MINNESOTA GEOLOGICAL SURVEY
Harvey Thorleifson, *Director*

THE INFLUENCE OF BEDROCK TOPOGRAPHY ON THE ORIGIN OF A MID-PLEISTOCENE EPOCH GLACIAL LAKE IN ROCK COUNTY, SOUTHWEST MINNESOTA

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Report of Investigations 72
ISSN 0076-9177

UNIVERSITY OF MINNESOTA
Saint Paul — 2017

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Date of release: June, 2017

Recommended citation

Southwick, D.L., 2017, The influence of bedrock topography on the origin of a mid-Pleistocene Epoch glacial lake in Rock County, southwest Minnesota: Minnesota Geological Survey Report of Investigations 72, 14 p.

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ISSN 0076-9177

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NOTE ON MEASUREMENTS USED IN THIS REPORT

Although the metric system is preferred in scientific writing, certain measurements are still routinely made in English customary units; for example, distances on land are measured in miles and depths in drill holes are measured in feet. Preference was given in this report to retaining the units in which measurements were made. To assist readers, conversion factors for some of the common units of measure are provided below.

English units to metric units:

To convert from	to	multiply by
inch	millimeter	25.40
inch	centimeter	2.540
foot	meter	0.3048
mile	kilometer	1.6093

Metric units to English units:

To convert from	to	multiply by
millimeter	inch	0.03937
centimeter	inch	0.3937
meter	foot	3.2808
kilometer	mile	0.6214

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David L. Southwick

ABSTRACT

A circular, closed depression 1.9 miles (3 kilometers) in diameter that was formerly occupied by a shallow lake is located in the glaciated landscape of northern Rock County, southwest Minnesota. The depression is partly framed by Sioux Quartzite and is situated above a bedrock swale on a broad, quartzite-supported upland that is thinly mantled by pre-Wisconsinan glacial deposits. The quartzite-supported upland has been a positive topographic feature since at least the Late Cretaceous Epoch; near the depression, its discontinuous cover of unconsolidated sediment consists of glacial till, outwash deposits, and loess that aggregate to a total preserved thickness between 1 and 82 feet (less than 1 to 25 meters). The depression originated from the melting out of a buried, tabular ice mass that was isolated near the stagnating margin of a mid-Pleistocene Epoch continental glacier. The ice mass was buried in outwash and then further buried by a thin till deposited when the glacier readvanced. The ice mass became isolated and was slow to melt because of its position in a bedrock swale on a topographic high that was near a dynamically fluctuating glacier margin; its relative thickness and protected location in the swale were key factors in its transient preservation. The closed depression that formed upon final melting of the ice mass has survived in the post-glacial landscape because of its location on a geomorphically persistent bedrock upland where the erosive energy of post-glacial and modern streams has been minimal.

It has been speculated that this bedrock-framed, geographically unique circular depression may be a deeply eroded meteorite impact structure. No supporting evidence for this speculation has been discovered in the field or laboratory.

INTRODUCTION

A circular, closed depression in the glaciated landscape of Rock County, Minnesota (Figs. 1, 2) has attracted sporadic interest among local residents, journalists, and geologists for at least 60 years. The feature is a closed, flat-bottomed low about 1.9 miles (3 kilometers) in diameter that is 33 to 49 feet (10 to 15 meters) lower in elevation than the surrounding gently rolling upland. Before being drained, it was a shallow, weedy lake known locally as "the marsh." Its floor is now agricultural land.

Local interest in this rather subtle feature of the rural landscape came about from the publicity given to lunar craters and their counterparts on Earth as the national space program developed. Could this round lake bed, located on high ground miles away from other lakes and framed partly by quartzite bedrock, be a deeply eroded meteorite impact structure analogous, perhaps, to the well-publicized Meteor Crater in Arizona? Experts in the field were asked about this possibility and several informal opinions were reported in the press that called upon glacial processes rather than an extraterrestrial impact to account for the round depression. So far, however, no geomorphic/glacial explanation has been fully developed and supported by hard scientific evidence. On the other hand, no credible evidence for the impact hypothesis has come to light either. The purpose here is to offer evidence in support of a geomorphic/glacial origin for this relatively unique lake bed, acknowledging at the outset that it has some aspects that do not fit readily into standard models for the formation of glacial lakes.

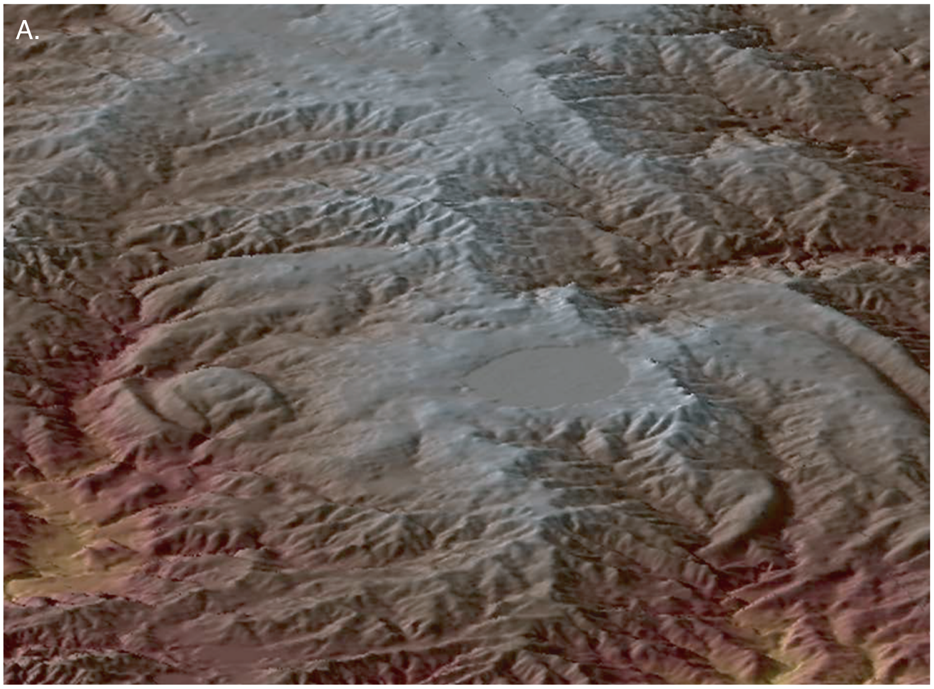


Figure 1. A. Oblique model of the present topography in northern Rock County, Minnesota, looking north, that shows the closed, circular depression southeast of Jasper (center, diameter about 1.9 miles [3 kilometers]) and its surroundings. The vertical scale of the image is greatly exaggerated. Image courtesy of M.P. Crane, U.S. Geological Survey.

