

THE SIGNIFICANCE OF AIR BUBBLES IN  
GLACIER ICE

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**ABSTRACT.** The study of air bubbles in glacier ice can give valuable information on the evolution of the ice. An analysis of the relation between an air bubble and the water associated with it shows that it may be possible to determine the maximum depth from which the ice containing the bubble has emerged. The shapes of the cavities containing water and air bubbles are described. They are found to reflect the anisotropism of ice crystals and reveal that the main crystallographic axis is polar. The question of the mechanism of elimination of air bubbles from glacier ice is raised. The investigations were made on the very old and coarse-grained ice from the foot of the Malaspina Piedmont Glacier in Alaska, which is a temperate glacier.

**ZUSAMMENFASSUNG.** Untersuchungen an Luftblasen in Gletschereis geben wertvolle Auskunft ueber die Vorgeschichte des Eises. Eine Analyse der Beziehung zwischen einer Luftblase und des die Blase umgebenden Wassers zeigt, dass die Moeglichkeit besteht, die maximale Tiefe zu bestimmen, aus der das Eis, welches die Blase einschliesst, emporgestiegen ist. Die Formen der Wassersaecke, in denen die Luftblasen sich befinden, sind beschrieben. Diese Formen wiederspiegeln die Anisotropie des Eiskristalles und bezeugen die Polaritaet der kristallographischen Hauptachse. Die Frage des Mechanismus der Luftblasenelimination aus Gletschereis wird aufgeworfen. Die Untersuchungen wurden an sehr altem, grobkoernigem Eis vom Fusse des maechtigen Malaspinagletschers in Alaska gemacht.

## ACKNOWLEDGEMENT

The investigations reported on below were made at Camp Malaspina, which was established on 13 July and struck on 24 August 1949. The Camp was located on a sand flat on the dead ice fringing the Malaspina Piedmont Glacier. The Camp location was approximately  $140^{\circ} 25' W.$  and  $59^{\circ} 43' N.$  Camp Malaspina was established as part of the "Snow Cornice" expedition of the Arctic Institute of North America and partly financed by a grant from the Office of Naval Research, U.S. Navy.

The expedition was under the expert leadership of Mr. Walter A. Wood. Dr. Robert P. Sharp ably organized the glaciological program. My special thanks are due to Mr. Alan Bruce-Robertson, who was my assistant and companion at the camp.

If we are to solve the riddle of the internal mechanism of glacier flow, we must follow all roads that promise enlightenment. In my reading on glaciology I was surprised to find a general lack of curiosity concerning air bubbles in glacier ice. Here we have a gas phase capable of large changes in volume; surely a potential source of information. A few notes were found mentioning pressure in air bubbles at glacier ends where ablation is severe, in capsized icebergs, and in "cold" ice—ice at any temperature definitely below its pressure melting point. That sharp observer Tyndall makes no mention of pressure but states that he has always seen water bags surrounding air bubbles, even in ice that has not been subjected to solar radiation. Both the omission and the statement are significant, and led me to invent the hypothesis which follows. As usual when deriving an hypothesis from insufficient data, one has to make a number of more or less reasonable assumptions. In this case there are five explicit assumptions:

1. As ice sinks in the accumulation region, near-equality of bubble air pressure with increasing hydrostatic pressure is established by compression of the air bubbles.
2. During descent of the bubbly ice mass in the accumulation basin any water originally enclosed with the air bubbles will freeze due to lower freezing-point in bubbles corresponding to lesser pressure (less than ambient hydrostatic pressure).
3. As ice rises in the ablation region near-equilibrium with hydrostatic pressure is established exclusively by pressure melting around the air bubbles.



4. The mass of air in a bubble is constant.
5. The glacier is "warm," *i.e.* the temperature of the ice is always close to the pressure melting temperature.

