STRUCTURE, PROPERTIES, AND GEOLOGICAL ASPECTS OF FROST IN A FREEZE-THAW ENVIRONMENT

---by Ronald Jan DeHaas

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Sidney E White
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INTRODUCTION

Periglacial, arctic, or other freeze-thaw environments have always played an important part in the geological history of the earth. With the advent of economic emphasis (such as oil interests) in such areas, the study of frost (frozen water contained in, or resting on the earth's surface) has become an important part of geological research.

The weathering of exposed surfaces by the action of frost was for many years thought to be primarily a form of physical weathering; now, more and more evidence is indicating that a great deal of the weathering by frost action may be by chemical means, and that the physical aspects of the weathering process may have been over-emphasized in geologic literature.

To understand better the effects of freezing water, it is perhaps best first to investigate the structure and properties of the phase boundary between ice and water. The first portion of this paper is dedicated to summarizing the most important concepts concerning the structure and properties of ice and water.

Kirk Bryan, in 1946, proposed a set of terms for the processes and results of frost action. While many geologists do not use this terminology for various reasons, the advantages of using the terminology probably outweigh by far the disadvantages. Other terms used to describe frost action have led to a great deal of confusion and inconsistency. In the interest of consistency, Bryan's terminology will be used in this paper where possible, and the organization of the topics discussed in this paper will be based on his terminology as originally proposed in 1946. A brief summary of his terminology is reproduced in Appendix A. Appendix B contains the frozen soil classification used by the U.S. Army Corps of Engineers. To avoid confusion, Bryan's terminology is superimposed on this classification (in parentheses).

STRUCTURE AND PROPERTIES OF ICE AND WATER

While most of the properties of water and ice are generally recognized and understood, the structure of water in its two non-gaseous phases is, at the present, barely known. Many theories have been proposed concerning this topic, and several of the most plausible and commonly accepted theories are presented here. (For a more thorough discussion, see Anderson (1967a and b, 1970), Brill (1957), Brill and Camp (1961), Camp (1963), Corte (1963 a and b), Hoekstra et al. (1965), McSaveney (1969), and Takagi (1965). Anderson (1967a) summarizes these theories as follows:

1.) A.A. Eucken postulated the existence of monomers, dimers, tetramers, and octamers, but the model he presents is too simple to be taken literally, and is in contradiction with observed measurements in water.

2.) L. Pauling proposed a theory of bonded cage networks in water, in which the bonded cages contain unbonded water. While there is the possibility of some localized cage structures, a network of these structures is rather rigid to explain such a low viscosity as that of water.

3.) The Bernal and Fowler (and Morgan and Warren) model shows independent H-bonded regions breaking up into smaller regions as the temperature decreases. This model, however, assumes as a prerequisite a quartz-like structure which would involve a considerable strain in the hydrogen bonds. Also, a quartz-like model has an apparent structure which would be overly rigid for water.

4.) H. Eyring and R.P. Marchi theorized for water a solid-like mass containing less viscous vacancy defects of molecular size. Migrating from site to site, these vacancies are controlled by energy flowing into and out of the system. In changing from ice to water, the number of these defects is thought to abruptly increase from about 0% to 10% of the number of molecules present. This increase would normally result in an increase of volume in changing from the solid to liquid states. However, thawing ice is viewed as changing from a hexagonal structure to a much denser (by about 20%) tetrahedrally-bonded structure. The net change in volume is about a 10% decrease. The theory also explains (but only by speculation) the continued decrease in volume with temperature rising 4° C. and increasing volume at temperatures higher than 4° C.

5.) H.S. Frank and W. Wen proposed the theory of "flickering clusters;" small clusters of water-like material "flicker" in ice at temperatures below 0° C. (for pure water not supercooled), and small clusters of ice-like material "flicker" in water at temperatures above 0° C. Frank and Wen suggest that bond formation is a co-operative phenomenon; bonds are formed several at a time such that at any one time small, short-lived clusters of hydrogen bonded regions will be surrounded by non-bonded molecules. According to Frank, it is a problem of connectivity: when liquid is surrounded by solid, there is ice, and vice versa.

According to present knowledge the ice lattice is formed by molecules consisting of two hydrogens and one oxygen, the oxygen atoms being arranged tetrahedrally with the hydrogen atoms on or very close to the line connecting two oxygens. In the oxygen tetrahedron, two equilibrium positions (for the hydrogen) exist on each line, the hydrogen atoms resonating between the two oxygen in such a way that only two hydrogens are bound to each oxygen. In a perfect single crystal, this situation would result in a polar C-axis if the dimensions of the lattice are as accepted at present (a=4.53 Å, c=7.41 Å). However, because of the existence of two equilibrium positions between two oxygens, it is very likely that ordinary single crystals are micro-twinned in such a way that the polarity of the c-axis is non-evident.

One of the interesting features of freezing water is that the ice front excludes ions and small particles. As the rate of freezing decreases, the freezing front is able to exclude larger particles. Thus, for very small particles, a very rapid rate of freezing may still exclude the particles. In this way, freezing water tends to sort particles by size, trapping large particles in place and carrying smaller particles in front of the ice. See Fig. 1.

