Late Pleistocene Palaeoenvironments of the Southern Lake Agassiz Basin, USA

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ISSN 0267-8179.
Received 8 September 2004; Revised 9 December 2004; Accepted 13 December 2004

ABSTRACT: Macroscopic plant remains, pollen, insect and mollusc fossils recovered from a cut bank on the Red River in North Dakota, USA, provide evidence that an extensive wetland occupied the southern basin of Lake Agassiz from 10 230 to 9900 14C yr BP. Marsh-dwelling plants and invertebrates had colonised the surface of a prograding delta during the low-water Moorhead Phase of Lake Agassiz. A species of *Salix* (willow) was abundant along distributary channels, and stands of *Populus tremuloides* (aspen), *Ulmus* sp. (elm), *Betula* sp. (birch), and *Picea* sp. (spruce) grew on the better-drained sand bars and beach ridges. Most of the species of plants, insects, and molluscs represented as fossils are within their existing geographic ranges. Based on a few species with more northerly distributions, mean summer temperature may have been about 1–2 °C lower than the present day. No change in species composition occurred in the transition from the Younger Dryas to Preboreal. At the time that the wetland existed, Lake Agassiz was draining either eastward to the North Atlantic Ocean or northwestward to the Arctic Ocean. The wetland was drowned during the Emerson Phase transgression that resulted in meltwater draining southward to the Gulf of Mexico after 9900 14C yr BP. Copyright © 2005 John Wiley & Sons, Ltd.

KEYWORDS: Lake Agassiz; North Dakota; pollen; plant macrofossils; fossil beetles and molluscs; Younger Dryas–Holocene.

Introduction

Lake Agassiz came into existence about 11 700 14C yr BP as meltwater accumulated south of the retreating margin of the Red River Lobe (Upham, 1895; Elson, 1967; Clayton and Moran, 1982; Teller et al., 1983; Teller, 2004). Although the lake was relatively short-lived, its drainage history was complex, controlled by advances and retreats of the southern margin of the Laurentide ice sheet, elevations of spillways, and isostatic rebound. At different times, the lake drained southward to the Gulf of Mexico, eastward to the North Atlantic Ocean, northwestern to the Arctic Ocean, and, in its final phase, northward to Hudson Bay (Teller and Thorleifson, 1983; Fisher and Souch, 1998; Leverington et al., 2000; Teller, 2001, 2004; Fisher, 2003). The eastward drainage of Lake Agassiz between 10 800 and 10 000 14C yr BP, via the Great Lakes and St. Lawrence seaway, has been cited as the trigger that shut down the thermohaline circulation of the North Atlantic Ocean and initiated the Younger Dryas Stade (Broecker et al., 1989; Teller, 1990, 2004; Clark et al., 2001). The plant and invertebrate fossils we report are from the last part of the low-water, Moorhead Phase of Lake Agassiz, deposited during a time when Lake Agassiz was draining through its northern outlets.

The sedimentary- and bio-facies enable us to reconstruct the palaeoenvironment of the southern Lake Agassiz basin during the Pleistocene to Holocene transition. Additionally, we discuss the vegetation and invertebrate biota in its regional context, and especially in relationship to a cold ‘lake effect’ that reportedly modified the regional vegetation (i.e., Whitlock et al., 1993). We also discuss the deposits in terms of reconstructions of the drainage history of Lake Agassiz, lending a new insight into a controversial topic (e.g., Teller, 2001, 2002, 2004; Karrow, 2002; Fisher, 2003).

Location, stratigraphy and age of deposits

The Trollwood Park site (46° 51' N, 96° 48' W) is located on the west bank of the Red River of the North within the northern city limits of Fargo, Cass County, North Dakota (Fig. 1). Since the site was excavated, the bank has been protected from further erosion by a boulder rip-rap, making the fossiliferous deposits less accessible than they were previously. The section measures 7 m from the top of the cut bank to the river water level (Fig. 2). Three formations are exposed (from bottom to top): the Brenna Formation (Unit A), Poplar River Formation...
(Unit B), and Sherack Formation (Unit C), as defined by Harris et al. (1974) and Arndt (1977). The sediments of Units A and C were deposited in deep water and those of Unit B in shallow water.

Each of the 16 rhythmites of Unit B consists of a fining-upwards sequence of fine sand, silty clay, and organic debris. Mollusc shells, including bivalves with both valves intact, occur in both the sand and silty clay beds. The rhythmite unit is capped by a 1.2 m thick, cross-laminated, fine sand containing abundant mollusc shells, but no organics. Three AMS 14C ages were obtained for the bottom, middle and top of the rhythmite unit (Table 1). In this paper, ages are stated in uncalibrated 14C years.