Let  $V_{am}$  be the volume of an air bubble at pressure  $P_m$ , the maximum hydrostatic pressure to which the ice containing the air bubble is subjected on its way through the glacier. Let  $V_{a1}$  be the volume of the air bubble at a pressure  $P_1 < P_m$ . Let  $V_{w1}$  be the volume of water associated with the air bubble  $V_{a1}$ . The actual pressure  $P_1$  of the air bubble can be determined by perforating the lower side of the water bag surrounding the bubble and measuring the increase in diameter.

$d_1$  = diameter of bubble at  $P_1$

$d_a$  = diameter of bubble at  $P_a$  (atmospheric pressure)

$$P_1 = \frac{P_a \cdot d_a^3}{d_1^3} \dots \dots \dots (1)$$

As the hydrostatic pressure decreases from  $P_m$  to  $P_1$  (as the ice rises in the ablation zone) the ice temperature increases, and the air bubble causes pressure melting in its host crystal, and increases in volume, the melt water being denser than its ice equivalent. The difference in volume of  $V_{am}$  and  $V_{a1}$  is equal to the difference between the volume of ice melted and the volume of the melt water  $V_{w1}$ .

$$V_{a1} - V_{am} = (\beta - 1)V_{w1} \dots \dots \dots (2)$$

where  $\beta = 1.09$ , the specific volume of ice.

The ice lattice is always practically air-free but the melt water will dissolve a volume  $\alpha V_{w1}$  of air from the bubble.  $\alpha = 0.029$ , the volume solubility of atmospheric air in water at  $0^\circ \text{C}$ .

The gas law yields the following relation, provided that there is no water with the bubble at  $P_m$ , *i.e.*  $V_{wm} = 0$ .

$$P_m \cdot V_{am} = P_1(V_{a1} + \alpha V_{w1}) \dots \dots \dots (3)$$

If we can measure  $V_{a1}$  and  $V_{w1}$ , or their ratio, we can compute  $P_m$ .

$$P_m = P_1 \frac{V_{a1} + \alpha V_{w1}}{V_{a1} - (\beta - 1)V_{w1}} \dots \dots \dots (4)$$

$P_m$  is close to the maximum pressure to which the ice has been subjected in the glacier. If  $V_{wm} \neq 0$ , then the real pressure was less than the computed one. There is a limit to the estimation of  $P_m$ , considering the ratio of volume of water to volume of free air in the bubble.

$$R_1 = \frac{V_{w1}}{V_{a1}} = \frac{1}{\beta - 1} \cdot \frac{P_m - P_1}{P_m + \frac{\alpha}{\beta - 1} P_1} = 11.1 \cdot \frac{P_m - P_1}{P_m + 0.32 P_1} \dots \dots \dots (5)$$

This ratio has its maximum value  $R_a$  when  $P_1 = 1$  atm. As  $P_m$  increases the value of  $R_a$  approaches  $1/(\beta - 1) = 11.1$ . The depth of ice corresponding to the hydrostatic pressure  $P_m$  is approximately  $11(P_m - 1)$  meters, and Table I (p. 445) is computed:

If  $R_1$  and  $P_1$  have been determined, then  $R_a$  can be computed.

$$P_m = P_1 \frac{\alpha R_1 + 1}{1 - (\beta - 1)R_1} \dots \dots \dots \text{from (5)}$$

$$R_a = \frac{1}{\beta - 1} \cdot \frac{P_m - P_a}{P_m + \frac{\alpha}{\beta - 1} P_a} = 11.1 \cdot \frac{P_m - 1}{P_m + 0.32} \dots \dots \dots (6)$$

TABLE I

$P_m$ Atmospheres	$11(P_m-1)$ Meters	$R_a=V_{wa}/V_{aa}$
3	22	6.67
5	45	8.33
10	100	9.65
15	155	10.13
20	210	10.38
25	260	10.52
35	375	10.70
50	540	10.82
100	1100	10.95
$\infty$	$\infty$	11.1

