Glacial stratigraphy and paleomagnetism of late Cenozoic deposits of the north-central United States

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ABSTRACT

The north-central United States preserves one of the best continental records of late Pliocene and early-middle Pleistocene glaciations in the Northern Hemisphere. The glaciogenic sequences of this region consist of multiple tills interbedded with paleosols and volcanic ashes. Here we present results on paleomagnetic measurements and till compositional data from glacial sedimentary sequences in Iowa, Nebraska, Kansas, and Missouri. Periods of normal polarity (Brunhes Chron) and reverse polarity (Matuyama Chron) were identified in the sedimentary sequences investigated. This chronology is further constrained by the presence of three volcanic ashes derived from dated eruptions of the Yellowstone caldera, which indicate that the oldest till was deposited >2.0 Ma. Based on these results we identify three groups of tills representing at least seven pre–Illinoian glaciations: two older groups of reverse-polarity tills containing low and intermediate proportions of crystalline clasts, respectively, and one younger group of normal-polarity tills enriched in crystalline lithologies. The clay mineralogy of the reverse-polarity tills is enriched in kaolinite and depleted in expandable clays relative to the normal-polarity tills, which are also characterized by a minor amount of chlorite. The silt fraction of tills also shows mineralogical contrasts whereby the normal-polarity tills are characterized by increases in calcite, dolomite, and feldspar, whereas the older tills show depletion in these minerals and a relative enrichment in quartz. These petrographic and mineralogic changes are indicative of an increase with time in the areal distribution of unweathered igneous and metamorphic source bedrock.

Keywords: glacial stratigraphy, paleomagnetism, Laurentide ice sheet, glaciation, midcontinent.

INTRODUCTION

The north-central United States (Fig. 1) encompasses some of the type areas from which the former stratigraphic classification of the North American Pleistocene glacial stages was originally developed (Hallberg, 1986). Early workers placed the glacial and nonglacial deposits of this region into a conceptual framework composed of four glaciations and interglaciations. This stratigraphic framework persisted until subsequent stratigraphic investigations revealed greater complexity of the older sedimentary sequences, ultimately requiring the abandonment of the Nebraskan-Aftonian-Kansan-Yarmouthian terminology and its replacement by the broader term ''pre-Illinoian'' (Hallberg, 1986; Richmond and Fullerton, 1986a, 1986b).

Evidence for a more complex stratigraphy arose primarily from the work of Boellstorff (1973, 1978a, 1978b), who demonstrated that numerous tills and paleosols were present beneath type localities and key sections of the Nebraskan-Aftonian-Kansan sequence. Moreover, fission track dating of the Pearlette volcanic ash bed indicated that what was thought to be a single marker bed consisted of three distinct volcanic ashes of significantly different ages (Boellstorff, 1973, 1976, 1978c). These results led Boellstorff (1978a, 1978b, 1978c) to propose a stratigraphic framework based on till compositional data and stratigraphic relationships of till units with paleosols and fission-track dated volcanic ashes. In this framework, the tills were grouped into three categories labeled ''A,'' ''B,'' and ''C'' tills. The ''A'' and ''C'' tills were further divided into four and two subgroups, respectively (Fig. 2). Easterbrook and Boellstorff (1984) later refined this chronology on the basis of paleomagnetic measurements. Examination of their data, however, reveals some inconsistencies, such as the occurrence of samples showing both normal and reversed polarity within single lithostratigraphic units. This was particularly common for the older till units (C tills), thereby raising the possibility of till sheets recording deposition during the latest part of the Gauss Normal Chron (Fig. 2). Many of the paleomagnetic inclinations reported from these sites were ambiguous near-horizontal results, making polarity assignment difficult. Nonetheless, an important contribution of Boellstorff (1978a, 1978b, 1978c) was to reconcile the continental record of glaciations with the deep-sea oxygen isotope ($\delta^{18}O$) record available at that time (Hays

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GSA Bulletin; January/February 2004; v. 116; no. 1/2; p. 30–41; DOI 10.1130/B25325.1; 10 figures; 3 tables.

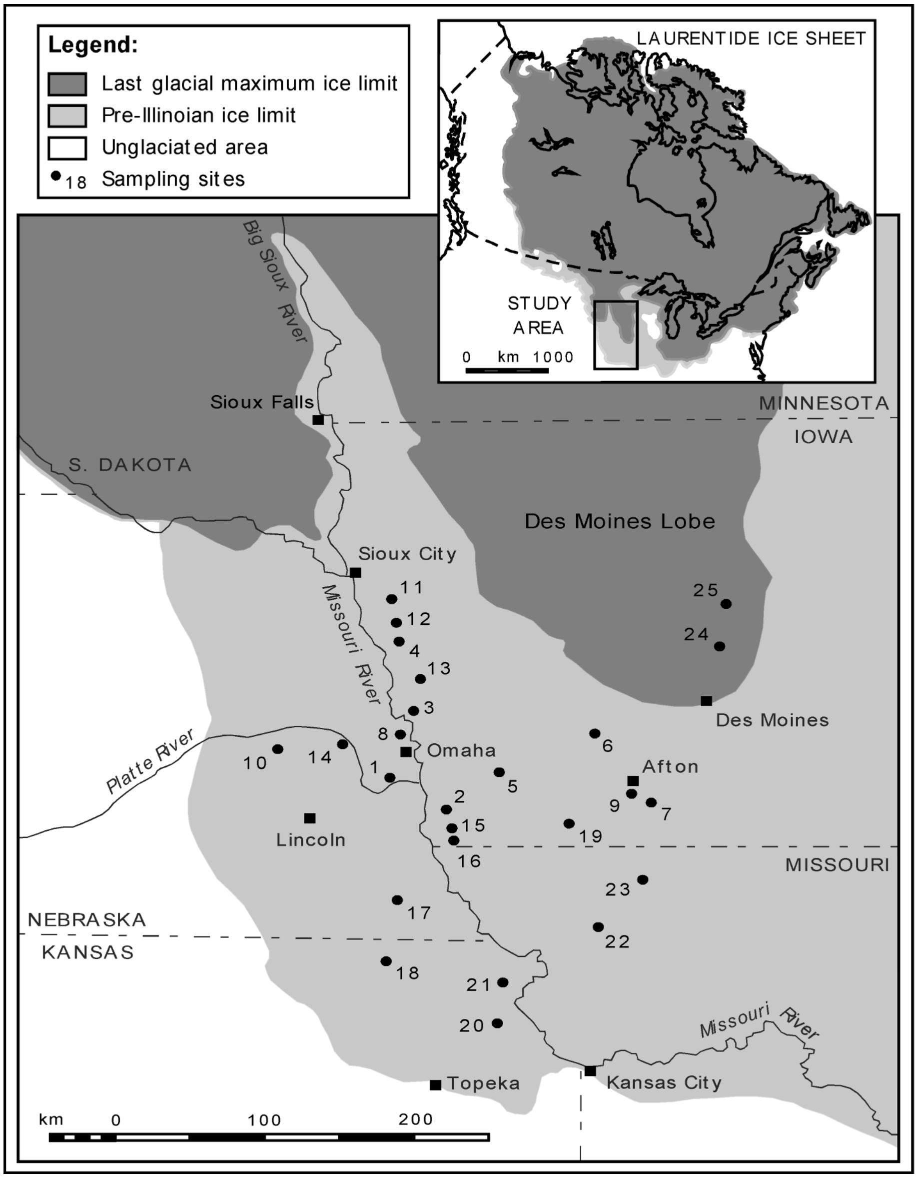

Figure 1. Location of stratigraphic sections investigated and maximum extent of pre–Illinoian and late Pleistocene ice sheets.

et al., 1976) in showing evidence for many more glaciations than originally suggested from the classic fourfold stratigraphic framework.

Here we report the results of the investigation of stratigraphic sections from the midcontinent region (Fig. 1). The purpose of this study is to develop an improved chronology for the midcontinent glacial deposits through paleomagnetic analyses and refinement of the relation of volcanic ashes to the composition of till units. Based on chronological and lithological constraints, we define three till groups that represent at least seven pre–Illinoian glaciations separated by major soil-forming intervals. This framework will facilitate correlations with the late Cenozoic record of glaciation elsewhere in the midcontinent (Hallberg, 1980; Aber, 1991; Kemmis et al., 1992; Rovey and Kean, 1996; Colgan, 1999).

METHODS

Sampling Sites and Field Methods

Field investigations and sampling were carried out at 25 localities (Fig. 1). Stratigraphic sections usually showed evidence for multiple glaciations (Table 1). Sampling sites consist mostly of outcrops associated with rock quarries and road cuts and a few natural sections exposed along rivers. We also drilled cores at three sites where Boellstorff (1973, 1976, 1978b) reported volcanic ashes. Volcanic ash beds or shards were also identified in the ash-bearing units reported in Table 1. In addition to pre–Illinoian deposits, we sampled till deposited by the late Wisconsinan Des Moines Lobe to obtain a more complete range of compositional data over the spectrum of late Cenozoic glaciations. Prior to sampling, the stratigraphic sections were cleaned over a width of at least a meter and to a depth of 50 cm. Till sampling interval was based on unit thickness and the nature of the exposure and varied from 0.5 to 1.5 m.

Paleomagnetic Sampling and Measurements

We collected 711 samples from 53 glacial and nonglacial units for paleomagnetic measurements. Prior to collection, we cleaned the sediment exposure to a vertical face and inserted 2.5-cm-diameter plastic cylinders horizontally into the sediment. We measured the azimuth of the samples using a magnetic compass corrected for local declination. Samples from fully oriented sediment cores were also obtained. Sampling and measurements of paleomagnetism in glacial sedimentary sequences may be complicated by the heterogeneous composition of till units. For example, the presence of a granitic pebble in a sample may obscure the detrital remanent magnetization signal. This problem was avoided, for the most part, by collecting multiple samples from each unit and by sampling in fine-grained intratill beds (clay to fine-sand beds). The till bounding intratill beds were also sampled.

