With diminished hardness, the workability of rocks improves but their stability decreases. Such is the case of many shales, clays, and similar materials, including decomposed rock. Fissility of the rock combined with the presence of nearby water basins located at a higher elevation may indicate a possibility of considerable water inflow into the tunnel. Similarly, the presence of surface springs from which warm water is issuing may indicate deep-seated water flows. Gas bubbles in nearby wells are a warning of possible gas at tunnel level.

Before the construction of a tunnel, it is desirable to have an idea as to the probability of excessive overbreakage and caving. Joints and especially faults are a major cause of severe caving ground in tunnels. Blocky ground may cause trouble if the contact surfaces between blocks are smooth. Surface reconnaissance or airphoto studies often are helpful in locating major fault systems and joint systems (see Sec. 7.18). Sometimes geological data can be obtained from nearby road cuts; e.g., in the preliminary survey for one tunnel, it was found that badly slacked material in an adjacent road cut was the same formation through which the tunnel was to be driven. This led to the correct conclusion that the overbreak in the tunnel would be excessive.[12d] The term "slacking" as used here refers to the surface change of the rock due to oxidation, carbonization, and hydration.

The presence of swelling rock often may be detected in the preliminary geological survey. Whether or not a rock is of the swelling type can be established only by tests on rock samples in their *natural* condition, with their *natural* moisture content fully preserved. Every shale or any other material known to be capable of swelling should be thoroughly investigated. The difference in the density of the rock upon its removal from the core barrel and after it has been exposed to the air for several days indicates the possible volume of swelling. The immersion test also may give indications of swelling ground.

Careful geological investigations prior to tunnel construction are of importance. Many tunnels, particularly those with rather small cross sections, are known to have been successfully built on the basis of an amazingly limited amount of geological information or practically none at all. However, these cases usually occur only when the builders are well acquainted with local geology through previous experience.

9.26. Geological Report. In this report, the results of the preliminary survey are outlined, along with all geologic features along the proposed tunnel line that may be helpful to the design and construction engineers. Complicated geological discussions should be avoided. It is essential to use clear, simple language. The items discussed in this chapter that are pertinent in the given case should be included in the report. Besides the purely technical aspects of the tunneling, the tunnel latter (about 9 per cent). Heaves corresponding to 20 or 30 per cent of the thickness of the frozen layer are not uncommon, however. This circumstance and the excess of water at thawed places suggest that during the freezing process, some additional water is drawn from a lower layer. Laboratory and field investigations have proved this point.[3]

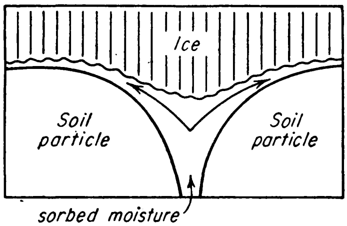


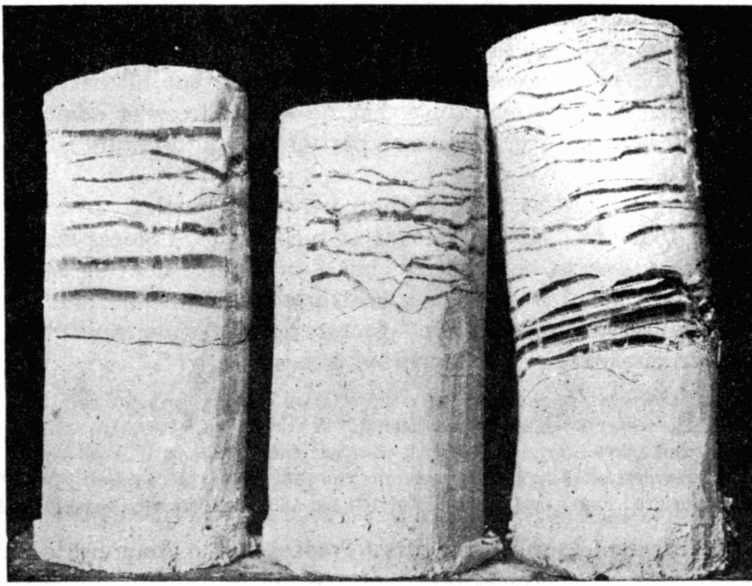
FIG. 10.1. Growth of ice crystals. (*After Beskow.*[2])

10.2. Freezing Point, Ice Crystals. The actual freezing point of water depends on the pressure on and in it. At a pressure of 1 atm it equals 0°C and is lower at greater pressures. In narrow soil pores, water is strongly compressed by attraction to the pore walls. Hence, while in wide soil pores water freezes at 0°C, the actual freezing point in narrower pores is below 0°C. Consequently at the 0° isotherm, i.e., the surface within the earth at which the temperature is 0°C, only a part of the water is frozen. Thus water in narrow soil pores is *overcooled.*

The freezing earth mass expands and exerts a heavy expansion pressure if confined; these phenomena are caused by the growing of *ice crystals.* For the formation of the ice crystals and ice lenses, water is required, and in addition to the interstitial or pore moisture, water is lifted up ("pumped") from the lower strata. There is a difference of opinion about the physical nature of that lifting agency. The growth of ice crystals may be explained in a simplified manner, however (Fig. 10.1). Before freezing, soil particles develop moisture films at their surface by capillary attraction from the water table (the latter is not shown in Fig. 10.1). When the ice crystal starts to grow, suction developed in this connection is stronger than the capillary attraction of moisture by the particle. In this way a soil particle loses its moisture film to the ice crystals which are being formed. The force of capillary attraction of the particles still persists, however, and moisture lost by the particle to the ice crystal is replenished by capillary attraction from the water table.

