Arturo E. Corte *

Bahia Blanca

PARTICLE SORTING BY REPEATED FREEZING AND THAWING

Abstract

By means of laboratory experiments a principle of particle migration by freezing is presented. The migrating particles are sorted into uniform size groups. The movement of particles depends on the amount of water between the ice-water interface and the particle, the rate of freezing, the distribution of particles by size and the orientation of the freeze-thaw plane. According to this principle sorting by freezing is accomplished in three different mechanisms: (1) sorting by uplifting (frost heaving), (2) sorting by migration in front of a moving freezing plane, and (3) mechanical sorting. Type (1) occurs when freezing and thawing are from the top; type (2) when freezing and thawing are from either (the top and sides); type (3) occurs when freezing is from the bottom and thawing is from the top, accompanied by mound formation.

When freezing and thawing occurs from the top, coarse particles move to the top and fines to the bottom of the freeze-thaw layer. Such sorting has been observed in laboratory experiments, in man deposited materials and under natural conditions. The resulting arrangement of particles is termed *vertical sorting.*

When freezing and thawing occurs from the sides, particles move away from the cooling front leaving the coarsest near the cooling side. Such sorting has been demonstrated experimentally and is observed in natural materials. The resulting arrangement of particles is proposed to be called *lateral sorting.*

Mechanical sorting occurs when mounds are formed. Another form of mechanical sorting occurs when freezing from the bottom up.

It has been demonstrated experimentally that once vertical sorting has been developed, lateral sorting can occur if the freezing direction is changed.

As a result of sorting the freeze-thaw layer shows an increase of volume which is due to rearangement of the particles. Volume changes produced by sieving, without freezing and thawing of well graded samples are a function of the uniformity coefficient.

The following model for sorting is proposed which can explain some naturally sorted features of cold regions: (1) Areas of fines can be an initial stage in the process of vertical sorting. (2) During the development of vertical sorting increase in volume can take place with a resulting production of mounds. From such mound mechanical sorting takes place; conditions 1—2 can be enhanced by lateral migration if side freezing takes place.

It is proposed also that the practical aplications of this sorting principle be determided.

INTRODUCTION

Frost action effects above the timberline, in both polar and alpine regions have the unique property of producing sorting (pl. 1). The actual mechanism of such process is not clearly understood, as evidenced by a score of hypothesis (Troll 1944; Cailleux & Taylor 1954; Washburn 1956). The present paper deals with laboratory experiments and field data on sorting by cyclic freeze—thaw action and the properties of a moving freezing plane.

* Universidad del Sur, Bahia Blanca, Argentina.

It is acknowledged that it is not possible to reproduce nature's complex behavior with a few experiments. However in the research of complex phenomenon it is necessary as a first step hypothetically isolate the important variables. In the second step, a suitable experimental set-up should be designed in order to simulate natural conditions for the study of such variables under controlled conditions. The third step is the formulation of a theory or a law which quantifies and predicts the phenomenon. This paper deals with the first two steps and rudiments of the third.

According to our present knowledge, the soils in the temperate regions freeze from the top down and thaw from both the top and bottom. In regions of perennially frozen ground (permafrost) the freeze—thaw layer freezes from both the top down and bottom up; it thaws only from the top down. In zones where there are abrupt changes in the relief such as terraces, river banks, retaining walls and roads embankments, etc., the soil may freeze and thaw from the sides. It will also freeze from the sides when there are changes in the heat conductivity of the soil, i. e., around stones which are emeriging at the soil surface and surrounded by finer particles. Therefore, one of the important variables in frost action is the direction of freezing.

It is also found that in certain regions of the earth some soils freeze slowly while others freeze very rapidly. Some areas are subjected to a single cycle of freeze—thaw per year, while other have a large number. Important variables in these cases are: rate of freezing and number of freeze—thaw cycles. The rates of freezing and thawing for the seasonal freeze—thaw layer varies from 0.2—1.0 mm/hr. Another important variables are the soil type, gradation, particle size and mineralogical composition.

Since the driving force in frost action is the change of water to ice, an important variables is the amount of water available to the freezing process.

Investigations on the role of some of these variables were accomplished under contracts (DA—11—190 ENG.) 83 and 118, between the Department of the Army and the author for "Basic Investigations in Permafrost and Annually Frozen Areas". This paper is a compendium of such published and unpublished reports (Corte 1957, 1961, 1962 a, b, c, 1963).

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Part I

PRELIMINARY EXPERIMENTS ON SORTING BY FREEZING

Three circular rows of marbles 1 cm in diameter were placed in a glass culture dish and covered by a layer of washed commercial sand. Water level was maintained in the dish 4 cm above the sand surface. The culture dish was brought into the —20 °C cold room for freezing and taken into the laboratory at +20 °C.

The sample froze and thaw predominantly from the bottom up, but also from the sides. Before the freeze—thaw cycles, the specimen showed a uniform sand surface layer. After 6 cycles the outer row of marbles and some of the inner ones appeared on the sand surface (pl. 2). After a total of 19 cycles, all the marbles from the two outer rows and two the central circles were extruded (pl. 3). The sand showed a very clear sorting of coarse sand on top and fine at the bottom. This simple experiment demonstrated that clean sand without particles finer than 0.074 mm can be sorted by repeated freeze—thaw action and that the coarsest particles are extruded to the surface. The implications of such movements were clear, and additional experiments were carried on in open containers in order to see the behavior of different geometric bodies.

Again clean non-compacted sand was used in non-insulated containers. Two geometric shapes were used: glass sphears 2.6 cm in diameter and ceramic tetrahedrons 2 cm high. Four tetrahedrons were placed inverted into the sand with only a small part of the base near the sand surface exposed so that its position could be observed. Four marbles were also placed into the sand so that the upper part of each was visible. The positions of the particles were determined with vernier calipers after every freeze—thaw cycle. There were no problems in measuring the particles while frozen but the thaw resulted in some slight downward movement of the particles. Therefore, the actual position of the particle was slightly higher than shown in the curve (fig. 1). It was found that the glass marbles moved upward faster than tetrahedrons, the average rate of heave being 0.22 mm/cycle for the marbles and 0.18 mm/cycle for the tetrahedrons.

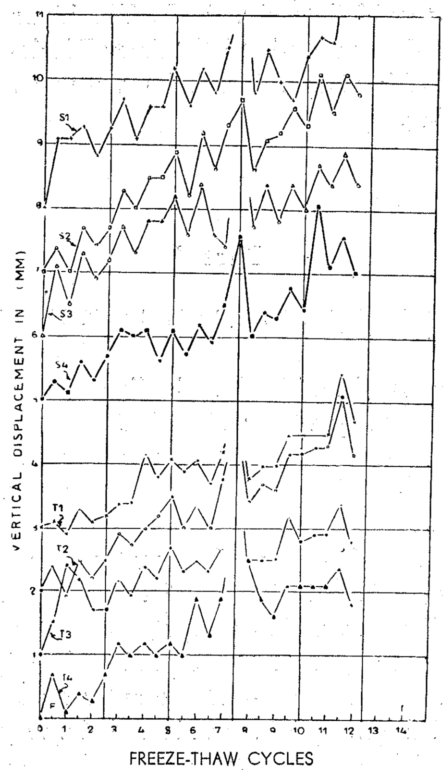

Fig. 1. Vertical migration of inverted ceramic tertahedrons T1—4 and glass marbles S1—4 in sand with freezing and thawing cycles

The rate of movement of the ceramic tetrahedrons was less when not inverted, 0.09 mm/cycle.

According to this preliminary experiment, it is possible to conclude that:

By freezing a clear saturated sand from all directions or from the bottom and sides, there is a tendency for the sand to become sorted. The coarse particles moving up, the fines particles down. The rate of vertical migration of different particles seems to depend on the geometric shape.

SORTING AND VOLUME CHANGES PRODUCED EXPERIMENTALLY BY CYCLIC FREEZE—THAW UNDER CONTROLLED CONDITIONS

FREEZING AND THAWING FROM THE TOP

In areas of seasonally and perennially frozen ground the soil freezes and thaws from the top down. In the second case the soil also freezes from the bottom up; and this problem is treated separately. Rates of freezing from 0.4 to 40.0 mm/hr where measured in the freeze—thaw layer of arctic soils (Cook 1955; and Poulin, personal communication). Rates of freezing for the layer of the temperate regions varied 0.2—1.0 mm/hr (Kreutz 1942).

Apparatus and experimental control

An insulated cabinet designed by Schmertmann (1958) was employed, which provided adequate temperature control, but could accomodate only one sample per cabinet. Caution was necessary to prevent the sample holder which was a Lucite cylinder from breaking as the water froze and expanded.

Material and experimental procedure

A clean sample of noncompacted commercial sand was placed in the cabinet; two marbles 2 cm in diameter and two stones, approximately 2 cm in diameter were buried in the sand at a depth of 12 cm. A thin piano wire was glued to each particle so that the position could be determined by measuring the position of the top of the steel wire. The sample container was a "closed system" with the water level being maintained at the top of the sample by adding into the cylinder from the top.

A similar sand sample, including marbles, tetrahedrons, and stones, in an open plastic pan was placed in the cold room along with the insulated container.

Experimental results

The sample in the plastic pan froze from all directions at rates 2 to 3 times greater than the insulated sample approximately 2.8 to 4.2 mm/hr.

In both tests the buried marbles, stones, and tetrahedrons moved upward, the upward movement being greater in the case of undirectional and slower freezing, than in the case of the faster multidirectional freezing. Figures 1 and 2 contain a plot of the average rate of the different geometric bodies. The linearity demonstrated by the broken line resulted from measuring only the thawed condition after every fifth cycle. In the undirectional freezing test, measurements were taken at the thawed and frozen stage of each cycle. A downward displacement of the originally loose sample. Subsequently the particles were heaved 6 mm in next 9 cycles, with an increase of sample height of 16 mm.

After 20 cycles of freezing and thawing, the sample from the insulated

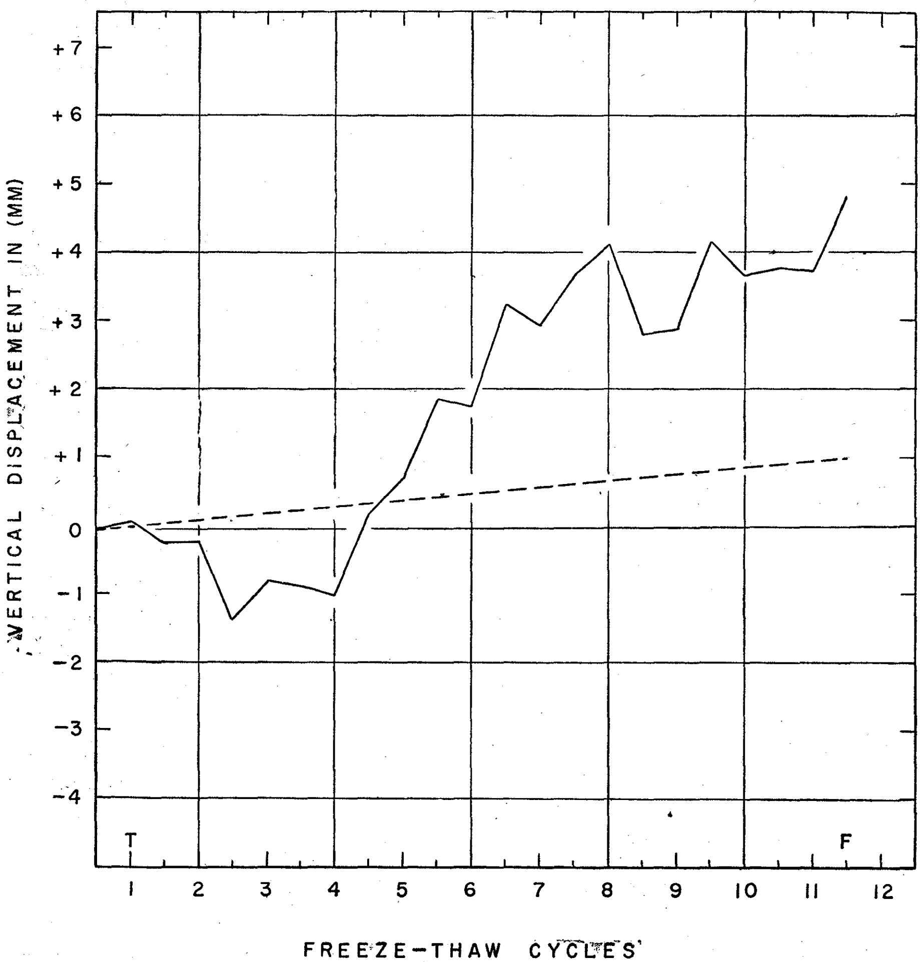

Fig. 2. Average vertical migration of marbles, ceramic tetrahedrons and stones in sand

Solid line — top freezing at 1.4 mm/hr; dashed line — freezing from all sides at speed 2—3 times greater than 1.4 mm/hr

cabinet was cut into horizontal layers and the grain size distribution determined. The curves (fig. 3) indicate that a distinctive vertical sorting did occur.

The results of this experiment indicate that:

(1) particle motion depends on the direction and rate of freezing,

(2) freezing and thawing from the top produces a definite sorting of soil particles by size, the larger moving up, the smaller moving down.

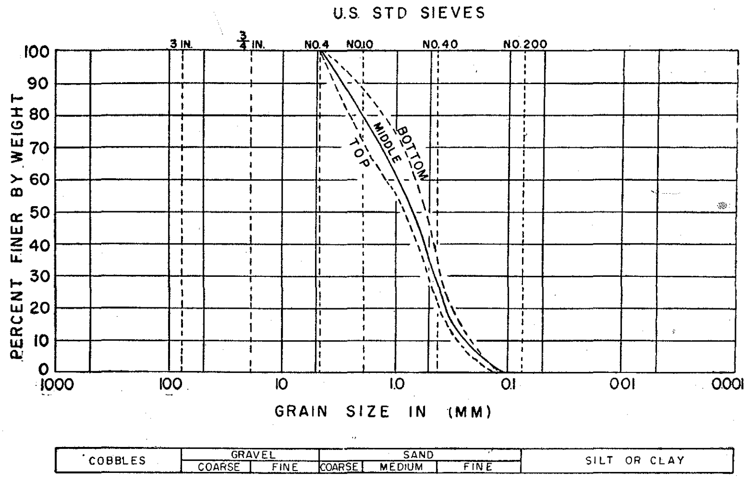

Fig. 3. Vertical sorting produced in a sample of commercial sand after 20 cycles of freeze—thaw from the top at 1.4 mm/hr

Total thickness of the layer is 21.5 cm; thickness of each analised layer — 3.0 cm

Experiments to test the effect of gradation on breakage by compaction and by breakage by freeze—thaw

The purpose of these experiments is to observe the effect of gradation on breakage by freezing and thawing and by compaction.

Apparatus and experimental control

The freezing cabinet in this test was a large tank which could hold a total of 6 brass cylinders, 12.5 mm in diameter and 15 cm high, with holes 2.3 mm in diameter in the bottom for water to enter. The brass cylinders, containing compacted samples, were put into the tank and a mixture of gravelly sand was placed around them. Water entered the container through a pipe connected to a reservoir which had an adjustable level. The water level was attained constant to the top of the specimens. An electrically controlled valve between the container and the water tank was opened during thawing and closed during freezing to create a confined condition such as occurs in the freeze—thaw layer in nature. Without a closed valve during freezing the expansion would have caused a rise in water level of the reservoir. In nature when a saturated layer freezes, there is no escape for the water confined between the frozen surface thaw and the underlying frozen soil; therefore, it is a "closed system". For this reason, a laboratory "closed system" better simulates the freeze—thaw layer than an "open system".

In order to reduce the frictional effects of heaving, the walls of the cylinders were covered with a layer of silicone grease. However, the grease rubbed away after a few cycles resulting in the soil adhering to the wall, and there by reducing the heaving and vertical sorting.

The temperature distribution in the freezing cabinet was measured with thermocouples placed vertically every 2 cm.

These measurements showed a flat freezing line within the specimen. The temperature was controlled by a heating tape at the bottom of the tank and the freezing rate was adjusted by a drop in voltage across the heating tape. A drop of 1/6 volts per hour was enough to produce a freezing-line penetration of 0.6 mm/hr. The thawing rate was about 6 mm/hr and it was produced from the top by infrared lamps placed above the freezing cabinet.

Material used and experimental procedure

Five samples, designated: a2, a3, a4, a5-1 and a5-2 were prepared from a commercial sandy gravel. All samples have a common origin at the No. 10 sieve with the end of each grain size curve located at equally spaced intervals between 0.037 mm and 10.0 mm (fig. 4). In this manner the uniformity coefficient $\frac{D\ 60}{D\ 10}$ increases in each sample by a multiple of approximately 2 (fig. 4). Two samples were prepared, designated as a5-1 and a5-2, with the same grain size distribution one of them, the 14% finer than No. 200 sieve is a cohesive fractions obtained from the Bloomington till and in the other the same fraction is made of quartz powder. In this way it was possible to see the effect of the mineralogical composition of the fines in the freeze—thaw action.

The line of the finest sample is tangent to the lower boundary of the so-called frost-susceptible soils (Beskow 1935, p. 125). These samples can be classified according to the Unified Soil Clasification system of the Corps of Engineers as follows: a2: GP; a3: GP—SP; a4: SP; a5-1: SC; a5-2: SM non-plastic fines.

Note: that straight graded samples such as a5-1, a5-2, would be classified as poorly graded according to the Unified Soil Classification System (1961), because the curvature coefficient $C_c = \frac{(D30)^2}{D60\ D10}$ is below 1. Such samples should be considered well graded because they contain equal weight increments of the following interval diameters: (9.5—4.76), (4.76—

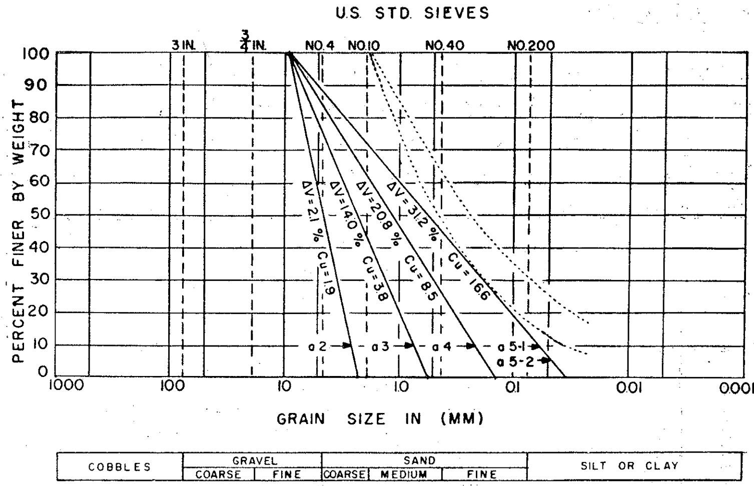

Fig. 4. Volume changes (Δv) produced by sorting without freezing and thawing straight graded samples a2, a3, a4, a5 (solid lines), compared with boundary lines of the so-called "non-frost-susceptible" and "frost-susceptible" soils (dashed lines) of Beskow

—2.38), (2.38—1.19), (1.19—0.59), (0.59—0,29), (0.29—0.149), (0.149——0.074), (0.074—0.037). Samples a5-1 and a5-2 are therefore made of eight size intervals, sample a4 is made of 6 intervals, and a3 is made of 4 intervals and sample a2 is made of 2 intervals.

Samples were compacted to the following dry densities:

Sample	g/cm³	Lb/ft³
a2	1.53	95.4
a3	1.66	103.0
a4	1.84	115.0
a5—1	1.82	114.0
a5—2	1.84	115.0

Samples weighing 2 kg each were placed in layers about a cm thick and were compacted by 18 blows of an 8 kg piston from 7 cm height. Special care was taken to prevent sorting by compaction. It was found less sorting was produced by compacting moist materials than dry. It was observed, however, that breakage was produced by compaction and, in general, decreased as the uniformity coefficient increased. This decrease is attributed to the grains which occupy the void spaces in the higher C_u samples, a5-1 and a5-2, whereas the coarse angular grains of a sample with low C_u such as a2, adjust themselves by breaking compaction.

Experimental results

Tests were run to determine the amount of breakage produced by cyclic freeze—thaw at different rates of freezing. The amount of breakage due to compaction and freeze—thaw shows a decrease as the uniformity coefficient increases (fig. 5). Figure 6 also suggests that soil particles which freeze at a low rate have a greater chance to break than particles

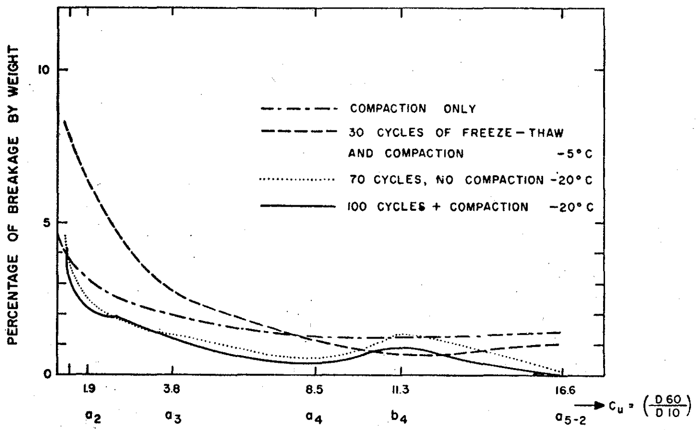

Fig. 5. Percentage of breakage as a function of the uniformity coefficient

which are frozen quickly. Taber (1950) indicated that the rate of freezing is important factor in the breakage of limestone boulders and considers this process to be the same as the frost heaving in soils. This problem and the effect of mineralogical composition of material should be a subject of a more detailed study.

In another experiment, samples a2, a3, a4, a5-1, and a5-2 were subjected to 22 cycles of freeze—thaw. During the cycling process it was observed that the samples increase in volume and that the volume increase was larger for samples with a higher uniformity coefficient. After 22 cycles the samples were taken out of the cabinet and grain size determined. Samples a2, a3, and a4 were cut into 3 layers 2.5 cm thick. Samples a5-1 and a5-2 were cut into 5 layers each 1.6 cm thick. The grain size analyses show that the bottom layers of all the samples had more fines than the top ones (fig. 6). The vertical sorting is more striking where the analysed layers were 1.6 cm thick. The fraction finer than No. 200 sieve (0,074 mm., fig. 7) decreased from 14% to 10% in the upper layer of a5-2 and increased from 14% to 21% in the bottom layer. This indicates that this fraction moved down

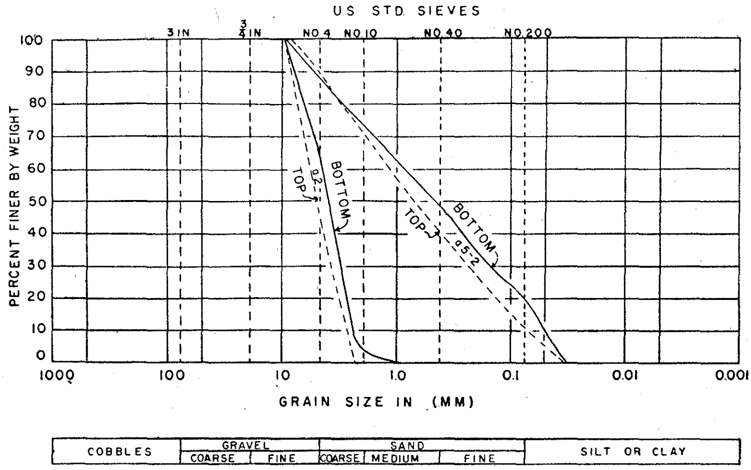

Fig. 6. Vertical sorting developed in samples a2 and a5—2 (Silicrete) after 22 cycles of freeze—thaw

Total thickness of the sample: 8.0 cm: thickness of three analysed layers in a2: 2.7 cm; thickness of five analysed layers in a5—2: 1.6 cm

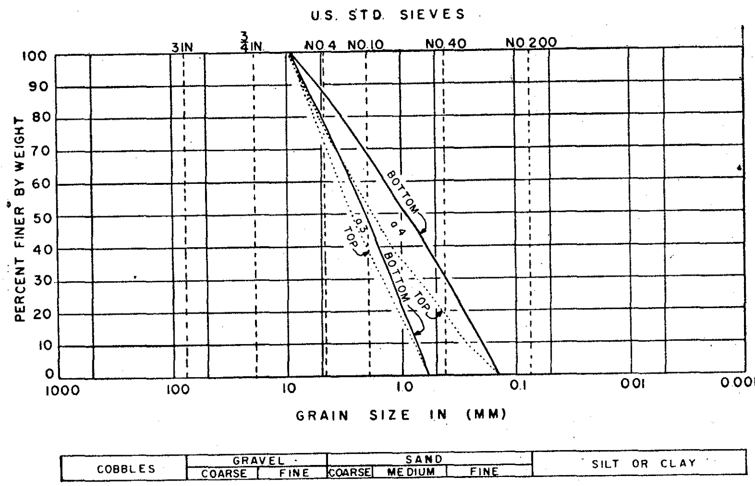

Fig. 7. Vertical sorting developed in samples a3 and a4 after 22 cycles of freeze—thaw

Total thickness of the sample: 8.0 cm; thickness of each analysed layer: 2.7 cm

at a rate of 0.2% per cycle and concentrated at the bottom at a rate of 0.3% per cycle, when a freezing rate of 0.6 mm/hr was used. In sample a5-1 where the fraction finer than 0.074 mm is cohesive, this fraction moved down only by 1% or 0.02% per cycle. This is attributed to the cohesive properties of the fines which adhere better to the larger particles than the noncohesive fines composed of quartz powder.

Hydrometer analyses performed on the fraction passing sieve No. 200, showed that the bottom layers are richer in colloids than the top layer.

This arrangement of coarse particles at the top and fines at the bottom of the freeze—thaw layer is proposed to be called *vertical sorting*. Lundqvist (1949—51) by means of field observations has stressed that the sorting of coarse particles upward and fines downward is the normal frost heaving profile both in theory and practice.

This experiment shows that:

(1) Compaction with a hammer and freeze-thaw action produces breakage of the soil grain. The amount of breakage for the kind of samples used decreases as the uniformity coefficient of the sample increases. The amount of breakage is greater at slower rates of freezing than at higher rates.

