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Insights into the late Cenozoic configuration of the Laurentide Ice Sheet from $^{40}Ar/^{39}Ar$ dating of glacially transported minerals in midcontinent tills

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[1] Glacial sedimentary sequences in the north central United States record multiple advances of the Laurentide Ice Sheet (LIS) since ~2 Ma. Although the tills found in these sequences were deposited by southward flowing glacial lobes, little information is available on the geometry of flow lines in the interior of the LIS during any one glaciation, and the provenance of glacial deposits older than the last ice advance is largely unknown. Systematic changes in the composition of midcontinent tills and other paleogeographic considerations, however, raise the possibility of significant shifts in the trajectory of flow lines feeding the lobes of the southwestern LIS margin. Here we constrain till provenance using $^{40}Ar/^{39}Ar$ ages of individual hornblende and feldspar grains retrieved from tills representing several glaciations since ~2 Ma. Hornblende grains show $^{40}Ar/^{39}Ar$ ages that indicate erosion of Paleoproterozoic (~1.7–2.0 Ga) and late Archean (>2.5 Ga) rock sources, whereas feldspar grains show a broad range of Paleoproterozoic ages (~1.4–2.4 Ga). Dating of hornblende and feldspar minerals in single pebbles suggests that this latter distribution of ages is related to the greater sensitivity of feldspars to thermal resetting during minor tectonic events. Accordingly, the range of $^{40}Ar/^{39}Ar$ ages for the predominant population of Paleoproterozoic hornblende and feldspar grains in our samples is consistent with a source from terrains forming the Churchill province of the Canadian Shield, while the small population of Archean-age grains likely reflects a source from the southwestern tip of the Archean Superior province that crops out near the study area. These results indicate that midcontinent tills were deposited by ice derived from the northwestern (Keewatin) sector of the LIS. The nearly identical distribution of hornblende and feldspar ages in the till samples identifies the Keewatin ice dome and the related ice flow to the midcontinent as long-standing features of the LIS throughout the late Pliocene-Pleistocene glaciations.

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1. Introduction

[2] The north central United States comprises the southernmost region once covered by the Laurentide ice sheet (LIS) (Figure 1). The glacial stratigraphy of the midcontinent region is characterized by extensive tills that record multiple advances of the LIS into this area since the late Pliocene [*Boellstorff*, 1978; *Roy et al.*, 2004a; *Balco et al.*, 2005]. Ice-flow directional data and former ice-margin positions in this region indicate that till was deposited by southward flowing ice lobes [e.g., *Aber*, 1999]. The geometry of the ice flow lines that terminated in the southwestern LIS lobes, as well as the configuration of the ice sheet throughout the late Cenozoic, is, however, largely unconstrained. Late-glacial advances of the Des Moines and James lobes are commonly assumed to have been derived from the northwestern (Keewatin) sector of the LIS (Figure 1), but geomorphological support for such a flow line is limited, and the provenance of the numerous older tills is mostly unknown. Paleogeographic reconstructions indicate significant displacements of the ice dispersal centers of the LIS during the last glacial cycle with attendant changes in regional flow line fields within the ice sheet [*Dyke and Prest*, 1987a, 1987b; *Veillette et al.*, 1999; *Dyke et al.*, 2002; *McMartin and Henderson*, 2004; *Veillette*, 2004]. The occurrence just north of the midcontinent region of glacial lobes (the Rainy and Superior lobes) that advanced through the Lake Superior basin from the northeastern (Labrador-Québec) sector of the LIS raises the possibility that not all tills in the midcontinent were derived from the same source, suggesting a complex behavior of the LIS throughout the late Pliocene-Pleistocene.

[3] The midcontinent glacial record also exhibits a systematic compositional change through time consisting of older tills enriched in sedimentary clasts, quartz, and kaolinite to younger tills enriched in crystalline clasts, feldspar, and expandable (mixed-layered) clays [*Boellstorff*, 1978; *Aber*, 1991; *Rovey and Kean*, 1996; *Colgan*, 1999; *Roy et al.*, 2004a]. These till compositional changes may record a change in provenance associated with the erosion of multiple rock-source regions of varying bedrock composition. Such changes in provenance would indicate significant shifts in the trajectory of flow lines that terminated in the glacial lobes of the southwestern LIS margin. Alternatively, the temporal changes in the lithological, mineralogical, and geochemical composition of midcontinent tills may record a change in the composition of a single rock-source region related to the progressive erosion of a widespread preglacial regolith and subsequent unroofing of unweathered Canadian Shield bedrock by successive ice advances of the LIS [*Clark and Pollard*, 1998; *Roy et al.*, 2004b; *Clark et al.*, 2006]. Distinguishing among these two scenarios is thus important in assessing long-term ice sheet dynamics.

[4] Here we constrain the provenance of midcontinent tills by using the $^{40}Ar/^{39}Ar$ method to date glacially transported hornblende and feldspar grains from 14 till samples that span the last ∼2 Ma. We evaluate two probable ice-flow trajectories originating from two of the primary ice dispersal centers of the LIS: the Labrador-Québec sector and the Keewatin sector (Figure 1). The trajectory of each flow path linking the potential rock-source regions to the study area involves the erosion of bedrock of the Canadian Shield with significantly different ages: the Archean rocks (>2.6 Ga) of the Superior province in the east, and the Paleoproterozoic rocks (∼2.0–1.7 Ga) of the western Churchill province in the west. Although both source regions have an Archean heritage, Churchill terrains are characterized by a distinct Paleoproterozoic radiometric overprint that resulted from their involvement in several orogens during that time interval. Provenance studies of this type have successfully identified source terrains for the ice-rafted deposits in North Atlantic marine sediments [e.g., *Gwiazda et al.*, 1996; *Hemming et al.*, 2000], while elsewhere in the midcontinent region, isotope-based approaches have been primarily used to characterize the composition of late Pleistocene till deposits [*Taylor and Faure*, 1981].

[5] It is important to note that accurately reconstructing former ice-flow patterns for the LIS is difficult. Flow lines such as the ones shown in Figure 1 are largely based on geomorphological and sedimentological data associated with late-glacial advances, for which chronological constraints are often lacking. Although some of these ice flow lines are likely asynchronous, and thus schematic, they provide important field-based information on the possible trajectories along which ice may have flowed from the dispersal center to the marginal areas. Documenting the provenance of tills that comprise the LIS depositional record further constrains our understanding of former ice flow patterns.

2. Midcontinent Glacial Sedimentary Sequences

[6] The midcontinent glacial record consist primarily of tills that were deposited prior to marine isotope stage 6, and they are commonly referred to as pre-Illinoian tills [*Hallberg*, 1986]. Younger advances of the LIS are restricted to northern Iowa (Figure 1). The sequences investigated generally expose one to three till units separated in places by nonglacial and glaciofluvial sorted sediments, and/or thick paleosols recording extended periods of ice-free conditions; most sections are capped by thick loess deposits. Tills are typically dark gray, fine grained, compact, and matrix dominated [*Roy et al.*, 2004a]. Till units are mostly homogeneous, both laterally and vertically. Striated bedrock and/or bullet-shaped boulders indicate southward ice flow ranging from N163° to N192°, in agreement with regional ice-flow data [*Aber*, 1999].

