The Quaternary of Wisconsin: a review of stratigraphy and glaciation history

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INTRODUCTION

Wisconsin was glaciated several times during the Quaternary and lies well north of the maximum extent of Quaternary glaciation (Fig. 1). However, the Driftless Area of south-western Wisconsin remained unglaciated even though areas to the south were glaciated several times. Glacial, periglacial, alluvial, and aeolian sediments from pre-Illinoian, Illinoian, and Wisconsinan Glaciations are present, but age control for all except Late Wisconsinan events is limit-ed to palaeosols and palaeomagnetic data (Whittecar, 1979; Baker *et al.*, 1983; Miller, 2000). Radiocarbon ages are abundant for the Late Wisconsinan deglaciation after 13,000 ^{14}C yr B.P., but they are much less common for earlier Wisconsinan events. All radiocarbon ages in this paper are reported in uncalibrated years unless stated otherwise.

Glacial sediment covers approximately three fourths of the 145,000-km^2 land surface in Wisconsin. Ice flowing from three major source regions deposited sediment (Mickelson *et al.*, 1984; Attig *et al.*, 1988). Ice from the Keewatin ice dome to the north-west (e.g. the Des Moines Lobe, Fig. 2) deposited silt-rich, calcareous tills. Ice from the Labradoran ice dome to the north-east flowed out of the Superior lowland and deposited red tills with Precambrian basalt, banded iron formation and red sandstone erratics (e.g. Superior Lobe and other smaller lobes, Fig. 2). Labradoran ice flowing out of the Green Bay and Lake Michigan lowlands (e.g. Green Bay and Lake Michigan Lobes, Fig. 2) deposited calcareous tills whose grain size was strongly influenced by pro-glacial lakes within those lowlands. Wisconsin provides an ideal laboratory for evaluating how the complex sedimentology, stratigraphy, and landform distribution reflect past ice dynamics. Here, the authors summarise the glacial history of Wisconsin and suggest areas of future research that would aid reconstruction of the region's glacial history.

EARLY WORK IN WISCONSIN

Glacial deposits in Wisconsin have been studied since the late 1870s, and they provide the basic stratigraphy and interpretative landform and sediment models for the rest of the Great Lakes region. The earliest work in the state resulted from a comprehensive inventory of the geology of Wisconsin published in four volumes (Chamberlin, 1877, 1880, 1882, 1883). Chamberlin (1883) recognised evidence for two glacial 'epochs.' Ice from the 'first glacial epoch' extended well south of Wisconsin, but left the south-western part of the state untouched (Driftless Area). Sediment from this event was largely deposited in western and north-central Wisconsin in landscapes later modified extensively by erosion (Strong, 1882; T.C. Chamberlin, 1883; R.T. Chamberlin, 1905, 1910; Weidman, 1907; Leverett, 1932).

In north-western Wisconsin, R.T. Chamberlin (1905, 1910) described two till units in valleys along the St. Croix River. The oldest unit (called the 'old gray' till by Leverett, 1932) was a grey, calcareous, and silt-rich till associated with a north-westerly (Keewatin) source. A palaeosol and erosional surface were described in the top of this unit. Chamberlin (1910) (and later Leverett, 1932) initially assigned this unit to the 'Kansan' Glaciation (now termed pre-Illinoian). The overlying unit (the 'old red' till of Leverett, 1932) contained reddish-brown, sandy till of a Lake Superior provenance (Labradoran ice). Chamberlin (1910) and Leverett (1932) assigned this unit to the Illinoian Glaciation based on the erosional surface below it and a similar degree of weathering on the 'old red' till and other Illinoian tills in Iowa.

In north-central Wisconsin, Weidman (1907) identified three till units within the area mapped by Chamberlin as part of the 'first glacial epoch.' Although some later workers disagreed with the interpretation of multiple till units outside the prominent young moraines (Hole, 1943; Black & Rubin, 1967-1968; Black, 1976b), later workers also recognised numerous till units in that area (Mode, 1976; Stewart & Mickelson, 1976; Baker *et al.*, 1983; Attig & Muldoon, 1989; Clayton, 1991).

In south-eastern Wisconsin, potential 'Kansan' and Illinoian tills were described by Alden (1918). Ice flowing from the east deposited these tills. Later workers refined the extent and stratigraphy of these units (Bleuer, 1970, 1971; Fricke & Johnson, 1983; Miller, 2000).

Glacial sediment from the 'second glacial epoch' of Chamberlin (1883) was deposited within relatively fresh landforms, the outermost moraine of which Chamberlin called the Kettle Moraine. Chamberlin (1895) named the last glaciation the Wisconsin Formation (now called the Wisconsinan Glaciation) based on the excellent examples of glacial landforms from this event in the State of Wisconsin.

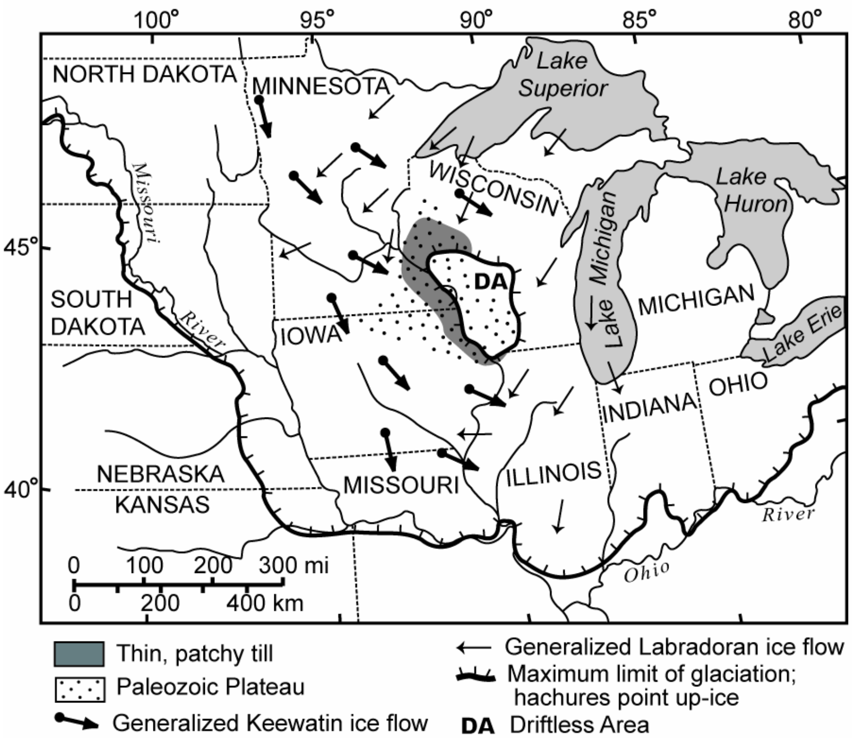

Fig. 1. Map of Wisconsin and surrounding states relative to the maximum extent of glacier ice during the Quaternary (modified from Hobbs, 1999). The Driftless Area in south-western Wisconsin does not show evidence for burial by glacier ice. The shaded area of patchy, eroded till displays the same deeply incised river valleys as the Driftless Area and has been referred to as the 'pseudo-driftless area' by Hobbs (1999).

Much of the early work on the Wisconsinan deposits was conducted in eastern Wisconsin (Chamberlin, 1877, 1878, 1883; Alden, 1905, 1918). These workers described the large 'Kettle Range' that formed in an interlobate position between the Green Bay and Lake Michigan Lobes. In the Green Bay and Lake Michigan lowlands, Chamberlin (1877, 1883) also observed grey to yellowish-brown glacial sediment overlain by reddish-brown, gravel-poor, and clay-rich sediment. Chamberlin interpreted the reddish-brown, clay-rich sediment as lake sediment, but Alden (1918) correctly identified much of the reddish-brown pebbly material as till. In addition, the Two Creeks forest bed (Fig. 3, location TC) was described along the western shore of Lake Michigan in the area with reddish-brown, clay-rich till (Goldthwait, 1907; Black, 1970a). Thwaites (1943) named this red till the 'Valders Till' at Valders, Wisconsin, and later Thwaites & Bertrand (1957) extended this name to all the red tills in eastern Wisconsin, including the red till overlying the Two Creeks forest bed. This interpretation was advocated by many workers (e.g. Black, 1976b, 1980). A long controversy followed (see Acomb *et al.* (1982) for details). Field mapping and lab analyses by McCartney & Mickelson (1982) and Acomb *et al.* (1982) later showed that some of the red till units were older than the Two Creeks forest bed and others were younger than the Two Creeks forest bed.

