



# A Short Introduction to Permafrost and Seasonally Frozen Ground

## ■ Freeze, Froze, Frozen: What These Words Mean

In keeping with the general plan followed in this book—to start with the fundamentals and work up from there—a good place to begin is with what people mean when they say that the ground freezes or that it is frozen. Their statements tacitly assume that everyone understands that the word freezing in its various forms pertains to the conversion of water to ice, and that when the ground freezes it is the contained water's change of *state (of matter)* from liquid to solid that makes frozen ground different from that not frozen. Because water changes from the solid state to the liquid state at 0°C (32°F), this is a big number in the frozen ground business. Zero degrees centigrade is the melting temperature of ice, and it is also called the freezing point of water—despite the fact that water does not always turn to ice at this temperature, but more of that later.

## ■ Frozen Ground in Turmoil

Like many other words, “frozen” has more than one meaning, so in addition to frozen ground we have things like frozen assets and people frozen in their tracks. Thus, frozen brings to mind both cold and immobility, but only the first really applies to frozen ground. Frozen ground definitely is mobile; it flows under load, it expands and contracts as its temperature

changes, its soil particles shift and deform, and molecules of water move around between them. In certain circumstances, freezing ground can swell up like a balloon, and when it thaws it can shrink to a fraction of its frozen size or slither away down a slope. Furthermore, the movements that accompany freezing and thawing within the ground can alter the makeup of a soil by reorienting soil particles, compressing them, changing their shape, and sorting them according to size. So it is best not to think of freezing and frozen soil as a static entity. Albeit in slow motion, it churns and seethes; it is a thing alive that leads a most interesting life involving time scales ranging from hours to thousands of years.

What causes such lively behavior of freezing, frozen and thawing ground? In a word: water. Water gives frozen ground its special character and causes all the turmoil when the ground freezes or thaws. So after the following brief examination of the geography and consequences of permafrost and seasonally frozen ground, the road ahead leads to a close look at water in its own right in Chapter 2 and then, in Chapter 3, examination of what happens when the ground contains water and the temperature goes down below 0°C.

## ■ Definition of Permafrost

As noted in the Preface, this book contains a glossary that provides definitions of words italicized in the text, in most cases when they initially appear. *Permafrost* is an early example. A widely accepted definition of permafrost is that it is ground that has a temperature lower than 0°C (32°F) continuously, for at least two consecutive years. Much permafrost is thousands of years old, and some is of recent origin. Permafrost is forming now in places previously unfrozen: under thickening moss of boreal forests, and in the ground on the north side of new buildings (in the northern hemisphere) where the midday sun no longer shines. However, the twentieth century has been largely an era of global warming so, by and large, the amount of permafrost is in decline. Each winter the ground in many places freezes to depths of 1 or 2 meters but no permafrost forms because the following summer's warmth brings the temperature up to 0°C or above.

This definition of permafrost on the basis of the ground's temperature alone has a generality that may be useful in certain circumstances since it includes material such as rock that might contain no water at all. Nevertheless, my experience is that a person is hard pressed to avoid thinking of permafrost as anything other than soil that remains frozen year around; that is, to think of permafrost as a substance rather than a condition—and anyone who has tried to dig up permafrost knows that it is a tough substance indeed.

The word “permafrost” (permanent + frozen) also is a catch-all term used to describe the general area of science relating to all aspects of frozen or nearly frozen ground, past, present and future. *Geocryology* (earth + cold + study) also is a term for this field, and yet another in use is *periglacial* (near + glacier) processes.

