Permafrost and Periglacial Processes, Vol 3: 203-208 (1992)

Short Communication

Vertical Movements of Boulders in a Subnival Boulder Pavement at 2800 m a.s.l. in the Alps (France)

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ABSTRACT

Vertical movements of boulders within a subnival boulder pavement were measured at 2800 m a.s.l. in the Alps over a period of 10 years. It was demonstrated that some boulders are undergoing sinking and others upheaving. The upheaving occurs in autumn during ground freezing, while the sinking of boulders probably occurs in springtime when the ground temperature is below 0 °C under the snow patch.

RÉSUMÉ

Les mouvements verticaux de blocs d'un dallage nival localisé à 2800 m d'altitude dans les Alpes françaises ont été mesurés pendant une dizaine d'années et ont montré que des blocs sortent du sol, tandis que d'autres s'enfoncent dans la boue. Les soulèvements résultent de l'apparition de glace de ségrégation en automne, tandis que l'enfoncement des blocs se produit vraisemblablement au printemps lorsque sous la plaque de neige la température du sol est de 0 °C.

KEY WORDS: Subnival boulder pavement Frost heaving Nivation Alps

WHAT IS A BOULDER PAVEMENT?

Stone or boulder pavements are accumulations of rock fragments in which the surface stones lie with a flat side up and are fitted together like a mosaïc (Washburn, 1979, p. 173).

Three kinds of stone pavements have been described in the literature.

(1) Those located on the shores of lakes and sea and on the banks of rivers. The first descriptions date from the last century in Spitzbergen (Garwood *et al.*, 1898), in Alaska and on the beaches and shorelines of the Great Lakes (e.g. Spencer, 1890; Dionne, 1970, 1974, 1989). They are caused by the weight of floating ice that has been pushed onto the beach or shore by winds or has accumulated during

1045-6740/92/030203-06$08.00

Received 1 November 1991
Accepted 1 February 1992

the spring discharge. The most important research on such features was carried out by Mackay and MacKay (1977) along the Mackenzie River and by Mansikkaniemi (1976) on the beaches of Finland.

(2) Boulder pavements which are located where icings form every year. These have been described from Alaska (Porter, 1966), Greenland (Washburn, 1979) and Spitzbergen (Åckerman, 1980). This mosaïc pattern was also explained by the weight of the ice. Åckerman (1980) has written that these pavements are clearest in places where icings grow early in the year.

(3) A third type of stone pavement, called an alpine subnival boulder pavement (White, 1972), was first described in the German literature at the beginning of the twentieth century (e.g. Walbaur, 1921; Stiny, 1926; Kinzl *et al.*, 1928; Salomon, 1929; Troll, 1944), in the French literature after World War II (e.g. Cailleux and Taylor, 1954; Tricart, 1967) and subsequently in the English literature (e.g. White, 1972; Embleton and King, 1974; Washburn, 1979). These boulder pavements are always located in the bottom of wet hollows, where snow accumulations remain during most of the year.

SUGGESTED ORIGINS

The origin of these 'alpine subnival boulder pavements' is currently under debate. Some people think that these features result from the weight of the snow in the same manner as the pavements found on the shores of lakes and below icings. Others think that the main process is the upheaving of boulders by frost and their accumulation at the ground surface. Sekyra (1960) in Czechoslovakia has shown that very few boulders are present in the layers immediately below a stone pavement, and he believes that such a stone distribution demonstrates the action of frost heave.

On the other hand, Bout and Godard (1973) have stated that, below the snow, the ground remains frozen and that under such conditions differential movement of boulders is not possible. They also believe that the main process acting to form the stone pavements is frost heaving.

DESCRIPTION OF THE BOULDER PAVEMENT STUDIED AT CHAMBEYRON

In order to measure the vertical movements of boulders, marks were painted on blocks of a subnival boulder pavement located in the Alps at 2800 m a.s.l. in the Chambeyron valley. This boulder pavement is located in the bottom of an elongate karstic hollow at the front of a rock glacier which was moving during the last century and whose front is very steep (41°) (Figure 1). The bottom of the hollow is very muddy and wet all year round. Every spring a snow patch forms in this place with its maximum thickness against the front of the rock glacier. It melts back progressively during the summer and usually completely disappears by the end of the warm season. Blocks coming from the top of the rock glacier and sliding down this snow patch are sometimes deposited directly on the boulder pavement (Figure 2). It is clear that not all the boulders are coming out of the deposit by frost heaving, and that some of the boulders have fallen from the rock glacier.

