INTERNAL TEMPERATURES OF A COLD GLACIER AND CONCLUSIONS THEREFROM

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ABSTRACT. Description of a horizontal tunnel driven through a cold, steeply sloping glacier, altitude 14,000 feet (4267 m.) on Monte Rosa, from its surface right through to bedrock, a distance of 302 feet (92 m.). Temperatures found deep within this cold glacier were 18° F. (−7·78° C.) compared with 8° F. (−13·33° C.) near its surface, and again near contact with its rock bed. This internal heat is interpreted as heat supplied from the interior of the earth, and as indicative of existence of ice at pressure-melting-point in all cold ice glaciers, if thickness of ice is sufficient. Existence of such an underlay of ice at pressure-melting-point, varying in distribution with varying supply of internal heat, is shown to explain (1) cirque erosion, (2) uniform elevation of cirques in any one region, (3) existence of extrusion flow under certain conditions, and (4) control of cycles of continental glaciation, under extreme limits.

ZUSAMMENFASSUNG. Beschreibung eines horizontalen Tunnels, durch einen kalten steil abfallenden Gletscher gelegt, 4267 m hoch, auf dem Monte Rosa, von der Oberfläche ganz durch zum Felsenbett, eine Entfernung von 92 m. Die Temperatur, die im Herzen dieses kalten Gletschers gefunden wurde, betrug −7,78° C im Vergleich zu −13,33° C nahe der Oberfläche und wiederum nahe dem Berührungspunkt mit dem Felsenbett. Diese innere Wärme wird als Wärme vom Innern der Erde betrachtet und als Hinweis für die Existenz von Eis beim Druck-Schmelzpunkt in allen kalt-Eis Gletschern, wenn die Dicke des Eises ausreichend ist. Es wird gezeigt, dass die Existenz einer solchen Unterlage von Eis beim Druck-Schmelzpunkt, deren Verbreitung sich mit wechselnder Zufuhr der inneren Hitze ändert, die folgenden Phänomene erklärt: 1) Kar-Erosion, 2) gleich-förmige Erhöhung von Karen in einer bestimmten Region, 3) die Existenz von „Extrusion Flow" unter gewissen Verhältnissen und 4) die Kontrolle von Zyklen bei kontinentaler Vergletscherung in extremen Grenzfällen.

AMPLE information is available on the temperature gradients in temperate* glaciers, all the way through from their surface to bottom. A number of bore holes have been drilled in cold glaciers in Greenland, Baffin Island, and the Antarctic, and temperatures noted therein. These holes, however, pierced but a small fraction of the total thickness of those cold glaciers and gave no directly observed data on temperatures of ice near their beds. The author, accordingly, some years ago, selected for study a truly cold glacier, yet readily accessible, on the north slopes of one of the coldest of the Alps, Monte Rosa (15,204 ft., 4634 m.), a glacier which might be a miniature replica of the Antarctic Ice Cap. This glacier, by reason of its steep pitch, greater accessibility and relative shallowness, seemed to offer the possibility of driving a tunnel right through it, from surface to bedrock, and of thereby observing temperature gradients, densities, and dip of stratification, right through its entire thickness, to its bed; from the small scale pattern of such data, there might be possibilities of extrapolating the temperatures within the Arctic and Antarctic continental glaciers.

The important influence of the cold area of a glacier on its economy, even in the Alps, is indicated by the fact that some 65 per cent of the snow areas of the Gorner Glacier, for example, lies above the firn line (cold), while only 35 per cent lies in the fully temperate or isothermal area; yet an overwhelming part of all glacier study has been confined to temperate areas—in fact, generally restricted to the very lowest reaches of the latter. Hence this decision to investigate the interior of this truly cold, yet accessible, glacier.

DESCRIPTION OF TUNNEL

Operations were started on this proposed tunnel, at an altitude of about 4200 m., in June 1952, with a crew of nine (two Swiss guides and six Cambridge University, England, men). Notwithstanding every effort to mark carefully its location in the autumn of 1952, it was lost in the next winter's snows, and only relocated with great difficulty in July 1953. Operations were continued through the summer of 1953 by a crew of six, consisting of two men from Norwich University (Vermont), two Englishmen, and the same two Swiss guides. Increased risk of ice avalanches at this tunnel site at the beginning of the next (1954) working season dictated the abandonment of that tunnel, and a new tunnel was started in June 1954 some hundreds of meters to one side

* "Temperate" where used here in describing glaciers is intended to refer to the lower, always isothermal, portion of such glaciers, and the word "temperate" is selected instead of the more accurate word "isothermal" because, further down in this paper, frequent references to "isotherm" will occur, and the juxtaposition of "isothermal" and "isotherm" might be confusing.

