1

Periglacial conditions

1.1 The significance of freezing in soils and rocks

Water is ubiquitous in the surface regions of the earth, and is unique in the extent of its occurrence in all three phases: solid, liquid and gaseous. Its formative influence on the nature of the earth's surface, on the behaviour of earth materials, and its role in the complex pattern of transfers of energy and mass in the ground and atmosphere mean that water is a central component of study in the earth sciences. However, the solid phase, and transitions between solid and liquid or vapour, have in this context received relatively little attention. While the subject of glaciology has concerned itself with snow and ice, the study of freezing and thawing within soils and rocks has been more limited and mainly of recent date.

Water freezes at 0 °C and in doing so expands by 9% of its volume. In freezing it may exert great expansive pressures. These statements serve for many everyday considerations. But they require qualification in that only pure water, under a pressure of one atmosphere, and in sufficient quantity, freezes at 0 °C. Those conditions are generally not met when freezing occurs within soil or rock materials. This is not a matter of mere scientific pedantry, of trivial deviations of freezing point arising from the fact that natural waters are never pure in the ultimate sense, or from the fact that they are commonly subject to some gravitationally produced pressure arising from weight. Freezing of water in most earth materials occurs over a range of temperature to many degrees below 0 °C (although never at temperatures significantly above 0 °C).

This circumstance should not cause surprise. The boiling point of water is 100 °C – but we do not assume that transitions of water to vapour are limited to that temperature. Meteorologists and climatologists accept as fundamental the role of transitions to and from the vapour phase at all naturally occurring temperatures in the earth's atmosphere, and this is essential to the understanding of the nature of the atmospheric climate.

Although the circumstances are different, phase transition, between solid and liquid, is the basic element in understanding frozen and freezing soil materials. We must consider thermodynamic and thermal properties, as well as the mechanical properties of the materials, in order to understand the behaviour of the ground.

Those parts of the earth's surface which experience freezing temperatures reveal this in a variety of ways. Where frost is an occasional or short-term occurrence the effect may be largely an ecological one, affecting the growth conditions for plant species, perhaps those species of economic significance, so that, for example, the study of night frosts is important in agronomy. But, for perhaps 35% of the earth's land area, mainly in the northern hemisphere, the effects of freezing, and freezing and thawing, are such as to radically affect the nature of the ground surface. This area is referred to as the periglacial regions. In comparison, only some 3% of the earth's surface is covered by perennial snow and ice.

The periglacial regions are characterised by unique displacements of soil material and migrations of water substance, the development of unique terrain features, and of distinctive vegetation, all related to freezing and thawing. These regions are by no means uniform in appearance, however. The cold northern forests, perhaps underlain by permafrost, are to the casual observer as distinct from the sub-arctic peatlands, or from the open tundra, as they are from the climatically quite different temperate regions and their varied terrains. Common to the diverse landscapes of the periglacial regions, however, is the particular behaviour and properties of the soils and rocks at freezing temperatures. The explanation of this involves the thermodynamics of phase transitions of the water in pores and other small openings within the granular mineral materials, the soils and rocks, at the earth's surface.

Perhaps we can imagine a different, and purely hypothetical situation, where freezing and thawing involved only the solidification and liquefaction of water contained in the soils or rocks, at a single temperature and without any of the attributes of the phenomenon as noted above. The effect would be to have two distinct mechanical states, one of rigidity and one of relative weakness. In addition, there would be two hydrological situations one of relative impermeability and the other of permeability. These characteristics are not at all uncommon in earth materials in general and, while they indeed have implications for the stability of slopes, for the moisture conditions of the ground and for the nature of the earth's surface, they are quite insufficient to explain the dominating peculiarities associated with periglacial conditions. Clearly, more is involved in the effects of freezing and thawing.