[7] On the basis of the paleomagnetism of glacial and nonglacial deposits in the context of the Matuyama/Brunhes reversal at ~0.8 Ma, and the relation of tills to three volcanic ashes derived from dated eruptions of the Yellowstone caldera at 0.6 Ma, 1.3 Ma, and 2.0 Ma [*Izett*, 1981], *Roy et al.* [2004a] grouped midcontinent tills into those

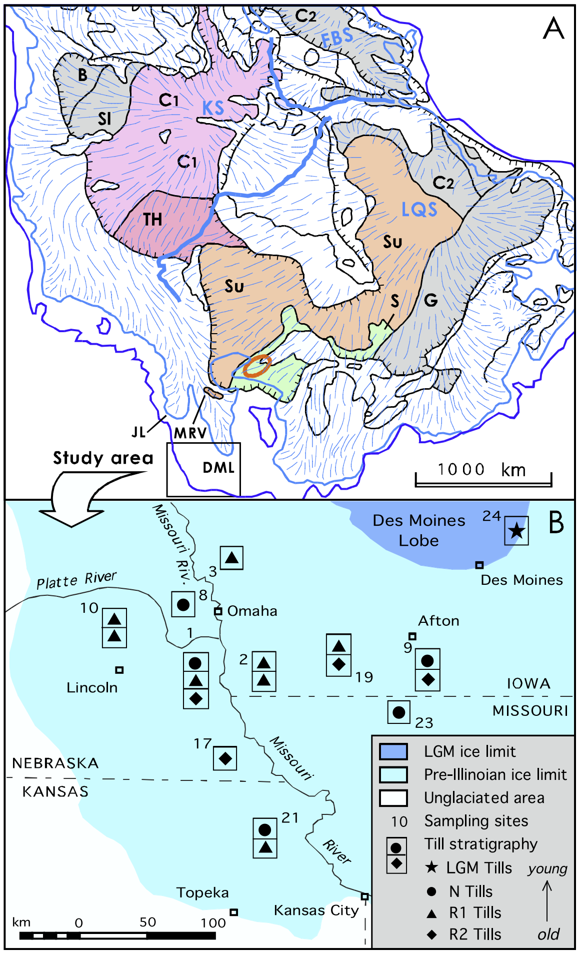

Figure 1. (a) Schematic map showing the main geological provinces of the Canadian Shield underlying the Laurentide ice sheet (LIS) at the last glacial maximum (LGM) [after *Dyke and Prest*, 1987a]. Darker blue line is the LIS maximum extent during earlier (pre-Illinoian) glaciations. Thin, discontinuous blue lines represent generalized flow lines emanating from the main ice dispersal centers: KS, Keewatin Sector; LQS, Labrador-Québec Sector; FBS, Foxe-Baffin Sector. The two thick dark blue lines within the LIS mark the approximate ice extent of each sector. To understand the compositional change present in midcontinent till sequences, we evaluate two possible flow lines feeding the midcontinent lobes: a western flow line linking the Keewatin ice dome to the study area, which would erode sedimentary and crystalline rocks, and an eastern flow line coming from the Labardor-Québec dome that would predominantly override crystalline rocks. Colored geological provinces represent potential source-rock regions for the midcontinent tills (see text for details): C1, western Churchill undifferentiated (2.0–1.8 Ga); TH, Trans-Hudson terrains (1.9–1.7 Ga); Su, Superior (>2.6 Ga); S, Southern; B, Bear; C2, eastern Churchill; G, Grenville; Sl, Slave [modified from *Hoffman*, 1989]. Orange oval shows the approximate location of the Midcontinent rift system (1.1 Ga) and the Rainy and Superior glacial lobes that advanced through the Lake Superior basin. DML, Des Moines Lobe; JL, James Lobe; MRV, Minnesota River Valley. (b) Location of samples. Tills in the midcontinent region were deposited by southward flowing glacial lobes such as the Des Moines and James lobes [*Aber*, 1999]. Till stratigraphy and site numbers from *Roy et al.* [2004a]: late Pliocene R2 tills; early Pleistocene R1 tills; middle Pleistocene N tills; and LGM tills.

deposited during the late Pliocene (R2 tills), the early Pleistocene (R1 tills), and the middle Pleistocene (N tills) (Figure 1). A fourth group consists of tills deposited by the Des Moines lobe around the last glacial maximum (LGM tills) (Figure 1).

3. Sampling and Methods

[8] We sampled 14 different till units from 11 stratigraphic sections (Figure 1b). Four samples are late Pliocene R2 tills, four samples are early Pleistocene R1 tills, five samples are middle Pleistocene N tills, and one sample is associated with the LGM. These till units were chosen because they were representative of the regional trend in compositional variations described above [*Boellstorff*, 1978; *Aber*, 1991; *Rovey and Kean*, 1996; *Colgan*, 1999; *Roy et al.*, 2004a]. Table 1 shows the position of each till unit in the stratigraphic section sampled.

[9] Bulk till samples of ~4 kg were sieved to study the lithology of the 4–12 mm clast fraction and to extract detrital hornblende and feldspar grains. For each sample, translucent grains were hand-picked from the 1–2 mm size fraction and put in a heavy-density liquid (Na-polytungstate) adjusted to a density of 2.6 g cm^{-3} to extract K-feldspars. From this light-mineral fraction, ~40 grains showing typical K-feldspar cleavage were selected under a binocular microscope. These feldspar grains were individually crushed in a mortar, and one fragment of 100–150 μm in size was selected for irradiation and subsequent dating. Between 15–20 hornblende grains were directly picked from the 150–300 μm fraction of the samples.

[10] Because of the large number of grains to be analyzed (n = 773), we used the total fusion method rather than extensive multiple-step heating experiments. $^{40}Ar/^{39}Ar$ analyses for individual grains were measured through CO_2 laser fusions. A single heating step can potentially mask a complex thermal history that could involve crystallization, multiple metamorphic events, and low temperature alteration. In order to assess potential difficulties in using total fusion ages, we conducted incremental (step) heating experiments on four single feldspar grains from an additional till unit (site 23).

[11] The $^{40}Ar/^{39}Ar$ ages of the glacially transported grains represent the time elapsed since the last major thermotectonic event (orogen, metamorphism) affected the rock source. Specifically, this is the time elapsed since the host rock cooled through a specific temperature, which varies according to the mineral dated. It is thus important to note that $^{40}Ar/^{39}Ar$ ages from hornblendes and feldspars from the same rock may differ. This discrepancy largely depends on the nature of the thermal (tectonic) history of the rock, and is also a function of the effective diffusion temperature below which these minerals retain argon during cooling. Because this closure temperature is lower in feldspars (~250°C) than in hornblendes (~450°C) [*McDougall and Harrison*, 1999], and given that Ar diffusion in K-feldspars can also persist (albeit slowly) to temperatures as low as 175–200°C, feldspars are more susceptible to loss of radiogenic Ar (i.e., age resetting) during thermotectonic events of lesser magnitude, particularly at temperatures below 450°C. Consequently, this raises the possibility that $^{40}Ar/^{39}Ar$ ages of feldspars may record slow cooling of an orogen subsequent to the main orogenic activity, or even reheating by younger events unrelated to a specific orogen. We assess the likelihood of this effect on the source rock(s) of these tills by dating hornblende and feldspar minerals (150–300 μm in size) extracted from individual crystalline clasts (2–12 mm in size) of 10 till samples.

