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[F O U R T H S E R I E S .]

ART. XXXII.—*Experimental Studies and Observations on Ice Structure*; by O. D. VON ENGELN.

Introductory.—A detailed account of these experiments has been published under the joint authorship of the late R. S. Tarr and the present writer in the *Zeitschrift für Gletscherkunde* (1915, vol. ix, pp. 81–139). In view of the restrictions imposed by the European situation, the fact that the *Zeitschrift* reaches only glacialists and that new points have come up since the writing of the longer article, it is deemed worth while to summarize the chief results obtained in an American periodical. Those specially interested in the subject are, however, referred to the fuller statement which contains the records, data, and methods followed in individual experiments, references to earlier literature, and acknowledgment to those who gave assistance in various ways.

The initiative in developing the work and some of the tentative conclusions are to be credited to the late Prof. R. S. Tarr. The experiments furthermore comprise the continuation of the investigations begun by Professor Tarr in the winter of 1910–11. The earlier results were published under the title "The Properties of Ice—Experimental Studies," by R. S. Tarr and J. L. Rich.* The experiments herein described were performed in the winter of 1911–12, when better facilities and apparatus were available.

Record of the Experiments.—The experiments were planned primarily to secure data bearing on the structure and flow of glacial ice. In the main they consisted of compression tests (*a*) on cubes of ice unsupported at the sides and (*b*) on cylinders of ice enclosed in metal cases of varying degrees of resistance up to complete rigidity under the pressures applied. The

* *Zeitschrift für Gletscherkunde*, vi, pp. 225–249, 1912.

tests were made with screw presses designed and calibrated by Professors Kimball and Wells of the Sibley College of Mechanical Engineering, Cornell University. (See fig. 1.) Both pond and glacier ice were used, in cubes $\frac{1}{2}$, 1, and 2 inches square and variously oriented with regard to the component crystal structure of the ice. It was found that the crushing

FIG. 1.

FIG. 1. Interior of Outdoor Laboratory. Shows large press with ice core projecting to right from lateral orifice of iron cylinder. Also shows small press (on table in background) with one of the small cubes between its plates.

strength of pond ice with pressure applied in the direction of the principal axes of the component crystals (all similarly oriented) is about 1000 lbs. per square inch. With pressure at right angles to the principal axes the crushing strength was approximately 350 lbs. to the square inch, while that of

glacier ice with variously oriented crystal grains was at some figure intermediate between 350 and 1000 lbs., and tended to the higher rather than the lower figure. These data were obtained with air temperatures between 18°F. and 20°F., but variations between 10°F. and 25°F. do not seem to have a notable effect on the strength of the ice. Great care was exercised to have the pressure faces as nearly parallel planes as possible and pressures were applied very slowly. In a number of instances increases of the load were made only after a number of hours interval; in several cases a single test occupied from 16 to 20 hours time.

The values of the crushing strength of ice here stated are notably higher than those obtained and approvingly cited by H. T. Barnes in recent papers.* The average values he quotes are 370 lbs. per sq. inch, pressure parallel to the principal axes, 356 lbs. pressure normal to the axes. The discrepancy in the first case is probably due to the following factors: (a) The ice used by Barnes was river ice and because of current action may not have had uniformly oriented crystals, especially as large size blocks, 7 inches square, were used in the tests; (b) the tests were made at air temperatures only a few degrees below freezing point and in some cases above that point; (c) the pressures were applied with comparative rapidity. The authors of the second paper cited use an average figure of 400 lbs. to the square inch as the crushing strength of ice in calculating the linear thrust of ice sheets against dams. As such thrust would be exerted at right angles to the principal axes the value of the crushing strength used is probably amply high for engineering practice.

It was repeatedly noted when working with cubes under pressure approaching the crushing point that cracking occurred when the pressure was relieved and that if the pressure release was at all rapid the ice actually broke apart. This indicates that ice yields elastically to pressures slowly and carefully applied and that the elastic rebound is not sufficiently rapid to enable the ice to withstand quick release of pressure, hence the differential stresses set up by the rapid release suffice to rupture the mass. On account of this elasticity it appears that there can not be any permanent deformation of ice until a certain minimum stress has been applied and the experiments showed that the yield-point is near the crushing strength of the ice.

If, however, pressures just below the crushing strength of the ice are applied and continued for a sufficiently long time

* Barnes, H. T. : The Crushing Strength of Ice, *Trans. Roy. Soc. Canada*, Third Series, vol. viii, pp. 19-22, 1914. Barnes, H. T., Hayward, J. W., and McLeod, N. : The Expansive Force of Ice, *ibid.*, pp. 22-49.

the ice will yield by flow without breaking. In this way the ice can be permanently deformed. Moreover, once such flow is initiated it continues for some time despite a progressive diminution of pressure. This experiment was repeated a number of times using cubes of ice $\frac{1}{2}$ -inch square. Thus on January 16, 1912, air temperature 8°F ., such a cube of pond ice was inserted in the press and a pressure of 260 lbs. applied in the direction of the principal axes. Nineteen hours later the cube had flattened to one and one-half its original area and pressure had fallen off to 230 lbs. In the cases of four other similar cubes the pressures fell off to 223, 223, 230, 226 lbs., a strikingly narrow range. The cubes were reduced to one half or one fourth their original thickness. Under the petrographic microscope it was apparent that the original crystal structure had been deformed, but the flattened ice was apparently as strong (coherent) as the original pieces, although the edges exhibited curved fractures parallel to the pressure direction. Glacier ice flowed and flattened similarly but only 185 lbs. of pressure could be initially applied to $\frac{1}{2}$ -inch cubes of such ice and at the end of flattening the pressure was about 159 lbs. As the air temperatures during these experiments were 20°F . and lower, it would seem that the yield and flow is not due to pressure melting and regelation unless this be conceived of as occurring between the particles of the crystal structure of the ice.