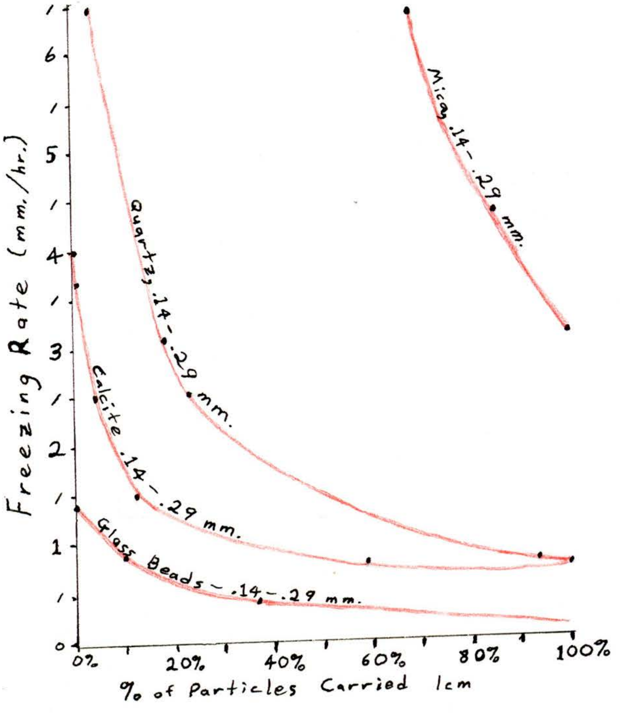

Fig. 1. Percentage, by weight, of glass beads, calcite, quartz, and mica which is carried 1 centimeter at varying rates of freezing. Illustrates the exclusion of particles by afreezing front. (Corte, 1963a)

INTERFACIAL STRUCTURES

The various properties and structures of water and ice at the interfaces with air, other water and ice, and silicate surfaces, have been investigated and are becoming more and more well known. Some of these properties are discussed here; for more detailed discussion and mathematical interpretations of these properties, refer to Anderson (1967a, 1970), Hoekstra et al. (1965), and Takagi (1965).

One normally thinks of the interface between ice and air as a mere surface of contact. However, investigation has shown that the interface may be complicated by a thin layer of water separating ice from air. This theory originates from the work of U. Nakaya and A. Matsumoto in 1953, which showed that when two spheres of ice are brought into contact, a neck builds between the two, indicating the possibility of a film of liquid. The thickness of this proposed film is on the order of 100Å at 0° C., deteriorating to near 0 Å at -70° C. This neck, however, may merely be an evaporation-condensation phenomenon. Further studies have shown that a dirty surface (NaCl) accelerates the neck growth and a pure ice surface may have no liquid film at all. Infra-red energy could also melt a thin layer of ice. However, geologically speaking, ice is rarely, if ever, pure, and infra-red rays are ever-present; there is therefore at least a liquid-like surface at the interface of ice and air.

The water absorbed on a silicate surface apparently takes on a pseudo-silicate structure near the interface, ranging from strongly adsorbed water at the interface to bulk water farther from the interface, with continuous transition zones. The water at the silicate-water interface is much more difficult to freeze than bulk water and is not as dense as bulk water. This interface could be many molecular layers thick.

Silicate surfaces were at one time thought to be nucleating sites for ice formation. It is likely, however, that a silicate surface, rather than acting directly as the nucleating agent, sets up long range, clay-water forces which stabilize and promote enlargement of the hydrogen bonded clusters in water, initiating crystallization.

The silicate-ice interface is probably the most complex of the interfaces. This interface may occur through one of two means: freezing by segregation and freezing in situ. These will be handled here as separate topics.

FREEZING BY SEGREGATION

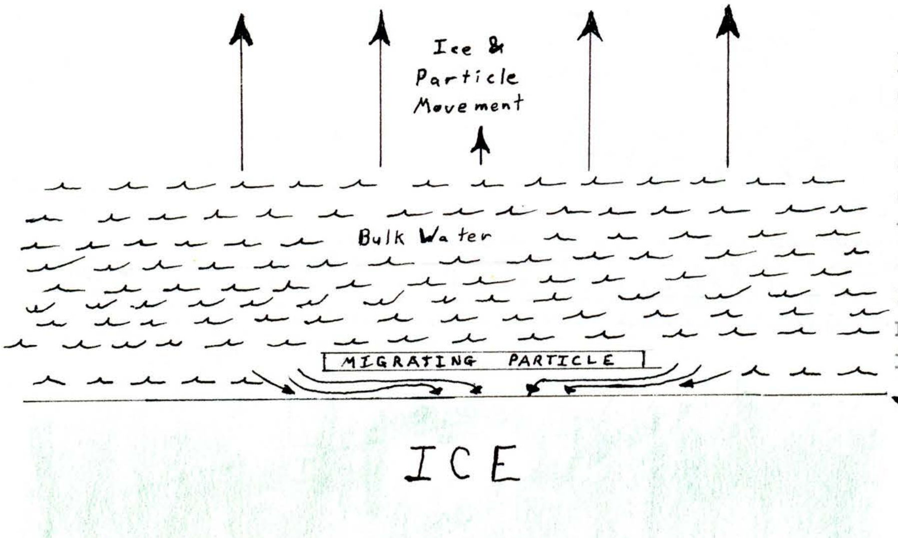

Fig. 2. Upward migration of a particle in front of a freezing plane. Arrows are drawn to indicate direction of flow of water entering layer of segregation. Larger arrows indicate direction of migration of particle and ice. (Corte, 1963a)

