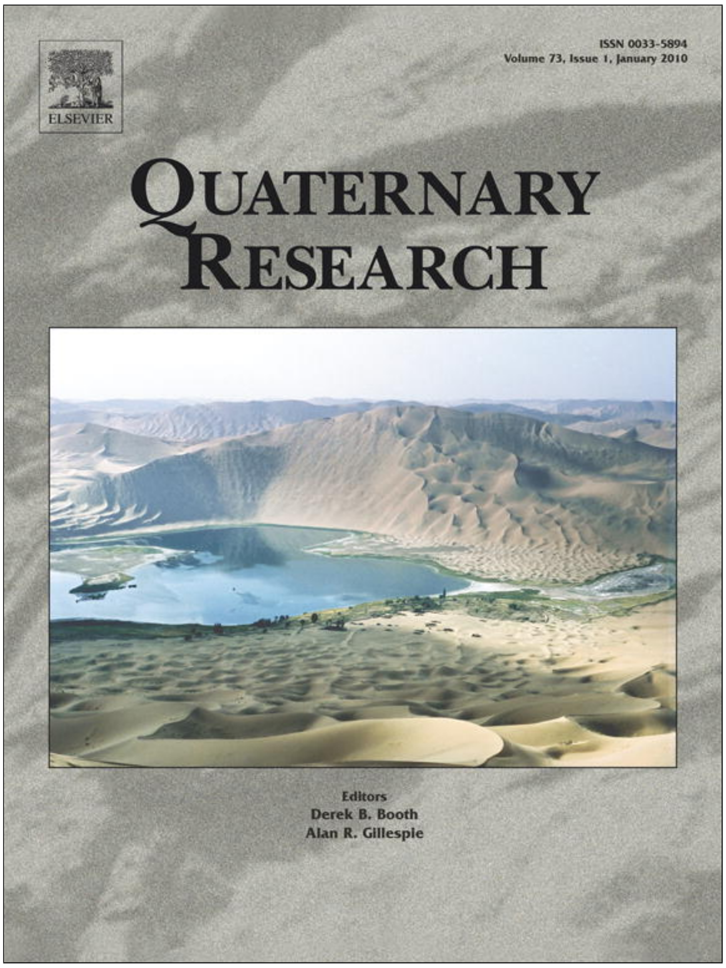

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Periglacial climate at the 2.5 Ma onset of Northern Hemisphere glaciation inferred from the Whippoorwill Formation, northern Missouri, USA

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ABSTRACT

The Whippoorwill Formation is a gleyed diamicton that is present locally within bedrock depressions beneath the oldest glacial till in northern Missouri, USA. Stratigraphy, paleomagnetism, and cosmogenic–nuclide burial ages show that it was deposited between the Matuyama–Gauss magnetostratigraphic boundary at 2.58 Ma and the first advance of the Laurentide ice sheet into Missouri at 2.47 ± 0.19 Ma. High cosmogenic–nuclide concentrations also show that the constituents of the Whippoorwill Formation experienced long exposure at a stable landscape surface with erosion rates of 1–2 m/Ma. However, cosmogenic–nuclide concentrations are invariant with depth below the Whippoorwill Formation surface, indicating active mixing of the soil profile shortly before burial by till. The Whippoorwill Formation retains numerous features indicative of cryoturbation. Therefore, we interpret it as a buried Gelisol, a soil formed under periglacial conditions in the presence of permafrost. At the onset of Northern Hemisphere glaciation, climate cooling established permafrost conditions and accelerated erosion by inducing landscape instability. Thus, weathered regolith materials were mobilized and redeposited by gelifluction shortly before the ice sheet overrode the landscape.

Introduction and history

The Whippoorwill Formation is an enigmatic diamicton locally preserved beneath the oldest glacial sediment in northern Missouri (Figs. 1 and 2). Geologists have long recognized that the Whippoorwill is comprised of highly weathered materials that were redeposited onto lower paleolandscape positions. Here we present new observations and data pertaining to its mode and timing of deposition. We conclude that the Whippoorwill Formation represents small remnant patches of the preglacial soil/weathering profile that were mobilized under periglacial conditions and then accumulated as gelifluction deposits within isolated depressions shortly before glaciation.

Variants of the name “Whippoorwill Formation” have been used inconsistently by different authors. Therefore, we provide additional background on the name's history to limit its application to the sense given above and to define it as a formal lithostratigraphic unit. Allen and Ward (1974) first applied the informal name “Whippoorwill Creek Till” to the oldest glacial sediment exposed in various clay pits south of New Florence, Missouri (Fig. 1). At the Deeker Clay Pit (Table 1) they described a cobbly till with prominent white chert clasts, which is capped by a thick paleosol and overlain by two younger tills. This lowest till and associated sediment is now formally defined as the Atlanta Formation (Rovey and Tandarich, 2006; Fig. 3). The two overlying tills are the Moberly Formation and the Fulton member of the McCredie Formation, respectively. Allen and Ward also noted a fine-grained leached diamicton (the Whippoorwill Formation of this work) below the oldest till and directly above bedrock. They interpreted this older diamicton as a preglacial paleosol without further description. Nevertheless, they surmised that the parent material had been derived from local high points of the surrounding bedrock, based on topographic relationships, the absence of unstable lithologies, and a concentration of angular reddish-brown chert clasts (very typical of local bedrock residuum) near the diamicton's base.

Guccione (1982, 1983, 1985) visited three sections in northern Missouri that exposed preglacial sediment above bedrock, including the Deeker Pit described earlier by Allen and Ward (1974). Guccione also recognized a basal diamicton lacking igneous erratics that is isolated within bedrock depressions and concluded that this material was mostly colluvium, derived locally from higher topographic positions. However, she concluded that Allen and Ward's “Whippoorwill Creek Till” was also part of this preglacial deposit. Thus, she used the informal name “Whippoorwill formation” to refer to a preglacial diamicton below the oldest till, rather than the till itself. This reassignment of the name “Whippoorwill formation” to preglacial sediment was followed by Guccione and Tandarich (1993), Tandarich et al., (1994), and Rovey and Tandarich (2006). However, some confusion in the use of the name “Whippoorwill” for preglacial sediment may remain. Apparently, the contact between the two

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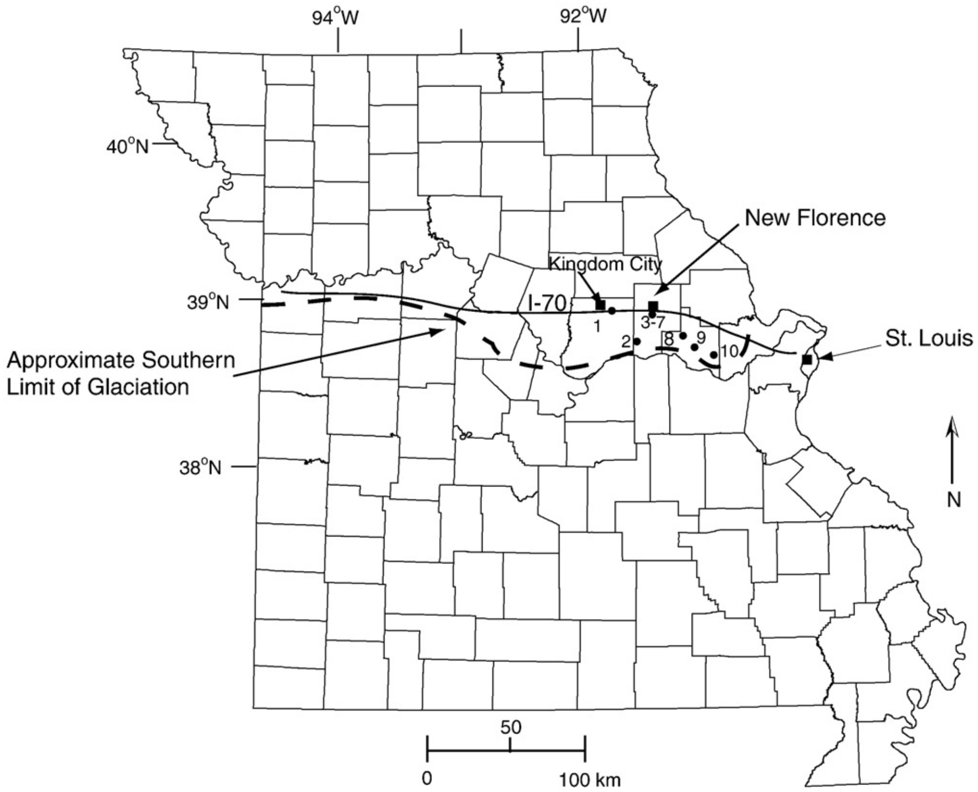

Figure 1. Location map of Whippoorwill Formation exposures (dots). Numerals correspond to sections listed in Table 1.

