SUMMER THAW DEPTHS IN COLD REGIONS AND FOSSIL CRYOTURBATION

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ABSTRACT

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An analysis of data from the literature, on summer thaw depths and cryoturbation in present-day cold areas, shows that the thickness of fossil cryoturbated deposits cannot be correlated to the July temperature of that time. It is suggested that the thickness of fossil cryoturbated deposits has been positively influenced by thermokarst.

INTRODUCTION

In 1947 POSER published a map of Western Europe on which the observed depths of summer thaw during the Würm were indicated. These depths were based on the thickness of cryoturbated layers dating from this time. Later, from the depths of fossil cryoturbations, WILLIAMS, (1975) and others, drew extreme conclusions on the climate of this time without making much use of data from arctic areas. As the depths of summer thaw in arctic areas became fairly well known and some data on cryoturbation in these areas were published as well, it seemed worthwhile to ascertain the relation between the thickness of cryoturbated deposits and the summer thaw depth, as well as the relation with the mean July air temperature.

In the following treatise we will first consider the active layer and the factors on which its thickness depends, then the occurrence of cryoturbations in cold regions and finally the question if conclusions on the July temperature can be drawn from data on the thickness of fossil cryoturbated deposits.

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THE ACTIVE LAYER

The 'active layer' usually means the top layer of ground above the permafrost table that thaws each summer and refreezes each autumn (BROWN & KUPSCH, 1974). In schematic sections a serried active layer is indicated in the zone of continuous permafrost as well as in that of discontinuous permafrost. KARTE (1974), however, justly indicates the active layer in the latter zone only when permafrost occurs in the subsoil. In the zone of discontinuous permafrost this is complicated by the fact that in many areas a layer occurs that does not freeze in the cold season (talik). In the zone of continuous permafrost the picture is much less complicated because the layer above the permafrost table freezes completely and thaws yearly.

It is a common idea that the thickness of the active layer increases going South from the High Arctic. BROWN's (1970) highly simplified section of the increase in thickness of the active layer from 0.5 m at 74° N.L. to 2-3 m at 61° N.L. is well-known. It is associated with a decrease in thickness of the permafrost.

The depth of the active layer (summer thaw) depends on many things, which we will discuss briefly.
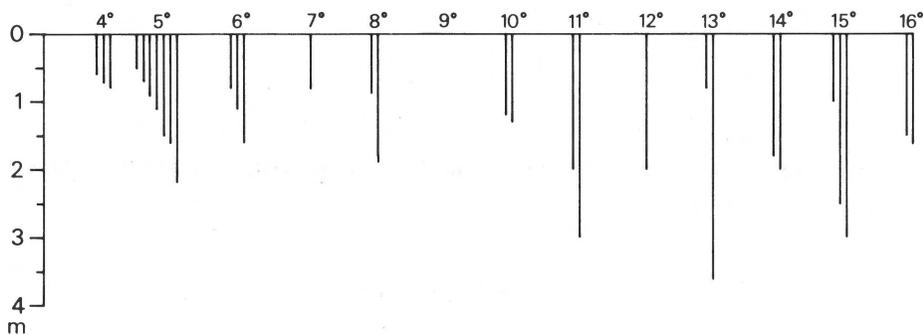
Fig. 1
Mean July air temperature (approx.) and the maximum depth of summer thaw in mainly clastic and non-groundwater-affected sediments, according to data (see Fig. 2) from Northern America, Greenland and Spitsbergen.

Climate

Commonly a relation is assumed between the number of thaw days, the temperature during this time and the depth of thaw. Thus BLISS (1978) mentions 150-600 accumulated degree days (0 °C) and a depth of thaw of 0.7-1.2 m in gravel for the High Arctic. In the same way he mentions 300-1000 accumulated degree days (0 °C) and a depth of thaw of 1-2 m in gravel for the Low Arctic. KARTE (1979) indicates a mean depth of thaw of less than 1 m for the polar desert zone (mean air temperature of the warmest month of 5 °C (or less). For the tundra zone (mean air temperature between 4 °C and 10 °C in the warmest month) a mean depth of thaw between 0.2 and 2 m is indicated.

In figure 1 a compilation of data concerning the approximate July air temperature and maximal thaw depth is presented. Although at high latitudes the low amount of solar energy caused by the small angle of incidence is compensated for by the length of the day in June and July (BROWN, 1972) it can be said that the maximal summer thaw depth is lowest in areas with lowest mean July air temperature. Concerning the thaw depth it is important that in areas with polar pack ice the maxima of spring cloud cover and autumn cloud cover seem to merge into one and the summers are characterized by a low cloud cover (BROWN, 1972).