The paleomagnetic remanence of samples was measured on an AGICO JR-5A spinner magnetometer at the Geological Survey of Canada-Pacific in Sidney, British Columbia. Stepwise alternating field demagnetization was carried out using a Schonstedt GSD-5 with tumbler in peak fields up to 100 mT. Samples were demagnetized using 5–10 step increments, and directions were determined by principal component analysis (Kirschvink, 1980).

Laboratory Methods for Sediment Analyses

For each of the 95 till samples, ~4 kg of material was sieved and the lithology of ~200 clasts of the 4–12.5 mm fraction of till was identified. Clast lithologies were divided into 14 classes that were later regrouped under two categories for the purpose of this study: sedimentary (e.g., limestone, dolomite, shale, and

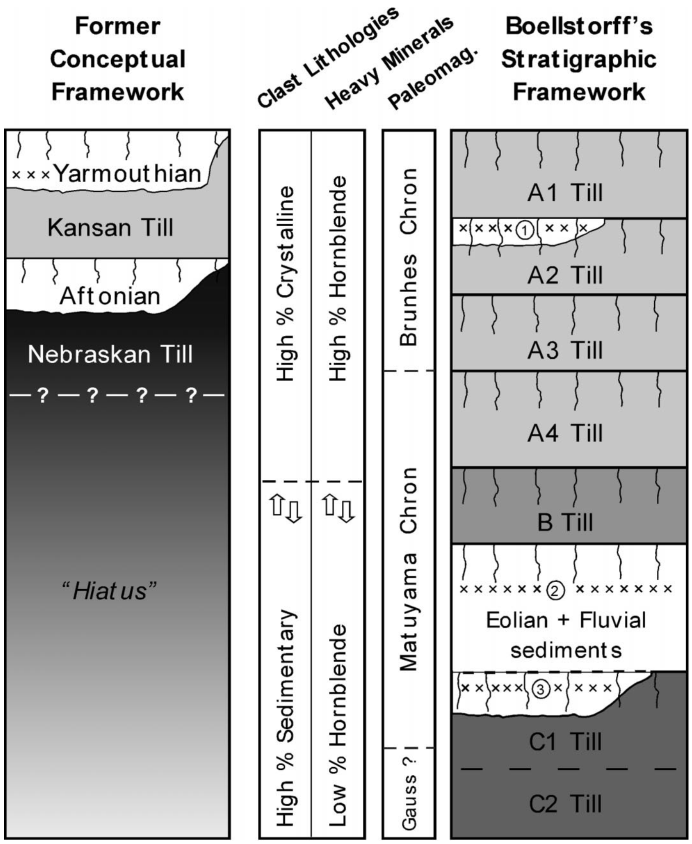

Figure 2. Simplified version of former conceptual framework for study area deposits. In this framework the Pearlette ash bed (Xs) was thought to be late Kansan or early Yarmouthian in age (modified from Reed and Dreezen, 1965). Stratigraphic framework of Boellstorff is shown for pre–Illinoian deposits of study area (modified from Boellstorff, 1978b; Easterbrook and Boellstorff, 1984). Paleosols are indicated by wavy vertical lines. Tephras are indicated by Xs: (1) 0.602 Ma Lava Creek B ash; (2) 1.293 Ma Mesa Falls ash; (3) 2.003 Ma Huckleberry Ridge ash. Petrographic and geochemical studies indicate that tephras originated from calderas of Yellowstone National Park in Wyoming (Izett, 1981). Ash ages after Gansecki et al. (1998).

sandstone) and crystalline (igneous and metamorphic) lithologies. The mineralogy of the clay (<2 μm) and silt (<15 μm) fraction of till was analyzed using standard X-ray diffraction techniques. X-ray diffraction (XRD) analyses were performed using a Phillips XRG3100 equipped with a focusing monochromater (Cu K(radiation, 0.02° 2 theta/step, 1 s count/step). The clay mineral content of the till samples was based upon the interpretation of weighted intensities of XRD pattern basal reflections, and the bulk sample mineralogy was determined using JADE+ software. The semi-quantitative analysis of the mineral phases present in till samples was based on comparisons (profile fitting) of peak area measurements of unknown samples to peak areas of internal standards with known mineral composition. These standards consist of five different XRD patterns that best represent the variety of XRD patterns obtained in this study. The composition and content of minerals present in the standards were determined through computer-assisted modeling using the NEWMOD program (Reynolds, 1985). The unknown XRD patterns were then compared to the modeled XRD patterns to identify which of the standards most closely resembled the mineral content of the unknown XRD patterns. The peak areas of the unknown patterns were subsequently measured. Knowing the content of each mineral phase present in the modeled patterns, comparisons of the peak areas of the unknown pattern with the modeled pattern allowed the determination of the amount of mineral phases present in each sample. The clay mineral abundances of the <2 μm fraction of tills were later normalized to 100% and expressed as weight % values.

GENERAL CHARACTERISTICS OF THE TILL UNITS

The study area is part of a gently rolling till plain deeply incised by streams that have exposed surficial units of different ages (Hallberg, 1986). The bedrock geology of the study area consists of upper Pennsylvanian limestone, shale, and sandstone. Most pre–Illinoian sections investigated lie directly on carbonate bedrock. The thickness of till units ranges from 2 to 18 m, with stratigraphic sections exposing up to 30 m of pre–Illinoian glacial sediments. The pre–Illinoian sections investigated typically expose one to three till units separated in places by nonglacial and glaciofluvial sorted sediments and/or thick paleosols developed on the upper part of till units (Fig. 3, Table 1). Most sections are capped by loess deposits of varying thickness; some of these contain soil-forming horizons of the last and previous interglacials.

The glacial deposits consist of fine-grained, matrix-dominated tills. Tills are mostly homogeneous, both laterally and vertically. Minor variations are related to slight upward color changes associated with post-glacial development of paleosols. Unweathered tills typically have a very dark gray color (Munsell color 5Y 3/1), which may show slight variations related to the lithological content of units. This massive appearance is interrupted in places by the presence of intra-till beds composed of sorted material. Sorted sediments are not abundant and appear erratically within the sedimentary sequences. These beds consist of fine sand to coarse gravel and range in thickness from a few centimeters to less than a meter. The beds are distributed horizontally in the till units, with flat to wavy lower and upper contacts, and some beds bear primary sedimentary structures. Most till units show sharp and planar contacts with the underlying and overlying deposits. The clast (4–12 mm) content of the tills is low, consisting, on average, of <2% of the deposits, and clasts are matrix supported. Large boulders (>1 m) are rare, and when present, they are found at the base of units. A few faceted, bullet-shaped clasts, some bearing striations, are also present. Compressed wood fragments are common within the deposits. Structural indicators of deformation, such as folds or boudinage structures, were encountered at only one locality (site 20). At five sites, information on ice flow directions was determined from striated bedrock and/or striated bullet-shaped clasts. In all cases, a general southward ice flow was documented, with azimuths ranging from 163–192°, consistent with models of ice deposition for the study area (Aber, 1999).

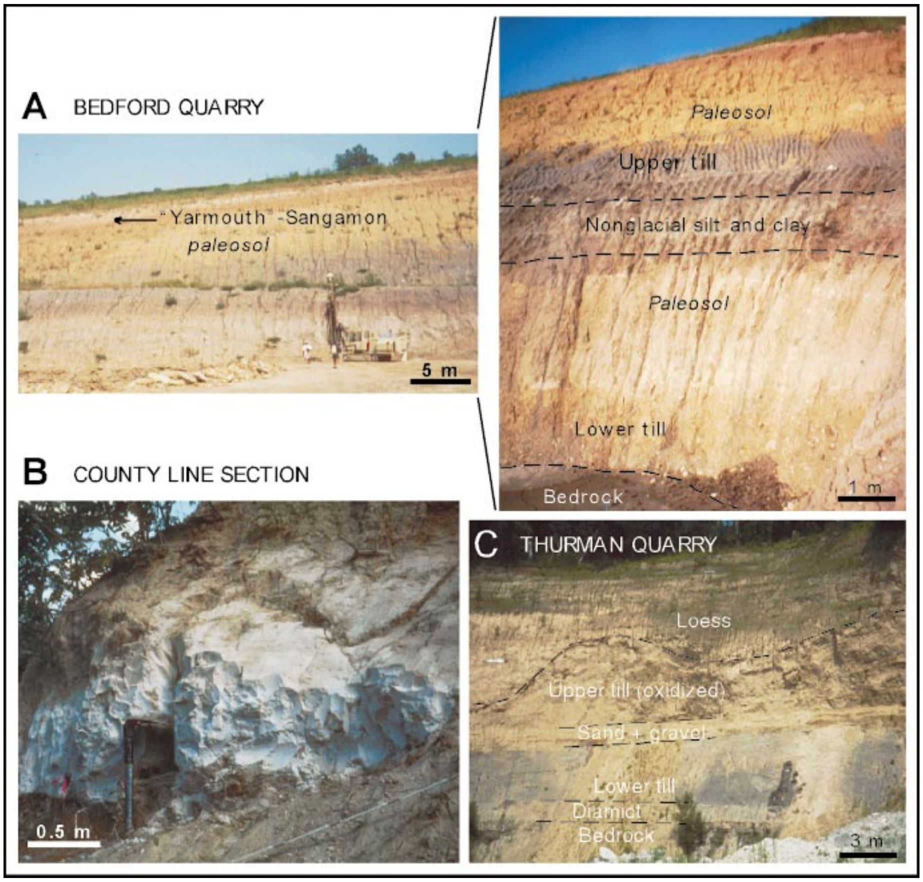

Figure 3. Examples of pre–Illinoian sections. (A) Two till units with paleosols separated by nonglacial silt and clay unit at site 19 (blow-up of units to left). (B) Lava Creek B ash (0.602 Ma) cropping out near site 4. (C) Two-till unit sequence capped by loess deposits at site 15. Lower till is truncated by sand and gravel unit whereas upper till is affected by paleosol development. Sandy diamicton is present between lower till and bedrock.

