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Strange Stones of Skull Creek: Basalt Glacial Erratics and Omars in Eastern Nebraska

Robert M. Joeckel
University of Nebraska-Lincoln, rjoeckel3@unl.edu

Jesse T. Korus
University of Nebraska-Lincoln, jkorus3@unl.edu

Judith Turk
University of Nebraska-Lincoln, jturk3@unl.edu

C. C. Arps
Lincoln, NE

N. V. Arps
Columbus, NE

See next page for additional authors

Authors
Robert M. Joeckel, Jesse T. Korus, Judith Turk, C. C. Arps, N. V. Arps, and Leslie M. Howard

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R. M. Joeckel, J. T. Korus, J. K. Turk, C. C. Arps, N. V. Arps, and L. M. Howard

ABSTRACT—We describe unusual stream-reworked glacially transported rocks (erratics) from a locality 50 km east of the limit of all pre-Illinoian (pre-190 ka) Pleistocene glaciations in the central USA. Almost all these erratics consist of the igneous rock basalt, and of those, the vast majority have at least one flat, smooth face. Some have two or more such faces that meet at obtuse angles along one or more well-defined, straight edges. We attribute these features, as well as laminations, plumose marks, and other features, to columnar jointing in ancient lava flows and shallow intrusions. The most likely source of these erratics is the Lake Superior region. After the Laurentide Ice Sheet deposited them, the erratics experienced at least one episode of erosion and deposition in local stream sediments as the regional landscape evolved during the Middle Pleistocene to Holocene times. Before it found its way into Skull Creek, one of the basalt erratics was polished and reshaped as a ventifact by sediment-laden Pleistocene winds as it lay exposed on an ancient land surface. We also found four examples of omars: very distinctive erratics that eroded from outcrops in Hudson Bay and transported 2,100 km into the study area.

Key Words: abrasion, columnar jointing, Nebraska Bohemian Alps, Pleistocene, pre-Illinoian glaciations

Introduction

We discuss two extraordinary types of glacially transported stones (erratics) discovered by two of us (CCA and NVA) in eastern Nebraska (Figs. 1A, 2). One type, basalt erratics, commonly bears markedly flat, planar surfaces. In many examples of this type, two such surfaces intersect, in several instances at an obtuse angle, to form a well-defined straight edge characteristic of columnar jointing. We propose that these and other attributes originated in the distant outcrops from which the erratics were eroded. We also identify a very few unusual erratics called "omars" that have attracted international attention (e.g., Prest 1990; Prest, Donaldson, and Mooers 2000; Cummings and Russell 2018). Both types of erratics originated far outside present Nebraska. The preservation of columnar jointing and associated features in basalt erratics that traveled hundreds of kilometers in potentially abrasive glacial environments is unexpected. To the extent of our knowledge, ours is the first account of basalt erratics with common relics of columnar jointing in the Midwest, if not in the entire eastern half of the USA. This article is the first full documentation of omars in Nebraska, detailing the southernmost examples of those erratics from west of the Mississippi River, and among the southernmost occurrences in North America (Prest, Donaldson, and Mooers 2000, fig. 2). The erratics we describe provide insights into large-scale flow patterns and sediment transport in the pre-Illinoian Laurentide Ice Sheet.

Glacial Erratics: Iceborne Insights

Glacial erratics are exotic rocks that were eroded by a glacier, transported long distances, and then deposited in a place where they contrast sharply with the local bedrock. The 19th-century recognition of ancient erratics—and of the ancient glaciers that bore them—

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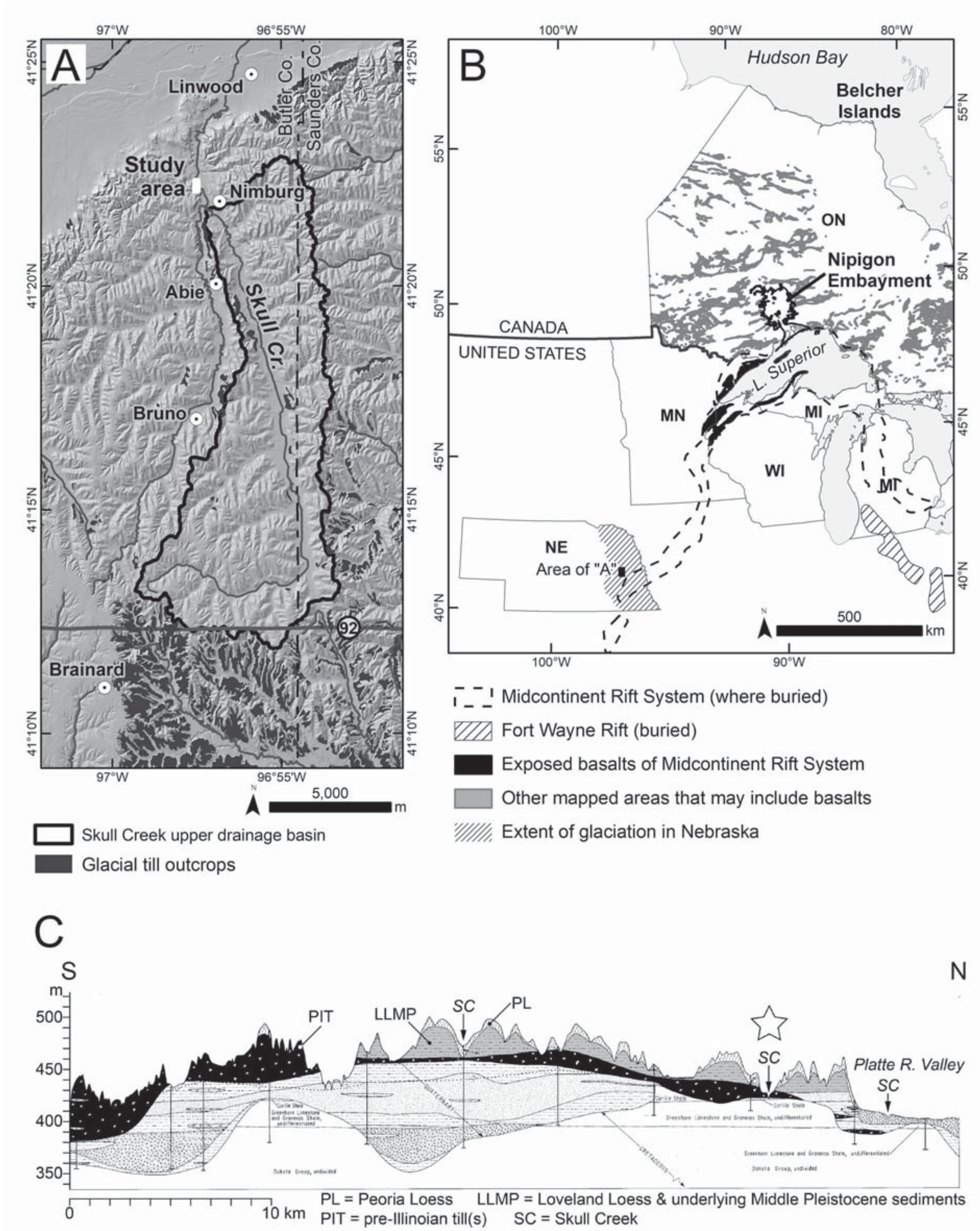

Fig. 1. ***A***, Map of the study area in Butler County, Nebraska. Note that there are only a few till outcrops (i.e., areas of glacial till soil parent material; USDA NRCS n.d.) in the upper basin of Skull Creek, but till underlies surficial loess deposits throughout the area. Skull Creek has eroded into till upstream of the study area, and Illinoian alluvium in the stream's banks contains erratics that were eroded and redeposited many tens of thousands of years ago, and which are now being reworked again into the modern creek (Fig. 2). ***B***, Map showing probable origin of basalt erratics in exposed basalts and associated rocks of the Midcontinent Rift System around present Lake Superior (after Morey and Van Schmus 1988), basalts and related igneous of similar age in the Nipigon Embayment, possible locations of other basalt bedrock in Ontario (Ontario Ministry of Energy, Northern Development and Mines n.d.), and origin of omars around the Belcher Islands in Hudson Bay (after Prest, Donaldson, and Mooers 2000). Light gray areas mapped in Ontario as possible locations of basalt bedrock are areas that include a variety of multiple other rock types as well (Ontario Ministry of Energy, Northern Development and Mines n.d.). ***C***, Geologic cross section of eastern Butler County, modified from Ginsberg (1983), showing the widespread distribution of glacial till under the area and the entrenchment of Skull Creek (SC, under star) into pre-Illinoian till a short distance upstream of the study area.

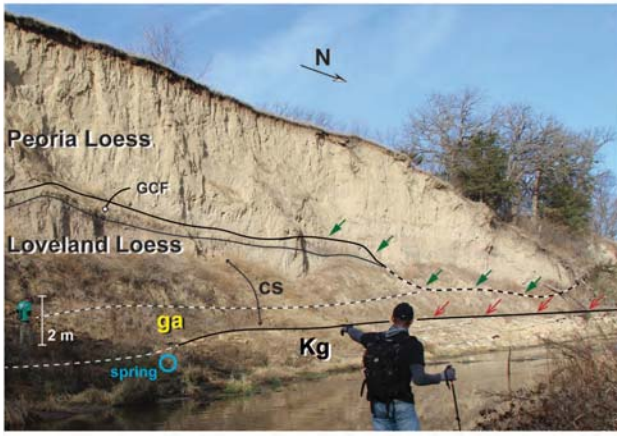

Fig. 2. Skull Creek and its banks in the study area, northeastern Butler County, Nebraska, with C. C. Arps in foreground and N. V. Arps in the background at left. Wisconsinan Peoria Loess and Gilman Canyon Formation (GCF) overlie Illinoian Loveland Loess and gravelly alluvium containing reworked glacial erratics (ga). Basal Loveland Loess and gravelly alluvium are mostly under a covered slope (cs). A spring emerges near the top of local bedrock, the Cretaceous Greenhorn Limestone (Kg). Note ancient slope eroded on Gilman Canyon Formation and Loveland Loess (green arrows) and subtle angular unconformity atop the Greenhorn Limestone (red arrows). Reworked glacial erratics are found in the creek's bed and in the Illinoian gravelly alluvium in its banks.

was a major scientific epiphany (Hansen 1970; Colgan 2009; Woodward 2014). Ice sheets in the Northern Hemisphere translocated rocks, minerals, and fossils during the Pleistocene Epoch (2.588 Ma–11.7 ka). Interesting examples include diamonds, native silver, native copper, bauxite, and fossils of long-extinct reptiles (Hobbs 1899; Glock 1935; Schwarcz 1965; Kaye 1967; Pabian 1976; Dort 2006; Anderson and Cutler Prior 2014; Taylor and Cruickshank 1993; Rosemeyer 2016; Sachs et al. 2016). The distributions of materials carried by ice sheets reveal ice-flow patterns and the locations of valuable deposits of base metals, diamonds, gold, niobium, rare-earth elements, and other commodities (McClenaghan and Paulen 2017; Cummings and Russell 2018). Erratics—many of igneous and metamorphic rock types that do not crop out in the state (Joeckel et al. 2018)—can be found across the glaciated eastern one-quarter of Nebraska (Swinehart et al. 1994). In more than a century and a half of geologic investigation, however, very little research has been done on erratics in Nebraska.

Columnar Jointing: Diabolical Deed?

Many of the basalt erratics that we describe bear evidence for joints, some of which we interpret more specifically as products of columnar jointing. Joints are innumerable, nearly ubiquitous, and frequently systematic fractures that form in bodies of rock subjected to tensile stresses. Their presence is an important factor in the breakup and breakdown of rock. Columnar jointing is a visually striking and very special case in which many parallel, straight to curved, prismatic columns of rock form, usually within igneous rocks such as ancient lava flows (Figs. 3, 4). Rock columns, which are tens of centimeters to several meters in width, can attain tens of meters in height, and are separated by polygonal networks of vertical, subvertical, and even curved joints (Figs. 3, 4). Individual columns are irregularly polygonal in cross section (Fig. 3). Perhaps half of all columns have six sides, but five- and seven-sided columns are common, and three-, four-, eight-, and nine-sided columns may be present as well (Spry 1990; Masaitis 1999; Hetényi et al. 2012; Phillips et al. 2013; Balen and Petrinec 2014). Columnar-joint faces are comparatively smooth planes, but they also bear low-relief ornamentation, breaks, and/or parallel bands ("striations" or "chisel-marks" of James 1920; Tomkieff 1940; Ryan and Sammis 1978; DeGraff and Aydin 1987; Tanner 2013; Sheth 2018, 114–24), which formed with the joints themselves.

