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SHORT NOTES

FURTHER RESULTS ON STUDIES OF TEMPERATURE-GRADIENT METAMORPHISM

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ABSTRACT. A correlation between temperature gradient in snow-pack and material strength is found to exist in laboratory studies on temperature-gradient metamorphism of snow. These results are in agreement with earlier field investigations and eliminate diurnal solar and temperature variations as reasons for the existence of the maximum temperature gradient in the zone of minimum strength. Also the laboratory studies have indicated that locally dense layers such as ice crusts tend to enhance weakness directly below the crust due to local alteration of the thermal regimen. Further studies are continuing to describe the thermodynamic process of temperature-gradient metamorphism more exactly.

RÉSUMÉ. *Nouveaux résultats des études de métamorphose de gradient thermique.* Au cours d'études en laboratoire sur la métamorphose de gradient thermique de la neige on a trouvé une corrélation entre le gradient thermique de la neige et la résistance mécanique du matériau. Ces résultats sont cohérents avec des investigations de terrain antérieures et éliminent le rayonnement solaire diurne et les variations de températures comme causes de l'existence d'un gradient thermique maximum dans les zones de moindre résistance mécanique. Les études de laboratoire ont également montré que des niveaux localement denses comme les croûtes de glace tendent à engendrer une zone fragile directement sous la croûte en raison de l'altération locale des régimes thermiques. De nouvelles études sont poursuivies pour décrire plus exactement les processus thermodynamiques de la métamorphose de gradient.

ZUSAMMENFASSUNG. *Weitere Ergebnisse über den Metamorphismus unter einem Temperaturgradienten.* Aus Laboruntersuchungen über den Metamorphismus von Schnee unter einem Temperaturgradienten geht hervor, dass eine Korrelation zwischen dem Temperaturgradienten in der Schneedecke und der Festigkeit des Materials besteht. Diese Ergebnisse stimmen mit früheren Felduntersuchungen überein; sie schliessen tägliche Schwankungen der Sonneneinstrahlung und der Temperatur als Ursache des Auftretens des maximalen Temperaturgradienten in der Zone geringster Festigkeit aus. Die Laborversuche haben weiter gezeigt, dass lokal dichte schichten, wie z.B. Eiskrusten, infolge lokaler Änderungen der Wärmehaushalts zu einer Erhöhung der Nachgiebigkeit direkt unter der Kruste führen. Weitere Studien werden unternommen, um den thermodynamischen Vorgang des Metamorphismus unter einem Temperaturgradienten noch genauer beschreiben zu können.

INTRODUCTION

During the process of temperature-gradient metamorphism of a snow-pack, an intricate relationship exists between temperature gradient in the snow-pack and material density, strength, crystalline properties, and the transfer of heat and mass in the pack. In order to develop a mathematical formulation of this complicated thermodynamic problem, a better grasp of the physical processes taking place at the crystalline level is needed. For the past several years, field and laboratory studies (Bradley and others, 1977[a], [b]; Armstrong, 1980) have been under way in order to gain a better understanding of this problem.

In earlier papers (Bradley and others, 1977[a], [b]), field investigations of temperature-gradient metamorphism indicated that a temperature-gradient anomaly existed at the point of weakest strength in alpine snow-pack. In these papers, it was noted that the weakest snow was usually subhedral depth hoar rather than the fully developed euhedral depth hoar at the bottom of the snow-pack. This subhedral zone, was often found 100 to 150 mm above the ground surface, and in this zone both minimum strength and maximum temperature gradient occurred.

These field observations were not fully verified by laboratory tests (Bradley and others, 1977[a]). The laboratory tests did indicate that the weakest snow was subhedral depth hoar located above the fully developed euhedral depth hoar, but no temperature-gradient anomaly was detected. The laboratory results did show a non-linear temperature gradient in the snow sample, but no local maximum in the temperature gradient was detected. This discrepancy was confusing, since under controlled laboratory conditions, a temperature-gradient anomaly such as seen in the field investigations should have been detected if it did exist. However, the existence of the local maximum gradient at the zone of weakest strength in the field was established beyond any doubt by numerous readings.