In freezing by segregation, the ice is separated from the silicate surface by a thin layer of water. This layer of water has been found to be much more viscous than bulk water (a rough calculation shows this segregating layer of water to be 3,000 times less fluid than water). In order to keep a constant thickness, this water must be replenished as it freezes to the ice front.

Corte (1963) showed this diagrammatically (see Fig. 2)

Experiments evidencing the existence of this layer started in 1937 when M. Fujita showed that soil needle ice (small needles of ice protruding from the surface) grows upward from the soil surface by sucking water from the soil.

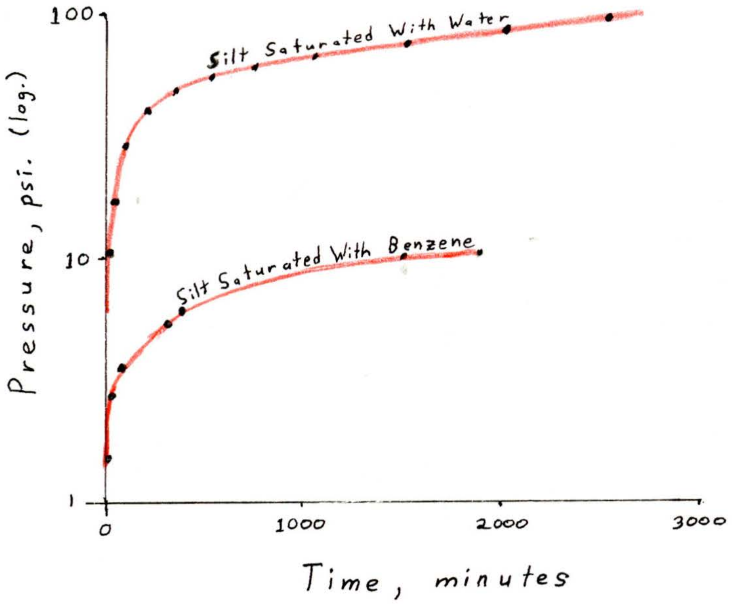

Fig.3. Pressure vs. time for samples saturated with benzene and water. The pressure is a measure of the pressure within the silt created by the freezing of the liquid. Illustrates how the expansion of water upon freezing does not explain pressures set up within the soil. (Hoekstra, et. al., 1965)

It was found that the subsurface soil water is responsible for the rate of growth. It was also discovered that if a smooth surface of clay is used rather than a rough soil surface, no needles form, rather a plate of ice forms. Fujita conjectured that this plate is due to the incapability of a smooth silicate surface to efficiently transmit heat (freezing being an exothermic phenomenon). Prof. U. Nakaya suggested that ice needles are merely a special case of ice wedges in soil; ice normally grows in soil by this means, and needles just happen to grow along the surface.

The segregating layer can produce up to 2000 Kg/cm^2. This force is not due to the expansion of water. Hoekstra et al. (1965) have shown that benzene (which contracts on freezing) has similar forces, (see Fig.3) apparently due to a similar interfacial liquid layer.

Anderson (1967a) showed that a clay soil is the most effective "absorber" of water; i.e., clay particles have a greater tendency than do other particles to bring water into the segregating layer up to the freezing front. A clay soil is also relatively impermeable, so that when ice (water for which was supplied by the segregating layer) thaws, the meltwater cannot escape. The result is a mushy, incoherent mass, very prone to solifluction.

As the pressure of the overburden increases, the segregating water layer becomes thicker; the freezing of water at the ice front increases the pressure of the overburden. Thus, the development of an ice wedge is self-perpetuating as long as other conditions are favorable. (These other conditions are discussed under freezing in situ.)

Recalling the capability of ice to exclude particles, it is interesting to note that the number of particles in the segregating layer can be very great. Bulk water entering this layer flows in against the osomotic gradient carrying more ions and particles with it, which cannot be trapped by the ice front until the whole segregating layer is frozen in situ.

Water in the interlamellar regions of the clay can be the source of water for this segregating layer. Interlamellar water is not frozen in place, but is sucked out to become extralamellar and is supplied to the freezing front. This action has the effect of desiccating the clay, and a decrease in volume of the silicate results.

FREEZING IN SITU

The process of freezing in situ is perhaps easily understood, but the reasons for the occurence of freezing in situ rather than freezing by segregation are somewhat more difficult to understand. Freezing in situ may be visualized as an ice front advancing toward a particle so fast as not to permit a layer of segregation to form; or it may be visualized as an ice front advancing toward a pitted surface along which no segregation layer can flow.

