PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

The Periglacial Environment of Great Britain During the Devensian [and Discussion]

E. Watson and A. V. Morgan

Phil. Trans. R. Soc. Lond. B 1977 **280**, 183-198
doi: 10.1098/rstb.1977.0105

Phil. Trans. R. Soc. Lond. B. **280**, 183–198 (1977) [183]
Printed in Great Britain

THE PERIGLACIAL ENVIRONMENT

The periglacial environment of Great Britain during the Devensian

BY E. WATSON

Department of Geography, University College of Wales, Aberystwyth, Dyfed SY23 3DB

The main question considered is the extent to which extra-glacial Britain had a permafrost environment in the Devensian, so the three features used in identifying contemporary permafrost are discussed. These are ice wedge polygons, pingos and thaw lakes. As their environments have been studied estimates of temperatures may be made when they are found in a Devensian context. A theoretical case can be made for regarding some involutions as representing the former active layer of permafrost but they have not been related to a contemporary environment. They cannot therefore give a measurement of Devensian conditions.

Fossil ice wedges are very widespread in Great Britain, being found from the English Channel to the Scottish Highlands, and associated with late Early, Middle and Late Devensian deposits. Today ice wedges grow in continuous permafrost where the mean annual air temperature is −6 to −8 °C or lower. Remains of pingos of the open system type which today develop in discontinuous permafrost with a mean annual air temperature of −3 to −6 °C, are found in Wales and East Anglia. These continued to form until the end of the Younger Dryas, and indicate that discontinuous permafrost in England and Wales thawed completely only with the beginning of the Flandrian. The pingos must have begun to form after the transition from continuous to discontinuous permafrost, which probably took place with the rise in temperatures ahead of the Allerød.

The area of continuous permafrost and ice wedge formation in Alaska is almost limited to the tundra. Apart from the coastal zone, discontinuous permafrost carries boreal forest with mean July air temperatures of around 15 °C, so that periods of tree growth in the Devensian do not necessarily imply the temporary disappearance of permafrost.

Continuous permafrost in southern England implies a minimum fall in mean annual air temperatures of 16–17 °C, and a fall in the July mean of 4–5 °C. During the maximum ice advance the fall in mean annual air temperatures is estimated to be as much as 25 °C, with a fall in the July mean of 10 °C.

1. INTRODUCTION

The term periglacial was introduced to describe phenomena produced by a severe frost climate in Poland south of the Baltic Ice Cap during the last glaciation, and it has often been used in western and central Europe in this sense of being around or marginal to an ice sheet. Investigation of frozen ground phenomena on a world scale has shown that some of the more widespread and obvious categories such as patterned ground and solifluxion deposits are formed whether the frozen ground cycle is diurnal, as in the high mountain areas of the arid tropics, or seasonal, as in mountain areas of the temperate zone. In neither are they formed in a surface layer which is underlain by perennially frozen ground. In the permafrost regions of high latitudes, the freezing of the surface layer is seasonal, but it takes place over perennially frozen ground. Some authorities use periglacial to include all three environments (cf. Troll 1958; Cailleux & Taylor

1954; Tricart 1970), so that although the original 'periglacial' area in Poland proves to have been part of a permafrost zone surrounding the Baltic Ice Cap, *periglacial* cannot be equated with *permafrost*, as Péwé reluctantly admits (1969, pp. 2–4). Since many periglacial phenomena occur in a number of environments it is often difficult if not impossible to draw precise conclusions from their presence. The aim of the author is, therefore, to concentrate on permafrost phenomena, and to consider how far Great Britain beyond the limits of glacier ice had a permafrost environment during the Devensian Cold Stage.

2. Indicators of contemporary permafrost

Contemporary permafrost is usually divided into two zones, that of continuous permafrost and that of discontinuous permafrost. In the former which is found in the more polar regions, high ground and low are perennially frozen below a shallow surface zone, the active layer, the only permafrost-free areas being below large rivers and lakes. In the discontinuous permafrost zone of the subpolar regions the permafrost is increasingly interrupted towards its outer limit, by areas subject only to surface seasonal freezing. These breaks are related to local factors such as aspect and permeability. South-facing slopes become permafrost-free while north-facing slopes retain it; coarse deposits and bedrock thaw out while fine sediments remain frozen. Formerly North American workers listed a zone of sporadic permafrost, where only isolated pockets of permafrost occur, but this is now regarded as the outer fringe of the discontinuous zone (Brown & Péwé 1973, p. 72).

In the mapping of contemporary permafrost three reliable indicators have generally been accepted, ice wedge polygons, pingos and thaw lakes. Though these have surface expression, they form within the permafrost. Other surface features such as solifluxion terraces, sheets and lobes, sorted patterned ground such as stone polygons, stone circles and stone stripes which form in the active layer, also occur in non-permafrost areas and can not be used as independent evidence (Hopkins, Karlstrom *et al.* 1955).

(*a*) *Ice wedge polygons*

Aerial photography has shown that large areas of the Arctic coastlands and islands are covered by a net of polygonal markings, which usually reflect surface differences in vegetation and microrelief. They are especially clear in the tundra, from which they are sometimes called tundra polygons, but they also occur on bare polar desert as in Antarctica and Greenland, and on sloping as well as on flat land. Where investigated, these polygonal nets have been found to overlie a lattice of vertical ice sheets, each of which tapers downwards so that it is wedge-shaped in vertical section. In the more arid areas, the wedges may be partly filled by ice and partly by blown sand or entirely filled by sand, apparently depending on the degree of aridity (Black 1973, p. 193).

An ice wedge consists of an accretion of thin vertical ice layers of variable length due to the freezing of water which seeps down a thermal contraction crack each spring. As the ice wedge widens, the expansion of the permafrost in summer increasingly deforms the sediments along its margins. When the ice subsequently melts, it is replaced by material falling in from above and from the sides. In well drained but cohesive material such as angular gravels, the infill comes largely if not entirely from above and a pseudomorph of the ice wedge is formed. The marginal deformation is preserved, though the infill differs to some degree from the material

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

on either side. A fairly accurate measurement of the original wedge can be made. In loose materials such as clean river gravels, collapse from the sides tends to destroy the marginal deformation; if bedded, the bedding appears to sag into the wedge and only approximate measurements of the width of the wedge may be made. Modern ice wedges may be forked, bent or hooked in profile and a study of the structures underlying a typical polygonal net in outwash gravels in central Alaska shows that the form of the sedimentary replacement may differ greatly from the idealized geometrical wedge form (Péwé, Church & Andresen 1969). Because they are part of a polygonal net, fossil ice wedges should occur in groups, though in a small exposure only one may be seen. Larger exposures may show several, usually irregularly spaced, as the polygons are irregular (cf. Morgan 1973, p. 286), and it may be possible to show that the wedges are linear in plan or that they form a net (cf. Worsley 1966*a*).

