Frost Heave

By Lorraine Manz

There was once a widely held belief among the rural inhabitants of several English counties that stones grew and multiplied. To the farmers and laborers who worked the land this explained why, when a field was cleared of stones, it would soon be littered with more. The common thought was that the stones grew from small pebbles in the soil and then somehow rose to the surface. Many people even went so far as to believe that the pebbles themselves were the offspring of so-called “mother-” or “breeding-stones,” in reality chunks of an unusual siliceous flint conglomerate that is also known locally as “puddingstone” because of its resemblance to an old-fashioned plum pudding (fig. 1).

Figure 1. Puddingstone is a type of conglomerate in which the color of the clasts contrasts sharply with that of the matrix giving it the appearance of an old-fashioned plum pudding. The photo shows an example of Hertfordshire puddingstone (named after the county of Hertfordshire in southern England where most of it is found), which consists of well-rounded brown and dark gray flint pebbles distributed throughout a strongly cemented, much lighter-colored siliceous matrix. In some parts of England rocks like this were known as “mother-stones” or “breeding-stones” in the belief that pebbles were their offspring. Photo courtesy of D.M. GAC Fossils and released by them into the public domain.

Mother-stones are still kept by some, but only as curiosities and conversation pieces. No-one in their right mind today would seriously bestow them with any procreative capability or believe that pebbles are baby rocks. And the arrival of yet another multitude of stones that in years past country people could only attribute to some sort of magic, we now recognize as nothing more than one manifestation of a natural process called frost heave. It is the same process, often aggravated by flooding and/or heavy traffic, that ruins miles of North Dakota’s roads every spring: the obstacle course of broken pavement, potholes, and carbuncle-like humps (fig. 2) that they become as winter loses its grip and the annual thaw sets in is primarily the result of frost heave.

Frost heave is a form of frost action, a physical weathering process involving the cyclic freezing and thawing of water in soil or rock. Heave in this context refers to the upward movement of the ground surface that occurs in response to the seasonal formation of ice in the underlying soil. The dynamics of this ostensibly simple process are exceedingly complex and still not fully understood; yet despite its intricacies, the incidence of frost heave is dependent on just three things: besides freezing temperatures, it only requires the right kind of soil and an abundant, readily available water supply.

Early investigators attributed frost heave to the expansion that occurs when water freezes, but this did not explain why the effects of frost heave are so frequently much greater than frozen soil alone is capable of producing. The discrepancy quickly becomes

Figure 2. Asphalt pavement on a Bismarck street damaged by frost heave. Several chunks of the surface course have been dislodged by the wheels of local traffic exposing the underlying aggregate base. Photo by Lorraine Manz.

apparent if you consider that when water freezes its volume increases by about 9%. That being the case, a soil with a water content of 50% (about as much as the average soil can hold) would only expand by half this amount. Yet even if this expansion was unidirectional (the old theory assumed it was upwards because that was the path of least resistance) it would only produce about half an inch of uplift per vertical foot of frozen soil. In a typical North Dakota winter the ground freezes to an average depth of about 4.5 feet (1.4 m) (Jensen, No date), but as figure 3 shows, heaving can far exceed the 1 or 2 inches (2.5-5 cm) this premise forecasts. Clearly, something else is going on.

Figure 3. Spring 2011. Frost heave on this Bismarck street has lifted parts of the road surface about 18 inches (46 cm). The maximum freeze depth in the Bismarck area for the winter of 2010-2011 was about 40 inches (100 cm)* (North Dakota State Climate Office, 2011). Photo by Lorraine Manz.

The problem with the theory that frost heave is caused by the expansion of water when it freezes is that it was based on an erroneous assumption, which was that soils behaved as closed systems (nothing in or out). Evidence to the contrary remained largely ignored until Stephen Taber, a geologist at the University of South Carolina, published the results of a series of investigations that debunked the old theory once and for all (Taber, 1929, 1930). Taber demonstrated that it was not expansion, but rather the formation of ice lenses by segregation of water from the soil as the ground freezes that is the principal cause of frost heave. Moreover, by experimenting with soils as open systems he was able to show that lens growth may be sustained by the addition of groundwater drawn from warmer zones below the freezing front, and also that liquids other than water (Taber used benzene and nitrobenzene) can induce frost heave. This last observation clearly confirmed that the volumetric expansion of water as it turns to ice could not be the driving force behind the vertical displacement of frozen soil because, like almost all liquids besides water, benzene and nitrobenzene contract as they solidify.