[12] Feldspar grains from tills were measured at Oregon State University (OSU). Hornblende grains from tills as well as hornblende and feldspar minerals separated from clasts were measured at Lamont-Doherty Earth Observatory (LDEO). Till feldspars and sanidine-monitor FCT-3 (28.04 Ma) were co-irradiated with fast neutrons for six hours. The remaining hornblende and feldspar grains were irradiated for ten hours, along with hornblende-monitor standard Mmhb (age of 525 Ma [*Samson and Alexander*, 1987]) and a sanidine standard (Cima, 18.9 Ma, relative to MMhb-1 age of 523.2 ± 2.3 Ma [*Spell and McDougall*, 2003]). All grains were irradiated in the Cd-lined, in-core facility (CLICIT) of the TRIGA reactor at OSU. Ages were calculated from Ar isotope ratios corrected for mass fractionation, interfering nuclear reactions, procedural blanks, and atmospheric Ar contamination. The analytical procedures are similar to those used by *Hemming et al.* [2000] and *Duncan* [2002].

4. Geological Setting and Potential Source Terrains

[13] The bedrock geology of the midcontinent region consists predominantly of Upper Pennsylvanian limestone and shale, and Upper Cretaceous shale; most sections investigated here lie directly on

Table 1. Stratigraphic Context and Lithological Content of Till Units Sampled for $^{40}Ar/^{39}Ar$ Analyses

Site[a]	Sample	Clast Content[b] Sed, %	Clast Content[b] Cryst, %	Position of Till Unit in Stratigraphic Section[c]	Data in Figure 2
				LGM Till	
24	WHA01	54.0	46.0	only one till unit present at section	Figure 2a
				N Tills	
1	CTY09	58.6	41.4	sample coming from uppermost till unit at section	Figure 2b
19	BEF03	50.1	49.9	sample coming from uppermost till unit at section	Figure 2c
21	WAT05	42.9	57.1	sample coming from uppermost till unit at section	Figure 2d
8	FLO01	49.6	50.4	only one till unit present at section	Figure 2e
9	AF151	56.3	43.7	sample coming from uppermost till unit at section	Figure 2f
				R1 Tills	
21	WAT02	62.8	37.2	sample coming from lowermost till unit at section	Figure 2g
10	DC139	65.8	34.2	sample coming from lowermost till unit at section	Figure 2h
2	GLW03	62.4	37.6	sample coming from lowermost till unit at section	Figure 2i
3	CRS02	61.5	38.5	only one till unit present at section	Figure 2j
				R2 Tills	
9	AF172	90.4	9.6	sample coming from lowermost till unit at section	Figure 2k
19	BEF02	85.0	15.0	sample coming from lowermost till unit at section	Figure 2l
1	CTY02	81.3	18.7	sample coming from lowermost till unit at section	Figure 2m
17	ELC02	96.7	3.3	only one till unit present at section	Figure 2n

[a] See Figure 1 for site location and text for definition of LGM tills, N tills, R1 tills, and R2 tills. Geographic coordinates for each site are provided in auxiliary material Table S1.[1]

[b] Lithological data from *Roy et al.* [2004a]. Sed, sedimentary: limestone, shale, sandstone clasts. Cryst, crystalline: igneous and metamorphic clasts; clasts are 4–12.5 mm in size.

[c] Till stratigraphy from *Roy et al.* [2004a]. Each sample analyzed for $^{40}Ar/^{39}Ar$ dating comes from a single till unit.

carbonate bedrock. The presence of abundant igneous and metamorphic clasts in the samples indicates that a substantial fraction of the rock source of midcontinent tills derives from crystalline bedrock of the Canadian Shield, of which the nearest outcrops occur ~350 km up-ice from the study area, in the Minnesota River Valley (Figure 1). The $^{40}Ar/^{39}Ar$ ages of the glacially transported feldspar and hornblende grains should thus reflect the main geologic divisions of the Canadian Shield from which they were derived.

[14] The Canadian Shield consists of an amalgam of structural provinces that were assembled during various Precambrian orogens [*Hoffman*, 1989]. The rocks forming these provinces carry a dominant radiometric imprint that is generally associated with the last major orogenic event to affect the province, which commonly overprinted previous orogenic events. Most provinces thus show a characteristic arrangement of terrain ages and thermotectonic resetting (i.e., age of metamorphic events), and rock-source regions for this study can be distinguished accordingly. The Superior and the western Churchill provinces are of particular interest because they were the loci of the Labrador-Québec and Keewatin ice domes, respectively, and because they lie on the trajectory of a flow path linking these two ice-dispersal centers to the study area (Figure 1).

[15] Crustal provinces of the Canadian Shield are generally defined according to U-Pb ages of zircons retrieved from gneisses and metasedimentary rocks. Division of these provinces on the basis of $^{40}Ar/^{39}Ar$ dating is relatively uncommon, making direct comparisons to our $^{40}Ar/^{39}Ar$ ages difficult. Nevertheless, the sensitivity of the K-Ar clock of these minerals to metamorphic events makes the $^{40}Ar/^{39}Ar$ ages of individual mineral grains good recorders of the resetting/cooling history of the sediment rock source(s), which can then be compared with the geological events that characterize the potential rock-source regions.

[16] The western Superior Province is composed of Archean basement rocks consisting of alternating high-grade metamorphic rocks, and volcano-plutonic and metasedimentary sequences [e.g., *Hoffman*, 1989; *Card*, 1990; *Corfu et al.*, 1998]. Detrital zircons from gneissic and metasedimentary rocks commonly yield ages >3 Ga while greenstone belts and late orogenic intrusions generally range from ca. 2.8 to 2.6 Ga. These terrains

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[1] Auxiliary materials are available at ftp://ftp.agu.org/apend/gc/2006gc001572.

represent fragments of microcontinents and juvenile oceanic crusts that were assembled during a series of orogenic events (2.72 to 2.68 Ga) commonly referred as the Kenoran orogen [*Stott*, 1997; *Percival et al.*, 2004]. Accordingly, feldspar and hornblende grains derived from the Superior Province should record the Kenoran overprint and have $^{40}Ar/^{39}Ar$ ages $\sim > 2.6$ Ga.

