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SHORTER CONTRIBUTIONS TO THE GEOLOGY OF THE SIOUX QUARTZITE (EARLY PROTEROZOIC), SOUTHWESTERN MINNESOTA

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PETROGRAPHY AND PALEOCURRENTS OF THE LOWER PROTEROZOIC SIOUX QUARTZITE, MINNESOTA AND SOUTH DAKOTA

By

Richard W. Ojakangas and Richard E. Weber

ABSTRACT

The lower Proterozoic Sioux Quartzite is exposed at several localities within an east-trending area 300 km long and 50 km wide between Mitchell, South Dakota, and New Ulm, Minnesota. The quartzite unconformably overlies Archean rocks and is overlain by Cretaceous strata and Pleistocene glacial materials.

The formation consists predominantly of orthoquartzitic sandstone. Minor quantities of interbedded conglomeratic orthoquartzite occur in the lower two-thirds of the section, and thin beds of mudstone occur in the upper third. The orthoquartzite is compositionally and texturally mature and is composed largely of well-rounded, well-sorted, monocrystalline quartz and lesser amounts of detrital chert and iron-formation. Grains of polycrystalline quartz are abundant at several places, including New Ulm where they were derived from underlying granite, and near Jackson where they occur in the lower half of the exposed section. The framework grains are coated with thin films of iron oxide and indurated by an epitaxial quartz cement. Multicycle grains with abraded quartz overgrowths beneath the latest cement are present in most orthoquartzite thin sections. Rounded zircon and minor rounded tourmaline make up the nonopaque detrital heavy mineral fraction.

Two types of conglomeratic rocks are present--coarse basal conglomerate and conglomeratic orthoquartzite. The basal conglomerates at two localities contain clasts, as large as 35 cm, of vein quartz, jasper, iron-formation, quartzite, and rhyolite. The conglomeratic orthoquartzite units are characterized by scattered pebble-size clasts of quartz in beds 1 to 10 cm thick. The pebble-rich beds are intercalated with units of cross-bedded, coarse-grained orthoquartzite.

Mudstone within the Sioux is red to dark purple in color, ranges from almost pure claystone to silty mudstone, and is composed dominantly of sericite, quartz, and hematite.

Trough cross-bedding, planar cross-bedding, symmetrical and asymmetrical ripple marks, and mud cracks are the major sedimentary structures. The cross-bedding consists predominantly of narrow troughs 60 to 140 cm wide and 15 to 30 cm thick. Some herringbone cross-bedding is present in the upper third of the section.

Measurements of 1,156 cross-beds have a vector mean of 162° and a variance of 2,668, implying a paleoslope inclined to the southeast. No major vertical or lateral changes in cross-bedding trends were observed. Analysis of 491 ripple marks also indicates a paleoslope inclined to the southeast. Bimodal-bipolar paleocurrent patterns occur in the upper part of the formation.

Most of the Sioux Quartzite is interpreted to have been deposited in a distal braided river-alluvial plain environment. However the upper third of the formation has sedimentary structures that possibly are indicative of a shallow marine, tidally influenced environment.

The Sioux is in part a multicycle sediment, with components derived from older quartzite and iron-formation. However, the great volume of monocrystalline quartz must have been chiefly derived from an extensive, deeply weathered, low-relief terrane of dominantly plutonic rocks that also contained some volcanic and metamorphic components. Paleocurrent patterns imply that this terrane existed to the north of the Sioux outcrop area.

INTRODUCTION

The Sioux Quartzite of early Proterozoic age is preserved as sporadic remnants in a west-trending belt in southeastern South Dakota, southwestern Minnesota, and the very northwestern corner of Iowa (Fig. 1). Known outcrops of the Sioux occur from about 8 km east of Mitchell, South Dakota, to about 8 km southeast of New Ulm, Minnesota, a distance of 300 km. The outcrop belt ranges in width from about 50 km in South Dakota to less than 10 km in the vicinity of New Ulm.

Much of the outcrop belt is characterized by widely scattered exposures that rise no more than a few meters above a ubiquitous till plain of Pleistocene age. However fairly extensive exposures can be found in a few places, particularly along major drainageways where deep, joint-controlled gorges have been cut by late glacial and postglacial streams. It is difficult, however, even in the well-exposed areas, to piece together a complete stratigraphic section.

