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Defining the Sheldon Creek Formation, a Middle Wisconsinan (MIS 3) till in Iowa, USA

STEPHANIE A. TASSIER-SURINE,[1]* PHILLIP J. KERR,[1] SUSAN M. KILGORE[2] and BRADLEY D. CRAMER[3]
[1]Iowa Geological Survey, University of Iowa, Iowa City, USA
[2]Environmental Studies and Sciences, Adelphi University, Garden City, NY, USA
[3]Department of Earth and Environmental Sciences, University of Iowa, Iowa City, USA

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ABSTRACT: A pre-Late Wisconsinan, post-Illinoian, till sheet has long been recognized in north-central Iowa, but has not been formally recognized or defined until now. Early researchers referred to these deposits as the 'Tazewell', and the term 'Sheldon Creek' was more recently used informally by the Iowa Geological Survey in guidebooks and reports. Recent mapping has extended the eastern margin significantly past previous interpretations. The Sheldon Creek Formation has similar lithologic characteristics to the overlying Alden Member of the Dows Formation, and the two units are distinguished mainly by stratigraphic position. Differentiation from underlying Pre-Illinoian till units is accomplished using lithology, primarily matrix grain-size and sand fraction lithology. A suite of 22 radiocarbon ages indicate two distinct, separate groupings within the Sheldon Creek data. These data strongly suggest ice advanced south to 42° N twice, once during Marine Isotope Stage (MIS) 3 and again during late MIS 3 or possibly early MIS 2. The presence of the Laurentide Ice Sheet in northern Iowa during MIS 3 has significant implications for ice sheet reconstructions during this interval. © 2024 The Authors *Journal of Quaternary Science* Published by John Wiley & Sons Ltd.

KEYWORDS: glaciation; Iowa; Laurentide Ice Sheet; Middle Wisconsin; MIS 3; North America; Quaternary; stratigraphy

Introduction

Iowa has one of the most complete Quaternary continental stratigraphic records with glacial sediments dating to the start of the Quaternary (Roy et al., 2004; Rovey and McLouth, 2015). However, the distribution and timing of some glacial advances remain uncertain. Based on the regional distribution and stratigraphic position, researchers in Iowa had long identified sediments from a post-Illinois, pre-Late Wisconsin Episode ice advance, but correlation and timing were problematic. These deposits were most commonly referred to as the Iowan by early researchers (Carman, 1931; Leverett and Sardeson, 1932; Kay and Graham, 1943) and later as the Tazewell drift (Ruhe, 1950, 1969) or 'Till 2' (Kemmis et al., 1981). The Iowa Geological Survey (IGS) has since given the sediments the designation of the Sheldon Creek Formation, but a formal description and nomination of type section has not been provided until now.

Recognition of a Middle Wisconsin glacial advance into the mid-continent has significant implications for Laurentide Ice Sheet reconstructions and global sea level models, as many glacial reconstruction models do not recognize ice as far south as Iowa during this interval (Kleman et al., 2010; Stokes et al., 2012; Pico et al., 2017; Batchelor et al., 2019; Dalton et al., 2019, 2022a, 2022b). Formally defining the sediment deposited by this glacial advance will help rectify discrepancies between terrestrial and oceanic records of global climate change during Marine Isotope Stage (MIS) 3. Additionally, establishing the presence of ice in Iowa at this time may also provide a source for distal loess and outwash that has been historically enigmatic in regional studies (Curry, 1998, Dendy et al., 2021).

The IGS currently recognizes three till packages in north-central Iowa: the Dows Formation, Sheldon Creek Formation, and Pre-Illinoian-age Wolf Creek and Alburnett formation tills (Fig. 1a). Units are regionally extensive and related to the Wisconsin and Pre-Illinois episodes (Fig. 1b). Illinois Episode tills are not present in this part of Iowa. Geologic contacts representing disconformities such as paleosol, loess, or sand and gravel separate these formations. The Sheldon Creek Formation can be identified by its stratigraphic position beneath the Late Wisconsinan Dows Formation or Peoria Formation eolian deposits, and above the Sangamon Geosol or Pre-Illinoian till.

Beyond the Late Wisconsin terminus, the youngest glacial till deposits of the Dows Formation are not present, and few glacial landforms, such as moraines or eskers, are identified (Tassier-Surine et al., 2018). A regional erosional event during the Late Wisconsin Episode subdued the topography and eroded older features and sediment, removing these landforms and eliminating key stratigraphic markers such as the Sangamon Geosol (Ruhe et al., 1968; Ruhe, 1969; Mason, 2015). As a consequence, determining which till (Sheldon Creek or Pre-Illinoian) is present at the surface is challenging, especially in northeast Iowa. Although stratigraphic evidence may have been removed, lithologic characteristics can be used to establish the existence and distribution of the Sheldon Creek Formation. The Pre-Illinoian tills and Sheldon Creek Formation materials may be differentiated by matrix grain-size, clay mineralogy, sand fraction lithology and weathering zone features.

The lateral extent of the Sheldon Creek Formation has been established by surface features as well as lithologic descriptions from drill cores. The western boundary has not been

*Correspondence: Stephanie A. Tassier-Surine, as above.
Email: stephanie-tassier-surine@uiowa.edu

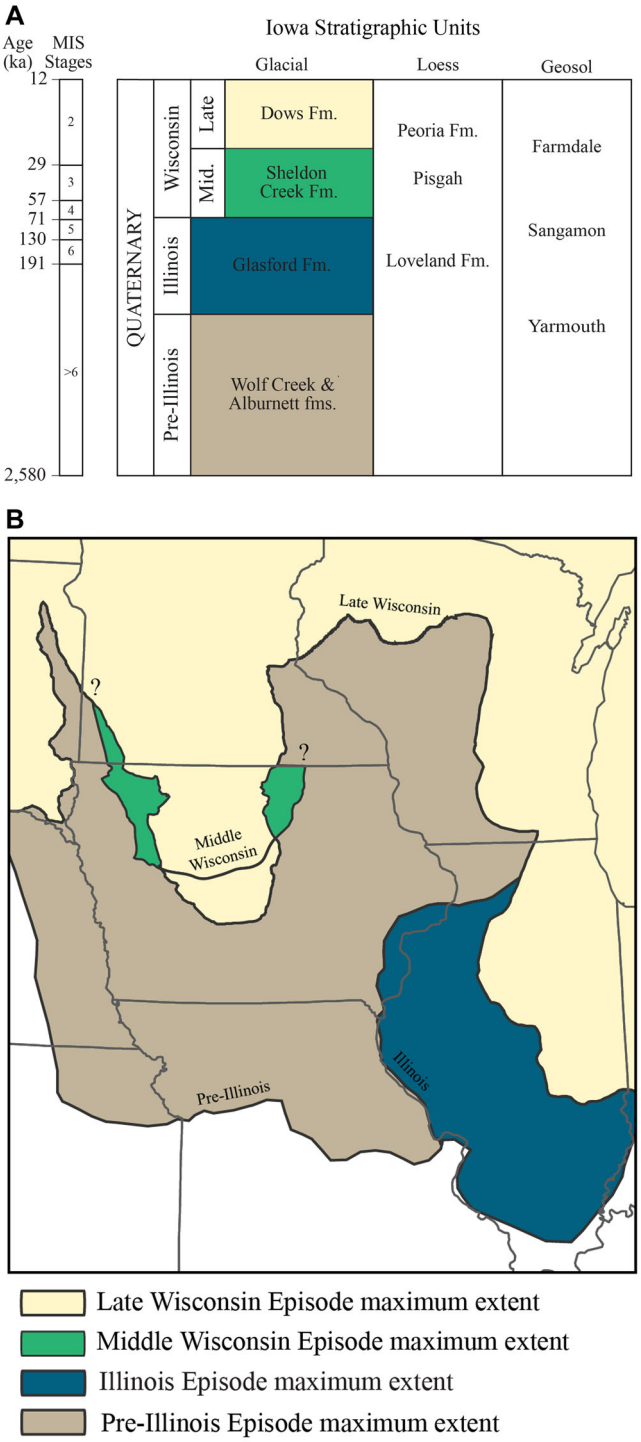

Figure 1. Quaternary stratigraphic units for Iowa and geographic extent of each glacial advance. [Color figure can be viewed at wileyonlinelibrary.com]

substantially changed from that originally delineated by Ruhe (1950). Ruhe focused on drainage class and density, whereby less well-developed drainage networks indicated a younger landscape, in this case the Sheldon Creek Formation landscape. Records from the IGS well drilling database and more recent data from core descriptions (Quade et al., 2005a; 2005a; Kerr, 2022) provide further evidence for this boundary including the intensity of surface weathering, oxidation depth and depth to unleached sediments. Recent mapping within Ruhe's western boundary further confirmed the chronology of the Sheldon Creek Formation till (Kerr, 2022). Mapping on the eastern border, completed by the IGS from 2010 to 2018 (Quade et al., 2012; Tassier-Surine et al., 2015; Tassier- Surine et al., 2016; Kerr et al., 2018), has significantly revised the boundary by extending it farther east than was previously mapped by Hallberg et al. (1991). Preliminary correlation with Minnesota suggests that the Sheldon Creek Formation is contemporaneous with the Verdi and/or Moland members of the New Ulm Formation, although no ages have been published for these units from within Minnesota (Johnson et al., 2016; Lusardi et al., 2019; Gowan, 2020a; 2020b).