B. Aerial photograph of the closed, circular depression in the present agricultural landscape. The view is extracted from a Google Earth image created from data acquired in 2010 by the Farm Service Agency, U.S. Department of Agriculture. The center of the depression is located at lat 43.831°N., long 96.301°W.

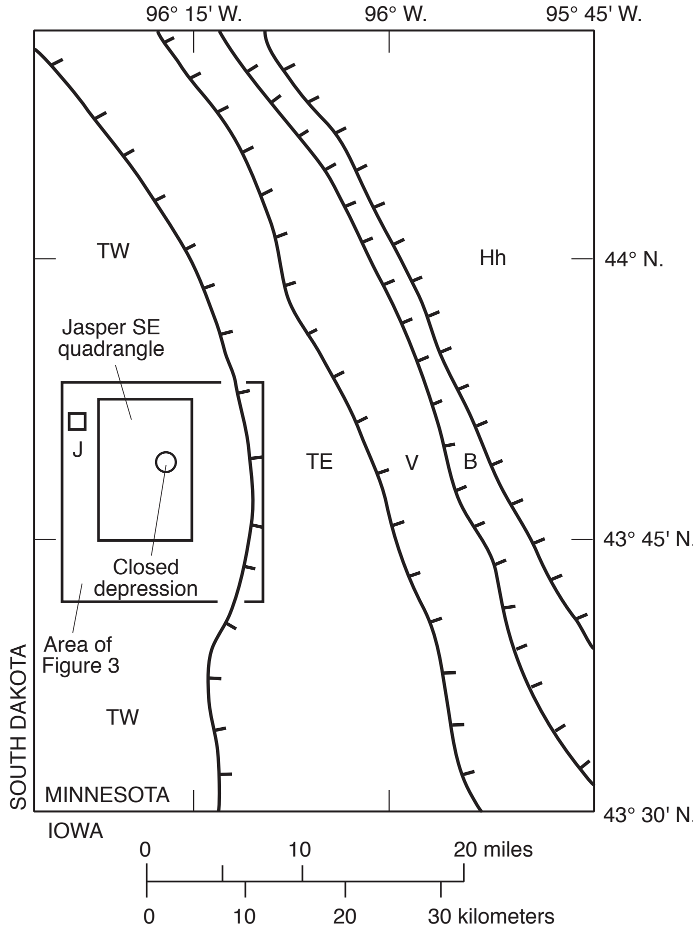


Figure 2. Map of southwestern Minnesota modified from Patterson (1997) that depicts the geomorphic regions recognized in regional investigations of the Quaternary surficial deposits. Hachured lines indicate positions of glacier margins; hachures are toward the glacier. TW—west Trosky region; TE—east Trosky region; V—Verdi till plain; B—Bemis moraine (Buffalo Ridge); Hh—hummocky highland region. Surface deposits in regions V, B, and Hh were deposited by phases of the Late Wisconsinan Des Moines lobe. Surface deposits in regions TW and TE are older. The area of Figure 3 (outer box), the Jasper SE 7.5-minute topographic quadrangle (inner box), the closed, circular depression, and the town of Jasper (J) are indicated.

REGIONAL GEOLOGY OF THE GLACIAL DEPOSITS

The closed depression is located in the central part of the Trosky geomorphic region of southwestern Minnesota (Patterson, 1997), which is an upland area of erosionally sculpted Sioux Quartzite (Late Paleoproterozoic Era) mostly covered by Quaternary deposits of glacial and periglacial sediment (Fig. 2). Regional geologic mapping and associated studies of surficial deposits in southwestern Minnesota (Patterson, 1995, 1997) show that the till and related glacial deposits in the Trosky region are pre-Wisconsinan in age, meaning that they are older than and project beneath the succession of sedimentary strata deposited from the Wisconsinan advances of Des Moines-lobe ice into south-central Minnesota and north-central Iowa between 30 and 11 Ka. The western limit of Des Moines-lobe deposits is a mapped boundary about 12 miles (20 kilometers) east of the present study area where deposits from the Verdi glacial advance (Verdi phase; about 30 to 20 Ka) overlap tills characteristic of the Trosky region (Fig. 2). Furthermore, the preserved pre-Wisconsinan section of glacial deposits is as thick as 328 feet (100 meters) or more throughout most of the Trosky region, except for a relatively restricted area of northern Rock County, where high-standing quartzite bedrock is close to the present land surface. The circular depression is located in the quartzite-floored area where the glacial deposits are thin.

Stratigraphic studies of the pre-Wisconsinan glacial deposits in southwestern Minnesota employ a nomenclature in which subsurface till units are numbered downward in sequence, starting with the uppermost till unit as number 1 (Patterson, 1995, 1997). Eight superimposed units of pre-Wisconsinan till are recognized in the subsurface about 19 miles (30 kilometers) north of the present study area (Patterson, 1997). Till units 1 through 5 encountered there correlate with a sequence of tills in northeastern South Dakota in which an ash bed dated at 610 to 740 Ka (the perlite O layer) occurs between till units 3 and 4 (Gilbertson and Lehr, 1989).

However, only till units 1 and 2 occur in the vicinity of the closed depression where they are recognized in scattered surface exposures and near-surface drilling intercepts. The age of these units therefore is bracketed stratigraphically between 740 Ka, the maximum age of the O layer ash, and 30 Ka, the maximum depositional age of the overlying Verdi-phase till.

A further age constraint comes from studies of cosmogenic radioisotopes ^{10}Be and ^{26}Al in samples from glacially scoured surfaces of Sioux Quartzite outcrops within the present study area that are overlain directly by till units 1 and 2 (Bierman and others, 1999). The abundance and ratios of these isotopes in samples of exposed rock surfaces are proportional to the length of time the surfaces have been exposed to cosmic radiation. When evaluated in various assumed scenarios of exposure history, such as continuous exposure versus periods of exposure interspersed with periods of cover, the isotopic data are interpreted to indicate that 575 ± 57 Ka have elapsed since the striated quartzite surfaces were last covered by glacial ice (Bierman and others, 1999). It appears, therefore, that the glaciation responsible for the deposition of till units 1 and 2 occurred between 740 and about 520 Ka (the mid-Pleistocene Epoch).