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(altitude 4240 m.) where a very able crew of six Austrian climbers, occupying a camp on the site for 10 weeks, together with the same two Swiss guides, finally holed this new horizontal tunnel through to bedrock, tunnelling a distance of 92 meters (302 feet). This new tunnel, 2 meters high by 2 meters wide, running, like a mine adit, horizontally into the steeply sloping cold ice mass, is shown diagrammatically in Figs. 1 (p. 585) and 2 (p. 587), as well as in the photographs reproduced on page 582.

(The location of this tunnel on the Swiss Topographical maps may be identified by co-ordinates 632·4 E.; 87·5 N., its axis running (horizontally) due south-east into the steep snow slope which leads up to the small Sattel, co-ordinates 632·7 E., 87·3 N.; the old 1952 tunnel had been started at 632·9 E., 88·2 N., axis about east-south-east).

Observations

The following is a record of the temperatures of the ice (Fahrenheit) on fresh exposure (and during subsequent days also) observed in the tunnel; the air temperature within the tunnel is also shown as well as the air temperature of the atmosphere outside, during the working season of 1954.

Temperature Record (Fahrenheit) Monte Rosa Tunnel, Summer of 1954

July

	Date:	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Outside Atmospheric Temperature	8 a.m.												21	26	30	32	30	30	30	19	18
	2 p.m.												32	32	34	34	36	32	32	28	28
	8 p.m.												26	32	32	30	32	29	—	23	14
Tunnel Air Temperature	8 a.m.												21	23	23	23	25	25	23	21	19
	8 p.m.												23	26	25	26	26	25	—	21	21
Temperature of Ice Inside Tunnel at Stated Distances in Metres from Tunnel Entrance	10 metres	7	8	10	11	12	12	12	12	12	12	12	12	13	13	14	14	14	14	13	13
	20 ,,												14	14	14	15	15	16	16	15	15
	30 ,,																			17	17
	40 ,,																				
	50 ,,																				
	60 ,,																				
	70 ,,																				
	80 ,,																				
	90 ,,																				
	92 (rock)																				

August

	Date:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Outside Atmospheric Temperature	8 a.m.	21	30	—	—	—	34	23	26	26	16	10	19	21	23	18	—	—	—	—	—	—	—	—	—	—	14	16	8	8	19	26
	2 p.m.	30	40	—	—	—	37	25	26	28	19	21	—	26	25	28	—	—	—	—	—	—	—	—	—	26	—	28	32	25	32	39
	8 p.m.	25	26	—	—	—	28	25	26	28	16	16	—	23	23	21	—	—	—	—	—	—	—	—	—	16	—	18	16	14	21	28
Tunnel Air Temperature	8 a.m.	21	21	—	—	—	21	19	21	21	18	16	17	18	18	19	—	—	—	—	—	—	—	—	—	—	16	14	16	14	16	16
	8 p.m.	21	21	—	—	—	21	19	19	21	19	18	—	21	21	19	—	—	—	—	—	—	—	—	—	16	—	16	16	16	16	18
Temperature of Ice Inside Tunnel at Stated Distances in Metres from Tunnel Entrance	10 metres	13	13	13	14	14																										
	20 ,,	15	15	15	16	16	16	16	16	18	18	19	19	18	18	18	18	18	18	18	18	18	18	—	—	17	17	17	17	17	17	17
	30 ,,	17	17	17	18	19	20	20	20	23	23	23	23	24	24	24	24	24	24	24	23	23	23	—	—	23	23	23	23	23	23	23
	40 ,,								15	16	17	18	18	18	18	18	19	19	19	20	20	20	20	—	—	20	20	20	20	20	20	20
	50 ,,												10	10	11	12	12	12	12	12	12	11	11	—	—	11	11	11	11	11	11	11
	60 ,,																															
	70 ,,																															
	80 ,,																															
	90 ,,																															
	92 (rock)																															