Initial radiocarbon ages presented by Ruhe (1969) indicated a Late Wisconsin age range for the Sheldon Creek Formation, but a limited number of age dates were available, and age dates produced decades ago are not considered to be as accurate as those generated using more modern techniques. More recent radiocarbon ages (Muhs et al., 2018; Kerr et al., 2021) have established a more robust chronology for the Sheldon Creek

Formation, placing it within the Middle Wisconsin and MIS 3 and possibly extending into MIS 2 (Fig. 2). A recent study by Kerr et al. (2021) indicates that two glacial advances are recorded within the Sheldon Creek Formation sediments using radiocarbon ages. The Fort Dodge Phase is entirely within MIS 3 and reached its maximum extent shortly after 42 ka. The Lehigh Phase reached its terminus sometime after 30 ka, placing it within late MIS 3 or early MIS 2.

Here, we combine lithologic, geochronologic and stratigraphic data to formally establish the Sheldon Creek Formation as a Quaternary geologic unit in Iowa. The formal identification of this unit in Iowa, and contemporaneous deposits throughout the upper Midwest, will provide significant new insight into the extent of Northern Hemisphere glaciation during MIS 3. Recently published ice sheet reconstruction models do not indicate ice advancing as far south as Iowa, so rectifying this discrepancy may play a large role in understanding the glacial dynamics of the Wisconsin Episode.

Past work

Stratigraphy

This paper will use Episode terms (Wisconsin and Pre-Illinois) to refer to geochronologic units (time) and glacial advances, and descriptive terms (Wisconsinan and Pre-Illinoian) for chronostratigraphic units describing the lithologic materials (Johnson et al., 1997). References to previous works will utilize the cited authors original terminology whether or not it follows the above convention.

Early stratigraphic studies in Iowa were hindered by a lack of till exposures and nearly nonexistent drilling data. Most correlation of Quaternary glacial units was determined from outcrop descriptions and geomorphic features. The first surficial geologic maps of Iowa utilized a five-part till stratigraphy including the Wisconsinan, Iowan, Illinoian, Kansan and Nebraskan (Kay and Apfel, 1929; Kay and Graham, 1943), although there was some level of disagreement as to the correlation and extent of the Iowan (Carman, 1931; Leverett and Sardeson, 1932). Researchers believed a till existed between the Late Wisconsinan and 'Kansan' sediments, but could not agree upon its age or relationship with the 'Iowan'.

Ruhe (1950, 1952, 1969) conducted several comprehensive studies on the geomorphology of Iowa and concluded that a relatively recent glacial advance existed in northwest Iowa that pre-dated the Late Wisconsin advance of the Des Moines Lobe. Ruhe (1950) reclassified the 'Iowan' of Carman (1931) and Leverett and Sardeson (1932) as the Tazewell drift and placed these deposits in the 'Tazewell' substage of the Wisconsin Episode after Leighton (1933). Even though Frye et al. (1968) removed the 'Tazewell' substage from the Wisconsin Stage, the use of Tazewell till continued well into the 1980s in Iowa (Hallberg and Kemmis, 1986). Prior (1976) termed this unique area in Iowa the Northwest Iowa Plains, and suggested a genetic relationship with northeast Iowa. Ruhe (1950) also initially believed that the region of northeast Iowa with subdued topography (the 'Iowan' surface) was the result of the Iowan glacier, although it would later be determined (Ruhe et al., 1968; Mason, 2015) to be an erosional surface and not a glacial feature. The genetic relationship between the

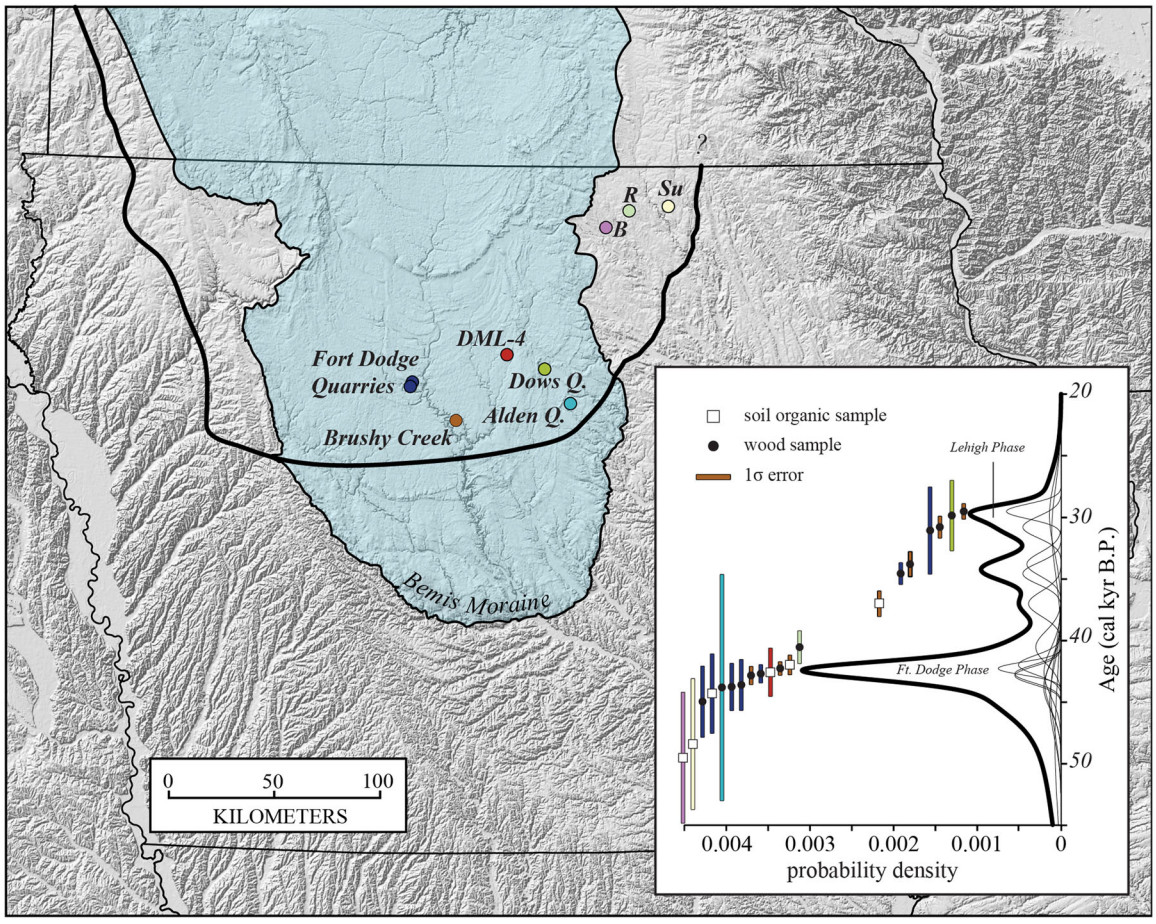

Figure 2. Locations of radiocarbon age samples for the Sheldon Creek Formation in Iowa. Inset shows the probability density curve for these dates and indicates two advances of the Sheldon Creek Formation, herein named the Lehigh and the Fort Dodge phases. Data are given in Table S1. [Color figure can be viewed at wileyonlinelibrary.com]

Northwest Iowa Plains and the 'Iowan' surface would not be established until many years later (Ruhe et al., 1968). Boellstorff (1978) and Hallberg (1980) later redefined the Pre-Illinoian stratigraphy, and Kemmis et al. (1981) laid the stratigraphic framework for the Late Wisconsinan Dows Formation. However, the 'Tazewell' was largely ignored, mostly due to a lack of accessible exposures and difficulty in differentiating the Dows and 'Tazewell' till units in drill cuttings.