Till units 1 and 2 are distinguished from each other on the basis of differing proportions of lithic grain types in the sand-size fraction of aggregate samples. Otherwise the two are very similar in color and bulk texture and therefore are difficult to distinguish in the field. Till unit 1 contains sand-size grains of Precambrian crystalline rock, Paleozoic carbonate rock, and Cretaceous shale in the average cumulative percentage ratio of 45:41:14; in till unit 2 the average grain ratio is 73:21:6. The Precambrian fraction in both till units includes grains specific to bedrock sources in the Lake Superior basin (agate, basalt, red felsite) as well as grains derived from bedrock sources widely present throughout the Canadian Shield (granitoid rocks, greenstone, metagraywacke, gray felsite).

Till units 1 and 2 have not been found in direct stratigraphic contact within the present study area and it appears likely that they are separated by an interval of lacustrine and fluviatile deposits over a considerable part of the Trosky geomorphic region. Lacustrine and/or fluviatile deposits are recognized between till units 1 and 2 in northeastern South Dakota (Gilbertson and Lehr, 1989) and in the rotary-sonic drill core that provided key stratigraphic support for the eight-fold subdivision of the pre-Wisconsinan till section in Minnesota (Patterson, 1997). Specific to the present investigation, drilling in the floor of the closed, circular depression (Southwick and others, 1993) penetrated two till units separated by an interval of lake clay and outwash sand. The lower of the two tills overlies Sioux Quartzite directly and is interpreted to be regional till unit 2. The upper till is interpreted provisionally to be regional till unit 1. Further details on the materials encountered in the subsurface of the closed depression are presented below.

Reconnaissance-level outcrop sampling and determinations of lithic sand-grain proportions indicate that till unit 2 predominates at the surface in the western sub-area of the Trosky geomorphic region (area TW in Fig. 2) and that till unit 1 predominates in the eastern sub-area (TE in Fig. 2). The boundary between sub-areas TW and TE is a former glacial margin mapped on geomorphic and geologic criteria that Patterson (1997) discussed in detail. This margin is interpreted to mark the approximate boundary between glacial ice on the northeast and open ground on the southwest when stagnating ice responsible for depositing till unit 1 was still on the landscape. A zone now occupied by the circular depression and its immediate surroundings would have been bounded by melting ice on the east and quartzite-cored hills on the west during this unmeasured but presumably brief interval of mid-Pleistocene time.

Immediately west and north of the depression the sequence of glacial deposits consists of a lower unit of gray to red-brown sandy to clay-rich till, provisionally interpreted to be mostly till unit 2, that contains rare clasts of Lake Superior-type banded agate and Keweenawan-type amygdaloidal basalt, and an upper unit of loess. Together these units sum to a thickness of less than 16 feet (5 meters) on the broad upland west the depression. In much of that area the till was eroded away prior to the deposition of loess, and loess directly overlies quartzite. South and east of the depression the sequence of glacial deposits is between 33 and 83 feet (10 and 25 meters) in thickness and includes a substantial fraction of outwash gravel and reworked gravelly till interstratified with in situ till and loess. In summary, the immediate west and northwest frame of the depression consists of quartzite bedrock mantled by thin till and loess, whereas the immediate frame on the northeast, east, and southeast consists of thicker till, outwash gravel, and loess.

BEDROCK TOPOGRAPHY AND ITS GEOMORPHIC IMPLICATIONS

Figure 3 is a contour map of the top of the Sioux Quartzite in its principal area of exposure in Rock County, Minnesota. The quartzite surface is uneven; in generalized terms it is an undulating upland of broad hills and intervening swales that is bounded by steep slopes and low cliffs on its west, south, and east sides. Short, steep valleys were cut into the marginal cliffs by pre-glacial streams that drained the upland into surrounding lower terrain. Some and possibly most of these valleys existed in Late Cretaceous time. Morphologically similar bedrock valleys in the edges of the Sioux highlands in southeastern South Dakota contain shallow marine and estuarine strata of Late Cretaceous age that were deposited when the Sioux highlands stood as a series of islands near the eastern margin of the Western Interior Seaway (Ludvigson and others, 1981; Shurr, 1981; Witzke and others, 1983; Hammond, 1988; Setterholm, 1994). Much of the Sioux highlands, including the portion in southwestern Minnesota, underwent deep subaerial weathering prior to the deposition of Upper Cretaceous marine and non-marine sedimentary strata (Austin, 1970). The principal effect of weathering was physical disintegration of the generally strong and chemically inert quartzite; during Late Cretaceous marine transgression the quartz sand and silt produced by weathering of quartzite were deposited close to the shorelines of the Sioux islands and were the principal sedimentary fill within the bedrock estuaries along the island coasts. After withdrawal of the Late Cretaceous sea the quartzite islands stood as topographic knobs and ridges above a relatively flat lowland floored by Upper Cretaceous sedimentary strata. The lowland landscape was modified by stream erosion during the 65 m.y. interval between the end of Late Cretaceous sedimentation and the onset of Pleistocene glaciation, but remained generally of low relief.

The circular depression is situated over a bedrock swale just above the head of a deep, south-trending box canyon in the paleotopographic surface of the Sioux Quartzite (Fig. 3). This box canyon is interpreted to have been the upper end of a coastal estuary during Late Cretaceous marine transgression. It continues southward from the present study area to the town of Hills, where a well drilled for water encountered a 26-foot (8-meter) interval of silica-cemented sandstone and black shale that is analogous in its composition and sedimentological properties to Upper Cretaceous estuarine deposits assigned to the Split Rock Creek Formation in South Dakota (Ludvigson and others, 1981; Setterholm, 1994).

The general shapes of the bedrock swale and the box canyon down slope from it appear to be governed by fracture patterns in the quartzite (Fig. 4). The dominant directions of vertical jointing are north–northeast and west–northwest. The vertical joints, coupled with subhorizontal joints, enable the quartzite to separate into blocks and to erode selectively along north–northeast and west–southwest trends. The tendency for joint-controlled low cliffs and step-like blocky slopes to form is well displayed in present-day quartzite outcrops, and prolonged tropical weathering along joints in pre-Late Cretaceous time would have enhanced the development of a blocky, joint-controlled, pre-glacial microtopography. It is reasonable to conclude, therefore, that the buried paleotopography of Rock County reflects joint control on a regional scale, and that joint-controlled cliffs a few feet to tens of feet high and trending north–northeast and west–northwest were prominent features of the pre-glacial landscape on the Sioux upland. A steep, north to northeast-trending, east-facing slope 40 to 45 feet (12 to 14 meters) high that is located in the quartzite topographic surface just west of the circular depression (Fig. 3) is likely to have been steeper and higher before glacial erosion and may have been an effective barrier to westward transport of glacially derived sediment during episodes of glacial melting. The south-draining box canyon south of the depression is likely to have been present prior to glaciation, and as previously emphasized, to have been partially filled with easily erodible Upper Cretaceous sedimentary rock. It may have served repeatedly as a conduit for glacial meltwater and its upper end may have been a waterfall or steep cascade that migrated headward in response to high meltwater discharge.