September

	Date:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Outside Atmospheric Temperature	8 a.m.	26	—	—	—	23	14	18															
	2 p.m.	42	—	—	30	19	25																
	8 p.m.	30	—	—	19	18	19																
Tunnel Air Temperature	8 a.m.	18	—	—	—	16	14	16															
	8 p.m.	18	—	—	16	16	16																
Temperature of Ice Inside Tunnel at Stated Distances in Metres from Tunnel Entrance	10 metres																						
	20 ,,	17	—	—	17																		
	30 ,,	23	—	—	23																		
	40 ,,	20	—	—	20	20	20	—	—	—	—	—	—	—	—	—	—	—	—	—	18	18	18
	50 ,,	11	—	—	11	11	11	—	—	—	—	—	—	—	—	—	—	—	—	—	10	10	11
	60 ,,				15	15	15	—	—	—	—	—	—	—	—	—	—	—	—	—	13	14	14
	70 ,,				17	17	17	—	—	—	—	—	—	—	—	—	—	—	—	—	16	16	16
	80 ,,																				6	6	6
	90 ,,																				8	8	8
	92 (rock)																						8

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Temperatures of the freshly exposed ice (indicative of conditions before exposure to the tunnel air) are also shown as a graph, in Fig. 2, whose X co-ordinates correspond, meter by meter, with the tunnel stationing. These observations disclose what at first appears as a fantastic and seemingly inexplicable double reversal of temperatures, through a range of more than 10° F. (5·5° C.), completed within a span of 92 meters of ice; inexplicable, until we consider other conditions observed in and about the tunnel, as follows:

First, it is reasonable, and we assume, that the coldest temperature, 8° F. (−13·33° C.), corresponds to the mean annual atmospheric temperatures at this altitude; the accepted lapse rate

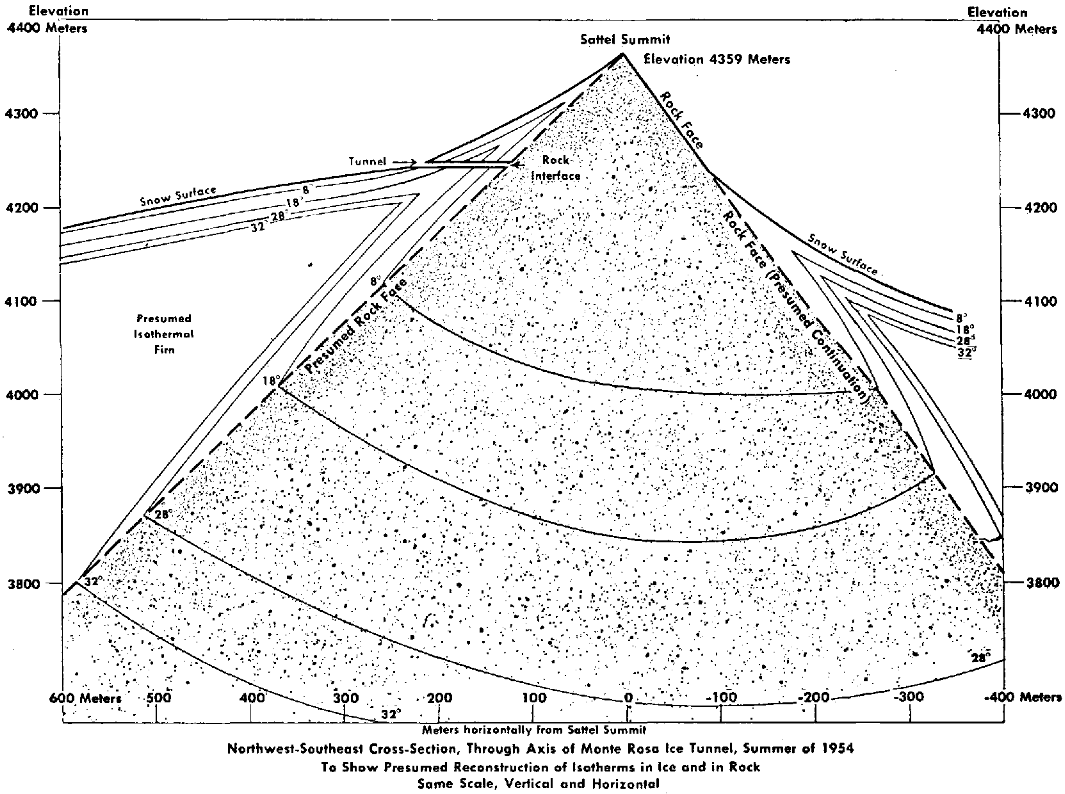

Fig. 1. Diagram of presumed normal distribution of temperatures inside uppermost tip of Monte Rosa Glacier

of the atmosphere, about 1° F. per 300 ft. of rise above sea level (0·6° C. per 100 m.), would just match this temperature in these latitudes. Warmer temperatures at depth must then indicate either thermal flow from the interior of the earth, or heat of friction of the glacier on its bed. From nowhere else could heat come.