Relief and aspect

The influence of slope and aspect on sub-surface temperatures depends on latitude. In high latitudes it is only slight because of the already mentioned small angle of incidence. HANNEL (1973) on Devon Island even found a greater thickness (5 to 10 cm) of summer thaw on a northfacing slope than on the southfacing slope. This is contradicted by BROWN's (1973) observations, also on Devon Island, of 0.5 m difference in the thickness of the active layer on a southfacing slope (1.10 m) compared with the northfacing slope (0.60 m). It must be assumed anyway that at lower latitudes clear differences related to slope and aspect are common (see, e.g., TEDROW, 1977).

Vegetation

The depth of the active layer is strongly related to the existence of a vegetation cover. The role of the vegetation is best expressed in the way it protects permafrost against solar heat during the summer period. The active layer is in general shallowest in areas mantled with peat, organic silt or a dense mat of living vegetation (HOPKINS ET AL., 1955).

From Mary River, Northern Baffin Island (subpolar desert) BROWN (1972) reports an active layer of 0.3 m thickness in peat, while in dry gravel with a sparse vegetation it reaches 1.5 m. According to BROWN & PÉWÉ (1973) the influence of the vegetation on the depth of the active layer is greatest in the zone of discontinuous permafrost, a zone which lies actually south of the tundra zone. NICHOLSON (1978) thus found a 0.5 m thick active layer under well-drained peat near Schefferville in the southern part of the discontinuous permafrost zone, while under another type of vegetation (lichen mat or mixed herbs with lichen mat) it was 3.6 m thick.

It can be stated in general that the shallowest active layer is found under dry peat, while it is deepest under a bare soil (see also BLISS, 1978). It is clear why fires greatly influence the thickness of the active layer. In the Mackenzie Delta HEGIN-BOTTOM (1973) noticed a 0.77 m thick active layer under undisturbed vegetation, while after a fire it reached 1.0 m, and, where the moss cover had been removed, a thickness of 1.38 m was recorded.

Hydrology

The moisture content of the soil is important for the depth of the active layer. If the moisture stems from ice lenses formed during the freezing period, the thaw of the soil is retarded. If we are dealing with an active circulation of water this will strongly promote the thawing of permafrost, depending on the temperature and the kind of water. Coarse, permeable sand or gravel in the zone of discontinuous permafrost is more likely to be free of permafrost than impermeable silt or clay (HOPKINS ET AL., 1955). From Schefferville, NICHOLSON (1978) indicates a range of the active layer from 1.8 m to 4 m for non-

groundwater-affected sites and thicknesses up to 15 m in groundwater-affected sites.

Snow cover

In polar areas the thickness of the snow cover is generally quite variable. For the Canadian Arctic Archipelago BROWN (1972) reports an approximate mean thickness of about 75 cm in the extreme southeast and about 25 cm in the northwest. Deep accumulations are found in small valleys, hollows and in the lee of obstacles. Some different periods can be recognized during the time of snow cover in arctic areas. Namely a period of snow accumulation, the pre-melt period of sublimation, followed by a short period of daily melting until rapid water release occurs (MING-KO WOO & SAURIAL, 1980). The snow cover strongly influences the maximum depth of the active layer. A thick snow cover will thus retard thawing of the top-soil, because it covers the ground and because of the meltwater. In some cases the top-soil can even be lowered by erosion through meltwater. In these areas, a shallower active layer will be found. In winter the top-soil in these spots will freeze up to the permafrost table because of erosion and shallow summer thaw, notwithstanding the strongly isolating effect of the snow cover. Near Schefferville, in the zone of discontinuous permafrost, the isolating effect of the snow cover is such that permafrost only occurs where the average snow depth is less than about 0.7 m (NICHOLSON & THORN, 1973).

Material

The influence of the composition of the soil on thaw depth is well-known. It is clearly demonstrated in a figure composed by MACKAY (see WASHBURN, 1979, p. 269). If for example the depth of the active layer in peats of the tundra and forest tundra is about 0.2 m, then it will be about 0.75 m on the transition from silt to sand. In those spots where the soil is composed of bare gravel, it will be more than 1.5 m. BROWN (1972) noticed a thickness of the active layer of 0.6 m in bare sandy silt and of 1.2 m in sand and gravel at Pond Inlet, Northern Baffin Island. These are values from the subpolar desert which are comparable to the above-mentioned values from the tundra and the forest tundra. The occurrence of fines in the soil can strongly enhance frost susceptibility, which means that ice lenses will be formed during the freezing period. This influences the thickness of the active layer during the period of thaw.

