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CRYOSTRUCTURE DEVELOPMENT ON THE FLOODPLAIN OF THE COLVILLE RIVER DELTA, NORTHERN ALASKA

Yuri L. Shur[1], M. Torre Jorgenson[2]

1. 2. ABR, Inc.,PO Box 80410,Fairbanks, AK
1. Harding Lawson Associates, Inc., 601 E. 57th Place, Anchorage, AK 99518
e-mail: yshur@harding.com

Abstract

The development of a sequence of cryostructures on the floodplain of the Colville River Delta in northern Alaska was studied in 1995-1996 to provide information for engineering design and assessment of potential environmental impacts of the proposed Alpine Oil Development Project. Existing cryostructure classifications were modified to develop a comprehensive morphological classification that incorporates observations of cryostructures from 8 bank exposures and continuous cores from 40 boreholes in the Colville River Delta with observations from Russian and Canadian studies. The processes that affect cryogenic structure are floodplain evolution, syngenetic permafrost formation, and ice wedge development. The cryostructures on the Colville River Delta are compared with those described from other arctic deltas to evaluate the uniformity of arctic fluvial and cryogenic processes.

Introduction

The development of a sequence of cryogenic structures on the floodplain of the Colville River Delta in northern Alaska was studied in 1995-1996 to provide information for engineering design and assessment of potential environmental impacts of the proposed Alpine Development Project. Our study involved three components: (1) description and analysis of cryostructures involving modification of existing classifications systems; (2) synthesis of patterns and processes of cryostructure development including a conceptual model of cryostructure development and an evaluation of the importance of syngenetic permafrost and ice-wedge development; and (3) comparison of our results with observations from several Russian arctic deltas to evaluate the uniformity of arctic fluvial and cryogenic processes.

Cryogenic structures (cryostructures) describe the forms, distribution, and volume of ice in soil, and are visible to the naked eye. The first introduction of different ice-soil structures was made by Kokonen (1926), but cryogenic structures were recognized as an important characteristics of permafrost only in the 1950's (Katasonov, 1954; 1960; Shumskiy, 1957). The need for a systematic classification and nomenclature to facilitate communication and comparison led to the development of several well-known classifications in Russia (e.g., Gasanov 1969, Zhestkova 1982). In the USA, an ice classification was developed by Linell and Kapler (1966) to differentiate certain ice characteristics (e.g., well-bonded, no excess ice; random oriented ice; stratified ice) but was insufficient for differentiating structures associated with specific cryogenic processes or geotechnical properties. Murton and French's (1994) recent synthesis of classification systems is a substantial improvement, yet, there is still a need for more integration. The morphological classifications, which differentiate the geometry of cryogenic structures, facilitate communication and comparison but provide little information on the processes involved. In contrast, morphogenetic classifications relate cryogenic structure to the genesis of permafrost soil (alluvial, colluvial, lacustrine, etc.) and usually require comprehensive field study. The first morphogenetic classification was developed by E. Katasonov (1960) for perennially frozen soil deposited on the floodplain of the Yana River, Northern Yakutia. Our classification effort was undertaken as part of a broader study of the evolution of the floodplain of the Colville River Delta (Jorgenson et al. 1997, 1998).

Methods

Cryostructures associated with syngenetic permafrost development were described from 8 bank exposures (2–4 m high) and 40 cores (1–6 m) obtained with a SIPRE corer. Numerous samples were taken for density, water content, electrical conductivity, particle-size distribution, and radiocarbon dating. To describe and analyze the changes in cryostructures found at various

Table 1. System for classifying ground-ice structures on the Colville River Delta

