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THE MECHANISM OF FROST HEAVING OF TREE SEEDLINGS

J. R. SCHRAMM

Professor Emeritus of Botany, University of Pennsylvania; Research Scholar, Indiana University

INTRODUCTION

THAT destructive soil heaving is not due significantly to the expansion of soil water on freezing *in situ* in the soil interstices but to the freezing of water progressively segregated from the soil, has been known for a long time. And the relation of this established fact to the mechanism of frost heaving of plants has, at least in a general way, been understood in certain quarters for many years. With the former, geologists and engineers especially are well acquainted. The importance of soil frost phenomena in railroad, highway, and airport construction has stimulated much research, as has the recent marked increase of interest in the arctic regions. But with the latter, i.e., the precise mechanism of frost heaving of plants, botanists—including many ecologists and foresters—appear on the whole to have little acquaintance. This is the more surprising since botanists (von Mohl, 1860; Sachs, 1860) made important contributions fundamental to an understanding of the process; and half a century later a forester (Hesselman, 1907) applied this theoretical knowledge in correctly explaining the heaving of tree seedlings. In the light of the foregoing there is an obligation to offer some justification for the present paper.

For some years the writer has carried on plant colonization studies on black wastes from anthracite mining operations.[1] On one type of these wastes (culm or "slush") frost heaving of tree seedlings occurs under certain conditions—in the same manner as on some soils, but on a scale so exaggerated as to offer unusual opportunity for studying the phenomenon. The nature of the culm and the magnitude of the heaves are such that the process is revealed with striking clarity. It is hoped that the present report will in some measure convey this clarity and acquaint a larger circle of plant workers with the mechanism of the important and widely occurring phenomenon of frost heaving of plants.

A second reason for this paper is that it may shed light on the specific mechanism whereby transplants and older seedlings of evergreen conifers, as contrasted with young seedlings, escape heaving to a greater or lesser extent. Forestry literature is replete with reports of striking differences between heaving damage to young conifer seedlings versus older seedlings and transplants. The explanations offered for these differences are in nearly all cases general and not particularly satisfying. In the studies here reported the immunity to heaving on culm is one hundred per cent in pine transplants and zero in one-year seedlings. Since the exact mechanism whereby this immunity is achieved became clear during the studies, it is recorded here in order that its significance, if any, may be explored in natural substrata, including nursery and forest soils.

OBSERVATIONS

In processing anthracite, the fine material is removed by washing. The suspended matter, consisting mainly of coal and ranging from very fine material to particles of larger size, is conveyed to natural or artificial basins to settle out. When operations are discontinued, the surface dries. Familiar and distressing are the black dust clouds swept up from these culm banks.

Pronounced heaving of seedlings on such banks occurs, so far as observed, only when the culm is (*a*) wet to the surface and (*b*) initially completely free of frost. If mild freezing temperatures then set in such that the water in only a thin surface layer of culm freezes *in situ*, additional water moves against gravity from below and in turn freezes. The latter water is not water frozen in the culm interstices as is that in the surface crust. Instead, it is water "segregated" (Taber, 1918*b*) from the culm and frozen as relatively pure ice, the culm below this ice stratum remaining unfrozen. But this segregated water does not

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[1] The observations to be reported were made on the disused culm bank of the former Silver Creek Colliery of the Philadelphia and Reading Coal and Iron Company, near New Philadelphia, Pennsylvania. The author is indebted to the Company for courtesies and assistance in many ways.

The interest and support of the late Colonel Edwin M. Chance of Philadelphia are also gratefully recorded.

freeze as a solid layer of ice underlying the frozen surface crust of ice-culm mixture. Instead, it takes the form of ice filaments grouped in columns arranged vertically to the surface, i.e., vertical to the cooling surface. It should be noted, too, as has Hay (1936), that the columns or groups of columns are more or less discontinuous laterally, i.e., there are vertical voids between them (*cf.* Woodd Smith's excellent description, 1884). Also, the ice columns contain air cavities (Sachs, 1860; von Mohl, 1860; Taber, 1930*a*; etc.), rendering them porous. On 900 sq. cm. experimental areas, Fukuda (1936) measured the height of the ice column layer which developed over night in the open, and determined the total weight of the columns on each area. Taking as 100 the space occupied by the ice column layer (product of the area by the height of the columns), he found that the actual ice occupied on the average only 7.06 per cent of this space, though the columns gave every appearance of being closely ranked. He cites data from a paper in Japanese by Goto and Inagaki (1897) who report corresponding values of 30 and 15 on very dense and loose soils, respectively. These facts are important, because for a given volume of segregated water a very much greater heave of the surface is achieved than if the same volume of segregated water froze as a solid ice stratum.

Thus are initiated more or less closely ranked vertical columns of ice which grow at their bases, and at their apices merge into the frozen surface crust of ice-culm mixture. As they grow the crust is pushed upward. Though the surface before freezing was level and smooth, the frozen elevated crust (fig. 2) was often fissured. Yet all, or nearly all, of the original surface was raised by the ice columns, though to different heights, probably because of highly localized differences in culm texture and therefore in the size of the interspaces. The resultant influence on water movement would affect the amount of growth of the ice columns.

When the ice in the crust and in the columns melts, the surface settles back to nearly its original level, with, however, much of the configuration of the elevated frozen condition temporarily retained. The process may be repeated night after night if moisture and temperature conditions are favorable. In fall and spring when there is no frost in the culm but mildly frosty nights follow frostless days, conditions are favorable for the process provided at the same time the culm is wet to the surface so that movement of "soil" water to the base of the ice columns forming near the surface can take place readily. Heaves of three or four inches in a single night are not uncommon at such times.

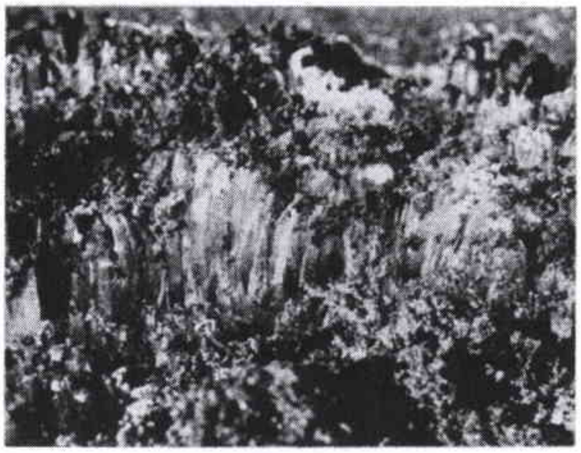

FIG. 1. Partial profile of basally growing ice columns pushing up frozen surface layer of culm in heaving process.

A profile of such heaves is shown in figure 1. Many of the ice columns are much flattened, predominantly in the same direction, giving the appearance of long incisor teeth. The reason for this was not explored. It is suspected, however, that it is related in some way to wind assortment of culm particles since the flat faces of the columns are oriented fairly consistently parallel to the prevailing northwest-southeast wind (the Silver Creek culm bank is subject to strong blowing in

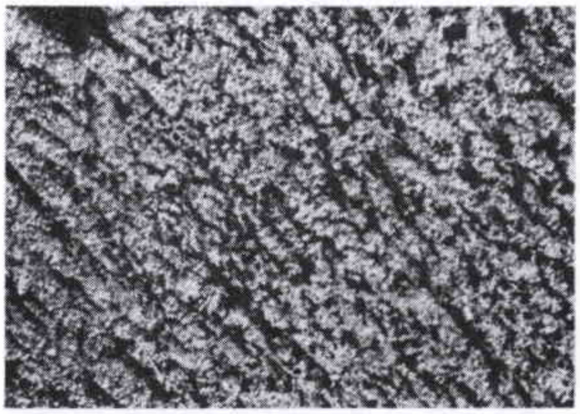

FIG. 2. Frost-heaved culm surface. The photograph, taken perpendicular to the surface, shows the surface in normal compass orientation. The anastomosing ridges and furrows are oriented parallel with the strong prevailing northwest-southeast winds.