Columnar jointing exists on all the continents, many oceanic islands, and even on Mars (Milazzo et al. 2009). It is common in extrusive igneous rocks that originated as lava erupted at the land surface and in some shallow intrusive rocks that formed below the surface; it can also be found in rocks derived from volcanic ashes (e.g., Wright et al. 2011; Lee et al. 2015). Columnar jointing is commonest in comparatively low-silica igneous rocks such as basalt and diabase (= dolerite outside North America) and is less common in rocks that contain more silica, such as andesites and rhyolites (e.g., Spörli and Rowland 2006; Wright et al. 2011; Balen and Petrinec 2014). There is widespread agreement (e.g., Spry 1962; Kattenhorn and Schaefer 2008; Goehring, Mahadevan, and Morris 2009; Hetényi et al. 2012; Goehring 2013) that rock columns form in response to stresses generated when molten rock or hot ejecta cools and contracts, particularly in the x–y plane (Fig. 3, inset), although alternative hypotheses exist (e.g., Kantha 1981; Gilman 2009; Guy 2010). Thermal stresses in a hot rock mass cause the joints to form and extend along paths perpendicular (i.e., parallel to the z–axis in Fig. 3, inset) to its cooler top and bottom surfaces (Goehring 2013). Rarely, columnar structures also form in sedimentary rocks (Spry and Solomon 1964; Young 2008; Gomes et al. 2014; Weinberger and Burg 2019).

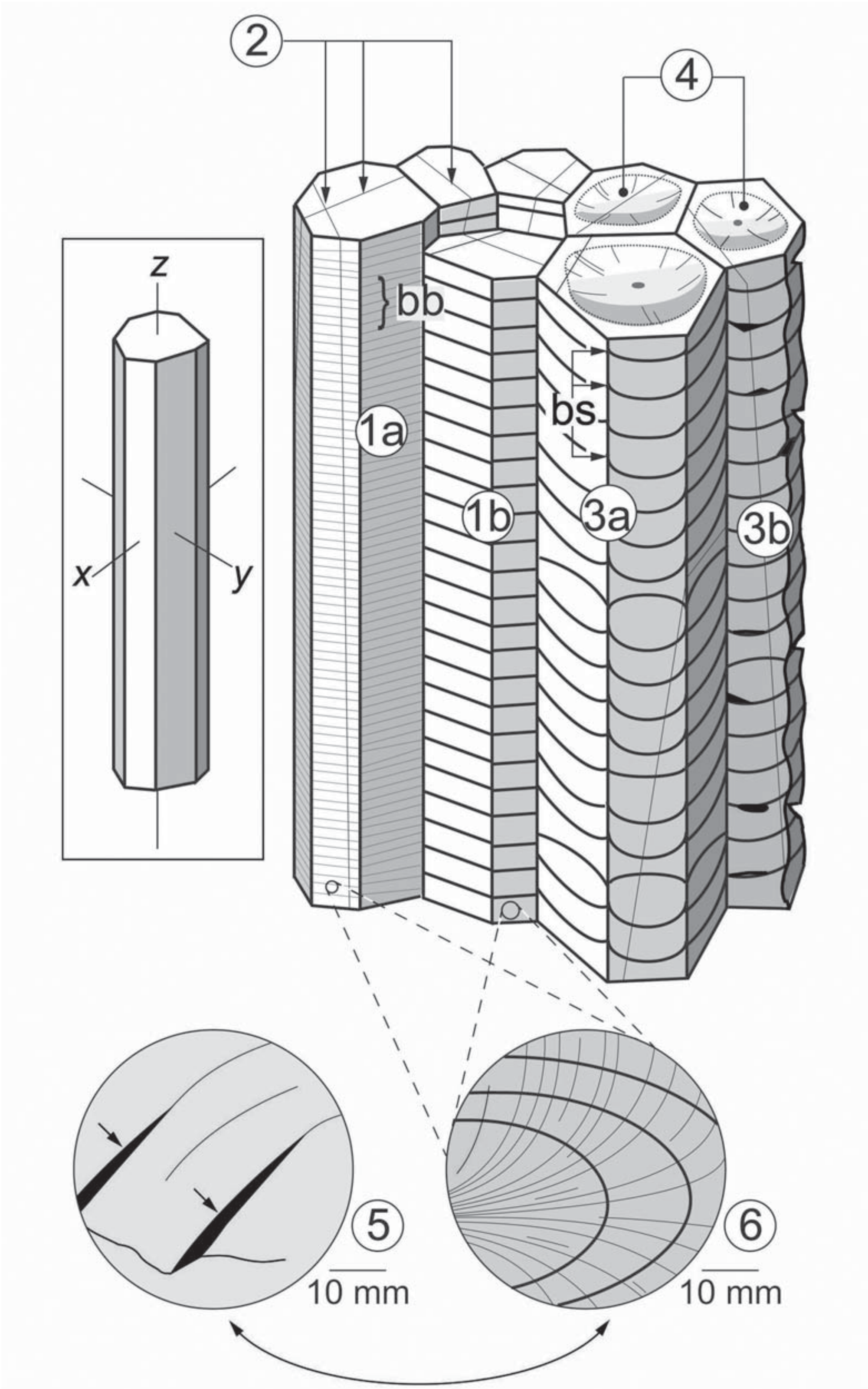

Fig. 3. Schematic diagram of columnar jointing in igneous rock. Some columns (1a, 1b) are comparatively straight-sided, and their surfaces may have large, parallel, and geometrically regular bands (bb) also called “chisel marks” or “striations” (e.g., James 1920; Ryan and Sammis 1978; Tanner 2013, fig. 4; Sheth 2018, fig. 5.27) by some authors, but they should not be confused with glacial striations. Planar, horizontal cross fractures may break columns into a “stack” of flat-topped and -bottomed segments (1a). Subvertical or vertical noncolumnar fractures (2) cut through columns and may be separate sets of joints. Other columns (3a, 3b) are cut by curved horizontal cross fractures. Columns are broken into segments with ball-and-socket or cup-and-ball structures, the “ball” or “cup” aspect of which can be seen on the exposed tops of columns (4). Arcuate breaks (5) and rib and plumose marks (6) are commonly present on the faces of columnar joints. Inset diagram shows a hypothetical rock column in *x*–*y*–*z* space, with *z* as the long vertical axis.

A fascination with columnar jointing was apparent even in the inchoate stages of geological science (Bulkeley 1693; Foley 1694a, 1694b; Molyneux 1694; Banks 1772 in Agnarsdóttir 2016, 67–72; Desmarest 1771; Raspe 1771, 1776 [see Carozzi 1969], Strange 1775a, 1975b). These accounts conspicuously predate the influential work of Hutton (1795) and Playfair (1802), who extolled igneous processes. Research remains very lively centuries later (e.g., Goehring et al. 2009; Almqvist et al. 2012; Bosshard, Mattsson, and Hetényi 2012; Hetényi et al. 2012; Woodell 2012; Goehring 2013; Forbes, Blake, and Tuffen 2014; Christensen et al. 2016; Lamur et al. 2018; Moore 2019). Columnar jointing has also inspired reverence, mythology, art, and whimsical place names (Fig. 4). Mato Tipila or He Hota Paha (Devils Tower in Wyoming), the quintessential American example of columnar jointing (Fig. 4A), retains major religious significance among indigenous Americans (Freeman 2007; Jenkins 2013; National Park Service n.d.). This iconic landform also served as a momentous plot device in the 1977 film *Close Encounters of the Third Kind*. Similarly memorable are the Devil's Honeycomb in Missouri (rhyolite; Fig. 4D), the basaltic Devils Postpile (California) and Devils Woodpile (British Columbia), and the equally basaltic—but apparently more righteous—Samson's Ribs in Edinburgh, Scotland. The famous Palisades along the Hudson River in New York and New Jersey is a 200-million-year-old columnar-jointed diabase sill emplaced as molten rock while the North Atlantic Ocean was opening (Marzoli et al. 2011). Scaled by British troops on their way to capture Fort Lee during the American Revolution, it was later commemorated in paintings by Jasper Cropsey, Thomas Doughty, Sanford Gifford, and William Joy. There are also the Palisades of the Pijitawabik in Ontario, Canada (diabase), and the Palisades Sill of New Mexico (porphyritic dacite). Organ Pipes and Sawn Rocks are imaginatively named examples of columnar jointing in basalts in Australia. Clochán na bhFomhórach or Giant's Causeway in Northern Ireland, a basaltic example that is arguably the most famous case of columnar jointing, inspired premedieval Gaelic mythology and then enjoyed a 1973 hard-rock redux on the cover of the Led Zeppelin album *Houses of the Holy*. The basalt erratics that we describe are also compelling.

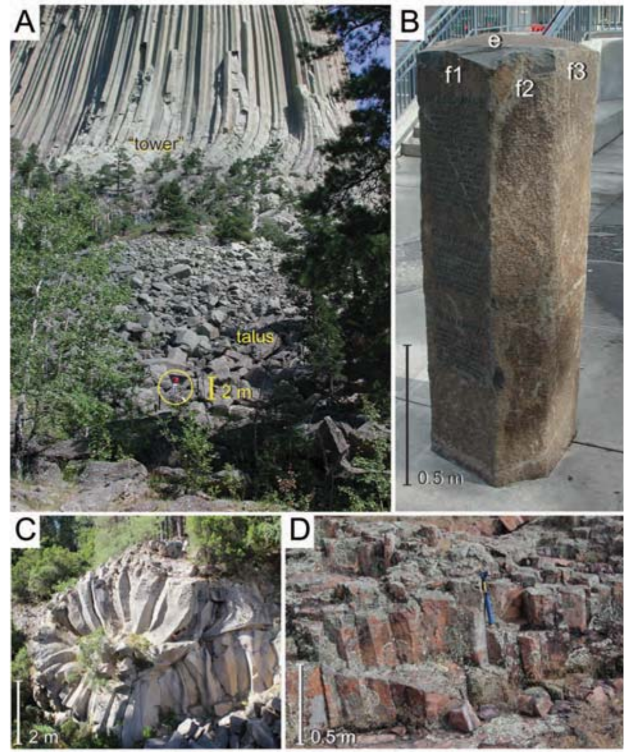

Fig. 4. Examples of columnar jointing in igneous rocks. ***A***, Immense columns in phonolite porphyry at Devils Tower, Wyoming; immense column fragments with polygonal cross sections comprise the talus at the base of the "tower" or steep fall face of the landform. Human figure, 1.8 m tall, is circled. ***B***, Individual basalt column, now used as a war monument, with three visible faces (f1–f3) and a slightly convex end (e) that may be a "ball" associated with a curved fracture and ball-and-socket joint (Fig. 3). ***C***, La Rosa de Piedra ("The Rose of Stone") in basalt along route TF-21, Tenerife, Canary Islands, Spain. In this case, fractures (columnar joints) radiate in all directions from a center, a configuration that is by no means exceptional (e.g., Sheth 2018, figs. 5.47–5.49). *D*, Devil's Honeycomb, a columnar-jointed rhyolite, atop Hughes Mountain in the Saint Francois Mountains, Washington County, Missouri. Note the significantly smaller sizes of columns, in width by as much as an order of magnitude, relative to *A–C*.

Omars: From So Far

Omars may be the archetype of very far-traveled erratics in North America. They were eroded from sedimentary strata of the Paleoproterozoic Omarolluk Formation by the Laurentide Ice Sheet (LIS) around the Belcher Islands of southeastern Hudson Bay in Nunavut, Canada (Ricketts 1981; Fig. 1B). During the Wisconsinan Glacial Episode, they were transported by ice into five Canadian provinces and at least nine US states (Prest 1990; Prest, Donaldson, and Mooers 2000; Cummings and Russell 2018), but almost nothing is known about their erosion and transport during earlier glacial episodes. Omars have very distinctive aspects, being composed of dark-colored greywacke (clay-rich sandstone) and containing particular kinds of concretions and pits, making them very easy to identify ("Omar," Illinois State Geological Survey n.d.; Keweenaw Geoheritage n.d.; Manitoba Agriculture and Resource Development n.d.; Prest, Donaldson, and Mooers 2000).

Geographic and Geologic Setting

The study site is on Skull Creek, a low-order northward-draining stream with a small basin lying mostly within Butler County, Nebraska (Fig. 1A). Our collection of stream-reworked erratics was made in the channel and banks of the creek approximately 1 km west–northwest to 1.2 km northwest of the unincorporated and abandoned hamlet of Nimburg in northeastern Butler County, Nebraska (Figs. 1A, 2). This site lies within in the so-called Bohemian Alps (e.g., Kooser 2002), a rolling, stream-dissected landscape on Pleistocene sediments.

