Distribution and probable age of relict permafrost features in south-western Ontario

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Over three hundred areas of polygonal ground principally developed upon the Tavistock Till, deposited by the Huron ice lobe, and the Port Stanley Till, deposited by the Ontario–Erie ice lobes, have been located in south-western Ontario. The polygons are believed to be the surface expression of either former ice-wedges, or sand-wedges. These were formed in the period from about 15,000 to 13,000 years B.P. and may involve more than one period of activity. Fossil insect faunas from Michigan and New York indicate that a climatic regime compatible with the existence of permafrost was present at 13,800 years B.P., but that it had disappeared prior to 12,700 years B.P. The periglacial zone in which the polygons were created was probably localized and may have existed elsewhere, at later dates, in positions where the morphology of the retreating Laurentide ice was favourable.

Plus de trois cents secteurs de sols polygonaux qui se sont principalement formés dans le till de Tavistock, déposé par le lobe glaciaire du lac Huron, et le till de Port-Stanley, déposés par les lobes glaciaires des lacs Ontario et Erié, ont été localisés dans le sud-ouest de l'Ontario. On pense que les polygones sont la manifestation en surface de pseudomorphose de coins de glace ou de sable, qui se seraient formés il y a 15 000 à 13 000 ans lors d'une ou plusieurs périodes d'activité. Les faunes d'insectes fossiles des états du Michigan et de New York indiquent qu'un régime climatique compatible avec la présence de pergélisol existait il y a 13 800 ans mais qu'il a disparu il y a plus de 12 700 ans. La zone périglaciaire dans laquelle se sont formés les polygones était probablement localisée et a pu apparaître ailleurs, par la suite, en des endroits où la morphologie de l'inlandsis laurentidien en régression en favorisait l'apparition.

Proc. 4th Can. Permafrost Conf. (1982)

Introduction

Polygonal patterned ground was first recognized in southern Ontario ten years ago (Morgan 1972; Morgan and Morgan 1977) although structures attributed to former permafrost regimes had been described earlier elsewhere in Canada (Berg 1969; Borns 1965; Brookes 1971; Dionne 1966, 1967, 1969, 1970, 1971; Gangloff 1970; Gangloff *et al.*, 1971; Morgan 1969; Westgate and Bayrock 1964). A summary of these early papers is provided by Brown and Péwé (1973), Péwé (1973), and Washburn (1973), while Black (1976) has provided critical comments on the supposed origins of many of the structures described in those papers. Summaries of the stratigraphy of parts of south-western Ontario are provided in papers by Dreimanis (1961, 1969), Harris (1967, 1970), and Karrow (1971, 1974).

The paper by Morgan (1972) described polygonal patterns, attributed to the surface expression of former ice-wedge cracks, in a geographically restricted area just to the east of Kitchener, Ontario. Examination of vertical air photographs taken for federal, provincial, and local governments, coupled with annual private flights in a light aircraft have revealed geographically widespread areas of polygonal patterns. The purpose of this paper is to describe the areal extent of the polygonal ground and the supposed age of the features. Some preliminary comments on fossil insect faunas have also been made. These faunas have been used to elucidate climatic conditions following the retreat of the late-Wisconsin Laurentide ice sheet.

The Nature and Areal Extent of Polygonal Ground

Although many vertical air photographs have been taken of parts, or all, of the area under discussion, the most useful coverage for detecting relict polygons is the 1955 series produced for the Ontario Department of Lands and Forests. These panchromatic photographs at a scale of 1:15,840 were taken in late June and early July, at a time when moisture differences in the soil were pronounced. The 1978 series also taken in late June and early July, although exhibiting some new areas of polygons as well as reconfirming the presence of polygons in other areas, do not reveal as many polygons as the 1955 series. Photographs taken in 1972 also fail to show the widespread extent of polygons exhibited in the 1955 series. This situation does not reflect the quality of the imagery, indeed, the 1972 and 1978 series are far superior to the 1955 photographs in terms of both definition and contrast. The timing of the flights is also not significantly different with practically all of the photographs being taken in June and July. Some interesting climatic comparisons can, however, be made between the 1955 and 1972 series. This information is summarized in Table 1, and shows four regions in the zone of maximum polygon development (tabulated from north to south, a distance of approximately 150 km) and centred on the towns of Waterloo, Woodstock, London, and Aylmer. In each of the four areas, precipitation for the month prior to the 1955 photographs was significantly lower than normal (in one case 90 per cent below normal). In 1972, precipitation was normal or above average.

The polygon outlines become well defined when there are pronounced differences in moisture content between the materials filling the wedges and those

TABLE 1. Precipitation comparisons; 1955 and 1972, by region

Region	Flight date	Year	Precipitation 30-day average prior to flight
Waterloo	June 30	1955	down by 90%
	June 28	1972	normal
Woodstock	June 30	1955	down by 50%
	June 30	1972	no data available
London	June 30	1955	down by 50%
	June 30	1972	up by 30%
Aylmer	July 10	1955	down by 45%
	July 31	1972	normal

forming the polygon boundaries. These differences are a reflection of water moving through the polygon network in the manner outlined by Morgan (1971*a*, 1971*b*). Long-rooted cereals, and to a lesser degree other plants, are able to take advantage of moisture differences between the wedge area and polygon centres and this enables differential growth and ripening across the polygons, a phenomenon recognized by a number of authors (Christensen 1974; Dimbleby 1952; Morgan 1971*b*; Svensson 1972, 1973). Generally these moisture differences cannot be seen at ground level when there is a crop cover, although they can be detected by small-scale resistivity profiling (Greenhouse and Morgan 1977). The moisture differences show up extremely well on air photographs taken under strongly evaporative conditions and illustrate that well-developed polygons visible in one year, may not be visible the next year (Figures 1 and 2). By utilizing the available vertical photographs for all of the region (1955, 1972, 1978) together with geographically restricted coverage (1963, 1966, 1968) and by supplementing these with oblique hand-held photographs, a comprehensive picture of the areal extent of patterned ground has gradually been creat-