The Sioux Quartzite consists essentially of three rock types -- orthoquartzite, conglomerate and conglomeratic quartzite, and mudstone. The orthoquartzite is typically pale red to moderate red in color, although white and deep purple varieties also are present. It is fine to coarse grained, and contains scattered lenses of small pebble- and coarse sand-size clasts set in a finer grained matrix. The conglomeratic quartzite units occur for the most part in the lower two-thirds of the formation. They are as much as 10 cm thick, contain pebbles as large as 6 cm in diameter, and form thin to very thick beds. True basal conglomerates are exposed near New Ulm and Pipestone, Minnesota. These units contain rounded clasts, set in a sandy matrix, that are as much as 35 cm in diameter at New Ulm and 16 cm in diameter at Pipestone. Sedimentation units of mudstone as much as 3.6 m thick generally occur as structureless units, but a few exhibit a laminated or very thin-bedded fabric. The units vary in color from brick red to purple. Basal contacts between mudstone and orthquartzite are sharp, whereas the upper contacts commonly pass into thin intervals of argillaceous quartzite and mud-chip conglomerate.

The relative proportions of the different rock types in the Sioux Quartzite are difficult to determine because exposures are small and scattered. On the basis of measurements made on the outcrop, Weber (1981) estimated that the formation is composed of 90 percent orthoquartzite, 8 percent conglomerate and conglomeratic quartzite, and 2 percent mudstone. However this estimate is undoubtedly somewhat biased, for as Baldwin (1951) noted, the conglomeratic quartzite units are resistant to erosion and consequently are well exposed, whereas the mudstone units are readily eroded and rarely form outcrops.

Metamorphism of the Sioux was very mild; diaspore, minor pyrophyllite, and possibly some of the common sericite, which are the only metamorphic minerals, indicate subgreenschist-facies conditions. Faulting, gentle folding and subsequent erosion may have resulted in the division of the Sioux into three "basins" (Southwick and Mossler, 1984, this volume). Undulose extinction in quartz is common, and is accompanied in some specimens by strain lamellae and healed fractures that cross two or more quartz grains and their quartz overgrowths.

STRATIGRAPHY

Although widely distributed, outcrops of the Sioux Quartzite occur extensively in only four areas: the Split Rock Creek area in Minnehaha County, South Dakota, and the New Ulm, Jeffers, and Jasper areas in Minnesota (Fig. 1). Even in these areas, stratigraphic columns must be compiled from scattered outcrops, and therefore are subject to the errors involved in projecting data from as far as 3 km into the plane of section. The lenticular nature of the strata, the uneven surface on which deposition occurred, and losses by subsequent erosion complicate any stratigraphic analysis of the Sioux Quartzite. Despite these complexities, Baldwin (1951) was able to describe the stratigraphic succession of the Sioux Quartzite in some detail, and what follows is modified from his original work.

Section at New Ulm, Brown County, Minnesota

At New Ulm, Minnesota, 19 m of conglomerate crops out 110 m east of a reddish-orange, somewhat weathered, porphyritic granite. Although obscured by modern floodplain deposits, the basal contact of the Sioux Quartzite is inferred to occur in the intervening area. The conglomerate has been subdivided by Miller (1961) into three stratigraphic intervals--a lower basal conglomerate, an intermediate cobble conglomerate, and an upper conglomeratic orthoquartzite.

In this paper, the entire unit will be referred to as basal conglomerate.

A covered interval separates the basal conglomerate from 215 m of orthoquartzite sporadically exposed 2 km to the east. The stratigraphically lower parts of this cluster of outcrops are dominated by orthoquartzite, but several intercalated beds of mudstone and argillaceous orthoquartzite also are present. The stratigraphically upper parts of these exposures also are dominated by orthoquartzite, but in contrast they contain thin to thick layers of conglomeratic orthoquartzite, characterized by scattered pebble-size clasts of siliceous rock fragments.

Section near Jeffers, Cottonwood County, Minnesota

Baldwin (1951) inferred that sporadic exposures in the Jeffers area of Cottonwood County (Fig. 1) represent a stratigraphic thickness of approximately 460 m of orthoquartzite. Outcrops in the lower 60 m of this stratigraphic section consist of quartzite, some of which is argillaceous, and many thin beds of very coarse grained orthoquartzite. The upper part of this interval also contains some very coarse grained beds containing conglomeratic clasts of intraformational mudstone and thin layers of conglomeratic quartzite characterized by small pebble-size clasts ranging in diameter from 5 to 12 cm.