From a study of the distribution of contemporary ice wedges in Alaska, Péwé (1966) concluded that they are growing in the continuous permafrost. 'In the discontinuous-permafrost zone the wedges are essentially inactive' (Brown & Péwé 1973, p. 82), and survive only in silt, the ice having already been replaced by a sedimentary fill in gravels. The claim that fossil ice wedges may indicate former discontinuous permafrost (Wright 1961, p. 942) needs to be qualified if they do not develop there; in such cases they indicate former continuous permafrost which has subsequently been degraded.

(*b*) *Pingos*

A pingo is an ice-cored mound formed within the permafrost; the permafrost table is found to be close to the surface so that almost the whole of the pingo is below the active layer. Borings and natural exposures suggest that the cores of many pingos are of clear ice, but others consist of stratified ice and sediments. A study of existing forms suggests that a pingo goes through a cycle of growth and decay which is unrelated to climatic change (Washburn 1973). In its growth stage it forms a mound, which as it grows larger, splits open at the summit to expose the ice core. The exposed core melts in summer to form a crater lake (figure 1). The heat of the water causes the lake to sink deeper into the core and to get wider as it melts the ice on its shore, undercutting the crater walls and causing the continued slumping of material down their inner face. These processes result in the surface of the crater lake being steadily lowered, and its area increased, until only the lowest part of the mineral skin of the pingo remains forming a rampart surrounding the lake. The field evidence on this point seems unequivocal; the skin collapses inwards into the central crater. This is a point of prime importance in the recognition of former pingos. The form of the pingo core is destroyed during its evolution; as the ice support for the surrounding skin or shell melts, the shell collapses. It is difficult to see a Pleistocene pingo core being replaced by a pseudomorph, by a lens-shaped basin of sediments with overhanging walls. The final form in the evolution of the pingo which is the initial form of the fossil pingo, consists of a basin, enclosed in whole or in part by a rampart. The basin has received a large part of the skin which forms its basal deposit, and in the central part fine material in suspension will have settled to form muds. Both have been laid down on the ice core, and must be subject to settling and deformation as the core thaws. Undisturbed stratification will start only when the core has entirely melted.

Contemporary pingos are usually classified in the two categories proposed by Müller (1959), the closed system and the open system. The former type results from the freezing of a pocket of unfrozen sediments beneath a lake in continuous permafrost, the excess water being expelled into the surface zone where it freezes to form a pingo. This is a 'non-repetitive process' which tends to produce a 'solitary hill' (Müller 1959, p. 101). Open system pingos, on the other hand, form in the discontinuous permafrost zone at the foot of valley sides, where the uplands are subject to seasonal freezing only but the valley floor deposits are perennially frozen (figure 2). Meteoric water percolates into the ground in the uplands, moves beneath the permafrost

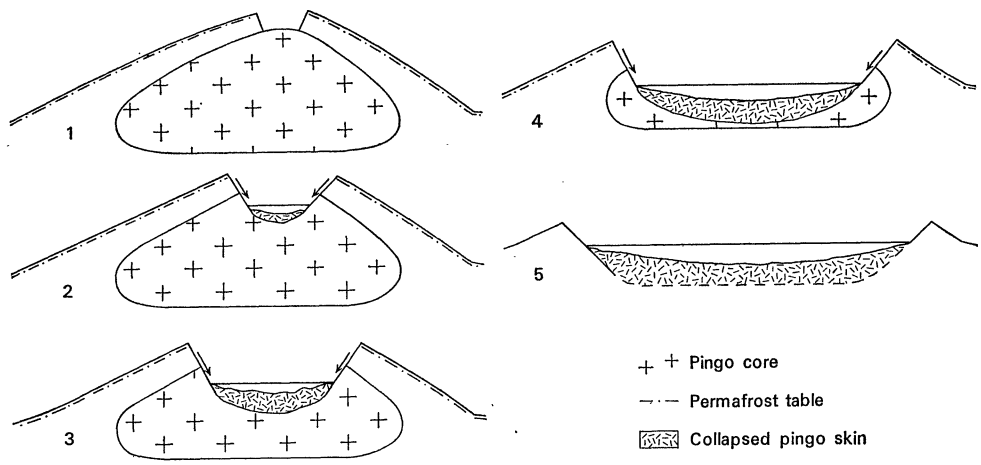

FIGURE 1. Collapse of a pingo. 1, the ice core is exposed by the rupture of the summit; 2–4, a pond develops on the exposed core and is enlarged by the melting back of the ice on its shores, which leads to the collapse of the overlying sediments into the crater; 5, the core has thawed and only the lower flanks of the mound remain, forming a low rampart around the pond.

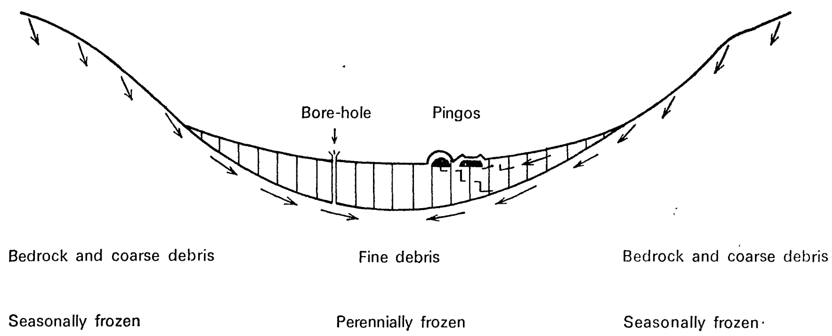

FIGURE 2. Hydrology of open system pingos in central Alaska. The permafrost (shown by vertical lines) is typically 30–45 m thick beneath these pingos. It is confined to the finer sediments of the valley bottom and is impervious except for any coarse beds which will be thawed. Water, entering through the upper permafrost-free slopes, is under pressure beneath the permafrost and rises to the surface in bores. It may reach the surface naturally to form a spring but where it freezes before reaching the surface it forms a pingo.

of the lower slopes and is under pressure beneath the valley floor (Hopkins *et al.* 1955). Unlike the closed system type, open system pingos continue to grow and decay in a favourable area so long as these hydrological conditions persist, so that 'clusters of mutually interfering pingos of different ages' are produced (Holmes, Hopkins & Foster 1968, p. 15).

As the two types of pingo represent two different environments, it is important to determine to which type fossil pingos belong. In brief, closed system pingos occur on a flat terrain, almost entirely on the sites of shallow lakes so that their skins are largely of lacustrine sediments. They tend to occur singly and their final form is an oval or circular rampart which completely surrounds the basin. Open system pingos occur in hilly country, are sited at the foot of valley slopes, involving slope deposits or valley floor deposits. They tend to occur in clusters. On slopes the ramparts may survive as a horse-shoe or crescent on the downslope side of the basin (Holmes *et al.* 1968, p. 27).