Pleistocene strata exposed in the banks of Skull Creek at the site (Fig. 2) are, in descending stratigraphic order: (1) the Late Pleistocene (Wisconsinan) Peoria Loess and Gilman Canyon Formation; (2) the Middle Pleistocene (Illinoian) Loveland Loess, the lower part of which is stratified; and (3) a thin layer of sand bearing exotic pebbles to boulders (Fig. 2, ga), which we consider to be Illinoian gravelly alluvium by virtue of its gradational upper contact with the overlying loess and the stratification within the lower part of the latter. These sediments postdate, by hundreds of thousands of years, the multiple pre-Illinoian (i.e., Early and early Middle Pleistocene) advances of the LIS into present Nebraska, as well as any of the tills that they deposited (e.g., Roy et al. 2004; Rovey and Balco 2011). Such tills are presumed to predate a widespread volcanic ash from an eruption of the Yellowstone Caldera about 631,000 years ago (Boellstorff 1977; Matthews, Vazquez, and Calvert 2015). In-situ pre-Illinoian glacial tills containing erratics crop out farther upstream within the Skull Creek basin, and tills are widespread either at the surface or at comparatively shallow depths across the eastern one-quarter of Butler County (Kerl, Babcock, and Halstead 1982; Ginsberg 1983, fig. 8c; our Fig. 1C). All of Butler County experienced glaciation during the Pleistocene, prior to 631 ka, yet the westward limit of the pre-Illinoian glaciations that reached Nebraska is only about 50 km to the west of the present study site (Swinehart et al. 1994).

Across Butler County, Wisconsinan and Illinoian loesses appear to mantle ancient landscapes (Ginsberg 1983, fig. 8a–d; our Fig. 1C) that eroded from older deposits during the Middle and Late Pleistocene. This erosion occurred during the tens of thousands of years between the deposition of the youngest regional glacial till and the deposition of overlying Middle Pleistocene sediments. We emphasize that the erratics we describe were not found in-situ in exposed glacial till. Rather, they are reworked erratics, which were eroded from the till and in the thin Illinoian alluvium on the banks of the stream and in its bed. The latter deposit directly overlies the eroded surface of the gently dipping Upper Cretaceous (Cenomanian–Turonian) Greenhorn Limestone, notable as perhaps the only angular unconformity visible at this scale in Nebraska (Fig. 2). The Greenhorn Limestone forms a stretch of the stream bed in the study area and produces a bedrock riffle, which appears to trap large stones being carried downstream (approximately northward) during higher-stage flows.

Materials and Methods

Over a period of years, two of the authors (CCA and NVA) made a collection of dark-colored pebbles, cobbles, and boulders—chiefly from the bed of Skull Creek but also from the Illinoian alluvium exposed in its banks (Fig. 2). Most of these stones are composed of basalt, but closer inspection reveals a second, very minor population of the exotic rock type characteristic of omars. A long-abandoned spur of the Chicago and North Western Railway crossed Skull Creek in the study area during the early 20th century and eventually connected to the eastbound main line of that system. That same railroad system had numerous spurs in southern Minnesota and Wisconsin as well as in three other states (American-Rails.com n.d.). We submit that long-distance transportation of uncrushed quarried basalt exhibiting a large range of particle sizes across this onetime vast and complex web of rails to Nebraska in the historic past is so unlikely as to be unworthy of consideration as an alternate hypothesis for the origin of the basalt erratics. Moreover, we found no evidence of the use of anything but locally available materials in railbed construction in the study area. Therefore, the strange stones of Skull Creek can only be glacial erratics reworked by stream action.

After a thorough washing, we examined erratics for the features described in the following section. We measured the long, intermediate, and short (a, b, and

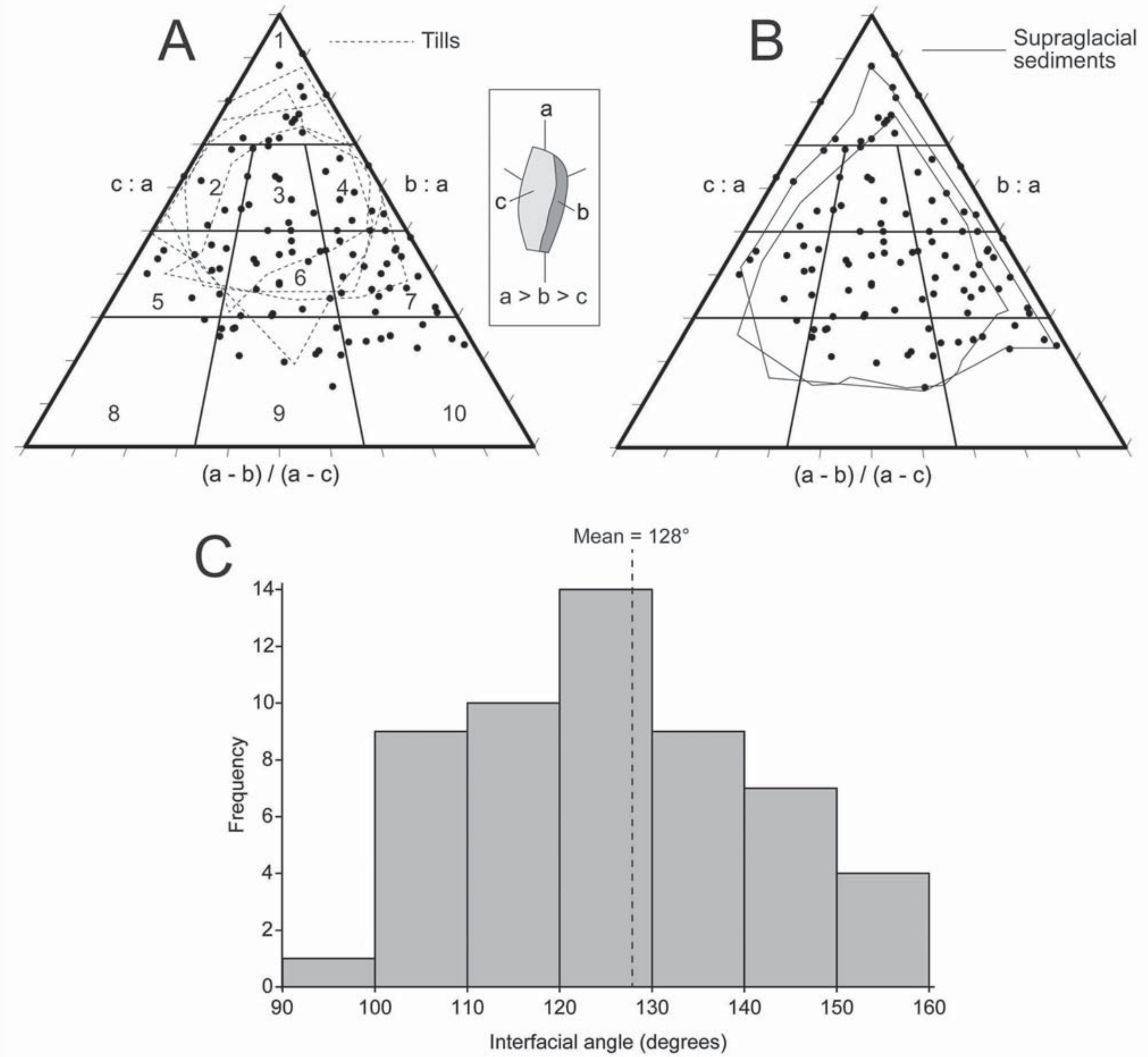

Fig. 5. *A–B*, Ternary diagrams illustrating the shapes of basalt erratics on the basis of their long (a), intermediate (b), and short (c) axes, as illustrated in inset diagram (see Sneed and Folk 1958; Benn and Ballantyne 1994). Each dot represents a single erratic. ***A***, Comparison of basaltic erratics from Skull Creek with polygons representing the populations of stones from five modern glacial tills (Benn and Ballantyne 1993), indicated by dashed lines. Note that many, but not all, of the Skull Creek erratics fall within the collective "footprint" of these polygons. ***B***, Comparison with two populations of supraglacial stones collected by the same authors. Note that the Skull Creek erratics fall entirely within the collective "footprint" of these polygons. ***C***, Histogram of all obtuse angles measured on basaltic erratics from Skull Creek. Mean of 128° diverges little from a mean of 120° for a population of regular hexagonal cross sections of prisms. Considering that the horizontal cross sections of rock columns produced by columnar jointing are typically irregular and that those polygons may have less than or more than six sides, the range of interfacial angles shown here seems appropriate.

c) axes of erratics with steel cranial calipers. We used a small steel woodworking protractor with a mobile arm to measure interfacial angles on small erratics and a 14-inch Conzett-type steel goniometer to measure the larger ones.

Results

Characteristics of Basalt Erratics

The reworked basalt erratics have a wide range of sizes and, even more so, of shapes (Table 1; Fig. 5A–B). Also, three-quarters of them are subangular or subround-

Table 1. Characteristics of reworked basalt erratics (*n* = 109) from the study area.

Size	
Largest	410 × 185 × 10 mm
Smallest	55 × 40 × 35 mm
Shape (terms and definitions from Sneed and Folk 1958)	
Compact (1)	13.8%
Compact-platy (2)	7.3%
Compact-bladed (3)	6.4%
Compact-elongate (4)	7.3%
Platy (5)	9.2%
Bladed (6)	16.5%
Elongate (7)	21.1%
Very platy (8)	0.9%
Very bladed (9)	10.1%
Very elongate (10)	7.3%
Roundness	
Very angular	0%
Angular	7.3%
Subangular	42.2%
Subrounded	32.1%
Rounded	17.43%
Faces and interfacial angles	
At least one flat face	85.3%
At least two intersecting flat faces	49.5%
Only right and acute interfacial angle(s)	12.8%
At least one obtuse interfacial angle	35.8%
Both acute or right and obtuse angles	9.2%

ed, and some remain angular, meaning that they have not been significantly abraded (Table 1). Several more specific characteristics can be identified with close examination:

1. Joint faces are interpreted from comparatively smooth, planar surfaces apparent on more than 85% of the basalt erratics (Figs. 6–7; Table 1). These surfaces are analogous to joint faces in outcrops of hard, brittle rocks like basalt (Table 1). At least two such well-developed faces meet at a well-defined, straight edge in nearly half of the erratics (Table 1).
2. Obtuse interfacial angles, or obtuse angles between interpretive joint faces, are common. More than one-third of all basalt erratics exhibit at least one obtuse interfacial angle (Figs. 5C, 6–7, 8A–B; Table 1).
3. Right and acute interfacial angles are less common than obtuse interfacial angles. In our sample, acute interfacial were all 30° or greater (Table 1). Fewer basalt erratics exhibit acute interfacial angles alone than exhibit at least one obtuse angle (Table 1).
4. Flat surfaces are planar features that appear on a few erratics (e.g., Fig. 9B–C: fs). These surfaces contrast in surface texture with the interpretive joint faces (#1, above) in that they have pockmarks and/or slight rugosities (#10, below).
5. Concave or convex surfaces appear on a very few of the erratics. These surfaces appear to have been parts of larger surfaces that existed prior to rock breakage during weathering, erosion, and transport (Fig. 9A–C: cs).
6. Plumose and rib marks (Fig. 8D–E), as well as some related features, are unmistakable features of joint faces (Hodgson 1961) in many rock outcrops. Plumose and rib marks are low-relief, concave and convex, curvilinear ornamentations on joint surfaces that form as a joint propagates within a rock mass (e.g., Hodgson 1961). They may be particularly common and form distinct, complex patterns on the faces of columnar joints (DeGraff and Aydin 1987; Tanner 2013).
7. Arcuate breaks (Figs. 7C, 8B) are low-relief, curved breaks or irregular steps on some of the interpretive joint faces. They are surficial features that are not directly associated with any cracks extending through the rock mass. These seemingly nondescript features have been illustrated, and even briefly described, in accounts of in-situ basalt columns (e.g., James 1920, fig. 9; DeGraff and Aydin 1987, fig. 10). As in the cases of striations and plumose and rib marks, these breaks have genetic significance because they are produced during the breaking-up of the intact rock mass under thermal stresses (DeGraff and Aydin 1987).
8. Millimeter-scale laminations are subtle, very fine apparent layers visible on the surfaces of rock columns in basalt outcrops (Tanner 2013). It has been presumed that these laminations extend through the interior of a column, and that they consist of roughly horizontal chains of plagioclase crystals, a solid phase that formed while some liquid silicate phase remained in a mass of cooling lava or magma (Tanner 2013). A few erratics

from Skull Creek show laminations (Fig. 8C) analogous to those figured by Tanner (2013, fig. 5).

9. Vesicles are roundish voids in igneous rocks (and particularly in basalts) produced by gas bubbles in the precursor lava. Given an identification of basalt as the rock type, vesicles are difficult, if not impossible, to confuse with any other feature. Sparse, small- to medium-sized (6–70 mm), smooth-walled, spherical to slightly ovoid vesicles appear in several of the erratics (Fig. 8B–C).

