

SHORT NOTES

ON DEPTH HOAR AND THE STRENGTH OF SNOW

By C. C. BRADLEY,* R. L. BROWN† and T. WILLIAMS

(College of Letters and Science, Montana State University, Bozeman, Montana 59715, U.S.A.)

ABSTRACT. It has long been known that a temperature gradient in the snowpack, when temperatures are less than 0°C, can metamorphose the snow to produce a fragile euhedral crystalline end product called "depth hoar" which is considered to be responsible for snowpack collapse and climax avalanches. The wave of metamorphism advancing through anhedral snow converts it, first to subhedral, and finally to euhedral depth hoar. Our field observations, which are at the moment supported by laboratory evidence, reveal that the zone of minimum snow strength in the gradient metamorphic layer is associated with the intermediate subhedral phase rather than with the euhedral end product.

RÉSUMÉ. Sur le givre profondeur et la résistance mécanique de la neige. On sait de longue date, qu'un gradient thermique dans le manteau neigeux à des températures négatives peut transformer la neige en fragiles cristaux, entièrement recristallisés. Ce produit final appelé "givre de profondeur", est tenu pour responsable des ruptures du manteau neigeux et des avalanches "climatiques". La progression de la métamorphose à travers une neige à grains quelconques, la transforme d'abord en un stade de début de recristallisation avant d'aboutir au givre de profondeur complètement recristallisé. Nos observations sur le terrain, jusqu'ici confirmées au laboratoire, révèlent que la zone de moindre résistance mécanique de la neige est liée au stade intermédiaire de demi-recristallisation plutôt qu'au produit final entièrement reconstruit.

ZUSAMMENFASSUNG. Über Tiefenreif und Schneefestigkeit. Seit langem ist bekannt, dass ein Temperaturgradient in der Schneedecke bei Temperaturen unter 0°C die Metamorphose des Schnees in ein fragiles kristallines Endprodukt veranlassen kann, das "Tiefenreif" genannt und für Zusammenbrüche der Schneedecke und Lawinen verantwortlich gemacht wird. Die Metamorphose-Welle, die durch Schnee vordringt, verwandelt ihn zuerst in und schliesslich in Tiefenreif. Unsere Feldbeobachtungen, die auch durch Laborversuche gestützt sind, zeigen, dass die Zone geringster Schneefestigkeit in der zunehmend metamorphen Schicht eher an die subhedrale Übergangsphase gebunden ist als an das Endprodukt.

INTRODUCTION

In the field of avalanche safety and control the association of depth hoar with some of our most treacherous avalanches was first reported by Paulke (1932). Seligman (1936, p. 72) considered the requirements for the formation of depth hoar to be: (1) a temperature gradient, (2) some space available for crystal growth, and (3) a stream of vapor to nourish the growth. Neher (in Bader and others (1939), English translation, p. 237) noted that depth hoar is not always lacking in strength, and he considered strong depth hoar to be a consequence of load hardening. In recent studies, Akitaya (1974) made exhaustive laboratory examinations of depth hoar development and defined various physical realms for different crystal types and strength changes. He related "hard depth hoar" to a high initial density and a fine texture of the snow.

In nature, the required temperature gradient is normally a function of the amount of heat stored in the ground during the summer. In areas of high geothermal flux, such as the Yellowstone National Park, depth hoar can result from the geothermal gradient. Many rammsonde profiles, pit studies, and most resistograms which involve depth hoar in the pack have suggested that the zone of minimum strength may be several centimeters above ground level, whereas the best euhedral depth hoar is often found in the basal layer of the snowpack. A coordinated laboratory and field study has been undertaken to examine this relationship and to discover whether the regimen which produces euhedral depth hoar is indeed different from that which produces the zone of minimum strength. This paper mainly discusses some preliminary results from the field study.

FIELD SITE AND METHODOLOGY

The site selected for the field investigation was a sector of snow-pack around the orifice of Old Faithful geyser in Yellowstone National Park. Previous studies in that area (Bradley and Alford, 1967; Alford and Bradley, 1968), indicated that the combination of abnormal geothermal gradient, cold winter

* Earth Science Department.

† Civil Engineering and Engineering Mechanics Department.

climate, and thin snowpack produces euhedral depth hoar and collapsing snow virtually every winter. The observations reported here took place during December 1974.

Three thermistor stacks were installed on a radial line from the Old Faithful vent in order to monitor the thermal gradient in the ground. They were placed so that the stack nearest to the vent would fall just within the edge of the snowpack, whilst the furthest from the vent would be in an essentially normal portion of the pack. These positions were a matter of experience. The thermistors were set at 100 mm and 250 mm depth below ground level. The temperature profile in the snow was measured by the use of a portable thermistor probe and was recorded on a "Rustrack" recorder. This system is capable of giving temperature readings accurate to within 0.2°C . Other observations included (1) the daily weather (especially maximum–minimum temperatures, the snow fall, and snow accumulation on the ground); (2) frequent temperature readings from below ground moving up through the snowpack and eventually into the air; and (3) frequent snow strength readings made with a resistometer. (The resistometer is a probe having a conical point and a spring mounted handle which is coupled to a sensitive displacement dial indicator. It is capable of giving accurate spot strength measurements of very weak snow at depth.) Snow-pit studies of metamorphic zoning, including a photographic record of grain size, crystal development, density distribution and whisk broom abrasion profiles were also made.