Next, for a short span just beyond Station 50 meters in the tunnel, the ice bands are stratified almost vertically up and down the tunnel wall; whereas they dip uniformly at about 40° elsewhere throughout the tunnel. These bands are remnants of former icy surface crusts, now buried under years of later accumulation of snow. A structural geologist would conclude from the locally altered dip of those strata that the ice region between Stations 50 meters and 60 meters has been tilted downwards; accelerated outflow of material beneath that region would bring that about. Faulting of the ice, incidental to down-tilting, is confirmed by the existence of voids, up to 1 cubic meter in volume, just before Station 50 meters—such voids can only be the surviving remnants of

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a fault zone, of a crevasse opened up presumably at the down-tilting of that up-glacier block. The assumption is that, in the recent past, the wedge of snow reaching up the slope from here was then thicker, such as to have permitted the 32° F. (0° C.) isotherm within the snow (see Figs. 1 and 2) to have extended up to or above the site of the tunnel. As will be explained below, the warm ice, within the bend of the 32° F. isotherm, is presumed to have drained off, undermining the overlying colder hard firn, and thus permitting its collapse into the newly created void.

Next let us sketch in such a down-tilted block in Fig. 2, and draw through it 8° and 18° isotherms at depths beneath its own former surface, corresponding to the depths at which 8° and 18° temperatures were first noted in this tunnel.

Thermal Conductivity of Ice and Rock

Next, let us allow for the fact that the rock core of the mountain is coarse granite. This granite core is exposed *naked*, on the opposite slope,* as shown in Figs. 1 and 2. The impact of such granite in this discussion is that granite possesses a thermal conductivity of about 6×10^{-3} cal./cm. sec. °C., 20 percent greater than that of solid ice; as to conductivity of the aerated firn at this altitude, the extremely steep temperature gradients observed within the tunnel itself are indicative of an extremely low thermal conductivity for this cold firn, certainly no greater than 1/10th of that of clear solid ice whose thermal conductivity is about $5{\cdot}3\times10^{-3}$ cal./cm. sec. °C.—that is, thermal conductivity of this firn should prove to be around 5×10^{-4}, less than 1/10th that of our adjoining Monte Rosa granite. This low thermal conductivity of dry cold firn is consistent with its texture, for this firn, formed by pressure-consolidation of cold powder snow, without appreciable admixture of rain or melt water, contains myriads of entrapped air-filled spaces, as shown by its density, 0·82 to 0·85; its thermal conductivity should in fact approach that of modern artificial insulating materials, around 2×10^{-4}, as estimated above.

As to internal friction as the source of this heat within the glacier, the maximum possible heat derivable by friction is of the order of 0·5° C. per 100 meters descent of the glacier, if all its gravitational potential energy were captured as heat from internal friction. (0·25 gram calories, enough to warm 1 gram of ice 0·5° C., is just about the equivalent of 10^7 ergs, and 1 gram of ice descending 100 meters would deliver $10^2\times10^2\times g=10^7$ ergs.) Admittedly, this small rise of temperature by friction, if completely concentrated at the region of friction, could locally exceed this 0·5° C. per 100 m.; but then all the rest of the body of ice would remain unchanged in temperature, which is not the fact; we must find an explanation for a 10° F. warming (or more) of a substantial part of the firn-mass, within a hundred or so meters of its source.

Assembling the preceding considerations, an 8° F. isotherm must run parallel to the snow surface; and the rock interface, even though here buried beneath the snow, must likewise carry an 8° isotherm (due to good thermal conduction of an immense area of exposure of the naked rock face to the atmosphere, on the opposite side of the mountain), all at this high altitude. (See the illustration cited in the previous footnote for the immensity of this bare rock exposure to the cold atmosphere, only a few hundred meters from the inside end of this tunnel.) Delving down into the rock core of the mountain (Fig. 1), we must find increasingly warmer isotherms in the rock, heat derived from the interior of the earth; 1° F. (0·5° C.) per 25 m. in rock, is about what to expect. But these isotherms, where they run into snow or firn, on either flank, must then be 1/10th as far apart as in the granite, due to thermal conductivity of the snow being 1/10th that of granite.

