The southern Laurentide Ice Sheet

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Changing Attitudes and Approaches

The publication of the *Quaternary of the United States* (Wright & Frey, 1965) for the 1965 INQUA Congress in Denver was a milestone that summarized our knowledge of the Quaternary of the U.S. in a single volume. Glacial geology was a major component of the volume, and it contained 125 pages on the Laurentide Ice Sheet (LIS) in the U.S. In the present volume, almost 40 years later, many fewer pages are devoted to the same topic, indicating the vast increase in other aspects of Quaternary studies. In the U.S., glacial geology has expanded greatly in knowledge and interest, and now glacial geologists have a much richer field and variety of techniques with which to study Quaternary history. The other chapters in this book are a clear indication of the diversity of fields that now make up what traditionally was classified as glacial geology or did not exist before 1965.

Radiocarbon dating remains the most important tool for determining the chronology of the last glaciation. Accelerator mass spectrometry (AMS) has allowed dating of smaller and somewhat older samples. Tree-ring calibration of the radiocarbon time scale has resulted in dating accuracy not possible 40 years ago. Newer dating methods such as thermoluminescence, amino-acid racemization, paleomagnetism, and cosmogenic-isotope methods have yielded mixed results, but have the potential to improve our interpretations of glacial chronology, especially those of the pre-late Wisconsin.

There have been revolutionary changes in the way we study glacial sediments and reconstruct their depositional environments. Genetic classifications have been replaced by descriptive lithofacies approaches, which focus on modern-process analogs for interpretations of depositional environments. Correlations of till units from one area to another are now approached with more caution, and the use of facies models facilitates the understanding of complex glacial sequences. Geophysical techniques have been used to explore lake basins and subsurface stratigraphy. Models of glacial landform genesis are also driven by modern analogs and interpretations made in modern glacier settings.

There have been major changes in our understanding of pre-late Wisconsin events since 1965. The terms "Nebraskan" and "Kansan" are no longer used, and now there is evidence of at least six pre-Illinoian glaciations in the continental record. Flint (1971), in a widely used textbook, hinted that there might be problems with correlations of what was called "Nebraskan Drift," but nevertheless used the terminology accepted at that time. Based on the oxygen-isotope record from the oceans, we now know that there were clearly more than four glacial and interglacial episodes during the Pleistocene. Much work remains to be done to unravel this continental record of early glaciations and correlate them to the ocean record. There has been debate about the extent of the early Wisconsin Glaciation as well. In many areas, particularly in northern Illinois and southern Wisconsin, deposits thought to be of this age now appear to be older.

Probably one reason for our rather poor understanding of pre-late Wisconsin glacial events is the decline of purely stratigraphic studies from the 1980s through the 1990s. State geologic surveys have in many cases reduced their staff and mapping has been displaced by topical studies and an emphasis on applied research related to groundwater and mineral extraction. In academia, traditional mapping and glacial stratigraphy have not been as common in the last 40 years as previously. Instead they have been replaced by, or combined with, studies of sediment genesis, glacial process, development of conceptual and quantitative models, and details of local chronology, and integrative studies of glacial deposits and other aspects of Quaternary history such as ice-marginal lakes, paleoclimatology, loess, soils, and the paleontologic record. In the 1990s the U.S. Geological Survey began to fund mapping projects in academia (EDMAP) and state geologic surveys (STATEMAP), and this has revitalized mapping of glacial deposits in the northern U.S. Since the late 1990s the Great Lakes Mapping Coalition, a joint effort of the U.S. Geological Survey and several state geologic surveys, has focused on detailed three-dimensional mapping that includes subsurface investigation. If this program continues to grow, it may re-stimulate interest in mapping glacial deposits.

Much of our improved understanding of the southern LIS has come from studies of the new field of paleoglaciology. Reconstruction of ice-sheet surfaces, interpretation of former bed conditions and discussions of sliding vs. subglacial deforming beds, estimates of sediment fluxes, interpretations of the nature and distribution of subglacial meltwater, new interpretations of landform genesis, and modeling have all been major areas of research in the last 40 years.

There have been several extensive compilations of the glacial record of the southern LIS since 1965 and we make no attempt to repeat these here. Instead, we highlight what we view as advances in our understanding of the southern LIS and its deposits since publication of the *Quaternary of the United States* in 1965. Events and processes along the southern margin of the LIS are closely tied to the behavior of the ice sheet in Canada, but much of this literature is not discussed here because of the scope of the book. Likewise, we refrain from discussing ancillary topics, like loess and

DEVELOPMENT IN QUATERNARY SCIENCE
VOLUME 1 ISSN 1571-0866
DOI:10.1016/S1571-0866(03)01001-7

the history of ice-marginal lakes, because these are covered elsewhere in the volume.

Mapping and Compilations of Glacial Geology and Geomorphology Since 1965

Since 1965 there have been several comprehensive reviews of the geology and geomorphology of the southern LIS. The "state-of-knowledge" was summarized by Flint in 1971 in part of his classic text. At this time, the deep marine record was only beginning to be discovered. Our understanding of modern ice-sheet dynamics in Greenland and Antarctica was in its infancy, and an understanding of surging glaciers and modern glacial environments was just emerging. Records of global climate change such as ice cores, pollen databases, loess records, and lake cores were fragmentary, few, and far between. Much of what was known was based on the incomplete terrestrial record of continental and mountain glaciation.

Throughout the 1970s and 1980s numerous records of the last glaciation were collected, analyzed, and combined into a global database (e.g. CLIMAP, 1976, 1984; COHMAP, 1988). For the INQUA meeting in Moscow, the U.S. INQUA Committee produced two volumes of edited papers on the Quaternary of the U.S. (Wright, 1983). These include a comprehensive review of the glacial record and a chronology of glacial and periglacial events during the late Wisconsin glaciation (Mickelson *et al.*, 1983). Included were maps showing the nature of the glacier bed, moraines and other ice-margin positions, and a generalized map of landform regions. Andrews (1987) summarized major issues in understanding the whole LIS: the thickness of the ice sheet, the extent of ice during the mid-Wisconsin (marine oxygen isotope stage 3), the timing of the late-glacial maximum, and the chronology of deglaciation. The publication *Quaternary Glaciations in the Northern Hemisphere* (Sibrava *et al.*, 1986), which contains several review papers on deposits of the LIS in the United States (Brown *et al.*, 2001; Eschman & Mickelson, 1986; Fullerton, 1986; Fullerton & Colton, 1986; Hallberg, 1986; Hallberg & Kemmis, 1986; Johnson, 1986; Lasemi & Berg, 2001; Matsch & Schneider, 1986; Stone & Borns, 1986), is the most recently published compilation covering all of the area of the LIS in the United States. Dyke & Prest (1987) and