## ■ Where Permafrost Exists

Permafrost is present beneath the surface of approximately one-fifth of the earth's land area (in the northern hemisphere, 22% of the land area) and *subsea permafrost* exists on the shallow continental shelves of cold polar seas. As **Figure 1.1** (bold face indicates the first reference to a figure or table) shows, permafrost is extensive at high latitudes, and much permafrost also exists in mountainous middle-latitude areas such as the Rocky Mountains in North America and the vast highlands of China and Tibet in Asia. Geocryologists call this perennially frozen ground *alpine permafrost*, but the physical characteristics of this permafrost are no different than that in the continuous and discontinuous permafrost zones. Notice that the Eurasian permafrost extends southward to beyond the thirtieth parallel, and thus to the latitude of Florida and southern Texas, a clear demonstration that permafrost is not just a polar, nor even an arctic, phenomenon.<sup>1</sup>

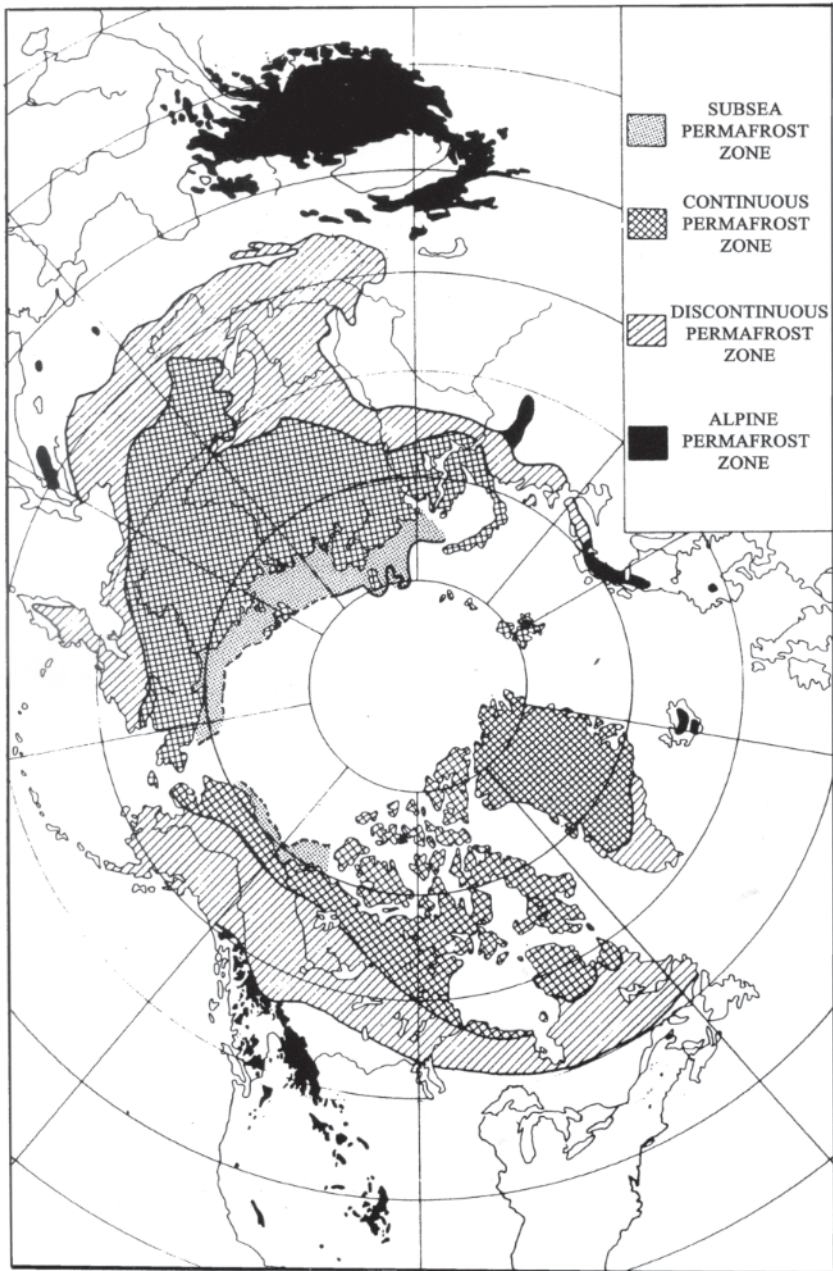
At locations where the mean annual temperature of the air is near 0°C isolated pods of permafrost are found. They appear below the typically 1- to 2-m thick surface zone of annual freeze and thaw (called the *active layer*) down to depths of 10 meters or so. Going north or up in altitude to cooler climes where the mean annual temperature is several degrees below 0°C, the active layer thins, and the layer containing permafrost thickens. Within this layer, perhaps 30 to 50 m thick near its southern fringe, permafrost is prevalent but discontinuous. In the northernmost parts of Alaska, Canada, and Siberia the active layer is very thin, perhaps only a few centimeters thick, and the permafrost layer in contact with it is continuous except near bodies of water that remain largely unfrozen. The permafrost can extend down to depths greater than 400 m; the deepest known is 1,450 m, at a location in Siberia.<sup>2</sup> See **Figure 1.2**.