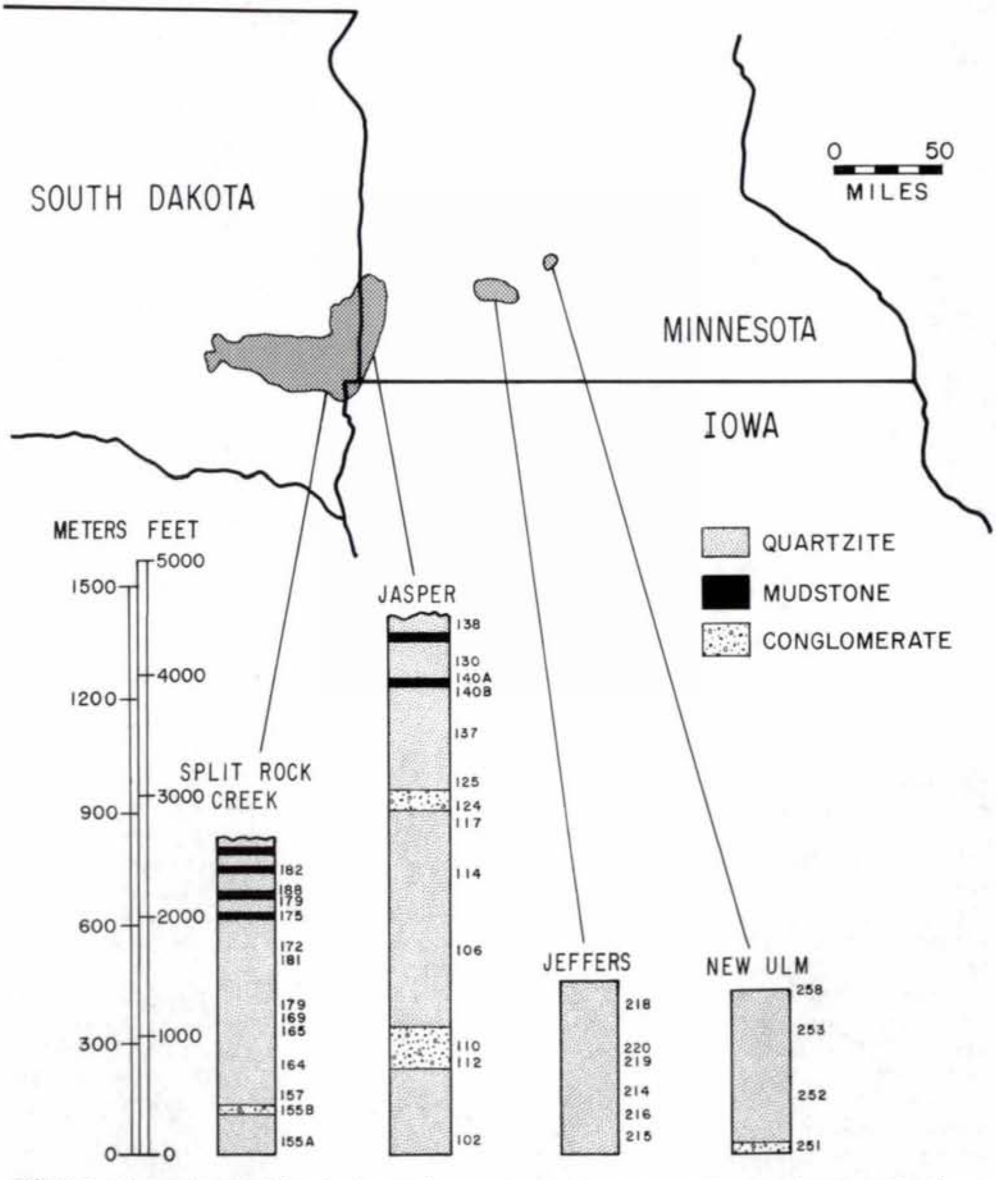


Figure 1. Generalized location map and measured sections of Sioux Quartzite. Numbers refer to samples for which modal analyses are presented in Table 1.

