Two relict pingos (P) display characteristic radial cracks and depressed summits. They occupy the centers of small lake basins on a stagnation moraine a few miles north of Loring, Montana. When the lakes drained, a mixture of water and clay-rich till froze and expanded upward as permafrost that surrounded the lake basins migrated inward. The ground stretched and cracked above the rising core of icy clay. When the ice melted, the clay remained to prop up the relict pingo.
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Viewing Stereo Images

The two small pictures at the top of each page are a stereo pair. To see the image in three dimensions, you need to look at the right image with the right eye and the left image with the left eye. To do this, pick out some prominent feature in the pictures and stare beyond the pictures. The two prominent features, one from each picture, should float together in the center. This center image will be in three dimensions. At first it may not be in focus. You are accustomed to associate convergence of your eyes with focus. If you continue to stare at the center image, your mind will ultimately relent and focus on the center image while your gaze remains parallel, each eye looking at its respective image.

A simple exercise may help prepare you for this unaccustomed way of viewing. With your hands at arm's length in front of your eyes, touch your two index fingers together as you look beyond them. You should see a sausage image between your two index fingers. Your eyes are parallel, the right one looking at the right finger, the left one at the left finger. The two images have floated apart, the right one to the left and the left one to the right to form the sausage. The feeling in your eyes is the one you should try to imitate when looking at the stereo images. Some will master the technique instantly. It will take longer for others. If you don't succeed at first, keep trying at odd times. Try sometime when you are really tired and tend to see double images anyway when you stare at objects. If I could learn to do it, anyone with two good eyes can. I worked at it off and on for over two years before I suddenly learned the knack.

Your eyes are just a few inches apart. With that small separation, you can see in three dimensions for about 1100 feet. Most of these images were taken from a small airplane flying at a velocity of about 100 mph. The interval between the two images varied from one second to several seconds, giving an effective eye base of between 100 and several hundred feet. With this eye-base, you can see in three dimensions for miles. These pictures produce spectacular three dimensional views not easily obtainable in any other way.
Origin of Pingos

Pingos is an Eskimo word for small hill that was first used in a scientific sense by Porslid in 1938 to denote conical ice-cored hills in Alaska and Canada.

Pingos can form in two ways. First, they may form in an open system where springs freeze while migrating upward through permanently frozen ground. As the spring water freezes, it expands and arches the overlying ground into a small hill. The ground at the top of the hill stretches and may crack radially. A depression may develop at the top of the hill when the upper part of the ice lens melts in the summer. Second, they may form in a closed system where permafrost that surrounds a talik, a hole through the permafrost, migrates inward to freeze the water and sediment of the talik. Expansion of the water as it freezes arches the ground upward into a hill that may be split by radial cracks. A depression may develop at the summit of the hill from melting at the top of the ice lens during the summer. In the arctic, taliks occur under lakes that are deep enough to prevent freezing to the bottom. If the lake is drained or filled, permafrost then migrates into the talik. Closed system pingos in northern Canada are shown on pages 3, 4, and 5.

According to Mackay (1973), of the thousands of pingos in northern Canada, fifty are probably growing now, and five are known to have started growing since 1935. They attain their maximum diameter early and then grow higher. The maximum growth rate of about 1.5 meters per year occurs during the first few years and then decreases inversely as the square root of time. The largest pingos may have grown for more than a thousand years.

When the climate changes and the permafrost melts, the pingo should collapse into a ring of sediment, a pingo ring, surrounding a central depression created by melting of the ice core.

Montana Pingo Rings and Relict Pingos

In 1993 Levish, Ostenaa, and Klinger recognized pingo rings near Kicking Horse and Ninepipe Reservoirs in the Mission Valley of Western Montana. Lakes occupied small depressions in the permafrost along the margin of glacial Lake Missoula. These lakes probably drained when glacial Lake Missoula broke through its glacier dam for the last time near Sand Point, Idaho, to spread a final catastrophic flood across eastern Washington. Small closed-system pingos formed as permafrost migrated under the drained lake basins to arch up the lake silts and clays into pingos. As the continental glaciers retreated and the climate warmed, the permafrost melted and the pingos collapsed into pingo rings shown on pages 6, 7, and 8.