The experiments on soil needle ice (Fujita) demonstrated some of the requirements for the formation of a segregating water layer. A source of water is necessary, and the surface must be rough enough so as to transmit the heat released when the water freezes. Takagi (1965) derived differential equations explaining freezing by segregation and freezing in situ in terms of the temperature of the freezing front. He explains that freezing by segregation will occur "if the current freezing temperature at the freezing front (determined by the weight on the freezing plane) is higher than the intrinsic freezing temperature of soil water at the freezing front (determined by the solutes contained in the soil water and by the shape of the solid-water and air-water interfaces)."

When the conditions for freezing by segregation are not satisfied, freezing in situ occurs. As the freezing front passes through a soil, freezing by segregation may alternate with freezing in situ, having the effect of inter-fingered bands of "pure" ice and dirty ice. "Pure" ice here means that ice which has been frozen by segregation such that particles have been excluded. This model is overly simplified, however, for conditions may vary laterally also, in which case the situation could be complex indeed.

PERGELISOL

Pergelisol is defined by Bryan (1946) as being permanently or perennially frozen ground (in 1948 he changed this definition to perennially frozen ground, since true permanence is nonexistent in geology). The more common name, permafrost, implies permanence and does not relate frost to ground, so is technically inaccurate and is misleading.

While it was originally thought that pergelisol forms in areas where the mean annual temperature is 0° C., it has been found that lower temperatures (-2° C. to -6° C.) are needed for the formation of pergelisol. This lower temperature is needed because of the thermal insulation effects of materials covering the ground such as snow or vegetation. Lakes which do not freeze solid in the winter can cause a melting of the pergelisol table (the top of the pergelisol) down to 30 or 40 feet below the level of adjacent areas. A single forest fire may melt several meters of the pergelisol. Figure 4 (Stearns, 1966) is a map of the pergelisol (permafrost) boundary of North America. A total of 26% of the land surface of the earth contains pergelisol. Note also in figure 4 that the southern boundary of pergelisol and the 0° C. mean annual isotherm are widely separated.

The ground containing pergelisol is subdivided into layers according to its annual reaction to changes in temperature. The mollisol is the region above the pergelisol (the active layer as called by English investigators) which may freeze in the winter but thaws in the summer. In warming regions, the upper portion of the pergelisol may become part of the mollisol. The mollisol is technically also a part of

(Stearns, 1966)