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Excerpt
More Information

One of the most fundamental phenomena, well known to inhabitants in cold climates, is that of *frost heave* (Figure 1.1). Many soils, when frozen, are found to have a far greater moisture content than they could possibly have in the unfrozen state. A sample of such soil, thawed in a beaker, may show several centimetres of water lying above the mineral material. The excess moisture accumulates in the soil, as ice, at the time of freezing. The 'heave' refers to the volume increase of the soil which results. It may be revealed by an extension of 10 or 20% or more, of the height of a soil column. This can have great practical significance, through displacement of

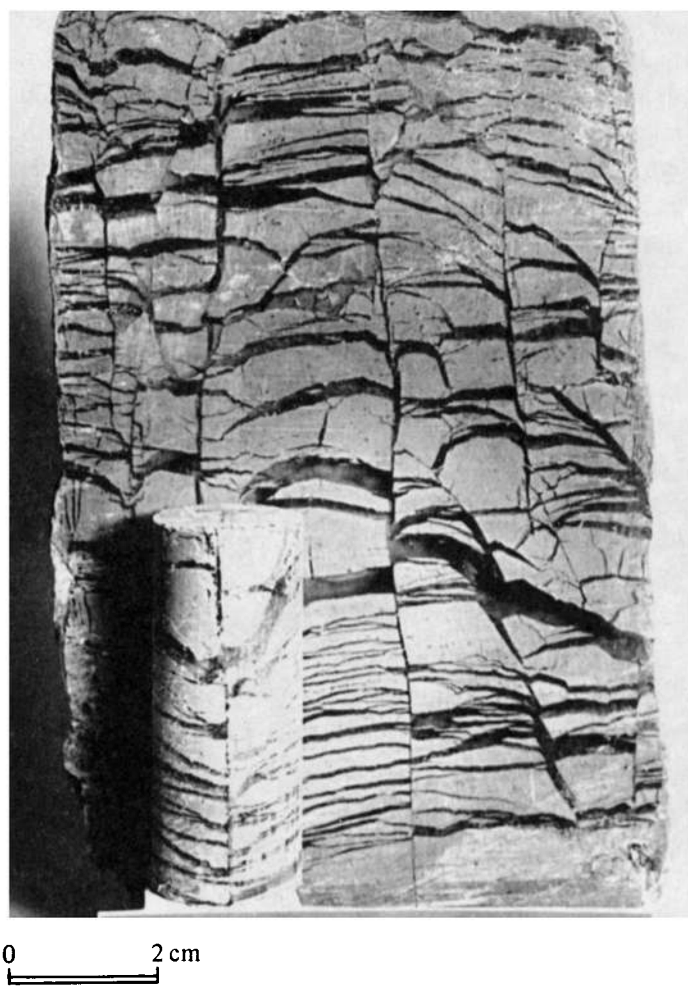

Figure 1.1 Frozen clay showing typical ice layers (or 'lenses'). This ice is mainly from water which is drawn to the freezing zone, and is the cause of the expansion constituting frost heave. See also Chapter 8, Figure 8.12. The ice layers vary greatly in size and form, from soil to soil. Photograph from Williams (1986).

building foundations or road surfaces. Equally important is the effect of thawing of such material (Figure 1.2); the large quantities of water released and the settlement that ensues as drainage occurs have wide-reaching implications. The frost heave process, and also the eventual consequences on thawing, are of the greatest significance in the explanation of many of the unique terrain features of cold regions.

1.2 Freezing and thawing in porous materials

The frost heave phenomenon relates to the occurrence of freezing at temperatures *below* 0 °C. A simple application of the principles of physical chemistry aids our understanding. A property of substances known as the Gibbs free energy is used in studies of phase transition (see, for example, Nash 1970; S. S. Penner 1968; Spanner 1964; also Chapter 7). Two phases coexist when the free energies of the phases are equal. This is a definition of freezing (or solidification, or melting) point. Strictly

Figure 1.2 Aklavik. Northwest Territories. Canada, 1957. Thawing of frost heaved material, with drainage impeded by permafrost, resulted in roads being impassable for wheeled vehicles every summer. Modern construction methods, based on an understanding of the freeze–thaw processes, overcome this problem. Photograph from Williams (1986).

speaking, it is the partial molar free energies which are equal, but we defer a more rigorous analysis until Chapter 7. At temperatures below the freezing point the free energy of the liquid, ΔG_L, is greater than that of the solid, ΔG_s:

At freezing point $\Delta G_s = \Delta G_L$

below freezing point $\Delta G_s < \Delta G_L$

The ΔG is used because we cannot actually measure free energies, but only differences of free energy, relative to some datum.