Various kinds and forms of ice, also snow, were compressed in metal cylinders to determine (a) whether any change in crystalline structure could be brought about by pressure only, and if so of what nature, and (b) whether actual continuous flow of ice could be induced by pressure at temperatures sufficiently low to render pressure melting and regelation inoperative. Lead cylinders, open at both ends, were first used but these yielded at pressures of 720 lbs. per square inch and the ice within crushed as the cylinder sides bulged outward. In later trials copper cylinders 4 inches in diameter, 12 inches high with walls $\frac{1}{16}$ inch thick were used.

Into such a copper cylinder a rough-hewn plug of pond ice was inserted with component crystals parallel to the length of the cylinder, and water frozen in the space between the rough-hewn core and the metal walls, making a solid ice filling. To the ends of this cylinder a pressure of 500 lbs. per square inch was applied, part of the load being borne by the metal edges of the casing. The air temperature when the pressure was applied was 17°F . and several hours later when the pressure was increased to 720 lbs. per square inch it had fallen to 15°F . On the next day at 9 A. M. the air temperature was 6°F . and no bulging of the cylinder or falling off in pressure was apparent. Accord-

FIG. 2.

FIG. 2. Ice compressed for 94 hours at air temperatures ranging between -4°F. and 20°F. , under pressures up to 1400 lbs. per square inch. Photographed immediately after removal from copper cylinder. Note that there is no distortion from the cylindrical shape. Note also the etched outlines of the outcropping ends of the crystals.

ingly the pressure was raised to 750 lbs. per square inch. The following night the temperature fell to a minimum of $-4^{\circ}\text{F}.$, and no change was apparent in the cylinder or pressure the next day. At four o'clock in the afternoon, air temperature $13^{\circ}\text{F}.$, the pressure was raised to 1400 lbs. per square inch, the upper limit of the calibrated scale of the press. At this pressure the cylinder was allowed to stand for 36 more hours, the air temperature meanwhile rising to $20^{\circ}\text{F}.$ Then the cylinder was removed from the press. It had been under varying pressures for some 94 hours at air temperatures ranging between $-4^{\circ}\text{F}.$ and $20^{\circ}\text{F}.$ On gently heating the metal cylinder it was found possible to slip the ice core out complete, indicating that there had been no bulging or distortion of the metal. (See fig. 2.)

The compressed ice was found to be of crystal clearness and homogeneous, showing no line of separation to mark the junction of the rough-hewn prism of pond ice and the water frozen around it. The most striking result, however, was the fact that *the ice mass had been completely recrystallized.* The original pond ice core was inserted with principal axes parallel to the pressure direction, the new crystals extended across the cylinder with their principal (and longer) axes at right angles to the pressure direction. On slow melting and evaporation in the laboratory the individual crystals $1/16$ to $3/16$ inches in diameter and averaging $3/4$ inch to 1 inch in length were outlined by grooves along their contact planes. A further singular phenomenon was the extension of the crystals straight across the cylinder instead of radially inwards as might have been expected by analogy to the structure of cakes of can-frozen artificial ice. The boundaries of the crystals were irregularly polygonal, an occasional one nearly hexagonal, much like glacier grains in cross section but differing from these in that the crystals of the cylinder were greatly elongated. (See figs. 3 and 4.) Under crossed nicols a section cut across one of the crystals exhibited parallel extinction, indicating that it comprised a single, uniform individual. Others showed wavy extinction in section, suggesting distortion, as is also true of glacier grains. In no case, however, were any traces of brecciation apparent. The elongated form and wedge-shaped terminations in the artificial crystals may have owed their difference from the glacier grains to the fact that the conditions of our experiment permitted of no movement in the ice mass involved.

In a later experiment this last deduction was in a sense verified. An annealed, softer, copper cylinder was filled with ice fragments of pond ice, glacier ice and snow in layers, and made solid by filling up the spaces with water and freezing. Pres-

FIG. 3.

FIG. 3. Same ice cylinder as shown in fig. 2 after reduction in size by slow melting and evaporation (mostly latter) in outdoor laboratory. Note outlines of crystals as shown by etching out of crystal boundaries into distinct grooves. Natural size approximately 8 in. high by 4 in. wide, original cylinder 12 in. by 5 in.

FIG. 4.

FIG. 4. End view of ice cylinder shown in fig. 3 and photographed at the same time. Shows roughly parallel orientation of crystals, their relative lengths and wedge-shaped terminations.

sure was applied to the top of this composite filling by means of a solid iron plunger turned to a diameter that would just permit its easy insertion into the open end of the copper cylinder. This insured all the load being borne by the ice itself. (See fig. 5.) Pressures varying from 500 to 900 lbs. per square inch were applied, over a period of five days. The cylinder bulged after the first few hours. As no notable change in the ice was apparent on removal from the cylinder after this treatment

FIG. 5.

FIG. 5. Diagram illustrating contents of annealed copper cylinder, using fitted iron plunger.

except the absence of fracturing and apparent flow indicated by the transparency and coherence of the mass, the same ice core was utilized again. This time an unannealed harder cylinder was probably used (our notes fail to state) and a solid ice mass assured by filling with water and freezing. Again using the iron plunger, pressures up to 1000 lbs. per square inch were applied and allowed to remain on over night. Next day the load had fallen off to 800 lbs. per square inch and the cylinder was very slightly deformed. The air temperatures during the time of the experiment ranged from 16° to 19° F.

