Geological Society of America
Special Paper 337
1999

Origin of the Driftless Area by subglacial drainage—a new hypothesis

Howard Hobbs
Minnesota Geological Survey, 2624 University Avenue, St. Paul, Minnesota 55114

ABSTRACT

There is no evidence that the Driftless Area of southwestern Wisconsin was ever covered by continental ice sheets, even though they extended far to the south in the Midcontinent region. The Driftless Area occupies the eastern part of the Paleozoic Plateau, a relatively high area of Paleozoic sedimentary bedrock that is generally permeable, and is deeply dissected by the Mississippi River and its tributaries. Bedrock of the Paleozoic Plateau acted as a giant sieve that was able to dewater the base of advancing ice. The exposed bedrock created pinning points that inhibited ice advance across the Paleozoic Plateau. Ice therefore flowed around the eastern and western margins of the Driftless Area, and continued its advance as far as southern Illinois and central Missouri. The southern extent of Midcontinent glaciation has been attributed in part to low subglacial shear stress associated with deformable substrates, and high pore-water pressure. This giant sieve hypothesis provides a speculative explanation for the origin of the Driftless Area.

THE DRIFTLESS AREA

The Driftless Area (Fig. 1) of southwestern Wisconsin and small adjacent parts of southeastern Minnesota and northwestern Illinois lacks a cover of glacial till and erratics (Chamberlin and Salisbury, 1885). There is no positive evidence for it ever having been covered by continental ice sheets. Bedrock within the Driftless Area is now covered by Quaternary sediment; the uplands are mantled by loess, and the lowlands locally contain glacial lake sediment. Some valleys within the Driftless Area contain outwash derived from ice sheets. The stream-dissected, bedrock-dominated uplands of the Driftless Area contrast sharply with most of the surrounding terrain, which has been smoothed and mantled by glacial sediment during repeated glaciations, and in which bedrock is only rarely exposed at the surface. The topography and Quaternary sediments of the Driftless Area would be quite unremarkable if juxtaposed with the dissected topography south of the glacial limit in the Midcontinent region. According to Black (1960, 1970a, b) the entire Driftless Area was covered by ice at least several times, most recently in an Early Wisconsinan event that he termed the Rockian. Black's (1960, 1970a, b) ideas have been subsequently refuted (Knox, 1982; Knox and Attig, 1988).

The topographic boundary of the Driftless Area does not coincide perfectly with the absence of glacial sediment. There is a pseudo-driftless area (Fig. 1, dark stipple) west of the Mississippi River in Iowa and Minnesota; it is geomorphically indistinguishable from the Driftless Area, but contains erratics and patches of old till on the uplands (Chamberlin and Salisbury, 1885; Trowbridge, 1966; Hobbs, 1984). The pseudo-driftless area was covered by pre-Illinoian ice sheets but not by more recent ones. The pseudo-driftless area also has been dissected by tributaries of the Mississippi River, especially in Minnesota and Iowa. The boundary between areas of patchy till and those areas from which till is absent can only be determined by detailed fieldwork. The hypothesis presented here to explain the origin of the Driftless Area also explains why the pseudo-driftless area has not been affected by more recent glaciations.

The region underlain by topographically high Paleozoic sedimentary rock in the vicinity of the Driftless Area is the Paleozoic Plateau (Hobbs, 1992). Paleozoic Plateau was first used in a more restricted sense to mean the pseudo-driftless area of Iowa (Prior, 1976). Almost all of the Driftless Area is included within the area of the Paleozoic Plateau, but a considerable amount of the Paleozoic Plateau also has been glaciated. The extent of the Paleozoic Plateau is approximated on Figure 1 by a light stipple,

Hobbs, H., 1999, Origin of the Driftless Area by subglacial drainage—a new hypothesis, *in* Mickelson, D. M., and Attig, J. W., eds., Glacial Processes Past and Present: Boulder, Colorado, Geological Society of America Special Paper 337.