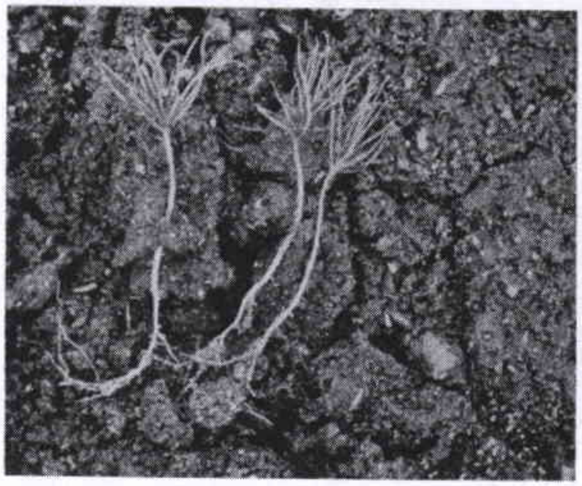

FIG. 6. One-year pine seedlings heaved out in one night. Thawing of the Kammeis responsible for the heave leaves the seedlings prostrate. Note the left-hand seedling where caked fragment of the crust, now thawed, still adheres to the mid-section of the stem. Splash cones were not involved, the shallow frozen surface layer constituting the sole grip on the stems.

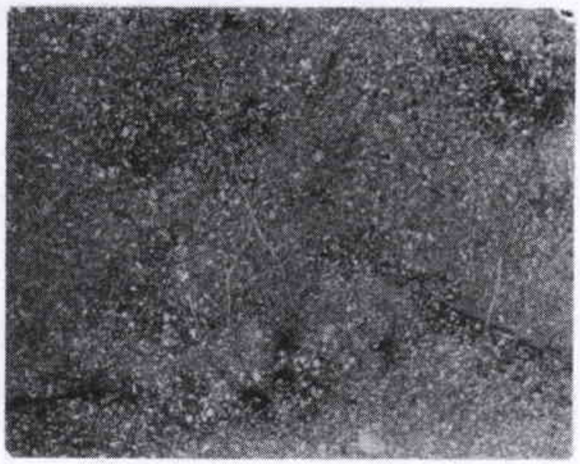

FIG. 8. One-year persimmon seedlings lying flat on the surface as a result of repeated heavings.

are severed—see below), representing successive hitches lower and lower on the stem and then on the tap root in repeated heavings; meanwhile the seedlings remain erect. In due time oak seedlings with tap roots fifteen and more inches long are pulled out completely and lie flat on the surface (fig. 7). The fate of the less robust seedlings of persimmon is similar (fig. 8).

When to the above factors one other was added, seedling injury in its most dramatic form was observed. This additional factor is hard rain, which splashes surface culm particles on the stems. The particles adhere to the stems and, in small evergreen conifer seedlings, also to the needle mass. In this manner a cone of wet culm is built up with its base on the surface (fig. 9). If mild freezing temperatures follow promptly, these cones lose heat rapidly and freeze tightly about the seedlings. Thus there is provided a very substantial collar with large basal area and vertically more extensively anchored to the stem than is the shallow horizontal layer which freezes around the stem to form the whole of the grip when no "splash cones" develop. Since hard rains produce such cones, favorable moisture conditions invariably ac-

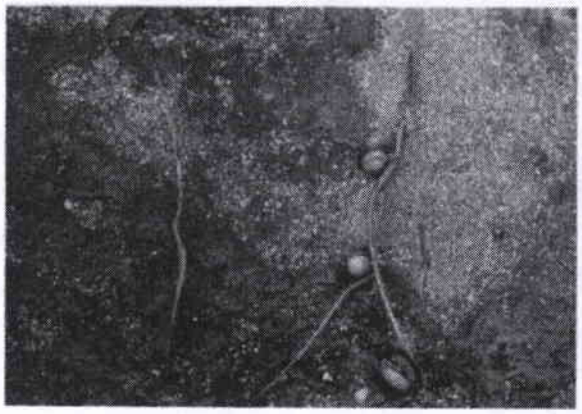

FIG. 7. One-year oak seedlings prostrate on the surface after repeated frost-heavings. These seedlings were not severed, and in most instances the cotyledons still in the seed coat were pulled out intact and attached.

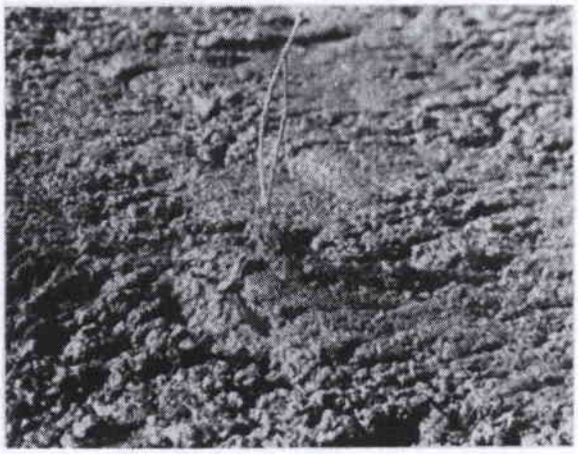

FIG. 9. A heaved one-year oak seedling with massive splash cone gripping base of stem. Apex of cone extends up to point where the two shoots appear to diverge, widening below until the broad base of the cone merges with the culm surface.

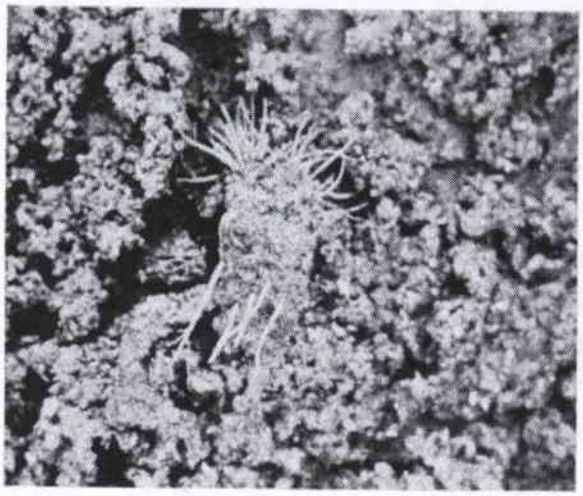

FIG. 10. One-year pine seedlings heaved out in one night and now prostrate on the surface following thawing. Though now thawed, the massive splash cone which gripped the seedling group, including needle tufts, still clings to the prostrate seedlings. The photograph, made at an angle, shows the under side of the caked cone with the stems projecting through it. Note that the four seedlings on the right were severed at about the transition between root and stem. In the left-hand seedling the major roots were torn.

company presence of cones. If suitable freezing temperatures follow promptly, the stage is set for spectacular injury.