From their siting and clustered character the rampart forms which have been reported so far undoubtedly belong to the open system type. Those in southwest Wales in particular resemble closely contemporary pingos in central Alaska and Yukon Territory, rather than those of east Greenland (Watson & Watson 1974, p. 222). Most of the Welsh ramparts are on sloping sites; they are interrupted on the upslope side, and the enclosed basin is asymmetrical. On flat sites on the valley bottom the rampart surrounds the basin whose profile is symmetrical (figure 3).

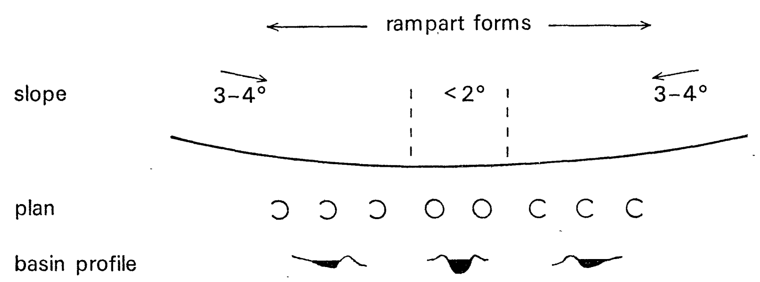

FIGURE 3. Relations between slope, rampart form and basin form in pingo remains in Wales.

Only general information is available on the diameters of contemporary open system pingos; in central Alaska the range is given as 15–440 m (Holmes *et al.* 1968, p. 30). In Wales typical basins have diameters between 30 and 60 m, while the external diameter of the ramparts is frequently 50–120 m. The diameter of the original mound would lie between these two measurements, for although marginal collapse into the pond as the core thaws would enlarge the basin, the movement of rampart material outwards by slope processes would increase the external diameter. The diameter of the former mounds in Wales may be estimated as typically between 45 and 90 m. This is comparable with the values given for contemporary *closed* system pingos in the Yakutsk basin in Siberia of 30–80 m for the higher steep-sided mounds and 50–100 m for low flat domes (Czudek & Demek 1973, pp. 53–54). None appear to be as large as the largest contemporary pingos. The largest basin measured in Wales has a diameter of 130 m, the largest in East Anglia, 120 m (Sparks, Williams & Bell 1972, p. 329). Available evidence, however, suggests that very large mounds form only a small percentage of contemporary pingos (Stager 1956).

Again little information exists on the depth to which pingo cores extend below the surface though Russian workers believe it is generally between 5 and 10 m (quoted in Maarleveld 1965, p. 8). In southwest Wales, the deepest basins which have been augered, exceed 10 m in depth.

(*c*) *Thaw lakes*

The upper layers of the permafrost, 'where fine grained materials are present, commonly contain 30 to 90 % of ice by volume' (Black 1969, p. 133; see also Mackay 1971). Many flat areas in both the continuous and discontinuous permafrost zones are pitted by lakes due to localized thawing of this ice. 'Simple lakes are round, oval or roughly rectangular in outline, but groups of lakes commonly coalesce to form compound water bodies with scalloped out-lines' (Hopkins *et al.* 1955, p. 140). These thaw lakes rarely exceed 300 m in diameter (Black, 1969, p. 138), and are generally less than 3 m deep.

Lakes 'similar in outline are common in areas in Alaska where little or no permafrost exists today' and they 'probably persist in recognizable form in areas where no frozen ground remains' (Hopkins *et al.* 1955, p. 140). But no systematic investigation of the possibility of thaw lake basins in the British Isles has been published so far, so that, although important in the identification of contemporary permafrost areas, they have not contributed to our knowledge of the extent of permafrost in Devensian Britain.

The author suggests that a thaw lake identification might be considered for small roundish lake basins in flat areas of silty or clay sediments including subdued (probably older) till. Kettle lake basins due to buried glacier ice are likely to be associated with gravelly (dead ice) deposits and some irregularity of surface. Former thaw lake basins might resemble pingo basins in shape and size but would lack ramparts.

3. Indicators of permafrost in Great Britain during the Devensian

(*a*) *Fossil ice wedges and polygonal crop markings*

The distribution of pseudomorphs and narrow collapse structures believed to represent former ice wedges together with polygonal crop markings is shown on figure 4. The latter resemble the polygonal nets overlying contemporary ice wedges (cf. Shotton 1960; Péwé *et al.* 1969), and in some cases have been shown to overlie fossil ice wedges (e.g. Gruhn & Bryan 1969; Morgan 1973). It should be emphasized that the map shows localities and not individuals; at this stage an attempt to show densities would be misleading and tend to overemphasize centres of active recording.

The outstanding feature of the distribution is that it extends from the south coast to the limit of the Loch Lomond readvance, some of the Scottish examples being as late as Pollen Zone III (Galloway 1961, p. 190). In many cases in east Scotland and the Midland Valley the wedges pre-date the last ice advance in the locality, and Galloway (1961) concluded that the majority of Scottish examples were of Pollen zone I age. In the northeast of England the same is probably true as some of the recorded examples are covered by later deposits. In general the evidence suggests that, inside the limit of the maximum extension of the Late Devensian ice, the area of ice wedge formation extended northwards as the ice cap diminished.

In mid-Wales, where recorded fossil wedges are much more numerous than figure 4 indicates, those on sloping sites are usually covered by 1–2 m of head which accumulated after the wedge ice had completely melted, since the overlying head has not been disturbed. The majority is probably of similar age to those of northern Britain.

A common location for fossil wedges is flat gravel terraces where they may extend up to the present soil. In these cases they may be of any age younger than the gravels they pierce. If the gravels are Late Devensian, one may estimate the age of the wedges to within a fairly small time error, but if they are Early Devensian, the possible time range is so great that the fossil wedges have little meaning in terms of chronology. Where the complete (or truncated) fossil wedge is within the body of the gravels, an attempt at dating can only be made after a careful study of its relation with the beds it intrudes. Such data exist only in a relatively small number of cases, and it is possible to discuss the significance of much of the wedge and crop pattern distributions only in very general terms. Collapsed wedge structures and casts have been found in association with datable deposits of Early Devensian age, as at Wretton (West *et al.* 1974) and Chelford (Worsley 1966*a*), and of Middle Devensian age, as at Four Ashes (Morgan 1973) and Syston (Bell, Coope, Rice & Riley 1972). It seems probable, therefore, that permafrost made its appearance as early as the latter part of the Early Devensian.