$V_{aa}$  and  $V_{wa}$  can be computed from the following two equations, corresponding to (2) and (3):

$$P_a(V_{aa} + aV_{wa}) = P_1(V_{a1} + aV_{w1}) \quad \dots \dots \dots (7)$$

$$V_{aa} - V_{a1} = (\beta - 1)(V_{wa} - V_{w1}) \quad \dots \dots \dots (8)$$

The solutions are

$$V_{aa} = \frac{\beta - 1}{\alpha + \beta - 1} \left[ V_{a1} \left( \frac{P_1}{P_a} + \frac{\alpha}{\beta - 1} \right) + aV_{w1} \left( \frac{P_1}{P_a} - 1 \right) \right] \quad \dots \dots \dots (9)$$

$$V_{wa} = \frac{1}{\alpha + \beta - 1} \left[ V_{a1} \left( \frac{P_1}{P_a} - 1 \right) + aV_{w1} \left( \frac{P_1}{P_a} + \frac{\beta - 1}{\alpha} \right) \right] \quad \dots \dots \dots (10)$$

Here, then, we apparently have a method for determining the maximum depth from which an ice specimen has emerged. However, there are difficulties as we shall see later.

If  $R_a$  is found to exceed 11.1 then there exists a pressure  $P_2$  at which the air bubble disappears, all the air being forced into solution in the water  $V_{w2}$ .

$$V_{w2} = V_{wa} - \frac{V_{aa}}{\beta - 1} \quad \text{(derived from (8))} \quad \dots \dots \dots (11)$$

$$P_2 = P_a \frac{1 + aR_a}{\alpha \left( R_a - \frac{1}{\beta - 1} \right)} \quad \text{(derived from (7) and (11))} \quad \dots \dots \dots (12)$$

$P_m$  is then not estimable, and the bulk density of the ice containing the air bubbles exceeds  $1/\beta = 0.917$ . If the density of such ice is found to be  $\delta$ , then

$$\frac{V_{w2}}{V_i} = \frac{\beta\delta - 1}{\beta - 1} \quad \text{where } V_i \text{ is the bulk ice volume} \quad \dots \dots \dots (13)$$

It is known (Seligman and Perutz) that as *névé* sinks in the accumulation basin and is compressed, the previously communicating pores are isolated from each other at a density of approximately 0.8. We then have fine-grained bubbly ice with bubble pressure  $P_a$ . To be on the safe side let us assume that the bubbly ice originates at a density of 0.84. The porosity of this ice is 8.4 per cent. A litre contains 84 ml. air and 916 ml. ice = 840 gr. Now let this ice sink to a depth of only 150 meters of ice load and re-emerge in the ablation zone sufficiently slowly for the postulated pressure melting to proceed in equilibrium with the hydrostatic pressure. Ratio



$R_a = 10 = 840/84$ . Thus  $V_{wa}$  accounts for the total ice mass, which would appear to have completely melted by the time it reaches the surface. But melting is only possible if heat is available and we shall see that another important factor intervenes to lessen melting.

Before carrying the discussion further, I will report on observations made on bubbly ice from the foot of the Malaspina Piedmont Glacier in Alaska.

The ice specimens to be examined were hewn out of the sides of crevasses, from spots that had not been subjected to solar radiation. A specially constructed pycnometer was used for the measurements. As considerable trouble was experienced with the sealing and with the shape of the cover it is proposed to use a different construction in the future, as sketched in Fig. 1 (p. 449).

#### PROCEDURE

1. Cool apparatus (Fig. 1) and bottle of liquid to approximately  $0^\circ$ . The liquid used was trichloroethylene, density 1.5.

2. Place specimen in empty pycnometer (capacity  $A$  ml.), and close lid. Stopcocks No. 1 and No. 2 open. The ice specimen should fill the pycnometer as much as possible, but should be rounded at the bottom in order to avoid trapping melt water and air bubbles there. The top of the specimen can be flat, and should have a sharp edge into which several nicks have been cut to allow air bubbles and water to escape upwards when the edge of the floating ice specimen is pressed against the lid.

