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Advances in Periglacial Geomorphology

by

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with 3 photos and 6 figures

Summary. The warming of the climate related to the modifications of the atmosphere will be the most marked in the Arctic. It will cause the formation of numerous thermokarstic features and mass movements of the slopes. These phenomena will be very important at the beginning of the warming because most of the ground ice is situated at the top of the permafrost. As the warming will occur principally during the winter, it is at the southern limit of the permafrost that we have to watch for the first thawing of the ground ice. Some temperature measurements in the permafrost indicate that a warming has probably already begun in the Alaskan Arctic.

Some recent advances in periglacial geomorphology are presented: the microstructures are useful to indicate former segregation ice; stratified scree deposits observed in the Andes and Tibet by B. Francou give a new and satisfactory explanation for these formations; discussions about the genesis of sorted circles and cryoturbations are mentioned; the importance of a book on permafrost terminology prepared by Canadian scientists is demonstrated.

Résumé. Les modifications provoquées par l'homme dans le composition atmosphérique entraîneront dans les prochaines décennies un réchauffement climatique. Celui-ci sera surtout marqué dans l'Arctique. Il provoquera des phénomènes thermokarstiques et des mouvements de masse à la suite de la fusion de la glace du sol. La glace du sol étant en majeure partie accumulée près du sommet du pergélisol, ces phénomènes seront surtout importants au début du réchauffement. Comme le réchauffement se produira principalement pendant l'hiver, c'est à la limite sud du pergélisol que l'évolution se manifestera la première. Des mesures de la température du pergélisol en Alaska semblent indiquer que le réchauffement a déjà commencé.

Quelques progrès dans le domaine du périglaciaire sont signalés. Citons, entre autres: l'importance des études microstructurales qui permettent de reconnaître les traces de glace de ségrégation; la description d'éboulis stratifiés actifs dans les Andes et le Tibet par B. Francou, découverte qui fournit enfin une explication nouvelle et satisfaisante pour ce type de formation; les progrès et discussions qui se rapportent à l'origine des cercles et cryoturbations sont mentionnés ainsi que l'intérêt d'un livre sur la terminologie du pergélisol préparé au Canada.

The present paper on periglacial geomorphology is subdivided into two parts. Firstly I shall consider the consequences of global climatic changes on the periglacial geomorphology in the near future. Secondly I shall speak about some recent significant advances in periglacial geomorphology.

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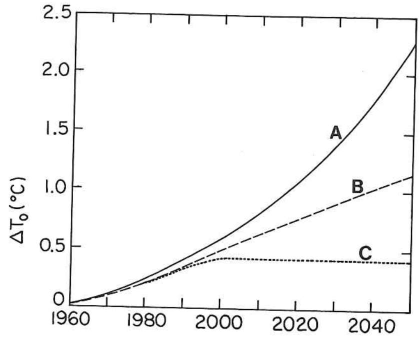


Fig. 1. The three scenarios proposed by Hansen et al. (1988) for the increase in temperature by greenhouse forcing (CO_2 and trace gases) for the next decades. Scenario B is perhaps the most plausible and is the only one that is considered in detail here.

1 *Global changes and periglacial geomorphology*

The increase in the amount of carbon dioxide (CO_2), trace gases and aerosols in the atmosphere will probably result in a warming of the climate. It is very important for people who are interested in the Arctic to realise that this warming will not be equal all over the world but will be greater in the high latitudes.

Let us consider the expected changes in climate if the amount of atmospheric CO_2 is doubled. In the 1980's, Flohn following a paper by Revelle (1982) studied climatic changes based on a climate model in which the amount of CO_2 was instantaneously doubled. For us, the most important result of this was not that the mean annual temperature was increased by 5 or 6 °C, but rather the distribution of the temperature changes in relation to latitude. The greatest changes in temperature occur in the high arctic: 16 °C at the most northerly latitude, and 8 °C at our latitude. Variations in the amount of precipitation and its distribution would also be greatest in the northern part of the globe: 75% for the north pole and less than 10% for our latitude. This increase in temperature is surely too great and predictions of changes in precipitation are still very unreliable but nevertheless today all scientists agree that the greatest changes will occur in the high latitudes.

Since the construction of this model, new and more complicated models have appeared and I shall now look at the results of a model prepared by the Goddard Institute for Space Studies and published in 1988 (Hansen et al. 1988); it is a three dimensional climatic model (with 8 by 10° horizontal resolution), which simulates the global climate effects of time dependent variations (rather than a single instantaneous doubling).