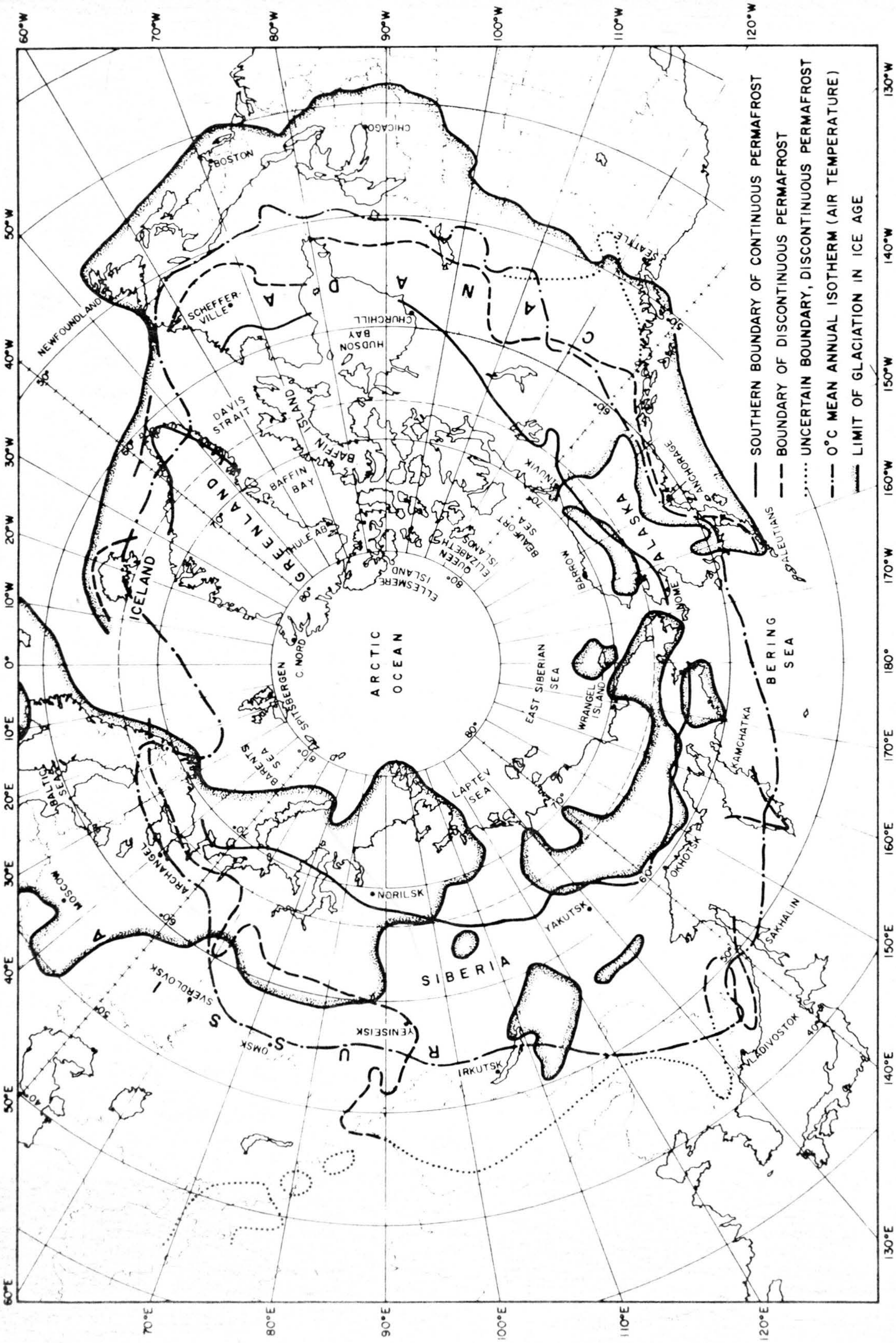

Figure 4. Permafrost in the Northern Hemisphere.
(compiled from many sources)

the tabetisol, which is defined as any unfrozen ground. The tabetisol may be underneath, on top of or included in the pergelisol. Robert F. Black (1954) further subdivides ice-containing soils according to the relation of ice to pore spaces. When ice is clearly visible, the soil is termed as supersaturated. Well cemented frozen ground with open pore spaces is undersaturated. Saturated ground has all pore spaces filled with ice.

A general warming trend in various areas over the past few centuries is evidenced by a comparison between temperatures at the pergelisol table, and temperatures of the pergelisol deeper in the soil. In the Greenland ice cap, for instance, temperatures at 50-100 meters are cooler than those at the pergelisol table. Moving up section, temperatures increase at an increasing rate, showing a recent warming trend. The lower temperature figures roughly correspond to the former annual temperature averages. These data are useful in plotting temperature curves over a period of several centuries. Some areas contain alternating layers of pergelisol (frozen) and tabetisol (unfrozen), the latter of which is referred to by many geologists as taliks. Areas where the interbedded tabetisols are more numerous and voluminous than the pergelisol are called areas of discontinuous pergelisol. Areas which were dry and unglaciated (during times of glaciation of other areas) generally developed and have retained deep permafrosts.

CONGELITURBATION

Bryan defines congeliturbation (sometimes termed cryoturbation) as frost action which involves differential and mass movements. Such terms as frost heaving (used by many geologists to describe the differential "heaving" of soil by pressures within the ground), solifluction (where frost is involved), sludging, etc., are included in congeliturbation. The corresponding noun for the mass of disturbed material is congeliturbate. Structures formed on congeliturbate in the form of patterned ground will be discussed under a separate topic.

Frost heaving, as defined by Stephen Taber, is differential uplift by frost. While the phrase "frost heaving" may not be as concise as is desirable, it is generally accepted as a type of congeliturbation.

The process has, as one of its most important controlling factors, the heat conductivity of pebbles in the soil. As pressures build up (due to freezing by segregation), in fine soils, the upper surface receives the most stress and is "heaved" vertically upward. This thrusting up of the surface carries pebbles held there by a frost crust, but whose base is still in the mollisol below. This mollisol, being pushed down by the frozen crust above and pulled down by the frozen ground below, fills in below these pebbles. With the onset of warmer temperatures, the pebble (if it has lower heat conductivity than the soil around it) remains suspended by a crust of frost under it. When this crust melts, the pebble sinks somewhat, but it at a higher level than its original position. With each freeze-thaw cycle, pebbles are raised. There is some question, however, as to the heat conductivity of pebbles. Many pebbles are more conductive than the surrounding soil, so such a principle of heaving cannot apply. When the pebbles are more conductive there may be some uplifting of the pebbles due to freezing by segregation; however the fines in the soil are probably raised at least as fast as the pebbles. Furthermore, if the pebbles are more conductive than the surrounding particles, the frost suspending them will melt first, allowing them to sink first. Generally, stones are more conductive to heat than are soils (see nets under Patterned Ground), so one might expect stones to sink as congeliturbation occurs. Congeliturbation would then often be very difficult to detect. But the opposite is true: generally the larger particles are raised and congeliturbation can be detected on the surface. More investigation in this area is obviously needed.

Frost heave often produces an uneven surface. Vegetation decreases the depth reached by the mollisol. The soil underneath absorbs a smaller quantity of water (therefore expanding less on freezing) than the surrounding bare ground, so that the vegetation is contained in small dips in the surface. Irregular subsidence is accentuated by man's cultivation, construction, and his clearing of vegetation. The karst micro-topography thus produced creates engineering problems where roads or pipelines are involved.