3. Fill pycnometer with  $B$  ml. from burette, expelling air and initial melt water through stopcock No. 1.

4. Close stopcock No. 1 and open burette towards pycnometer. Allow ice to melt completely, adding measured amounts of liquid to burette as necessary. This gives a measure of the contraction on melting, providing a useful check on further measurements. (Melting was achieved in about one hour by allowing lukewarm water to drip on to the pycnometer from a bucket held at a higher level.)

5. Cool pycnometer to close to  $0^\circ$ . (This was done by dripping of ice water, continued until contraction stopped, *i.e.* until liquid level in burette ceased dropping (about two hours). This cooling process should not be hurried as it takes time to saturate the melt water with air without shaking. With trichloroethylene, shaking of the pycnometer is not permissible due to emulsifying of water. It would be an advantage to use another liquid which permits shaking.)

6. Level meniscus in burette with air meniscus in pycnometer. The difference in density between the liquid columns may be corrected for, but the error of not correcting is rather small. The object of this operation is to establish atmospheric pressure in the air space in the pycnometer.

7. Open stopcock No. 1 and expel air from pycnometer with  $C$  ml. liquid from burette.

8. Expel water from pycnometer with  $D$  ml. liquid from burette. (In the poor light in my laboratory hewn into the ice, it was very difficult to see the meniscus between water and trichloroethylene. The use of a funnel-shaped lid would be a great help in showing up the meniscus.)

#### COMPUTATION

$V_i = A - B =$  Bulk volume of ice specimen

$D =$  Volume of water = Weight of ice specimen

$C =$  Volume of free air at  $0^\circ$  and  $P_a$

$D/V_i =$  Bulk density of ice specimen

$V_t = C + aD =$  Total volume of air in specimen at  $0^\circ$  and  $P_a$

$V_{am}^* = V_i - \beta D =$  Volume of air in bubbles at  $0^\circ$  and  $P_m^*$ . ( $V_{vm} = 0$ )

$P_m^* = P_a \cdot V_t / V_{am}^*$



From (2) and (3) we compute :

$$V_{a1} = \frac{\beta - 1}{\alpha + \beta - 1} \cdot V_{am}^* \left( \frac{P_m^*}{P_1} + \frac{\alpha}{\beta - 1} \right) = 0.755 V_{am}^* \left( \frac{P_m^*}{P_1} + 0.32 \right) \dots (15)$$

$$V_{w1} = \frac{1}{\alpha + \beta - 1} \cdot V_{am}^* \left( \frac{P_m^*}{P_1} - 1 \right) = 8.41 V_{am}^* \left( \frac{P_m^*}{P_1} - 1 \right) \dots (16)$$

When there is little air in the ice specimen, it will completely dissolve and *C* becomes 0. The range of applicability of the described pycnometer method is given by  $V_i > \alpha D$ . It may be possible to extend the range of usefulness of the method by lowering the solubility of air by the addition of salt, which would require some modification of technique. Data for the solubility of air in concentrated salt solutions could not be found so a determination was made. The value for concentrated NaCl solution at 0° was found to be  $\alpha^1 = 0.0025$ , but this measurement is of doubtful reliability.

In Table II I offer the results of four pycnometer tests made on visually similar ice specimens from the lower edge of the Malaspina. I do not feel too happy about the results as I was handicapped by a poor instrument (a second better pycnometer arrived broken). Yet the results are not too much at variance.

The measurements reveal two very striking features.

1.  $P_m^*$  is smaller than  $P_m$ , corresponding to only some 20 meters of ice load.
2. Several per cent of the bulk ice mass is present in the form of water.