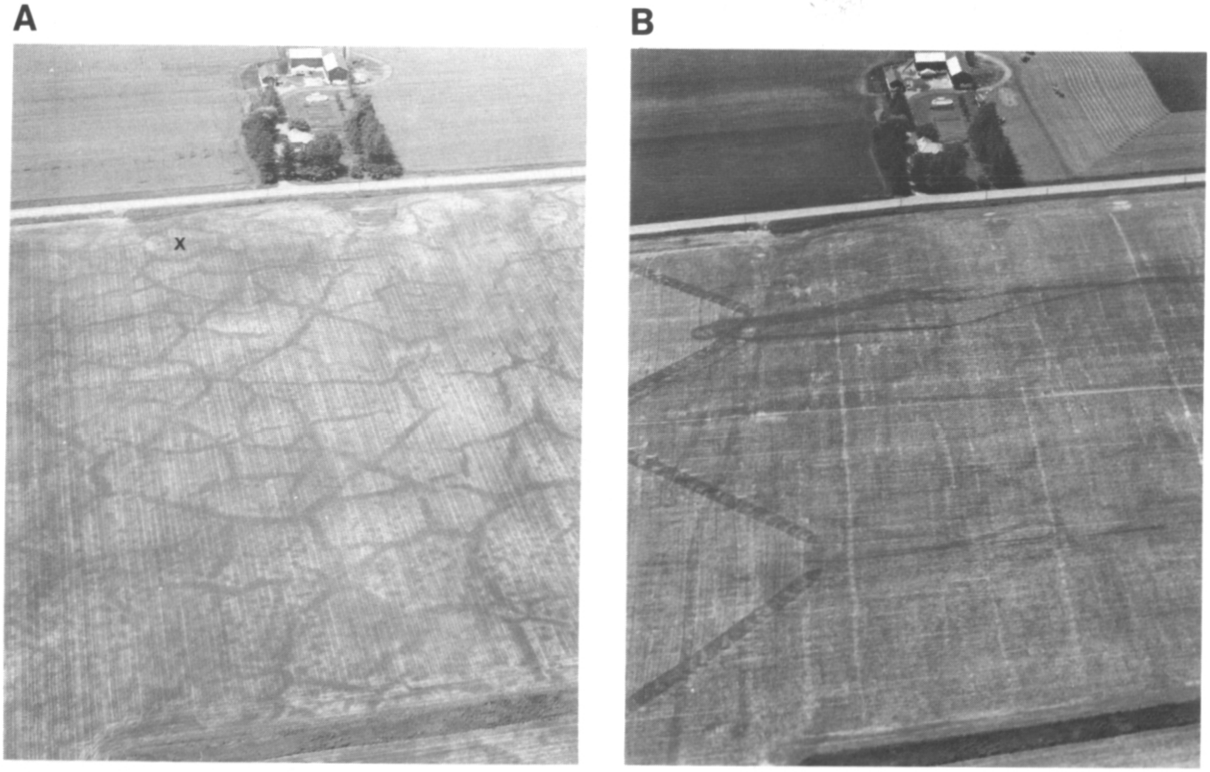

FIGURE 1. Comparative views of a polygon network at Muir, near Woodstock, Ontario, photographed from 154 m elevation: **a** in July, 1975, with corn (maize) 20 cm high in the field (x indicates the position of the polygon with a person *see* Figure 4); and **b** in June, 1977, when the polygon outlines can only be discerned after close study.

A

B

FIGURE 2. **a** Comparative views of polygonal ground at Belwood Lake, north of Waterloo, Ontario, in two fields near the centre of the picture: in August, 1963, when polygons were clearly visible. Note that the lake level is low, enhancing the moisture differential seen in the ripening crops. (Grand River Conservation Authority (Northway Survey Corp. Ltd.) photograph #4425-100); and **b** at the end of June 1955, when polygons do not show up (Ontario Dept. Lands and Forests photograph #55-4334-20-123). North is at the top of both photographs.