In this paper, three projections of global warming have been presented for the future. I shall speak only about scenario B (Fig. 1), the most probable scenario which assumes a reduced linear growth of trace gases. In this model the mean annual global surface air temperature is increased by more or less 1 °C by the year 2010 with the greatest warming in the high Arctic (see maps in Hansen et al. 1988). In all the permafrost zones, the mean annual air temperature is increased by between 1 and 3 °C.

The results of such models are surely not accurate, nor certain in their predictions but they do show the direction of future change in the permafrost zones. It is interesting to try and visualise the possible change in the limits of the permafrost zones brought about by a warming of 1.5 °C as predicted by the model. The modifications of the permafrost map are significant as Fig. 2 shows for Canada. In this figure, the mean air temperature at the limits of the permafrost zones is kept within the same range of air temperature as it is today. The consequence of this, is a shifting of the permafrost limits several hundreds of kilometers to the north. However, the response time for changes in the limits of discontinuous and continuous permafrost will be probably different.

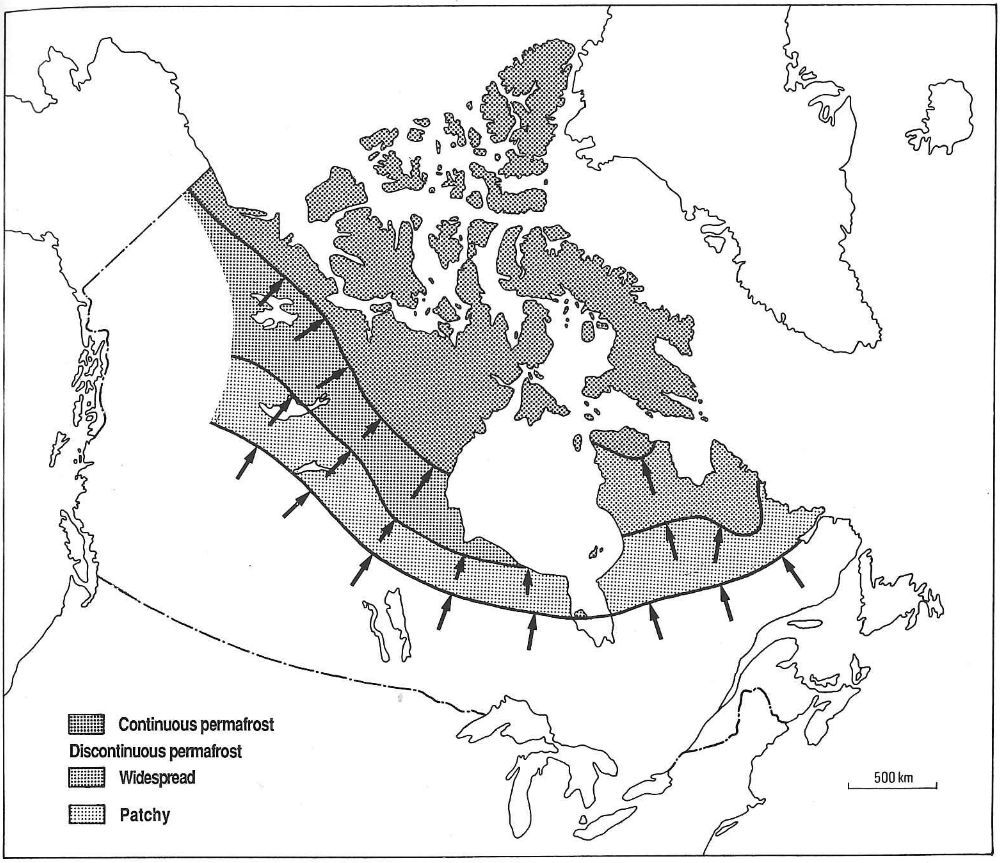


Fig. 2. Possible limits of the permafrost zones in Canada predicted for the year 2010 in the scenario B proposed by Hansen et al. (1988). The arrows indicate the possible displacements of the permafrost limits if the mean air temperature increase by 1.5 °C.

The geomorphological results of such displacements of the permafrost zone are obvious to any geomorphologists: ground ice will melt and many thermokarst features will appear. Sinking of the ground will occur wherever there is ground ice, giving closed depressions, ponds and lakes on horizontal surfaces. On slopes, the melting of ground ice will cause important mass movements. Thermokarst ponds will enlarge and coastal thermokarst action will give rise to a rapid retreat of coastal lowlands with soft rocks that contain large amounts of ice. This latter process will be all the more efficient because the warming of the climate will cause a rise in sea level.