[17] The western Churchill Province is a complex aggregate of basement rocks that include severely deformed relics of Archean crust, known as the Hearne and Rae domains [*Hoffman*, 1989; *Hanmer et al.*, 1995, 2004]. These terrains have been episodically reworked during several Paleoproterozoic orogens, notably through the Thelon-Taltson orogens (~2.0–1.8 Ga) that border the northwestern sector of the province [*Bickford et al.*, 1994; *Orrell et al.*, 1999; *McNicoll et al.*, 2000]. Of particular interest here is the southeastern half of the province where collision between the Churchill and Superior provinces during the Trans-Hudson orogen resulted in a wide suture zone (Figure 1) in which rocks underwent intense deformation, plutonism (post- and anorogenic), and metamorphism between ~1.9 and 1.7 Ga [*Lewry and Stauffer*, 1990; *Lucas et al.*, 1996; *Chiarenzelli et al.*, 1998]. Hudsonian-age intrusions also cover extensive areas in the western Churchill Province. Accordingly, grains derived from this region should yield $^{40}Ar/^{39}Ar$ ages that cluster predominantly around ~2.0–1.7 Ga.

[18] Additionally, a flow path originating from the Labrador-Québec sector could also have overridden the Southern Province (Figure 1), which comprises inliers of Archean basement rocks (~2.6 Ga) and restricted areas of juvenile Paleoproterozoic crust formed during the Penokean orogen (1.86–1.80 Ga) [*Hoffman*, 1989; *Sims*, 1993]. Intensive rifting at ~1.1 Ga also produced distinctive sequences of volcanic rocks (the Keweenawan Formation) that crop out extensively in the southwestern Lake Superior region [e.g., *Ojakangas et al.*, 2001]. Ice advances over the Southern Province should thus record erosion of the rocks of the Midcontinent rift system, and be distinguished by tills having abundant grains with $^{40}Ar/^{39}Ar$ ages of ~1.1 Ga.

5. Results and Discussion

[19] The till units investigated for provenance show the typical increase in the content of crystalline clasts that characterizes progressively younger tills in the midcontinent region (Table 1). $^{40}Ar/^{39}Ar$ dating of glacially transported grains of these tills indicate that all but two of the 14 samples (discussed below) show a nearly identical distribution of hornblende and feldspar $^{40}Ar/^{39}Ar$ ages, regardless of the age of the till group to which they belong (Figure 2). Hornblende grains are generally characterized by a bi-modal distribution of ages that consists of a late Archean population (>2.5 Ga) and a Paleoproterozoic population (~1.7–2.0 Ga). In contrast, feldspar grains are part of a broad population showing Paleoproterozoic ages ranging from ~1.4 to 2.4 Ga, and no Archean-age grains were obtained. Understanding the difference between the hornblende and feldspar age distributions is important when trying to identify the bedrock source of these tills. The complex tectonic setting of the potential source regions strongly suggests that this offset could be related to the different responses (closure temperatures) of feldspar and hornblende to thermotectonic events.

[20] The dating of feldspar and hornblende minerals within individual clasts provides insights into the nature of this age offset, as well as on the geological history of the rock source of these tills. The ten pebbles analyzed contain hornblende minerals with late Archean $^{40}Ar/^{39}Ar$ ages (2.3–2.7 Ga) (Figure 3). Unlike the hornblende minerals, the feldspar minerals yielded a broad range of $^{40}Ar/^{39}Ar$ ages, generally varying from early Paleoproterozoic to late Archean (~1.5–2.5 Ga). Considering that K-feldspars have a lower closure temperature than hornblendes (250°C versus >450°C, respectively), the age difference between hornblendes and feldspars in individual clasts suggests that the rock source of tills records a complex thermal history that likely includes minor thermotectonic (reheating) episodes subsequent to the last major (Archean) thermotectonic event recorded by hornblendes (identified below).

[21] In the context of the provenance of detrital sediments coming from a crystalline rock source, the presence in each till sample of hornblende grains with Paleoproterozoic ages strongly suggests that some of the feldspars must also derive from a Paleoproterozoic rock source. This assessment is supported by incremental heating experiments of four feldspar grains from one till sample (Figure 4). The results show plateau ages comprising a majority of the gas released, which we interpret as crystallization ages or the age of complete metamorphic resetting. The plateau ages and the total fusion ages are indistinguishable (both