In a single fall night when these ideal conditions prevailed, rows of oak seedlings of the preceding spring were raised three and four inches, or in many cases were severed at or just above the cotyledonary node[2] some inches below the surface (figs. 3 and 4). Red oak seedlings a year old are stout and woody. That they should be severed by a linear pull testifies both to the extensive development of anchoring root systems in the culm and to the impressive upward thrust exerted on the collar by the basally meristematic ice columns.

As melting occurs, more or less of the cone usually continues to adhere to the seedling. In current season pine seedlings pulled out in one lift this was true even after they toppled over (fig. 10). In seedlings with longer underground axes (e.g., oak), a portion of which remains in the soil so that the plant continues erect after the heaved culm surface returns to its normal level as a result of thawing, these cones may also persist temporarily. But now their truncated bases occupy a position above the general surface by a distance equal to the vertical extent of the heaving (height of ice columns) which took place, the ice columns responsible for the lift having meanwhile melted. A photographic record of such seedlings was not made. Figure 11 shows the same phenomenon as observed simultaneously on heaved marker stakes nearby, although in this case the cones were exceptionally slender.

By late October all seedlings (persimmon (*Diospyros virginiana*), pine (*Pinus virginiana* and *P. rigida*), and oak (*Quercus alba*, *Q. borealis*, and *Q. bicolor*)) from the spring seeding had been severed or pulled out in the manner just detailed. But in some four hundred pine transplants[3] (*Pinus banksiana*, *P. strobus*, *P. sylvestris*, and *P. rigida*) of various ages planted out nearby on the same culm bank in the same spring, not one showed evidence of heaving or heaving injury. This has continued to be true, not only of these transplants but of hundreds planted on the site subsequently. That pine transplants escape this injury so devastating to seedlings, deciduous and evergreen alike,

FIG. 11. Marker stakes with caked remnants of slender splash cones adhering, heaved four inches in one night. The space between the truncated bases of the elevated cones and the present surface of the culm was occupied by the four-inch ice columns (now thawed) responsible for the heave. So far as could be determined, the stakes did not settle back appreciably into their sockets when thawing returned the culm surface approximately to its original level. Note that the ridges of the heaved surface usually remain after the culm surface returns to its initial level.

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[2] Since the break invariably occurred at this point, to a linear pull the latter is evidently structurally the weakest region of the axis below ground level. Perhaps the crook in the axis at this point contributes to the weakness.

[3] Kindly supplied by the late Mr. D. C. Lefevre of the Clearfield Bituminous Corporation nurseries.

was puzzling and obviously significant and of practical importance.

It was at first suspected that the transplants were stouter and more firmly rooted—the explanation most often encountered in forestry literature for the greater heaving of young evergreen seedlings versus transplants and older seedlings. Some of the pine transplants, however, were no larger in stem diameter than the better oak seedlings. And in firmness of rooting the oak seedlings usually excelled, though without thereby achieving any immunity. It was ascertained, too, that the adjoining transplant and seedling areas were equally subject to heaving. Since pine stems are rougher (former needle attachments), the collar frozen around the stem might be expected to be even less likely to slip under upward thrust than on the smoother stems of oak and persimmon. This should make for greater heaving in pine transplants.

The explanation proved to be surprisingly simple. Pine transplants, being evergreen, present at all times considerable surface. Even very gentle air currents sway them more or less. By this motion the woody and relatively stiff stem exerts lateral pressure on the culm. Inasmuch as destructive heaving occurs only when the culm is initially unfrozen and wet to the surface, the culm is displaced laterally by the swaying stem and, because it is wet, does not cave in when the pressure is relaxed. In this way the stem works itself completely loose from the culm (fig. 12). The radial extent of the free space surrounding the stem (greatest at the surface because the swaying stem, pivoting somewhere below the surface, here describes the greatest arc) is very variable. Its dimension depends on velocity of air currents, resistance area presented to the wind by the aboveground portion of transplants, ease with which the stem is swayed as a result of depth of planting and firmness of root anchorage, resistance of the surrounding culm, etc. It may be under an eighth of an inch; yet, as will be seen presently, this is sufficient to confer immunity. If now the culm surface freezes, what was described earlier in the seedlings as a collar tightly gripping the stem, is in the pine transplants a frozen ring free from the stem. Thus, when ice columns form and push upward the frozen surface crust, the ring moves harmlessly up the stem, leaving the transplant undisturbed (fig. 13).

FIG. 12. Annular free space about the stem of a pine transpant produced through lateral pressure on the moist unfrozen culm by the swaying stem. Note the absence of ridges on the frost-free surface.

FIG. 13. Heaved culm surface about a pine transplant. Note the free annular space around the stem, formed before freezing and heaving started (see fig. 12). As a result the crust does not grip the stem. As freezing and heaving occur, the crust moves harmlessly up the stem, leaving the transplant undisturbed. Note deeply ridged crust.

Deciduous seedlings like oak are stiff and, at heaving seasons, bare, presenting little surface. Very strong winds would be required to sway them sufficiently to free the stems even minutely from the wet culm. No such free annular space was ever observed around oak or even the less rigid persimmon seedlings. In living pine transplants, on the other hand, very gentle air movements suffice; apparently these are always present at such times, at least on the Silver Creek culm bank. In observations on successive lots of young pine transplants over a period of years no heaving injury has occurred, and the "free ring" was noted on all occasions. Strong corroborative evidence is provided by the transplants themselves, for very different was the fate of those which died and shed their needles. No longer presenting a large surface, they too now require stronger air currents to free the stems from the wet culm. As currents of requisite velocity do not dependably accompany heaving conditions, it is not surprising that such dead and bare pine transplants heaved almost as commonly as did deciduous seedlings. No oak or other deciduous transplants were at hand for comparative observation. But there appears no reason to doubt that their fate on culm is accurately predictable from the behavior of the denuded pine transplants.

It remains to comment on the difference in behavior of first-year pine seedlings versus pine transplants. At the end of the first growing season pine seedlings are thin-stemmed and very flexible; and the needle tuft is close to the soil surface, where incidentally velocity of air currents is reduced. When such seedlings bend under wind stress the stems are so pliable that not sufficient lateral pressure is exerted to displace the wet culm and free the stems: the bending occurs above the soil surface. In consequence, when freezing occurs the seedling stems become tightly gripped by the frozen surface crust. Given requisite moisture conditions and temperature gradients, seedlings so situated, as noted above, are heaved out completely in one night (figs. 6 and 10).

As mentioned earlier, the thrust of the basally growing ice columns which lifts or severs one-year oak seedlings is obviously substantial. In laboratory experiments on cylinders of clay in contact with water at the lower end (open system) and cooled from above, Taber (1930*a*) obtained heaving pressures from growing ice columns of up to nearly 12 kgm. per sq. cm. Effectively to exert this thrust upward on the under side of the frozen crust gripping the seedlings, the ice columns must rest on a relatively unyielding base. Such a compact base was indeed present at the base of the ice columns about a heaved or severed oak seedling. With care this moist and unfrozen foundation is easily and neatly separated from the lower end of the ice columns,[4] revealing on its upper surface (the ice column-generating region) the pressure imprints of the bases of the clusters of ice columns (fig. 14). The ice-generating layer owes its firmness to the natural consistency of the fine-grained stratum. But that some packing of its surface results from the thrust of the ice columns in lifting or severing oak seedlings is indicated by the following fact. When ice columns were similarly separated from the unfrozen generating stratum in areas free of seedlings (where the columns merely pushed up the thin frozen surface crust), the irregular angular imprints on the generating niveau were absent. Troll (1944) reports that in the high mountains of South Africa where conspicuous columnar ice development occurs diurnally, lifting only a very thin surface crust, the unfrozen generating level is absolutely smooth and level ("butterbrotglatt"). Hesselman (1907) likewise found the unfrozen segregation level in drained peat bogs in Sweden completely even. Many others record the same fact.