GLACIAL STRIATIONS AND INFERRED LOCAL PATTERN OF ICE FLOW

Outcrops of Sioux Quartzite throughout the study area display a remarkable array of glacial striations that record multiple directions of ice transport. In general, the freshest striations (the grooves that are least degraded by weathering) are interpreted to record the directions of the most recent ice movements. Inasmuch as the glacial advances from which till units 2 and 1 were deposited are the two that most recently traversed the area, the freshest striations are interpreted to be a record of their local flow paths. Sixty striation directions were measured on 45 quartzite outcrops within the study

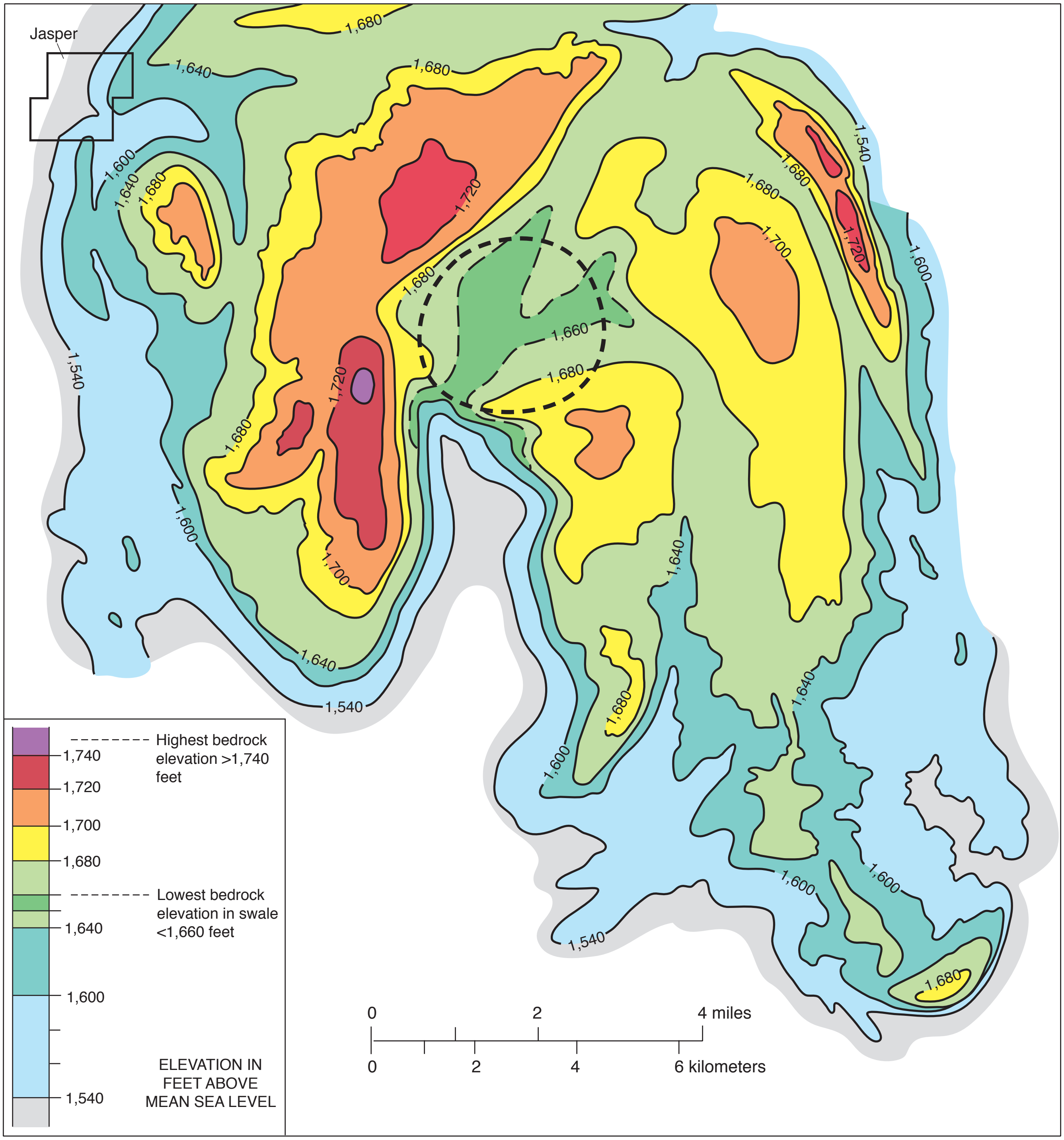


Figure 3. Generalized bedrock topography of the study area scaled to emphasize features discussed in the text; the closed depression is shown by a black dashed line. Note that the vertical intervals between contours are not equal. Map modified from Patterson (1997).

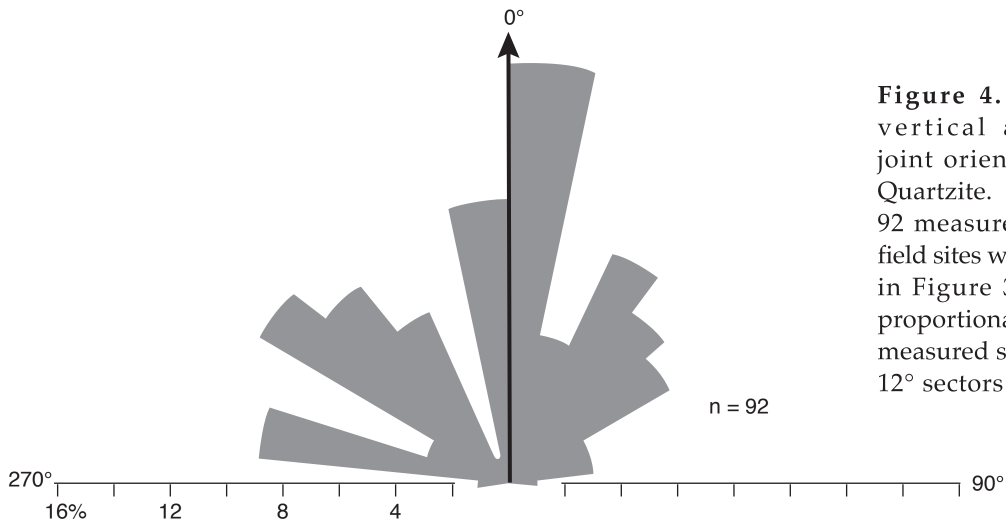


Figure 4. Rose diagram of vertical and near-vertical joint orientations in the Sioux Quartzite. The diagram includes 92 measured orientations at 45 field sites within the area depicted in Figure 3. Vane lengths are proportional to the percentage of measured strike azimuths within 12° sectors of arc.