10. Pockmarks and slight rugosities appear on certain surfaces of a few erratics, and chiefly on flat surfaces (Fig. 7F: r). If they are present on one surface, they are typically absent from any other surfaces of the same erratic.

11. Erosional striations appear on very few of the erratics (Fig. 7G–H). These striations are subparallel to parallel, tens of millimeters in length, and closely spaced at distances of a few millimeters or less. Sets of parallel erosional striations cross each other at random angles (Fig. 7H).

12. Unilateral surface polish, or any polish at all, is absent in almost all of the basalt erratics. A single small specimen notably contrasts with the other erratics we examined because it has an exceptionally high degree of natural polish—as well as a few fine (≤1 mm in diameter) pits—on one side, but not on the obverse side (Fig. 9D–E). Thus, it is unilaterally polished.

13. Weathering rinds (Figs. 7E, 9F) are thin zones of alteration around the outsides of rocks subjected to chemical weathering at and near Earth's surface. In the case of our basalt erratics, the rinds are accumulations of secondary iron (III) oxide and/or oxide-hydroxide minerals—possibly hematite and/or goethite—at and just below the rock surface. These rinds are generally less than 5 mm or less in thickness and they are discontinuous. A few of these rinds exhibit Liesegang banding (Fig. 9G), a self-organizing pattern of concentric rings related to the diffusion of ions, in this case those liberated by the chemical weathering of the rock and subsequent precipitation (Singer and Navrot 1970; Nabika, Itatani, and Lagzi 2020). Ferromagnesian (iron- and magnesium-bearing) silicate minerals are essential constituents of basalts and, theoretically, weather rapidly, relative to a geologic sense of time, under typical Earth-surface conditions.

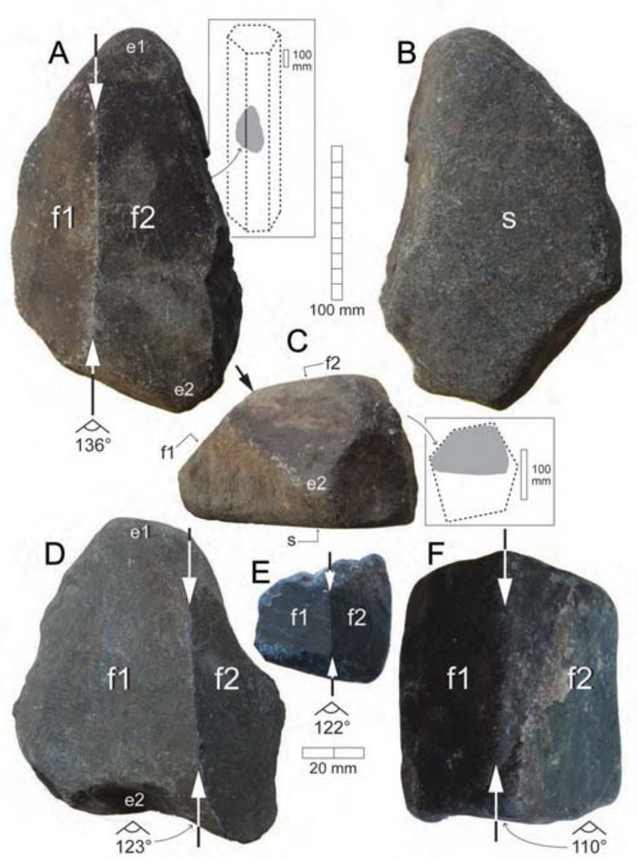

Fig. 6. Basalt erratics preserving interpretive columnar joint faces intersecting at obtuse angles at well-defined edges. These examples preserve more of the vertical (*z*–axis, inset figure) aspect of rock columns. ***A***, Erratic with two interpretive columnar joint faces (f1, f2) intersecting at an obtuse angle with a pronounced edge (large black and white arrows) and two rounded ends (e1, e2). Inset schematic diagram shows hypothetical position of erratic within an intact column. Rounding of ends (e1, e2) may have resulted from glacial abrasion alone or one of the two may be partially a result of the former presence of a ball-and-socket joint (see text). ***B***, Flat, obverse side (s) of same erratic may be a glacial facet developed on a preexisting noncolumnar joint surface (see text). ***C***, End-on view at end e2 of same erratic, showing relationships of features. Inset schematic diagram shows hypothetical position of *x–y* cross section (see Fig. 3, inset) of this erratic within a hypothetical hexagonal *x–y* cross section of an intact column. ***D***, Erratic with two faces (f1, f2) and one convex end (e1) and one concave one (e2), which may also relate to the original existence of a ball-and-socket joint (see Fig. 3). (Scale as in *A–C* above.) ***E***, Pebble-sized erratic that still preserves two faces (f1, f2) intersecting at an acute angle with pronounced edge (arrows), despite its small size. ***F***, Erratic with two faces (f1, f2), intersecting at an acute angle with a pronounced, but somewhat rounded, edge (arrows). (Scale as in *A–C* and *D* above.)

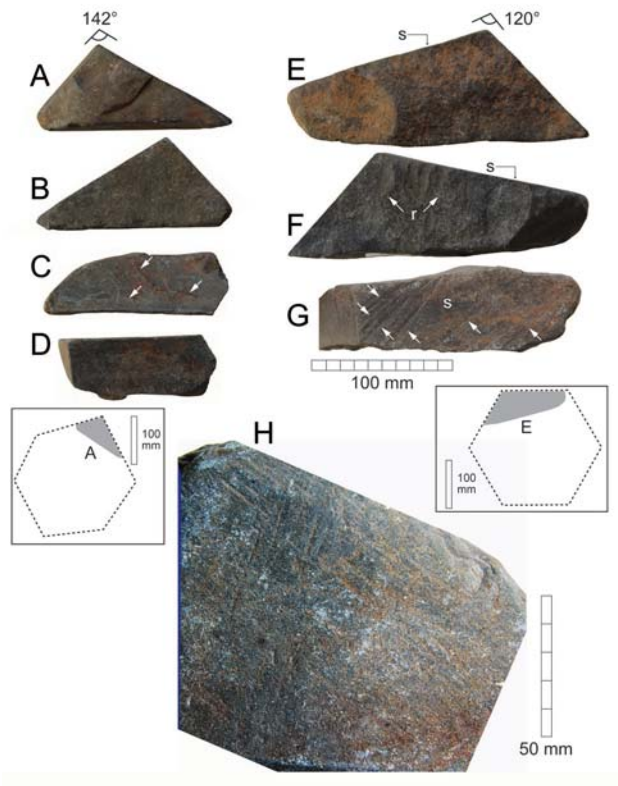

Fig. 7. ***A–B***, Tabular basalt erratic viewed down *z*-axis (Fig. 3, inset), exhibiting interpretive columnar joint faces intersecting at an acute angle with a pronounced edge (large arrows). The flatness of this erratic may reflect an origin breakage of intact columns along cross joints (see text). ***C–D***, Relatively smooth surfaces of putative joint faces in same erratic, although one face (*C*) exhibits subtle arcuate breaks (white arrows; see text). Inset diagram shows hypothetical position of view shown in *A* within the cross section of a basalt column viewed in its *x–y* plane. ***E–G***, Another tabular basalt erratic with a thin rind of reddish-brown iron (III) oxide and/or oxide-hydroxide minerals (possibly hematite and/or goethite) from the chemical weathering of component ferromagnesian silicates on one surface (*E*) and a slightly rugose (r) and essentially unweathered surface on the obverse side (*F*). *G*, One face (s) of the same erratic exhibits surficial features that are likely to be glacial striations (white arrows). (One-hundred-millimeter scale is the same for all of *A–G*.) Inset diagram (below *G*) shows hypothetical position of view *F* within the cross section of a basalt column viewed in its *x–y* plane. ***H***, Glacial striations on a flat surface (not a columnar-joint face) on yet another erratic. Note that yellowish-red iron oxide/hydrous iron oxide staining in concentrated within striations, suggesting that this aspect of weathering occurred after the erratic was deposited in Nebraska.

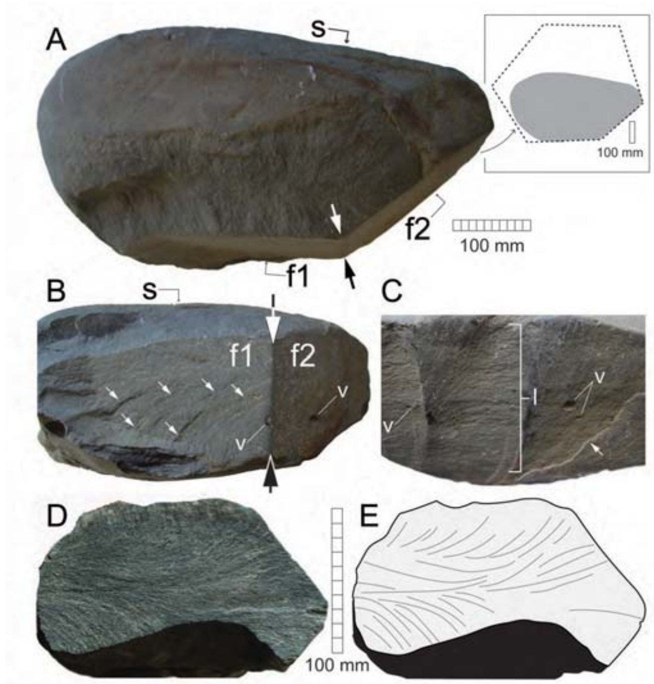

Fig. 8. ***A***, Large basalt erratic viewed from above, exhibiting interpretive columnar joint faces (f1, f2) intersecting at an acute angle with a pronounced edge (large arrows). Another surface (s) appears to be a noncolumnar joint face. ***B***, Columnar-joint faces (f1, f2) of same erratic, showing pronounced edge (large black and white arrows), several arcuate breaks of variable depths (small white arrows), and two vesicles (v) are visible. ***C***, Closeup of part of noncolumnar joint face ("s" in *A* and *B*) showing laminations (l), three vesicles (v), and an irregular arcuate break (small white arrow) similar to those described from putative columnar-joint faces. (One-hundred-millimeter scale is same in *A–B*.) ***D–E***, Photograph and drawing of well-developed plumose marks, formed long before glacial erosion of the source rock, preserved on a joint surface on a basalt erratic. But a single joint surface is preserved on this erratic.

Characteristics of Omars

The total collection of erratics from Skull Creek includes four nonbasaltic, pebble- to cobble-sized erratics that were mistaken for basalt in the field because of their dark colors (Fig. 10A–C). Close inspection with a magnifying lens revealed that the rock type in these four erratics is a dark-colored greywacke rather than basalt. The rock type and characteristics of these much rarer erratics from Skull Creek match those omars illustrated in multiple accounts (e.g., Prest, Donaldson, and Mooers 2000, fig. 1; Illinois State Geological Survey n.d.; Keweenaw Geoheritage n.d.; Manitoba Agriculture and Resource Development n.d.). Three of the four omars from the Skull Creek sample also contain large, light-colored, calcium-carbonate-cemented concretions with circular to oval cross sections (Fig. 10A: cc)—a distinctive features of omars found elsewhere in the USA and Canada. Furthermore, pits from the partial to complete erosion of concretions also exist on the surfaces of the same three omars (Fig. 10A–C). Multiple sources consider these pits equally characteristic of omars, so much so that they are typically a means of identification in the

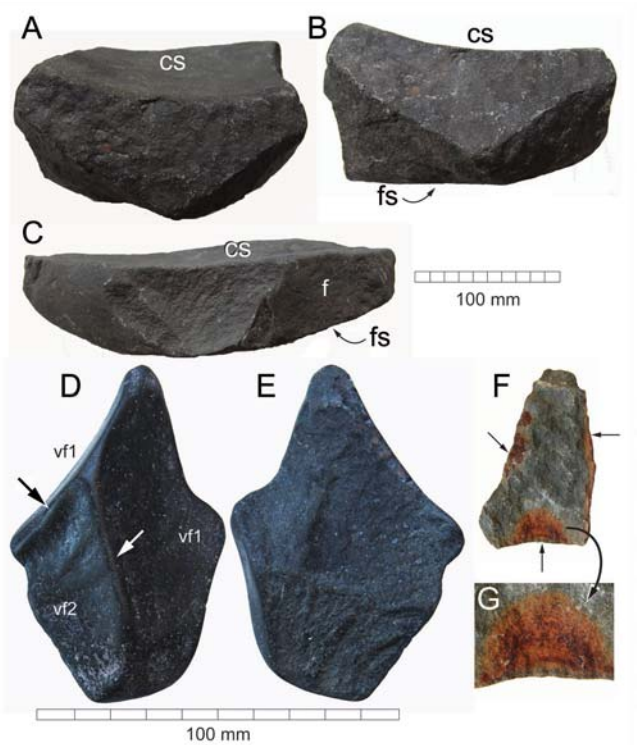

Fig. 9. Slightly oblique (***A***) and side (***B***) views of a basalt erratic with a notably concave side (cs) and an obverse flat surface (fs), which we interpret to be an example of cup-and-ball structure within a formerly intact rock column (see Fig. 3). ***C***, Another, more tabular, basalt erratic with a more gently concave surface (cs), a flat surface (fs), and at least one surface (f) that we interpret to be a remnant of a columnar joint face. (One-hundred-millimeter scale is the same for *A–C*.) ***D–E***, Two sides of a pebble-sized basalt erratic with one highly polished, slightly pitted surface that bears two keels (arrows) and three faces (vf1–vf3). Obverse side of this erratic (*E*) exhibits no polishing or pitting, and instead showing irregular, arcuate fractures produced by rock breakage. These characteristics identify the erratic as a ventifact (see text), in which case the polished and keeled face (*D*) would have been exposed at a postglacial Pleistocene land surface and subjected to the abrasive and polishing effects of sediment-laden winds, whereas the underside (*E*) would have remained rough. Note that the keels intersect at only 50°, rather than the approximately 90° relationship that would exist between columnar-joint-face edges and horizontal cross joints. ***F***, Freshly broken surface of a basalt erratic showing partial weathering rinds stained by iron (III) oxide and/or oxide-hydroxide minerals (possibly hematite and/or goethite), produced through the chemical weathering of ferromagnesian silicate minerals in the rock. (Scale as in *A–C* above.) ***G***, Closeup of one of the discontinuous weathering rinds in *F*, showing concentric banding characteristic of Liesegang banding (see text). (Scale in *G* as in *D–E* at left.)