We distinguish three parts in this subnival boulder pavement. The lowest (A on Figure 1) is extremely wet and is under water during most of the year; no vegetation grows here. Part B, which is a little higher, is not flooded as frequently and less than 50% of the ground is covered with vegetation. Part C is higher and never flooded, and is largely covered with vegetation. In part A, which is the wettest, about 100 probings were made with a stick. In 60% of the probes, stones were encountered at depths of less than 15 cm, while in 30% a stone was encountered between 15 cm and 30 cm; in the remaining 10%, the top 35 cm were stone-free.

We have no measurement of the thickness of the snow during the winter for this location. However, 40 km to the north of Chambeyron and, at 2 450 m a.s.l., one of us has measured a thickness of 2 m in May–June with a density of approximately 0.5 g/cm^3. This probably represents a minimum thickness.

The boulder pavement is best-developed in the wettest part. This is in close proximity to the rock glacier, where the maximum thickness of the snow accumulates due to wind action.

OBSERVATIONS

Twenty-two boulders were marked with horizontal coloured lines and numbers which give the distances between the lines and the ground between the boulders in centimetres. Some blocks have only one mark, while others have up to three lines located on several faces of the blocks, which permit the measurement of any rotational movements. In 1979, marks were painted on 15 boulders (1–15,

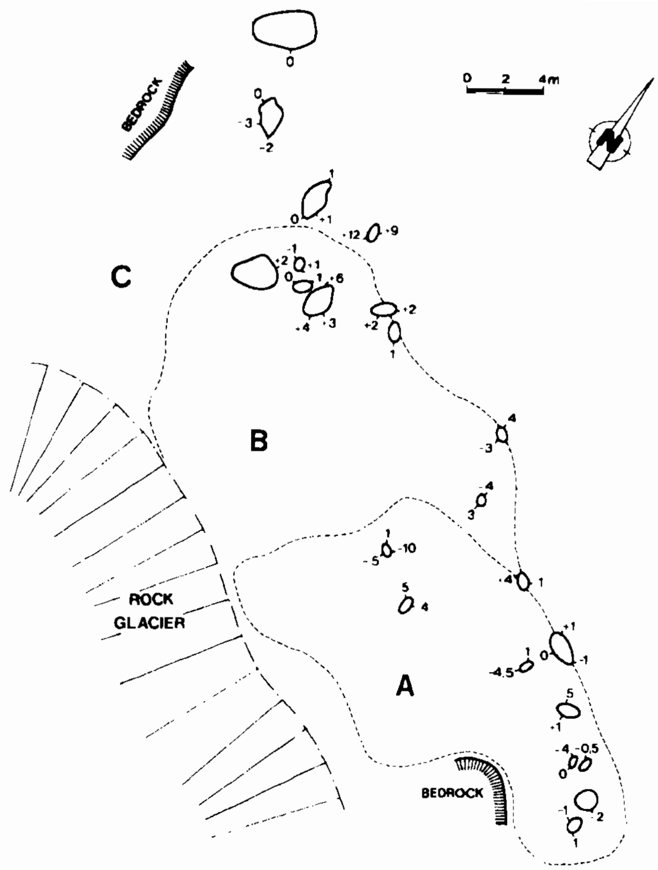

Figure 1 The position of the boulders for which the displacements have been measured. The numbers show the displacements in cm observed over the period 1979–1991 for 15 boulders and over the period 1983–1991 for the 7 boulders in zone A.