The consequence of global warming will be the gradual retreat of the permafrost zones all over the Arctic. This evolution does not mean that periglacial studies are losing their interest. On the contrary, the melting of ground ice gives new significance to periglacial studies and especially those involved with thermokarst processes. We need more research on ground ice and on thermokarstic features in order to be better prepared for these great changes.

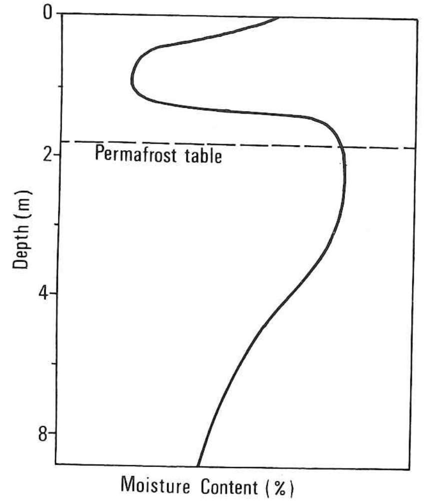


Fig. 3. Typical profile of total moisture content through the upper layers of permafrost after freeze-back in winter (Harris 1986, p. 27).

The most useful information to collect concerns the distribution of ice in the ground. Not only is it necessary to know the cartography of the ground ice, but also a knowledge of the vertical distribution of ground ice is of great value.

I would like to underline the importance of this new information, namely – that the greatest amount of ground ice is near the permafrost table. St. Harris (1986) has presented a typical moisture profile (Fig. 3) showing how the ice is localized in the ground. Shur (1988) in a paper presented last year in Trondheim wrote: "An analysis of available publications and the author's own observations have shown that an intermediate layer, ice saturated, occurs practically throughout the permafrost regions, whatever facies, lithology and cryogenic genesis of soils the latter had".

This distribution of ice is caused by several mechanisms that I shall consider below.

1. In the active layer, the most favourable conditions for the growth of segregation ice occur just above the permafrost table. At this level, not only the humidity is high but also, at the end of the summer, the refreezing is very slow. The refrigeration proceeds from the permafrost table as shown by Washburn (1979, p. 59). Slow freezing, high moisture content and fine grained sediments are the conditions under which segregation ice grows and these conditions exist at the surface of the permafrost table and explain the formation of ice at this level.

When the climate becomes colder or when the surface conditions change and form a better layer of insulation, then the rise of the permafrost table will trap the ice which accumulated at the base of the active layer. This ice which previously was formed in the active layer, is called aggradation ice.

2. On the other hand, in the upper layers of the permafrost which by definition remain below 0 °C, fluctuations of temperature occur. These changes in temperature cause the growth of ice wedges which have their greatest width at the permafrost table. They also explain the accumulation of segregation ice lenses which grow progressively as has been shown by laboratory experiment.

For example, Pissart (1971, p. 29) measured the increase in volume of a soil sample which was subjected to variations in temperature between 0 °C and –20 °C. It was found that unfrozen water is progressively extracted to feed the ice lenses.

Because water is able to move in a soil the temperature of which fluctuates just below 0 °C, the variations in temperature result in an accumulation of ice.

In any case, with or without aggradation ice, it is clear that the amount of ice is greatest in the upper layer of the permafrost. This fact explains why the greatest number of thermokarstic features are likely to appear at the beginning of the climatic warming. We can expect the most important processes related to the melting of ground ice to occur within the next few decades.

Coming back again to the mathematical model of Hanssen et al., it is important to know whether or not the warming will occur equally during winter and summer.

This model predicts that the warming will occur mainly during winter and that it will be weak during the summer months. As theoretically, in the continuous permafrost zone where the winter is colder than necessary for the permafrost conservation, a warming of the winter will not give any modification. A lowering of the permafrost table will occur however if the spring thaw occurs early or if the fall freezing arrives later than today. It is not the same in the discontinuous permafrost zone where the cold of the winter counterbalance the heat of the summer. As a consequence, it is at the southern limit of the discontinuous permafrost that we have to watch for the first thawing of the ground ice.