Sampling, fossil preparation and analysis

Sixteen silty-clay organic layers within the rhythmite facies (Unit B) were sampled for pollen, plant macrofossils, insects and molluscs. Sample sizes (wet weight) were 1 g for pollen, 250 g for plant macrofossils, and 5 kg for insects and molluscs.

Pollen

Preparation, counting, and identification of the pollen samples followed standard procedures outlined in McAndrews et al. (1973), Faegri and Iversen (1975), and Bates et al. (1978). Identifications of pre-Quaternary palynomorphs were based on descriptions and illustrations in Kapp (1969). A sum of more than 300 upland pollen types (including Cyperaceae) was counted per sample. These sums were used to calculate pollen percentages in a TiliaTM spreadsheet and plotted using a combination of Tilia.graphTM, TGViewTM, and Adobe IllustratorTM (Fig. 3). Taxonomic nomenclature, distribution, and autecology of plant species are based on Stevens (1963), the Great Plains Flora Association (1986), and Looman and Best (1987).

Plant macrofossils

Plant macrofossils are the best preserved and most diverse of all the fossil groups at the Trollwood Park site. They occur throughout the rhythmite facies but are especially well preserved and abundant in the beds between 4.8 and 6 m depth. Sediment samples were sieved using nested screens with 425- and 212-μm-mesh openings. Plant macrofossils were sorted and identified following standard procedures (Martin and Barkley, 1961; Montgomery, 1977; Birks, 1980, 2001). Total counts of seeds, fruits, buds and leaves are presented as numbers per 250 g of sediment and were plotted using the software listed above. Plant macrofossils were also inspected for wear to provide information about subaerial exposure, transport and redeposition within the local depositional environment (Glaser, 1981).
Identifications were made by comparison of the fossils with voucher specimens in reference collections. Detailed morphological descriptions for many of the fossil taxa are provided in Yansa and Basinger (1999). Identification of *Potamogeton* species was based on their distinctive seed morphologies exposed by longitudinal sectioning of the drupes. The fossils were reposited in the Pollen and Soils Laboratory, Michigan State University.

### Invertebrates

Each sample was wet sieved using a 300-μm mesh and the mollusc shells and larger fragments of chitin were collected from the plant matrix. The residue was then subjected to a standard kerosene flotation technique to concentrate insect remains (Ashworth, 1979). The fossils, after ultrasonic cleaning, were mounted on micropalaeontological slides and reposited in the collections of the Quaternary Entomology Laboratory, North Dakota State University.

Neither molluscs nor insects were as abundant as plant macrofossils. There did not appear to be any particular significance to the stratigraphic distribution of the taxa and in this report they are considered to belong to a single assemblage zone. This includes molluscs occurring in the sand immediately above the rhythmites. The number of individuals was too small for quantitative analyses.
Figure 3  Pollen percentage diagram for the fossiliferous rhythmite facies of the Trollwood Park site (most common taxa shown). See Fig. 2 for the legend of the lithology.
Interpretations

Pollen

The number of indeterminable palynomorphs exceeds that of identified pollen and spores (Fig. 3), and in this respect is similar to other deposits associated with the Moorhead Phase (McAndrews, 1967a; Bajc et al., 2000). Also, Cretaceous-age palynomorphs, including Appendicosporites tricornatus Weyland & Greifeld, Reticuloooides dentatus Pflug, Coll., Hamulatisporis hamulatus Krutzsch., Aquilapollonites pulvinus Stanley, Hystrichosphaeridium tuberulum (Ehrbg.) Coll, and Hystrichosphaeridium recurvatum (White) Coll., are relatively abundant. Some of them have previously been reported from Lake Agassiz basin sediments in Manitoba (Nam-budini et al., 1980).

The large number of degraded palynomorphs is consistent with the interpretation of a sedimentary facies in which deposits were continually being eroded and reworked by streams. Of the identifiable pollen, Salix sp. (willow; 8% to 59%), dominates the AP with the greatest values in the middle of the zone. High pollen values for Salix sp., species of Cyperaceae (sedges; 7–24%), Pediasstrum sp. Meyen (green alga; 0–8%) and small amounts Potamogeton sp. (pondweed; not shown in Fig. 3) and Typha latifolia L. (broad-leaved cattail) support the interpretation of a wetland. The pollen values for coniferous and deciduous trees suggests that the uplands surrounding the Lake Agassiz basin were forested and that trees were able to disperse into the wetland and colonise river banks. Pollen of grassland vegetation, namely species of Poaceae, Artemisia, Ambrosia, Chenopodiaceae, and Asteraceae, is less well represented, suggesting that extensive grasslands were not present in the area.