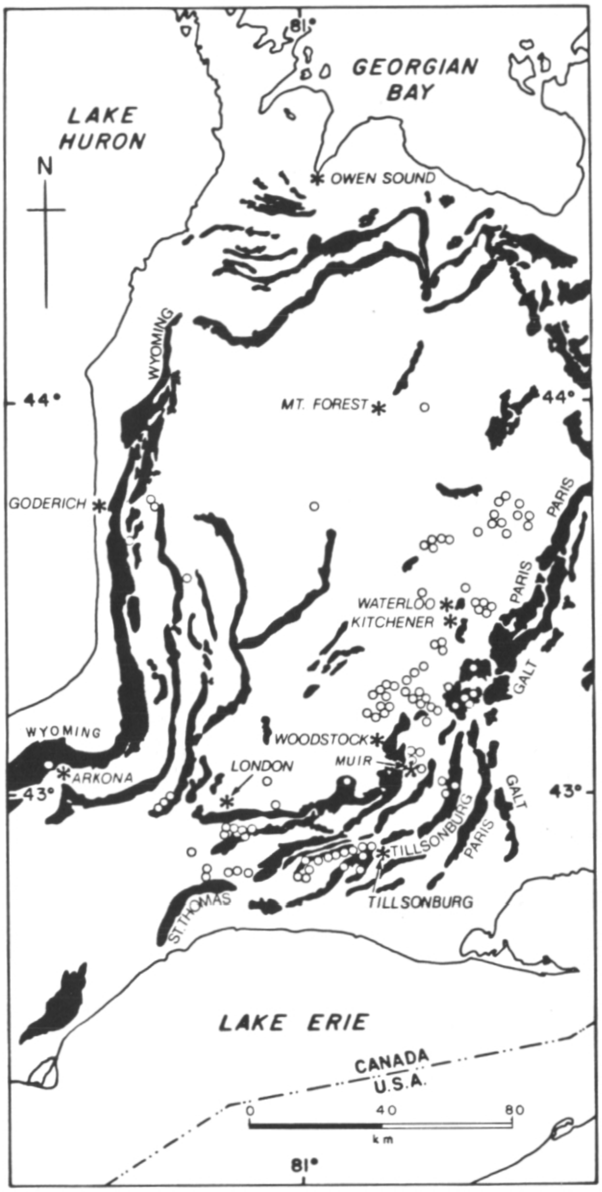

FIGURE 3. Relationship of polygon areas (open circles) to major end-moraine systems in south-western Ontario (*Modified after* Chapman and Putnam 1966). Most of the polygons are located between the St. Thomas–Tillsonburg–Paris moraines, and the towns of London, Kitchener–Waterloo, and Mt. Forest.

ed. On some vertical photographs anastomosing patterns, looking rather like water-modified degenerate ice-wedge polygons, can be seen. Putting aside these problematical pseudo-polygonal patterns, there are many areas of well-defined polygons, with regular and sharp boundaries, within a belt running from Mt. Forest to London, and in the scattered occurrences paralleling the shore of Lake Huron. Approximately 12,000 km^2 have been examined and over 500 discrete areas of polygonal ground have been detected. These range in size from individual fields of about 1000 m^2 to areas of up to 10 km^2. About 350 of these areas are believed to show definite polygonal networks while the remaining areas of polygonal markings have varying degrees of uncertainty attached to their interpretation. The location of the definite polygonal pattern areas are shown in Figure 3.

One of the greatest difficulties in studying polygonal ground is relating the patterns, which are often seen quite readily from the air, to features which are

FIGURE 4. View east across polygon networks at Muir, Ontario in May 1977. The polygon with figure standing is *ca.* 20 × 30 m; (*see* x in Figure 1**a**).

difficult, or impossible to see from the ground. Techniques used include direct measurement from air photographs of the distance of polygon boundaries to specific objects on the ground, such as trackways, telephone poles etc., or the use of the electrical resistivity method mentioned above. Air to ground communication, using hand-held two-way radios has also been attempted with an observer in an aircraft directing a person in a field with known polygonal networks. This technique was not successful, but it probably would work if electrical interference in the radio used in the aircraft could be resolved. These attempts were made to establish the exact position of the polygon margins so that they could be excavated with minimal cost. Excavations are necessary to establish the nature of the structure beneath the polygon boundary.

Wedge Structures and their Relationship to Till Units

Occasionally, polygonal networks can be recognized at ground level if moisture contrasts are sufficiently pronounced.

In the last week of May 1977 an area of polygons at

FIGURE 5. The Muir polygons being marked out prior to trenching. Surveying tape has been placed along the polygon boundaries. The trees in the background stand in front of the farm (*see* Figure 1**a** and **b**).

FIGURE 6. The Muir polygons being trenched. Photographed only six hours after Figure 5, the polygon outlines have disappeared due to strong evaporation from the soil surface. Surveying tape placed perpendicular to the polygon boundary, aligns the trench to cut across the polygon. The machine is about to cut Wedge #4.

Muir, near Woodstock was excellently exposed at ground level because of strongly evaporative weather conditions (Figure 4). The moisture differential remained long enough (approximately 30 hours after first observation) for the area to be marked out accurately (Figure 5). The polygon boundaries were trenched, using a backhoe (Figure 6) and in each case a wedge-shaped form, infilled with fine to medium sand, was found penetrating the till (Figure 7). As each polygon boundary was cut by the backhoe, water seeped from the wedge into the trench. Water flow at the Muir polygons was estimated at between 2 and 6 litres per hour, allowing some piping to take place near the base of the wedge in the bottom of the trench.

Sediment samples were removed from the wedge-infill and from the till on the side of the wedge. The analyses from three of the wedges, together with the adjacent till are given in Figure 8. The average analyses of the till (25.5 per cent clay; 56.0 per cent silt; 18.5 per cent sand) are similar to analyses (28.2 per cent clay; 56.4 per cent silt; 15.4 per cent sand) of five representative till samples taken in the area (Cowan 1975). The nature of the infilling debris at Muir is quite different from the materials observed in the wedges excavated near Kitchener, Ontario and described by Morgan (1972). In the latter examples, the wedges were infilled with sand and gravel, with vertically aligned pebbles along the margins. The Muir wedges were filled with an orange-brown, fine- to medium-grained sand. There was no discernable sign of vertical lineations in the sand (as is frequently seen in sand-wedge casts) nor were there signs of upwarping or downwarping of the till adjacent to the wedge margins (as is often encountered in ice-wedge casts).