area. At 13 of the sites there are two generations of well-preserved striations readily distinguishable as "older" and "younger" on the basis of observable cross-cutting criteria. Nine of these sites are located on the relatively flat top of the quartzite-supported upland west of the closed depression. There, the older striation directions cluster tightly around azimuth 202 (implied ice flow toward the south–southwest; Figs. 5, 6A), and the younger striation directions cluster tightly around azimuth 170 (implied ice flow slightly east of south). Single striation directions measured at 19 other sites on the smooth upland align with one or the other of the directions observed at the doubly striated locations. The striation picture is less regular east and southeast of the closed depression where the bedrock topography is lower, more dissected, and generally much rougher than on the smooth upland to the west (Fig. 3). Four doubly striated quartzite outcrops were found in that general area; the older measured directions cluster around azimuth 180 (implied ice flow due south; Figs. 5, 6B) and the younger directions cluster loosely around azimuth 221 (implied ice flow toward the southwest). As in the upland setting, the striation directions measured on singly striated outcrops align with one or the other of the directions observed at the doubly striated locations. It is inferred from these data that the overall direction of ice transport across the area was south–southwest, but that local flow paths were influenced by the knobby, uneven pre-glacial topography developed on the geomorphically strong Sioux Quartzite. It is further inferred that the ice from which till unit 2 was deposited moved across the top of the quartzite highland approximately on azimuth 202 and that the ice responsible for till unit 1 crossed approximately on azimuth 170. It does not follow that these flow paths necessarily pertain to the regional flow of the pre-Wisconsinan glacier across the relatively flat and smooth paleotopography of north-central Minnesota and adjacent areas of North and South Dakota, north and northeast of the quartzite highland.

WIND ABRASION AND INFERRED WIND DIRECTION

Many outcrops of Sioux Quartzite in the study area exhibit small-scale features of eolian abrasion such as polished, pitted, scalloped, or fluted surfaces, faceted corners, and rounded, smoothed, polished edges. Meter-scale quartzite blocks and boulders that rest on quartzite pavement also display evidence of eolian abrasion. The eolian features invariably are on west- or northwest-facing surfaces, indicating that the abrading airborne sediment was driven by winds from the west and northwest. In several places the glacial striations on the outcrop and even the primary ripplemarks on quartzite bedding planes have been partly to totally obliterated by eolian abrasion.

As previously noted, Bierman and others (1999) concluded from isotopic evidence that exposed quartzite surfaces in this area were last covered by ice and/or sediment about 520,000 years ago. In other words, the most recent glacier left the area in the mid-Pleistocene Epoch, creating the possibility that eolian scour of exposed quartzite surfaces could have begun roughly a half million years ago. The observed degree of scour supports the contention that the outcrops of hard quartzite have been exposed to the wind for a long time, and that

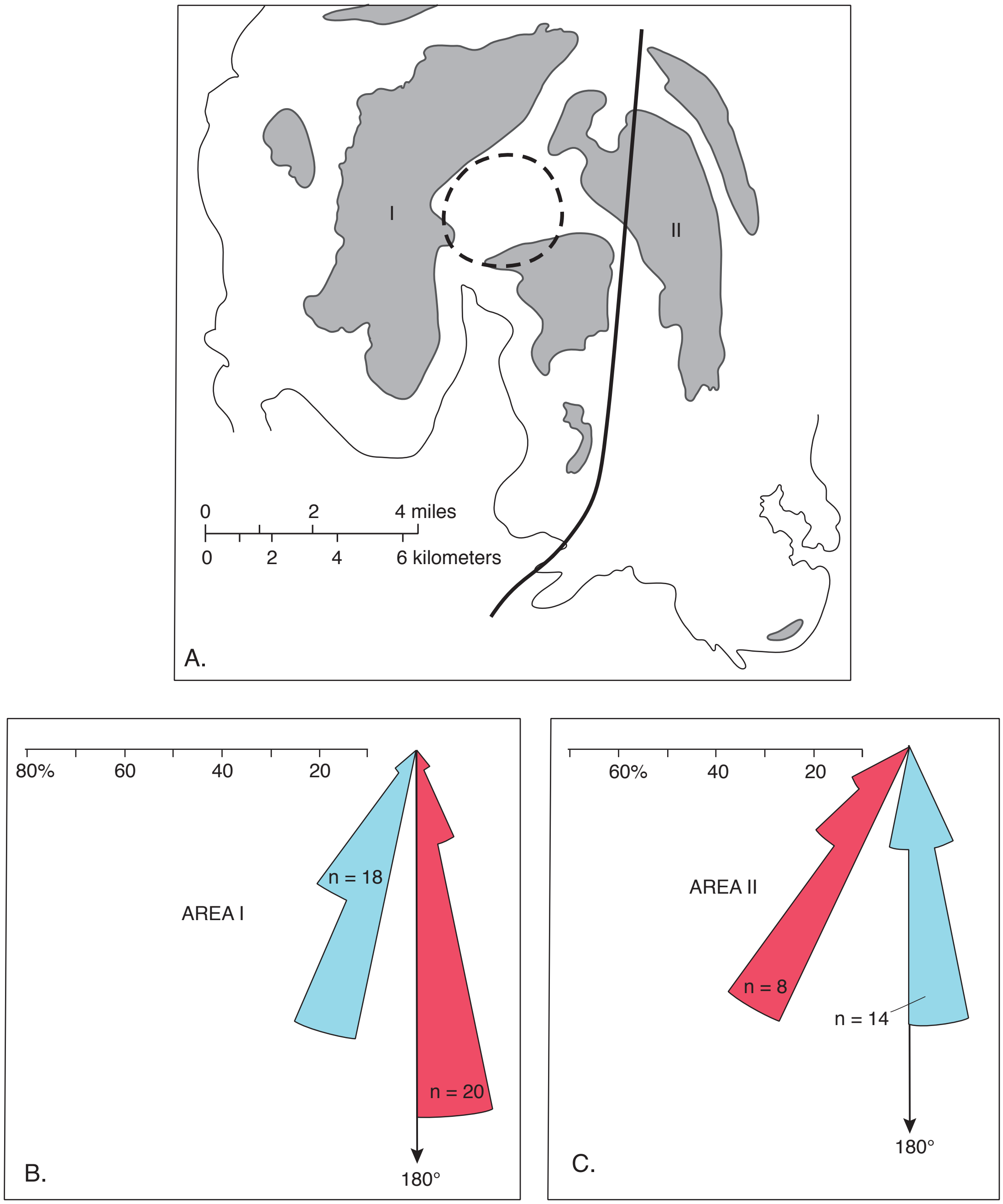


Figure 5. Rose diagrams of glacial striation azimuths measured on outcrops of Sioux Quartzite. Vane lengths are proportional to the percentage of measured lineation azimuths within 12° sectors of arc.