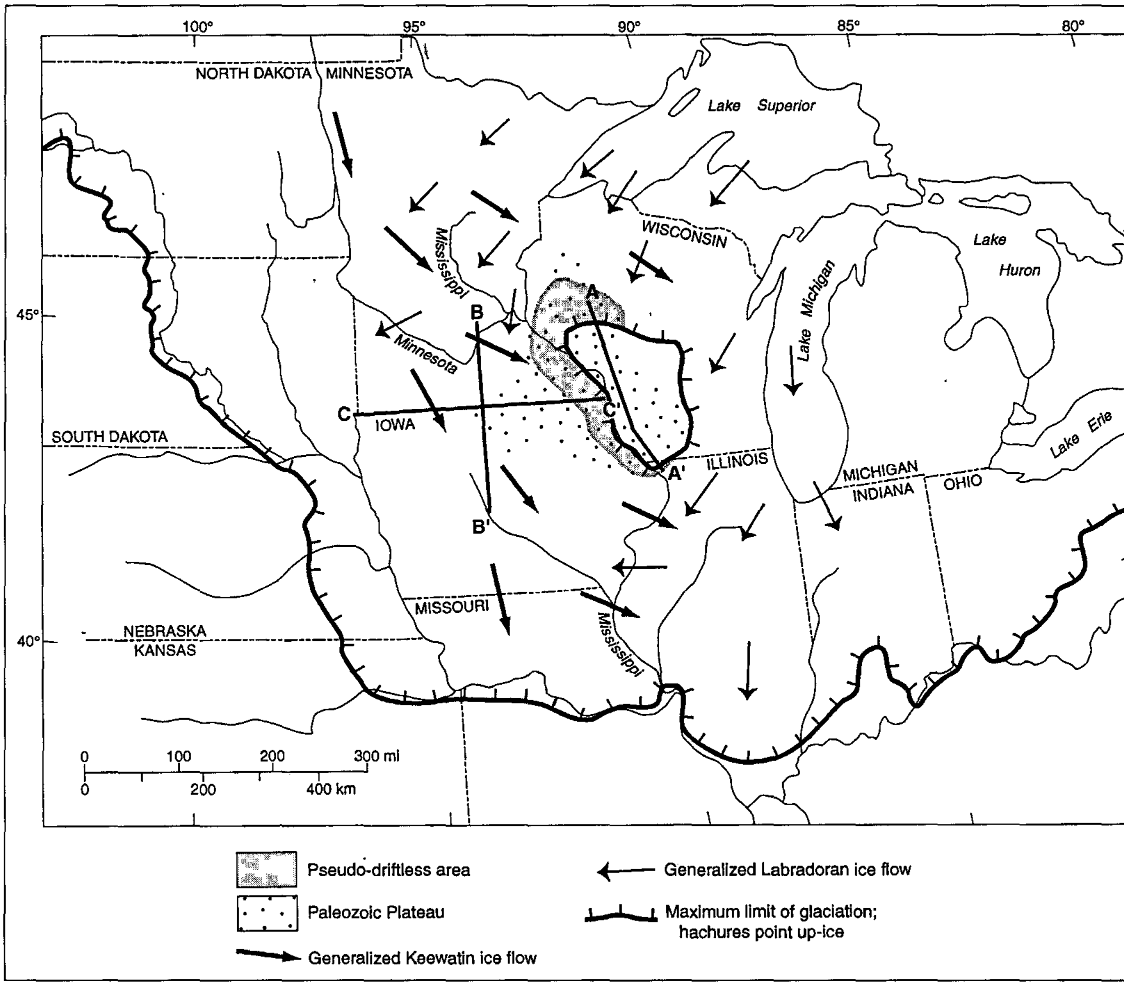

Figure 1. Map of the Midcontinent region showing maximum limit of Late Cenozoic glaciation and location of the Driftless Area and the Paleozoic Plateau. Ice margins were sketched from the Quaternary Geologic Atlas of the United States (U. S. Geological Survey Miscellaneous Investigations Series I-1420, sheets NJ-14, NJ-15, NJ-16, NJ-17, NK-14, NK-15, NK-16, NK-17, NL-14, NL-15) and modified from the author's experience in southeastern Minnesota. The extent of the Paleozoic Plateau was compiled from Morey et al. (1982), Mossler (1983), and the maps of bedrock topography in Iowa (U.S. Geological Survey Miscellaneous Geological Investigations Maps I-717, I-933 and I-1080). Generalized ice flowlines are from several glaciations. A–A′ and B–B′ are profiles shown in Figure 3. C–C′ is profile shown in Figure 4.

which shows the area underlain by Paleozoic rocks that lie above 300 m in elevation. The type and extent of bedrock in Minnesota and Wisconsin is shown by Morey et al. (1982).

PREVIOUS MODELS FOR THE ORIGIN OF THE DRIFTLESS AREA

Models for the origin of the Driftless Area have in the past focused on the role of the Mississippi River as an ice-marginal stream that became entrenched. The timing of Mississippi River entrenchment, and the way in which the entrenchment may have influenced the spread of ice sheets and the development of the Driftless Area are key issues. Past models have also drawn on the role of Midcontinent uplift and preglacial topography as factors controlling the spread of ice sheets.

A remnant of preglacial topography

Early geologists interpreted the Driftless Area as a remnant of preglacial topography. They thought the bedrock topography of surrounding drift-covered areas was just like that of the Driftless Area, only buried (Chamberlin and Salisbury, 1885; McGee, 1891; Leverett, 1921). Subsurface data, mainly from water wells, showed that bedrock valleys are filled with more than a hundred meters of Quaternary sediment in the Minneapolis–St. Paul area (Sardeson, 1916). The bedrock valleys appear to be stream cut, at least in the area underlain by Paleozoic bedrock, because they form a dendritic stream pattern draining to the Mississippi (Olsen and Mossler, 1982).

Trowbridge (1921, 1954, 1966) argued that the deep dissection of the Mississippi and its tributaries postdated the earliest glaciation(s), but predated Kansan glaciation. Trowbridge suggested that in areas traversed by glacial ice during Kansan glaciation, glacial sediment mantles the uplands and fills deep bedrock valleys. In areas beyond the limits of Kansan glaciation (basically in the pseudo-driftless area), patchy pre-Kansan drift occupies the uplands but is absent from the valleys. He interpreted these relations to indicate general uplift and deep dissection of the region in early Pleistocene prior to Kansan glaciation. Willman and Frye (1969) also accepted the idea that the stream network had been greatly deepened since the earliest glaciation, on the basis of old outwash at a high level in the Driftless Area of Illinois, which was apparently derived from the region west of the Mississippi River. Willman and Frye (1969) concluded that the Mississippi River was not in its present position until after the Nebraskan glaciation.

Entrenchment of the Mississippi River

The origin and Pleistocene development of the Mississippi has been extensively debated, although it has not been recently summarized; some field trip guides provide useful minireviews (Knox, 1982; Lively, 1985; Hobbs, 1990). Two main interpretations exist: (1) the gross alignment and general drainage area of the preglacial Mississippi was similar to that of today, and (2) the Mississippi River adjacent to the Driftless Area originated as an ice-marginal stream associated with early glaciation. Both interpretations included variants which postulate that the Mississippi River north of LaCrosse originally flowed north.

Chamberlin and Salisbury (1885), Leverett (1921), and Trowbridge (1921) believed that the Mississippi existed prior to Plio-Pleistocene glaciation, although Trowbridge (1921) presented the idea that the preglacial course was the result of stream capture. He interpreted the original stream network as consequent on the bedrock structure; the ancestral Mississippi initially flowed northwest from a drainage divide at LaCrosse. After the drainage network reached grade at the Dodgeville Peneplain (the highest erosion surface that he recognized in the Driftless Area), the south-flowing drainage captured the north-flowing stream. Trowbridge later (1954) concluded that the Mississippi was an ice-marginal stream associated with Nebraskan glaciation, because its course approximates the southwestern edge of the Driftless Area, and because its present course is out of adjustment with bedrock structure. He suggested that its preglacial course was west of the current Mississippi River, and is now deeply buried by glacial sediment. Anderson (1988) agreed that where the Mississippi River borders the Driftless Area, it had its origins as an ice-marginal stream. But Anderson (1988) postulated that the Mississippi River had a preglacial origin along the axes of the Wisconsin and Kankakee Arches of the Driftless Area. He interpreted the ice-marginal Mississippi River to have become deeply entrenched as land was raised by a glacial forebulge during an early glacial advance, and that the Mississippi River remained in its new valley after ice retreated.

Alternatively, it is possible that the Paleozoic Plateau represents a preglacial continental divide; the northern part of which drained to the north (Hobbs, 1997). The divide between the north- and south-draining streams would have been in the area of La Crosse, Wisconsin. Drainage capture was accomplished by a south-flowing meltwater stream that demarcated the maximum extent of the early glaciation, or perhaps the lowest ice-free divide. The meltwater stream eroded headward such that it ultimately captured much of the formerly north-flowing drainage in Minnesota and Wisconsin. In this scenario, it is not necessary to postulate tectonic uplift to explain the great amount of fluvial downcutting accomplished by the Mississippi where it flows through the Paleozoic Plateau.

If the modern course of the Mississippi River across the Paleozoic Plateau resulted from early glacial diversion (regardless of where the preglacial drainage ran), the incision and development of the tributary system represents a youthful phase of dissection initiated in the late Pliocene. In many places the bedrock bluff tops overlooking the Mississippi Valley are nearly as high as the average bedrock elevations tens of kilometers from the river. This indicates that the upland topography has not yet fully adjusted to a major valley running through it. In this scenario the Driftless Area is not a remnant of unaltered preglacial topography, but a newly formed geomorphic region. The preglacial valleys would have been less deeply incised, but were taken over and deepened by the modern drainage net, so that no trace of their original rock walls remain, although their gross alignment may be the same.