The relationship of the polygonal patterns to the respective till units is illustrated in Figure 9. Since the polygons are probably time-transgressive and can only be formed following the retreat of the ice depositing the respective till unit, the age of the till sheet provides the maximum age of the polygon network. The till sheet upon which the Muir polygons are located was described by Cowan (1975) as Port Stanley Till. This is a generally stiff clayey-silt or silt till, deposited by the Erie ice lobe during the Port Bruce stadial. An examination of all the polygon occurrences on the Woodstock (1:250,000) map sheet reveals that the patterned ground lies either upon Port Stanley Till or upon the informally named Zorra Till (Cowan 1975). The Zorra Till (originating from the Huron ice lobe) has subsequently been renamed Tavistock Till and also is of Port Bruce stadial age (Cowan *et al.* 1975). Polygonal ground is preferentially developed upon the Tavistock Till (of west, north-west, and north-east provenance) and the Port Stanley Till (derived from the east and south-east). These two major till units are silt-rich and were deposited approximately contemporaneously, about 15,000 to 14,500 years age (Cowan *et al.* 1978). Other tills which show polygon networks are the Wentworth Till of the Ontario Lobe, and possibly the Rannoch Till of the Huron lobe. The Wentworth Till in the area of Kitchener–Waterloo is a silty-sandy till (Karrow 1971) while the Rannoch Till (paralleling, and inland from, Lake Huron) is a silty-clay till (Cowan *et al.* 1975). Both the Wentworth and the

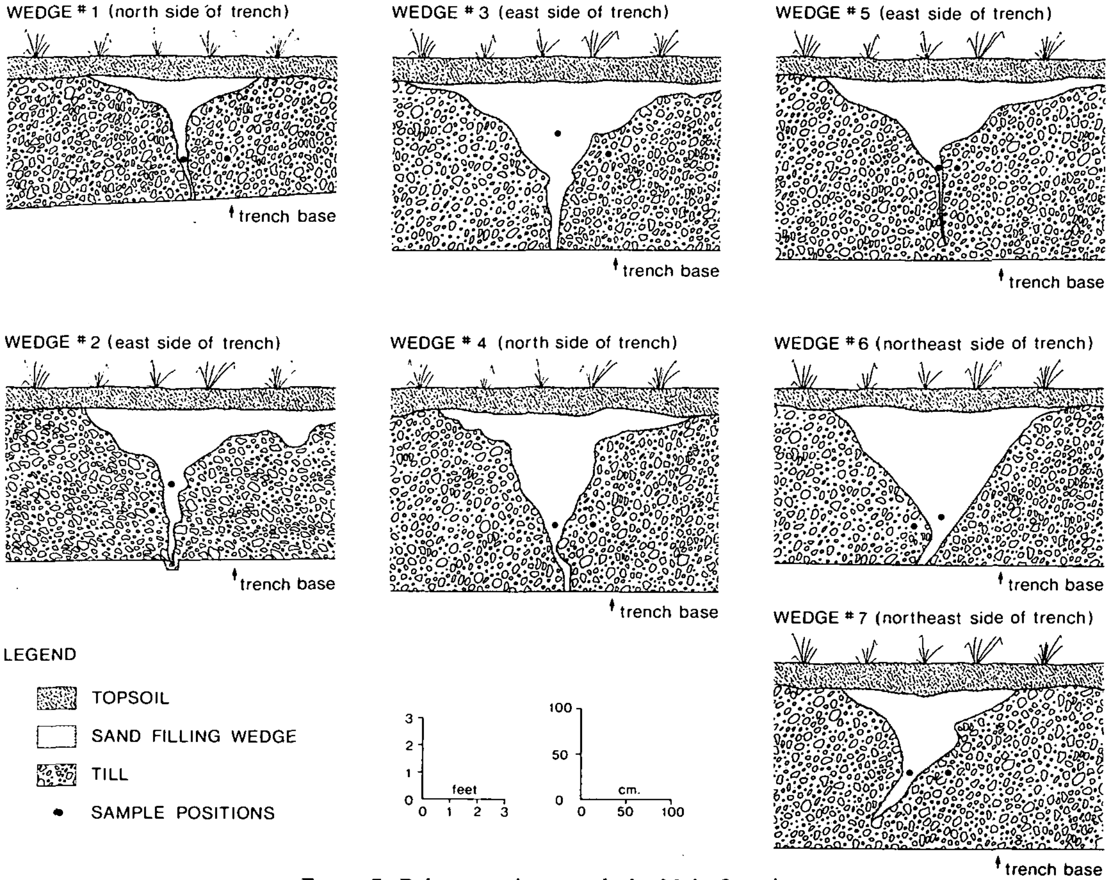

FIGURE 7. Polygon sections trenched at Muir, Ontario.

Rannoch tills are believed to be the youngest tills of the Port Bruce stadial and apparently were deposited about 14,000 years ago (*see* Figure 9).

The areas of youngest polygons so far detected occur on St. Joseph Till west of Arkona, Ontario, and in the area south of London extending eastward toward the town of Tillsonburg. The St. Joseph Till limit in the Arkona region approximately delimits the Wyoming moraine which was deposited by Huron lobe ice during the Port Huron stadial approximately 13,000 years ago. In the area south of London, the polygonal patterns are developed almost exclusively upon Port Stanley Till, but a few areas appear on what has been mapped by Dreimanis (1964) as silt and clayey-silt glacio-lacustrine materials. The age of these deposits is uncertain but they must be of younger Port Bruce stadial, Mackinaw interstadial, or oldest Port Huron stadial age.

The area south of London is a complex region of end moraines which were inundated by glacial lakes Maumee, Arkona, Whittlesey, and Warren (Dreimanis 1964). Beach levels are particularly difficult to trace because they apparently formed in stagnant ice areas. In the vicinity of Tillsonburg the youngest polygons seem to be developed either upon, or adjacent to, marginal deposits of glacial Lake Whittlesey. It is possible that the mapping of lithological boundaries or the depth of the lacustrine deposits may influence this apparent interpretation, however, the Whittlesey deposits and those of the Arkona area are approximately the same age at 13,000 years B.P. So far no polygonal ground areas have been found in south-western Ontario on materials which are younger than this age, and all of the occurrences lie outside moraines of Port Huron stadial age.