(2) Cyclic freezing and thawing from the top produces vertical sorting with the bottom layer finer than the top one. This vertical sorting is observed in the so called "non-frost susceptible" soils. Non-cohesive soils segregate faster than cohesive materials. This segregation is valid for the colloids also.

Experiments to test the volume changes produced by cyclic freeze—thaw

In order to determine the volume changes produced by freeze—thaw cycles a new experiment was run in the same freezing cabinet. A "Starret" dial gage capable of reading 0.01 mm vertical displacements was inserted in the wall of each brass cylinder.

Samples a2, a3, a4, a5-1, and a5-2 were compacted in the same manner as in the preceding experiments. Two more samples were included in the previously described cabinet: b4 and d1. All samples are "non-frost-susceptible" according to present engineering standards.

Samples were compacted to the following densities (tab. I). The freezing was performed in the same manner as the previous experiments, with a top-down freezing rate of 0.6 mm/hr, and thawing from the top at about 6.0 mm/hr. As in the preceding experiment, samples were subjected to 22 cycles of freeze—thaw no surcharge. Sample height was observed during and after the freezing and thawing process. The volume and density were computed for the thawed phase. All samples show volume changes (fig. 8). The volume changes are greater for samples with a larger uniformity

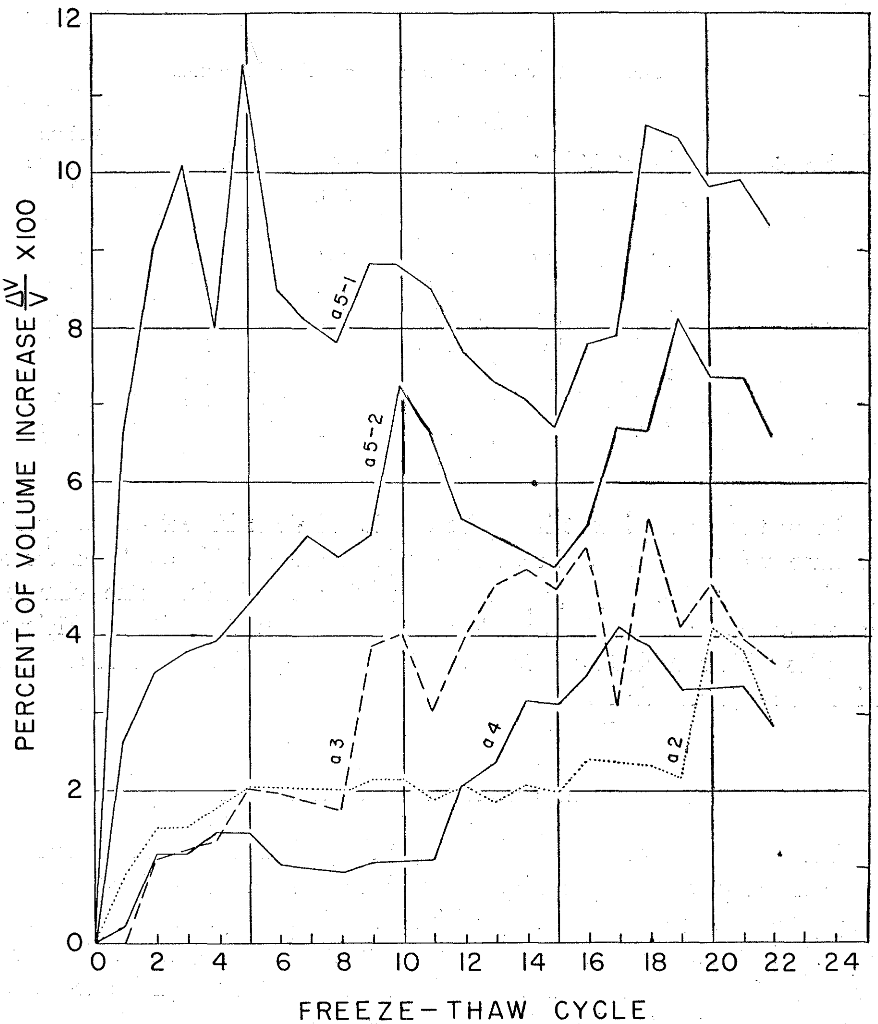

Fig. 8. Volume changes as a function of the number of freeze—thaw cycles in straight graded samples a2, a3, a4, a5—1 and a5—2

In a5—1 the 14% finer than 0.074 mm are cohesive particles; in a5—2, they are non-plastic fines made of quartz powder

coefficient. There is a compaction stage in samples a5-1 and a5-2 between cycles 11 and 16. This is attributed to a rearrangement of the grains after the descompaction of cycles 1 to 10. Sample a5-1 experienced more volume changes than sample a5-2. This indicates that the mineralogical composition of the minus No. 200 (0.074 mm) sieve is important in the cyclic freeze—thaw action. The density and volume changes after 22 cycles are shown in table I.

Table I

The density and volume changes after 22 cycles

Sample	Dry density				C_u	Volume increase %
	before cycling		after 22 cycles			
	g/cm³	Lb/ft³	g/cm³	Lb/ft³		
a2	1.89	118	1.82	114	1.9	2.82
a3	1.96	122	1.89	118	3.8	3.68
a4	2.08	130	2.03	127	8.5	2.78
b4	2.06	129	1.98	123	11.3	4.10
a5—1	2.14	134	1.96	122	16.6	9.31
a5—2	2.03	127	1.91	119	16.6	6.58
dl	1.69	106	1.64	102	—	3.20

From these experiment it can be concluded that: Freeze—thaw cycles produce volume changes in samples which are considered "non-frost-heaving-susceptible" by present engineering standards. The changes in volume are greater for samples with a larger uniformity coefficient. Samples with cohesive fines have a greater volume changes than samples with non-cohesive fines.

FREEZING AND THAWING FROM THE SIDES

The freeze—thaw layer above perennially frozen 'ground as well as the seasonally frozen layer will freeze with a vertical or inclined freezing plane depending on topography and heat conductivity. The soil freezes laterally in terraces, river banks, retaining walls, culverts, etc. It is necessary therefore to know what are the cyclic effects of a lateral freeze—thaw plane upon natural and artificial materials.

Kersten (1949, p. 61) has shown that the thermal conductivity at a given density and moisture content is greater for coarse-textured than for finer soil. The higher thermal conductivity of the coarse materials with respect to the fines was shown in field measurements by Romanovsky (Cailleux & Taylor 1954, p. 58), Taylor (1956, p. 189), and others. In a partly embedded stone, the freeze—thaw plane will be normal to any point on that stone. Therefore, a larger particle partly exposed at the surface will create a vertical freeze—thaw plane in the surrounding finer material.

Apparatus and experimental control

The apparatus for this side freezing experiment was a square box with a cross-section of 15 cm square constructed from 5 cm thick plywood (pl. 4). The bottom and sides of the freezing cabinet were treated with shellack to make them water-tight. A heating tape was placed in the side of the cabinet opposite the cooling surface to control the freezing rate and a vertical freeze—thaw plane was obtained. By regulating the voltage drop across the heating tape, freezing rates could be varied from 2 mm/hr to 40 mm/hr. Freezing rates between 30 to 40 mm/hr were used. As in the preceding experiments tests were run for 22 cycles.

Material used and experimental procedure

The straight graded sample a5-2 was tested (fig. 9). Before the cyclic test, the samples were compacted to a dry density of approximately 1.8 g/cm^3 (112 lbs/ft^3) using a small rubber piston to avoid crushing the grains. A Lucite plate was placed on the soil sample surface as a bearing surface

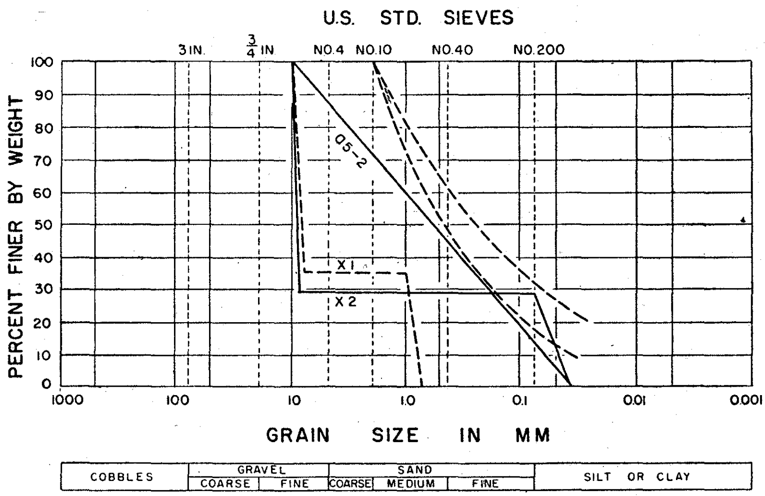

Fig. 9. Grain-size curves of three samples a5-2, ×1 and ×2 which developed horizontal sorting under the effect of a vertical freeze-plane compared with frost limiting curves of Beskow (two top curves)

for a dial gage installed to measure the soil heave. Water was added every five cycles to maintain complete saturation throughout the tests. No surcharge was applied in this closed system condition. Side freezing tests were performed at freezing rates of 30, 33, and 42 mm/hr with the thawing rate of 25 mm/hr.

Experimental results

The experiment indicated that the soil surface changes during cyclic freeze—thaw. The originally horizontal surface of the soil near the cooling surface became deeply inclined toward the cooling plate while the average height of the sample continuously increased. After six cycles of freeze—thaw it can be observed that the volume changes are greater at slow freezing rates (fig. 10). After 22 cycles of freeze—thaw, the sample was divided

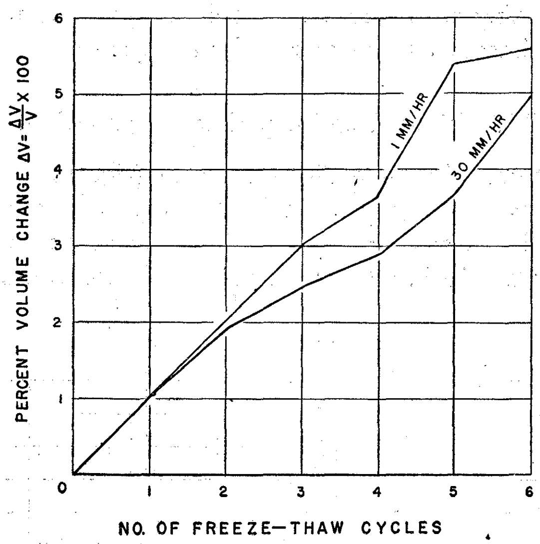

Fig. 10. Volume changes by side freezing as a function of freeze—thaw cycles for a5-2 samples under 1 and 30 mm/hr freezing rates. Initial density 1.8 g/cm³ or 112.4 lbs/ft³

into 9 blocks 15 × 5 × 2.7 cm, and a grain size analysis was made, the percentage by weight of particles finer than 0.074 mm was determined. After 22 cycles with a freezing rate of 30.0 mm/hr, the percentage of particles finer than 0.074 mm increased away from the cooling plate (fig. 11). The difference in concentration between the cold face and the warm face was 3.5% with an average rate of migration of 0.15% per cycle. There was a tendency for the fines to increase from the surface downward. Points having equal percentage of fines show a tendency to be parabolic with the axis pointing away from the cooling front.

A second test was performed under similar conditions with a rate of freezing of 33.0 mm/hr. It was observed again that the soil close to the cooling plate dropped, while the height at the opposite side increased slightly. After 20 cycles the sample was divided into 9 rectangular slabs,

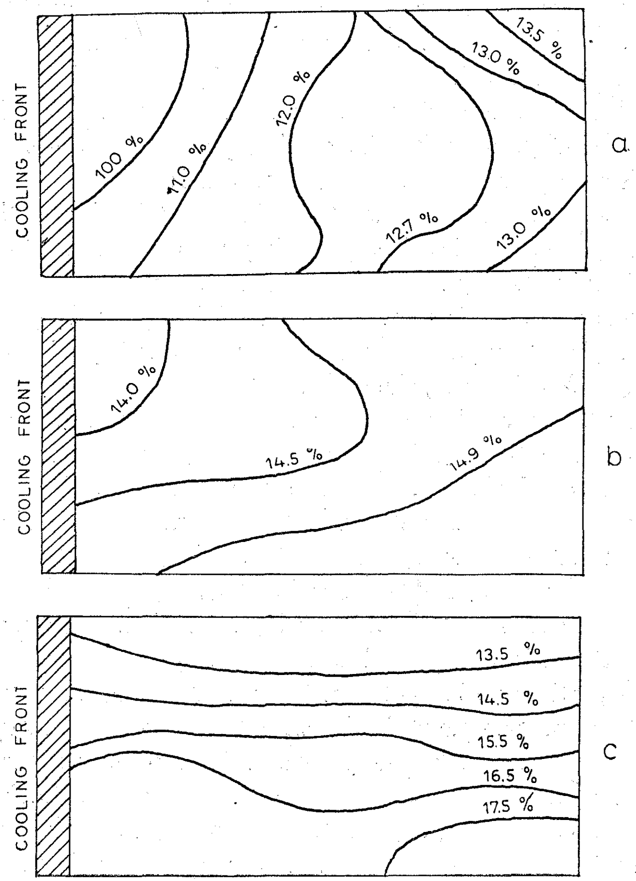

Fig. 11. Isograms showing the distribution of fraction finer than 0.074 mm after 22 cycles of freeze—thaw, at different rates of freezing: a — 30 mm/hr; b — 33 mm/hr; c — 42 mm/hr

a grain size analysis (using wet sieving) indicated that fines migrate away from the cooling plate and downward. The difference in concentration between the cold and warm face was 0.9% indicating that fines moved at a rate of 0.04% cycle (fig. 11-b).

The isograms are inclined toward the cooling plate but are less inclined than those of the preceding experiment with a slower freezing rate, 30 mm/hr. It is possible that the inclination of isograms is a consequence of the freezing rate.

A third experiment was performed at the same initial density with a freezing rate of 42 mm/hr.

After cycle No. 20 was completed, it was observed that the soil adjacent to the cold plate dropped 1.7 cm and the overall height of the sample increased. The grain size analysis of 9 sections in the sample revealed that the isograms are more horizontal than in preceding experiments with slower rates of freezing. With the exception of 17.4% close to the freezing plate, there was clear vertical sorting across the samples with a maximum concentration of 18.2% opposite the cooling plate (fig. 11-c).

From these experiments it can be concluded:

There is a tendency of the ice to exclude certain size particles which are in front of the growing ice. Freezing rates between 30—42 mm/hr cause the finer fraction (0.074 mm) to move away from the cooling front in a parabolic path. This parabolic path might be produced because of the collision of smaller particles with larger ones and gravitational forces. With increased freezing rate, the isograms tend to become flatter. It seems that at high rates of freezing, particles are knocked down rather than being pushed in front of the freezing line. However, this observation requires further experimental clarification. The rate of volume change by lateral freeze-thaw cycles is greater at slower freezing rates than at higher rates. It is proposed that this rearrangement of particles to be called *horizontal--vertical sorting* or more simply: *lateral sorting*.

In order to demonstrate the actual migration of particles, a new experiment was set up with samples x1 and x2 (fig. 9). Sample x1 is a mixture of 2 sizes of particles: 76% between 10 and 7.93 mm, and 34% between 7.93 and 0.71 mm. Sample x2 is also a mixture of two sizes, 71% between 10 and 7.93 mm, 29% between 0.074 and 0.037 mm. All three samples a5-2, x1 and x2 are located in the so-called "never-frost-heaving-moraine soils" of Beskow (1935, p. 125). The coarsest particles were placed at the bottom of the freezing cabinet and surrounded by the finer material (pl. 5). The thickness of the layer was less than the maximum particle size, 7.9 mm. Accidentally, before subjecting the sample to the cycles of freeze—thaw, some of the coarse sand from the upper half, x1, moved on top of the finer material, x2. However, the accident was an asset to the experiment. It can be seen that after 7 cycles, the coarse sand which accidentally moved over the white "Silicrete" has been pushed away from the cooling plate by the freezing front.

It is also noted that the silicrete had moved away from the cooling plate. Initially, only 7 stones were visible and after 17 cycles, (pl. 5-b) more than 18 stones be counted within 4 cm of the cooling side cover the stones at the lower center of the box.

Also these experiments show that the largest particles (1 cm in diameter) did move as much as 1 cm away from the cooling front. This experiment supports previous ones that particles move away from the cooling front with a freezing rate of 30.0 mm/hr. For such rates of freezing the fraction finer than 7.93 mm and larger than 0.71 mm moved little compared to the finer material. It is likely that the lower freezing rates and wider channel openings between particles will aid the movement of finer particles.

From this experiment, the following conclusions can be made: At a rate of 30.0 mm/hr, particles finer than 0.074 mm and particles between 10.0 and 7.93 mm migrated away from the cooling front.

The size more likely to migrate is the one which can fit between the openings of the pores. It is envisaged that the migration rate of a certain particle size depends upon the rate of motion of the interface plane, where the particle is riding. This problem is treated with more detail in Part II.

FREEZING FROM THE BOTTOM UP AND THAWING FROM THE TOP DOWN

The freeze—thaw layer above perennially frozen ground freezes from the top down as well as from the bottom up (Cook 1955; Taylor 1956). Temperatures measured by Cook at Resolute Bay indicate that the clay freezes ten times faster from the top down than from the bottom up. Rates are: 0.4 and 0.04 mm/hr respectively.

Apparatus and experimental control

A new kind of cabinet was developed (pl. 6). The freezing is produced by means of an aluminium plate 2 cm thick and located at the bottom of the sample. By changing the voltage on the heating tape located on top of the cabinet, different rates of freezing penetration could be obtained. A top to bottom thawing cycle was produced by increasing the voltage across the top heating tape. The rate of freezing could be easily controlled over the height of the sample except for the 2 cm nearest freezing plate where the soil sample always froze rapidly.

The sample was put in a transparent Lucite cylinder 7.5 cm in diameter and 12.5 mm thick, enclosed in another Lucite cylinder of 15 cm diameter with a 12.5 mm wall thickness. A 12.5 mm air space between the two cylinders served as an insulation. The conditions of the sample could be observed very clearly through these Lucite cylinders (pl. 6). The position of the freezing line was determined by thermocouple measurements and by direct observation of the freezing line through the Lucite cylinder. An excess of water, about 5 cm, on top of the sample, could migrate to the freezing plane at different rates, according to the rate of freezing. Several screens were superimposed in the water on top of the soil sample, and the dial gage rested on top of them above the water on a small Lucite plate. The author proposes to call this freezing and thawing set up an *Inverted Open System.* This system simulates the freezing and thawing of the lower part of the seasonally thawed soil over perennially frozen ground. When this thaw zone is flooded and freezes from the bottom up, the water supply above the freezing front migrates down to the freezing plane to build ice lenses.

It can be noticed that in the bottom up freezing cabinet, friction between the soil and cylinder wall is negligible compared to that in the top down freezing. In the bottom-up freezing the unfrozen part moves up and the frozen part becomes fixed.

Material used and experimental procedure

For this test a sand sample from Lake Michigan was used, a5-2. As in the preceding cases the 14% finer than 0.074 mm is silicrete (fig. 4). The sample was placed in the inner Lucite cylinder and compacted with a small rubber piston.

The tests were performed under four different rates of freezing: 0.6 mm/hr, 10.0 mm/hr, 30 mm/hr, and 60 mm/hr. The initial density of the sample was 2.07 g/cm^3 for 0.6 mm/hr and 2.14 g/cm^3 for all other freezing rates.

Experimental results

Figure 12 shows volume change as a function of the number of freeze—thaw cycles for four rates of freezing. As was demonstrated before, the volume increase is an inverse function of the rate of freezing. It was observed that the soil samples do not exhibit any appreciable sorting at rates of freezing greater than 0.6 mm/hr. Nearly all sorting takes place at rates of freezing less than 0.6 mm/hr for this particular sample (fig. 12). Plates 7 and 11 show top and side of the sample after cycle 1 and 7.

One of the most important observations was that sorting was produced on top of the soil column when the freezing line was 5 cm beneath the surface. In other words, coarse particles appeared on the soil surface when the freezing line was in the lower part of the soil specimen. This indicates that the principal cause for the extrusion of coarse particles on the soil surface when the freezing line moves from the bottom up is purely mechanical. This sorting is started as soon as the water in the fines at the bottom of the sample begins to freeze. Since the grain sizes are different, the amount of frozen water varies from one pore to another which creates a differential

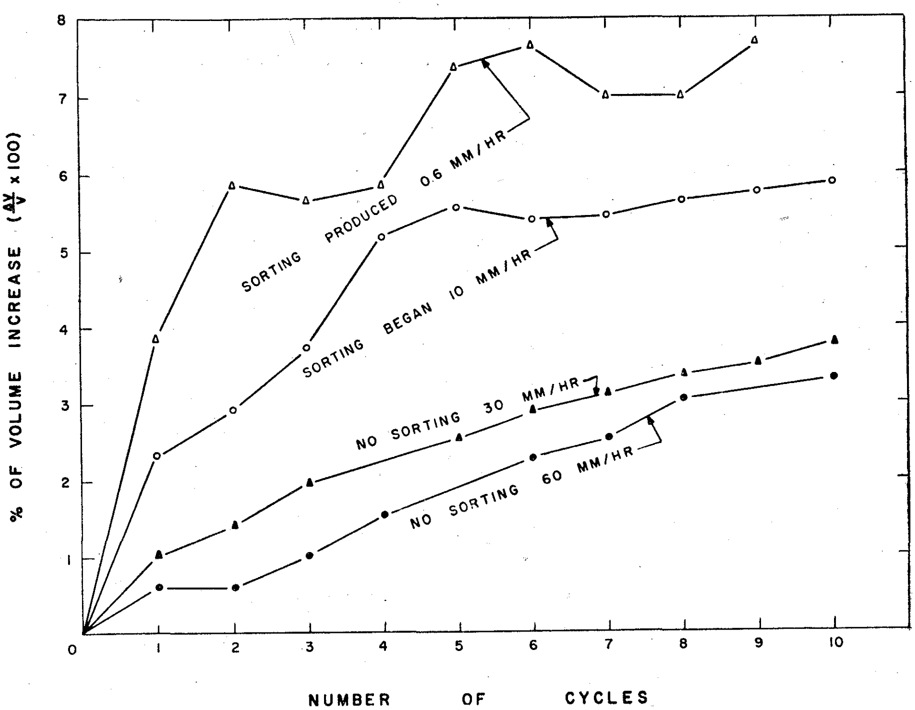

Fig. 12. Vertical sorting and relationship between volume increase and number of freeze—thaw cycles for four rates of freezing

Using „inverted open system" freezing cabinet — freezing from the bottom, thawing from the top. Sample a5-2 initial density: 2.06 g/cm³ (129.1 lb/ft³) for 0.6 mm/hr rate; 2.11 g/cm³ for the other three rates

movement of the grain located at the top of the freezing plane. This differential movement of the particles results in sorting.

This mechanism is clearly shown during cycle No. 7. The freezing line has been moved up at a very low rate, about 1 mm/day. In one week, an ice layer 7 mm thick was built. The next thawing process melted the ice and a layer of particles finer than 0.074 mm about 5 mm in thickness, was formed in place of the ice lens. This indicates that, during the very slow freezing process, fine particles are migrating downward to the freezing line. It was observed that during the building of an ice lens, both coarse and fine particles migrated in front of the plane (pl. 11). For that reason, it is concluded that the formation of a layer of fines in front of an ice lens is produced mechanically. Such a layer of fines is the place where an ice lens will be formed in the next freezing cycle. It was demonstrated by Taber (1930), Beskow (1935), Casagrande (1931), and others, that ice lenses are more likely to develop when the amount of fines, by weight increases. We can see the implication of this process of sorting: A soil that is not susceptible to building ice lens during the first cycle become more susceptible to build ice lens at the bottom as more fines migrate down. For this reason the engineering criteria based on the percentage of certain particle size challenged.

During vertical sorting, fines do not migrate evenly downwards or coarse come up evenly to the surface. During such a process areas of coarse and fines appear at the surface. Such sorting is produced without the formation of mounds.

Table II

Distribution (percent) of particles finer than 0.074 mm in a sample 7 cm high, freezing from the bottom at a rate of 0.6 mm/hr for a sample of sand and gravel grains (Lake Michigan) and glass beads

Sample	Lake Michigan		Glass beads	
No. of cycles	16		5	
Depth of layer in cm	7		7	
Initial percent of 0.074 mm fraction	14.0		20.6	
(1) Top	min. 12.6	layer of mechanical sorting	min. 13.6	layer of mechanical sorting
2	14.6		17.3	
3	13.1		23.5	
4	13.2		max. 24.2	
(5)	max. 16.4		21.9	
6	13.4		21.5	
(7) Bottom	15.2		22.2	
Difference between initial and min.	1.4		7.0	
Difference between initial and max.	2.4		3.6	

After the sample was subjected to 14 cycles of freeze—thaw, it was separated into 7 layers, each 1 cm thick, a grain size analysis was performed (tab. II). It indicates a concentration of fines at the lowest part of the freeze—thaw layer. Close to the bottom the percentage of the fraction fines than 0.014 mm sieve is 15,2%; the next layer is 13.4%; and the next layer where the ice front was maintained for a week, is 16.4%. As indicated in the experimental control, the rate of freezing close to the plate, sample 6 and 7, was difficult to control and was too fast, therefore samples 6 and

7 should not be considered. The lowest concentration of fines is at the top with 12.6%.

Since the vertical sorting developed here is purely mechanical sorting should increase if the sphericity of the sample increases. Another experiment was performed for that purpose with a straight graded sample of glass beads, 20.6% of beads finer than No. 200 (0.074 mm) sieve. The sample was subjected to 5 cycles of freeze—thaw only and cut into 7 layers, each 1 cm thick. The grain analysis shows, as in the previous case, that the upper part of the layer becomes coarse and the lower middle layer become richer in fines. It is shown that vertical sorting of the upper layer is more sharp and distinctive for glass beads after 5 cycles than for the Lake Michigan soil sample after 16 cycles.

The upper layers where sorting is observed can be called *layer of mechanical sorting*, a better temperature control of the freezing line at the bottom of the cabinet, the *layer of mechanical sorting* could possibly extended throughout the entire sample.