Two phases of differing free energy cannot coexist in a stable fashion. Instead, the quantity of the phase of lower free energy is augmented at the expense of that of higher free energy. Thus, for pure water under normal conditions, lowering the temperature through 0 °C results in all the water being transferred to ice, which has the lower free energy.

In soils the situation is different. The water commonly contains some dissolved salts, which lower the free energy. As is well known, pure ice forms on the freezing of a solution. But, because the solution has a lower free energy than pure water, for ice to form it too must have a different free energy from ice forming in pure water. Changing the temperature changes the free energy of substances, and in the case of ice at a slower rate than that of the solution. Accordingly, as illustrated in Figure 1.3, at some temperature below 0 °C the free energy of ice is lower than that of the solution, such that ice forms from the solution. This is referred to as a *depression of the freezing point*, and the phenomenon is not limited to solution.

Generally, the concentration of dissolved salts in the soil water is so weak that the freezing point is only 0.1 °C or so below 0 °C on this account. As ice forms in the pores of soils or rocks, however, a far more important effect occurs. The decreasing amount of water is increasingly affected by *capillarity* and *adsorption*. These phenomena cause the free energy of the water to fall further. Consequently for freezing to continue a still lower temperature is required.

Capillarity is an effect associated with molecular forces at the interface between phases, when the interface is confined. The rise of water in capillary tubes follows from the confinement, in the capillary tube, of the interface (the meniscus) between the air and water. The rise is greater as the tube diameter is smaller. The rise is often referred to as the effect of a suction generated in the water at the meniscus. This suction can be equated with a decrease in free energy relative to normal, or 'free' water at the same temperature.

In the freezing soil, formation of ice results in the water being confined progressively in smaller spaces. The free energy of the water falls on this

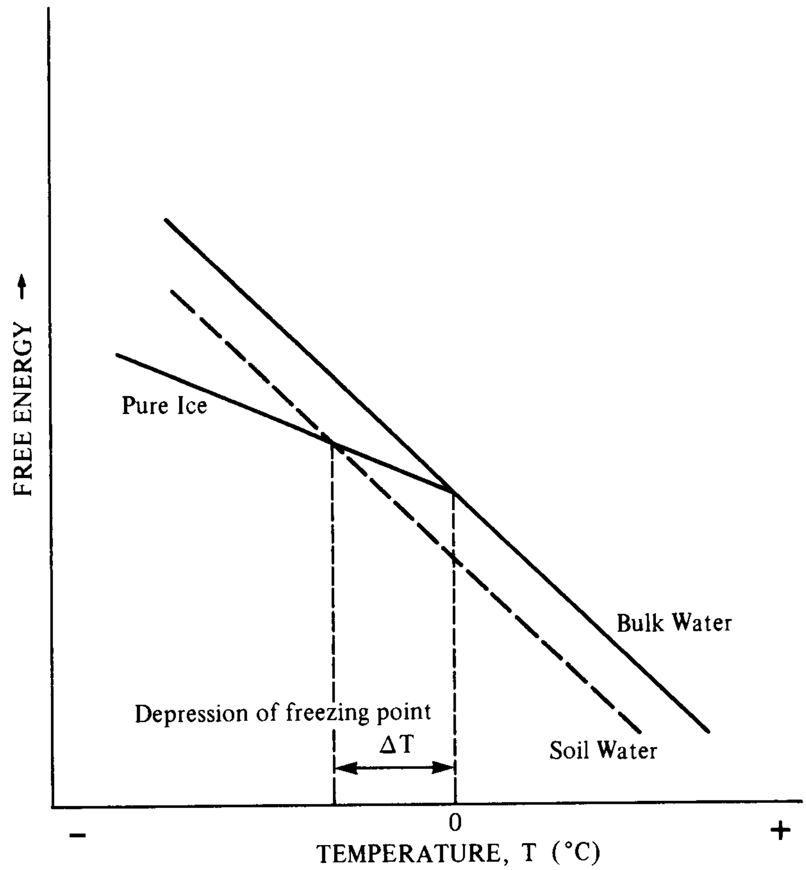

Figure 1.3 Ice and water normally coexist (have equal free energies) at 0 °C. But if the free energy of the water is reduced (dashed line) the freezing point is changed by ΔT (diagram modified after Everett 1961).

account. This effect can be referred to as the *suction*, or *cryosuction*, generated by soil freezing, and it is the cause of migration of water to the freezing zone.

