THE INTERNAL STRUCTURE OF A CIRQUE GLACIER

REPORT ON STUDIES OF THE ENGLACIAL MOVEMENTS AND TEMPERATURES

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ABSTRACT. This report is of a preliminary nature; detailed analyses are being carried on at the present time. The tunnel project on a small cirque glacier in the Jotunheim area of Norway, made possible observations of englacial movements in August and December of 1951 which are correlated with surface movements. Emphasis was placed on detailed three-dimensional studies. A marked divergence of flow lines was noted in both the vertical and horizontal planes. Bands previously thought to be thrust planes were found to be of sedimentary origin and not to be discrete planes of shear. Rates of contractions of tunnel sections up to a depth of 50 m. were observed and the englacial temperature distributions were taken in both zones of ablation and accumulation.

ZUSAMMENFASSUNG. Dies ist ein einführender Bericht; eingehende Analysen werden augenblicklich ausgeführt. Das Stollen-Projekt am kleinen Kar-Gletscher in dem Jotunheim-Gebiet Norwegens hat Beobachtungen von Gletscherbewegungen im August und Dezember 1951 ermöglicht, die mit Oberflächenbewegungen im Zusammenhang stehen. Nachdruck wurde auf eingehende drei-dimensionale Studien gelegt. Sowohl in den senkrechten wie auch in den wagerechten Lagen wurde ein ausgesprochenes Auseinanderlaufen der Strömungslinien beobachtet. Es stellte sich heraus, dass Bänder, die früher als Druckverschiebungen angesehen wurden, sedimentären Ursprungs waren und nicht von abgesonderten Scherflächen herrührten. Der Grad der Zusammenziehung von Stollen-Sektionen wurde bis zu einer Tiefe von 50 m beobachtet, und die glaziale Temperaturverteilung wurde sowohl in Zonen der Ablation als auch der Akkumulation festgestellt.

INTRODUCTION

The need for detailed studies of englacial movement has long been recognized. With this in mind, a tunnelling project was carried out during the summer of 1951 on the Skauthöe glacier * in Jotunheimen, Norway at the instigation of Mr. W. V. Lewis. One of the objects of the work was to put to direct test his theory of rotational slip, [1, 2] for it had been partially evolved from surface features on this particular cirque glacier. The project formed a part of a glaciological research programme in this region which has been under Mr. Lewis's supervision since 1946.

This report is of a preliminary nature and has the immediate aim of describing some of the more obvious discoveries in regard to the englacial movements and temperature distributions. The topics covered are: the absolute and the relative movements, the contraction rates of tunnel sections, the nature of the ice-contact with the rock-bed, the sedimentary dirt bands, and the englacial temperatures. Complete description of the techniques of observation and excavation has been omitted. All measurements were taken in three dimensions where possible—an aspect which, despite its rather obvious importance, has been neglected in a great many velocity measurements. The observations were made in August and December 1951 and most of the detailed analyses are not yet complete. The field studies will be carried on in April and August of 1952, thus recording the seasonal fluctuations.

CONTROL POINTS

The initial requirement at the site was to establish a network of control points to which all subsequent studies could be related. The triangulation plan of the points is shown in Fig. 1 (p. 123). The estimated shape of the rock-bed, as shown in the long profile section, was based on the known points and slopes at the back wall, namely the interior ends of the upper and lower tunnels, soundings of the lake and the outcrop at reference object RO N. The three exterior theodolite stations TP's A, B, and C, were located on the crescent-shaped moraine at the glacier snout. In order to

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* A small, unnamed, north-east facing cirque glacier close eastward of Skauthöe, shown in lat. 61° 37·5′ N, long. 2° 16·3′ W. of Oslo, on *Kart over Midt-Jotunheimen*, 1·50,000. Oslo, Norges Geografiske Oppmaling, 1935. [The prime meridian of Oslo is 10° 43′ 22·5″ E. of Greenwich.]

check on possible movement of this moraine, resection targets RO's N, W, E, and CL were painted on solid rock outcrops on the surrounding heights. Up to December, all stations had maintained steady positions. In order to determine the movement of the glacier surface, horizontal and vertical angular fixes were taken at various intervals of time from the stations to points on the surface stakes, R through X, each of which was emplanted to a depth of 3 m. in the surface. TP A was the base station and from it were controlled the tunnel centre lines which have a common azimuth with the line of stakes.

