svalbard, expanded joints in coal-bearing siltstone and shale bedrock are filled with subglacial regelation ice derived from basal meltwater from adjacent glaciers (Christiansen et al., 2005) (Fig. 4C). Elsewhere, as in unglaciated southern Siberia and northern interior Yukon, expanded joints are commonly seen in sedimentary bedrock exposed at the surface (Fig. 4D).

## 6. Cryostructures in poorly-lithified sediments

Russian classifications of cryostructures are both complex and unwieldy. For example, Katasonov (1969) lists 18 different cryostructures and Popov et al. (1985) list 14 categories. A simplified North American cryostructural classification (Murton and French, 1994) encompasses the range of main cryostructures found in permafrost (Fig. 5; Table 2). Several Russian terms are transliterated. A code, similar to that used by Miall (1978) and Eyles et al. (1983) for sediments and sedimentary rocks is applied. All cryostructures can be recognized by the naked eye. A similar classification was subsequently applied by Shur and Jorgenson (1998) to the contemporary syngenetic permafrost in the Colville River Delta, Alaska.

Fig. 6 shows examples of a *lenticular cryostructure* (Fig. 6A), a *reticulate cryostructure* (Fig. 6B), and the juxtaposition of *micro-lenticular and irregular-reticulate cryostructures* (Fig. 6C/D). The best known, but probably least common, cryostructure is that of an ice

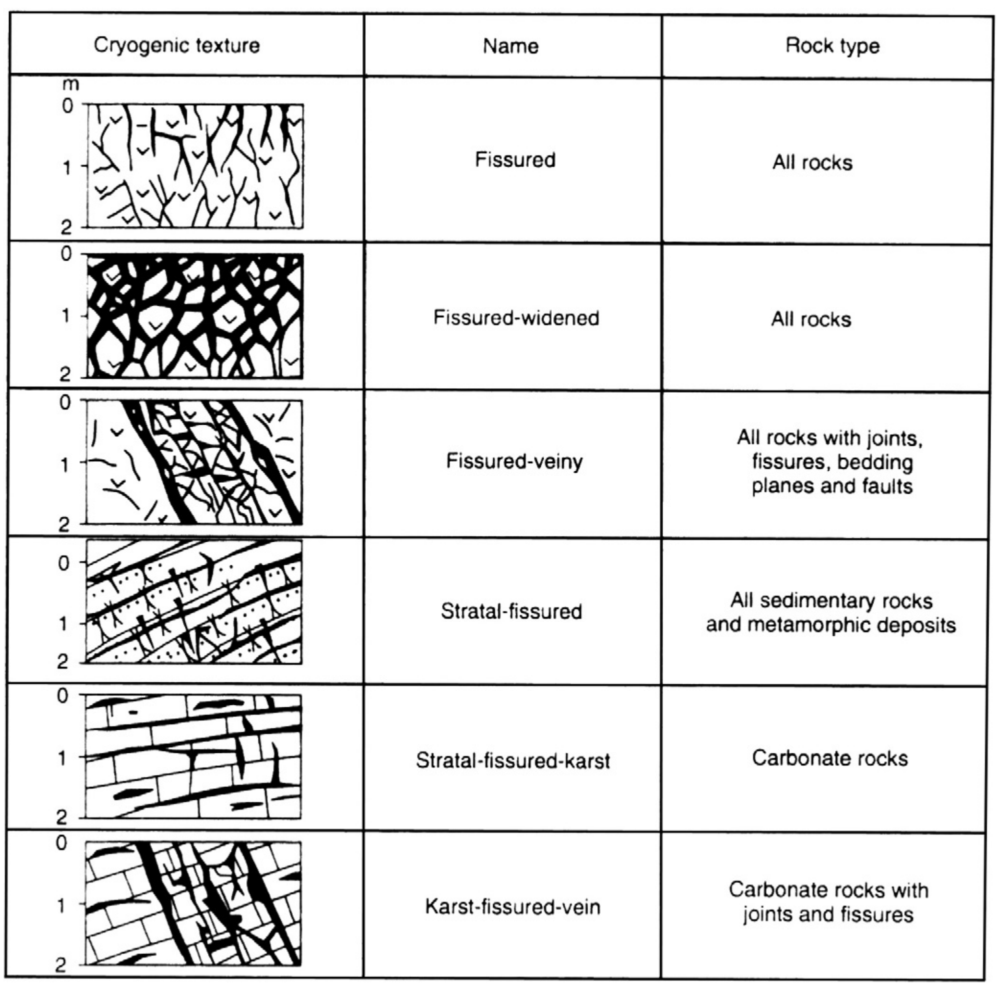



**Fig. 3.** Cryogenic textures associated with solid and semi-solid rocks. From Mel'nikov and Spesivtsev (2000).

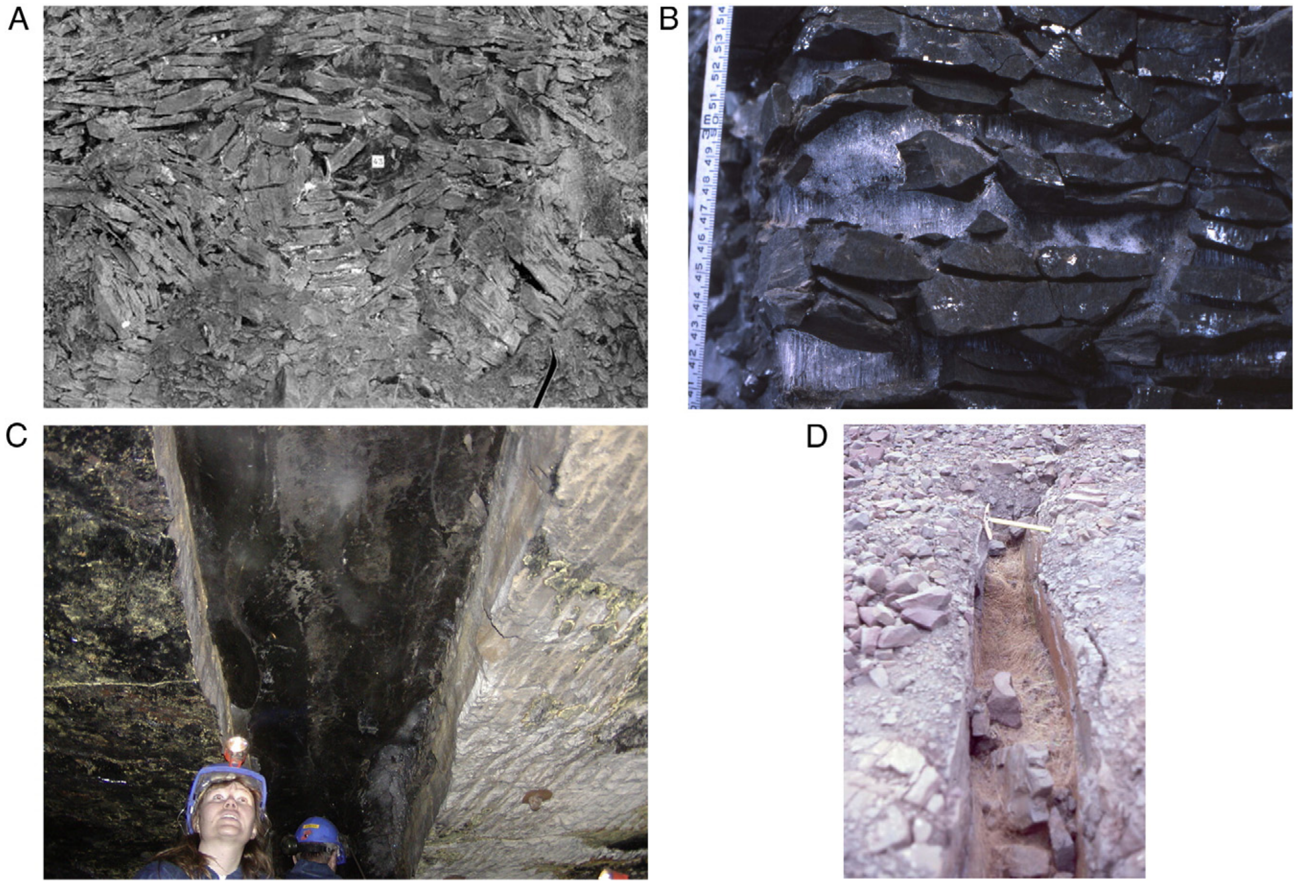


**Fig. 4.** Cryostructures in bedrock. (A) Ice in schist bedrock, Northern Yakutia. Photo: Y. Shur. (B) Brecciated shale bedrock at a depth of 1.7–3.0 m exposed beneath 0.6–1.25 m of cryoturbated ice-rich bedrock at the Sherrard Bay F-34 well site, Melville Island, Arctic Canada. The exposure was excavated during the 1983–1984 winter and the ice crystal structure has been destroyed by blasting. A thaw unconformity separates the two cryolithographic units. Photo: H. M. French. (C) Ice fills a 50 cm-wide expanded joint in the main tunnel of the Gruve-7 coal mine, Adventdalen, Svalbard. The ice is clear and contains mineral inclusions (i.e. a suspended cryotexture). Oxygen-isotope values suggest the ice is basal meltwater/subglacial regelation ice. Photo: courtesy of O. Humlum. (D) Frost-widened joint in shale bedrock exposed in a borrow pit, kilometer 366, Dempster Highway, northern Yukon Territory, Canada. Photo: H. M. French.

crust or rim around a rock clast; this is the *crustal cryostructure* that forms by localized ice segregation around frost-susceptible clasts and commonly observed just beneath the permafrost table. In the case of lenticular cryostructures, the orientation of ice lenses reflects the orientation of the freezing front and/or the structural properties, such as bedding, of the sediment. Lenticular cryostructures are best described by their inclination, thickness, length, shape and relationship to each other. That shown in Fig. 6A is best described as 'lenticular, parallel, curved'.

