Gelisols: Part I. Cryogenesis and State Factors of Formation

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Editor’s note: This is the first in a two-part series on Gelisols. Part I examines the cryogenesis and the state of formation, and part II in the next issue of Soil Horizons will look at classification and related issues.

Gelisols are soils affected by permafrost. It was the 12th order added to Soil Taxonomy, the U.S. soil classification system. They are classified as Cryosols in both of the World Reference Base and the Canadian System of Soil Classification, and Cryozem in the Russian soil classification system. In the second edition of Soil Taxonomy (1999), Gelisols are defined as soils that have (1) permafrost within 100 cm of the soil surface; or (2) gelic materials within 100 cm of the soil surface and permafrost within 200 cm of the soil surface.

According to A.L. Washburn, a noted geocryologist, permafrost is defined as a thermal regime rather than a material presence. Thus any material—soil, rock, or water in the form of ground ice—that has temperature below the freezing point of water throughout the year for two consecutive years or more is considered permafrost. However, the permafrost material that receives most attention is the ice-cemented permafrost because of the phenomena associated with ice formation, freeze–thaw cycles, and frost heave. To most field soil scientists, in practice, permafrost refers to frozen soils and ice contained in those soils. The permafrost environment has been a challenge to agricultural, urban, and industrial development and more recently has received greater attention because of its unusually high carbon (C) storage and the impact on global climate. Gelisols occupy about 12% of the land surface on earth and store ~30% of the total terrestrial C.

Cryogenesis and Cryostructure Formation

The original intent and reasoning for establishing the Gelisol order was to recognize the presence of ice-cemented permafrost consisting of layers and lenses of segregated ice and different forms of massive ground ice, including ice wedges. The presence of ice is the most limiting factor in human land use practices. Based on thermal regime, a typical Gelisol pedon consists of two parts: the upper part subject to seasonal freeze and thaw called the active layer and the lower part, which is actually the upper permafrost. Soil freezes when the ambient temperature drops below 0°C and soil water moves toward the freezing front. As freezing advances deeper into the soil, horizontally oriented ice layers form with each increment of freezing, resulting in the most common cryostructure—stratified lenses of frozen soil without visible ice and segregated ice layers (ice lens). The thickness of ice lenses vary from <1 mm to > 2 cm, the latter of which are called ice belts.

A second freezing front rises from the permafrost below. Toward the end of summer, solar radiation decreases, and the active layer freezes from the bottom upward. Thus soil water in the active layer moves to two different freezing fronts, toward the surface and the permafrost table. Layered cryostructures form in both the upper and lower parts of the active layers, drawing soil water away and leaving the middle part of the active layer relatively dry, with either coarse platy structure or massive conditions.

Soil structure develops in alignment with cryostructure formation. As water moves to the freezing front(s), drying soil shrinks with water loss, causing cracking and formation of vertical ice lenses during further freezing. The horizontal and vertical cracking and ice lens formation result in “ice nets” in which soils are partitioned into elongated platy and blocky structures, which correspond to “lenticular” and “reticulate” cryostructures, respectively, according to geocryologists H. French and Y. Shur. Through freeze–thaw cycles, these
cryostructures accumulate more water (ice), and eventually the soil material blocks appear to be “floating” in an ice matrix, in which the ice occupies >50% of the volume and is termed “suspended cryostructure” in the English literature and “atexitic” structure in the Russian literature. This zone of ice-rich lenticular, reticulate, or more often suspended, cryostructures occurs in the lower part of the active layer and upper permafrost. It may thaw and become part of the lower active layer during a warm period and may stay frozen as part of the upper permafrost during cold periods. Thus this zone is called the “transition zone.”

Another significant process in frozen soils is the buckling up of the ground surface, termed frost heave, a result of ice segregation and ice lens formation. Although horizontal expansion is limited, it is enough to create stress that in turn produces crooked or tilted lenticular and reticulate structures. Differential frost heave eventually deforms originally flat horizons into warped or wavy horizons. When soil freezes on the two freezing fronts in conditions where water is not limiting, a saturated zone becomes sandwiched between the fronts and builds up cryostatic pressure that eventually causes the “mud-paste” in this zone to “erupt” through weak spots. This phenomenon is a type of diapirism—deformable materials forced through brittle layers—which is caused by thermal convection.