While the concept of an early or mid-Wisconsinan or 'pre-late' Wisconsinan till sheet was introduced relatively early in the glacial studies of Iowa, these deposits did not receive serious investigation for decades. Lucas (1977) conducted a study of the sand fraction lithology in northwest Iowa that differentiated the Tazewell till sheet from the Pre-Illinoian deposits west of the Late Wisconsin terminal moraine. Studies by the IGS in the 1980s described a post Pre-Illinoian and pre-Late Wisconsinan till sheet in various core and outcrop descriptions, although the unit was often termed 'Tazewell?' or 'undifferentiated'. The name Sheldon Creek was sometimes informally applied to deposits in this stratigraphic position by the IGS. The first publication containing 'Sheldon Creek' is a stratigraphic column in *Landforms of Iowa* (Prior, 1991, p. 35), but no mention of the unit is made in the text. Bettis et al. (1996) first presented the Sheldon Creek Formation in more detail at an Iowa Geological Survey Bureau field trip and again at a North-Central Section GSA presentation (Bettis, 1997). Subsequent mapping projects by the IGS in north-central Iowa encountered these till deposits in several cores. The availability of new samples led Kilgore (2008) to conduct an updated sand fraction lithology study to compare these new samples with those of Lucas (1977). Not only did this work suggest that the Sheldon Creek Formation could be differentiated by these methods, but it also proposed that two Sheldon Creek Formation advances may be present.

Beginning in 2010, the IGS began surficial mapping east of the Late Wisconsin margin in conjunction with a soil survey update of Worth County by the Natural Resources Conservation Service (NRCS) to investigate several problematic soil series. Researchers questioned whether these soil units could be indicative of Sheldon Creek Formation till as the soil parent material. Over the course of the next 8 years, over 200 cores, typically ranging in depth between 7.5 and 15 m (25 and 49 ft), were drilled in north-central Iowa and the results (Fig. 3) determined that the Sheldon Creek boundary was much farther east than was previously mapped (Quade et al., 2012; Tassier-Surine et al., 2015, 2016; Kerr et al., 2018).

Chronology

The advent of radiocarbon dating provided much needed chronologic data. Ruhe (1969) produced a catalogue of radiocarbon ages which included two ages associated with till in western Iowa (Supporting Information Table S1). One of these samples (I-1864A and I-1864B) was collected in 1965 from a buried soil 1.9 m below the surface under a sequence of 0.7 m of silt (loess) over 0.8 m of calcareous diamicton (till) over 0.4 m of silt (loess). The entry in Ruhe (1969) noted a connection with the modern solum and the possibility of contamination from modern carbon. The total sample returned an age of 20.5 ± 0.4 ^{14}C ka (24.7 ± 0.5 cal ka BP) (I-1864A),

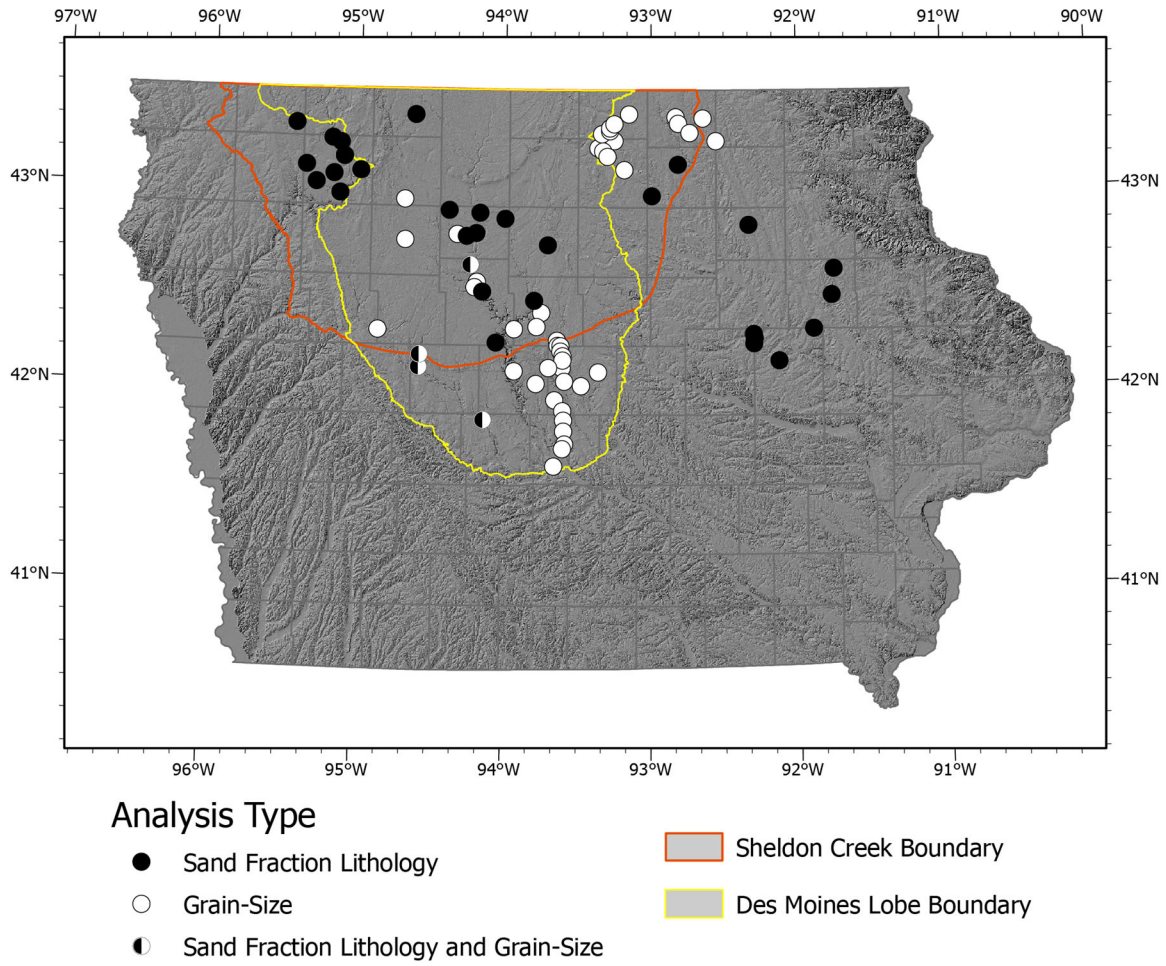

Figure 3. Map showing locations of samples collected for matrix grain-size and sand fraction lithology data (see Tables S2 and S3). [Color figure can be viewed at wileyonlinelibrary.com]

while the humic acid fraction from that sample returned an age of 13.4 ± 0.6 ^{14}C ka (16.1 ± 0.9 cal ka BP) (I-1864B). The other reported age, O-1325, was submitted in 1961 from wood found in an unweathered section of till. The sample had an age of 20.0 ± 0.8 ^{14}C ka (24.2 ± 0.9 cal ka BP). The ages were interpreted to relate to an ice advance during the middle of the Late Wisconsin (Table S1).

A later summary on Wisconsinan Glaciation by Hallberg and Kemmis (1986) cited two ages for the 'Tazewell', 20 and 25.5 ^{14}C ka BP, from Ruhe (1969) without sample identification. One of these ages matches O-1325 (20.0 ^{14}C ka BP), but there is no reported ^{14}C age in Ruhe (1969) that matches the 25.5 ^{14}C ka BP value. However, Hallberg and Kemmis (1986) also presented an age from wood collected in the early 1980s from the base of the' Tazewell' till which was buried by the Dows Formation of 25.4 ± 0.6 ^{14}C ka BP (29.8 ± 2.8 cal ka BP) (Beta-1764). Kerr et al. (2021) provide an in-depth examination of the chronology of the Sheldon Creek Formation.

Methods

Newly collected core and outcrop descriptions, matrix grain-size data, sand fraction lithology analysis and radiocarbon ages were synthesized with previous data and are presented here for the first time. All previous data were compiled into an integrated framework, and new laboratory data were collected by utilizing recently collected core data (Fig. 3). The primary focus of the new analyses was to fill gaps from previous studies, both geographic and stratigraphic. These new studies create a more robust data set to establish unit characteristics and assess spatial trends across the state. Data from the eastern flank of the Sheldon Creek Formation edge were compared with older data from till deposits beneath the Dows Formation to establish the presence of Sheldon Creek Formation materials to the east of the Late Wisconsin margin. Regional trends that may be related to source area were also evaluated.

Core and outcrop descriptions and sampling

More than 200 new cores were collected in north-central Iowa between 2010 and 2018 by IGS and NRCS personnel. Most cores were collected as continuous 5–7.5-cm (2–3-inch) diameter core and were typically 7.5–15 m (25–49 ft) in depth. The top 6 ft (solum) was described according to the NRCS *Field Book for Describing and Sampling Soils* (Schoeneberger et al., 2012), and sediments below the solum were described following IGS procedures and weathering zone terminology established by Hallberg (1978). Particular attention was paid to weathering indicators, such as oxidation and leaching status, as these represent disconformities between till units. Samples were typically collected at 1.5-m (5-ft) or smaller intervals and included each stratigraphic or lithologic horizon in the event a unit thickness was less than 1.5 m (5 ft) thick. Additional samples collected and stored as part of previous IGS activities were utilized throughout the project as necessary.