FIG. 14. Vertical view of the water-segregating level of the subsurface fine-grained layer where the ice columns are generated. The fragment photographed (in center of figure and roughly square) immediately adjoined a heaved oak seedling. Note the irregular angular imprints made by the thrust of groups of ice columns. Note also the clay-like character of the generating stratum in contrast to the coarse-grained surface layer (the coarse particles at upper left and lower right corners of the fragment were inadvertently dislodged from the surface).

It is apparent that in heaves of as much as four inches in a single night, actually not over one-half inch of culm was heaved—the surface layer. All the rest of the heave consisted of porous needle ice formed from water supplied from the unfrozen culm below, the latter not disturbed in its position in any way. And this heaved surface layer is also the only part of the heave which is actually frozen culm, i.e., with the water frozen *in situ* in the culm voids. Since this surface layer is thus

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[4] Growing ice fibrils are not frozen to the generating substrate; indispensible for their growth is the presence of a film, however thin, of liquid water between the base of the fibril and the immediately subjacent soil particle or particles.

the only component of the entire heave complex in which the expansion of *in situ* water on freezing contributes to the total heave, it is of interest to calculate the approximate magnitude of this contribution. According to Taber (1929) the water content of an average soil is seldom as much as 50 per cent. It is doubtful whether it approached this figure in the culm, especially in the coarse-grained and easily drained surface layer which forms the crust. But it will be assumed that the water content was 50 per cent and that the crust was one-half inch thick. With water increasing roughly 10 per cent in volume on freezing, and assuming that all this expansion is exerted vertically upward, the frozen layer would have registered a maximum vertical elevation of 1.27 mm. In a total heave of four inches, this contribution is thus 1.25 per cent (1.66 per cent in a three-inch heave), leaving over 98 per cent to be accounted for by the columnar ice formed from water segregated from the unfrozen culm beneath. Here may be recalled the immunity to heaving of the pine transplants. The soil about the transplants underwent as much freezing as that about the seedlings. That the former were undisturbed but the latter heaved out in one night, dramatizes the negligible role in heaving played by the expansion of water in freezing *in situ* in culm.

The essential morphology of a soil in the act of heaving plantlets (or other objects projecting through the surface) comprises a relatively thin surface ice-soil crust pushed up by immediately subjacent vertical ice columns, the latter growing at their bases resting on unfrozen soil. For this structural entity, in which the component crust and columns are equally essential, there is not, so far as the author is aware, a satisfactory recognized English term. Taber's "needle ice" (1918*a*) is admirably descriptive of the segregated ice component; but the term does not, and was not intended to, suggest the inclusion of the ice-soil crust.

The Old World literature contains a number of terms—adopted from the vernacular—such as the Finnish "Rouste," the Swedish "Pipkrake," the German "Kammeis," etc.; also the Japanese "Shimobashira" (Wagener, 1877). Of these, "Kammeis" (comb-ice) appears, as it did to von Mohl a century ago, peculiarly apt and descriptive, with the back of the comb represented by the crust and the subtended teeth by the ice columns. Von Mohl's comment on the term (1860) merits quoting:

> Dieser Ausdruk [Kammeis] ist vortrefflich, indem die dünne durch das Eis in die Höhe gehobene oberflächlich liegende und gefrorene Erdschichte gar nicht übel dem in der Technologie sogenannten Felde (d.h. dem Theile, von welchem die Zähne ausgehen) des Kammes und die Eisnadeln den Zähnen desselben entsprechen.

The suggestion is ventured that "Kammeis," in the sense used by von Mohl, be used to designate the morphological entity under consideration, avoiding a rendering into English; for the latter ample precedent exists.

In making this suggestion the author is aware that probably in most cases in which the term has been and is being used it is synonymous with needle ice, i.e., does not include the surface ice-soil component. Confusion would be avoided if "Nadeleis" or "needle ice" were used to designate columnar ice formed from segregated water, restricting "Kammeis" to the composite morphological entity involved in frost heaving of plants and other objects projecting into or through the surface crust. Troll (1944) suggested "Borsteneis" (brush ice) as even more descriptive than "Kammeis" because the ice columns are analogous to the bristle tufts of a brush in that they are composed of bundles of ice filaments. Apt as is this analogy, the term again applies only to the columnar ice and does not include both components of the integrated structure involved in plant heaving.

DISCUSSION

Culm surfaces dry rapidly, the high absorption of radiant energy by the black material being an important factor. Thus, black dust clouds may be whipped up by the wind within an hour after a drenching rain. But the thin dry surface layer formed acts as a mulch progressively retarding further and deeper drying. In observations covering several years the line of obvious free moisture was never noted more than two or three inches below the surface, even during summer droughts.

With winds carrying off the very fine material, the heavier coarser particles are left behind as the major components of a shallow surface layer (*ca.* one-half inch). Only this shallow layer froze under the conditions when seedling heaving occurred. This stratum, having little very fine material, probably freezes at or very nearly at 0° C., the water being in large voids and its freezing point therefore not appreciably depressed. It was below this coarse-grained layer, where fine material definitely predominated, that water segregation took place and the vertical ice columns were generated which raised the surface crust with its water frozen in the large voids.

As noted, figure 14 shows a surface view of the exact ice column-generating layer (always unfrozen so long as it acts as the generating layer). No mechanical analyses of grain size were made, but it is apparent from the photograph that this layer is composed predominantly of very fine-grained material as contrasted with the surrounding coarse-grained culm of the surface layer which freezes. Beginning at the generating level the culm is almost clay-like in consistency whereas that of the thin layer above which freezes to form the surface crust is sand-like.

The important question arises: what interplay of factors determines the precise level at which, in any given set of circumstances resulting in heaving, water segregation and ice column formation are initiated; or put in another way, what determines the level at which frost penetration stops and water segregation and column formation begin? The problem centers first of all in the physical-chemical properties of water and the interfacial relations of water with the soil particles—a water-soil system. Complicated by the involved array of variables presented by soils, the question raised is obviously complex—one which is outside the competence of the author to treat at the theoretical level. For the purposes of the present paper, however, some approximation to an answer may aid in envisaging the heaving process. In making the attempt, the writer is aware that his is a limited familiarity with the voluminous and widely scattered literature.

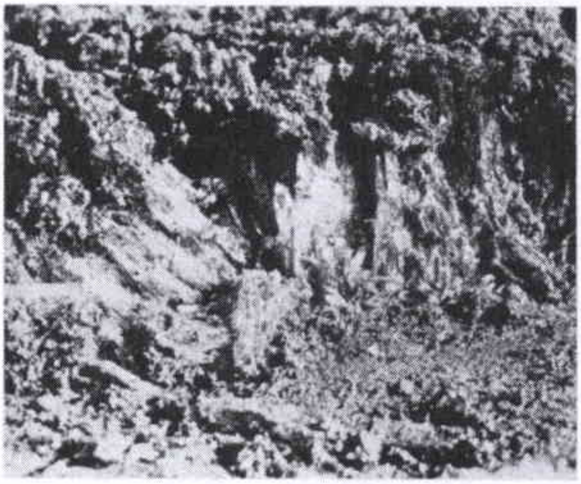

FIG. 15. Profile of Kammeis showing the homogeneously frozen crust pushed up by the subjacent vertical columns of pure ice (needle ice). Columns on the left have partly fallen over as a result of onset of thawing.