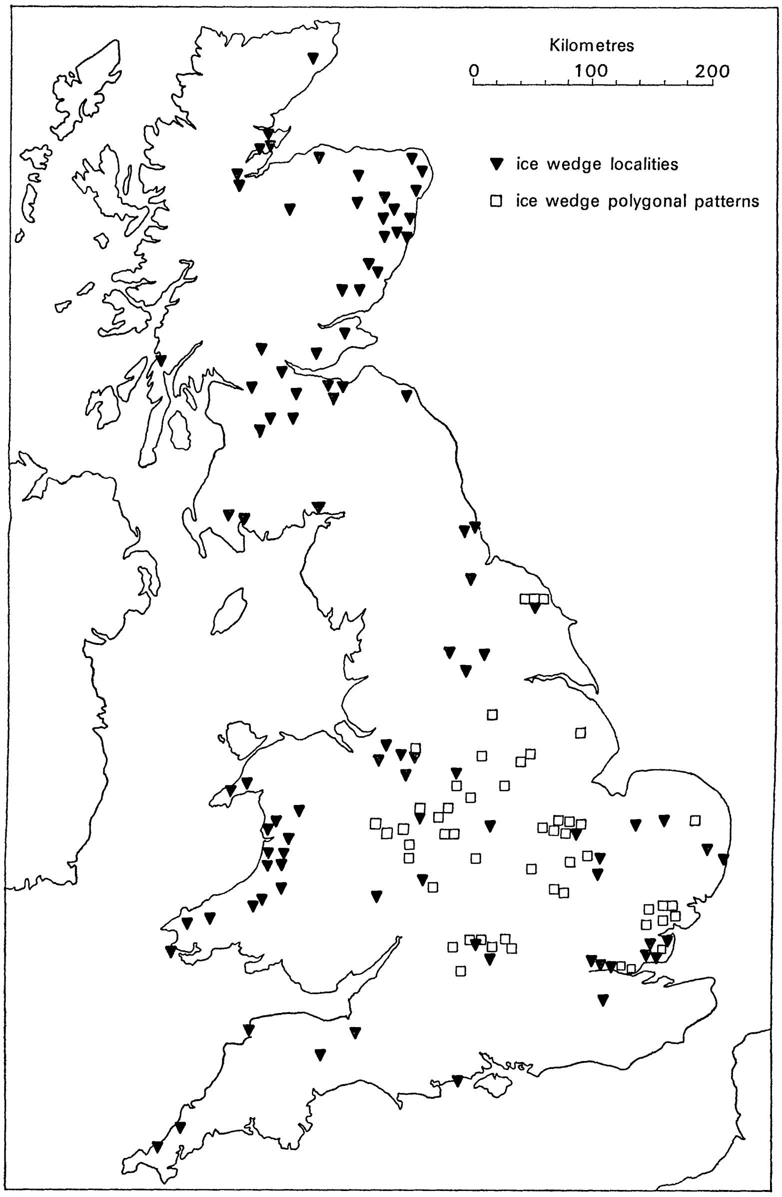

FIGURE 4. Fossil ice wedges and polygonal crop markings in Great Britain.

The map must be regarded as an interim compilation, and no doubt some of the blank areas will be eliminated as more sites are recorded. Not all will disappear, for ice wedge polygons are not found in all parts of the contemporary continuous permafrost zone, but are replaced by other types of patterned ground. Such appears to be the case in the blank representing the chalk areas (cf. figure 4 with Fig. 4.8 in Sparks & West 1972, p. 115). In the present state of

BIOLOGICAL SCIENCES
THE ROYAL SOCIETY
PHILOSOPHICAL TRANSACTIONS OF

knowledge, fossil ice wedges add much more to our understanding of the Late Devensian than in earlier periods where the information they give tends to be of a general character.

(*b*) *Fossil pingos*

Rampart forms representing Devensian pingos have been found in two main areas, Wales and East Anglia (figure 5). In southwest Wales they occur in groups in minor valleys scattered over a considerable area (Watson 1971; Watson & Watson 1972, 1974). In East Anglia they tend to be located in the valleys of the western edge of the chalk plateau (Sparks *et al.* 1972).

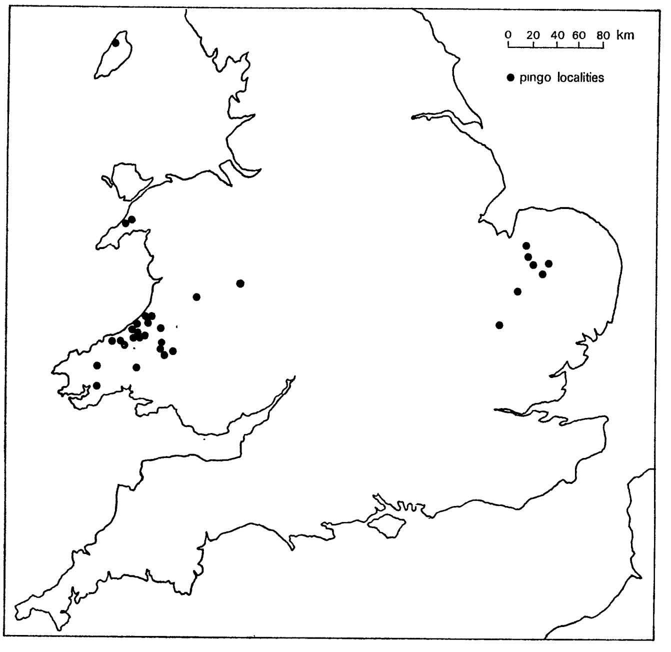

FIGURE 5. Remains of open system pingos in England and Wales.

In both areas they resemble most closely the open system pingos of central Alaska and Yukon Territory which occur in the central axial belt of the discontinuous permafrost zone (Brown & Péwé 1973, p. 81). They appear to be localized by closely defined hydrological conditions (Holmes *et al.* 1968, pp. 30–32), which recently glaciated terrain does not readily provide, as 'pingos are extremely rare in areas glaciated within the last 25000 years' (Brown & Péwé 1973, p. 81). This must be borne in mind in any attempt to explain the distribution of former pingos. One may, however, postulate a zone of discontinuous permafrost from Wales to East Anglia at the time of the formation of the British pingos.