Grain-size

The majority of matrix grain-size analyses were completed at IGS facilities using pipette methods (Hallberg, 1978). Approximately 10 g of each sample was weighed, pretreated with acetic acid and hydrogen peroxide, and then heated to remove organics. The remaining sample was dispersed by adding sodium hexametaphosphate and shaking overnight. Pipette draws were completed for the clay (<2 μm) and fine silt (2–20 μm) fraction followed by drying, weighing and calculating their total proportion (%). Sand percent was determined by wet sieving and weighing the remaining sample to calculate the total percent. The remaining amount comprised the coarse silt (20–62 μm) component. Data were plotted on a ternary diagram (sand–silt–clay) overlain with the standard USDA Soil Survey classifications (Fig. 4). Additional data acquired from guidebooks were assumed to use pipette methods unless otherwise specified. Samples that were determined to be inter- or intra-till materials (sand bodies, loess, colluvium, lake deposits) or paleosols were not included in the overall averages. Samples with a stratigraphic assignment, but no lithologic designation, were included.

Sand fraction lithology

Methods for sand fraction lithology analysis were adapted from Hallberg's (1978) standard procedures. Care was taken to choose unaltered samples. Most samples utilized were unleached and either reduced or unoxidized to minimize the effects weathering could have had on the sand fraction. Approximately 150 g of bulk till from each sample location was ground and dry sieved through standard number 10 and 18 sieves (2 and 1 mm, respectively). The sieved samples were disaggregated by soaking in water and a small amount of sodium hexametaphosphate (4%) overnight. The sample was then wet sieved through standard number 10 and 18 sieves. Dried samples were split, and one-half was stained with a solution of alizarine red dye and 1.5% hydrochloric acid for easier identification of carbonate fragments. The stained sample was split to obtain a sample size of ~100–160 grains.

Using a binocular microscope and laboratory counter, sand grains were identified and tabulated into several groups: limestone, dolostone, shale, quartz/feldspar, chert, light-colored igneous/metamorphic, dark-colored igneous/metamorphic and other. Limestone and dolostone grains were differentiated by placing grains into 20% hydrochloric acid. Calcite grains effervesced rapidly, whereas dolostone grains produced a small trail of bubbles. To facilitate graphical analyses using ternary diagrams (Fig. 5), these tabulations were grouped into three major categories: carbonate, shale and crystalline.

Radiocarbon ages

Previously reported radiocarbon ages (Hallberg et al., 1981; Muhs et al., 2018; Kerr et al., 2021) were combined with newly collected ages (Supporting Information Table S1). Organic material was collected from both drill core and outcrop for this study. Samples were collected using metal tools and sent to the Penn State Radiocarbon lab (PSUAMS) for pretreatment and analyses. All ages were calibrated using Oxcal version 4.4, which uses the North American Calibration curve based on IntCal20 (Ramsey, 2009; Reimer et al., 2020). All age dates are reported as calibrated thousands of years before present (ka) unless noted otherwise. Snails collected are of the terrestrial genus *Succinea* which have been shown to yield reliable ^{14}C ages (Pigati et al., 2013).

Radiocarbon ages from organic material above a till act as a minimum age for timing of glacial activity, whereas ages returned from wood incorporated in glacial diamicton represent maximum ages of ice advance and those collected from the base of a till may be a close approximation for when ice advanced over an area (Lowell, 1995). Results from samples of soil organic material (humic acids) beneath units are also maximum ages, but are more problematic. Unlike wood, soil is an open system, and the returned ages represent a combination of accumulated organic material during the formation of the solum. The returned age, then, is probably

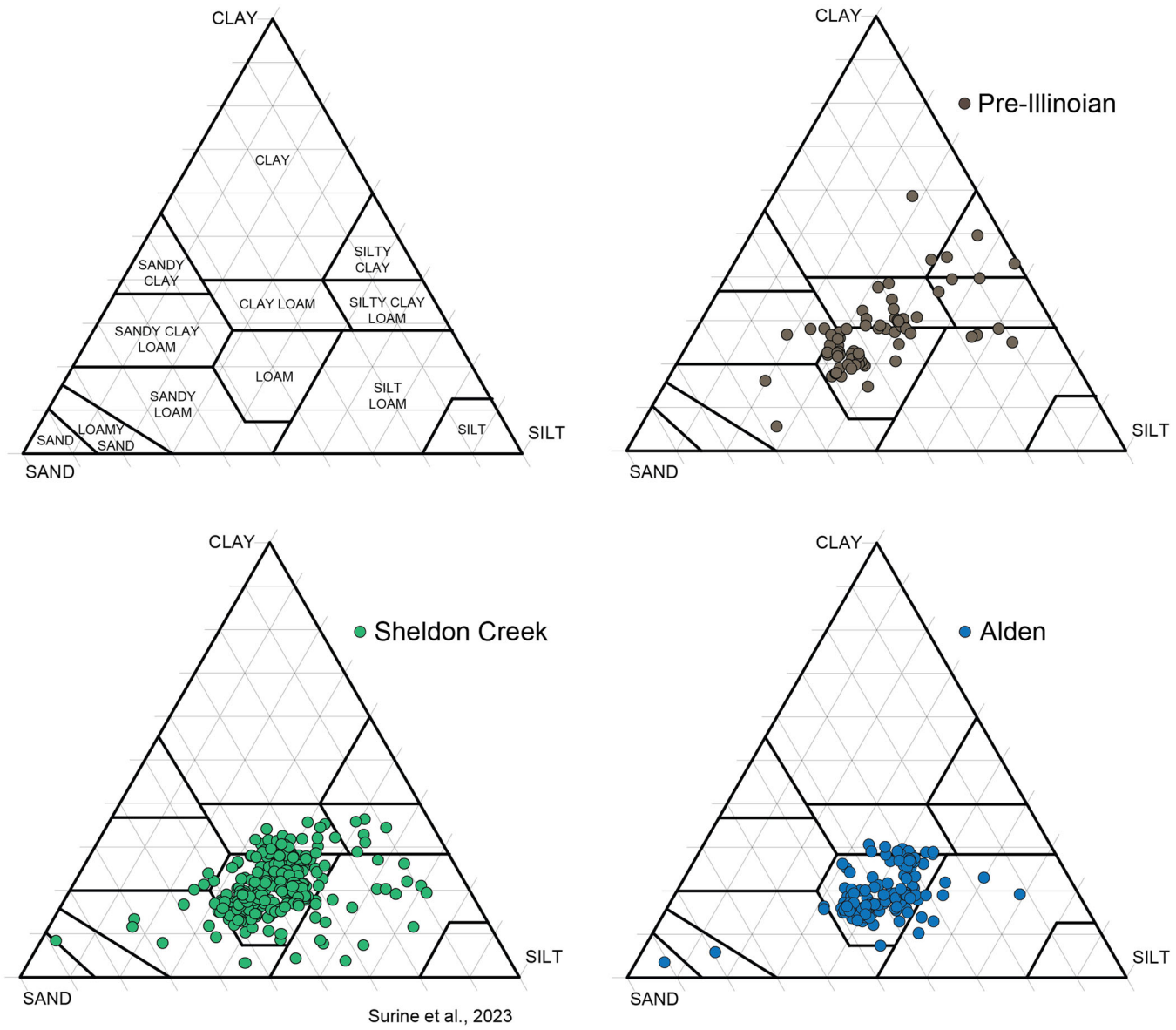

FIGURE 4. Ternary plots of matrix grain-size data (sand–silt–clay) for the Alden, Sheldon Creek and Pre-Illinoian glacial units (data are given in Table 0S2). The Alden and Sheldon Creek formation data generally overlap. The Sheldon Creek typically has more silt than the Pre-Illinoian till units, making this a key diagnostic for differentiating the two tills. [Color figure can be viewed at wileyonlinelibrary.com]

an overestimation of when the soil was disconnected from the atmosphere, i.e. potentially considerably older than the event which buried the soil (Wang et al., 1996). Samples between tills act as a maximum age for the upper till and a minimum age for the lower till.

Results

Matrix grain-size (sand–silt–clay) and sand fraction lithology (shale–crystalline–carbonate) were plotted on ternary diagrams to help determine if the basal unit from the three primary till advances in the study area could be differentiated. For matrix grain-size (Fig. 4), the Dows Formation Alden Member and the Sheldon Creek Formation generally overlap, whereas both show a higher component of silt and less clay than the Pre-Illinoian tills. The Dows Formation Alden Member averages 40 ± 10% sand, 41 ± 7% silt and 19 ± 5% clay and the Sheldon Creek Formation averages 37 ± 10% sand, 42 ± 9% silt and 21 ± 7% clay. The Pre-Illinoian formations (undifferentiated) collectively average 38 ± 13% sand, 36 ± 10% silt and 26 ± 7% clay.

