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RECOGNITION OF FORMER FROST MOUNDS IN PLEISTOCENE DEPOSITS AND THEIR USE AS INDICATORS FOR PAST ENVIRONMENTS

Abstract

Formerly active frost mounds (pingos, palsas) can sometimes be recognized as relicts in sediments from areas that formed part of the periglacial zone during cold periods in the past. This is because the mounds can leave deformation structures indicative of the former growth and decay. Today active forms develop and decay under specific conditions within periglacial areas. Different form groups have different characteristics and associated local and regional environmental requirements. This means that if parallels can be made between a past and a corresponding present form with a fair degree of certainty, and further that the requirements for growth and decay of the present forms are well known, it might be possible to make reconstructions of past environments from Pleistocene remnants. Uncertainties with comparisons and assessments stem from the limited number of published open profiles representing frost mounds in present periglacial areas and Pleistocene formerly cold regions, as well as from insufficient knowledge of present environmental requirements of specific form groups, and, not least, discontinuous Pleistocene sedimentary records. Yet, once reconstructions can be made they may provide information for terrestrial areas otherwise poorly represented in relation to palaeoenvironmental reconstructions. Based upon literature this paper attempts to present a general outline of sedimentological and structural identifications of some presently active forms as well as some remnants.

INTRODUCTION

In the reconstruction of past environmental changes, the traditional dominance of evidence from terrestrial palynological records, deep sea and ice cores and glacial records has increasingly become supplemented with sedimentological and geomorphological data sets from dry terrestrial areas, so that the picture of the development in the past is becoming geographically and environmentally more balanced, and a broader and more precise picture of past climatic developments and their direct effects upon the terrestrial environments is emerging.

One of the disciplines that can contribute much to this development is the use of past periglacial deposits and phenomena for palaeoclimatic reconstruction. For two reasons frost mounds may (together with thermal

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contraction cracks) potentially fulfill the requirements for reconstruction to a higher degree than most other sedimentary deposits and periglacial phenomena. First, their growth and decay can, in many cases, leave geomorphologically distinctive traces, such as ramparts with characteristic sedimentary structures, and second, in present periglacial environments specific frost mounds are found in areas with certain hydrological characteristics and their geographical distribution is within certain climatic regions. If the present requirements of a specific type of frost mound are well known, the fossil records can therefore be used to deduct climatic conditions in the past. The reliability of the reconstructions is much dependent on an awareness of diversity and underlying processes in relation to the individual form groups and of a sufficiently accurate knowledge of the climatic requirements, including the boundary conditions, for each feature, as well as on improved dating techniques to ascertain the palaeogeographical distribution of periglacial form that were active at the same time.

In this paper the emphasis is on the recognition and interpretation of frost mounds in the sedimentary records. Below, some general criteria are presented and the potential and limitations of the reconstruction method are commented upon. For convenience the term frost mound is used in a very general sense in the following, i.e. it includes perennial mounds that have developed due to local accumulation of an ice core, be it from ice segregation or hydrostatic pressure.

FROST MOUNDS

Over the last ca. 50 years, frost mounds have been studied in selected areas in increasing detail. A variety of forms and transitions between them have been recognized so that the classical picture of two characteristic form groups, i.e., pingos and palsas, is gradually becoming more complex. Pingos are large mounds that have developed due to freezing of water in relation to hydraulic or hydrostatic pressure in open or closed systems (e.g. MÜLLER, 1959; MACKAY, 1978, 1979). Palsas owe their growth to ice segregation (tjällyftning: WRAMNER, 1967), but other mechanisms have also been proposed (e.g., OUTCALT & NELSON, 1984). Their growth may take place in pure peat or, more commonly, in peat over frost sensitive mineral soils (e.g. WRAMNER, 1965; ÅHMAN, 1977; HARRIS, 1998). Relatively recently the term lithalsa (HARRIS, 1993) has been added for palsa like mounds without peat cover that have previously been described in the literature in more descriptive forms (e.g. ÅHMAN, 1977; WRAMNER, 1972).

In many cases further subdivisions of frost mounds can be made (e.g. FRENCH, 1996, 77, 102ff; HARRIS, 1998) and general overviews of characteristics of these and related forms are also given by, for example, LUNDQVIST (1969), WASHBURN (1979) and PISSART (1983b).