However, many uncertainties remain because factors other than temperature may play a part in thermokarstic evolution. One such factor may be the increase in precipitation which will follow, the climatic warming. Bosikov (1988), in a recent paper on Yakutia demonstrated the intensification of thermal abrasion on the shores of alass lakes, as well as intensification of thermokarst processes within interalass areas, during years of increased precipitation. Both the increase in temperature and the increase in precipitation will work together in the same direction to cause the disappearance of ground ice. We know also that the response to the increase of temperature will be complicated by other factors and for instance by the modifications of vegetation which are induced by the climatic change itself. We do not consider here these important problems.

We must be fully aware of the practical importance of this warming for human facilities such as roads, buildings and airfields. The usual protection against the thawing of ground ice is to place layers of gravel on the surface so as to keep the active layer far from the icy permafrost table. It is clear that these protective strategies will not be appropriate to the consequences of an important climatic warming. Our problem here is not only an academic one but also an applied one.

It is interesting to note that a regional warming in the Arctic has been detected by precision measurements of permafrost temperature in the Alaskan Arctic coastal plain. These measurements reported by Lachenbruch et al. (1988) indicate a variable but widespread warming (typically 2–4 °C) at the permafrost table during the 20th century, over much of an area of more than 100.000 km^2.

These variations in temperature occur at the permafrost table which lies beneath the active layer whose thickness is variable. The changes in temperature at this level are not necessarily the result of a warming of the air. Other explanations are possible, such as changes in the albedo of the snow cover as was suggested by Lachenbruch et al. (1988).

Because the physical relations between air temperatures and temperatures at the permafrost table are not well known, it is impossible to give a uniquevocal explanation of the observed fluctuations with any great degree of certainty. However, Lachenbruch et al. (1988) have shown with the statistical treatment of 100 years of sparce Arctic weather records a probable total increase in air temperature of the same general magnitude as indicated by the changes in the geothermal profiles.

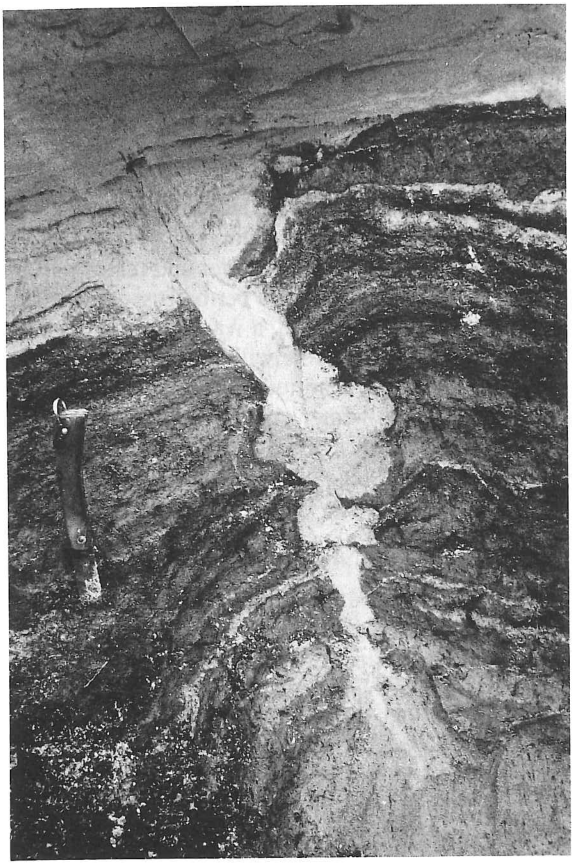


Photo 1. Distinctive shape of an ice wedge cast from Moerkerke (Belgium), shape probably related to the presence of large amounts of ice in the silts where the ice wedge has grown.

To follow the modification in the limits of the permafrost zones, many scientists are convinced that it is necessary to collect all the information concerning permafrost evolution and, in Trondheim, Barry (from Boulder) suggested the formation of a new international group in order to collect, standardize and archive permafrost related data.

2 *Some significant advances in periglacial geomorphology*

After this first part of my review concerning the geoecology and the changes connected with global climatic changes, I will present some of the recent advances in periglacial geomorphology. Some recent advances have been put together not only in the Biuletyn Peryglacjalny, which unfortunately is very irregularly published, but also in books and special volumes published (editors: Boardman 1987, Clark 1988, Koster & French 1988, French & Koster 1988) after the meetings of the periglacial commission of the IGU which was lead by Prof. Hugh French. Another publication of great value is the Proceedings of the fifth Permafrost International Conference (Senneset 1988) which was organized in Trondheim last year. More than 500 abstracts were submitted in response to the initial call for papers, and a great number were connected with geomorphological problems. This demonstrates the present great activity and interest in periglacial and permafrost research.