One possibility for the failure to detect the temperature-gradient anomaly in the laboratory studies was the coarse grid of temperature measurements. Thermistors were placed in the snow samples at 0.1 m intervals, thereby precluding good resolution in calculating the temperature gradient. However, the possible importance of other effects such as diurnal variations of radiation and air temperature required further laboratory studies.

Laboratory investigation

During the winters of 1978–79 and 1979–80, further laboratory studies were carried out. All snow used for the experiments was obtained from a natural alpine snow-pack, with the exception of the test labelled 4-80 (Figs 3 and 7). Snow used for this test was obtained during a snow-fall, and at the time of collection was unsintered with predominantly stellar crystals. The resistant layer that is displayed in Figures 3 and 7 was obtained by using older snow from deeper within the snow-pack. This fine-grained snow was sifted on top of the partial sample of fresh snow to obtain a thin layer of locally dense snow. The remainder of the desired sample height was reached using freshly fallen snow. In this way a fairly uniform sample with a resistant layer was obtained. This sample was then allowed to sinter in the laboratory under essentially isothermal conditions for several weeks before testing.

At the time of testing all samples consisted, generally, of rounded grains of fairly uniform size and well-developed bonding. Using the Sommerfeld–LaChapelle system, the samples could generally be classified as IIB2 with grain size generally less than 0.5 mm. The samples were all obtained from the upper half of midseason snow-pack in order to obtain snow that was of fairly low density and had not shown significant temperature-gradient effects prior to testing.

During the laboratory procedure, temperatures were recorded every 5.0 cm with a resolution of 0.1 K. Specimens were placed on a heated reservoir held at −1.5°C. The sides of the specimens were well insulated so that the heat flux from the reservoir to the top surface was primarily vertical. The air temperature was generally held at −20°C. The samples had a 0.5 m × 0.5 m cross-section and a height of about 0.4 m. During the testing period of from 6 to 29 d, there was usually some settlement, but this was generally less than 1 cm.

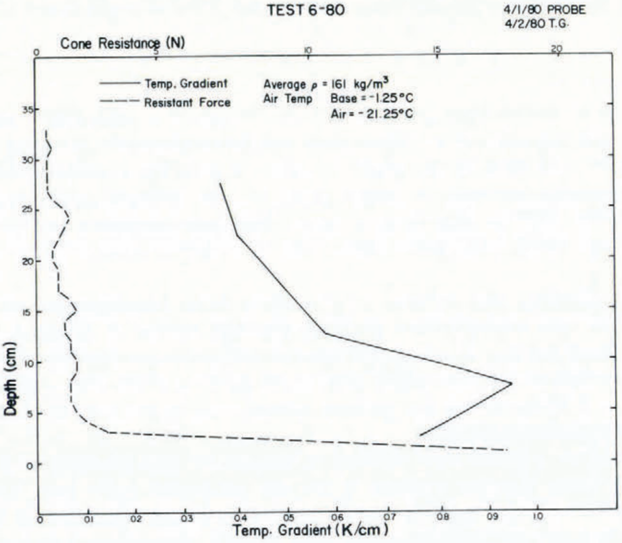

Fig. 1. Correlation between temperature gradient and snow strength within a fairly homogeneous snow-pack. It indicates the tendency for the temperature gradient to decrease with height.