On removing the ice from this second cylinder it was found to be completely recrystallized. Ends of individual crystals had diameters $1/8$ to $3/8$ inches, some were smaller. The

originally glacier ice was coarsest, the crushed top ice finest, but all parts showed the same granular structure, but not elongated crystals, and the grains were also variously oriented crystallographically. The appearance of this cylinder is shown in fig. 6.

As the ice of this cylinder had a complicated history the experiment was repeated with an annealed cylinder filled with cracked pond ice and snow only, no water frozen in. This was compacted with pressures up to 1400 lbs. per square inch with much swelling of the cylinder. Then the plunger was removed and more filling of snow and cracked ice put in. This experiment was carried on for about 5 full days, air temperatures meanwhile ranging between 5° and 27° F. On removal from the cylinder the cracked ice layers were found to be clear and glassy, the snow layers glassy but clouded with innumerable air bubbles; the whole was a homogeneous ice mass. On melting down the characteristic, granular structure, obtained in previous experiments, was found to have developed in this also in all parts, but the grains were larger in the layers of cracked ice. Under crossed nicols extinction was found to be uniform within a given grain boundary. Similar results were obtained on compressing snow alone.

It seems from these experiments that a granular ice can be developed from snow by pressure with accompanying movement at air temperatures eliminating the possibility of pressure melting and regelation. The pressures required to bring about flow and change of structure are also interesting, in that they correlate so nearly with the yield point pressures obtained in the unsupported cube experiments. It is to be remembered, however, that the pressure figures for most of the metal cylinder experiments are by no means exact, inasmuch as the area to which pressure was applied must have been constantly changing as the cylinder swelled, and can hardly have been transmitted uniformly per unit of area throughout the mass during the progress of the experiment.

In the second type of the compression experiments with metal cylinders it was planned to test the possibility of free and continuous flow of ice at temperatures sufficiently low to eliminate the development of pressure melting and regelation. A heavy iron cylinder bored out to 2 5/16 inches diameter, with a lateral orifice 3/4 inch in diameter, near the solid base was used. A solid steel plunger was turned to fit very accurately into the larger opening of the cylinder. It was proposed to force ice placed in the cylinder through the lateral orifice by applying pressure by means of the steel plunger. The arrangement of the experiment is clearly shown in fig. 1.

On March 5th at an air temperature of 22° F. the cylinder

FIG. 6.

FIG. 6. Ice cylinder of fig. 5 after second compression. Position and boundaries of different kinds of ice used in filling as marked. Note that lines of juncture of different kinds of ice are nearly obliterated and that the crystal ends bridge them. Outline of the old top of ice from first compression shown faintly under the snow ice, indicating transparency of latter. Granules shown to be largest in glacial ice.

was filled with ice fragments and a pressure of approximately 3400 lbs. per square inch applied by 5 P. M. of that day. During the night the air temperature decreased to 4°F. Before 10:30 A. M. of the next day, when the air temperature was 14°F. 3 inches in length of solid ice core had been forced out of the lateral orifice at the base, and the pressure had fallen off to 3000 lbs. per square inch. (See fig. 7.) The projecting

FIG. 7.

FIG. 7. Flow of ice under compression. Photographed at 12.15 P. M. on March 6, 1912. Air temperatures ranged between 22°F. when pressure first applied, to 4°F. during night and 14°F. in morning when 3 inches of ice had been protruded. In this figure approximately 4 inches of the "squeezed out" ice rod are shown. Streaks are due to iron substance from orifice and indicate the movement outward. Note downward bend of rod. Parallel rings near end are original, their cause not understood.

ice rod curved downwards, its end being one-half inch below the level of the orifice. By 2:30 P. M. 4 1/2 inches were projected. By 4:30 P. M. another inch had been squeezed out, the pressure had fallen off slightly and the air temperature had risen to 29°F., at approximately which point it stayed until 10 A. M. next morning when 14 inches of ice rod had been

pushed forth. Two hours later the air temperature rose to the freezing point and the pressure had fallen off to 2000 lbs. per square inch. The air temperature continued to rise slowly, and by 2 P. M. water from pressure melting began to ooze out at the top of the cylinder between its bore and the steel plunger but no water came out of the lateral orifice with the ice rod, which had meanwhile increased another two inches in length, making 16 inches in all; the load at the end being 1100 lbs. per square inch. That the water oozing out at the top was from pressure melting was indicated by the fact that it refroze in feathery crystals on the outside of the cylinder.

Microscopic sections cut on March 6th from the part of the rod protruded at the lowest temperatures on examination proved the ice to be perfectly clear, glassy and compact. Under crossed nicols individual particles proved to be differently oriented but exhibited parallel extinction within a given boundary. The outer circumference was finer grained than at the core, shear lines and breccia bands could be identified but there were some apparently real crystal boundaries. "Undoubted breccia bands and undoubted boundaries of breaking, but looks for all the world like a medium-grained granite rock, with a very few apparent crystal edges but not usually. The fact that this is clear compact ice shows beautiful flow." (Tarr's laboratory notes.)

The downward bend of the rod may have been due to more rapid emergence at the top than the bottom of the orifice. If so, the differential movement may account at least in part for the breaking and shearing. However, the rod may have bent of its own weight or because of internal stresses. Clay squeezed through like orifices in clay-working machinery bends down similarly because of irregularities in the material.