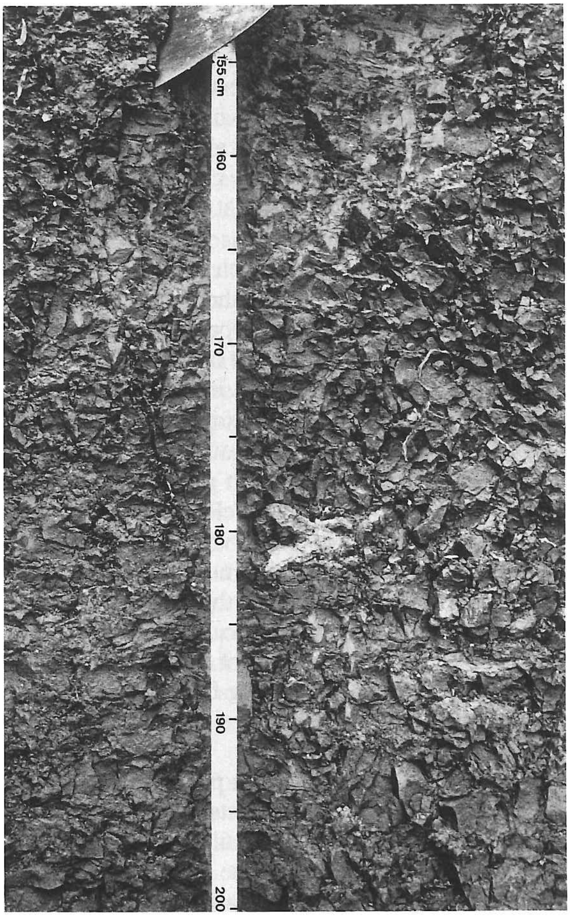


Photo 2. Cryogenic structure between 150 and 200 cm in depth in clayed soil from Ungava Bay (Canada).

It is evident that it is impossible for me to summarize here the hundreds or thousands of papers which have been published recently. I apologize to those colleagues whose research will not be mentioned in this lecture and I will add that the choice of subjects was also related to the slides I had at my disposal.

Ground ice

Firstly, I will discuss the phenomenon of "ground ice". I have already shown that if a climatic warming occurs the consequences to accumulated ground ice at the top of the permafrost will be immediate. Now we shall consider other consequences of this ice accumulation.

The accumulation of ice near the permafrost table explains some of the shapes seen in the casts of ice wedges, an exemple of which is presented on Photo 1. It is probably because large amounts of ice disappear in the surrounding material in which the ice wedge has grown that the shape of the wedge shows such a deformation.

More interesting, and as a direct consequence of the formation of segregation ice in the ground and especially near the permafrost table, is the cryogenic structure which remains after the melting of the ice. Such a structure is very hard to destroy unless the soil is dried out completely. It is still possible to recognize such cryogenic structure from the last glaciation in loess sections. This structure results not only from the overcompression of the material related to the movements of water towards the segregation lenses but also from the pressure induced by the growing lenses. This cryogenic structure is clearly identifiable macroscopically (Photo 2) and also microscopically: after the melting of the ice, voids with smooth surfaces remain in the ground. Several scientists, and among others B. Van Vliet-Lanoë (1987), have shown that this structure gives new information on present day and fossil periglacial phenomena.

The location of layers such as these which have undergone such an overcompaction often indicates the position of the former permafrost table. Along the slopes, such cryogenic structures are modified and appear as rounded aggregates which are typical of solifluction processes. Another application of these cryogenic structures is their use in determining the presence of former permafrost in caves. In this environment, it may be a new indicator of the depth and of the southern limit of the fossil permafrost (Pissart et al. 1988).

A surprising feature of ground ice formation is the ice lenses that Russian scientists have made in experiments with gravels. Their formation is explained by a new mechanism of moisture migration that Feldman (1988), from the Permafrost Institute of Yakutsk (USSR), has explained as a "vacuum filtration mechanism of moisture migration". This mechanism is associated with multiple oscillations of the freezing boundary in the presence of a water source (to appear, this mechanism needs gravels saturated with water). In the zone of freezing, a thawing vacuum is formed due to the reduction in volume of ice during its thawing. Under the action of this vacuum, waterfiltration is started in the thawing zone (9% volume) and the following freezing fixes the introduced water.