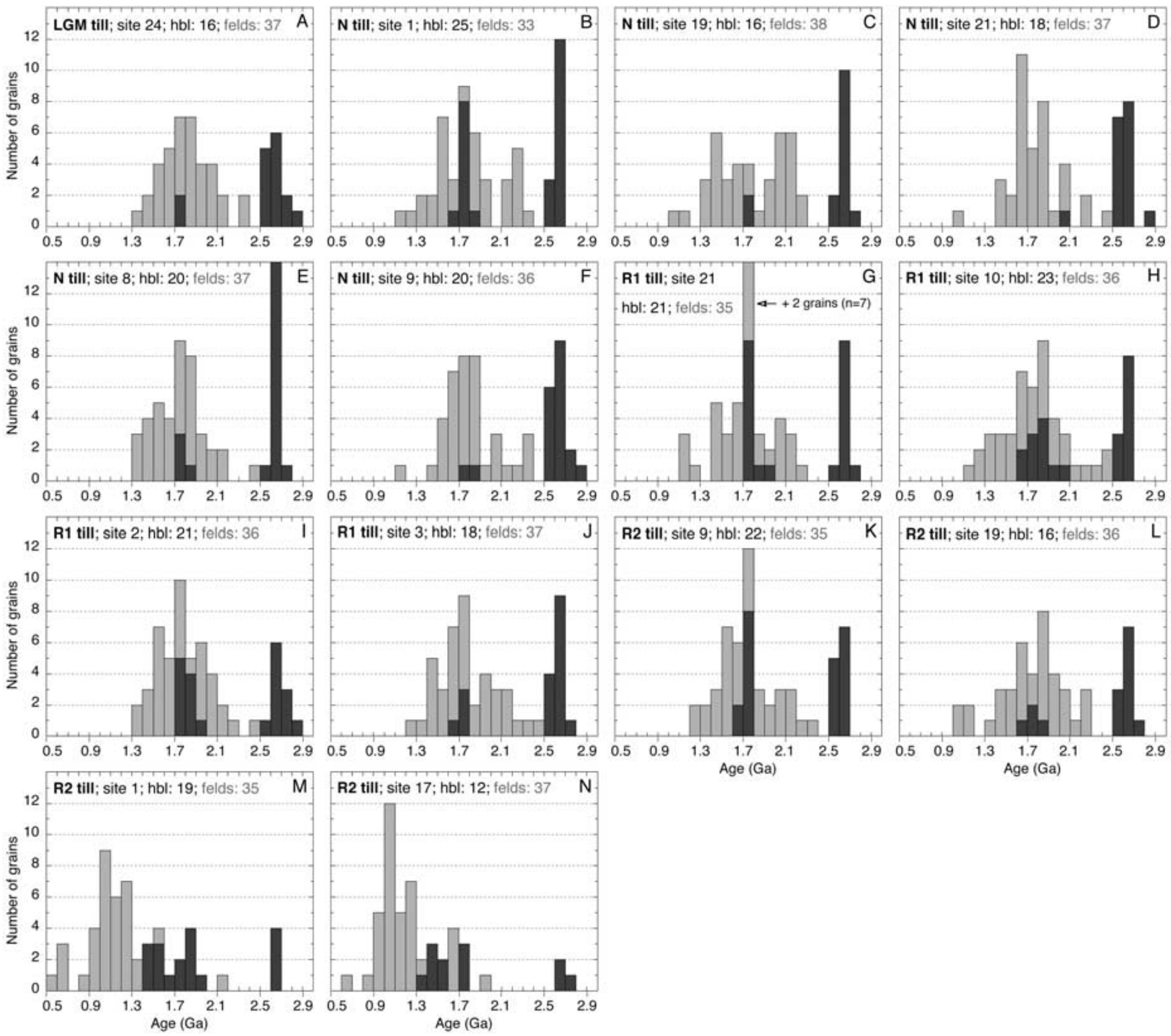

Figure 2. Stack histograms showing the distribution of ^{40}Ar/^{39}Ar ages of hornblende and feldspar grains from 14 till samples (x and y axes are identical in all histograms; 100-Myr bins). Each sample was taken from a single till unit. Till group, site number, and number of dated hornblende grains (hbl; black bars) and feldspar grains (felds; grey bars) in each sample are given at top of histogram. The complete ^{40}Ar/^{39}Ar data set is given in auxiliary material Table S1.

Paleoproterozoic), thus suggesting that the total fusion ages for the feldspar grains are good estimates of the age of closure. We thus believe that glacial feldspars with older ages (~>1.8 Ga) likely belong to a late Archean source rock that was slightly reheated by younger events subsequent to the main orogen, while the remaining younger feldspar grains likely derive from the same Paleoproterozoic rock source as the Paleoproterozoic hornblende grains that predominantly range from 1.7 to 2.0 Ga.

[22] The age range of Paleoproterozoic hornblende grains and associated feldspar grains in the till samples is consistent with the geological history of the western Churchill Province outlined above, which is primarily characterized by a suite of Paleoproterozoic events consisting of intense orogenic deformation, associated crust formation and extensive magmatism that took place between ~2.0 and 1.7 Ga. These results imply that the crystalline rock source of midcontinent tills derives from the erosion by ice coming from the Keewatin sector of the LIS. Deposition by ice originating from the Labrador-Québec sector is considered unlikely because an eastern flow line would have predominantly overridden rocks of the Superior Province, and thus resulted in midcontinent tills dominated by a large number of late Archean-age

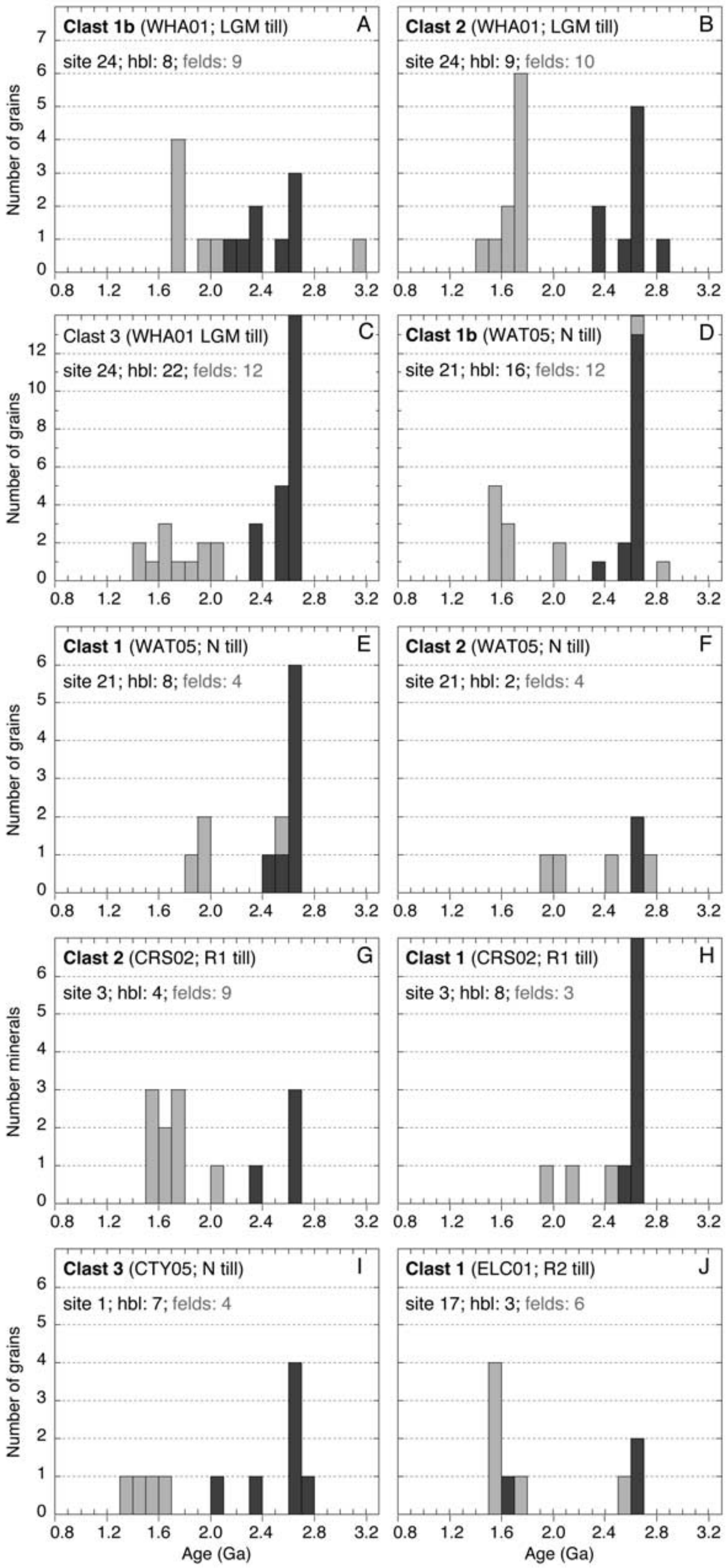
Clast 1b (WHA01; LGM till) A
site 24; hbl: 8; felds: 9
Clast 2 (WHA01; LGM till) B
site 24; hbl: 9; felds: 10
Clast 3 (WHA01 LGM till) C
site 24; hbl: 22; felds: 12
Clast 1b (WAT05; N till) D
site 21; hbl: 16; felds: 12
Clast 1 (WAT05; N till) E
site 21; hbl: 8; felds: 4
Clast 2 (WAT05; N till) F
site 21; hbl: 2; felds: 4
Clast 2 (CRS02; R1 till) G
site 3; hbl: 4; felds: 9
Clast 1 (CRS02; R1 till) H
site 3; hbl: 8; felds: 3
Clast 3 (CTY05; N till) I
site 1; hbl: 7; felds: 4
Clast 1 (ELC01; R2 till) J
site 17; hbl: 3; felds: 6
Number of grains
Number minerals
0.8 1.2 1.6 2.0 2.4 2.8 3.2
Age (Ga)

Figure 3

grains. Furthermore, a flow line from the Labrador-Québec sector could not explain the presence in tills of Paleoproterozoic hornblende grains.