Picea sp. (spruce) pollen varies from 13% to 45% (Fig. 3). Some of the spruce pollen grains are degraded, suggesting reworking, but others are in better condition and probably are of local origin. Pinus sp. (pine; 0–10%) pollen, on the other hand, is probably all from long-distance transport. Even though represented by small percentages, the pollen of Quercus sp. (oak; 0–7%), Ulmus sp. (elm; 0–5%), Betula sp. (birch; 0–3%), Acer sp. (maple; 0–6%; some tentatively identified as A. negundo L. (box elder)), and Fraxinus sp. (ash; 0–10%, some identified as F. nigra Marsh. (black ash)), suggests that deciduous trees were growing on better-drained soils within the wetland. Populus sp. (poplar; 2–16%) pollen, a type that does not preserve well (MacDonald, 1990), suggests that trees of this taxon were present. Two taxa are tentatively identified, Populus tremuloides Michx.-type (aspen poplar) and Populus balsamifera L.-type (balsam poplar). Small amounts of pollen (≤ 2%) of Shepherdia canadensis (L.) Nutt. (rabbitbrush), and species of Alnus (alder), Careya (hickory), Ostrya/Carpinus (hop hornbeam/hornbeam), Corylus (hazel), Juglans (walnut), Epheeda (Mormon tea) and Rosaceae (rose family) are included together in the total arboreal pollen sum (AP). Some of these were probably of local origin, but others, such as Epheeda sp., were undoubtedly from long-distance transport (Maher, 1964).

The site is located within what was once an extensive marsh. In addition to the aquatic and semiquatic taxa, the sand bars and channel levees may have been colonised by a vegetation that included spruce, aspen, balsam poplar, oak, elm, black ash, box elder, and some prairie herbs. Except for spruce, species of all of these taxa occur today in riparian habitats along the Red River. At present, the southernmost occurrence of native spruce is in the boreal forest, 400 km to the north.

Plant macrofossils

Well-preserved fossils considered to be contemporaneous with the deposition of the sediments are those of woodland, mudflat, emergent and aquatic vegetation, the most common of which are shown in Fig. 4. Illustrations of some of these taxa are shown in Fig. 5. Low numbers of Picea sp. (spruce) needles were recovered, and many were broken and worn, appearing to have been reworked. Some of these needles were also charred. Woodland or parkland is represented by macrofossils of deciduous trees and shade-intolerant shrubs. Populus tremuloides (aspen poplar) and Populus balsamifera (balsam poplar) were identified from terminal bud scales (a scale of the former is shown in Fig. 5G). They are plotted together as Populus sp. in Fig. 4. Catkins of Betula sp. (birch; Fig. 5D) and fruits of Rubus idaeus L. (red raspberry), Prunus cf. P. penvsylvania L. (pin cherry), and Viburnum edule (Mich.) Raf. (squashberry; Fig. 5H) were also identified. One seed of Salix sp. (willow) was also recovered, which is significant, since seeds of this taxon are rarely preserved (Birks, 1980).

Fossils of plants of slightly alkaline mudflats and wet meadows are represented by several species. They include Lycopus americanus Michl. ex Bart (water hoarhound), three species of Ranunculus (R. cf. R. gmelini DC. (small yellow buttercup), R. cf. R. pennsylvanicus L. (bistly buttercup) and R. cf. R. sceleratus L. (ditch buttercup)), Potentilla norvegica L. (rough cinquefoil), Caltha palustris L. (marsh marigold), Polygonum lapathifolium L. (pale smartweed; Fig. 5A), Cirsimium cf. C. floridani (Rydby.) Arthur (Flodman’s thistle), Grindelia squarrosa (Pursh) Dun. (curly-top gumweed), Rumex maritimus L. (golden dock; Fig. 5F), Mentha arvensis L. (field mint), Stachys sp. (hedge-nettle), Aster sp. (aster), a species of Apiaceae (parsley family), and Chenopodium sp. (goosefoot), some of which were identified as C. rubrum L. (red goosefoot). The low number of Chenopodium rubrum seeds and the absence of other brackish-water indicators, such as Zannichellia palustris L. (Yansa, 1998), suggest a relatively fresh-water wetland.