The subglacial theodolite station, TP D, was constructed on the exposed rock-bed in the lower tunnel. The arrangement of the tunnel observation alcoves in relation to TP D and the moraine station, TP A, is sketched in the isometric view in Fig. 2 (p. 124). The positions of each alcove
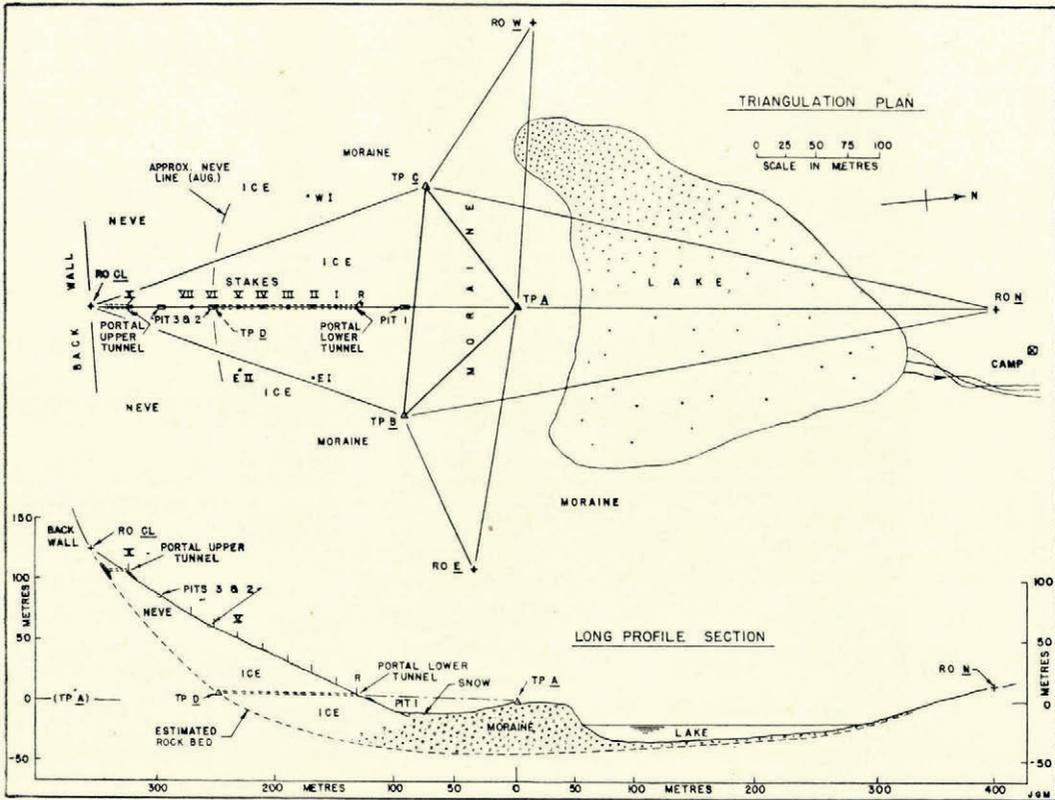
Fig. 1

roof peg relative to the line of sight between D and A gave the control basis for all interior measurements. This precise control was necessary because of the small movements, a condition which is in our favour, for one can therefore expect no catastrophic distortion of the tunnel prior to the completion of the year's programme.

ABSOLUTE MOVEMENTS

The magnitude and direction, in the vertical plane,* of the absolute velocities of the surface stakes and the tunnel roof pegs are shown by the heavy arrows, *i.e.*, velocity vectors, in the profile

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* Regarding the third dimension, all the stakes and roof pegs are drifting slightly to the east, *i.e.* out from the plane of the drawing at an angle of approximately 5 degrees.