Ternary plots of the three sand fraction lithology components illustrate that shale content is the primary component to differentiate these units (Fig. 5). The primary difference noted is the lack of shale in the Pre-Illinoian samples when compared with the Alden Member and the Sheldon Creek Formation. The majority of the Sheldon Creek Formation samples that are low in shale (less than 10%) are located on the eastern margin of the till advance. Pre-Illinoian tills average less than 2% shale, whereas the Alden Member (23 ± 11%) and Sheldon Creek Formation (16 ± 12%) shale averages are significantly higher. Sand fraction lithology percentages for the Sheldon Creek Formation were also plotted west-to-east and showed general trends for each component (Fig. 6). Shale percent decreased significantly in the eastern-most samples and the percent crystalline was lowest in the west.

Radiocarbon ages range from 49.9 to 29.5 ka and place the Sheldon Creek Formation within MIS 3 (Kerr et al., 2021). A probability density curve groups these ages into two

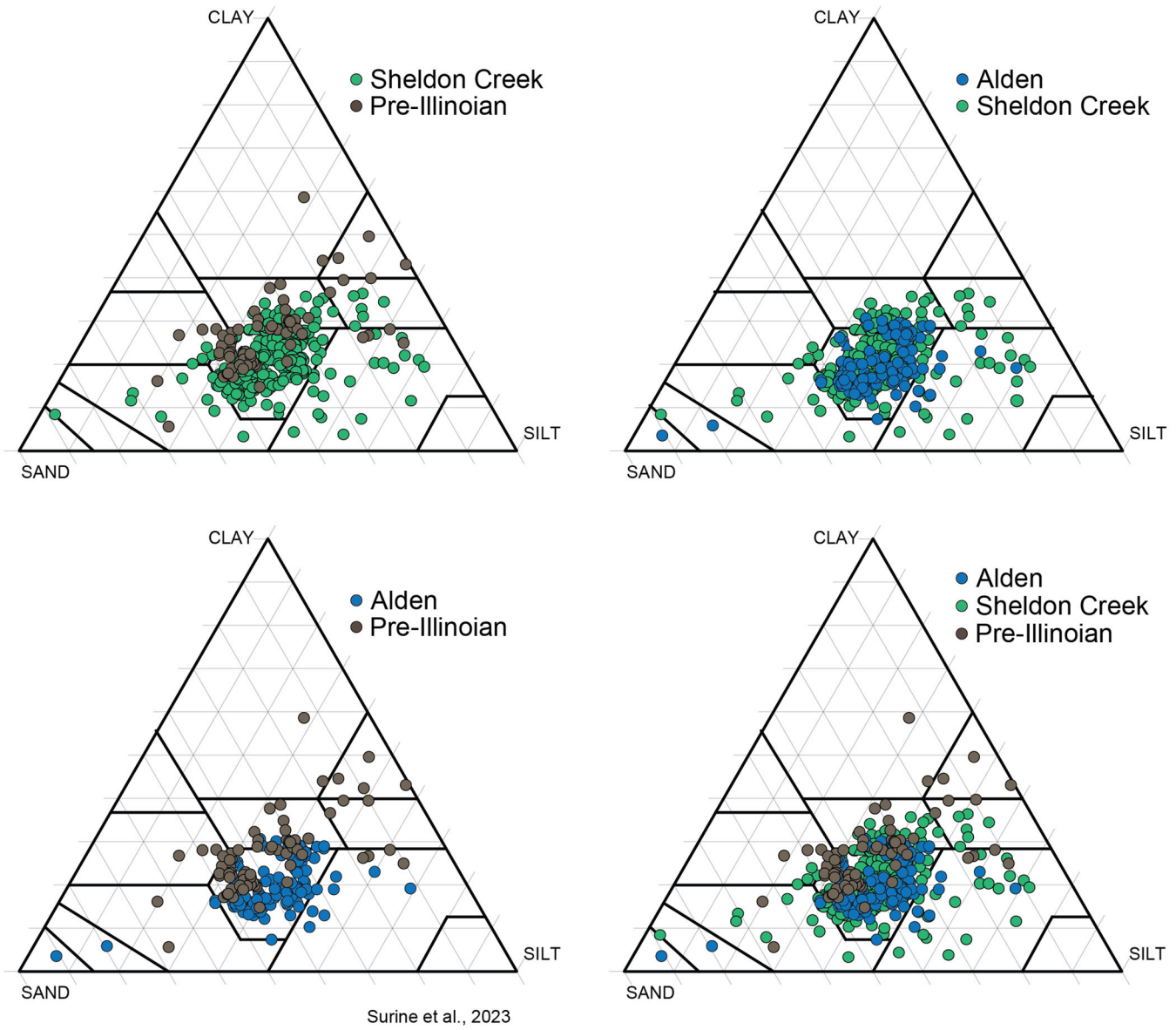

FIGURE 4. Continued.

categories, one ranging from 29 to 34 ka and the other from 40 to 49 ka. Age dates from between the two units (paleosol, organics, colluvium) indicate a minimum age of the underlying unit and a maximum age for the overlying unit. Two sites, Brushy Creek and National Gypsum, have more than one stratigraphic horizon with an age date from each (see Supporting Information Table S1), providing further evidence for two advances (Kerr et al., 2021).

Discussion

The data presented above help to clearly delineate the Sheldon Creek Formation as a separate stratigraphic unit that lies above the Pre-Illinoian and below the Dows Formation. Below, we present a formal description of the unit including correlation with other regional strata.

Unit description

The Sheldon Creek Formation is a glacial unit that is present in north-central Iowa. Where overlain by Late Wisconsinan Dows Formation deposits, the Sheldon Creek Formation is defined primarily by its relative stratigraphic position and secondarily by lithologic properties. In stratigraphically complete sections, the Sheldon Creek Formation is underlain by Pre-Illinoian tills and overlain by the Alden Member of the Dows Formation. These units are separated by paleosols, loess, sand and gravel, or weathering zones. Beyond the Late Wisconsin margins, where bracketing geologic units are absent, distinctive textural and lithologic signatures aid in distinguishing the Sheldon Creek Formation from the older Pre-Illinoian tills.

Type section and source of name

The Sheldon Creek Formation is named for Sheldon Creek in Franklin County, Iowa. The original holotype section was located in the Martin-Marietta Alden Quarry (formerly Weaver Construction Company Quarry) in Hardin County (42.513° N, 93.356° W). The original location is referenced in Kemmis et al. (1981), and the radiocarbon data sheets are in the IGS GeoSam database (W#66661 and W#91322), though this section has since been removed during quarry expansion.

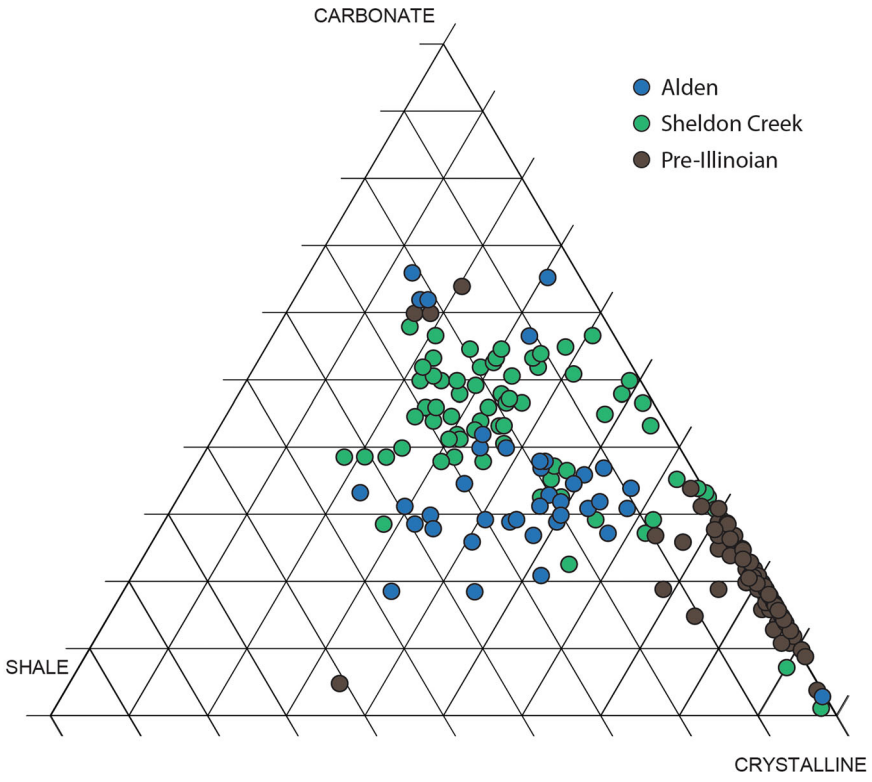

Figure 5. Ternary plots of the sand fraction lithology data separated into the shale, carbonate and crystalline fractions (data are given in Table S2). The lack of shale in the Pre-Illinoian till is a primary characteristic to distinguish these deposits from those of the Sheldon Creek Formation. [Color figure can be viewed at wileyonlinelibrary.com]

Here, we designate a nearby exposure (42.5091° N, 93.3629° W) within the same quarry as a neostratotype section.