Another form of congeliturbation is that caused by soil needle ice (refer to Fujita's experiments under Freezing by Segregation), with the modification that the needles (pipkrakes of Tricart and others) are contained within the soil. These grow downward or laterally from the surface of a pebble which is more heat conductive than the surrounding soil. If the pebble is near the surface, it rapidly cools to freezing temperatures, allowing the needles to form. On level ground, the stone is lifted straight up and down, causing minor disturbances. On sloping ground, however, the needles still generally form perpendicular to the surface of the ground, pushing the particles out at an angle. When thawed, the pebble is displaced by gravity, obliquely to the surface of the ground, in a solifluction-type of motion.

In fine clay soils, as mentioned before, the clays absorb a great deal of water by means of the layer of segregation. During thaw, the near-impermeable clay becomes a fluid-like paste (sometimes referred to as a soliflual). The phase change from liquid to solid also modifies the electrical state of the ground, resulting in modifications of the colloidal structure of soils; these modifications also may increase the fluidity of the soil, making it more prone to solifluction. This action may result in sorting of particles by size (see Patterned Ground).

PATTERNED GROUND

In cold regions, there have often been found, in connection with frost action, various patterns formed on the surface. In discussing these patterns, it is always important to remember that no one reason can be given to explain them.

Polygonal forms include tundra polygons, mud polygons, stone polygons (including stone rings or circles), non-sorted polygons, and varieties of nets. Tundra polygons form when frost "wedges" (see Fig. 5) develop under bare patches of ground or other places where the ground is susceptible to frost penetration. These frost wedges develop from contraction cracks caused by intense freezing. With each freeze-thaw cycle, more contraction cracks form in the ice. These in turn may fill with water. The water expands on freezing, forcing the ice wedge to push outwards on the adjacent soil. Mud polygons are started when freezing by segregation desiccates the soil, creating mudcracks. These cracks may fill

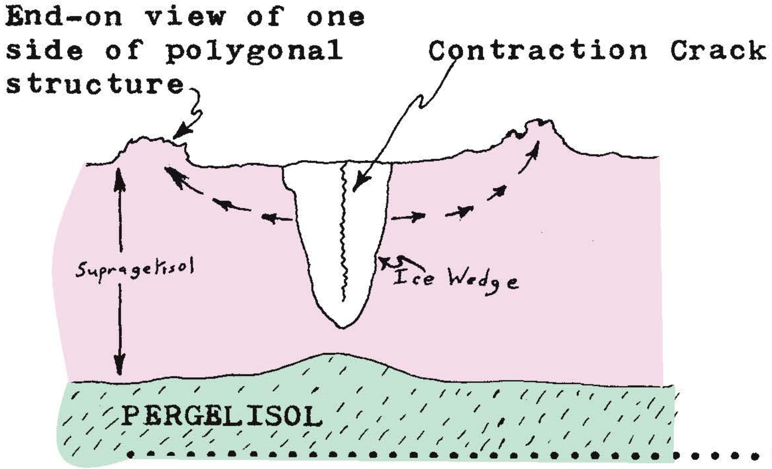

FIG. 5 - ice wedge in soil with contraction crack. Arrows indicate direction of semi-fluid motion of the soil when pressure is applied by the wedge. (R.P.Goldthwait)

with water and form ice wedges as in tundra polygons. Stone polygons and stone circles (or rings) are formed when the major process of frost action is congeliturbation by soil needle ice (pipkrakes mentioned under Congeliturbation). Stone particles are sorted by size, with the coarsest particles forming the perimeter of the polygon. Several stone circles close to each other may form polygonal structures. Non-sorted polygons form in much the same way as these polygonal structures, but occur in relatively homogeneous material, so no sorting is possible. Plants may concentrate along the borders of these polygons. Nets may be formed by differential heat conduction: larger rocks generally transmit heat faster than small rocks. The excess heat transmitted by the larger rocks forms depressions under these rocks. These depressions are in turn filled by other rocks (pulled down by gravitational force). Such depressions may develop lateral extent, and join with other depressions. The surface expression of these is a "net" where larger rocks are concentrated in the depressions.

When polygons form on slopes, the pattern becomes elongated parallel to the strike of the slope. As the slope becomes steeper, the polygons degenerate into lines, called stripes. The transition from polygons to stripes occurs at slope angles of between 2 and 8 degrees. Stripes may also in meltwater channels, where larger rocks are pulled down more readily by gravity, and fines which happen to be pulled down are generally washed away. Coarse material is left behind.

CONGELIFRACTION

Statements "confirming" the importance of congelifraction (also referred to as frost wedging, frost splitting, frost shattering, gelivation, etc.) in freeze-thaw environments are common in the literature. Congelifraction is the breaking up of rock by the expansion of ice through cycles of freezing and thawing. Only recently, question has been raised as to the true importance of congelifraction.

Congelifraction depends upon the distribution of water in the rock, the supply of water to the pore spaces and cracks within the rock, the strength of the rock, and the intensity of freezing.

If freezing ice can escape into pore spaces, little or no pressure is exerted on the rock; certainly the forces are not enough to break the rock. The most effective distribution is achieved when the rock is traversed by tiny cracks a few tenths of a millimeter to a few millimeters wide. When the cracks are wider than a few millimeters, the ice may be able to expand outward and not affect the rock.