In western and north-central Wisconsin, Wooster (1882) and Weidman (1907) described younger glacial deposits that were associated with hummocky end moraines. Two young glacial tills were identified: a red sandy till with abundant clasts from the Lake Superior basin (Labradoran ice), overlain by a gray, calcareous till deposited by a glacier flowing from the west (a Keewatin source, R.T. Chamberlin, 1905, 1910; Leverett, 1932). These units have been studied in detail by numerous workers verifying the conclusions of the early workers (e.g. Clayton, 1984; Johnson, 1986, 2000; Attig, 1985, 1993; Ham & Attig, 1997).

Wisconsin glacial sediments are now formally defined in a lithostratigraphic framework (Mickelson *et al.*, 1984; Attig *et al.*, 1988, Fig. 4). Detailed field mapping during the last thirty years has identified numerous glacial phases primarily associated with Late Wisconsinan end moraines and other ice-marginal landforms (Fig. 3). The rest of this paper summarises the current state of knowledge about the glacial stratigraphy and chronology of Wisconsin.

PRE-ILLINOIAN GLACIATIONS

Several tills in Wisconsin have been attributed to events pre-dating the Illinoian Glaciation. Tills of the Pierce Formation of western Wisconsin (the 'old gray' till of Leverett, 1932) and Marathon Formation in north-central Wisconsin are the most extensive (Figs 4, 5).

Western Wisconsin

Pierce Formation tills in western Wisconsin are grey to brown, calcareous (where unleached), silt-rich, kaolinite-rich, and they probably represent an ice advance from a Keewatin source during at least two phases (Baker *et al.*, 1983; Mickelson *et al.*, 1984; Johnson, 1986; Attig *et al.*, 1988; Thornburg *et al.*, 2000). Aber (1999) proposed calling this pre-Illinoian ice lobe the Minnesota Lobe. If the Minnesota Lobe behaved in a similar way as the Late Wisconsinan Des Moines Lobe, then it is possible that the

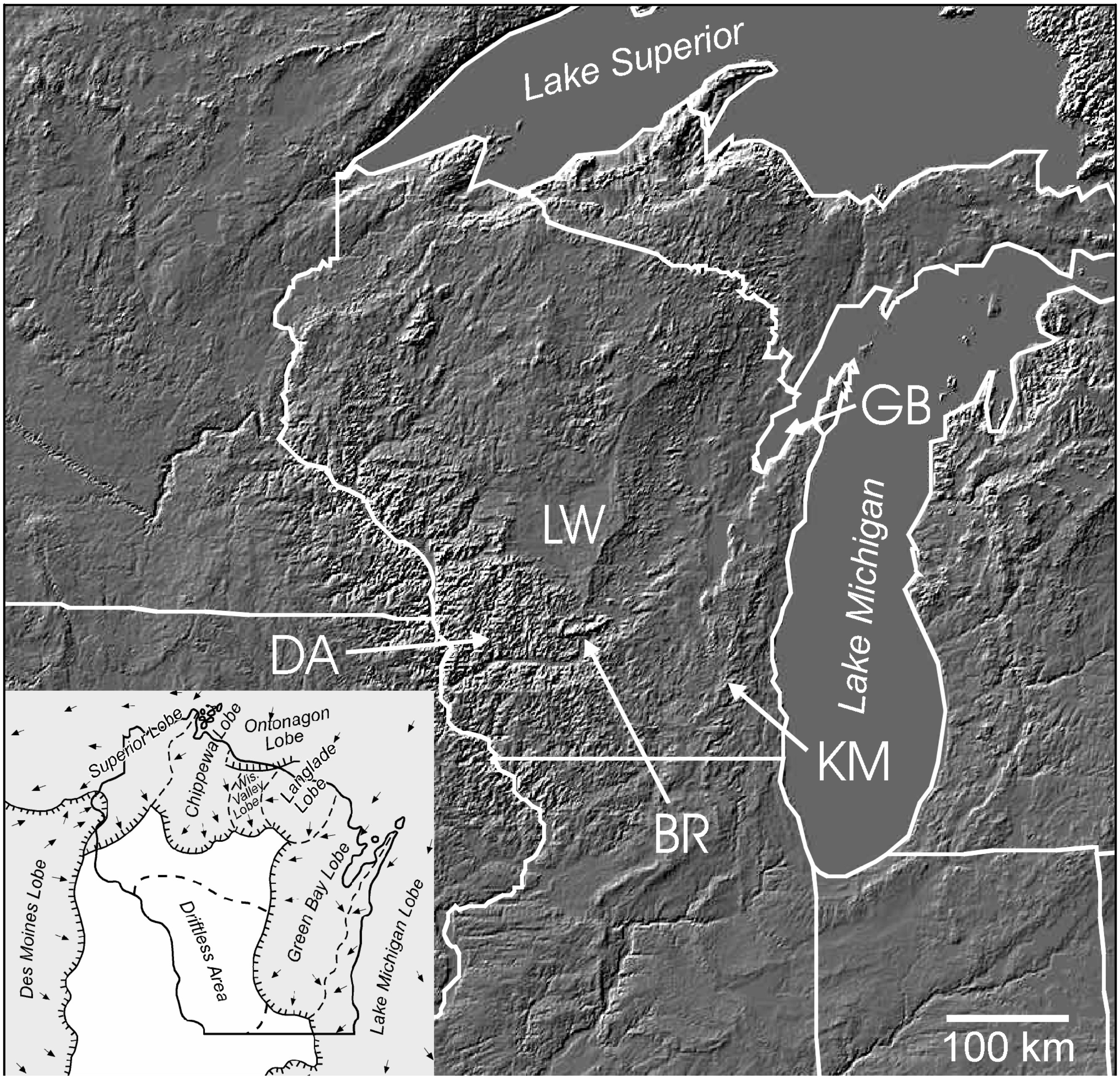

Fig. 2. Major ice lobes during the Late Wisconsinan Glaciation (inset, modified from Clayton et al. (1992)). The shaded relief image of Wisconsin shows the following major features: BR, Baraboo Range; DA, Driftless Area; GB, Green Bay; KM, Kettle Moraine; LW, proglacial Lake Wisconsin bed. Image was created from USGS 3 arc-sec digital elevation data. Illumination direction is approximately 315 degrees and sun angle is 25 degrees.

Pierce Formation in north-west Wisconsin was deposited by a sublobe of the Minnesota Lobe. Till of the Woodville Member of the Pierce Formation marks the first ice advance recognised (Fig. 5). Lake sediment of the Eau Galle Member of the Pierce Formation is present below the Woodville till, and peat and wood are found above the Woodville till at the type section (Attig *et al.*, 1988, pp. 8 and 11). It is unclear if the peat and wood above the Woodville till indicate a major interglacial.

Keewatin ice flowed south-east across the Mississippi River during the later Reeve Phase, deposited the Hersey Member of the Pierce Formation in western Wisconsin, and dammed the major south-easterly flowing tributaries of the Mississippi River (Baker *et al.*, 1983; Johnson, 1986). The resulting proglacial lakes extended at least tens of kilometres east of the modern Mississippi River valley. Silt-rich and clay-rich lake sediment of the Kinnickinnic Member of the Pierce Formation was deposited in these