TABLE II

	I	II	III	IV
A	450.1 ml.	448.5 ml.	448.0 ml.	448.0 ml.
B	86.4	92.7	151.6	112.7
C	5.85	11.1	8.35	6.7
D	324.7	319.0	265.5	300.0 (computed)
$V_i$	363.7 ml.	355.8 ml.	296.4 ml.	335.3 ml.
Bulk density	0.894	0.896	0.894	0.894 (assumed)
$V_t$	15.3	20.3	16.1	15.4
$V_{am}^*$	9.7	8.3	6.9	8.3
$P_m^*$	1.58 atm.	2.45 atm.	2.33 atm.	1.86 atm.
$V_{aa}$ for $P_a$	13.8 ml.	17.3 ml.	13.7 ml.	13.6 ml.
$V_{wa}$ for $P_a$	46.3	101.0	77.0	60.0
$V_{a1.5}$ for $P = 1.5 P_a$	10.0	12.2	9.7	9.7
$V_{w1.5}$ for $P = 1.5 P_a$	3.8	44.5	31.8	16.7
$R_a$	3.3	5.8	5.6	4.4
Per cent. of Bulk Volume of Ice				
$V_{aa}$	3.8%	4.8%	4.6%	4.0%
$V_{wa}$	12.7	28.4	26.0	17.9
$V_{a1.5}$	2.7	3.4	3.3	2.9
$V_{w1.5}$	1.0	12.5	11.0	5.0
$V_t$	4.2	5.7	5.5	4.6

Microscopic measurements showed air pressures in the bubbles to vary between 1 and 2 atmospheres absolute, hence the computed values for  $P = 1.5 P_a$  in the table.

MICROSCOPIC OBSERVATIONS

Unfortunately only a very limited time could be devoted to the microscopic study of Malaspina bubbly ice, due to other work and to *force majeure* (lumbago). I was further handicapped by the fact that my binocular microscope lacked a second eyepiece to match the ocular micrometer. This



rendered accurate measurements practically impossible due to shifting of the field of view on changing of eyepieces.

The smallest frequent air bubble diameter is not much below 0.1 mm. About one-third of the bubbles falls into this size group. Of the bubbles larger than 0.1 mm., a little over one-third is smaller than 0.3 mm., one-fifth is between 0.3 and 0.5 mm., one-fifth between 0.5 and 0.7 mm., one-tenth between 0.7 and 0.9, and one-tenth larger than 1 mm. The maximum frequent size is 1.5 mm. Bubbles larger than 3 mm. are rare. The number of bubbles per cu. cm. was roughly estimated to be around one hundred, not counting the smallest ones. The bubbles surrounded by water are not smooth, but appear to be surfaced by a fine scum of unknown nature. The water is always quite clear. It was noted that the bubbly ice was always quite clear, showing only rare microscopic solid inclusions.

The anisotropism of the ice crystals is reflected in the fact that the water bags containing the air bubbles are never spherical. The dominating shape is a rotational body, always with the axis of rotation parallel to the crystallographic axis of the host crystal. Fig. 2 (p. 449) shows sketches of sections through axis of rotation. (a), (b) and (c) are by far the most common forms. The ratio of diameter to thickness varies from 10 : 1 to 1 : 1, the larger ratios dominating. The more or less truncated, pyramidal forms (d) and (e) are also fairly frequent and the rest rather rare, (k) being quite abnormal due in some manner to the behavior of the air bubble. Form (j), perhaps reflecting deformation by lattice translation, is very rare. This may be due to two causes: either deformation of crystals by translation is unimportant near the surface of the glacier, or non-symmetrical water bag forms are unstable.

A single crystal often shows many different water bag shapes. The distribution of hemimorphic forms in a single crystal is very interesting. Sometimes they all point in the same direction but more often in opposed directions, usually in alternating groups. Sometimes they appear in an apparently random distribution, which I am inclined to interpret as indicating interpenetration twinning according to the basal plane. The hemimorphic water bag forms strengthen my belief that ice crystallizes in either the class  $C_{3v}$  or  $C_{6v}$  (trigonal or hexagonal hemimorphic).