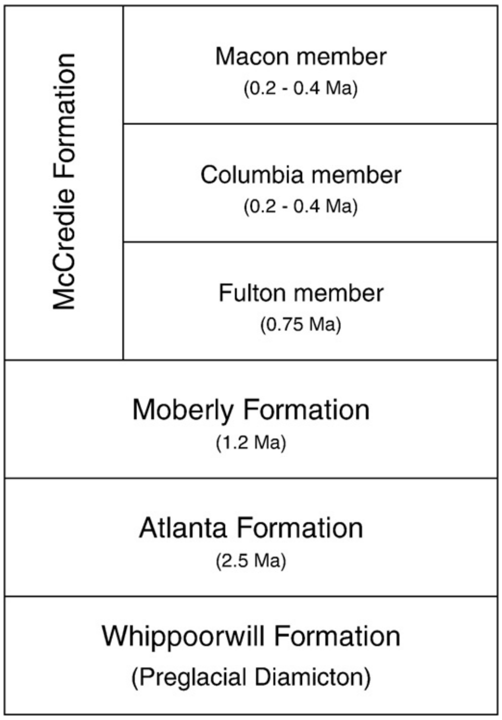

Figure 2. Stratigraphy of glacial sediments and related deposits, northern Missouri. All units except for the Whippoorwill Formation are mostly glacial till. See Rovey and Tandarich (2006) for a description and definition of these units; members within the McCredie Formation remain informal. Ages are based on the cosmogenic–isotope burial dating method; error limits for the Atlanta are ±0.19 Ma (this paper), while error limits for the Moberly and Fulton are approximately ±0.1 Ma. The ranges for the Macon and Columbia members reflect larger overlapping error limits for those units. See Balco and Rovey (2008) for the methodology; we have included one additional unpublished age determination in the 0.75 Ma estimate for the Fulton member.

lowest diamictons at the Deeker Pit (today's Whippoorwill and Atlanta Formations) was not exposed during Guccione's visit. Thus, she interpreted both units at that pit as a single preglacial deposit, based on the absence of erratics near the base. In fact, the upper diamicton (the diamicton now defined as the Atlanta Formation) contains crystalline erratics and is a true till (Rovey and Tandarich, 2006). Therefore, some of Guccione's descriptions pertaining to thickness and a mature upper paleosol in the Whippoorwill Formation actually refer to the Atlanta Formation and not to the Whippoorwill Formation as discussed in this work.

Relationship to paleotopography

The Whippoorwill Formation does not outcrop at the natural ground surface but is present in numerous clay-mine pits throughout the study area (Fig. 1 and Table 1). The 10 sites listed in Table 1 are all clay pits, and in fact, the Whippoorwill Formation is present in all of the clay pits examined along the I-70 corridor during this study. In contrast, road cuts along local state highways during the 1990s did not expose the Whippoorwill Formation, despite reaching bedrock along many segments. Moreover, the Missouri State Geological Survey recently completed ~150 boreholes along the same (I-70) corridor between the western St. Louis suburbs and Kingdom City (Fig. 1), and none of these cores encountered the Whippoorwill Formation.

Why is the Whippoorwill Formation common in clay pits, but absent elsewhere? This is the case because current mining operations exploit a very specific portion of the preglacial bedrock topography, namely, paleokarst depressions. These mines produce "fireclay," a kaolinitic shale from the basal Pennsylvanian Cheltenham Formation (Keller, 1968). In this particular mining subdistrict, deposition of the basal Cheltenham, which is the highest grade of ore, was isolated within sinkholes in the underlying Mississippian-age limestones (Searight, 1967). Thus, the mines are localized within paleokarst networks, which were topographic depressions prior to glaciation,

Table 1
Locations and names of Whippoorwill Formation exposures.

1. Harrison Pit. SW 1/4, S. 1, T. 48 N., R. 9W, Calwood and Kingdom City 7.5′ Quadrangles.
   Latitude: 38°57.73′N. Longitude: 91°52.70′W.
2. Readsville Pit. SW1/4, S. 7, T.46N, R.6W, Readsville 7.5′ Quadrangle.
   Latitude: 38°45.66′N. Longitude: 91°38.41′W.
3. Parker–Russel Pit. SW1/4, S.34, T.48N, R.5W, New Florence 7.5′ Quadrangle.
   Latitude: 38°52.79′N. Longitude: 91°27.95′W.
4. Johnson Pit. NW1/4, S. 2, T.47N, R.5W, Pinnacle Lake 7.5′ Quadrangle.
   Latitude: 38°52.20′N. Longitude: 91°27.10′W.
5. Deeker Pit. NW1/4, S. 11, T.47N, R.5W, Pinnacle Lake 7.5′ Quadrangle.
   Latitude: 38°51.57′N. Longitude: 91°26.74′W.
6. Unnamed Pit. NE 1/4, S.11, T.47N, R.5W, Pinnacle Lake 7.5′ Quadrangle.
   Latitude: 38°51.46′N. Longitude: 91°26.25′W.
7. Musgrove Pit. SE1/4, S. 2 and SW 1/4, S. 1, T.47N, R.5W, Pinnacle Lake 7.5′ Quadrangle (type section of the Whippoorwill Formation).
   Latitude: 38°51.80′N. Longitude: 91°26.10′W. Elevation: 253 m
8. Pendleton Pit. SE1/4, S.33, T.47N, R.3W, Jonesburg and Warrenton 7.5′ Quadrangles.
   Latitude: 38°47.28′N. Longitude: 91°15.11′W. Elevation: 239 m
9. Polston Pit. SE1/4, S.7, T.46N, R.2W, Warrenton 7.5′ Quadrangle.
   Latitude: 38°45.79′N. Longitude: 91°10.45′W.
10. Warrenton Pit. NW1/4, S. 28, T.46N, R.1W, Marthasville 7.5′ Quadrangle.
   Latitude: 38°43.08′N. Longitude: 91°1.67′W.

Locations are numbered west-to-east and correspond to those shown in Figure 1. All of these locations are clay mines; we have not found the Whippoorwill in any other type of exposure. The Musgrove Pit (#7) is designated here as the type section of the Whippoorwill Formation. Due to the ephemeral nature of exposure for most Quaternary-age sediment, we also designate the heavily mined area south of New Florence (including locations 3–7) as a type area for the Whippoorwill Formation. Elevations for the top of the Whippoorwill are given for the two cosmogenic-isotope dating sites (Musgrove and Pendleton pits).

and these low spots acted as small depocenters for locally derived mass-flow sediments.