section of Fig. 2. They are the average ten-day movement for the period August to December and are magnified 500 times relative to the scale of the drawing. Although not actually shown, flow or stream lines based on the velocity vectors can be seen to be markedly divergent in the ablation zone.* When considering Stake *V* and Alcove *VI*, there is a divergence amounting to an angular
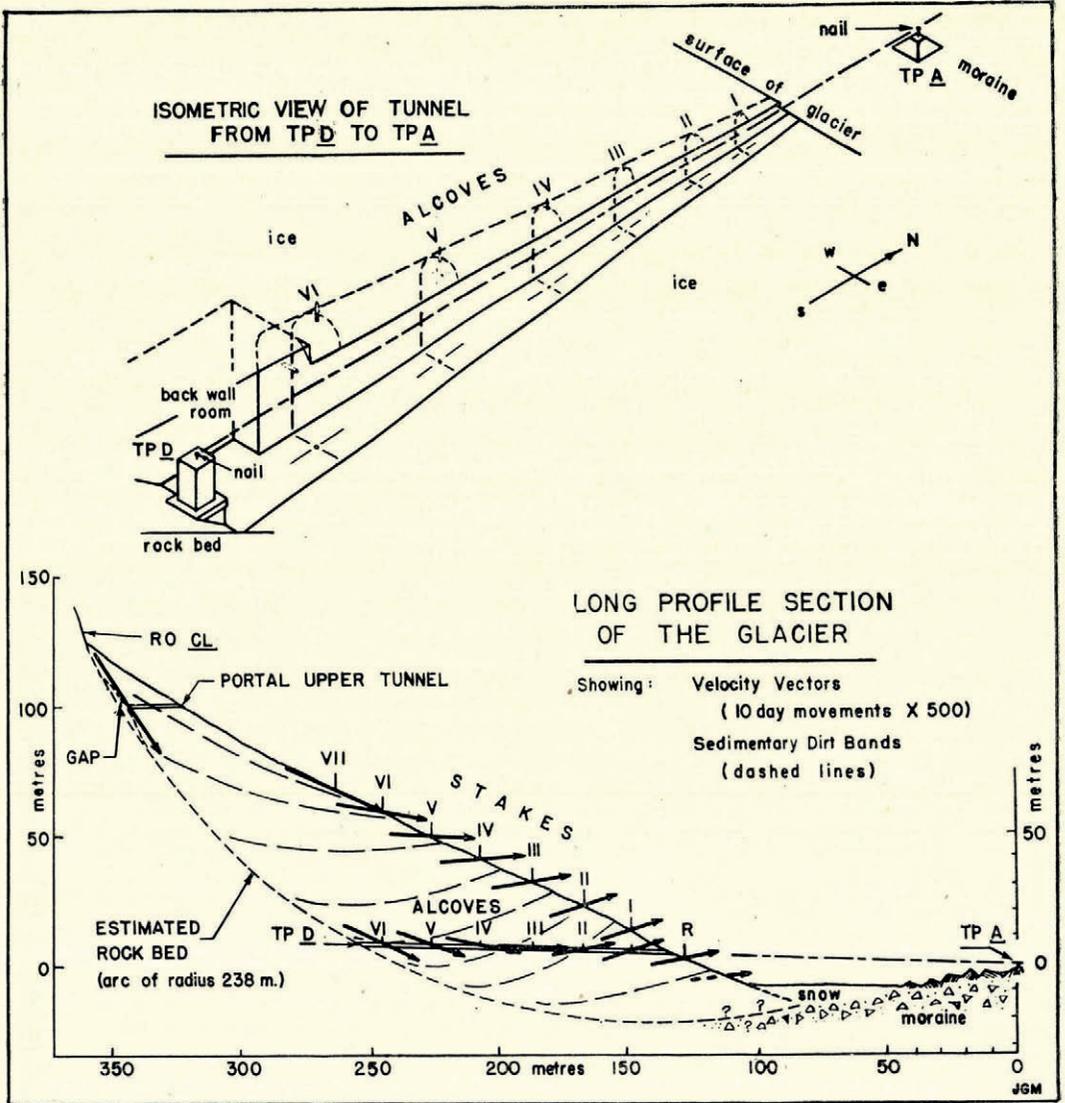

Fig. 2

deviation of 23 degrees; this results in a thickening of the glacier if ablation is not considered. It is interesting to reflect on the effect such a vertical divergence would have on the pipe method of measuring velocity distribution through depth.[3]

The shape of the rock-bed has been drawn as an arc of radius 238 m. This arc coincides well with the known points and slopes at the back wall above the glacier and on the rock-bed as exposed

* The flow lines are in remarkable accordance with Reid's work of 1896.[5]

TUNNEL DISPLACEMENT

FOR PERIOD 21/7/51 – 19/12/51 (120 DAYS)