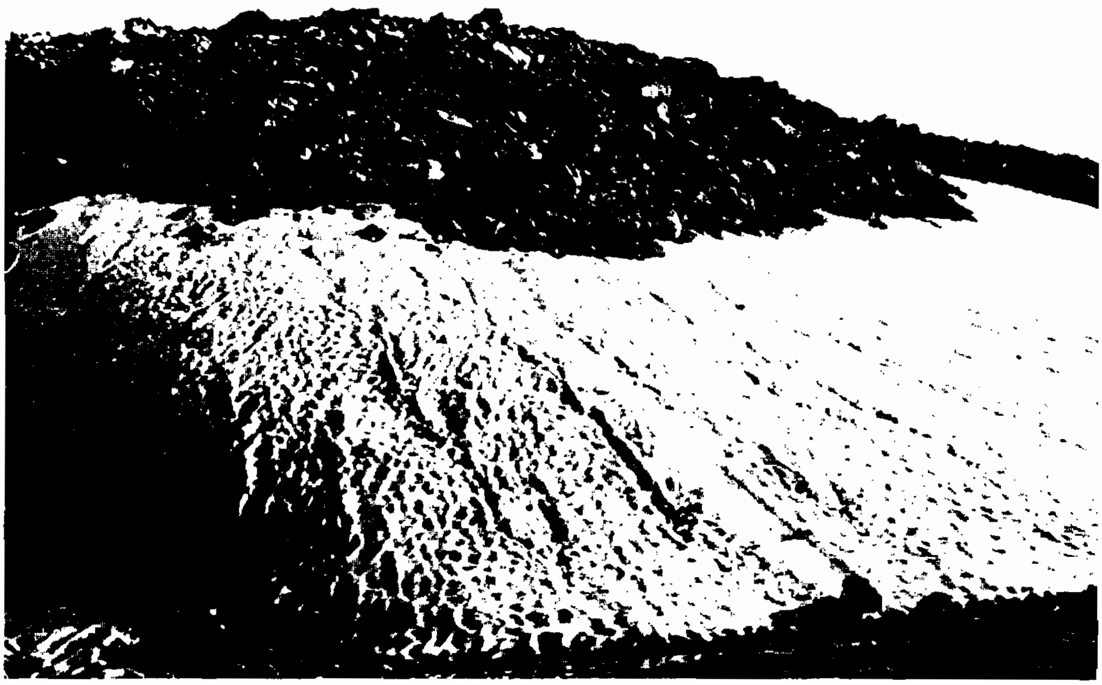

Figure 2 Photograph showing the displacement of a boulder sliding over a snow patch and arriving in the middle of the subnival boulder pavement.

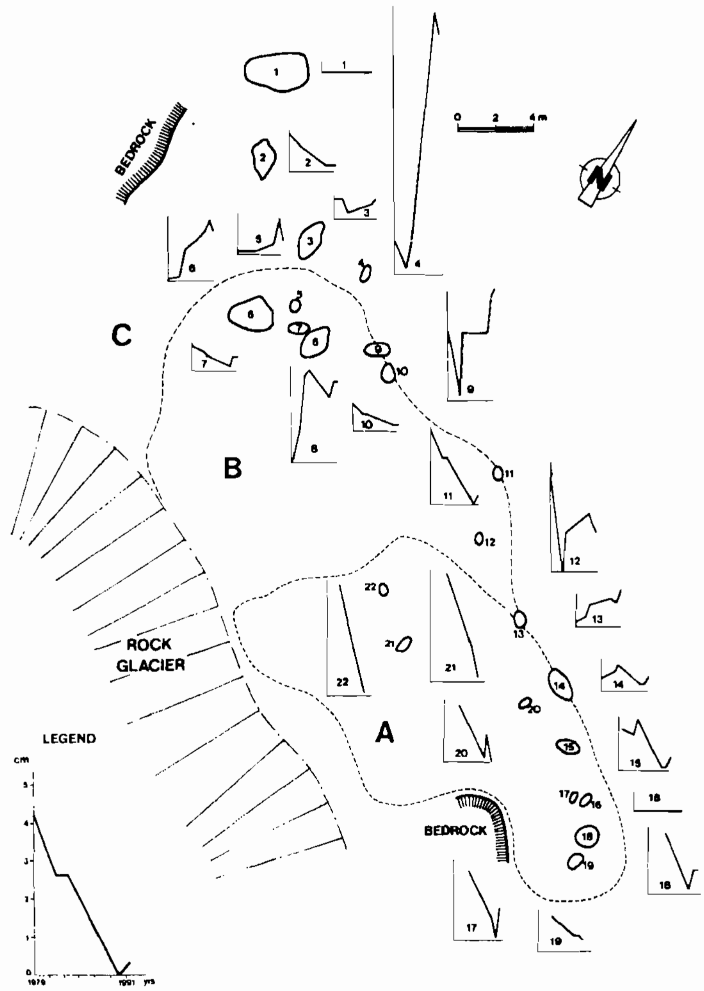

Figure 3 The figures indicate the numbers of the boulders to which the diagrams apply. The diagrams show in cm the displacements of the boulders (average measurement obtained each year for each boulder) between 1979 (start of the diagram) and 1991 (end of the diagram), with measurements in 1982, 1983, 1989, 1990. Legend enlarged by a factor of 2.