Interpretation and Application of the Experiments.—Ice crystallizes in the hexagonal system. The habitus of the crystals and their orientation vary according to their origin. In the lake ice the crystals occur in bundles of prisms with the basal planes of the mass parallel to the refrigerating surface. In glacier ice more or less nodular grains, each a crystal unit, form an interlocking aggregate with the principal axes of the individuals variously oriented, although some observers claim that there is a measurable tendency for the grains in the basal layers of glaciers to be disposed with their principal axes parallel to the direction of gravity. Water freezing in crevasses in glaciers has been noted to develop columnar ice crystals with principal axes extending at right angles from the opposing walls of the fissure. In artificial ice frozen in cans submerged in ammonia-cooled brine the crystals have their principal axes extending radially from the outer

surface to the center of the cake. Emden* has clearly shown that ice grains as large as hazel nuts may be grown from snow slush with originally small ice nuclei, kept in sealed vessels for several weeks at a constant temperature of 0°C. In this case growth proceeds from the center outward, the accretion and orientation of each crystal being determined by the orientation of the original nucleus. Accordingly the orientation of the grains in the mass is irregular like that of glacier grains. From these observations it seems safe to conclude that under normal atmospheric pressure the orientation of ice crystals is determined by the position of the original surface or center of refrigeration, consequently the orientation of glacier grains is determined by the position of the crystal axes in the original snow and névé grains.

As originally shown by McConnel and later more fully formulated by Mügge and confirmed by the experiments of Tarr and Rich, an ice crystal is made up of molecularly thin, flexible laminae lying in a plane normal to the principal axes. Under pressure, with the ends of the principal axes supported, these laminae will glide over one another and this gliding property may account for such uniform orientation of ice crystals in the basal layers of glaciers as may exist. It can not be assumed that such uniformly oriented crystals develop and grow in the direction of least resistance, in ice masses under pressure, for similarly orientated mica flakes in slates and schists which are presumed to have grown under like conditions are distinctly tabular, whereas the uniformly oriented glacier grains are not described as having any greater basal diameter than adjacent ones that are irregularly oriented. On the other hand, it is quite possible that the presence of a number of similarly oriented crystals may be the result of shear along the gliding planes brought about by differential pressure in the general direction of the movement of the glacier. Regrowth of the two parts of an individual crystal completely separated by such shear would result in adjacent crystals with similar orientation. This is in accord with Emden's contention that the essentially progressive growth of glacier grains from the névé to the ends of glacier tongues results from the absorption of small granules by adjacent larger ones, and with Deeley's assertion that the growth of glacier grains results from the transference of molecules from crystal to crystal under differential pressures in the ice.

Water is at its maximum density at a temperature of 4°C. and between that temperature and the freezing point, 0°C., it

*Emden, Robt.: *Über das Gletscherkorn*, Denkschriften d. schweiz. naturf. Ges., xxxiii, Zürich, 1892. Separates published by Zürcher and Furrer, Zürich.

has been suggested that the liquid phase consists of a mixture of ice molecules (H_2O_2) and water molecules (H_2O). Similarly it is quite possible that a residuum of water molecules exists in the solid phase, ice, at temperatures below, but near the freezing point. As the change from the liquid phase, water, to the solid phase, ice, is accompanied by expansion it follows that compression of the ice will result in the lowering of its melting point. Under uniform pressure this has been experimentally determined to amount to 0.00722°C . per atmosphere of pressure. Johnston and Adams* contend that what is ordinarily termed the compression of solids is resolvable into uniform pressure and shearing stress. They further insist that permanent deformation of crystalline aggregates results from the effects of non-uniform pressure or shearing stress and that such deformation is occasioned by the real melting of those particles that at any instant bear the brunt of the load. On this basis they assert that non-uniform pressure lowers the melting point of ice 0.09°C . per atmosphere of pressure. Considered in connection with the possibility of a residuum of water molecules in ice at temperatures near the freezing point this concept of the nature of compression effects on solids suggests the probability of a considerable volume of water being evolved by moderate pressure on ice at or near the freezing point temperature and such an effect has been noted by Hess† in exact experimental studies.

Ice masses do not consist of single crystals but, as shown above, of aggregates of comparatively small units variously oriented. The resistance of such masses to deforming stresses would appear to be due to three factors: (a) the nature of the interlocking of the units, (b) the molecular cohesion of the ultimate particles of a unit crystal, (c) the molecular cohesion existing at the contact of adjacent crystal faces. It follows that experimental studies of ice under compression with reference to glacial phenomena should be directed toward ascertaining the behavior of ice as a crystalline aggregate rather than to the investigation of the physical properties of unit crystals.

That there is a very considerable difference between the value of molecular cohesion of the particles of a unit ice crystal and that between particles of adjacent crystal faces is indicated by the differences in crushing strength exhibited by the pond ice put under compression (a) with principal axes of the component prisms parallel to the pressure direction and (b) normal to it, the crushing strength in the second case being

* Johnston, J., and Adams, L. H.: On the Effect of High Pressures on the Physical and Chemical Behavior of Solids, this Journal, xxxv, 205, March, 1913.