The micro-morphology of cryostructures can be observed using an environmental scanning electron microscope (ESEM). Fig. 7 shows *structureless* (i.e. 'massive'), *lenticular-layered and micro-lenticular* cryostructures viewed both conventionally and by ESEM (Bray et al., 2006).

## 7. Cryostructures of epigenetic and syngenetic permafrost

Field studies indicate that certain cryostructures are diagnostic of either epigenetic or syngenetic permafrost formation.

Rhythmically organized (i.e., layered and lenticular) cryogenic structures appear typical of syngenetic permafrost. They reflect, or mirror, the progressively aggrading depositional surface that is being subject to cold-climate conditions. In essence, as the permafrost table progressively rises through the sediment, the depth zone in which the temperature gradient encourages the formation of ice-rich sediment (i.e., the zone of 'active cryodiagenesis'; see earlier) also rises. Three cryogenic structures thought typical of syngenetic permafrost formation have been described in detail from the CRREL permafrost tunnel, near Fox, Alaska (see Figs. 14 and 18; Table 3) (Shur et al., 2004; Bray et al., 2006; Fortier et al., 2008; Kanevskiy et al., 2008). These are:

(1) A micro-lenticular cryostructure. This is the most common; it is formed by thin and short lenses of ice practically saturating the soil (see Fig. 7C). The thickness of straight and wavy ice inclusions is generally less than 0.5 mm. This cryostructure is typical of syngenetic permafrost. Several varieties of micro-lenticular cryostructure can be distinguished (e.g., latent micro-lenticular and micro-braided).
(2) A layered cryostructure. This is represented by repeated layers of ice with thickness of between 0.2 and 1.0 cm. The layers form series with the spacing between layers of between 2 and 5 cm. Usually the layered cryostructure is combined with a micro-lenticular cryostructure; this probably reflects different rates of sedimentation.
(3) A lenticular-layered cryostructure. This is formed by ice lenses with a thickness from 0.5 to 1.5 mm and a length from a few millimeters to 1 cm. These lenses form continuous ice layers with soil inclusions.

The different cryostructures that form during syngenetic freezing of subaqueous lake-bottom sediments are especially well documented in the Russian literature (e.g., Katasonov, 1962; Gravis, 1974) (Fig. 8A). Syngenetic freezing of the seasonally-thawed layer occurs from below and typical rhythmically-organized ('lamellar' and 'girdle-like') structures form. These are horizontal, concave or wavy

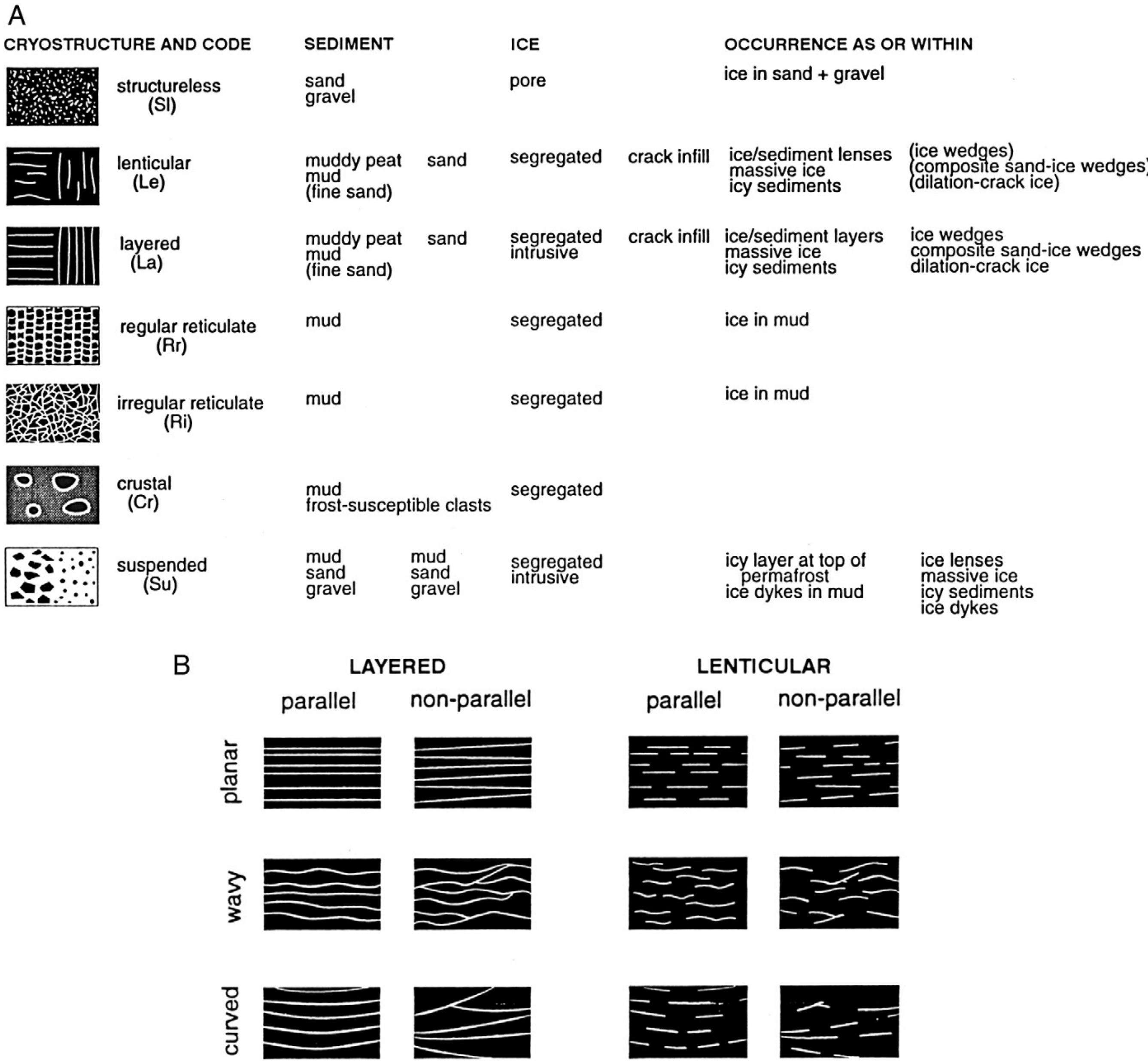



**Fig. 5.** A North American classification of cryostructures proposed by Murton and French (1994). (A): Cryostructure types and codes. Ice is shown in white and sediment in black. In lenticular and layered cryostructures, lenses and layers may comprise either ice or sediment. (B): terms and illustrations used to describe layered and lenticular cryostructures. Structureless (Sl) and reticulate (Rr, Ri) cryostructures result from epigenetic freezing; layered (La) and lenticular (Le) cryostructures result from syngenetic freezing.

in nature. However, freezing of water-saturated sediments beneath the lake gives rise to latticed and reticulate structures that may be slanting or vertical reflecting the position of the advancing freezing front. An example of a cryostructure formed by syngenetic subaqueous freezing of glacio-lacustrine clay is illustrated by the inclined ice lenses in Fig. 6A. In this case it is presumed that freezing occurred mainly downwards from the base of the lake ice while upward freezing from underlying permafrost was limited by the gentle thermal gradient. A second field example is illustrated in Fig. 8B. The Russian permafrost scientist, E. M. Katasonov named the process of freezing of a lake tálik from the side in association with partial lake drainage as *parasyngenesis* (Katasonov, 1962).

Reticulate cryostructures are usually associated with epigenetic permafrost formation in which the freezing front progressively moves downwards from the surface. Reticulate cryostuctures are thought to reflect desiccation and shrinkage as sediment progressively freezes and moisture migrates to the advancing freezing front (e.g., Mackay, 1974). They may be regular or irregular. Regular-reticulate cryostructures are especially common in fine-grained shrinkage-susceptible sediments such as clay (see Fig. 6B). In contrast, irregular-reticulate cryostructures are more common in heterogeneous sediments that are less prone to shrinkage following desiccation.

The suspended cryostructure is puzzling since the mechanism by which suspended aggregates of soil form in segregated, segregated-injection, and intrusive ice is unclear. The same cryostructure also forms in debris-rich basal glacier ice (e.g., Knight, 1997).

## 8. Thaw unconformities

Discontinuities in the nature and distribution of ground ice bodies are the result of either thawing of frozen material or subsequent refreezing of previously-thawed material. These discontinuities, termed 'thaw unconformities', allow inferences to be made as to past permafrost conditions. The most obvious and widespread thaw unconformity is that

**Table 2**
A list of the different types of cryostructures present in ice-rich sediments in the Pleistocene Mackenzie Delta, NWT, Canada. From Murton and French (1994).