PALEOMAGNETISM RESULTS

Of the 711 samples analyzed for paleomagnetism, ~80% gave coherent results. The remainder had incoherent directions or unstable magnetization (Table 2). The natural remanent magnetization (NRM) intensities of the samples range from 0.5 to 43.1 mA/m (geometric average = 5.6 mA/m). Loess provided the highest NRM, followed closely by intratill silt beds. Tills tend to show lower NRM as well as a larger magnitude variation in NRM. The relatively intense magnetization and demagnetization features of the samples suggest that magnetite is the main mineral carrier for the remanent magnetization.

Samples with coherent directions and within-site homogeneity accurately record the Earth's paleofield. Samples showing a larger degree of scatter within a single horizon less faithfully record the paleofield but are still useful in assigning polarity to such units. Our samples reveal both positive (downward) and negative (upward) inclinations, representing units with normal and reverse polarity, respectively (Fig. 4). Incoherent directions in glacial samples are attributed to the presence of very weak or unstable magnetizations, and/or the presence of crystalline pebbles that mask the ambient magnetic field of the sediment matrix. The presence of such pebbles in a sample was verified after analysis. Samples with incoherent directions were therefore rejected from the data set. Our results allowed the identification of 12 till units with normal polarity and 21 till units with reversed polarity. Incoherent results precluded the assignment of a polarity to four till units. At a few sites containing multiple-till sequences, normal-polarity units consistently overlie reverse-polarity units. Intratill beds yielded directions in general agreement with the one of the bounding till unit, and all loess samples revealed normal polarity.

Here we interpret that the normal and reversed polarities recorded by the sediments can be assigned to the Brunhes Normal Chron and Matuyama Reverse Chron, respectively, and do not represent deposition during subchrons. This interpretation is required by the lack of other dating control on the sedimentary sequences but is supported by several considerations. Subchrons exhibit relatively short time spans (~10–100 k.y.) with respect to chrons (~1000 k.y.), thus increasing the likelihood that we sampled sediment recording the polarity of a chron rather than a subchron. Some subchrons also fall almost entirely during interglacials. Where multiple-till sections exhibit units with different polarity, the stratigraphic succession always consists of a reverse-polarity unit overlain by a normal-polarity unit. At no site was a normal-polarity unit found underlying a reverse-polarity unit. Nevertheless, the occurrence of normal and reverse polarity subchrons within the Brunhes and Matuyama Chrons has the potential to complicate our record, and the development of independent dating methods may eventually identify evidence of deposition during a subchron.

TILL COMPOSITIONAL RESULTS

Clast Lithology of Tills

The composition of the 4 to 12.5 mm clast fraction of tills shows wide variations. Within the context of the paleomagnetic polarity of the till units, however, there are significant lithological similarities (Fig. 5). Till units with reverse polarity are primarily dominated by sedimentary lithologies whereas till units with normal polarity show an increase in crystalline lithologies. Further lithological distinction within the group of reverse-polarity tills suggests that two populations are present (Fig. 5): one, named R2 tills, is composed almost entirely of sedimentary lithologies (>77%; average of 85%), and the other, R1 tills, is intermediate between the latter cluster and the group of normal-polarity tills (R1-till average: 63% of sedimentary clasts). The average composition of normal polarity tills (53% of sedimentary clasts) is nearly identical to the composition of Wisconsinan tills (55%). Wisconsinan tills are also characterized by a clast content that is on average nearly three times greater than that of pre–Illinoian tills.

The stratigraphic relation of some of our till samples to volcanic ashes suggests that the R2 tills are older than the R1 tills. Till units associated with volcanic ashes are present at four localities (Fig. 6A). Till beneath a nonglacial silt containing the 2 Ma Huckleberry Ridge ash (Boellstorff, 1978c) (site 9) contains 90% sedimentary clasts, whereas the up-

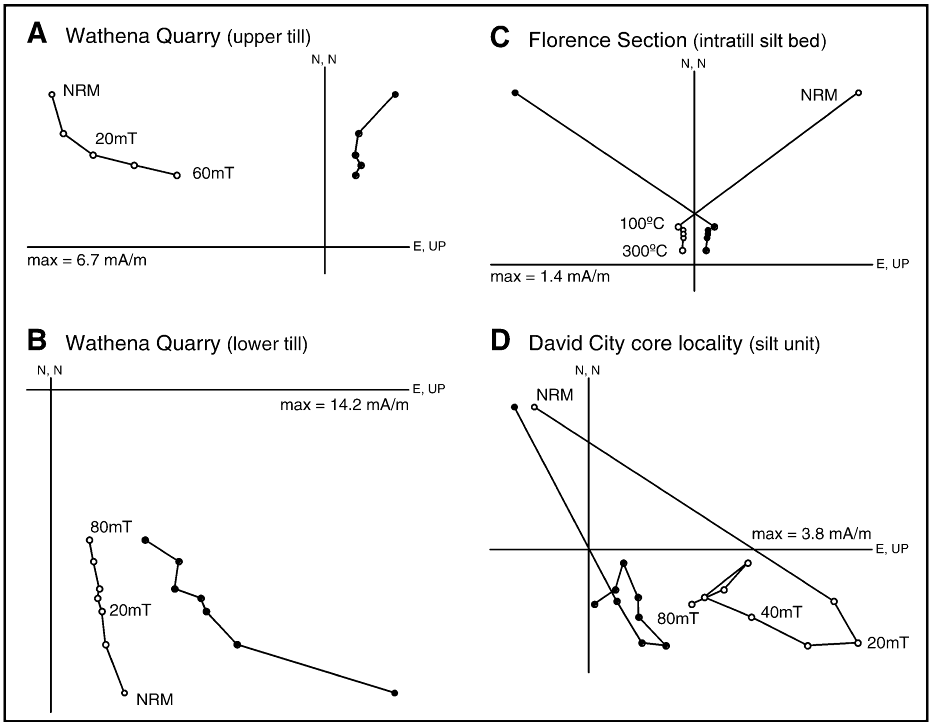

Figure 4. Demagnetization characteristics of pre–Illinoian units. Horizontal component of magnetization after stepwise alternating demagnetization is marked with solid circles; vertical component is marked with open circles (NRM—natural remanent magnetization). Alternating field steps are given in mT; thermal steps are given in °C. (A) and (B) are from normal- and reverse-polarity till units at site 21; (C) is from normal-polarity intratill silt bed at site 8; and (D) is from reverse-polarity silt unit containing 1.3 Ma ash at site 10 and depicts complex nature of some magnetization records. Initial demagnetization steps (0–20 mT) removed soft (normal) viscous overprint possibly due in part to Brunhes-age weathering phase. Steps 20–50 mT reveal original (reversed) detrital remanent magnetization component. Hard overprint (over 50 mT) likely reflects chemical remanence associated with authigenic formation of hematite and/or goethite.

per till with a normal (?) polarity contains 56% sedimentary lithologies. A till with a reversed polarity overlying a silt unit containing the 1.3 Ma Mesa Falls ash (Boellstorff, 1973) (site 10) has a sedimentary clast content of 66%. No polarity could be assigned to the overlying till, but its composition is the same as that of the underlying till. A normal-polarity till that is overlain by the 0.6 Ma Lava Creek ash (site 8) has a sedimentary clast content of 50%. A similar stratigraphic setting (site 4) exposes the 0.6 Ma Lava Creek ash overlying a till unit with a relatively low sedimentary clast content of (53%). This unit, however, is weakly magnetized, and while its polarity cannot be assigned unequivocally, it appears to be reversed.

Based on relative age of till units determined by stratigraphic superposition in individual outcrops, we also find a consistent decrease in sedimentary lithologies and a concomitant increase in crystalline lithologies in younger tills (Fig. 6B, Table 3). At the sites exposing multiple tills with the same polarity, the clast lithology of the lower unit is either similar to or is enriched in sedimentary clasts relative to the overlying unit. Where the unit succession consists of a reverse-polarity till overlain by a normal-polarity till, a similar upward decrease in sedimentary clasts is documented. These results are consistent with the clast composition of the till units present at the volcanic ash localities described above (Fig. 6A). Taken together, these results tend to suggest the presence of a compositional trend consisting of a decrease in sedimentary clasts in progressively younger till sequences.

Mineralogy of the Clay and Silt Fractions of Tills

The clay mineralogy of tills is sensitive to pedogenic alteration during interglacial periods. For this reason we focused our work on unweathered tills (i.e., tills not affected by paleosol development). The X-ray diffraction (XRD) analyses indicate that illite, kaolinite, and interstratified illite/smectite (expandable clays) are the main clay mineral constituents of the <2 μm fraction of tills, along with minor amount of chlorite. Intensity changes in the XRD patterns show variations in the abundance of these minerals among the till samples that, when placed within the context of the paleomagnetic and ash chronology, reveal mineralogical differences between tills of different ages (Table 3).

The clay mineralogy of the reverse-polarity tills is characterized by a lower abundance of expandable clays and by higher abundance of kaolinite compared to that of normal-polarity tills (Fig. 7). Wisconsinan tills are also distinct from their older counterparts with a composition of 58% expandable clays and 4% kaolinite. The Wisconsinan tills and the normal-polarity tills can also be distinguished from the reverse-polarity tills by the occurrence of minor amounts of chlorite, which is most abundant in the Wisconsinan tills. The content of illite does not vary significantly among the till groups, showing abundances ranging from 32% to 36%. Contrary to the clast lithological content of tills, distinctions cannot be made within the reverse-polarity tills using clay mineralogy. This, however, may be related to the small number ($n = 5$) of R2 till samples analyzed. Nevertheless, the R2 tills are slightly depleted in expandable minerals compared to the R1 tills.