A. Sketch map that delineates sub-areas I and II (thick black line). Areas in which the bedrock surface is higher than 1,680 feet (512 meters) are shaded. The closed depression is shown by a dashed line.

B. Measured orientations in sub-area I.

C. Measured orientations in sub-area II.

the prevailing wind direction throughout the long period of exposure has remained consistently from the west and northwest.

STRATIGRAPHIC OBSERVATIONS WITHIN AND NEAR THE CLOSED DEPRESSION

The stratigraphic section of surficial deposits above quartzite near the center of the circular depression is known from a single scientific exploration boring completed in 1990 (Southwick and others, 1993). The 52.8-foot (16.1-meter) thick section consists, from the base upward, of about 23 feet (7 meters) of weakly calcareous, clay-rich pebbly till of mixed regional provenance, about 2.1 feet (6.4 meters) of interbedded sand, clay, and poorly sorted clayey gravelly sand that are interpreted to be a sequence of outwash and lake deposits, about 4.9 feet (1.5 meters) of very calcareous clay-rich till of mixed provenance, and about 3.9 feet (1.2 meters) of plastic lake clay rich in organic matter. A shallow seismic sounding within the depression about 0.52 mile (0.83 kilometer) due north of the exploration boring determined a thickness of 47.9 feet (14.6 meters) for the Quaternary section. A second sounding about 656 feet (200 meters) beyond the north rim of the depression determined a thickness of 82 feet (25 meters) for the Quaternary section. Thicknesses reported in the descriptive logs of water wells drilled within 1.2 miles (2 kilometers) of the east and southeast sides of the depression range between 46 and 82 feet (14 and 25 meters). Thus the thickness of the surficial deposits beneath the depression is commensurate with thicknesses outside the depression on all sides except the west and northwest, where the surficial deposits are much thinner.

The complex 21-foot (6.4-meter) section of interstratified sandy beds and lake-clay beds that was encountered in the subsurface of the depression demarcates an interval of meltwater flow and ponding between the ice advances that are recorded in the subjacent and superjacent units of till. This view is substantiated by drillers' logs for water wells drilled in the arcuate area of thick surficial deposits southeast of the depression that describe interbedded units of hard clay, sand, and smooth clay. These descriptive units are interpreted to be till, outwash, and lake clay, respectively, and to indicate a stratigraphic history of interspersed ice advance and meltback consistent with conditions at the margin of a waning and stagnating glacier. The inferred stratigraphic history is also consistent with that obtained from rotary-sonic drilling in sub-area TE of the Trosky geomorphic region about 19 miles (30 kilometers) to the north (Patterson, 1997).

ORIGIN OF THE CIRCULAR DEPRESSION

The geomorphic origin proposed for the circular depression is predicated on the following observations, interpretations, and assumptions:

1. The depression is located close to the top of a geomorphically resistant bedrock highland that has been a topographic high for at least 65 million years. Quartzite bedrock is overlain by thin glacial deposits on the northwest side of the depression and somewhat thicker glacial deposits on the southeast side. The glacial deposits are of pre-Wisconsinan, mid-Pleistocene age.

2. Regionally, the pre-Wisconsinan sequence consists of as many as eight till units but only the uppermost two (units 1 and 2) occur near the depression. These tills are younger than the maximum age of 740 Ka determined on the O perlite layer in South Dakota and older than the bedrock exposure age of 575 ± 57 Ka determined isotopically on glacially striated surfaces in the immediate vicinity of the closed depression. Therefore the depression cannot have formed earlier than roughly 520,000 years ago, and given the absence of evidence for glacial activity younger than that in the Trosky geomorphic area, it is likely that it formed as a consequence of processes associated with the two most recent mid-Pleistocene glacial advances.

3. The stratigraphic sequence of surficial deposits beneath the depression consists of a basal carbonate-poor till, a medial unit of sandy deposits and clay layers indicative of outwash and lacustrine depositional environments, and a thin upper unit of carbonate-rich till. The basal till is correlated with regional till unit 2, as mapped by Patterson (1995, 1997), and the upper till unit is correlated with regional till unit 1.

4. The glacier responsible for both till units advanced from the north–northeast or northeast. The earlier advance surmounted the quartzite upland west of the circular depression and deposited regional till unit 2 directly on quartzite bedrock (Fig. 6A). Eventually, the glacier melted off the top of the quartzite upland, and its western margin retreated eastward to a position a few miles east of the depression, where it apparently remained for a significant but undetermined length of time.