OBSERVATIONS

By the time the seasonal snowpack was 280 mm deep, depth hoar appeared at the base of the pack in one or two days during a period of cold weather. Three well defined zones emerged as gradient metamorphosis proceeded. These zones had, in order, euhedral, subhedral, and anhedral structures, with the euhedral snow at the base. As expected, crystal size was related to euhedral development, with the coarsest snow at the base. Both whisk-broom abrasion tests on the pit face and resistometer readings showed a well defined band of weakness in the subhedral section of the metamorphosed layer (this occupied the middle third) with the strongest snow being the basal euhedral zone. Densities in the metamorphosed layer ranged from 0.16 to 0.20 Mg m^{-3} . There was a very slight, but persistent, high value for the density of the intermediate weak zone with the basal strong zone having the lowest density in general. This suggests that upward mass transfer has taken place between the basal and intermediate layers.

The thermal profiles in nearly every case showed a marked increase in the temperature gradient associated with the intermediate weak zone, and thus there was a good correlation between snow weakness, ambient thermal gradient, and the subhedral phase of metamorphism. After the portion of the pack which had undergone gradient metamorphosis had attained a thickness of about 180 mm, depth hoar was well formed and the three zones were delineated. There was little evidence of the widening of the zones with time. There was, however, a general strengthening and perhaps a slight densification of all layers during this intermediate period. During the final period of observation, when the pack had attained a depth of 400 mm, both the anomaly in the thermal gradient and the anomaly in the strength had largely disappeared, even though the textural zoning was still clearly present. Throughout the period of zonal weakness there was a strong tendency for the snowpack to collapse onto the weak zone.

The laboratory portion of this study is incomplete, but so far it tends to support the field observations.

CONCLUSIONS

1. Gradient metamorphism provides an advancing wave of change moving through the pack, usually up from the ground. First, there is a weakening of the snow, later, a period of strengthening occurs as recrystallization modifies the texture from finer anhedral snow to coarser euhedral snow.

2. It seems likely that the metamorphic process itself generates the thermal gradient anomaly in the mid-zone, which in turn becomes the region of most rapid change accompanied by weakening. The state of minimum strength may be ephemeral in that it tends to disappear with the decreased thermal gradient as the pack deepens and mass transport diminishes.

3. We suspect that the thermal gradient anomaly is in part a function of zonal differences in thermal conductivity and in part a function of sublimative heat exchange. The basal euhedral depth hoar probably represents a quasi-stable end product of gradient metamorphism. Its well sintered bonds and high permeability would favor conduction, convection, and the observed low thermal gradient. The subhedral zone on the other hand, represents the active front of metamorphism. Sublimative mass

transfer from this zone to the upper zone would cause heat loss in the middle zone and heat gain in the upper zone which in turn could account for the observed anomalous inflections in the thermal gradient through those zones.

4. Since a slight extra loading of the snowpack produced compressive failure and collapse of the pack on the weak zone *above* the euhedral zone, it seems unlikely that the strength of the euhedral zone can be attributed to load hardening.

A full report of this study is planned after the conclusion of the laboratory investigation of the phenomenon.

ACKNOWLEDGEMENTS

This research was supported jointly by the office of Army Research, Durham under Grant No. DA-ARO-D-31-124-71-G59 and the National Science Foundation under Grant No. NSF FA-3943. The authors wish to thank the Yellowstone Park Service for making the Old Faithful area available for us to conduct the field research, as well as furnishing housing for the observer.

MS. received 26 January 1976 and in revised form 22 April 1976

REFERENCES

- Akitaya, E. 1974. Studies on depth hoar. *Contributions from the Institute of Low Temperature Science*, Ser. A, No. 26.
- Alford, D. L., and Bradley, C. C. 1968. The relationship of soil temperature to snow pack depth and density. *Atmospheric Sciences Research Center, State University of New York at Albany. Publication No. 68.*
- Bader, H., and others. 1939. Der Schnee und seine Metamorphose, von H. Bader, R. Haefeli, E. Bucher, J. Neher, O. Eckel, C. Thams, P. Niggli. *Beiträge zur Geologie der Schweiz. Geotechnische Serie. Hydrologie*, Lief. 3. [English translation: *U.S. Snow, Ice and Permafrost Research Establishment. Translation 14, 1954.*]
- Bradley, C. C., and Alford, D. L. 1967. Depth hoar formation in Yellowstone Park. *Atmospheric Sciences Research Center, State University of New York at Albany. Publication No. 45.*
- Paulke, W. 1932. Aus meinen "Natlaborator" für Schnee- und Lawinenforschungen. *Bergsteiger* (Wien), 1932, No. 6, p. 332-42.
- Seligman, G. 1936. *Snow structure and ski fields; being an account of snow and ice forms met with in nature and a study on avalanches and snowcraft.* London, Macmillan and Co. [Reprinted, Jos. Adam, Brussels, 1962.]