The supply of water is probably the singly most important factor in congelifraction. Severely jointed rocks on a cliff wall may stand unaffected for thousands of years if the rocks are not liable to complete penetration by water.

The strength of the rock (in conjunction with the texture) determines the amount of rock broken and the size of congelifracts (fragments). Exposed rock breaks into larger congelifracts than does rock buried under debris. The congelifractate formed under debris is therefore more susceptible to solifluction.

Generally, the intensity of freezing is also an important factor. If all other conditions are equal, rocks break up faster (and into larger congelifracts) as temperature decreases. Thus, freeze-thaw cycles of little temperature change may only cause slight breakage; rock exposed to intensive freezing may break up extremely rapidly.

APPENDIX A

(Bryan, 1946)

Cryopedology: the science of intensive frost action and permanently frozen ground including studies of the processes and their occurrence and also the engineering devices which may be invented to avoid or overcome difficulties induced by them.

Cryoplanation: land reduction by the processes of intensive frost-action, i.e., congeliturbation including solifluction and accompanying processes of congelifracts. Includes the work of rivers and streams in transporting materials delivered by the above processes.

Congelifraction: frost-splitting or frost riving.

Congelifract: the individual fragment produced by frost-splitting.

Congelifractate: a body of congelifracts, a mass of material of any grain size produced by congelifraction.

Congeliturbation: frost-action including frost-heaving and differential and mass movements. Includes solifluction, sludging, etc.

Congeliturbate: a body of material disturbed by frost action; warp, trail, head, Coombe rock, Erdfliessen, Brodelerde, etc. These materials are characterized by surface forms: structure, soils, soil stripes, blockfields, mounds, etc. In places, structures characteristic of the surface forms are recognizable in the congeliturbate.

Pergelisol: permanently* or perennially frozen ground: "tjale" or "permafrost".

Pergelisol table: top of pergelisol.

Subgelisol: zone of unfrozen ground below permanently frozen ground.

Supragelisol: zone above the pergelisol.

Dry pergelisol: material having the requisite mean temperature to be permanently frozen but lacking water content or "dry."

Pergelation: the act or process of forming permanently frozen ground in the present or in the past.

De-pergelation: the act or process of thawing permanently frozen ground.

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* Bryan discarded the word "permanently" in 1948.

Mollisol: seasonally thawed ground above the pergelisol: "active layer" of Muller.

Mollition: the act or process of thawing the mollisol.

Intergelisol: pereletok, a layer of frozen ground between the pergelisol and the mollisol, which may persist for one or several years.

Tabetisol: talik, unfrozen ground above, within, or below the pergelisol.

Tabetification: the act or process of forming tabetisol.

--APPENDIX B--
(Stearns, 1966)