[23] The trajectory of the inferred western (Keewatin) flow path also overrides a small portion of the southwestern part of the Superior province, on the eastern edge of the area covered by advances of the midcontinent lobes (Figure 1). Accordingly, we consider the most likely source of late Archean grains to be the crystalline rocks cropping out in the Minnesota River Valley. The segment of the southern margin of the Canadian Shield that encompasses the Minnesota River Valley structural entity was also affected by repeated tectonic (reheating) episodes of various extent and intensity throughout the Paleoproterozoic [e.g., *Holm et al.*, 2005; *Schmitz et al.*, 2006], thus offering a possible explanation for the broad distribution of feldspar ^{40}Ar/^{39}Ar ages in tills.

[24] Samples from two tills differ from the 12 others in having feldspar grains with ages between 0.9 and 1.3 Ga, as well as feldspar and hornblende grains with the same ages as the other samples (Figures 2m and 2n). The nearest rocks of this age crop out in the southwestern Lake Superior region and are represented by the Keweenawan volcanic lithologies associated with the formation of the Midcontinent Rift System [*Ojakangas et al.*, 2001]. Because this region lies to the east of a flow path originating from the Keewatin sector (Figure 1), the presence of these younger grains may indicate deposition by southwesterly flowing ice that originated from the Labrador-Québec sector and traversed the Lake Superior basin. However, these two till units contain no other petrologic or mineralogic indicators associated with this flow path, such as volcanic or agate clasts typical of the Lake Superior region. Furthermore, the size (1–2 mm) of feldspar grains dated is too large to be associated with the fined-grained volcanic rocks of the Midcontinent rift system. Another possible explanation is that these samples record a mixture of two source regions, whereby sediments derived from the Lake Superior region were deposited to the southwest, in the path of subsequent ice advances originating from the Keewatin sector. Additional information is needed to test this hypothesis and to fully regard these two samples as diagnostic of source region.

[25] Finally, considering the Churchill province as the source rock of midcontinent tills implies long distances of glacial transport. This is not unusual in glacial environments. Mapping of glacial indicators consisting of distinct bedrock lithologies indicates transport on the order of 100s of km [e.g., *Shilts et al.*, 1979; *Clark*, 1987; *Prest and Nielsen*, 1987; *Veillette*, 2004]. The precise amount of glacial transport in the course of a single glaciation is, however, a difficult parameter to constrain. Similarly, determining the amount of recycled material from older till deposits in a particular till unit is also problematic. This is mostly related to the fact that mechanisms of glacial erosion and transport vary according to numerous parameters, such as substratum geology, hydrological and thermal conditions at the bed, topography, distance from the ice divide, etc. [*Paterson*, 2001; *Menzies and Shilts*, 1996]. Modeling efforts have attempted to replicate subglacial erosion and sediment transport by the LIS [*Hildes et al.*, 2004]. Although the documented dispersions of known lithologies were crudely reproduced, the temporal aspect of sediment transport was largely unconstrained and the recycling of older deposits was not specifically addressed. Nonetheless, paleogeographic consider-

Figure 3. Stack histograms showing ^{40}Ar/^{39}Ar ages of hornblende (hbl; black bars) and feldspar (felds; grey bars) minerals extracted from individual clast of till samples. The results suggest that the clasts derive from a rock source that last saw temperatures above 450°C (thermal resetting threshold of hornblende) in the late Archean or early Paleoproterozoic ($\sim >$2.4 Ga). The ^{40}Ar/^{39}Ar ages of feldspar minerals show a wide spread of ages ranging from $\sim$1.5 to 2.5 Ga, thus suggesting that the entire source region either remained above $\sim$200°C or was reheated (to temperatures $<$ 450°C) at various times during the Paleoproterozoic. This also indicates that the source region remained below $\sim$200°C since the end of the Paleoproterozoic. None of the 10 clasts yielded hornblende minerals with Paleoproterozoic ages. This may reflect the fact that the coarse size fraction of midcontinent tills likely derives from a proximal rock source, which in the case of crystalline clasts corresponds to the outlier of late Archean rocks of the Minnesota River Valley. Far-traveled sediments, such as for material originating from Keewatin, are subjected to greater glacial crushing due to the longer distance of glacial transport, thereby likely causing Churchill-age clasts to be less abundant than Archean-age clasts that originate from the nearby Superior Province. Additional clasts should be dated to better define this pattern. The clast of sample ELC01 yielded mixed results, identical to the distinct age distribution obtained for the glacially transported grains (Figure 2n). Note that the y axis of the upper two rows of histograms is different than others.

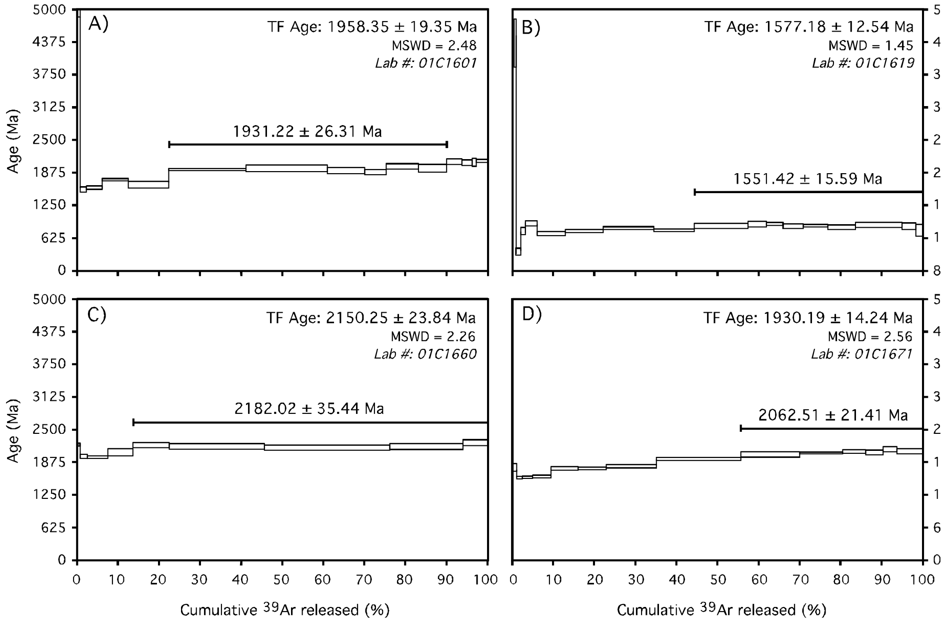

Figure 4. The $^{40}Ar/^{39}Ar$ incremental heating experiments on single feldspar grains of till sample MER03 (site 23). The bold horizontal line in each diagram corresponds to the weighted plateau age, interpreted here as crystallization ages or the age of complete metamorphic resetting. Plateau ages are similar to the total fusion ages, which were obtained by adding all step gas compositions together. Total fusion (TF) ages are shown on the upper part of each diagram. Age errors are 2σ. MSWD is an F-statistic of within-step variability divided by between-step variability and is significant <2.6.

ations tend to suggest that the mapped patterns of sediment dispersal result from multiple episodes of transport. More important to this study is the fact that the sedimentological nature of till represents a homogenization of the different lithologies eroded along the length of a flow line, thereby reinforcing our conclusions that the provenance results presented are a good estimate of the source rock of midcontinent tills, whether the till unit results from a single glaciation or is the product of episodes of recycling during the course of multiple glaciations.