As –under undisturbed conditions– the vegetation is often less dense as the material increases in coarseness, and as coarse materials are strongly permeable and hardly any ice lenses are formed in them during wintertime, the thickest active layers are found in coarse material.

Figure 2 shows the maximum values of the active layer – as found in the literature– for soils mainly unaffected by groundwater or by seawater. It must be stressed, however, that not all data in this figure were recorded at the time of maximum thaw

depth. In many cases no data of more than one year are available, which is important because the depth of thaw strongly varies year by year and fluctuations up to 25% of the total depth are normal (NICHOLSON, 1978). In spite of these shortcomings the values indicated in figure 2 will get near the actual thickness of the active layer in many cases. Data have been arranged according to zones distinguished by TEDROW (1977), because these coincide with phytopedological zones. The polar desert zone (A) and the subpolar desert zone (C) are sometimes thought to belong to the High Arctic and the tundra zone (B) as belonging to the Low Arctic (BLISS, 1978). The data have further been arranged according to latitude because it fits best with the arrangement of BROWN (1970).

It appears from these data that in the polar desert (A) the maximum depth of summer thaw reaches to little more than 1 m, a value that is comparable to those indicated by KARTE (1979). In the subpolar desert zone (C) values of little more than 2 m occur. BLISS (1978) indicates a maximum value of 1.2 m for the High Arctic. In the tundra zone (B) –the Low Arctic– a maximum of 3 m was found (in one spot only). Both KARTE (1979) and BLISS (1978) indicate maximum values of 2 m for this zone. The highest value found in literature by the present author for the zone south of the tundra with discontinuous permafrost in North America is 3.6 m.

In order to see if any conclusions can be drawn from the data in figure 2 with regard to summer temperatures during the maximum of the last ice age based on the thickness of cryoturbated layers, it is important to know how the vegetation cover at that time influenced the depth of the active layer and which material was cryoturbated. As far as the vegetation is concerned it can be stated that in Western Europe at least no appreciable peat layers occurred during the coldest part of the last ice age. This means that values, as far as vegetation cover is concerned, must be compared to those of the polar desert zone or of the subpolar desert zone (High Arctic). BLISS (1978) indicates a mean July air temperature between 3 °C and 6 °C for this zone.

The fossil material now being considered has been cryoturbated and mostly consists of sandy as well as silty, clayey or peaty layers; material which is frost susceptible.

The values as expressed in figure 2 can only be used inasfar as the material consists of silt or loam, while the maximum values must be diminished with about 50% to make them comparable.

Before going further into this matter we must see what is known of cryoturbation in present-day cold areas. It is important to know if cryoturbation in these areas is vertically limited to the active layer and if so, to which part of it. And further it is important to know if cryoturbations in present-day cold areas are comparable to fossil disturbances known under the same name in Western Europe.