The ramparts vary considerably, with quite steep-sided forms occurring alongside low subdued ones, both formed of the same materials and subject to similar agricultural hazards. The pingo basins contain a variable thickness of grey clay overlain by organic deposits. In southwest Wales the base of these organic deposits has been sampled for radiocarbon dating in three basins in the Cledlyn valley and one in the Cletwr valley (Shotton & Williams 1973, pp. 460–461; Shotton, Williams & Johnson 1974, p. 287, and 1975, pp. 257–258). All gave dates between 9500 and 10000 B.P. The same deposits were also sampled for pollen analysis, and show that organic sedimentation began prior to the 'initial expansion of *Juniperus* at the opening of the Flandrian'

(Handa & Moore 1976, p. 205). As the deposits include those surrounded by the steepest freshest rampart, it may be concluded that all the pingo ice had thawed by this time. Similar results from pollen analysis have been obtained for pingo basins at Llangurig in east Wales (Trotman 1963) and in East Anglia (Sparks *et al.* 1972), indicating that the discontinuous permafrost of the pingo belt ended with the beginning of the Flandrian.

It is more difficult to date the beginning of the phase of pingo development. A group of ramparts does not represent a group of mounds which grew together, but a series of mounds which grew individually over a period time. Thus the form of the ramparts indicates successive growth (Watson 1971, p. 386), and the fresher, more obvious ramparts stand on the ruins of older. The older pingos must generally have collapsed completely before the later pingos grew, otherwise the later ramparts must have suffered deformation in the overlap area. Though there are no measurements concerning rates of growth and collapse of open system pingos, it is believed that in central Alaska they have been 'forming continuously for several thousand years' (Holmes *et al.* 1968, p. 37). It is highly probable that pingo development in England and Wales lasted longer than the conventional Pollen Zone III, and that the transition from continuous to discontinuous permafrost took place with the climatic amelioration that ushered in the Allerød.

(*c*) *Involutions*

In the continuous permafrost zone today, considerable areas do not have ice wedge polygons, but have instead various types of sorted and unsorted patterned ground. The active layer or surface zone in which these patterns develop thaws and freezes annually. Its base, the top of the permafrost, is known as the permafrost table.

Since the 1920s, 'involutions' have been regarded by many as representing the fossil active layer. These consist of deformations of former sedimentary structures often as a series of pockets, but sometimes highly contorted and at times resembling load structures. As such convolutions of bedding and load structures are widespread in sedimentary deposits, they must be carefully considered in the context of their deposition. If they were formed in an active layer they must relate to a former surface and to a limited horizon. Discontinuous and random structures are suspect, as are those in deposits likely to be lacustrine (cf. Fries, Wright & Ruben 1961).

In many cases the involution layer lies just below the present surface which slopes at $< 2°$. The depth of the deformation varies within narrow limits, and in a large exposure often appears remarkably constant. The base truncates dipping beds, and may reasonably be interpreted as a fossil permafrost table. Even where the pockets consist of sand and gravel sunk in clay or silt, if the base of the deformation is parallel to the surface and can be followed for a considerable distance, it probably represents a former active layer. But very often the question of load structures does not arise; the pockets are of silt or clay sunk in sandy or gravelly material. These pockets in gravel, called festoons, are usually accompanied by erected pebbles or vertical stones where elongated pebbles have their long axis vertical (Watson & Watson 1971). Figure 6 is an example from the west coast of Wales, south of Aberystwyth, where the thickness of the deformed layer varies between 2 and 3 m over a distance of about 200 m. Below its base the till is undisturbed, as is shown by its constant preferred stone orientation. Elsewhere on the coast, festoons are developed in coarse fluvial gravels and in fluvio-glacial gravels, with the imbrication in the former, and the bedding in the latter, preserved undisturbed below the base.

The context of these systematically developed involution horizons is periglacial, in that they are developed on flat surfaces where surrounding slopes have developed periglacial slope deposits. In a few cases where the head at its outer limit is thin, it has been involved in festoons (cf. Watson & Watson 1971, pp. 111). The distribution of involutions in Britain seems to be limited to south England and Wales, and they may well be related to the maximum of the last glaciation, as many workers in central and western Europe believe (cf. Washburn 1973, p. 247). Poser's map (1948, p. 59, Fig. 2 – reproduced in Washburn 1973, p. 249) shows they indicate a depth of thaw of < 1.5 m in East Germany and western Poland, 1.5 to 2.0 m in West Germany and > 2 m in the low countries and in the area on both sides of the English Channel. In Cardigan Bay it reaches 3 m. Such a thickening active layer with decreasing continentality might appear anomalous, but it probably reflects the fact that 'heat is distributed through earth materials more rapidly by circulating water than by direct conduction' (Hopkins *et al.* 1955, p. 117).

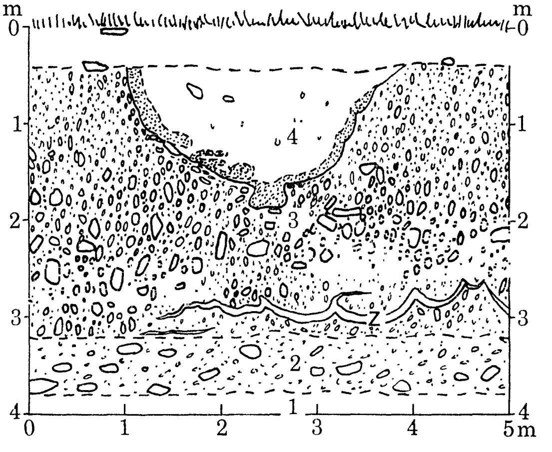

FIGURE 6. Festoon in vertical stones south of the River Clydan, near Aberystwyth. 1, modern beach; 2, undisturbed local till; 3, cryoturbated local till; 4, festoon of decalcified Irish Sea till surrounded by a deformed layer of gravelly coarse sand; z, deformed lens of silty clay and sand.

In Britain, there also appears to be a second involution layer which is shallower, 0.8 m thick, and is not consistently developed but patchy in distribution. It is found north of the deeper type considered above, extending to Scotland (Galloway 1961). South of Aberystwyth, both types may be seen together in cliff exposures, the shallower being developed in the surface zone of upper alluvial gravels which overlie the festoons of the deeper type.

Some of the processes which have played a part in involution layers also operate in the active layer of the continuous permafrost zone; the churning of the material beneath unsorted circles (Hopkins & Sigafoos 1951), the tendency for elongated stones to migrate vertically towards the surface (Washburn 1973, pp. 66–80). The case for permafrost remains hypothetical however, as it has yet to be demonstrated that structures comparable with festoons or other involutions are forming in permafrost regions today. It is therefore not possible to define the conditions under which they form, as one can for ice wedges (cf. Jahn 1975, p. 134), nor to use them with confidence for an environmental reconstruction of the Devensian.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

4. The periglacial environment of Devensian Britain

(*a*) *The contemporary permafrost environment*

In an attempt to interpret the environment of Great Britain during the Devensian, Alaska, with its west coast situation, is probably the most instructive of contemporary permafrost regions. Furthermore, it has also been the scene of many studies of the relationship of permafrost phenomena to the natural environment in the last 20 years so that considerable data are available.