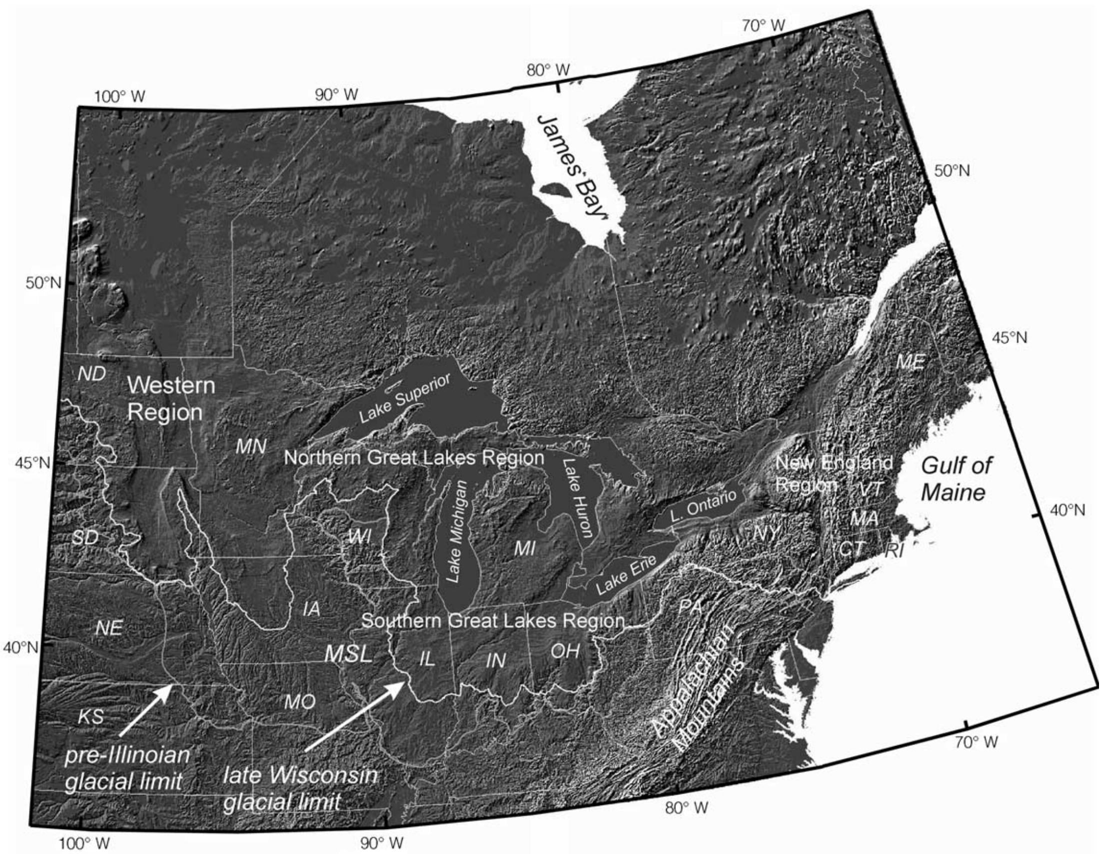

Fig. 1. A shaded relief image created from digital elevation data (USGS ETOPO5) showing southern limits of selected ice advances, location of Great Lakes, and names of states (CT, Connecticut; IA, Iowa; IL, Illinois; IN, Indiana; KS, Kansas; MA, Massachusetts; ME, Maine; MI, Michigan; MN, Minnesota; MO, Missouri; ND, North Dakota; NE, Nebraska; NH, New Hampshire; NY, New York; OH, Ohio; PA, Pennsylvania; RI, Rhode Island; SD, South Dakota; WI, Wisconsin). MSL is location of isotope record of Dorale et al. (1998). Scale in km is given in Fig. 2.

Dyke *et al.* (2002) summarize what is currently known about the extent and timing of the entire LIS during the last glacial maximum.

A major contribution to our understanding of regional aspects of the glacial record is the compilation of Quaternary geologic maps at 1:1,000,000 scale for all of the area. Organized by G.M. Richmond and D.S. Fullerton, these maps, with many authors, are published as U.S. Geological Survey Miscellaneous Investigations Series I-1420. All of the southern LIS is covered by these maps, and although they were in most cases compiled from older mapping, they represent the most up-to-date regional maps available. Soller (1998) and Soller & Packard (1998) published a map of the thickness and character of surficial deposits across the area of the U.S. covered by the LIS. It portrays very thick deposits filling pre-late Wisconsin valleys and in interlobate areas.

Many states have mapping programs that have added to our knowledge of glacial deposits and several different map scales are being used. Much of this mapping has been driven by the need for geologic information to help solve environmental problems or to help locate groundwater and mineral resources. Many states (Fig. 1) also have developed specific derivative maps (e.g. contamination potential, aggregate resources) based on maps of Quaternary deposits. Almost all states have glacial or Quaternary geology maps at 1:500,000 or smaller. A summary of recently active mapping programs is shown in Table 1.

Massachusetts and Connecticut (Fig. 1) have been mapped mostly by the U.S. Geological Survey in cooperation with state agencies, and many of these maps are available at a scale of 1:24,000 as open file reports. Several states have had more limited recent mapping of glacial deposits (Vermont, New Hampshire, Michigan, Iowa, and South Dakota). The U.S. Geological Survey in cooperation with Ohio, Indiana, Illinois, and Michigan recently formed the Central Great Lakes Geologic Mapping Coalition. They are sharing resources to produce detailed (1:24,000) three-dimensional maps of Quaternary deposits in the southern Great Lakes area. This effort is reinvigorating interest in mapping of glacial deposits in the area, and in the future it may extend across all of the area covered by the LIS.

Table 1. Typical map scales used in states with recent published mapping and a representative reference to each.

Illinois	1:100,000 or 1:24,000	Curry *et al.* (1997), Grimley (2002)
Indiana	1:24,000	Brown & Jones (1999)
Maine	1:24,000	Thompson (1999)
Minnesota	1:100,000	Hobbs (1995)
New Jersey	1:24,000	Stanford *et al.* (1998)
New York	1:250,000	Muller & Cadwell (1986)
North Dakota	1:125,000 or 1:250,000	Harris & Luther (1991)
Ohio	1:62,500	Totten (1988)
Vermont	1:24,000	DeSimone & Dethier (1992)
Wisconsin	1:100,000	Clayton (2001)

New Data Sources

During the last four decades the number of new data sources with which to study Quaternary landforms and sediments has increased greatly. These include better topographic maps, digital raster graphics, digital elevation models, remotely sensed data acquired by satellite-based systems, and improved drilling and geophysical techniques. Most of the advances in this area have been driven by advances in satellite technology, low-cost computing power, the increased availability of geographic information systems (GIS), and the efforts of government agencies in creating large spatial databases.