NOTE: ORDINATE SCALE FOR RELATIVE DISPLACEMENTS MAGNIFIED
BY FACTOR OF 10 FOR CLARITY.
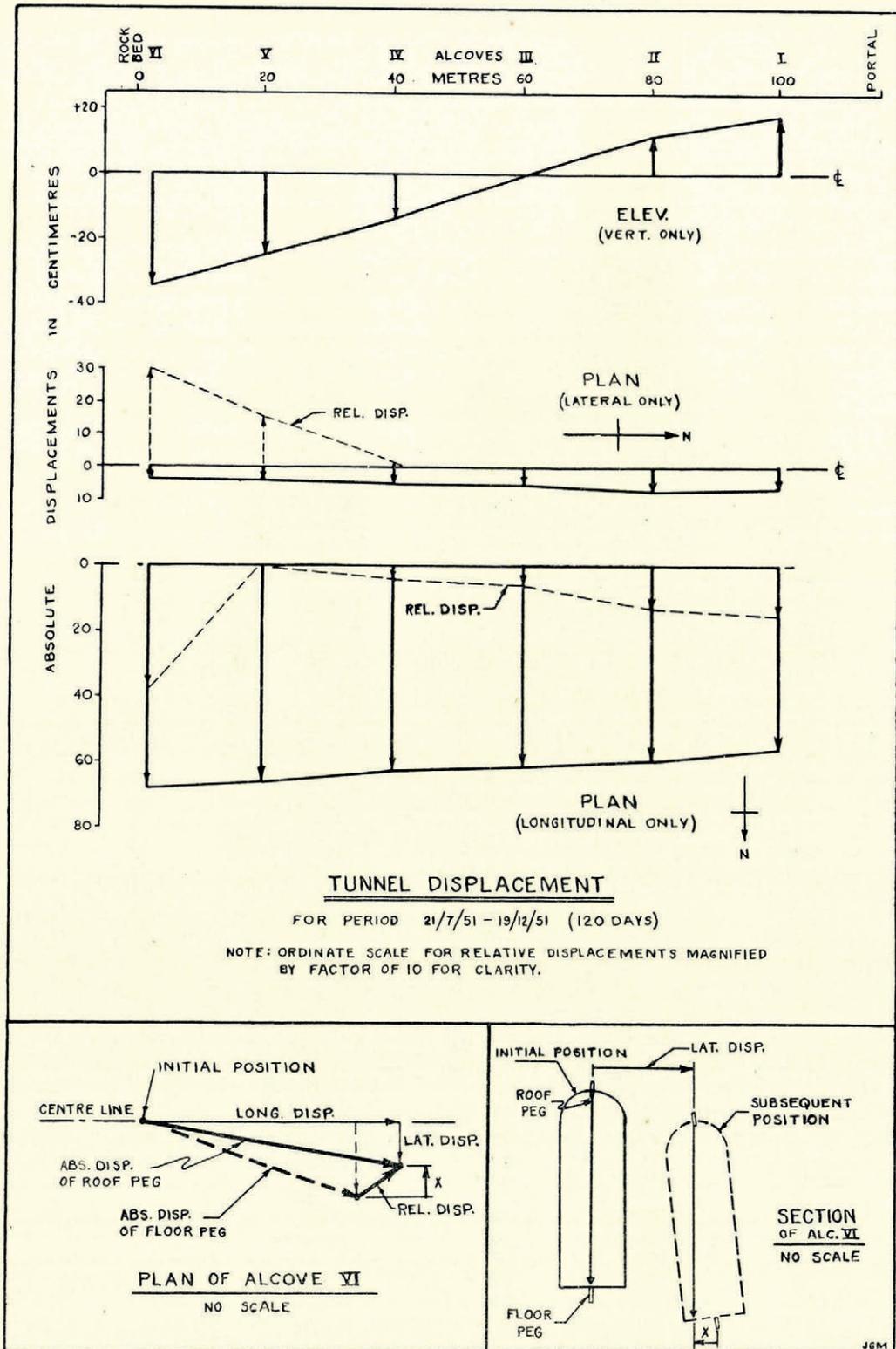
Fig. 3

by the upper and lower tunnels. Whether this shape is the result of a rotational slip [1] or whether the movement pattern is the result of the shape are open questions until more complete quantitative analyses and definitions are forthcoming.[4]

Comparison of the velocities in December with those in August shows a slight decrease in the lower region of the glacier and a slight increase in the *névé* region. The latter is due to the creep of the new snow,[6a] drifted here to a depth ten times greater than at the snout.[7] This means that there are two types of motion to account for in winter, *i.e.* the movement of the glacier proper, and superimposed upon it, the creep and compaction of the snow.