Table 1. Features of the permafrost area of the northwest of North America

permafrost	ground ice features		mean air temperatures °C: annual	mean air temperatures °C: July	vegetation
continuous	active ice wedge polygons in fine and coarse sediments	closed system pingos	−13/−15	4/6	polar desert ……… tundra
	……………………		−6/−8	10/11	………………
discontinuous	inactive ice wedge polygons in fine sediments	open system pingos			coastal tundra ⋮ interior boreal forest
			0/−1	13/17	

It may be urged that the Bering Sea and Arctic Ocean are no counterpart for the North Atlantic, but the evidence indicates that the latter had a much reduced climatic influence on the British Isles during the Devensian. There is consistent evidence for a great expansion westwards of the present Siberian permafrost region as far as the British Isles. This can only have taken place with a great increase in continentality of climate and very cold winters, while the considerable drop in the surface temperatures of the North Atlantic would have resulted in cool cloudy summers (Velitchko 1974).

On the northwestern coast of North America the continuous permafrost zone falls into two main vegetation zones. The polar desert is found on the Canadian Arctic Archipelago north of 68°–72° N, while the tundra occupies a small part of the islands south of this and occurs largely on the mainland, its western part being in Alaska between 66 and 70° N. In both areas mean annual precipitation is low, being generally < 125 mm in the polar desert, and < 250 mm in the tundra, and a high proportion falls in the summer months as rain. Even in the polar desert about 50 % falls in the three months with a mean temperature above 0 °C. The cool summers have a high percentage of cloud cover. Snowfall is relatively light so that the ground is not insulated from frost. Mean January air temperatures are generally < −20 °C. In the polar desert or High Arctic, the surface is very largely bare rock debris with saline crusts and alkali flats. In the southern marginal zone, the subpolar desert or Middle Arctic, plantless areas are still common and a stony sedge-moss-lichen tundra is characteristic (Brown 1972).

In the discontinuous permafrost zone not only are temperatures generally higher but there are important differences between the coastal area and the interior. There is a decrease in

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

rainfall inland, but its distribution is similar to that in the continuous permafrost zone. In the coastal area the mean January air temperature is around −15 °C, but with cloudy summers the July figure reaches only 10–11 °C. The vegetation for up to 300 km inland is tundra. In the interior, the January air temperature falls to around −24 °C, but in July with a lower average cloud cover, the mean air temperature is around 15 °C. With June, July and August mean temperatures between 12 and 16 °C, the coastal tundra is replaced by a boreal forest of spruce, birch, aspen, balsam poplar, alder and willow except on badly drained areas and uplands.

The environment of the two permafrost indicators used in this discussion for Devensian Britain has been studied in Alaska (see Brown & Péwé 1973). Active ice wedges are limited to continuous permafrost and by a mean annual air temperature of −6 to −8 °C. They are virtually all on the tundra. Open system pingos are found in both the coastal tundra and the interior forest of the discontinuous permafrost, the great majority between isotherms −3 and −6 °C.

(*b*) *Great Britain during the Devensian*

(i) *The Early Devensian, preceding* 50000 B.P.

As yet there is very little evidence for permafrost which can confidently be assigned to this period. The undisturbed birch-pine-spruce woodland horizon at Chelford dated 60800 B.P. has been interpreted as representing boreal forest with a mean July air temperature of about 15 °C (Simpson & West 1958). Intraformational fossil ice wedges in the sands covering the above bed indicate continuous permafrost subsequent to the forest phase (Worsley 1966*b*). An undated horizon with birch, pine and spruce pollen (FG) at Wretton has been tentatively equated with the Chelford organic layer, though the beetle assemblages of the two suggest very different environments (R. G. Coope in West *et al.* 1974, pp. 414–418). Fossil ice wedge horizons above and below FG indicate continuous permafrost, which suggests the probability of at least discontinuous permafrost during the birch-pine-spruce period. In the overlying horizon (H), halophytes are well represented, suggesting conditions approaching polar desert by the end of the sequence, and that it was already becoming as severe as in the Middle Devensian.

(ii) *The Middle Devensian*, 50000–26000 B.P.

Fossil ice wedges are known associated with dated deposits which span most of this period (e.g. Earith, 42000 B.P. and >45000 B.P., Syston, 37420 B.P. and Four Ashes, with radiocarbon dates between 42000 and 30000 B.P.), so that permafrost was present. Pollen and beetle assemblages indicate that the landscape was treeless, and as this is broadly the period of the 'full-glacial floras' which include obligate and facultative halophytes (Bell 1969), conditions were fairly arid with probably subpolar desert at times. This picture of a permafrost environment fluctuating between tundra and subpolar desert is interrupted only in the period between 42530 and 38500 B.P. (Coope, Morgan & Osborne 1971).

(iii) *The Late Devensian* 26000–10000 B.P.

Although no fossil ice wedges are datable to the period of maximum glaciation, they occur in the most recent till at Four Ashes (Morgan 1973) and Chelford (Worsley 1966*b*). As the insect assemblage from Dimlington (18500 B.P.) has few species and these are tolerant of very low summer temperatures (Coope *et al.* 1971, p. 93), it is probable that polar desert with continuous permafrost existed south of the ice margin.

Fossil ice wedges in northern England and southeast and east Scotland suggest that continuous permafrost was established as these areas were uncovered by ice, and some in central Scotland overlain by glacial deposits may indicate permafrost in the period preceding the Aberdeen–Lammermuir Readvance and in that preceding the Perth Readvance. In Wales, it has already been suggested that the fossil ice wedges are broadly Pollen Zone I. In England and Wales polar desert with continuous permafrost probably continued until around 15000 B.P., and the barren silty-clay deposits in lake basins which frequently underlie the lowest late-glacial pollen bearing material probably result from rain and melting snow run-off flowing over a surface with a very reduced vegetation cover.

In the period preceding the development of open birch woodland in the Allerød, the permafrost of England and Wales probably became discontinuous. Mean July air temperatures during the Allerød were probably about 12–13 °C, while on the Alaskan model, Ireland would have been in the coastal zone with slightly lower July temperatures and a tundra vegetation. Though the Younger Dryas saw the replacement of birch woodland by tundra, discontinuous permafrost persisted until the beginning of the Flandrian, when open system pingos which had been forming throughout most of the discontinuous permafrost period, ceased to develop. In Scotland, however, fossil ice wedges suggest continuous permafrost in the Younger Dryas, as in southern Scandinavia (Svensson, 1974). If we assume that the fossil pingos in Wales and East Anglia occupy the same position within the discontinuous permafrost belt as the open system pingos of Alaska today, the southern limit of discontinuous permafrost should have lain in the English Channel area, and the northern limit in the English–Scottish border area, with continuous permafrost and active ice wedges north of this.