The combined effect with frost heave is formation of patterned ground features called circles. For soils without rock fragments, soils within and outside the circle have the same general texture and are classified as “nonsorted” circles. Rock fragments in the soil tend to heave up and are eventually pushed to the outer edge of the circle by repeated cycles of frost action and thus appear to have segregated domains. Hence, they are termed “sorted” circles. On mountain slopes, gravitational forces will cause both nonsorted and sorted circles to deform downslope and develop into stripes or stone stripes. In the processes of circle formation, the surface organic mat is often ruptured, forming discontinuous surface organic horizons; hence the “ruptic” formative element incorporated in the Gelisol classification.

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Cryoturbation and Soil Morphology

The most striking soil features associated with patterned ground (i.e., nonsorted and sorted circles) is the broken, involute, or warped horizons within the profile caused by cryoturbation. Commonly, circle centers are devoid of vegetation or are only sparsely vegetated, and the areas outside the circles have tundra vegetation with thick organic horizons. Due to the lack of surface thermal insulation, the mineral-dominated circles tend to thaw faster and deeper and also freeze faster, resulting in deeper active layers, whereas areas outside the circle insulated by thick organic layers have shallow active layers and higher soil moisture content during thaw cycles. As it freezes faster, the mineral-dominated circles attract more water to form ice lenses, which displace greater volumes than liquid water and induce heaving and deformation to a greater extent than the adjacent insulated tundra. This differential frost heave often causes the organic matter (OM) and, in some cases, the vegetative cover to be frost-churned down to the lower active layer or the upper permafrost.

The importance of cryoturbation has long been recognized by pedologists. In the 1970s, Pettapiece, Tarnocai, and Zoltai studied the cryoturbated profiles of earth hummocks in the Canadian Arctic and found the depth of the permafrost table is reverse to the surface microtopography, i.e., the active layer is deepest in the center of the earth hummock and shallowest in the depressions around the hummocks. They all noted the buried and discontinuous organic horizons occurred at depth and attributed this “buried” OM phenomenon to cryoturbation. Concurrently, O. Makeev and his colleagues also found such cryoturbated OM at the permafrost table from 100 to 200 cm depth in northeastern Russia.
Soil Horizons

Soil-Forming Factors

Climate

Gelisols occur in the polar, arctic, subarctic boreal, and alpine regions where mean air temperature is below 0°C. The mean July air temperature is usually <2°C in the polar and arctic regions and may be as high as 10°C in areas with strong continental climate. Winter temperature and temperature gradient from summer to winter play a controlling role for cryogenesis to manifest, resulting in cryostructures and cryoturbation. The amount and timing of snow makes differences in the active layer depth. Early deep snow insulates the still “warm” soil, and the active layer continues to deepen due to stored heat even as the air temperature drops below freezing. However, in the event of a dry and cold fall and winter without the benefit of adequate snow cover, the ground freezes rapidly and deeply, and the next thaw cycle will start within a shallower active layer.

Cold temperatures limit biological activity, slowing OM decomposition rates and favoring accumulation of OM in thickened surface organic (O) horizons. Surface O horizons are split apart by frost cracking or patterned ground formation and then are frost-churned down to the bottom of the active layer and the surface of the permafrost. This cryoturbated OM is eventually preserved (sequestered) with permafrost aggradation, i.e., a rising permafrost table through seasonal cycles.

The cryoturbated organic matter has a sharp boundary with the mineral matrix.

Parent Material

Gelisols form in a wide range of parent materials, including, but not limited to, eolian deposit (loess), alluvium, glacial deposits, OM, residuum, colluvium, and lacustrine deposits. The texture of unconsolidated parent materials affects patterned ground formation and hence cryoturbation processes. Silty soils are most susceptible to nonsorted circle and cryostructure formation because there is a lack of cohesion between particles, but they are small enough to deform and orient along the freezing front. Sandy materials lack the viscosity required for segregation processes. Based on field measurements, the diameter and the height of observed circles show a positive relationship with percent (clay + silt). It is observed that most nonsorted circles have silty or loamy textures, and earth hummocks tend to have clayey texture. Clay particles tend to hold more associated water and thus tend to maintain unfrozen water in the permafrost and seasonal frost, which microbially communities can use to sustain their biological activities in winter or under frozen conditions. Clay hydration and its ability to readily cohesively deform contributes to cryogenic diapirism. Soils associated with sorted circle stone stripes and oriented rocks occur in parent materials containing rock fragments such as glacial deposits, colluvium, and residuum.