Adsorption has a similar effect. It refers to the influence of forces emanating from the mineral particle surfaces, which reduce the free energy in a thin layer, the 'adsorbed layer', of water on the particles. For freezing to continue, it is increasingly this water which must be converted to ice, and consequently lower and lower temperatures are required.

Figure 1.4 shows the amounts of water remaining unfrozen at temperatures below 0 °C, in different soils. Below about −1.5 °C this is almost exclusively 'adsorbed'. At temperatures between −1.5 °C and 0 °C this capillarity is responsible for much of the freezing point depression. The term freezing point is somewhat awkward in the case of a soil since freezing occurs progressively over a range of temperature, any particular tem-

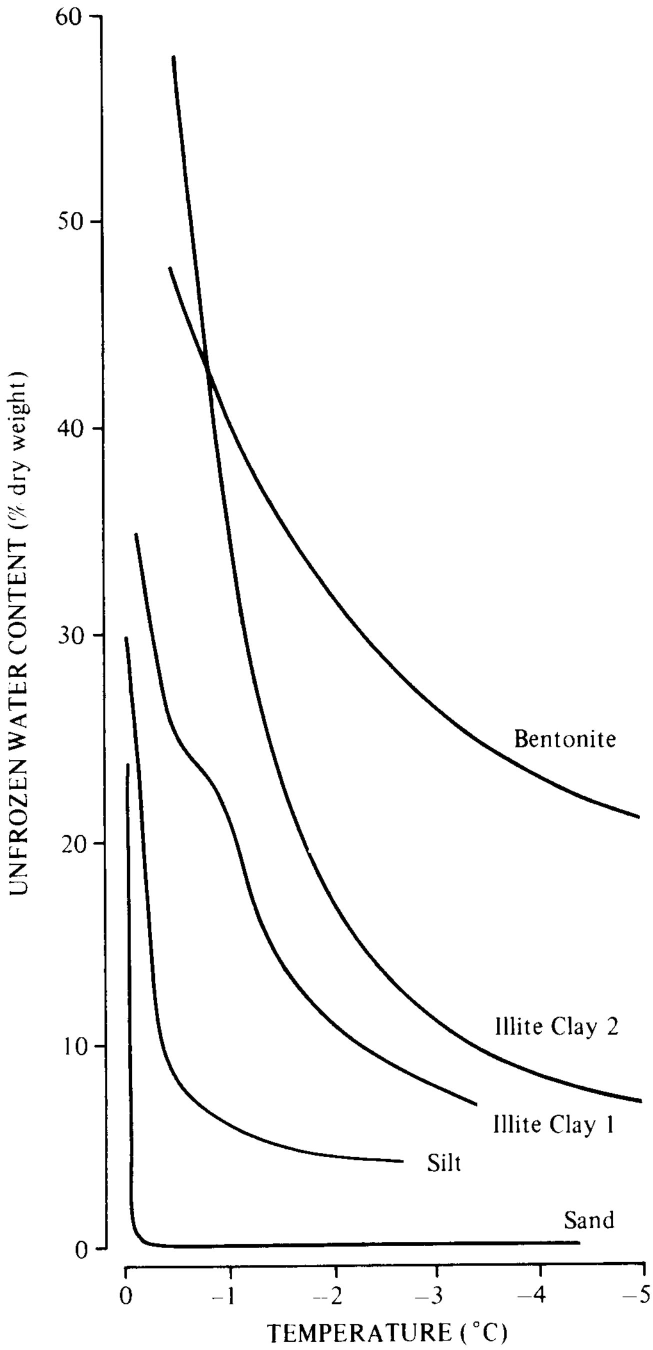

Figure 1.4 Amount of water remaining unfrozen at temperatures below 0 °C, various soils.

perature being associated with a particular quantity of water remaining. Regardless of what temperature is considered, the free energy of the ice and water are equal, or at least are in the process of immediately becoming so. Furthermore, the free energy depends on the temperature and not on the type of soil.