Relict Polygonal Ground and Paleoclimates

Because of the three-dimensional relationship of wedge structures and polygons, the extensive areas of polygonal ground patterns in south-western Ontario are believed to represent the surface expression of former ice-wedges or sand-wedges. Alternative hypotheses including bedrock joint patterns, soil tongues, and associated soil phenomena, dessication polygons, jointing in till, and seasonal frost cracks were discussed by Morgan (1972). The recognition of many

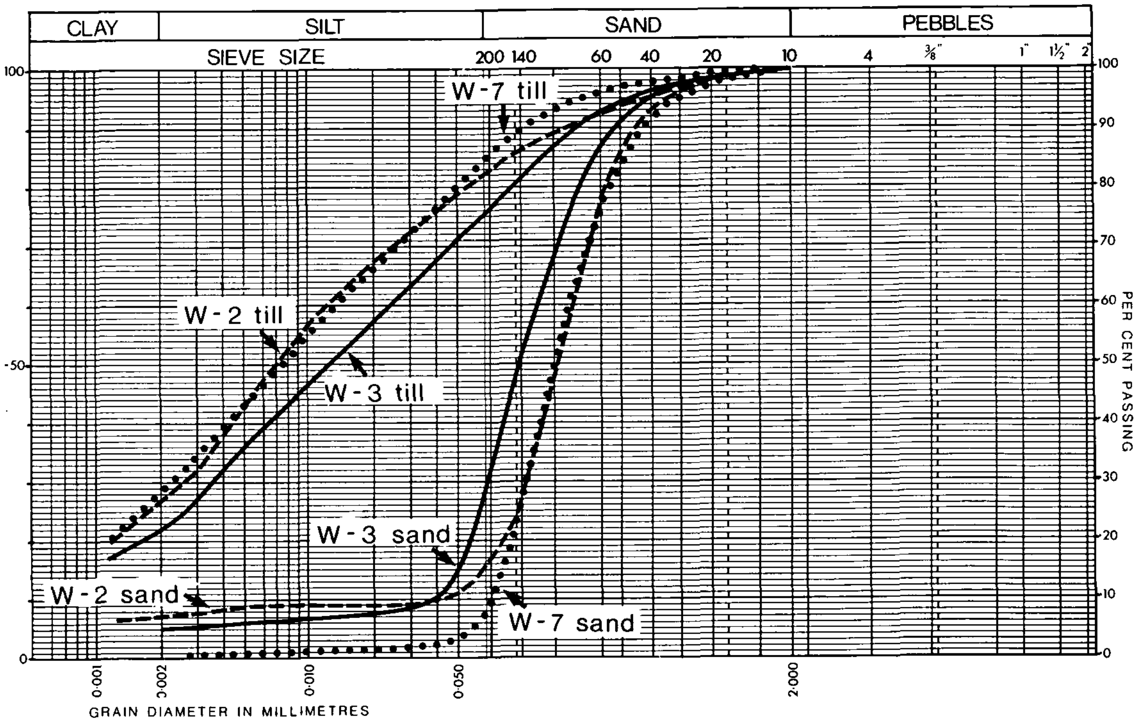

FIGURE 8. Granulometric analyses of samples taken from the wedges and the adjacent till at the Muir polygons. The till is predominantly silty, whereas the wedges are infilled with fine-medium grained sand. W-7 refers to Wedge #7 (*see* Figure 7).

more areas of polygons developed upon tills of the same age re-confirm the ideas expressed in this earlier paper. More recent work has not yet resolved the problem of whether the distribution of wedges are lithologically controlled as well as being time-dependent, (i.e. formed in chronologically restricted intervals, such as the Port Bruce or early Port Huron stadials) and both factors may play an important part in their distribution. Generally the polygon networks are best seen on tills which have high percentages of silt, but there are exceptions, and other tills which also have relatively high silt contents, such as the Mornington and Elma tills, do not show polygonal patterns. Both the Tavistock and the Port Stanley tills exhibit the strongest patterning and, significantly, both are contemporaneous although deposited by different ice lobes. The development of the polygonal patterns must post-date the deposition of these tills, and, as such, must be younger than *ca.* 15,000 yrs. B.P. Similarly, since the youngest deposits exhibiting polygons are approximately 13,000 years old, the phase of polygon development encompasses approximately 2000 years. This time span is certainly long enough for ice-wedge polygons to develop, (Leffingwell 1915; Mackay 1974) although some of the patterned ground areas would not have had the full 2000 years for the wedge systems to form. The incomplete polygonal networks seen in some areas may have been arrested before they had time to develop into fully integrated polygon systems. Similarly the 'anastomosing' network patterns seen in many regions may represent surficial stream flow systems

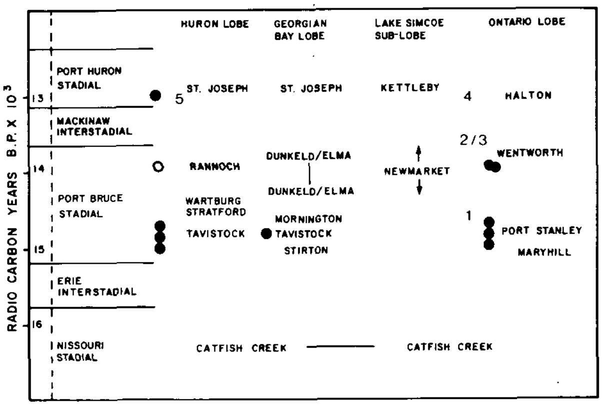

FIGURE 9. Relationship of polygon networks, till sequences, and radiocarbon age estimates for south-western Ontario (*modified after* Cowan *et al.* 1978). Black circles represent till exhibiting 'definite' patterned ground. The open circle represents possible areas of polygonal ground. Numbers refer to moraines: 1, Tillsonburg, 2/3, Paris/Galt; 4, Waterdown; 5, Wyoming. As seen in Figure 10, the Port Huron, Wyoming, Palgrave, and Waterdown moraines are believed to be approximately contemporaneous.

partially developed upon thawing wedge forms as the short-lived permafrost regime ended. Nevertheless, the question which needs to be answered is whether there is any other evidence for a climatic regime rigorous enough to support a periglacial climate during ice-retreat from south-western Ontario? Unfortunately only a few organic sequences which might be used to elucidate past climate are known within the area under discussion.