1. 'structureless' (SI) — refers to frozen sediment in which ice is not visible and consequently lacks a cryostructure (this category is termed 'massive' in the Russian transliterated literature).
2. 'lenticular' (Le) — lens-like ice bodies that are described by inclination, thickness, length, shape and relationship to adjacent cryostructures.
3. 'layered' (La) — continuous bands of ice, sediment or a combination of both.
4. 'regular-reticulate' (R) — a regular three-dimensional net-like structure of ice veins surrounding a block of structureless soil.
5. 'irregular-reticulate' (Ri) — an irregular three-dimensional net-like structure of ice veins surrounding a mud-rich block.
6. 'crustal' (Cr) —refers to the ice crust or rim around a rock clast and gravel
7. 'suspended' (Su) — refers to grains, aggregates and rock clasts suspended in ice (this category is termed 'ataxitic' in the Russian transliterated literature).

of the current *active layer–permafrost interface* that separates seasonally-frozen from perennially-frozen ground.

There are several other types of ice discontinuities that may be recognized in both the continuous and discontinuous permafrost zones.

In the continuous permafrost zone of high latitudes (Fig. 9A), the active layer is a near-surface layer lying above permafrost that thaws during summer. The active layer–permafrost interface is, therefore, a *primary thaw unconformity*. If the active layer were thicker in the past, one should be able to recognize a *relict active layer* lying beneath the modern active layer but now perennially frozen. This so-called 'paleo-active layer' would then incorporate the current active layer and the relict active layer. The top of the relict permafrost body represents a *paleo-thaw unconformity*. A well documented paleo-thaw unconformity occurs in the continuous permafrost zone of the Western Canadian Arctic where the Holocene Thermal Maximum (Kaufman et al., 2004) caused widespread active-layer deepening (e.g., Mackay, 1978; Burn, 1997).

In parts of the discontinuous permafrost zone of the subarctic (Fig. 9B), a zone of deep seasonal frost commonly overlies relict permafrost. Often, a *residual thaw zone* lies beneath the modern depth of seasonal frost penetration and above the underlying (relict) permafrost body. Because the top of the relict permafrost body represents a paleo-thaw unconformity, it is possible to recognize a *secondary (i.e. paleo-) thaw unconformity*. This is not the same as the thaw unconformity that marks the base of the seasonally frozen layer.

Permafrost in the mid-latitudes must have degraded and reformed several times during the fluctuating climate of the Pleistocence. Therefore, it is instructive to consider the manner in which permafrost degrades and subsequently reforms.

An initial syngenetic permafrost sequence (Fig. 10A) is assumed possessing lenticular/layered cryostructures. As thaw proceeds (Fig. 10B), a residual thaw layer forms and the base constitutes a *primary thaw unconformity* (T-U[1]). At this time the ground experiences only seasonal freezing and thawing. But in this process, an ice wedge that had formed in a thermal-contraction crack during permafrost conditions partially thaws and, because of the warming climate, cracking is no longer occurring. When the climate subsequently deteriorates (Fig. 10C) and permafrost aggrades, the base of the active layer again becomes the primary thaw unconformity and the earlier unconformity becomes a *secondary thaw unconformity* (T-U[2]). Thermal-contraction cracking of the ground surface commences once again and an epigenetic ice wedge is formed while the partially-thawed (inactive) ice wedge remains at depth. The relict active layer, now frozen, is shown to possess an epigenetic cryostructure (here identified as 'massive' or structureless) rather than the syngenetic cryostructure of the initial permafrost body. In sum, the paleo-thaw

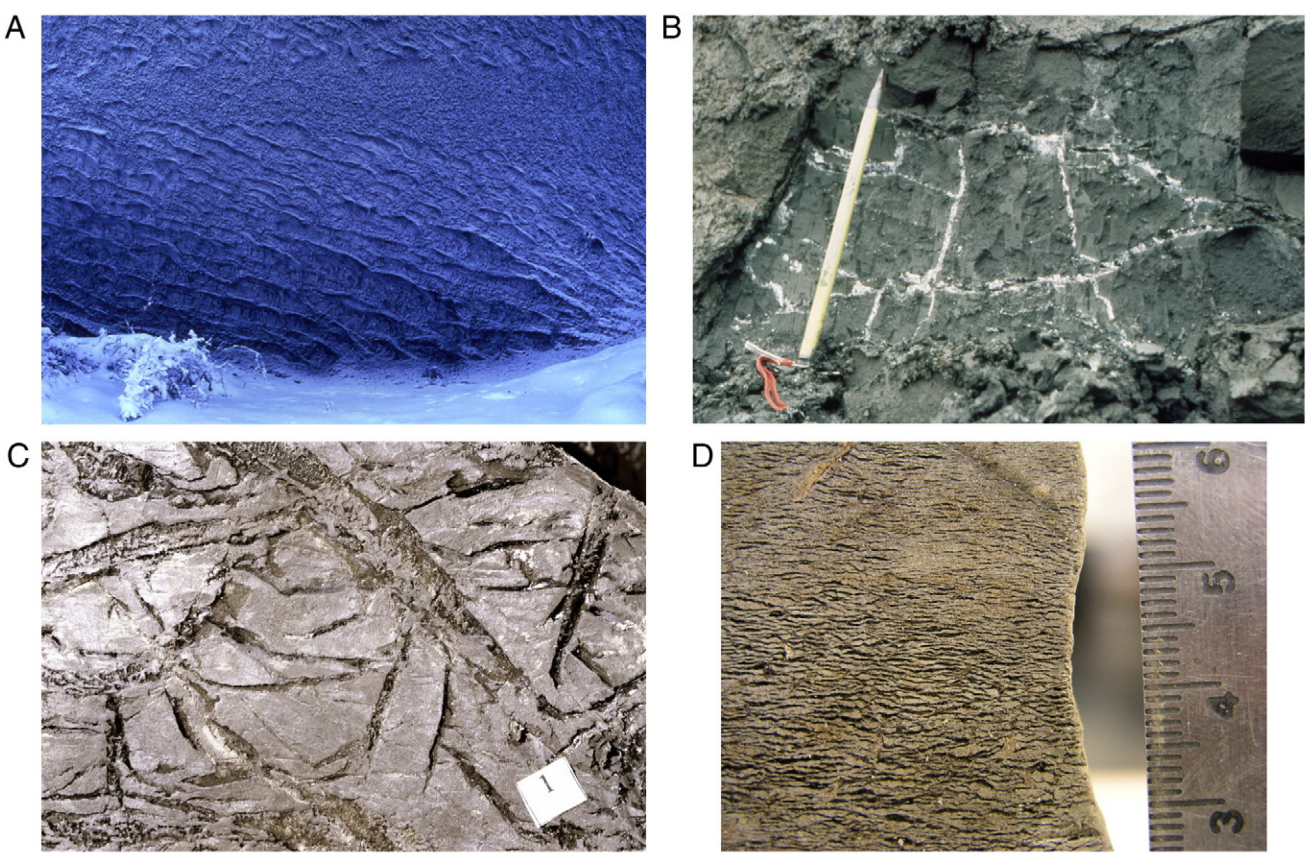



**Fig. 6.** Cryostructures in poorly-lithified sediments. (A): A lenticular-layered cryostructure, with ice lenses 30–80 cm long and 5–10 cm thick, formed during the subaqueous freezing of glacio-lacustrine silty clay near Mayo, Yukon Territory, Canada. Photo: H. M. French. (B): A network of reticulate ice veins formed in silty clay diamicton, Pelly Island, Pleistocene Mackenzie Delta, NWT, Canada. Photo: H. M. French. (C) Reticulate-chaotic cryostructure (location marker is 1.25 × 1.25 cm in size), CRREL permafrost tunnel, Alaska. Photo: Y. Shur. (D) Lenticular cryostructure, core diameter is 5 cm CRREL permafrost tunnel, Alaska. Photo: Y. Shur.