FACTORS CONTROLLING THE ORIGIN OF THE DRIFTLESS AREA

The puzzle is not so much in what the Driftless Area *is*, but why it is so far north. Chamberlin and Salisbury (1885) were the first to map the Driftless Area and environs. They asked (p. 315), "What were the conditions that enabled the driftless area to escape the glaciation that repeatedly intruded itself upon the surrounding country?" Chamberlin and Salisbury (1885) argued that bedrock elevation was not sufficient to prevent glaciation, because higher bedrock to the north and west had been covered by glacial ice. They agreed with Winchell's (1877) observation that "this driftless tract" was in the lee of Precambrian rock highlands in northern Wisconsin and upper Michigan. This protective barrier or shield was enhanced by the troughs of Lake Superior and Lake Michigan, which diverted or channeled the ice past the Driftless Area to the south. The bedrock shielding and lowland channeling of glacial ice are valid mechanisms for the development of the Driftless Area; their explanation that the northern Great Plains were depressed before and during glaciation relative to the current elevation is no longer tenable.

The Driftless Area lies equidistant from the ice accumulation centers that controlled the southern margin of the Laurentide Ice Sheet. The Labradoran ice accumulation center lay to the northeast, and the Keewatin ice accumulation center lay to the northwest. The location would not have created the driftless area in and of itself, but it may have enhanced the effects of topography, shielding, and channeling.

The four major factors recognized to date as controlling the flow of the ice around the Driftless Area are (1) the elevation of bedrock surface of the Driftless Area is greater than in adjacent glaciated areas, (2) the Driftless Area is located at the maximum distance from both the Labradoran and Keewatin ice accumulation centers, (3) the bedrock highlands in northeastern Wisconsin and the Upper Peninsula of Michigan protect the Driftless Area on its northeast side, and (4) the basins of Lakes Michigan and Superior channeled Labradoran ice around the Driftless Area.

Elevated bedrock surface

Glaciated bedrock south and east of the Driftless Area is generally at a lower elevation than that of the Driftless Area; glaciated bedrock to the north, west, and southwest is as high on average, and higher in places. These relations imply that while elevation may have been a factor in limiting the spread of ice across the Driftless Area from the east, it cannot explain what held back the western ice. Most of the author's mapping experience has been in southeastern Minnesota, near the western margin of the Driftless Area (Hobbs, 1984, 1985, 1987, 1988, 1992, 1995); this paper focuses on why the Driftless Area was not covered by ice from the west.

Distance from ice-accumulation centers

Glacial ice moved from west to east, and from east to west, both south and north of the Driftless Area (Fig. 1), but did not cross the Driftless Area itself. Ice from the Labradoran (northeastern) ice accumulation center, from which the Superior and Rainy lobes were sourced, extended far west of the Driftless Area into Minnesota at many times (Meyer, 1997). Ice of the Lake Michigan lobe (also Labradoran) crossed what is now the Mississippi River into southeastern Iowa during the Illinoian (Richmond et al., 1991). On the other hand, pre-Illinoian gray tills of Keewatin provenance are known from northern Wisconsin (Attig and Muldoon, 1989). The pre-Illinoian Banner Formation of Illinois is of northwestern provenance as far east as the Illinois River (Richard Berg, Illinois State Geological Survey, oral communication, 1997). Thus, the existence of two ice-accumulation centers and their associated ice streams as well as their distance from the Driftless Area may have influenced the flow of ice around the Driftless Area, but these were not major factors controlling the development of the Driftless Area.

Bedrock shielding and lowland channeling

Before we attempt to evaluate the role of bedrock shielding and lowland channeling in the development of the Driftless Area, let us turn the question around. Rather than ask, "why does the driftless area extend so far north?," ask "why did ice extend so far south in the Midcontinent?" The maximum glacial boundary runs north-northwest to south-southeast in the Great Plains (Fig. 1), apparently reflects, and is possibly controlled by increased topographic elevation to the west and southwest. Elevation also seems to control the spread of ice onto the Appalachian Plateau. Extensive Midcontinent glaciation can be partially explained by topographic control of ice movement by the central lowlands. The Driftless Area, however, is topographically lower than the ice margins to the east and west at comparable latitudes. The roles of bedrock shielding and lowland channeling of ice in controlling the spread of ice across the Midcontinent region and the flow of ice around the Driftless Area are best explained in the context of mechanical models for ice flow that include subglacial pore-water pressure, deformable substrates, and basal sliding.

Mechanical models for ice flow

Fisher et al. (1985) reconstructed the Laurentide Ice Sheet at 18 ka B.P., using a mathematical model similar to the one developed by Reeh (1982) for the Greenland ice cap. The model included the ice margin, the present-day topography, and an assumed yield stress; no assumptions were made about ice divides or flow lines. The model was successfully tested by comparing the predicted ice margins with geological evidence. To generate a reasonable reconstruction, and to agree with Peltier's (1981) reconstruction of ice thickness based on rebound, Fisher et al. (1985) used a low value for yield stress in the Prairies and Great Lakes region (the region outside the Canadian Shield). They suggested that the low yield stress is due to deforming beds under ice that overrides tills derived from sedimentary rocks. The model indicates the dominance of thin ice with low slopes in the region outside the shield.

Clayton et al. (1985) attribute low yield stress in the Prairie and Great Lakes regions to high subglacial pore-water pressure that supported the overlying ice together with enhanced subglacial sliding. Much of this region is covered by thick, low-permeability tills, and bedrock under a large part of the Prairie region is shale. Clayton et al. (1985) noted that ice margins were extremely lobate and typically unstable in the region of fine-grained till, where they alternated between surging and stagnation. By contrast, in the sandy-till area (the Canadian Shield), ice margins were smoother and less influenced by bed topography. Ice in the Hudson Bay area was intermediate between smooth and lobate. Clayton et al. (1985) concluded that the main factor controlling subglacial friction was the ease with which water escapes from under the glacier.

Clark (1992) reconstructed several Late Wisconsinan ice lobes in the Midcontinent, and found them to be relatively thin and gently sloping, especially those that extended farthest south. Clark (1992) interpreted Midcontinent ice lobes as analogous to the distal ends of West Antarctic ice streams, whose low-gradient margins have been attributed to basal sliding or deforming substrate. Patterson (1997) postulated that the Des Moines lobe is the outlet glacier for a surging and stagnating ice stream. The Des Moines lobe was able to advance as long as adequate water pressure was maintained, but stagnated when subglacial water drained away through tunnel valleys. In summary, Late Wisconsinan ice lobes in the Midcontinent were probably thin and extensive because of low yield stress at their base. Pre-Wisconsinan ice lobes are more difficult to reconstruct. Aber (this volume, chapter 11) suggests that at least some pre-Wisconsinan Midcontinent ice lobes had low marginal gradients, low subglacial yield stresses, and were strongly controlled by topography.