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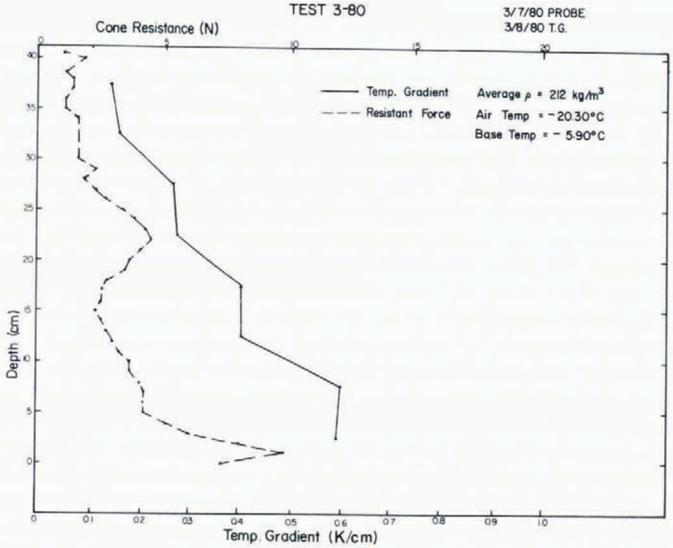

Fig. 2. Correlation between temperature gradient and snow strength within a fairly homogeneous snow-pack.

The temperature profile was measured every day and a strength profile was then taken every three days or once a week, depending on the length of the test. This was done by driving a conical probe into the snow specimen with an Instron testing machine. Load resolution with this apparatus was ± 0.2 N. The cone had a base diameter of 1.5 cm and a cone angle of 60°. While the probe measurements did not give a direct measure of either shear strength or compressive strength, it did give a good indication of the relative strength of the different layers in the snow-pack.

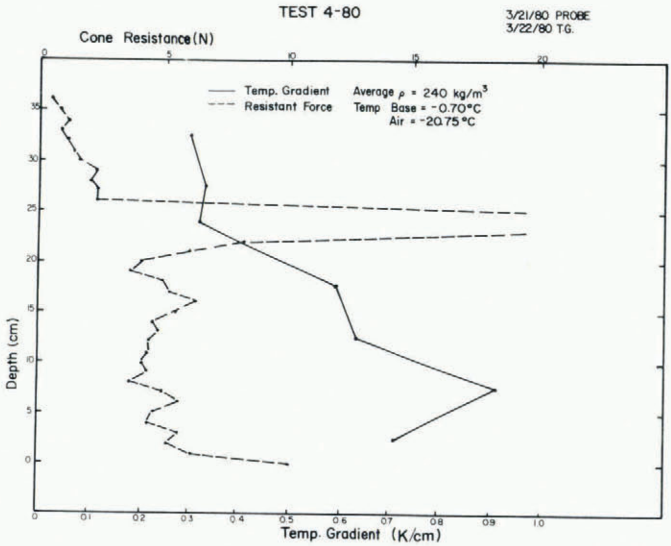

Fig. 3. Correlation between temperature gradient and snow strength in a snow-pack with a distinct resistant layer. The tendency for temperature gradient to decrease with height is demonstrated.

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Discussion of results and conclusions

Figures 1 and 2 demonstrate a trend which is typical of results found when a temperature gradient was imposed on a sample of fairly uniform strength. These figures show the temperature gradient and cone resistance plotted against distance from the bottom of the sample. The samples for Figures 1–3 were of low density and poorly bonded when collected. As a result, settlement of approximately 10–20% of the original height occurred during transportation to the laboratory. This compaction took place predominantly in the lower portion of the samples. While in the laboratory the snow was permitted to sinter before a temperature gradient was induced, this resulted in a high relative strength at the base. There is a tendency for the temperature gradient in a uniform sample to decrease with increasing height.

The samples associated with Figures 3, 4, and 5 are representative of non-uniform snow-packs possessing distinct layers of high relative strength.

Figure 3 also shows the tendency for the temperature gradient to decrease with height. What should be noted, however, is the sharp decrease in the temperature gradient associated with the single resistant layer situated at the 20–25 cm region. From Figures 4 and 5, it can be readily observed that zones of weakness are associated with areas of local maximum in temperature gradient and zones of strength with minimum temperature gradient.