Ice lenses are lens-shaped masses of almost pure ice that form in frozen soil or rock. Lens formation takes place at, or a short distance behind, the freezing front at any depth where conditions are favorable and will continue until those conditions change. Because they form perpendicular to the direction of heat flow, ice lenses tend to grow with their long axes oriented parallel to the ground surface. Most lensing is periodic, giving rise to multiple lenses separated vertically from one another by a layer of frozen soil. Single, thick lenses are rare in temperate climatic zones because their formation depends on persistent, steady state conditions. Ice lenses range in size from hair-thin slivers, barely visible to the naked eye, to laterally very extensive structures several feet thick.

An up-close examination of an ice lens reveals a structure composed of a multitude of thin, hair-like crystals that give the lens what has been described as a "satiny" appearance. The crystals develop, and are thus oriented; parallel to the direction of heat flow and it is their growth, not the path of least resistance, that controls the direction of heave.

The ground freezes from the surface down, progressing along a front parallel to the surface and perpendicular to the direction of heat flow, thereby creating a thermal gradient as the ground loses heat to the cold air above it. An ice lens also forms from the top down and grows by the addition of water to its lower, warmer surface from soil below the freezing front (fig. 4). This is a far-from-straightforward process because it requires a set of conditions that will allow water to (i) defy gravity and flow upwards and (ii) co-exist with ice at temperatures below freezing.

In a porous medium like soil, getting water to flow upwards is not difficult because it will rise naturally by capillary action. If the water is moving through unfrozen soil towards the freeze front, then this rise is aided by virtue of the fact that it is moving down the thermal gradient. Water in freezing soils is also moved around by cryogenic suction forces that are produced within a partially frozen region, or frozen fringe, just below the basal surface of the

* No data available for Bismarck weather stations. This figure was estimated using deep soil temperatures from the nearest NDAWN station at Streeter in Stutsman County, approximately 65 miles (100 km) east of Bismarck.

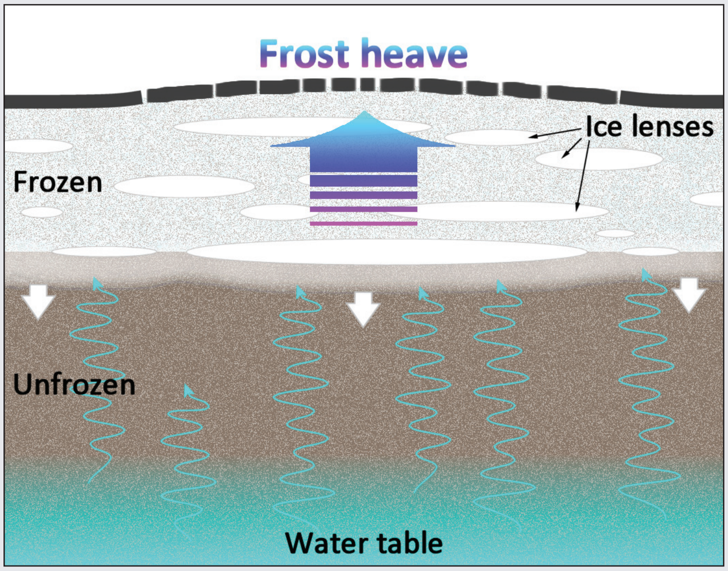

Figure 4. Formation of ice lenses in frozen ground overlain by pavement. Freezing takes place from the surface down (white arrows). When conditions are favorable, an ice lens begins to form a short distance behind the freezing front. Fed by liquid groundwater from warmer zones deeper in the soil profile, the lens will continue to grow for as long as the controlling mechanisms allow. Multiple lenses reflect fluctuations in these controls due to changes in surface temperature (which affects the rate of freezing), soil texture, and water availability. The amount of vertical displacement (heave) is roughly equal to the combined thicknesses of the underlying ice lenses. Heaving causes the pavement to crack, resulting in the kind of damage shown in figures 2 and 3.

growing ice lens (fig. 5). The microscopic interactions between soil grains, ice, and water that are responsible for these suction forces are also the fundamental controlling influence on ice lens formation and growth, and thus, ultimately drive the whole process of frost heave. They are also the reasons why water can sometimes remain in liquid form at sub-zero (0°C) temperatures.