From these tests by freezing from the bottom up and thawing from the top down, it is possible to conclude that:

(1) Fines in the upper part of the sample move downwards. This sorting is observed to be purely mechanical and happens in the upper unfrozen zone while the lower parts are being frozen. The downward migration of fines and upward migration of coarse is not uniform in the layer. Areas of coarse and fines form without mounds.

(2) Samples of glass beads segregate faster than samples of commercial sand indicating that the sphericity of the particles is important in such type of sorting.

(3) The fact that layers of fine particles can be built by a slow moving freezing plane introduces a new concept in the formation of sorted features, and the engineering criteria for construction in cold regions.

Part II

MIGRATION OF PARTICLES IN FRONT OF A MOVING FREEZING PLANE

From the data of the top and side freezing experiments, it was postulated that the ice had a tendency to segregate or exclude particles which were in front of the moving ice front. The migration of particles was inferred from grain size analyses of soil samples after many cycles of freeze—thaw, but actual migration was neither observed nor recorded.

APPARATUS AND EXPERIMENTAL CONTROL

The cabinet used in this experiment consisted of two transparent Lucite cylinders 12.5 cm and 15.0 cm in diameter and a 7.5 mm wall thickness. Between the two cylinders was a 7.5 mm air space. The cylinders were transparent and the phenomenon of particle migration was clearly observed (pl. 13). An aluminum plate attached to the bottom of the cylinders produced unindirectional freezing from the bottom up. The cylinders were covered by a wooden box 2.5 cm thick which enclosed a heating tape. Rates of freezing from 0.2 to 7.0 mm/hr were obtained with heating tape and placing the cabinet in either the −5 °C, −10 °C, or −20 °C cold room.

The inner cylinder was filled with destilled water which froze at the contact with the aluminum plate in such a way that a horizontal freezing plane was obtained. The cylinder was graduated in mm for measurement of the freezing line height.

MATERIAL AND EXPERIMENTAL PROCEDURE

Good control of the moving ice front could not be obtained until the ice was 2 to 3 cm above the aluminum plate. At this height it was possible to place the particles in contact with the ice to observe their behavior. At the beginning of the experimentation, particles were suspended from fine thread and contact with the ice was made as the ice front moved upwards. This method was not satisfactory because the tedious technique necessary permitted only a small number to be tested. The method which proved most satisfactory was the "seeding" method described below.

The particles to be tested were washed several times with distilled water. In general 50 grams of particles were tested except in the case of mica where only 20 grams were used. A small beaker containing the particles and 50 cc of distilled water was cooled to approximately the freezing point. In this way the particle temperature was close to that of the ice interface. The particles were seeded by lifting the cover of the cabinet and pouring the water containing the particles into the cylinder. Particles were spread in such a way that a uniform layer of particles about 1 to 3 cm thick was formed on top of the ice. The interface height was measured after seeding. After the particles were carried about 1 cm by the interface, they were removed by siphoning (with a hose) and the percentage of particles carried expressed on a weight basis. During the experiment it was observed that if the particles were not removed they would move continuously providing that the rate of freezing remained constant or was decreased.

Photograph (pl. 13) shows the migration of sand and gravel particles of 0.1 to 0.7 mm in diameter. It can be observed that while the coarse particles were trapped by the ice close to the seeding place, the finer particles migrated continuously for 15 cm to the top of the freezing cabinet. Intermediate sizes were caught by the ice at in between these extremes intermediate heights.

At this stage of the experiment the following materials were tested: Glass beads, broken glass (window), quartz crystals, calcite, rutile, shale, and mica.

The densities of the materials expressed in g/cc were:

Glass broken	beads	Quartz	Mica	Shale	Calcite	Rutile
2.6	2.4	2.5—2.6	2.6—3.1	2.6—3.3	2.7	4.1—5.3

Glass beads, broken glass, and quartz crystals have approximately the same density while the contact area of the particles with the interface varies, making it possible to observe the effect of shape and contact area on migration.

If we assume that for broken quartz and rutile particles the surface properties and contact area are approximately the same, the effect of density on migration could be observed. Shale and mica also have essentially the same density but the thickness of shale is 5 to 10 times greater than mica. Therefore, the weight or pressure on the interface of the shale is greater than that of mica. Mica has the greatest contact area with the interface because of its smoothness.

The contact area of the particle with the ice increase in the following order: Glass beads, broken glass, quartz, shale, and mica.

At the same time the pressure of the particle, on the interface is greatest for glass beads and smallest for mica flakes.

Characteristic crystal-forms were chosen for the preparation of quartz, calcite and mica samples. The crystals were crushed in a mortar and sieved on a shaker for ten minutes through the 2.38, 1.00, 0.59, 0.29 and 0.14 mm sieves. The material retained on each sieve except the 2.380 mm was used. As a consequence four groups of grain sizes were tested: 2.380—1.000; 1.000—0.590; 0.590—0.290; and 0.290—0.149 mm. Without measurements of the surface area, it is possible to say that for the same size, the contact area of calcite is greater than glass beads and smaller than shale.

EXPERIMENTAL RESULTS

The migration of sizes 0.14—0.29; 0.29—0.59; and 0.59—1.0 mm for broken glass, calcite, rutile, quartz, and shale is shown in figures 13—19. Because of the great migration of mica particles, a large size between

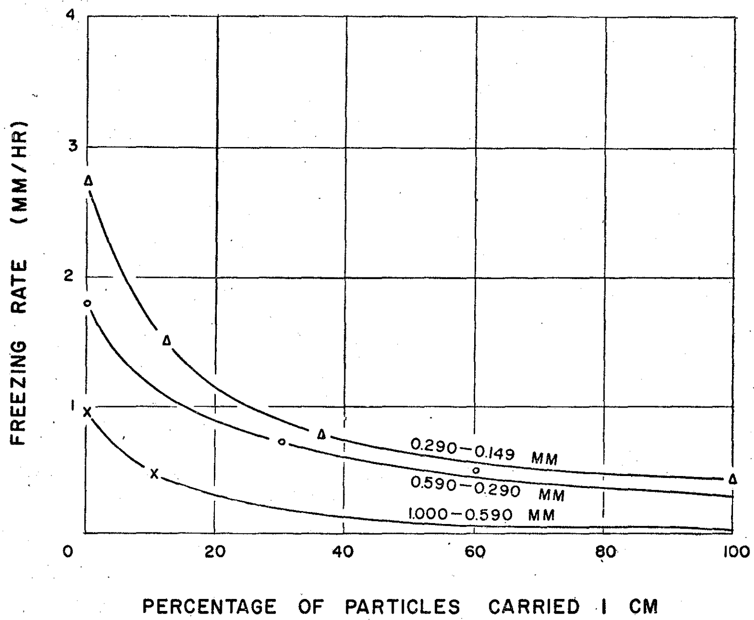

Fig. 13. Percentage (by weight) of broken glass particles carried 1 cm in front of the freezing plane under different rates of freezing

1.0—2.39 mm was tested also. Glass beads exhibited the least migration and the only values obtained were for 0.149 mm diameter. The migration of particles is expressed as the percentage by weight of particles carried 1 cm in front of the interface versus the rate of freezing. It can be observed in all the curves that more of the finer particles migrated than coarser ones of the same material. Also, the percentage of particles carried increases as the rate of freezing decreases. This effect is less important in glass beads than in other tested materials, probably because of the uniformity in shape and size of the spherical particles.

Fine particles migrate under a wide range of rates of freezing and coarse ones migrate at a narrow and slow rate. The migration of the 0.149 mm glass beads and 0.149—0.29 mm broken glass and quartz show the least migration. Particles of similar material such as quartz and broken glass of large sizes with less sphericity and greater contact area show a greater migration. Figure 20 shows the migration of 0.29—0.14 mm calcite, rutile, quartz, shale and mica. Calcite particles of rhombohedral shape should have the smallest contact area and the greatest weight per unit area with the interface.

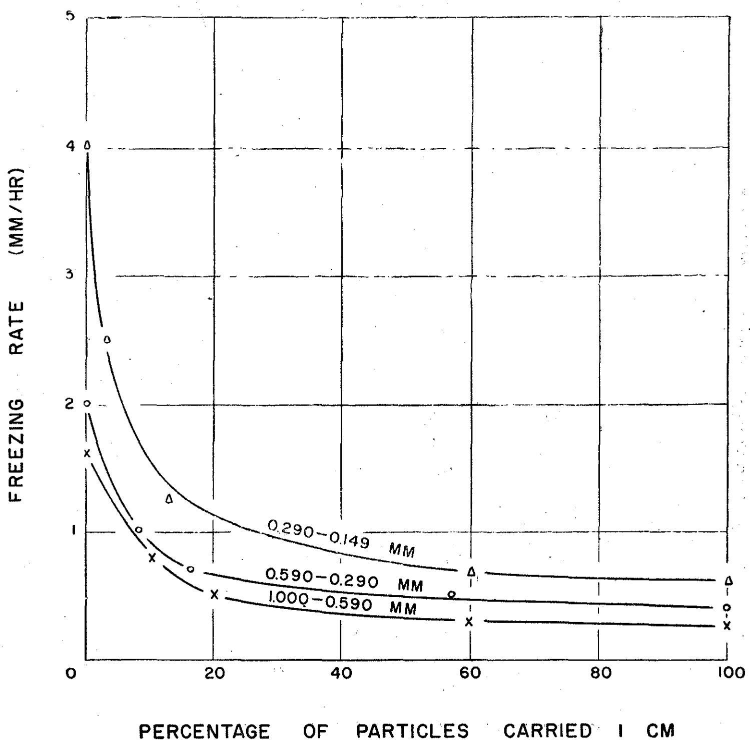

Fig. 14. Percentage (by weight) of calcite particles carried 1 cm in front of the freezing plane under different rates of freezing

The contact area of rutile and quartz is not known; it is not yet possible to say that the small amount of migration of rutile is caused by its greater density.

Although shale and mica have the largest contact area, mica is 5—10 times thinner than shale, and therefore has the least weight per unit area on the interface and exhibit the greatest migration.

It is, therefore, clear that increasing the contact area of the particle while decreasing the weight on the interface increases migration. This is observed by comparing materials of different composition such as calcite, rutile, quartz, shale, and mica, therefore the pressure on the interface decreases as the contact area increases.

A family of curves for different minerals can be made by using the rates of freezing at which 100% of seeded particles are carried in front of the freezing plane. Figure 21 shows the diameter of particles which

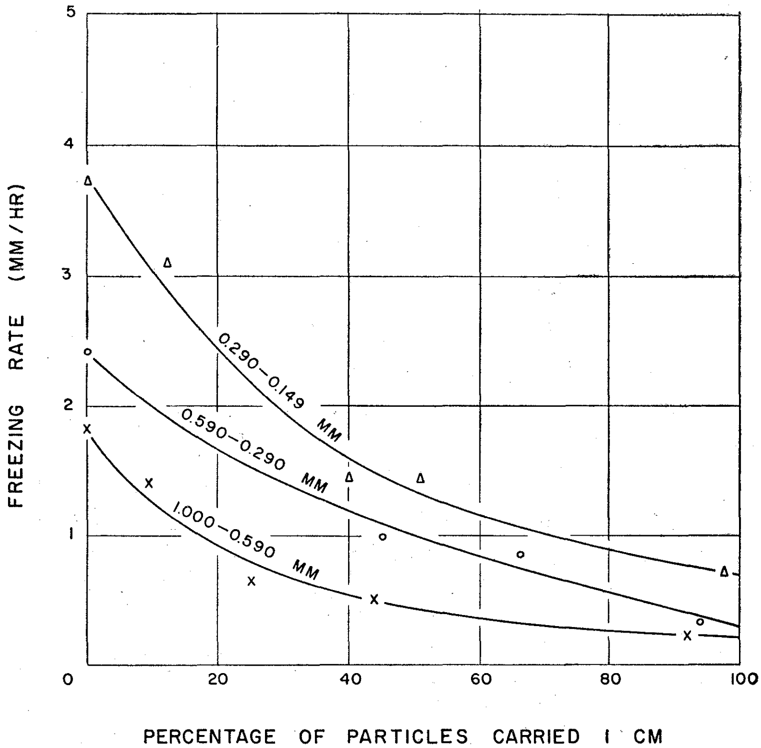

Fig. 15. Percentage (by weight) of rutile particles carried 1 cm in front of the freezing plane under different rates of freezing

migrated 100% in front of the freezing plane at different rates of freezing. It is demontrated that each particle size requires a certain rate of freezing in order to migrate continuously without being overcome or incised in the ice. This is clearly shown in an experiment where different sand diameters ranging from 0.1 to 7 mm were seeded on top of the interface (pl. 13). The smallest particles traveled 12.5 cm up to the top of the freezing cabinet while larger sizes were trapped by the ice closer to the seeding place. Fine particles can move continuously in front of the interface in a wider range of freezing rates than coarser ones. The range of freezing rates is largest for mica, smaller for shale, and smallest for quartz (fig. 21).

For a particle to migrate, it is postulated necessary that a layer of water must be continuously present between the particles and the ice front. The integrity of that layer must be assured for a particle to move continuously. It is assumed that the thickness of the water layer must be small.

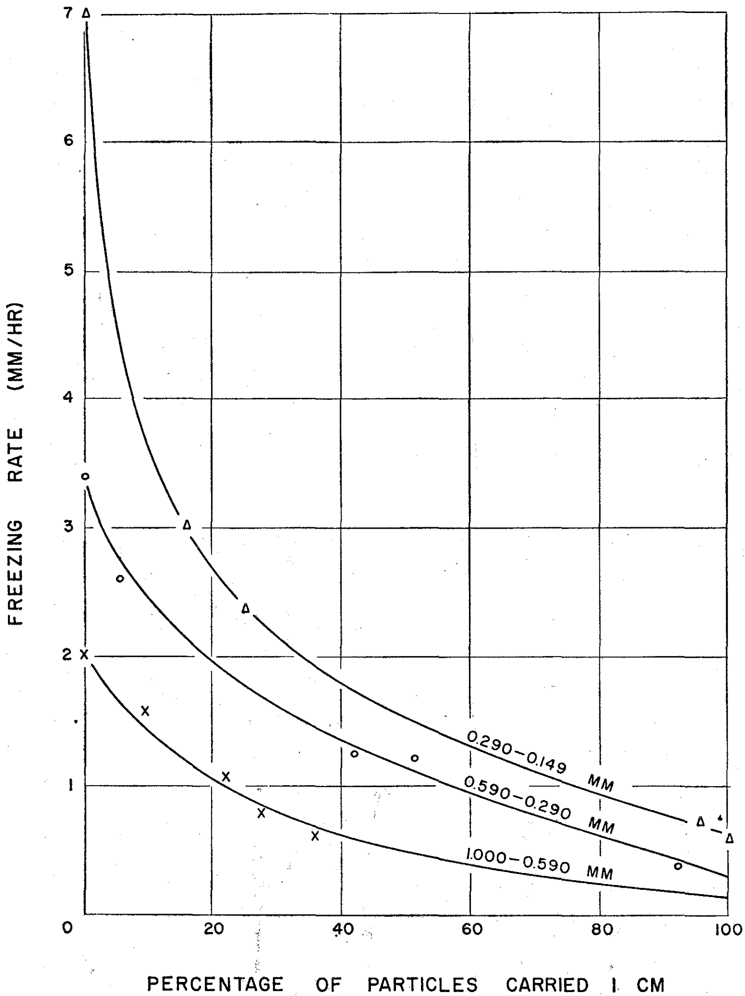

Fig. 16. Percentage (by weight) of quartz particles carried 1 cm in front of the freezing plane, under different rates of freezing

In this way it is possible to explain why small particles migrate under a wide range of rates of freezing and in order to migrate. A thin film of water between the ice lens and soil particles has been proposed by Taber (1930) as nesessary for the ice lens to grow.

During the experiment it was observed that migrating particles leave behind a trail or stream of bubbles. Photo (pl. 13) shows the bubbles left by the upward migration of sand particles ranging from 0.1—7.0 mm

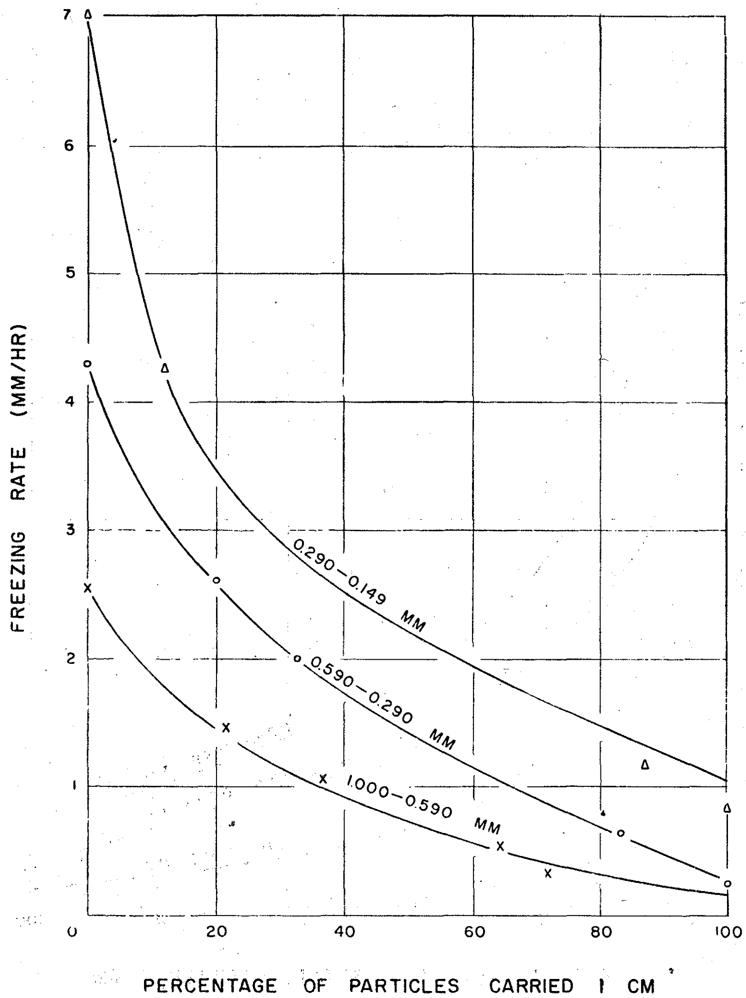

Fig. 17. Percentage (by weight) of shale particles carried 1 cm in front of the freezing plane under different rates of freezing

diameter. In this photograph it is also observed that coarser particles up to 7.0 mm diameter were lifted as much as 1 cm leaving a bubble trail as wide as the particle. These bubble trails are vertical where particles do not change position during their migration (fig. 22). But when particles are rotating the bubble trails are spirals.

The presence of the bubbles can be explained in the following way: When the ice front advances from the bottom up, the air dissolved

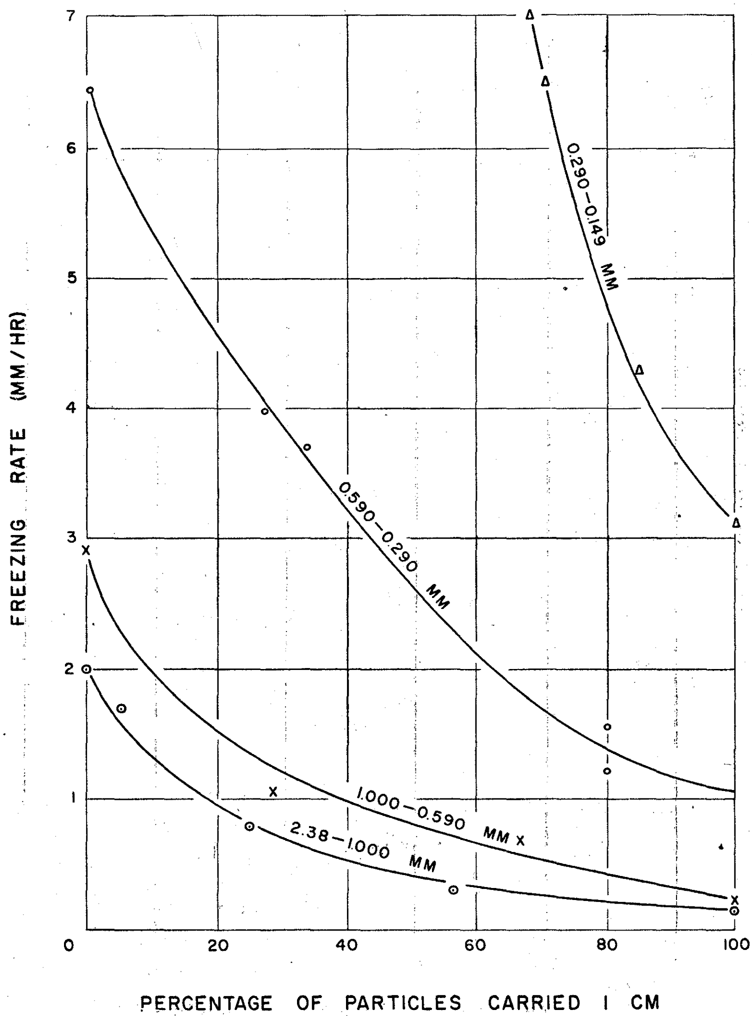

Fig. 18. Percentage (by weight) of mica particles carried 1 cm in front of the freezing plane under different rates of freezing

in the water is evolved because of the change of state. Bubble-free ice occurs where the air has not been impeded from scoping to the surface. Where the particle is located in front of the moving ice, the excluded air is trapped beneath the particle.

In the conventional tests for the determination of frost behavior of soil the samples are frozen from the top down, and friction between the soil cylinder testing walls is a serious handicap (ACFEL Ref. 43, Vol. 1, with

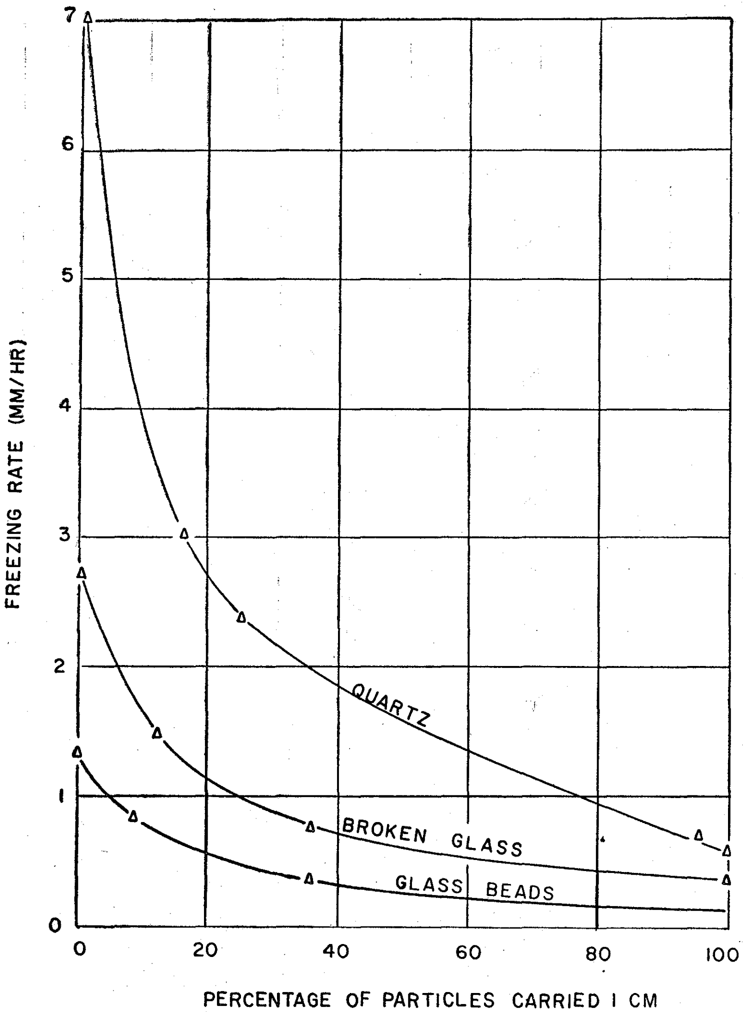

Fig. 19. Percentage (by weight) of glass beads (0.14 mm) quartz and broken glass (0.14—0.29 mm) carried 1 cm under different rates of freezing

Ap. AB—1958). In the present set up friction is eliminated because freezing proceeds from the bottom up and the part which moves is unfrozen. The present method of freezing has more similarity to freezing of the seasonal thaw layer above the cold perennially frozen soil, from the bottom up. From the experimental data it is possible to forsee a new way of assesing the frost behavior of soils. It could be based on the range of freezing rates under which a certain amount of particles will migrate in front of the freez-

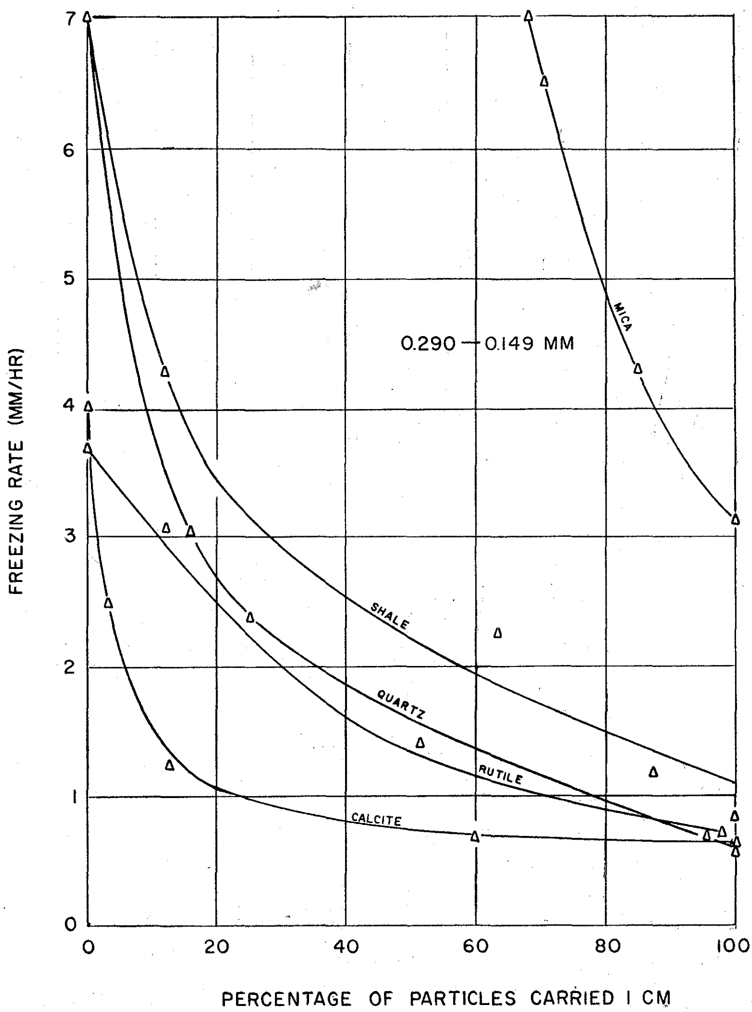

Fig. 20. Percentage (by weight) of 0.14—0.29 mm particles of calcite, rutile, quartz, shale, and mica carried 1 cm under different rates of freezing

ing plane. The larger the range of freezing rates, the more susceptible a soil becomes to ice lenses. By using the present experimental demonstration of particle migration Takagi (1963) has developed a new theory on frost heaving.