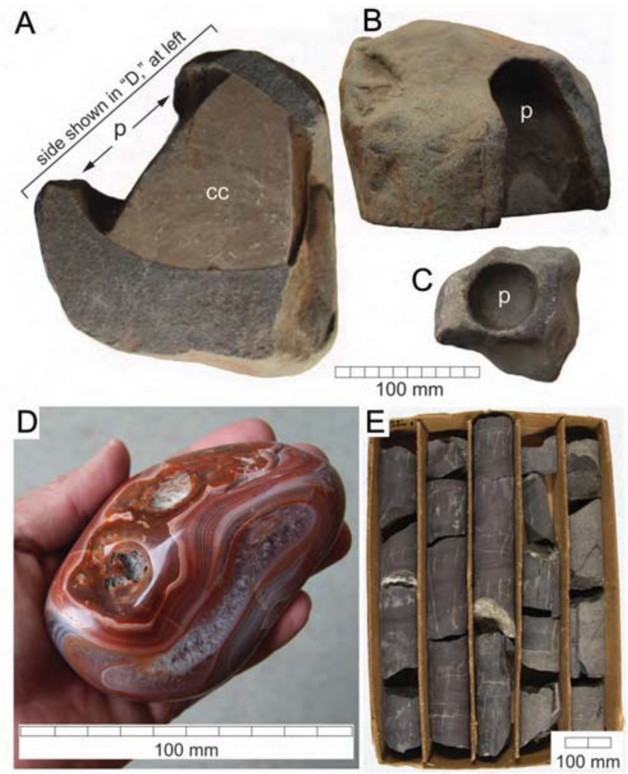

Fig. 10. ***A***, One surface of a large omar (see text) from Skull Creek with a characteristic carbonate concretion (cc) that has been partially weathered away to form a shallow pit (p). ***B***, Another side of the same erratic, showing the extent of the aforementioned pit (p). ***C***, Pebble-sized omar with a very large pit (p) from which a calcium carbonate concretion was eroded. ***D***, Polished Lake Superior agate that formed in a vesicle in a Mesoproterozoic "Keweenawan" lava flow in the Lake Superior area and was found as a glacial erratic in eastern Nebraska. ***E***, Cored Mesoproterozoic "Keweenawan" basalt from the Midcontinent Rift System, retrieved from 548 to 551 m (1798–1807 ft) depth in the Chester Williams #1 Radenslaben exploratory borehole, drilled in southeastern Saunders County, Nebraska (20–25 km NNE of Lincoln) in 1962. Marshall and Lidiak (1996) identified five separate tholeiitic basalt flows in the 56.7 m of core from this borehole and assigned an approximate age of 1097 Ma to the succession.

field (e.g., Buehner 2012). Omars also exhibit yellowish brown to reddish iron oxide or oxide-hydroxide stains from weathering and they are usually well rounded. The omars from Skull Creek exhibit such staining, and three of the four are rounded, but the largest example is subangular. One omar in our collection exhibits a glacial facet.

Discussion

Imprint of Columnar Jointing on Basalt Erratics

A crucial attribute of some of the basalt erratics is the existence of obtuse angles between comparatively smooth, planar faces that meet at well-defined edges. This attribute is compatible with the commonness of obtuse angles between joint faces in columnar-jointed rock masses. Four essentially universal observations can be made about columnar-jointed basalts. (1) There are innumerable columns in an outcrop or three-dimensional body of rock. (2) Each column has three to nine instances of joint faces intersecting at an edge that runs along the length of the column (*z*-axis in Fig. 3, inset). (3) Columns are by no means small, being a few meters to tens of meters in length. (4) Any individual column is likely to be broken into many smaller pieces by joints or other fractures along its long axis (*z*-axis in Fig. 3, inset). Therefore, large outcrop of columnar-jointed basalt has the potential to produce an abundant supply of eroded rocks with relics of columnar jointing.

The angular relationships between putative joint faces on basalt erratics are explained by the basic geometric attributes of common shapes. Regular polygons with five or more sides—or the equivalent polygonal cross sections of three-dimensional prisms (*x*–*y* plane in Fig. 3, inset)—have angles between all sides or faces (internal angles) ranging from 108° in pentagons to 140° in nonagons ("Shape," Math.com n.d.). Importantly, this range of polygons includes the cross sections of most rock columns in colonnades, even though their polygonal cross sections are usually irregular rather than regular. In irregular polygons, or the equivalent polygonal cross sections of prisms—such as rock columns—obtuse internal angles should still dominate, and it is even likely that some of those angles will exceed 140° as the number of sides or faces increases toward nine. Indeed, we found 54 examples of interfacial angles of 96° to 159° in the erratics we examined, and 72.2% of all instances of obtuse angles were in the range of 110° to 140°, inclusive. We also identified types of ornamentation described from columnar-joint faces (e.g., Tomkieff 1940; Ryan and Sammis 1978; DeGraff and Aydin 1987; Tanner 2013; Sheth 2018, 114–24) in our sample of basalt erratics.

Right and acute interfacial angles on basalt erratics can still be accommodated in a columnar jointing hypothesis. In many cases of columnar jointing (e.g., Phillips et al. 2013, fig. 6; Sheth 2018, figs. 5.32, 5.56), individual columns are cut at irregular intervals and angles by a secondary, typically nonsystematic population of joints (Fig. 3, basalt columns identified as 2). Some of the faces associated with right and acute interfacial angles in our sample may still have been columnar joint faces, but almost certainly not all of them, given the geometric characteristics of polygons with more than four sides. Therefore, we propose that at least some of the interpretive joint faces associated with right and acute angles were produced by cross-cutting joints.

Flat surfaces, pockmarks, and slight rugosities appear to be the products of "cross fractures" (Spry 1962, 1990), that is, horizontal fractures (Fig. 3, basalt column 1b) cutting across columns in *x*–*y* space (Fig. 3, inset), normal to their long axes (*z*-axis in Fig. 3, inset). These fractures effectively break columns in-situ (within an outcrop) into a stack of many tabular pieces (e.g., James 1920; Tomkieff 1940) like stacked sandwich cookies ("biscuit segmentation" of Sheth 2018, 124). We attribute the pockmark and rugosities to rock breakage in outcrop because the alternative explanation, abrasion during transport by glacial ice, would tend to plane off surface irregularities. Nevertheless, we were unable to find a parallel phenomenon described in published literature on columnar jointing. Plumose and rib marks, as well as arcuate fractures, are nearly unmistakable features of joint faces in basalts and similar rocks.

Abrasion and Weathering of Basalt Erratics

Many of the erratics are subangular to subrounded (Table 1), and thus they do not evince extreme abrasion by any agent. A few erratics, however, appear to have undergone significant abrasion in glacial transport, not only because their corners and edges are rounded, but also because they bear flat surfaces unattributable to the preservation of joint faces and many very fine to fine, parallel, erosional striations that are identical to striations produced by glacial abrasion (e.g., Fig. 7H). Other abraded, and even striated, faces may have developed on preexisting joint faces (Fig. 6B–C: s; 7G). Facets and striations have long been considered diagnostic glacial transport by many authors (e.g., Wentworth 1936; Boulton 1978; Domack, Anderson, and Kurtz 1980; Huggett and Kidd 1983). Abrasion by stream transport need not have been substantial because the erratics were probably eroded and transported by running water within a comparatively small area.

Erosional facets, and even striations, are produced through abrasion by particles transported in winds (resulting in the faceted rocks called ventifacts), in streams or shoreline waves (resulting in aquefacts), and even by fault movement (Wentworth 1925, 1928; Maxson 1940; Kuenen 1947; Winterer and Von der Borch 1968; Atkins 2003; Ruano and Galindo-Zaldívar 2004; Knight 2008; Laity and Bridges 2009; Durand and Bourquin 2013). Of these possibilities, wind abrasion is worthy of further consideration. Many authors have also stressed the prominence of surface polish on ventifacts as a criterion for identification (e.g., Christiansen and Svennson 1998; Gillies, Nickling, and Tilson 2009). Ventifacts also may have as many as four, and possibly more, facets that meet at well-defined—but not necessarily sharp or perfectly straight—edges (or "keels," e.g., Knight 2008). Not only do the characteristics of ventifact keels differ somewhat from those of the edges between columnar-joint faces, ventifact keels are not constrained by any formative mechanism to meet at any particular angle. Ventifacts are further distinguished by clast polarity—the tendency of the wind-eroded side of a rock to be smoother than the obverse side that was not exposed to wind—and some other, smaller-scale surface features (Durand and Bourquin 2013). A single basalt erratic exhibits the ventifact characteristics of well-developed polish, clast polarity, and slightly undulating facets meeting at smooth keels (Fig. 9D–E).

Pleistocene ventifacts are common, having been described from buried land surfaces across the midwestern United States, including Nebraska (e.g., Alden and Leighton 1917, 114, 153; Fidlar 1939; Thiesmeyer and Digman 1942; Wilson 1945; Wayne 1991; Wayne and Guthrie 1993; Zanner and Nater 2000). Given the numerous accounts of Pleistocene ventifacts in the Midwest, as well as the tendency of ventifacts in general to appear in great numbers on extant wind-eroded planetary surfaces (e.g., Knight 2008; Laity and Bridges 2009), we speculate that there may be abundant ventifacts atop the formerly exposed (i.e., for millennia), but now mostly buried, surfaces of glacial till bodies in the study area.

Weathering rinds on some of the reworked basalt erratics formed either (1) in the source area prior to glacial transport, or (2) during postglacial weathering in Nebraska. The second hypothesis is likely because the rinds commonly exist on and under surfaces that were clearly produced by the breakup of rock outcrops; furthermore, weathering appears within some glacial striae (Fig. 7H), indicating that weathering occurred after glacial transport. The "lifespans" of single grains of the ferromagnesian silicates in basalts may be only 10^3–10^4 years (e.g., Lasaga et al. 1994; Olsen and Rimstidt 2007). Moreover, field and laboratory studies suggest that a 5-mm-thick rind can form in 10^4–10^6 years (Coleman and Pierce 1981; Sak et al. 2004), a timespan less than the more than 600,000 years that have passed since the last wholesale glacial advance into eastern Nebraska.