There are two thermodynamic processes that allow liquid water to persist at below-freezing temperatures. The first is the Gibbs-Thomson effect, which is a surface phenomenon that causes melting point depression. When ice freezes in a porous medium, solidification takes place along a curved interface that is convex-outward with respect to the ice. Freezing progresses by the penetration of this solid-liquid interface into increasingly smaller pore spaces; and in the same way that the radius of curvature of the meniscus formed by capillary action at a liquid-vapor boundary is proportional to the internal radius of the capillary tube, i.e., the narrower the pore space, the higher the convexity of the ice surface. At a particular sub-zero temperature a level of pore space confinement is reached where the energy required to further reduce the curvature of the ice-solid interface would exceed the amount required to maintain a small volume of water in its liquid form. As the temperature continues to fall, ice is able to move into more confined spaces and the amount of liquid water decreases until eventually it is all frozen.

Liquid water may also persist at below-freezing temperatures as a nanometers-thick, "premelted" film that forms along the surface contacts between individual soil grains and ice. Premelting is an effect that is surprisingly common in nature, and besides frost heave is known to have a controlling influence on a number of other natural phenomena including the electrification of thunderclouds, the formation of sea ice, and possibly even the development of planetary systems (Dash et al., 2006). The molecular interactions that cause premelting are complex, but the reason for the liquid films is simple enough: they are a barrier, set in place to attenuate the solid-solid electrostatic forces of repulsion between the surfaces of the ice and soil grains.

Water is transported along these liquid pathways from the zero isotherm to the base of the ice lens by pressure differences generated by the same forces that produce premelted films. The liquid film surrounding a soil grain within the frozen fringe is thicker on its lower (warmer) side (fig. 6). This variation in thickness is accompanied by a corresponding pressure change within the film (Dash, 1989), which establishes a pressure gradient across the soil grain parallel, but in the opposite direction, to the thermal gradient. The grain is thus pushed away from the ice lens towards warmer temperatures as water is drawn (sucked) through the film around the grain to feed the growing lens (Rempel, 2010). The process is sustained by the continuous supply of liquid water from

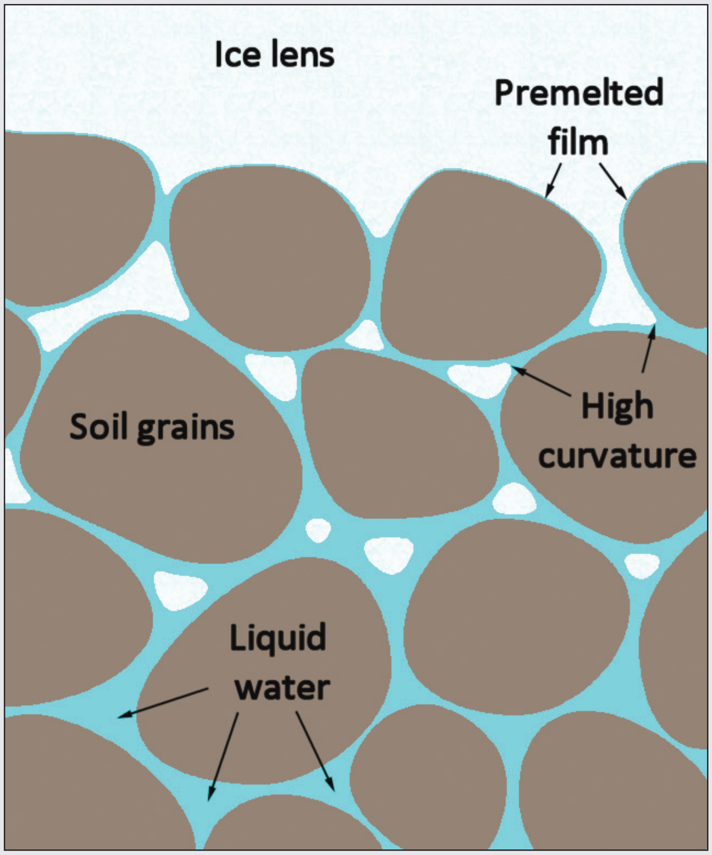

Figure 5. The frozen fringe below a growing ice lens (represented by the hazy area below the lowest ice lenses in figure 4). Even though the temperature here is a few degrees below freezing, liquid water is able to exist in equilibrium with ice owing to (i) melting point depression caused by the Gibbs-Thomson effect and (ii) premelting at the ice-soil interface. Modified from Rempel, 2010.

below the frozen fringe, and is an example of pressure-induced regelation.