Outcrops throughout the remainder of the section are small and isolated, but seem to consist mostly of coarse grained orthoquartzite with scattered thin beds of conglomeratic quartzite. The stratigraphy of the Sioux Quartzite in Cottonwood County is discussed in some detail by Southwick and Mosser (1984, this volume).

Section near Jasper, Rock County, Minnesota

Baldwin (1951) interpreted the structure of the Jasper area to be a closed syncline, defined by inward-dipping conglomerate layers. This structural interpretation requires that the total section of Sioux Quartzite in the basin is at least 1,540 m and possibly 2,100 m thick. However, because the rocks are not continuously exposed, Baldwin had to piece together the stratigraphic column from scattered outcrops by assuming that specific conglomerate layers were correlative over a broad area. Given the generally fluvial nature of the Sioux Quartzite, this assumption has been questioned by Morey (1984, this volume).

What appears to be the lowest part of the section exposed at Jasper consists of medium- to coarse-grained orthoquartzite containing a few thin layers of siltstone less than 3 cm thick. It is overlain by units of conglomeratic orthoquartzite--the lower conglomerate of Baldwin (1951)--that form an aggregate thickness of more than 120 m. Clasts in the lower 15 m are as much as 7 cm in diameter, but in the remainder of the conglomeratic orthoquartzite are 3 cm or less in diameter. Baldwin inferred that approximately 550 m of orthoquartzite occurs between his lower conglomerate and a second sequence of conglomeratic orthoquartzite some 60 m thick. Most pebbles of the second sequence are less than 1 cm in diameter, but a few pebbles as much as 2 cm in diameter can be found. Baldwin inferred that the remaining 650 m of the section near Jasper consists of orthoquartzite except for two thin mudstone beds.

Section along Split Rock Creek, Minnehaha County, South Dakota

Several writers, including Baldwin (1951), have constructed generalized stratigraphic sections along Split Rock Creek near Garretson in Minnehaha County, South Dakota, where the Sioux is sporadically exposed for approximately 11 km in a direction almost perpendicular to strike. The stratigraphic section constructed by Baldwin (1951) suggests that the Sioux has an aggregate thickness of at least 830 m in this area. However Gries (1983) notes that Baldwin assumed sedimentation on an essentially horizontal surface and thus the true thickness may be considerably less, "should the recorded dips be in part due to original angles of deposition." In fact, Gries (1983) suggests that the Sioux Quartzite over much of South Dakota does not exceed 330 m in thickness and generally is less than 150 m thick.

The lowermost part of the section along Split Rock Creek consists of about 20 m of medium- and coarse-grained orthoquartzite. Many of the quartzite beds contain a few scattered pebble-size clasts immediately above subjacent bedding surfaces. A covered interval of 50 m separates these rocks from approximately 18 m of conglomeratic orthoquartzite characterized by pebble-size clasts 1 to 2 cm in diameter. Beds of orthoquartzite crop out throughout the remainder of the section exposed along the creek; the lower part of this interval is typified by beds having scattered, but abundant pebble-size clasts, whereas the upper part contains argillaceous beds and four discrete mudstone units that are 1 to 3 m thick.

SEDIMENTARY STRUCTURES

Three types of bedding structures are common in the Sioux Quartzite--cross-bedding, parallel bedding, and rippled bedding. Cross-bedding is most abundant, but parallel bedding is also present in most outcrops (Fig. 2). Bedding surfaces are generally marked by thin clay films or by scattered lenses of coarse sand or small pebbles. Beds range in thickness from less than 1 cm to 100 cm; beds 1 to 10 cm thick are the most common.

Three kinds of cross-bedding are present. Trough cross-beds, both medium- and large-scale (Fig. 3), are much more common than planar and herringbone cross-beds. Individual cross-laminae within the troughs range in thickness from less than 1 mm to more than 1 cm. Grain-size differences, placers of heavy minerals, and post-depositional iron staining commonly accentuate the laminae. The traces of the laminae are markedly curved and tangential to the lower surface of the trough. The cross-beds dip at angles of 14° to 27°, because the master beds have dip angles of less than 5°.