Source and Significance of Basalt Erratics

Truly comprehensive studies of the provenance of erratics in Nebraska and immediately adjacent areas, except for those composed of the effectively unmistakable Sioux Quartzite (e.g., Willard 1980), are lacking. Nevertheless, for nearly a century, basalt erratics found as far south as the southern limit of Laurentide glaciation in northeastern Kansas have been attributed to the erosion of Mesoproterozoic "Keweenawan" basalts in the Lake Superior area (e.g., Schoewe 1924; Dort 2006, fig. 3-5). The widespread outcrops of such basalts and some other igneous rocks around present Lake Superior in Wisconsin, Minnesota, Michigan, and Ontario also exhibit columnar jointing (e.g., Huber 1973; Green 1979; Van Schmus and Hinze 1985; Morey and Van Schmus 1988; Fig. 1B). Basalts and other rocks of the Midcontinent Rift System, some 1100 million years old (Fig. 1B), are particularly prominent around the southwestern margin of Lake Superior. Basalts around Lake Superior easily could have been eroded and transported by glacial ice into Nebraska by one of several advances of the LIS during the Early and early Middle Pleistocene prior to 631 ka (e.g., Boellstorff 1977; Aber 1999; Roy et al. 2004; Rovey and Balco 2011). Alluding to the provenance of unspecified erratics, Wayne (1985) proposed that a hypothetical Minnesota Lobe of the pre-Illinoian LIS extended southwestward from the eponymous state (including the Lake Superior region) and "dominated the movement" of the ice sheet into eastern Nebraska. A similar conceptualization of at least some of the pre-Illinoian ice advances persists in later sources (e.g., Aber 1999, fig. 4; Illinois Geological Survey n.d., "Glaciers Smooth the Surface," fig. 4), but the configuration of the pre-Illinoian LIS can be hypothesized only at a very coarse spatial scale. The form of the ice margin and patterns of flow probably differed in detail from those of the Wisconsinan Des Moines and James lobes of the ice sheet during its last advance, which did not reach the present study area.

Evidence for the glacial transport of materials from the vicinity of present Lake Superior into Nebraska in pre-Illinoian times is undeniable from the outset. A case in point are the eponymous and very distinctive Lake Superior agates (Fig. 10D), which are comparatively common as far-traveled glacial pebbles and cobbles in eastern Nebraska and northeastern Kansas (Pabian 1976; Pabian and Zarins 1994). As semiprecious stones, these agates have been sought by collectors for many decades, and hence, their geographic distribution is widely understood. Moreover, they are known to have formed in vesicles in Mesoproterozoic "Keweenawan" basalts (e.g., Moxon 2002; Rosemeyer 2006).

In comparison with data from modern glacial sediments presented by Benn and Ballantyne (1993), the very broad range of shapes of the basalt erratics we studied is compatible with shapes exhibited either by supraglacial erratics or a combination of supraglacial sediment and till (Fig. 5A–B). We also observe that the development of glacial facets and striations correlate with rock characteristics (e.g., Glasser et al. 1998; Atkins 2003) and the location of a rocks within a glacier (Boulton 1978; Benn and Ballantyne 1993, 1994). The comparative rarity of these features in our sample of basalt erratics may be related to the hardness of that rock itself or perhaps a dominance of passive transport of the erratics within the ice as englacial sediment or atop it as supraglacial sediment (cf. Boulton 1978; Benn and Ballantyne 1993, 1994). A very recent paper (Korus et al. 2021) notwithstanding, almost nothing is known about ice-marginal environments in Nebraska during pre-Illinoian advances of the LIS. Nevertheless, given the proximity of the study area to the westernmost extent of pre-Illinoian glaciation, our sample may record the wholesale deposition of sediment, including erratics, from englacial and supraglacial positions in masses of stagnant ice at the margin of the LIS (cf. Schomacker and Benediktsson 2018).

Significance of Omars

During the Last Glacial Maximum (26.5–19 ka), within the Wisconsinan Glacial Episode, one of the ice domes of the LIS, from which ice spread (albeit not as far as the present study area), was located near the Belcher Islands and southern Hudson Bay (e.g., Lacelle et al. 2018). At that time, omars were eroded in that area and transported in multiple directions, including southwestward as far as the northern border of present Nebraska (Prest, Donaldson, and Mooers 2000). Wisconsinan ice-sheet dynamics are comparatively well understood because of the widespread preservation of contemporary glacial sediments and depositional topography. Our discovery of pre-Illinoian omars in Butler County, Nebraska, indicates that there was a generally similar configuration in the ice sheet during at least one of the advances of the LIS into Nebraska prior to 631 ka and that erratics eroded in the vicinity of southern Hudson Bay were transported even farther southwestward than during the Wisconsinan Glacial Episode. This observation is important because the depositional topography (e.g., moraines) left by pre-Illinoian advances has been eroded (Aber 1999) and comparatively little is known about ice-flow patterns and the configuration of the LIS during those advances.

Conclusions

The erratics that we describe have unique aspects that suggest complicated histories. The most parsimonious explanation of planar surfaces that intersect at obtuse angles along well-developed, straight edges in the basalt erratics is that they are preserved relics of columnar jointing that formed in source outcrops long before glaciation and hundreds of kilometers away. Other features of the basalt erratics are entirely compatible with that hypothesis. Even though some of the basalt erratics have been rounded by abrasion, or even faceted and striated during transport by glacial ice, most of them preserve at least some relict surface features that formed in source outcrops. We are surprised by this characteristic in far-transported erratics because there is a general assumption that glacial abrasion tends to remove primary diagnostic features on the surfaces of stones. We do not propose that this is a singular case; rather, we emphasize that comprehensive studies of erratics in Nebraska and nearby areas are exceedingly few and baseline knowledge is minimal. In fact, we are unaware of any other accounts that describe a parallel case in far-transported igneous-rock erratics. Perhaps many of the basalt erratics were transported chiefly within or atop the Laurentide Ice Sheet and suffered less abrasion. The closest and most likely source for these erratics is the present Lake Superior region (Fig. 1B), specifically the equivalent sequence of ancient lava flows in the Midcontinent Rift System that now lies buried hundreds under bedrock hundreds of meters below the land surface in eastern Nebraska (Fig. 10E). Our identification of omars extends the geographic distribution of that very distinctive type of erratic considerably farther south than was mapped by Prest, Donaldson, and Mooers (2000, fig. 2). At 2100 km southwestward from the source outcrops in Hudson Bay (Fig. 1B), Skull Creek is one of the southernmost locations of omars in North America. Furthermore, an azimuth from the Belcher Islands to Skull Creek crosses southwestern Lake Superior, the proposed source of basalt erratics. All of the erratics we describe were eroded from glacial till and transported by streams in the general vicinity of Butler County at least once. It is likely that some of them were transported more than once, given the existence of reworked erratics in Illinoian alluvium in the banks of Skull Creek. Serendipitously, we also found a single, unmistakable example of an erratic-turned-ventifact (by wind erosion atop once-exposed glacial sediments) that also found its way into Skull Creek. More ventifacts probably lie buried atop one or more ancient land surfaces in the study area.

Studies of glacial erratics can inform about the geologic past in even more sophisticated ways, such as the accurate determination of provenance by U-Pb geochronology and geochemical analyses and the application of cosmogenic nuclide dating to determine how long individual erratics have been exposed at the land surface (Doornbos et al. 2009; Tylmann et al. 2019). Therefore, future detailed studies of glacial erratics in Nebraska may elaborate on the provenance of basalt and other rock types and produce insights of even greater importance than those we present herein.

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R. M. Joeckel (rjoeckel3@unl.edu), Conservation and Survey Division, School of Natural Resources, Department of Earth and Atmospheric Sciences, and University of Nebraska State Museum, University of Nebraska–Lincoln, Lincoln, NE 68583

J. T. Korus, Conservation and Survey Division, School of Natural Resources, University of Nebraska–Lincoln, Lincoln, NE 68583

J. K. Turk, Conservation and Survey Division, School of Natural Resources, University of Nebraska–Lincoln, Lincoln, NE 68583

N. V. Arps, Columbus, NE 68601

C. C. Arps, Lincoln, NE 68505

L. M. Howard (lhoward3@unl.edu), Conservation and Survey Division, School of Natural Resources, University of Nebraska–Lincoln, Lincoln, NE 68583

References

Aber, J. S. 1999. “Pre-Illinoian Glacial Geomorphology and Dynamics in the Central United States, West of the Mississippi.” In *Glacial Processes Past and Present*, ed. D. M. Mickelson and J. W. Attig, 113–19. Geological Society of America Special Paper 337. Boulder, CO: Geological Society of America.

Agnarsdóttir, A., ed. 2016. “The Iceland Journal of Sir Joseph Banks, Part I: 12 July–6 September 1772.” *Sir Joseph Banks, Iceland and the North Atlantic 1772–1820: Journals, Letters, and Documents*. London: Routledge (for the Hakluyt Society).

Alden, W. C., and M. M. Leighton. 1917. “The Iowan Drift, a Review of the Evidences of the Iowan Stage of Glaciation.” *Iowa Geological Survey Annual Report* 26:83–156.

Almqvist, B. S. G., S. A. Bosshard, A. M. Hirt, H. B. Mattsson, and G. Hetényi. 2012. “Internal Flow Structures in Columnar-Jointed Basalt from Hrepphólar,” Iceland, II: Magnetic Anisotropy and Rock Magnetic Properties. *Bulletin of Volcanology* 74:1667–81.

American-Rails.com. n.d. “Chicago & North Western Railway: ‘Route of the 400.’” https://www.american-rails.com/cnw.html.

Anderson, R. R., and J. Cutler Prior. 2014. “Erratics: Glacial Boulders in Iowa.” Iowa Geological Survey. https://www.iihr.uiowa.edu/igs/erratics-glacial-boulders-in-iowa/.

Atkins, C. B. 2003. “Characteristics of Striae and Clasts in Glacial and Non-Glacial Environments.” PhD diss., Victoria University of Wellington, New Zealand.

Balen, D., and Z. Petrinec. 2014. “Development of Columnar Jointing in Albite Rhyolite in a Rapidly Cooling Volcanic Environment (Rupnica, Papuk Geopark, Croatia).” *Terra Nova* 26:102–10. https://doi.org/10.1111/ter.12075.

Benn, D. I., and C. K. Ballantyne. 1993. “The Description and Representation of Particle Shape.” *Earth Surface Processes and Landforms* 18:665–72.

Benn, D. I., and C. K. Ballantyne. 1994. “Reconstructing the Transport History of Glacigenic Sediments: A New Approach Based on the Co-variance of Clast Form Indices.” *Sedimentary Geology* 91:215–27.

Boellstorff, J. 1977. “Chronology of Some Late Cenozoic Deposits from the Central United States and the Ice Ages.” *Transactions Nebraska Academy of Science* 6:35–49.

Bosshard, S. A., H. B. Mattsson, and G. Hetényi. 2012. “Origin of Internal Flow Structures in Columnar-Jointed Basalt from Hrepphólar, Iceland, I: Textural and Geochemical Characterization.” *Bulletin of Volcanology* 74:1645–66.

Boulton, G. S. 1978. “Boulder Shapes and Grain-Size Distributions of Debris as Indicators of Transport Paths Through a Glacier and Till Genesis.” *Sedimentology* 25:773–99.

Buehner, K. 2012. “Discovery of Rock Raises Questions.” *Globe Gazette* (Mason City, Iowa), October 19. https://globegazette.com/news/local/discovery-of-rock-raises-questions/article_a8a842fa-1a5f-11e2-8ba5-001a4bcf887a.html.

Bulkeley, R. 1693. “Part of a Letter from Sir R. B. S. R. S. to Dr. Lister, Concerning the Giant’s Causeway in the County of Antrim in Ireland.” *Philosophical Transactions of the Royal Society of London* 17:708–10.

Carozzi, A. V. 1969. “Rudolf Erich Raspe and the Basalt Controversy.” *Studies in Romanticism* 8 (4): 235–50.

Christensen, A., C. Raufaste, M. Misztal, F. Celestini, M. Guidi, C. Ellegaard, and J. Mathiesen. 2016. “Scale Selection in Columnar Jointing: Insights from Experiments on Cooling Stearic Acid and Numerical Simulations.” *Journal of Geophysical Research: Solid Earth* 121:1462–82. http://dx.doi.org/10.1002/2015JB012465.

Christiansen, H. H., and H. Svensson. 1998. “Windpolished Boulders as Indicators of a Late Weichselian Wind Regime in Denmark in Relation to Neighbouring Areas.” *Permafrost and Periglacial Processes* 9:1–21.

Coleman, S. M., and K. I. Pierce, 1981. “Weathering Rinds on Andesitic and Basaltic Stones as a Quaternary Age Indicator, Western United States.” *U.S. Geological Survey Professional Paper* 1210.

Colgan P. M. 2009. “Glacial Erratics.” In *Encyclopedia of Paleoclimatology and Ancient Environments*, ed. V. Gornitz, 354. Encyclopedia of Earth Sciences Series. Dordrecht, Netherlands: Springer. https://doi.org/10.1007/978-1-4020-4411-3_90.

Cummings, D. I., and H. A. J. Russell. 2018. “Glacial Dispersal Trains in North America.” *Journal of Maps* 14 (2): 476–85. https://doi.org/10.1080/17445647.2018.1478752.