---

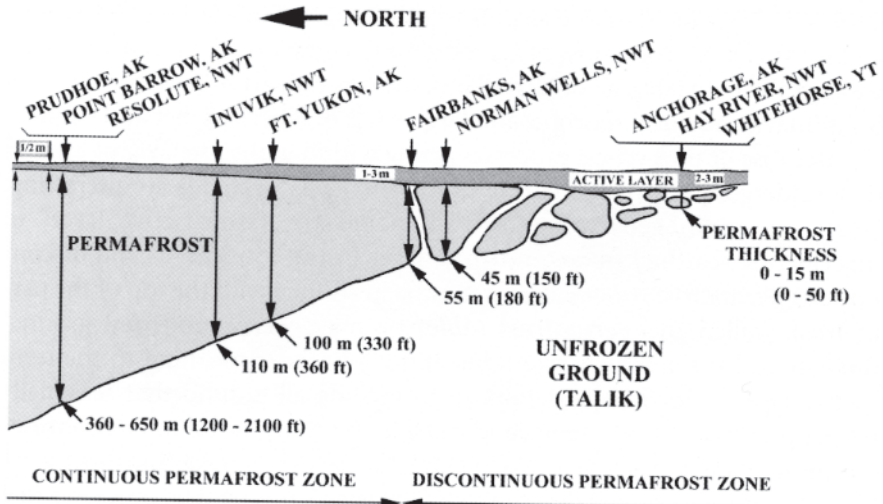
1. Pointed out by Peter J. Williams, a reviewer of the manuscript.

2. Grave (1956), cited by Washburn (1980).





**Figure 1.1** Permafrost in the northern hemisphere; After Péwé (1975a), modified slightly from his Figure 17.2.



**Figure 1.2** Thickness of the active layer and vertical distribution of permafrost in Alaska and western Canada. Based on Figure 4 by R. J. E. Brown (1975) with data added from Péwé (1982) and Washburn (1980).

Around the fringes of the Arctic Ocean is a region identified in Figure 1.1 as the subsea permafrost zone. The permafrost here is a relic of former times, having been formed beginning about 20,000 years ago or even earlier during times when sea level was some 90 meters lower than at present because so much water was locked up in glacial ice. The mean annual temperature at the sea floor off Alaska ranges from  $-0.7^{\circ}$  to  $-3.4^{\circ}\text{C}$ , so using the strict definition of permafrost as a condition of temperature requires that the material in the sea floor be called permafrost. However, because of the salinity of the nearby water and other factors, the upper 10 to 100 meters of the sea floor does not contain ice, and therefore is not frozen.<sup>3</sup> Deeper down, ice does bond the soil into a hard entity. The depth to the bottom of this bonded permafrost layer is not known.<sup>4</sup>

Notice in Figure 1.1 that the region of continuous permafrost extends outward from the pole to encompass the northern halves of Alaska and Canada, the northern two-thirds of Greenland and substantial parts of Siberia, Tibet, and China. The zone of discontinuous permafrost extends to