Planar cross-bedding is present in about 10 percent of the studied outcrops. The cross-sets consist of straight laminae commonly dipping at angles greater than 27°. The sets range in thickness from a few decimeters to a meter or more; individual laminae are commonly 1 to 2 cm thick.

Herringbone cross-beds (Fig. 4) were observed at four localities. The difference in the direction of dip between adjacent planar cross-bed layers of this type of cross-bed is approximately 180°.

Asymmetrical current ripples are the most common ripple type (Fig. 5). Straight and sinuous forms dominate, lunate and linguloid

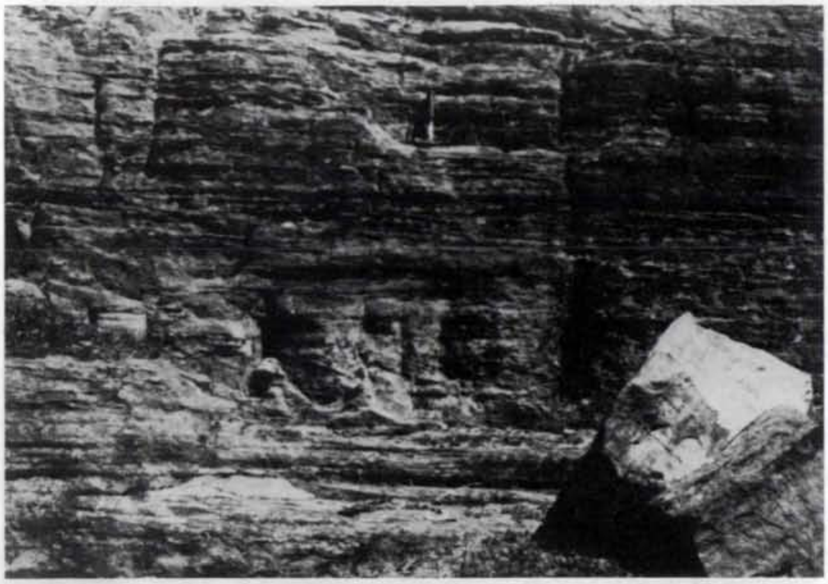


Figure 2. Parallel-bedded (top), very low angle cross-bedded (center) and higher angle cross-bedded (near bottom) orthoquartzite; sec. 8, T. 104 N., R. 46 W.

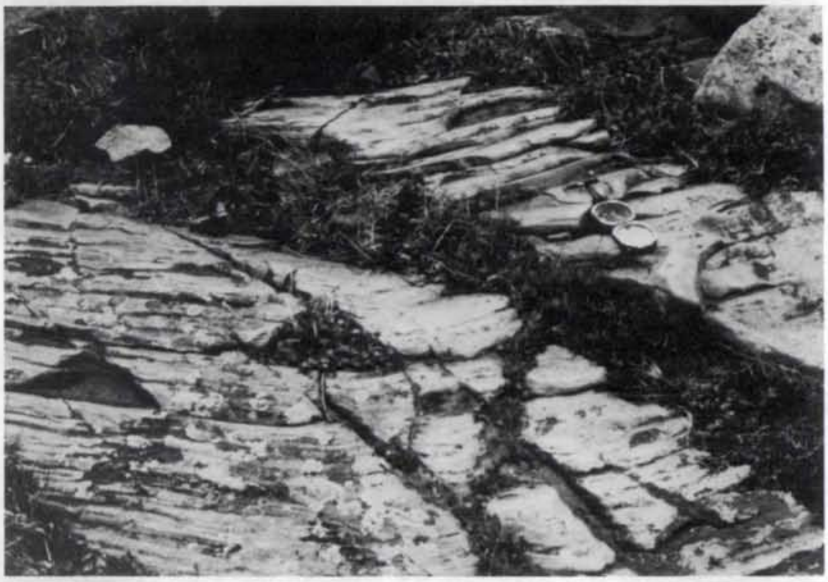


Figure 3. Trough cross-bedding in orthoquartzite; sec. 5, T. 104 N., R. 46 W.

Figure 4. Herringbone cross-bedding in orthoquartzite; sec. 15, T. 100 N., R. 48 W.

forms also are common, and in-phase, asymmetrical climbing-ripples and interference types are rare. Most current ripples have wavelengths of 3 to 7 cm and amplitudes of 1 to 2 cm. Symmetrical ripples have sharp or rounded, straight crests and rounded troughs, an average wavelength of 2.5 cm, and an average amplitude of 0.5 cm. Large ripples have wavelengths as great as 30 cm and amplitudes of 4 to 8 cm.