We also find significant mineralogical contrasts in the silt fraction of the different till groups. Semi-quantitative analyses of the mineralogy of the silt fraction are complicated by the wide variety of minerals and the corresponding overlap of their intensity peaks in XRD patterns and thus prevent true assessment of mineral abundance. For this reason, we discuss only ratios of the peak areas of quartz relative to the peak areas of calcite and dolomite, and to the ones of feldspars. The R2 tills show the largest quartz/carbonate ratio (0.94), followed by the R1 tills (0.51), the normal-polarity tills (0.37), and the Wisconsinan tills (0.17) (Fig. 8A). This trend can be attributed to some combination of a decrease of quartz and an increase of carbonate minerals in the silt fraction of tills with time.

The group of feldspar minerals shows a wide range in composition, which is reflected in XRD patterns by subtle variations in the position of the individual feldspar peaks. Therefore, to obtain information on the ‘‘total’’ feldspar content of samples, we integrated the total area under the segment comprising most of the feldspar peaks in the

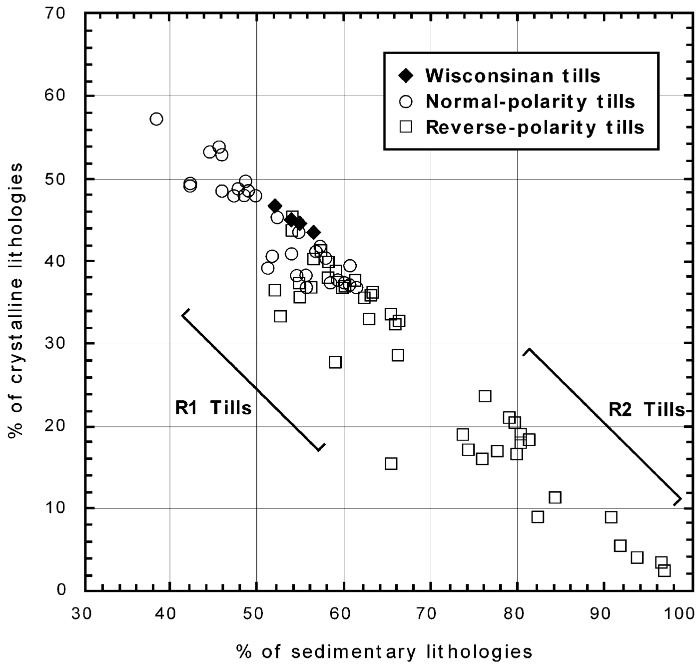

Figure 5. Relationship between clast (4–12.5 mm) content of crystalline and sedimentary lithologies of tills placed in context of paleomagnetic results. See text for details on clusters labeled R1 tills and R2 tills. Not every sample sums to 100% because some lithologies could not be determined.

XRD patterns of samples. The XRD intensities of feldspar peaks are also very sensitive to crystal orientation on the smeared slides and thus have the potential to produce apparent large intensities if the feldspars of the analyzed samples have any preferred orientation. For these reasons, ratios involving feldspars should be regarded as highly qualitative and attention should only be placed on large changes between the main till groups (i.e., reverse- and normal-polarity tills). Our results reveal significant changes in the till groups and indicate that the reverse polarity tills show the largest quartz/feldspar ratio (1.12), followed by the normal-polarity tills (0.91), and the Wisconsinan tills (0.55) (Fig. 8B; Table 3). This trend is related to some combination of an increase of feldspar and a decrease of quartz in progressively younger glacial sequences.

STRATIGRAPHIC IMPLICATIONS

Comparisons to Previous Work

In this study, we have documented a compositional change in the glacial sedimentary sequences of the midcontinent that is best seen in the clast lithological content of tills, although the mineralogy of the clay and silt fractions of tills also shows significant changes between the reverse- and normal-polarity tills. Boellstorff (1978b) previously established a stratigraphic framework for the study area based on general till compositional variations in younging glacial sequences that are similar to those we describe here. In this framework, Boellstorff (1973, 1978b) used the heavy mineral content of the fine-sand fraction of tills and the lithology of the pebble fraction of tills to distinguish three groups of tills (A, B, and C tills). The A and C tills were further

TABLE 1. SUMMARY OF STRATIGRAPHY EXPOSED AT SAMPLING SITES

Site[†]	Latitude (N)	Longitude (W)	Site name (state)	Unit summary[‡] (from bottom to top)	Ref.[§]
1	41°04′27″	95°57′50″	City Wide Quarry (NE)	bedrock/till-*psl*/till-*psl*/silt/till/loess	[1]
2	41°06′09″	95°49′20″	Glenwood Quarry (IA)	bedrock/diamicton/till/sand+gravel/till-*psl*/loess	new
3	41°20′59″	95°53′46″	Crescent Quarry (IA)	bedrock/till-*psl*/silt+sand/loess	new
4	41°51′20″	95°59′13″	County Line Section (IA)	bedrock/sand/till/s.+gr./silts (0.6 m.y. ash)/loess	[1]
5	41°09′40″	95°22′12″	Macedonia Quarry (IA)	bedrock/till-*psl*/loess	new
6	41°27′32″	94°25′51″	Greenfield Quarry (IA)	bedrock/till-*psl*/till/sand+gravel/loess	new
7	40°59′38″	94°02′25″	Thayer Quarry (IA)	bedrock/gravel+sand+silt-*psl*/till-*psl*	new
8	41°22′21″	95°56′51″	Florence Section (NE)	till/silt (0.6 Ma ash)/loess	[1]
9	40°59′46″	94°12′16″	Afton drill site (IA)	bedrock/till/silts (2.0 Ma ash)/till-*psl*/loess	[1]
10	41°14′59″	97°10′00″	David City drill site (NE)	bedrock/silt (1.3 Ma ash)/till-*psl*/s.+gr./till-*psl*/loess	[1]
11	42°50′25″	96°08′56″	LeMars Landfill (IA)	till-*psl*/loess	new
12	42°03′46″	95°59′13″	Turin Section (IA)	till-*psl*/loess	new
13	41°28′51″	95°52′56″	Loveland Section (IA)	bedrock/till-*psl*/loess	new
14	41°23′59″	96°31′24″	Fremont Section (NE)	till-*psl*/till-*psl*/loess	[1]
15	40°51′24″	95°45′30″	Thurman Quarry (IA)	bedrock/diamicton/till/sand+gravel/till-*psl*/loess	new
16	40°45′05″	95°42′45″	Thurman Section (IA)	till-*psl*/loess	new
17	40°15′56″	96°09′37″	Elk Creek Section (NE)	till-*psl*/sand+gravel	[1]
18	39°49′37″	96°03′09″	Seneca Section (KS)	till-*psl*/diamicton	new
19	40°40′24″	94°15′02″	Bedford Quarry (IA)	bedrock/till-*psl*/silt/till-*psl*/loess	new
20	39°32′29″	95°10′09″	Atchison Section (KS)	till/till-*psl*/loess	[2]
21	39°44′34″	94°56′38″	Wathena Quarry (KS)	bedrock/gravel+silt+sand/(slump) till/till-*psl*/loess	[3]
22	40°17′32″	94°00′13″	Bethany Quarry (MO)	bedrock/till-*psl*/loess	new
23	40°30′31″	93°28′55″	Mercer Quarry (MO)	bedrock/till-*psl*/loess	new
24	42°01′45″	93°35′48″	Whatoff Quarry (IA)	bedrock/Wisconsinan till-*psl*	new
25	42°31′33″	93°22′15″	Alden Quarry (IA)	bedrock/diamicton-*psl*/till/sands+loess/Wisconsinan till	new

Notes: [†]See Figure 1 for location; site coordinates given for latitude north and longitude west.
[‡]till-*psl* indicates till unit with well-developed paleosol (>1 m in thickness); s. + gr. indicates sand and gravel unit.
[§]References for sites previously studied: [1] Boellstoff (1973, 1978b); [2] Aber (1991); [3] Dort (1985); and references therein.