The temperature-gradient anomaly may be explained in terms of changes in thermal conductivity due to metamorphism. During the process of temperature-gradient metamorphism, the grain bonds generally decrease in cross-sectional area relative to the grain-size. This degradation of the inter-granular bonding results in decreased strengths, and it must also result in a decrease in the thermal conductivity, since a good portion of the heat transfer must take place through the solid ice structure comprising the snow. This results in locally high gradients in areas of poor bonding in order to conduct heat at the required rate.

Another phenomenon which was noticed during laboratory investigation warrants mention. Observing Figures 6 and 7, attention should be drawn to the region below the zones of high relative strength. These figures indicate that the greatest loss of strength developed immediately below these resistant layers. The snow above such a layer shows little initial change in strength. Eventually a weakening of the entire pack took place but the areas of local weakness remained.

Figure 6 shows the changes which developed after nine days. There is a general weakening of the entire pack below the layer situated from 27–31 cm, with the greatest weakening immediately beneath this layer. At this time little change had taken place above the resistant zone. This test was continued, with a resulting strength decrease throughout the pack, but the areas of local weakness which had developed persisted.

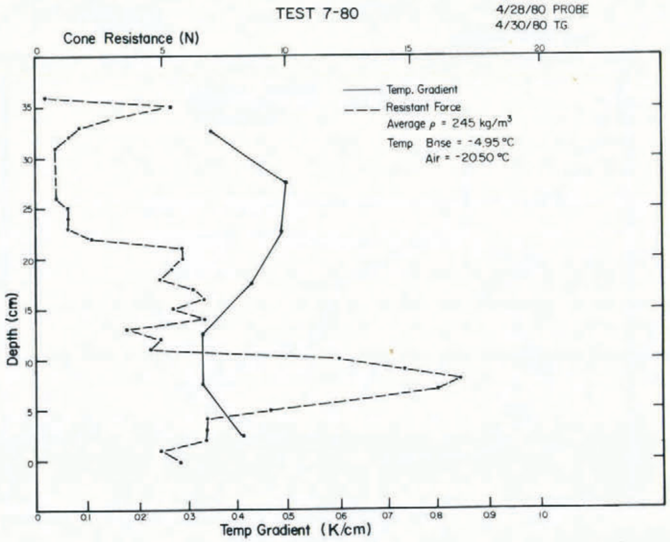

Fig. 4. In inhomogeneous snow, zones of weakness are associated with areas of local maximum temperature gradients and zones of strength with local minimum temperature gradients.

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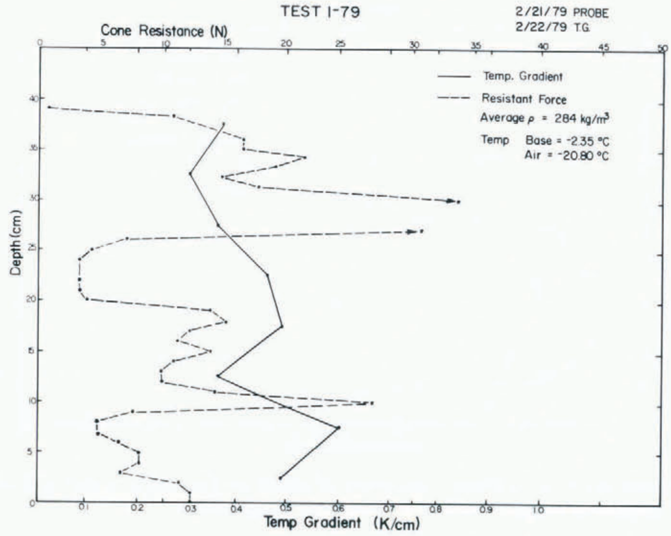

Fig. 5. In inhomogeneous snow, zones of weakness are associated with areas of local maximum temperature gradients and zones of strength with local minimum temperature gradients.

The major temperature-gradient peak in this test was located in the region between 5–10 cm for the first four days. After this time the temperature-gradient peak became dominant at the 20–25 cm level. This result indicates that, had a strength test been run on the fourth day, the major weakening would have appeared in the zone beneath the resistant layer located at 11 cm.