Cryogenic mounds

O. Ferrians (1988) describes a pingo which is about 60 m high at 40 km south-east from Prudhoe Bay on the Arctic coastal plain of Alaska. It is probably the highest pingo recorded to day. Ross Mackay, who is still the best scientist for closed system pingos, used leveling a few years ago to show that the altitude of some pingos changes by a few centimeters over short periods of times and he called them pulsating pingos. By making borings, he was able to demonstrate that such changes in altitude are related to injections of water below the ice core, a process he allowed to explain the circular faults which are apparent at the base of several pingos (Mackay 1979).

D. St. Onge has observed in the Canadian Arctic pingos over 20 m which have grown by closed systems in flat lying dolomites (in preparation). It seems that such features were not previously known.

The study of remnants of fossil periglacial mounds in temperate countries has focussed attention on other cryogenic mounds. Palsas, which appear in peat, are well known but cryogenic mounds with a core of segregated ice and without peat on the top were discribed mainly by geomorphologists from Quebec. It seems that remnants of cryogenic mounds from Belgium which are composed of a hollow filled with peat and surrounded by a rim, are remnants of the latter. J. C. Dionne (1978) has suggested calling them mineral palsas but this proposal was not unanimously accepted. These periglacial mounds are distributed in the colder part of the discontinuous permafrost where the mean annual temperature is below –4 °C, a value which may be useful in paleoclimatic reconstructions (Pissart 1987).

Stratified scree deposits
One of the most important recent advances in periglacial geomorphology is the results from the observations made by B. Francou (1988) a french geomorphologist working in the mountains of South America and Tibet, on the origin of present day stratified scree deposits.

Such deposits are numerous, well known and well described in the South and West of Europe. They appear to be typical fossil periglacial deposits of the temperature zone. There have been many hypothesis proposed during the last few decades to explain the genesis of such deposits and until recently it was generally agreed that the role of snow was of primary importance. This view was again put forward in a good paper by Y. Dewolf in the book edited by M. Clark (1988). The successive layers of thin and coarse granulometry were related to discontinuous phenomena that are very variable in space and time.

However, if one considers the observations collected by B. Francou it becomes apparent that the genesis of stratified scree deposits must be quite different to that proposed above. B. Francou has observed a typical present day stratified scree deposit 130 km east of Lima in Peru, at an altitude between 4400 and 4900 m. The slope inclination is between 33 and 35 °. The distinguishing feature of such a scree is the development of great lobes which, as with all solifuxion lobes, are moving very slowly (a few centimeters a year). A section through the deposit, just at the limit of such a lobe, shows not only the internal structure of the stratified scree but also explains the genesis of the different layers. The key to understanding the deposit is to consider the way in which the lobes of thin granulometry move (Fig. 4): the lobes move very slowly and unroll like a carpet causing pebbles to be buried under the lobes. At the same time, the frost heaving pulls out more pebbles from the fine grained material. These pebbles come to the surface and move by frost creep and needle ice action with a much higher speed than the solifluction lobes. The pebbles arrive quickly at the front of the lobes and where they keep accumulating despite the burrying action due to the progression of the lobes.