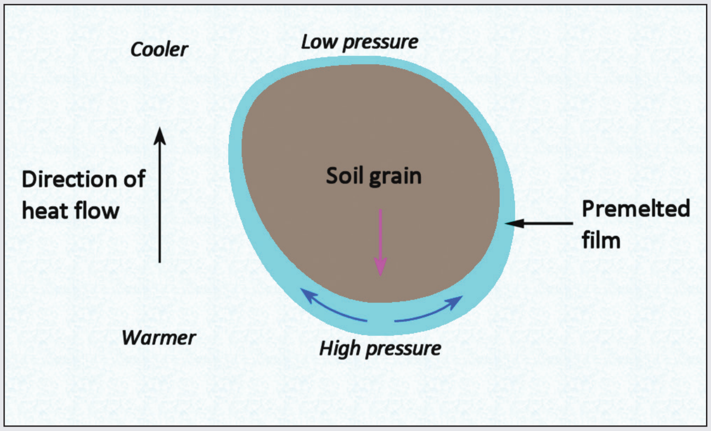

Figure 6. Segregation of soil and ice by regelation. The thickness of the premelted film surrounding a soil grain subjected to a temperature gradient is greater on its warmer side. Water in the premelted film migrates down the resulting pressure gradient (blue arrows) from the lower, warmer side of the grain to its upper, cooler side where the water refreezes, forcing the soil grain downwards (away) from the growing ice lens (red arrow).

Not all soils are susceptible to frost heave

At about the same time that Taber was conducting his laboratory experiments in South Carolina, Gunnar Beskow (1935), a geologist with the Swedish Institute of Roads, launched an investigation to address the costly problem of frost damage to Scandinavia's transportation network. In what was the first in-depth field study of frost heave, Beskow noted that the magnitude of its effects is largely determined by the particle size of the soil, an observation consistent with Taber's experimental findings.

They both found that the effects of frost heave are most pronounced in soils that facilitate capillary flow. Frost-susceptible soils thus tend to be fine-textured; with silts, loams, and very fine sands providing the optimum balance of moisture affinity (favored by high particle surface to volume ratios, i.e. small soil grains), pore size, permeability and hydraulic conductivity. Many glacial soils fall within this textural range, which is unfortunate for North Dakota because they quite literally cover a lot of ground here. Clays are hygroscopic, highly porous, and permeable but have low hydraulic conductivity because of their small void size. The consequent reduction in capillary flow tends to lessen the severity of heaving because it impedes lens formation. Frost heave is very rare in coarse-grained soils especially clean, well-drained sands and gravels. Their pore spaces are too large to permit capillary flow or the formation of ice lenses, so any pore water simply freezes in-place with no segregation.

Differential frost heave, freeze-thaw cycles and frost jacking

Frost heave, if laterally uniform, is comparatively benign because there is no surface deformation and thus no threat to the integrity of pavements and other structures. Most frost damage is caused by non-uniform or differential heave. This occurs as a result of lateral variations in the conditions that control ice lens formation and other freezing behavior. The main influences are soil texture and the availability of water (i.e. the height of the water table). Other factors such as the presence or absence of vegetation, fluctuations in the thermal regime, and overburden pressure are also important but of lesser significance.

Differential frost heave is what turns our roads into roller coasters every spring and causes the kind of damage shown in figures 2 and 3. Heaving is more destructive at that time of year, not only because the freeze depth is at or near its maximum, but also because its effects are intensified by an influx of water from melting snow and ice, and the wear and tear the road has been subjected to all winter.

Figure 7. Load restrictions are imposed to prevent damage to roads weakened by meltwater saturation during the spring thaw. Photo by Lorraine Manz.