Applications of Observations

We can, accordingly, plot out schematic isotherms, in rock and in snow, as in Fig. 1. Running through our snow field, they will curve back at the apex, where the snow field pinches out up slope above the tunnel; the coldest, 8° F., will parallel the air surface and, also, the rock contact.

* This opposite slope, bare rock, is beautifully shown in the illustration before page 9 in the Jan. 1955 number of the *Bollettino del Club Alpino Italiano* "Il Monte Rosa; Punta Dufour e Zumstein".

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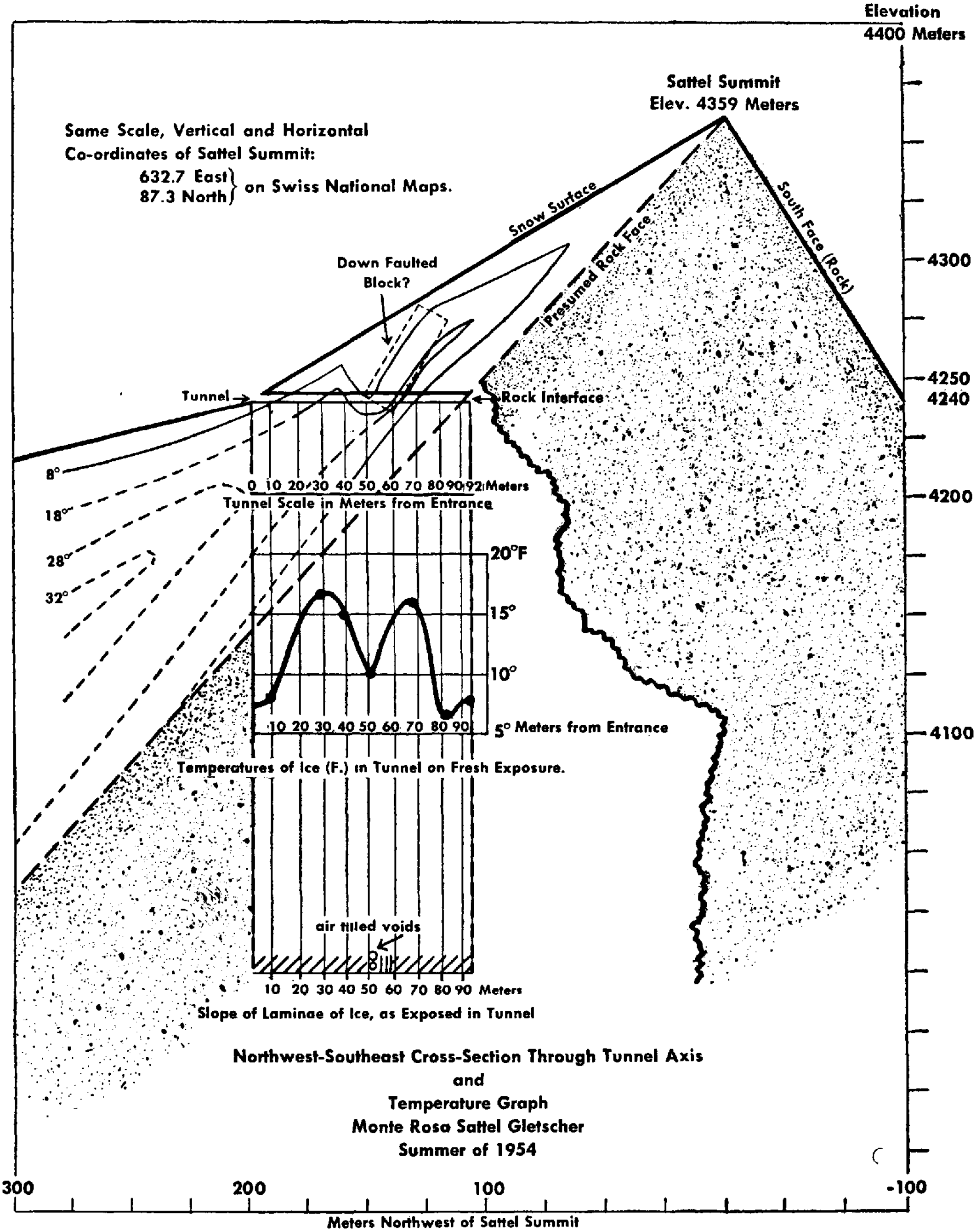

Fig. 2. Diagram of actual present distribution of temperatures inside uppermost tip of Monte Rosa Glacier

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(It will be understood that if this particular rock contact at the inner end of the tunnel, in Fig. 1, did not possess such overwhelming nearby contact with the atmosphere, the rock would be much warmer than 8° F.)