The drastic heaves, which by early fall had destroyed every experimental seedling on the Silver Creek culm bank, all occurred when the night temperatures dropped only very moderately below the freezing point. Temperature records at the site were not obtained. In Pottsville, Pennsylvania, five miles away, the official temperatures on the nights in question were only slightly below freezing. Three other facts suggest that the temperatures could have been only a little below the freezing point. (1) Though the black culm loses heat very rapidly, only a thin (not over one-half inch) surface layer froze, i.e., the water frozen *in situ* in the large voids in the coarse-grained surface material. (2) On the October mornings following the spectacular heaves, melting began with the first rays of sunshine. The photograph reproduced in figure 15 and representing a profile of the crust and subjacent ice columns was made at sunrise. Before camera focusing could be completed, melting had set in as evidenced by the partial toppling over of the columns on the left side of the photograph, which occurred just before the exposure could be made (*cf.* Mohaupt, 1932). Very soon such collapses became general along the profiles cut, lending an aspect of animation to the scene. (3) On the early morning following the night of the most spectacular heaving, there were scattered very local patches where the ice columns were not topped by a frozen crust, i.e., the columns arose at or very near the surface of the culm (fig. 16), apparently no culm surface being raised. In these local areas, therefore, frost had for all practical purposes not penetrated at all, though ice columns two inches or more high had formed. Thus the stratum generating the ice columns was essentially the surface of the culm. Such a state of affairs could hardly come about except with air temperatures but little below freezing.

It is regrettable that the nature of the culm in these local patches was not more carefully examined, still more that no analyses were secured of the grain sizes of these areas and of those of the large expanses characterized by a surface crust raised by subsurface ice columns. The surface of some of the areas in which free-standing ice columns appeared had been disturbed very recently in the course of the experimental work. This obviously was the case in the area represented in

FIG. 16. Free-standing ice columns generated approximately at the culm surface. Arrow indicates position of a palisade of ice columns (8 columns visible) which have pushed up a continuous but very thin frozen crust.

figure 16. Though the writer cannot be certain that the phenomenon was confined to disturbed areas, the possibility suggests itself that the disturbances had exposed local irregular patches of the subsurface fine-grained culm. With very gentle temperature gradients between air and this material, the freezing point depression of the water in the small voids of the latter might have sufficed to arrest frost penetration almost at once and long enough for water segregation and ice column formation to begin—virtually at the surface. Actually, at the tips of some of the columns in figure 16 binocular examination reveals a very small mass of culm. And in at least one instance (arrow in fig. 16) the masses are appreciable and joined laterally so that the palisade of some eight ice columns terminates in a common horizontal and continuous surface crust of frozen culm. Thus, it is probably more correct to say that in these patches frost penetrated the surface before water segregation and ice column formation began, though to so negligible a depth that only rarely and very locally was a continuous frozen crust formed—and then only a very thin one. The great majority of ice columns were separate, at most topped by a tiny frozen culm cap, and free-standing, like the "ice flowers" reported so frequently, especially in the older literature, as arising under similar conditions of temperature and moisture from dead plant parts or from ground surfaces (Herschel, 1833; LeConte, 1850; Caspary, 1854; Coblentz, 1914; etc.).[5]

As noted, the freezing point of the water in the large interspaces of the surface layer is not depressed appreciably. On the other hand, at least some of the water in the small voids in the subjacent clay-like culm is subjected to greater stresses with consequent depression of its freezing point. (This is a stable condition and is not to be confused with supercooling, an unstable condition with which we are not here concerned (Dorsey, 1948).) An air temperature at or only very slightly below freezing suffices to freeze the water in the large interspaces of the surface layer, giving rise to the crust. When the advancing frost line reaches the clay-like culm, it encounters water with a freezing point slightly lower (depressed). If the temperature gradient between air and soil is very gentle, this differential may suffice to halt frost penetration and allow time for water to move from the unfrozen culm below to the base of the ice already formed and there enter the ice phase. That is to say, the temperature at the base of growing ice columns is appreciably below the freezing point. In two series of laboratory tests on soft clay soils (U.S.A. Corps of Engineers, 1949) temperatures at the base of ice lens formation were 28.4–30.2° F. and 30.7–31.1° F., respectively. MacKintosh (1936), in laboratory tests of clay soils in cylinders undergoing freezing, reports that the 32° F. line was 2½ inches below the lower limit of ice formation.

Since water as ice has less free energy than liquid water, the ice already present may roughly be thought of as acting as a "sink" for free water molecules from below to move to the region between the base of the ice filaments and the immediately subjacent soil particles and there be added as ice to the base of the filaments.[6] This process obviously can go on at any given level only so long as frost does not penetrate more deeply to freeze *in situ* the water in the voids of the unfrozen stratum where the water segregation is taking place; also, only so long as there is

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[5] Though no seedlings were present in any area displaying free-standing ice columns, it is safe to assume that no heaving injury would have befallen them. Not being gripped by a surface crust of frozen culm, the elongating ice columns would be powerless to exert an upward thrust on the plantlets.

[6] No attempt will be made to deal with the question of the precise forces involved in and responsible for this movement of soil water. But whatever the nature and contribution of these forces (e.g., whether the water molecules are pulled into the film between the base of a growing ice fibril and the subjacent soil particles or reach it through the action of other forces), it is the forcible entry of water molecules into the film, which is constantly being attenuated by congelation, which directly and primarily accounts for the heaving force.

abundant water below so that the films of water moving to the "energy sink" at the base of the ice filaments are not interrupted.

Since, in the several heaves which destroyed all experimental seedlings on the culm bank by early fall, neither storied needle ice nor stratified frozen culm (see below) were ever encountered, it follows that all the water segregation which effected a heave of three to four inches in a single night occurred at one and the same level. This is to say that, once frost penetration was arrested and water segregation initiated at a given level, the latter continued to be the ice column-generating niveau throughout a given heave. Frost penetration, once arrested, was not resumed. This fact likewise emphasizes that freezing temperatures representing only a very moderate gradient between air and culm, other conditions being favorable, are conducive to the most destructive heaves.

Since the passage of water from the liquid to the solid phase is accompanied by a substantial release of energy as heat, this heat—and that of the relatively warm water moving from below to feed the growing ice fibrils—are important factors in the maintenance of the frost line at a given level once frost penetration has been halted long enough for water segregation and ice column formation to be initiated. And though ice is a much better conductor of heat than is water (Patten, 1909), the ice-column stratum is so porous (see above) that it has an insulating effect similar to that of snow (Krumme, 1935) in retarding loss of heat from the substrate, likewise tending to retard frost penetration to deeper levels. Thus, once a water-segregating and ice fibril-forming level has been established, it tends to perpetuate itself, and indeed does so if heat supply and heat loss continue to be essentially in balance at the segregating level—always assuming that water supply is adequate.