Very few data exist concerning cryoturbation phenomena in present-day polar areas. It is possible that its being tied to layers of certain grain sizes is the reason for this. Also these
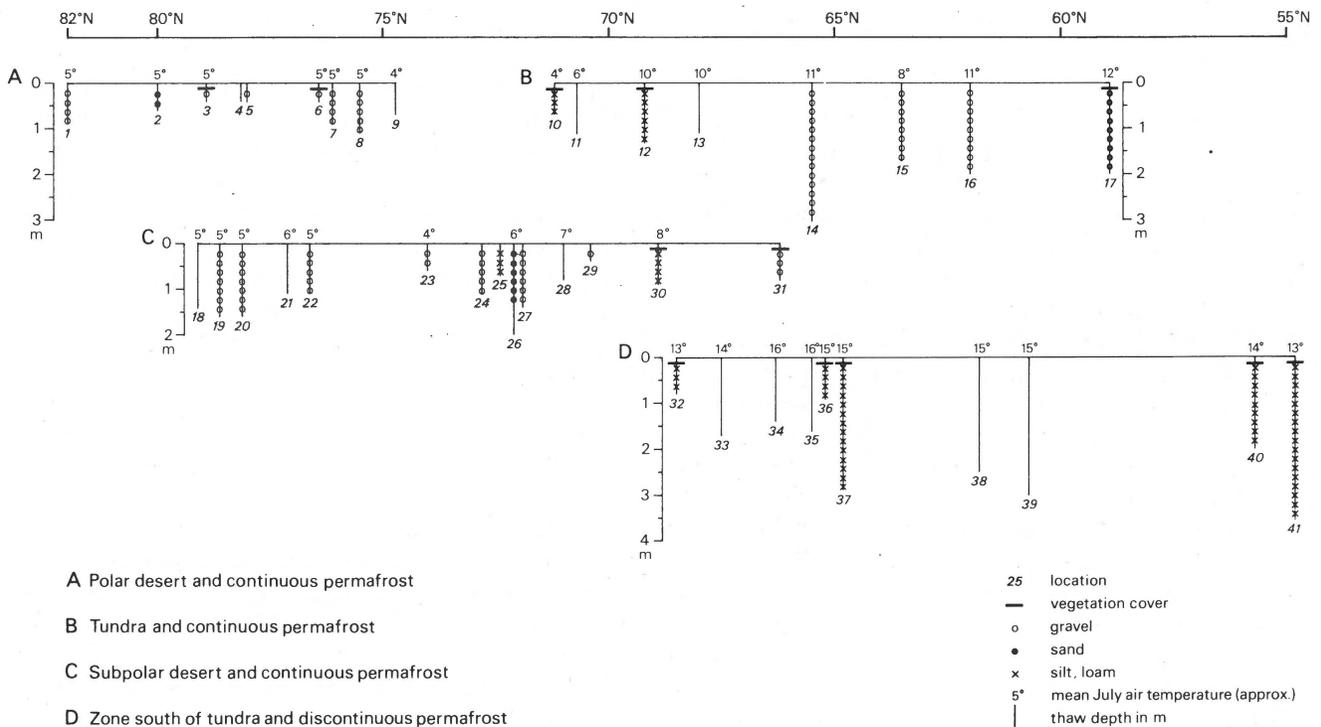
Fig. 2

Maximum depths of summer thaw in mainly clastic and non-groundwater-affected sediments, in pedologic zones (Tedrow, 1977) and in permafrost zones (Péwé, 1978) according to data from Northern America, Greenland and Spitsbergen.

Locations: 1 = Lake Hazen (Brown, 1972); 2 = Axel Heiberg (Brown, 1972); 3 = Alexandra Fjord (Brown, 1972); 4 = Stauferland (Semmel, 1969); 5 = Cape Lee (Stäblein, 1970); 6 = Grize Fjord (Brown, 1972); 7 = Cape Sparbo (Brown, 1972); 8 = Devon Island (Brown, 1973); 9 = Resolute (Ming-Koø Woo & Sauriol, 1980); 10 = North Meadow Lake (Kelley & Weaver, 1969); 11 = Peard Bay (Owens & Harper, 1977); 12 = Jacobshavn (Stäblein, 1977); 13 = Anatuvuk Pass (Porter, 1966); 14 = Northern Seward Peninsula (Hopkins et al., 1955); 15 = Frobisher Bay (Brown, 1972); 16 = Kaminak Lake (Shilts, 1978); 17 = Churchill (Rouse, 1981); 18 = Kongs Fjord (Stäblein, 1970); 19 = Oscar II Land (Plichta, 1977); 20 = Oscar II Land (Federoff, 1966); 21 = Hornsund-North (Szerszen, 1968); 22 = Thule (Corte, 1963); 23 = Beaufort Plain (French, 1970); 24 = Pond Inlet (Brown, 1972); 25 = Sachs Harbour (French & Egginton, 1973); 26 = Mester Vig District (Washburn, 1969); 27 = Mary River (Brown, 1972); 28 = Holman (Washburn, 1950); 29 = Clyde (Brown, 1972); 30 = Cambridge Bay (Brown, 1972); 31 = Pangnirtung (Brown, 1972); 32 = Inuvik (Heginbottom, 1973); 33 = Fort McPherson (Heginbottom, 1978); 34 = Fort Good Hope (Heginbottom, 1978); 35 = Norman Wells (Heginbottom, 1978); 36 = Glenn Creek (Dingman, 1973); 37 = Fairbanks (Péwé, 1965); 38 = Fort Simpson (Heginbottom, 1978); 39 = Hay River (Brown, 1973); 40 = Thompson (Brown, 1973); 41 = Schefferville (Nicholson, 1978).

phenomena may have escaped observation because often only terrain forms are described in cold areas and no study of the vertical sections has been made.