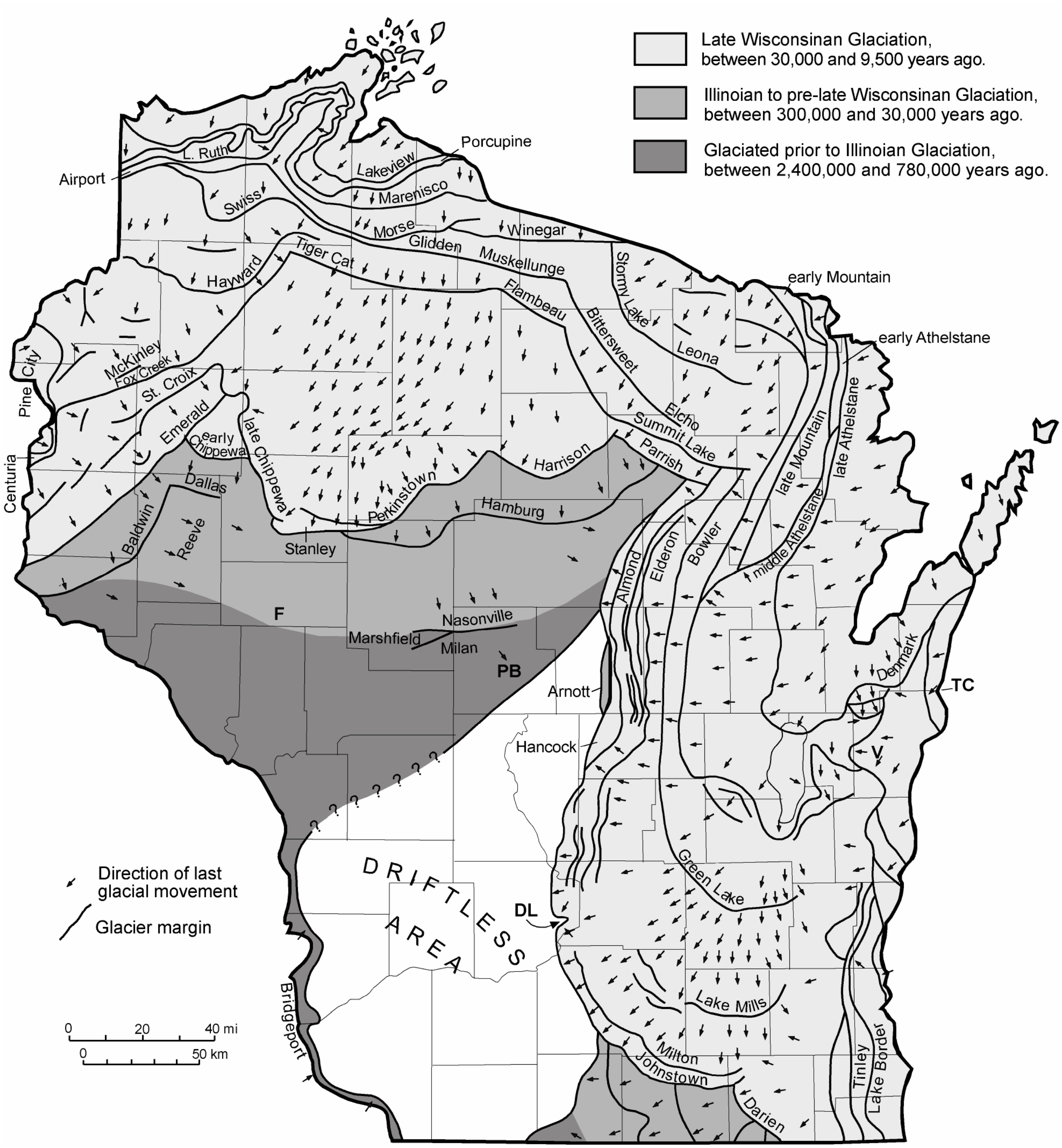

Fig. 3. Phases of glaciation in Wisconsin. These phases are events that probably represent at least a minor advance of the ice sheet. Letters indicate important localities mentioned in the text: DL, Devils Lake; F, Foster; PB, Powers Bluff chert fan; TC, Two Creeks forest bed; V, Valders. Age estimates are in calendar years. Modified from Clayton et al. (1992) using information from Johnson & Mooers (1998), Johnson (2000) and Syverson (in preparation).

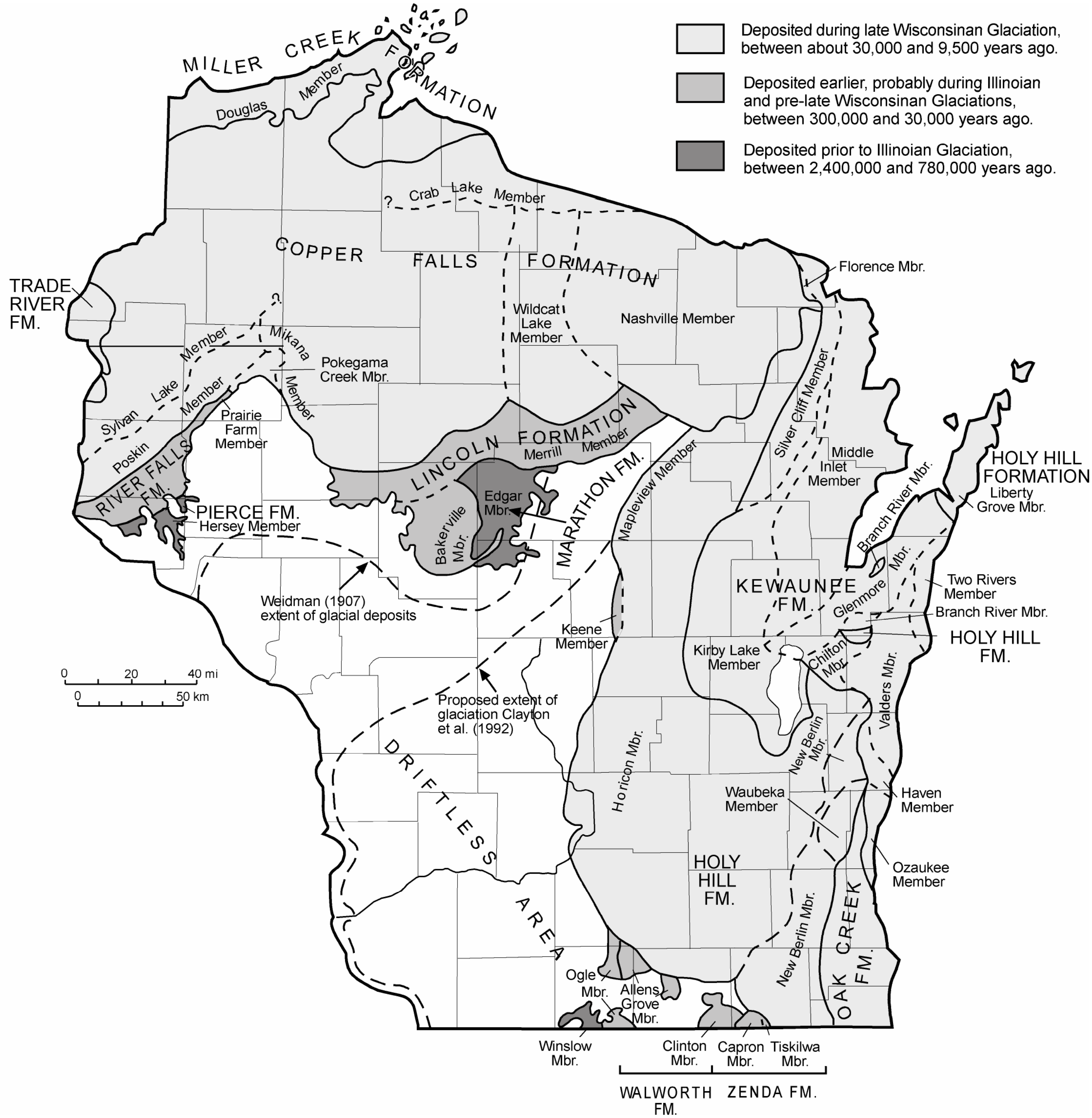

Fig. 4. Pleistocene lithostratigraphical units for till in Wisconsin. Age estimates are in calendar years. Modified from Clayton et al. (1992) using information from Mickelson & Syverson (1997) and Johnson (2000).

lakes (Fig. 5). Based on lake sediment elevations and counting varves, Baker (1984a) estimated that the lakes were major features that might have covered an area of 5800 km^2 for more than 1200 years.