Mud cracks are present on many bedding planes. The polygons range in size from a few centimeters to more than 0.5 m across, and the desiccation cracks are 0.5 cm to 2.5 cm wide (Fig. 6). Red-colored mud-chip clasts are fairly common in orthoquartzite.

Parting lineation is an uncommon sedimentary structure; it was noted in only two exposures of fine sandstone.

PALEOCURRENT ANALYSIS

Measurements of cross-bed and ripple-mark orientations were made at numerous outcrops to determine paleocurrent patterns (Fig. 7). A number of measurements were made at each outcrop where multiple sets of cross-beds or rippled surfaces are exposed. However only one

Figure 5. Symmetrical (large) and asymmetrical ripple marks in orthoquartzite; sec. 23, T. 104 N., R. 49 W.

Figure 6. Mud cracks in thin sandstone beds. Note camera lens cap for scale; sec. 18, T. 107 N., R. 35 W.

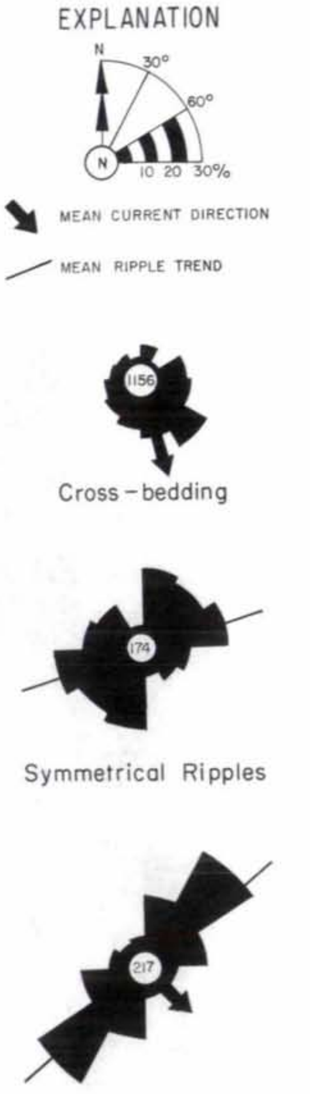


Figure 7. Rose diagrams of cross-bedding, asymmetrical ripples, and symmetrical ripples in Sioux Quartzite. N, number of measurements.

measurement was made for each set of cross-beds or for each rippled surface. A total of 1,109 measurements were made on trough cross-bedding; most (about 95 percent) were the actual trough axes. In addition, 47 measurements were made of planar cross-beds.

The vector mean of all cross-bedding is 162°. Paleocurrent directions toward the south-southwest and south-southeast predominate in all except two of the 27 townships in which cross-beds were measured (Fig. 8). The exceptions are T. 101 N., R. 53 W. in South Dakota and T. 110 N., R. 30 W. near New Ulm, Minnesota. At both of these locations, well-defined unimodal current distributions give paleocurrent means toward the north-northeast.

Plots of cross-bed paleocurrent directions on stratigraphic sections generally show only the expected small variations. In the New Ulm area, however, a major paleocurrent change was observed between the basal conglomerate and overlying orthoquartzite. The cross-beds in the basal conglomerate have a vector mean of 148°, whereas the overlying orthoquartzite shows paleocurrent directions toward the northeast and northwest. The cause of this reversal is unknown.

Bimodal-bipolar cross-bedding was observed in four orthoquartzite outcrop areas. In each, a northward paleocurrent system is present in addition to the normal southward direction (Fig. 9). Each of the outcrops contains herringbone cross-stratification, which indicates that current reversals were periodic. The geographic location of these bimodal outcrops near the southern edge of the Sioux outcrop belt implies that they are restricted to the exposed upper third of the formation.