Continuity	Primary Bedding Property or Shape	Secondary Property	Size
Pore (P) (structureless)	Nonvisible (n) Visible (v)		Not applicable Very fine (<0.5 mm) (v) Fine (0.5 - <1 mm) (f) Medium (1-3 mm) (m) Coarse (3-5 mm) (c) Large (>5 mm)(l)
Organic-matrix (O)	Nonvisible (n) Visible (v)		Same as above
Crustal (C)	Entire (e) Partial (p)		Same as above
Vein (V)	Vertical or inclined (v) Irregularly oriented (i)		Same as above (thickness)
Lenticular (L)	Horizontal (h) Inclined (i) Crossbedded (c) Grouped (g)	Planar (p) Wavy (w)	Very fine (<0.5 mm) (v) Fine (0.5 - <1 mm) (f) Medium (1-3 mm) (m)
Layered or Bedded (B) (<10 cm thick)	Sparse (<5%) (s) (density of layers) Medium (5-25%)(m) Dense (25-50%)(d)	Planar (p) Wavy (w) Curved (c)	Same as at top (thickness)
Reticulate (R)	Trapezoidal (prismatic) (t) Lattice (regular, blocky) (l) Foliated (platy) (f)		Width of inclusions Fine (<5 mm) Medium (5-10 mm) Coarse (>10 mm)
Ataxitic (A) (suspended)	Medium (50-75% ice) (m) Dense (75-95% ice) (d) Very Dense (95-99% ice) (v)	Round (r) Angular (a) Blocky (b)	Same as above
Solid (S) (>10 cm thick)	Clear (c) Opaque (o) Dirty (<1% soil particles) (d) Porous (p) Columnar (r) Sheet, horizontally stratified (h) Wedge, vertically stratified (w)		

stages of floodplain development, we modified existing classifications (Katasanov, 1960; Murton and French, 1994) to better differentiate changes in continuity of ice, horizontal and vertical structures, primary and secondary bedding properties and shape, and size (Table 1). Our incorporation of field observations from numerous Russian and some Canadian studies also makes the classification more comprehensive than previous ones.

Most of our sampling was done along 7 toposequences, which incorporated the various stages of floodplain development, to relate changes in cryostructures to changes in surface environments. Using this approach, similar to that used by Zaikanov (1987) under the supervision of Y. Shur on the low Yana River in Northern Yakutia, Russia, each successive stage that is studied includes all the previous ones; finally, a sequence with the last stage can be divided into hori-

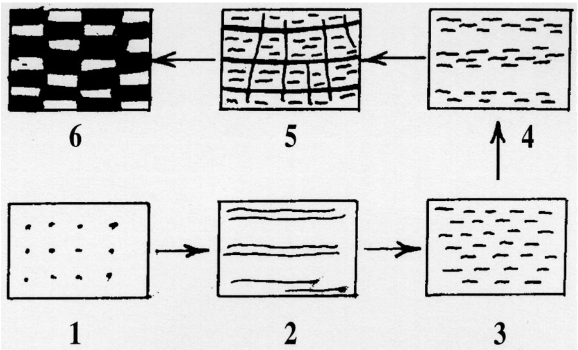

Figure 1. Morphogenetic classification of main types of cryogenic structures in the Colville River Delta. Illustrations include: (1) massive (pore ice) cryogenic structure of riverbed deposit, (2) layered cryogenic structure of silt inclusions of active-floodplain, (3) lenticular cryogenic structure of active deposit, (4) dense lenticular cryogenic structure of the transition zone from active to inactive floodplain, (5) composite cryogenic structure of inactive floodplain, (6) ataxitic cryogenic structure of upper part of inactive and abandoned floodplain.

zons using observations and insights gained by the study of earlier ones. Thus, the toposequences allowed us to approximate the chronosequence of cryostructure development and link the development of near-surface cryostructures to specific depositional environments. This approach is particularly useful in the analysis of syngenetic permafrost because the lowest deposits became perennially frozen earlier than upper ones.

Results and discussion

CRYOSTRUCTURES OF THE COLVILLE RIVER DELTA

Analyses revealed a sequence of simple and complex cryostructures that are associated with specific stages of floodplain development ranging from sandy riverbed deposits to thick organic accumulations over fine-grained cover deposits (Figures 1 and 2). We recognized two types of channel deposits (sandy riverbed, and lateral-accretion deposits along bars) and three types of overbank deposits (active-, inactive-, and abandoned-cover deposits). In the following description of cryogenic structures of floodplain deposits, we conceptualize the deposits as continuous three-dimensional bodies. The surface extent of the cryosequence is equal to the surface area of an ice wedge polygon ($100–1000\ m^2$). It extends from the highest point of the floodplain down to the underlying riverbed deposits. It can be approximated by a two-dimensional cross-section of a low-centered polygon.