North-central Wisconsin

The Wausau Member of the Marathon Formation in north-central Wisconsin is silt-rich and very weathered (Fig. 5). No similar till units have been found in Wisconsin, and the Wausau till may be evidence for an extremely old glacial event in the state. Calcareous, silt-rich tills of the Marathon Formation (Medford and Edgar Members) were deposited in north-central Wisconsin during the Stetsonville and Milan/Marshfield Phases, respectively (Figs 3, 4, 5). These till units contain less kaolinite than the Hersey Member of the Pierce Formation, but otherwise they are very similar (Mickelson *et al.*, 1984; Attig *et al.*, 1988; Muldoon *et al.*, 1988; Attig & Muldoon, 1989; Thornburg *et al.*, 2000). The

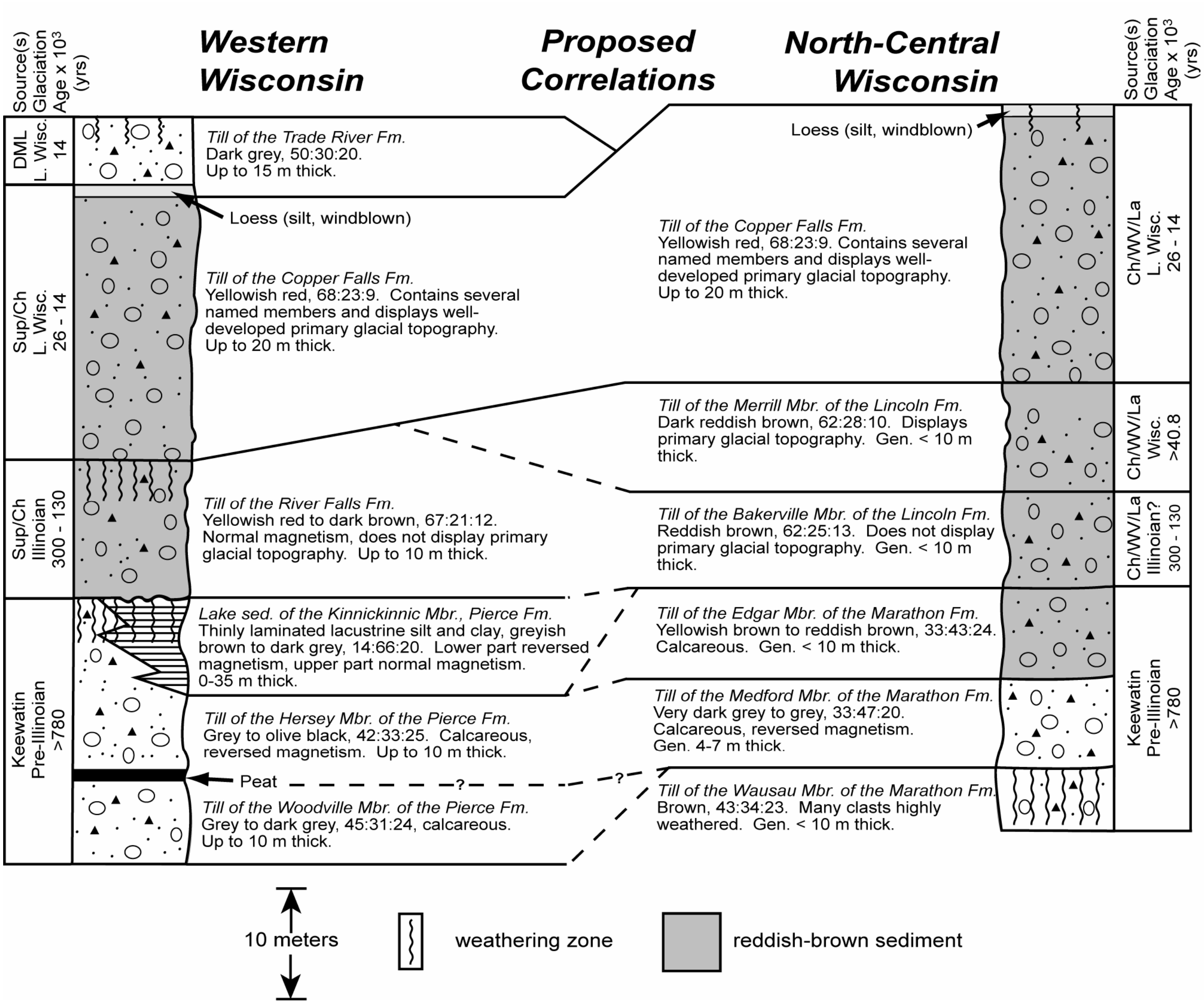

Fig. 5. Glacial lithostratigraphy in western and north-central Wisconsin. Vertical scale is only approximate, and mean grain size is reported as sand:silt:clay percentages. Sources for the sediment are indicated as follows: Ch, Chippewa Lobe; DML, Des Moines Lobe; Keewatin, derived from Keewatin ice dome to the north-west; La, Langlade Lobe; Sup, Superior Lobe; WV, Wisconsin Valley Lobe) as well as proposed ages/correlations for glacial units. Ages for Wisconsinan units are in ^{14}C yr B.P., and ages from earlier events are in calendar years. Modified from Syverson (1998) and Treague and Syverson (2002) using information from Baker et al. (1983), Mickelson et al. (1984), Attig et al. (1988) and Johnson (2000).

Marshfield moraine contains 30-50 m of Edgar till (Weidman, 1907, p. 452; Clayton, 1991), and this is the only primary glacial landform that remains from these pre-Illinoian ice advances.

Southern Wisconsin

Alden (1918) recognised that pre-Wisconsinan till units were present in south-eastern Wisconsin outside of the Wisconsinan end moraines. Bleuer (1970, 1971) and Whittecar (1979) proposed that some units were related to a pre-Illinoian ice advance from the east out of the Lake Michigan lowland. Miller (2000) recently described till of the Winslow member that he has informally placed in a new unit called the Monroe formation. (In Illinois, the Winslow member has been defined as part of the Glasford Formation by Willman & Frye, 1970). The Winslow member contains silt-rich, calcareous gray till that is located in scattered erosional remnants. The Winslow member has been observed beneath Illinoian till of the Walworth Formation in southern Wisconsin (Bleuer, 1971, p. 143; Miller, 2000, p. 116).

Ice extent and chronology

Details concerning these pre-Illinoian glacial events are poorly known. Any original glacial landforms other than the Marshfield moraine have been completely removed by

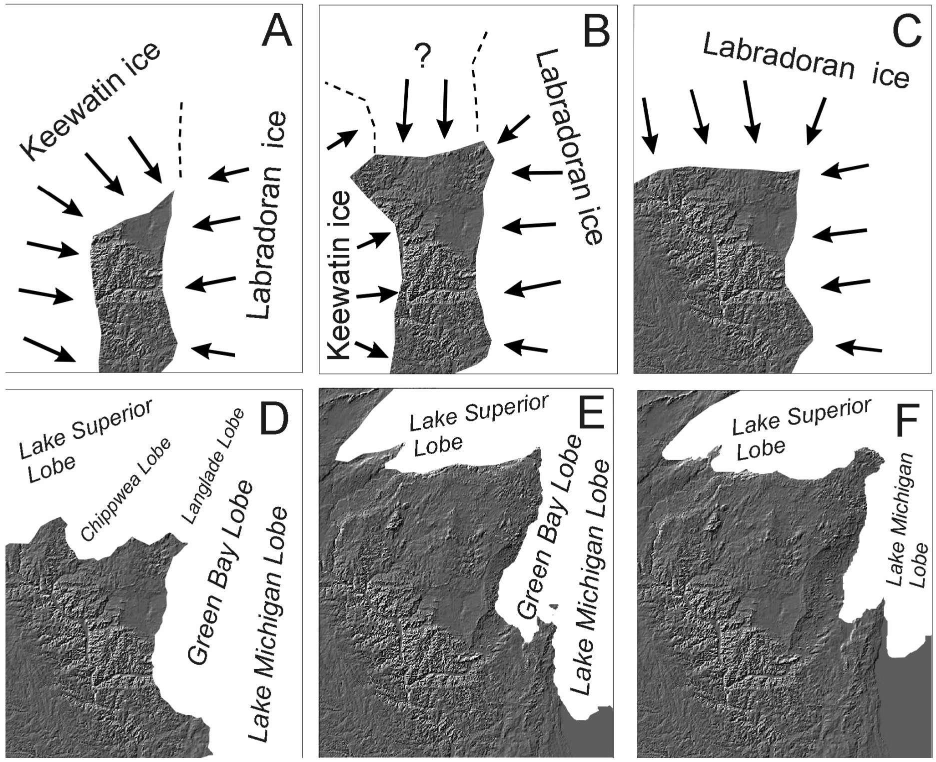

Fig. 6. Reconstructions of six different phases of glaciation in Wisconsin (plotted on the shaded relief base map from Fig. 2). A. Pre-Illinoian glacial maximum, Stetsonville Phase. Limit based on interpretation of Clayton et al. (1992). The ice margin shown here may have been diachronous. B. Pre-Illinoian Reeve Phase during the deposition of the Hersey Member (till) and Kinnickinnic Member (lake sediment) of the Pierce Formation. C. Illinoian Glaciation maximum, Nasonville Phase in north-central Wisconsin. D. Late Wisconsinan maximum ice position at approximately 21,000 ^{14}C yr B.P. E. Late Wisconsinan ice margin reconstruction at approximately 13,500 ^{14}C yr B.P. during initial deposition of Kewaunee Formation. Ice margin extends south to the vicinity of Milwaukee along the Lake Michigan shoreline. F. Ice-margin positions at approximately 11,800 ^{14}C yr B.P. (just after Two Creek forest bed is covered by ice and the Two Rivers Member of the Kewaunee Formation is deposited).