The presence of a deformable substrate and subglacial water played an important part in keeping yield stresses low. Water could not easily escape into the substrate beneath the Midcontinent ice lobes. Water could escape from the edge of the ice through englacial and subglacial channels, but only very slowly through the substrate, which was mainly loam-textured till, derived for the most part from the underlying and up-ice sedimentary rocks (Richmond and Fullerton, 1983; Richmond et al., 1991). Drainage of water near the margins would have reduced the pore-water pressure and thus steepened the gradient at the ice margin, which would tend to enforce a lobate shape on the ice margin, in addition to any topographic constraints. In Minnesota, ice from the Keewatin center generally moved southward across the deformable substrate of older tills. The preglacial surface beneath the older tills was mainly Cretaceous shale and deeply weathered Precambrian rock. Local pinning points did exist, such as the Sioux Quartzite in southwestern Minnesota, but hard bedrock made up only a small proportion of the area. Ice advancing from the Labradoran center (Rainy and Superior lobes) was in contact with hard Precambrian bedrock over much of its extent in Minnesota during the Late Wisconsinan, and probably also during the Illinoian. Soller (1997) shows the total thickness of glacial sediment to be less than 15 m (50 ft) in much of the area covered by Labradoran ice; bedrock outcrops are locally extensive (Morey et al., 1982). Not surprisingly, the Labradoran-sourced ice lobes became pinned by bedrock, and extended only as far south as the northern border of the Driftless Area (Richmond and Fullerton, 1983).

The bedrock highlands northeast of the Driftless Area and the troughs of Lakes Superior and Michigan may have directed ice around the Driftless Area, but the impermeable soft substrate on either side of the Driftless Area allowed the ice to extend far southward. Was Late Wisconsinan ice prevented from extending across the Driftless Area due to the local reversal of the factors that brought it so far south elsewhere? Did the Paleozoic Plateau allow a reduction in subglacial pore-water pressure, resulting in higher shear stresses and the pinning of glacial ice?

THE GIANT SIEVE HYPOTHESIS

The Mississippi River and its tributaries are deeply incised into the Paleozoic Plateau. Ice that encroached onto the margins of the Driftless Area eroded weathered rock and older tills from the surface of the Paleozoic Plateau, exposing bedrock to the glacier sole. Although the exposed carbonate bedrock was relatively soft, and could be readily smoothed and striated by the encroaching ice, it was not deformable like till. At the margins of the Paleozoic Plateau, soft sediment at the base of the ice was trapped locally in the bedrock valleys (Fig. 2). Most of the bedrock forming the Paleozoic Plateau is highly permeable sandstone and karsted limestone. Water could infiltrate the bedrock wherever the base of the ice was in contact with bedrock; water could flow laterally through bedrock aquifers, and discharge into valleys outside the ice margin. Although these ice sheets were probably fringed by zones of permafrost, the depth of freezing would have needed to exceed at least 100 m to block flow in the bedrock aquifers. The net result was to dewater any wet-based ice lobe that advanced onto the Paleozoic Plateau, and to hold it back. The ice east and west of the plateau continued south until it reached a melting equilibrium. In short, the dissected highland acted as a giant sieve—it let through the water but held back the ice.

South of the Driftless Area the elevation of the bedrock surface decreases. The elevational difference between the upland surface and the valley bottoms also decreases; the sieve thus becomes less effective, and ice crosses from west to east, and east to west. There is no evidence for the Driftless Area ever being surrounded by ice at any one time. If it had been, the whole area would have flooded. McGee (1891) interpreted the loess mantling the Driftless Area as lake silt, and proposed that the area had been flooded by Lake Hennepin. The loess is now recognized to be an aeolian deposit; there is no evidence for widespread lacustrine deposition on the Paleozoic Plateau.

Profile reconstructions

In order to evaluate the effect of bedrock elevation on preventing the spread of glacial ice across the Driftless Area, the topographic profile of the Driftless Area (Fig. 3, profile a) was superimposed on the north-south profile inferred for the axis of the base of the Des Moines lobe (Fig. 3, profile b), which is derived using the current elevation of the Des Moines till as a proxy for the base of the ice. The highest points on the Driftless Area profile are only slightly higher than the most elevated parts of the base of the Des Moines lobe profile. In order to assess the effect of the topographic barrier presented to the Des Moines lobe ice by the Paleozoic Plateau, the thickness of the Des Moines lobe deposits must first be subtracted from the land surface. Des Moines lobe sediments are less than 50 m thick on average, and make little difference to the comparison. The most significant difference is in large-scale roughness of the Paleozoic Plateau compared to that of the Des Moines lobe.

A longitudinal ice profile of the Des Moines lobe based on Figure 5 of Clark (1992) is also shown (Fig. 3, profile c). The Des Moines lobe certainly appears capable of crossing the Driftless Area, if elevation alone was the sole consideration. The hypothetical elevation for ice sheets that extended farther south during earlier glaciations is also shown (Fig. 3, profile d). The elevation for the upper surface of these ice sheets was determined by translating Clark's profile for the Des Moines lobe (which

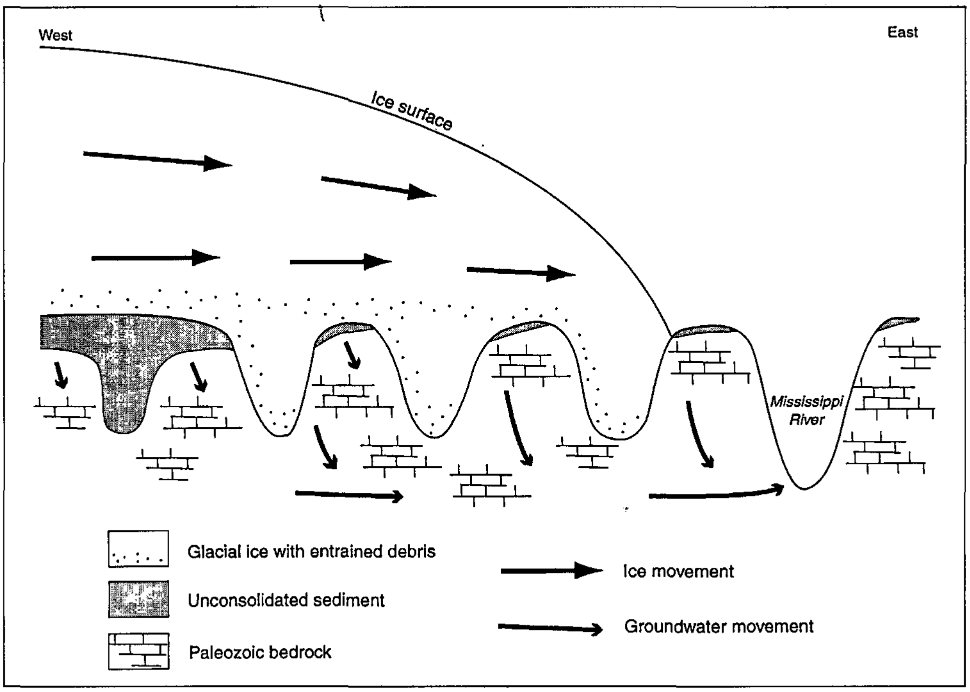

Figure 2. Schematic diagram showing proposed drainage of subglacial meltwater where ice sheet encroaches on the Paleozoic Plateau. Length of arrow on ground-water flowpaths indicates relative amount of subglacial meltwater draining into the bedrock.

terminated at Des Moines, Iowa) southward to the known limit of early glaciation in central Missouri. The upper surface of the ice was then extrapolated up-ice beyond the level indicated in Clark's (1992) curve. This ice sheet should have been even more capable of crossing the Driftless Area, but there is no evidence for it having done so. The elevation for the margin of the most extensive pre-Illinoian ice sheet (Fig. 3, profile e) is sketched on the profile at the north side of the Driftless Area for comparison. In order to attain the thickness required for the ice sheet to advance to its southern limit, the ice margin has to be steep adjacent to the Driftless Area. These hypothetical ice profiles are all relatively flat compared to profiles for most existing ice sheets.