The Whippoorwill Formation is generally 1–2 m thick but can range up to at least 3.6 m (Table 2). In some of the larger exposures, the observed thickness decreases towards the center of the pit in a wedge or ramp-like geometry. In these cases, the thickness also varies with the slope of the underlying bedrock surface, implying topographic control in the deceleration and accumulation of mass flows. The Parker–Russel Pit is the best such example to date, and the geometry there strongly supports a mass-flow origin for the Whippoorwill Formation (Fig. 4). On the eastern side of the pit, the Whippoorwill Formation thickens above a break in the slope of the underlying bedrock surface. Westward, however, the Whippoorwill thins to zero toward the middle of the pit, and it is absent entirely along the western half, indicating a localized source area at higher elevations to the east. Near its terminus, the Whippoorwill Formation rests directly upon a prominent B horizon developed in residuum. Eastward and upslope from this terminus, the paleosol and residuum are progressively truncated. These features indicate that the Whippoorwill Formation is composed of the preglacial residuum/paleosol, which was mobilized and eroded from the higher landscape positions and then deposited as the Whippoorwill Formation.

Characteristics

Composition and redox state

The Whippoorwill Formation is an unstratified, leached, and gleyed diamicton with segregation of iron oxides into distinct, prominent mottles (Table 2 and Figs. 5A and B). The matrix color consistently has high values (≥6), very low chromas (≤2), and hues ranging between 5Y and Gley 1–2. We have found no trace of stratification in any of the exposures examined for this study.

The Whippoorwill Formation also contains irregular concentrations of organic material, both fibrous and humus. These concentrations seem to be randomly located, both laterally and with respect to depth. Carbonized rizoliths are likewise present in apparently random clusters.

The matrix composition of the Whippoorwill Formation varies among different exposures (Table 2) but is vertically homogeneous at the outcrop scale. The consistency in composition at individual sites seems to reflect homogenization during deposition, while the differences among sites reflect the influence of different source materials surrounding local accumulations. Small chert pebbles are dispersed nearly evenly throughout the deposit, while larger cobbles are present but rare. The larger clasts are concentrated in places, and

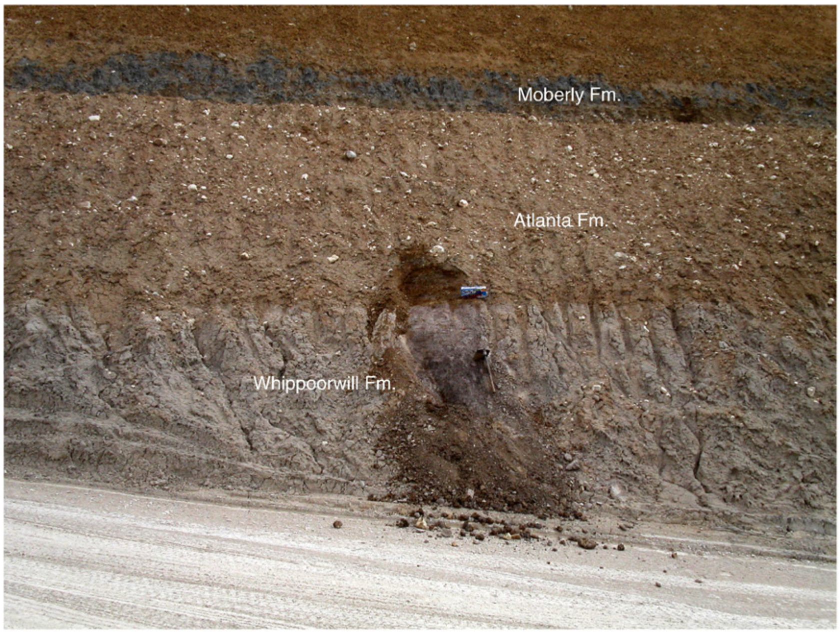

Figure 3. High wall exposure in the Musgrove Pit. The Musgrove Pit is designated here as the type section of the Whippoorwill Formation. The upper Whippoorwill Formation contact is at the shovel. The base of the Atlanta Formation till is at the box. The gray material between the Whippoorwill and the overlying till is a laminated (proglacial) silt locally present within swales along the Whippoorwill surface. The contact between the Atlanta and Moberly Formations is at the abrupt transition to an unoxidized (near base) diamicton with fewer clasts.

Table 2
General characteristics and pedogenic features of the Whippoorwill Formation.

Location	Thickness (m)	Profiles–Structure[a]	Overlying unit	Color (moist) (C Horizons)	Texture				Clay mineralogy			
					Sa	Si	Cl	(*n*)	E	I	K + C	(*n*)
Harrison Pit	1.2–2.7	[b]Bt/C	Moberly	Reduced (greenish gray	4 [0.7]	47 [2.8]	49 [3.5]	(2)				
Johnson Pit	~1	C – ma	Atlanta	Reduced (light bluish gray) with oxidized mottling								
Musgrove Pit	1.0–3.6	A/C – ma/ma	Atlanta	Reduced (light bluish gray) with oxidized mottling	14 [7.6]	61 [6.5]	26 [4.2]	(5)	78 [10.]	4 [2.7]	18 [10.]	(5)
		Bwg/C – 1-2, vf-f, oxidized mottling abk/ma										
Parker–Russel Pit	0.0–3.1	C- ma	Atlanta	Reduced (light olive gray) with oxidized mottling								
Pendleton Pit	0.9–1.5	C-ma	Atlanta	Reduced (light bluish gray) with oxidized mottling	14 [3.6]	52 [3.8]	34 [3.4]	(5)	31 [3.6]	7 [4.0]	62 [4.4]	(5)
Polston Pit	0.3–1.8	C-ma	Atlanta	Reduced (light bluish gray) with oxidized mottling								
Readsville Pit												
(Whippoorwill)	1.5	C-3, m-c,pl	Atlanta	Reduced (light bluish gray) with oxidized mottling	6 [0.6]	56 [1.3]	38 [1.8]	(4)	41 [7.9]	40 [7.0]	19 [1.0]	(3)
(Residuum)					9 [1.4]	50 [0.0]	41 [1.4]	(2)	49	37	14	(1)
Warrenton Pit	~0.7	Bwg-1,f,abk	Atlanta	Reduced[c] (light olive gray) with oxidized mottling								

Locations are listed alphabetically.

Abbreviations: Sa, sand; Si, silt; Cl, clay; (*n*), number of samples; E, expandable clay minerals; I, illite; K + C, kaolinite + chlorite. Numbers in brackets are standard deviations. Samples for textural and clay mineral analyses were taken in vertical profiles spanning the respective unit and with approximately equal spacings. See Rovey and Tandarich (2006) for procedures.

[a] 1, weak; 2, moderate; 3, strong; vf, very fine; f, fine; m, medium; c, coarse; abk, angular blocky; pl, platy; ma, massive.

[b] The Bt horizon at the Harrison Pit was poorly exposed during our visits. See Guccione and Tandarich (1993) for a more complete description of that horizon.

[c] Color here refers to the Bw horizon.

locally the deposit resembles a till. However, these concentrations are uncommon, and all of the clasts examined to date are reddish-brown chert, which is ubiquitous in the local residuum and as a lag atop the bedrock surface. Crystalline lithologies (erratics) are absent within the Whippoorwill Formation, which is a stark contrast with their common occurrence within the overlying tills.

The Whippoorwill Formation is related genetically to the local bedrock residuum. For example, at the Readsville Pit the Whippoorwill rests directly upon reddish-brown residuum, which grades downward into weathered bedrock. The composition of the Whippoorwill Formation at this site is indistinguishable from that of the residuum (Table 2). Moreover, sand grains within the Whippoorwill are uniformly coated with a red patina, as is nearly universal for such grains within the residuum. Thus, our observations here accord with interpretations of previous authors: the Whippoorwill Formation is derived closely from the local soil/bedrock residuum.

Contacts and pedogenic features

Generally, both the upper and lower contacts of the Whippoorwill Formation are sharp, with the lower resting atop bedrock and the upper overlain by various facies of the Atlanta Formation. In places, however, the gleyed Whippoorwill lithology grades downward into oxidized chert-rich material, typical of bedrock residuum (Fig. 5B). In several instances, the lower contact sharply overlies oxidized residuum, which locally (Parker–Russel and Warrenton pits) retains characteristics of a Bt horizon.