DeGraff, J. M., and A. Aydin. 1987. “Surface Morphology of Columnar Joints and Its Significance to Mechanics and Direction of Joint Growth.” *Geological Society of America Bulletin* 99 (5): 605–17.

Desmarest, N. 1771. “Mémoire sur l’origine et la Nature du Basalte à Grandes Colonnes Polygones, Déterminées par l’Histoire Naturelle de Cette Pierre, Observée en Auvergne.” *Histoire de l’Academie Royale des Sciences* 87:705–75.

Domack, E. W., J. B. Anderson, and D. Kurtz. 1980. “Clast Shape as an Indicator of Transport and Depositional Mechanisms in Glacial Marine Sediments: George V Continental Shelf, Antarctica.” *Journal of Sedimentary Petrology* 50:813–20.

Doornbos, C., L. M. Heaman, J. P. Doupé, J. England, A. Simonetti, and P. Lajeunesse. 2009. “The First Integrated Use of In-Situ U-Pb Geochronology and Geochemical Analyses to Determine Long-Distance Transport of Glacial Erratics from Mainland Canada into the Western Arctic Archipelago.” *Canadian Journal of Earth Sciences* 46 (2): 101–22.

Dort, W., Jr. 2006. “AMQA Post-Meeting Field Trip 3: Multiple Pre-Illinoian Tills and Associated Sediments and Paleosols, Northeastern Kansas and Central Missouri.” In *Guidebook for the 18th Biennial Meeting of the American Quaternary Association*, ed. R. Mandel, 3-1–3-18. Kansas Geological Survey Technical Series 21.

Durand, M., and S. Bourquin. 2013. “Criteria for the Identification of Ventifacts in the Geological Record: A Review and New Insights.” *Comptes Rendus Geoscience* 345:111–25.

Fidlar, M. M. 1939. “Wind-Polished Pebbles from Northern Newton County, Indiana.” *Proceedings of the Indiana Academy of Science* 48:121–23.

Foley, S. 1694a. “An Account of the Giants Causeway in the North of Ireland.” *Philosophical Transactions of the Royal Society of London* 18:170–72.

Foley, S. 1694b. “Answers to Sir Richard Bulkeley’s Queries Relating to the Giants Causeway, Wrote Down When We Were upon the Causeway.” *Philosophical Transactions of the Royal Society of London* 18:173–75.

Forbes, A. E. S., S. Blake, and H. Tuffen. 2014. “Entablature: Fracture Types and Mechanisms.” *Bulletin of Volcanology* 76:820. https://doi.org/10.1007/s00445-014-0820-z.

Freeman, E. 2007. “Protecting Sacred Sites on Public Land: Religion and Alliances in the Mato Tipila–Devils Tower Litigation.” *American Indian Quarterly* 31 (1): 1–22.

Gillies, J. A., W. G. Nickling, and M. Tilson. 2009. “Ventifacts and Wind-Abraded Rock Features in the Taylor Valley, Antarctica.” *Geomorphology* 107:149–60.

Gilman, J. 2009. “Basalt Columns: Large Scale Constitutional Supercooling?” *Journal of Volcanology and Geothermal Research* 184:347–50.

Ginsberg, M. H., 1983. *Hydrogeology of Butler County, Nebraska*. Conservation and Survey Division, University of Nebraska–Lincoln, Nebraska Water Survey Paper 55.

Glasser, N. F., K. R. Crawford, M. J. Hambrey, M. R. Bennett, and D. Huddart. 1998. “Lithological and Structural Controls on the Surface Wear Characteristics of Glaciated Metamorphic Bedrock Surfaces: Ossian Sarsfjellet, Svalbard.” *Journal of Geology* 106:319–29.

Glock, W. S. 1935. “Copper and Rare Types of Lost Stones in Glacial Tills.” *Pan-American Geologist* 63 (2): 90–96.

Goehring, L. 2013. “Evolving Fracture Patterns: Columnar Joints, Mud Cracks and Polygonal Terrain.” *Philosophical Transactions of the Royal Society, A* 371:20120353.

Goehring, L., L. Mahadevan, and S. W. Morris. 2009. “Nonequilibrium Scale Selection Mechanism for Columnar Jointing.” *PNAS* 106 (2): 387–92.

Gomes, C. B., A. M. Castillo Clerici, M. Gadea, and P. Comin-Chiaramonti. 2014. “Polygonal Jointing in Sandstones from Eastern Paraguay.” *Serie Correlación Geológica* 30 (1): 13–23.

Green, J. V. 1979. *Field Trip Guidebook for the Keweenawan (Upper Precambrian) North Shore Volcanic Group, Minnesota*. Minnesota Geological Survey Guidebook Series 11.

Guy, B. 2010. "Comments on 'Basalt Columns: Large Scale Constitutional Supercooling?' by John Gilman (JVGR, 2009) and Presentation of Some New Data [J. Volcanol. Geotherm. Res. 184 (2009), 347–350]." *Journal of Volcanology and Geothermal Research* 194:69–73.

Hansen, B. 1970. "The Early History of Glacial Theory in British Geology." *Journal of Glaciology* 9 (55): 135–41.

Hetényi, G., B. Taisne, F. Garel, E. Médard, S. Bosshard, and H. B. Mattsson. 2012. "Scales of Columnar Jointing in Igneous Rocks: Field Measurements and Controlling Factors." *Bulletin of Volcanology* 74:457–82.

Hobbs, W. H. 1899. "The Diamond Field of the Great Lakes." *Journal of Geology* 7 (4): 375–88.

Hodgson, R. A. 1961. "Classification of Structures on Joint Surfaces." *American Journal of Science* 259 (7): 493–502.

Huber, N. K. 1973. "The Portage Lake Volcanics (Middle Kemweenawan) on Isle Royale, Michigan." *U.S. Geological Survey Professional Paper* 754-C.

Huggett, O. J., and R. B. Kidd. 1983. "Identification of Ice-Rafted and Other Exotic Material in Deep-Sea Dredge Hauls." *Geo-Marine Letters* 3:23–29.

Hutton, J. 1795. *Theory of the Earth, with Proofs and Illustrations. In Four Parts*. Edinburgh: Printed for Messrs Cadell, junior, and Davies, London; and W. Creech.

Illinois State Geological Survey. n.d. "Glaciers Smooth the Surface." https://isgs.illinois.edu/outreach/geology-resources/glaciers-smooth-surface

Illinois State Geological Survey. n.d. "Omar." https://isgs.illinois.edu/outreach/geology-resources/omar.

James, A. V. 1920. "Factors Producing Columnar Structure in Lavas and Its Occurrence Near Melbourne, Australia." *Journal of Geology* 28 (5): 458–69.

Jenkins, M. 2013. "Devil's Tower, Sacred Space." *Virginia Quarterly Review* 89 (1): 232–37.

Joeckel, R. M., R. F. Diffendal Jr., P. R. Hanson, and J. T. Korus. 2018. "Geologic Mapping in Nebraska: Old Rocks, New Maps, Fresh Insights." *Great Plains Research* 28:119–47.

Kantha, L. H. 1981. "'Basalt Fingers'—Origin of Columnar Joints?" *Geological Magazine* 3:261–64.

Kattenhorn, S. A., and C. J. Schaefer. 2008. "Thermal-Mechanical Modeling of Cooling History and Fracture Development in Inflationary Basalt Lava Flows." *Journal of Volcanology and Geothermal Research* 170 (3–4): 181–97.

Kaye, C. A. 1967. "Fossiliferous Bauxite in Glacial Drift, Martha's Vineyard, Massachusetts." *Science* 157 (3792): 1035–37.

Kerl, D. E., M. Babcock, and G. Halstead. 1982. *Soil Survey of Butler County, Nebraska*. United States Department of Agriculture, Soil Conservation Service, in cooperation with University of Nebraska, Conservation and Survey Division.

Keweenaw Geoheritage. n.d. "Beach Rocks: Omars." http://www.geo.mtu.edu/KeweenawGeoheritage/BeachStones/Omars.html.

Knight, J. 2008. "The Environmental Significance of Ventifacts: A Critical Review." *Earth-Science Reviews* 86:89–105.

Kooser, T. 2002. *Local Wonders: Seasons in the Bohemian Alps*. Lincoln: University of Nebraska Press.

Korus, J. T., R. M. Joeckel, J. D. Abraham, A.-S. Høyer, and F. Jørgensen. 2021. "Reconstruction of Pre-Illinoian Ice Margins and Glaciotectonic Structures from Airborne ElectroMagnetic (AEM) Surveys at the Western Limit of Laurentide Glaciation, Midcontinent U.S.A." *Quaternary Science Advances* 4:100026. https://doi.org/10.1016/j.qsa.2021.100026.

Kuenen, P. H. 1947. "Water-Faceted Boulders." *American Journal of Science* 245 (12): 779–83.

Lacelle, D., D. A. Fisher, S. Coulombe, D. Fortier, and R. Frappier. 2018. "Buried Remnants of the Laurentide Ice Sheet and Connections to its Surface Elevation." *Science Reports* 8, 13286. https://doi.org/10.1038/s41598-018-31166-2.

Laity, J. E., and N. T. Bridges. 2009. "Ventifacts on Earth and Mars: Analytical, Field, and Laboratory Studies Supporting Sand Abrasion and Windward Feature Development." *Geomorphology* 105:202–17.

Lamur, A., Y. Lavallée, F. E. Iddon, A. J. Hornsby, J. E. Kendrick, F. W. von Aulock, and F. B. Wadsworth. 2018. "Disclosing the Temperature of Columnar Jointing in Lavas." *Nature Communications* 9:1432. https://doi.org/10.1038/s41467-018-03842-4.

Lasaga, A. C., J. M. Soler, J. W. Ganor, T. E. Burch, and K. L. Nagy. 1994. "Chemical Weathering Rate Laws and Global Geochemical Cycles." *Geochimica et Cosmochimica Acta* 58:2361–86.

Lee, C., M. Huh, K. Yi, and C. Lee. 2015. "Genesis of the Columnar Joints from Welded Tuff in Mount Mudeung National Geopark, Republic of Korea." *Earth, Planets and Space* 67:152. https://doi.org/10.1186/s40623-015-0323-y.

Manitoba Agriculture and Resource Development. n.d. "Have You Seen an Omar (Omarolluk Erratic)?" https://www.manitoba.ca/iem/geo/surficial/omar_erratics.html.

Marshall, L. P., and E. G. Lidiak. 1996. "Geochemistry and Paleomagnetism of Keweenawan Basalt in the Subsurface of Nebraska." *Precambrian Research* 76 (1–2): 47–65.

Marzoli, A., F. Jourdan, J. H. Puffer, T. Cuppone, L. H. Tanner, R. E. Weems, H. Bertrand, S. Cirilli, G. Bellieni, and A. De Min. 2011. "Timing and Duration of the Central Atlantic Magmatic Province in the Newark and Culpeper Basins, Eastern U.S.A." *Lithos* 122 (3–4): 177–88.

Masaitis, V. L. 1999. "Impact Structures of Northeastern Eurasia: The Territories of Russia and Adjacent Countries." *Meteoritics and Planetary Science* 34 (5): 691–711.

Math.com. n.d. "Shape." https://www.math.net/shape.

Matthews, N. E., J. A. Vazquez, and A. T. Calvert. 2015. "Age of the Lava Creek Supereruption and Magma Chamber

Assembly at Yellowstone Based on $^{40}Ar/^{39}Ar$ and U-Pb Dating of Sanidine and Zircon Crystals." *Geochemistry, Geophysics, Geosystems* 16 (8): 2508–28.

Maxson, J. H. 1940. "Fluting and Faceting of Rock Fragments." *Journal of Geology* 48 (7): 717–51.

McClenaghan, M. B., and R. C. Paulen. 2017. "Application of Till Mineralogy and Geochemistry to Mineral Exploration." In *Past Glacial Environments*, 2nd ed., ed. J. Menzies and J. M. van der Meer, 689–751. Amsterdam: Elsevier. http://dx.doi.org/10.1016/B978-0-08-100524-8.00022-1.

Milazzo, M. P., L. P. Keszthelyi, W. L. Jaeger, M. Rosiek, S. Mattson, C. Verba, R. A. Beyer, P. E. Geissler, A. S. McEwen, and the HiRISE Team. 2009. "Discovery of Columnar Jointing on Mars." *Geology* 37 (2): 171–74. https://doi.org/10.1130/G25187A.1.

Molyneux, T., 1694. "Some Notes upon the Foregoing Account of the Giants Causeway, Serving to Further Illustrate the Same." *Transactions of the Royal Society of London* 18:175–82.

Moore, J. G. 2019. "Mini-Columns and Ghost Columns in Columbia River Lava." *Journal of Volcanology and Geothermal Research* 374:242–51.