The ground thaws from the surface down, which can seriously impede soil drainage. Unless there is sufficient gradient to allow throughflow, meltwater will accumulate and remain trapped in the upper part of the soil until the layer of frozen ground beneath has completely thawed. A road with water trapped under it in this way can lose 50% or more of its normal load bearing capacity (Mokwa, 2004). This is why the North Dakota Department of Transportation imposes load restrictions on certain roads for about a month after the onset of the spring thaw (fig. 7), which is when they are at their weakest. Refreezing after a temporary thaw also exacerbates frost heave because the increased water content of the near-surface soil results in a correspondingly higher degree of segregation.

Shallow footings and foundations can crack under the influence of differential frost heave, which may render the structure they support unsound. Small buildings, especially if they are unheated, are particularly vulnerable to this problem, as are many other lightweight constructions such as decks, retaining walls, transmission towers, and so on.

The vertical displacement of an isolated structure (as opposed to part of a road or parking lot, for example) by frost heave is known as frost jacking, or frost pull. But whereas a road lifted by frost heave will gradually subside to its original level after the ground beneath it has thawed, uplift caused by frost jacking tends to be permanent. The sequence of drawings in figure 8 explains why.

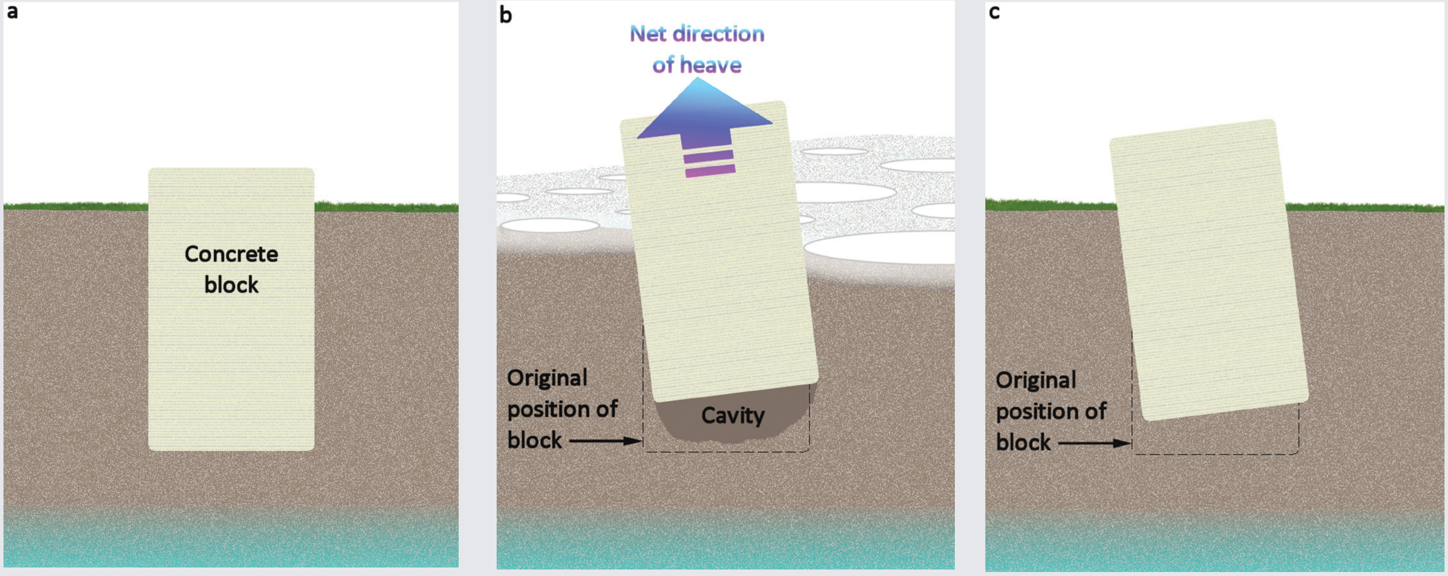

Figure 8. A cross-sectional view of a block of concrete partially buried in a moist, frost-susceptible soil. (a) Before the onset of freezing. (b) Frozen soil adheres to the sides of the block, forming bonds that become strong enough to overcome the downward shear and other resistant forces. Heave from growing ice lenses is transmitted to the block through these bonds, which lifts the block along with the surrounding soil, leaving a cavity that may collapse or fill with unfrozen debris. Frost jacking and differential heave commonly work in tandem, causing the block to tilt as it rises. (c) The block is unable to return to its original position when the ground thaws. If the cycle is allowed to repeat over several winters, the block will continue to be "jacked" upwards and possibly even forced completely out of the soil.