Horizonization is absent within the Whippoorwill Formation in most cases, and mature B horizons are not present, except where the Atlanta Formation is absent and the Whippoorwill is overlain instead by the much younger Moberly Formation, for example, at the Harrison Pit. At that site, a prominent paleosol reflects a much longer duration of surface exposure and weathering before burial by the Moberly till. At two locations, however (the Musgrove and Warrenton pits), the upper Whippoorwill Formation contact is marked locally by weakly expressed horizons that are consistent with subdued pedogenesis. In places within the Musgrove Pit, a surface (A?) horizon ~20 cm thick is darker than the underlying materials by one to two Munsell values (Figs. 6A and B). The darker values may be due to incipient melanization, but the structure typical of A horizons is absent. Laterally, this horizon thins and disappears, and where this occurs, vestiges are marked by wavy (darker) color bands protruding downward into the underlying gley (Fig. 6A).

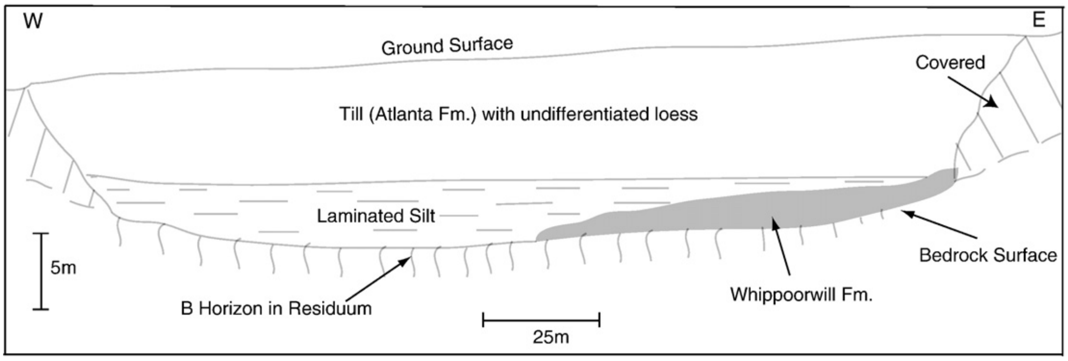

Figure 4. Relationship between the Whippoorwill Formation and bedrock topography, Parker–Russel Pit.

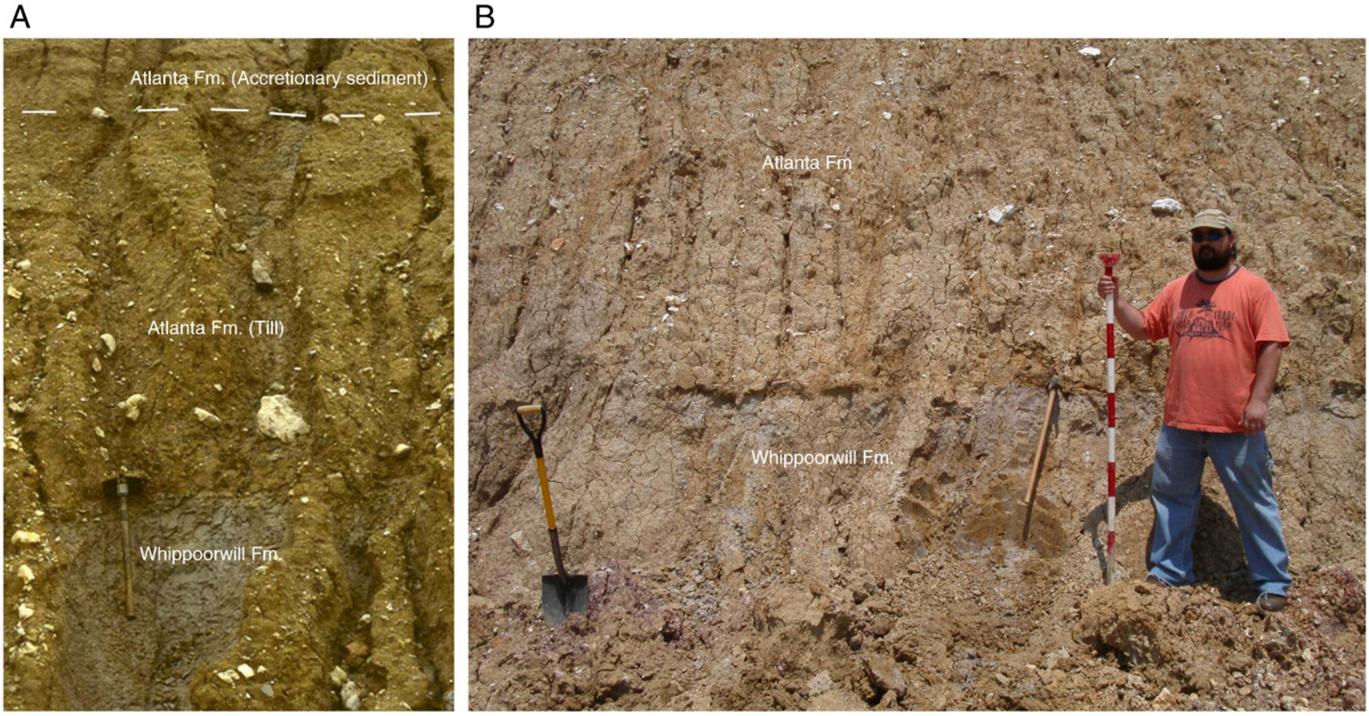

Figure 5. (A) Contact between the Whippoorwill and Atlanta Formations, Johnson Pit. The upper Whippoorwill contact is at the shovel. (B) Whippoorwill Formation exposure, Pendleton Pit. The Whippoorwill–bedrock contact is at the base of the shovel. The upper Whippoorwill contact is at the blade of the pick-axe. Note the downward transition to a more-oxidized state.

At other places in the Musgrove Pit, the Whippoorwill exposure is capped by an ~25 cm layer interpreted as a Bw horizon. This horizon has weak, angular–blocky structure lacking clay cutans; ped boundaries are marked by pressure faces. Some of these peds tend toward a trapezoidal or wedge shape, which is generally associated with shrink–swell action (e.g., Schaetzl and Anderson, 2005). A high percentage of expandable clay at this site may account for this structure, but slickensides, which are generally present in vertic soils, are absent. A weak angular–blocky structure is also present throughout the thin (~0.7 m) exposure at the Warrenton Pit, and at the Readsville Pit, a strong, medium-coarse platy structure is present throughout the deposit. In all other observed sections, the Whippoorwill Formation is massive.

Cryogenic features

The Whippoorwill Formation preserves numerous features associated with cryoturbation or frost churning. The color bands that protrude downward from the surface horizon (Fig. 6A) resemble involutions produced between horizon boundaries during cryoturbation. The upper surface at two pits also preserves wedge-shaped casts. Figures 6A and B show small-scale examples in cross-sectional view at the Musgrove Pit. The size, shape, and depth of these features resemble soil wedges or seasonal frost cracks, which commonly form in the active layer above permafrost (French, 1996), although similar features may form in more temperate regions. Thus, these small casts are consistent with a permafrost origin but are not completely diagnostic.

Much larger casts were briefly exposed along a ramp leading into the nearby Johnson Pit (photographs not available). These larger casts are ≥25 cm wide near the top and extend below the base of the Whippoorwill into the underlying soft shale. In plan view, they form a polygonal network with diameters up to ~5 m; therefore, they are typical of features routinely interpreted as ice-wedge casts (Johnson, 1990; Wayne, 1991; Walters, 1994), which form only under permafrost conditions (e.g., Péwé et al., 1969; Black, 1976; Harry and Gozdzick, 1988).