Finally, referring to Fig. 2, if we conceive of that block of ice faulting down, as outlined above, and carrying within itself the isotherms which it inherited from its earlier undisturbed position, we obtain exactly the sequences of double reversed temperature gradients in the tunnel which at first seemed so fantastic and inexplicable, in the shape of the isotherms near the tunnel, as in Fig. 2, thus correlating the schematic theoretical isotherms of Fig. 1 with the temperatures actually observed in the tunnel.

As to how long the presently distorted path of isotherms through this down-faulted block in Fig. 1 will persist, calculation shows that it will take several years for these distorted isotherms to readjust themselves to the smooth paths, symmetrical to the cross-section of the snow field, as sketched in Fig. 1. So great is the insulating quality of this dry aerated firn!

Updraft of Heat Through Isothermal Ice

As to flow of heat from the true bed of the glacier, once the ice adjacent to the bed has warmed to pressure-melting-point (as in a temperate glacier), it must be understood that transfer of heat from the glacier bed upwards through such temperate (isothermal) ice is *not* by thermal conduction —such conduction is impossible because, with the depression of the freezing-point temperature at depth, an inverted temperature gradient faces any flow of heat in its attempt to rise upwards through such temperate (isothermal) ice. Instead of conduction, there takes place a beautifully designed repetition of *heat absorption* and *heat release*. For example, x grams of temperate ice, lying against the heat source (the bedrock at the bottom) absorbs $77x$ calories, without change of temperature, on melting; melted, it migrates upward as cold water, through capillary passages in the ice; but the instant that it has progressed upwards into an area of minutely smaller overlying pressure, it is, under that lesser pressure, too cold to exist as water—it solidifies again as ice, releasing those $77x$ calories into its new-found surrounding ice (less only that minute fraction of a calorie required for the infinitesimal warming of those x grams of water). This release of calories into ice, which is everywhere by definition *temperate* (at pressure-melting-point), will cause an equivalent mass of this second stratum of ice to melt into water, which rises in turn with its own heat of fusion calories, and the process repeats itself all the way up, to the uppermost surface of the temperate ice, be that uppermost surface air, water, rock, or an overlay of cold ice. Thus, heat is carried seemingly against an inverted temperature gradient through temperate (isothermal) ice all the way up through an isothermal glacier.

Capillary-passage Depression of Freezing Point

It has long been known* that the freezing point of water in small capillary passages is lower than that of water in quantity; while the presence of ice in such capillary tubes largely kills this depression of freezing point, there should be, in this capillary-depression phenomenon, even in ice, some small leaning over towards water, at temperature t_0, remaining liquid, even after it has penetrated capillaries reaching up into ice whose temperature is minutely greater than t_0—thus accelerating the above described physical transfer of heat substantially above the velocity to which such transfer of heat would be held, were the sequences of refreezing and remelting restricted to the infinitely small differences of a differential in Calculus.

While we expect, next Summer, to further confirm these presumed (schematic) isotherms with bore-hole temperature measurements at several points, from 4200 m. down to firn line, the mere existence of temperatures 10° F. above the mean annual ambient atmospheric temperature, only a relatively few meters below the surface of a cold snow field, can be attributable only to heat supplied by the interior of the earth, for that temperature requires still warmer firn beneath,

* Hosler, C. L., *and* Hosler, C. R., *Transactions, American Geophysical Union*, Vol. 36, No. 1, 1955, p. 126–32.

limited only to firn at pressure-melting-point at sufficient depth below surface. This last condition justifies conclusions as follows:

Broad Conclusions

1. Because the "viscosity"* of temperate (isothermal) firn ice is substantially less than that of firn or ice at even a few degrees below pressure-melting-point, a relatively small change in the supply of internal heat of the earth, moving the critical location of the 32° Fahrenheit isotherm horizontally up or down the bed of a glacier, will either accelerate or retard the flowability of a greatly magnified volume of glacier ice and snow. That amount will be in proportion to the co-tangent of the slope of the bed; if that up-glacier ice mass flow is accelerated, a flood of firn supply will be delivered to the lower glacier, creating at first an advance, to be quickly followed by starvation and retreat of the lower glacier when the up-glacier mass of added supply is exhausted. If a retardation, it will at first cause a starvation and retreat of the lower glacier; eventually, by increasing accumulation above the "cold line", the upper areas could conceivably continue to accumulate indefinitely until even a continental ice cap were built up, if, at the extreme, the 32° F. isotherm crept far enough down the glacier bed. However, finally, increasing thickness (and weight) of overlying firn will depress the melting point of the basal ice sufficiently to reinvigorate flowage; any contemporaneous increase in the supply of internal heat of the earth, beneath that glacier, would materially expedite this transition towards more flowable ice. The result might be a catastrophic outflow down-valley of a vast vertical accumulation of firn, suddenly given increased flowability.

Even without any supply whatever of heat from within the earth, the previously described warming of ice purely through conversion of kinetic energy of descent into heat, about 0·5° C. per 100 m. descent, would eventually produce ice at melting point, for almost any glacier. For instance, the slow transfer of ice from surface to bed in a continental ice cap 10,000 m. thick (the eventual top limit of thickness accumulation would cease there) would be of the order of 50° C. warming of that ice, and that would pretty well guarantee that the basal layer of such an ice cap, even with no internal heat of the earth, would be melting.

2. Thus, *if* one can conceive of fairly substantial changes in the supply of internal heat over wide areas, maintained over long periods of time, such changes in the supply of internal heat could be the basic cause of cycles of glaciation. Wide differences in the supply of internal heat are known over the surface of the earth, and it is reasonable, then, to expect that such supply of heat has varied at any one locality, over past times.

3. It follows, as a corollary to (1) that the temperate (isothermal) under-levels of a cold glacier must flow out more rapidly than its overlying surface skin of cold ice, *if side walls of rock grip that cold ice-skin and restrain it from freely moving down stream with the more flowable underlying mass. This special condition is extrusion flow*, but extrusion flow can therefore develop *only in cold, narrow, cirque glaciers*; it presumably will not exist at all in wide ice caps which are not pierced by any nunataks, or are not intimately fenced in by mountain ranges rising above the surface of the ice cap. That is apparently why extrusion flow has not been observed at the many test holes in Alaska's wide glaciers (or near the Jungfraujoch?).

4. When inside a glacier the location of this same critical 32° F. isotherm oscillates up and down against a cirque wall, by reason of small variations in the supply of internal heat, it will expose the affected rock wall to corresponding alternations of deep-seated temperature stresses, involving at the same time the once-discarded W. D. Johnson thaw-freeze process, and thus apply active cutting action to a particular contour-line of the cirque wall. That contour-line then becomes the base of the cirque wall because all rock above its undercut collapses down by gravity, and no

* High values for viscosity of small blocks of ice at pressure-melting-point, observed in laboratory tests, do not hold true for ice at identical pressure-melting-points in a glacier. Slow capillary penetration of water through all temperate ice of a glacier produces an ice-water mixture throughout the latter with higher calorie content which differs greatly as to viscosity from any small nearly water-free specimen of temperate ice in any laboratory.

appreciable erosion exists below it. This is the key to cirque erosion, as Johnson pointed out fifty years ago; only his variations of temperature came primarily from variation of internal heat of the earth, not from ambient atmospheric fluctuations.

5. Inasmuch as the location of this critical 32° F. isotherm, buried under the ice in a glacier-filled cirque, is directly related to the existing lapse rate of atmospheric temperatures by thermal conduction down the rock of the cirque walls (during any period of constant mean supply of internal heat), it follows that the mean elevation of this active cutting region will be pretty uniform, as to absolute altitude, during any one erosion cycle in any one mountain area of reasonably uniform summit altitudes. This explains the remarkable uniformity of altitude of the floors of cirques,