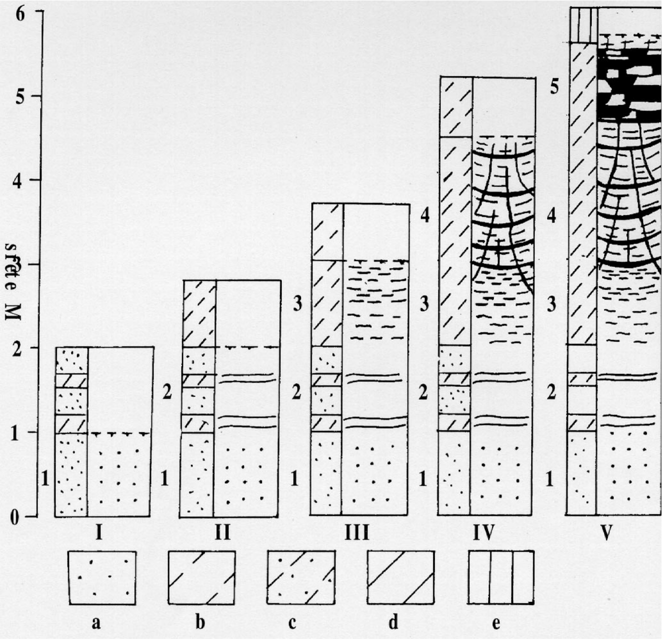

Figure 2. Cryogenic structures of floodplain deposit during its development (see text for explanation).

CRYOSTRUCTURES IN RIVERBED DEPOSITS

Riverbed (channel) deposits comprise medium to coarse sands that are either massive or cross-bedded. The deposit probably becomes perennially frozen when water depths are less than 2-m deep (less than the winter ice cover). The deposit has a solid (massive) cryogenic structure with pore ice (structureless) (Figure 2, layer 1). Volumetric ice content (water content x 1.09) indicates little to no excess ice (mean = 42%, SD = 13%, n = 15). Riverbed deposits were found under most floodplain deposits, although thaw lake and high-water channel deposits also were found.

CRYOSTRUCTURES IN LATERAL ACCRETION DEPOSITS

Lateral-accretion deposits occur along the margins of channels and bars and are composed of interbedded medium and fine sand, silt, and detrital organic material, and are cross-bedded to rippled (Figure 2, layer 2). The thin (0.1–5 cm thick) layers of detrital peat, deposited on bars during waning flood stages, are particularly diagnostic of these deposits. Layers of silt (1–5 cm thick) have a fine or very fine dense layered (horizontal or inclined) cryogenic structure made by fine ice lenses (<1 mm thick, spaced 1–5 mm apart). Sandy layers have pore ice (structureless), although the sandy matrix may be massive or cross-bedded. Fine, densely packed lenticular cryostructures are typically found in silt lenses in between coarser layers.

CRYOSTRUCTURES IN ACTIVE-FLOOD PLAIN DEPOSITS

These deposits have horizontally stratified silts and fine sands, or massive silts, and occur close to the channel. The cryogenic structure is mainly horizontal lenticular; ice lenses typically are 5–10 mm long and vary in thickness from hair-like to medium (2–3 mm) size (Figure 2, layer 3). They are underlain by lateral-accretion riverbar deposits that have cross-bedded lenticular and pore ice structures associated with cross-bedding. The upper part of the horizon frequently has lenticular structures formed in dense groups (1–3 cm thick) which are interbedded with layers (5–10 cm thick) of structureless soil with pore ice. Some vertical ice veins occasionally occur and together with horizontal lenses, form an incomplete reticulate structure. Ice contents are intermediate (mean = 60%, SD = 12%, n = 49).

CRYOSTRUCTURES IN INACTIVE-FLOOD PLAIN DEPOSITS

These deposits have interbedded alluvial silt and in-situ peat at the surface, underlain by massive silt associated with buried active-floodplain deposits (Figure 2, layer 4). The interbedded silts and peats are usually contained within the active layer and the underlying massive silt in the permafrost has a composite cryogenic structure. Layered ice (0.5–3 cm thick and spaced 10–40 cm apart) forms the primary cryogenic structure (ice belts in Russian permafrost literature). The layers are strongly curved (concave-upward) at the contact with ice wedges. The secondary structure between the ice layers usually is fine (inclusions <5 mm wide) or medium (inclusions 5–10 mm wide) reticulate. The upper part near the permafrost table has a cryogenic structure termed "ataxitic or basal" in Russian permafrost literature and "suspended" by Murton and French (1994). Ice contents are high (mean = 72%, SD = 10%, n = 141).