In order to recognize different frost mounds a number of features need to be detected in as far as possible both with the active forms and the remnants. These include geomorphological characteristics (size, shape), general setting within the landscape (slope, flat area, bog, single or in clusters), hydrological conditions, sediments (composition, deformation structures), climate and vegetation.

A gleaning of the literature shows that there seems to be no clear cut distinction between pingos and palsas in all cases in terms of their development and the associated type of the ice in the cores. For clarity, this discussion is left out in the following, even if genetically transitional types can be of importance with the interpretation of fossil forms.

PINGOS IN PRESENT PERMAFROST AREAS

Present active pingos are usually round or elongate in horizontal outline (e.g. MÜLLER, 1959; MACKAY, 1979 and later papers), a geomorphological feature they share with most other frost mounds. Pingos can reach the highest areal dimensions amongst the frost mounds with diameters up to 500 m (SPARKS *et al.* 1972) and heights of about 50 m (MACKAY, 1979). It seems that no specific lower limit is indicated for pingos even if small forms are usually not included in the term (e.g. FRENCH, 1996, p. 103 and 107).

Closed system pingos seem to be restricted to areas of continuous permafrost where favourable requirements such as 'lake sites with appropriately sized taliks, sandy sediments, and rapid lake drainage' (MACKAY, 1988, p. 508) are fulfilled so that sufficient pore water expulsion and freezing can take place to create high pore water pressure.

Open system pingos need sloping terrain together with downslope sub-surface water movement (hydraulic system) for pingo growth. Open system pingos are normally found in areas of shallow, discontinuous permafrost and may often occur at the transition between slope sediment and valley fill deposits (e.g. BALLANTYNE, HARRIS, 1994, p. 65, 67). The minerogenic cover over ice cores of open pingos may be up to 20 metres thick and it can consist of bedrock or more commonly of frozen unconsolidated sediments of a range of grain sizes (MÜLLER, 1959, p. 116).

Both pingo types have cores of ice and during growth of these cores, the slopes of the pingos may become too steep for the top sediments to remain stable and as a consequence slope wash and mass movement takes place. In addition displacement can take place along the periphery due to pressure upward and outward (MACKAY, 1988). Both closed and open system pingos require permafrost for their development, yet, since the closed system type requires continuous permafrost this would normally mean colder ground (and air) boundary temperature conditions than for the open

type. MACKAY (1988) has drawn the attention to the relationship between temperature, time and pingo size. He suggests that there is a limiting mean annual ground temperature of –2°C for pingo growth, and for large pingos to reach full size the minimum would be in the order of –3 or –4°C (MACKAY, 1988, p. 508) and require a long period of time.

In spite of the many investigations in Arctic and Subarctic regions there are relatively few examples of vertical sections through active pingos and pingo ramparts in present permafrost areas, probably mainly because the making of open profiles in frozen ground is too difficult and exposed sections of pingos along coastal sections are few. General outlines through whole pingos are presented by, for example, MÜLLER (1959), MACKAY (1985) and PISSART, FRENCH (1976). After 500 working hours MÜLLER (1959, p. 84f) could present a profile (reproduced in Fig. 1) through an active pingo in the Mackenzie River area. In the summit area, on top of the ice core, the stratigraphy shows ice alternating with fragments of layered silt and organic material as well as sand. The bulges

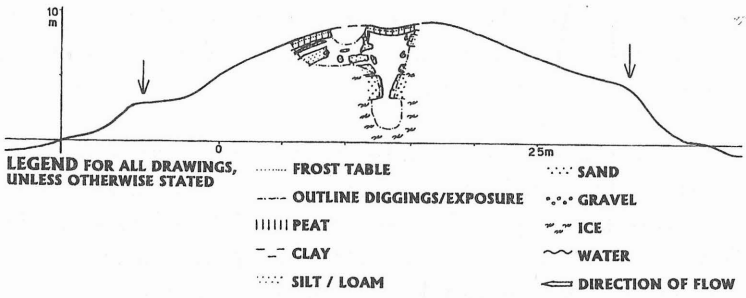

Fig. 1. Section through a pingo in NW Canada composed from figures 34 and 35 in MÜLLER (1959, p 84f). The arrows indicate the bulges in the lower slope area. The white parts without signature indicate ice