3. Osterkamp and Harrison (1976).

4. Rawlinson (1983) pp 4-8.

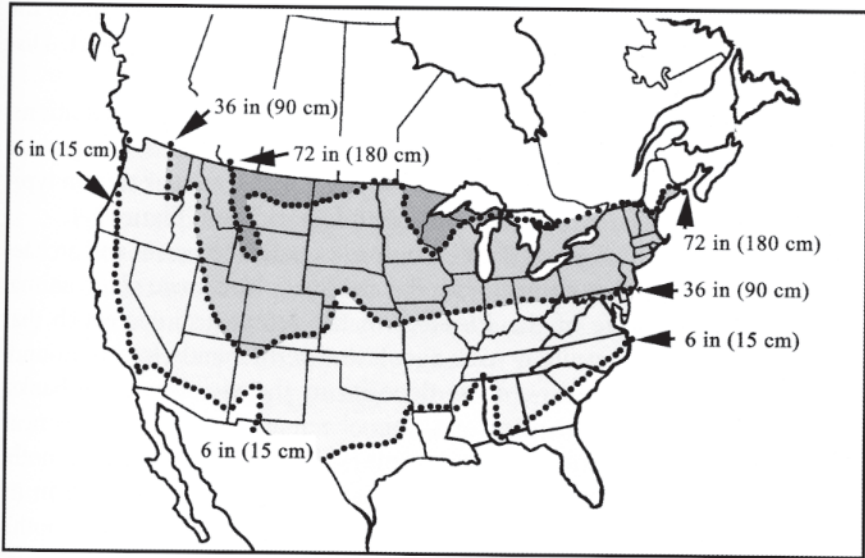
cover nearly all of Alaska (except low-altitude parts of the Aleutian Islands and southeast Alaska), most of Canada, parts of the Rocky Mountains in the western United States, all of Greenland, the central part of Iceland, northern Scandinavia, northern Europe, and large parts of Siberia, Tibet and China.

Because of the cyclical processes acting within it, the top layer of ground that undergoes seasonal freezing and thawing is particularly interesting. North American geocryologists tend to use the term “active layer” to describe the seasonal freeze-and-thaw layer in the continuous and discontinuous permafrost zones where it may be in contact with the top of the permafrost (called the *permafrost table*) or may overlie unfrozen ground. Russian and Chinese geocryologists apply a broader meaning to the term “active layer,” allowing its definition to include all ground that seasonally freezes and thaws, both inside and outside the continuous and discontinuous permafrost zones. The Russian and Chinese usage makes the most sense because “active” is highly descriptive of the layer’s mechanical processes that move water and soil to create (geologically speaking) rapid and profound changes occurring with or without underlying permafrost. Defined in the broad (Chinese and Russian) sense, the active layer covers much territory: in the northern hemisphere, 48% of the land area. As **Figure 1.3** shows, the layer covers virtually all of the mainland United States, and it dips down into the high country of Mexico. The thickness of the active layer (or what North American geocryologists call the *seasonally frozen layer*) is nearly zero close to the southern boundary of the United States, but it increases northward and with altitude to become near two meters in southern Canada. Farther north, underlying permafrost enforces a decrease in the thickness of the active layer, until, in the very far north, it declines to a few or few tens of centimeters. In the discontinuous permafrost zone layers of unfrozen soil, called *talik*, may lie between the permafrost table and the bottom of the active layer, as well as between blocks of frozen soil.