Figure 7 also demonstrates this pronounced weakening below with little change above the layer of dominant strength. The base temperature-control device allows a fluctuation of approximately 1.5 K. During the course of this test, the basal temperature periodically rose above and below the melting point, forming a melt–freeze snow type, and therefore a shortening of the sample near the base. In order to demonstrate the change in stratographic strength, the graph has been arranged so the resistant layer coincides for the two days represented.

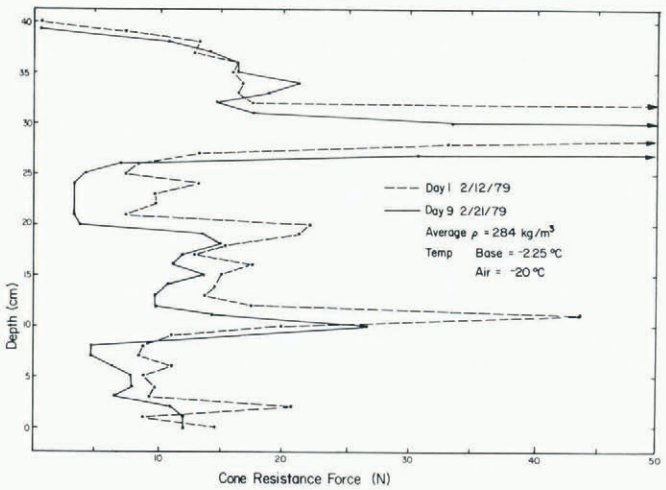

Fig. 6. Changes in strength which developed after nine days of a constant temperature gradient.

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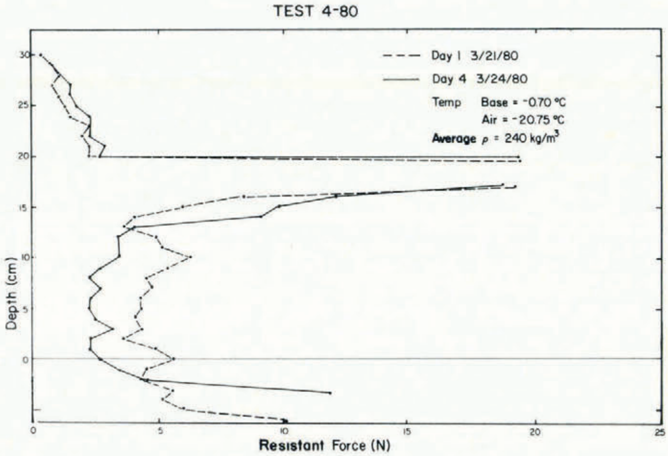

Fig. 7. Change in strength due to a constant temperature gradient for four days. A loss of strength has taken place below the most strongly bonded layer, with little change in strength above.

Field observations verify these laboratory results, at least in part. Numerous qualitative observations indicate that when a layer of high relative strength is located, it is underlain by an area of weak, partially temperature-gradient metamorphosed snow. In the field, the layers of high strength were usually wind or ice crusts which formed while on the snow-pack surface.

The cause for this phenomenon has not been researched thoroughly enough to be fully understood. A plausible cause, however, might be related to the higher thermal conductivity associated with areas of strength, as discussed previously. The well-bonded layer acting as a heat sink may cause a local rise in temperature gradient directly below it. This increases the rate of metamorphism, thereby resulting in the well-established weakness associated with this recrystallization.

Future studies are planned. In particular low-density snow $(0.15 \text{ Mg m}^{-3}) \leqslant \rho \leqslant (0.25 \text{ Mg m}^{-3})$ will be tested. Temperature gradients will be measured directly in increments of 0.02 m with a probe that has a resolution of 1.0 K m^{-1}, so that a very accurate evaluation of this complicated thermodynamic problem can be further evaluated.

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