In addition, fossils of emergent plants which grow in shallow water of less than 1 m depth, are also very abundant. They include Scirpus validus Vahl (common bulrush), S. microcarpus Presl (small-fruited bulrush; Fig. 5B), Eleocharis sp. (spike-rush), Typha latifolia L. (broad-leaved cattail), Sagittaria latifolia Willd. (broad-leaved arrowhead; Fig. 5C), Cicuta cf. C. maculata L. (water-hemlock), Sparganium sp. (bur-reed), and three species of Carex (sedge; Fig. 5E).

The aquatic flora are also very diverse, and include Wolffia (watermeal), Myriophyllum verticillatum L. (whorled watermilfoil), Hippuris vulgaris L. (mare’s tail), and Lemna minor L. (ivy-leaved duckweed). Also eight species of Potamogeton (pondweed) were identified: P. filiformis Pers. (inland pondweed); P. gramineus L. (variable pondweed); P. natans L. (floating-leaf pondweed; Fig. 5I); P. obtusifolius Mert. & Koch (bluntleaf pondweed); P. pectinatus L. (sago pondweed); P. pusillus L. (small pondweed); P. richardsonii (Benn) Rydb. (Richardson’s pondweed); and P. vaginatus Turcz. (sheathed pondweed). Oocysta of Chara sp. (green algae) and leaves and stems of Drepanocladus sp. (sickle-branch moss) were also recovered. These aquatic plants indicate eutrophic, fresh to slightly alkaline water, of depths of up to 1–2 m. All species represented by macrofossils at present occur within the region, except for Picea sp. and Pota-mogeton obtusifolius (blunt-leafed pondweed), which today occur in the boreal forest to the north.

Invertebrates

The fossils are mostly those of aquatic species of molluscs, insects, crustaceans and a bryozoan. Shells of lymnaeid gastro-
Figure 4: Plant macrofossil abundance diagram for the fossiliferous rhythm facies of the Trollwood Park site (most common taxa shown). See Fig. 2 for the legend of the lithology.
pods, represented by Amnicola limosa (Say), Fossaria sp., Gyraulus deflectus (Say), Gyraulus parvus (Say), Planorbula armigera (Say) and Valvata tricarinata (Say), and the sphaeriid bivalve, Pisidium compressum Prime, occur throughout the rhythmite facies (Fig. 2). The habitat of P. armigera, which lives among vegetation in most kinds of perennial-water habitats, especially stagnant eutrophic habitats in which the substrate is mud, is typical for the assemblage (Clarke, 1981). The bivalve P. compressum is found in vegetation in shallow perennial water bodies with a wide range of substrates (Clarke, 1981).

Other fossils of invertebrates include hysterosomata of oribatid mites, ephippia of the cladoceran Daphnia sp. and statoblasts of the freshwater bryozoan, Cristatella mucedo Say, whose colonies attach themselves to the submerged stems of emergent vegetation. Collectively, the invertebrate fauna is one which would be associated with a nutrient-rich, eutrophic wetland. No fossils of vertebrates were found.

Discussion

Comparison to other Moorhead Phase sites in the Fargo–Moorhead area

Two other investigations of plant fossils have been reported from deposits of the Poplar River Formation in Fargo–Moorhead (Fig. 1, inset): the Moorhead site (Station 2) (Rosendahl, 1948); and the Seminary site (McAndrews, 1967a). Wood samples dated from these sites are comparable to the youngest
Table 2  List of fossil Coleoptera (beetles) identified at the Trollwood Park site, compared to those reported for the nearby Seminary site (Kompelian and Schwert, 1986). The habitat and author describing the association of beetles with their habitats is also listed. Skeletal parts include: H = head(s); P = pronotum(a); LE = left elytron(a); RE = right elytron(a); F = fragment(s)