## ■ Consequences of Permafrost and Seasonally Frozen Ground

1. Frozen ground is far less pervious to water than unfrozen ground, so by curtailing the downward seepage of water, permafrost modifies the environment for plants and animals, typically making that environment more wet in low areas—and even on hillsides, as much to their chagrin, officials of the U.S. Bureau of Land Management (BLM) recently discovered. As a consequence of building a





**Figure 1.3** A highly generalized map based on one by Strock and Korel (1959) showing the approximate maximum depth of the active layer (the layer of seasonal freeze and thaw) in inches (cm). Because of local variations in climate, soil conductivity, and terrain, the actual depth of freezing at any location may differ greatly from that indicated on the map.

road across hillsides north of Fairbanks, Alaska, without benefit of permit to disturb land designated as wetlands, BLM was recently charged by the U.S. Corps of Engineers with breaking federal law. The corps believes that 48% of Alaska is federally designated wetland that cannot be disturbed without the corps' permission. The legal hassle arises because permafrost allows moss, sedges, bushes and trees normally found only in lowland areas to grow on upland areas, particularly those sloping to the north.<sup>5</sup>

2. Where the permafrost table comes close to the ground surface it forms an impenetrable barrier to roots. Plants and trees that grow atop this shallow permafrost have shallow root systems, and they tend to grow slowly because the soil is always cold.
3. Frost action, the process of freezing and thawing, changes the composition of the ground by altering soil particles and sorting

5. *Fairbanks Daily News-Miner* (1997).

- them according to size, and it also can modify the very shape of the ground surface through erosion and downslope transport. Distinctive landforms are the result.
4. Events that cause permafrost to melt—such as climatic variations, forest fires, or human activities that destroy overlying ground cover—may create *thermokarst* topography, irregular terrain typically containing sinks and “drunken forests,” as in **Figure 1.4**.
  5. Permafrost literally puts paleozoologists, paleontologists, and archaeologists in direct contact with the ancient cold-climate plant, animal and human life of the *Pleistocene*, the recent geologic epoch that began 1.6 to 3 million years ago. Some permanently frozen ground, such as the extensive *loess* deposits in the vicinity of Fairbanks, Alaska, are rich in plant and animal remains preserved in or near original form. One famous example is Siberia’s Beresovka mammoth, found in the early 1900s nearly intact and with flowers still in its mouth. Although it died 45,000 years ago, some of the mammoth’s fleshy parts remained intact. Another important discovery made dur-



**Figure 1.4** An island covered by dying trees sinks into a thermokarst lake near where the Alaska Highway crosses the Alaska-Canada border, in a region where warming during recent decades has caused shores to collapse as the permafrost below melts. See also Plate 1.