The oldest organic-bearing unit post-dating the retreat of Laurentide ice is the Wildwood Silts (Karrow 1977; Sigleo and Karrow 1977) exposed near Wildwood Lake north-east of London. This bed is believed to have been deposited in the Erie interstadial, and predates the deposition of the Tavistock Till. Examination of the pollen and spores recovered from these sediments shows the local vegetation consisted of grasses, mosses, and herbs. Relatively high percentages of *Pinus* and *Picea* pollen probably reflect long-distance transport from areas further south or west although Sigleo and Karrow (1977) suggest a forest-tundra or near tundra environment during the deposition of the Wildwood Silts. Sometime shortly after the silt deposition, both the Huron and Ontario–Erie Lobes re-advanced, and later, retreated. It was at this time that the first abundant polygon networks formed upon tills deposited during the Port Bruce stadial, *ca.* 15,000–14,000? yrs. B.P. (*see* Figure 9).

An organic sequence exposed in clayey-silts in the Weaver Drain site near the town of North Branch, Michigan (Figure 10) produced a small but interesting flora and fauna which has helped to clarify the paleoenvironment about 13,800 years ago (Morgan *et al.* 1981). Both the pollen and plant macrofossils indicate open ground conditions, and this is substantiated by the insects also recovered from the site. A number of ground beetles indicate open ground (tundra-like) conditions with some of the species reflecting dry, sandy substrates. Although the plant and insect assemblages point to open conditions, the presence of boreal species including one bark beetle probably means that trees were not far from the site. July temperatures were probably at or above 10°C with the mean annual temperature below 0°C, possibly in the −1 to −4°C range. The Weaver Drain site encompasses part of the time when polygonal ground was believed to be active less than 150 km to the east. In south-western Ontario mean annual temperatures may have been as high as −3 or −4°C, a conservatively warm estimate for the formation of ice-wedge or sand-wedge polygons (A.L. Washburn, *pers. comm.* 1978).

Using insects as paleoclimatic indicators it is inter-

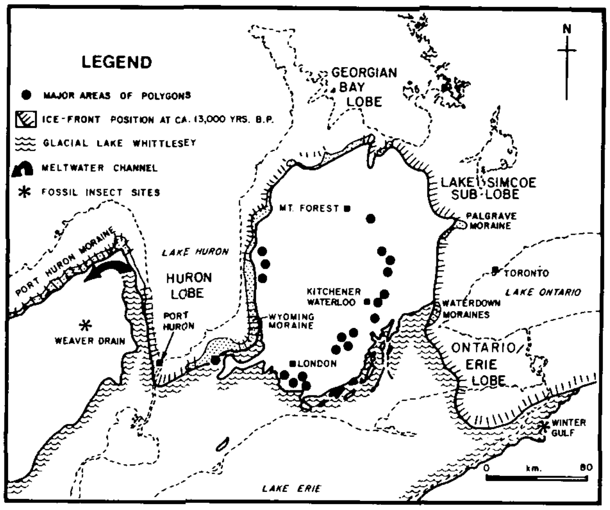

FIGURE 10. Paleogeographic reconstruction of the area at the time of the Port Huron advance (*ca.* 13,000 yrs. B.P.). The northern margin of glacial Lake Whittlesey, the position of polygons to the respective ice lobes and associated end moraines, and the locality of fossil sites mentioned in the text are shown.

esting to compare the next youngest fauna, recovered from the Winter Gulf site, near North Collins, New York. The floral assemblage from this site was studied by McAndrews (Calkin and McAndrews 1980) whilst the insects have been described by Schwert and Morgan (1980). The climatic interpretation made from the flora (−3 to 0°C mean annual) differs from the temperature estimate provided by the beetle fauna (2 to 4°C mean annual.) Such discrepancies have been recorded on a number of occasions in Europe (Coope and Brophy 1972; Morgan 1973), and seem to reflect differences in the rapidity of response by the plant and animal communities. The insects responded more rapidly than the plants to ameliorating climatic trends. The fauna of the Winter Gulf site, deposited when the Ontario Lobe stood less than 50 km to the north and dated at approximately 12,700 yrs. B.P., is a boreal fauna and one which does not seem to be compatible with an active permafrost regime.

Summary and Discussion

Numerous and extensive areas of polygonal ground have been observed on air photographs in south-western Ontario. A few areas have been trenched using a backhoe and the polygon boundaries are underlain by wedge-shaped tapering structures several metres in depth. These are presumed to be epigenetic ice-wedge casts, infilled with sand following the degradation of the ice filling and formed in a permafrost environment shortly after ice retreat. It is possible that some of the wedges may be sand-infilled, sand-wedge structures for the insects in the Weaver Drain site do indicate dry substrates around a small pond. The wedges are, however, quite dissimilar in both structure and form from the numerous and well-formed soil tongues seen frequently in gravel pit faces and excavations throughout much of the region (Grubb and Bunting 1976). The largest areas of polygons are found upon the silt-rich Tavistock and Port Stanley tills and could not have formed until after 15,000 yrs. B.P. Since the polygons are probably time-transgressive and could only have been formed following the retreat of the ice depositing the respective till unit, the age of the till sheet provides the maximum age of the polygon network. This would also apply to glacial lakes and associated lacustrine deposits unless the lacustrine sediments are thin enough for moisture differences to show through from an underlying deposit.