If on the other hand the temperature gradient between air and soil is very steep, frost penetration is so rapid that no water segregating- and ice column-generating zone can be established. In these circumstances the soil freezes homogeneously (Jung, 1932; Taber, 1929; Beskow, 1935). The slight heaving at such times is limited to the volume change (roughly one-tenth) of the water as it passes from the liquid to the solid phase. Such heaving is of little or no consequence to plants, at least outside the arctic and colder temperate regions.

If, finally, the air-soil gradient is less steep but still sufficient for frost sooner or later to penetrate the initial water-segregating level and freeze enough of its water *in situ* to stop the growth of the ice columns, a new and deeper segregating layer may be established and function for a time, until it too is overtaken by frost penetration and supplanted by a yet deeper segregating layer. A profile of such a soil shows many and progressively deeper segregated ice layers separated by layers of soil. Such ice layers are usually of small vertical extent, occur at irregular or more or less regular intervals, and in general are roughly parallel to each other. The heave of a soil with this structure is, as nearly as can be measured, equal to the sum of the vertical dimensions of these segregated ice layers (Taber, 1930*a*). Here too, then, the heaving is due almost entirely to the freezing of water segregated at intervals of depth from deeper layers of soil. For a detailed report on the regular and widespread occurrence of this type of structure in nature in soils with requisite grain composition, the reader is referred to the detailed studies of Kokkonen (1926) in Finland. Taber (1929), Beskow (1935), and others induced essentially the same structure in open cylinders of clay resting at the bottom in a water supply (i.e., open system), insulated against cooling on the sides, and subjected to a steep air-soil temperature gradient.

Though early fall heavings had destroyed all experimental seedlings before it made its appearance, another well-known pattern of segregated ice—storied needle ice (fig. 17)—became common on the culm bank later in the fall. While this pattern, like the preceding stratified one, was not involved in the seedling heaving described, it merits brief comment. In its ideal form it is

FIG. 17. Profile of culm heaved by storied needle ice.

characterized by two or more strata of needle ice without intervening soil layers. That is, the several stories of needle ice are generated at the same water-segregating level but with interruptions in time, the interruptions resulting in the lines demarking the stories.

In its simplest form (two stories) the development of such a pattern, assuming requisite moisture and soil texture, may be envisaged somewhat as follows: (1) A night in which an initial Kammeis develops; (2) a succeeding day with no appreciable thawing but one not cold enough to sustain uninterruptedly the needle ice development of the preceding night; hence the initial layer of needle ice ceases to grow, but persists; (3) a second night cold enough to reactivate needle ice formation and water segregation at the same level at which these processes were interrupted during the preceding day, but not cold enough for frost to penetrate more deeply into the soil to initiate a new segregating layer. The result is a new story of needle ice in immediate contact with the base of the initial story which pushes up the first (now the upper) story with its covering frozen crust. Thus the second story is generated at and by the same level as was the initial one. Roberts (1903) describes eight such stories formed in as many nights. Among numerous other reports are those of LeConte (1850), B. Woodd Smith (1884), Bouyoucos (1923), Nimmo (1928), Krumme (1935), and Hay (1936).

Conditions in nature usually alter this ideal structure more or less. Chief among these is thawing from the surface, which obliterates in whole or in part one or more of the upper (older) needle-ice stories. Recurrent thawings and their varying intensity may so destroy or blur the original storied structure that its exact history cannot be told with certainty (fig. 17).

Heaves generated by such storied needle ice, always topped by an ice-culm crust, became common on the culm site later in the season—long after all seedlings had been destroyed by simple (single-storied) Kammeis in the earlier fall. In some locations considerable areas were heaved uniformly. In others the heaves were highly localized, manifesting themselves as flattened hummocks projecting slightly above the general surface and averaging perhaps a foot in diameter (fig. 17). Doubtless local differences in culm texture, with their attendant dynamic effects on the contained water, are mainly responsible for these differential heavings.

In a period of storied ice development the temperature on an occasional night may go low enough for frost to engulf the water-segregating level, with the result that a new and deeper one is established. When this occurs a layer of soil separates the needle-ice layer produced at the new level from the layer formed at the superseded one. In the measure that this occurs the total pattern, though still essentially storied, takes on somewhat the character of both the storied and of the stratified types noted earlier. Indeed a thin soil layer may be present between all stories (Hay, 1935; Müller, 1937), each succeeding story having been generated at a new and slightly deeper level because of deeper frost penetration at each succeeding growth period.

Fukuda (1936) reports an interesting pattern which in a sense is intermediate. Needle ice 3–3.5 cm. high developed in a single night in the open. Across the needle palisade ran five horizontal and parallel bands characterized by having soil particles incorporated in the needles. Between the bands the needles were uncontaminated. The continuous temperature record of the night revealed five steep declines with intervening periods of gentler slope, both differing in duration. It was during the abrupter declines that soil particles became engulfed at the base of the growing ice needles to give rise to the five horizontal bands, the intervening uncontaminated bands corresponding to the periods of gentler decline. Moreover, the width of the bands was correlated with the duration of the respective steep and gentle declines. Apparently frost penetration during the periods of sharper temperature drops was sufficient for occasional soil particles or aggregates to become enclosed in the base of the forming ice columns; but not rapid enough to bring water segregation to a halt and initiate a new and deeper segregating layer. In consequence the ice needles were not interrupted in their growth but merely rendered turbid by the incorporated particles, hence the turbid bands. In the periods of gentle decline, on the other hand, not even this incipient frost penetration occurred, hence the clear bands corresponding to these intervals.

No such neat parallel banding was observed on the culm site, perhaps because at the time the writer was not alert to the theoretical significance of such details. However, it was noted on certain mornings that the ice columns in some areas, though continuous, contained sufficient incorporated culm particles to render them blackish, in contrast to the silky white appearance in areas with uncontaminated needle ice. Kokkonen (1926) determined the amount (by weight) of scattered soil particle inclusions in needle ice as developed on some Finnish soils under certain conditions.

It was pointed out above that the heaved culm surface often was fissured in a pattern parallel to the prevailing northwest-southeast winds which sweep the bank. Troll (1944), in describing frost-heaved soils in the high mountains of Africa (Kenya and Basutoland), reports somewhat similar surface ridges and furrows oriented parallel to the prevailing cold and high winds of the region, though he does not speak of any flattening of the ice columns. For this phenomenon he proposes the term "Windstreifung des Kammeises" or "windgestreifter Auffrierboden." He recognizes that the ridges and furrows were not formed by the wind moving surface material prior to Kammeis development, but came into being in the course of Kammeis formation itself (longer and shorter—or lacking—columns, respectively). This conclusion is fully shared by the writer with respect to the ridging of heaved culm surfaces.

Troll sees in the unidirectional cold and high winds the direct cause of the differential Kammeis development which results in parallel heaved ridges and furrows, micromovements of the air induced by projecting soil aggregations also being implicated. If the writer interprets Troll correctly, this would mean the assumption that sufficient temperature differences are created at the ice column-generating level to result in a pattern of longer and shorter (or lacking) ice columns such that the surface is differentially heaved in more or less parallel ridges and troughs.