erosion, and weathered remnants are widely scattered and buried by much younger sediments. The Powers Bluff chert dispersal fan indicates that pre-Illinoian Keewatin ice flowed toward the south-east in central Wisconsin (Fig. 3, location PB, Weidman, 1907, p. 444; Clayton, 1991). Based on this ice-flow direction and the lower elevations in south-western Wisconsin, Clayton *et al.* (1992) proposed a north-east-southwest-trending ice margin through south-western Wisconsin (Figs 3 and 6a). However, field evidence for this ice margin is lacking in south-western Wisconsin. Knox & Attig (1988) described till in the Bridgeport terrace of the Wisconsin River (*c*. 3 km east of the Mississippi River junction). Knox & Attig (1988) suggested that this till formed during a pre-Illinoian ice advance across the Mississippi River in south-western Wisconsin, and Clayton *et al.* (1992) proposed an ice margin that closely followed the location of the Mississippi River (Figs 3 and 6a).

In western Wisconsin, the Eau Galle Member of the Pierce Formation may represent sedimentation in proglacial lakes dammed by the advancing ice that deposited the Woodville till. Baker *et al.* (1987) proposed that a Keewatin ice lobe deposited the Hersey Member of the Pierce Formation and the Medford Member of the Marathon Formation at the same time. They cited evidence such as the Powers Bluff chert fan, similar grain sizes, similar stratigraphic positions, and common carbonate and black shale sources to the north-west. Baker *et al.* (1983) and Baker (1984b) state that till of the Hersey Member of the Pierce Formation and the lower part of the Kinnickinnic Member display reversed remanent magnetism, and the uppermost part of the Kinnickinnic Member displays normal remanent magnetism. R.W. Baker (2001, personal communication) reports that the Medford Member also displays reversed remanent magnetism. This suggests that the Kinnickinnic Member (and the interfingering Hersey Member) as well as the Medford Member were deposited during pre-Illinoian time at Emperor/Brunhes boundary 460,000 yr B.P. or Matuyama/Brunhes boundary 780,000 yr B.P. (or perhaps during an earlier palaeomagnetic event boundary).

Syverson & Johnson (2001) concurred that the Hersey and Medford tills might have been deposited at approximately the same time by Keewatin ice. If so, the Medford till must have been deposited by a different lobe with a flow line that incorporated less kaolinite from the dominant Cretaceous source materials in Minnesota (Morey & Setterholm, 1997). If the Marathon and Pierce Formation tills are time-equivalent, it seems likely that the Reeve Phase and the deposition of the Kinnickinnic Member lake sediment represent recessional events.

In south-central Wisconsin, Miller (2000) recently reported that till of the Winslow member and interbedded lake sediment of the Silveria member of the Monroe formation display reversed remanent magnetism. Miller (2000) suggested that these units likely were deposited by pre-Illinoian ice from the Lake Michigan/Green Bay regions during the Matuyama Chron >780,000 yr B.P. (Figs 4, 6a).

Magnetically-reversed till units have been described in Iowa (Boellstorff, 1978) and northern Missouri (Rovey & Kean, 1996, 2001), and much work remains to be done in order to understand how these units relate to tills with reversed remanent magnetism in Wisconsin. Clearly the maximum ice extent was reached prior to the Illinoian

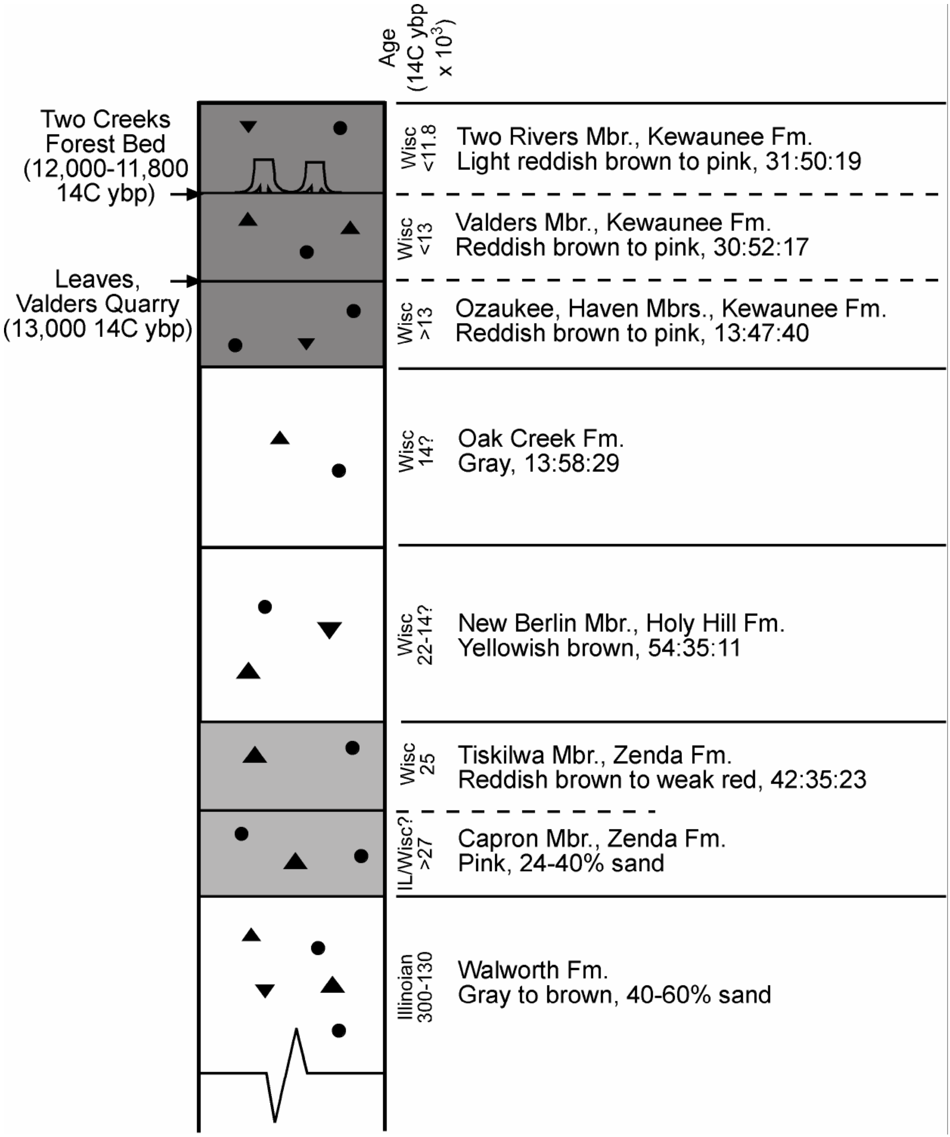

Fig. 7. Schematic stratigraphical column for tills deposited by the Lake Michigan Lobe in eastern Wisconsin. Shaded units display reddish colours. Uncalibrated radiocarbon ages indicated are from Kaiser (1994) and Maher and Mickelson (1996). The leaves at Valders Quarry were located above Holy Hill Formation till and below till of the Valders Member. Estimated ages for Wisconsinan units are in ^{14}C yr B.P. and ages from earlier events are in calendar years. Stratigraphical information compiled from Mickelson et al. (1984) and Attig et al. (1988).

Glaciation, and most of Wisconsin except the Driftless Area probably was covered by these glaciations. Sediment from these older events might be preserved in buried valleys and rare remnants below Late Wisconsinan deposits. Future work should include drilling in buried valleys to find such deposits. Cosmogenic burial dating of palaeosols (Bierman *et al.*, 2002) could provide much-needed age estimates for this enigmatic part of the glacial record in Wisconsin.