6. Conclusions

[26] Late glacial advances of the southwestern midcontinent lobes have been traditionally associated with ice coming from the northwestern (Keewatin) sector of the LIS on the basis of geomorphologic features and the composition of surficial tills, but little information is available on the geometry of flow lines older than the LGM. $^{40}Ar/^{39}Ar$ dating of detrital feldspar and hornblende grains from midcontinent tills recording ice advances spanning the last 2 Ma indicates that the crystalline fraction of these tills was derived from the glacial erosion of a Paleoproterozoic rock source with minor contribution from late Archean rocks. The large population of Paleoproterozoic grains shows a range of $^{40}Ar/^{39}Ar$ ages (1.7–2.0 Ga) that is consistent with the episodes of intense tectonic reworking recorded in rocks of the Churchill province, thus indicating deposition by ice coming from the Keewatin ice dome. The presence of late-Archean grains (>2.6 Ga) is in agreement with the Keewatin-derived ice flow trajectory, which overrode a small portion of the Superior province bedrock in the Minnesota River Valley.

[27] The distribution of feldspar and hornblende $^{40}Ar/^{39}Ar$ ages is nearly identical in all samples analyzed, thereby indicating that the rock-source region for midcontinent tills has remained the same since the late Pliocene. The absence of evidence for a provenance change in midcontinent till sequences thus lends support to the idea that the compositional changes documented from these deposits reflects the glacial erosion of a preglacial weathered rock mantle and subsequent unroofing of fresh crystalline bedrock during late Cenozoic glaciations [*Roy et al.*, 2004b]. This change in subglacial substrate may have had a profound impact on ice sheet dynamics and possibly modified their response to orbital forcing [*Clark and Pollard*, 1998; *Roy et al.*, 2004b; *Clark et al.*, 2006].

[28] These results indicate that the midcontinent lobes were fed by a western flow line since at least 2 Ma, thereby identifying the Keewatin ice dome as persistent feature of the LIS throughout the course of late Cenozoic glaciations. Evidence for a Labrador-Québec ice dome as early as the late Pliocene is indirectly suggested by a planktonic oxygen isotopes record (δ^{18}O) from the Gulf of Mexico showing discharges of glacial meltwater starting at ~2.3 Ma [*Joyce et al.*, 1993], because southward routing of LIS meltwaters implies the presence of Labrador-Québec ice blocking the eastward draining outlets of the St. Lawrence River and/or Great Lakes region. Consequently, this suggests that the overall configuration, as well as the maximum extent [*Boellstorff*, 1978; *Roy et al.*, 2004a] of the LIS has remained largely the same since the inception of Northern Hemisphere glaciation ~2.4 Ma.

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References

Aber, J. S. (1991), The glaciation of northeastern Kansas, *Boreas*, *20*, 297–314.

Aber, J. S. (1999), Pre-Illinoian glacial geomorphology and dynamics in the central United States, west of the Mississippi, in *Glacial Processes Past and Present*, edited by D. M. Mickelson and J. W. Attig, *Geol. Soc. Am. Spec. Pap.*, *327*, 113–119.

Balco, G., C. W. Rovey, and J. O. H. Stone (2005), The first glacial maximum in North America, *Science*, *307*, 222.

Bickford, M. E., K. D. Collerson, and J. F. Lewry (1994), Crustal history of the Rae and Hearne provinces, southwestern Canadian Shield, Saskatchewan: Constraints from geochronological and isotopic data, *Precambrian Res.*, *68*, 1–28.

Boellstorff, J. (1978), Chronology of some Late Cenozoic deposits from the central United States and the Ice Ages, *Trans. Nebr. Acad. Sci.*, *6*, 35–49.

Card, K. D. (1990), A review of the Superior Province of the Canadian Shield, a product of Archean accretion, *Precambrian Res.*, *48*, 99–156.

Chiarenzelli, J. R., L. B. Aspler, M. Villeneuve, and J. F. Lewry (1998), Paleoproterozoic evolution of the Saskatchewan Craton, Trans-Hudson orogen, *J. Geol.*, *106*, 247–267.

Clark, P. U. (1987), Subglacial sediment dispersal and till composition, *J. Geol.*, *95*, 527–541.

Clark, P. U., and D. Pollard (1998), Origin of the middle Pleistocene transition by ice sheet erosion of regolith, *Paleoceanography*, *13*, 1–19.

Clark, P. U., D. Archer, D. Pollard, J. D. Blum, J. A. Rial, V. Brovkin, A. C. Mix, N. G. Pisias, and M. Roy (2006), The middle Pleistocene transition: Characteristics, mechanisms, and implications for long-term changes in atmospheric pCO_2, *Quat. Sci.*, 3150–3184.

Colgan, M. (1999), Early middle Pleistocene glacial sediments (780000–620000 BP) near Kansas City area, northeastern Kansas and northwestern Missouri, USA, *Boreas*, *28*, 477–489.

Corfu, F., D. W. Davis, D. Stone, and M. L. Moore (1998), Chronostratigraphic constraints on the genesis of Archean greenstone belts, northwestern Superior Province, Ontario, Canada, *Precambrian Res.*, *92*, 277–295.

Duncan, R. A. (2002), A time frame for the construction of the Kerguelen Plateau and Broken Ridge, *J. Petrol.*, *43*, 1109–1119.

Dyke, A. S., and V. K. Prest (1987a), Paleogeography of northern North America, 18,000–5,000 years ago, *Map 1703A*, Geol. Surv. of Can., Ottawa, Ontario, Canada.

Dyke, A. S., and V. K. Prest (1987b), Late Wisconsinan and Holocene history of the Laurentide ice sheet, *Geogr. Phys. Quat.*, *41*, 237–263.

Dyke, A. S., J. T. Andrews, P. U. Clark, J. H. England, G. H. Miller, J. Shaw, and J. J. Veillette (2002), The Laurentide and Innuitian ice sheets during the last glacial maximum, *Quat. Sci. Rev.*, *21*, 9–31.

Gwiazda, R. H., S. R. Hemming, and W. S. Broecker (1996), Evidence from ^{40}Ar/39Ar ages for Churchill province source of ice-rafted amphiboles in Heinrich layer 2, *J. Glaciol.*, *42*, 440–446.

Hallberg, G. R. (1986), Pre-Wisconsinan glacial stratigraphy of the central plains region in Iowa, Nebraska, Kansas, and Missouri, *Quat. Sci. Rev.*, *5*, 11–15.

Hanmer, S., M. Williams, and C. Kopf (1995), Striding-Athabasca mylonite zone: Implications for Archean and early Proterozoic tectonics of the Western Canadian Shield, *Can. J. Earth Sci.*, *32*, 178–196.

Hanmer, S., H. A. Sandeman, W. D. Davis, L. B. Aspler, R. H. Rainbird, J. J. Ryan, C. Relf, and T. D. Peterson (2004), Geology and Neoarchean tectonic setting of the Central Hearne supracrustal belt, Western Churchill Province, Nunavut, Canada, *Precambrian Res.*, *134*, 63–83.