The presence of the air bubble in the water bag introduces an element of inhomogeneity. Not infrequently the rotational form is deformed as illustrated in Fig. 2 (k) and Fig. 3 (axis normal to figure). (d) and (e) are rare and probably the product of fusion of two bags. Very rarely water bags without air bubbles were observed. It appears that a bubble can move out of its bag and become sealed off.

Fig. 4 (p. 449) shows sections through bubbles at grain boundaries. Bell-shaped forms are the rule as in (d) and (e), located on one side of the boundary, but forms (a), (b) and (c) are not infrequent. There is no water associated with these bubbles. The indentations, almost invariably pointed inward except at the grain boundary itself, are characteristic. Case (f), containing water, must be very transient, for I observed it only once. This was a happy observation permitting significant conclusions. Bubble (h) was under pressure excess of some tenths of an atmosphere, while (g) did not expand on perforation of the water bag with a needle. A few dozen bubbles of type (a) to (e) were perforated and all found to be at ambient hydrostatic pressure (atmospheric). Although the distorted shapes of Fig. 3 suggest that bubbles and their water bags may be capable of moving in the host crystal (up or down?), cases (a), (b) and (c) of Fig. 4 indicate that it is the grain boundary which is moving, one crystal growing at the expense of the other. The water bag of bubble (g) had obviously only recently been encroached upon by the moving grain boundary. Where this happens, two relatively rapid processes apparently take place:

1. Bubble pressure decreases to ambient hydrostatic pressure, *i.e.* water is pressed into the intergranular boundary layer. From this one might conclude that dense glacier ice is not quite impermeable to water.



2. The water remaining in the bag freezes, *i.e.* the temperature of the bubbly ice is close to the melting temperature corresponding to the pressure in the bubbles rather than to the hydrostatic pressure.

It is obvious that pressure melting around the bubbles can only take place if heat flows. Bubbly ice layers in the glacier must receive heat by conduction from the surrounding clear ice. The