† Hess, H.: Über die Plastizität des Eises, Annalen der Physik, (4), xxxvi, pp. 449-492, 1911.

only one-third that of the first. In the first case the load is borne by the columns of basal plates of the ice crystals, in the second it is transmitted through the mass along the adjacent parallel planes of the crystal prism faces. That the interlocking, irregularly oriented, crystals of glacier ice supported loads of intermediate value lends further confirmation to this deduction. In this connection it is interesting to consider the experiment with the pond ice under compression in the unyielding cylinder which resulted in the complete recrystallization of the ice with principal axes normal to the pressure direction, involving a rotation of 90° . If it be assumed that films of water were produced by non-uniform pressure or shear melting, in the initial adjustment of the mass to the load, then, since ice is of less density than water, it would follow that the stable condition under pressure would be such that the load was carried by the water, and that the water be of minimum volume and maximum bearing surface. This condition seems to have demanded the reorientation of the ice crystals with principal axes normal to the pressure direction.

Ice exists under natural conditions at temperatures near its melting point, hence change of phase due to increasing pressure or temperature is readily initiated and the velocity of transformation is quite high. Furthermore, as suggested in an earlier paragraph, residual water molecules may coexist with the polymerized ice molecules at temperatures near the freezing point. These relations would appear to have an important bearing on the plastic yield obtained in our experiments when cubes of pond ice with principal axes parallel to the pressure direction, and cubes of glacier ice, were subjected to pressures approximating the crushing strength, applied slowly. At the air temperatures at which the experiments were made these pressures were not great enough to induce melting by uniform pressure ($0.0072^\circ\text{C. per atm.}$) but would induce internal melting by non-uniform pressure, the effect of which is 12 times as great according to Johnston and Adams. As our bearing surfaces could not have been ideally plane-parallel, some portions of the ice must have borne a considerably higher load per unit of area than was registered by the scale of the press. Hence it seems quite probable that the yield achieved was due to internal liquefaction of the ice. The continuance of the yield, once started, with slightly diminished pressure and increased surface area would be ascribable to the fact that deformation of the cube would tend successively to exaggerate the localization of the whole load on certain small units of the bearing surface. Flow once started would also be facilitated by gliding movement between the basal plates of the ice crystals. On release of pressure the dissociated ice

molecules (water) developed in the crystal structure would, owing to high reaction velocities, readily change back to the solid phase and thus preserve the ice clear and coherent throughout.

The lower molecular cohesion of ice masses along the contact planes of adjacent crystals, as indicated by the lower crushing strength, suggests that such internal liquefaction as occurs under non-uniform pressure may be localized between the crystal units and also between the basal plates of the single crystals. Such a deduction is corroborated by other evidence, and this leads to some very interesting conclusions regarding the structure of ice aggregates. These can best be presented by first considering the premises on which they are based.

Practically all natural waters carry considerable quantities of dissolved mineral salts. It is to be expected, therefore, that such material will be to some extent incorporated in ice formed on ponds, lakes and rivers. In large part, these soluble mineral salts in land waters are leached from rock substance. In the case of glacier ice, however, there is little or no opportunity for the incorporation of such material if it must be derived from rock leaching. But one of the commonest soluble salts, sodium chloride, in natural waters, is for the greater part not derived from rock leaching but is carried by the wind during storms as fine dust particles from the ocean and local salt deposits to points remote from its origin. The difficulty of accounting for the chlorine in inland waters and the well-known excess of chlorine in the ocean are the facts responsible for investigations that have shown, e. g., that in England at Cirencester an average annual deposit of 36.1 lbs. of sodium chloride has been for 26 years brought by the wind to each acre of surface. Hence there is no difficulty about the incorporation of a considerable quantity of this salt in glacial ice. Moreover, it is suggestive that the regions of present day notable glaciation are almost without exception favorably located for receiving supplies of wind-borne salt, directly from the ocean, from saline basins and from the surface of sea ice.

An aqueous solution of sodium chloride will completely crystallize at its eutectic point, $-22^{\circ}\text{C}.$, forming what has been termed cryohydrate, a mixture of salt and ice crystals, each distinct, in the proportions 23.5 per cent NaCl and 76.5 per cent H_2O . If the solution is originally more dilute than these percentages the excess of water crystallizes out progressively with fall of temperature until the eutectic concentration is reached at $-22^{\circ}\text{C}.$

As pointed out above, sodium chloride must be carried by the winds in appreciable quantities to the snowfields of glaciers. In the change from snow to granular névé a process akin to

the freezing out of the excess of water in the dilute aqueous solution must take place and the salt content of the snow concentrated in films between the névé granules. If the temperature of the névé is at or below -22°C . these films will consist of the cryohydrate solid. But as it is unlikely that so low temperatures as -22°C . exist far below the surface in any glacial masses it is much more probable that liquid films of salt solution develop between the pure ice granules and that this salt solution is of a concentration, therefore a thickness, dependent on the temperature and the size of the pure ice granules. At comparatively high temperatures, i. e., near the freezing point of pure water, a comparatively dilute solution must remain in the liquid phase. Again, the smaller the ice grains the greater their total surface area, consequently the thinner the film of salt solution that surrounds each at a given temperature. Since glacier grains are generally observed to increase in size from the surface toward the interior and from the head to the terminus of an ice tongue and the temperature of the interior ice to approach the pressure-temperature melting point, it follows that the interstitial films of salt solution will be progressively thicker toward the lower end of the glacier.

Possibly, also, there is a tendency for the salt solution to drain away from the surface zone of the ice and to be concentrated in the interior below the limiting depth of crevasses. Except then as the films of salt solution are held by capillarity the surface portions of the ice will be made up of ice grains that are very closely adjacent whereas there will be a corresponding concentration of the liquid films between the grains at greater depths.