The surface zone of upward movement between Stakes *R* and *IV* is marked by a distinct bulging. Since no evidence of active thrust planes [1] was found, one must consider the words of Demorest, "Experiment shows that deformation of ice, even at the surface of the glacier, is primarily a result of flowage rather than of discontinuous movements on discrete shear planes." [8a] The dotted vector below Stake *R* is hypothetical and drawn in to illustrate how the movement probably dies out with a decrease in both the horizontal and vertical component. This situation will be checked during the next period of observation.

In comparing the magnitude of velocity at the surface with that at the basal zone, the section between Stake *V* and Alcove *VI*, approximately perpendicular to the bed, gives a fair basis. The surface Stake *V* has a resultant average daily movement of the order of 8 mm. When this value is compared to that at Alcove *VI*, a decrease of 10 per cent over the 50 m. depth is noted. This means that 90 per cent of the total movement is concentrated in the sliding * of the ice over the bed and only 10 per cent is distributed up through the ice as a differential movement. At no point could the latter quantity be detected as a thrust along a discrete plane.

Before continuing the topic of differential movements, a few explanatory remarks are necessary concerning Fig. 3 (p. 125). In this figure the absolute movements of the alcove roof pegs are resolved into their three components and plotted, in heavy lines, as the tunnel displacements. The components are treated singly in respect to the tunnel centre line and are termed the vertical, the lateral, and the longitudinal displacements. The magnitudes of these are plotted as the ordinates against the distance along the tunnel as the abscissae. The elevation view illustrates how the tunnel slope is changing by a fall of the rear and a rise of the front. The diagram of the lateral plan shows how the tunnel as a whole is drifting sidewards to the east, away from the apparent centre of the glacier and away from the centre of the basin as formed by the sedimentary bands (see section on sedimentary bands below). In the longitudinal plan, a comparison of the components indicates that the tunnel as a whole is moving forward, but with the inner portion moving faster than the outer. The result is an overall contraction of length, *e.g.* of the order of 0·25 per cent between Alcoves *I* and *II* for a period of 120 days.

Relative Movements

Returning to the topic of differential movements, these have been termed relative displacements in the diagrams of Fig. 3. These relative displacements were measured in the horizontal plane by suspending a plumb line from each roof peg and recording the sense and magnitude of the deviation of the bob point from a point on the head of the floor peg beneath, *i.e.* the movement of the roof peg relative to the floor peg. The deviation was resolved into lateral and longitudinal components and plotted on the respective plan views of Fig. 3. No suitable direct method of obtaining the vertical component could be devised, although a mathematical solution involving vertical rates of contraction and divergence appears possible. In considering the plan views, the longitudinal components of both relative and absolute displacement are of the same direction, while the laterals are of opposite sense. This means that flow lines, passing through the same line normal to the bed, can diverge in respect to a horizontal plane as well as to a vertical (see Fig. 2); or, in other words,

* The term "sliding" denotes yielding of the ice on the under surface of the glacier sole, as suggested by Orowan[9] and Nye.[10]

the base of a glacier need not be moving in the same direction as the surface. The horizontal divergence appears to be confined to the basal portion of the glacier and is probably the result of an irregularity of the bed, as observed elsewhere by Carol [11] and Demorest.[8b]*

In an attempt to clarify this phenomenon, the two sketches at the bottom of Fig. 3 have been drawn. Using Alcove *VI* for the example, the plan view (left) shows the initial position of the roof and floor pegs, lying on the same vertical line and representing respective flow lines. Subsequent movement of the glacier takes the roof peg and the floor peg along the vectors indicated. The difference between the subsequent positions is the relative displacement. The sketch on the right
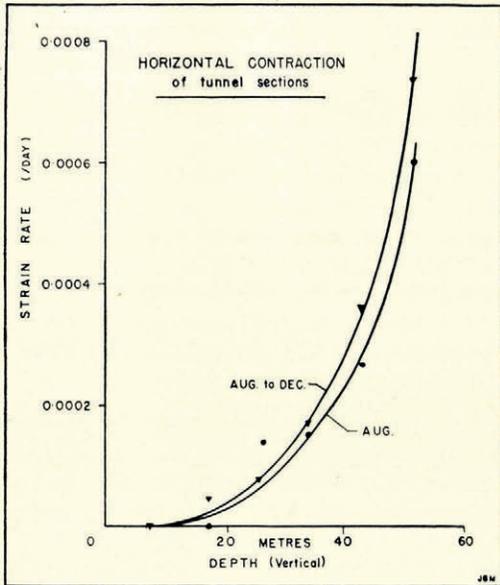