5. During and following this meltback interval, meltwater stream deposits and local lake deposits

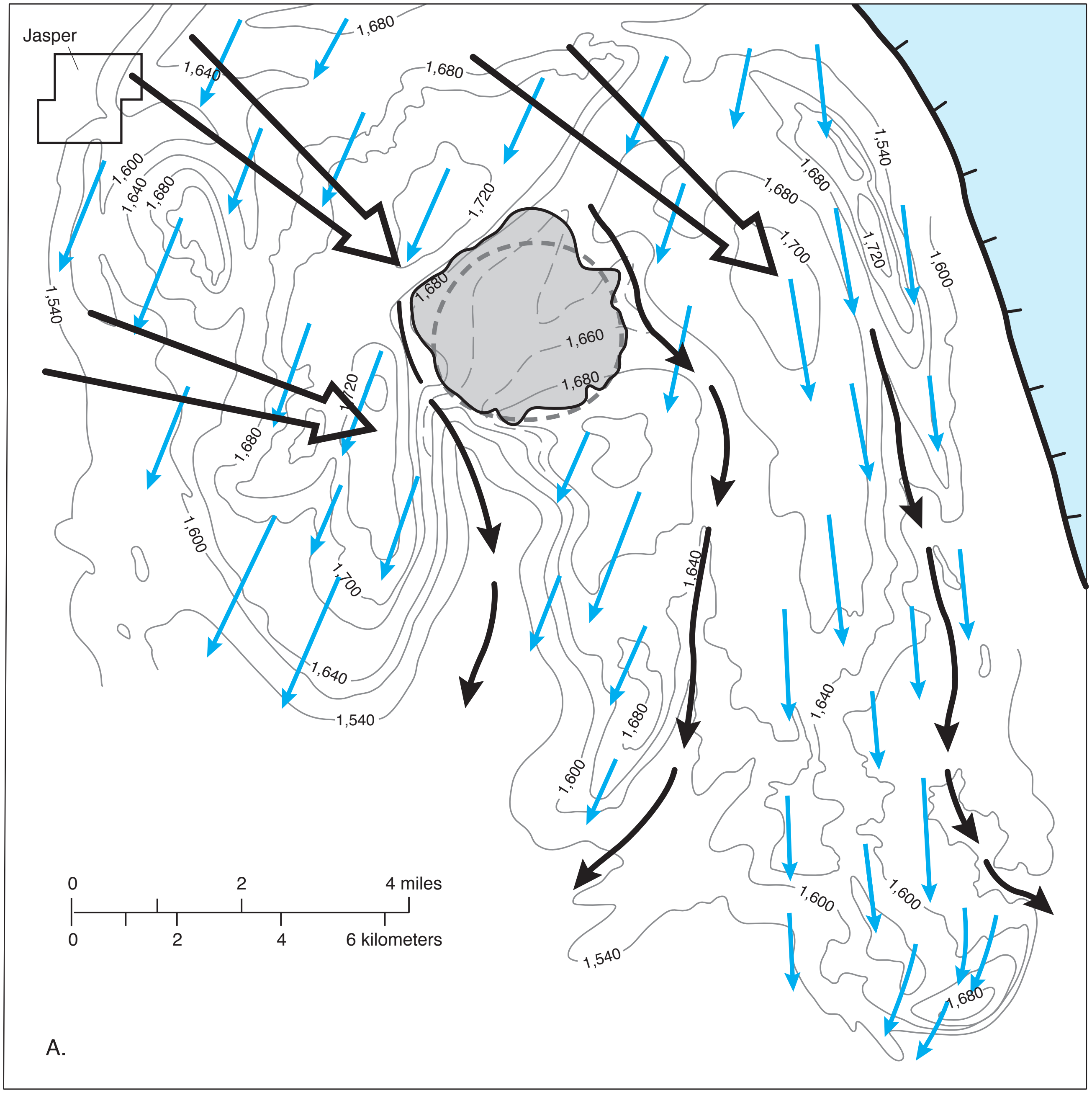
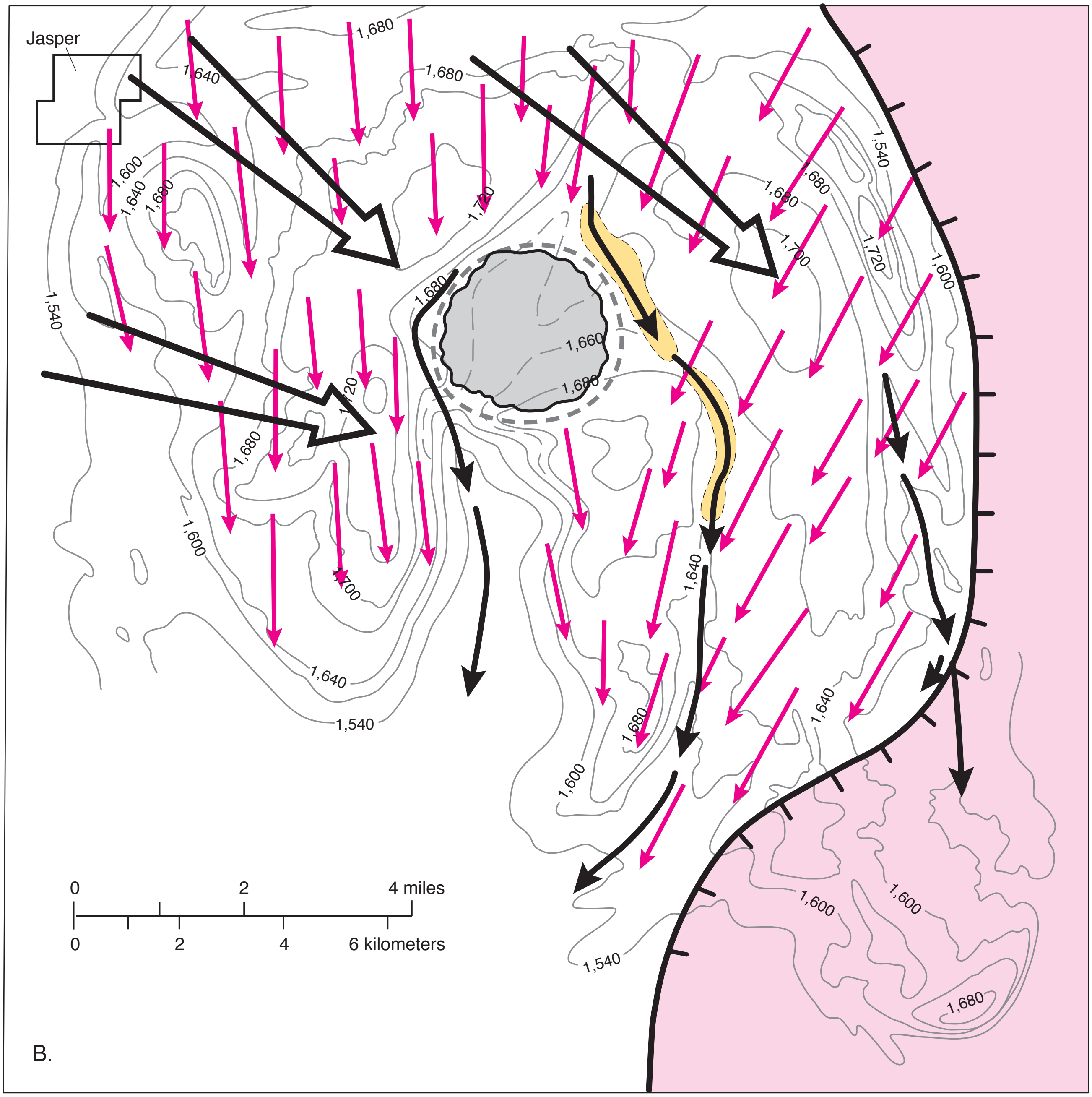


Figure 6. Genesis of the closed depression in two schematic snapshots superimposed on the bedrock topography of Figure 3; the closed depression is shown by a thick dashed line. Large, open arrows denote the prevailing wind direction; black arrows represent meltwater streams. Note that the contour intervals are not equal.