In the circumpolar regions, loess deposition contributes to syngensis of soils and permafrost because of its intermittent nature of deposition. Permafrost aggrades as new loess is added to the surface, leading to weakly developed stratified soil horizons encased in rising permafrost, which can reach up to >50 m depth with massive ice wedges developed within. Loess deposits may be reworked through a combination of fluvial processes, permafrost aggradation, and massive ice wedge formation into an ice complex with a thickness >30m, such as the well-known Yedoma Formation of the arctic islands and lowlands of northeast Russia, the Beringian Province of northwestern Alaska/northeastern Siberia, interior Alaska, and northwestern Canada.

An ice wedge exposed by coastal erosion along the Beaufort Sea coast, Alaska. Note the pattern of organic matter distribution due to cryoturbation. Photo courtesy of M. Kanevskiy.

Landform

Landform controls the redistribution of energy, i.e., solar radiation and precipitation, and drainage patterns. Slope gradient and aspect play an important role in controlling vegetation community and Gelisol formation in the discontinuous permafrost regions of the subarctic. In the northern hemisphere, south- and southwest-facing slopes receive maximum solar radiation and are thus warmer and drier, favoring the formation of Inceptisols (Cryepts) rather than Gelisols. The north- and northeast-facing slopes are cooler and wetter due to the low sun angle and reduced solar radiation input, thus favoring the formation of permafrost and Gelisols. On moderate to steep slopes, cryoturbated soils (Turbels) form due to gelifluction processes. The soils show minimal or no cryoturbation (Orthels) under forest and dense understory cover on toeslopes and floodplains. In lowlands, broad basins, and depressions, the poorly drained conditions favor OM accumulation and the formation of Histels. In mountain ranges, sorted circles dominate the summit grading to gravity-induced stripes and gelifluction lobes on shoulder and backslopes.

In the circumarctic regions, sorted circles dominate glaciated uplands, and nonsorted circles dominate where there is a thick loess mantle. On these landscapes, Turbels are the dominant soil types. On the low-lying coastal plains in northern
Along the edge of the polygon, a micro-Alaska, Canada, and Russia, there are the high centered polygon, a common patterned ground feature, is caused by the presence of ice wedge polygon formation. Thaw lakes form due to thermokarsting (i.e., localized melting) of permafrost or thawing of ice wedges. When thaw lakes grow in size, they are often locally drained and a basin forms. The flat basin is poorly drained, and initially Orthels form in the flat-lying ground. Gradually, ice wedges reform within the sediments, creating ice wedge polygons, with diameters ranging from a few meters to >20 m across. Along the edge of the polygon, a micro-toposequence develops. The ice wedge pushes soil apart into a rim on both sides and leaves a trough over the ice wedge in between, while the polygon center remains flat. The trough is wet and generally accumulates organic materials or organic-rich sediments over the ice wedges below, favoring the formation of Glacistels. Turbels form along the rim where cryoturbation is most pronounced, and Orthels usually occur in the polygon center. However, with time, the ice wedges degrade and melt due to climate warming or disturbance, forming deep troughs. The once flat- or low-centered polygon interiors become high-centered polygons, which induce surface cracking, and enhanced cryoturbation is manifested through nonsorted circle formation, resulting in Turbels and the eventual initiation of thermokarst, starting the thaw lake cycle again.