(iv) *Devensian temperatures*

The minimum fall in mean annual air temperature compared with the present day, which continuous permafrost in England implies is of the order of 16–17 °C. This is based on the continuous permafrost limit at −7 °C determined for central Alaska. Active ice wedge formation, on which the identification of former continuous permafrost has been based in this paper, probably implies a somewhat lower figure, say −10 °C, giving a fall of around 20 °C.

At the maximum of the Devensian ice advance the fall in temperature was greater than this, for the southern limit of ice wedge formation in the last glaciation lay some 500 km south of the southern English coast (Kaiser 1960, Plate 1, reproduced in Washburn 1973, p. 250). In the northwest of North America today, the northern limit of the tundra is about 500 km north of the continuous permafrost limit, and has a mean annual air temperature of −14 to −12 °C. Full polar desert conditions probably existed in the English Midlands with mean annual air temperatures of at least −16 to −17 °C. There is a scarcity of floristic and faunistic data on this point but what does exist, indicates very severe conditions (cf. Coope *et al.* 1971, pp. 92–93).

On the evidence of the pingos, the mean annual air temperature of southern England and Wales in the Younger Dryas was between −4 and −5 °C, representing a fall of 13–14 °C compared with the present day.

Table 2 summarizes the temperatures deduced for the English Midlands–East Anglia at various points of time. The fall in the July mean temperatures compared with those of today is small. The great difference between temperatures in Britain today and those of permafrost regions is in the winter temperatures.

Table 2. Estimated Devensian temperatures (°C)

	mean air temperatures		fall from present	
B.P.	annual	July	annual	July
10500	−5	10	15	5
11500	−4	12/13	14	3
13000	−7	10	17	5
18000	−15	5	25	10
55000	−7	11	17	4

5. General conclusions

1. Ice wedge casts remain the most useful indicator of former permafrost, partly because they are the most widespread and partly because more is known about contemporary forms, about recently thawed forms and about their environment.

2. Pingos are more restricted in distribution but their remains may be important in discriminating between continuous and discontinuous permafrost. Considerable work is being done on contemporary forms and their environments, but little has been recorded about the final rampart stage and especially on the internal structure. This is urgently required as identification of fossil pingos at present depends very largely on the survival of their surface form.

3. Boreal forest may occur in permafrost or permafrost-free areas. The mean July air temperatures may have much the same range in both cases.

4. Once continuous permafrost is established the short-term replacement of tundra by boreal forest is likely to be within permafrost conditions rather than to represent a change to permafrost-free conditions.

The author thanks D. B. Smith for unpublished information on ice wedge casts in north-east England.

References (Watson)

Bell, F. G. 1969 The occurrence of southern, steppe and halophyte elements in Weichselian (Last Glacial) floras from southern Britain. *New Phytol.* **68**, 913–922.

Bell, F. G., Coope, G. R., Rice, T. J. & Riley, T. H. 1972 Mid-Weichselian fossil bearing deposits at Syston, Leicestershire. *Proc. geol. Ass. Lond.* **83**, 197–211.

Black, R. F. 1969 Thaw depressions and thaw lakes. *Biul. Peryglacj.* **19**, 131–150.

Black, R. F. 1973 Growth of patterned ground in Victoria Land, Antarctica. In *Permafrost, N. American Contribution to 2nd Int. Conf. on Permafrost*, pp. 193–203. Nat. Acad. Sci., Washington, D.C.

Brown, R. J. E. 1972 Permafrost in the Canadian Arctic Archipelago. *Z. Geomorph.* N.F., Suppl. Band **13**, 102–130.

Brown, R. J. E. & Péwé, T. L. 1973 Distribution of permafrost in North America and its relationship to the environment: a review, 1963–1973. In *Permafrost, N. American Contribution to 2nd Int. Conf. on Permafrost*, pp. 71–100. Nat. Acad. Sci., Washington, D.C.

Cailleux, A. & Taylor, G. 1954 *Cryopédologie.* Paris: Hermann.

Coope, G. R., Morgan, A. & Osborne, P. J. 1971 Fossil Coleoptera as indicators of climatic fluctuations during the Last Glaciation in Britain. *Paleogeog. Paleoclimatol. Paleoecol.* **10**, 87–101.

Czudek, T. & Demek, J. 1973 Die Reliefentwicklung während der Dauerfrostbodendegradation. *Rozpravy ČSAV, Řada matemat. a přírod.* **83**, seš. **2**.

Fries, M., Wright Jr., H. E. & Rubin, M. 1961 A Late Wisconsin peat at North Branch, Minnesota. *Am. J. Sci.* **259**, 679–693.

Galloway, R. W. 1961 Ice wedges and involutions in Scotland. *Biul. Peryglacj.* **10**, 169–193.

Gruhn, R. & Bryan, A. L. 1969 Fossil ice wedge polygons in southeast Essex. In *The periglacial environment* (ed. T. L. Péwé), pp. 351–363. Montreal: McGill-Queens University Press.