From these experiments we can conclude:

(1) fine particles move under a wide range of rates of freezing and coarse ones under a narrow range. Below a certain freezing rate, finer

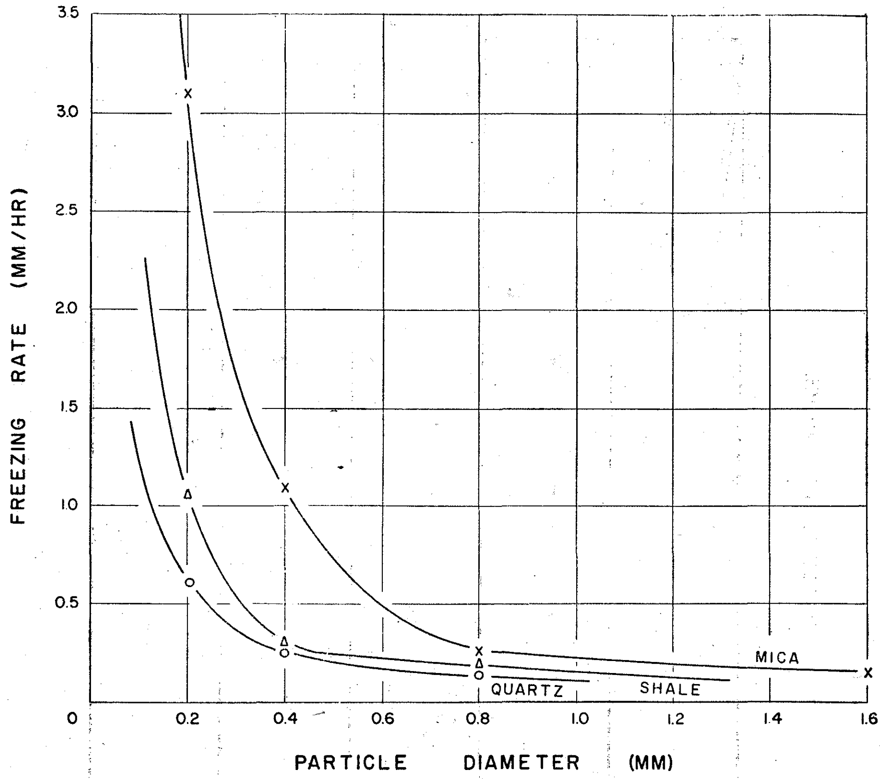

Fig. 21. Freezing rates required for a 2—3 mm layer of particles of different diameters to move continuously in front of the interface

particles travel more than coarser ones. This means that heterogeneous mixture has to become sorted by freezing. It is proposed that this should be considered a clue factor of sorting by freezing in nature;

(2) the migration of particles is influenced by the contact area of the particle on the interface;

(3) under a constant rate of freezing, different shapes can be carried;

(4) each particle moves upward leaving behind a stream of air bubbles. These bubbles are formed when the dissolved air in the water is expelled during the freezing process. The air outside the particles is expelled into the water. When a barrier or particle is in front of the evolved air, bubbles accumulate at the barrier surface (particle surface);

(5) a new way of assesing the frost behavior of soils is proposed; it is based on the range of freezing rates under which certain grain sizes can be carried in front of a moving freezing plane.

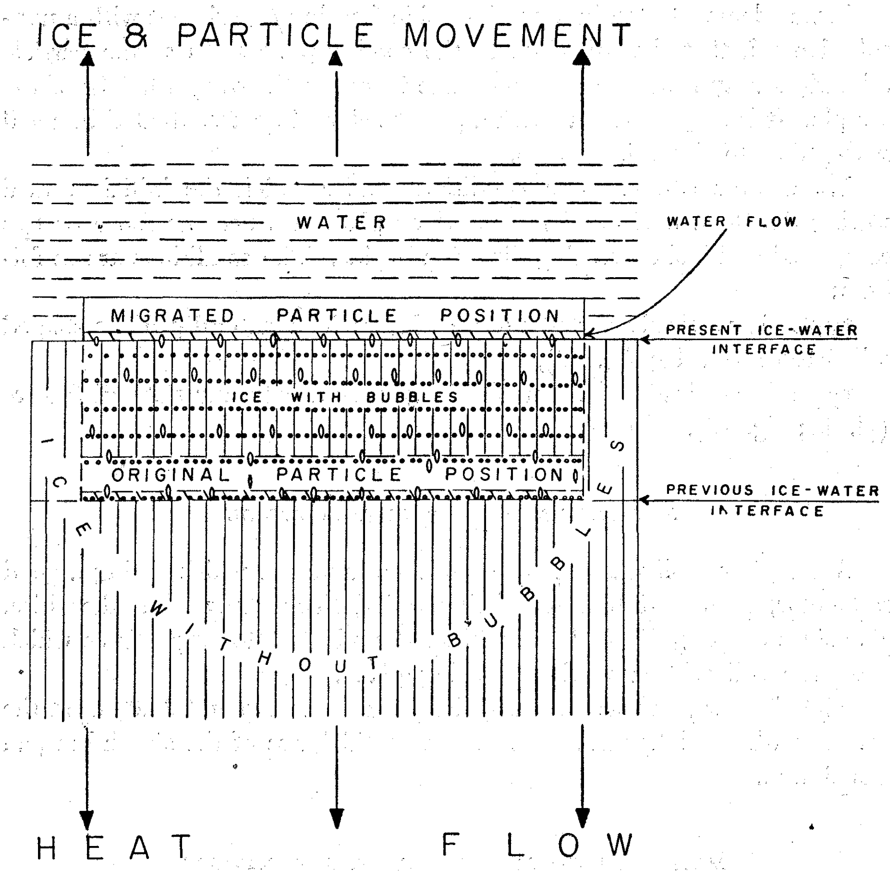

Fig. 22. Upward migration of a particle in front of the freezing plane. Under the particle air bubbles are trapped; where there is no particle, air is expelled into the water

Part III

CHANGES FROM VERTICAL TO HORIZONTAL SORTING BY CHANGING THE FREEZING DIRECTION

Suppose that a heterogeneous soil freezes from the top or from the top and bottom and the process of vertical sorting causes large particles to emerge at the soil surface in a random distribution. Since the large particles have a greater heat conductivity than the surrounding finer material, the finer particles adjacent to the stones experience the effect of a vertical freeze—thaw plane, as explained earlier.

It was demonstrated in a previous side freezing experiment with a non-cohesive soil that the soil close to the cooling plate sinks as the particle migration away from the freezing plane increases the overall height of the sample. It is suggested that such a process should be accentuated in a soil susceptible to form ice lenses.

We assume two types of conditions under which the initial vertical sorting due to a horizontal freeze—thaw plane has become more or less completed and a side freezing direction begins. The conditions are as follows:

type A, vertically sorted uniform layers in a naturally dome-shaped soil feature (pl. 14; fig. 23),

type B, vertically sorted uniform layers in a naturally flat soil feature (pl. 14; fig. 23).

APPARATUS AND EXPERIMENTAL CONTROL

A sample of soil was placed in an aluminum pan which, being a good conductor, permitted the soil to freeze and thaw easily from the sides. The sides of the pan could be considered equivalent to large stones which froze the soil with a vertical freezing plane.

The circular pan was 22 cm in diameter at the top and 20.0 cm at the bottom with a height of 8.0 cm. The wall thickness of the aluminum pan was 3 mm.

MATERIAL USED AND EXPERIMENTAL PROCEDURE

Vertical sorting was simulated in the pan by placing 4 layers of different particle sizes one on top of the other (fig. 23). The bottom layer was 5 cm of Bloomington silt. The physical properties of the silt had been already determined from an experiment by Higashi (1958).

Specific Gravity	2.63
Liquid limit	31.4%
Field Moisture content	22.2%
Plastic limit	13.9%
Plasticity index	17.5%
Shrinkage limit	12.0%

The silt fraction of the Bloomington till is a good material for ice-segregation (Higashi 1958). The layer of Bloomington silt was covered by 3 layers of fine, medium, and coarse sand each with a thickness of 0.5, 0.5 and 1.0 cm respectively.

Water was poured into the pan to the top of the silt layer. The total amount of water was 42% by weight. Throughout the experiment, water was maintained at a constant weight content by weighing the pan, and replacing lost water.

EXPERIMENTAL RESULTS

It was observed during the freezing and thawing cycles that the soil froze from the top, sides, and bottom. The soil adjacent to the pan wall sank as the center began to rise. Both experiments developed a mound shape, and nearly all the sand has left the mound in Experiment A and Experiment B has little sand remaining on the mound which was formed during the cycles from an initially flat surface. Measurements during the frozen state shows that the moisture content is higher at the perifery of the silt layer than at the center.

After cycle 33, the samples were removed from the pans at the frozen stage. It could be observed that the silt particles migrated from the pan wall towards the center of the sample (pl. 14 d).

The silt next to the wall has been replaced by the fine, medium, and coarse sand in Experiment A and by the coarse and medium sand in Ex-

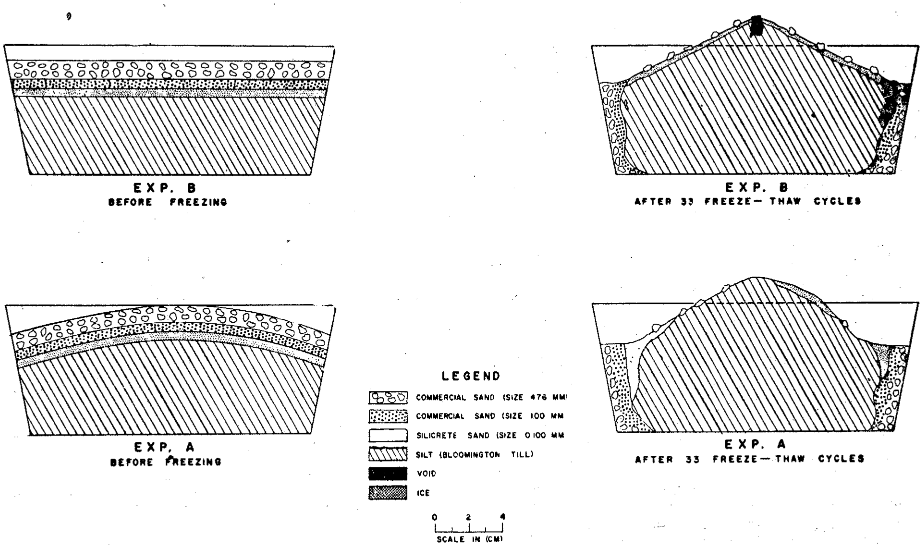

Fig. 23. The effect of side freezing on two vertically sorted soil layers: one domed (Experiment A) and other flat (Experiment B)

Side freezing changes vertical sorting into horizontal sorting. Left — figures before freezing, right — figures after 33 cycles of freeze-thaw periment B. It is also observed that the sand itself has been sorted; the coarsest is close to the wall and the fine sand near the silt.

The interpretation of such a change from vertical to horizontal sorting is as follows.

The soil freezes from the top, sides, and bottom; moisture is drawn from the center towards the freezing plane near the wall to form ice lenses. As ice is formed particles are segregated towards the center of the pan. Therefore, the finer particles are forced to the center of the sample by the formation of ice lenses at the side. The center is subjected to a compaction process and the sides become decompacted. During this process, a mound is formed and the large particles gravitate from the mound to the space left by the melting ice next to the wall during thawing. As sand particles are falling next to the sides of the aluminum pan, they become sorted according to the principle of segregation in front of a freezing plane i.e. finer particles migrate more than coarser ones (see p. 198), which produce horizontal sorting.

The rate of freezing determines the thickness of ice close to the sides of the good conductors (pan walls or large stones). Several investigators have shown that the ice segregation is a direct function of the rate of freezing (Nakaya & Mogono 1944; Higashi 1958; Taber 1930; Beskow 1935; Linell & Kaplar 1959; and others). However other researchers, such as Penner (1960), propose an inverse function. This apparent disagreement is possibly attributed to the different rates of freezing. These authors have used different samples and different apparatuses. It is proposed that the slower the rate of freezing the more particles are pushed and more ice will be formed at the sides and the greater the mound will be.

In the domeshaped surface, all sand sizes are sorted (Experiment A), whereas in flat surface (Experiment B) only the coarse and medium sand was sorted. This indicates that the area of finer fraction also depends upon the change of the uniformity coefficient along a horizontal plane through the layers (fig. 23; pl. 14 a—d).

Troll (1944) postulated that the size of the sorted areas or of the finer fraction is related to the thickness of the freeze—thaw layer. However, it can be visualized that different sorted areas could be produced using the same sample thickness and changing the uniformity coefficient or the spacing of the conductors.

In the model for sorting proposed (p. 234—235) emphasis is placed upon changes in uniformity coefficient, vertical sorting, volume changes and lateral sorting. It needs to be acknowledged that since the pan is circular, lateral sorting will produce a sorted circle. Therefore this experiment cannot be used to explain sorted circles in nature. It is used only as example of lateral freezing efects.

From this experiment it is possible to make the following conclusions:

(1) Horizontal layers of fine particles become dome-shaped by a vertical freeze—thaw plane.

(2) Vertical sorting in such a layer can be changed into horizontal sorting by changing the direction of the freezing plane.

(3) Two kinds of sorting can be differentiated:

a — sorting by migration in front of a freezing plane (movement of particles from the pan wall towards the center of the pan);

b — mechanical sorting by gravitation from the top of the mound to the sides to fill in the voids left by the melting ice.

Therefore, it can be stated that gravitational sorting is a consequence of sorting by migration in front of the moving plane.

(4) The area of fine particles formed by side freezing depends on the:

a — diameter of the pan in the laboratory and on the size and spacing of the large particles which are moving to the soil surface by vertical sorting in nature;

b — rate of freezing: the slower the rate of side freezing, the larger the ice segregation around the conductor and the greater the migration, as consequence the mound will be higher;

c — changes in grain size distribution along a horizontal plane through the layers. Materials in Experiment A will be sorted faster than an area with no such grain size changes, Experiment B.

The effect of the thickness of the freeze—thaw layer remains to be determined.

Part IV

VOLUME INCREASE BY SIEVE SORTING STRAIGHT-GRADED SAMPLES WITHOUT FREEZING AND THAWING

A basic question which may be asked about the sorting phenomenon is what volume change is produced when a heterogeneous mixture is sorted by mechanical means rather than freezing and thawing. In order to answer this question, a series of straight graded samples were prepared (fig. 24). All gradation lines have a common point of 0% at the No. 200 (0,074 mm) sieve and each sample had a maximum grain size of ten times the previous one. By increasing the maximum grain size by a multiple of aproximatelly 3 (see fig. 24) samples a2 to a5-1-2 and sample b4 were also tested.

The procedure for determining the volume changes was the following:

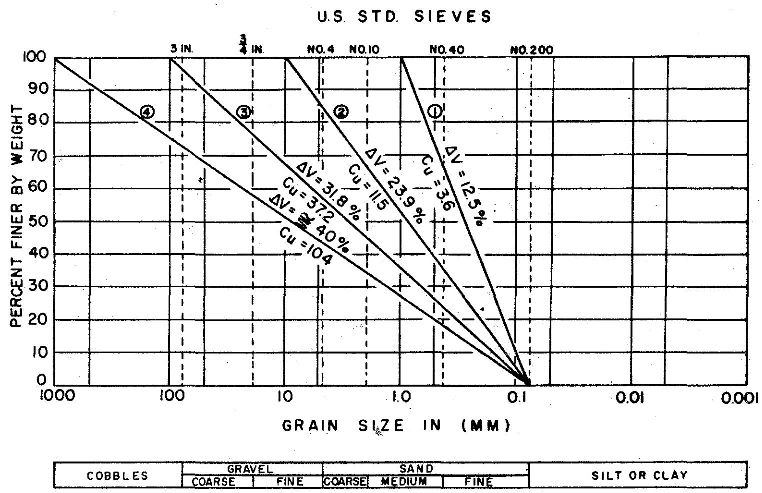

Fig. 24. Relationship between uniformity coefficient $C_u = \frac{D\,60}{D\,10}$ and volume changes (Δv) in straight graded series

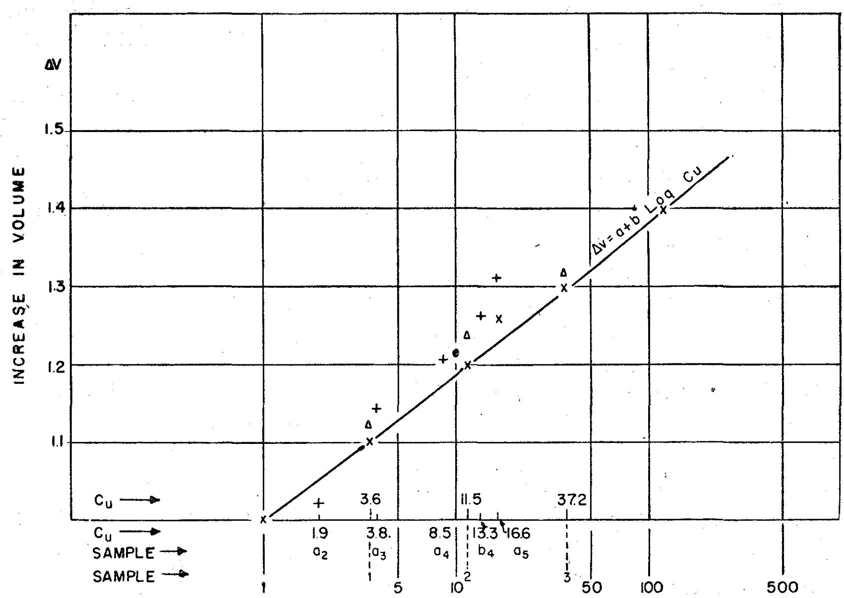

Fig. 25. Relation between volume changes $\frac{\Delta\,v}{v}$ by sorting and $C_u = \frac{D\,60}{D\,10}$ for different kinds of samples

Crosses are values obtained from commercial sands. Triangles are values obtained from sand samples from the Lake Michigan shore. Dot is a value for glass beads. Straight line or X is the 10% volume increase each time the maximum size is increased in 10 mm

The samples were sieved with screen openings differing by a multiple of 2. For example, sample a2 passing 9.5 mm sieve and retained on 2.38 mm sieve was separated into two parts on 4.76 mm sieve. Sample a3 passing 9.5 mm sieve was separated into the four fractions retained in sieves 4.76 mm, 2.38 mm, 1.19 mm, and 0.59 mm. The same procedure was applied in the other samples. In this manner sample a2 was separated into two fractions, a3 into four, a4 into six, and a5-1 and a5-2 into eight fractions. Samples were sieved and each fraction was placed as a layer in a graduated cylinder without compaction and the corresponding percent of volume increase was determined. An increase in the maximum size of 10 times corresponds at least a 10% increase in volume by sorting (fig. 25). Sample no. 1 with a $C_u = 3.60$ gave a 12.5% volume change. Sample no. 2 with a $C_u = 11.5$ gave 23.9% of volume change and sample no. 3 with a $C_u = 37.2$ gave 31.8% of volume change. It can be predicted that a sample like no. 4 (fig. 24) will give more than a 40% volume change. The values obtained are presented in the following table (III).

Table III

Relationship between uniformity coefficient (C_u) and volume changes by sieving $\left(\frac{\Delta v}{v} \times 100\right)$

Sample	C_u	$\left(\frac{\Delta v}{v} \times 100\right)$
1	3.6	12.5
2	11.5	23.9
3	37.2	31.8
a2	1.9	2.1
a3	3.8	14.0
a4	8.5	20.8
b4	11.3	26.5
a5—1	16.6	31.2

This shows by increasing the uniformity coefficient of a sample the volume changes are also increased. Figure 25 illustrates the relationship of volume change as a function of the uniformity coefficient plotted on semi-log paper. The solid straight line is the line of the 10% volume increase when the maximum size is increased 10 times. It indicates that the volume change is a simple function of the uniformity coefficient. If the gradation of the sample is linear we can write:

$$\Delta v = a + b\ (\log C_u)$$

Where: Δv = volume increase, Cu = (D 60/D 10), v = 1.000 + + 0.19075 (log C_u).

If the gradation line is not straight, this relationship will not hold.

It can be concluded that:

(1) the volume changes produced by sorting of a heterogeneous mixture is a function of the uniformity coefficient (C_u).

(2) an increase in the maximum size of the particles in the mixture by a factor of 10 produces an increase in volume of at least 10%.

Part V

SORTING PRODUCED IN NATURE WITH MATERIAL PLACED BY MAN

Two areas of man-deposited materials were investigated by excavating trenches, the Fairbanks Research Area located at the USA CRREL Alaska Field Station in Fairbanks and another area at the Livengood Reservoir 60 miles north of Fairbanks.

The Fairbanks research area has various gradations of materials in different plots which were man deposited during the summer of 1946. Trenches were dug in the summer of 1961 to investigate if sorting had been produced after 15 years of freeze—thaw cycles. A drainage channel dug around the experimental area to keep water from flooding the test

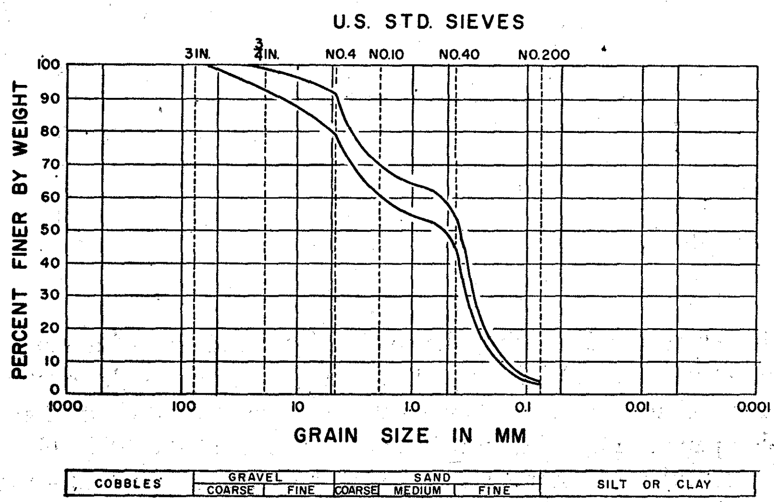

Fig. 26. Vertical sorting in a layer of sandy gravel placed by man. Place: Alaska Field Station, U.S.A. CREEL, Fairbanks, Alaska

Top grain size curve is the bottom of the layers, lower grain size curve is the top of the layer site was successful in area 2, and the soil did not have saturated conditions during the freezing cycles. Therefore, the chance of sorting in this area is small because of the lack of water. In area 1, however, drainage was not successful.

A concrete slab in Section D, which was painted black, produced a local melting of the perennially frozen ground and a lowering of the ground surface of approximately 1 meter.

The water table rose about 30 cm above the surface of the slab during the spring. Trenches were dug by hand along concrete slab and samples were taken at 8 cm intervals in the vertical plane and every 1 meter along the trench from the highest and driest to the lowest flooded area. The grain size analyses show that the amount of vertical sorting is the largest in the lower flooded level compared to the higher area with less water (figs. 26, 27, 28). Figure 26 is the grain size curve of the lowest and the wettest point and Figure 28 is the driest. Also some sorting was observed between the top and bottom of the sand layer underneath the concrete slab in the wettest place (fig. 29).

According to the unified Soil Classification System (1953—60) this material should be clasified as (S.P.) poorly graded sandy-gravel.