The trends of 217 asymmetrical current ripples were measured in 15 townships (Fig. 10). The vector mean current direction is 137° (Fig. 7). No systematic geographic or stratigraphic changes were noted, except for a bimodal distribution of a few current-ripple measurements in sec. 23, T. 104 N., R. 49 W. It is significant that herringbone cross-bedding and bimodal-bipolar cross-bedding were also observed at the same locality. A few current ripples giving northward current directions were also observed in sec. 14, T. 103 N., R. 58 W. and sec. 35, T. 110 N., R. 30 W. (Fig. 9); in both, bimodal-bipolar cross-bedding substantiates the existence of a current system oriented 180° to the dominant south-southeast system. All outcrops showing opposite current-ripple systems are in the upper third of the stratigraphic column.

Trends of 174 symmetrical ripple marks from 17 townships were measured to provide information on wave direction and possible shoreline orientation of standing bodies of water. Although some geographic variations do occur,

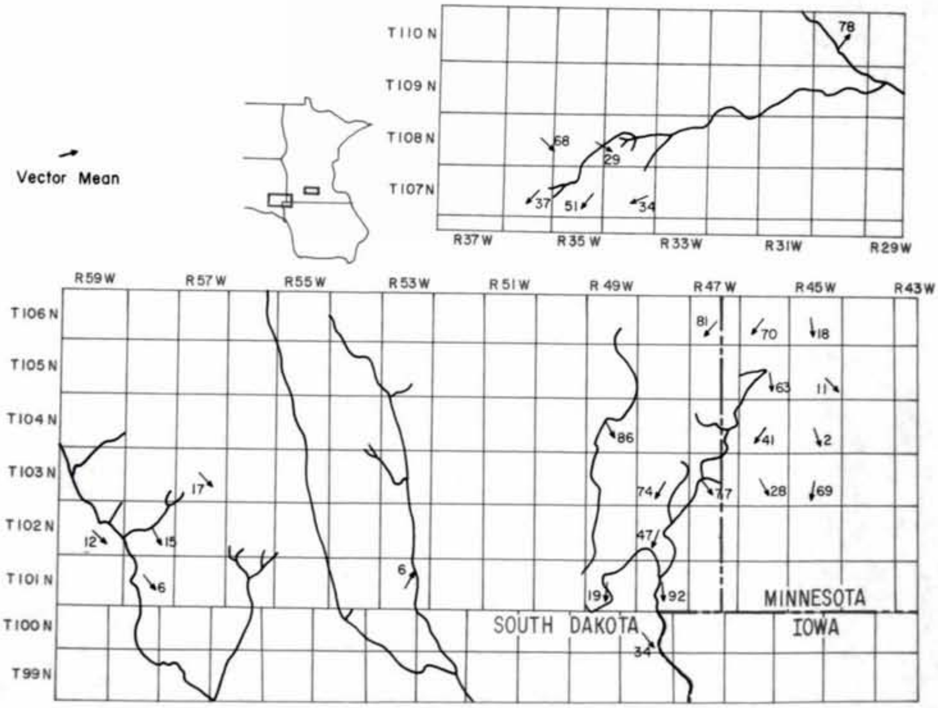


Figure 8. Map showing number of cross-bed measurements and vector mean for each township.

the trends of the ripples are generally northeast-southwest (Fig. 11). In most outcrops, more than 50 percent of the measured directions plot within a 30-degree interval. No major stratigraphic changes in orientations were noted.

In summary, cross-bedding, current ripples, and symmetrical ripples all show a dominant paleocurrent trend to the southeast in the Sioux Quartzite. Two previous paleocurrent analyses of the Sioux have been made. Pettijohn (1957) obtained a mean of 162° (the same as this study) on 39 cross-beds measured at an unspecified number of locations. Dott and Dalziel (1972) plotted 355 cross-bedding measurements and 53 ripple marks from seven locations; they calculated vector means of 269° for trough axes, 178° for cross-beds, and 42° for the trends of ripple crests. The poor agreement between the cross-bedding measurements of this investigation and the orientations of trough axes as determined by Dott and Dalziel may be because more than one-quarter of their measurements were from the New Ulm locality--an area shown by this study to have anomalous paleocurrent orientations with respect to those elsewhere in the Sioux outcrop area.

PETROLOGY

Ninety thin sections of orthoquartzite were studied in detail. Texturally, all samples are very mature. The sand grains are nearly all well to very well rounded, but some grains less than 0.25 mm are subrounded (Fig. 12). Most samples contain only sand-size particles; the mean grain size ranges from very fine sand (0.088 mm) to coarse sand (1.0 mm). Nearly all samples are estimated to be well sorted or very well sorted; five samples in which the sizes of 300 grains were measured are well to very well sorted and skewed slightly towards the coarser grains.