The comparison between the gentle profile down the axis of a lobe with the elevation of an area off to the side of the main lines of advance is somewhat biased. An east-west cross section along the entire length of the Minnesota-Iowa boundary (Fig. 4) shows the elevation and distribution of bedrock and glacial sediments, and again shows Clark's (1992) profile for the Des Moines lobe (Fig. 4, profile a). The upper surface of the ice has a much higher elevation in the west than in the east; it also slopes rather sharply at its eastern margin. This asymmetry may result from the nonsymmetrical distribution of subglacial bedrock and till.

Note that the western portion of the cross section is composed of thick pre-Wisconsinan tills overlying clayey Cretaceous sedimentary rocks that are underlain by Precambrian crystalline rocks; water could not easily escape through this substrate. In contrast, the eastern part is underlain by thin pre-Wisconsinan tills that overlie permeable Paleozoic sedimentary rocks, which form an aquifer that allows escape of water to the Mississippi Valley.

Using the Des Moines lobe profile as a model, what would ice profiles for the more extensive earlier glaciations have looked like? Two hypothetical pre-Illinoian ice profiles (Fig. 4, profiles b and c) are sketched above the Des Moines lobe profile. They show (b) the maximum ice elevation (estimated using Clark's, 1992, Des Moines lobe profile, translated south), and (c) an intermediate position. The main constraint in developing the maximum profile was that the ice surface had to terminate near the Mississippi, and not enter the Driftless Area. The intermediate profile represents glaciations that exceeded the extent of the Des Moines lobe, but did not reach the glacial maximum.

These profiles show that the Midcontinent ice lobes had steep lateral slopes adjacent to the Driftless Area, particularly when compared to their longitudinal slopes. The features illustrated in Figures 2 and 4 are analogous to the end-member states presented by Boulton and Dobbie (1993, Fig. 8) in their rigorous treatment of subglacial ground-water flow and soft-bed glacier dynamics.

The western part of Figure 4 is comparable to Boulton and Dobbie's (1993) low-permeability and poor drainage scenario; (case D) the substrate is saturated and cannot transmit enough meltwater, so most of it escapes through subglacial channels. This results in deformation of the substrate, and maintenance of low slopes for the ice surface. To the east where the cover of glacial sediment is thinner and the Paleozoic rocks thicken, the situation comes to resemble case B (low permeability and good

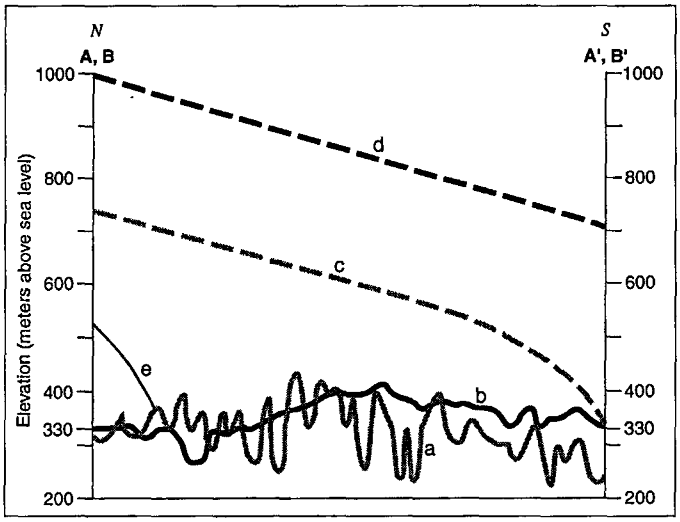

Figure 3. Profiles (vertical exaggeration ×3600) showing: a, topography of the Driftless area for section A–A′ on Figure 1; b, inferred elevation of the base of the Des Moines lobe as determined from the surface of the Des Moines till for B–B′ at approximately 94° longitude; c, Longitudinal ice profile for the upper surface of the Des Moines lobe ice, based on Clark (1992); d, Profile for the upper surface of the ice sheet(s) associated with the Midcontinent pre-Illinoian glacial maximum. See text for details of profile determination; e, Profile showing predicted slope of ice margin for the most extensive pre-Illinoian ice sheet at the northern margin of the Driftless Area.

drainage; Boulton and Dobbie, 1993). Most of the meltwater can be transmitted through the low-permeability till into the underlying aquifer, but the necessary pressure drop is great, and the upper part of the till deforms. Farther to the east the till is thin and patchy, and ice that extends this far will encounter case A (high permeability and good drainage; Boulton and Dobbie, 1993). Here, all the water is discharged into the aquifer and the thin till cover is not deformed. Ice is thus unable to advance eastward due to the low subglacial pore water pressure, and the consequent development of high yield stress and the lack of a deformable substrate; the ice becomes pinned, and a steep eastern ice margin develops.

Glacial recharge of aquifers

Can recharge of aquifers by former ice sheets be demonstrated? Research has necessarily concentrated on the characteristics of water in the aquifer. For example, Carlson (1994) identified an isotopic and hydrochemical anomaly in what is now the discharge area of the Fox Hills aquifer in North Dakota, which she interpreted as evidence for subglacial recharge. Low-chloride water in the discharge area is anomalously fresh compared to water upgradient in the aquifer, which is of the sodium-bicarbonate-chloride type. Moreover, stable-isotope data from the anomalous water suggests that it was precipitated in a cooler climate. However, Carlson (1994, p. 83) cautions that, "Modeling the response of an aquifer to Pleistocene glaciation is a speculative endeavor because of our limited knowledge of both the pre-glacial aquifer system and the ice sheet configuration and hydraulics. Assumptions must be made that will *directly* influence the outcome of the simulation. Thus, attempts at simulating an aquifer's response to glaciation can only indicate the feasibility of various postulated ways in which the aquifer could have behaved under the specified conditions."

If the sieve mechanism proposed herein for the origin of the Driftless Area is valid, the composition of the ground water in the bedrock aquifers should provide geochemical evidence compatible with glacial recharge. Siegel (1984, 1989) reports evidence for major recharge of lower Paleozoic aquifers of the Midcontinent region during glaciation. Distribution of "fresh" ground water (low total dissolved solids), and oxygen-isotope ratios suggest flowpaths much different from those of today, but consistent with recharge from thick ice sheets. The relative contribution of the most recent ice sheets versus that of earlier ice sheets could not be determined.

More recently, Siegel (1991) identified anomalous water (low dissolved solids) in the Cambrian-Ordovician aquifer of Iowa, which he interpreted to result from recharge during the last glaciation. The anomaly extends across a geographic area equivalent to that of the Des Moines lobe at its maximum extent, but is displaced 100 km southeast from the Des Moines lobe, down the regional flowpath. Siegel (1991) calculated that the anomaly could have formed by vertical recharge over 600 years, even though it had to pass through hundreds of meters of confining beds; it is significant that such a large amount of glacial meltwater can be transferred to a bedrock aquifer despite the existence of an aquitard. Based on the dynamic behavior of the Des Moines lobe, and on the amount of water required to completely displace preglacial water, only a small proportion of the total amount of meltwater from the Des Moines lobe would have been able to infiltrate the aquifer through the aquitard.