As of June 2022, the Sheldon Creek Formation was still exposed and the bounding units were also present (Fig. 7, full description in the Supporting information Appendix). The Dows Formation, both the supraglacial Morgan Member and the basal Alden Member, are present at the top of the section. A 3-m deposit of Peoria Formation loess separates the Dows and Sheldon Creek formations. The thickness of the Peoria Formation is variable throughout the quarry face and generally decreases to the south. The current quarry face has nearly a 6-m section of reduced and unoxidized loam-textured Sheldon Creek Formation till. Intervening fine to coarse sand bodies are present in the lower part of the unit. The Sheldon Creek Formation overlies the Sangamon Geosol grading downward to unoxidized dense basal Pre-Illinoian till. The entire section is benched on bedrock of the Mississippian-aged Gilmore City Formation. The neostratotype section description from Alden Quarry for the Sheldon Creek Formation and its bounding units is as follows:

Depth (m)	Horizon/ W. Zone	Description
Peoria Formation		
5.36–8.33	OU	Dark greenish gray (10 G 4/1) silt loam; massive to stratified; friable; common fine Mn accumulations, along stratifications and throughout; *Succinea* snails from approximately 6.5 to 8.33 m depth; strongly effervescent; clear boundary
Sheldon Creek Formation		
8.33–10.56	RU	Dark grayish brown (2.5Y 4/2) grading downward to dark greenish gray (10Y 4/1) loam with gravel and pebbles; top 1 m mixing zone with above unit; massive; many fine to medium dark yellowish brown (10YR 3/6) Fe concentrations, decreasing with depth; strongly effervescent; firm; gradual boundary
10.56–14.2	RU	Dark gray (2.5Y 4/1) loam with gravel and clasts generally 1–2 in; discrete zones of stratified dark yellowish brown (10YR 4/6) to light olive brown (2.5Y 5/4) fine to coarse sand and bodies of fine to medium sand, dissipate to south, probably glaciofluvial deposits; few fine light olive brown (2.5Y 5/4) Fe concentrations; strongly effervescent; slightly firm; abrupt boundary
Sangamon Geosol		
14.2–14.48	4Bt1b	Very dark gray (5Y 3/1) clay loam, no gravel or pebble fraction; moderate fine subangular blocky structure; firm; leached; gradual boundary
14.48–14.68	4Bt2b	Dark olive gray (5Y 3/2) clay loam, trace fine sand; strong fine subangular blocky structure; moderately firm; leached; gradual boundary
14.68-17.74	4Bt3b	Olive brown (2.5Y 4/3) clay loam with common fine sand; strong fine angular blocky structure; firm; leached; clear boundary

Unit characteristics

The Sheldon Creek Formation consists of glacial deposits, predominantly till, but may also include colluvial, fluvial or lake deposits. Where unweathered, it is a massive uniform gray loam diamicton of moderate density. The unit is normally massive, but stratified fine to medium sand or silt seams may be present. Where weathered or reworked, it may exhibit a wide range of characteristics, and is usually brown to

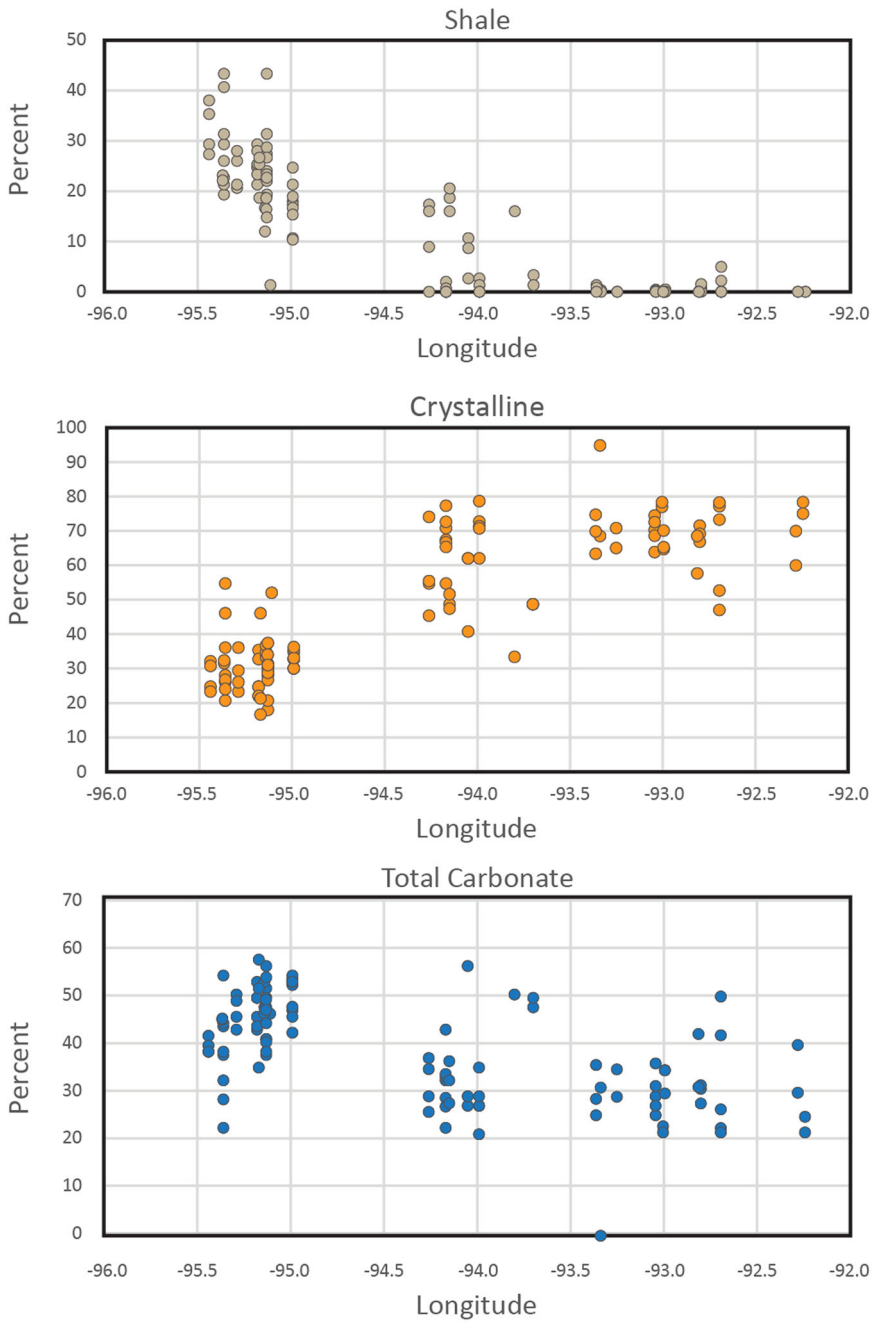

Figure 6. Sand fraction lithology data for the Sheldon Creek Formation indicates a geographic shift with a greater shale component to the west that decreases to the east. During MIS 3 the ice path picked up shale from the Manitoba Escarpment Cretaceous deposits on its western margin. [Color figure can be viewed at wileyonlinelibrary.com]

yellow-brown, lower density, may be poorly consolidated, and may be stratified with significant sand and gravel bodies. The till is generally thought to be a basal till, but the presence of sand and gravel sequences in the upper part of the unit could indicate a supraglacial facies instead of the current interpretation of colluvial deposits.

The matrix grain-size averages 37 ± 10% sand, 42 ± 9% silt and 21 ± 7% clay (Fig. 4; Supporting Information Table S2). The sand fraction lithology averages 40 ± 13% carbonate, 16 ± 12% shale and 45 ± 21% crystalline grains (Fig. 5; Table S3). Results are limited, but the clay mineralogy of the fine-grained matrix of massive Sheldon Creek Formation diamictons average 65 ± 4% expandables, 18 ± 2% illite and 18 ± 2% kaolinite plus chlorite (Lucas, 1977). For comparison, the clay-mineral composition of 15 Pierre Shale fragments taken from the Dows Formation is 67 ± 3% expandables, 27 ± 3% illite and 6 ± 2% kaolinite plus chlorite (Kemmis et al., 1981).