Fig. 4
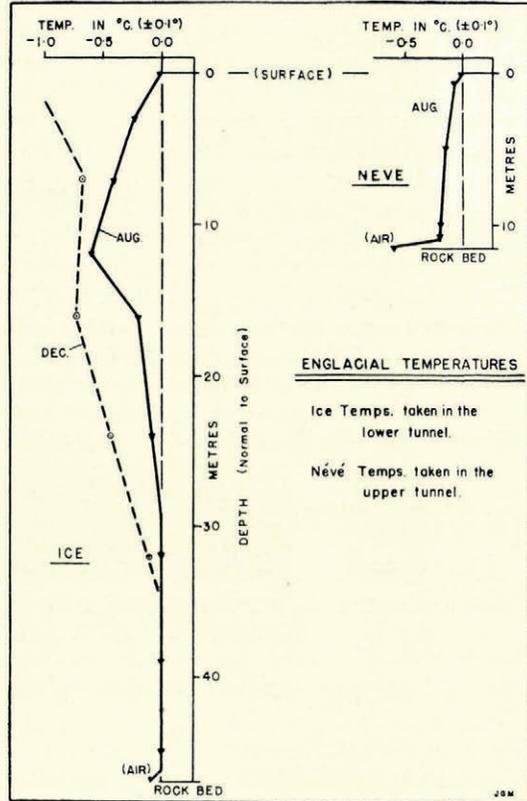
Fig. 6

shows this situation in a lateral elevation as seen looking out through the tunnel. It is emphasized here that if only one set of components is considered, the lower layers have the appearance of moving faster than the upper. To obtain the complete three-dimensional aspect is most important.

CONTRACTION OF TUNNEL SECTIONS

Contraction measurements were made in each alcove section and the results have been plotted as strain rate against vertical depth in Fig. 4 (above). If the pressure is assumed to increase proportionately to the depth, a stress-strain diagram is obtained and the shape of the curve is similar to that arrived at experimentally by Glen,[12] and to that as used by Nye in his theory of glacier

* However, contrary to Demorest's ideas, the presence of small isolated gaps (up to 3 cm. in width) between the ice and the rock-bed indicates that the ice at 50 m. depth is still rigid enough to resist flow into all the bed irregularities.

flow.[10] The strain rate became detectable at approximately 10 m. depth and increased rapidly at depths exceeding 30 m. These values are those set forth by Orowan[9] in his assumption of the yield stress of ice and by Seligman[13] in his work on the depth of crevasses.

Only the horizontal contraction rates have been shown, for uniform closure of the tunnel sections did not occur. Perhaps this was due to such factors as the non-circular section or the divergence of flow lines in the vertical plane; at any rate the vertical contractions were so erratic that they have been omitted pending further study.

THE ICE-ROCK CONTACT

The flash exposure, Fig. 5 (p. 131), portrays the nature of the ice-rock contact as found in the lower tunnel. The instrument shown in the picture, a Chamberlin-type shear meter,[14] was installed for the purpose of recording qualitatively the sliding of the ice over the rock-bed. Only two trouble-free 12-hour records were obtained and they indicated a smooth type of motion, not spasmodic as found by Chamberlin over a thrust plane. During the month of August, no fluctuation in the daily movements was detected. Battle[15] and Washburn[16] have reported pronounced daily fluctuations in surface velocities on other glaciers.

Behind the meter and in contact with the bed lies a layer of dark ice approximately 30 cm. thick. Macroscopically, this ice is of a distinctly different nature from the ice above; it is transparent, bubble-free, band-free and full of concentrations of rock debris ranging in size from rock flour to fragments 20 cm. or more across. The presence of the rock flour and of striations on the bed indicate active abrasion with no apparent plucking on this limited exposure. The term "sole" has been applied to this layer and its origin is probably as follows: some of the water running down the back wall finds its way to the bottom of the *Randkluft* or other gaps * and freezes, incorporating the fragments of debris lodged there. This deposit is then pulled along in a continuous manner by the movements of the glacier, thus forming the sole. It is the rock fragments in the sole that abrade the bed.