| Carabidae      | Agonum sp.                      | E     | Trollwood | River banks | Lindroth, 1963 |
| Carabidae      | Bembidion nigripes Kby.         | P     | Trollwood | Lake margins | Lindroth, 1963 |
| Carabidae      | Bembidion pseudocatatum Lith.   | E     | Seminary | River banks | Lindroth, 1963 |
| Carabidae      | Bembidion sordidum Kby.         | P     | Trollwood | River banks | Lindroth, 1963 |
| Carabidae      | Dyschirius sp.                  | E     | Trollwood |             |               |
| Gyrinidae      | Gyrinus sp.                     | H,E   | Trollwood | Aquatic     |               |
| Haliplidae     | Haliplus sp.                   | E     | Trollwood | Aquatic     |               |
| Dytsicidae     | Agalbus sp.                    | P     | Trollwood | Aquatic     |               |
| Dytsicidae     | Calymbetes sp.                 | IE    | Trollwood | Aquatic     |               |
| Dytsicidae     | Hydroporus sp.(2)               | IE    | Trollwood | Aquatic     |               |
| Hydrophilidae  | Helophorus sp.                 | IE    | Trollwood | Aquatic     |               |
| Hydrophilidae  | Paracymus sp.                  | E     | Trollwood | Aquatic     |               |
| Hydrophilidae  | Enochrus sp.                   | E     | Trollwood | Aquatic     |               |
| Hydrophilidae  | Cercyon sp.                    | E     | Trollwood | Aquatic     |               |
| Hydrophilidae  | Hydrolyinus sp.                | IE    | Trollwood | Aquatic     |               |
| Hydroaenidae   | Octthebuis sp.                 | P,E   | Trollwood | Aquatic     |               |
| Scydmaenidae   | Sp. indet.                     | E     | Trollwood |             |               |
| Staphylinidae  | Aleocharini spp. indet.        | H,P,L | Trollwood |             |               |
| Staphylinidae  | Stenus sp.                     | P,L   | Trollwood |             |               |
| Staphylinidae  | Bledius sp.                    | P     | Trollwood | Aquatic margin |               |
| Staphylinidae  | Pselaphini sp. indet.          | E     | Trollwood | Lake margin  | Helgesen and Post, 1967 |
| Scarabaeidae   | Aphodius cf. omvisus LeC.       | E     | Trollwood | Running water |               |
| Elmiidae       | Stenelmis sp.                  | E     | Trollwood | Aquatic margin |               |
| Heteroceridae  | Heterocerus sp.                | P,E   | Trollwood | Aquatic     |               |
| Helodidae      | Cyphon sp.                     | H,E   | Seminary | Emergent veg. |               |
| Coccinellidae  | Anisosticta bitriangularis Say | E     | Seminary | Emergent veg. |               |
| Chrysomelidae  | Donacini sp. indet.            | E     | Seminary |             |               |
| Curculionidae  | Bagous sp.                     | H,P   | Trollwood | Aquatic     |               |
| Curculionidae  | Orthotomicus caelatus Eichoff  | E     | Trollwood | On conifer(s) | Wood, 1982    |
| Curculionidae  | Hylastes sp.                   | E     | Seminary | On conifer(s) | Wood, 1982    |
| Curculionidae  | Sp. indet.(2)                  | H,P   | Trollwood |             |               |

14C age for the Trollwood Park site; the Moorhead site has an age of 9930 ± 280 14C yr BP (W-388) (Ruben and Alexander, 1958), and the Seminary site an age of 9900 ± 400 14C yr BP (W-993) (McAndrews, 1967a). The fossiliferous deposits at the Seminary and Moorhead sites are only 0.15 m and 0.6 m thick, respectively, and thus provide less complete stratigraphic and fossil records than the 2 m thick deposit we studied.

The Trollwood Park, Seminary and Moorhead sites share an almost identical assemblage of mudflat/wet prairie, emergent and aquatic herbaceous taxa, as identified from macrofossils. The relative abundance of and aquatic herbaceous taxa, as identified from macrofossils. The relative abundance of Picea sp. (spruce) varies between

Table 3  Mean temperatures and precipitation values from meteorological stations at Fargo, North Dakota, and the University of Manitoba’s Delta Marsh Field Station on the southern shore of Lake Manitoba. Data based on the climate normal years 1961–1990 for Fargo (Owenby and Ezell, 1992) and 1967–1990 for Delta Marsh (McGinn, 1992)

<table>
<thead>
<tr>
<th>Meteorological station</th>
<th>Temperature (°C)</th>
<th>Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Jan.</td>
<td>Mean July</td>
</tr>
<tr>
<td>Fargo, North Dakota</td>
<td>−14.5</td>
<td>21.7</td>
</tr>
<tr>
<td>46° 55’ N, 96° 48’ W</td>
<td>(Trollwood Park site)</td>
<td></td>
</tr>
<tr>
<td>Delta Marsh Field</td>
<td>−19.8</td>
<td>19.1</td>
</tr>
<tr>
<td>Station, Manitoba</td>
<td>50° 11’ N, 98° 23’ W</td>
<td></td>
</tr>
</tbody>
</table>
We agree with both Rosendahl (1948) and McAndrews (1967a) that some of the fossils were transported fluvially from the morainic uplands surrounding the basin. Others, however, especially those of aquatic and emergent plants, and the majority of the invertebrates, inhabited the depositional environment. The Seminary site pollen spectrum is dominated by *Picea* sp. and in this respect is different from that of the Trollwood Park site. The differences can be explained in terms of the pollen assemblages being reworked to different degrees by fluvial processes active on a delta top.