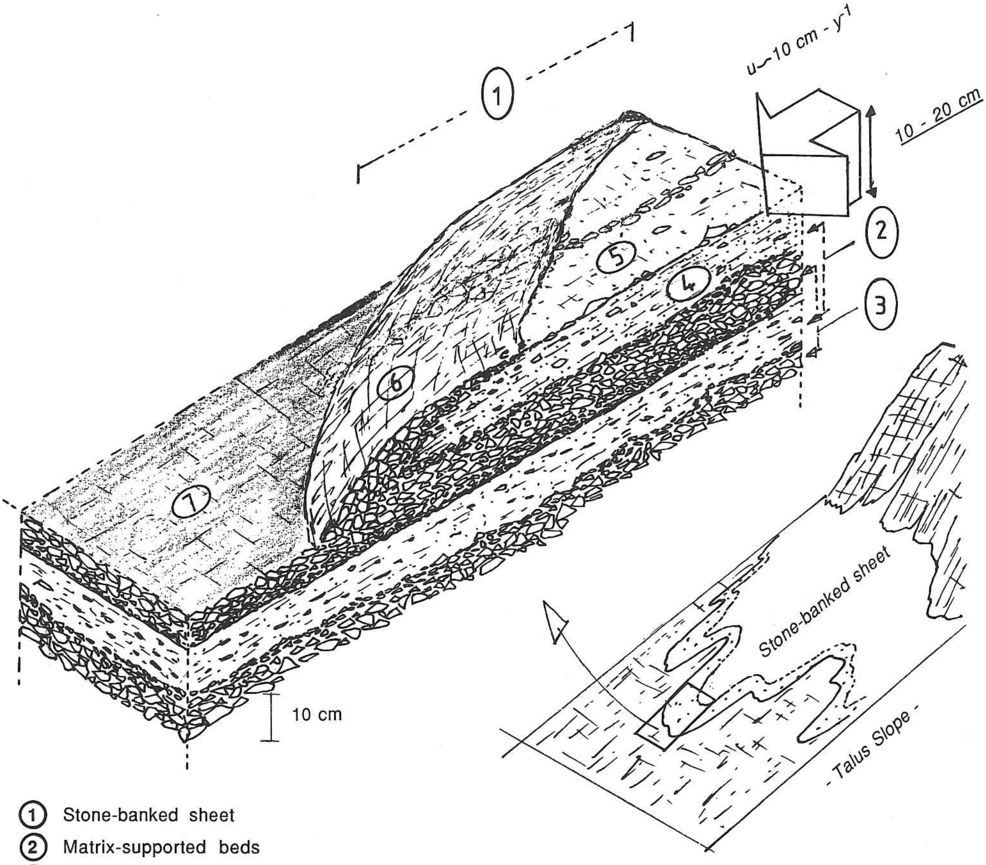
In the Andes, at the place from which this description comes, the frost did not penetrate more than 15 or 20 cm in depth and the freezing cycles are numerous: close to 200 a year.

In Kuen Lun (Tibet) where B. Francou has observed similar features, the slope is the same: 33–35°. The altitude is between 4800 and 5100 m, the mean temperature is below 0 °C with probably more than 150 cycles of freezing and thawing a year.

B. Francou is now looking for a paleoclimatic interpretation of the fossil stratified deposits of Europe. If the mechanisms are similar, the presence of fossil stratified scree deposits indicates very numerous cycles of freezing and thawing, and freezing and thawing which does not penetrate deep into the ground, both features which are in accordance with the climate data on stratified scree deposits in the Andes.

Sorted circles
Some advances in the study of the formation of sorted circles, structures which are very well represented in Spitsbergen, result from recent work at the Seattle Laboratory for Quaternary research. Experiments performed by A. L. Washburn in Resolute (Canadian Arctic) and by B. Hallet et al. (1988) in Svalbard have demonstrated that the movements at the surface of the fine domain are from the center of the circle to the sides.

Such movements have been postulated by a few scientists but have never been so clearly shown as in these experiments. These very careful observations are a new step forward to a better understanding of the evolution of these periglacial features. However, we need more observations in order to definitely explain the genesis of such structures because the observations made to date do not seem sufficient to define the causes of the movement.



(1) Stone-banked sheet
(2) Matrix-supported beds
(3) Open work beds (with vertical sorting)
(4) Frost ejection of clasts and frost creep
(5) Pipkrakes and washing
(6) Fall and washing (longitudinal sorting)
(7) Steady clasts

Fig. 4. Genesis of stratified scree deposits after B. Francou (1988). See explanation in the text.

The interpretation of these movements by Hallet and his collaborators is shown on the drawing they presented in Trondheim (Fig. 5). They spoke about a convective motion with several plausible driving mechanisms including buoyancy forces resulting from a vertical gradient in soil moisture that arises naturally in thawing ice rich soils.

However, this is not the only possible explanation. The movements that I have outlined on Fig. 6 show another possible displacement at depth that would retain the same surface motions. These movements could be driven by gravity at the surface during the thawing and by freezing pressure at depth during the freezing.

Anyway the results of the careful experiments by Hallet and collaborators are an important step forward in the knowledge of the formation of these structures.

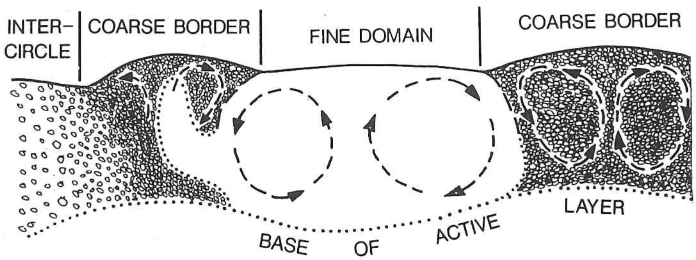


Fig. 5. Movements in sorted circles proposed by Hallet et al. (1988).