As shown on the cover and pages 9 through 12, relict pingos occur in north-central Montana north of Loring near the Canadian border. These pingos, still 40 to 50 feet high, developed under drained lake basins on a stagnation moraine as the continental ice sheets retreated. The stagnation moraine developed as great blocks of stagnant ice
separated from the actively moving ice of the glacier to waste away slowly and drop their irregular loads of debris. When lakes blocked by masses of ice suddenly drained, permafrost migrated under them and arched the overlying unsorted debris into pingos. Because the glacier in this area rode across and gouged up Cretaceous shales rich in smectite clay, its unsorted debris (its till) is rich in this clay*. When this clay mixed with water, its crystal lattice spread apart to absorb large amounts. When the mixture of clay and water froze, the mixture expanded as it migrated into the core of the pingo. When the permafrost melted, the clay carried into the core of the pingo remained to prop up the relict pingo. A sample of this till frozen in a cylindrical container made a perfect miniature pingo that remained undiminished in height after thawing (page 13). In contrast, an experimental pingo made by freezing carrot soup collapsed to about half its frozen height when thawed (page 14).

Other glacial features associated with relict pingos on stagnation moraine near Loring are prairie mounds and ice-hole deposits. Gravenor's explanation for the origin of prairie mounds is given on page 11. Ice holes on Kuskulana Glacier are shown on page 15. Ice-hole deposits are shown on page 16. Low arcuate ridges of till occur on a till plain near Turner in north-central Montana. How they formed is unknown, but similar-appearing arcuate dirt bands occur in the piedmont portion of La Perouse Glacier. They may have been brought up from the base of the glacier by ice thrust faults, and if the ice stagnates as the glacier retreats, they could be let down to form arcuate ridges of till on a till plain.

*Richard Berg of the Montana Bureau of Mines and Geology x-rayed a sample of the till to identify the clay minerals. Smectite is the dominant clay mineral.

References

Levish, Dan; Ostenaa, Dean; Klinger, Ralph, 1993, Quaternary geology of the Mission Valley, Montana", Seismotectonic Report 93-7, Friends of the Pleistocene 1993 Rocky Mountain Field Trip Guidebook, Bureau of Reclamation, Geotechnical Engineering and Geology Division.
Ibyuk Pingo is about 5 miles southwest of Tuktoyaktuk on the MacKenzie River Delta in northern Canada. A pingo is a hill formed by an intrusion of ground ice. Because of the high specific heat of water, the ground is unfrozen under lakes that do not freeze to the bottom. When the lake is either drained or filled by sediment, permafrost migrates under it, expanding as it freezes, pushing up and stretching the ground over it. Ibyuk pingo displays the typical central depression over its ice core and radial gullies that follow cracks developed as the ground stretched. Picture taken by Doug Dresser, July, 1986.
Pingos and ice-wedge polygons are permafrost features of the coastal plain along the Beaufort Sea in Canada's Northwest Territory. As permafrost migrated inward under the pond that was ancestral to the asymmetric pingo, the last part to freeze was probably the deepest part of the pond, under the peak of the pingo. Ice-wedge polygons start to form when the ground cracks as it contracts under the deep cold of winter. In summer, water runs into the cracks, freezes and expands, the process repeating with the seasons over many years to form polygonal ice wedges that push up narrow ridges around the centers of the polygons. Polygons developed on impermeable muck have low, dark centers, many of which are occupied by standing water in summer when the upper few inches of the permafrost thaws. Those developed on more permeable sediment have light, high centers, the thawed permafrost draining into the adjacent ice-wedge cracks. Because ice wedges grow slowly, the faint ice-wedge polygons on the surface of the asymmetric pingo indicate that it is probably at least a thousand years old. Picture taken by Doug Dresser, July, 1986.
A talik, which is a hole through the permafrost, probably existed under a pond at this site when sea level was lower during the last glacial maximum. Permafrost persisted even as the glaciers melted and sea level rose. When the spit migrated over the pond, cold penetrated downward and concentrically into the talik from the surrounding permafrost, and ground water under the spit expanded as it froze to form an ice core that arched the frozen spit sediments into a pingo. The pingo is evidence that permafrost still underlies the southern, shallow Beaufort Sea. According to Mackay*, the permafrost under nearshore areas is 300 to 400 meters thick. Picture taken in Northwest Territories, Canada, by Doug Dresser, July, 1986.