In contrast, the proposed sieve mechanism would drain nearly all of the meltwater into the bedrock aquifers; most of the water would ultimately discharge into the Mississippi River system. The giant sieve may have been most active during the most extensive pre-Wisconsinan glaciations, because the farther the ice rode onto the Paleozoic Plateau, the more effectively it would drain.

Earliest glaciations: thin extensive ice sheets

The deep-sea oxygen-isotope record for the late Pliocene–early Pleistocene implies that global ice volume was only about half to two-thirds that of the late Pleistocene (Shackleton et al., 1984; Morley, 1991). If late Pliocene–early Pleistocene ice sheets were more extensive than the Late Wisconsinan ice sheet, something about them must have been different. Field evidence for the earlier glaciations having extended farther towards the Driftless Area does not appear to be compatible with lower ice volumes. In a very general way, late Pleistocene ice sheets were thick over the hard rock and thin, sandy tills of the Canadian Shield, but thin and gently sloping over the sedimentary rocks and thicker, finer-

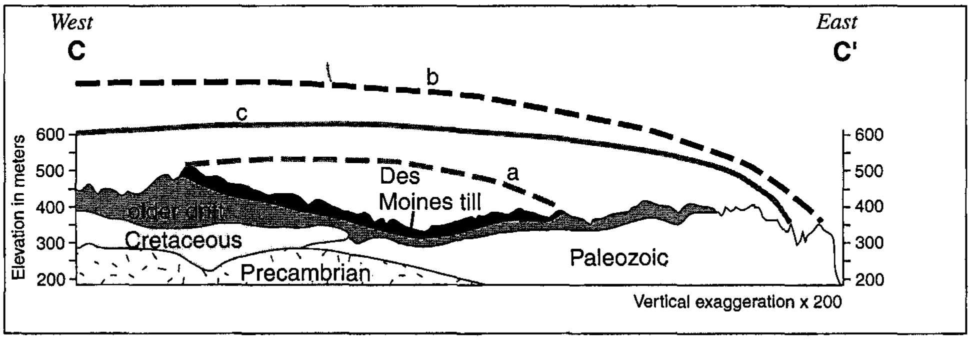

Figure 4. Topographic and generalized stratigraphic profile along the Iowa-Minnesota border (C–C′ on Fig. 1) at latitude 43°30′N, and hypothetical ice profiles. Vertical exaggeration ×200. a, Upper surface of Des Moines lobe ice from Clark (1992); b, Maximum elevation of upper surface of ice during pre-Illinoian glacial maximum; c, "Intermediate" elevation of the upper surface of the ice during pre-Illinoian glacial maximum. See text for discussion of curves b and c.

grained tills. The decreased global ice volume indicates that the early continental ice sheets were thin throughout.

Boellsdorf (1978) reports that a till in southwestern Iowa underlies volcanic ash that is dated at 2.2 Ma. The site is inside the all-time glacial limit, but lies to the south of the Driftless Area, implying that the southern margin already was showing the differential southern limit which has characterized the later glaciations. The tentative correlation of the old till described by Boellsdorf (1978) with old tills fringing the Driftless Area on its west side suggests that the Paleozoic Plateau was acting as a barrier during early stages of Plio-Pleistocene glaciation, otherwise pre-2.2 Ma glacial sediments should be found in the Driftless Area.

Prior to the Late Cretaceous a thick weathering saprolith had developed over the Canadian Shield in Minnesota (Parham, 1970). It is still fairly thick and extensive in Minnesota where protected by Cretaceous sedimentary rocks and thick glacial sediment (Setterholm et al., 1989) but is thin and extremely patchy in areas of the state where glacial sediments are thin. Presumably it has been stripped away by repeated glaciation. Was saprolith thick and widespread over the Canadian Shield before the first glaciation? If so, there would have been essentially no hard substrate anywhere to provide pinning points, and subglacial meltwater could not easily percolate into the underlying jointed bedrock. Then the whole ice sheet would have behaved as the extra-shield part of the ice sheet did in later glaciations; it would have been thin, gently sloping, and unstable.

Clark and Pollard (1998) tested this idea with an ice sheet and bedrock model that included transport of sediment and ice by subglacial sediment deformation. They demonstrated that a widespread deforming layer maintains thin ice sheets that respond to the dominant orbital forcing of 23 and 41 k.y. Moreover, repeated runs of the model progressively removed the sediment layer, and eventually caused a transition to thicker ice sheets with a dominant timescale of 100 k.y. Thus it is quite plausible that the patchy tills of the pseudo-driftless area were deposited by one or more very early, very extensive ice sheets. More recent pre-Illinoian glaciers, though they contained more ice, may not have been able to extend as far east onto the Paleozoic Plateau.

Testing the giant sieve hypothesis

Possible avenues for testing the hypothesis fall into three main groups: (1) karst geology, (2) aquifer geochemistry, and (3) numerical modeling of ice sheets. Each method has its limitations, and a definitive test is not likely in the near future.

The karst geology of the Paleozoic Plateau could provide some clues to the glacial recharge of aquifers, because much of the recharge took place through sinkholes and solution cavities that presumably still exist. Many bedrock sinkholes in the area are filled with sediment, and have no surface expression; they can only be seen in roadcuts and quarry walls. However, unweathered till is scarcely ever observed in them. Most of the fills present in the karst areas of southeastern Minnesota consist of weathering products of bedrock mixed with weathered pre-Illinoian drift. They were emplaced long after the most recent local glaciation, and do not hold a record of glacial events. The shape of the solution cavities themselves might contain evidence of rapid recharge under pressure, but it is not certain what this shape should be. Even if it can be established that large amounts of glacial meltwater were discharged through the karst system, it would not prove that this discharge held back the ice from the Driftless Area.

Geochemical studies of water in bedrock aquifers are unlikely to provide definitive answers regarding the role of the giant sieve in controlling aquifer recharge or in controlling the spread of ice sheets across the Paleozoic Plateau, because most of the glacial recharge was quickly discharged into the Mississippi River. It is possible that deep, seldom-used aquifers contain some record that has been erased in the shallower aquifers, although sampling opportunities in deep aquifers are limited.

Numerical modeling of former ice sheets offers the best prospect for testing the giant sieve hypothesis, but the pitfalls of such an approach should not be underestimated. The elevation and location of a considerable length of a correlative ice margin needs to be specified, and at least an approximation of the subglacial topography of the entire portion of the ice sheet modeled. This is most easily done for more recent glacial periods; Late Wisconsinan ice margins are recognized by their morphology, and the subglacial topography can be approximated by the modern topography. But even in this case, errors are not hard to find. In many places, the modern topography is much higher than the base of the last ice sheet, because Late Wisconsinan deposits are 50 m to more than 100 m thick. Temporal variability also induces errors; the deposition of terminal Late Wisconsinan deposits is not synchronous.