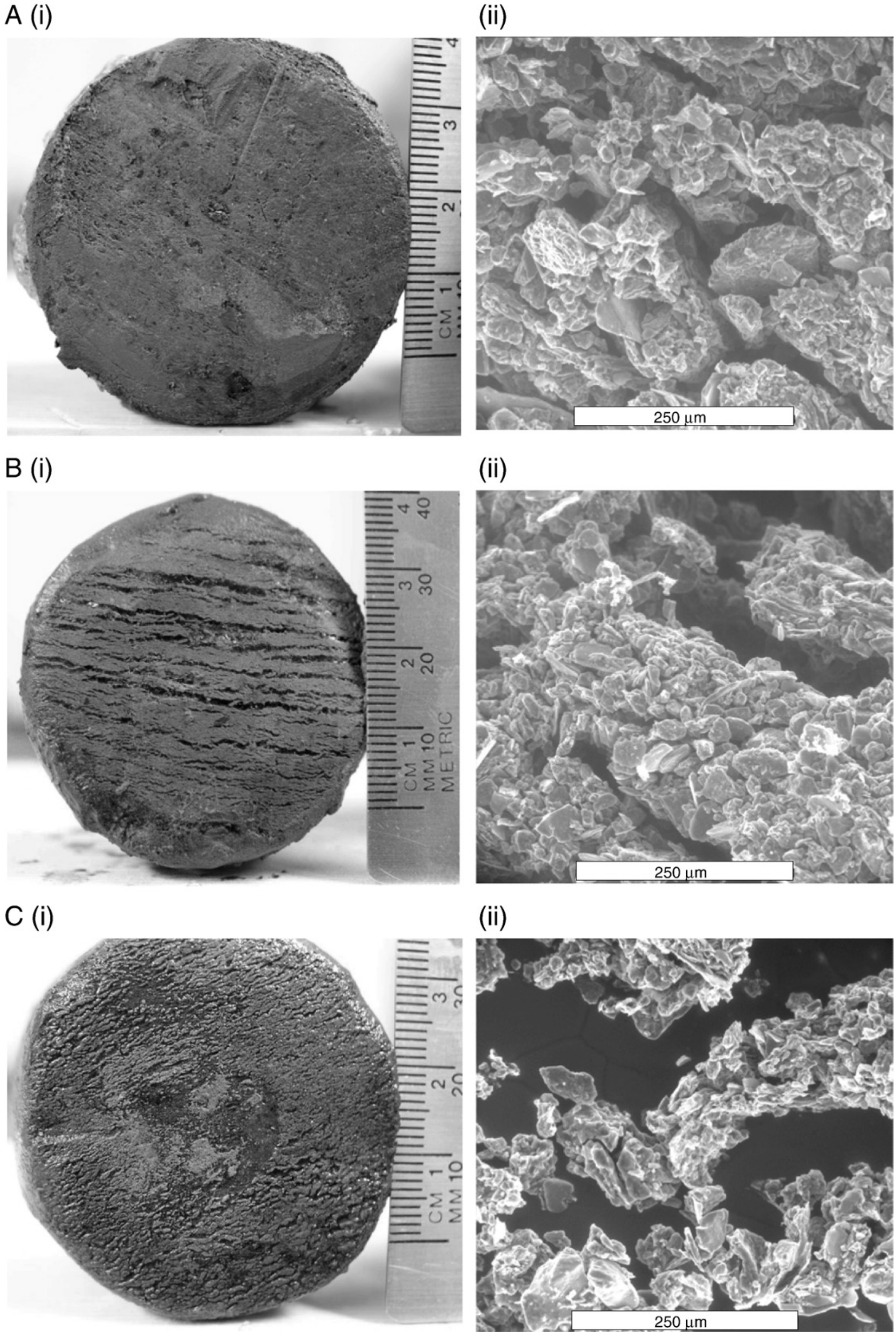



**Fig. 7.** Examples of cryostructures from the CRREL permafrost tunnel viewed (i) conventionally and (ii) under ESEM. The bar scale for the images in (ii) is 250 μm. (A) Massive cryostructure; (B) Lenticular-layered cryostructure; (C) Micro-lenticular cryostructure. From Bray et al. (2006).

unconformity can be recognized by both the truncated ice wedge and by different cryostructures above and below the unconformity.

Glacio-lacustrine sediments provide a good example of the different cryostructures that form during the growth, degradation and subsequent refreezing of deposits. Typically, such sediments exhibit ice lenses of highly variable size and distribution. For example, Ferrians (1971) described rapid vertical and horizontal changes in properties and unpredictable distribution of ice-rich facies. This distribution makes

**Table 3**
Cryo-lithostratigraphic units, ice bodies and other features in the CRREL permafrost tunnel, Fox, Alaska. From Bray et al. (2006).

1. Cryo-lithostratigraphic units
   Sscs: Fairbanks silt, representative of the original syngenetic permafrost, characterized by micro-lenticular and layered cryostructures.
   Average gravimetric water content is 130%.
   Snscs: Fairbanks silt, characterized by a massive cryostructure that is indicative of secondary modification. It contains no cryostructures typical of syngenetic permafrost. The average gravimetric water content is 69%.
   Sor: Fairbanks silt with a massive cryostructure and possessing organics (rootlets, wood, animal bones etc).
   Ssor: Sandy organic silt with a massive cryostructure and possessimng rootlets, wood and animal bones.
   Gr: Gravel deposits; sandy, silt, imbricated. Where near the tunnel entrance, they may represent slope deposits. Deeper within the tunnel, the gravel deposits are directly related to the fluvial erosion and thaw-modification of ice wedges.
2. Ice bodies
   Ice lenses: lenses of ice that range in length from 10 cm to several meters and with thickness of between 0.5 and 10 cm. They form part of the micro-lenticular and layered cryostructures.
   Clear ice: Lenticular-shaped ice bodies, often with aligned bubbles toward souter edges, and usually associated with reticulate-chaotic cryostructures in adjacent sediments. The ice is interpreted as thermokarst-cave ice.
   Wedge ice: Foliate ice with vertical soil laminations, often grey to brownish in colour.
3. Other features
   Pseudomorphs: Bodies of mineral soil ranging in composition from gravel to silt, commonly possessing high organic contents and often possessing reticulate-chaotic cryostructures. Interpreted as replacement deposits within previously-eroded and truncated ice-wedge structures.

geotechnical characterization complicated and hinders effective prediction of permafrost behavior and design. As stated by Johnston et al. (1963) '…care must be taken in locating structures under these conditions'.

Shur and Zhestkova (2003) recognize three cryostructure sequences that are typical of glaciolacustrine deposits (Fig. 11). The first is a layered cryogenic structure formed by continuous ice layers that vary in thickness from several to dozens of centimeters and whose ice content may be as high as 85%. This makes soil extremely thaw-susceptible with vertical strain reaching 40% in some cases. The second is a soil sequence with uniformly low water content, very thin ice lenses, and unfilled voids. The third is a combination of the two previous sequences with ice-poor soil in the upper and ice-rich soil in the lower parts of the sequence.

Most known areas of glacio-lacustrine deposits are located in the discontinuous permafrost zone where permafrost has been affected by Holocene climate changes and numerous wildfires. These areas have also experienced human impact during the last 100 years. As a result, permafrost has either thawed partially in some places, with later refreezing in some areas, or it has completely degraded in others. Refreezing after thawing and consolidation of the glacio-lacustrine permafrost does not lead to the original cryogenic structures being replicated. The first sequence of cryogenic structure described above is considered to be the original one. The second is formed by the refreezing of previously thawed soil. This is reflected by low measurements of soil water and visible ice contents. The combination of these two sequences often occurs with the ice-poor part overlying the ice-rich one. Degrading permafrost, with a lowered permafrost table, also occurs frequently and tends to overly ice-rich permafrost. Completely degraded permafrost is the last type. All these types occur simultaneously over a short distance at many sites.

Thaw unconformities can also be inferred by differences in ice content above and below the unconformity, by differences in stable isotope values of the ice, by differences in weathering and possibly heavy mineral assemblages (e.g., Xing et al., 1980; Burn et al., 1986), by pollen, organic and faunal assemblages (e.g., Vasil'chuk and Vasil'chuk, 1998; Kotler and Burn, 2000), and by horizons of enhanced or different micro-organisms (Gilichinsky and Wagener, 1995). At a more general level, different types of ground ice may be inferred from their isotopic and gas compositions (e.g., Mackay, 1983; Vasil'chuk and Trofimov, 1988; Arkhangelov and Novgorodova, 1991; Moorman et al., 1996; Lacelle et al., 2007; Cardyn et al., 2007).

## 9. Aggradational ice

The upward freezing of previously unfrozen (or seasonally frozen) sediment may occur for a number of reasons. For example, sediment accretion (e.g., deltaic and alluvial sedimentation, or mass wasting on slopes) may lead to the upward migration of the permafrost table. The same might result from an accumulation of organic matter, due to its

