coast of Greenland and not much less common than on the rain-swept coast of Norway, but owing to the low temperatures the total amount is not large, the average being estimated from the firn layers as equivalent to 12·4 in. of water a year. Direct measurement of the snowfall was impracticable owing to drift.

The frequency of easterly winds was not due entirely to katabatic winds from the ice divide to the east, for it is as marked in the strong winds as in the weak. Rather it implies that depressions pass mainly to the south, but extend their influence right to the centre of the ice cap. There is now no difficulty about the supply of moisture, which is derived from the Atlantic Ocean and carried inland, overriding the violent but shallow katabatic winds of the coast, to be condensed into snow over the ice shed and swept on to be gradually deposited on the leeward slopes. Atmospheric pressure is undoubtedly higher than it would be if the surface, at the same level, were not ice covered, but it appears that the subcontinent is not big enough to form the basis for a self-supporting glacial anticyclone. Antarctica is another question ; owing to its greater extent and polar position a permanent glacial anticyclone is more likely to be found there than in Greenland, but even in Antarctica, as Sir George Simpson has shown, Hobbs' mechanism for the supply of ice is inadequate and must be replaced by something more effective.

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## PERMANENTLY FROZEN GROUND AND FOUNDATION DESIGN. R. M. Hardy (Part I), and E. D'Appolonia (Part II). *The Engineering Journal*, Montreal, January 1946, pp. 1–11

During recent years a number of practical papers have appeared relating to construction difficulties in lands where the ground is subject to transient or permanent deep freezing. As is often the way, natural phenomena are not studied quantitatively until they become involved in economic problems. In the development of the Canadian North the frozen ground, which may extend to a depth of several hundred feet, is stated to be the most serious obstacle to the engineer. It is estimated that one fifth of the earth's land surface is permanently frozen. Further studies may therefore be expected as development proceeds in northern North America and Siberia,[9] particularly in relation to the extension of air travel and mining operations. In consequence the present time seems opportune to review the phenomena broadly in conjunction with an abstract of this recent paper.

Apparently most of the permanently frozen ground is frost heaved. Frost heaving occurs when the freezing of the soil results in the formation of layers of segregated ice at various depths. Each lens of ice is generally separated by a layer of soil, whose water content does not change but simply freezes solid. The ice lenses vary in thickness from a fraction of an inch to a foot or more, and their spacing is of the same order. The total heave of the soil surface is approximately equal to the total thickness of all the ice lenses.[1, 3, 7] Therefore the water which goes to form the latter is drawn in from the unfrozen soil beneath. The process, in fact, introduces more water into a soil than is possible by any other means and under favourable conditions the volume increase may be over 100 per cent., whereas the volume increase caused by the water in the soil voids changing direct to ice is only about 5 per cent. Consequently when frost heaved ground is suddenly thawed at the surface, large volumes of water are released within its mass and this water cannot drain through the still frozen ground below. The soil thus becomes like mud and is incapable of supporting any appreciable load. The effects of frost heaving upon the soil and the site conditions under which it occurs are fairly clear, but the physics of the process is by no means fully understood.

Part I of the paper sets down the theory of frost heaving as broadly presented by Stephen Taber,[7] who carried out some pioneer work on the mechanics of the process. This is the generally accepted theory and there is no doubt that it explains the formation of the vast areas of permanently frozen ground. Under the influence of a slowly descending zero isothermal ice crystals begin to form in the centre of the voids of a saturated soil. These crystals grow principally in the direction of heat transfer, i.e. vertically; eventually they press against the thin absorbed water films surrounding the soil particles. These water films possess very different properties to those of ordinary water because they are so closely bonded to the soil minerals; for instance, they have a freezing-point lower than that in the main body of the voids. There follows a transfer of molecules from the films to the growing crystals. To maintain pressure equilibrium, water is somehow sucked into the films from the unfrozen soil below. Equilibrium is probably established at a temperature of less than 0° C.[6] and the ice layer continues to grow at a rate determined by the permeability of the soil below.

The exact manner in which one ice layer stops growing and another starts a little deeper down has not been ascertained. It is difficult to understand and further experimental work is needed. It is evident, however, that for the ice lenses to continue their growth the supply of water must be maintained. The continued supply requires two conditions; first, that the soil in contact with the ice should have a sufficient number of voids of such a size as to remain full under the suction developed by freezing; second, that there should be a source of water, for instance a layer of saturated soil, which can release large supplies for only a small rise in suction and which can feed water up through the voids as fast as it is withdrawn by the growing ice crystals.