Examples of structures which in some way or another are comparable to fossil cryoturbation are known from all the zones mentioned in this study with the exception of the polar desert zone. From the subpolar desert zone WASHBURN (1969) published a cross section of a non-sorted circle (excavation 61-7-29) with disturbed sandy and sandy silt clay layers to a depth of 95 cm. It is not possible to see if this is the maximum depth of disturbance. FEDEROFF (1966) mentions much shallower disturbances (up to about 30 cm) in fine material on Spitsbergen. PETTAPIECE (1975) studied frost-disturbed layers in so-called earth hummocks. The disturbed material in this case consisted of fine textured and organic material and reached to a depth of about 0.6 m, which might not be the maximum depth. ZOLTAI ET AL. (1978) studied the age of cryoturbated material in about 150 non-sorted circles (earth hummocks) in the subpolar desert zone as well as in the area south of the tundra zone. The diameter of these forms vary from 1 to 2 m and the height is about 40-50 cm. The forms and climax forms do not grow together, even to polygonal nets (STÄBLEIN, 1977-a) and this cryoturbation is associated with high soil-moisture levels and low temperatures. The cryoturbation process has been occurring for thousands of years and ZOLTAI ET AL. (1978) report that the earth hummocks studied by them are almost always underlain by a layer of pure ice or high ice content material up to 1 m thick.

Cryoturbate structures are also found in so-called mudpits or mudboils (SHILTS, 1978). It here concerns bare spots of fines, with a diameter of 0.3-3 m within a more or less closed vegetation. Earth hummocks and mudpits are always isolated, in contradiction with certain forms of fossil cryoturbation. Only a few examples of cryoturbate structures of any extent are known from present-day cold areas. PISSART (1975) from Banks Island described a vertical section in non-sorted stripes consisting of silty sands with pebbles, sands and humiferous sands. From the tundra zone an example of comparable

disturbances is known as well (see TEDROW, 1977, p. 159). Here it consists of mineral, organic-mineral and organic matter. Neither of the sections mentioned reach any deeper than about 0.6 m and the true depth of the disturbances is not known. Unfortunately we have hardly any information on the kind of disturbances that are the result of the thaw of permafrost (thermokarst). PÉWÉ (1965) mentions the occurrence of slump structures in this process.

In spite of the many observations of mudboils by SHILTS (1978) it is clear that the depth to which cryoturbate structures are found in present-day cold areas is not well enough known. If the above-mentioned cryoturbate forms and structures are the result of frost or caused by mud bursts during thaw periods (SHILTS, 1978), then we have to assume that cryoturbation in permafrost regions is tied to the active layer. This is the case for earth hummocks and mudpits according to KARTE (1979) and SHILTS (1978). Naturally this is not the case for thermokarst deformations. If cryoturbate disturbances are tied to the active layer then its depth, because of the grain size of the materials involved in cryoturbation, is about half the depth of the active layer in coarse material. The maximum values found (see Fig. 2) for the polar desert are then about 0.5 m and about 1 m for the subpolar desert.

FOSSIL CRYOTURBATION

The maximum thickness of fossil cryoturbation (predominantly of the chaotic type), dating from the maximum of the Last Ice Age, is about 2 m at Harrislee in Northern Germany (KOLSTRUP, 1980), about 1.5 m in the neighbourhood of Hamburg (EHLERS, 1978), about 1.5 m with a maximum of 2.3 m in the central part of The Netherlands (KOLSTRUP, 1980), maximum 2.5 m in England, East Anglia and the Midlands (WILLIAMS, 1975) and at a maximum of about 2 m in Belgium (HEYSE, 1979). These are all values which, as far as vegetation cover concerned, must be compared to those of the polar desert or the subpolar desert, and do not fit in with the depth of the active layer in these zones of North America.

CONCLUSIONS

Although there are indications that at least part of the fossil disturbances is tied to the occurrence of permafrost, it is not known to what extent disturbances occurred during permafrost degradation (thermokarst). The fact that hardly any frost fissures of any significance are found in cryoturbated deposits, points to the possibility that this is indeed the case, and it is at the same time an explanation of the thickness of cryoturbated deposits. It also means, however, that the thickness of cryoturbated deposits is no indication for the July air temperature of that time.

Finally we must point out that in studies of fossil cryoturbate structures, in contrast to present-day phenomena, the disturbances are almost always studied in vertical sections. Up to now we know far too little about these structures in horizontal sections and about the terrainforms that these disturbances represent. It is striking that the excellent study in which the term cryoturbation was introduced (EDELMAN ET AL., 1936) was an exception to this rule.

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