Palaeoecology and palaeoclimate of the Moorhead Delta

The productive wetland that we interpret was situated within the Moorhead Delta, which formed along the southern shore of Lake Agassiz in the vicinity of Fargo–Moorhead during the late Moorhead Phase (Figs 1 and 6). This delta has been previously identified in Fargo–Moorhead from borehole data and is believed to have been formed by deposition from the ancestral Sheyenne, Red, Buffalo, and Maple Rivers when the lake was at its Ojata shoreline (Fig. 6B; Harris et al., 1974; Arndt, 1977; Brophy and Blumle, 1983; Fenton et al., 1983).

The Trollwood Park site record indicates that by 10,230 14C yr BP, Lake Agassiz had transgressed southward to Fargo–Moorhead (Fig. 6A). This transgression followed a regression during the early Moorhead Phase when subaerial weathering and pedogenesis occurred in the southern basin (Moran et al., 1971; Arndt, 1977; Teller and Last, 1981; Fenton et al., 1983; Reid and Olson, 1996; Bajc et al., 2000; Teller et al., 2000).

We propose that the Delta Marsh, a protected wetland and wildlife refuge in south-central Manitoba, Canada, located...
about 390 km north of the Trollwood Park site, is the modern analogue for the Moorhead Delta. Delta Marsh is situated within the middle of a 110 km wide belt of aspen parkland, which forms a transitional vegetation zone between grassland to the south and boreal forest to the north. The Delta Marsh complex of channels and lagoons forms where the Assiniboine River and its tributaries enter Lake Manitoba (Teller and Last, 1981). Over 75% of the plant species identified at the Trollwood Park site exist today at Delta Marsh (flora described by Shay, 1999), and the botanical associations were probably similar (Fig. 6C). The sand bars and beach ridges of the Moorhead Delta were probably occupied by Acer negundo (box elder), Populus tremuloides (aspen), Ulmus sp. (probably U. americana L., American elm), Betula sp. (birch), Quercus sp. (probably Q. macrocarpa Michx., bur oak), Fraxinus nigra (black ash), and in some places Picea sp. (spruce). A zone of Salix sp. (willow) most likely existed along the shores of the lagoonal marshes within the delta. The shallow waters of these marshes were inhabited by abundant aquatic and emergent vegetation, molluscs and insects. Periodic flooding of the marshes in the Moorhead Delta would have killed the vegetation, resulting in a cyclic pattern of vegetation dieback and renewal, similar to that observed today at Delta Marsh (Shay, 1999). Periodic disturbance by flooding may account for the high species diversity (Collins et al., 1995).

The majority of the plant, mollusc and insect species at the Trollwood Park site occur within their existing distributional limits. The exceptions are the aquatic plant Potamogeton obtusifolius (blunt-leaved pondweed) and Picea sp. (spruce). Investigations at the nearby Seminary site (Fig. 1, inset) provide more conclusive evidence for spruce forest with the occurrence of Picea sp. and the oomaline staphylmid beetle, Olophrum rotundicolle C. R. Sahlb (McAndrews, 1967a; Kompelian and Schwert, 1986), a species which we have collected from saturated mosses beneath willows on the margins of a spruce-lined lake in northern Minnesota. The occurrence of spruce, either on the margins of the basin, or on islands within the wetland, also suggests a climate that was slightly cooler and wetter than today.

Based on the occurrence of a few taxa with more northerly distributions than they have today, we estimate that the average summer temperature was probably 1–2°C cooler at the Trollwood Park site during the late Moorhead Phase. Summer insolation was about 7% higher during the Pleistocene-Holocene transition than today, but any increase in temperature that might have been expected was offset by regional cooling resulting from the Laurentide Ice Sheet to the north (Kutzbach et al., 1993). Ice still filled the Lake Superior basin to the east, and formed the northern and northeastern boundaries of Lake Agassiz in central Manitoba and western Ontario, respectively (Dyke and Prest, 1986).