Samples were also taken from the experimental plots in Area no. 2 where drainage channels kept the area dry. Samples of the whole layer could not be taken because of the summer rain which caused flooding

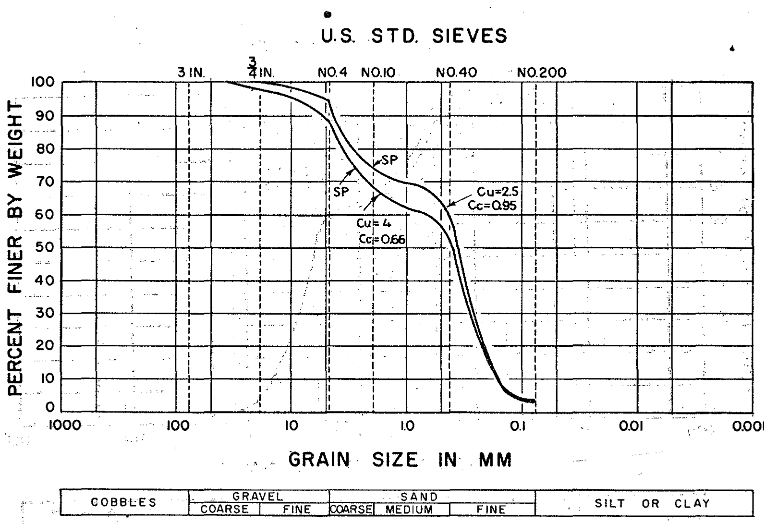

Fig. 27. Vertical sorting produced in the same layer as in Fig. 26, but higher and less moisture. Top and bottom grain size curves are less separated

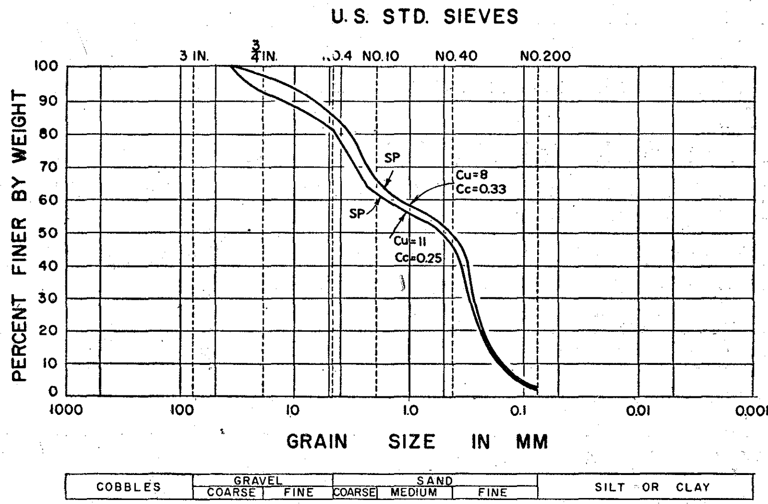

Fig. 28. Vertical sorting produced in the same layer as in Figs. 26—27, but at higher and drier place. Top and bottom grain size curves became closer

at the bottom of the experimental plots. It was observed during the excavation of the trenches that every large stone in the experimental plots had an accumulation of fines at the top and coarse particles at the bottom. This is clear evidence that fines are shifting or migrating downward. Such accumulation of fines was observed beneath as well as outside the slab

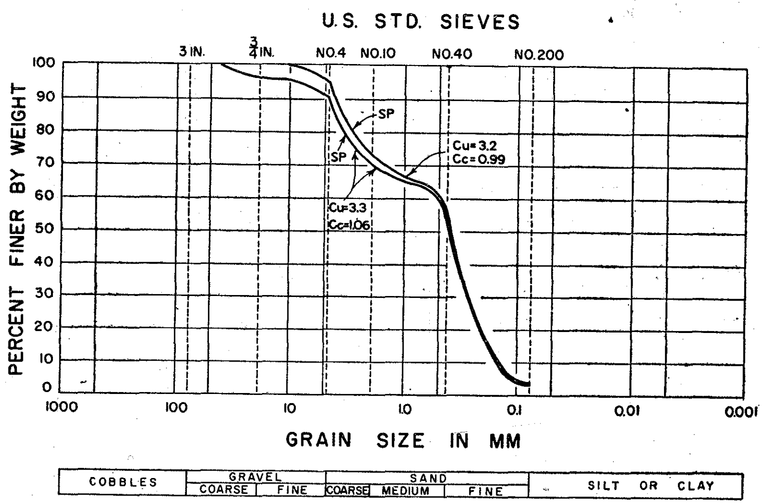

Fig. 29. Vertical sorting observed under a 15 cm concrete slab in front of samples (Fig. 26), flooded

which points to the fact that vertical sorting can be produce in non cohesive materials when water is only at the base of the freeze—thaw layer.

At the Livengood Reservoir 60 miles north of Fairbanks, bulldozers moving material for the construction of the dam had left some of the material in small ridges in different places with various heights and slopes in 1939—40. A pit was dug in a low flooded area where fine particles would not have been washed away by the water. A ridge was cut for a grain size analysis. Samples were taken at 5 cm intervals in the upper 15 cms. Other cuts were made, and in general it was observed that vertical sorting has been produced in 10 and 15 cm layers after 20 years of freeze—thaw cycles (fig. 30). Such material is considered poorly graded, according to the Unified Soil Classification System (1953—1960).

From these field observations, it can be concluded that: Coarse poorly graded sandy gravel layers with and without fines (0.02—0.07 mm) become vertically sorted after 15—20 years or cycles of freezing and thawing. A layer without fines requires saturation conditions in order to become sorted; in such a soil, sorting decreases as moisture decreases. A flooded coarse layer shows sorting even under a concrete slab, which indicates that vertical sorting is developed under a load of 45 g/cm². Vertical sorting under a load of 200 g/cm² was reported for the thaw zone at Thule, Greenland (Corte 1961—62b).

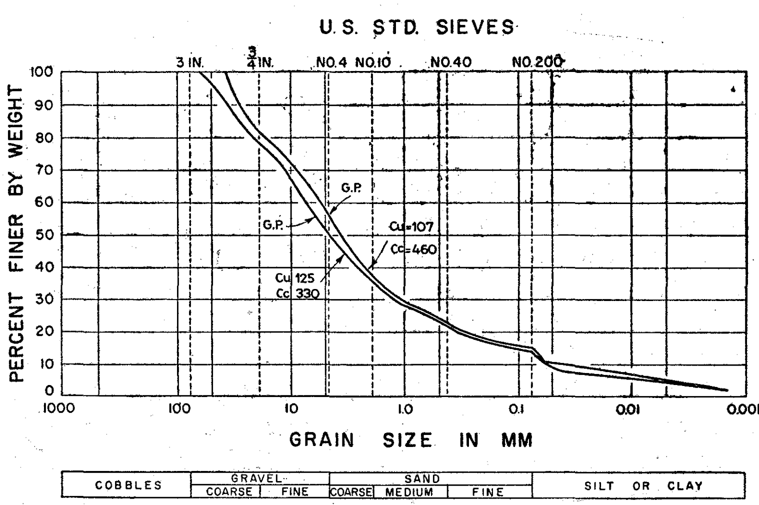

Fig. 30. Vertical sorting produced after 20 years in a cohesive soil in Livengood reservoir, Alaska

Part VI

SORTING PRODUCED IN NATURE WITH MATERIAL DEPOSITED BY GEOLOGICAL ACTION

VERTICAL SORTING

It is common to hear reports from areas of intense winter freezing about new stones appearing at the ground surface of fields and the heaving of fence posts. These stones and fence posts are thought to be forced out of the soil by repeated freezing and thawing. Högbom (1908—09), Hamberg (1915), Beskow (1930) and others explain this phenomenon as a result of expansion during freezing. Högbom and Hamberg consider that the formation of ice at the bottom of the stones is a necessary condition for the heaving.

The stones do not settle back to the original position during thawing because of the reorientation of soil particles. The literature on formation of features produced by freezing and thawing is voluminous and the problem of sorting is treated in more than 20 theories (Troll 1944, p. 568—69). In spite of the many theories, there has been until now no basic field investigations nor laboratory experiments performed on the problem of sorting.

One of the better available areas for field data on vertical sorting is the active layer near Thule in Northwest Greenland where contractors have been scraping off the thawed material in order to obtain construction materials. By following the paths of the bulldozers and loaders, an excellent view of the phenomenon can be seen.

A good approach to the phenomenon of vertical sorting was obtained from field observations and the partial analysis of several hundred meters of excavations made in the seasonally thawed soil during the summers of 1956—1957 (Corte 1962a). It was noted that the thawed layer showed vertical sorting where the fraction finer than No. 200 (0.074 mm) was greater than 3%. Taylor (1956) presents data of an area where this layer has a finer average grain size and it too shows vertical sorting. Such freeze—thaw layer is found in higher places where water could not accumulate. With the available information, it was predicted that coarse materials should show vertical sorting if they are or were previously flooded.

In the summer of 1960, excavations were made in low areas in Northwest Greenland where water was abundant. Large trenches were cut with a bulldozer in order to drain the melt water, and samples were taken at regular intervals from the top of the thawed layer into the permafrost.

The average soil gradation of the active layer is found to be approximately equal to that of the perennially frozen ground (fig. 31). The materials

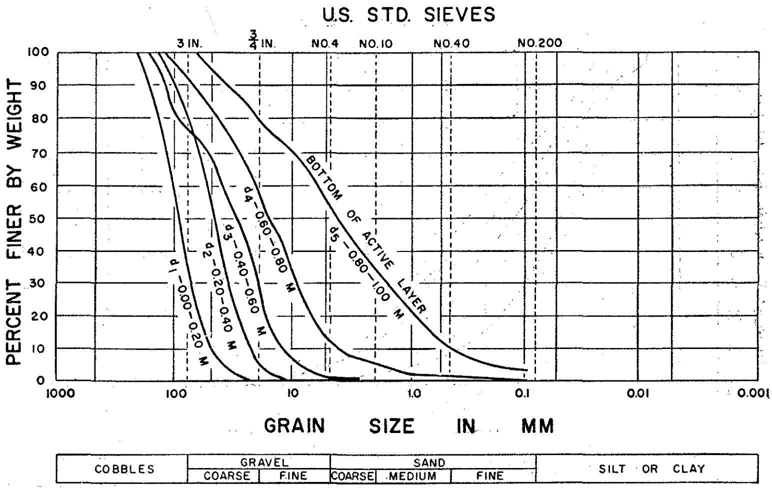

Fig. 31. Vertical sorting in the active layer in the Thule area. Vertical sorting ends at the bottom of active layer. Each curve corresponds to a 20 cm analysed layer

in which vertical sorting is observed can be classified as: WG, well graded, according to the Unified Soil Classification System (1960, p. 20—21). The Uniformity coefficient $\left(C_u = \frac{D\,60}{D\,10}\right)$ is greater than 4 and the Curvature coefficient $\left(C_c = \frac{(D\,30)^2}{D\,60 \times D\,10}\right)$ is between 1—3.

It has been seen that sorting of straight graded sample with a uniformity coefficient between 30 and 40 gives a volume change greater than 30%. Therefore, a volume change of over 30%, can be expected in an area such as d8 (fig. 32) with a $C_u = 30$. This indicates that the freeze—thaw layer was originally 100 cm thick and that sorting has increased it to 130 cm. Another factor which may promote vertical sorting in nature is washing by streams and rain especially after the thaw has loosened the soil. Unfrozen samples have been washed in the laboratory with 1 liter of water to simulate rainfall and no appreciable amount of vertical sorting was developed.

It was observed in general, that a perfect vertical sorting was established in the layer (pl. 16, 17). The perfection of the sorting depends upon the original grain size distribution as well as the amount of moisture available. Vertical sorting also occurs on slopes where the active layer contain the necessary percentage of fines (pl. 18). But when fines are predominant and have a high plasticity, the coarse particles behave as if they are floating in a plastic medium without being able to reach the surface (Corte 1962a).

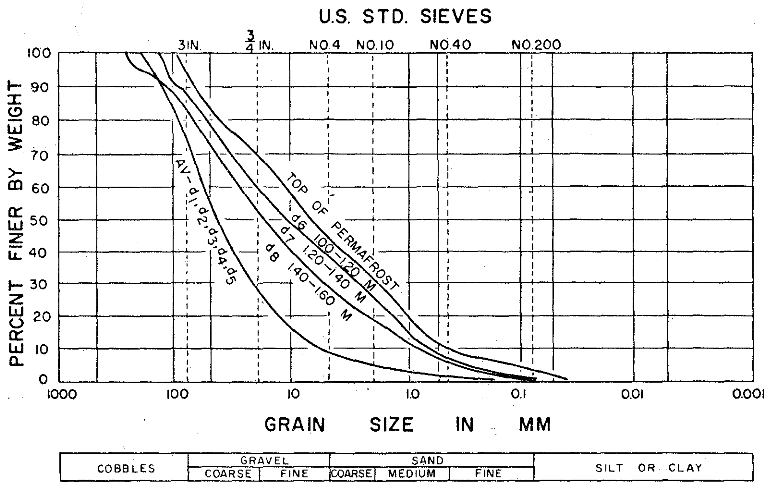

Fig. 32. Continuation of profile (Fig. 31) showing reverse of vertical sorting; down into the permafrost the soil tends to approach the average grain size of the active layer (lower curve)

From the studies made in the freeze—thaw layer, we can say that vertical sorting is:

(1) observed in well graded materials with and without fines (0.074 mm) if they are or had been saturated;

(2) not restricted to a specific grain size range, has been observed in the so called "non-frost susceptible" soils.

HORIZONTAL—VERTICAL SORTING OR LATERAL SORTING

Horizontal sorting at the soil surface is a common phenomenon in the periglacial regions of the world. It is observed in low lying areas and above the timberline in mountainous country. Such sorting can be identified at the soil surface by "circles" or islands of fine particles surrounded by coarse ones. The diameter of such islands of fine material ranges from a few centimeters to several meters (pl. 19), for one meter average depth of the freeze—thaw layer. Such layer freezes and thaws once every year, according to temperature measurements of A. Poulin (USA CRREL, personal communication). The finer area can be flat, dome shaped, or depressed and may also be isolated or closely spaced (pl. 20). If they are continuous, the coarse part has the appearance of a "polygonal" pattern, these are called *stone nets* (Troll 1944, p. 653) or *sorted nets* (Washburn 1956, p. 2).

If the pattern is distinctly polygonal they are called *sorted polygons*. Sorting in a flat saturated area tends to produce a circular patterns whereas sorting on a slope tends to elongate the feature (pl. 19).

Size frequency distribution curves were prepared from aerial photos and plane table maps of sorted areas which had been investigated near Thule. Figure 33 is the frequency distribution of 161 circles in pl. 1, and

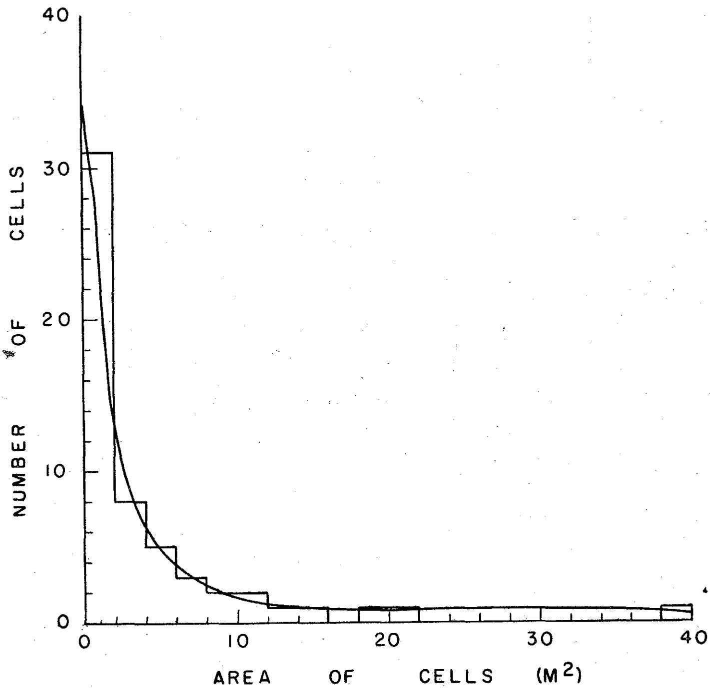

Fig. 33. Size frequency curves of sorted areas ranging from 2 to 40 m²

the curve shows that the freguency increases as the size decreases. In one area of northwest Greenland, the sorted features are large, ranging up to 42 m² (pl. 1) while within one mile of the same place the size range is from a few cm² to 200 cm² in the same type of soil and depth of the freeze—thaw layer (fig. 34). Troll (1944) reported that the small sorted nets a few centimeters square in area are produced by daily freeze—thaw action in a shallow layer while the larger sorted features are produced by yearly cycles in a deep saturated layer. This problem will be discussed after the field data are presented.

Since grain size composition is an important variable in soil frost action, the first step in field work is to determine the range in grain size needed

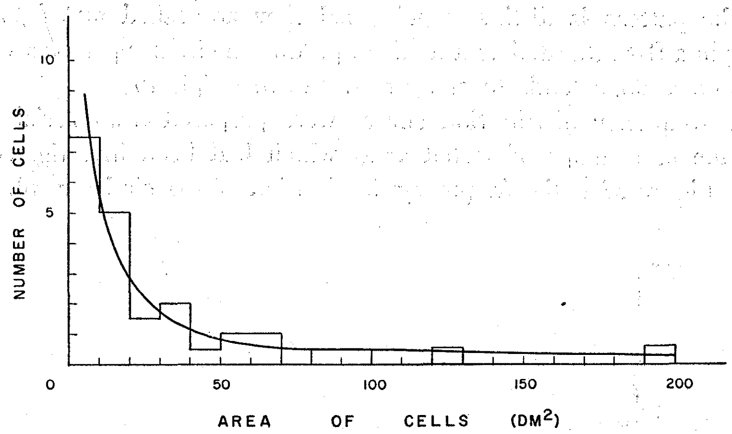

Fig. 34. Size frequency curves of sorted areas ranging from 10 to 200 dm^2

for segregation. Field data were obtained at the border of the ice cap near Thule, Greenland, where this segregation process has been taking place in river transported materials, moraine deposits, and soils.

For clearness and simplicity it was decided to analyse isolated areas which exhibited variations in their grain-size composition. Eight sorted circles with diameters ranging from 20 to 100 cm were analyzed (fig. 35).

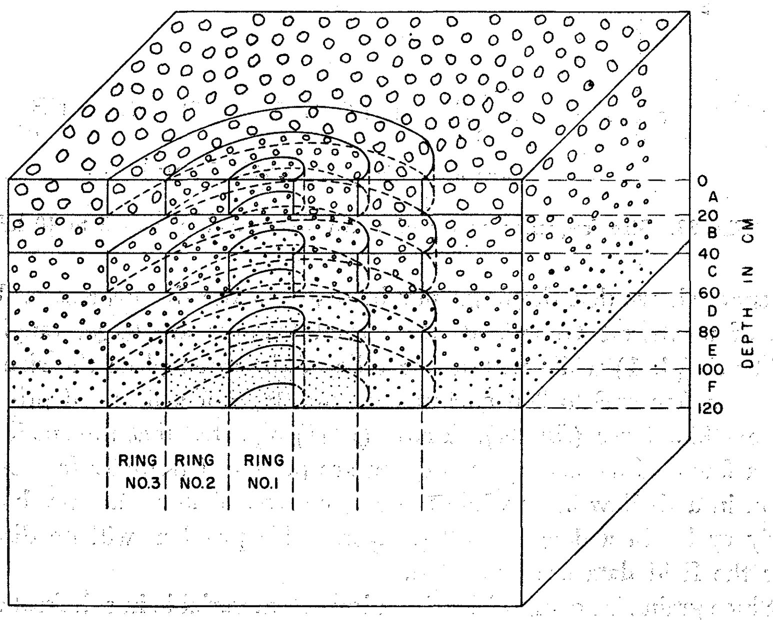

Fig. 35. Diagram of sampling procedure of sorted circles

For the analysis of each center of fines, samples were taken from concentric rings with the origin in the center of the circle.

The width of the rings were equal to the diameters of the circle of fines. When the surface showed uniform size, only one ring was sampled.

A grain size analysis showed that in all eight circles the mean particle size increased away from the center and decreased downward. This has been called "horizontal—vertical sorting" or lateral sorting. Three circles with varying amounts of fines are discussed: Circles No. 3 (pl. 21), No. 1 (pl. 23 a, b), and No. 8 (pl. 22).

In all three sorted circles analyzed, horizontal sorting shows a maximum at the surface and decreases downward (figs. 36, 37, 38). Vertical sorting increases with distance away from the center of fines (figs. 39, 40, 41). Computation of the average grain size value shows that these sorted features are developed in materials which contain 0.1 (No. 8), 1.0 (No. 1) and 2.5% (No. 3) by weight of particles finer than 0.02 mm (fig. 42). Sorted circles 8, 1, and 3, have uniformity coefficients of 10, 428, and 182, respectively and a curvature coefficients of 6.3, 1.1, and 1.2 respectively. Therefore "lateral sorting" is observed in a well graded (GW) materials, sorted circle no. 1 and 3, and poorly graded (PG) materials, sorted circle no. 8 (Unified Soil Classification System 1960, p. 20—21) (fig. 41).

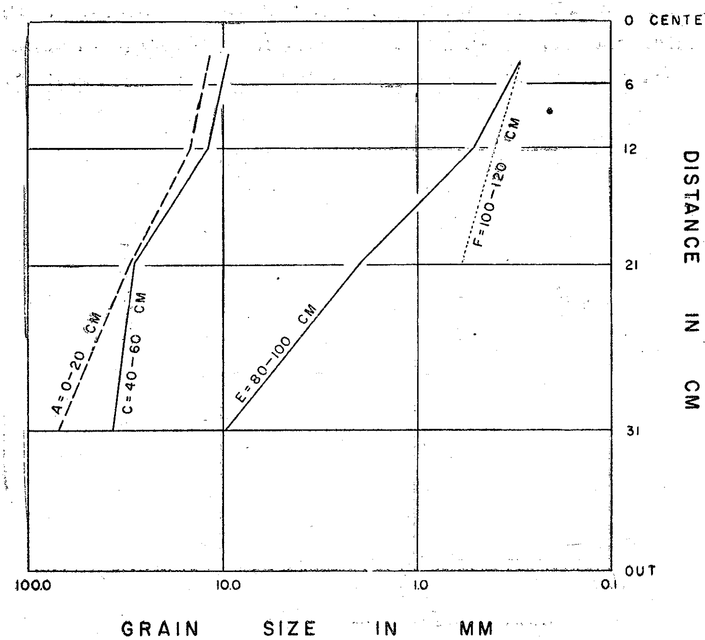

Fig. 36. Horizontal sorting in circle 1 expressed as change of average grain size (median value) with distance from the center of sorting for different depths

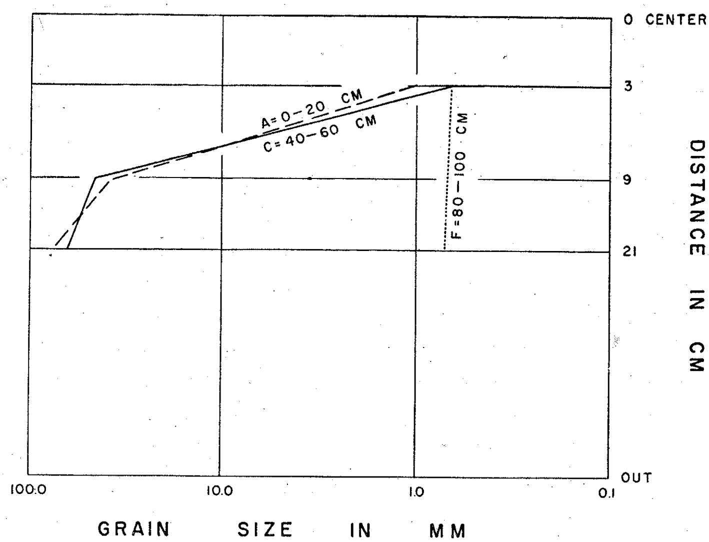

Fig. 37. Horizontal sorting in circle No. 3, expressed as change of average grain size (median value) with distance from the center of sorting for different depths

Comparing the grain size curves with the Beskow frost susceptibility limiting curves shows that horizontal-vertical sorting occurs in the zone of "negligible ice segregation" or "never-frost-heaving moraine soils" (fig. 41). Kulling and Ahlmann (1936) and Corte and Somoza

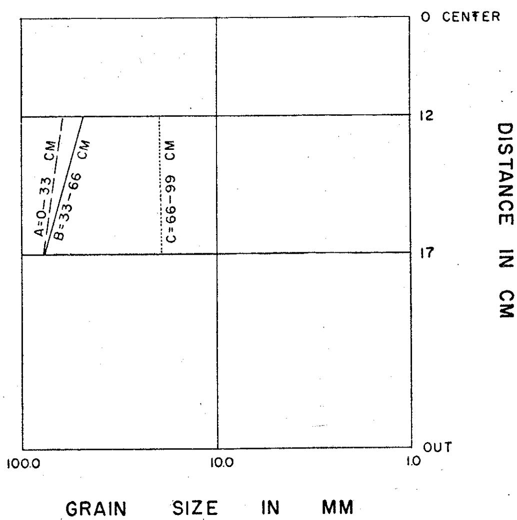

Fig. 38. Horizontal sorting in circle No. 8, expressed as change of average grain size (median value) with distance from the center of sorting for different depths

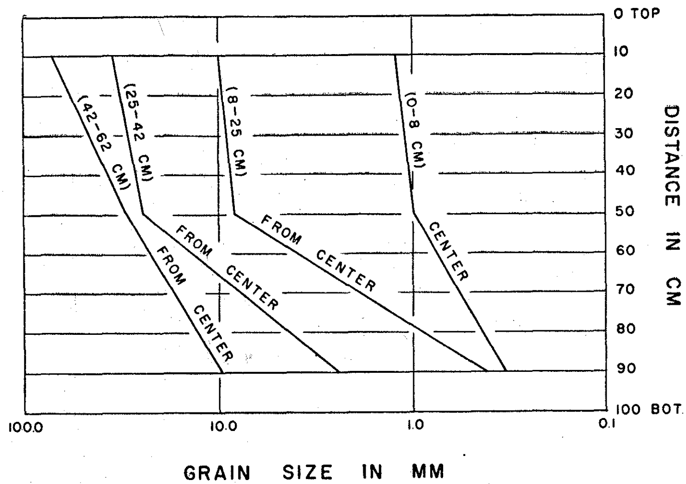

Fig. 39. Vertical sorting in circle No. 1, expressed as change of average grain size (median value) with depths at different distance from the center of sorting

(1957) have shown that the grain size curves of sorted features are located in the frost susceptible zone of Beskow (1935). These authors were considering in their sampling the fraction finer than 2.0 mm. Such soil samples should not be considered representative of the field conditions. It is therefore necessary to find out if sorted islands or sorted nets are formed in "frost susceptible" (Engineering criterion) materials.