Numerical modeling of pre-Wisconsinan ice sheets is even less certain. To test the giant sieve hypothesis, one would need (at minimum) to specify correlative Labradoran and Keewatin ice margins along the border of the Driftless Area, and include the area at least as far north as the International Boundary (area covered by Soller, 1997). Although individual ice margins are recognized within this area, they cannot be correlated, because (1) subsequent erosion has removed most of the geomorphic evidence, and (2) sediments associated with these old margins are beyond the range of radiocarbon dating.

Any viable modeling efforts depend on advances in pre-Illinoian glacial stratigraphy. Ice margins can theoretically be correlated by their till sheets, which would also provide rough elevations of the base of the glacier throughout its extent. The accessibility, complexity, and poorly understood nature of the pre-Wisconsinan glacial records renders it difficult to attempt this type of modeling. However, a rough reconstruction could be attempted, using the maximum position of ice, and the modern topography as a proxy for the subglacial surface.

CONCLUSIONS

The roles of substrate and subglacial drainage in controlling the extent of glacial ice and the location of the ice margin are crucial; they control the amount of subglacial yield stress, and the likelihood of the ice being pinned to the bedrock. The dissected limestones and sandstones of the Paleozoic Plateau prevented the spread of glacial ice onto the Driftless Area, because they allowed dewatering at the base of the ice sheet.

REFERENCES CITED

Anderson, R. C., 1988, Reconstruction of preglacial drainage and its diversion by earliest glacial forebulge in the Upper Mississippi Valley region: Geology, v. 16, p. 254–257.

Attig, J. W., and Muldoon, M. A., 1989, Pleistocene geology of Marathon County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 65, 27 p., scale 1:100,000, 1 sheet.

Boellsdorf, J., 1978, North American Pleistocene stages reconsidered in light of probable Pliocene-Pliestocene continental glaciation: Science, v. 202, p. 305–307.

Black, R. F., 1960, "Driftless Area" of Wisconsin was glaciated [abs.]: Geological Society of America Bulletin, v. 71, no. 12, pt. 2, p. 1827.

Black, R. F., 1970a, Blue Mounds and the erosional history of southwestern Wisconsin, *in* Pleistocene geology of southern Wisconsin: Wisconsin Geological and Natural History Survey Information Circular No. 15, p. H1–H11.

Black, R. F., 1970b, Residuum and ancient soils of the Driftless Area of southwestern Wisconsin, *in* Pleistocene geology of southern Wisconsin: Wisconsin Geological and Natural History Survey Information Circular No. 15, p. I1–I12.

Boulton, G. S., and Dobbie, K. E., 1993, Consolidation of sediments by glaciers: relations between sediment tectonics, soft-bed glacier dynamics and subglacial ground-water flow: Journal of Glaciology, v. 39, p. 26–44.

Carlson, C. A., 1994, Identification of an isotopic and hydrochemical anomaly in the discharge area of the Fox Hills Aquifer, south-central North Dakota: Evidence for Pleistocene subglacial recharge? [Ph.D. thesis]: East Lansing, Michigan State University, 215 p.

Chamberlin, T. C., and Salisbury, R. D., 1885, Preliminary paper on the Driftless Area of the Upper Mississippi Valley: U.S. Geological Survey 6th Annual Report, p. 199–322.

Clark, P. U., 1992, Surface form of the Laurentide Ice Sheet and its implications to ice-sheet dynamics: Geological Society of America Bulletin v. 104, p. 595–605.

Clark, P. U., and Pollard, D., 1998, Origin of the middle Pleistocene transition by ice sheet erosion of regolith: Paleoceanography, v. 13, p. 1–9.

Clayton, L., Teller, J. T., and Attig, J. W., 1985, Surging of the southwest part of the Laurentide Ice Sheet: Boreas, v. 14, p. 235–242.

Fisher, D. A., Reeh, N., and Langley, K., 1985, Objective reconstructions of the Late Wisconsinan Laurentide Ice Sheet and the significance of deformable beds: Geographie Physique et Quarternaire, v. 39, no. 3, p. 229–238.

Fullerton, D. S., 1995, Quaternary geologic map of the Dakotas Quadrangle, United States: U.S. Geological Survey Miscellaneous Investigations Series I-1420(NL-14), Scale 1:1,000,000.

Fullerton, D. L., and Richmond, G. M., 1991, Quaternary geologic map of the Lake Erie Quadrangle, United States and Canada: U.S. Geological Survey Miscellaneous Investigations Series I-1420(NK-17), scale 1:1,000,000.

Hobbs, H. C., 1984, Surficial geology, Plate 3, *in* Balaban, N. H., and Olsen, B. M., eds., Geologic atlas of Winona County, Minnesota: Minnesota Geological Survey County Atlas Series C-2, scale 1:100,000.

Hobbs, H. C., 1985, Quaternary history of southeastern Minnesota, *in* Lively, R. S., ed., 1985, Pleistocene geology and evolution of the Upper Mississippi Valley, Winona, Minnesota, August 13–16, 1985, Abstracts and Field Trip Guide: Minnesota Geological Survey, 105 p., 1 pl.

Hobbs, H. C., 1987, Quaternary geology of southeastern Minnesota, *in* Balaban, N. H., ed., Field Trip Guidebook for the upper Mississippi Valley Minnesota, Iowa, and Wisconsin: Geological Society of America, North-Central Section 21st Annual Meeting: Minnesota Geological Survey Guidebook Series no. 15, 185 p.

Hobbs, H. C., 1988, Surficial geology, Plate 3, *in* Balaban, N. H., ed., Geologic atlas, Olmsted County, Minnesota: Minnesota Geological Survey County Atlas Series C-3, scale 1:100,000.

Hobbs, H. C., 1990, Geologic history and development of the Upper Mississippi River, *in* Hammer, W. R., and Hess, D. F., eds., Geology Field Guidebook: Current perspectives on Illinois Basin and Mississippi Arch geology: Geological Society of America, North-Central Section 24th Annual Meeting, April 1990, Macomb, Illinois, p. F1–F52.

Hobbs, H. C., 1992, Paleozoic Plateau of southeastern Minnesota, *in* Nater, E. A., ed., Soils-geomorphology pre-conference tour guidebook, Oct. 29–Nov. 1: Annual Meeting of the Soil Science Society of America, Nov. 1–6, 1992, Minneapolis, Minnesota, unpaginated.

Hobbs, H. C., 1995, Surficial geology, Plate 3, *in* Mossler, J. H., project manager, Geologic atlas of Fillmore County, Minnesota: Minnesota Geological Survey County Atlas Series C-8, Part A, scale 1:100,000.

Hobbs, H. C., 1997, The preglacial Upper Mississippi River flowed north and west into the Arctic Ocean: Geological Society of America Abstracts with Programs, v. 29, p. 20.