Comparison to contemporaneous regional vegetation

The pollen records of several lakes (Fig. 1) on adjacent morainic uplands provide a regional palaeoenvironmental context in which we can also interpret the palaeovegetation and palaeoclimate of the Trollwood Park site. At the time of deposition of the Moorhead Delta, the pollen spectra from several lakes (Moon, Rice, Kettle, Coldwater, and Spiritwood) and ponds (Wendel and Seibold) (Fig. 1), indicate that an extensive parkland of deciduous hardwoods and prairie had replaced the previous open white spruce forest (or parkland) (McAndrews et al., 1967; Barnosky et al., 1987; Laird et al., 1996, 1998; Grimm, 2001; Yansa, 2002). Similar changes in the pollen profile during this time are also reported from Pickeral and Medicine Lakes (Fig. 1) on the Prairie Coteau of South Dakota (Watts and Bright, 1968; Radle et al., 1989). Grimm (2001) interpreted the regional vegetation during this time to be a mosaic in which the better-drained morainic hilltops supported prairie and the poorly drained low areas supported groves of trees, first Picea glauca (white spruce) and later species of Betula (birch), Populus (poplar), Ulmus (elm) and Quercus (oak).

In contrast, the succession of postglacial plant communities on the upland east of the southern Agassiz basin was different. The pollen spectra of several lakes on the Itasca Moraine in northwestern Minnesota (Fig. 1) indicate that the spruce forest was replaced by a pine woodland (e.g. McAndrews, 1967b; Shay, 1967, 1971; Whittle et al., 1993; Hu et al., 1997). This fluvistic transition is dated at about 9,100 14C yr BP at Elk Lake (Whittle et al., 1993), and at 10,230 14C yr BP at nearby Deep Lake (Hu et al., 1997). Hu et al. (1997) considered the younger age for the transition at Elk Lake to be erroneous, because of a dating problem.

The timing of the extirpation of spruce, however, may vary between lowland and upland sites. At the Mosbeck site, a lagoon on the eastern margin of Lake Agassiz situated at a similar latitude to Elk Lake, Picea mariana (Mill.) B.S.P. (black spruce) wood and cones, and a fossil beetle assemblage indicate the existence of a spruce forest at 9,940 14C yr BP before the site was drowned by the final high-water Emerson Phase of Lake Agassiz (Ashworth et al., 1972). This age is similar to that of a buried spruce log at the nearby Snake Curve Section site, which was deposited at the transition from the Moorhead to Emerson Phases (Moran et al., 1971). By 9600 14C yr BP, prairie herbs and deciduous trees and shrubs had colonised the area of Big Stone Lake, situated within what was earlier the southern outlet channel (River Warren) of Lake Agassiz, 160 km south of Fargo (Yansa, 2002).

Farther north, in the Rainy River area of northwestern Ontario (Fig. 1), Bajc et al. (2000) described fossil plants, insects and molluscs from deltaic and fluvial deposits ranging in age from 10,800 to 9500 14C yr BP. Their data indicate that the vegetation during the Moorhead Phase was similar to existing boreal forest. The differences in floristic composition between the Trollwood Park site and other Moorhead Phase sites to the northeast imply a latitudinal vegetational zonation, similar to that of today.

Considering that the Trollwood Park pollen assemblage has been modified by reworking, it shows remarkable similarities with the Moon Lake (Laird et al., 1996) and Pickeral Lake (Watts and Bright, 1968) pollen spectra, the closest records to the west and south, respectively (Fig. 1). In those records, a pioneering open spruce forest was being replaced by deciduous parkland at the time the Moorhead delta was being deposited.

Younger Dryas and lake effect

Bartlein and Whitlock (1993) used various statistical techniques to convert pollen data from Elk Lake, Minnesota (Fig. 1), to climatic parameters, namely mean January and July temperatures and annual precipitation. Their results showed a marked climatic reversal towards cooler and wetter conditions dated from 10 500 to 9200 14C yr BP. While it is tempting to correlate the climate change with the Younger Dryas Stade, as Bartlein and Whitlock (1993) did, it begins and ends too late by several hundred years. Our data suggest that there were no
changes in biota during the transition from the Younger Dryas to the Holocene.

Bartlein and Whitlock (1993) also discussed the possibility that Lake Agassiz modified the regional climate by exerting a lake effect, much as the Great Lakes do today; that is warmer winters, cooler summers, and greater precipitation on leeward shores. They proposed that when the lake returned to fill the basin during the Emerson Phase at 9900 14C yr BP, the winds coming across the cold lake waters produced downwind colder and wetter conditions that affected vegetation development in the Itasca Moraine area of western Minnesota. As appealing as this idea may be, the climatic effect is not correlated especially well with major changes in lake levels. In the Elk Lake record (Bartlein and Whitlock, 1993), the colder and wetter conditions of the climatic reversal began during the low-water Moorhead Phase, several hundred years earlier than the Emerson Phase during which the lake reoccupied the southern basin.