As soon, therefore, as freezing commences and the temperature falls below 0 °C, the free energy of the remaining water is less than that of 'normal' water. Now, it is an additional attribute of the free energy property that a transfer of mass tends to occur along a free energy gradient. If the water in the soil adjacent to ice has a lower free energy than the water further away from the frozen zone, then a migration of water towards the frozen zone will occur. It is this migration which is ultimately the cause of frost heave. The water accumulates as ice, commonly in layers or 'lenses' (Figure 1.1).

We may refer to potential of the water, in this context the term being essentially synonymous with free energy. Reference has also been made to suction as being approximately equivalent to free energy, and all the terms have implications for water movement. Suction suggests a hydrostatic pressure effect. Suction, and also negative pore water pressure, are frequently referred to in studies of soil–water relations, but it should be remembered that the changes of free energy discussed are not limited to hydrostatic pressure effects in a strict sense. With this qualification, the terms are useful because they permit ready analysis of the pressures produced by the heaving soil under different ground water conditions.

The amount of heave occurring depends greatly on soil type, on ground water conditions, rates of freezing and other factors. It is absent when the pores are large, that is, in purely coarse-grained materials. A considerably more detailed analysis is necessary before the nature of frost heave can be properly understood, and this is undertaken in Chapters 7 and 8. We will merely note that the suctions leading to frost heave are often very great, and may be thought of as tensile stresses of many atmospheres (1 atmosphere is about $10^5\,N\,m^{-2}$ or 100 kPa).

1.3 Climate and ground freezing

Frozen materials are limited to a fairly thin surface layer of the earth. The maximum depth of frozen ground exceeds 1000 m in rather limited areas. Over much larger areas, frozen ground is only tens or hundreds of metres thick, while probably the greater part of the earth's land surface experiences repeated short-term freezing of a much thinner layer.

Ultimately, all specific knowledge of the extent of frozen ground has its origin in direct observation involving sampling procedures or measurements of ground temperature. Such procedures are costly and give information only on the immediate vicinity of the observations. Prediction of the extent of frozen ground at different times and places is one of the most pressing geotechnical problems and the subject of much current research. Problems arise because the temperatures in the ground are related in a complex fashion to atmospheric climate, and consequently, are not immediately predictable by reference to commonly measured climatic parameters (see Chapter 3).

The temperature of the surface layers of the earth's crust follows from heat flows in upward and downward directions. Firstly, the high temperatures of the earth's interior give rise to a flow of heat outwards, the geothermal flux. It varies somewhat from place to place but varies little with time, and is in any case relatively small, some $0.05 \, W \, m^{-2}$. Secondly, there is a continually changing but usually orders of magnitude greater, flux to or from the ground surface, affecting the upper metres or tens of metres of the ground. The origin of this ground heat flux is a variety of heat transfer processes at the ground surface, which are ultimately of extra-terrestial origin. The radiative energy from the sun arriving at the surface is dissipated in various ways, by reflection, absorption, reradiation, involvement in evaporation and in some part in warming the air and the ground. The latter process reverses during night time, with flow of heat out of the ground and consequent cooling. The energy exchange at the earth's surface is illustrated in Figure 1.5 where the physical processes involved and their relative importance as energy paths are shown.