We attribute differences in cryogenic structure between active and inactive to changes in soil texture (increasingly massive silts) and development of ice wedges and low-centered polygons. The active layer in low-centered polygons is always saturated with water, and freezing of the active layer from the bottom begins in an open system in which the freezing front is in contact with a source of free water. The association of the belt (thick-layered) cryogenic structure with low-centered polygons was first recognized by Katasonov (1960).

CRYOSTRUCTURES IN ABANDONED-FLOODPLAIN DEPOSITS

Abandoned-floodplain deposits are characterized by high-density, high-relief, low-centered polygons resulting from ice wedge growth over a long period of time. The upper layer of the permafrost typically has large accumulations (2-3 m) of massive organic material, or interbedded organics and silts deposited during the inactive stage and that have been deformed by ice-wedge development. Ice within this organic matrix is visible, but has an amorphous form which we termed "organic-matrix" ice. Ice contents are very high (mean = 79%, SD = 9%, n = 23).

OTHER DEPOSITS

There are several other deposits (thaw basin, high-water channel or oxbow, and tidal flat) related to depositional environments at the lower stages of floodplain development that can be difficult to recognize. Thaw basin deposits under floodplain deposits were described by Rosenbaum (1973) and Zaikanov (1987). Oxbow and thaw basin deposits were found in several boreholes. They are ice-rich and have a reticulate cryogenic structure.

MASSIVE ICE

Wedge ice is the main type of massive ice in the Colville River Delta. Thermal contraction cracking starts on the active-floodplain deposits, but extensive ice wedge development takes place in inactive- and abandoned-floodplain deposits. Ice wedges are epigenetic in relation to riverbed, lateral-accretion, and active-floodplain deposits and they are syngenetic in relation to inactive-floodplain deposits. The average width of ice wedges during the later stages of development is about 1.5 m.

Massive ice in sheet form (25-50 cm thick) occasionally was found (6% of sites) in the centers of low-centered polygons. (Shur and Jorgenson, 1996). This form also has been found in parts of West Siberia, where it was described as buried (Trofimov, 1975; Trofimov, 1986) or segregated ice (Danilov, 1978). We speculate that the sheet ice formed either at the bottom of the active layer under shallow ponds of low centered polygons or during the initial freezing of newly exposed sediments after lake drainage.

IMPORTANCE OF SYNGENETIC PERMAFROST FORMATION

The formation of syngenetic permafrost is fundamental to the evolution of cryogenic structures on arctic floodplains (Table 2). During syngenetic permafrost formation, sedimentation adds new material to the soil surface and temporarily increases the thickness of the active layer. The thickness of the active layer is limited by climatic and local conditions, however, and the increase in the active layer at the top must be compensated by its decrease at the bottom (i.e., the permafrost table). Thus, there are two upward moving surfaces, the ground surface as it receives new sediment, and the permafrost table as the active layer adjusts to new conditions. As a result, syngenetic permafrost formation takes place synchronously with deposition of soil material (French, 1976 uses the more precise word "paralleled"). Contrary to epigenetic permafrost, in which the thickness of frozen material grows downward, the thickness of syngenetic permafrost grows upward.

Differences in the formation of syngenetic and epigenetic ice have large effects on the structure and properties of permafrost. For example, epigenetic permafrost has a variable ice content that often is ice-poor, whereas, syngenetic permafrost always is ice-rich. These important differences in geothechnical properties need to be considered in engineering design. The phrase "permafrost is a condition rather than substance" (Linnel and Tedrow, 1981, p. 14) is often correct about

Table 2. The formation of syngenetic permafrost

Epigenetic permafrost	Syngenetic permafrost
deposition in absence of permafrost	deposition above permafrost
age of ice decreases with depth	age of ice increases with depth
compacted soil	uncompacted soil
initial soil water and groundwater supply	surface water supply
temperature regime limits thickness	sedimentation limits thickness
epigenetic ice wedges	syngenetic ice wedges

epigenetic permafrost but never about syngenetic permafrost.