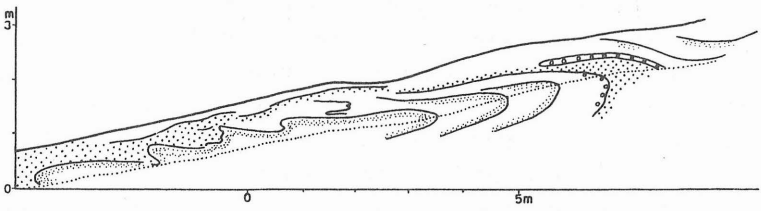

Fig. 2. Profiles through the lower slopes of a pingo simplified from a part of figure 7 in PISSART, FRENCH (1976 The center of the mound is to the right)

in the outline of the lower part of the slope of the pingo indicate that there are sediment accumulations concentric to the periphery. Sections through the lower part of active pingo slopes presented by PISSART and FRENCH (1976) show that layered, steeply tilted sediments can be recognized in open profiles (generalized outline in Fig. 2), and also that the overburden sediments often undergo solifluction and frost creep, in particular in the active layer (for further details see PISSART, FRENCH, 1976; MACKAY, 1988).

Pl. 1. Palsa in the Kevo area, Finnish Lappland

PALSAS IN PRESENT PERMAFROST AREAS

Palsas, of which an example is shown in Pl. 1, may be round in outline as pingos are, but they can also take the form of strings and peat plateaus (e.g. ÅHMAN, 1977). Palsas, often, but not always, occur in groups (SALMI, 1970; ÅHMAN, 1977). The size of the more regularly rounded forms ranges from around two metres (MEIER, 1996) to a few tens of metres in diameter (ÅHMAN, 1977) and may even reach more than 50 m (BROWN, PÉWÉ, 1973). To some extent the height is dependant on the lithology of the form, from around ca. half a metre up to about 10 m, with 1–4 m being typical, and with the minerogenic palsas being higher than palsas in pure peat (HARRIS 1998). Mineral cored palsas often have faulting of blocks along the periphery as shown by PISSART & GANGLOFF (1984) (see also Fig. 3) and ÅHMAN (1977). In the central, ice rich part, there is silt with a grain size distribution within the frost sensitive spectrum (e.g. ÅHMAN, 1977, see also BESKOW, 1935, p. 121ff.) or other frost sensitive sediment like silty diamicts (e.g. WORSLEY *et al.*, 1995) and on top there is a peat cover. Lithalsas are similar to mineral cored palsas except that they lack a peat cover on top (ÅHMAN, 1977; HARRIS, 1988; WRAMNER, 1972).

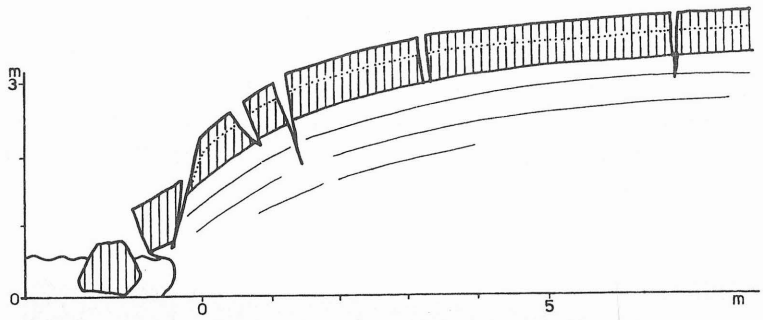

Fig. 3. Profile through a palsa composed from own observations and descriptions in Åhman (1977). The center of the mound is to the right.

Palsas occur in flat, boggy areas within negative mean annual ground temperature regimes and owe their growth to cryosuction in frost sensitive sediments. Due to the isolating quality of dry peat, penetration of heat into the frozen core is hampered during the summers and during succeeding winters the ice may accumulate further whereby the palsas can grow (ÅHMAN, 1977). Lack of an isolating snow cover during the winter has been demonstrated to further the development of palsas (SEPPÄLÄ, 1982). With time the slopes of palsas may become unstable due to over-steepening and cracks can develop along the sides followed by so-called block-erosion along the periphery (SVENSSON, 1962) and dilation cracks may occur due to tension of the peat of the summit (ÅHMAN, 1977).