The ground heat flux changes continually with time but the sums of ingoing and outgoing values through one year commonly approach zero. During the summer months there is a net cumulative intake of heat by the surface layers, which is more or less completely lost through the surface during the winter season. The annual passage of the seasons is a cyclic change occurring in a regular and repeated manner. Consequently, the mean annual ground temperature at the surface of a particular site remains fairly constant from one year to the next, the day by day and annual cycles of temperature change occupying a predictable range about this mean. The mean annual temperature will change, however, if there is a significant change of the nature of the surface. The situation where there is, year after year, a repeated small net intake or repeated loss of heat through the surface is not rare and is extremely important. But it should preferably be regarded as a deviation about the normal quasi-equilibrium situation since it is necessarily preceded by a change in environmental conditions and is always a transient event. If it were not, the earth would be either steadily

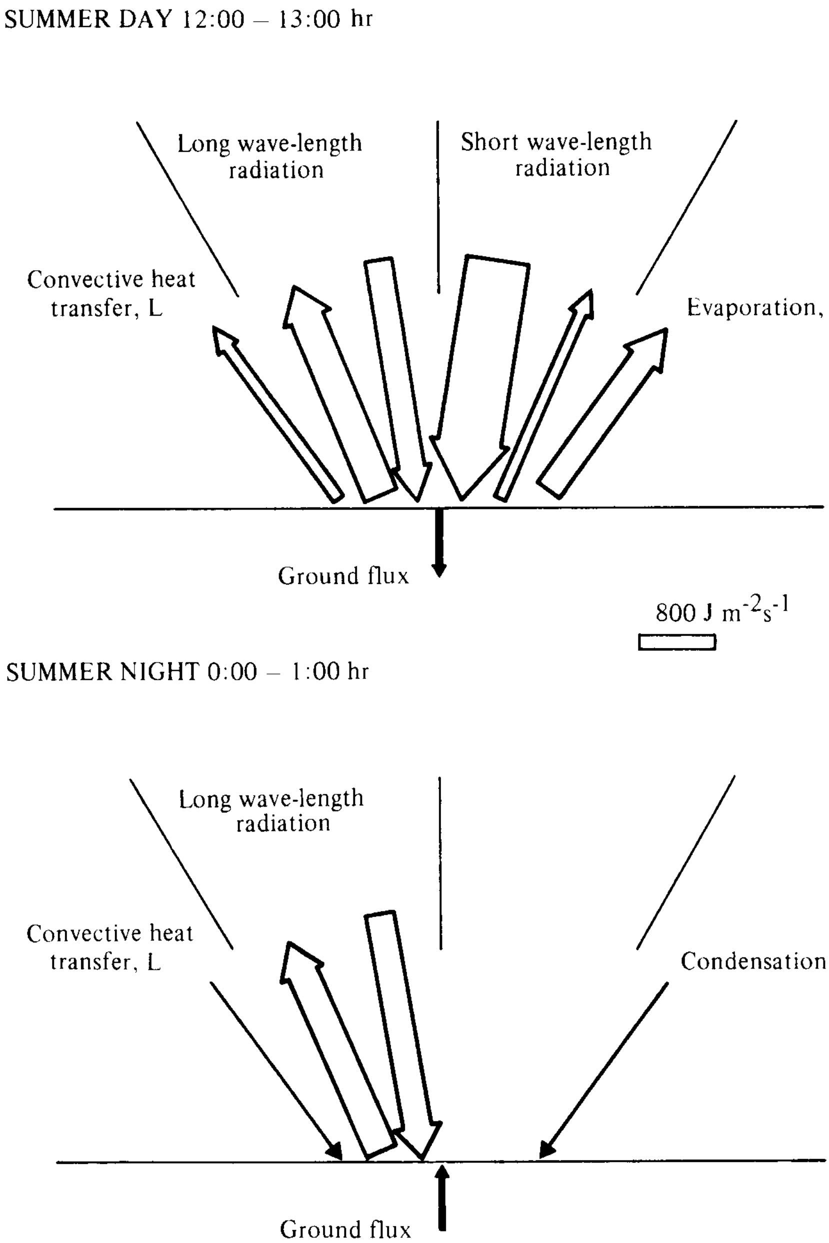

Figure 1.5 Energy exchange at the ground surface for two times. The width of the arrows corresponds to the rate of energy transfer (energy flux) by each path. This example is for Potsdam, Germany and modified from Geiger (1965).

cooling or steadily warming, with catastrophic implications. Such is found not to be the case (we ignore the slow loss of heat from the earth due to internal radioactivity).

The various flows of heat energy to and from the surface of the ground can be expressed by an equation for the heat balance, which in its simplest