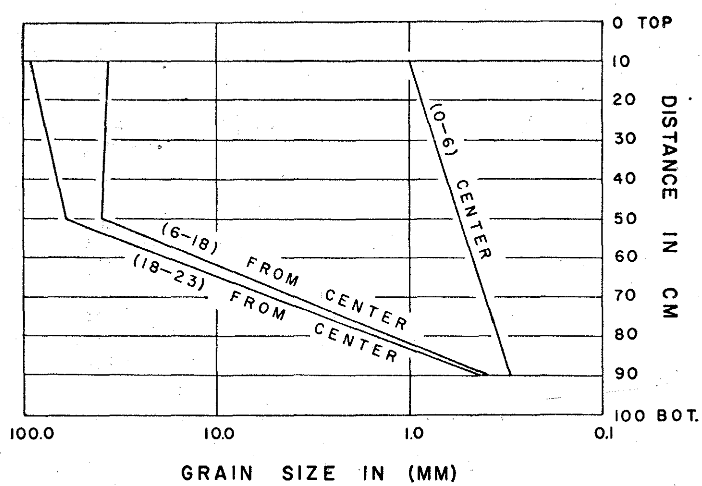

Fig. 40. Vertical sorting in circle No. 3, expressed as change of average grain size (median value) with depths at different distances from the center of sorting

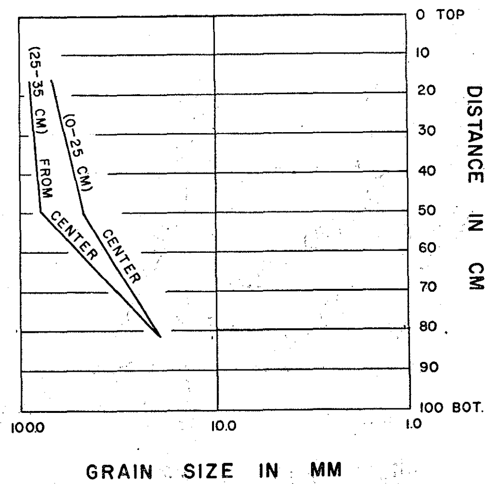

Fig. 41. Vertical sorting in circle No. 8, expressed as change of average grain size (median value) with depths at different distances from the center of the sorted area

The distribution of the fraction finer than 0.074 mm in sorted circles 1, 3 and 8 was measured and the points having equal percentages were connected (figs. 43, 44, 45). The percentage increases toward the center and downward. The isograms indicate that, when horizontal sorting is present, vertical sorting is also present. In the case of sorted circle No. 3 (fig. 44) it is seen that the finer fraction has risen to the surface and is "flowing" over it.

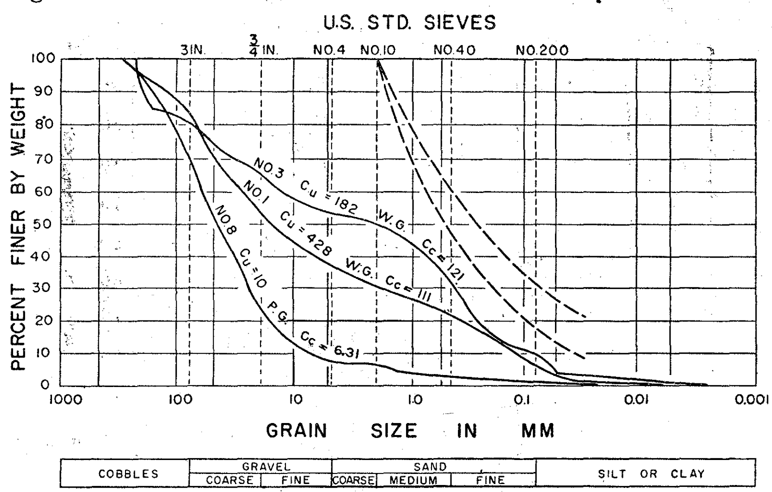

Fig. 42. Average gradation curves for sorted circles No. 1, 3, and 8 for a freeze—thaw layer 0—100 cm in depth. Solid lines are Beskow's frost susceptibility boundaries

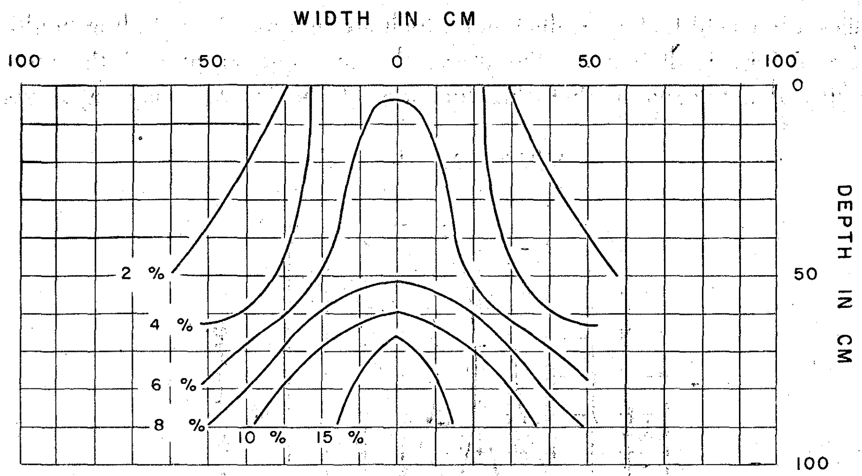

Fig. 43. Distribution of equal percentage of material finer than No. 200 sieve in sorted circle 1 between 0—100 cm depth

It has been shown that the islands of fines vary from a few cms in diameter to several meters (pl. 19) in the same thickness of the freeze—thaw layer. The spacing is random and it is easy to find only one sorted circle in a large bouldery area (pl. 20) or many scattered or closely spaced. The matrix in which sorting is present varies from gravel at the center to pebbles at the border or from sandy silt at the center to cobbles and boulders at

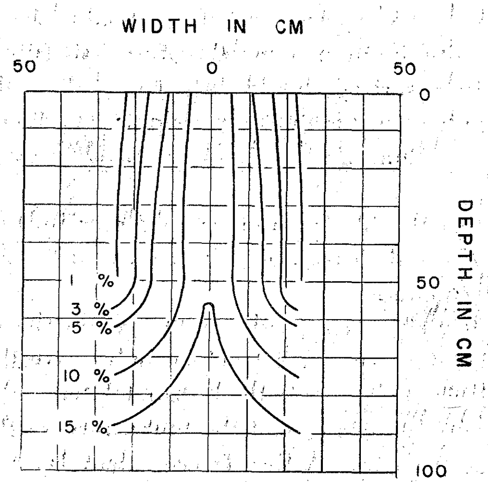

Fig. 44. Distribution of equal percentage of material finer than No. 200 sieve in sorted circle no. 3 between 0—100 cm depth

the border. In the Thule area, near Cape Athol, there are small sorted circles a few centimeters in diameter which are in a matrix including boulders 5 meters in diameter. Therefore, the size and spacing of the areas of fines depends on neither the thickness of the freeze—thaw layer nor

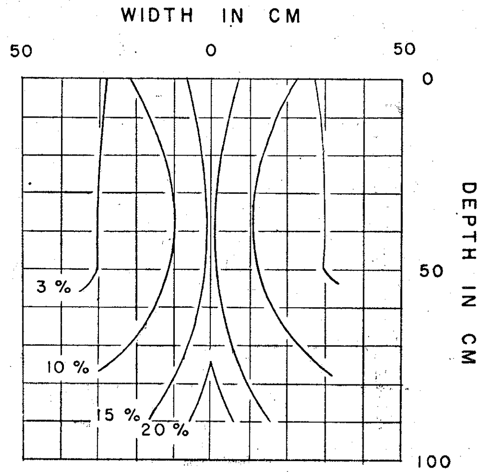

Fig. 45. Distribution of equal percentage of material finer than No. 200 sieve in sorted circle No. 4 between 0—100 cm depth

the size range of the matrix. Laboratory experiments (see pp. 177—208) have shown that particles move away from the cooling front, the finest move farther than the coarsest ones.

Large stones at the soil surface in nature should have the same effect as the side of the aluminum pan in laboratory experiments with lateral freezing (p. 188—193), sorting should start around them if the soil freezes with a horizontal gradient as it is shown by field measurements. It is realized that a sorted circle is obtained in the aluminum pan because of the geometry of the container.

It is proposed that the spacing and size of the islands of fines depends of the changes of C_u and distribution of coarser elements around which finer particles will migrate.

We can visualize that a layer with no changes in the uniformity coefficient in the horizontal plane will produce only vertical sorting. When the uniformity coefficient changes in the horizontal plane, the area of sorting will be determined by the changes of the uniformity coefficient or by the spacing of the large particles. A thin freeze—thaw layer with changes in C_u or large particles scattered over long distances will produce a wider area of sorting than a thick layer which includes closely spaced boulders and cobbles. This point of view disagrees with Troll's (1944) that the size of the sorted circles depends on the thickness of the freeze—thaw layer. Further experimental work on the effects of the layer thickness and changes in C_u in the sorting process is required.

From this field data it is possible to make the following conclusions:

(1) The horizontal plane of sorted features shows an increase in particle size from the center out, and the vertical plane shows a decrease in particle size downward producing the phenomena called "vertical—horizontal sorting" or simply "lateral sorting". Horizontal sorting at the surface is a two dimensional phenomenon in which sorting is produced along two directions, horizontal and vertical.

(2) "Lateral sorting" has been observed in well graded and poorly graded material with and without fines (0.074 mm fraction).

(3) The size and spacing of the sorted features does not depend on the thickness of the freeze—thaw layer. It is considered that the initial distribution of particles and the change in particle size or uniformity coefficient in the horizontal plane is an important factor in both size and spacing.

(4) The average grain size range where this process has been observed is in the range of the so-called "non-frost-susceptible soils". It is to be expected that the same phenomenon should be present also in materials which include a greater percentage of less than 0.02 mm fraction. Since vertical and horizontal sorting happens in the so-called "non-frost-susceptible" range, it is concluded that sorting in such coarse soil has no relation with heaving or ice lens formation by freezing. This point is made clear in the demonstration of migration of particles in front of the freezing plane (p. 197). However, it is necessary to emphasize that fine soil which is able to produce ice lenses can accelerate the process of sorting (p. 209).

Part VII

CORRELATION OF LABORATORY EXPERIMENTS WITH FIELD DATA

The experiments of freezing from the top down simulated the rates of freezing of the upper part of the active freeze—thaw layer. At freezing rates near 0.6 mm/hr coarse particles move up and fines down (fig. 46).

In bottom-up freezing and thawing from the top down, although sorting began at approximately 10 mm/hr, the amount did not become significant until smaller than 0.6 mm/hr were obtained.

A freezing plane moving from the bottom, on which a layer 2 to 3 mm thick of particles 0.1 to 2.0 mm in diameter have been seeded, will carry fine particles upwards while the coarse ones will be left near the seeding position. In a layer 70 mm thick a reverse sorting is observed in the upper part of the sample (mechanical sorting, p. 193—197).

A great difference exists between freezing from the top and from the bottom. When the freezing line penetrates the soil from the top, the grains of the lower part are not affected.

However, when freezing proceeds from the bottom the whole unfrozen layer is subjected to "shaking" as ice begins to form. This permits particles to move differentially with respect to others depending on particle size and the amount of water which is being frozen at the interface. Since the grain sizes are different, the amount of water which freezes in the pores varies from place to place. This produces the differential movement of the particles located above the freezing plane and is considered the main cause of the upward migration of coarse particles and the downward migration of the fines.

Goldthwait (Washburn 1956, p. 856) suggested that "multigelation" might produce sorting comparable to artificial vibration. Such kind of sorting was observed only in the bottom up freezing in a sandy layer 70 mm thick.

In the side freezing experiments sorting occurs by migration in front of the freezing plane. When the migrating particles produce a mound, mechanical sorting from the mound to the depressions is observed (pan experiments).

Other experiments show that mounds and depressions can be produced when the uniformity coefficient changes (Part I—V).

It is observed in nature (Part VI, p. 220), that some sorted areas have a domed surface. It is therefore postulated that a mound is a necessary, but not the only condition, for lateral sorting.

However the factors of mound formation require further research. Another aspect to be considered is the loading effect. Bottom up freezing of the freeze—thaw layer shows vertical sorting regardless of the total dead of the layer. The average in place dry density of the soil in the layer where vertical sorting has taken place is about 2.0 g/cm^3 (125 lb/ft^3). Assuming an average thickness of 100 cm for the freeze—thaw layer would yield a load of 200 g/cm^2 (373 lb/ft^2). This indicates that vertical sorting can take place under large loads and large boulders can even be heaved to the soil surface.

Vertical sorting has also been observed in material deposited by man over the past 15—20 years in the Fairbanks area. Here the soil freezes from the top down. Sorting was observed under saturated conditions and shows a decrease as the moisture content decreases. Some sorting was

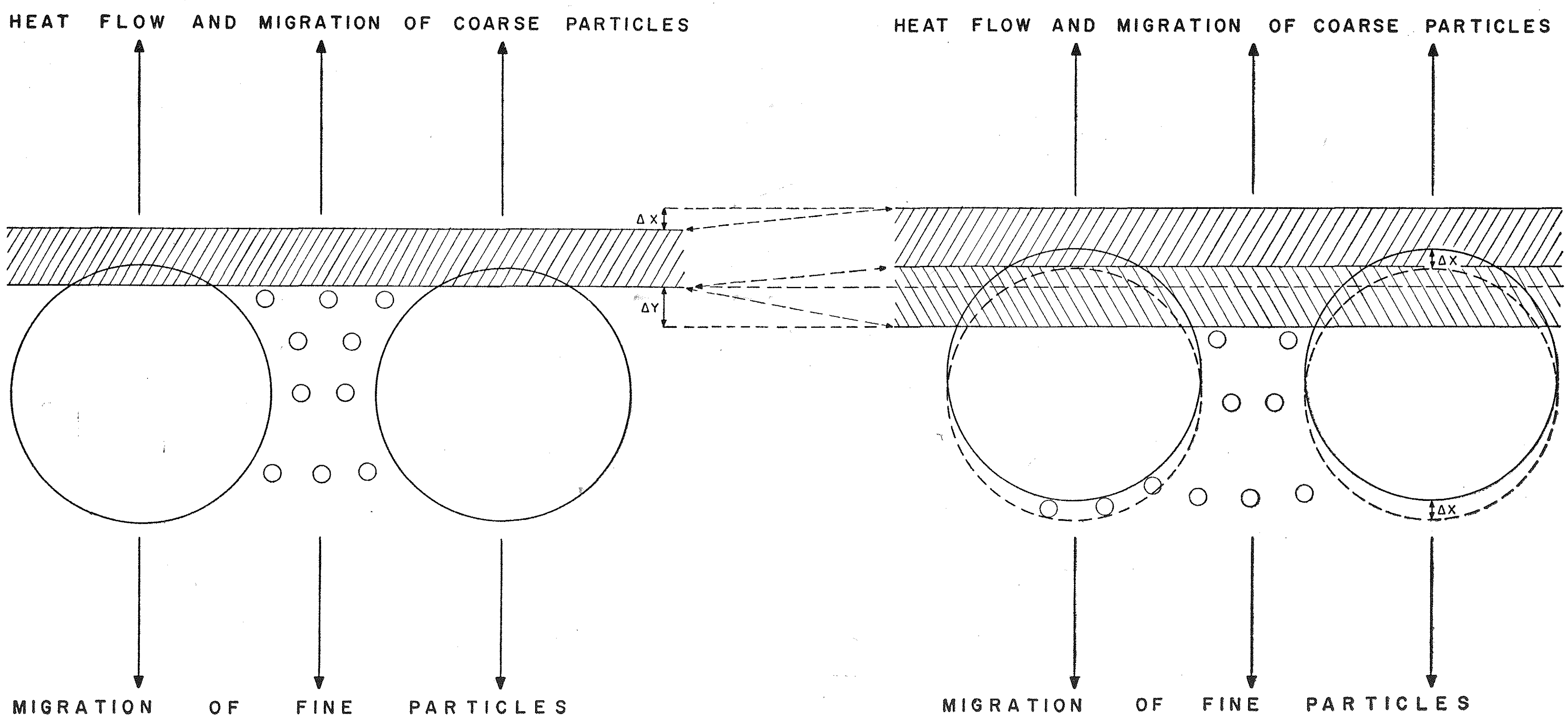

Fig. 46. Diagrammatic representation of the upward migration of coarse particles and downward movement of the fines by top down freezing

also observed under a 15 cm concrete slab which had been flooded during freezing.

Since coarse particles move up and fines down, any coarse particles located in the layer act as an "umbrella" for the fines which are moving down. This is the reason why a concentration of fines is located on the top of stones and none underneath (Corte 1961—1962b).

The presence of coarse particles under the stones observed by Vilborg (1955) is considered a part of the process of sorting.

According to laboratory and field experiments and field data vertical and lateral sorting are not restricted to a specific grain size range or slope of the gradation curve (figs. 47, 48). However, it is necessary to continue researches in this area. It has been observed in the so called "non-frost-susceptible" soils of Beskow. Since particles migrate, a "non-frostsusceptible" soil become "frost-susceptible" when the finer fraction susceptible to ice lens formation becomes concentrated.

Experiments which were performed with a vertical freeze—thaw plane (Part I p. 188) and with freezing rates between 30—42 mm/hr did not exactly simulate the natural rates of freezing of the active layer. The experimental rates of freezing were too high compared with those in the order of 2.4 mm/hr reported by Taylor (1956, p. 189) for the upper part of the freeze—thaw layer in the Thule area and a maximum of 12 mm/hr reported by K. A. Linell (USA CRREL, personal communication). It was demonstrated, however, that sorting is produced by particle migration in front of a vertical moving freezing-plane even in spite of the use of a "closed system". It has been showing (Part I, pp. 178 and 193) that particle segregation is the greatest for slow rates of freezing and it is, therefore, clear that segregation should increase as the rate freezing decreases in side freezing.

It was postulated (Part II) that a film of water must be maintained between the particle and the ice front for it to migrate continuously in front of a freezing plane. In other words, particle migration decreases as the water supply decreases. This has been demonstrated in laboratory experiments as well as observed in natural processes.

It was also demonstrated (Part II) that a constant rate of freezing moved 7.0 mm particles slightly and the intermediate sizes (3—2 mm) more before trapped by the ice; whereas the finer particles (0.1 mm) moved continuously in front of the freezing plane. It was also shown that the finer fraction (0.1—0.5 mm) moved under a wide range of rates of freezing while coarser ones (1—2 mm) migrated under a much narrower range. This indicates that the finer fraction of a mixture migrates more than the coarser fraction which contributes to lateral sorting.

Comparing the shape of the isograms of the side freezing experiments (fig. 11: a, b, c) with the isograms of the sorted areas in the freeze—thaw layer in Greenland (figs. 42, 43, 44) it is possible to say that the shape of the isograms depends on the inclination of the freezing plane and the inclination depends on the relative concentration of coarse and fine particles. Less well understood is the effect of rate of freezing.

MODEL FOR SORTING PROPOSED

With this information it is possible to propose the following model for the effect of freeze—thaw cycles in two different layers: (1) a uniform layer with no changes in the uniformity coefficient (C_u), and (2) a layer with changes in the C_u across short distances along a horizontal plane.

(1) A coarse soil layer without changes in the uniformity coefficient in either the vertical or horizontal plane will start to freeze along a horizontal plane. Large particles will move up and the fines down. The result will be a uniform volume increase and vertical sorting within the layer (Part I, p. 178—197). Freeze—thaw cycles in such a layer develop either a "boulder field" or a "boulder stream". Because of differential migration of coarse and fines during the process of vertical sorting, areas of fines are observed at the surface. Such fines can be brought more close together as a result of lateral freezing.

These experiments show that the formation of mounds are not essential for lateral sorting. From this point of view an area of fines can be considered as a stage in the development of vertical sorting.

(2) A soil layer with changes in the grain size gradation along the horizontal plane develops vertical sorting. The volume increase will be greater in areas with a high C_u than in areas with a low C_u (Part I—IV). Sorted circles such as 1, 3, and 8 (fig. 41) with a C_u of 428, 182, and 10 are capable of producing volume changes of 43%, 42% and 18% respectively (Part IV; fig. 25). Since this sorting occurred in a heterogeneous material about 1 meter thick and with a C_u between 100 and 400, volume changes of 35% to 45% have to be expected. Volume changes by freezing and thawing lead to the phenomenon of vertical and lateral sorting which create mounds in the soil and cause particles to gravitate to the lower surrounding area. Coarse particles reaching the surface will gravitate down the slope of the mounds leaving a concentration of fines in the center (p. 178—213).

According to this model, an area of fines can be a stage in the development of vertical sorting. During the development of vertical sorting mounds can be formed. As a result mechanical sorting from the mounds should follow, creating lateral sorting. As a consequence, vertical sorting and volume expansion should be primary factors in lateral sorting.

THE IMPLICATIONS OF SORTING BY FREEZING

Layers of certain size particles can be produced by a slow moving freezing plane. An important conclusion is that the contorted layers which have been thought to be folded by frost action can also now be considered as layers formed by the differential movement of particles in front of a freezing plane. Therefore, the texture of a deposited material can be altered by freezing.

The fact that particles can be concentrated at certain places within a layer brings evidences against the present frost criteria used for engineering applications (Casagrande 1931; Beskow 1935; Schaible 1953—54), which is based on certain the percentage of the 0.02 mm.

Figures 47 and 48 show some of the materials which developed either vertical or lateral sorting in the laboratory or in the field. They are compared with the frost heaving curves of Beskow (1935).

The chances for the formation of ice lenses, which are detrimental in construction, increase with the greater amount of fines for different kinds of minerals (Linell & Kaplar 1959, p. 96). Beskow (1935, p. 54) also demonstrated that ice segregation increases when the uniform

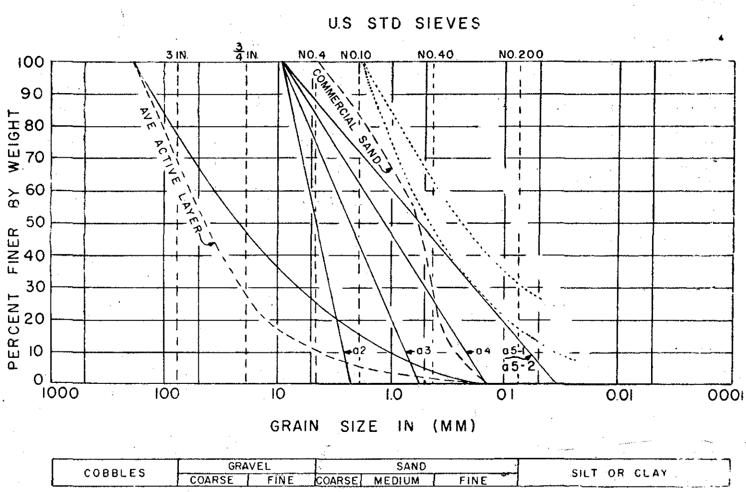

Fig. 47. Grain size curves of materials in which vertical sorting has been produced in laboratory—field experiments and natural processes

Notice that vertical sorting can be observed in the so-called "never-frost-heaving moraine soils" of Beskow

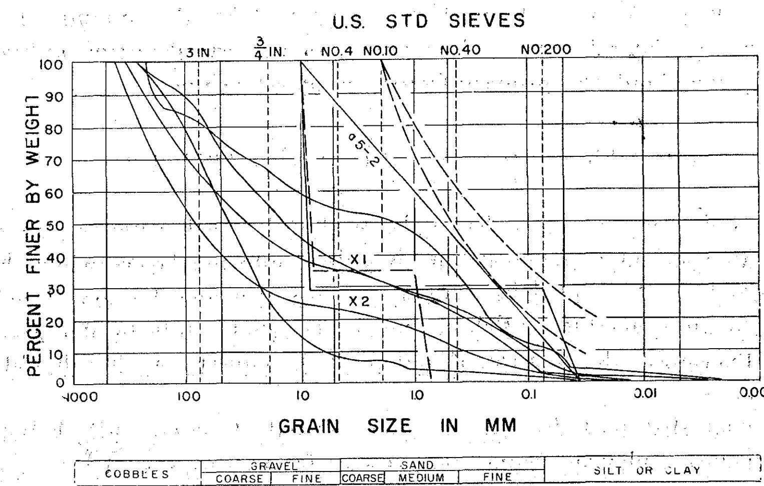

Fig. 48. Grain size curves of materials in which *lateral sorting* have been produced in laboratory experiments and natural processes

Notice that such sorting is observed in the so-called "never-frost-heaving moraine soils" of Beskow

particle size decreases to a certain size. These experimental demonstrations of sorting by freezing pose a challenging problem to the engineering constructions; a heterogeneous soil layer which contains a certain percentage of fines (silt and clay) have a tendency to become sorted when subjected to a sufficient number of cycles of freeze—thaw, under optimum moisture conditions, and lack of vegetation.

The chances of frost heaving or ice lens formation will increase as more fines become concentrated. The actual increasing frost heave in roads as produced by a concentration of particles has not yet been reported in the literature.

Laboratory and field studies and field analysis have demonstrated that particle migration is not restricted to a specific grain-size range. It has been observed in the so-called "non-frost-susceptible" soil. Because particles migrate, a "non-frost-susceptible" soil becomes "frost-susceptible" when the finer fraction responsible for ice lens formation becomes concentrated.

It is predicted that the soil adjacent to a retaining wall will have a tendency to become less and less "frost-susceptible" as fines move away from it. A road embankment, if frozen from the sides, will have a tendency to become more susceptible to ice lenses at the center than at the sides.

A new approach to the problem of frost behavior in soil is presented as a range of freezing rates within which particles migrate in front of the freezing plane.

It is theorized that a layer of water between the particles and the ice front is necessary for a particle to migrate. Taber (1930) proposed that a thin film of water must be present between the growing ice lenses and the soil. If such a water layer exists it might have influence on the process of solifluction in the cold regions. The soil layer could glide on such a thin film of water between the ice layer and the soil particles. The study of the physical properties of the ice-water-particle, interfaces is therefore of primary importance. Making use of the experimental results on particle migration (Part II) Takagi (1963) has proposed a new theory of frost heaving. In his theory such a water layer is assumed.

CONCLUSIONS

From the investigations up to date the following relationships are known in the mechanism of sorting:

(1) Moisture: Sorting decreases as moisture supply decreases.

(2) Rate: Under saturation conditions, a large number of sizes can be sorted at a slow rate of freezing. A coarse heterogeneous soil which is flooded and freezes very fast will produce little sorting compared to the same soil which is also flooded but freezes very slowly. Since lateral sorting was obtained in the laboratory with freezing rates between 30—33 mm/hr, which are much higher than under natural conditions, lateral sorting in nature should not be limited to a maximum rate of 12 mm/hr, at least for the type of samples used in the laboratory.

(3) Grain size: Fine particles can be sorted under a wide range of rates of freezing; while coarse ones migrate under a narrow range of rates of freezing. Under a certain rate of freezing, skip-graded mixtures of soil will be sorted faster than heterogeneous mixtures containing many sizes. When the uniformity coefficient changes, mounds will be formed producing mechanical sorting.