To the writer the phenomenon, at least on culm, seems more likely due to prior assortment and deposition of culm particles by strong prevailing winds. These local and oriented deposits, since they differ in grain-size composition, would have differing capacities for supplying water to the bases of the growing ice columns, resulting in longer and shorter columns. Preference for this interpretation of the phenomenon on culm rests on the following considerations. (1) Grain size profoundly affects the water segregating and needle-ice potential of soils (Taber, 1929, 1930*a*; Jung, 1932; Beskow, 1935; etc.). On another type of accumulated anthracite mining waste ("rock banks"—rock, but containing enough carbon to render it black) only very slight frost heaving was observed and seedling injury never occurred. After prolonged weathering the surface of such banks contains much sandlike material but none as fine as dust; at any rate, in contrast to culm banks, no dust clouds arise even on old weathered banks swept by strong winds. (2) On culm, the surface of which was level and smooth the evening before pronounced heaving occurred in the night, the anastomosing compass-oriented ridges and furrows described earlier (figs. 2, 9, 11) developed even when at most gentle winds occurred. (3) The temperature differential (assumed by the author to be implicit in Troll's suggestion), to be effective, must exist at the level where water segregation and growth of ice columns occur, i.e., even initially beneath the frozen crust. And as growth of needle ice proceeds and pushes up the crust, the critical generating level not only becomes further removed from the surface but also progressively insulated from it by the enlarging porous needle-ice stratum. It is difficult to see how in these circumstances the temperature differences in the surface layer, which must at best be slight, could be propagated to the increasingly remote generating level—especially in so consistent a pattern as to result in the anastomosing ridges and valleys on culm and the parallel ridges and furrows observed on soil by Troll.

HISTORICAL

The limited scope and objectives of the present paper preclude more than consideration of a few of the more important landmarks prior to about 1935. By that time sufficient knowledge had accumulated to provide a general understanding of frost heaving of soil in milder temperate climates. Broad coverage of the literature is available in such reviews as that of Johnson (1952). Attention is called also to several extensive bibliographic tools (*Arctic Bibliography* and *Annotated Bibliography on Snow, Ice, and Permafrost*) which, though recently inaugurated, are retroactive.

In the emergence of a correct interpretation of the mechanics of frost heaving of plants, the independent and almost simultaneous contributions of von Mohl (1860) and of Sachs (1860) deserve greater attention than has been accorded them—at least in the American literature. This is so despite the fact that neither botanist concerned himself directly with frost heaving of plants. Encountering Kammeis—for the first time in his experience—on a frosty November morning in the Schwarzwald immediately following mild rainy weather, von Mohl gives a lucid and accurate description of its structure and genesis which is paraphrased here: A surface layer of frozen soil pushed up by subsequently developing pure ice columns resting on unfrozen soil, the columns forming from water continuously moving slowly ("nachsickern") from below through the soil voids to feed the basally growing columns. Von Mohl does not speak of the water as segregated; but there can be no doubt he clearly understood that the marked heaving of the frozen soil surface is not due to the expansion of water freezing *in situ* in the soil but to basally meristematic ice columns developing from water drawn and segregated from the unfrozen soil below. Having correctly interpreted the essential dynamics of Kammeis development on soil, he then applies—again correctly—the same interpretation to the formation of ice layers in the abscission region of leaves of woody plants. This application was not made lightly. It was the result of rigorous logic following penetrating observations on the form and structure of the developing ice layers in relation to the anatomy and histology of the immediately adjacent plant parts. (It is to be recalled that as a plant anatomist and histologist von Mohl had no peer.)

Sachs (1860) studied intensively, largely with the microscope, ice column formation on slices of pumpkin, of root crops (carrot, turnip, etc.), and to a lesser extent on soil. His keen observations, experiments, and reasoning led him to agree with von Mohl's conclusions, to which he finds it appropriate only to add some refinement in physical-chemical terminology in describing the general dynamics of the ice formation. However, Sachs goes much further than did von Mohl in analyzing the forces involved in the phenomenon, including especially the nature and behavior of water imbibed in tissues. This water, Sachs concludes, is the immediate source of the water which feeds the basally growing ice columns on plant tissues so long, and only so long, as the tissues remain unfrozen. With steep temperature gradients between air and tissue substrates no columns formed and the tissue slices froze. Gentle gradients, on the other hand (minus 3–6°R.), resulted in good column development, the height increasing with time, the tissue slices meanwhile remaining completely unfrozen. Needle ice was successfully produced on soil, it being pointed out that development is always at right angles to the surface however the latter is oriented. Sachs further concludes that in form and mode of formation the ice columns studied by him agree with those described by Elliott (1827), Herschel (1833), LeConte (1850), Caspary (1854), and others on soil and on living and dead plant parts. It should be noted, too, that Sachs presents also a highly interesting account of what may quite properly be called the anatomy and histology of ice columns, as revealed in ingenious microscopic studies on developing columns on plant tissue slices. No comparable account is known to the writer.

An earlier publication of LeConte (1850) noted above, merits more than passing mention. Prior to the work of von Mohl and of Sachs it is the most important contribution on the subject known to the writer. LeConte reported excellent observations on Kammeis development on clay soils in the southeastern United States, and on ice ribbons forming on stems of *Pluchea*. Simple experiments having convinced him that in the origin of the latter the physiology of the plant plays no part (a conclusion with which Caspary (1854) disagreed), LeConte concluded that the two phenomena are ascribable to the same and purely physical causes. Close reasoning and simple calculations led him to reject various current theories of causation: that the needle ice is in the nature of hoar frost, i.e., that the moisture came as vapor from the atmosphere or from the soil; that the cold contracts the surface layer, thus forcing up the moisture which freezes at the surface; that the protrusion of the needle ice is caused by the mere expansion of water during freezing in the soil capillaries; that its expansion between 4° and 0° C. forces the water out of the capillaries, which then freezes at the surface.

The explanation proposed by LeConte, which cannot be presented fully here, recognized that the ice filaments form essentially at the surface from water supplied from below by capillary forces. But to make the system operative, LeConte postulates an elaborate apparatus involving conically enlarged endings of the soil capillaries at the surface. The sudden freezing of the water in these endings results in the forcible upward projection of ice threads, leaving the inverted cones (or pyramids) partially empty. This ushers in capillary activity to refill the cones with water, subsequent freezings repeating the ejections. The process is thus intermittent ("paroxysmal"), consistent, Le Conte believed, with the wavy striated structure of the extruded ice columns. This conception, in which each ice fibril arises from the flaring terminus of a soil capillary, is rejected by Sachs

(1860). However, it was reenunciated by Broun (1880) decades later, though no reference to LeConte appears.

Among LeConte's other conclusions it is significant that the maintenance of the soil below the ice columns in an unfrozen state is ascribed to (1) the continual movement of warm water from below to the scene of congelation, and (2) the large amount of latent heat released as this water freezes. He recognizes further that, when Kammeis thaws, the amount of moisture at the soil surface is vastly in excess of that present before freezing. "This is the case under circumstances which are incompatible with the idea of the deposition of dew: the water must therefore have been elevated from the depths of the earth." LeConte thus quite correctly accounts for the muddiness that accompanies thawing of soil which, immediately before Kammeis developed, was well drained.

Hesselman (1907) appears to have been the first to describe clearly the essential mechanism of frost heaving of plants—conifer seedlings on drained peat bogs subject to conspicuous Kammeis development. Familiar with the work of von Mohl and of Sachs, the Swedish forester places the heaving mechanism on a sound theoretical basis by recognizing that the concept, developed by the German botanists, of the dynamics of needle-ice development in soil and on plant tissues applied equally in the plant-heaving process mediated by Kammeis. Högbom (1914) agrees with Hesselman, as does Hamberg (1915).