Handa, S. & Moore, P. D. 1976 Studies in the vegetational history of mid-Wales. IV. Pollen analyses of some pingo basins. *New Phytol.* **77**, 205–225.
Holmes, G. W., Hopkins, D. M. & Foster, H. L. 1968 Pingos in central Alaska. *U.S. Geol. Surv. Bull.* 1241-H.
Hopkins, D. M., Karlstrom, T. N. V. *et al.* 1955 Permafrost and groundwater in Alaska. *U.S. Geol. Surv. Prof. Paper* 246-F.
Hopkins, D. M. & Sigafoos, R. S. 1951 Frost action and vegetation patterns on Seward Peninsula, Alaska. *U.S. Geol. Surv. Bull.* 974-C.
Jahn, A. 1975 *Problems of the periglacial zone.* Warsaw: Polish Scientific Publishers.
Maarleveld, G. C. 1965 Frost mounds, a summary of the literature of the past decade. *Mededelingen van de Geologische Stichting*, N.S. **17**.
Mackay, J. R. 1971 The origin of massive icy beds in permafrost, western arctic coast, Canada. *Can. J. Earth Sci.* **8**, 397–422.
Morgan, A. 1973 The Pleistocene geology of the area north and west of Wolverhampton, Staffordshire. *Phil. Trans. R. Soc. Lond.* B **265**, 233–297.
Müller, F. 1959 Beobachtungen über Pingos. *Meddr Grønland* **153**, no. 3.
Péwé, T. L. 1966 Palaeoclimatic significance of fossil ice wedges. *Biul. Peryglacj.* **15**, 65–73.
Péwé, T. L. 1969 The periglacial environment. In *The periglacial environment* (ed. T. L. Péwé), pp. 1–9. Montreal: McGill-Queens University Press.
Péwé, T. L., Church, R. E. & Andresen, M. J. 1969 Origin and palaeoclimatic significance of large scale polygons in the Donnelly Dome area, Alaska. *Geol. Soc. Am. Spec. Pap.* **109**.
Shotton, F. W. 1960 Large scale patterned ground in the valley of the Worcestershire Avon. *Geol. Mag.* **97**, 404–408.
Shotton, F. W. & Williams, R. E. G. 1973 Birmingham University Radiocarbon Dates VII. *Radiocarbon* **15**, 460–461.
Shotton, F. W., Williams, R. E. G. & Johnson, A. S. 1974 Birmingham University Radiocarbon Dates VIII. *Radiocarbon* **16**, 287.
Shotton, F. W., Williams, R. E. G. & Johnson, A. S. 1975 Birmingham University Radiocarbon Dates IX. *Radiocarbon* **17**, 257–258.
Simpson, I. M. & West, R. G. 1958 On the stratigraphy and palaeobotany of a late-Pleistocene organic deposit at Chelford, Cheshire. *New Phytol.* **57**, 239–250.
Sparks, B. W. & West, R. G. 1972 *The Ice Age in Britain.* London: Methuen.
Sparks, B. W., Williams, R. B. G. & Bell, F. G. 1972 Presumed ground-ice depressions in East Anglia. *Proc. R. Soc. Lond.* A **327**, 329–343.
Stager, J. K. 1956 Progress report on the analysis of the characteristics of pingos east of the Mackenzie delta. *Can. Geogr.* **7**, 381–392.
Svensson, H. 1974 Distribution and chronology of relict polygon patterns on the Laholm plain, the Swedish west coast. *Geogr. Ann.* **54**A, 159–175.
Tricart, J. 1970 *Geomorphology of cold environments.* London: Macmillan.
Troll, C. 1958 *Structure soils, solifluction and frost climates of the earth.* U.S. Army SIPRE Trans. **43**.
Trotman, D. M. 1963 Peat deposits within a pingo near Llangurig, Wales. *Z. Geomorph.* N.F. **7**, 168–171.
Velitchko, A. A. 1974 Paragenesis of a cryogenic (periglacial) zone. *Biul. Peryglacj.* **24**, 89–110.
Washburn, A. L. 1973 *Periglacial processes and environments.* London: Arnold.
Watson, E. 1971 Remains of pingos in Wales and the Isle of Man. *Geol. J.* **7**, 381–392.
Watson, E. & Watson, S. 1971 Vertical stones and analogous structures. *Geogr. Ann.* **53**A, 107–114.
Watson, E. & Watson, S. 1972 Investigations of some pingo basins near Aberystwyth, Wales, *Rep. 24th Int. Geol. Congr.* (Montreal), Section 12, 212–233.
Watson, E. & Watson, S. 1974 Remains of pingos in the Cletwr basin, southwest Wales. *Geogr. Ann.* **56**A, 213–225.
West, R. G., Dickson, C. A., Catt, J. A., Weir, A. H. & Sparks, B. W. 1974 Late Pleistocene deposits at Wretton, Norfolk. II. Devensian deposits. *Phil. Trans. R. Soc. Lond.* B **267**, 337–420.
Worsley, P. 1966*a* Fossil frost wedge polygons at Congleton, Cheshire, England. *Geogr. Ann.* **48**A, 211–219.
Worsley, P. 1966*b* Some Weichselian fossil frost wedges from east Cheshire. *Mercian Geologist* **1**, 357–365.
Wright, H. E., Jr 1961 Late Pleistocene Climate of Europe: a review. *Geol. Soc. Am. Bull.* **72**, 933–984.

Discussion

A. V. Morgan (*Department of Earth Sciences, University of Waterloo, Waterloo, Ontario, Canada*). (In reply to a question by Dr Starkel to Dr Watson requesting an estimation of the time elapsed for the formation of periglacial features.)

There are well developed ice-wedge casts and fossil polygonal ground present within the

Late Devensian Irish Sea till in the area north and west of Wolverhampton. Assuming that the maximum ice advance position at the Wolverhampton Line was reached *ca.* 20000–18000 a B.P., then the relict permafrost zone must post-date ice retreat. About 12 km north of Wolverhampton the Late Devensian ice-wedge casts are overlain by glacio-fluvial terrace gravels. The glacio-fluvial gravels have been cut and filled with an organic sequence at Stafford, dated at 13490 ± 375 a B.P. (Birm. 150). Although the fauna associated with this date could co-exist in an environment with permafrost, it seems likely that perennially frozen ground was disappearing about this time. The permafrost regime must, therefore, have existed (in the Late Devensian) from ?18000 a B.P. to about 13500 a B.P. in the west English Midlands. It is possible that it may have reappeared *ca.* 10800–10200 a B.P. when coleopteran faunas indicate a return of severe climatic conditions.

A number of colour slides were shown illustrating the sequence exposed at the Devensian type section at Four Ashes, Staffordshire, between 1967 and 1970. Dr Morgan pointed out that over 50 organic sites had been collected from the gravel sequence which ranged in thickness from 50 cm to over 5 m. All of the organic lenses came from a restricted geographic area *ca.* 400 m × 100 m and all had fragments of Coleoptera preserved within them. Eight lenses were dated and provided ages ranging from 30500 ± 440 a B.P. (Birm. 195) to in excess of 45000 a B.P. (Birm. 44). Because of the fauna and flora within the gravel sequence it was shown to have been deposited in a time period ranging from the Ipswichian Interglacial through the Early Devensian Chelford episode (Brørup equivalent) to the Middle Devensian Interstadial complex, and finally covered by a Late Devensian Irish Sea till. Fossil ice-wedge casts at the base and within the sequence indicated at least two severe climatic deteriorations within the gravel deposit, although, at Four Ashes, there was no evidence of an Early Devensian ice advance. The dates of 30500 and 30655 ± 700 a B.P. (Birm. 25) indicate that the Late Devensian ice crossed the area sometime later, although how much later is uncertain. Following ice-retreat permafrost conditions prevailed resulting in the ice-wedge casts, polygonal ground and cryoturbation affecting the Late Devensian deposits at Four Ashes.

At Stafford, 15 km to the north, investigations have begun on a thick (19.1 m) Late Devensian and Holocene sequence consisting of clay, silts, gyttjas and peats. A sample at the 15.1 m level has provided a date of 13500 a B.P. Well preserved pollen, plant macrofossils, diatoms, cladocera, molluscs, ostracods, beetles and other insects will hopefully provide a detailed picture of biological change, while geochemical analyses of the core sediment and molluscs both for major and trace elements as well as stable isotopes should help provide additional data for this important time period.