A new series of 1:24,000 U.S.G.S topographic quadrangle maps has made it possible to compare landforms over all of the glaciated United States. These maps are now available as digital raster graphics (DRG) for the conterminous United States, Hawaii and portions of Alaska. By far the most important new data source is the digital elevation model (DEM). These arrays of elevations have revolutionized the way topography can be visualized, categorized, and analyzed. The first 3 arc-second DEMs (1×1 degree) were created from the processing of 1:250,000 scale topographic maps and, as a result, had relatively low spatial resolution (90×90 m), and contained numerous processing artifacts. The most recent series of 30- and 10-meter DEMs have improved on these problems. DEMs allow classification of slope, aspect, and many other parameters of interest to Quaternary scientists. Images derived from the raw DEMs allow the creation of visually stunning shaded-relief views, contour maps, and orthographic perspective views with overlying drapes of color-coded contour intervals or satellite images. Fairly subtle geomorphic features (such as small moraines and flutes) have been discovered from these DEMs. They have also allowed recognition of regional patterns by allowing areas much larger than a single 7.5-minute quadrangle to be viewed at once. An early example of a shaded relief image is the *Digital Shaded Relief Map of the Conterminous United States* (Thelien & Pike, 1989), and a smaller scale one is portrayed in Fig. 1. In the last 10 years numerous workers have used DEMs for mapping glacial features.

Satellite images such as those from the Landsat Multi-spectral Scanner and Thematic Mapper have been used in a few studies (e.g. Boulton & Clark, 1990), but their use has been limited because of their relatively low spatial resolution (~80 and 30 m respectively) compared to traditional low-altitude aerial photography (<1 m). In addition, there are now many other satellite image systems available, producing visible bands, infrared, and radar images. Traditional low-altitude aerial photographs, although still essential for mapping landforms, have always been limited by their lack of georeferencing. Image processing and GIS software now allow all aerial photos (and stereopairs) to be rectified and georeferenced. Traditional low-altitude aerial photographs are very useful because they are available back into the 1930s and can be used in determining land use changes as well as mapping subtle geomorphic features, which are only visible during certain times of the year. Computer mapping from digital sources is now routinely used as GIS software has advanced and because many data sources are now in digital format. This combination of digital data, GIS, and cheap computing power has led to regional scale mapping and landform genesis studies that focus on an entire continent (e.g. Aber *et al.*, 1995; Soller & Packard, 1998).

Geophysical methods have been used to study lake deposits and subsurface geology. Probably the best example is the work of Mullins & Hinchey (1989) and Mullins *et al.* (1996). They used seismic reflection techniques to describe the sediment filling the Finger Lakes of New York. The sediment fills the deep bedrock valleys to depths as great as 306 meters below present sea level. Coleman *et al.* (1989) also provided geophysical data from Lake Michigan to show the thickness of glacial sediment in the south end of the lake.

Advances in Glacial Sedimentology and Geomorphology

In the last 40 years, there have been major advances in the way glacial sediments are studied. In the 1960s classification of glacial sediments was commonly driven by a genetic terminology based on interpretations of depositional environment. Much of the descriptive information about boreholes and outcrops was never published leaving later workers little on which to judge these classifications. Research carried out in modern glacier environments (e.g. Anderson & Sollid, 1971; Boulton, 1970a, b, 1971; Clayton, 1964; Goldthwait, 1974; Hooke, 1970, 1973; Lawson, 1979, 1981) helped to focus glacial geologists' attention on the reconstruction of past depositional environments (e.g. Gustavson & Boothroyd, 1987). In the 1970s and 1980s glacial geologists began to use lithofacies analysis and modern-process approaches similar to those being used by sedimentologists in other fields. At this time the term "diamicton" was more widely used as a purely descriptive term for the several genetic types of till (e.g. lodgment till, meltout till). The papers included within special volume 23 published by the Society of Economic Paleontologists and Mineralogists exemplify the trend toward modern sedimentologic methods in glacial geology (Jopling & McDonald, 1975). Eyles *et al.* (1983) presented an important synthesis of the lithofacies approach and Johnson & Hansel (1990) have since applied this method to the glacial sequence in Illinois.

As advances in glacial sedimentology followed modern trends, so did interpretations of landform genesis. An important early paper by Clayton & Moran (1974) established the idea of the process-form model in glacial geology. They emphasized that glacial-landscape form is directly related to the glacial processes active in the past. They also stressed the fact that glacial environments are composites, including both palimpsest landforms (landforms partially hidden by later forms) and superimposed forms (most recent forms). Finally, they showed that postglacial processes must be understood in order to understand the current form of glacial landscapes.

Our expanding knowledge of the Antarctic and Greenland ice sheets has greatly influenced our current interpretations of the southern LIS margin (e.g. Hughes *et al.*, 1985). Papers included in a 1987 Journal of Geophysical Research Special Volume on fast glacier flow helped to focus attention on the physics of real ice sheets, especially the ice streams and outlet glaciers that drain modern ice sheets (e.g. Bentley, 1987; Clarke, 1987; Raymond *et al.*, 1987; Whillans *et al.*, 1987). Interpretations of the southern LIS have also been influenced by new discoveries on the mechanics of surging glaciers as well as the sediment and bed conditions beneath these enigmatic glaciers (e.g. Clarke *et al.*, 1984; Kamb *et al.*, 1985). The use of modern analogs as a guide to the interpretation of past ice sheets has led to the development of a new field in glacial geology called paleoglaciology.

Paleoglaciology Comes of Age

The study of the physical nature of past glaciers, what is now called paleoglaciology, has blossomed in the last 40 years. There has been a major focus on understanding the paleoclimate, flow dynamics, and physical processes responsible for the landforms and deposits that we see along the southern LIS margin. There are clearly different landform zones across the area covered by the southern LIS (Colgan *et al.*, 2003; Mickelson *et al.*, 1983), but confidently ascribing the formation of certain landforms to a certain set of glaciological conditions has been elusive.

Although there had been a few attempts to reconstruct physical characteristics of the southern LIS previous to 1965 (e.g. Harrison, 1958), Wright's (1973) suggestion that the Superior lobe had a low ice-surface profile and Mathews' (1974) reconstruction of ice-surface profiles in the southwest part of the ice sheet were the first modern attempts at reconstructing ice-surface slopes of lobes of the LIS based on glacial geomorphic data. They represented a major step forward in understanding ice dynamics of the southern LIS. Because ice-surface slope is controlled by, among other things, resistance at the bed, the shape of the ice surface is intimately tied to bed conditions. Was there water present? Was the bed soft and deforming or hard and rigid? Was the ice surging? Were there ice streams? Were there large areas of stagnant ice near the margin or did ice remain active during retreat? Did the nature of the bed control the formation of drumlins, tunnel channels and other landforms? How much were ice-margin fluctuations controlled by climate, and how much was climate controlled by the ice? All of the above questions have been asked and speculated upon from various points of view and we review these below.