A. Interglacial stage following the first ice advance. Bedrock outcrops have been engraved with the older set of striations (blue arrows) and till unit 2 has been deposited. The glacier margin (blue) has retreated to a position east of the closed depression; an isolated remnant of ice is preserved in a bedrock swale in a position that corresponds to the eventual surface location of the depression (gray). Prevailing northwest winds deposit loess on the denuded highland and the remnant outlier of glacial ice. South-flowing meltwater streams deposit sediment around the ice remnant and eventually on top of it; loess deposition continues.



B. Meltback position following the second glacial advance. The main glacier (pink) has expanded southwestward to a margin beyond the bedrock-supported highland and then retreated to a marginal position east of the closed depression. Bedrock outcrops are engraved with the younger set of striations (magenta arrows) and till unit 1 has been deposited. The remnant block of older ice (gray; now somewhat smaller) and its blanket of stream deposits and loess were overridden by ice and topped by till unit 1; loess deposition continues. The depression preserved in the present topography was produced when the buried block of older ice eventually melted and the surface above it collapsed. Yellow polygons outline stream gravel deposits.

accumulated between the western edge of the stagnant glacier and the eastern slope of the quartzite upland. Loess blown from the recently exposed upland by the prevailing northwesterly wind was deposited in the same area.

6. The glacier expanded southwestward a second time, overriding outwash, loess, and lacustrine deposits that had accumulated along its western margin during the meltback interval. The western margin of this relatively minor expansion may have stalled temporarily at or near the steep, east-facing bedrock slope just west of the circular depression before surmounting the bedrock highland and moving an unknown distance farther southwest. Most of the till deposited from it on the highland (such as regional till unit 1) apparently has been lost to post-glacial erosion.

The scenario proposed for the origin of the circular, closed depression is a site-specific variant of the classic buried ice-block model for the formation of closed, glacial lake basins in outwash plains. In this case, however, the local environment was not a typical outwash plain in that the total section of glacial sediment was only a few tens of feet thick, consisted principally of till rather than outwash, and was deposited on an irregular bedrock surface that was resistant to modification by glacial processes. Rather, it is inferred that specific conditions in the immediate vicinity of the yet-to-form depression were conducive to isolating and temporarily preserving a mass of glacial ice against the eastern flank of the quartzite upland during the meltback stage that followed the first glacial advance (Fig. 6A). In particular, ice may have accumulated to greater thickness in the bedrock swale than elsewhere in the vicinity and therefore was late to melt. Furthermore, shadowing from the late-day sun would have retarded melting near the east-facing slope on the west side of the swale, and once surficial deposits atop the upland were exposed, the prevailing northwesterly winds would have blown loess onto the surface of residual ice located on the lee side of the upland. The covering of loess would have further retarded melting. In all likelihood the residual ice mass was more or less tabular or lenticular in shape, that is, it was thin relative to its horizontal dimensions and not an approximately equant block.

Eventually, outwash and lacustrine deposits surrounded and buried the isolated mass of stagnant ice. Upon southwestward resurgence of the main glacier (Fig. 6B), here termed the second glacial advance, the buried ice lens and its covering of periglacial outwash sediment and loess were overridden by coherent glacial ice and regional till unit 1 was deposited on top of them. The highly calcareous composition of till unit 1 in the vicinity of the circular depression may be due in part to calcareous loess incorporated from the overridden periglacial section. When ice of the second advance and the older isolated ice lens finally melted, a collapse depression formed in the revealed landscape where the ice lens had been. In time the depression became a shallow, marshy lake.

The conditions and sequence of events proposed to account for the closed depression may have been unique. The model depends critically on a relatively shallow bedrock swale being located close to the fluctuating margin of a stagnating but sporadically resurgent glacier. Bedrock swales in which isolated slabs of stagnant ice may have survived for appreciable lengths of time are uncommon in the generally hilly, subglacial topography of Rock County (Fig. 3), and none other than the one under discussion is located close to a mapped glacial margin. Moreover, the long-term preservation of a closed depression partly framed in unconsolidated sediment would require a favorable position with respect to erosional potential in the periglacial and post-glacial landscapes. The Rock County depression is located near the top of the quartzite upland that undergirds the present landscape and was also a prominent high in immediate post-glacial time. In this position it was in the headlands of streams in the periglacial and post-glacial environments and therefore was relatively unaffected by energetic stream erosion. In summary, it is concluded that the combination of site-specific origin and favorable location with respect to long-term geomorphic preservation is sufficient to explain the unique existence of the Rock County closed depression in the quartzite-floored part of the Trosky geomorphic region.

WHAT ABOUT METEORITE IMPACT?

Although the depression is intriguingly circular in plan view (Fig. 1), the underlying bedrock surface does not exhibit the circular crater shape that would be expected if a meteorite struck either outcropping quartzite prior to glaciation or quartzite thinly covered by ice or glacial deposits during glacial or post-glacial time (Fig. 3). Field investigations within and near the closed depression have not revealed any geologic indicators of hypervelocity impact in the quartzite bedrock or the overlying glacial deposits. No shatter cones, impact breccia, or impact-melt rocks have been found in quartzite outcrops or in glacial clasts large enough to retain those features. Furthermore, no deformation lamellae have been found in quartz that indicate the passage of a hypervelocity shock wave through the Sioux Quartzite, despite thorough petrographic search for them in samples from quartzite core in the interior of the depression and quartzite outcrops within a zone about 1.2 miles (2 kilometers) wide northwest of the depression rim. Other sorts of lamellae are present in the quartz (Southwick and others, 1993) that indicate applied stresses in the range of 100 to 200 MPa (Drury, 1993), a condition commonly reached in the environments of rock diagenesis and low-grade regional metamorphism. Missing are specific crystallographic and morphologic types of deformation lamellae that develop under conditions of shock metamorphism in which transient stresses of 5 to 20 GPa and higher are attained (Alexopoulos and others, 1988; Officer and Carter, 1991; Drury, 1993; Stoffler and Langenhorst, 1994). Therefore, in the absence of recognition criteria typically associated with hypervelocity meteorite impacts elsewhere on Earth (French and Short, 1968; Officer and Carter, 1991; Stoffler and Reimold, 2006; French and Koeberl, 2010), there is no reason to perpetuate the meteorite-impact hypothesis for the origin of the singular closed lake basin southeast of Jasper in Rock County, Minnesota.

ACKNOWLEDGEMENTS

Discussions over the years with colleagues Carrie Jennings, Dale Setterholm, G.B. Morey, and P.W. Weiblen shaped my thinking on this topic and are gratefully acknowledged. I am especially indebted to Morey for his thorough review of this paper in 2012. Bevan French and Jan Tullis examined images of deformation lamellae in quartz grains in Sioux Quartzite and concluded that the lamellae were not produced by hypervelocity shock. I thank these experts on impact metamorphism and quartz deformation for their input.

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