SEDIMENTARY BANDS

The term "sedimentary bands" is used here to identify the thin dirt layers found throughout the mass of the glacier. Only this type of band is discussed. A small section of such bands can be seen in Fig. 5 as the many faint parallel bandings above the meter; their overall englacial shapes in the vertical plane are drawn in as dashed lines in Fig. 2. Only a few of them are indicated, their shape being based on dips at the surface and in the tunnel walls. In the limited exposure at the rear of the lower tunnel, these bands, although roughly parallel to the bed and following its undulations, do not quite touch it [1, 2]; they merge gradually into the sole, Fig. 5. Here they are roughly parallel to the bed and appear to have been greatly elongated. The spacing interval and dirt content of the bands are therefore much reduced. This is reasonable for in this zone was found the greatest relative displacement. This was to be expected according to the suggestion of Orowan, that the maximum shearing occurs in the basal layers.[9] The dashed lines demonstrate roughly the tectonic history of a band: deposited originally as a concentration of dirt (largely organic material) on the summer surface, incorporated into the glacier by the addition of snow, subjected to distortion in its journey down-glacier and eventually dying out at the snout. Seen in three dimensions they are basin-shaped with the major axis transverse to the glacier; their outcrops form a series of sweeping, concentric curves running across the glacier surface. The reversal of the direction of the dips of the bands when progressing down the glacier surface is due to the components of velocity, normal to the band, being greater at depth than at the surface. A reversal of this situation causes the decrease in dip below Stake *I*, *i.e.* the surface component surpasses that at depth. For other ideas on this phenomenon see Clark and Lewis.[2] Recently Haefeli made the suggestion that the maximum

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* At the rear of the upper tunnel was found a large gap formed where the ice arched away from the steep back wall. This can be seen in the profile section of Fig. 2. For a description of another such gap, see Haefeli.[6b]

downward velocity component occurs at the axis of the "syncline" * which is indicated by the two dimensional band exposures in a tunnel wall.[6b] This situation was not found in our case. The maximum downward component was found in the basal layers while the axis of the basin occurred at a point 15 m. from the bed out along the tunnel centre line.

Lewis has suggested in his theory of rotational slip [1, 2] that the sedimentary dirt bands are thrust planes, but quantitative observations showed that the "overthrusted" appearance of each band at the surface is the result of differential ablation and not of differential movement, *i.e.* the bands are not discontinuities of shear or thrust, of the type described quantitatively by Chamberlin,[14] and by Perutz and Seligman.[17] In addition, the following observations were made. Only a few random bits of debris were encounted during the excavation of the lower tunnel; if the debris was being brought up from the bed by a rotational slip, a somewhat constant distribution along the bands would be expected. The limited rock-bed exposures in both tunnels showed no evidence of debris being pulled up from the bed into the ice above. A composite sample of the fine debris from thirty bands indicated an absence of rock flour; such material should be present if the debris were derived from the bed. Finally, a calculation involving the measured rates of movement shows that, if the relative displacement observed in Alcove *I* was concentrated along one of the bands in that vicinity, 750 years would be required for a piece of rock to move from the bed to the surface along the band, while only 100 years would be required for the band to move completely out of the zone where such overthrust conditions might exist.

Therefore, the patches of rock debris found on the glacier surface probably originate as suggested by Gibson and Dyson.[7] That is, rock falls occur down the back wall, depositing the debris as a patch or random blocks on the surface of the *névé* with the major axis of the larger fragments orientated on or parallel to the dirty summer surface. The debris then undergoes a history identical to that of a sedimentary band as previously described. Eventually the rocks are exposed impassively by ablation; they are not thrust to the surface by differential movement. Their protruding or "thrusted" nature [1, 2] is the result of their original orientation on the *névé*. Additional confirmation of this idea was gained by the facts that many rock falls to the surface of the glacier were witnessed and that the upper tunnel cut through a relatively thick patch of debris lying at a depth of 8 m. from and approximately parallel to the surface of the *névé*.

TEMPERATURES

The englacial temperatures, taken with a resistance thermometer at intervals along the tunnels, have been roughly summarized in Fig. 6 (p. 127). The temperatures are plotted against the depth normal to the surface, *i.e.* along the thermal gradient. The solid curves signify conditions in August while the dashed curve shows the December temperatures taken with an ordinary mercury in glass thermometer.

In the ice mass, the cold zone extending from the surface to a depth of 30 m. was distinguished by a deposition of hoar frost on the tunnel walls. Since this situation persisted in August and was present again in December, the assumption that the temperature there never quite came up to 0° C. throughout the past year seems a reasonable one.[13,18] The inner zone of 0° C. was distinguished by water inflows and numerous puddles on the tunnel floor, puddles which were found and remained unfrozen in December. A relatively small decrease in temperature was noted in the transition from the ice to one of the small isolated air gaps between the ice and rock-bed.