Paleomagnetism

The Whippoorwill Formation retains a well-defined depositional magnetic remanence (a detrital remanent magnetization) with reversed polarity (Rovey et al., 2006). The strong and consistent magnetic remanence implies that these materials were deposited in a saturated condition, which favors uniform orientation of magnetic grains into alignment with Earth's field upon deposition (e.g., Tarling, 1983). Because normal pedogenic processes destroy a sediment's depositional remanence, the Whippoorwill Formation is not a typical soil profile that was homogenized *in situ* by bioturbation/pedoturbation. A more plausible interpretation is that the Whippoorwill Formation is periglacial sediment, which developed weakly expressed pedogenic features shortly before burial by an advancing glacier.

Cosmogenic–nuclide measurements

^{26}Al–^{10}Be burial dating

We measured cosmogenic ^{26}Al and ^{10}Be concentrations in quartz from the Whippoorwill Formation for two purposes: first, to date the emplacement of the overlying Atlanta till using the method of ^{26}Al–^{10}Be burial dating; and second, to investigate the exposure history and pedogenic processes experienced by the Whippoorwill Formation materials prior to burial.

The basis of burial dating using the ^{26}Al–^{10}Be nuclide pair is that these two nuclides are produced at a fixed ratio in quartz exposed to the cosmic-ray flux at the Earth's surface. If the quartz is then buried deeply enough to shield it from further cosmic-ray irradiation, ^{26}Al and ^{10}Be production halts, and their concentration diminishes by radioactive decay. As ^{26}Al has a shorter half-life than ^{10}Be, the ^{26}Al/^{10}Be ratio decreases over time and can be used as a burial clock

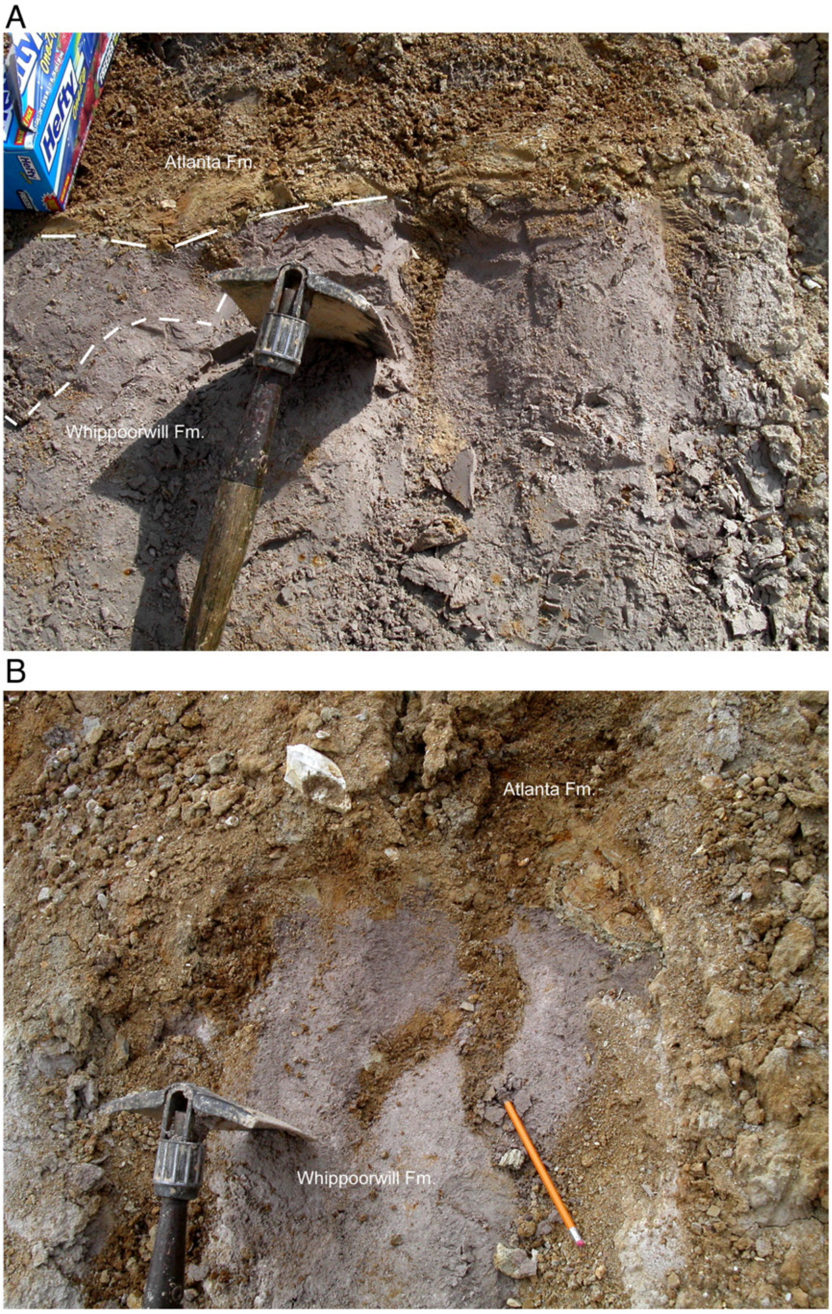

Figure 6. (A) Faint horizonization in the upper Whippoorwill Formation, Musgrove Pit. Note the darker color at the very top of the Whippoorwill, which locally marks an upper surface (A?) horizon within the Musgrove Pit. The lower dashed line follows faint irregular protrusions of this horizon boundary (involutions) into the underlying gley. Also note the (very) small wedge-shaped cast to the right of the shovel. (B) Wedge-shaped cast at the top of the Whippoorwill Formation, Musgrove Pit. This cast bifurcates downward as a pseudo flame structure, a characteristic feature of soil wedges in active layers. The infilling material is identical and continuous with the materials at the base of the overlying Atlanta Formation.

(Granger, 2006, gives a detailed summary of burial dating methods). As the Whippoorwill Formation was exposed at the surface and then buried by emplacement of the Atlanta till, this method can be used to date the Atlanta till. In previous work (Balco et al., 2005), we applied this method to two samples from the Whippoorwill Formation at the Musgrove Pit. In this present work, we analyzed an additional four samples from the Whippoorwill Formation at a different site, the Pendleton Pit, where the Atlanta similarly overlies the Whippoorwill.

Table 3 shows the results of ^{26}Al and ^{10}Be measurements from the Musgrove and Pendleton pits. The methods of quartz separation and Al and Be purification are as described in Balco et al. (2005) and employed a low-blank Be carrier prepared from deep-mined beryl. All Al and Be isotope ratio measurements were made at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory. Full carrier and process blanks for both ^{10}Be and ^{26}Al were 0.1–0.8% of the total number of atoms measured in each sample. ^{26}Al concentrations are normalized to the isotope ratio standards of Nishiizumi (2004). Be isotope ratios of Musgrove Pit samples were referenced at the time of measurement to the standard LLNL3000, and those of Pendleton Pit samples were referenced to the standard 07KNSTD3110. In this work, we renormalized the Musgrove Pit measurements to 07KNSTD3110 according to Nishiizumi et al. (2007); this is reflected in the ^{10}Be concentrations in Table 3. We calculated the burial ages using the method described in Balco et al.

Table 3
$^{26}Al/^{10}Be$ concentrations and burial ages from the Whippoorwill Formation at Musgrove and Pendleton clay pits.