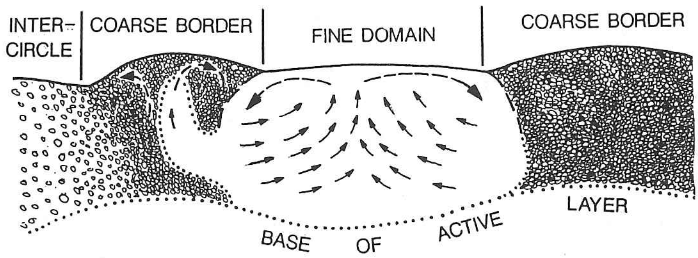


Fig. 6. Another possible explanation of the movements observed on the surface by Hallet et al. (1988).

Cryoturbations

Research on the formation of sorted circles is directly connected with studies which have been conducted over a period of decades into the genesis of cryoturbations. This latter problem is not yet solved to the extent that there remains no debate between the concerned scientists. B. Van Vliet from Caen has constructed a general theory to explain all kinds of cryoturbations by direct frost action. It is suggested that, more or less high freezing pressures depending on the characteristics of the material, determine the direction of mass displacements. I favour her hypothesis because I have demonstrated experimentally the occurrence of similar mass movements by frost action.

Nevertheless it is still clear that the different theories explaining cryoturbations have their convinced supporters.

Ice rafting and erosion of the fluviatile bed

During recent years several scientists but particularly J. C. Dionne (Laval) have demonstrated the action of ice rafting in coastal geomorphology and also on the morphology of the river bed. Such a process results in strong erosion as has been described many times for beaches of the St Laurent estuary. Photo 3 taken by J. D. Dionne, demonstrates that such erosion may sometimes be very important in the beds of rivers. It is because the water of this river have been diverted that it is possible to see the strong effect of the ice rafting erosion on the river bed.

Permafrost terminology

To end this miscellanea of some recent research on periglacial processes, I want to mention the very important publication for those interested in periglacial and permafrost features, which is the book on Permafrost terminology published last year by the Canadian Com-

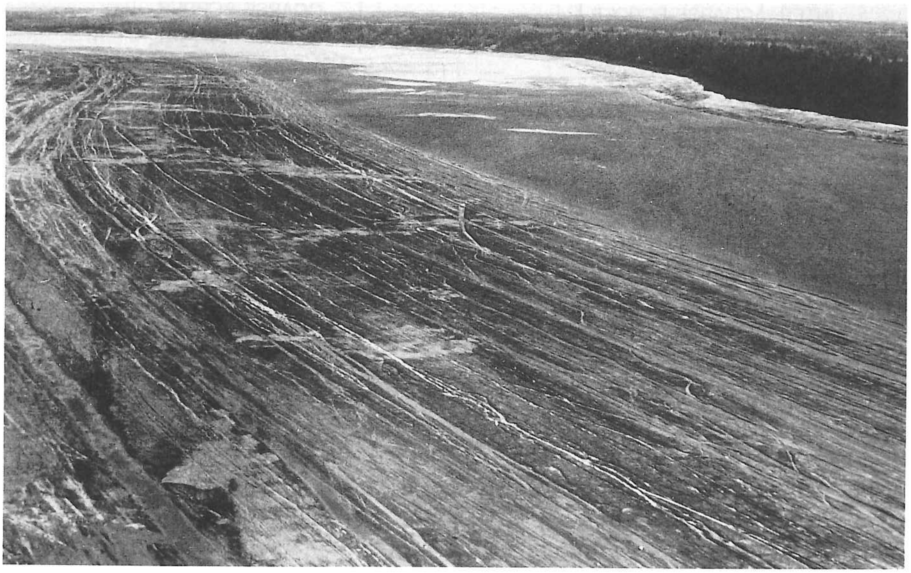


Photo 3. Photo taken by J. C. Dionne in Quebec showing how ice rafting may be important in the beds of some periglacial rivers.

mittee on permafrost (1988). The Chairman of this committee was St. Harris from Calgary. This book, published in French and English, defines features which are related to permafrost and the illustrations clearly show what is meant. It proposes a distinction between frozen soils which contain ice and cryotic soils. The name cryotic soil indicates a soil below 0 °C which may be without ice.

Acknowledgements
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