Morey, G. B., and W. R. Van Schmus. 1988. "Correlation of Precambrian Rocks of the Lake Superior Region, United States." *U.S. Geological Survey Professional Paper* 1241–F.

Moxon, T. 2002. "Agate: A Study of Ageing." *European Journal of Mineralogy* 14:1009–1118.

Nabika, H., M. Itatani, and I. Lagzi. 2020. "Pattern Formation in Precipitation Reactions: The Liesegang Phenomenon." *Langmuir* 36:481–97.

National Park Service. n.d. "A Sacred Site to American Indians." https://www.nps.gov/deto/learn/historyculture/sacredsite.htm.

Olsen, A. A., and J. D. Rimstidt. 2007. "Using a Mineral Lifetime Diagram to Evaluate the Persistence of Olivine on Mars." *American Mineralogist* 92:698–702.

Ontario Ministry of Energy, Northern Development and Mines, undated. "Bedrock Geology." https://www.mndm.gov.on.ca/en/mines-and-minerals/applications/ogsearth/bedrock-geology.

Pabian, R. K. 1976. *Minerals and Gemstones of Nebraska: A Handbook for Students and Collectors*. Educational Circular 2. Lincoln: Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln.

Pabian R. K., and A. Zarins. 1994. *Banded Agates: Origins and Inclusions*. Conservation and Survey Division Educational Circular 12. Lincoln: Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln.

Phillips, J. C., M. C. S. Humphreys, K. A. Daniels, R. J. Brown, and F. Witham. 2013. "The Formation of Columnar Joints Produced by Cooling in Basalt at Staffa, Scotland." *Bulletin of Volcanology* 75:715. https://doi.org/10.1007/s00445-013-0715-4.

Playfair, J. 1802. *Illustrations of the Huttonian Theory of the Earth*. Edinburgh: Printed for William Creech.

Prest, V. K. 1990. "Laurentide Ice-Flow Patterns: A Historical Review, and Implications of the Dispersal of Belcher Island Erratics." *Géographie Physique et Quaternaire* 44:113–36.

Prest, V. K., J. A. Donaldson, and H. D. Mooers. 2000. "The Omar Story: The Role of Omars in Assessing Glacial History of West-Central North America." *Géographie physique et Quaternaire* 54 (3): 257–70. https://doi.org/10.7202/005654ar.

Raspe, R. E. 1771. "A Letter from Mr. R. E. Raspe, F. R. S. to M. Maty, M. D. Sec. R. S. Containing a Short Account of Some Basalt Hills in Hassia [*sic*]." *Philosophical Transactions of the Royal Society* 61:580–83.

Raspe, R. E. 1776. *An Account of Some German Volcanos, and Their Productions: With a New Hypothesis of the Prismatical Basaltes; Established upon Facts; Being an Essay of Physical Geography for Philosophers and Miners, Published as Supplementary to Sir William Hamilton's Observations on the Italian Volcanos*. London: Printed for Lockyer Davis.

Ricketts, B. D. 1981. "A Submarine Fan—Distal Molasse Sequence of Middle Precambrian Age, Belcher Islands, Hudson Bay." *Bulletin of the Canadian Society of Petroleum Geology* 29 (4): 562–82.

Rosemeyer, T. 2006. "News from the Keweenaw, Part 3—Recent Mineral Finds in Michigan's Copper Country." *Rocks and Minerals* 81 (4): 260–76.

Rosemeyer, T. 2016. "Collector's Note: An Unusual Glacial Silver Find in Michigan's Keweenaw Peninsula." *Rocks and Minerals* 91 (2): 176–78.

Rovey, C. W., II, and G. Balco. 2011. "Summary of Early and Middle Pleistocene Glaciations in Northern Missouri, USA." In *Quaternary Glaciations—Extent and Chronology: A Closer Look*, ed. J. Ehlers, P. L. Gibbard, and P. D. Hughes, 553–61. Developments in Quaternary Science 115. Amsterdam: Elsevier.

Roy, M., P. U. Clark, R. W. Barendregt, J. R. Glasmann, and R. J. Enkin. 2004. "Glacial Stratigraphy and Paleomagnetism of Late Cenozoic Deposits of the North-Central United States." *Geological Society of America Bulletin* 116:30–41.

Ruano, P., and J. Galindo-Zaldívar. 2004. "Striated and Pitted Pebbles as Paleostress Markers: An Example from the Central Transect of the Betic Cordillera (SE Spain)." *Tectonophysics* 379:183–98.

Ryan, M. P., and C. G. Sammis. 1978. "Cyclic Fracture Mechanisms in Cooling Basalt." *Geological Society of America Bulletin* 89 (9): 1295–1308.

Sachs, S., J. J. Hornung, H.-J. Lierl, and B. P. Kear. 2016. "Plesiosaurian Fossils from Baltic Glacial Erratics: Evidence of Early Jurassic Marine Amniotes from the Southwestern Margin of Fennoscandia." In *Mesozoic Biotas of Scandinavia and Its Arctic Territories*, ed. B. P. Kear, J. Lindgren,

J. H. Hurum, J. Milan, and V. Vajda, 149–63. Geological Society Special Publication 434. London: Geological Society.

Sak, P. B., D. M. Fisher, T. W. Gardner, K. Murphy, and S. L. Brantley. 2004. "Rates of Weathering Rind Formation on Costa Rican Basalt." *Geochimica et Cosmochimica Acta* 68 (7): 1453–72.

Schoewe, W. H. 1924. "Glacial Erratics in Shawnee, Douglas and Johnson Counties, Kansas." *Transactions of the Kansas Academy of Scienc*e 31:106–9.

Schomacker, A., and I. Ö. Benediktsson. 2018. "Supraglacial Environments." In *Past Glacial Environments*, ed. J. Menzies and J. Van der Meer: 159–79. Amsterdam: Elsevier.

Schwarcz, H. P. 1965. "The Origin of Diamonds in Drift of the North Central United States." *Journal of Geology* 73 (4): 657–63.

Sheth, H. 2018. *A Photographic Atlas of Flood Volcanism*. Cham, Switzerland: Springer.

Singer, A., and J. Navrot. 1970. "Diffusion Rings in Altered Basalt." *Chemical Geology* 6:31–41.

Sneed, E. D., and R. L. Folk. 1958. "Pebbles from the Lower Colorado River, Texas: A Study in Particle Morphogenesis." *Journal of Geology* 66:114–50.

Spörli, K. B., and J. V. Rowland. 2006. "'Column on Column' Structures as Indicators of Lava/Ice Interaction, Ruapehu Andesite Volcano, New Zealand." *Journal of Volcanology and Geothermal Research* 157:294–310.

Spry, A. 1962. "Origin of Columnar Jointing, Particularly in Basalt Flows." *Journal of the Geological Society of Australia* 8 (2): 191–216.

Spry A. 1990. "Columnar Jointing." In *The Encyclopedia of Igneous and Metamorphic Petrology*. Encyclopedia of Earth Sciences 16, ed. D. R. Bowes. New York: Van Nostrand Reinhold.

Spry, A. H., and M. Solomon. 1964. "Columnar Buchites at Apsley, Tasmania." *Quarterly Journal of the Geological Society* 120:519–44.

Strange, J. 1775a. "An Account of Two Giants Causeways, or Groups of Prismatic Basaltine Columns, and Other Curious Vulcanic [*sic*] Concretions, in the Venetian State in Italy; With Some Remarks on the Characters of These and Other Similar Bodies, and on the Physical Geography of the Counties in Wich [*sic*] They are Found." *Philosophical Transactions of the Royal Society* 65:5–47.

Strange, J. 1775b. "An Account of a Curious Giant's Causeway, or Group of Angular Columns, Newly Discovered in the Euganean Hills, Near Padua, in Italy. In a Letter from John Strange, Esq. F. R. S. to Sir John Pringle, Bart. P. R. S." *Philosophical Transactions of the Royal Society* 65:418–23.

Swinehart, J. S., V. H. Dreeszen, G. M. Richmond, M. J. Tipton, R. Bretz, F. V. Steece, G. R. Hallberg, and J. E. Goebel. 1994. "Quaternary Geologic Map of the Platte River 4 × 6 Degree Quadrangle, United States." *U.S. Geological Survey Miscellaneous Investigations I-1420 (NK-14)*. Scale: 1:1,000,000.

Tanner, L. H. 2013. "Surface Morphology of Basalt Columns at Svartifoss, Vatnajökulsþjóðgarður, Southern Iceland." *Journal of Geological Research* 2013, 482067. http://dx.doi.org/10.1155/2013/482067.

Taylor, M. A., and A. R. I. Cruickshank. 1993. "A Plesiosaur from the Linksfield Erratic (Rhaetian, Upper Triassic) Near Elgin, Morayshire." *Scottish Journal of Geology* 29 (2): 191–96.

Thiesmeyer, L. R., and R. E. Digman. 1942. "Wind-Cut Stones in Kansan Drift of Wisconsin." *Journal of Geology* 50 (2): 174–88.

Tomkieff, S. I. 1940. "Basalt Lavas of the Giant's Causeway." *Bulletin of Volcanolo*gy 6:89–143.

Tylmann, K., V. R. Vincent, R. Rinterknecht, P. P. Woźniak, D. Bourlès, I. Schimmelpfennig, V. Guillouc, and ASTER Team. 2019. "The Local Last Glacial Maximum of the Southern Scandinavian Ice Sheet Front: Cosmogenic Nuclide Dating of Erratics in Northern Poland." *Quaternary Science Reviews* 219:36–46.

USDA NRCS (United States Department of Agriculture Natural Resources Conservation Service). n.d. "Web Soil Survey." https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm.

Van Schmus, W. R., and W. J. Hinze. 1985. "The Midcontinent Rift System." *Annual Reviews of Earth and Planetary Sciences* 13:345–83.

Wayne, W. J. 1985. "Drainage Patterns and Glaciations in Eastern Nebraska." *Ter-Qua Symposium Series* 1:111–17.

Wayne, W. J. 1991. "Ice-Wedge Casts of Wisconsinan Age in Eastern Nebraska." *Permafrost and Periglacial Processes* 2 (3): 211–23.

Wayne, W. J., and R. S. Guthrie. 1993. "Permafrost and Periglacial Winds around the Wisconsinan Ice Margin in the Northern Plains of the USA." In *Proceedings, Permafrost, Sixth International Conference, 5–9 July 1993, Beijing, China*, 694–99. Wuschan: South China University of Technology Press.

Weinberger, R., and A. Burg. 2019. "Reappraising Columnar Joints in Different Rock Types and Settings." *Journal of Structural Geology* 125:185–94.

Wentworth, C. K. 1925. "Chink-Faceting: A New Process of Pebble-Shaping." *Journal of Geology* 33:941–54.

Wentworth, C. K. 1928. "Striated Cobbles in Southern States." *Geological Society of America Bulletin* 39 (3): 260–67.

Wentworth, C. 1936. "An Analysis of the Shapes of Glacial Cobbles." *Journal of Sedimentary Petrology* 6 (2): 85–96.

Willard, J. E. 1980. "Regional Directions of Ice Flow along the Southwestern Margin of the Laurentide Ice Sheet as Indicated by the Distribution of Sioux Quartzite Erratics." Master's thesis, University of Kansas, Lawrence.

Wilson, L. R. 1945. "Pebble Band Ventifacs on Iowa Till in Linn County, Iowa." *Proceedings of the Iowa Academy of Science* 52 (1): 235–41.

Winterer, E. L., and C. C. Von der Borch. 1968. "Striated Pebbles in a Mudflow Deposit, South Australia." *Palaeogeography, Palaeoclimatology, Palaeoecology* 5 (2): 205–11.

Woodell, D. R. 2012. "Constraints on Formation of Columnar Joints in Basaltic Lava." Master's thesis, University of British Columbia.

Woodward, J. 2014. "Erratic Boulders and the Diluvium." In *The Ice Age: A Very Short Introduction*, 23–40. Oxford: Oxford University Press.

Wright, H. M. N., C. Lesti, R. A. F. Cas, M. Porecca, J. G. Viramonte, C. B. Folkes, and G. Giordano. 2011. "Columnar Jointing in Vapor-Phase-Altered, Non-Welded Cerro Galán Ignimbrite, Paycuqui, Argentina." *Bulletin of Volcanology* 73:1567–82.

Young, G. M. 2008. "Origin of Enigmatic Structures: Field and Geochemical Investigation of Columnar Joints in Sandstones, Island of Bute, Scotland." *Journal of Geology* 116 (5): 527–36.

Zanner, C. W., and E. A. Nater. 2000. "Late-Quaternary Landscape Evolution in Mower County, Minnesota." In *Contributions to the Geology of Mower County, Minnesota*, ed. J. H. Mossler, 63–73. Report of Investigations 50. St. Paul: Minnesota Geological Survey.