(4) Freeze—thaw plane: By changing the orientation of the freeze—thaw plane, it is possible to change "vertical sorting" into "lateral sorting".

Some sorted circles or sorted nets can be developed in the following sequence:

(1) the formation of vertical sorting produces,
(2) volume expansion by sorting producing mounds,
(3) mechanical sorting into depression,
(4) lateral sorting by migration enhances sorting.

RECOMENDATIONS

Based on laboratory and field experiments a mechanism of sorting is proposed. However it should be stressed this might not be the only process of sorting by freezing. As proposed by Washburn (personal communication) there should be some concentration due to an upward mass movement of the fines.

It is recommended that experiments be performed in order to find out what other processes of sorting by freezing are operating. It is possible that materials below 0 °C and having a depressed freezing point could flow onto other materials producing sorting. The processes by which mounds and depressions are formed and the associated sorting with need to be determined.

It is necessary to excavate trenches in roads and air fields sub-bases, retaining walls and other foundations in order to determine the engineering implications of this sorting process.

It is necessary to find out how mechanical sorting is affected by increasing or decreasing thickness of the layer.

It needs to be demonstrated if partly exposed stones will produce sorting by migration around them.

In view of the engineering applications by freezing and thawing from the sides and from the bottom up, it is necessary to perform experiments in order to develop criteria.

We need more information on the sorting effects when the thickness and the uniformity coefficient of the layer changes.

Field analysis are necessary in order to find out if circular sorted features are formed in materials which should be considered "frost susceptible". Sampling of such features should include the whole unit until reaching a uniform size, and should not be made of only the finer central portion.

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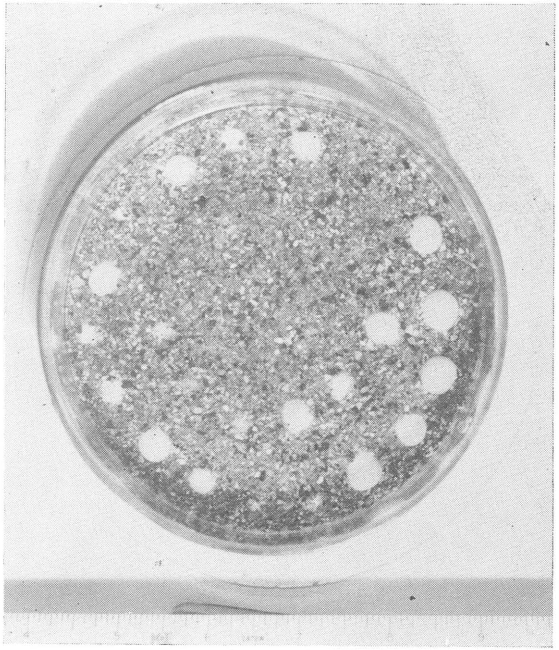
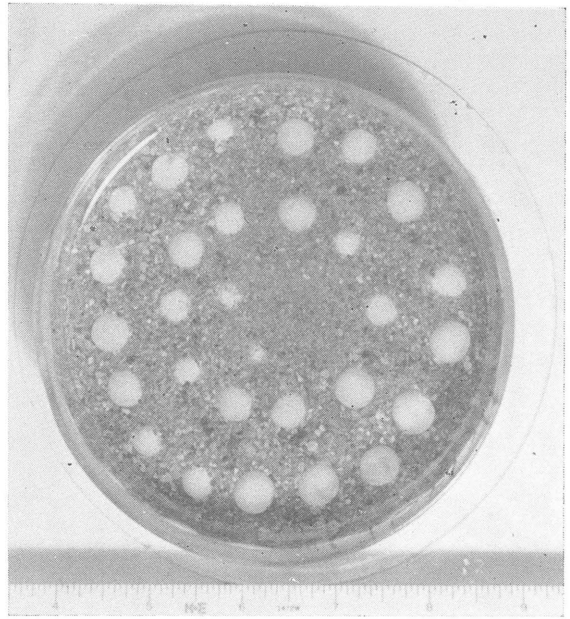
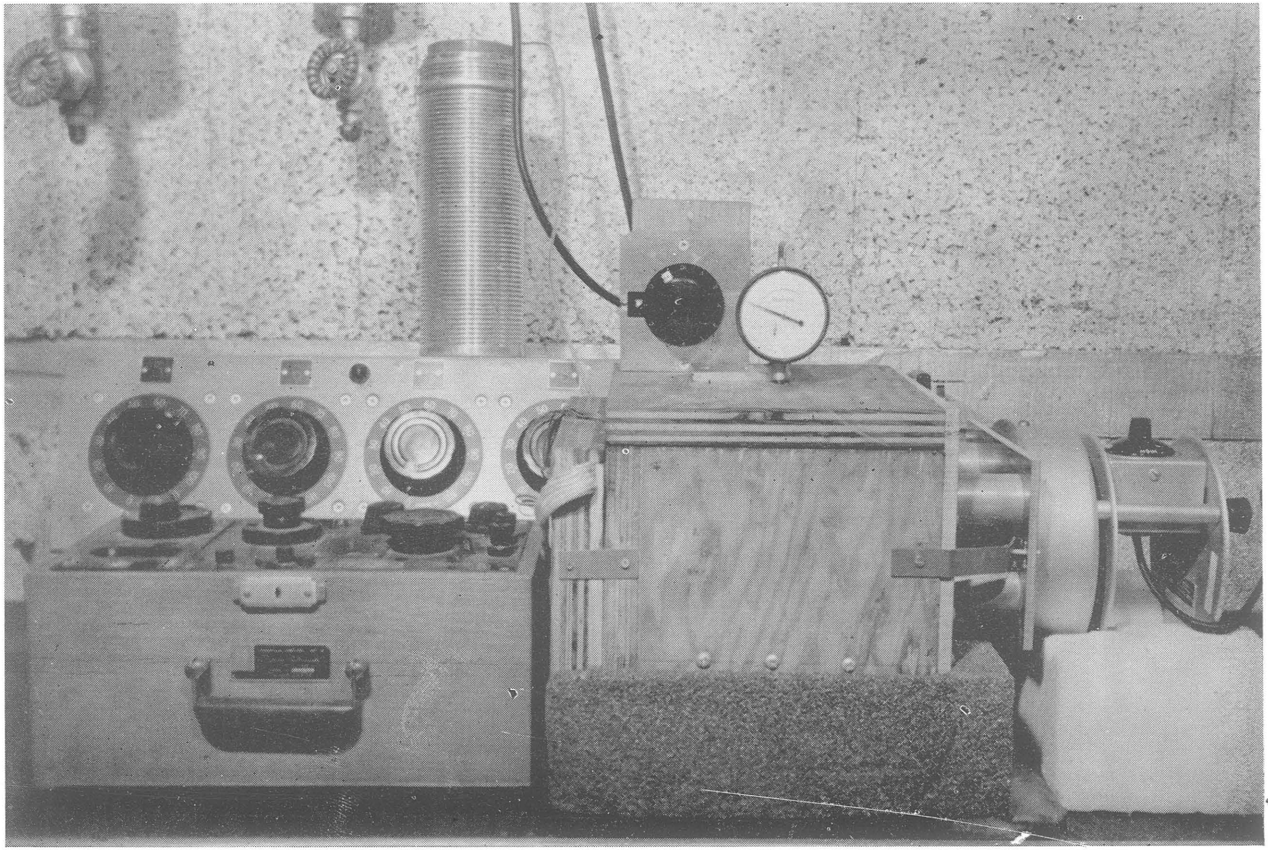
Pl. 1. Air view of islands of fines ranging in area from a few dm^2 up to several hundreds of m^2 formed in the outwash material. Thule, Greenland



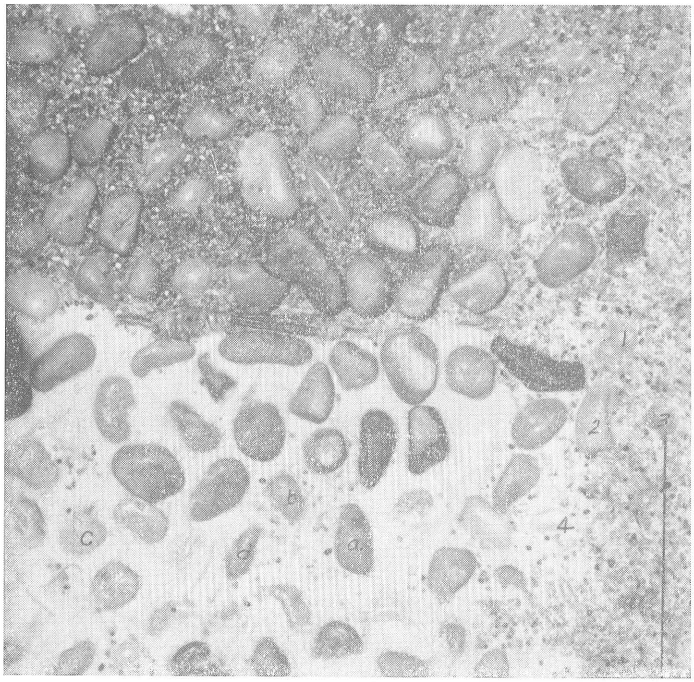
Pl. 2. Heaving of marbles in sand, after 6 cycles of freeze—thaw. At cycle 0 a layer of sand covered the marbles



Pl. 3. Heaving of marbles in sand, after 19 cycles of freeze—thaw



Pl. 4. Side freezing "closed system" cabinet which allows a sample to freeze from the sides at different rate of freezing. A heating tape at the back controls rate of freezing



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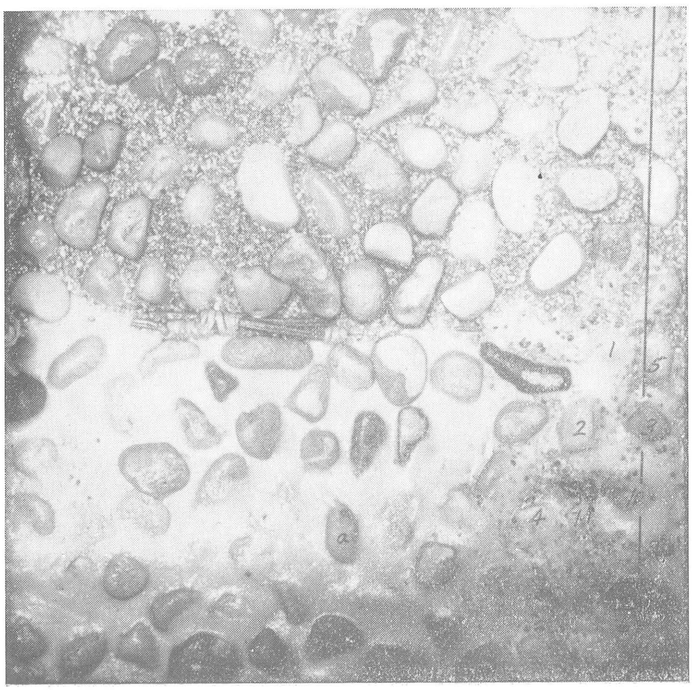

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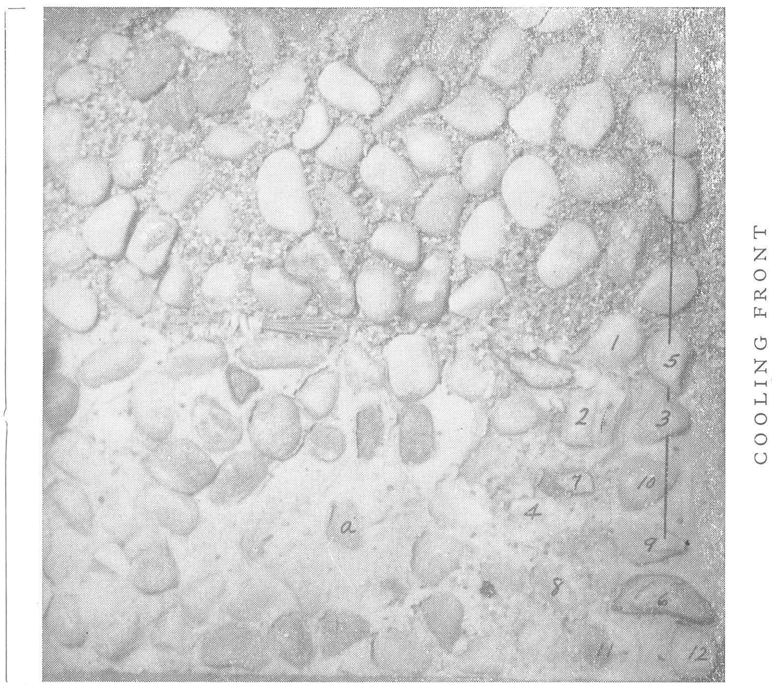
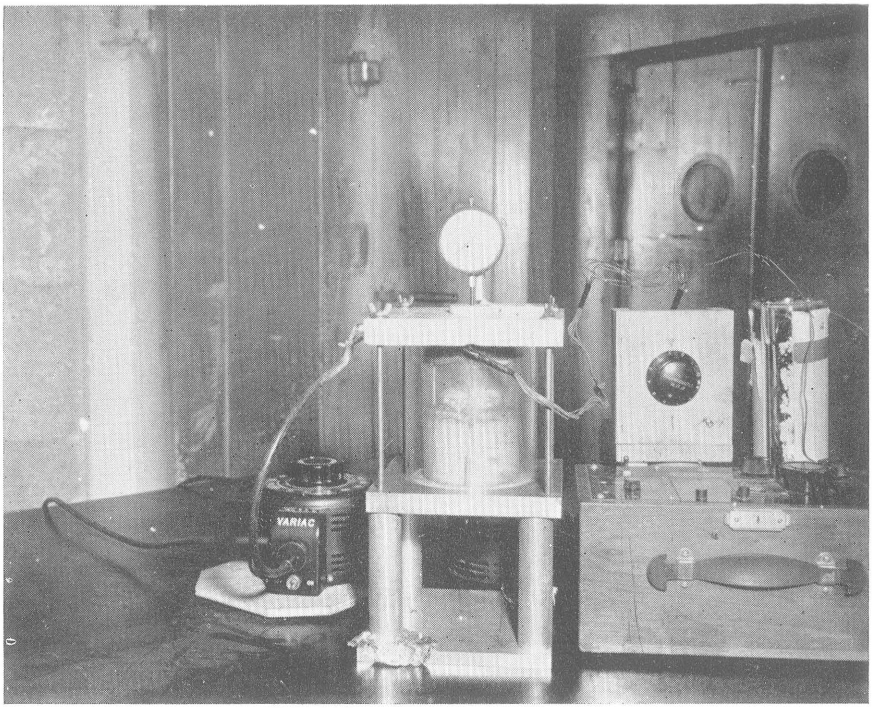
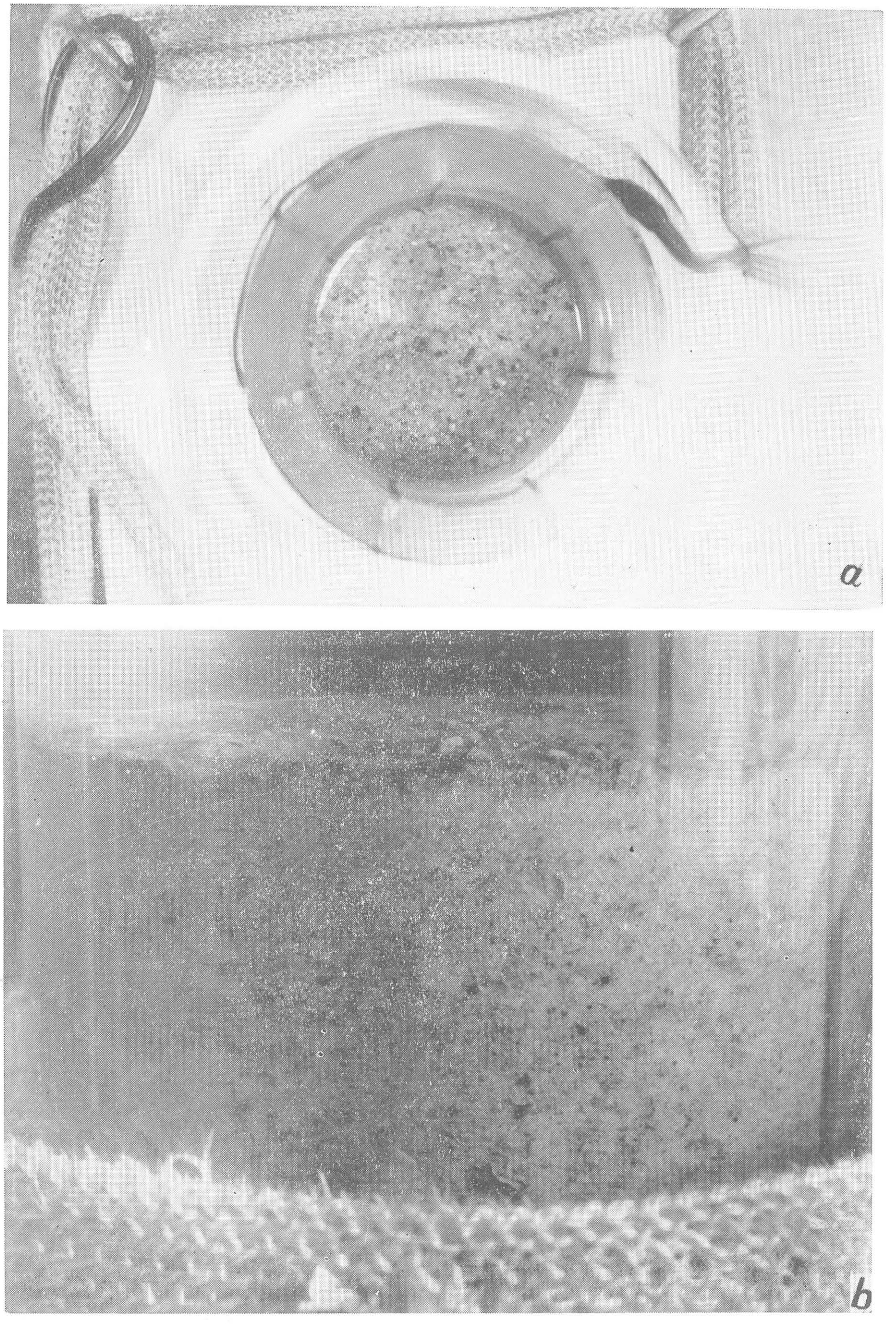


Pl. 5. Plan view of side freezing tests with samples ×1 and ×2: a — before cycle of freeze—thaw; b — after cycle No. 17; c — after cycle No. 30

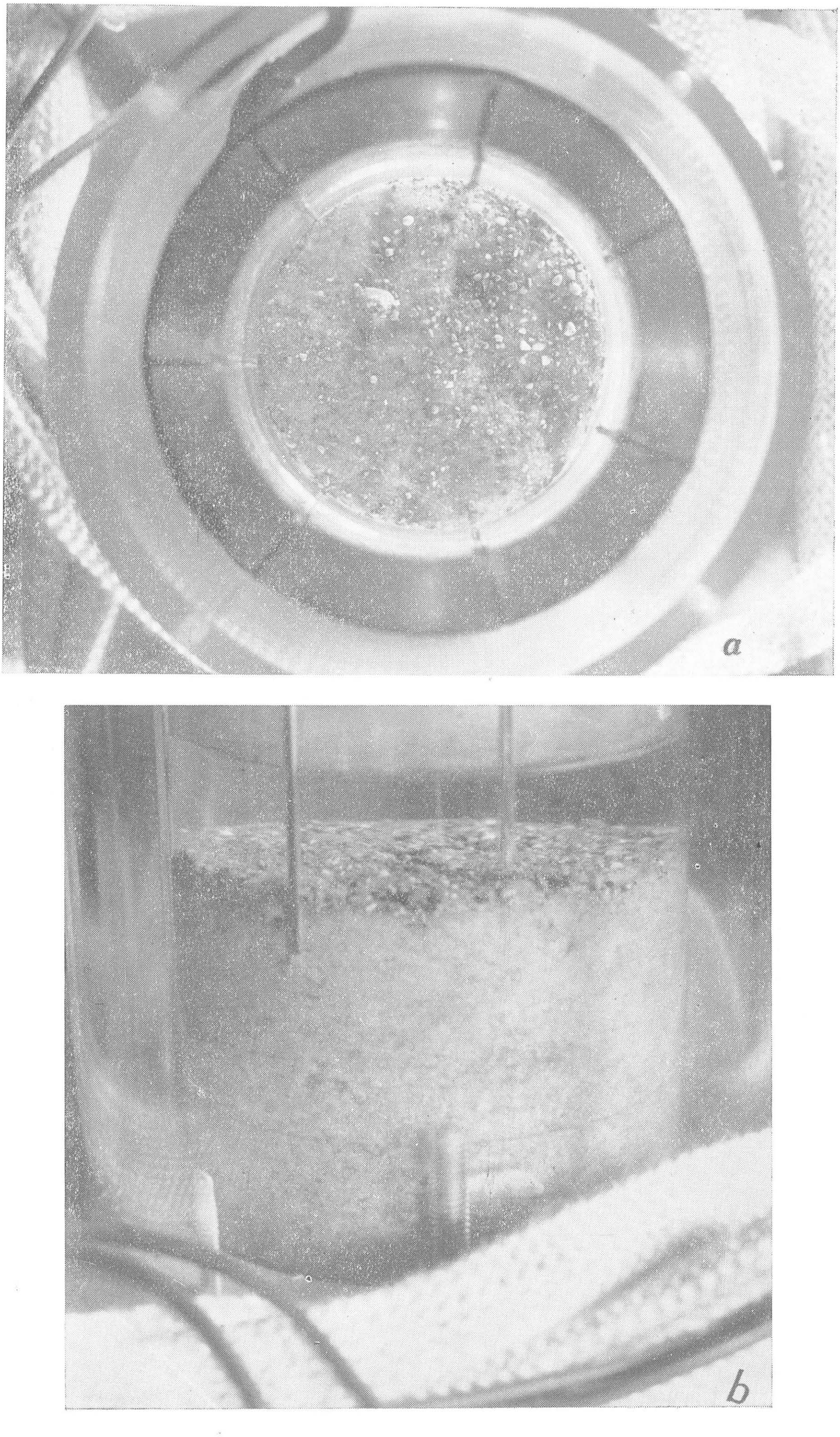


Pl. 6. "Inverted open system" freezing cabinet, which allows a sample to freeze from the bottom upward at different rates of freezing. A heating tape located on the wooden top controls freezing speed

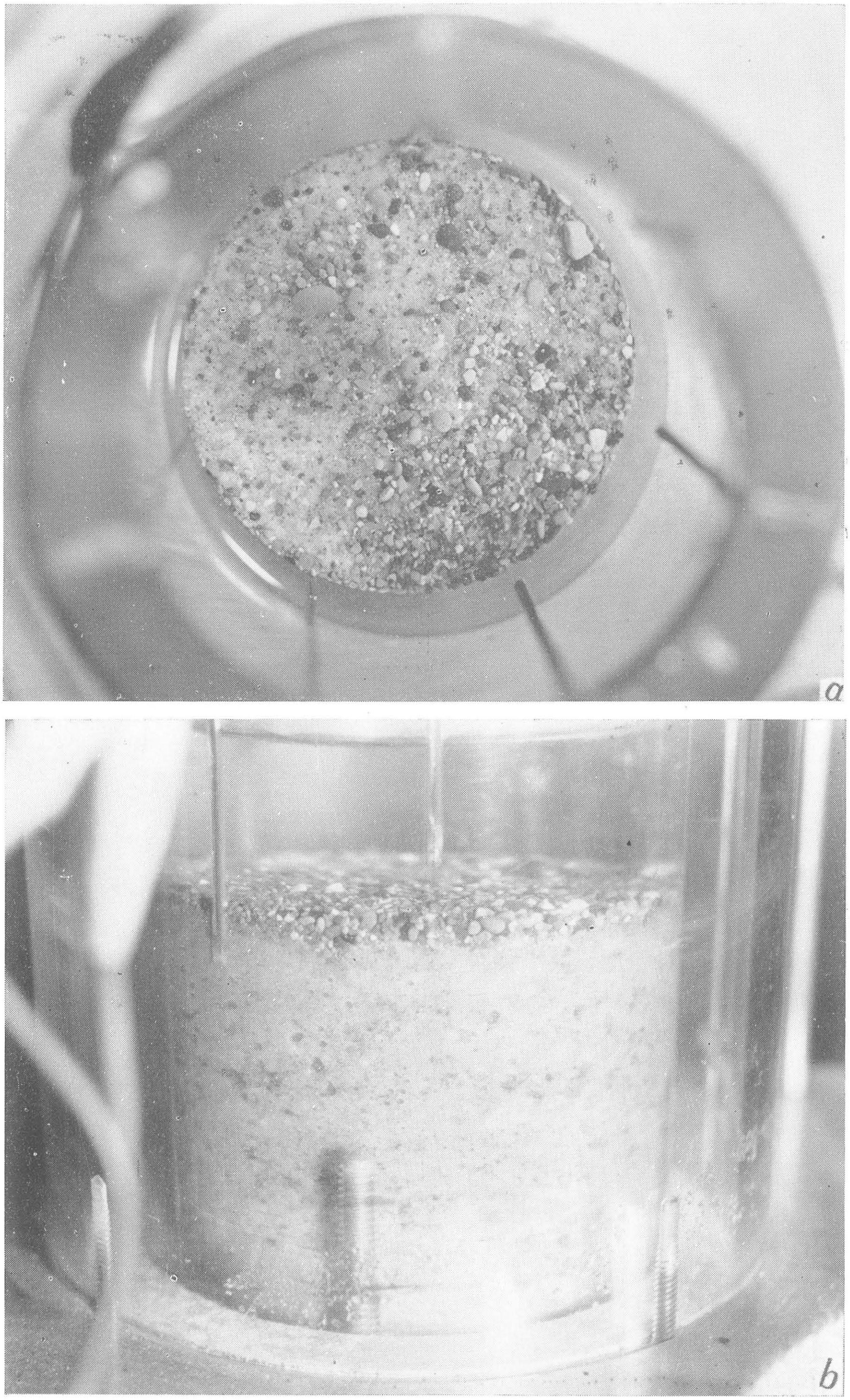
Pl. 7. Top (a) and side (b) view of "inverted open system" cabinet showing a5-2 sample at cycle 1, freezing at a rate of 0.6 mm/hr