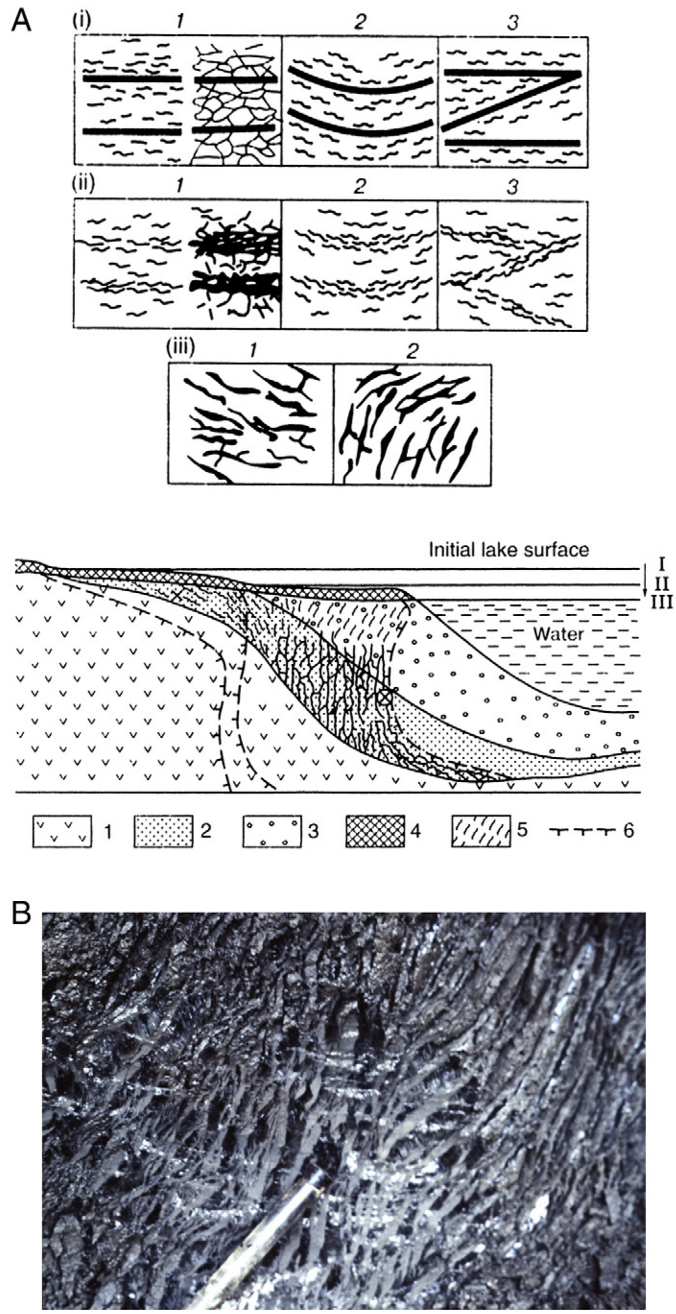



**Fig. 8.** The different cryostructures that form during syngenetic freezing of subaqueous lake-bottom sediments (A) Schematic illustration of the cryostructures that form during freezing of lake sediments. Legend: 1 — thawed material beneath original lake; 2 /3 — lake bottom sediments; 4 — seasonally thawed layer; 5 — reticulate cryostructure; 6 — permafrost boundary at different stages of lake infilling and water-level lowering. From Kudryavtsev (1978)and Mel'nikov and Spesivtsev (2000). (B) The freezing of sediment in a lake tálik from the side caused by partial lake drainage (parasyngenesis), illustrated here from near Cherski, Siberia. Photo: Y. Shur.

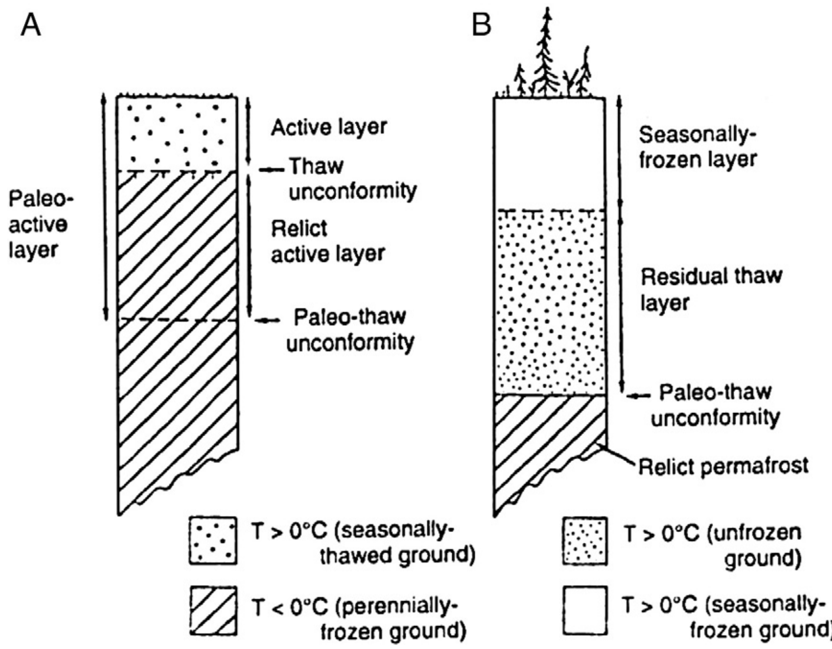



**Fig. 9.** Types of ice discontinuities commonly found in perennially-frozen sediments: (A) Arctic regions of continuous permafrost; (B) Sub-arctic regions of discontinuous permafrost or deep seasonal frost. From French (2007).

low thermal conductivity, or when regional climate cooling occurs. Under these conditions, lenses of so-called 'aggradational' ice (Mackay, 1972, 10; Burn, 1988) may form, essentially a type of segregated ice.

One of the most obvious examples of permafrost aggradation is provided by the rejuvenation of ice wedges and the growth of secondary and even tertiary wedges (Fig. 12). In a sense, this is the beginning of

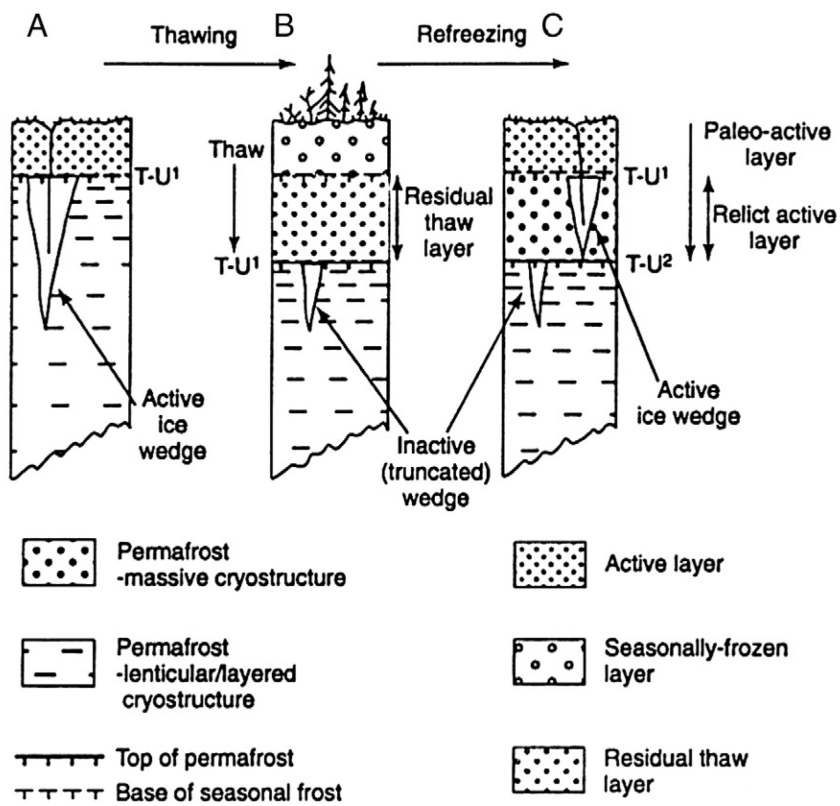



**Fig. 10.** Schematic diagram illustrating the cryostratigraphic evidence associated with the degradation and subsequent aggradation of permafrost: In (A) and (B) an initial permafrost sequence is subject to downward thawing, possibly as the result of climate warming. The cryostructure of the permafrost is indicated as being lenticular-layered. A primary thaw unconformity (T-U$^1$) forms below a residual thaw layer. In (C) permafrost aggrades, the base of the active layer becomes the primary thaw unconformity (T-U$^1$) and the previous thaw unconformity, now frozen, becomes a secondary (relict) thaw unconformity (T-U$^2$). In (C) a massive cryostructure is indicated. From French (2007).

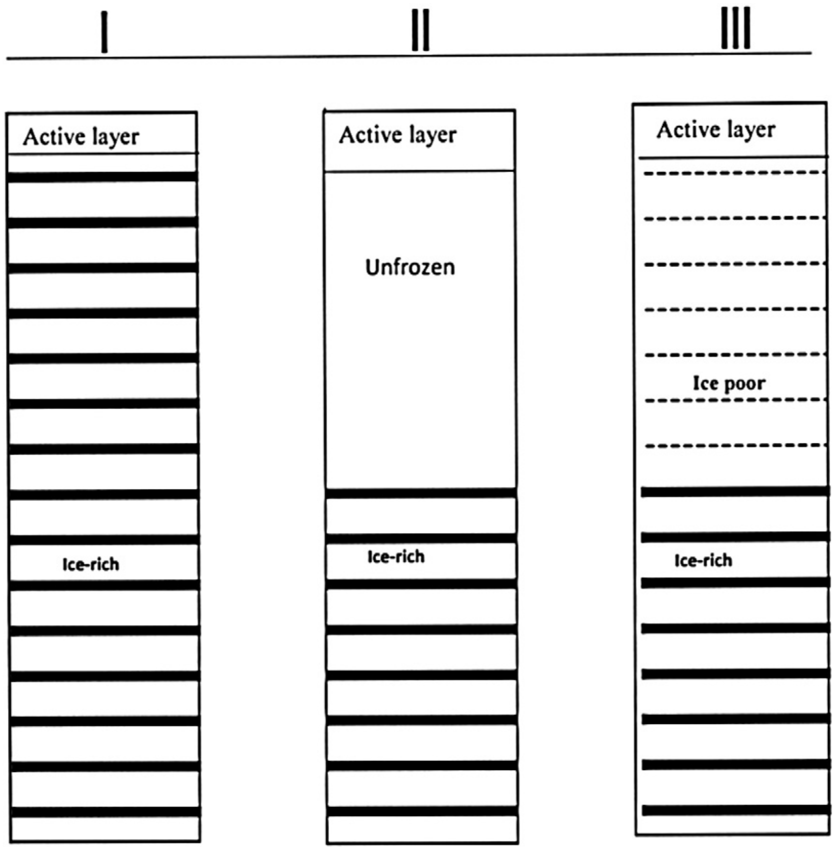



**Fig. 11.** Typical sections of glacio-lacustrine sediments in permafrost. Legend: I — undisturbed original permafrost, II — degrading with lowered permafrost table, III — with refrozen upper part. Adapted from field data presented in Johnston et al. (1963) and Shur and Zhestkova (2003).

syngenetic growth. The other example is formation of the *intermediate layer* (see Fig. 1).