Deforming Bed or Sliding of Basal Debris-Rich Ice?

Subglacial sediment transport mechanisms have been a focus of research all over the world, and the southern LIS is no exception. Since the importance of a soft deforming bed was suggested by, among others, Boulton & Jones (1979) and

Boulton & Hindmarsh (1987), for glaciers in general, and Alley *et al.* (1986, 1987) for Whillans Ice Stream (formerly Ice Stream B), the extent and thickness of a wet, deforming bed beneath the southern LIS have been debated. Boulton & Jones (1979) suggested that the south margin of the LIS was very thin because of low basal shear stress (ca. 5 kPa). Beget (1986) suggested a conceptual model for the Lake Michigan lobe that incorporated a combination of sliding and soft sediment deformation. He suggested that deforming till with a low yield strength (*ca.* 8 kPa) produced ice-surface profiles with an ice thickness of only 500 m about 200 km north of the terminus. Alley (1991) hypothesized that all of the southern LIS was underlain by a thick deforming layer and further argued that thick till in ice marginal areas could only be explained by the high sediment fluxes produced by a soft deforming bed. Clark (1992a), building on the approach of Mathews (1974), stressed the widespread distribution of low ice-surface slopes and related these to the existence of a soft deforming bed. This concept was expanded (Clark, 1994, 1997) when he pointed out the interrelationships between the distribution of sedimentary bedrock, and the continuity of soft, fine-grained sediments, low driving stresses, and relative lack of eskers that would have formed in "R" channels. Colgan & Mickelson (1997) and Colgan (1999a) showed that ice-surface profiles in the Green Bay lobe changed with time and profiles were probably steepest during the LGM and during readvances. Ice surface slopes were very low during retreat. Another approach was taken by Hooyer & Iverson (2001), who combined field observation and experiments of deformation in a ring shear device. Ice-surface profiles of the southeastern LIS have also been reconstructed by Ridky & Bindschadler (1990) in the Ontario lobe and by Shreve (1985) in Maine.

A major issue has been the interpretation of evidence of deformation from the sediments themselves. We cannot review all of the literature on this topic, but some is pertinent to the southern LIS. Clearly diamictons have been deformed. The issue of whether the deformation was as a thick wet sediment layer, a very thin wet sediment layer, or as debris-rich ice is still debated (Piotrowski *et al.*, 2001). Clayton *et al.* (1989) have argued that careful examination of the sediment record suggests that if a soft deforming bed were present, it must have been a thin layer based on the continuity of sedimentary layers and the presence of sand lenses and sand clasts in diamicton. They suggest that most sediment was transported as debris-rich ice and deposited as meltout till, based mostly on observations along the southwest edge of the ice sheet and in the Green Bay lobe (Fig. 2). In fact, there may be real differences between the sediments deposited in the far southern part of the ice sheet, in Ohio, Indiana, and Illinois, compared to just a short distance farther north. The landform record is certainly different (Colgan *et al.*, 2003;

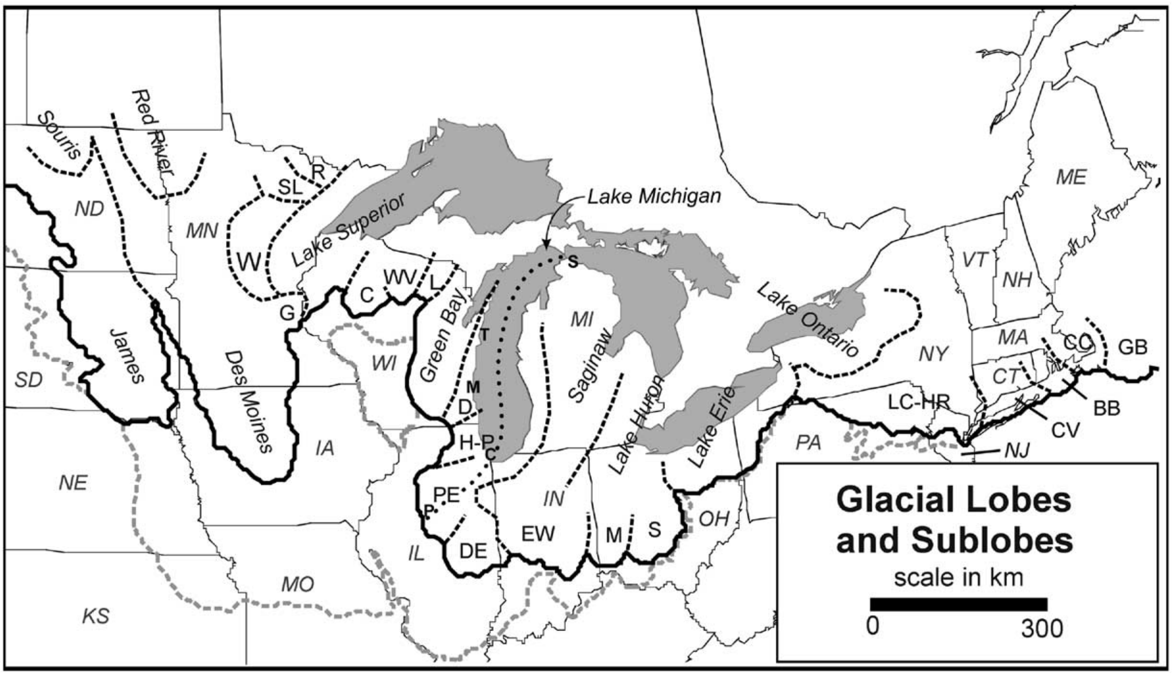

Fig. 2. Glacial lobes and sublobes of the southern Laurentide Ice Sheet during the late Wisconsin Glaciation. State abbreviations are explained in caption of Fig. 1. Major lobes are labeled and sublobes are as follows: G = Grantsburg, W = Wadena, SL = St. Louis, R = Rainey, C = Chippewa, WV = Wisconsin Valley, L = Langlade, D = Delevan, H-P = Harvard-Princeton, PE = Peoria, DE = Decatur, EW = East White, M = Miami, S = Scioto, LC = Lake Champlain, HR = Hudson River, CV = Connecticut Valley, BB = Buzzards Bay, CC = Cape Cod, GB = Georges Bank. Dotted line along axis of Lake Michigan lobe shows location of time-distance diagram shown in Fig. 3 (P, Peoria; C, Chicago; M, Milwaukee, T, Two Rivers; S, Straits of Makinac). Latitude and longitude are given in Fig. 1. Light dashed line shows the maximum limit of the ice-sheet.

Mickelson *et al.*, 1983), and modeling (discussed below) also suggests there were substantially different subglacial conditions from north to south in the southern LIS.