DESCRIPTION AND CLASSIFICATION OF FROZEN SOILS

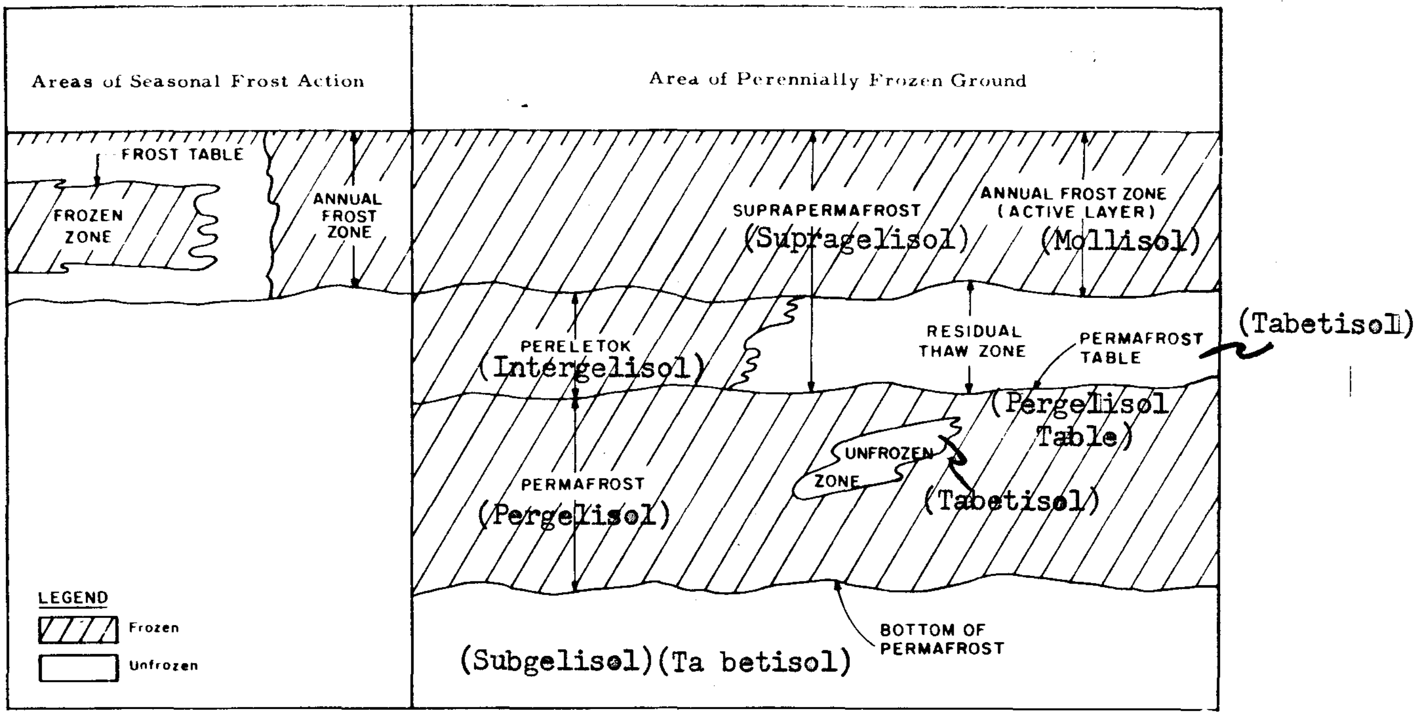


Illustration of frozen soil terminology.

DEFINITIONS OF SOIL AND OTHER TERMS RELATING TO FROZEN GROUND AREAS *

Annual frost zone (active layer). The top layer of ground subject to annual freezing and thawing. In arctic and subarctic regions where annual freezing penetrates to the permafrost table, suprapermafrost and the annual frost zone are identical.

Excess ice. Ice in excess of the fraction which would be retained as water in the soil voids upon thawing.

Frost table. The surface, usually irregular, which represents the level, at any time in spring and summer, to which thawing of the seasonal frozen ground has penetrated.

Frozen zone. A range of depth within which the soil is frozen. The frozen zone may be bounded both top and bottom by unfrozen soil, or at the top by the ground surface.

Ground ice. A body of more or less clear ice within frozen ground.

Ice wedge. A wedge-shaped ice mass in permafrost, usually associated with fissure polygons.

Icing. A surface ice mass formed by freezing of successive sheets of water.

Muskeg. Poorly drained organic terrain consisting of a mat of living vegetation overlying peat of varying thickness, from a few inches to many feet.

Permafrost. Perennially frozen ground.

Permafrost table. The surface which represents the upper limit of permafrost.

Pereletok. A frozen layer at the base of the active layer which remains unthawed for one or two summers.

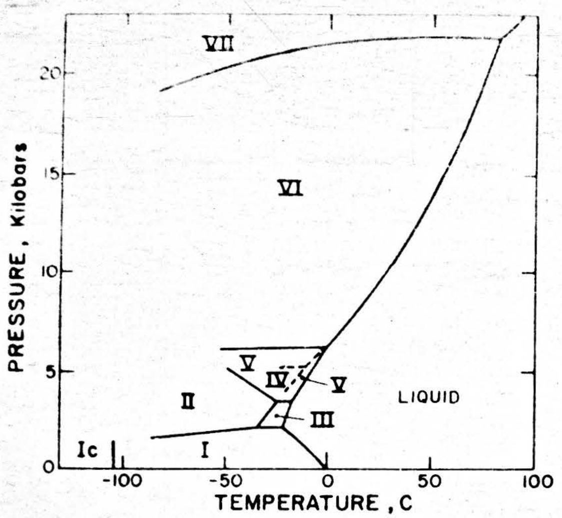
Residual thaw zone. A layer of unfrozen ground between the permafrost and the annual frost zone. This layer does not exist where annual frost extends to permafrost.

Suprapermafrost. The entire layer of ground above the permafrost table.

*For more complete list of definitions, see Hennion, F., "Frost and Permafrost Definitions," Highway Research Board Bulletin 111, 1955.

--APPENDIX C--

(Anderson, 1967)



Phase diagram for water. The solid phases (ice polymorphs) are identified by the roman numeral designations assigned by Bridgman, upon whose data the diagram is based. The field of ice IV in relation to ice VI and liquid, shown by dotted lines within the ice V field, is plotted by analogy to D_2O ice, for which the field was actually measured; ice IV is everywhere unstable relative to ice V. Ice Ic ("cubic ice") is shown schematically below the temperature of about -105C, below which it forms by vapor condensation and above which it inverts to ice I; it is not known to have a field of actual stability. (after Kamb, 1965)

X-ray structural data for ice polymorphs at atmospheric pressure and -175C. (after Kamb, 1965)

Ice	Density (g cm^{-3})	Crystal system	Space group	Cell dimensions (Å)	Z*
I	0.92	Hexagonal	$P6_3/mmc$	a4.48, c7.31	4
Ic	0.92	Cubic	Fd3m	a6.35	8
II	1.17	Rhombohedral	$R\bar{3}$	a7.78, α113.1°	12
III	1.14	Tetragonal	$P4_1 2_1 2$	a6.79, c6.79	12
IV	1.28				
V	1.23	Monoclinic	A2/a	a9.22, b7.54 c10.35,† β109.2°	28
VI	1.31	Tetragonal	$P4_2/nmc$	a6.27, c5.79	10
VII	1.50	Cubic	Pn3m	a3.41	2

*Number of molecules in the unit cell.
†Kamb's value was inadvertently printed 1035.

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