In America the earliest accurate description known to the author of the mechanism of seedling heaving is that of Haasis (1923). Later Bouyoucos and McCool (1928, 1929), in observations on agricultural crops, arrived at the same conclusion as regards the mechanism of plant heaving. In neither publication is European literature referred to, and the later authors apparently were unacquainted as well with the earlier work of Haasis.

Meanwhile, starting in the second decade of the present century, there began to appear the experimental studies of Taber at the University of South Carolina. Growing crystals (K_2SO_4, $CuSO_4$, etc.) in supersaturated solutions were shown to exert pressure and to lift weights, provided other crystals not under pressure are not present or do not appear (Taber, 1916, 1917). This was true "even when the crystals were of a substance that separated from solution with a net decrease in volume." Having proved this, Taber turned his attention to frost heaving in soils. Metal weights placed on moist clay subjected to freezing during cold nights were lifted by virtually pure ice ("needle ice") forming between the surface of the clay and the bottom of the weights. On sand similarly treated no such pure ice formed on the surface nor were the weights lifted, though the water in the sand interstices was frozen, binding the weights to the sand (Taber, 1918*a*, 1918*b*). The distance through which the weights were elevated on clay approximately equaled the thickness of the layer of needle ice. The volume increase water undergoes on freezing thus played no perceptible role in the heaving of the weights, the latter attributed by Taber wholly to the basal growth of the needle ice at the expense of water moving up from below.

This water movement and needle-ice formation is possible because of the depressed freezing point of water in the minute interstices of clay, i.e., frost did not penetrate the clay when the rapid cooling of the metal weights had initiated ice formation in the film of water between the weights and the clay substrate. In sand the freezing point of water in the relatively large voids is not appreciably depressed. When, therefore, the cooling weights similarly initiated ice formation in the corresponding water film, frost penetrated the sand, progressively freezing the interstitial water, with no perceptible lifting of the weights though subject to the expansion of water on freezing.

Of Taber's subsequent extensive laboratory studies (1929, 1930*a*), employing principally open system cylinders of soil insulated on the sides and cooled only from the top by controlled temperatures, Münichsdorfer (1935), Johnson (1952), and many others have provided more or less extensive digests. It is therefore unnecessary to do more here than to recall those findings in Taber's pioneering studies which have a more immediate bearing on the subject of the present paper.

(1) The negligible role which (at least in temperate climates) the expansion of water on freezing plays in soil heaving was demonstrated further by subjecting to surface cooling soil cylinders in which nitrobenzene or benzene was substituted for water. In both cases heaving of the surface occurred as in water-moist soil, i.e., segregated frozen layers of the organic liquids formed, despite the fact that both liquids freeze with a net decrease in volume.

(2) The common assumption that soil heaves upward because this is the pathway of least re-

sistance was disproved. Simple ingenious experiments demonstrated that, except at great pressures, the direction of heaving corresponds with the dominant direction of heat loss. In test tubes filled with moist clay buried up to the open end in insulating dry sand and subjected to freezing temperatures only from above, the segregated ice needles developed vertically, i.e., in the direction of principal cooling, or at right angles to the cooling surface. Cracks developed in the unfrozen clay below as water was withdrawn to nourish the growing needle ice above—an actual shrinkage of the soil. And no tube broke.[7] If, on the other hand, the tubes were cooled from the sides, the segregated needle ice again developed parallel to the principal direction of heat loss and perpendicular to the cooling sides of the tubes. But in doing so it was not following the line of least resistance, for all the tubes were ruptured by the pressure the growing needle ice exerted on the walls.

In other experiments, heavy copper bars were inserted vertically in open system cylinders of wet clay contained in cylindrical cartons. The latter were plunged vertically in dry insulating sand and subjected to freezing temperatures. By this arrangement the cooling was applied at the upper end of the clay cylinders, including the ends of the inserted copper bars. Copper being a vastly better conductor of heat than is moist clay, the buried bars became the principal pathways for conducting heat away from the interior of the soil to the top of the cylinders; i.e., the cooling of the soil was essentially radial—perpendicular to the bars. Radially arranged needle ice 1 cm. thick formed around the copper bars, that is, the ice crystals grew in the direction of principal heat flow (cooling). And as in the test tube experiments, all cartons were ruptured by the pressure of the radially growing needle ice, which here again did not follow the pathway of least resistance. In control experiments identical except for the absence of copper bars, the needle ice developed perpendicular to the upper surface—parallel to the dominant direction of cooling. That no cartons were ruptured in these controls obviously was not due to the segregated ice crystals having followed the line of least resistance in their growth.

(3) The approximate maximum pressure developed by a heaving pure clay soil was determined. In insulated open system cylinders of clay cooled from above, and with an arrangement for registering the heaving force of the surface, heaving (crystal growth) ceased when the surface load (pressure) reached nearly 12 kgm. per sq. cm. But when the apparatus was so arranged that the water with which the bottom of the cylinder of clay was in contact was put under pressure, crystal growth occurred despite the high pressure on the clay. Taber concludes that in the former case crystal growth ceased not because ice could not form under greater pressure but because under such pressure water could no longer reach the base of the crystals.

(4) The relation to heaving of the size of soil particles (and the attendant effects on the size and other characteristics of the soil voids) also received attention. In general, heaving increased with decrease in particle size down to a point at which the soil became impervious, thus interfering with water movement. Above a grain size of about 0.07 mm. little or no segregation occurred, even under favorable conditions of temperature and water supply. Good segregation, on the other hand, took place in soils with grains 1 μ or less in size. In mixtures, e.g., sand and clay, the fine grained component had to be substantial (*ca.* 30 per cent) before segregation and heaving occurred.

Important work in Sweden, notably that of Beskow (1935), confirmed the principles established by Taber and added greatly to both theoretical and applied knowledge in this rapidly expanding field.

KAMMEIS AND PLANT COLONIZATION

The problem of plant colonization of culm sites in Pennsylvania will be dealt with elsewhere; but it may be remarked here that it probably is rare indeed that any of the vanishingly few seedlings which may survive the harsh vicissitudes of the growing season fail to succumb later to the frost heaving described. The latter must be considered another powerful factor in the extremely slow spontaneous colonization of culm areas, many of which in fact remain completely barren. Though the role of Kammeis in plant colonization cannot be pursued here, attention is called to the valuable

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[7] In this experiment the system was obviously a closed one, the only water available for needle-ice formation being that contained in the moist clay within the tube. In open system procedures, on the other hand, the cylinders of soil stand in water at the lower end, providing an unlimited supply of water. In closed system experiments Taber found that needle-ice development at the expense of water from below invariably resulted in soil shrinkage, usually accompanied by the appearance of tensional cracks.

summary Troll (1944) provides on the geographical distribution of Kammeis with reference both to effects on soil morphology and on vegetation. In this connection his observations on the influence of Kammeis on vegetation of high mountains, notably in tropical regions, are especially interesting. Here, where striking Kammeis formation and thawing tend to be diurnal rather than seasonal in occurrence, even fertile areas subject to marked Kammeis action may remain completely devoid of vegetation. At the same time, on nearby talus slopes and other unfavorable and less fertile terrain not subject to Kammeis action, vegetation ascends to considerably higher altitudes. Here may be recalled also Hesselman's observations (1907) on drained peat bogs in Sweden, areas of which remain almost without vegetation because of the destructive action on seedlings of the abundant Kammeis. Mohaupt (1932) also contributes observations on the effects of Kammeis on vegetation of alpine regions.

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