Knox, J. C., 1982, Quaternary history of the Driftless Area: Wisconsin Geological

and Natural History Survey Field Trip Guidebook 5, 169 p.
Knox, J. C., and Attig, J. W., 1988, Geology of the pre-Illinoian sediment in the Bridgeport Terrace, lower Wisconsin River Valley, Wisconsin: Journal of Geology, v. 96, p. 505–513.
Leverett, F., 1921, Outline of the Pleistocene history of the Mississippi Valley: Journal of Geology, v. 29, p. 615–626.
Lively, R. S., editor, 1985, Pleistocene geology and evolution of the Upper Mississippi Valley, Winona, Minnesota, August 13–16, 1985, Abstracts and Field Trip Guide: Minnesota Geological Survey, 105 p., 1 pl.
Meyer, G. N., 1997, Pre-late Wisconsinan till stratigraphy of north-central Minnesota: Minnesota Geological Survey Report of Investigations 48, 67 p.
McGee, W. J., 1891, The Pleistocene history of northeastern Iowa: U.S. Geological Survey 11th Annual Report, p. 199–586.
Morey, G. B., Sims, P. K., Cannon, W. F., Mudrey, M. G., Jr., and Southwick, D. L., 1982, Geologic map of the Lake Superior region; Minnesota, Wisconsin, and northern Michigan: Minnesota Geological Survey State Map Series S-13, scale 1:1,000,000.
Morley, J. J., 1991, Evolving Pliocene-Pleistocene climate: A North Pacific perspective: Quaternary Science Reviews, v. 10, p. 225–237.
Mossler, J. H., 1983, Bedrock topography and isopachs of Cretaceous and Quaternary strata, east-central and southeastern Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-52, scale 1:500,000.
Olsen, B. M., and Mossler, J. H., 1982, Geologic map of Minnesota, bedrock topography: Minnesota Geological Survey State Map Series S-15, scale 1:1,000,000.
Parham, W. E., 1970, Clay mineralogy and geology of Minnesota's kaolin clays: Minnesota Geological Survey Special Publication Series SP-10, 142 p.
Patterson, C. J., 1997, Southern Laurentide ice lobes were created by ice streams: Des Moines Lobe in Minnesota, USA: Sedimentary Geology, v. 111, p. 249–261.
Peltier, W. R., 1981, Ice age geodynamics: Annual Review of Earth and Planetary Sciences, v. 9, p. 199–226.
Prior, J. C., 1976, A regional guide to Iowa landforms: Iowa Geological Survey Educational Series 3, 71 p.
Reeh, N., 1982, A plasticity theory approach to the steady-state shape of a three-dimensional ice sheet: Journal of Glaciology, v. 28, no. 100, p. 431–455.
Richmond, G. M., 1994, Quaternary geologic map of the Platte River Quadrangle, United States: U.S. Geological Survey Miscellaneous Investigations Series I-1420(NK-14), scale 1:1,000,000.
Richmond, G. M., and Christiansen, A. C., 1993, Quaternary geologic map of the Wichita Quadrangle, United States: U.S. Geological Survey Miscellaneous Investigations Series I-1420(NJ-14), scale 1:1,000,000.
Richmond, G. M., and Fullerton, D. S., 1983, Quaternary geologic map of the Minneapolis 4 × 6 quadrangle, United States: U.S. Geological Survey Miscellaneous Investigations Series I-1420(NL-15), scale 1:1,000,000.
Richmond, G. M., Fullerton, D. S., and Christiansen, A. C., editors, 1991, Quaternary geologic map of the Des Moines 4 × 6 Quadrangle, United States: U.S. Geological Survey Miscellaneous Investigations Series I-1420(NK-15), scale 1:1,000,000.
Richmond, G. M., and Fullerton, G. S., 1983, Quaternary geologic map of the Chicago Quadrangle, United States: U.S. Geological Survey Miscellaneous Investigations Series I-1420(NK-16), scale 1:1,000,000.
Richmond, G. M., and Fulerton, G. S., 1991, Quaternary geologic map of the Louisville Quadrangle, United States: U.S. Geological Survey Miscellaneous Investigations Series I-1420(NK-16), scale 1:1,000,000.
Richmond, G. M., and Weide, D. L., 1993, Quaternary geologic map of the Ozark Plateau Quadrangle, United States: U.S. Geological Survey Miscellaneous Investigations Series I-1420(NJ-15), scale 1:1,000,000.
Richmond, G. M., Fullerton, D. S., and Christiansen, A. C., 1991, Quaternary geologic map of the Blue Ridge Quadrangle, United States: U.S. Geological Survey Miscellaneous Investigations Series I-1420(NJ-17),
Sardeson, F. W., 1916, Minneapolis–St. Paul folio: U.S. Geological Survey Geologic Atlas of the United States, 14 pl., maps, photos.
Setterholm, D. R., Morey, G. B., Boerboom, T. J., and Lamons, R. C., 1989, Minnesota kaolin clay deposits: A subsurface study in selected areas of southwestern and east-central Minnesota: Minnesota Geological Survey Information Circular 27, 99 p.
Siegel, D. I., 1984, Isotopic evidence for glacial meltwater recharge to the Cambrian-Ordovician aquifer, north-central United States: Journal of Quaternary Research, v. 22, p. 328–335.
Siegel, D. I., 1989, Geochemistry of the Cambrian-Ordovician aquifer system in the northern Midwest, United States: U.S. Geological Survey Professional Paper 1405-D, 76 p.
Siegel, D. I., 1991, Evidence for dilution of deep confined ground water by vertical recharge of isotopically heavy Pleistocene water: Geology, v. 19, no. 5, p. 433–436.
Shackleton, N. J., Blackman, J., Zimmerman, H., Kent, D. V., Hall, M. A., Roberts, D. G., Schnitker, D., Baldauf, J. G., Desprairies, A., Homrighausen, R., Huddlestun, P., Keene, J. B., Kaltenback, A. J., Krumsiek, K. A. O., Morton, A. C., Murray, J. W., and Westberg-Smith, J., 1984, Oxygen isotope calibration of the onset of ice-rafting and history of glaciation in the North Atlantic region: Nature, v. 307, p. 620–623.
Soller, D. R., 1997, Map showing the thickness and character of Quaternary sediments in the glaciated United States east of the Rocky Mountains; northern and central plains states (90 to 102 degrees West longitude): U.S. Geological Survey Map I-1970-C, scale 1:1,000,000.
Trowbridge, A. C., 1921, The erosional history of the Driftless Area: University of Iowa Studies in Natural History, v. 9, p. 55–127.
Trowbridge, A. C., 1954, Mississippi River and Gulf Coast terraces and sediments as related to Pleistocene history—a problem: Geological Society of America Bulletin, v. 65, p. 793–812.
Trowbridge, A. C., 1966, Glacial drift of the "Driftless Area" of northeast Iowa: Iowa Geological Survey Report of Investigations 2, 28 p.
Willman, H. B., and Frye, J. C., 1969, High-level glacial outwash in the Driftless Area of northwestern Illinois: Illinois State Geological Survey Circular 440, 23 p.
Winchell, N. H., 1877, The geological and natural history of Minnesota: The Fifth Annual Report, submitted to the President of the University [of Minnesota]: Saint Paul Pioneer Press, 205 p.

MANUSCRIPT ACCEPTED BY THE SOCIETY OCTOBER 8, 1998