## 10. Cryostratigraphic mapping

Although numerous cryostratigraphic studies have been undertaken in Russia over the last 40 years, many of them concerning the ice-rich 'Yedoma' deposits of central Yakutia and the Siberian coastal lowlands (e.g., Nekrasov and Gordeyev, 1973; Katasonov and Ivanov, 1973; Katasonov, 1975; 1978; Gravis, 1969; Meyer et al., 2002; Seigert et al., 2002; Sher et al., 2005; Schirrmeister et al., 2008; Andreev et al., 2009), relatively few studies of a similar detailed nature have been undertaken in the permafrost lowlands of Arctic North America.

Cryostratigraphic mapping in North America adopts many of the principles of modern sedimentology. Many cryostructures are composite or transitional, either merging into adjacent categories or mixing two categories. They may be hierarchical, although such hierarchies do not necessarily imply genesis. For example, 'cryofacies' are defined according to volumetric ice content and ice-crystal size, and then subdivided according to cryostructure. One such system, developed for ice-rich unconsolidated sediments in the Pleistocene Mackenzie Delta region (Murton and French, 1994), is illustrated in Table 4 where five cryofacies are distinguished according to arbitrarily-defined volumetric-ice-content values. Cryofacies can also be described according to cryostructure; where a number of cryofacies form a distinctive cryostratigraphic unit these result in a 'cryofacies assemblage'. For example, ice-rich sand (IRS) and sand-rich ice (SRI), if exposed in a stratigraphic sequence below an ice-poor diamicton and above various non-ice sedimentary structures, would constitute a cryofacies assemblage.

In Canada, one of the earliest attempts at cryostratigraphic mapping occurred on Melville Island when, during the summer of 1979 and winter of 1981–82, geotechnical analyses and field ditching trials were

**Fig. 12.** A rejuvenated ice wedge, southern Banks Island, Canada, shows multi-stage upward growth of the wedge that is enclosed by horizontal lenses of aggradational ice. Photo: H. M. French.

**Table 4**
Cryofacies types applicable to ice-rich unconsolidated sediments in the Pleistocene Mackenzie Delta, NWT, Canada. From Murton and French (1994).

| Cryofacies type | Volumetric ice-content (%) | Cryofacies | Code | Cryostructures |
|---|---|---|---|---|
| Pure ice | 100 | Pure ice | I | Le, La |
| Sediment-poor ice | >75 | Sand-poor ice | SPI | Le, la, Su |
| | | Aggregate-poor ice | API | |
| Sediment-rich ice | >50 to ≤75 | Sand-rich ice | SRI | |
| | | Aggregate-rich ice | ARI | Le, La, Su |
| Ice-rich sediment | 25 to ≤50 | Ice-rich sand | IRS | SI, Le, La |
| | | Ice-rich mud | IRM | Le, La, Rr, Ri, Cr |
| | | Ice-rich diamicton | IRD | |
| Ice-poor sediment | ≤25 | Ice-poor mud | IPM | SI; various |
| | | Ice-poor sand | IPS | Non-ice |
| | | Ice-poor gravel | IPG | Sedimentary |
| | | Ice-poor diamicton | IPD | Structures |
| | | Ice-poor peat | IPP | |

performed as part of a terrain evaluation for a proposed oil pipeline (EBA Engineering Consultants Ltd., 1979, 1983; Hayley et al., 1984). Subsequently, the cryolithology of the various Palaeozoic, Mesozoic and Cenozoic-age rocks of the area and the cryostratigraphy of shale bedrock exposed near an adjacent exploratory well site were summarized by H.M. French et al. (1986). Another early cryostratigraphic study in Canada concerned an ice-rich exposure in glaciolacustrine clay near Mayo, central interior Yukon (e.g., Burn et al., 1986; see Fig. 6A). A more detailed study that included isotopic analyses was undertaken in the Mackenzie Delta region, NWT, in the early 1990s (Murton and French, 1993a,b, 1994). There, a near-surface relatively ice-free *sand and diamicton cryofacies assemblage* was identified above a *layered cryofacies assemblage* consisting of massive icy beds. At the contact between the two cryofacies assemblages was an isotopic (thaw?) discontinuity. More recent cryostratigraphic studies in North America include those of deltaic sediments of the Colville River Delta, Alaska (Shur and Jorgenson, 1998) and organic-rich 'muck' deposits of the Klondike District, Central Yukon, Canada (Kotler and Burn, 2000; Fraser and Burn, 1997) (Fig. 13).

Cryostructure mapping of the Colville River Delta revealed the close relationship between cryostructures and terrain units (Shur and Jorgenson, 1998).

Where spatial mapping is the objective, the cryofacial method originally proposed by Katasonov (1978) is useful. This integrates the relationship between cryostructure assemblages and specific sediment units. Cryofacial analysis is especially applicable to the study of syngenetic permafrost where a time framework for permafrost formation and growth is involved. It can be illustrated by the recent study of syngenetic permafrost in the CRREL permafrost tunnel undertaken by Kanevskiy et al. (2008). Seven thin organic-rich horizons can be observed at a depth of 12–14 m below the ground surface (Fig. 14). At a depth of between 0.4 and 0.6 m below each horizon, there are distinct ice-rich layers and numerous thin cracks partially filled with ice (ice veins) that extend downwards from the organic horizons and which form polygons up to 0.5 m across in the horizontal plane. The cryostratigraphy clearly illustrates the progressive accretion of the ground surface under permafrost conditions and the upward migration of the active layer-permafrost interface. Thermal erosion of the permafrost terrain can also be inferred from the presence of gullies and underground channels filled with ice and sediment that have different properties to the original syngenetic permafrost (see below: Ice, sand and soil pseudomorphs).

## 11. Icy bodies

It is not uncommon to encounter icy bodies within permafrost (e.g., see Shumskii, 1959; Popov, 1973). In consolidated rock, icy bodies are usually restricted to joints and bedding planes. This causes brecciation,

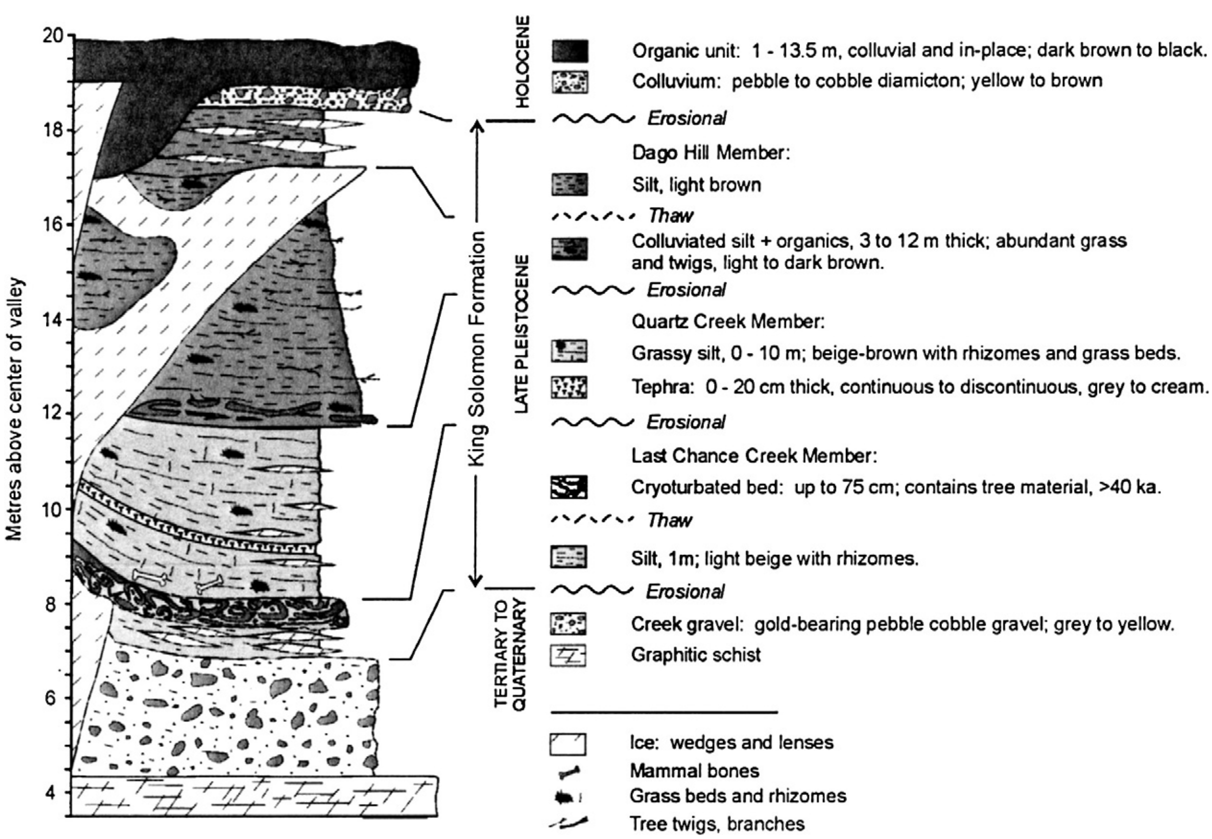



**Fig. 13.** Generalized cryostratigraphy of frozen, sediments ('muck') in the Klondike area, Yukon Territory, Canada. The figure combines sedimentological, organic and geocryological characteristics and identifies cryostratigraphic units. From Kotler and Burn (2000).