Other investigators have argued the presence of saline solutions between the pure ice crystals of glacier and pond ice. Buchanan* points out that rain and snow contain seven parts per million of chlorine and that when glacier ice has a temperature as high as -0.07°C . it will consist of 1 per cent liquid brine or water. To the presence of such films he ascribes the effect of the sun's rays in disarticulating granular glacier ice and in developing the Forel lines that mark out the basal plates of the ice crystals. Thick pond ice similarly becomes "rotten" after a spring thaw and breaks up rapidly because it is disintegrated by melting in the planes of such films. Quincke† characterizes glacier grains as "foam cells" filled with pure ice and separated one from another by walls of "oily" salt solution. The origin of the salt solution he ascribes

* Buchanan, J. Y.: In and around the Morteratsch Glacier, *Scot. Geog. Jour.*, xxviii, pp. 169-189, 1912 and other earlier papers.

† Quincke, G.: The Formation of Ice and the Grained Structure of Glaciers, *Nature*, lxxii, pp. 543-545, 1905.

to the disintegration of rock debris incorporated in the ice. He accounts for the gliding planes of ice crystals, the development of Forel's stripes and of capillary fissures in the ice, on the basis of the presence of such films of salt solution. Elsdén* endorses the same idea, quoting Buchanan.

On slowly melting and evaporating, in the experimental laboratory, at air temperatures near and below the freezing point, the ice crystals of the compressed ice cylinders were individually marked out by well-defined grooves. A block of glacier ice (from the Illecillewaet Glacier, Canada) similarly preserved showed the same phenomenon. Like grooves commonly develop on the surface of cakes of artificial ice slowly melting in refrigerators and if such ice is split with a sharply pointed ice pick it will be found that the mass will commonly break up into prismatic crystals, the grooves marking the surface outcrop of the crystal boundaries. The fact that in all these cases the grooves have a considerable width, from 1/32 inch to 1/16 inch, shows that the volume of the separating films is quite appreciable. The fact that these grooves develop on melting slowly in air temperatures near the freezing point indicates that the melting point of the interstitial material is lower than that of the bulk of the granules. It does not follow, however, that the width of the grooves is an index to the thickness of the interstitial films in the interior of the ice, for a very dilute salt solution would be very effective in developing a channel by melting at the surface in contact with air at temperatures above the normal melting point of pure ice. In the interior of the ice the film is probably much thinner and the solution more concentrated than in the outcropping grooves.

Before the writer knew of the writings of Buchanan and Quincke his attention was called to the possibility of there being different solubilities at the centers and peripheral zones of glacier grains by phenomena attendant upon the melting of icebergs from Alaskan tidal glaciers in sea waters. On the surface of those portions of berg that had been melting below the sea-water surface a unique "hammered silver" effect developed. (See fig. 8.) The centers of each of the polygonal ice grains were hollowed out and these concave depressions met in ridges where the grains came in contact with their neighbors. The ice under such surfaces was solid, transparent, clear blue. When, however, such bergs melted in the air (after stranding at low tide) the surfaces became smooth, the ice lost its transparency, the grains became disarticulated, colored solutions could be filtered through the intergrain fissures and the surface of the grains became marked with an arborescent sys-

*Elsdén, J. V.: Principles of Chemical Geology, London, 1910, p. 136.

tem of grooves. Apparently the melting of the ice in air and sea water is diametrically opposite with respect to the relative rate of the process at the centers of the grains and their inter-crystal zones. The theory of the common ion seems best to fit the case of melting under sea water. In solutions so dilute that dissociation is approximately complete, the solubility of a given electrolyte will be lowered by the addition of a solution containing an ion common to it and the electrolyte, and con-

FIG. 8.

FIG. 8. Iceberg, stranded at low tide, with "hammered silver" surface developed by melting in sea water. Note the polygonal granules hollowed at the center. Photographed Aug. 2, 1909, Yakutat Bay, Alaska.

versely, the solubility of one salt may be increased by the presence of another salt not containing a common ion. The sea water contains dissociated Na and Cl ions, hence the solubility of the saline interstitial film is decreased while that of the pure, H_2O , ice crystal centers is increased. The development of the "hammered silver" surface by such differential solubility probably requires the maintenance of favorable and rather delicate equilibrium of temperature in that the sea water needs to be at or near the freezing point of fresh water.

Since the sea surface in the region (Yakutat Bay, Alaska) where these observations were made is often quite completely covered with floating ice, this temperature relation is not impossible of attainment,—its existence was in fact confirmed by thermometric observations by the writer in 1909. Incidentally, if the theory of the common ion does apply to the phenomenon, as here suggested, the “hammered silver” berg surfaces afford a most striking and interesting natural example of the action of a comparatively little known principle.

The application of the experimental and other observations considered above to the structure and flow of glaciers has considerable significance. In the first place the position taken by the late Professor Tarr, that experimentation with ice to have a bearing on glacial phenomena must be done on ice aggregates and not on single crystals, seems to be borne out by the evidence indicating the presence of an interstitial film of saline solution between ice grains. The crushing strength tests on the cubes indicate that at sufficiently low temperatures crevasses may extend approximately 2000 feet deep from the surface without closing by flow. Hence it is apparent why the upper zones of glaciers seem quite brittle.