TABLE 2. PALEOMAGNETIC RESULTS

Site	Lithostratigraphy at each site	n[†]	Polarity[‡]	Paleomagnetic properties of units[§]						
				NRM	X_0	k_n	Dec	Inc	k	α_{95}
1	Loess	8	N	36.1	11.0	0.82	4.2	57.9	134.4	4.8
	Upper till *(underlying silt)*	7	N	12.0	6.5	0.55	0.5	50.5	51.3	8.5
	Middle till	28	R	1.8	2.2	0.22	186.9	−48.2	3.0	20.8
	Lower till *(upper part)*	8	R	2.1	5.8	0.11	171.4	−53.4	16.0	32.1
	Lower till *(lower part)*	37	R	1.3	1.8	0.17	184.9	−58.3	7.5	16.0
2	Loess	8	N	1.8	8.3	0.55	18.1	61.6	282.1	5.5
	Upper till	16	R	1.3	1.3	0.25	215.8	−57.5	21.0	14.3
	Lower till	21	R	2.2	2.7	0.21	180.6	−51.6	6.0	17.1
3	Silt+sand	7	N	12.0	3.0	0.80	2.6	58.0	183.3	4.5
	Till	15	R	1.0	1.6	0.16	167.5	−48.0	14.9	16.5
4	Silts	6	N	11.2	1.1	2.65	358.1	52.4	84.4	7.3
	Till	18	R?	1.2	1.4	0.21	180.6	−61.7	4.2	24.0
5	Loess	7	N	18.0	7.5	0.41	342.6	56.7	33.0	16.2
	Till	22	i	1.3	2.5	0.15	~	~	~	~
6	Loess	12	N	12.0	2.5	0.80	358.9	58.6	39.7	8.9
	Cut and fill	20	N	1.8	1.3	0.33	8.6	42.0	22.9	9.7
	Paleosol (upper till)	9	N?	3.6	1.9	0.50	10.1	47.0	10.0	22.2
	Upper till	10	R	1.2	1.0	0.30	166.0	−50.3	7.0	27.3
	Intratill silt bed (upper till)	14	i	3.1	0.8	0.90	5.6	20.1	37.4	8.0
	Lower till	28	R	1.9	2.6	0.18	192.0	−57.6	4.2	23.1
7	Till	41	i	1.0	1.9	0.13	~	~	~	~
	Sand and silt unit	15	N	3.2	1.4	0.57	359.8	47.5	13.2	13.8
8	Till	8	i	2.2	0.7	0.77	~	~	~	~
	Intratill silt bed	7	N	5.2	0.6	2.11	275.9	36.6	27.6	11.7
9	Upper till	16	i	1.2	1.8	0.20	~	~	~	~
	Silt (2.0 m.y. ash)	18	i	~	~	~	~	~	~	~
	Lower till	12	R	1.8	1.1	0.45	154.0	−34.8	4.4	24.6
10	Upper till	12	R??	5.8	2.7	0.55	180.7	−14.3	45.6	18.5
	Lower till	32	R	0.9	1.9	0.13	183.2	−60.6	13.0	10.6
	Silts (1.2 m.y. ash)	12	R	4.0	3.5	0.29	137.0	−58.3	40.3	7.3
11	Till *(upper part)*	4	N	18.0	1.7	1.90	8.1	38.9	168.6	7.1
	Till *(lower part)*	3	R?	1.4	0.8	0.60	147.5	−46.1	136.2	59.3
12	Till	8	R?	1.6	0.9	0.47	194.6	−49.7	7.8	41.7
13	Till	6	R	0.9	0.8	0.28	162.3	−55.7	13.4	31.3
14	Silt	6	N	11.7	2.8	1.07	346.8	67.9	438.6	4.4
	Upper till	20	N	8.4	2.3	0.90	357.2	60.9	31.7	7.5
	Lower till *(upper part)*	12	N	5.7	2.5	0.47	343.3	60.7	46.6	11.3
	Lower till *(lower part)*	9	i	1.4	1.8	0.19	~	~	~	~
15	Upper till	3	R	6.1	2.3	0.65	163.7	−35.8	472.2	30.8
	Silt	6	R?	1.4	0.7	0.49	112.5	−45.2	31.4	20.2
	Middle till	6	R	3.5	2.3	0.38	195.0	−64.7	35.2	30.2
	Lower till *(diamicton)*	5	R	6.9	4.8	0.36	182.7	−42.0	29.6	42.0
16	Till	4	N	4.8	2.5	0.47	349.1	60.4	16.4	23.4
17	Intratill silt bed	6	R	13.3	1.1	3.04	142.4	−32.0	63.4	8.5
	Till	6	i	1.1	1.1	0.26	~	~	~	~
18	Till	8	R	2.1	0.5	1.11	173.1	−13.8	7.3	27.0
19	Upper till	7	R?	0.5	7.3	0.19	127.2	−79.7	4.5	57.2
	Nonglacial silt	18	R	1.9	1.2	0.27	194.3	−33.3	15.9	9.0
	Lower till	9	R	0.8	1.2	0.17	245.6	−44.1	7.4	24.6
20	Upper till	6	R	1.9	0.5	0.89	203.5	−22.9	6.9	27.9
	Sand unit	3	R	1.2	1.3	0.25	166.8	−34.4	10	48.4
	Lower till	6	R	8.8	0.8	3.50	199.3	−19.8	10.5	21.7
21	Upper till	6	N	4.3	0.8	1.60	65.3	38.6	7.5	26.3
	Lower till	8	R	4.2	0.7	1.57	146.8	−24.0	7.8	23.1
22	Till	9	i	0.8	0.9	0.22	~	~	~	~
23	Till	6	N	5.1	1.0	1.20	6.4	54.7	13.1	21.9
	Intratill silt bed	13	N	5.5	8.9	1.20	350.3	34.9	19.8	11.9
24	Wisonsinan till	~	~	~	~	~	~	~	~	~
25	Wisonsinan till	6	N	12.0	2.5	1.20	345.8	61.2	38.0	11.0
	Nonglacial sand, silt, loess	8	N	43.1	5.0	2.18	352.8	61.1	99.9	5.6
	Middle till	6	N	5.2	3.1	0.40	154.1	83.0	8.3	24.7
	Lower till	14	N	3.3	0.6	0.40	2.8	61.6	17.3	10.2

Notes: [†]n—number of sample analyzed; ~—no data.

[‡]n—unit with normal polarity (Brunhes Chron); R—unit with reverse polarity (Matuyama Chron); N?, R?—unit with weak remanent magnetism suggesting a normal, reverse polarity, respectively; N??, R??—unit with faint remanent magnetism suggesting a possible normal and reverse polarity, respectively; i—unit with indeterminate polarity; (N.B.: N?? or R?? units are considered as i units in treatment of till compositional data).

[§]NRM—natural remanent magnetization (mA/m); X_0—bulk magnetic susceptibility (10E-4 SI/vol); K_n—Koenigsberger ratio (unitless); Dec—declination (degree); Inc—inclination (degree); k—precision parameter; α_{95}—circle of confidence (P=0.05).

divided into subunits based on their relations to paleosols and their paleomagnetic signature (Fig. 2), although these subunits could not be distinguished using their lithological or heavy-mineral content.

Although Boellstorff's stratigraphic framework was not intended for regional use, subsequent stratigraphic studies elsewhere in the midcontinent have correlated till units to those defined by Boellstorff (Hallberg, 1980; Aber, 1991; Kemmis et al., 1992; Rovey and Kean, 1996; Colgan, 1999). In the context of relatively weak geochronological constraints, namely the absence of tephras and the small number of paleomagnetic analyses, these correlations were largely based on till compositional changes. Some of these correlations were also based on clay mineralogy and/or grain size analyses, even though Boellstorff (1973) could not distinguish tills on the basis of these two criteria.

Despite the wide use of Boellstorff's framework, the occurrence of different till groups with identical polarity and with nearly similar composition (e.g., B and A4 tills) makes till unit recognition difficult, and this problem is further accentuated on a regional scale. For instance, the validity of A4 till as a separate stratigraphic unit has been questioned in a stratigraphic study in north-central Missouri (Rovey and Kean, 2001). However, all these studies demonstrate a similar stratigraphic succession whereby older tills are distinguished from younger tills by their composition. Some pre–Illinoian till sequences at various locations in the midcontinent region also show a change in polarity, and this provides a chronological marker for regional correlations (Rovey and Kean, 2001). Consequently, these compositional changes and occurrence of magnetic reversals emerge as recurrent characteristics of midcontinent glacial sequences that can be used to improve the regional stratigraphic framework.

Proposed Stratigraphic Framework

Similar to previous studies (e.g., Aber, 1991; Rovey and Kean, 1996), we have documented compositional criteria that enable the identification of till groups of different age. In particular, our results are in agreement with those of Boellstorff in showing a change in clast lithology with time. We also report a high proportion of expandable clay minerals in normal-polarity tills and a lower proportion of expandable clays in reverse-polarity tills that is consistent with a regional pattern documented in eastern Iowa (Hallberg, 1980; Kemmis et al., 1992) and north-central Missouri (Rovey and Kean, 1996).

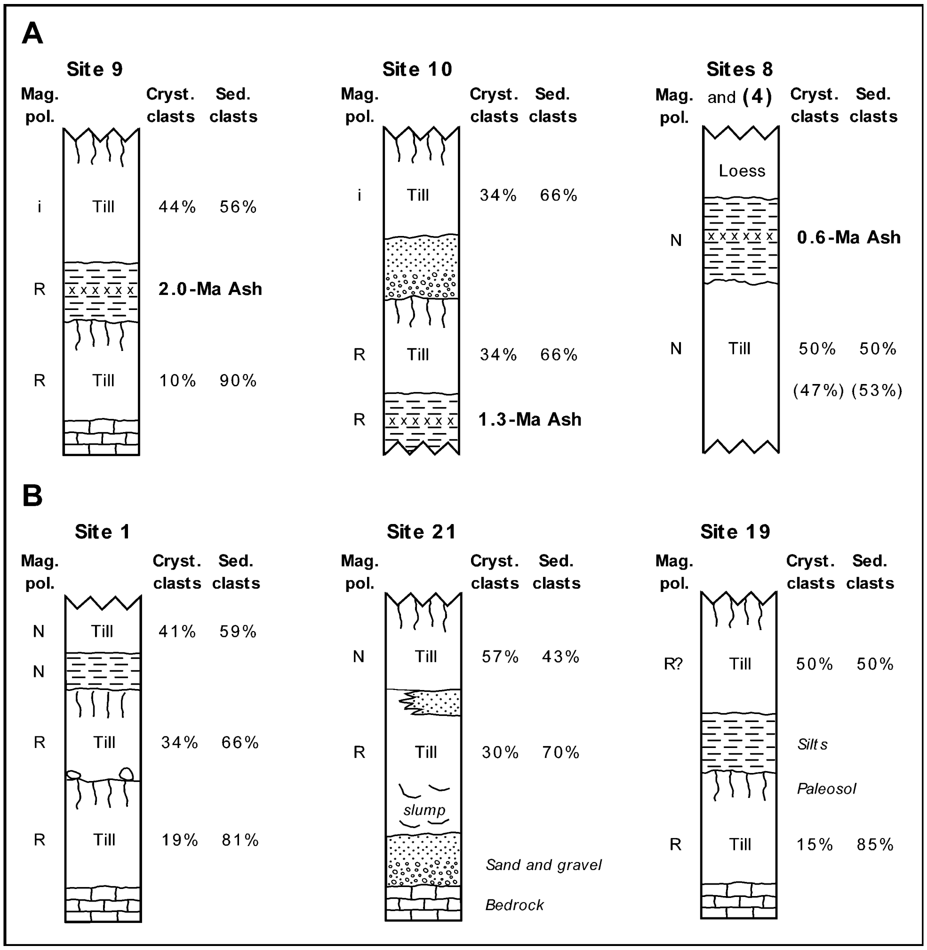

Figure 6. Schematic stratigraphic sections showing increase in crystalline lithologies in progressively younger sedimentary sequences (see text for details). (A) Sites of tills in contact with volcanic ashes. (B) Multiple-till sections containing units of reversed and normal magnetic polarity or units showing significant contrast in composition. Symbols: N, R, and i indicate units with normal, reverse, and indeterminate polarity, respectively. Mag. pol.—magnetic polarity; Cryst. and Sed.—crystalline and sedimentary lithologies, respectively.