There have been relatively few detailed sediment descriptions, and even then, they describe deformation features without a definitive demonstration of conditions under which the sediments were deformed. Hicock & Dreimanis (1992a) examined three widespread diamicton units on the north sides of Lakes Ontario, Erie, and Superior where pre-advance lake sediment was overridden and incorporated into the sediment. They found evidence of viscous, ductile and brittle deformation based on fold types and orientation, fractures, the nature of striations on clasts, distribution of sand clasts, and other sedimentary features and concluded that there was evidence for soft-sediment deformation, but also deposition by lodgement of basal melt-out. They suggest that the evidence of the relative importance of deforming soft bed and sediment deposition from debris-rich glacial ice is indeterminate. Based on laboratory measurements, reconstructed ice-surface profiles, effective stress reconstructions, and clast fabrics, Hooyer & Iverson (2003) suggest that plowing was an important process at the base of the Des Moines Lobe (Fig. 2). In the area covered by the southern Lake Michigan lobe (Fig. 2), diamicton genesis has been studied extensively at Wedron, Illinois (Hansel & Johnson, 1987; Hansel *et al.*, 1987; Johnson & Hansel, 1990) and later at other sites (Hansel & Johnson, 1999). Although these authors point out that there is still room for doubt about the origin of much of the diamicton in moraines in Illinois, they favor accumulation of subglacially deformed wet sediment as a primary mechanism of deposition. They base this on the consistency of their observations with theoretical predictions of what the sedimentary record should resemble. In particular, they cite the uniformity of the till, the lack of supraglacial sediment in moraines, local derivation of homogeneous diamicton, characteristics of multiple channel fills, orientation of pebbles plunging down ice or into channels, and pebble concentrations on contacts as evidence of a deforming bed.

The deforming bed model has also been incorporated into two-dimensional numerical simulations of ice-sheet behavior along the Lake Michigan lobe flow line (Clark *et al.*, 1996; Jensen *et al.*, 1995, 1996) by assuming no sliding and a viscoplastic behavior of subglacial sediment. Hard bed and deforming bed were two end member conditions used, and strength properties of the subglacial sediments were assumed to be similar to properties of the present day till measured by Vela (1994). As predicted by Boulton & Jones (1979) (the "bowler hat" model), the ice surface on the up-ice, hard-bed end of the profile has a steeper ice-surface gradient and higher driving stress than the deforming soft bed. Modeling of sediment flux indicates that there would be sufficient velocity to produce the large sediment fluxes estimated by Johnson *et al.* (1991) only under a fairly narrow range of subglacial pore pressures. An important contribution of the modeling is the suggestion that the rapid ice-margin fluctuations documented in the southern part of the Lake Michigan lobe might be controlled by slight changes in subglacial sediment viscosity as opposed to being directly driven by climate change. The physical behavior of southern LIS lobes is still poorly known and recent numerical reconstructions of the LGM LIS by Marshall *et al.* (2002) fail to reproduce the known configuration of the southern margin because present numerical models do not reproduce all the lobe-scale processes of a real ice sheet.

Temperature Conditions at the Glacier Bed

There appear to have been distinct differences in the nature of the glacier bed across the southern LIS (Colgan *et al.*, 2003; Mickelson *et al.*, 1983) in addition to the "hard bed/soft bed" differences described above. In the far southern area (Ohio, Indiana, and Illinois), and in younger readvance deposits around the Great Lakes, the landscape is dominated by wide moraines with low internal relief. Between the moraines are flat till plains with only a few low flutes locally present (Hansel & Johnson, 1999). North of about the latitude of Chicago (Fig. 1), the end moraines have higher relief, and drumlins dominate the landscape between moraines. Tunnel channels (or valleys) are abundant to the north and rare, or absent, farther south. Drumlins and tunnel channels occur in areas where there was a soft bed as well as a hard bed, so some other explanation for the huge differences in landscape must be involved.

An explanation for this remarkable difference in subglacial landscape is likely the presence or absence of permafrost during ice advance, and therefore basal ice temperatures in the marginal zone of the ice sheet. The last twenty years has seen growth in our knowledge of the extent and effects of permafrost along the south margin of the LIS. The most convincing evidence of permafrost includes fossil ice-wedge casts and ice-wedge polygons seen in aerial photographs (Péwé, 1983). Such features are relatively common in Ohio (Konen, 1995), Illinois (Johnson, 1990), Wisconsin (Clayton *et al.*, 2001), Minnesota (Mooers, 1990b), Iowa (Walters, 1994), and in the Dakotas (Clayton *et al.*, 1980) and have been dated at between 21,000 and 16,000 ^{14}C yr B.P. Baker *et al.* (1986) showed that a boreal forest/tundra transition zone was present in southeast Iowa at between 18,090 and 16,710 ^{14}C yr B.P. based on abundant plant and animal fossils preserved in a silt-filled swale. In the east, an extensive permafrost zone is suggested by numerous periglacial phenomena in the Appalachian Plateau and Ridge and Valley province just south of the glacial border (Clark & Ciolkosz, 1988).

Ice-wedge casts on till surfaces in the southern parts of the Lake Michigan, Saginaw, and Huron lobes (Fig. 2) (Johnson, 1990) indicate the presence of permafrost, but it seems likely this was established during retreat from the glacial maximum, not during advance. Numerous radiocarbon dates on *Picea* wood indicate a lack of continuous permafrost during advance to the maximum. Ice-wedge casts are widespread farther north in Wisconsin and presumably in the remainder of the northern part of the U.S. covered by the LIS (Péwé, 1983). Recently, a two-dimensional model has been adapted to the topography and reconstructed climate of the Green Bay lobe in eastern Wisconsin. The climate record used to drive the advancing ice is a speleothem record from the vicinity of St. Louis (MSL on Fig. 1) (Dorale *et al.*, 1998). The model clearly demonstrates the development of permafrost in front of the advancing ice and that the permafrost slowly disappears after being covered by ice, taking several thousand years to do so (Cutler *et al.*, 2000, 2001). The model is at present being adapted to other southern LIS lobes, but the use of models for anything but the most crude representations of what actually took place is limited by our lack of good climate information. Although there are several fossil-derived climate records in the southern LIS area that extend back into or beyond the late Wisconsin (Baker *et al.*, 1986; Birks, 1976; Curry & Baker, 2000), they only constrain temperature somewhat and provide almost no information about precipitation. So far, the only semi-quantative information on precipitation is what is generated by global climate models.