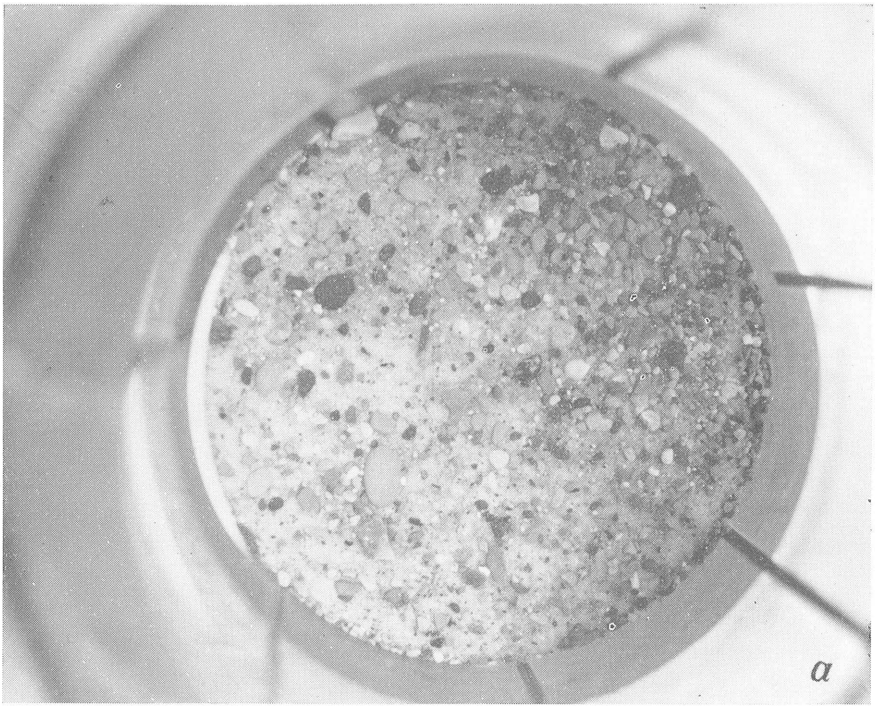
Pl. 8. Top (a) and side (b) view of same experiment at cycle 3 (pl. 7)



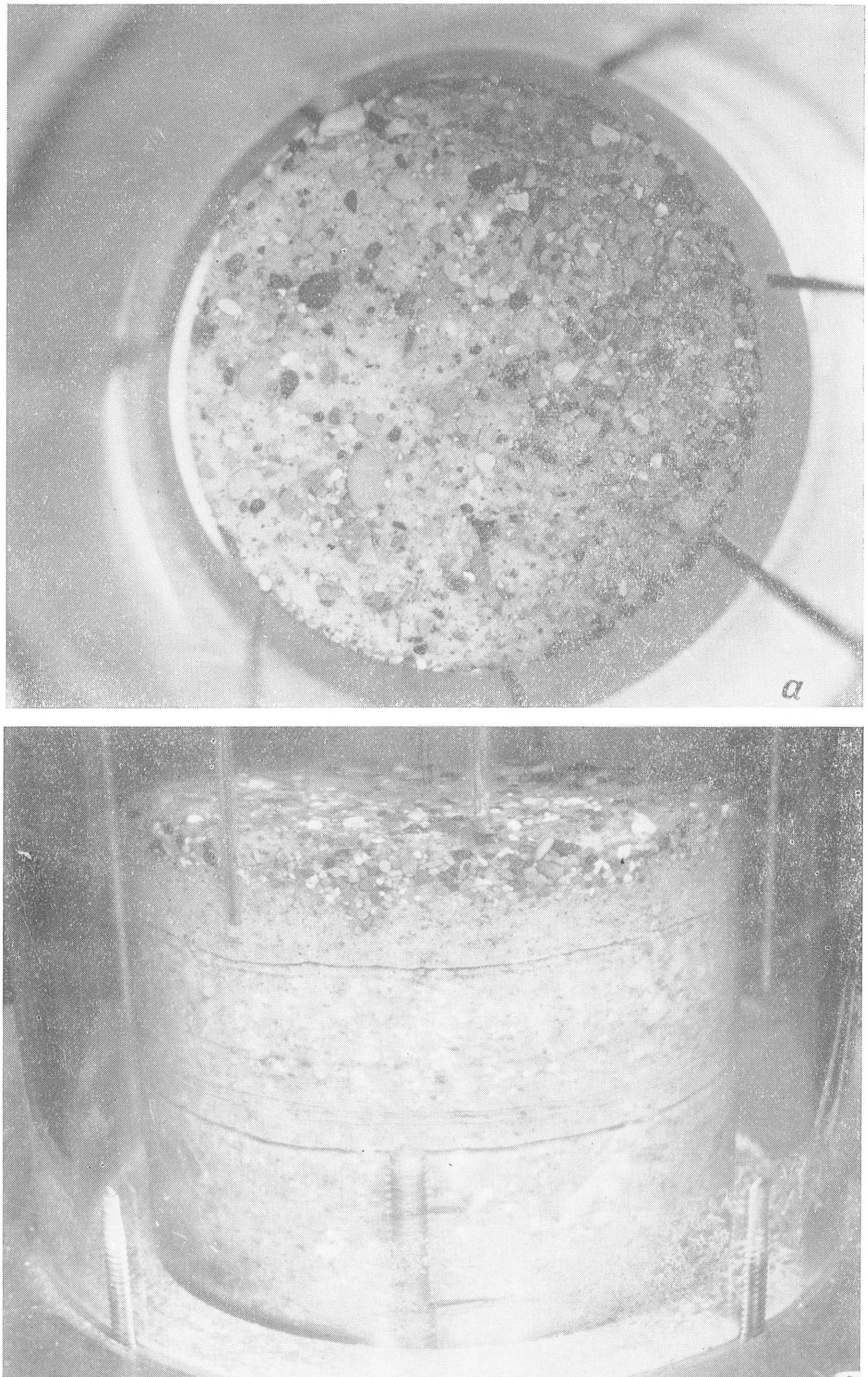
Pl. 9. Same experiment at cycle 5



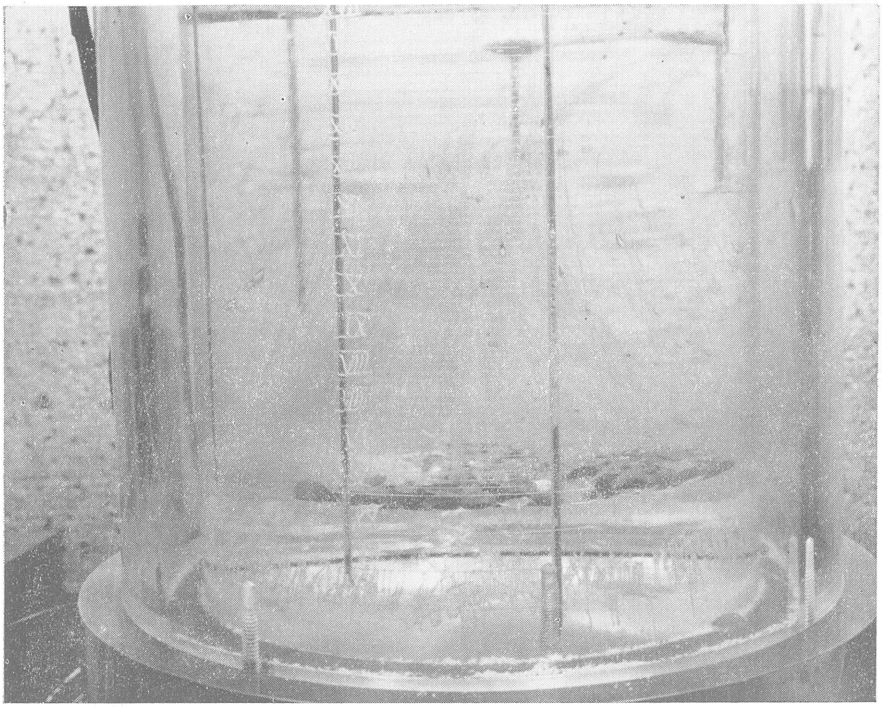
Pl. 10. Same experiment at cycle 6



Pl. 11. Same experiment at cycle 7

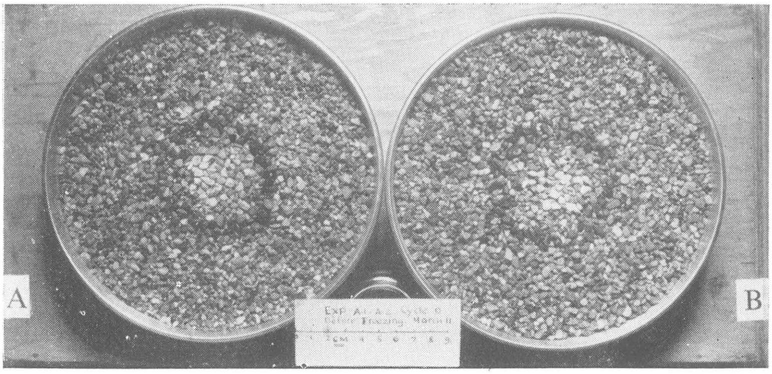


Pl. 12. Same experiment at cycle 8



Pl. 13. Transparent freezing cabinet which allows a sample of distilled water to freeze from the bottom upwards

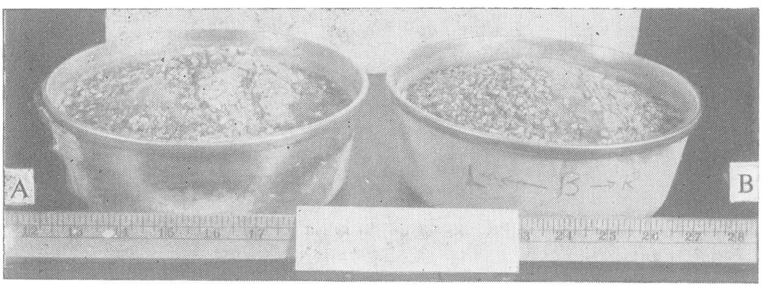
Vertical migration of three sizes of sand (0.1—7.0 mm) which were seeded close to the bottom. Fine particles were carried to the top and coarser ones trapped by the ice close to the seeding position. Notice the stream of bubbles underneath the particles


A
B

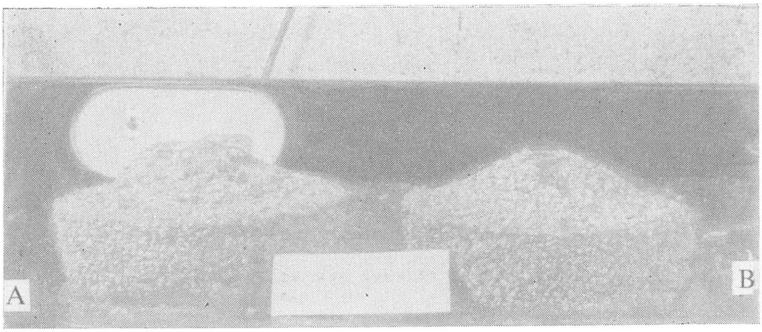
a)


A
B
EFFECT OF SIDE FREEZING ON SILT UNDER
SAND LAYERS, FLAT SURFACE

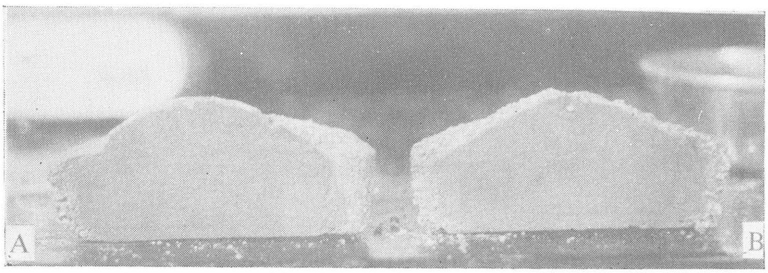
b)


A
B

c)



d)

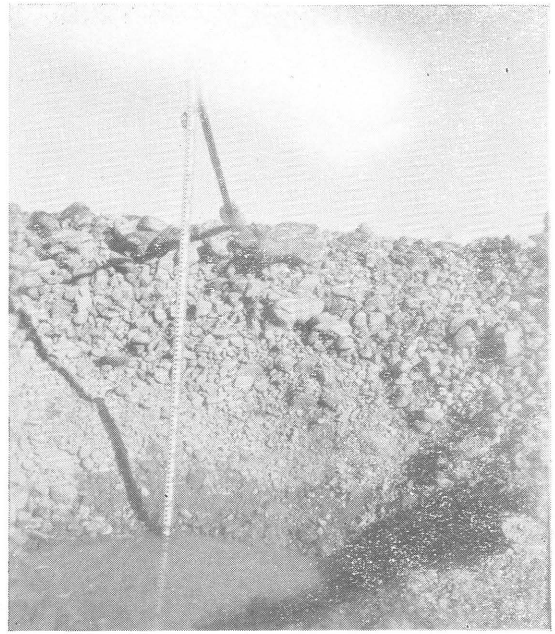


e)

Pl. 14. Experiment A (domed layers) left and Experiment B (flat layers):
- a — before cyclic freeze—thaw
- b — after 18 cycles of freeze—thaw
- c — after 33 cycles of freeze—thaw
- d — out of the container after 33 cycles
- e — cross section during frozen stage, at cycle 33; notice that surface of Exp. A has less coarse particles than surface of Exp. B

Pl. 15. General view of plain at border of ice cap, Thule area.

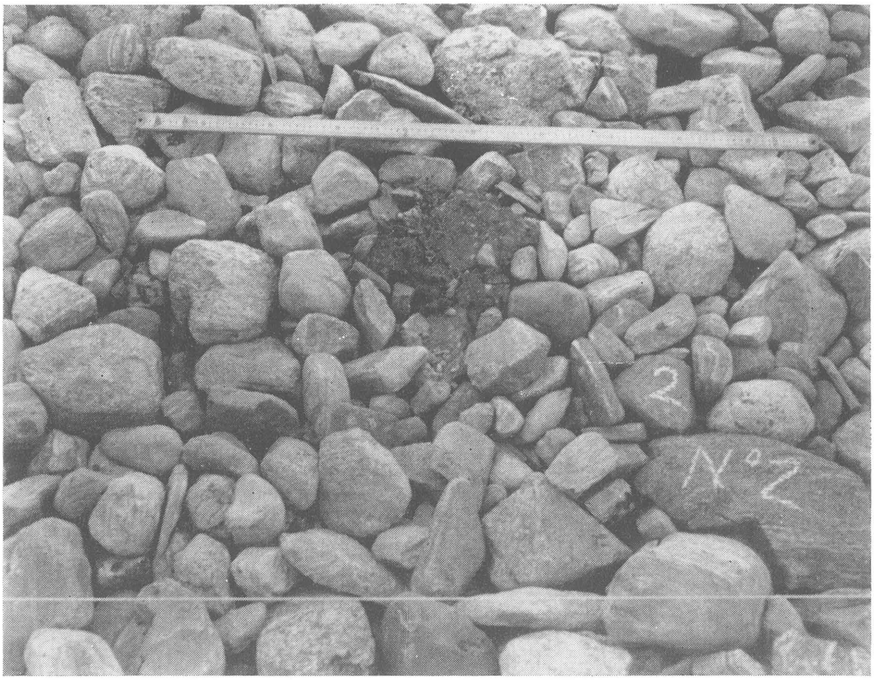
Active layer in lower left corner removed to deeper level than at foot of trench wall. Active layer also removed in middle background (white areas). Coarse particles near barrel were put here during excavation



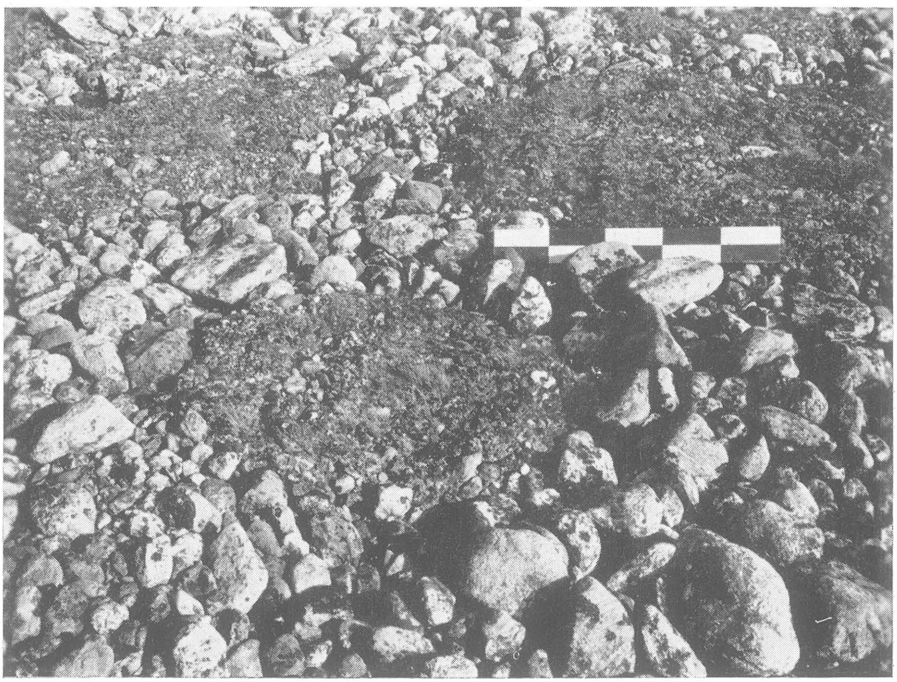
Pl. 16. Vertical sorting in flat terrain, Thule area. Scale rests about 29—30 cm below permafrost table

Pl. 17. Vertical sorting on a gentle slope around "islands" or "centers" of fines

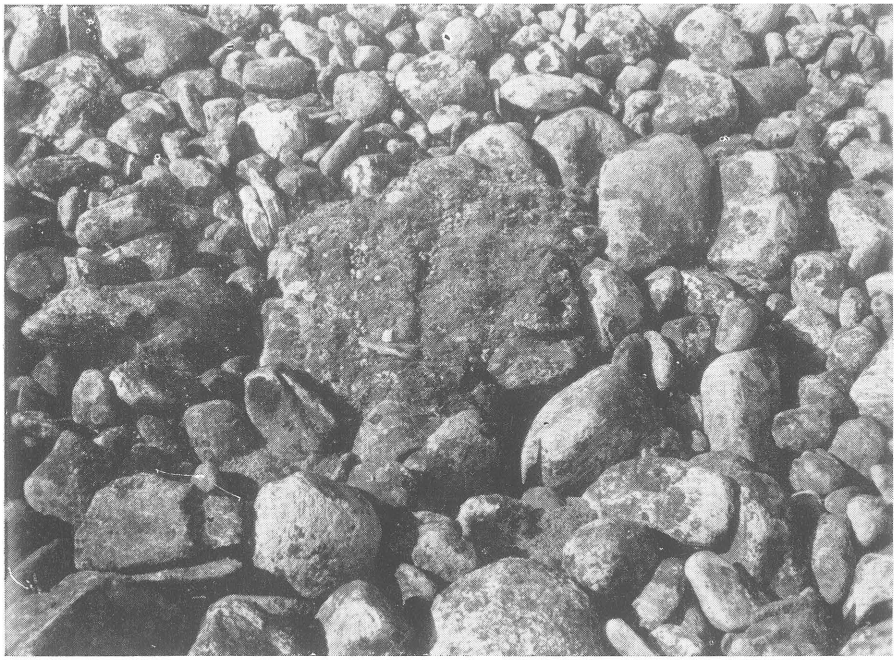
Pl. 18. Vertical sorting on a steeper slope. Scale rests on permafrost



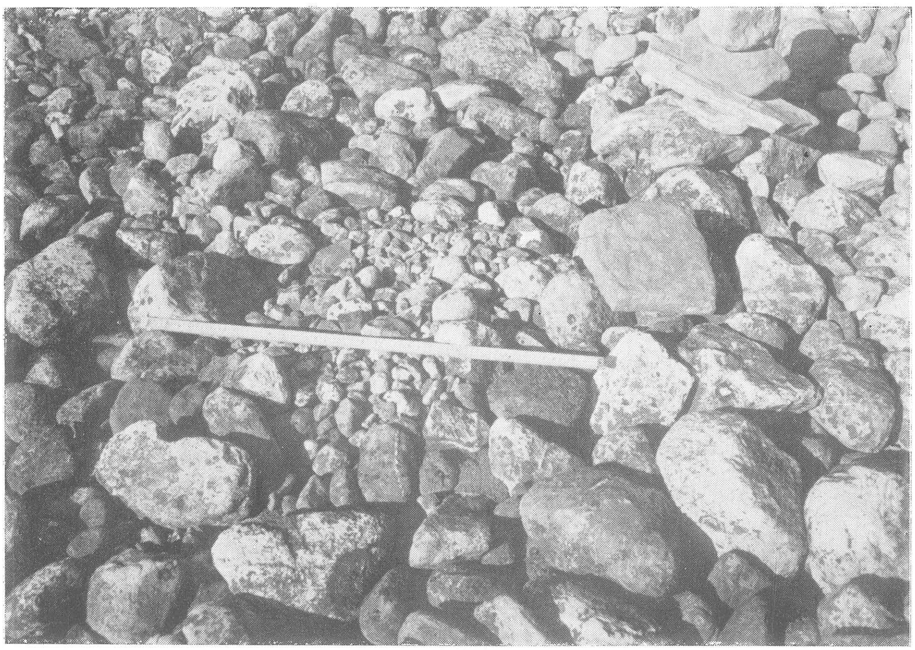
Pl. 19. Accumulation of fines 15 cm in diameter



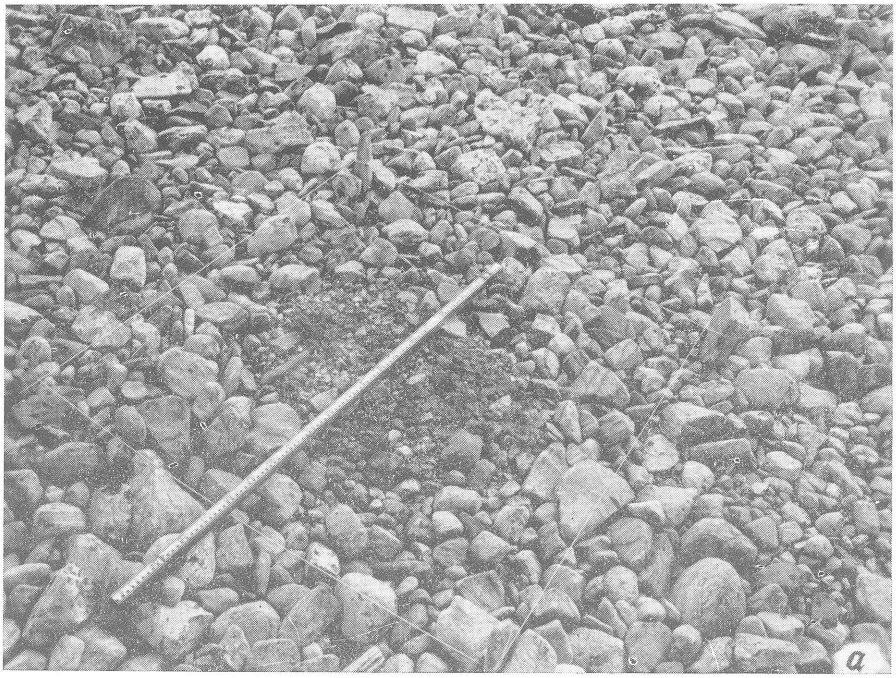
Pl. 20. Closely spaced centers of fines which give the appearance of a polygonal feature

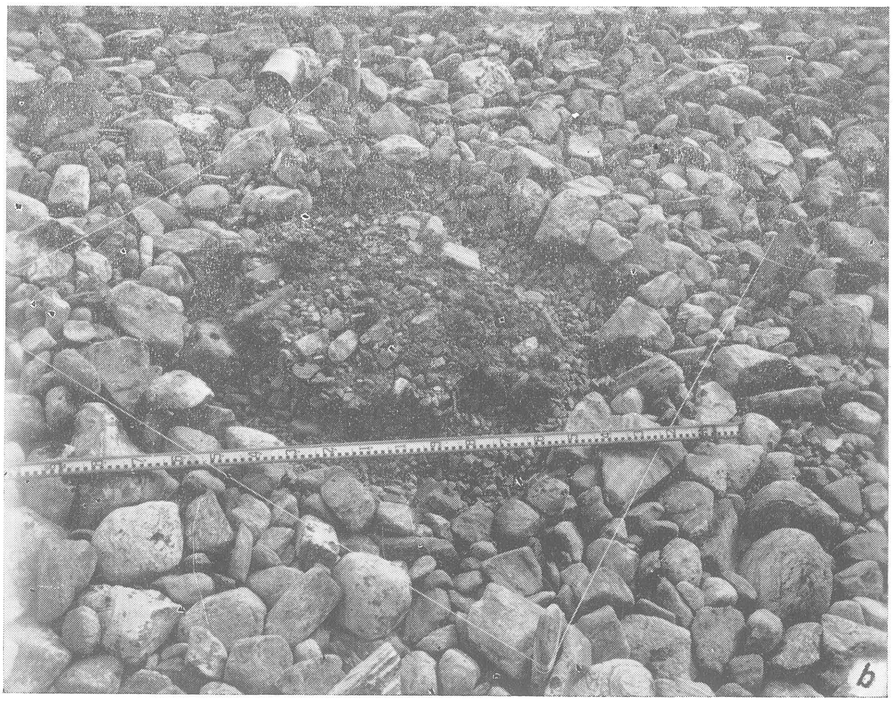


Pl. 21. Sorted circle No. 3



Pl. 22. Sorted circle No. 8 developed in sand and gravel without fines





Pl. 23. Sorted circle No. 1: (a) prior to excavation for sampling, and (b) after removal of outer coarse particles showing the layer of finer particles beneath