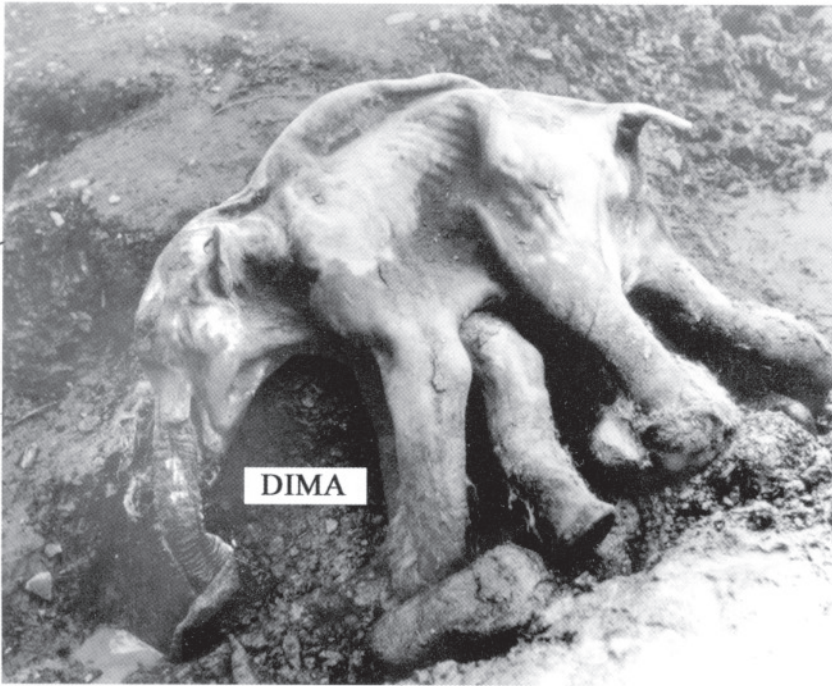
- ing mining operations just north of Fairbanks, Alaska, in 1979 was of a nearly intact 36,000-year-old mummified bison now known as Blue Babe. Paleontologist R. Dale Guthrie of the University of Alaska Fairbanks in his book *Frozen Fauna of the Mammoth Steppe, the story of Blue Babe*<sup>6</sup> details the unearthing and study of the bison and provides a fascinating account of the setting and conditions that permitted preservation of the bison mummy, which is on display at the University of Alaska Museum in Fairbanks. (**Figure 1.5**)
6. Permafrost also provides indirect information about variations in climate during the Pleistocene because the existing distribution of temperature with depth depends in part on past mean annual air temperatures. By measuring the temperatures in holes drilled into thick permafrost, it is possible to gain some insight into air temperatures during past millennia.
  7. A significant engineering problem associated with the freezing of the ground is **frost heave**. In places having fine-grained soils and plenty of water, frost heave can exert powerful forces that lift objects such as telephone poles and pilings up out of the ground.
  8. Mainly because it can contain deposits of pure or nearly pure ice, permafrost is a serious geological hazard. As long as it remains frozen, permafrost typically is a tough material capable of supporting heavy loads (at least on short time scales), but when permafrost thaws, the melting of the ice can create voids in the ground and soupy mud flows. These ground failures destroy manmade structures such as roads, pipelines, homes, utility systems, and public buildings. Some examples:
    - a. Thawing permafrost made a quagmire of parts of the Alaska (Alcan) Highway when it was first constructed in World War II, and in fact the word “permafrost” came into common use because of that experience (**Figure 1.6**);
    - b. The permafrost underlying its 800-mile (1,300-km) route required that half of the trans-Alaska pipeline be built above ground, on expensive pilings that helped preserve the permafrost below (**Figure 1.7**);
    - c. Within a few miles of the University of Alaska campus at Fairbanks—where they teach engineers and architects about the hazards of permafrost—many people have built homes over permafrost and then seen them become distorted or destroyed as the permafrost below melted (**Figure 1.8**).