The effects of frost jacking are usually quite subtle but if the process is repeated over several winters, the cumulative damage can be significant. Properly observed, engineering guidelines and building codes designed to mitigate frost jacking (and other forms of frost heave) have proven highly successful; so reports of foundation piles being "jacked" 24 inches in a single year, or 11 feet over several winters (Péwé and Paige, 1963) should be a thing of the past. Nevertheless, there is no one-size-fits-all solution to frost heave, and what works well in one situation may fail miserably in another; so until we have a better understanding of the process, there are no guarantees.

Landforms associated with frost heave

Frost heave is indiscriminate and anything we put in or on the ground, or which belongs there naturally (e.g. rocks and vegetation), is fair game. Railroads, bridges (Péwé and Paige, 1963), pipelines, utility poles, coffins (McFadden and Bennett, 1991), unexploded ordnance (Henry et al., 2004), trash, small trees, fence posts, lawn edging, the list is endless and bizarre. As for the land itself, it is now plain to see that the annual appearance in spring of yet more stones on farmland cleared of them the previous year is due primarily to frost pull, probably aided a little by differential heave (Washburn, 1980).

This seemingly uncanny ability of frost heave to sort unconsolidated material by size is taken to a whole new level in regions underlain by permafrost, where intense cold, recurrent diurnal and seasonal freeze-thaw cycles, and poorly drained soils all serve to enhance the processes of frost action. Differential heave is a key mechanism in the formation of some types of patterned ground

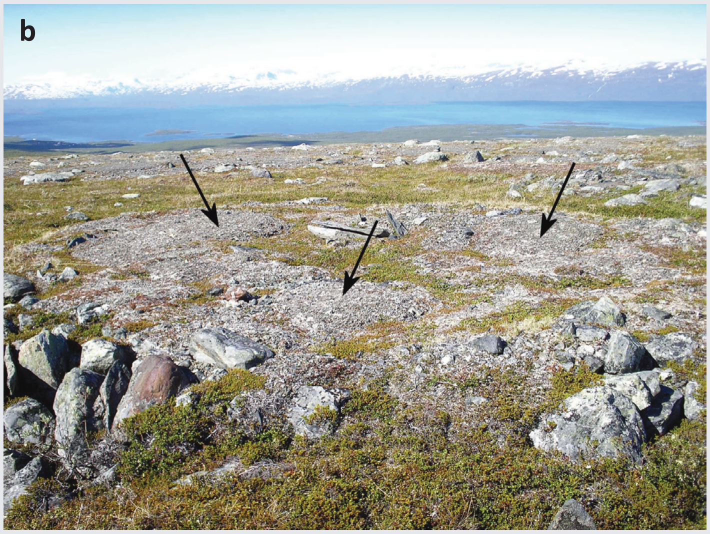

Figure 9. Two examples of patterned ground. (a) Stone circles in the Svalbard Islands, northern Norway. Photo by Hannes Grobe. (b) Frost boils (indicated by the arrows) in Abisko National Park, Lapland, Sweden. Photo by Dentren at en.wikipedia

(Kessler and Werner, 2003; Peterson and Krantz, 2003, 2008), the reorganization of surface materials into regular arrangements of various geometric shapes, commonly circles (fig. 9), polygons and lines (stripes). Sorted patterned ground, such as the stone circles in figure 9a, develops on till and other diamictons. The stones are moved upward and outward by repeated freezing and thawing leaving the finer-grained material in the center of the ring. Frost boils (fig. 9b) are a type of non-sorted patterned ground consisting of circles of bare earth formed by a combination of frost heave and cryoturbation (soil disturbance caused by frost action) (Peterson and Krantz, 2008). They are usually separated by areas of vegetation or peat and are not ringed by stones.