ILLINOIAN GLACIATION

Western Wisconsin

Two pre-Late Wisconsinan tills in western Wisconsin are thought to represent events during the Illinoian Glaciation. The River Falls Formation (the equivalent of the 'old red' till of Leverett (1932)) and the Bakerville Member of the Lincoln Formation were deposited by ice from the Superior region (Figs 4 and 5). The River Falls Formation displays normal remanent magnetism and unconformably overlies deeply-weathered Pierce Formation till in western Wisconsin. Both the River Falls and Bakerville till units contain reddish-brown, sandy till with abundant Precambrian basalt and red sandstone clasts from the Lake Superior region. Both of these tills are extensively eroded and do not display primary glacial topography (Baker *et al.*, 1983; Johnson, 1986; Clayton, 1991). Proximal stream sediment of the River Falls Formation is common in western Wisconsin and is extremely weathered. Soil-derived clay extends to depths of 5 m and cements the stream sediment in some cases (Syverson, in preparation).

Southern Wisconsin

Alden (1918) proposed that glacial deposits in south-central Wisconsin were pre-Wisconsinan. Most of these units extend into northern Illinois where the Illinoian Glaciation was first defined. Illinoian tills in south-central Wisconsin

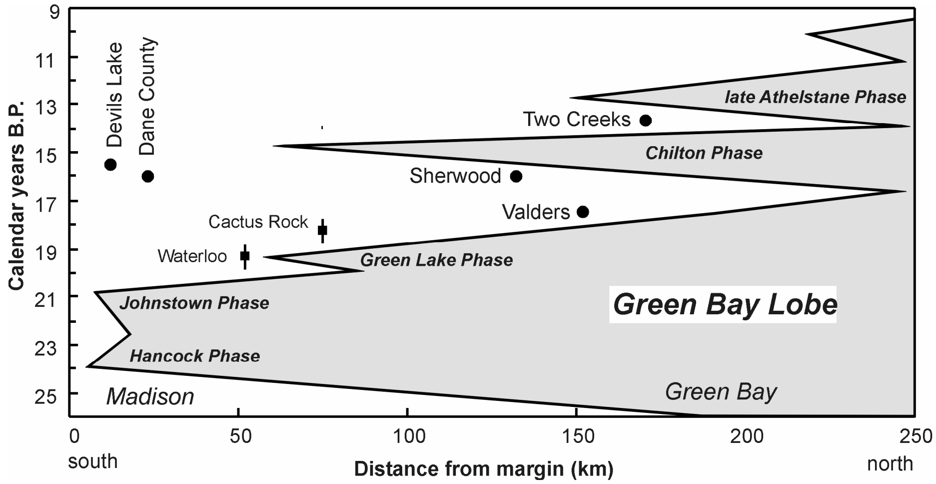

Fig. 8. Time-distance diagram for the Green Bay Lobe (modified from Colgan et al., 2002). Dots are radiocarbon dates converted to calendar years using CALIB 4.1 (Stuiver & Reimer, 1993). Cross bars are cosmogenic isotope dates from Colgan et al. (2002) using the production rates of Stone et al. (1998). Bar lengths represent one sigma analytical uncertainty. Yellowish-brown, sandy till of the Holy Hill Formation was deposited during the Hancock, Johnstown, and Green Lake Phases. Reddish, fine-grained till of the Kewaunee Formation was deposited during the Chilton and late Athelstane Phases.

are members of the Walworth Formation (Figs 4, 7, Bleuer, 1971; Mickelson *et al.*, 1984). The tills are generally yellowish brown, silt-rich to sandy in texture, contain abundant dolomite pebbles and they become more dissected by erosion from east to west (Alden, 1918, p. 151; Bleuer, 1970, 1971; Mickelson *et al.*, 1984; Miller, 2000). Weathered loess units located in the Driftless Area (Wyalusing and Loveland Formations) also have been attributed to the Illinoian Glaciation based on stratigraphic position and palaeosols (Leigh & Knox, 1994; Jacobs *et al.*, 1997).

Ice extent and chronology

The River Falls Formation and Bakerville Member of the Lincoln Formation of western and north-central Wisconsin are associated with the Baldwin/Dallas and Nasonville Phases, respectively (Fig. 3, Johnson, 1986; Attig & Muldoon, 1989). The lack of primary glacial landforms makes it difficult to determine the maximum extent of glacier ice and the number of events that deposited these units. Baker *et al.* (1983) and Syverson (in preparation) have attributed the deep weathering of River Falls Formation till and stream sediment to the Sangamon interglacial and used this to support an Illinoian age for the sediment. The Bakerville till does not display deep weathering, but based on its stratigraphical position and eroded nature, workers such as Johnson (2000) have tentatively correlated the Bakerville and River Falls tills.

Bement & Syverson (1995) described weathered proximal outwash, reddish sandy till, and large Precambrian glacial erratics near Foster, Wisconsin (Fig. 3, location F), that mark an Illinoian ice-margin position just outside the 'first drift' limit of Weidman (1907) (Figs 4 and 6c). The maximum extent of Illinoian ice in Fig. 4 is further south than that proposed by Clayton *et al.* (1992). This modified boundary is based on the glacial sediment near Foster and proximal glacial stream sediment with Superior Lobe indicators near the city of Eau Claire.

In south-central Wisconsin, tills of the Walworth Formation clearly were deposited by ice flowing westwards out of the Lake Michigan lowland during several events. The maximum Illinoian ice extent in south-central Wisconsin is uncertain because of the erosional western boundary and the patchiness of the till (Fig. 6c). No ages have been determined for any of these events.

WISCONSINAN GLACIATION

Landforms and sediment from the Wisconsinan Glaciation (75,000-9,500 ^{14}C yr B.P.) are abundant within the state. Few glacial deposits have been attributed to times other than the last part of the Wisconsinan Glaciation, and age control is scarce for events other than the last part of the Wisconsinan. Thus, the subdivisions of the Wisconsinan Glaciation proposed by Johnson *et al.* (1997) (Athens and Michigan Subepisodes of the Wisconsin Episode), have not been used in Wisconsin. Most workers in Wisconsin use the terms 'pre-Late Wisconsinan' (>27,000 ^{14}C yr B.P.) and 'Late Wisconsinan' or 'last part of the Wisconsinan' (27,000-9,500 ^{14}C yr B.P.) to refer to sediment ages.

Pre-Late Wisconsinan events in north-central Wisconsin

Till units that appear relatively fresh, display little to moderate stream incision and lack well-developed weathering horizons at the surface have been interpreted as pre-Late Wisconsinan. The most extensive till unit attributed to the pre-Late Wisconsinan is the Merrill Member of the Lincoln Formation in north-central Wisconsin (Figs 4, 5). This reddish-brown, sandy till unit was deposited during the Hamburg Phase (Fig. 3), and it displays some streamlined glacial landforms and low-relief hummocky topography. Thus, it is probably younger than pre-Illinoian or Illinoian deposits that usually display no primary glacial topography. Stewart and Mickelson (1976) presented clay mineral evidence for greater weathering than the Late Wisconsinan Copper Falls Formation till (Fig. 4), but Thornburg *et al.* (2000) could not reproduce this trend.

Stewart & Mickelson (1976) reported an age of >40,800 ^{14}C yr B.P. for organic material overlying till of the Merrill Member.

Pre-Late Wisconsinan events in southern Wisconsin

The Capron Member of the Zenda Formation in south-eastern Wisconsin is interpreted as a pre-Late Wisconsinan till unit (Figs 4 and 7, Mickelson *et al.*, 1984). In Illinois this unit, called the Capron Member of the Winnebago Formation by Willman & Frye (1970), was initially considered between 40,000 and 28,000 ^{14}C yr B.P. based on loess ages. However, more recent work by Curry (1989) suggests that this unit may be much older (pre-Wisconsinan). Dates from the base of the Roxana Formation, a loess unit derived from the Mississippi River valley in the Driftless Area, range from a infinite date >47,000 ^{14}C yr B.P. to 45,200 ± 2650 ^{14}C yr B.P. (Leigh & Knox, 1993, 1994). Grimley (2000) used the magnetic susceptibility and clay mineralogy of the Roxana Formation to infer that the Superior, Wadena and Des Moines Lobes were contributing meltwater (and sediment) to the Mississippi River during this time.