---

6. Guthrie (1990).



**BLUE BABE**

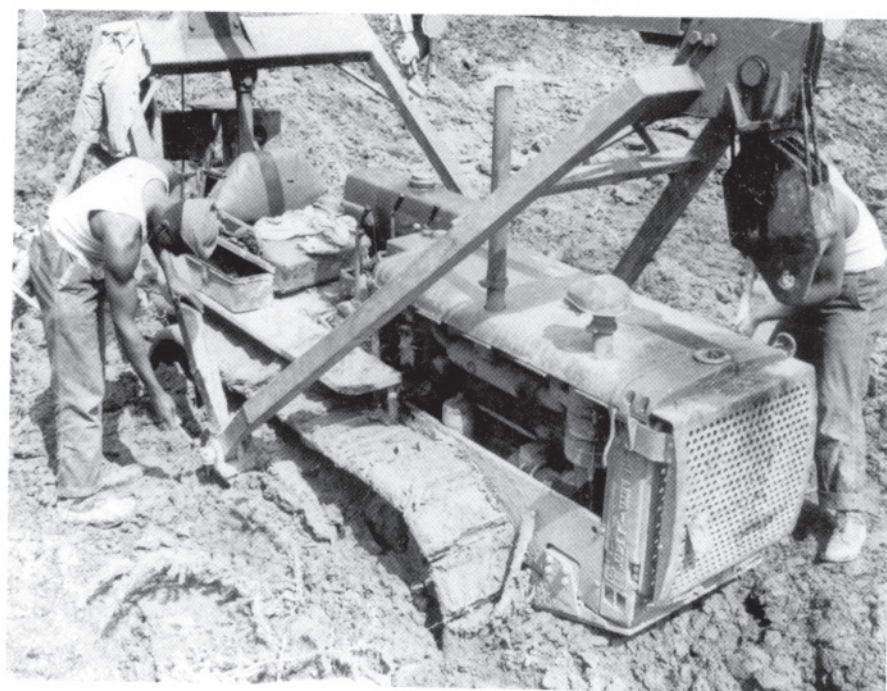


**Figure 1.5** Top: Blue Babe, a mummified bison that died 36,000 years ago, now resides in the University of Alaska Museum in Fairbanks.<sup>a</sup> (Photo: University of Alaska Museum). Bottom: Dima, a well-studied baby mammoth 7 to 8 months old when he died, was found in 1977 during gold mining operations in Siberia, north of Magadan. Dima, now displayed in the Leningrad Museum of Natural History, has reddish fur (mostly slipped off except around the feet) and is 144 cm high at the shoulder. He died more than 9,000 years ago, perhaps as long as 40,000 years ago.<sup>b</sup> Photograph courtesy of Dr. Kontrimavichus, Institute of Biological Problems of the North, Magadan, and the University of Alaska's Institute of Arctic Biology, Fairbanks, Alaska.

<sup>a</sup>. Guthrie, Mary Lee (1988); Guthrie, R. Dale (1990).

<sup>b</sup>. Guthrie, R. Dale (1990) pp 7–24.





**Figure 1.6** At top a Caterpillar tractor tows a loaded sled and two trailers through the quagmire created by thawing permafrost during the construction of the Alcan Highway in 1942, and at bottom two soldiers face the daunting task of digging out a Cat unable to proceed on its own. University of Alaska Fairbanks Archives, Donovan B. Correll Collection.



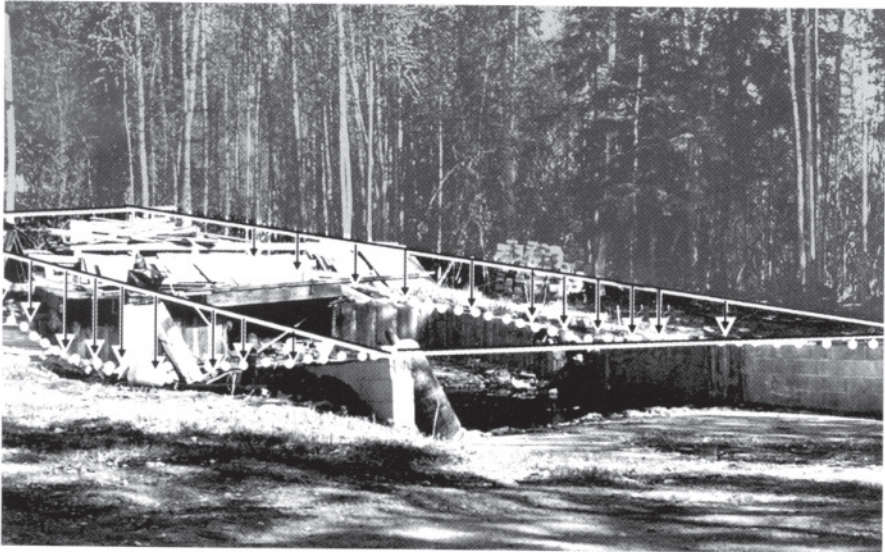


**Figure 1.7** A forest of refrigerated pilings supports the trans-Alaska pipeline where it snakes through the Alaska Range north of Isabel Pass. See also Plate 2.

## ■ The Mystery of Frozen Ground: Where Did All the Ice Come From, and How Did It Get There?

A long-standing challenge in the study of permafrost has been to explain the observation that frozen soil typically contains pods or layers of pure or nearly pure ice. Some of these may be only a millimeter thick while others may be several meters, as in **Figure 1.9**. Where did this pure ice come from, and exactly how did it get there?