Excavation in frozen soils often shows the presence of ice lenses, or layers. In clean sands or gravels, the formation of such lenses, or layers, is simply the freezing of small inner pools of water. In silts or silty sands, ice lenses, or layers, are formed if freezing proceeds gradually, because sufficient water can be pulled up and frozen. In the case of rapid cooling, however, there is no such pull of water from lower strata, and only available pore moisture freezes. Figure 10.2 shows ice lenses in frozen soil cylinders obtained in Taber's experiments.[1] In freezing soils, ice also appears in the form of thin layers ("fibrous ice").

The capacity of rapidly changing temperature, known as *diffusivity,* is about eight times greater in ice than in water. At the boundary of frozen and unfrozen soil there is a zone (or curtain) where freezing and melting occur somewhat simultaneously before the soil definitely freezes. In fact, when ice is formed, heat is liberated, and before adjacent warmer water also freezes, ice melts. But when ice melts, heat is consumed (latent heat of fusion) and water freezes.



10.3. Frost Heaves in Temperate Zones. The phenomenon of heaves can be explained by (1) the increase in volume of the available pore moisture during freezing and (2) the drawing of additional water from deeper strata and its subsequent freezing to form ice lenses within the mass. This additional water may reach the freezing layer at a high rate if the following conditions are satisfied: (1) There is a nearby source of water supply from which water may be pulled, e.g., *a high water table* (i.e., a water table close to the ground surface); (2) the soil is capable of pulling water upward from that high water table; i.e., it contains a certain percentage of *fine particles*, as coarse soils can pull moisture through a very short distance only; and (3) the path between the water table and the freezing layer is unobstructed; i.e., the soil possesses *good permeability*.

Conditions (2) and (3) are satisfied by silts and clays, whereas condition (3) is best satisfied by silts. Hence, it may be concluded that the beginning of the Pleistocene or Ice Age, perhaps a million years ago. Validity of this glacial origin theory has not yet been proved, however. If the last glaciation was responsible for originating the permafrost, its deposits should be decreasing by now. Observations show that apparently because of climatic changes, permafrost deposits vary in their thickness and areal extent. Where the mean annual temperature is below freezing, permafrost may be forming even at the present time. Generally, an increase in thickness of a permafrost deposit is termed *permafrost aggradation;* and conversely, decrease in thickness is *permafrost degradation.*

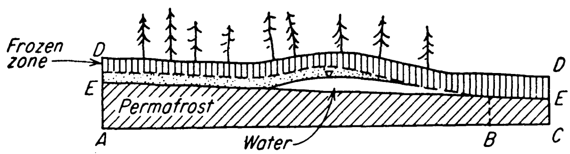


FIG. 10.3. "Drunken Forest." *DE* **is the thickness of the active zone; frost zone between** *B* **and** *C* **coincides with the active zone.**

Permafrost underlies approximately one-fifth of the land area of our globe. Permafrost areas include about 80 per cent of Alaska, half of Canada, a considerable part of Siberia, and some areas in China. Presumably, there is permafrost in the antarctic. General information on permafrost, both geological and technical, may be found in Refs. 6 through 10.

10.6. Basic Features of Permafrost. The permafrost terminology contains many terms borrowed from Russian, though an attempt has been made to replace these terms by those of pseudo-Greek origin.[11]

The top and bottom surfaces of permafrost deposits are not horizontal. The irregular top surface of a permafrost deposit is the *permafrost table.* All ground above the permafrost table is designated as the *active zone.* The upper part of the active zone is subject to intermittent freezing and thawing and is called the *frost zone.* Where seasonal freezing penetrates to the permafrost table, both frost zone and active zone coincide (Fig. 10.3); otherwise, between the bottom of the frost zone and the permafrost table there is unfrozen soil known as *talik* (Fig. 10.4). If a cold summer is followed by a cold winter, a frozen layer may develop at the bottom of the active zone. The product of this upward permafrost degradation that may remain unthawed during one or more summers is called *pereletok.* Water contained in permafrost is mostly in the form of ice, though fine capillaries may contain fluid water and there may be groundwater flow in permafrost (Sec. 10.11). Ground perennially frozen but containing no ice, as in the case of some sandy materials or some bedrock, is *dry permafrost,* or dry ground. Dry ground is not subject to heaving