The insect fauna from Weaver Drain near North Branch, Michigan (approximately 70 km west-northwest of Sarnia) indicates that open ground (tundra-like) and tree-line species were living immediately west of the area under discussion about 13,800 yrs. B.P. A second insect fauna from Winter Gulf, south of Buffalo, N.Y., is not compatible with a tundra environment, or a permafrost regime. The youngest periglacial structures formed at the outer limits of the Wyoming moraine, and on the margins of the glacial Lake Whittlesey, about 13,000 yrs. B.P. Since the Winter Gulf site is dated at 12,700 yrs. B.P., the severe climate necessary for the formation of polygonal ground must have disappeared shortly after 13,000 yrs. B.P. It is possible that south-western Ontario may not have been consistantly cold throughout the period from 15,000 to 13,000 yrs. B.P. Periglacial structures may have formed on a number of occasions, associated with major ice lobe re-expansion, i.e. either 15,000 yrs. B.P. (Port Bruce stadial) and shortly before and up to *ca.* 13,000 yrs. B.P. (early Port Huron stadial). Although there is no evidence for permafrost conditions in south-western Ontario after 13,000 yrs. B.P., the presence of tundra insect faunas near the margins of the Champlain Sea in Québec (Mott *et al.* 1981) approximately 11,000 yrs. B.P. indicates that scattered occurrences of tundra (and possibly permafrost?) may have followed the retreating ice northward. This hypothesis would be quite compatible with the suggestion made by Dionne (1975) that discontinuous permafrost occurred in lowland areas near the margin of the retreating Laurentide Ice Sheet in southern Québec between 13,000 and 11,000 yrs. B.P. The permafrost 'zone' would probably have been narrow and restricted to climatically favourable areas, possibly where katabatic winds may have drained off the receding Laurentide ice. Such areas may not have been stable long enough for well-developed ice-wedge polygon networks to form, but almost certainly incipient or poorly developed frost cracks or small, single wedges would have been created under such a regime. Further research will undoubtedly uncover similar, localized areas of former permafrost, which, in a diachronous manner followed the retreating Laurentide ice sheet northward.

Acknowledgements

Work on the distribution of polygonal ground and the analysis of fossil insect sites in the area under discussion has been supported by an NSERC Team grant (A 8294) to A.V. and A. Morgan.

References

BERG, T.E. 1969. Fossil sand wedges at Edmonton, Alberta, Canada. Biul. Peryglacjalny, vol. 19, pp. 325-333.

BLACK, R.F. 1976. Periglacial features indicative of permafrost: Ice and soil wedges. Quaternary Res., vol. 6, pp. 3-26.

BORNS, H.W. 1965. Late glacial ice-wedge casts in northern Nova Scotia, Canada. Science, vol. 148, pp. 1223-1226.

BROOKES, I.A. 1971. Fossil ice-wedge casts in western Newfoundland. Marit. Sediments, vol. 7, pp. 118-122.

BROWN, R.J.E. AND PÉWÉ, T.L. 1973. Distribution of permafrost in North America and its relationship to the environment: A review, 1963-1973. *In*: Permafrost: North Amer. Contrib. to 2nd Int. Conf. Natl. Acad. Sci., Washington, D.C., pp. 71-100.

CALKIN, P.E. AND MCANDREWS, J.H. 1980. Geology and paleontology of two late Wisconsin sites in western New York state. Geol. Soc. Amer. Bull., vol. 91, (1), pp. 295-306.

CHAMPMAN, L.J. AND PUTMAN, D.F. 1966. The physiography of southern Ontario. Toronto Univ. Press (2nd. ed.) 386 p.

CHRISTENSEN, L. 1974. Crop marks revealing large-scale patterned ground structures in cultivated areas, southwestern Jutland, Denmark. Boreas, vol. 3, pp. 153-180.

COOPE, G.R. AND BROPHY, J.A. 1972. Late glacial environmental changes indicated by a coleopterous succession from North Wales. Boreas, vol. 1, pp. 97-142.

COWAN, W.R. 1975. Quaternary Geology of the Woodstock area, southern Ontario. Ont. Div. Mines, GR119, 91 p.

COWAN, W.R., KARROW, P.F., COOPER, A.J., AND MORGAN, A.V. 1975. Late Quaternary stratigraphy of the Waterloo-Lake Huron area, southwestern Ontario. Geol. Assoc. Can., Field Excursions Guidebook (Waterloo '75), Field trip 7, pp. 180-222.

COWAN, W.R., SHARPE, D.R., FEENSTRA, B.H., AND GWYN, Q.H.J. 1978. Glacial geology of the Toronto-Owen Sound area. Geol. Assoc. Can., Field Trips Guidebook (Toronto '78), pp. 1-16.

DIMBLEBY, G.W. 1952. Pleistocene ice-wedges in north-east Yorkshire. J. Soil Sci., vol. 3, pp. 1-19.

DIONNE, J.C. 1966. Fentes en coin fossiles dans le Québec méridional. C.R. Acad. Sci. (Paris), vol. 262, pp. 24-27.

———. 1967. Fentes de gel fossiles dans le comté de l'Islet. Cah. Géogr. Qué., vol. 22, pp. 96-100.

———. 1969. Nouvelles observations de fentes de gel fossiles sur la côte Sud du Saint-Laurent. Rev. Géogr. Montréal, vol. 23, (3), pp. 307-316.

———. 1970. Fentes en coin fossiles dans la région de Qué. Rev. Géogr. Montréal, vol. 24, (3), pp. 313-318.