With regard to environmental conditions palsas and lithalsas require wet frost sensitive sediments to develop (ÅHMAN, 1977). There are various more specific temperature requirements for palsas in the literature but generally speaking the mean annual air temperature needs to be below 0°C with less than 400 mm yearly precipitation (SALMI, 1970; ÅHMAN, 1977) for the warm boundary condition. Most palsas occur within the discontinuous permafrost zone but occasionally they may be found in the continuous permafrost zone (BROWN, PÉWÉ, 1973; ÅHMAN, 1977; WASHBURN, 1983). Generally speaking lithalsas are found in areas with somewhat colder summer temperatures than palsas are (ÅHMAN, 1977, p. 131) and in Canada they are found in the northern part of the discontinuous permafrost area where the mean annual air temperature is –6°C (PISSART *et al.* 1998).

Sections through palsas, in particular mineral cored palsas, are more common than in pingos, probably because palsas have attracted the interest of more scientists, they are relatively more frequent and accessible, and they can decay more easily through thermal erosion from the sides thus exposing various vertical traverses of the forms. Further, digging

through them is easier due to their smaller size. As a consequence the inner outlines of palsas are fairly well known (see e.g. SALMI, 1970, ÅHMAN, 1977; MEIER, 1991 for mineral cored palsas).

In spite of the frequently exposed sections through palsas, published accounts of cross sections through palsa ramparts, including those of mineral cored palsas and lithalsas, from present palsa areas where a fairly certain affiliation to growing forms can be made are rare in the international literature. It seems as if the palsas themselves rather than their 'fossil' expression has attracted the interest of the researchers. One of the few exceptions is shown in general outline in figure 4. This example was originally presented as a photograph from the Karlebotn area in MEIER (1996, Photo 15, p. 103). In this sandy rampart, which is still frozen, there are small–scale reverse faults are found towards the outer side.

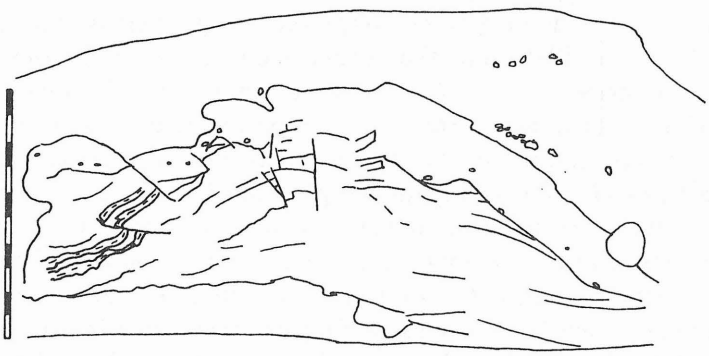

Fig. 4. Sketch of transect through a minerogenic rampart drawn on the basis of photo 15, p. 103 in MEIER (1996). The sediments are glaciofluvial delta sediments of sand and gravel that are almost horizontal next to the locality. The lowermost sediment unit in the sketch is frozen silty sands. The right hand part in the figure is towards the center

DEGRADATION OF FROST MOUNDS AND RECOGNITION OF REMNANTS

When the ice core in frost mounds thaws, either because of a climate warming or due to other factors, the morphology of the mounds changes radically. The surface materials that had moved down the slopes and accumulated along the periphery during the active stage become ring walls (ramparts) around depressions in the place where the ice-rich cores used to be.

Some general criteria for recognition of remnants of pingos have been proposed by DE GANS (1988) and MACKAY (1988). Putting their lists

together gives a series of criteria that include 1) the presence of a rampart around a depression, 2) the rampart volume in relation to the volume of the central depression, 3) a lower depression floor in relation to the surroundings, 4) outward dipping strata at the outer fringe associated with sediments deriving from slope processes and 5) presence of organic material buried by the slope deposits, among others. MACKAY also mentions presence of peripheral normal faults. It may be proposed here that for