Hemming, S. R., G. C. Bond, W. S. Broecker, and W. D. Sharp (2000), Evidence from ^{40}Ar/^{39}Ar ages of individual hornblende grains for varying Laurentide sources of iceberg discharges 22,000 to 10,500 yr B. P., *Quat. Res.*, *54*, 372–383.

Hildes, D. H. D., G. K. C. Clarke, G. E. Flowers, and S. J. Marshall (2004), Subglacial erosion and englacial sediment transport modelled for North American ice sheets, *Quat. Sci. Rev.*, *23*, 409–430.

Hoffman, P. H. (1989), Precambrian geology and tectonic history, in *The Geology of North America—An Overview*, edited by A. W. Bally and A. R. Palmer, *Decade North Am. Geol.*, vol. A, pp. 447–512, Geol. Soc. of Am., Boulder, Colo.

Holm, D. K., W. R. Van Schmus, L. C. MacNeil, T. J. Boerboom, D. Schweitzer, and D. Schneider (2005), U-Pb zircon geochronology of Paleoproterozoic plutons from the northern mid-continent, USA: Evidence for subduction flip and continued convergence after geon 18 Penokean orogenesis, *Geol. Soc. Am. Bull.*, *117*, 259–275.

Izett, G. A. (1981), Volcanic ash beds: Recorders of upper Cenozoic silicic pyroclastic volcanism in the western United States, *J. Geophys. Res.*, *86*, 10,200–10,222.

Joyce, J. E., L. R. C. Tjalsma, and J. M. Prutzman (1993), North American glacial meltwater history for the past 2.3 My: Oxygen isotope evidence from the Gulf of Mexico, *Geology*, *21*, 483–486.

Lewry, J. F., and M. R. Stauffer (1990), The early Proterozoic Trans-Hudson of America, *Geol. Assoc. Can. Spec. Pap.*, *37*, 505 pp.

Lucas, S. B., E. C. Syme, B. A. Reily, and D. J. Thomas (1996), Intraoceanic tectonics and the development of continental crust: 1.92–1.84 Ga evolution of the Flin Flon Belt, Canada, *Geol. Soc. Am. Bull.*, *108*, 602–629.

McDougall, I., and T. M. Harrison (1999), *Geochronology and Thermochronology by the* ^{40}*Ar/*^{39}*Ar Method*, 269 pp., Oxford Univ. Press, New York.

McMartin, I., and P. J. Henderson (2004), Evidence from Keewatin (central Nunavut) for paleo-ice divide migration, *Geogr. Phys. Quat.*, *58*, 163–186.

McNicoll, V. J., R. J. Thériault, and M. McDonough (2000), Taltson basement gneisses: U-Pb and Nd isotopic constraints on the basement to the Paleoproterozoic Taltson magmatic zone, northeastern Alberta, *Can. J. Earth Sci.*, *37*, 1575–1596.

Menzies, J., and W. W. Shilts (1996), Subglacial environments, in *Past Glacial Environments: Sediments, Forms and Techniques*, edited by J. Menzies, pp. 15–136, Butterworth-Heinemann, Oxford, U. K.

Ojakangas, R. W., G. B. Morey, and J. C. Green (2001), The Mesoproterozoic Midcontinent Rift System, Lake Superior region, USA, *Sediment. Geol.*, *141–142*, 421–442.

Orrell, S. E., M. E. Bickford, and J. F. Lewry (1999), Crustal evolution and age of thermotectonic reworking in the western hinterland of the Trans-Hudson Orogen, northern Saskatchewan, *Precambrian Res.*, *95*, 187–223.

Paterson, W. S. B. (2001), *Physics of Glaciers*, 3rd ed., 480 pp., Pergamon, Tarrytown, N. Y.

Percival, J. A., W. Bleeker, F. A. Cook, T. Rivers, G. Ross, and C. van Staal (2004), PanLITHOPROBE workshop IV: Intraorogen correlations and comparative orogenic anatomy, *Geosci. Can.*, *31*, 23–39.

Prest, V. K., and E. Nielsen (1987), The Laurentide ice sheet and long distance transport, *Geol. Surv. Finland Spec. Pap.*, *3*, 91–101.

Rovey, C. W., II, and W. F. Kean (1996), Pre-Illinoian stratigraphy in north-central Missouri, *Quat. Res.*, *45*, 17–29.

Roy, M., P. U. Clark, R. W. Barendregt, J. R. Glassmann, and R. J. Enkin (2004a), Glacial stratigraphy and paleomagnetism of late Cenozoic deposits in the north-central U.S., *Geol. Soc. Am. Bull.*, *116*, 31–40.

Roy, M., P. U. Clark, G. M. Raisbeck, and F. Yiou (2004b), Geochemical constraints on the origin of the middle Pleistocene transition from the glacial sedimentary record of the north-central U.S., *Earth Planet. Sci. Lett.*, *227*, 281–296.

Samson, S. D., and E. C. Alexander Jr. (1987), Calibration of the interlaboratory ^{40}Ar/^{39}Ar dating standard, MMhb-1, *Chem. Geol.*, *66*, 27–34.

Schmitz, M. D., S. A. Bowring, D. L. Southwick, T. J. Boerboom, and K. R. Wirth (2006), High-precision U-Pb geochronology in the Minnesota River Valley subprovince and its bearing on the Neoarchean to Paleoproterozoic evolution of the southern Superior Province, *Geol. Soc. Am. Bull.*, *118*, 82–93.

Shilts, W. W., C. M. Cunningham, and C. A. Kaszycki (1979), Keewatin ice sheet—Re-evaluation of the traditional concept of the Laurentide ice sheet, *Geology*, *7*, 537–541.

Sims, P. K. (1993), The Lake Superior region and Trans-Hudson orogen, in *The Geology of North America*, vol. C-2, *Precambrian Conterminous U.S.*, edited by J. C. Reed, pp. 11–120, Geol. Soc. of Am., Boulder, Colo.

Spell, T. L., and I. McDougall (2003), Characterization and calibration of ^{40}Ar/^{39}Ar dating standards, *Chem. Geol.*, *198*, 189–211.

Stott, G. M. (1997), The Superior Province, Canada, in *Greenstone Belts*, edited by M. J. de Wit and L. D. Ashwal, *Oxford Monogr. Geol. Geophys.*, vol. 35, pp. 480–507, Clarendon, Oxford, U. K.

Taylor, K. S., and G. Faure (1981), Rb-Sr dating of detrital feldspar: A new method to study till, *J. Geol.*, *89*, 97–107.

Veillette, J. J. (2004), Ice-flow chronology and palimpsest, long-distance dispersal of indicator clasts, north of the St. Lawrence River valley, Quebec, *Geogr. Phys. Quat.*, *58*, 187–216.

Veillette, J. J., A. S. Dyke, and M. Roy (1999), Ice-flow evolution of the Labrador Sector of the Laurentide Ice Sheet: A review, with new evidence from northern Québec, *Quat. Sci. Rev.*, *18*, 993–1019.