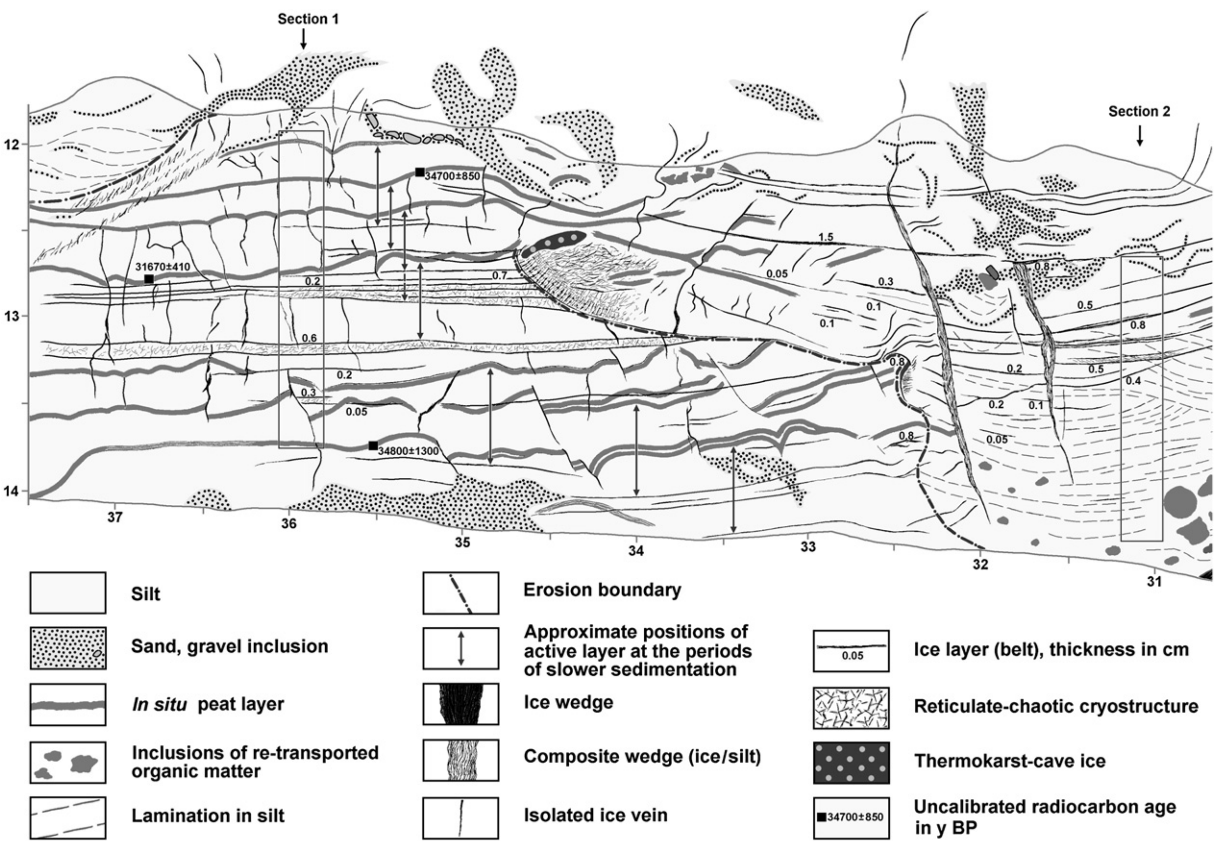



**Fig. 14.** Cryostratigraphic map of part of the wall of the CRREL permafrost tunnel, Fox, Alaska. It shows bodies of syngenetic permafrost separated by an erosional (thaw) boundary. From Kanevskiy et al. (2008).

as discussed earlier. Joint widening is particularly common in sedimentary strata (see Fig. 4D). Bodies of injection ice and buried ice, the former occurring within pingos, the latter usually of glacial origin, are also encountered. Because both of these ice types have been discussed in recent years (e.g., Mackay, 1998; Mackay and Dallimore, 1992; Murton et al., 2005) they are not considered further in this paper.

By far the most common type of icy body that is encountered in the field is *vein ice*. This is formed by the freezing of surface water that

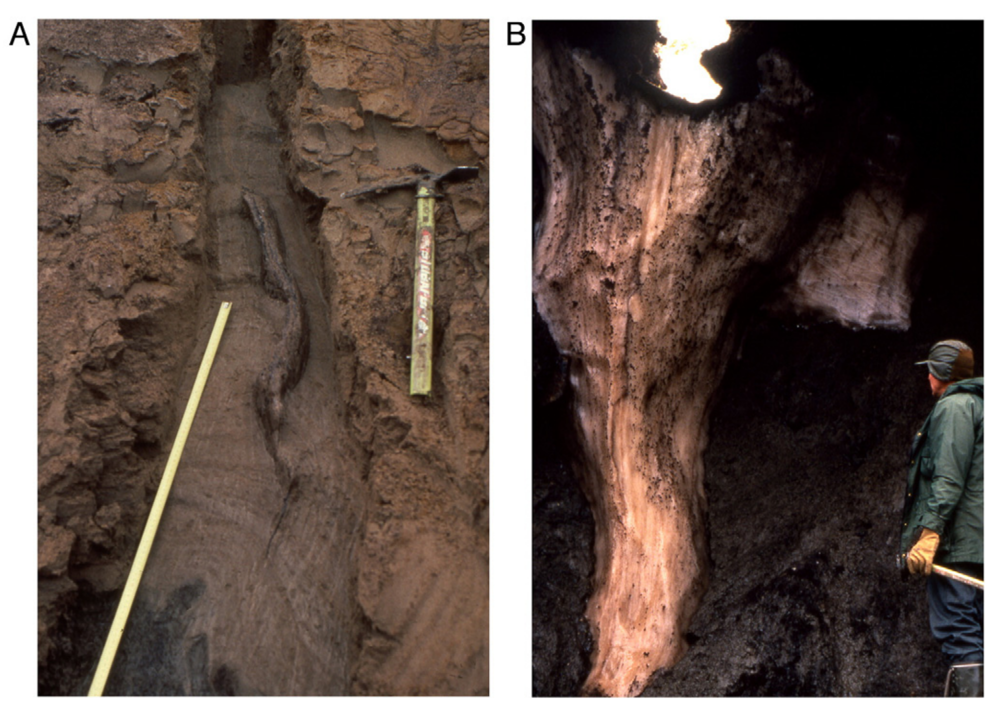



**Fig. 15.** Typical examples of vein ice: (A) Small syngenetic ice vein formed in outwash sand, Sachs River Lowlands, southern Banks Island, NWT, Canada. Photo: H. M. French. (B) Epigenetic ice wedge, Tuktoyaktuk area, NWT, Canada. Photo: H. M. French.