Figure 3) and in 1983 on another 7 boulders (16-22, Figure 3). Measurements of the distances between the coloured lines and the top of the mud were made in 1982, 1983, 1989, 1990 and 1991.

RESULTS

Figure 1 gives all the vertical displacements observed—that is to say, between 1979 and 1991 for 15 boulders and between 1983 and 1991 for the other 7. Only one boulder did not show any movement at all: boulder 1 in Figure 3. The other boulders show either an upheaving or a sinking. The maximum downward displacement is −10 cm in 8 years (mean: −1.2 cm/yr) and the maximum upward movement is +12 cm in 12 years (mean: 1 cm/yr). One boulder (# 15), which had sunk into the mud to a depth of 5 cm on one side, was uplifted 1 cm on the other side, thus undergoing rotational movement. The majority of the marked boulders (15) show a sinking movement, and a minority (6) show upheaving.

Figure 3 indicates the average of the different movements measured for each boulder and for each measurement, and shows that the movements generally have no continuity in either speed or direction. For some blocks a sinking movement changes

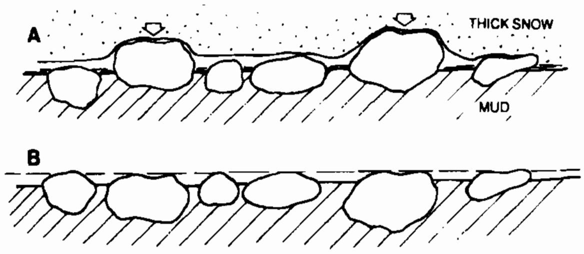

Figure 4 Supposed role of snow pressure on the formation of a subnival boulder pavement. (A) Boulders of different sizes rest on the mud. A deep snow patch covers everything and begins to melt from the base. The bigger boulders support the total weight of a snow patch, which pushes the boulders into the mud. (B) The resultant subnival boulder pavement.

to upheaving, while others do the reverse. The sinking movements are predominantly in the wet part (A, Figure 3) and the upheavings are located mainly in the dry part (C, Figure 3). We do not find any relationship between the different years and the direction of the movements; at any one time, some boulders are sinking, while others are rising.

DISCUSSION

We are familiar with the process of upheaving of stones which occurs during ground freezing. The sinking of the boulders under the weight of the snow has not been studied, but it could easily be understood when one considers that, under a thickness of 2 m of snow of density of 0.5 g/cm^3, a pressure of 1 kg/cm^2 is generated. It is also clear that the upheaving and sinking of the boulders cannot occur at the same time: upheaving occurs during the freezing when lenses of segregated ice are growing; sinking only occurs when the soil has enough plasticity to undergo deformation under the weight of snow.

Observations of ground temperature made by Francou (1983, 1987), 40 km to the north-northwest at 2450 m a.s.l. near the Col du Lautaret, give some useful indications about the conditions in this environment. The ground freezes from October to December or January, when the snow cover is thinner than 50 cm. Later the ground temperature increases very slowly under the geothermal gradient and remains at approximately 0 °C until the snow disappears. At this time the snow is thicker (usually more than 3 m). The temperature rises above 0 °C only after the snow has disappeared.

With these indications, we believe that the upheaving of the boulders occurs in autumn during freezing of the ground and that the sinking of boulders occurs in springtime when the temperature is at 0 °C. At that time the snow is thickest, the ice within the thin material has probably melted and the layers of segregation ice at 0 °C have the greatest plasticity.

We presume that the pressure of the snow on the boulders increases because the snow patch begins to melt in the deepest part when heat is introduced by meltwater which drains into the karstic hollow, and that the weight of the snow is supported by the highest boulders of the pavement (Figure 4, Pissart, 1987). In such conditions the pressure on these boulders will be greater than the uniform pressure of 1 kg/cm^2 which we mentioned earlier.

If this idea is correct, the alpine subnival boulder pavement will only be found where the ground remains at 0 °C during the spring under the front of the snow patch—that is to say, in places where permafrost does not exist. Precise temperature measurements below snow patches are necessary to verify the hypothesis discussed here.

ACKNOWLEDGEMENTS

We should like to extend our appreciation to Professor S. Harris and Mrs Harris for assistance with the English in this paper.

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Pissart A., Francou Bernard (1992)

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Permafrost and Periglacial Processes, 3, 203-208

ISSN 1045-6740