The many circular and oval depressions were identified as pingo rings in 1993.* These were most probably closed system pingos developed on illitic clays and silts after glacial Lake Missoula drained catastrophically across the scablands of Washington. Ice lenses in the permafrost pushed the sediments up and outward into small conical hills that collapsed when the ice melted, leaving ramparts around the depressions. Soft, water-logged sediments may have added to the ramparts by sliding off the pingo hills as their ice cores melted. Western Montana, October, 1993.

*Levish, Dan; Ostenaa, Dean; Klinger, Ralph, 1993, “Quaternary Geology of the Mission Valley, Montana”, Seismotectonic Report 93-7, Friends of the Pleistocene 1993 Rocky Mountain Field Trip, Bureau of Reclamation, Geotechnical Engineering and Geology Division.
You are looking toward the southwest at pingo rings next to and under Kicking Horse Reservoir in the Mission Valley of western Montana. The central depressions of the rings formed as the dirty ice cores of the pingos melted. Those that contain lakes have impermeable clay floors. The dominant clay mineral here is illite, derived from the laminated sediments deposited on the bottom of glacial Lake Missoula. Even though the crystal lattice of illite does not expand strongly when the mineral contacts water, the tiny particle size and platy shape of the illite clay crystals allows them to join together to form an impermeable seal. Picture taken October, 1993.
You are looking toward the west at pingo rings between Ninepipe and Kicking Horse Reservoirs in the Mission Valley of western Montana. Permafrost migrated from frozen ground into unfrozen sediments under ponds that drained after glacial Lake Missoula broke its ice dam near Sand Point, Idaho and flooded catastrophically across eastern Washington. The groundwater froze into dirty ice lenses that arched the overlying sediments into pingo. As the ice cores of the pingos melted, the sediments collapsed into low ramparts around depressions left by the melted ice cores. Lakes occupy the depressions that have impermeable clay bottoms. Picture taken October, 1993.
You are looking toward the southeast at relict pingos and prairie mounds developed on a stagnation moraine about five miles northeast of Loring in north-central Montana. The relict pingos are marked by "P" on the picture and rise about 45 feet (15 meters) above the pond basins in which they developed. The radial, star-like pattern of the drainage and the depressions at their tops are typical of pingos. Why have these pingos not collapsed into pingo rings when their ice cores melted? Probably, it is because they developed on clay-rich till dominated by the mineral smectite. The smectite expanded when saturated by glacial meltwater, and it is this clay mush that froze to push up the pingos when permafrost migrated under the drained ponds. After the ice melted, the clays remained to prop up the hills.
You are looking southward at a meltwater channel, a glacial sluice, cut through the stagnant ice block that produced this stagnation moraine about eight miles north of Loring, Montana. The sluice is bordered by ice-contact ridges of till. According to Parizak*, dirt slipped and washed down the steep face of the stagnant ice to accumulate as ridges and it may have squeezed out from under the stagnant ice that bordered the sluice. Because this till is rich in smectite clay that expands when wet, it seems likely that it would have squeezed out easily from under the ice. Later, as permafrost migrated under drained ponds, the water-saturated till expanded as it froze to arch the overlying till into pingos. The three distant relict pingos are shown in closer view on the next page.