———. 1971. Fentes de cryoturbation tardiglaciaires dans la région de Québec. Rev. Géogr. Montréal, vol. 25, (3), pp. 245-264.

———. 1975. Paleoclimatic significance of late Pleistocene ice-wedge casts in southern Quebec, Canada. Palaeogeogr., Palaeoclimatol., Palaeoecol., vol. 17, pp. 65-76.

DREIMANIS, A. 1961. Tills of southern Ontario, *In*: Soils in Canada: Royal Soc. Can. Special Publ. 3, pp. 80-96.

———. 1964. Pleistocene geology of the St. Thomas area (west half). Ont. Dept. Mines, Prelim. Geol. Map 238.

———. 1969. Late-Pleistocene lakes in the Ontario and Erie Basins. 12th Conf. Great Lakes Research Proc., pp. 170-180.

GANGLOFF, P. 1970. Structures de gélisols reliques dans la région de Montréal. Rev. Géogr. Montréal, vol. 24, (3), pp. 241-253.

GANGLOFF, P., CLERMONT, J.P. AND PAQUETTE, G. 1971. Le problème du tardiglaciaire au Québec méridional. Rev. Géogr. Montréal, vol. 25, (3), pp. 305-308.

GREENHOUSE, J.P. AND MORGAN, A.V. 1977. Resistivity mapping of fossil permafrost patterns in southwestern Ontario. Can. J. Earth Sci., vol. 14, (3), pp. 496-500.

GRUBB, A.M. AND BUNTING, B.T. 1976. Micromorphological studies of soil tonguing phenomena in the Burford Loam, southern Ontario, Canada. Biul. Peryglacjalny, vol. 26, pp. 237-252.

HARRIS, S.A. 1967. Origin of part of the Guelph drumlin field and the Galt and Paris moraines, Ontario: A reinterpretation. Can. Geogr., vol. 11, pp. 16-36.

———. 1970. The Waterloo Kame-moraine, Ontario, and its relationship to the Wisconsin advances of the Erie and Simcoe ice lobes. Z. Geomorphol., vol. 14, (4), pp. 487-509.

KARROW, P.F. 1971. Quaternary geology of the Stratford-Conestogo area, Ontario. Geol. Surv. Can. Paper 70-34, 11 p.

———. 1974. Till stratigraphy in parts of southwestern Ontario. Geol. Soc. Amer. Bull., vol. 85, pp. 761-768.

———. 1977. Quaternary geology of the St. Mary's area, southern Ontario. Ont. Div. Mines, G.R., vol. 148. 59 p.

LEFFINGWELL, E.K. 1915. Ground ice wedges. J. Geol., vol. 23, pp. 635-654.

MACKAY, J.R. 1974. The rapidity of tundra polygon growth and destruction, Tuktoyaktuk Peninsula. Richards Island area, N.W.T. Geol. Surv. Can., Paper 74-1, (A), pp. 391-392.

MORGAN, A. 1973. Late Pleistocene environmental changes indicated by fossil insect faunas of the English Midlands. Boreas, vol. 2, (4), pp. 173-212.

MORGAN, A.V. 1969. Intraformational periglacial structures in the Nose Hill gravels and sands, Calgary, Alberta, Canada. J. Geol., vol. 77, pp. 358-364.

———. 1971*a*. Fossil permafrost features and their effect on a gas pipe-line trench in the West Midlands. Quart. J. Eng. Geol., vol. 4, (2), pp. 111-114.

———. 1971*b*. Polygonal patterned ground of Late Weichselian age in the area north and west of Wolverhampton, England. Geogr. Ann., vol. 54A, (3-4), pp. 146-156.

———. 1972. Lake Wisconsinan ice-wedge polygons near Kitchener, Ontario, Canada. Can. J. Earth Sci., vol. 9, (6), pp. 607-617.

MORGAN, A.V. AND MORGAN, A. 1977. The age and distribution of fossil ice-wedge polygon networks in southwestern Ontario, Canada. X INQUA Congr., Birmingham, England. p. 308.

MORGAN, A.V., ELIAS, S.A., AND MORGAN, A. 1981. Paleoenvironmental implications of a late-glacial insect assemblage from south-east Michigan. Abstr., Geol. Assoc. Can. Annual Meeting (Calgary), 6, p. A-41.

MOTT, R.J., ANDERSON, T.W., AND MATTHEWS, J.V., JR. 1981. Late-Glacial paleoenvironments of sites bordering the Champlain Sea based on pollen and macrofossil evidence. *In*: Quaternary Paleoclimate, Geoabstr., Norwich, England, pp. 129-171.

PÉWÉ, T.L. 1973. Ice wedge casts and past permafrost distribution in North America. Geoforum, vol. 155, pp. 15-26.

SCHWERT, D.P. AND MORGAN, A.V. 1980. Paleoenvironmental implications of a Late glacial insect assemblage from northwestern New York. Quaternary Res., vol. 13, pp. 93-110.

SIGLEO, W.R. AND KARROW, P.F. 1977. Pollen-bearing Erie Interstadial sediments from near St. Mary's, Ontario. Can. J. Earth Sci., vol. 14, (8), pp. 1888-1896.

SVENSSON, H. 1972. The use of stress situations in vegetation for detecting ground conditions on aerial photographs. Photogramm., vol. 28, pp. 75-87.

———. 1973. Distribution and chronology of relict polygon patterns on the Laholm Plain, the Swedish west coast. Geogr. Ann., vol. 54A, (3-4), pp. 159-175.

WASHBURN, A.L. 1973. Periglacial processes and environments. St. Martins Press. New York.

WESTGATE, J.A. AND BAYROCK, L.A. 1964. Periglacial structures in the Saskatchewan gravels and sands of Central Alberta. J. Geol., vol. 72, pp. 641-648.