Sample name	Site	Depth below Whippoorwill surface (cm)	$[^{10}Be]$ (10^6 atoms g^{-1})	$[^{26}Al]$ (10^6 atoms g^{-1})	Burial age (Ma)	Uncertainty in burial age			Pre-burial erosion rate (m/Ma)	Uncertainty in erosion rate[d]
						Analytical uncertainties only[a]	Analytical and site- specific uncertainties[b]	All uncertainties[c]		
MO-MP-1[e]	Musgrove Pit	0–10	0.837 ± 0.012	1.543 ± 0.032	2.489	0.050	0.071	0.20	1.26	0.32
MO-MP-5[e]	Musgrove Pit	0–10	0.840 ± 0.010	1.486 ± 0.032	2.573	0.048	0.068	0.19	1.34	0.31
Error-weighted mean from Musgrove Pit					2.532		0.062			
PP-WH-0	Pendleton Pit	0–15	0.705 ± 0.013	1.634 ± 0.061	2.259	0.097	0.12	0.21	2.05	0.44
PP-WH-0.5	Pendleton Pit	15-31	0.699 ± 0.018	1.459 ± 0.104	2.52	0.18	0.20	0.27	1.76	0.46
PP-WH-1	Pendleton Pit	31–53	0.709 ± 0.018	1.568 ± 0.075	2.36	0.13	0.14	0.23	1.91	0.44
PP-WH-1.75	Pendleton Pit	53–69	0.700 ± 0.018	1.566 ± 0.077	2.33	0.13	0.14	0.23	2.00	0.45
Error-weighted mean from Pendleton Pit					2.330		0.091			
Error-weighted mean of both sites					2.470			0.19		

^{10}Be measurements are normalized to the Be isotope ratio standards of Nishiizumi et al. (2007). The data from the Musgrove Pit were previously reported in Balco et al. (2005); here we have renormalized the ^{10}Be measurements and recalculated the burial ages with the revised values. ^{26}Al measurements are normalized to the Al isotope ratio standards of Nishiizumi (2004).

[a] Includes only uncertainties in ^{26}Al and ^{10}Be measurements. These values should be used to compare burial ages from the same site.

[b] Includes uncertainties in all measurements and assumptions that differ between sites, including densities and assumed erosion rate for overburden units as well as the depth of soil mixing prior to burial. These values should be used to compare burial ages from different sites.

[c] Includes all uncertainties including those in the ^{26}Al and ^{10}Be decay constants. These values should be used to compare burial ages to ages determined by other dating methods.

[d] Includes all uncertainties.

[e] Mean of two measurements.

(2005). However, we revised some of the ages and erosion rates of overburden units required as input parameters for that method using more recent results from Balco and Rovey (2008). These parameters are listed in Table 4. We calculated spallogenic ^{10}Be and ^{26}Al production rates using the scaling scheme of Stone (2000) and the production rate calibration data set from Balco et al. (2008). We calculated production rates by muons using a MATLAB implementation, described in Balco et al. (2008), of the method of Heisinger et al. (2002a, 2002b). We adjusted the reference ^{10}Be production rate and muon interaction cross-sections from those sources to be consistent with the 07KNSTD3110 standard. We used the ^{26}Al decay constant (9.83×10^{-7} yr^{-1}) of Nishiizumi (2004), and the revised ^{10}Be decay constant (5.10×10^{-7} yr^{-1}) of Nishiizumi et al. (2007). Mainly because of this revision of the ^{10}Be decay constant, burial ages for Musgrove Pit samples shown in Table 3 differ somewhat from those originally reported in Balco et al. (2005).

Burial ages at each individual site agree within measurement uncertainties, and those from the two sites agree with each other within uncertainties that include both measurement error and uncertainties in estimating the site-specific parameters needed to calculate a burial age. Averaging ages from both sites indicates that the Atlanta till was emplaced at 2.47 ± 0.19 Ma (Table 3 and Fig. 7). This result is not significantly different from that of Balco et al. (2005), but the agreement between two separate sites is a significant improvement on that result because it increases confidence in the key assumption of the burial dating method, that ^{26}Al and ^{10}Be concentrations were at equilibrium with steady erosion at the time of burial (see Granger, 2006, for discussion of this assumption). This, in turn, significantly increases confidence in the accuracy of the age.

Exposure history of the Whippoorwill Formation prior to burial

In addition to an age for the Atlanta till, which provides a minimum age for the Whippoorwill Formation, the cosmogenic–nuclide measurements provide information about the exposure history of the samples prior to burial.

First, given the assumption that the erosion rate at the site was steady for a long period of time (long enough to remove ~2 m of rock or sediment), the absolute magnitude of the nuclide concentrations can be equated with the surface erosion rate at the site before it was buried (Granger, 2006). We have argued above that the Whippoorwill Formation did not itself experience a long period of steady erosion in its present configuration but instead was formed by relatively rapid redeposition of weathered regolith that had previously experienced a long period of slow erosion. In this scenario, given that the length of time between deposition of the Whippoorwill Formation and

Table 4
Measurements and assumptions regarding overburden units used in calculating burial ages.

Site	Overburden unit	Thickness (m)	Density (g cm^{-2})	Assumed age (Ma)	Assumed erosion rate after emplacement (m/Ma)
Musgrove Pit	Atlanta Formation	6.1	2.23 ± 0.10	–	10 ± 5
	Moberly Formation	11.6	1.98 ± 0.10	1.2 ± 0.3	10 ± 5
	Loess	2.5	1.50 ± 0.20	0.125 ± 0.05	10 ± 5
Pendleton Pit	Atlanta Formation	5.0	2.23 ± 0.10	–	10 ± 5
	Moberly Formation	1.5	1.98 ± 0.10	1.2 ± 0.3	10 ± 5
	Fulton Formation	2.5	2.11 ± 0.10	0.8 ± 0.1	10 ± 5
	Loess	1.5	1.50 ± 0.20	0.125 ± 0.05	10 ± 5

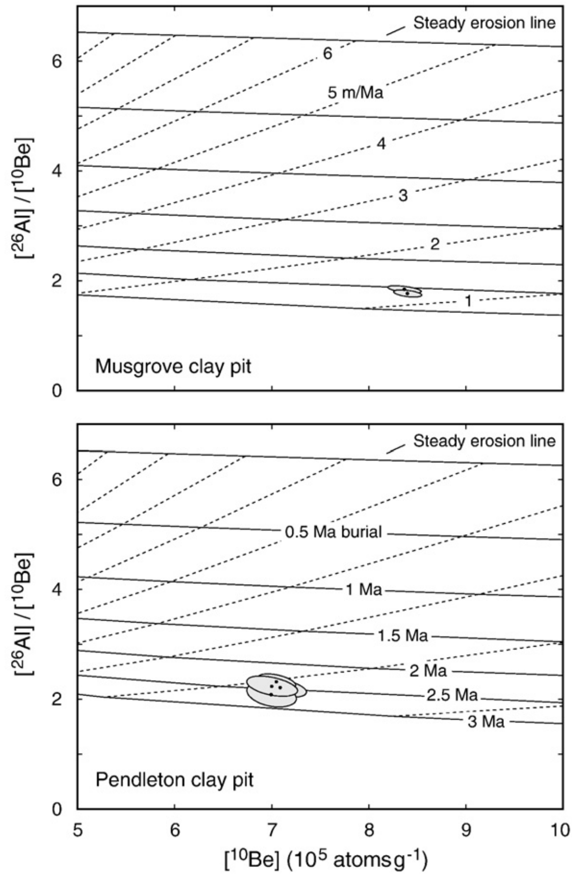

Figure 7. ^{10}Be–^{26}Al/^{10}Be two-isotope diagram showing ^{26}Al and ^{10}Be measurements from the Whippoorwill Formation at the Musgrove and Pendleton pits. See Granger (2006) for a description of this diagram. The dashed lines are contours of surface erosion rate prior to burial and are labeled in the upper panel; the solid lines are contours of burial age and are labeled in the lower panel. In each diagram, the contours of burial age are drawn for the present burial depth of the Whippoorwill Formation surface. The gray ellipses are 68% confidence regions reflecting measurement uncertainty.

emplacement of the Atlanta Formation was short relative to the length of time the pre-Whippoorwill residuum experienced steady erosion (see discussion below), the nuclide concentrations in the Whippoorwill reflect the long-term erosion rate that prevailed prior to Whippoorwill deposition. With these assumptions, the measured ^{26}Al and ^{10}Be concentrations imply erosion rates of 1–2 m/Ma (Table 3 and Fig. 7). These rates are consistent with the presence of a deeply weathered residuum reflecting extended surface exposure at a low erosion rate, as well as with early and middle Pleistocene erosion rates inferred from other burial-dating studies in central North America (Granger et al., 1997, 2001).