You are looking toward the southeast at features developed on a stagnation moraine about eight miles northeast of Loring, Montana. The relict pingos grew as permafrost migrated under drained lake basins after the stagnant glacier ice melted. The pingos are surrounded by smaller mounds, many of which have depressed summits. According to Gravenor*, who named them “prairie mounds”, these mounds formed where superglacial dirt filled a depression in the stagnant glacier ice, insulating the ice beneath it. The surrounding cleaner ice melted faster than the dirt-insulated ice, inverting the relief, and leaving a dirt mound covering a core of ice. When the ice core melted, it left a depression in the top of the mound. A possible origin for ice-contact ridges is described on the preceding page.

A relict pingo that grew on a stagnation moraine shows radial gullies and the depressed summit characteristic of modern pingos. It developed in a drained pond basin as a closed system pingo and retains its pingo features because it developed on till rich in smectite clay that expanded as it absorbed water and froze to form the clay-ice core of the pingo. After the core ice melted, the clay remained to support the relict pingo. The relict pingo is surrounded by prairie mounds, many of which have depressions at or near their summits, as shown by the three to which the arrows point. The origin of prairie mounds is described on the preceding page. Picture taken July 23, 1991 about five miles north of Loring, Montana.
Experimental Pingo in Smectite-rich Clay

Dirt was collected from a roadcut into the side of a relict pingo (p.9) about 3 miles north-east of Loring, Montana. About 20% by weight of water was added, stirred to make mud, and then frozen in a cylindrical container about 12 cm in diameter by about 16 cm deep. A pingo having a relief of about 15 mm developed.

The pingo remained about 15 mm high after thawing (two days at room temperature). As the mud mixture froze, the smectite clay particles must have been rearranged to form support for the structure. Twenty-one days later the pingo still maintained its cracked structure and a relief of 15 mm even though the mud in the container shrank and cracked as it dried.
Just for fun:
Experimental Pingo in Carrot Soup

Spicy carrot soup was frozen in a cylindrical container 17 cm in diameter by 14 cm deep to develop this experimental pingo.

When the spicy carrot soup thawed, the pingo collapsed to about half its frozen height.
You are looking toward the northeast at Mount Blackburn and Kuskulana Glacier in the Wrangell Mountains of Alaska. As the stagnant ice at the end of the glacier downwastes, debris concentrates, covering the ice with till. Holes melted through the ice contain small lakes. Weight of the ice around the hole and water-induced plasticity of the till may combine to squeeze till out from under the ice into a small ridge surrounding the lake sediments in the hole. Debris washing down the sides of the hole may also produce ridges or add to “squish ridges”. Depressions on the ice fill with till which then insulates the underlying ice. As the glacier downwastes, till-capped pinnacles of ice slowly melt away to leave mounds of till, often containing small depressions in their summits from the final melting of the underlying ice core. These were named “prairie mounds” by Gravenor.* Picture taken June 29, 1990.

The two flat areas surrounded by "squish ridges" were probably formed by sediment deposited in ponds confined by holes in stagnant ice. The weight of the ice surrounding the hole may have squeezed out the saturated smectite-rich till to form squish ridges encircling the ponds. The ridges might also form from dirt washed down the sides of the ice hole, or this process might add to the squish ridges.* Arrows point to three of the abundant prairie mounds that surround the ice-hole deposits. Cattle pose for scale below the ice-hole deposit near the center of the picture. Picture taken July 23, 1991 on a stagnation moraine a few miles north of Loring in north-central Montana.

You are looking northward at La Perouse Glacier in the Fairweather Range of Alaska. Ogives are arcuate wrinkles that form on the glacier surface below icefalls. Arcuate dirt bands follow parts of ogives in the lower part of the glacier. The dirt bands may have been brought up along thrust faults that extend through the ice to the base of the glacier. If the part of the glacier containing dirt bands stagnates when the glacier retreats, the dirt bands might be left as small arcuate ridges of till on the underlying surface. Picture taken June 26, 1989.
You are looking northward at arcuate till ridges on a till plain* a few miles southwest of Turner in north-central Montana. The ridges are three to five feet high. Because a few of the ridges extend under moraine of the last glaciation (the Wisconsin) at the edge of this low plateau, they probably formed during the earlier (Illinoian) glaciation.*

*Information from conversation with Roger Colton, USGS, now retired, during a field inspection in 1987.