Hu et al. (1997) compared the δ18O and pollen records of nearby Deep Lake, Minnesota (Fig. 1), to evaluate lake effect. They inferred a climatic reversal to cooler and wetter conditions, based on the isotopic data, which coincides with the refilling of the southern Lake Agassiz basin during the Emerson Phase (Preboreal not Younger Dryas). The climatic change associated with the lake effect, however, was too small to have produced any response in the vegetation at Deep Lake. The replacement of spruce forest by pine woodland, which had begun at about 10 500 14C yr BP at this lake, appeared to have continued unabated through the inferred climatic change.

Our data from the late Moorhead Phase suggest that at least in the southern part of the basin the surface lake waters were warm. The plants and animals that inhabited the Moorhead Delta could not have existed if the winds coming from the lake were frigid. While it is improbable that there was a lake effect in the southern basin during the Moorhead Phase, we cannot rule out a lake effect later during the Emerson Phase. The absence of fossils, except for rare valves of the cold-water-adapted ostracode Candona subtriangulata Benson & Macdonald in Emerson Phase sediments, was interpreted by Curry (1997) to indicate cold unproductive water. Boulder-size dropstones suggest that ice bergs drifted south of Fargo during this time (Clayton et al., 1965; Bluemle, 1972; Thorleifson, 1996). Melting ice bergs could have chilled the surface waters and produced cooler summers on the eastern shores after 9900 14C yr BP. This cold surface water, according to Hostetter et al.’s (2000) regional climate model simulations, probably created anticyclonic air flow over the surface of the lake. This type of circulation would have blocked the penetration of moisture from the south and west, causing reduced precipitation eastwards. This climatic pattern may explain why on the Itasca Moraine, spruce forest was replaced by a drought-tolerant pine woodland rather than deciduous forest.

According to Teller (2001, 2004), differential isostatic uplift raised the eastern outlet causing the lake to reoccupy the southern basin and once again overflow through its southern outlet between ca. 10 200 and 10 100 14C yr BP. Ice retreat then uncovered the northwestern outlet and the lake drained to the Arctic Ocean. Subsequent isostatic uplift and ice advance caused the northwestern outlet to become blocked and the lake once again reoccupied the southern basin, overflowing the southern outlet between ca. 9920 and 9830 yr BP.

An alternative scenario is provided by Fisher (2003). Borehole data from the southern outlet indicate that this outlet was operating sometime between 9900 and 9400 yr BP, but for an unknown duration. The northwestern outlet opened at 9900 yr BP and was operational for a few hundred years (Fisher and Smith, 1994). Fisher (2003), consequently, suggested that drainage through the southern outlet occurred for a few hundred years before the final abandonment of this outlet at 9400 yr BP.

The Trollwood Park site, in the axis of the southern Lake Agassiz basin, is in a critical position to examine the complex drainage history outlined by Teller (2001) and Fisher (2003). The Sherack Formation, which overlies the rhythmite facies of the Poplar River Formation (Fig. 2), was deposited at a time when the lake overflowed through the southern outlet. At this time, the water level was 30 m above the fissiliferous horizon (262 m a.s.l.). The flooding of the southern Agassiz basin at the onset of the Emerson Phase is dated at about 9900 yr BP based on 14C ages at the Trollwood Park and other sites (Moran et al., 1973).

Our data are in agreement with Teller’s (2001, 2004) interpretation of drainage through the southern outlet after 9920 yr BP, but they do not support his interpretation for the southern outlet being active between 10 200 and 10 100 yr BP. The organisms in the Moorhead Delta wetland would be very sensitive to changes in water depth, and while they might have been able to survive a seasonal flooding of 1–2 m, it would be impossible for them to have survived flooding to a depth of 30 m associated with the refilling of the basin to the extent that it overflowed the southern outlet.

The drowning of the Rainy River landscape by the rise in lake levels associated with the Emerson Phase occurred after 9920 yr BP in northwestern Ontario (Bajc et al., 2000), at about 10 000 yr BP in southern Manitoba (Teller et al., 2000), and at about 9920 yr BP at the Trollwood site, about 300 km to the south. The transgression appears to have been more or less synchronous over a very large area. This suggests to us that an ice advance blocking an outlet is a more probable cause for the Emerson phase transgression than isostatic uplift. Great advances have been made with respect to the sequence of events in the drainage history of Lake Agassiz, but the complex interaction between the southern, eastern and northwestern outlets is still not satisfactorily explained. At this time, our data fit the ‘conventional chronology’ for the outlets most recently revised by Fisher (2003) rather than the ‘new chronology’ proposed by Teller (2001, 2004).

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