It can be seen, therefore, that a rather delicate flow balance is necessary for the continued formation of an ice layer. As Taber[8] has suggested, the upward flow of water from the soil below the ice lens is probably slowly throttled by the gradual formation of ice at a slightly higher temperature in the soil voids, beginning with the larger ones. The cold front then descends more rapidly as the latent heat is no longer being absorbed, until a point is reached when the conditions are again favourable. So far no detailed laboratory studies have been made of the suction developed during the various stages of the growth of an ice lens.

Under natural rates of frost penetration and with favourable ground water conditions it has been found that considerable ice segregation only occurs in soils containing more than a small percentage of grains of less than 0·02 mm. diameter; the soils which give most trouble are the fine sands and silts. The author states that clays are so impervious that they are seldom susceptible to serious frost action, nevertheless many examples of frost heaving in roads built on clay were found in Germany[2] in the winter of 1939–40. Moreover, in England during the war all the examples of frost heaving under cold stores occurred in sandy clays and clays.[3] The rate of advance of the cold front in the latter case is retarded by a cork installation under the cold store, and is therefore generally slower than in nature under climatic frost. With these conditions frost heaving might be expected in finer, less permeable soils than is usually found in open country.

Taber[8] has recently described many of the geological processes that occur in cold climates in terms of frost heaving and thawing, and considers this process to be the chief cause of disintegration and transportation. He explains the mechanics of most of the solifluction* phenomena, such as stone stripes, altiplanation terraces and turf-banked detritus benches, in a most satisfactory manner.

In Part II of the paper the various structural problems encountered in building on frost heaved ground are considered. In areas of permanently frozen ground the upper few feet freeze and thaw seasonally and it is therefore generally necessary to anchor the structure in the deeper, non-active layers. The removal of insulating layers of muskeg,† such as occurred on stretches of the Alaska

* The term *solifluction* is used to describe in a broad way all the downhill movements that occur on slopes as a result of the action of gravity on a soil undergoing alternations of frost heaving and thawing.

† *Muskeg* is a local word used quite widely to describe a layer of matted decayed vegetation which forms good insulation against frost. It is, in effect, boggy material or surface peat.

Highway, only results in a deeper active zone with disastrous effects, and it is clearly desirable to increase the surface insulation or to introduce a neutralizing layer of cold air, particularly under warm buildings.

Even in England we have frost heaving in the hilly districts. During the severe winter of 1939–40 examples of frost heaving on the roads were seen in the Cotswolds and on the Great North Road, whilst in Switzerland [4, 5] Sweden [1] and Germany [2] it constitutes one of the main difficulties in road construction.

It is of interest to note the climatic conditions under which permanently frozen ground occurs in relation to the conditions required for glaciers and ice caps. In Alaska, where the deep freezing is a relic of the Pleistocene age, the mean annual temperature seems to be about $-2°$ C. or lower, but there is evidence of one or more warmer periods of partial thawing and refreezing since Pleistocene times and there is further evidence of gradual thawing to-day. Over most of the perennially frozen ground the annual precipitation is less than 38 cm. Cool, dry climates are therefore necessary for permanently frozen ground, whilst cool humid climates are required for ice caps and glaciers. Presumably it is the insulation of the ice that prevents frozen ground occurring under the lower parts of glaciers.

Many intricate soil structures are likely to result from the thawing of frost heaved silts and fine sands and it seems probable that some of those interesting patterns seen in the so-called late fluvioglacial deposits can be explained on this basis.

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## BRITAIN'S STRUCTURE AND SCENERY. By L. Dudley Stamp. London: Collins, 1946, pp. xvi + 255

This excellent book dedicated to that true lover of the countryside the Rt. Hon. the Lord Justice Scott, P.C., is one of a series termed the "New Naturalist," whose aim is to interest the new reader in the wild life of Britain by recapturing the inquiring spirit of the old naturalist. This particular volume, in the method of its approach and in the hands of such an experienced exponent of geology and geography as Professor Dudley Stamp, certainly goes a long way to achieve the object in view.