IMPORTANCE OF ICE WEDGE FORMATION

The formation of ice wedges in syngenetic permafrost affects surface topography and elevation of the floodplain, hydrologic regime, sedimentation, plant growth and organic accumulation, and deformation of previously formed permafrost. It also affects how we should sample and describe the three-dimensional architecture of cryostructures.

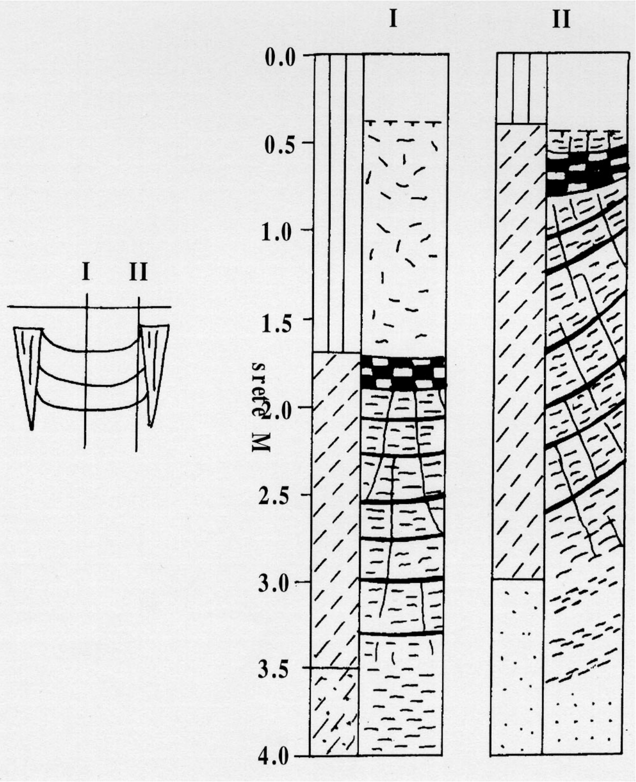

Figure 3. Site dependence of cryogenic structure showing sequences in the middle part of a polygon (I) and next to an ice wedge (II).

The expansion of ice wedges and the deformation of the soil around them causes the formation of a polygonal net of rims on the ground surface and low-centers within the polygons (Leffingwell, 1919; Konishchev and Maslov, 1966; Romanovsky, 1977). The surface microtopography associated with rim development changes surface hydrology, sedimentation, and permafrost formation, and is a large factor in the evolution of the floodplains of arctic rivers. Syngenetic permafrost of the floodplain is made of three components: mineral material, organic material, and ice. The relative contribution of these materials is altered by the relative elevation of the floodplain and by polygonal formation. During the later stages of floodplain evolution, when ice wedges become prominent, sedimentation is greatly reduced (although minor eolian input continues) and organic material accumulation becomes relatively important. Ice (massive and ice inclusions) also develops in situ at the bottom of the active layer and in the upper permafrost, and inside thermal cracks. Rims contribute to peat and ice accumulation by impounding water, which reduces soil oxygen, decomposition rates, and nutrient input from the movement of suprapermafrost groundwater, which in turn reduces plant productivity. In the Colville River Delta, 2–2.5 m of peat was found in polygon centers, whereas, only 0.1–0.2 m was found on nearby polygon rims above the ice wedges. Thus, the difference between elevations of the mineral surface at the edge of polygons and at their center is often more than 2 m.

Ice-wedge development also causes deformation of previously horizontally layered sediments and ice lenses, especially in the vicinity of the ice wedges. It changes the relative positions of the depositional layers; older layers can be deformed and raised to elevations higher than younger layers. Leffingwell (1919) and Romanovsky (1977) gave examples in which sand deposited at the first stage of floodplain formation was