It seems likely that distribution of drumlins and tunnel channels, and the internal relief of end moraines are closely tied to the difference in permafrost history from north to south. Although there are some small drumlins that may be depositional features, many drumlins show evidence that widespread subglacial erosion carved them out of pre-existing sediments by freeze-on to the base of the ice, by streaming subglacial sediment, or flowing water (Attig *et al.*, 1989; Boyce & Eyles, 1991; Colgan, 1999a; Newman & Mickelson, 1994; Whittecar & Mickelson, 1979). The drumlins in the northern part of the area covered by the southern LIS may have formed during disappearance of the frozen bed beneath the ice sheet, which would have produced an inhomogeneous bed allowing the drumlins to form by differential erosion and deposition (Cutler *et al.*, 2000; Stanford & Mickelson, 1985). Colgan & Mickelson (1997; Colgan, 1999a) demonstrated that advances of the Green Bay lobe that produced drumlins had steeper ice-surface profiles than advances that did not produce them, suggesting that driving stress and therefore bed resistance, was higher in the drumlin forming areas than in areas of flat till plains.

It has also been suggested that the permafrost wedge near the glacier margin was instrumental in the development of tunnel valleys or channels, although there is continuing debate about the genesis of these features. Wright (1973) suggested that tunnel valleys drained water catastrophically from beneath a wet bed glacier that had a frozen bed zone around its edge. Much the same explanation for these features was used by Patterson (1994), Clayton *et al.* (1999), and Cutler *et al.* (2002). Mooers (1989), however, has argued that the tunnel valleys in the area covered by the Superior lobe (Fig. 2) are valleys that were cut by relatively small, non-catastrophic flows that eroded their banks as channels migrated laterally, producing a wide channel under wet bed conditions. Neither of these interpretations of tunnel channel formation requires the huge, widespread, sheet flows of water that are discussed below.

The nature of internal relief in moraines also increases from south to north in the area covered by the southern LIS. The internal relief apparently is related to the thickness of sediment that accumulated on the ice surface during still stands of the ice margin. It has been postulated that this thick supraglacial sediment was a result of a frozen bed near the ice margin which caused compressive flow and upward movement of sediment within the ice. Subsequent melting out would have produced a thick sediment cover over stagnant ice that later collapsed (Ham & Attig, 1996).

Extent and Thickness of a Subglacial Water Layer

The presence of subglacial water, its abundance, and its importance in forming large-scale subglacial landforms has been much debated in the last 40 years. Although probably accepted by only a minority of researchers, the idea that large subglacial floods (megafloods) occurred under much of the southern LIS has been argued on theoretical grounds (Shoemaker, 1992a, b, 1999) and from field evidence (Shaw, 1989; Shaw *et al.*, 1989; Shaw & Gilbert, 1990; Shaw & Sharpe, 1987). These papers interpret drumlins and a variety of other streamlined and transverse forms as bed forms developed by a sheet of subglacial water flowing rapidly toward the margin for a relatively short time. In southern Ontario, a series of interdrumlin channels, called tunnel channels by Brennand & Shaw (1994), appear to be distinctly different than tunnel channels described by Clayton *et al.* (1999). Brennand & Shaw (1994) suggest that the channels were eroded by waning flows of the thick water layer as the glacier bed came back into contact with the landsurface. The question remains: Were there deep water sheet flows from beneath the southern LIS or were these catastrophic flows confined to tunnel channels? Clearly there were catastrophic floods of subglacial water, but most evidence suggests that the flows were channelized in tunnels or valleys (Clayton *et al.*, 1999; Pair, 1997) and were not widespread water layers tens-of-meters thick.

Other Aspects of Ice Dynamics

Along with the concepts of gentle ice-surface slopes and deforming beds, the idea that advances of lobes of the southern LIS were surges or longer lasting ice streams has been argued. Unfortunately the chronology of advances and retreats, even where relatively well controlled by radiocarbon age determinations, is not detailed enough to accurately determine advance and retreat rate in most places. Clayton *et al.* (1985) estimated glacier margin advance and retreat rates during deglaciation in the southwestern area covered by the LIS of about 2 km/yr, somewhat higher than 0.7 km/yr estimated by Mickelson *et al.* (1981). These rapid rates are calculated for the later stages of deglaciation, after about 14,000 ^{14}C yr B.P. It has been suggested by many that as climate warmed during deglaciation, bed conditions changed, and that there were numerous retreats and readvances in a relatively short time, indicating very active, fast-flowing ice. This change in bed conditions appears to have migrated northward between 14,000 and 11,000 ^{14}C yr B.P., producing a different landform record than earlier advances (Mickelson *et al.*, 1983; Mooers, 1990a, b) when temperatures were colder.

Another indicator of former surges in the southwestern part of the ice sheet is the sediment and landform record. Thrust masses (Bluemle & Clayton, 1984) and thick supraglacial sediment (usually indicated by high-relief hummocky topography) indicate compressive flow and upward movement of sediment that was melted out at the ice surface. These features are common in modern glaciers that have surged and have been used as an indicator of surging in the southwest part of the LIS where clayey till is present (Clayton *et al.*, 1985; Colgan *et al.*, 2003). Evans *et al.* (1999) have attributed similar features, farther to the north in Alberta, Canada, to surging of the ice sheet by analogy with Icelandic glaciers. Ice streams feeding the Des Moines and James lobes (Fig. 2) have also been proposed for the southwestern part of the LIS by Patterson (1998).

The origin of high-relief hummocky topography, which is widespread in the area covered by the southern LIS, continues to be an issue of debate. The traditional view that it reflects thick supraglacial sediment (Clayton & Moran, 1974; Gravenor & Kupsch, 1959) has been challenged by resurrecting an older alternate hypothesis (Stalker, 1960) that suggests that hummocks are pressed forms developed on a soft deforming bed (Eyles *et al.*, 1999a, b). It has also been proposed that they were eroded by a megaflood beneath the ice (Munro-Stasiuk & Sjogren, 1999).

Chronology and Climate History

Since publication of *Quaternary of the United States* (Wright & Frey, 1965) there have been many advances in our understanding of the timing of events along the southern margin of the LIS. These advances include knowledge of the number and timing of pre-Wisconsin glaciations, the extent of an early Wisconsin glaciation, and details of the timing of late Wisconsin advances.

By the late 1960s and early 1970s it was becoming clear that the classic four-fold North American Stage terminology had become inadequate to describe the complexity of pre-Wisconsin glacial deposits (e.g. Dort, 1966; Reed & Dreezan, 1965). During the 1970s, fission-track dating applied to Yellowstone ashes interbedded between glacial tills of the central plains, showed that the terms Nebraskan and Kansan had little stratigraphic meaning, since five pre-Illinoian tills were documented, at least one older than 2 million years (Boellstorff, 1973, 1978). In Iowa and Nebraska, some tills previously classified as Kansan were proven to be older than those called Nebraskan (Boellstorff, 1973, 1978). During the 1980s, paleomagnetism (Easterbrook & Boellstorff, 1984) further helped to define the till stratigraphy in the classic type areas of the Nebraskan and Kansan sediments now informally referred to as pre-Illinioan (Hallberg, 1986) or early to middle Pleistocene (Richmond & Fullerton, 1986). As it stands now, at least six till units are recognized in the central plains region and tephrochronology, paleomagnetism, and paleopedology are increasingly being used to shed light on the pre-Illinoian record of the southern LIS (e.g. Aber, 1991; Colgan, 1999b; Guccione, 1983; Rovey & Keane, 1996).