Second, the relationship of cosmogenic–nuclide concentrations to depth below the surface of the Whippoorwill Formation provides information about soil mixing prior to burial. Nuclide production rates decrease exponentially with depth below the surface, so in the absence of soil mixing, cosmogenic–nuclide concentrations in soil will also show an exponential decrease. In the opposite case of pervasive soil mixing, nuclide concentrations will not vary with depth. At the Pendleton Pit, we measured ^{26}Al and ^{10}Be concentrations in a 0.9-m profile that spanned the thickness of the Whippoorwill Formation at that site. Nuclide concentrations were invariant with depth, indicating pervasive vertical mixing (Fig. 8).

To summarize, both absolute ^{26}Al and ^{10}Be concentrations and the depth-invariance of the nuclide concentrations are consistent with the interpretation that the Whippoorwill Formation reflects remobilization and downslope transport, shortly before ice-sheet advance, of a preglacial weathering profile developed during a long period of landscape stability. The high nuclide concentrations show that the material that makes up the Whippoorwill Formation experienced extended surface exposure at a low erosion rate, and the fact that the nuclide concentrations do not change with depth is consistent with the stratigraphic evidence that it originated by downslope transport and redeposition of existing regolith shortly before emplacement of the Atlanta till. The Whippoorwill was mixed during transport and deposition and, at deposition, had ^{26}Al and ^{10}Be concentrations that were invariant with depth. The invariance of nuclide concentrations with depth also implies that only a relatively short time elapsed between deposition of the Whippoorwill and burial by the Atlanta till. The weakly developed soil horizonization in some of the Whippoorwill Formation exposures indicates that there must have been at least a brief period of surface stability during or after Whippoorwill deposition, but before burial by the Atlanta till. However, if this period of stability had been long enough for significant nuclide production to take place, greater nuclide production rates near the surface would have caused the nuclide concentration–depth profile to diverge from the well-mixed state at the time of deposition, and ^{26}Al and ^{10}Be concentrations would decrease with depth. No such gradient is present, so any period of stability between Whippoorwill Formation deposition and burial must have been short enough that any resulting vertical gradient in ^{10}Be concentrations is near or less than our ^{10}Be measurement precision. Carrying through this calculation implies that no more than 40 ka elapsed between homogenization of the Whippoorwill Formation and its burial by the Atlanta till.

Inferred age of the Whippoorwill Formation

If we accept that the Whippoorwill Formation cannot predate the Gauss Normal Chron (beginning at ~3.6 Ma), then the reversed detrital remanent magnetization shows that it must postdate the boundary between the Matuyama (reverse) and Gauss (normal) chrons at 2.58 Ma. This age is indistinguishable from the 2.47 Ma age of the Atlanta till inferred from ^{26}Al–^{10}Be burial dating (Table 3). Thus, the Whippoorwill Formation could have acquired its reversed detrital remanent magnetization only within a short interval of time during the early Matuyama Chron. This observation is consistent with the lack of strongly developed pedogenic features in the Whippoorwill Formation and the depth-invariance of ^{26}Al and ^{10}Be concentrations,

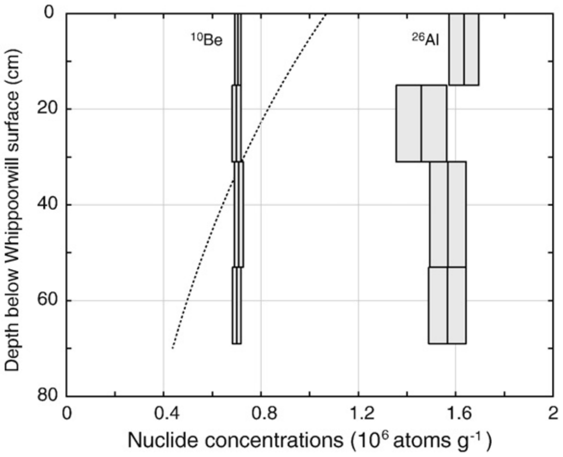

Figure 8. ^{26}Al and ^{10}Be concentrations in a profile through the Whippoorwill Formation at Pendleton Pit. The vertical extent of the boxes indicates the depth range of each sample. The horizontal extent of each box shows the 1σ uncertainty in the concentration measurements. The dashed dark line shows the expected ^{10}Be profile for a soil with the same average ^{10}Be concentration, but no vertical mixing.

which suggests that the length of time between deposition and burial of the Whippoorwill Formation was a few tens of thousands of years or less. To summarize, the Whippoorwill Formation is preglacial in a sense, but not by much.

The Whippoorwill Formation as a Gelisol

Definition

In this section, we argue that the Whippoorwill Formation is a buried Gelisol. A Gelisol is a soil formed under periglacial conditions and is defined by the presence of permafrost (Soil Survey Staff, 1999). For this soil order, geologic and pedologic processes overlap, and their distinction is somewhat arbitrary and provincial (e.g., Bockheim et al., 2006).

Characteristics of Gelisols and gelifluction deposits

Gelisols are frequently subjected to mass flowage (gelifluction) due to saturation within the active layer above permafrost. Gelifluction can be an efficient mechanism of erosion, which strips soil and weathering products from hillslopes and transports them to lower landscape positions where they are deposited as massive diamictons (Washburn, 1973; Benedict, 1976). This flowage occurs preferentially in silty materials, because these are coarse enough to lack significant cohesion but fine enough to impede drainage within the active layer. These mass flows accumulate in a variety of geometries, but they are usually 1–2 m thick and rarely thicker than ~4 m. Gelifluction deposits typically are gleyed with mottling, due to their restricted drainage with partial seasonal aeration (Benedict, 1976; Gerrard, 1992; Höfle et al., 1998).

Gelifluction is one of the few processes (most of which involve ice) that produce unstratified diamictons. Mudflows and debris flows, for example, generally preserve some combination of flow structure, irregular stratification, and graded bedding (Nilsen, 1982; Prothero and Schwab, 2004). Accretionary deposits (i.e., slopewash) likewise preserve stratification; such deposits are commonly preserved in Pleistocene landscapes in the central US. Gelifluction lobes and sheets, however, are massive and unstratified due to their low rates of flowage, typically just a few centimeters per year (Matsuoka, 2001).

Several other features are diagnostic of soils in periglacial regions. Cryoturbation (frost churning) and liquifaction disperse organic materials into irregular concentrations within the subsurface (Gerrard, 1992; Bockheim and Tarnocai, 1998, 2000; Höfle et al., 1998). Horizonization is poorly defined or absent in these materials, depending on the degree of cryoturbation and mixing. Where present, horizons are deformed and discontinuous, and boundaries are wavy or involuted (Bockheim et al., 1997; Bockheim and Tarnocai, 1998, 2000; Höfle et al., 1998). Ice wedges and deformed ice-wedge casts are also common in Gelisols and represent extreme forms of cryoturbation.

Clay translocation and melanization is impeded within Gelisols due to restricted vertical drainage and a lack of faunal mixing and deep root systems (Gerrard, 1992). Hence, Bt horizons are generally absent. The most common mineral horizons in Gelisols are therefore C, Bw, Bg, and weakly expressed A horizons (Bockheim et al., 1997; Bockheim and Tarnocai, 1998; Höfle et al., 1998). Structure, if present, is produced by pressure effects caused by segregation of ice into discrete lenses and layers; hence, platy, blocky, and massive structures are the most common (Bockheim et al., 1997; Höfle et al., 1998). Pressure effects caused by ice segregation can also impart distinctive microstructures to Gelisols (Bockheim et al., 1997; Bockheim and Tarnocai, 2000). To date, we have not carried out thin-section analysis of the Whippoorwill Formation, so we limit our comparison between the Whippoorwill and Gelisols to macroscopic features.