Relative sand fraction lithology percentages of the Sheldon Creek Formation also demonstrate a clear west to east trend, exhibiting a significant decrease in shale (Fig. 6). Shale clasts are far less common, or entirely absent, in the easternmost deposits. The decrease in shale from west to east is probably related to the flow path of the Middle Wisconsin glacial advance where ice straddled the zero-edge of a shale unit up ice from Iowa. The Manitoba Escarpment, formed from Cretaceous marine units, includes shales (Muehlbauer et al., 2014) and, as such, the Sheldon Creek Formation tills picked up Cretaceous clasts, which would have been more common along the western margin. Paleozoic carbonates comprise the bedrock surface east of this regional topographic high.

Contacts

The Sheldon Creek Formation most typically unconformably overlies older Quaternary materials including Pre-Illinoian till of the Wolf Creek or Alburnett formations, the Sangamon Geosol, or other bounding units, such as sand and gravel, colluvial and/or loess deposits. Where bedrock is shallow, the

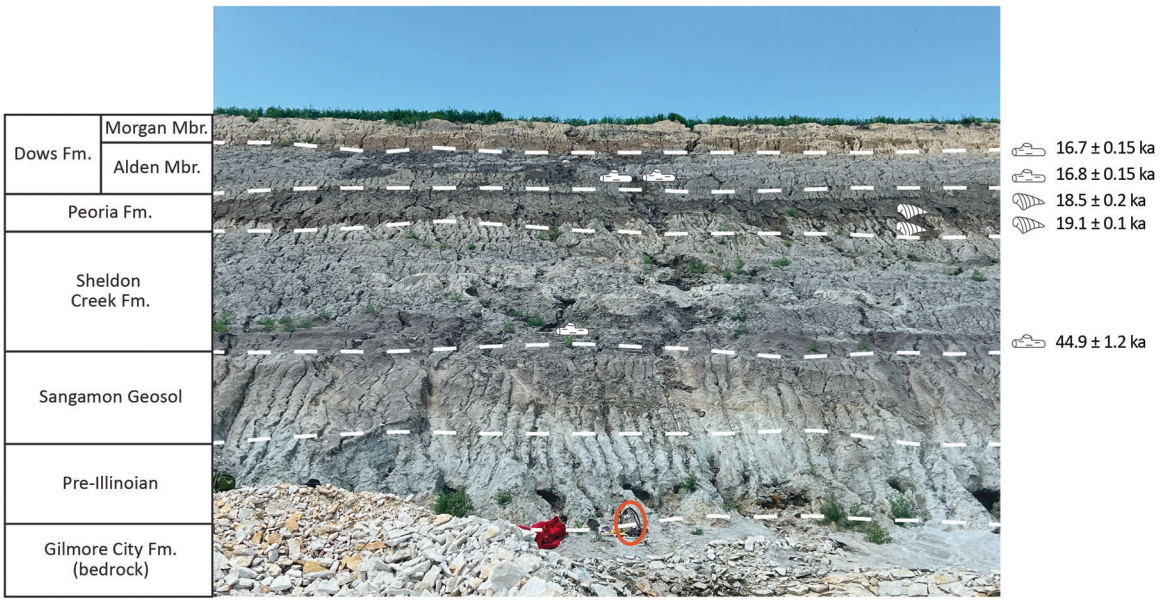

Figure 7. Neostratotype section described at Alden Quarry in July 2022. Stratigraphic units identified include (oldest to youngest) Pre-Illinoian till, Sangamon Geosol, Sheldon Creek Formation, Peoria Formation, and Dows Formation including both the Alden and Morgan members. Unit boundaries are delineated with white dashed lines. A backpack (circled in orange) provides the scale. Locations of materials collected for age dating and corresponding radiocarbon ages are designated on the figure (wood and shells). [Color figure can be viewed at wileyonlinelibrary.com]

Sheldon Creek Formation may overlie regional bedrock units, which may include Cretaceous shale, Pennsylvanian sedimentary rocks, or Mississippian and Devonian carbonates.

Depending on the geographic location, the Sheldon Creek Formation is overlain by either younger Wisconsinan deposits or Iowan Erosion Surface sediments. In north-central Iowa, the Sheldon Creek is beneath the Late Wisconsinan Dows Formation deposits, and to the east and west it is the first till deposit encountered at the surface (Fig. 1). Behind the Late Wisconsin margin, the Sheldon Creek Formation is most commonly overlain by the Dows Formation, but in isolated cores and outcrops the Peoria Formation loess has been identified between the units (Fig. 7). To the west of the Late Wisconsin moraine, the Sheldon Creek Formation is overlain by Peoria Formation loess, typically 2–3 m (6–10 ft) thick. To the east of the Late Wisconsin margin, erosion or nondeposition results in very thin or absent Peoria Formation eolian materials on top of the Sheldon Creek Formation, and in many cases the Sheldon Creek Formation is the surficial unit. Only in isolated areas to the east of the Late Wisconsin moraine is the Sheldon Creek Formation overlain by greater than 1 m (3 ft) of Peoria silt or sand. More commonly, the Sheldon Creek Formation is mantled with colluvial deposits related to the Iowan Surface. These materials range from poorly consolidated and reworked materials with a loam to sandy loam texture, to a relatively thick (7 m) sequence of poorly sorted sand and gravel.

Differentiation from other units

The Sheldon Creek Formation and the younger Dows Formation have similar lithologic characteristics, presumably due to a similar source area and nature of glaciation, but there are slight differences in their properties. The Dows Formation is subdivided into the Morgan and Alden members, which have different physical properties from each other due to their mode of deposition (Kemmis et al., 1991; Bettis et al., 1996). The Morgan Member is a supraglacial facies and contains significant sand bodies that are often stratified, and as such, is unlikely to be confused with the Sheldon Creek Formation. In contrast, the Alden Member is a uniform, dense, basal till unit that may be confused with the Sheldon Creek Formation without stratigraphic context. Both the Alden Member and Sheldon Creek Formation average a loam texture and have a similar density. The Sheldon Creek Formation has slightly higher silt and clay content whereas the Alden Member is higher in sand (Fig. 4). The sand fraction lithology shows higher carbonate percentages for the Sheldon Creek Formation (Fig. 5). Although the physical properties provide some evidence for variation between the units, they are primarily differentiated based on stratigraphic superposition. On the Late Wisconsin till plain, the Dows Formation is the till at the surface, and it overlies the Sheldon Creek Formation. They may be separated by the Peoria loess, a weathering horizon (paleosol), or in some cases a sand body. Given that the Alden Member is the unit most likely to be mistaken for the Sheldon Creek Formation, their stratigraphic superposition is an extremely important component in differentiating these units.

Differentiation of the Sheldon Creek from the underlying Pre-Illinoian glacial deposits can be determined by both chemical and physical properties, in addition to stratigraphic superposition. The Pre-Illinoian deposits are generally denser and have a much thicker and more developed weathering profile. Redoximorphic features and secondary carbonate are common. When present, these characteristics may allow the two tills to be differentiated relatively easily in the field. The Pre-Illinoian tills also have a higher clay percentage in the matrix, while the Sheldon Creek Formation has a greater silt content. Compared to the Wisconsinan tills, the Pre-Illinoian deposits have little to no shale in the sand fraction and a much lower carbonate percentage (Figs. 4 and 5).

Regional extent and thickness

The regional extent of the Sheldon Creek Formation roughly mimics the shape of the Late Wisconsin Episode ice advance in Iowa but does not extend as far south. The maximum southern extent is difficult to determine absolutely as it is overlain by the Dows Formation, and only a limited number of drill cores are available to constrain this boundary. IGS drilling records indicate that the maximum southern extent roughly coincides with the Altamont I moraine, with a southern terminus crossing 42° N (Fig. 3).

In quarry exposures the Sheldon Creek Formation ranges from 6 to 10 m (20–33 ft) thick. Due to the limited number of complete penetrations in drilling records, the total and average thickness are difficult to ascertain, but range from 6 to 23 m (20–75 ft) in thickness in most localities below the Late Wisconsin Dows Formation. To the west, the Sheldon Creek Formation generally ranges in thickness from 5 to 18 m (16–60 ft) and reached a maximum thickness over 30 m (98 ft) in one core located in northwest Iowa. When present, the thickness of the Sheldon Creek Formation east of the Late Wisconsin moraine ranges in thickness from 7 to 15 m (23–49 ft). The distribution to the north is assumed to continue into Minnesota, but is difficult to establish due to thick Late Wisconsinan till cover in Minnesota and no reported ages (Meyer and Knaeble, 1998, Johnson et al., 2016; Lusardi et al., 2019; Gowan, 2020a; 2020a).