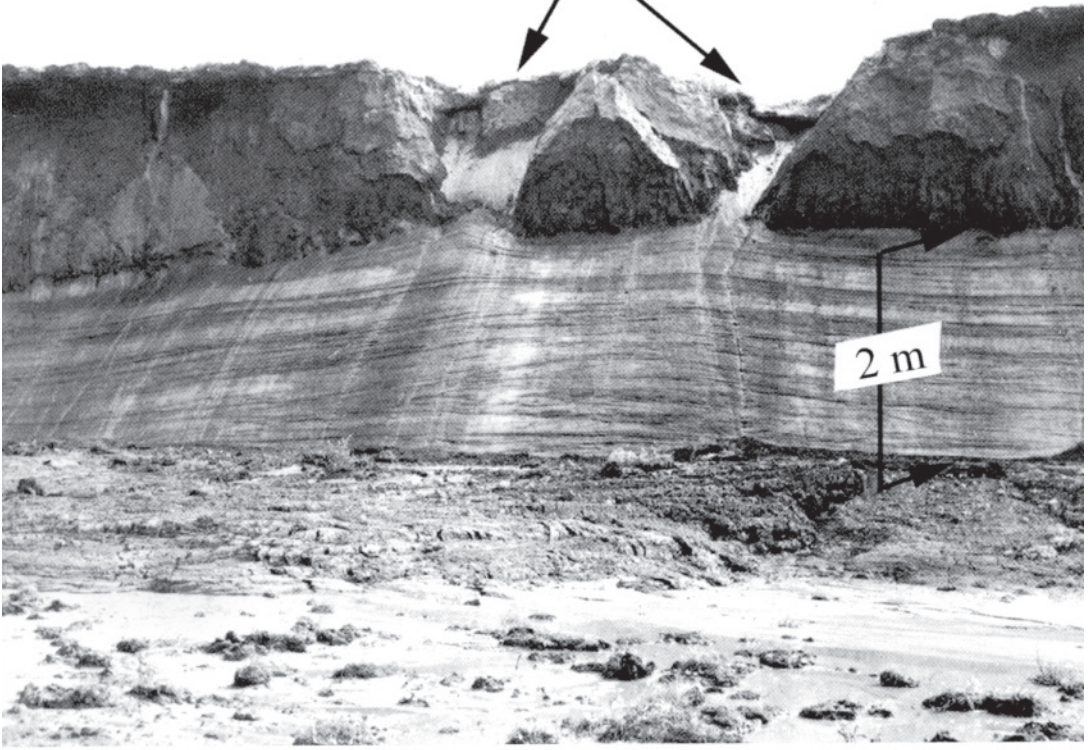
The answer to this question is bound up in three general characteristics of water molecules: 1) in liquid form they tend to cling to each other more than most other kinds of molecules, 2) when they solidify into ice they cling to themselves so well that they tend to exclude molecules of other kinds, and 3) water molecules are capable of moving through unfrozen soil, frozen soil, and even ice, typically in the direction toward the coldest parts of these substances. Ordinary water is not an ordinary substance, and therein lies an interesting story.



**Figure 1.8** Built over an ice wedge that melted, this house near the University of Alaska Fairbanks campus became so swaybacked that it had to be abandoned and destroyed. The collapse occurred quickly because this house was heated by hot water pipes placed in the concrete floor of the basement. The rows of white dots in the lower photograph mark the approximate location of the top of the house's foundation just before it was demolished. Top photo courtesy of Richard Reger.



ICE WEDGES



**Figure 1.9** A layer of ice 2 meters thick below ice wedges extending to the top of the permafrost. Photographed by Troy L. Péwé near Tuktoyaktuk on the Arctic seacoast.