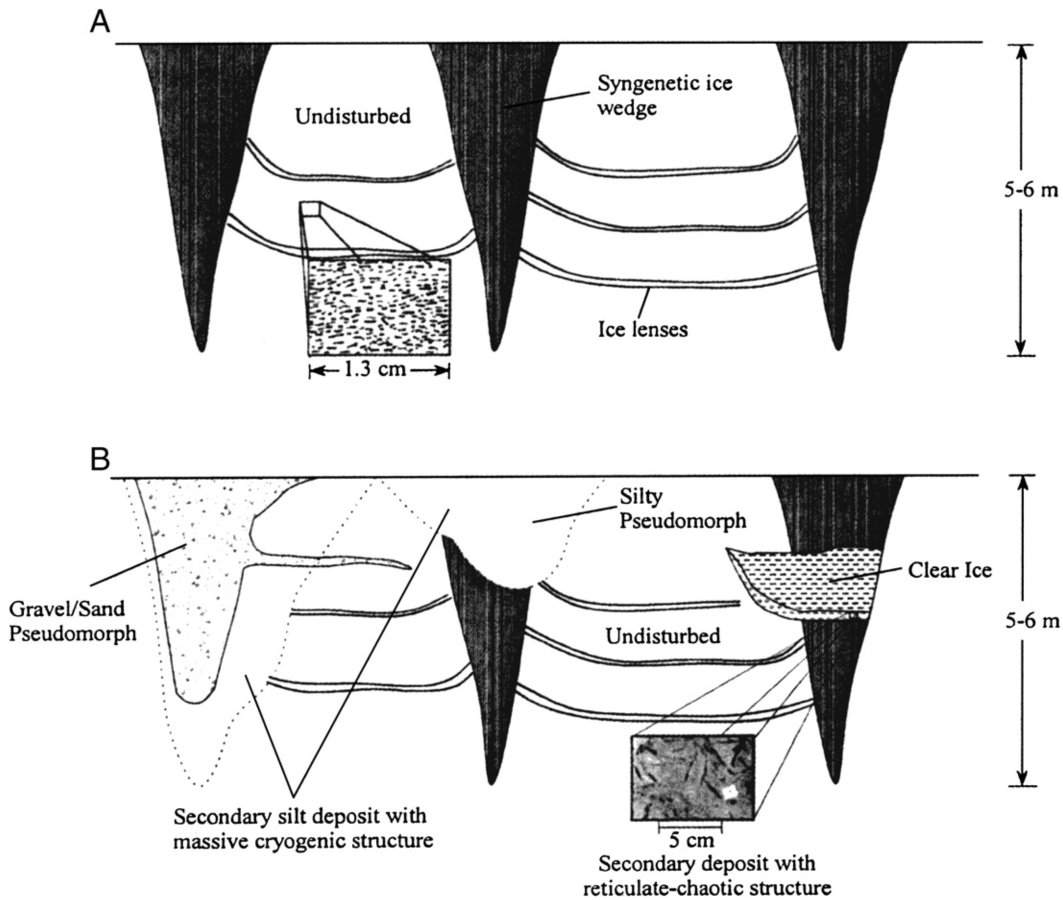



**Fig. 16.** Schematic diagram showing how thermokarst may modify a permafrost body: (A) undisturbed syngenetic permafrost body containing micro-lenticular cryostructures that is penetrated by large syngenetic ice wedges. (B) Thermokarst modification. The 3 ice wedges have been thaw-modified to (i) an ice-wedge pseudomorph (left), (ii) a partially-thawed (truncated) ice wedge (centre), and (iii) an ice pseudomorph (thermokarst-cave ice) that fills a tunnel in the wedge (right). The extent of secondary (thaw-modified) deposits is indicated schematically. From Bray et al. (2006).

penetrates thermal-contraction cracks in the spring. Vein ice varies from single veins, less than 1 cm in width and 1 m in vertical extent (Fig. 15A), to massive wedge-shaped bodies of foliated ice (ice wedges) up to 50 m deep and between 0.5 and 4 m wide near the surface (Fig. 15B). Vein ice is usually regarded as being either epigenetic or syngenetic in nature. Many syngenetic ice wedges are assemblies of epigenetic wedges. By definition, most actively-cracking ice wedges are epigenetic and vein ice always forms in a near-surface stratigraphic position. Not all thermal-contraction cracks are filled with ice; many are filled with mineral soil and wind-blown material, to form sand wedges and composite wedges (e.g., Murton, 2007).

Identification of the different types of vein ice and their possible thaw-truncation greatly assist in cryostratigraphic interpretation. Fig. 16 is a schematic diagram showing how thermal-erosion processes may modify a permafrost body containing vein ice.

A useful scenario can be seen in the CRREL tunnel where many ice veins and ice wedges have been thaw-modified by fluvio-thermal erosion. Clear ice bodies, apparently randomly distributed, are also present. These are interpreted as *thermokarst-cave ice* (Shur et al., 2004; Bray et al., 2006), known colloquially in North America as 'pool' ice (Mackay 1997; Kotler and Burn, 2000). Syngenetic permafrost is highly susceptible to thermal erosion that promotes the formation of subterranean channels, especially along the axes of ice wedges. When these channels are finally closed by roof collapse or sediment accumulation, water that has become impounded behind the blockage begins to freeze. This process results in the formation of thermokarst-cave ('pool') ice. Fig. 17 shows veins of wedge ice penetrating a horizontal body of clear thermokarst-cave ice. This relationship demonstrates that formation of the wedge did not terminate when the cavity was filled with water that subsequently froze. Instead, it indicates that thermal-contraction cracking, ice-wedge formation, and permafrost growth continued after emplacement of the thermokarst-cave ice.

**Fig. 17.** A near-horizontal layer of thermokarst-cave ice in CRREL permafrost tunnel, Fox, Alaska, USA. The photo shows vein ice penetrating thermokarst-cave ice. Photo: Y. Shur.

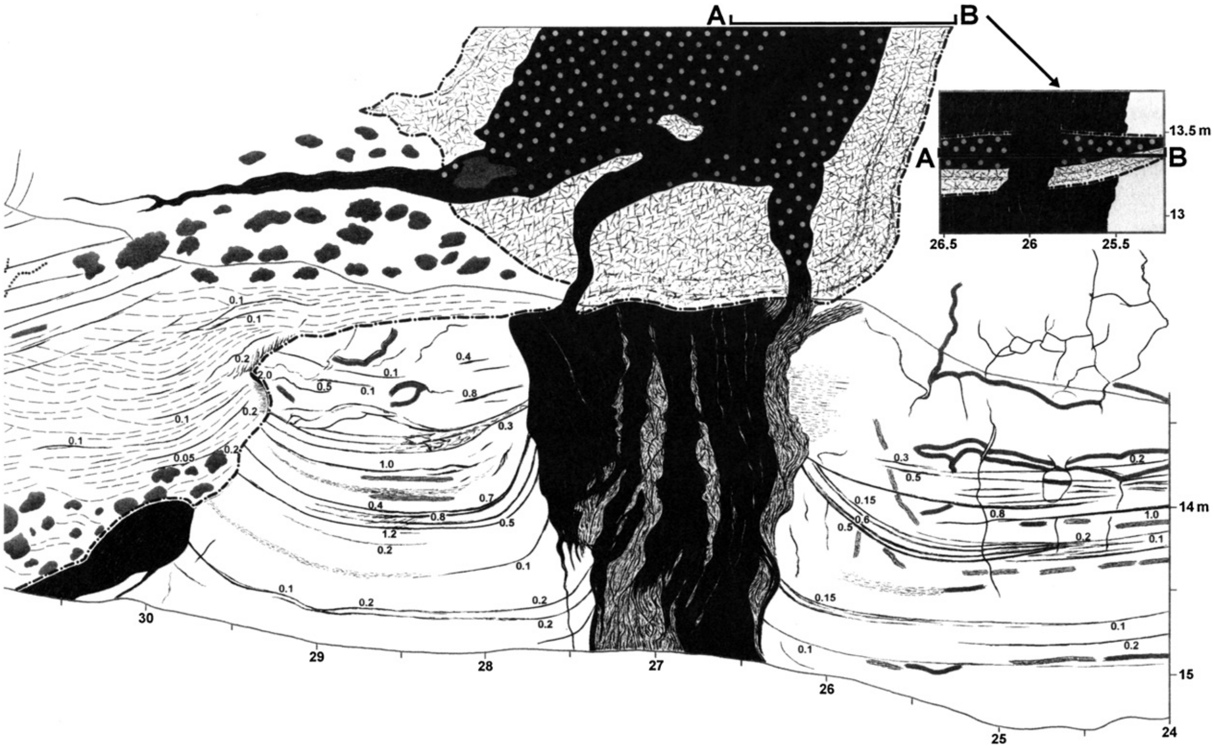


**Fig. 18.** Cryostratigraphic map of part of the wall of the CRREL permafrost tunnel that illustrates an ice pseudomorph above a thaw unconformity that truncates an ice wedge. Different cryostructures occur above and below the thaw unconformity. Legend as in Fig. 14. From Kanevskiy et al. (2008).

## 12. Ice, sand, and soil pseudomorphs

Pseudomorphs related to the thaw-modification of ice wedges take the form of either open voids in permafrost or ice, sand, and soil bodies (Murton and French, 1993b; Murton, 2007, 2162–2167). *Soil pseudomorphs* are formed by silt, sand, or gravel filling the void left by the eroded ice wedge. *Ice pseudomorphs* are formed by thermokarst-cave ice filling the void. Both structures represent secondary infilling; ice, sediment, or an ice–sediment mix constitutes the infill. Not surprisingly, the cryogenic properties of these infill materials differ from those of the enclosing permafrost; typically, the cryostructures are epigenetic (often reticulate). Ice pseudomorphs are especially difficult to recognize because some have been subsequently modified by the penetration of ice veins (see Fig. 17). The cryofacial mapping of an ice pseudomorph present in the CRREL permafrost tunnel is illustrated in Fig. 18.

## 13. Conclusions

Modern cryostratigraphy has borrowed and adapted many of its concepts and terminology from Russian geocryology. This process commenced in the mid-1970s following upon the Second International Conference on Permafrost, held in Yakutsk, Siberia, USSR. Although isolated informal visits had occurred earlier, this was the first occasion when North American permafrost scientists and engineers were formally introduced, in the field, to Soviet cryostratigraphy. The interaction of Russian permafrost scientists with others in the international permafrost community continues today within the framework of the International Permafrost Association. North American cryostratigraphic studies have contributed significantly to an understanding of the peculiarities of permafrost terrain and to cold regions geotechnical engineering.

Areas of future cryostratigraphic research include (1) development of a genetic classification of cryogenic structures that would establish the direct relationship between cryogenic structure and genesis of frozen sediment; (2) experimental formation of cryostructures to test hypotheses concerning their genesis, (3) isotopic dating of ground ice sequences, (4) understanding the thaw of past permafrost and its relation to global climate change and methane release and (5) characterization and understanding of planetary permafrost.

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