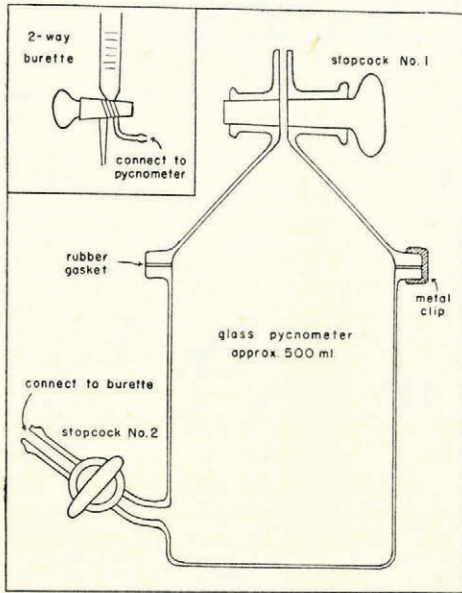


Fig. 1 Pycnometer

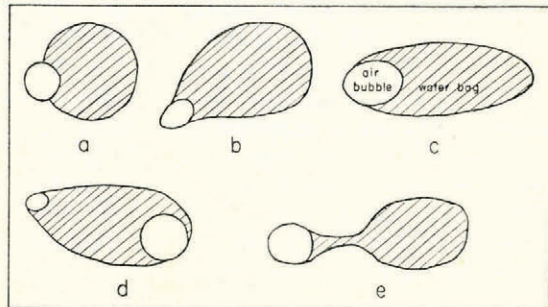


Fig. 3 Air bubbles and water bags in glacier ice

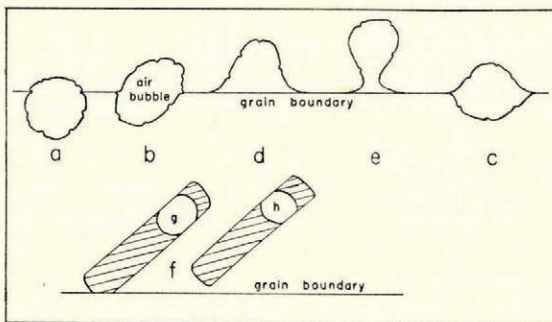


Fig. 4 Air bubbles at grain boundaries

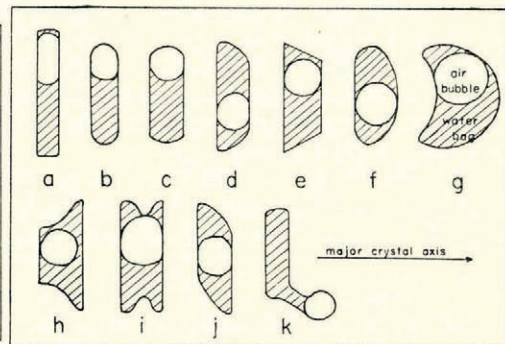


Fig. 2 Air bubbles and water bags in glacier ice

temperature gradients are certainly very small corresponding to the small pressure excess of the bubbles over ambient hydrostatic pressure. Yet in the Malaspina heat flow has been sufficient to melt several per cent of a layer of bubbly ice over 100 feet (30 m.) thick, due to a time factor of at least several hundred years, the ice path length being 40 to 70 miles (64-112 km.). The problem is open to mathematical investigation. Heat of internal friction may have to be considered.

We can now understand why statistically (by pycnometer)  $P_m$  and  $R_d$  are found to be much too small. Every time a grain boundary moves past a bubble, water is eliminated, resulting in a



low ratio of  $V_w$  to  $V_a$ . We can only hope to determine a useful value for  $P_m$  by measurements on a large number of bubbles. The ones showing the largest value of  $R$  would be the ones possibly unaffected by recrystallization.

Information on the mechanism of metamorphism by recrystallization may possibly be obtained by determination of  $R$  on individual bubbles over larger cross sections of ice. My limited observations did not reveal any significant change of  $R$  as a function of distance from the grain boundary. Although  $R$  is by no means constant in a single crystal, the changes of  $R$  from crystal to crystal can be larger. The fact that  $R$  was rarely observed to be smaller near the grain boundary than further inside the grain may be due to the freezing of bubble water at grain boundaries as described above. This freezing would raise the temperature in the vicinity of the boundary and accelerate pressure melting in neighboring bubbles.

Let us follow this argument a little further. The crystals with their intracrystalline water are at a lower temperature than the pressure melting point corresponding to the hydrostatic pressure. This means that the grain boundary layer must be abnormally thin, rendering bubbly ice perhaps less plastic than neighboring clear ice. It also seems reasonable to assume that the water expelled from the water bags on encroachment by grain boundaries will freeze after being injected into the boundary layer. It is then concluded that the bulk volume of the bubbly ice increases (by  $\Delta V_i$ ) as the ice rises in the ablation zone. The air thus liberated is either re-incorporated in the bubbles or forms new small bubbles. It is evident that

$$\Delta V_i = V_{am}^* - V_{am} \dots \dots \dots (16)$$

and as  $V_{am}^* \cdot P_m^* = V_{am} \cdot P_m$

$$\frac{\Delta V_i}{V_i} = \frac{V_{am}^*}{V_i} \left( 1 - \frac{P_m^*}{P_m} \right) \dots \dots \dots (17)$$

Taking  $P_m \sim 50$  atm., the Malaspina bubbly ice is computed to have increased in volume by  $2\frac{1}{2}$  per cent since reaching its lowest point in the glacier.

A further interesting observation is that although generally air bubbles are located at the top of the water bag, one occasionally finds crystals where they are all or in part at one side or at the bottom. This should be further investigated as possibly indicating rotation of crystals.