The interpretation of younger Illinoian and Wisconsin stratigraphy has also experienced change in the last two decades. Tills formerly thought to be early Wisconsin have recently been reinterpreted as Illinoian in many key locations where they were first described, such as Illinois, Indiana, and Ohio (Fig. 1) (Clark, 1992b; Clark *et al.*, 1993; Goldthwait, 1992). These conclusions are based on reinterpretations of loess records and paleosols (Curry, 1989), and new dating techniques such as thermoluminescence and amino-acid methods (Miller *et al.*, 1992; Szabo, 1992). Because absolute dates are few and these methods are still problematic, many of these reinterpretations need to be tested. Debate has also focused on the extent of the early Wisconsin (OIS 4) LIS near Lake Ontario with some arguing that ice remained north of the lake (Eyles & Eyles, 1993), and others arguing that ice was grounded in the lake and advanced south of the lake (Dreimanis, 1992; Hicock & Dreimanis, 1989, 1992b). In New England (Fig. 1), tills older than late Wisconsin have been interpreted as both Illinoian (Newman *et al.*, 1990; Oldale & Coleman, 1992) and early Wisconsin (Colgan & Rosen, 2001; Stone & Borns, 1986). Unfortunately, the problem of the extent of an early Wisconsin advance is and will continue to be plagued by a lack of reliable dating methods that are effective beyond the 50,000-year range of radiocarbon. Hopefully future investigations with new dating methods will help solve the uncertainty in the extent of the early Wisconsin LIS.

The late Wisconsin history of ice advance and retreat continues to be refined with more radiocarbon dates, and new radiocarbon methods. A recent compilation of radiocarbon dates shows that the LGM southern LIS margin continues to be the best-dated ice margin in the world (Dyke *et al.*, 2002). Accelerator mass spectrometry (AMS) has allowed for smaller sample sizes and dates in areas where wood samples are rare (e.g. Maher *et al.*, 1998), but with smaller sample sizes come the problems of contamination and reworking of older materials. Tree-ring and coral-based calibration of radiocarbon dates has greatly improved the accuracy of dates younger than ~20,000 ^{14}C yr B.P. (Stuvier & Reimer, 1993; Stuiver *et al.*, 1998a, b). As was suggested by Mickelson *et al.* (1983), much less is known about the initial advance of the ice margin to its LGM position than is known about its subsequent retreat.

Much of the late Wisconsin chronology detailed by Mickelson *et al.* (1983) remains the same. Ice advanced into the northern U.S. about 26,000 ^{14}C yr B.P., yet the LGM extent was reached at different times in different places. Lobes in the Great Lakes and New England regions reached their maximum well before 21,000 ^{14}C yr B.P. Rapid decay of the ice sheet began after 14,500 ^{14}C yr B.P. Although lobes to the west of the Great Lakes also advanced before 21,000 ^{14}C B.P., they reached their maximum extent at about 14,000 ^{14}C yr B.P., out of phase with the rest of the ice-sheet margin (Hallberg & Kemmis, 1986). Readvance of lobes, some perhaps as surges, are recorded all along the southern LIS margin at 13,000 ^{14}C yr B.P., 11,800 ^{14}C yr B.P., and

9800 ^{14}C yr B.P. Ice retreated out of the northern U.S. shortly after 9800 ^{14}C yr B.P.

Advances in our knowledge of ice sheet chronology have occurred in New England also. In southern New England the date of the earliest advance is recorded by the youngest dates (~21,750 ^{14}C yr B.P.) found in the ice-thrust moraines of Long Island (Sirken & Stuckenrath, 1980). Retreat of the ice began at about 15,600 ^{14}C yr B.P. based on the number of varve years recorded in Glacial Lake Hitchcock and AMS dates at the north end of the lake (Ridge & Larsen, 1990; Ridge *et al.*, 2001). Numerous dates in coastal Maine have continued to refine ice-retreat history, retreat rates, and sea-level history (see papers in Retelle & Weddle, 2001).

In the Great Lakes regions, new dates have refined our knowledge of the deglaciation chronology (Attig *et al.*, 1985; Ekberg *et al.*, 1993; Hansel & Johnson, 1996) and revisions to the long established stratigraphic classification in Illinois have been adopted (Johnson *et al.*, 1997; Karrow *et al.*, 2000). The Lake Michigan lobe may have advanced to a maximum position as early as ~26,000 ^{14}C yr B.P. along its northwest edge (Hansel & Johnson, 1996), and then, subsequently retreated and readvanced to near its LGM position at ~22,500, 18,500, 17,500, and 15,500 ^{14}C B.P. Hansel & Johnson (1992) produced a time-distance diagram for the axis of the Lake Michigan lobe that is reproduced with slight modification in Fig. 3. It shows slightly different maximum advance times. Mickelson *et al.* (1983) assumed that glacial retreats and readvances along the southern LIS margin were synchronous because they could see no clear evidence otherwise. Lowell *et al.* (1999) have recently shown that most of the glacial retreats in this region were synchronous based on analyses of numerous radiocarbon dates. Lowell *et al.* (1999) and Clark *et al.* (2001) also show that advances and retreats of the southern LIS margin can be correlated with climate events recorded in the Greenland ice cores. This suggests that both the southern LIS and the Greenland Ice Sheet were responding to changes in North Atlantic climate. Although their results are convincing, as in the past, it has been extremely difficult to prove synchrony because of the inherent uncertainty in the radiocarbon method (as much as 1500 years in samples older than 10,000 years).