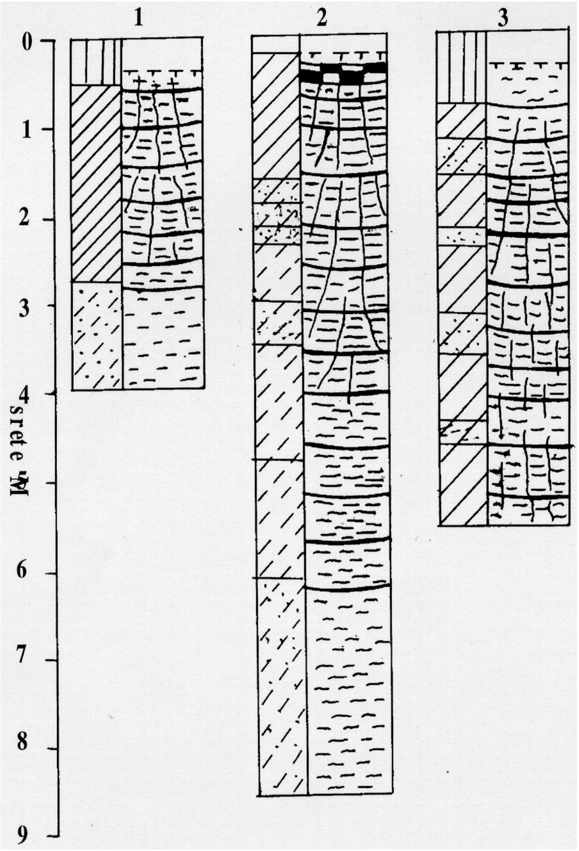

Figure 4. Cryogenic structures of floodplain deposits in Russian Arctic, including: (1) West Siberia, the Gidan Peninsula, Yuribey River, based Dubikov (1967); (2) Northern Yakutia, Yana River, based on Zaikanov (1987); and (3) Chukotka Peninsula, Vankarem River, based on Gasanov (1969).

brought near the surface by ice wedge deformation. We have not seen such large effects on the delta, but deformation and raising of older deposits was frequently observed adjacent to ice wedges.

Permafrost investigations must recognize the importance of the three-dimensional nature of cryostructures resulting from the growth of polygonal nets of ice wedges and their deformation of adjacent cryostructures. For example, there are large differences in cryostructures between the center and edge of low-centered polygons (Figure 3), although the change is gradual. Typically, field studies involve coring (one-dimensional) and bank exposures (2-dimensional), when three-dimensional views are really required for complete understanding of structures.

Comparisons with Other Arctic Regions

A comparison of our observations with field descriptions made from arctic floodplains in West Siberia (Dubikov, 1967; Trofimov, 1975, 1986), Northern Yakutia (Katasonov, 1960; Rosenbaum, 1973; Zaikanov, 1987), Chukotka (Gasanov, 1969; Vtyurin, 1964) and northern Alaska (Canning River, Leffingwell, 1919) revealed that the cryosequence of floodplain deposits is similar throughout the Arctic. Figure 4 presents three sequences of floodplain deposits from West Siberia (Dubikov, 1967), Northern Yakutia (Zaikanov, 1987), and Chukotka (Gasanov, 1969) based on written descriptions or graphical representations. The most notable similarity in cryogenic structure of alluvial deposit of the arctic rivers is the common sequence from structureless cryogenic structure (pore ice) in riverbed deposits at the bottom, to the composite cryogenic structure of the inactive-floodplain cover deposits, which include layered and reticulate ice in recurring bands and ataxitic ice near the permafrost table. The widespread occurrence of organic-matrix ice in the abandoned-floodplain cover deposits that we observed on the Colville River Delta are not well-documented in other studies.

Conclusions

Field studies in the Colville River Delta in Northern Alaska revealed that cryostructures follow a regular sequential pattern during floodplain development that includes: (1) pore ice (structureless) in massive to cross-bedded sandy channel deposits, (2) interbedded pore ice and lenticular structures in cross-bedded to rippled sands, silts, and detrital peat in lateral-accretion deposits, (3) mostly lenticular cryostructure in active-floodplain deposits, (4) mostly layered and reticulate cryostructures, with some ataxitic cryostructures near the permafrost table in inactive-floodplain deposits, and (5) organic-matrix ice within thick organic deposits in abandoned-floodplain deposits. A comparison of our results with other descriptions from Russian studies indicates that this cryosequence is common on the floodplains of arctic lowland rivers. Factors contributing to this sequence include: (1) the nature of syngenetic permafrost formation and changes in sediment, organic, and ice accumulation during floodplain development, and (2) the effects of ice-wedge formation on surface topography, hydrologic regime, and sedimentation and subsurface stratigraphic deformation.

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