If one is interested in measuring the degree of disequilibrium between bubble pressure and hydrostatic pressure, it is important to work in the shade, as exposure to sunlight will establish equilibrium within a half hour.

The bubbly ice contains clear bands parallel to its boundaries with the clear ice masses. The width of nearly bubble-free bands measures millimeters to several centimeters. Bubble counts should be made to determine whether these bands were originally bubbly, the bubbles having been "pushed aside" in the course of differential motion. It must be mentioned here that the boundary between bubbly and clear ice bands is generally quite sharp, but usually not marked by a grain boundary. This may be due to recrystallization after shearing has ceased (assuming that shearing is responsible for the clear bands).

Finally one more observation is offered. On fresh saw-cuts a fine mosaic is always observable. The "grain" of this mosaic measuring 0.1 to 0.4 mm. is independent of the size of the saw teeth. Its thickness is probably less than one hundredth of a millimeter. Crystal grain boundaries do not cut through the mosaic grain. No explanation is offered.

From my observations and rather speculative deductions, it appears to follow that there exists no mechanism for elimination of air bubbles from glacier ice, except in narrow bands. I am inclined to believe that clear ice was cleared of air by soaking in water at the *névé* stage. This may well be true, as a water table has been observed in the Seward *névé* field which feeds the Malaspina, and also on the Juneau Ice Cap.



However, if air bubble elimination from large masses of ice after closing of communication between pores should exist (reports of Arctic and Antarctic expeditions on clear ice in "cold" glaciers are inconclusive), then the mechanism of elimination would have to be considered one of the major problems of glacier mechanics. Even elimination from narrow bands remains to be explained.

The validity of the hypothesis suggested in this paper depends on the validity of the premises. It can reasonably be argued that we do not know how deformation of the crystals by basal translation will affect air bubble volume and pressure, and that we may not therefore assume that bubble pressure will lag behind hydrostatic pressure as the ice sinks, and will remain higher than hydrostatic pressure as the ice rises.

The grain size of the Malaspina bubbly ice is of the order of magnitude of inches. The structure of this ice, which shows marked departure from random orientation, will be described elsewhere.

*MS. received 14 February 1950.*

## UNGLACIATED ENCLAVES IN GLACIATED REGIONS

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FROM the time when the hypothesis that regarded the "drifts" as the products of a glacial submergence was abandoned in favour of the view that attributed them to land ice, it has been recognized that some parts of Britain within the general area which was overrun by ice may never have been so invaded. Yet there has been no unanimity about the number or extent of such unglaciated enclaves. James Geikie<sup>1</sup> in 1894 represented practically the southern half of the Pennines as unglaciated, though he believed that ice filled the vales of York and Trent; Jukes-Browne<sup>2</sup> in 1922 reversed the representation indicating no ice in the lowland south of the Escrick moraine but covering the adjoining upland with a field of Pennine ice. Such contradictory views clearly imply a rather fundamental lack of agreement as to the criteria that may be held to demonstrate the existence of unglaciated areas, and it therefore seems desirable to draw attention to the present position of this still very open problem.

The criteria that may be used in this matter are of three kinds:

First, there is the negative evidence, namely the absence from the area in question of moraines, boulder clay and erratic blocks. Though negative, this evidence may on occasion be conclusive, as when an upland rises above the altitudinal limit of the drifts of a lowland ice-mass. Farrington<sup>3</sup> has discussed just such cases in the south of Ireland.

Second, there is the evidence—positive as far as it goes, but limited in its direct application to certain phases of the glaciation—provided by marginal drainage and overflow channels. As is well known such evidence shows that the moors of north-east Yorkshire were ice-free during the glacial episode that was responsible for the "newer drifts" of England and for the terminal moraines at Escrick and York. But this evidence cannot inform us what was happening in north-east Yorkshire during the periods of the "older drifts."