Cosmogenic isotope methods have recently been applied to late Wisconsin landscapes in New England (Larsen, 1996), the Great Lakes region (Colgan *et al.*, 2002), and along the southwestern LIS margin (Jackson *et al.*, 1997, 1999). Larsen (1996) dated a boulder resting on the LGM end moraine in New Jersey and estimated its exposure time as about 21,500 yr, consistent with the radiocarbon chronology. Colgan *et al.* (2002) sampled striated bedrock overridden by the Green Bay lobe in Wisconsin and found that ice began to retreat from its LGM margin probably well before 17,000 yr ago. They also found that bedrock near the ice margin contained inherited isotopes that made cosmogenic dating near (within 30 km) the margin impossible. Jackson *et al.* (1997, 1999) showed

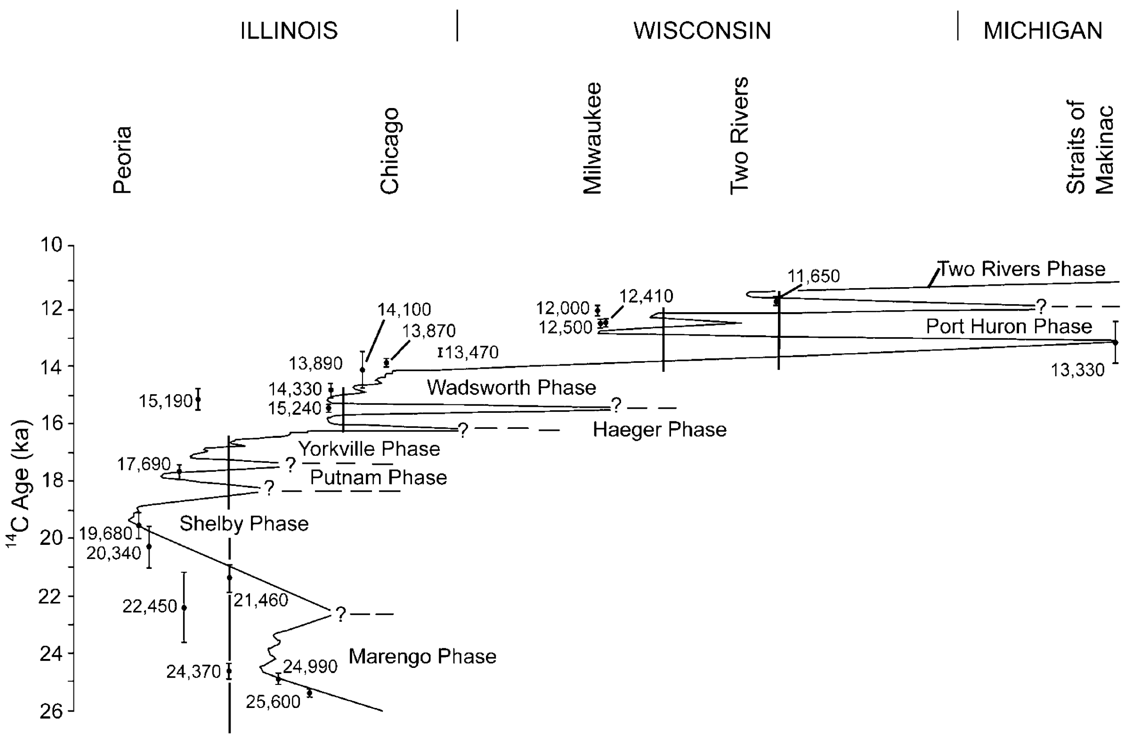

Fig. 3. Time-distance diagram showing glacial phases during the late Wisconsin glaciation in the Lake Michigan lobe. Representative radiocarbon age control (not calender years) is shown. Locations of the flow line and points on the flow line are shown in Fig. 2. Modified from Hansel & Johnson (1992).

that the southwestern LIS margin reached its greatest extent during the LGM sometime before 18,000 yr ago. These methods hold the promise of more closely limiting the age of glacial events if the problems of inheritance can be overcome, and uncertainty in isotope production rates can be reduced.

The amount of information about global climate history has exploded in the last 40 years. The deep-ocean drilling program of the late 1960s to the present has provided a detailed record of glacial and interglacial stages over the last 2.4 million years (e.g. Broecker & van Donk, 1970; Shackelton & Opdyke, 1973). The variations in ice sheet size and sea level history have been tied to changes in solar insolation driven by changes in Earth's orbit (e.g. Hays *et al.*, 1976). Ice cores from both Antarctica and Greenland have also produced detailed records with both excellent resolution and age control (e.g. Stuvier & Grootes, 2000). These records suggest that climate is driven by changes in solar insolation, internal ice sheet dynamics, changes in ocean currents, and changes in atmospheric composition (Mayewski *et al.*, 1997).

It is also apparent, based on the ocean record, that the LIS has discharged massive numbers of icebergs about every 5000–7000 years into the North Atlantic (Broecker *et al.*, 1992; Heinrich, 1988). Workers along the southern margin of the LIS have correlated local ice-lobe behavior to Heinrich events (Mooers & Lehr, 1997; Mullins *et al.*, 1996). Rapid drawdown in ice over Hudson Bay may have shifted ice divides and caused retreats along the southern LIS margin (Mooers & Lehr, 1997). It is clear from what we know about the chronology that ice retreated in many southern lobes shortly after the three youngest Henrich events ∼21,000 (H2), 14,500 (H1), and 11,000 yr ago (H0 or Younger Dryas). These new studies that link southern LIS behavior to that of other ice sheets and major climate events is beginning to illuminate how the LIS responded to and influenced global climate. Future work along the LIS will continue to try to link the advances and retreats of lobes to both internal and external forcing mechanisms.

Conclusions

Glacial mapping and new data sources have led to a renewed interest in Quaternary mapping. Applied research helps to support new mapping initiatives. Glacial geology has become much more diverse, more oriented to global issues, and more connected to modern studies in paleoclimatology, glaciology, and sedimentology than in the past. Glacial sedimentology has flowered and embraced modern-process analogs and work in modern glacial environments.

Glacial geologists have used new information about the physics of modern ice sheets and glaciers to found a new discipline called paleoglaciology. This field has led the way in producing new models of past ice sheets. The late Wisconsin southern LIS consisted of thin, gently sloping lobes with low driving stresses. The southernmost lobes had a wet bed to the margin and surges were probably common. Ice lobes in lowlands may have been fed by ice streams. Farther north, ice advanced over permafrost and had a frozen bed near the margin. Not until after the late glacial maximum did ice warm to the margin. There are profound differences in the distribution and character of landforms such as moraines, drumlins and tunnel channels and likely there were differences in subglacial processes, with a soft deforming bed occurring in places, and sliding dominating in others.

There is general agreement that the pre-Wisconsin stratigraphic record is much more complex than thought in 1965. The terms "Nebraskan" and "Kansan" are no longer used, and the term "pre-Illinoian" is used in their place. The extent of early Wisconsin and mid-Wisconsin ice is now thought to have been less extensive than previously interpreted. A wide array of global climate records shows that the LIS responded to climate changes and may have also caused changes in climate because of discharges of meltwater and icebergs into the North Atlantic. Heinrich events may be correlated to major retreats of the southern LIS margin at about 21,000, and 14,500 ^{14}C yr B.P.

Acknowledgments

We thank Ardith Hansel and Thomas Lowell for their comments and constructive ideas on the manuscript. Richard Berg and Donald Luman also provided helpful comments, especially on the GIS and mapping discussion. Cornelia Winguth, Ben Laabs, Hans Hinke, and Steve Kostka kindly read and corrected near final drafts of the manuscript. We apologize to the many scientists who have contributed to our knowledge of the LIS during the last 40 years, but who are not cited here. Space limitations required that only representative references be cited.

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