The curve for the conditions in the *névé* was plotted from the set of observations obtained eighteen hours after the completion of the upper tunnel. Subsequent readings showed a rise in temperature to 0° C. at all points, the result of the abnormal and continuous circulation of air created by the penetration of the large gap † by the tunnel. The curve indicates again a negative

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* When this synclinal feature is considered in three dimensions, it is seen to be actually a basin or a synclinal trough with upturned ends.

† See the footnote pertaining to the gap in the section on the ice-rock contact, above.

condition existing in August and a relative decrease in temperature when passing from *névé* to the air of the gap.

CONCLUSION

In conclusion, the author would like again to emphasize the preliminary nature of this report. It is far from complete and has the immediate aim of criticizing some of the current suggestions advanced on the topic of englacial phenomena. Only a few inferences can be drawn at this time. They are:

1. Three-dimensional studies of glacier movement are of absolute importance for the plotting of flow lines and velocity gradients.
2. Ice movement at the snout of a glacier can have a marked upward component.
3. The basal layers of a glacier need not be moving in the same direction as the surface, either in respect to the vertical or the horizontal.
4. Rates of contraction of the tunnel cross-sections help to confirm that the nature of ice is quasi-viscous.
5. There is no effective over-thrusting along the sedimentary dirt bands as suggested in the theory of rotational slip.
6. The temperature of the surface zone of this temperate glacier remained at slightly negative values throughout the summer.

ACKNOWLEDGEMENTS

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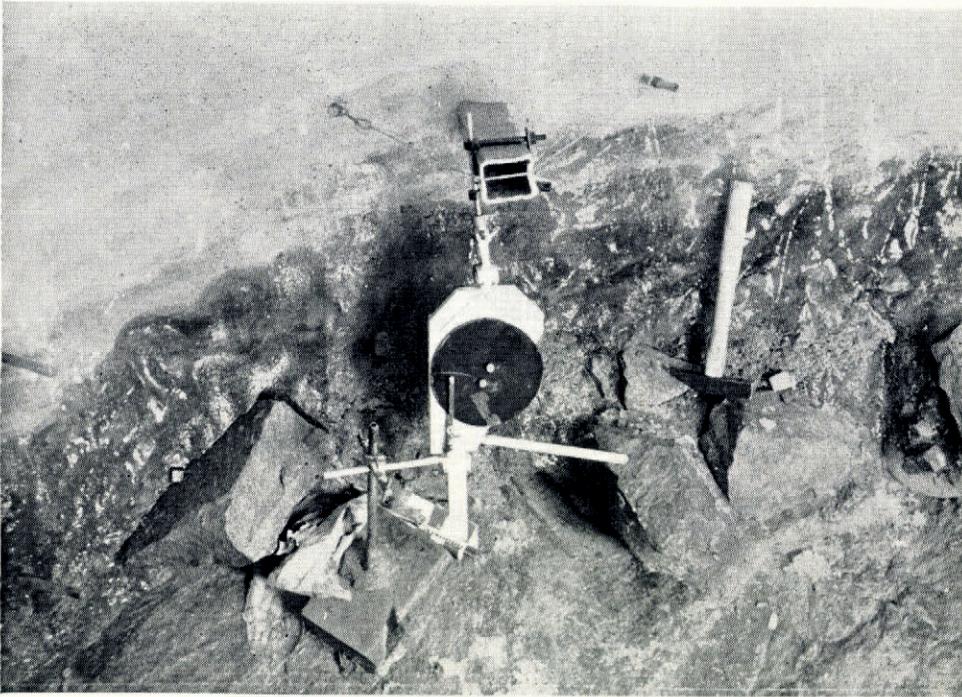
Fig. 5. (See text, p. 128) The ice-rock contact as seen in the lower tunnel at depth of 50 m. The hammer is resting on rock fragments in the sole. Below this is the rock bed. The instrument shown is a Chamberlin-type shear meter. The faint bandings above the dark sole are the sedimentary dirt bands

Fig. 1. (See text, p. 142) Tasman Glacier and Malte Brun Range, Southern Alps, New Zealand. The "vegetation line," with which remnants of a lateral moraine of the same age and approximately the same height are associated, is parallel to the present glacier surface for twenty-two km. from the terminal face. The greater part of the down-wasting however occurred later in the upper part of the glacier than in the lower part