The development of crevasses to the maximum depth of 2000 feet would, however, necessitate lower temperatures than the evidence at hand shows to exist in the interior of glaciers. Hess and Blümcke* bored holes to a maximum depth of 153 meters in the Hintereisferner glacier. They found that the temperature of the interior ice was only so much below the melting point, under atmospheric pressure, as would be brought about by the pressure of the superincumbent ice masses at any given depth. Moreover, the temperatures at different depths were very closely accordant with the calculated depression of the melting point by a column of ice of that height. On the other hand J. Vallot† observed a constant annual temperature of -16.6° in the névé snow of the summit of Mont Blanc at a depth of 10 to 13 meters below the surface. As the snow from the highest parts of the névé field is that which eventually constitutes the bottom layers of a valley glacier, and as the deeper ice has progressively lower temperatures on account of the pressure relations, it would appear that the bottom of a glacier constitutes its coldest portion, also the thicker an ice tongue the lower its interior temperatures may be. But the factors that would need to be considered in an attempt to deduce the body temperatures of an ice tongue of large size are so various that a discussion of them would need to be long

*Hess, H.: *Die Gletscher*, pp. 151-153 and pp. 319-320. Later 200 meters depth was attained with same results.

†Quoted by Hess, H.: *Die Gletscher*, p. 164.

to be at all adequate. The average annual temperatures of the snow fields vary according to latitude and elevation. As snow is a poor conductor of heat it may be that quite low temperatures are imparted to the body of the glacier from its upper reservoir sources. Whether, during the course of its movement from the *névé* source to the end of the tongue, there is enough inflow of earth heat at the bottom of the ice to bring it to the pressure-temperature melting point would depend on the original degree of cold, the length of the glacier's course and its rate of flow. In any event, earth-heat would tend to raise the temperature in some measure. Since below the *névé* line sufficient heat is supplied to melt some of the ice, it follows that the surface temperatures of a glacier in summer must be at the melting point. The amount of surface melting is representative of the excess of heat supplied over that capable of being conducted from the surface, at the melting point, to the colder masses of the interior ice. Such conduction will continue until the interior portions have the temperature of the pressure-determined melting point. But as the near-surface portions will acquire this temperature earlier than those at greater depths, the conduction of heat to the deeper interior parts will be progressively slower from the surface downward. In other words, an increasing proportion of the excess heat will be utilized in near-surface melting. Thus, while in small glaciers, like the *Hintereisferner*, pressure-temperature equilibrium may be established for a considerable thickness of the ice tongue, it does not follow that this is the case for all the mass of glaciers of great thickness. Yet it may be concluded that, while it is by no means certain that the bottom temperatures of great ice masses are at the pressure-temperature melting point, it is improbable that they exhibit any extreme degree of cold.

Vallot found that the process of glacier-granule growth was distinctly in evidence in the *névé* of Mont Blanc at depths 10 to 13 meters below the surface (hence below the zone of surface water infiltration) where constant annual temperatures of -16.6°C . prevailed. Emden* has clearly demonstrated that ice granules as large as hazel nuts may be grown from originally small, snow-slush nuclei, kept in sealed vessels for several weeks at a constant temperature of 0°C . This growth he contends is due to the absorption of small granules by adjacent larger ones with consequent molecular readjustment. Deeley† also insists that the growth of glacier grains results from the transference of molecules from crystal to crystal under differential pressures.

* Emden, R.: *Über das Gletscherkorn*, *Denkschriften d. schweiz. naturf. Ges.* xxxiii, Zürich, 1892. Separates published by Zürcher and Furrer, Zürich.

† Deeley, R. M. and Fletcher, G.: *Structure of Glacier Ice*, *Geol. Mag.*, Decade IV, ii, p. 155, 1895.

Under these conditions of progressive granular growth it is readily perceivable how the segregation of pure ice nuclei from the saline interstitial films takes place. Moreover, on the basis of the evidence stated above it seems unlikely that the body temperatures of glacier ice are very low. Hence, with only the development of comparatively slight pressures, through continued accumulation of snow above, it would appear that the growth of granules would be much facilitated and the flow of the ice initiated. That ice can be completely recrystallized under comparatively moderate pressures (1400 lbs. per sq. in. or less; equivalent to an ice column about 3500 feet high) at air temperatures a number of degrees below the freezing point (-4°F. to 20°F.) was shown by the compression experiment with the unyielding copper cylinder. Moreover, the crystals developed were of quite large size showing that the velocity of the reaction is great; in other words, large crystals can grow in a short time. The permanent deformation by flow of the ice cubes under pressures approaching their crushing strength (650 to 1000 lbs. per sq. in., equivalent to an ice column 1600 to 2500 feet high) clearly demonstrates the ability of ice to yield plastically under differential pressure without disintegration and at temperatures a number of degrees below the pressure-melting point. Such yield may be in part due to shear, but in accordance with the known properties of the ice crystals can be more certainly ascribed to internal liquefaction in the planes of the basal gliding plates. The cause of this readier yield or gliding in the basal planes in turn may find its explanation in the presence of a residuum of saline material between the basal plates of the crystal as argued by Buchanan and Quinke. Another possibility is that it is due to an increase, under pressure, in the volume of water molecules (H_2O_2) included with the polymerized ice molecules (H_2O_3) in the solid phase, ice, at temperatures near the transition point, with consequent lessened viscosity or internal friction between the crystalline particles. Whatever the explanation, it is clear that such yield would account for the continuous deformation of even quite cold ice at great depths below the surface in the bottom zones of large glaciers.

That the lubricating effect of the saline interstitial films, increased in volume under pressure, and of the plastic internal yield described above, amply suffice to promote the free flow of ice without loss of coherence, was proved by the experiment in which the ice rod was caused to emerge from the lateral orifice of the rod cylinder to a total length of 16 inches.