Figure 10 (left). Large pingos near Tuktoyaktuk in the Mackenzie Delta in Canada's Northwest Territories. The one in the foreground is Ibyuk Pingo, Canada's highest at 161 feet (49 m) and the second-highest in the world. It is still growing at a rate of about three-quarters of an inch (2 cm) a year and is estimated to be at least 1,000 years old. Photo by Emma Pike.

Figure 11 (right). An aerial view of a group of well-developed palsas in northern Sweden. Photo by Dentren at en.wikipedia.

The small ice-cored hills known as pingos (from the Inuit word pinguq, meaning "little hill") are unique to the permafrost environment and their relict forms in modern temperate zones are indicative of an earlier, much colder climate. Viewed from above, pingos are either circular or elliptical in shape with basal diameters ranging from a few feet to more than a third of a mile (Washburn, 1980). Up to 200 feet (70 m) high, they are generally rounded in profile although the summits of many of the larger ones are cratered and fractured, giving them the appearance of a small volcanic cone (fig. 10). These ruptured surfaces are caused by tensile stress generated by the growing, typically massive ice core, which is often exposed as the displaced overburden of soil and vegetation slumps to lower elevations.

Most pingos may be classified as one of two types, based on their origin. Both types involve the formation of segregated ice, the principal difference between the two classes being the source of the water supply. Closed-system pingos develop in recently drained shallow lake basins, where liquid groundwater persists in a layer of unfrozen ground, or talik, within the former lake bed. Stripped of its insulating cover of lake water, the surface of the talik begins to freeze, completely enclosing the remaining water in permafrost. Hydrostatic pressure from the encroaching ice forces the water upward until it, too, eventually begins to freeze and heave the frozen overburden into a mound. Closed-system pingos are most common in areas of perennial permafrost and are generally the larger of the two types.

Open-system pingos are mainly associated with discontinuous permafrost zones, where taliks and mobile ground water are common, typically forming on slopes where they obtain their water via artesian flow.

Palsas resemble small pingos, although unlike their larger counterparts, they are not limited to the permafrost environment and their genesis is different (Gurney, 2001). Aptly named (palsa is a Finnish modification of the Northern Sami word balsa, meaning "a hummock rising out of a bog with a core of ice"), palsas typically occur in peat bogs and other wetlands as low, oval-shaped mounds that rarely exceed 300 feet (100 m) in length or rise much higher than about 30 feet (10 m) (fig. 11). They consist of a core of alternating layers of segregated ice and peat or fine sediment that, insulated by a covering of vegetation, often remains perennially frozen, growing a little thicker each winter as more ice is added.

Whereas the core ice of pingos is derived from water under hydrostatic or hydraulic pressure, palsas are formed by cryosuction in more-or-less the same way as the hummocks that appear on our roads every spring. Besides the abundant water supply, their apparent affinity for boggy ground is due to bare spots where the wind has removed most or all of the snow cover, allowing frost to penetrate deeper into the subsurface than in the surrounding areas. Once a palsa has begun to form, its continued growth is favored by its increasing surface elevation, which the wind is more likely to keep clear of snow. Moreover, as the palsa rises higher above the water table, its covering of wetland vegetation starts to dry out, which makes it a more effectual insulator of the frozen core. An increase in surface albedo, brought about by a change in vegetation from peat mosses to lighter-colored plant species such as Cladonia (reindeer or cup lichens) may also influence palsa formation.

Heave is also the underlying cause of frost creep, the downslope movement of soil in response to cyclic expansion and contraction induced by freeze-thaw action. In combination with solifluction or gelifluction (its frozen-ground equivalent), frost creep operates on gradients as low as 1° but is most effective on 5°-20° slopes. Landforms are genetically similar and are usually classified morphologically. Features include lobes, benches, sheets, and streams.

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Staff changes at the Oil and Gas Division

New Hires

Bismarck office
David Burns – Engineering Technician
Tom Delzer – Engineering Technician
Kevin Connors – Carbon Capture and Storage Supervisor

Dickinson office
Cody Flammond – Field Inspector
Robyn Koppinger – Field Technician

Farewell

Long-time employee Karla Lorentzen retired from her Office Assistant position on July 15 after 22 years of service to the Oil and Gas Division.