However, we provide additional mineralogical criteria that, with the clast lithology data and within the context of our extensive paleomagnetic dating control at each site investigated, identify three regionally significant lithostratigraphic units (Figs. 9 and 10).

In light of these findings, we propose a simple stratigraphic framework based on the temporal changes in till composition as constrained by stratigraphic relations of till units to each other, to volcanic ashes, and to the Brunhes/Matuyama magnetic reversal (Fig. 9). This stratigraphic framework represents a revision of the till stratigraphy proposed by Boellstorff in two ways. First, our intermediate-age till group (R1 tills) includes the B and A4 tills, and our youngest pre–Illinoian till group (N tills) includes the A3, A2, and A1 tills. Secondly, we cannot distinguish regional subgroups by composition alone; paleomagnetic measurements are also needed. These conclusions are based on the results presented above as well as on data we obtained for two sites at which Boellstorff reported B and A4 tills. For instance, Boellstorff interpreted the upper till at site 1 as A4 till despite the lack of paleomagnetic measurements on that unit. Our results, however, indicate that the polarity of this unit is normal, thus ruling out the possibility that this is an A4 till (Boellstorff's A4 tills are reversed). Moreover, the composition of this unit is comparable to other normal-polarity tills. In addition, Boellstorff interpreted two tills at site 10 that are separated by highly weathered silts and fine gravels as B and A4 tills. We are unable to assign a polarity to the upper till, but our results indicate that the lower till is reversed. The absence of compositional differences between these tills suggests that they belong to the same till group (i.e., R1 tills). These results thus indicate that the reverse-polarity B and A4 tills cannot be distinguished from each other by composition.

Nevertheless, each of our three till groups contains several till units that are separated by paleosols, thus suggesting, within the present stratigraphic setting, that each of these groups may represent multiple ice advances. However, determining the exact number of advances, their age and duration, and their significance to the regional stratigraphy requires further dating control. Consequently, the main distinction of our proposed framework relative to Boellstorff's is that it indicates that individual pre–Illinoian lithostratigraphic units cannot be correlated accurately but instead can simply be regrouped under categories defined by broad chronological constraints.

The oldest till group, R2 tills, consists of till units with a reversed polarity and >77% of sedimentary clasts. Low amounts of expandable clays, substantial amounts of kaolinite, and the absence of chlorite characterize the clay mineralogy of R2 tills. The mineralogy of the silt fraction of R2 tills is rich in quartz and depleted in calcite, dolomite, and feldspar. This till group includes a till unit that underlies the 2.0-Ma Huckleberry Ridge ash, thus indicating deposition sometime between ~2.5 Ma (onset of Northern Hemisphere glaciations) (Mix et al., 1995) and 2.0 Ma. Although we do not know whether the other R2 tills were deposited during this interval, the close compositional affinities of the remaining R2 tills with the >2 Ma unit suggest that the R2 tills may have been deposited during the early part of the Matuyama Chron. The R2 till group is similar in composition to the C tills of Boellstorff (1973, 1978b), and R2 tills were found in all four states investigated.

The intermediate group, R1 tills, comprises till units that also have a reverse polarity but with a lithological composition ranging from 70% to 55% of sedimentary clasts. The clay mineralogy of R1 tills is similar to that of R2 tills. The silt fraction of R1 tills is slightly richer in carbonate minerals than R2 tills but contains about the same amount of feldspar as the R2 tills. The R1-till group includes two till units that overlie the 1.3 Ma Mesa Falls ash, thus indicating at least two glaciations between 1.3 Ma and 0.8 Ma. The compositional similarity of the other R1 tills suggests that they may have been deposited during this interval, although further dating control is re-

TABLE 3. LITHOLOGICAL AND MINERALOGICAL CONTENT OF TILL UNITS

Site	Mag. pol.†	Lithostratigraphy	Till group	Sample number	Clast lithology‡		Clay mineralogy§				Silt mineralogy#	
					Sedi.	Cryst.	Kao.	Exp.	Ill.	Chl.	Qtz/Felds.	Qtz/Carb.
1	N	Upper till	N	CTY09	58.6	41.4	12.0	56.3	31.7	0.0	0.94	0.51
					58.6	**41.4**					**0.94**	**0.51**
	R	Middle till	R1	CTY08	69.9	30.1	∼	∼	∼	∼	∼	∼
				CTY07	68.1	31.9	∼	∼	∼	∼	0.54	0.65
				CTY06	61.4	38.6	∼	∼	∼	∼	0.74	0.83
					66.5	**33.5**					**0.64**	**0.74**
	R	Lower till	R2	CTY05	82.1	17.9	∼	∼	∼	∼	∼	∼
				CTY04	81.0	19.0	∼	∼	∼	∼	∼	∼
				CTY03	79.5	20.5	∼	∼	∼	∼	0.81	1.01
				CTY02	81.2	18.8	∼	∼	∼	∼	0.83	0.79
				CTY01	82.8	17.2	∼	∼	∼	∼	0.84	0.89
					81.3	**18.7**					**0.82**	**0.90**
2	R	Upper till	R1	GLW06	63.7	36.3	29.8	48.5	21.7	0.0	1.56	0.36
				GLW07	59.1	40.9	14.8	59.3	25.9	0.0	1.38	0.36
					61.4	**38.6**	**22.3**	**53.9**	**23.8**	**0.0**	**1.47**	**0.36**
	R	Lower till	R1	GLW05	67.0	33.0	16.1	53.2	30.7	0.0	2.51	0.36
				GLW04	59.6	40.4	21.4	50.8	28.6	0.0	1.77	0.37
				GLW03	60.5	39.5	∼	∼	∼	∼	∼	∼
					62.4	**37.6**	**18.8**	**52.0**	**29.6**	**0.0**	**2.14**	**0.37**
3	R	Till	R1	CRS03	60.3	39.7	23.2	46.3	30.4	0.0	1.04	0.41
				CRS02	63.8	36.2	24.0	42.3	34.2	0.0	1.07	0.27
				CRS01	60.5	39.5	26.2	40.0	33.9	0.0	1.39	0.37
					61.5	**38.5**	**24.5**	**42.9**	**32.8**	**0.0**	**1.17**	**0.35**
4	R?	Till	R1	SHM02	55.8	44.2	16.6	42.9	40.4	0.0	1.39	0.40
				SHM05	50.0	50.0	17.5	53.0	28.7	2.1	0.81	0.26
					52.9	**47.1**	**17.0**	**48.0**	**34.6**	**1.0**	**1.10**	**0.33**
5	i	Till	i	MCD03	54.3	45.7	∼	∼	∼	∼	1.82	0.49
				MCD02	55.0	45.0	∼	∼	∼	∼	1.42	0.45
				MCD01	49.1	50.9	∼	∼	∼	∼	1.74	0.42
					52.8	**47.2**					**1.66**	**0.45**
6	R?	Upper till	R1	GRN01	54.5	45.5	∼	∼	∼	∼	∼	∼
				GRN02	60.8	39.2	27.7	37.5	34.8	0.0	1.17	0.79
					57.6	**42.4**	**27.7**	**37.5**	**34.8**	**0.0**	**1.17**	**0.79**
	R?	Lower till	R1	GRN05	59.4	40.6	∼	∼	∼	∼	∼	∼
				GRN06	58.9	41.1	∼	∼	∼	∼	1.26	0.73
				GRN07	60.3	39.7	25.8	49.5	24.7	0.0	1.15	0.37
					59.5	**40.5**	**25.8**	**49.5**	**24.7**	**0.0**	**1.20**	**0.55**
7	N	Till	N	THA05	46.0	54.0	∼	∼	∼	∼	∼	∼
				THA04	48.4	51.6	31.8	32.6	33.8	1.8	1.77	0.78
				THA03	59.1	40.9	32.1	33.1	32.8	2.1	1.18	0.66
				THA02	45.5	54.5	26.6	40.8	30.7	1.9	1.16	0.71
				THA01	49.2	50.8	31.7	31.0	35.4	1.9	∼	∼
					49.6	**50.4**	**30.5**	**34.4**	**33.2**	**1.9**	**1.37**	**0.71**
8	N	Till	N	FLO02	49.2	50.8	∼	∼	∼	∼	∼	∼
				FLO01	50.0	50.0	23.7	37.3	37.3	1.7	0.71	0.27
					49.6	**50.4**	**23.7**	**37.3**	**37.3**	**1.7**	**0.71**	**0.27**
9	i	Upper till	i	AF119	54.6	45.4	∼	∼	∼	∼	∼	∼
			i	AF151	57.9	42.1	∼	∼	∼	∼	∼	∼
					56.3	**43.7**						
	R	Lower till	R2	AF172	90.4	9.6	∼	∼	∼	∼	0.91	0.91
					90.4	**9.6**					**0.91**	**0.91**
10	i	Upper till	i	DC120	66.1	33.9	∼	∼	∼	∼	1.57	0.24
					66.1	**33.9**					**1.57**	**0.24**
	R	Lower till	R1	DC139	65.8	34.2	21.4	40.9	37.7	0.0	2.81	0.38
					65.8	**34.2**	**21.4**	**40.9**	**37.7**	**0.0**	**2.81**	**0.38**
11	N	Till	N	LMR02	46.3	53.7	∼	∼	∼	∼	∼	∼
				LMR01	45.7	54.3	10.6	59.0	27.3	3.1	0.69	0.19
					46.0	**54.0**	**10.6**	**59.0**	**27.3**	**3.1**	**0.69**	**0.19**
12	R?	Till	R1	TUR02	58.5	41.5	∼	∼	∼	∼	∼	∼
				TUR01	59.5	40.5	17.0	50.0	33.0	0.0	0.68	0.46
					59.0	**41.0**	**17.0**	**50.0**	**33.0**	**0.0**	**0.68**	**0.46**
13	R	Till	R1	LOV02	63.7	36.3	∼	∼	∼	∼	∼	∼
				LOV01	58.1	41.9	∼	∼	∼	∼	∼	∼
					60.9	**39.1**						
14	N	Upper till	N	FRE06	61.8	38.2	∼	∼	∼	∼	0.61	0.14
				FRE05	62.4	37.6	∼	∼	∼	∼	0.24	0.17
				FRE04	61.0	39.0	∼	∼	∼	∼	0.82	0.20
					61.7	**38.3**					**0.56**	**0.17**
	N	Lower till	N	FRE07	56.4	43.6	2.1	65.3	30.2	2.4	∼	∼
				FRE03	60.7	39.3	2.7	68.6	26.3	2.4	0.68	0.26
				FRE02	55.6	44.4	3.4	62.8	31.2	2.5	0.78	0.46
				FRE01	56.6	43.4	2.8	62.9	31.8	2.5	1.30	0.56
					57.3	**42.7**	**2.8**	**64.9**	**29.9**	**2.5**	**0.92**	**0.43**
15	R	Upper till	R1	THU06	62.0	38.0	∼	∼	∼	∼	0.78	0.19
				THU05	60.8	39.2	∼	∼	∼	∼	1.21	0.20
					61.4	**38.6**					**0.99**	**0.19**