Late Wisconsinan events

Ice during the Late Wisconsinan Glaciation crossed the drainage divide south of Lake Superior by 26,000 ^{14}C yr B.P. This is based on spruce wood in western Wisconsin buried by 60 m of glacial stream sediment (26,060 ± 800 ^{14}C yr B.P., Black, 1976b; Attig *et al.*, 1985). Clayton & Moran (1982) proposed that ice may have reached its Late Wisconsinan maximum by 20,000-18,000 ^{14}C yr B.P. and remained there until approximately 15,000 ^{14}C yr B.P. (Fig. 6d). This is not well constrained in Wisconsin because organic material is uncommon from 26,000 to 13,000 ^{14}C yr B.P. Clayton *et al.* (2001) attribute this lack of organic material to the presence of permafrost in Wisconsin, yet many areas not subject to permafrost also suffer from a lack of radiocarbon dates during this period.

Numerous tills were deposited during Late Wisconsinan glacial phases (Figs 3 and 4, Clayton *et al.*, 1992). The Copper Falls and Holy Hill Formations are the most extensive (Figs 4, 5 and 7). During the earliest phases of the Green Bay Lobe (the Hancock/Johnstown Phases), the ice margin intersected the Baraboo Range, blocked the Wisconsin River drainage, and formed proglacial Lake Wisconsin in the central part of the state (Fig. 2, locations BR, LW). This lake was up to 115 km long and 50 m deep, and its outlet was to the west via the Black River. The ice dam broke as the ice thinned, and catastrophic drainage of proglacial Lake Wisconsin around the east side of the Baraboo Range incised deep, branching bedrock channels that are now part of the Wisconsin Dells (Clayton & Attig, 1989, pages 44-45, 1990).

The Superior Lobe advanced to its Late Wisconsinan maximum during the Emerald Phase (Johnson, 2000, Figs 2, 3). Emerald Phase ice deposited thin till of the Poskin Member of the Copper Falls Formation, indistinct landforms, and small outwash plains. The Superior Lobe then retreated more than 15 km to the St. Croix Phase ice-margin position where a markedly different suite of landforms was deposited (Fig. 3). The St. Croix moraine displays numerous large hummocks, ice-walled-lake plains, and tunnel channels. The Spooner Hills are located north-west of (and in a zone parallel to) the St. Croix moraine (Johnson, 1999, 2000). The Spooner Hills are equidimensional to slightly elongate in a northwest-southeast direction, up to 60 m high, and separated by a network of branching valleys that in places connect with tunnels channels cutting the St. Croix moraine. In addition, St. Croix Phase outwash plains are extensive. Johnson (2000) proposed that the Superior Lobe was a cold, non-surging glacier during the Emerald Phase and a less cold, surging glacier during the St. Croix Phase. Johnson hypothesised that this warming effect produced more meltwater that shaped the landscape during the St. Croix Phase. Johnson (1999, 2000) suggested that the Spooner Hills may have been incised by subglacial meltwater erosion during the St. Croix Phase.

A small sublobe of the Des Moines Lobe advanced from the west-southwest into western Wisconsin during the Pine City Phase and deposited till of the Trade River Formation (Figs 3, 4 and 5). This Keewatin ice occupied an area previously covered by the Superior Lobe. Trade River Formation till is silt-rich and calcareous, similar to the till of the pre-Illinoian Pierce and Marathon Formations, but Trade River Formation till exhibits a low degree of weathering and erosional modification (Johnson, 2000). The Pine City Phase ice margin dammed the St. Croix River drainage along the Minnesota and Wisconsin border and proglacial Lake Grantsburg formed. Varves within this sediment suggest that this lake lasted at least 80 to 100 years (Johnson & Hemstad, 1998; Johnson, 2000). No dates exist for the Pine City Phase in Wisconsin. Johnson (2000) estimates that the Pine City Phase occurred at approximately 14,000 ^{14}C yr B.P. based on the well-dated advance of the Des Moines Lobe to the Bemis margin in central Iowa.

As the ice margins wasted to the north of the Superior, Green Bay and Lake Michigan drainage divides, proglacial lakes formed within these deep bedrock basins. Modern outlets toward the east were blocked by ice, so the lakes drained to the south via the St. Croix (e.g. Lakes Nemadji, Duluth), Wisconsin (Lake Oshkosh) and Illinois (Lake Chicago) River systems (Clayton, 1984; Hansel & Mickelson, 1988; Colman *et al.*, 1995). Fine-grained lake sediment was captured by these lakes, and ice readvancing out of the lake basins eroded the silt- and clay-rich sediment. Till units deposited by these later advances contain 70-90% silt and clay and tend to be rather stone poor (Miller Creek Formation in northern Wisconsin, Oak Creek and Kewaunee Formations in eastern Wisconsin, Figs 4 and 7; Schneider, 1983; Mickelson *et al.*, 1984; Simpkins, 1989; Simpkins *et al.*, 1990; Ronnert, 1992). This explains why it was difficult for early workers such as Chamberlin (1877, 1883) and Alden (1918) to determine if the sediments were lake sediment or till.

The reddish color of the Kewaunee Formation is quite different from the grey to yellowish-brown till units deposited previously by the Late Wisconsinan Green Bay and Lake Michigan Lobes (Figs 4 and 7). Alden (1918, p. 315) proposed that water carried iron oxides from the Lake Superior basin into the Green Bay and Lake Michigan lowlands during a time of ice-margin retreat, an event that must have occurred >13,000 ^{14}C yr B.P. Readvancing ice subsequently eroded red lake sediment and deposited the red tills of the Kewaunee Formation to a point as far south as Milwaukee along the Lake Michigan shoreline (Ozaukee Member, Figs 4, 6e and 7, Rovey & Borucki, 1995). Maher & Mickelson (1996) reported a date of 12,965 ± 200 ^{14}C yr B.P. for leaves below till of the Valders Member of the Kewaunee Formation at the type section (Figs 3, location V; 7). This site provides a maximum age for the westward advance of the Lake Michigan Lobe into this area.

The Two Creeks buried forest bed along the western Lake Michigan shoreline (Fig. 3, location TC) contains spruce wood and has been recognised as an important interglacial marker bed within the Late Wisconsinan sedimentary sequence of the Great Lakes region (Goldthwait, 1907; Black, 1970a, 1974). The Two Creeks forest bed is first overlain by lake sediment and then till of the Kewaunee Formation (Black, 1970a; Kaiser, 1994). Acomb *et al.* (1982) have interpreted this sequence to represent an ice advance into the Lake Michigan basin that blocked the eastern drainage, caused a lake-level rise that flooded and buried the forest, and deposited till of the Two Rivers Member of the Kewaunee Formation as the site was overridden by glacier ice (Figs 6f, 7). Kaiser (1994) used dendrochronology and AMS dates to delimit the growth period of the Two Creeks forest to between 12,050-11,750 ^{14}C yr B.P.

Ice margins in Wisconsin displayed marked oscillations during the last part of the Wisconsinan Glaciation (Fig. 8). Colgan & Mickelson (1997) showed that ice surface slope probably changed from a steep ice margin at the Late Wisconsinan maximum to less steep margin during deglaciation phases. Other palaeo-reconstructions of the ice lobes in Wisconsin during retreat from the glacial maximum suggest gentle ice-surface slopes, thin ice, and low basal shear stress values that are typical for fast-moving outlet glaciers or surging glaciers (Clark, 1992; Colgan, 1999; Socha *et al.*, 1999). This could reflect an increase in meltwater generation during deglaciation and/or a rapid lowering of the ice surface during retreat.

Cosmogenic isotope age estimates have been reported by Colgan *et al.* (2002) for the Late Wisconsinan retreat of the Green Bay Lobe (Fig. 8). Because of the lack of radiocarbon dates, there has been much uncertainty about the timing of the Green Bay Lobe's retreat from its maximum position. Some suggest an early retreat before about 15,500 ^{14}C yr B.P. (Clayton *et al.*, 1992; Colgan 1996, 1999), while others have suggested a later retreat beginning at about 12,500 ^{14}C yr B.P. (Maher, 1982; Maher & Mickelson, 1996). Numerous small moraines, interpreted as annual moraines, are found on the deglaciated surface uncovered by the Green Bay Lobe (Colgan, 1996; Clayton & Attig, 1997). These moraines suggest that the Green Bay Lobe retreated at a rate of approximately 50 m/yr. If so, the ice must have begun its retreat from the maximum position early to allow adequate time for retreat out of the Lake Michigan basin as well as the subsequent ice readvances that deposited the red Kewaunee tills starting more than 13,000 ^{14}C yr B.P. While some of the cosmogenic age estimates reflect inheritance due to low erosion rates near the margin, two sites farther from the margin produced reasonable deglaciation estimates. The cosmogenic exposure dates at two sites more than 50 km from the maximum extent of the Green Bay Lobe suggest that ice had retreated before 17-19,000 calendar years B.P. (equivalent to about 15,500 ^{14}C yr B.P.).