The Sheldon Creek Formation deposits extend beyond the Late Wisconsin boundary to both the west and east, with a maximum extent ranging from 92.7° to 96.3° W. It is mostly continuous in upland positions and is often mantled with a thin (2–3 m) layer of Peoria Formation loess. The boundary to the west has been little changed from the extent given by Ruhe (1950, 1969). This also correlates with the thickness of weathered till noted in the IGS well record database. Older Pre-Illinoian tills have been exposed on the surface for longer and therefore are expected to have a much thicker oxidized zone. Well drilling records west of the Sheldon Creek Formation boundary generally have a weathered horizon greater than 15 m (49 ft).

The eastern margin defined by Hallberg et al. (1991) roughly coincides with the eastern margin of the Late Wisconsin terminus. This boundary has recently been redefined by IGS STATEMAP county-scale surficial mapping projects (Quade et al., 2012; Tassier-Surine et al., 2015; Tassier- Surine et al., 2016; Kerr et al., 2018). The Sheldon Creek Formation is the first till exposed at the surface to the east of the Late Wisconsin till plain. However, due to significant areas of shallow bedrock and the influence of periglacial erosion in northeast Iowa during the Late Wisconsin, its distribution is not continuous. Erosion has erased any clear ice-marginal geomorphic expression (moraine deposits) that may have been present on the eastern margin. Therefore, stream drainage alignment and significant sand and gravel bodies, presumed to be outwash, have been utilized to refine the boundary that was established with the stratigraphic framework from drill cores.

Chronology

The combination of 22 finite radiocarbon ages presented in Kerr et al. (2021) and those in this study (Supporting Information Table S1 and Fig. 2) indicate that the Sheldon Creek Formation was deposited during the Middle Wisconsin (MIS 3 and possibly extending into early MIS 2). Maximum radiocarbon ages cluster into two groups: one with ages ranging from 42 to 50 ka that are associated with the Fort Dodge Phase, and a second group with ages from 35 to 30 ka that comprise the Lehigh Phase. The younger Lehigh Phase may have spanned into early MIS 2, and the lack of identified datable material does not remove the possibility of deposition during later portions of MIS 2.

New minimum ages for the Sheldon Creek Formation and maximum ages for the Dows Formation were collected at the Alden Quarry as part of this project (Fig. 7). Two *Succinea* snail shells were collected from Peoria Formation loess which lies disconformably above the Sheldon Creek Formation and beneath the Dows Formation. The gastropod shells returned ages of 19.1 ± 0.1 cal ka BP (PSUAMS-11737) and 18.5 ± 0.2 cal ka BP (PSUAMS-11736). Samples from two logs found at the Dows and Peoria formation interface had ages of 16.8 ± 0.15 cal ka BP (PSUAMS-11734) and 16.7 ± 0.15 cal ka BP (PSUAMS-11735). The logs were part of a zone that included multiple wood fragments which had no level of peatification and were probably not far traveled.

Radiocarbon ages presented in Kerr et al. (2021) and those in this study (Supporting Information Table S1 and Fig. 2) disagree with interpretations and validity of two ages in Ruhe (1969). The stratigraphic interpretation described for the I-1864A and I-1864B ages raises doubts about this sample being from the Sheldon Creek Formation The thin diamicton described between the two loess units above the buried A horizon is interpreted by the authors to be reworked, colluviated sediments, due to periglacial conditions during the Late Wisconsin in the study area (Kerr, 2022). In contrast, the suite of ages collected after 1980 indicate that the Sheldon Creek Formation was deposited during the Middle Wisconsin (MIS 3) rather than the Late Wisconsin (MIS 2). Maximum radiocarbon ages from wood within the Sheldon Creek Formation till and soils buried by the till cluster into two groups: one with ages ranging from 42 to 50 ka and a second group with ages from 35 to 30 ka. The older cluster is associated with the Fort Dodge Phase and indicates ice advanced over the sites around 42 ka, while the younger grouping places Lehigh Phase ice in Iowa at 30 ka (Kerr et al., 2021). An organic-rich silt, considered to be in a weakly expressed soil, from the Brushy Creek site is a bounding age of 37.0 ± 1 ka. This indicates a period of subaerial exposure between the two advances. The Fort Dodge and Lehigh phases may correlate with Heinrich events 3 and 5 (Hemming, 2004; Rasmussen et al., 2006; Cheng et al., 2021; Denton et al., 2022).

There is a paucity of radiocarbon ages from organic material in till in Iowa during the Last Glacial Maximum. This seeming gap spans from 30 to 17 ka, i.e. between the Lehigh Phase and the rapid advance of the Des Moines Lobe (Heath, et al., 2018; Muhs et al., 2018; Kerr et al., 2021). The few minimum ages for the Sheldon Creek Formation that are reported, such as 19 ka from the Alden Quarry, could indicate that ice was in Iowa across the MIS 2/3 boundary, potentially well into MIS 2. However, an alternative explanation is that there was no ice present in Iowa to deposit till during the glacial maximum.This interpretation is supported by the sediments which mantle the Sheldon Creek Formation beyond the younger MIS 2 margin. Periglacially derived materials generated during the Late Wisconsin typically overlie the Middle Wisconsinan tills both to the east and west of the Des Moines Lobe margin (Quade et al., 2012; Tassier-Surine et al., 2015; Tassier- Surine et al., 2016; Kerr et al., 2018, Kerr, 2022). Other indicators of relic frozen ground, such as ice wedge casts and pingo scars, can be found in this region. These periglacial sediments and landforms cannot have formed under an ice sheet, i.e. they require a period of subaerial exposure (French, 2007). In addition, the landscape-wide mass wasting also eroded the Farmdale and Sangamon geosols (Mason, 2015).

Correlation with other units

The Sheldon Creek Formation correlates with the Verdi Member and/or Moland Member of the New Ulm Formation in Minnesota (Patterson, 1997; Lusardi et al., 2019). The Toronto Till in South Dakota may also correlate with the Sheldon Creek Formation. Radiocarbon ages from two wood samples within the Toronto Till returned ages of 34.2 cal ka BP (GX-14675) and 30.4 cal ka BP (GX-2864) (Gilbertson, 1990) and suggest the Toronto Till may correlate with the Lehigh Phase of the Sheldon Creek Formation. Limited age dates are available from Wisconsin for this time period, but may suggest equivalent deposits from an Early to Middle Wisconsin ice advance (Syverson and Colgan, 2011;

Syverson & Clayton, Attig, et al., 2011; Carlson et al., 2018; Ceperley et al., 2019). The Sheldon Creek or its equivalent has not been identified in the adjacent states of Illinois (Curry and Pavich, 1996), Nebraska or Missouri (Swinehart et al., 1994; Martin et al., 2004; Roy et al., 2004).

Conclusions

The data presented herein are used to formally name the Sheldon Creek Formation. The combination of stratigraphic, chronologic, distribution and lithologic data demonstrates that the Sheldon Creek Formation can be differentiated from the overlying Late Wisconsinan Dows Formation and the underlying Pre-Illinoian till deposits. Physical characteristics, primarily matrix grain-size, sand fraction lithology and density, are used to distinguish the Sheldon Creek Formation from the underlying Pre-Illinoian tills. Ice that deposited the overlying Dows Formation is thought to have a similar provenance to the Sheldon Creek Formation, and therefore, the physical attributes are similar. The presence of Cretaceous shale clasts indicates that western sourced ice from the Keewatin sector advanced south into Iowa during this time. Stratigraphic parameters are utilized to differentiate the Dows and Sheldon Creek formations. Radiocarbon ages establish that two MIS 3 advances of the Sheldon Creek Formation occurred, near 42 and 30 ka. Identification of an MIS 3 age ice advance into Iowa has significant implications for ice sheet reconstructions and climate interpretations during the Middle Wisconsin and provides a source for regional loess and outwash.

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Conflicts of interest—The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

The data that supports the findings of this study are available in the supplementary material of this article

Supporting information

Additional supporting information can be found in the online version of this article.

Table S1. Radiocarbon ages for the Sheldon Creek Formation deposits and upper bounding Late Wisconsin units in Iowa. Ages were calibrated using Oxcal version 4.4 using the North American Calibration curve base on IntCal20.

Table S2. Matrix grain-size data (sand–silt–clay) compiled for the Alden Member, Sheldon Creek Formation and Pre-Illinoian deposits.

Table S3. Sand fraction lithology data (shale–carbonate–crystalline) for the Alden Member, Sheldon Creek Formation and Pre-Illinoian deposits.

Supporting information.

Abbreviations. IGS, Iowa Geological Survey; MIS, Marine Isotope Stage; NRCS, Natural Resources Conservation Service.

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