Corresponding characteristics of the Whippoorwill

The processes that delivered Whippoorwill Formation materials to their current position mixed and homogenized highly weathered soil materials without producing stratification. Most such diamictons in the midwestern US are glacial tills, but the geographic distribution, stratigraphy, nearly identical composition to the underlying bedrock residuum, and lack of erratic clasts preclude glacial deposition as a possible origin for the Whippoorwill Formation and instead indicate an origin by localized processes. The widespread preservation of the Whippoorwill Formation, albeit within isolated low paleolandscape positions, indicates that these processes were widespread across the preglacial landscape. The timing of deposition is another important factor that limits possible origins of the Whippoorwill. As discussed above, transportation and deposition of the Whippoorwill occurred shortly before glaciation. Therefore, periglacial processes appear to be the only mechanism that could account for all of these features.

In periglacial environments, the upper weathered (gelic) materials are relatively mobile, and hence, they commonly have features that overlap in character between sedimentary deposits and soils. In a geologic sense, these materials are a sediment due to the prevalence of slow mass movement above the permafrost table (gelifluction). In a pedologic sense, however, these materials are a soil (Gelisol), because they consist of weathered materials that support some vegetation. The Whippoorwill Formation displays this same mix of geologic and pedologic traits.

The most durable soil features are structure, horizonization, and redox state. These features tend to persist upon burial and therefore are used most commonly in classifying buried soils (Nettleton et al., 2000) and assessing their maturity (Follmer, 1998; Hall and Anderson, 2000). The most common structures within Gelisols include massive, platy, and angular–blocky forms (Bockheim et al., 1997; Bockheim and Tarnocai, 2000; Höfle et al., 1998), which are produced in this case by compressional forces generated during formation of ice layers and lenses. These structures are consistent with those present within the Whippoorwill Formation (Table 2), although they occur in additional soil orders, and various other structures may be present within Gelisols. Therefore, we concentrate on other properties that are more unique to Gelisols and/or have a smaller range in character.

Involutions are highly diagnostic of gelic materials, and these are present within the Whippoorwill Formation, although they are subtle and have only been found at one location. Possibly there was little color differentiation between mineral horizons to begin with, so these features are not prominent. The polygonal network of wedge-shaped casts are the single most convincing evidence of permafrost and cryoturbation (e.g., Black, 1976, 1983; Harry and Gozdzik, 1988). The diameter (~5 m) is smaller than that of the primary networks described by Péwé et al. (1969) but are within the range observed by Black (1976) for secondary networks, which grow between larger polygons. Thus, these casts are very strong evidence of cryoturbation within the Whippoorwill Formation.

In all of the Whippoorwill Formation casts examined to date, the infilling material is continuous with the basal Atlanta Formation till. We are unaware of previous reports of ice wedges filled by till, but this may be due to the locations of the observations. Most such reports are either from modern arctic environments (e.g., Péwé et al., 1969; Black, 1976; Harry and Gozdzik, 1988) or from areas that were in a periglacial environment during the last glacial maximum (Wisconsinan, or MIS 2) but were not eventually covered by that ice (Johnson, 1990; Wayne, 1991; Walters, 1994). Black (1983) and Boulton (2006) reported wedge-shaped till bodies that were emplaced subglacially, but the host materials in these cases were bedrock crevices, not ice wedges within unconsolidated material. Boulton (1987) also described wedge-shaped till casts near the margin of a modern glacier in Iceland and interpreted them as injection features filling hydrofractures beneath subglacial deforming beds. This mechanism, however, seems insufficient to account for the polygonal network of the larger casts at the Johnson Pit. Polygonal cracks are associated universally with shrinkage, as accompanies permafrost growth; hence, they are unlikely to form during hydrofracturing.

In principle, soil and ice wedges could be replaced by till, if an ice margin overrides active or relict permafrost. The ice in such wedges would initially prevent the host material from collapsing as it was overridden, but later, subglacial sediment would settle into and fill the underlying void after the ice reached the pressure–melting point. We interpret the casts in the Whippoorwill Formation to have formed in this manner. If this interpretation is correct, cryoturbation was active within the Whippoorwill up to the time of burial by the advancing ice.

Summary and conclusions

Origin of the Whippoorwill Formation

The Whippoorwill Formation is found within and around bedrock depressions along a ~20-km-wide band that is roughly parallel to the southern limit of Laurentide ice sheet advances in Missouri. The distribution, geometry, and composition of Whippoorwill Formation deposits show that they were formed by downslope transport and redeposition of an existing, deeply weathered, residual soil. Other properties, such as the strong detrital remanent magnetization, the unstratified nature, and the lack of erratics, respectively, eliminate normal pedogenic processes, most types of mass flows, and direct glacial deposition. Cryogenic features, including ice-wedge casts and horizon involutions, indicate that cryoturbation and gelifluction were the primary agents responsible for the transport, homogenization, and deposition of the Whippoorwill Formation.

The Whippoorwill Formation as a buried Gelisol

Transport and redeposition of soil materials in the presence of permafrost accounts for the mix of geologic and pedologic traits previously noted by other authors. In one sense, the Whippoorwill Formation is a sedimentary deposit, and hence a normal lithostratigraphic unit. Alternatively, the Whippoorwill Formation also could be classified as a pedostratigraphic unit, namely a buried paleosol. If the Whippoorwill is formally defined as a pedostratigraphic unit, and if “Gelisol” may be applied to buried soils that currently lack permafrost, the Whippoorwill Formation represents a Gelisol Geosol.

The one essential and defining characteristic of modern Gelisols is permafrost (Soil Survey Staff, 1999). Obviously, the Whippoorwill Formation does not preserve permafrost under the current climate. Nevertheless, we argue that the Whippoorwill Formation should be classified as a buried or Paleogelisol, because it preserves many characteristics of modern Gelisols. Defining characteristics of other soil orders (particularly Mollisols) are not always preserved upon burial, but such buried examples may still be classified as a paleosol within that order, based on other more-persistent characteristics (e.g., Nettleton et al., 2000).

Age and paleoclimatic significance of the Whippoorwill Formation

Cosmogenic–nuclide burial ages show that the initial expansion of the LIS reached northern Missouri at approximately 39°N latitude by 2.47 ± 0.19 Ma. This advance and associated cooling induced widespread landscape instability and degradation, resulting in the redeposition of previously stable regolith as isolated flow materials in lower topographic positions. These materials are formally defined here as the Whippoorwill Formation.

The burial ages, paleomagnetic measurements, stratigraphic inference, and the depth-independence of cosmogenic–nuclide concentrations closely constrain the age of the Whippoorwill Formation. The Whippoorwill Formation was deposited between the Gauss–Matuyama magnetic reversal at 2.58 Ma and the emplacement of the Atlanta Formation till at 2.47 ± 0.19 Ma. Therefore, the Whippoorwill Formation most likely was deposited within a few thousand to tens of thousands of years before being overridden by the first known advance of the Laurentide ice sheet into central North America. The periglacial origin of the Whippoorwill shows that the mean annual temperature at 39°N was below 0°C at this time. This observation provides a rare and nearly unique window into early Pleistocene terrestrial climate in the glaciated region of North America. At present, climate–ice sheet models that seek to reproduce and explain the onset of the late Cenozoic Northern Hemisphere ice ages are almost entirely based on inference from marine geochemical records of global ice volume and paleoceanographic conditions. However, understanding how large continental ice sheets first advanced to low latitudes largely depends on the treatment of ablation at continental ice margins; this, in turn, depends on a reconstruction of continental surface climate (Raymo and Huybers, 2008). Geologic constraints on early and middle Pleistocene climate near the margins of continental ice sheets are, to date, rare if not nonexistent, largely because of the difficulty of accurately dating continental glacial–interglacial sequences of this age. The periglacial origin of the Whippoorwill Formation provides such a constraint.

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