The last glacial advance into Wisconsin occurred south of Lake Superior during what has been called the Lakeview Phase (Fig. 3, Clayton, 1984). Black (1976b) reported wood dates from red clay-rich till of this event in northern Wisconsin (9,730 ± 140 ^{14}C yr B.P. and 10,100 ± 100 ^{14}C yr B.P.). Clayton (1984) correlates this 9,900 ^{14}C yr B.P. advance with the Marquette Phase in the Upper Peninsula of Michigan and estimates that the glacier margin wasted out of Wisconsin for the last time by 9,500 ^{14}C yr B.P.

Late Wisconsinan landform overview

A well-developed suite of Late Wisconsinan glacial landforms is present in the state. The Kettle Moraine of eastern Wisconsin runs approximately parallel to the Lake Michigan shoreline for more than 125 km. This time-transgressive ridge formed as meltwater was concentrated in the interlobate region between the Lake Michigan and Green Bay Lobes. Much fluvial sediment was deposited in contact with glacier ice, and today the Kettle Moraine contains hummocky stream sediment, pitted outwash plains, outwash plains and eskers (Chamberlin, 1883; Alden, 1918; Black, 1969, 1970a; Syverson, 1988; Mickelson & Syverson, 1997; Clayton, 2001). Moraines along the western margin of the Green Bay Lobe (Johnstown and Milton Phases, Fig. 3) tend to display single ridge crests that can be traced for more than 100 km (Attig *et al.*, 1989). The moraines marking the ice maximum in northern Wisconsin (St. Croix, late Chippewa, Perkinstown, Harrison Phases, Fig. 3) are hummocky complexes up to 20 km wide that contain supraglacial sediment and numerous ice-walled-lake plains (Attig, 1993; Johnson *et al.*, 1995; Ham & Attig, 1996). Prominent tunnel channels cut the outermost hummocky moraines but are not associated with recessional moraines (Attig *et al.*, 1989; Clayton *et al.*, 1999; Cutler *et al.*, 2002). Well-developed, radiating drumlin fields are also present in areas formerly covered by the Green Bay Lobe (Alden, 1918; Borowieka & Erickson, 1985; Colgan & Mickelson, 1997) and Lake Michigan Lobe (Whittecar & Mickelson, 1977, 1979; Stanford & Mickelson, 1985).

Ice-wedge casts indicate the former presence of permafrost in Wisconsin (Black, 1965, 1976a; Mason *et al.*, 1994; Colgan, 1996; Holmes & Syverson, 1997; Clayton *et al.*, 2001). Clayton *et al.* (2001) hypothesised that permafrost was present from 26,000 to 13,000 ^{14}C yr B.P. in south-eastern Wisconsin. Mickelson *et al.* (1983) and Attig *et al.* (1989) proposed that drumlins formed via glacial erosion under thawed-bed conditions away from the glacier margin. They suggested that a frozen bed at the glacier margin enhanced compressive ice flow, increased the shearing of sediment to the ice surface, and produced high-relief, broad hummocky moraine complexes. Workers also have proposed that tunnel channels were caused by water escaping through the frozen bed of the glacier margin (Attig *et al.*, 1989; Clayton *et al.*, 1999), perhaps as geothermal heat melted the frozen bed at the glacier margin (Cutler *et al.*, 2000).

Colgan & Mickelson (1997) have suggested that the Green Bay Lobe drumlins did not all form while the ice was at its maximum position, but rather formed in several stages associated with different phases. If this is true, and if permafrost is critical to drumlin formation, then this suggests that ice readvanced over permafrost that redeveloped on the recently deglaciated surface. Abundant ice-wedge-cast polygons on the drumlin surface clearly show that permafrost did redevelop as ice retreated before 13,000 yr B.P. (Colgan, 1996; Clayton *et al.*, 2001). Colgan & Mickelson (1997) cited the absence of tunnel channels associated with these younger ice-margin positions to argue against a catastrophic subglacial flood origin for the drumlins (Shaw, 2002), because if drumlins formed via subglacial meltwater erosion, many flood channels should be associated with the younger phases.

The Kewaunee Formation in eastern Wisconsin is associated with subdued moraines and till plains. Low basal shear stress values for the Green Bay Lobe Chilton and Denmark (late Athelstane) Phases (2 and 3 kPa, respectively) suggest that the ice lobe may have been surging because of elevated subglacial water pressures that enhanced basal sliding and/or subglacial sediment deformation (Socha *et al.*, 1999, Figs 3, 4 and 8). Colgan (1996) described offset moraine segments associated with the Chilton Phase that suggest small-scale surges into proglacial lakes as the ice margin retreated. Attig *et al.* (1998) attributed major changes in ice-flow direction associated with the Chippewa and Wisconsin Valley Lobes to glacial surges (Fig. 2). An example of these flow relationships is observed north of the Perkinstown Phase ice margin in north-central Wisconsin (Fig. 3). Attig *et al.* (1998) proposed that the Chippewa Lobe surged after the Perkinstown Phase to the late Chippewa Phase ice margin, caused discontinuous moraine ridges in that area (Fig. 3), and helped construct the highest relief portion of the Chippewa moraine.

DRIFTLESS AREA

The Driftless Area of south-western Wisconsin is characterised by deep river valleys incised in Palaeozoic bedrock, and this topography is not modified by glacial sediments (Figs 1, 2, Chamberlin & Salisbury, 1885). Baker *et al.* (1998) have shown that these river valleys were eroded as the Mississippi River incised before 780,000 yr B.P. Most early workers accepted that evidence for glaciation was lacking in the Driftless Area, but Black (1970b, c) summarised evidence for glaciation of the Driftless Area, perhaps as recently as Early Wisconsinan time. Mickelson *et al.* (1982) examined Black's evidence for glaciation in the Driftless Area and concluded that no solid evidence supported glaciation of the entire Driftless Area. Hobbs (1999) provides an excellent review of various hypotheses used to explain the origin of the Driftless Area. Chamberlin & Salisbury (1885) supported the idea that bedrock highlands in northern Wisconsin and the Upper Peninsula of Michigan deflected ice to the east and west and 'protected' the Driftless Area from glaciation. Based on numerical ice sheet modeling, Cutler *et al.* (2001) have argued recently that the presence of the deep Lake Superior basin retarded ice advance into central Wisconsin and perhaps funneled ice to the west and east, leaving the Driftless Area unglaciated. Therefore, they conclude that Driftless Area owes its existence to the deep structural basin to its north. Hobbs (1999) proposed that permeable Palaeozoic bedrock dewatered the glacier bed and inhibited ice from flowing into the Driftless Area from the west.

FUTURE WORK

The glacial history of Wisconsin is complex and interesting because it reflects ice advances from both the Keewatin and Labradoran ice domes of the Laurentide and earlier ice sheets. Several major questions about the glacial history still need to be answered. When did ice first advance into Wisconsin? Evidence from Nebraska suggests that glaciers advanced into the central lowlands as early as 2.1 million years ago (Boellstorff, 1978). How many glaciations reached Wisconsin? The marine oxygen-isotope record suggests there were more than a dozen glaciations, far more than can be recognised from the geological record in Wisconsin. Will it ever be possible to date pre-Late Wisconsinan events with any confidence? Cosmogenic isotope dating of buried palaeosol surfaces is one possible technique that has yet to be applied to pre-Late Wisconsinan events. Clearly new methods are needed to answer these basic stratigraphical questions.

Acknowledgments

This paper was strengthened by comments from Lee Clayton, Mark Johnson, Jonson Miller, Charles Hanson, John Attig, Robert Baker, David Mickelson, Carrie Patterson, Barbara

Stiff, and Ardith Hansel. Gene Leisz, Jeremy Treague, and Karen Havholm assisted with figures.

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