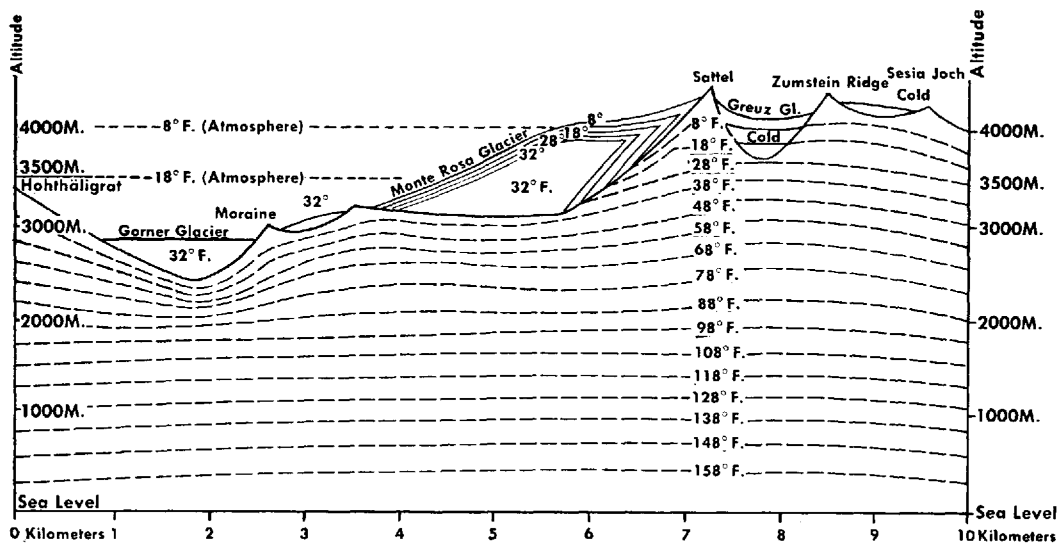

Fig. 3. Presumed distribution of temperature within the ice and rock, on cross-section from the Zumsteinspitze of Monte Rosa, north-west to the Hohthäligrat

Northwest–Southeast section through Monte Rosa, from Hohthäligrat, through Sattel, and Sesia Joch

(Same scale, vertical and horizontal)

All isotherms are summer-season temperatures; in winter a colder skin-condition would exist, as to both snow and rock.

Isotherms in atmosphere are actual.

Cross-sections of, and isotherms in, snow are based on available observations, or on presumptions.

Isotherms in rock are presumed, approximating available observations.

Closing-in of isotherms in rock, beneath Gorner Glacier (32° F.), illustrates how supply of internal heat will be accelerated into intrenched masses of ice.

in any one area; for cirque floors will always be at the elevation of cutting-level established by the 32° F. isotherm within the mountain's rock mass.

A still broader application of the underlying principle that the thermal conductivity of rock is greater than that of ice, and much greater than that of cold firn, is illustrated by Fig. 3 (above). In this Figure, a cross-section NW to SE right through the entire Monte Rosa Massif (the same plane as used for Figs. 1 and 2, except that Fig. 3 covers a much wider area), the reader will note how rock beneath accumulation of snow or glacier ice possesses a closer spacing of isotherms, which means that internal heat of the earth flows faster up against snow or ice than against surfaces

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exposed to the atmosphere. Coupled with the obvious necessity that, somewhere near the rim of high altitude snow masses there must be 32° F. (and colder) isotherms, this greater flow of heat into snow and ice masses means that every massive accumulation of snow or ice on a high mountain invites accentuated cirque wall erosion mechanism, as described above.

Acknowledgement to Natural Laws

It seems fitting, before closing, to digress for a moment and pay homage to the extraordinary balances and checks which time and again are seen to exist between the parameters of the many different properties of water, air and our earth. Just for example, the reader cannot fail to be impressed by the close agreement between the increase of temperature of ice due to conversion into heat of its kinetic energy, in descending x meters, and the comparable increase in the temperature of the ambient atmosphere, on descending those same x meters (due to its "lapse rate"). In fact, grave consequences to our earth might be predicted did not these two processes keep fairly in step, and other balances reappear in checking every observation of a glacier. Truly, an observer of glaciers cannot fail to appreciate the truths behind those ancient allegories in the first chapter of Genesis.

Acknowledgements to Twenty-two Workers

Credit for the final holing through of this Monte Rosa ice tunnel is due, primarily, to my two Swiss guides, Felix Julen, father and son; great appreciation is due to Norwich University for its substantial assistance in many ways; to Charles Hickox and Charles Goodrich; to the several members of the Cambridge University group, and to Klaus Kubiena, Bruno Wintersteller, and their four associates, all members of the Austrian Alpine Club, all of whom worked so faithfully in chopping and hauling very cold ice, under most adverse conditions above 4,000 m., for three summers. All photographs are by Bruno Wintersteller. It is a tribute to their combined ability that not one of the twenty-two men involved at one time or another suffered any injury whatever, not even a frostbite.

MS. received 15 *March* 1955