Moreover, the fact, that, while at the beginning of the flow the temperatures were low, pressure relatively high and the emergence slow, in its later progress when pressures were

much lower and temperatures higher the flow was much more rapid, indicates that with temperatures near the pressure melting point the yield of the ice is much easier and also, as shown by the experiments with the cubes, that flow once initiated continues under diminished pressure. This latter principle seems to be an important factor in that, applied to glaciers, it explains the rapid waves of advance accompanied by a swelling of the glacier tongues that have been noted in Alaska* and elsewhere.

A conception of the flow of glaciers as developed from the results of the experiments and consideration of the constitution and physical properties of glacier ice does not permit of characterization as either plastic or viscous. It is a plastic flow in the sense that the ice mass as a whole is permanently deformed by the movement, but its component grains are not subject or capable of such plastic deformation except in one direction and this appears to be a minor factor. Much more important is the movement that seems to be conditioned by the presence of the interstitial film of low freezing liquid, which may be characterized as viscous movement, by analogy like that of a stiff cement-concrete mixture.

From this point of view the glacier grains must be regarded as the rock-fragment units of the concrete mixture and the interstitial film as the liquid cement or lubricating substance diminishing the inter-unit, hence internal friction between them, thus facilitating movement analogous to that between the molecules of a viscous solid.

It may be questioned whether the volume of the interstitial film can be sufficiently great to permit of the degree of articulation between the ice grains required for continuous flow without involving the distortion or destruction of the crystalline units, hence preventing their progressive growth in size from the upper to the lower portions of an ice tongue. In this connection a calculation by Chamberlin† is interesting. He figures that in the interlocking, granular portion of a glacier six miles long, with a movement of three feet per day, an individual granule would need to move the length of its own diameter, with reference to its neighbor, only once in thirty years. On this basis it would appear that only a very slight thickness of interstitial film in the liquid state would be required to permit of all necessary readjustments between the crystalline grains, while keeping their interlocking structure intact and permitting their growth in size. Where differential pressures exist and an accelerated local flow is demanded this will be

* Tarr, R. S.: Recent Advance of Glaciers in the Yakutat Bay Region, Alaska, *Bull. Geol. Soc. Amer.*, xviii, pp. 257-286.

† Chamberlin, T. C.: A Contribution to the Theory of Glacial Motion. Decennial Publications of the Univ. of Chicago, Chicago. First series, vol. ix, p. 201, 1904.

facilitated by an accompanying increase in the volume of the interstitial film in that area.

Summarizing, the phenomena of a valley glacier may be conceived as follows. In the reservoir area the increasing depth of accumulating snow gradually augments the pressure on its bottom layers. In the mass, meanwhile, the growth of ice crystals proceeds by molecular transference of particles and the absorption of small grains by adjacent larger nuclei. At the same time the saline matter is being segregated in the intergranular spaces. Compression itself involves a rise in temperature and such rise is further increased by inflow of surface heat and heat from the earth. When pressure and heat attain sufficiently high points flow is initiated. During the period of snow accumulation the snow and ice mass in the reservoir is under practically uniform pressure. Once flow is started non-uniform pressures are introduced with resulting increases and decreases of the thickness of the interstitial films.

The continued movement of the ice tongue so started results both from the pressure due to its own thickness and thrust from the continuation of the tongue up slope. If the snow supply in the reservoir is cut off an equilibrium of pressures will be established and the glacier will then melt away without further flow. If the snow supply is insufficient to provide great enough accumulations for continuous flow pressures, there will be alternative waves of advance and stagnation. Apparently the latter condition is only attained under exceptional conditions because flow is more readily maintained than initiated.

The surface portions of the ice tongue are relatively rigid and brittle. The viscous (?) underflow gives rise to tensional and shearing stresses in the upper, rigid ice layers with resultant crevassing. These crevasses are commonly developed on a greater scale in the upper ice tongue, partly because slopes are steeper, partly also, probably, because the ice of the upper portions of the ice tongues is colder. In the lower expanded portions of ice tongues pressure-temperature equilibrium has been established throughout the thickness of the ice, hence flow is possible over lower slopes and with thinner ice than at and above the *névé* line. Near-surface melting in the lower parts of the tongue is localized in the intergranular spaces, the resulting water tends to drain away and thus leaves the ice grains "loose in the socket." On the bottom of the glacier, near the very front, the establishment of pressure-temperature equilibrium combined with the continued inflow of earth-heat and friction may result in pressure melting and thus give rise to submarginal glacial streams, whose volume is augmented by the surface-melting water percolating through the frontal

portions of the crumbling ice tongue or finding its way to the bottom through crevasses and moulins.

In the middle portions of the flowing ice tongue three separate zones may be conceived as existing from the surface to the bottom. At the top is the brittle, crevassed mass, below it the viscously(?) flowing ice, and under that a colder ice layer, continuing to the bottom, which is being plastically (?) deformed by reason of the pressure of the overlying ice and the frictional pull the viscous intermediate layer is exerting on its upper surface. On this basis a decreasing rate of flow from the surface to the bottom of a glacier could be accounted for, and a greater erosive power could be ascribed to the relatively more rigid, colder bottom layers.

Future Experimentation.—It would be very interesting to freeze a number of blocks of ice from saline solutions of progressively increasing density and slowly melt them, noting the relative development of the inter-crystal grooves. Where glacier ice is accessible the relative concentration of saline material in the granules and in the interstitial spaces might be tested by picking out a number of granules, washing them with distilled water and then analyzing them for salt content in comparison with a coherent mass of glacier ice. It would also be worth while to attempt the compaction of snow into ice under long-continued pressure and cause this to flow from a lateral orifice. This experiment the writer hopes to attempt in a succeeding winter.

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