**Vegetation**

Vegetation plays an important role in controlling the soil temperature regime and permafrost dynamics. In boreal forests, vegetation provides shading to cool the ground, and the surface O horizons provide insulation to the soil below to buffer against rapid temperature changes. Once vegetation canopy or surface O horizons are removed either by fire or land use practices, the exposed soil warms up rapidly and underlying permafrost recedes to a greater depth, often forming thermokarst in ice-rich Gelisols. In the boreal and subarctic regions, L. Viereck conducted a classic study demonstrating the dynamic relationship between vegetation succession and soil development following a fire cycle on a floodplain in interior Alaska. Once the fire destroyed forest cover, the permafrost started to thaw and the depth of the active layer increased. Grass and herbaceous species began to populate the bare ground, followed by shrubs, then mixed deciduous forest, and eventually a nearly monoculture spruce forest within 80 to 120 years. After fire, soil drainage improves due to thawing permafrost (deepened water table), and soils change from Gelisols to well- to poorly-drained Inceptisols and eventually cycle back to Gelisols after permafrost shallows to <1 m depth as the pre-fire forest community again dominates the landscape. Thus, there is a very dynamic relationship between vegetation and permafrost/Gelisol development.

In lowlands where black spruce dominates, or in bogs with scattered black spruce, the active layer in mineral soils seldom exceeds a depth of 40 cm because of the effective insulation of the thick moss layer associated with the black spruce community, despite the fact that the mean air temperature of boreal regions is much warmer than that of arctic regions. In the tundra region, the ground cover community and the surface organic layer play a critical role in patterned ground formation and active layer dynamics because of insulating effects. In the northern fringe of the Arctic Foothills and the southern edge of the Arctic Coastal Plains of Alaska, well-developed nonsorted circles were observed to have centers nearly devoid of vegetation. According to V. Romanovsky, the maximum frost heave observed in the center during the winter can reach 25 cm, but the tundra around the circles only showed a maximum of 5 cm upward deformation, and the observed active layer depth under the circle is more than twice the depth under the tundra.

**Time**

In Gelisol formation, the time factor can be offset by permafrost or cryogenic processes that respond to time-insensitive factors such as local climate shift or fire. In unglaciated areas such as interior Alaska, loess sequences have been dated back to the early Pliocene, but present surface soils (within 2 m) are mostly of the Holocene age because of syngegetic processes (i.e., previously formed soils buried by newly added deposits). On glaciated uplands, cryoturbated OM churned to the top of permafrost under the circles are commonly used as a time marker for the period of cryoturbation activity. Radiocarbon dates of cryoturbated OM under nonsorted circles found in the Arctic Foothills of Alaska range from 7,000 to 9,000 YBP, up to 13,000 YBP. The Beringian Province of western Alaska and eastern Siberia was not glaciated during the most recent glacial episodes, and several paleosol studies using ^14C dating of cryoturbated OM revealed that those soils were of late-Pleistocene age. Similar dates were found for the soils on the Arctic Coastal Plains of Alaska. Unlike the adjacent Coastal Plain, the Arctic Foothills of Alaska experienced multiple glacial events that resulted in deposits of varying ages. T. Hamilton noted a chronosequence of moraines dated from the late Pliocene scattered along the northern fringe of the Arctic Foothills with descending ages from Early Wisconsin to mid-Holocene southward to the foothills of the Brooks Range. Soils formed in the youngest moraine (6,000 YBP) tend to have high base saturation and slightly alkaline reactions and support moist nonacid...
tundra vegetation. In the older moraines (>12,000 YBP), bases have been leached, soil reaction is more acidic, and land-cover transitions to moist acidic tundra community.

One question that persists in the study of this locality: why are there no paleosols of Early Wisconsin or older found on foothill moraines of that age? It is easy to answer this question when looking at the landscape, dominated by solifluction and nonsorted circles creeping down the slopes. Gravity-driven cryoturbation and cryo-erosional processes gradually erased evidence of ancient soils, moving materials down slope and into drainages and valleys. Thus, peat deposits of >2 m depth in the lowland positions have $^{14}$C age of >18,000 YBP, whereas organic samples at the bottom of the nonsorted circles on mid-slopes dated only from 3,500 to 6,000 YBP. This suggests that normal chronological models of soil formation developed for other soil orders are not always applicable to Gelisols, where patterned ground formation, cryoturbation, and gelifluction processes episodically “reset” the soil-forming clock.