(Continued)

TABLE 3. *(Continued)*

Site	Mag. pol.†	Lithostra-tigraphy	Till group	Sample number	Clast lithology‡		Clay mineralogy§				Silt mineralogy#	
					Sedi.	Cryst.	Kao.	Exp.	Ill.	Chl.	Qtz/Felds.	Qtz/Carb.
	R	Lower till	R1	THU04	66.1	33.9	23.6	44.0	32.4	0.0	1.47	1.18
				THU03	60.5	39.5	~	~	~	~	1.61	0.37
				THU02	55.2	44.8	21.4	50.0	28.6	0.0	1.73	0.34
					60.6	**39.4**	**22.5**	**47.0**	**30.5**	**0.0**	**1.60**	**0.63**
	R	*Diamicton*	*n.a.*	THU01	*82.9*	*17.1*	~	~	~	~	~	~
16	N	Till	N	STR01	57.7	42.3	11.3	60.9	27.8	0.0	0.69	0.38
					57.7	**42.3**	**11.3**	**60.9**	**27.8**	**0.0**	**0.69**	**0.38**
17	R	Till	R2	ELC03	97.7	2.3	~	~	~	~	0.93	1.53
				ELC02	96.6	3.4	~	~	~	~	0.82	1.46
				ELC01	96.0	4.0	~	~	~	~	0.72	1.24
					96.7	**3.3**					**0.82**	**1.41**
18	R	Till	R1	SEN02	62.0	38.0	29.9	39.8	31.2	0.0	2.20	0.23
				SEN01	67.1	32.9	24.9	38.3	36.8	0.0	1.41	0.26
					64.6	**35.4**	**27.4**	**39.1**	**34.0**	**0.0**	**1.81**	**0.24**
19	R?	Upper till	R1	BEF04	49.4	50.6	27.0	40.8	30.0	3.1	1.16	0.78
				BEF03	50.8	49.2	33.4	37.5	29.1	0.0	1.24	0.74
					50.1	**49.9**	**30.2**	**39.1**	**29.5**	**1.5**	**1.20**	**0.76**
	R	Lower till	R2	BEF02	81.7	18.3	24.3	43.0	32.7	0.0	1.03	1.39
				BEF01	88.2	11.8	23.2	34.2	42.6	0.0	0.77	1.17
					85.0	**15.0**	**23.7**	**38.6**	**37.7**	**0.0**	**0.90**	**1.28**
20	R	Upper till	R2	ATC05	79.0	21.0	~	~	~	~	~	~
				ATC04	76.5	23.5	~	~	~	~	~	~
					77.7	**22.3**						
	R	Lower till	R2	ATC03	81.0	19.0	23.8	41.6	34.7	0.0	0.68	0.35
				ATC02	79.7	20.3	25.1	39.1	35.8	0.0	0.60	0.33
				ATC01	81.6	18.4	26.6	41.7	31.7	0.0	0.75	0.26
					80.8	**19.2**	**25.1**	**40.8**	**34.0**	**0.0**	**0.68**	**0.31**
21	N	Upper till	N	WAT05	39.8	60.2	~	~	~	~	~	~
				WAT04	45.9	54.1	~	~	~	~	1.08	0.17
					42.9	**57.1**					**1.08**	**0.17**
	R	Lower till	R1	WAT03	63.8	36.2	23.0	38.7	38.3	0.0	1.86	0.73
				WAT02	61.9	38.1	27.3	30.9	41.7	0.0	1.94	0.64
					62.8	**37.2**	**25.1**	**34.8**	**40.0**	**0.0**	**1.90**	**0.69**
22	i	Till	i	BET03	94.3	5.7	~	~	~	~	~	~
				BET01	91.1	8.9	~	~	~	~	0.88	2.24
					92.7	**7.3**					**0.88**	**2.24**
23	N	Till	N	MER05	61.3	38.7	~	~	~	~	1.14	0.25
				MER04	58.6	41.4	~	~	~	~	0.89	0.41
				MER03	60.0	40.0	~	~	~	~	0.53	0.21
				MER02	53.4	46.6	23.8	37.3	37.2	1.7	1.06	0.43
					58.3	**41.7**	**23.8**	**37.3**	**37.2**	**1.7**	**0.91**	**0.32**
24	Wisco	Till	Wisc.	WHA02	55.2	44.8	~	~	~	~	~	~
				WHA01	52.8	47.2	~	~	~	~	~	~
					54.0	**46.0**						
25	Wisco	Upper till	Wisc.	ALD06	54.6	45.4	4.3	55.2	36.7	3.9	0.58	0.18
				ALD05	56.6	43.4	3.2	60.5	32.7	3.7	0.52	0.15
					55.6	**44.4**	**3.8**	**57.8**	**34.7**	**3.8**	**0.55**	**0.17**
	N	Middle till	N	ALD04	57.6	42.4	1.9	66.5	29.3	2.4	0.80	0.36
				ALD03	60.3	39.7	1.6	67.2	28.8	2.3	0.82	0.39
					58.9	**41.1**	**1.8**	**66.9**	**29.0**	**2.4**	**0.81**	**0.37**
	N	*Diamicton*	*n.a.*	ALD02	~	~	~	~	~	~	~	~

Notes: Mean of each till unit is shown in bold and large numbers; ~—no data.

†Mag. pol—magnetic polarity; N—unit with normal polarity; R—unit with reverse polarity; N?, R?—unit with weak remanent magnetism suggesting a normal, reverse polarity, respectively; N??, R??—unit with faint remanent magnetism suggesting a possible normal, reverse polarity, respectively; i—unit with indeterminate polarity; (N.B.: N?? or R?? units are considered as I units in treatment of till compositional data).

‡4–12.5 mm size-fraction: Sedi.—sedimentary and Cryst.—crystalline lithologies.

§<2 μm size fraction: Kao.—kaolinite, Exp.—expandable clays, Ill.—illite, and Chl.—chlorite.

#<15 μm size-fraction: Qtz/Felds.—quartz to feldspar ratio and Qtz/Carb.—quartz to carbonate ratio.

quired to support this assumption. The R1 till group includes the B and A4 till types of Boellstorff (1973, 1978b). R1 tills were found in all states but Missouri.

Finally, the youngest group of pre–Illinoian tills, N tills, consists of till units with a normal polarity and with a lithological content of $<62\%$ of sedimentary clasts. The clay mineralogy of N tills is characterized by the appearance of minor chlorite, the largest amount of expandable clays, and the lowest amount of kaolinite of the three groups of pre–Illinoian tills. N tills also show the greatest amount of feldspar and carbonate minerals in the silt fraction. This group includes at least one till unit overlain by the 0.6 Ma Lava Creek ash, thus suggesting that some of these units were deposited between 0.8 and 0.6 Ma, but also later, as indicated by two sites with a till overlying the 0.6 Ma ash (Boellstorff, 1973). The N till group is considered to include the A1, A2, and A3 tills of Boellstorff (1973, 1978b). N tills were found in all four states investigated.

CONCLUSIONS

Lithological and mineralogical analyses of pre–Illinoian glacial deposits indicate that the glacial sequences of the north-central United States display a wide variation in composition. Paleomagnetic analyses clearly identified units with normal polarity (Brunhes Chron) and reverse polarity (Matuyama Chron). One important contribution of our paleomagnetism study is to remove the ambiguity related to the magnetic polarity of the oldest glacial deposits of

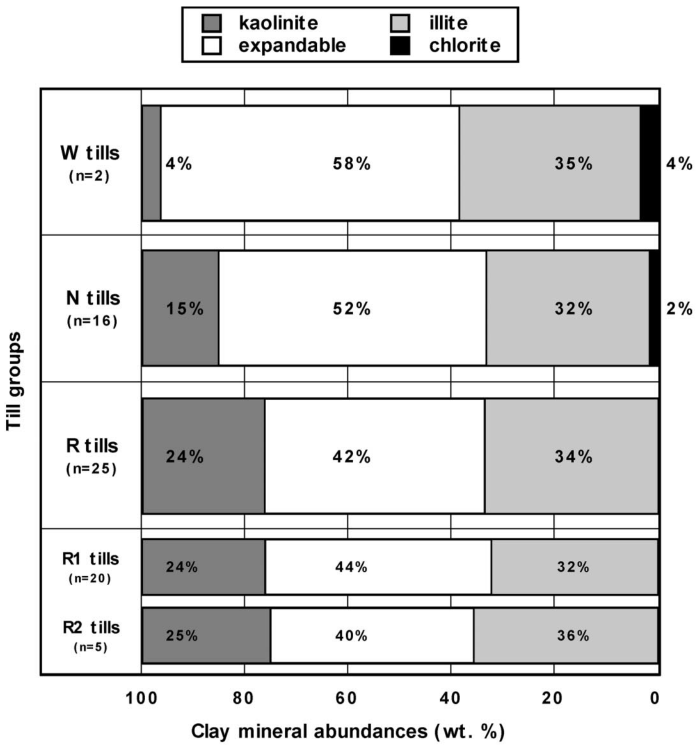

Figure 7. Clay mineral abundances (weight %) in various till groups. W—Wisonsinan; N—normal-polarity; R—reverse-polarity; see text for R1 and R2 tills.

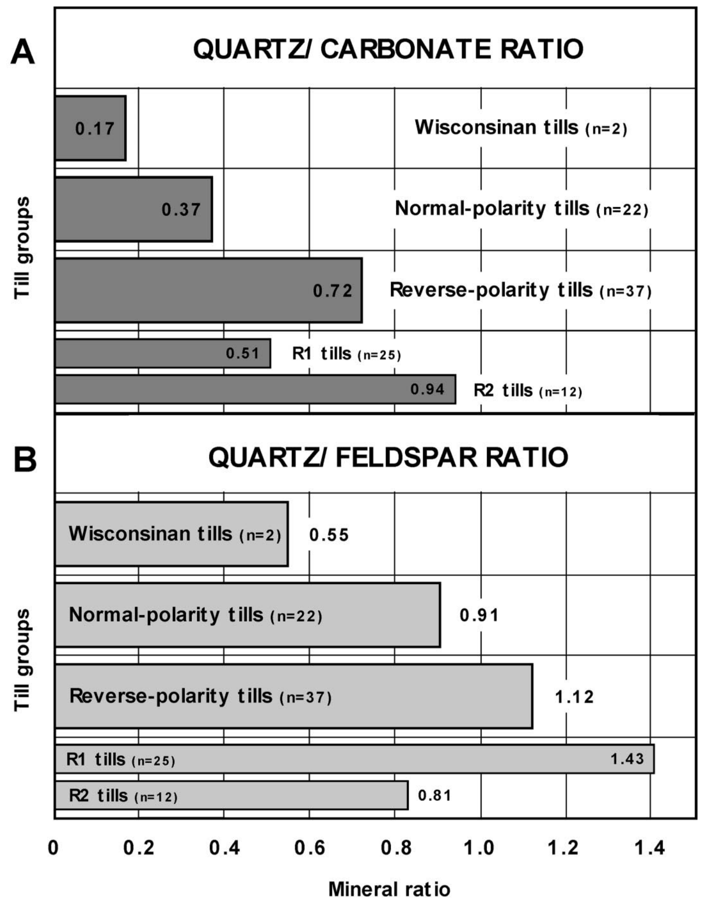

Figure 8. Mineral ratios in silt (<15 μm) fraction of tills derived from peak areas of minerals. (A) Ratio of quartz/calcite + dolomite (quartz/carbonate). (B) ratio of quartz/feldspar.

the study area. For instance, our data indicate that the till underlying a 2.0 m.y. ash-bearing silt unit has a reverse polarity, thus suggesting deposition during the earlier part of the Matuyama Chron. The compositional data indicate that the multiple-till sequences consistently show an upward (younging) increase in the amount of crystalline lithologies in tills. When placed in the context of paleomagnetic data and the three volcanic ashes of known age, however, we find a compositional change whereby clasts in the older (> 0.8 Ma) reversely magnetized tills (Matuyama Chron) contain a relatively high percentage of sedimentary lithologies and a corresponding low percentage of crystalline lithologies, whereas the younger (<0.8 Ma), normally magnetized tills are relatively depleted in sedimentary lithologies and rich in crystalline rocks. Two groups can be further distinguished within the reverse-polarity tills on the basis of their composition. The changes in the mineralogy of the clay and silt fractions of the reverse- and normal-polarity tills also show significant changes. When compared to the reverse-polarity tills, the clay fraction of the normal-polarity tills is rich in expandable minerals and poor in kaolinite. The silt fraction of the normal-polarity tills is also enriched in carbonate and feldspar minerals and depleted in quartz with respect to the reverse-polarity tills. Taken together, these data may reflect an unroofing sequence of the Canadian Shield that involved the removal of a former saprolite mantle (weathered rocks) by ice sheet erosion, progressively exposing a greater surface area of fresh crystalline rocks (Clark and Pollard, 1998).

Based on these results and lithostratigraphic considerations, we propose a simple stratigraphic framework in which we divide the pre–Illinoian tills into three groups. The oldest group, R2 tills, consists of reverse-polarity tills having >77% of sedimentary lithologies. The intermediate group, R1 tills, shows a transitional composition between the two other pre–Illinoian till groups and contains till units that were deposited sometime between 1.3 and 0.8 Ma. The younger group, N tills, is composed of normal-polarity tills that show approximately equal proportions of sedimentary and crystalline lithologies. The low resolution of our chronology prevents the identification of individual ice advances in the study area, but within the present stratigraphic context, the presence of paleosols developed in tills of different age and composition suggest a record of at least seven pre–Illinoian advances of the Laurentide ice sheet to a position south of the Last Glacial Maximum.

ACKNOWLEDGMENTS

We thank Greg Balco, Howard Hobbs, and Charles Rovey for critically reviewing the manuscript. Art Bettis and Joe Mason provided useful discussions in the field and assistance in finding stratigraphic sections. Joe Mason and the drilling crew of the Nebraska Geological Survey were instrumental in obtaining core samples. This work was supported by the National Science Foundation (ATM 9709684), a Geological Society of America Graduate Research Grant, and the Research Funds in Natural Science of the Province of Quebec (FCAR).

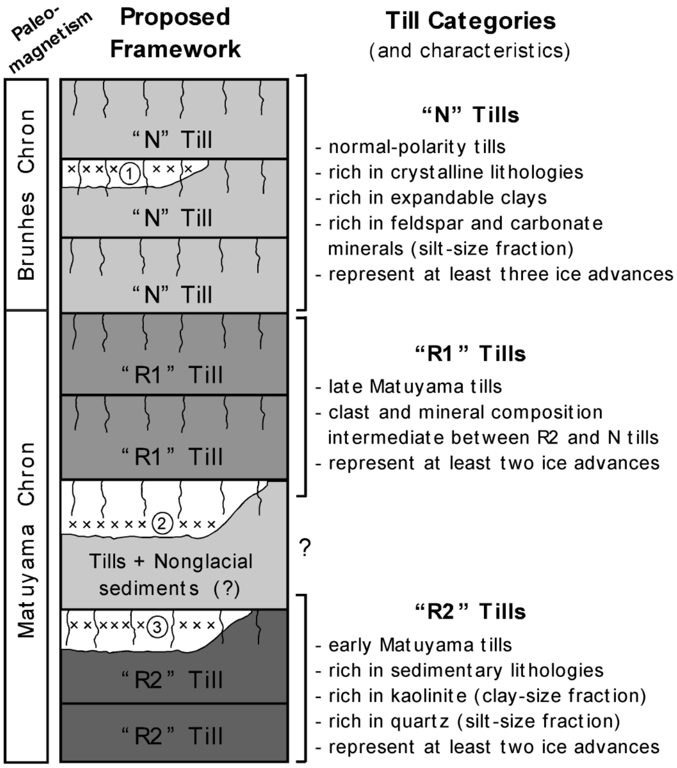

Figure 9. Proposed stratigraphic framework for north-central U.S. region. See text for details. Legend for symbols and tephra ages is same as in Figure 2.

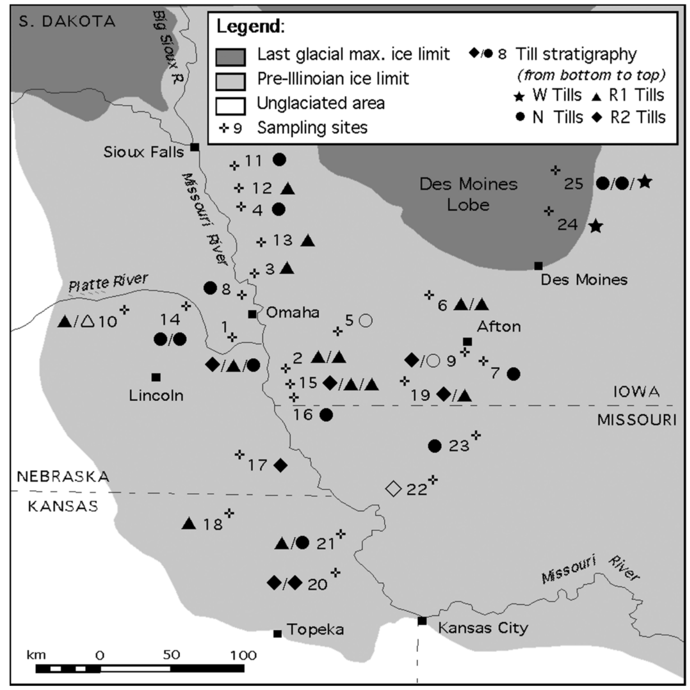

Figure 10. Distribution of various till units at each stratigraphic site with respect to three till categories identified. Open symbols correspond to till units with indeterminate magnetic polarity but of general clast composition suggesting they belong to one of the three till groups. Volcanic ash localities: sites 4, 8, 9, and 10. Max.—maximum.

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MANUSCRIPT RECEIVED BY THE SOCIETY 31 JANUARY 2003
REVISED MANUSCRIPT RECEIVED 27 JUNE 2003
MANUSCRIPT ACCEPTED 12 JULY 2003

Printed in the USA