Point-counts of 600 points per thin section were made for modal analyses by Weber (1981); some results are reproduced in Table 1. Monocrystalline quartz commonly composes never more than 95 percent of the framework grains. However, in the section at New Ulm, polycrystalline quartz similar to that in the underlying granite constitutes as much as 77 percent of the grains, and in the lower half of the section near Jasper, it commonly composes 15 percent of the grains. Chert, some hematitic, is present in trace to minor amounts. Grains of iron-formation and quartzite are rare. A careful scan of each slide at high power showed that abraded quartz overgrowths beneath younger overgrowths occur in 84 percent of the samples; some slides contain as many as 25 such grains (Fig. 13). No feldspar was detected by staining in any samples investigated in this study, and none was detected by previous workers (Baldwin, 1951; Miller, 1961). However, Southwick and Mossler (1984, this volume) noted trace amounts of feldspar in drill core samples, and thus diagenetic breakdown of feldspar to clay is indicated.

Fifteen heavy mineral separates revealed an abundance of well-rounded zircon, commonly zoned, and minor well-rounded brown and blue tourmaline grains. These two minerals make up the nonopaque, detrital, heavy mineral assemblage.

Authigenic quartz cement commonly makes up 5 to 10 percent of the rock. Some chert cement is present in the New Ulm area. Hematite cement is commonly present beneath quartz overgrowths, and sericite is present as crystalline aggregates replacing quartz cement. Diaspore replaces the quartz cement, and commonly occurs in about three-fourths of the samples as irregular masses or as tabular crystals. Austin (1972) noted that diaspore is present in surface samples but appears to be absent in samples from deeper levels in quarries, and suggested that the diaspore may have formed during Mesozoic weathering. However, diaspore is now known to occur at depths greater than 250 m below the present land surface (Southwick and Mossler, 1984, this volume) and can be interpreted as the result of feldspar diagenesis (Vander Horck, 1984).

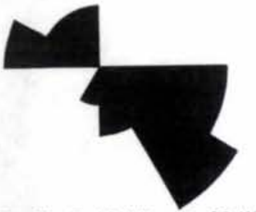
Conglomerate

The basal conglomerate at New Ulm (Fig. 14), although probably resting on granite, contains no granitic clasts (Miller, 1961). The stable rock types that are present are vein quartz, chert, iron-formation, and quartzite. According to Miller (1961), the clasts of iron-formation and chert are similar to the lower Proterozoic iron-formations of the Lake Superior region. The quartzite clasts in the New Ulm conglomerate are similar in all respects to the quartzite in other parts of the Sioux, and their presence raises important questions about the synchronicity of red quartzites in the Lake Superior region (e.g., Dott, 1983). The quartzite clasts are composed of fine to medium, subrounded to rounded grains, more than 90 percent of which are monocrystalline quartz. The grains are covered by a thin film of iron-oxide and are cemented by epitaxial quartz. The sandy matrix of the conglomerates is chiefly polycrystalline quartz similar to that in the underlying basement. Authigenic sericite has replaced some of the quartz cement.

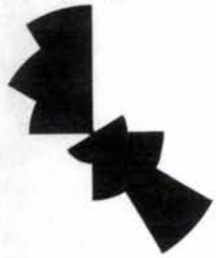
A second conglomerate, inferred on structural and lithologic evidence to be basal, is exposed near Pipestone, Minnesota, in sec. 36, T. 106 N., R. 47 W. This conglomerate is composed of boulders and cobbles of orthoquartzite, vein quartz, hematitic chert, mudstone, rhyolite and welded rhyolite tuff (Southwick, oral comm.,

Sec. 22, T. 104 N., R. 49 W.
N = 12

Sec. 17, T. 102 N., R. 49 W.
N = 5



Sec. 23-24, T. 101 N., R. 49 W.
N = 19



Sec. 15, T. 100 N., R. 48 W.
N = 20

Figure 9. Plots of bimodal-bipolar paleocurrent measurements at four outcrops of orthoquartzite. N, number of readings.

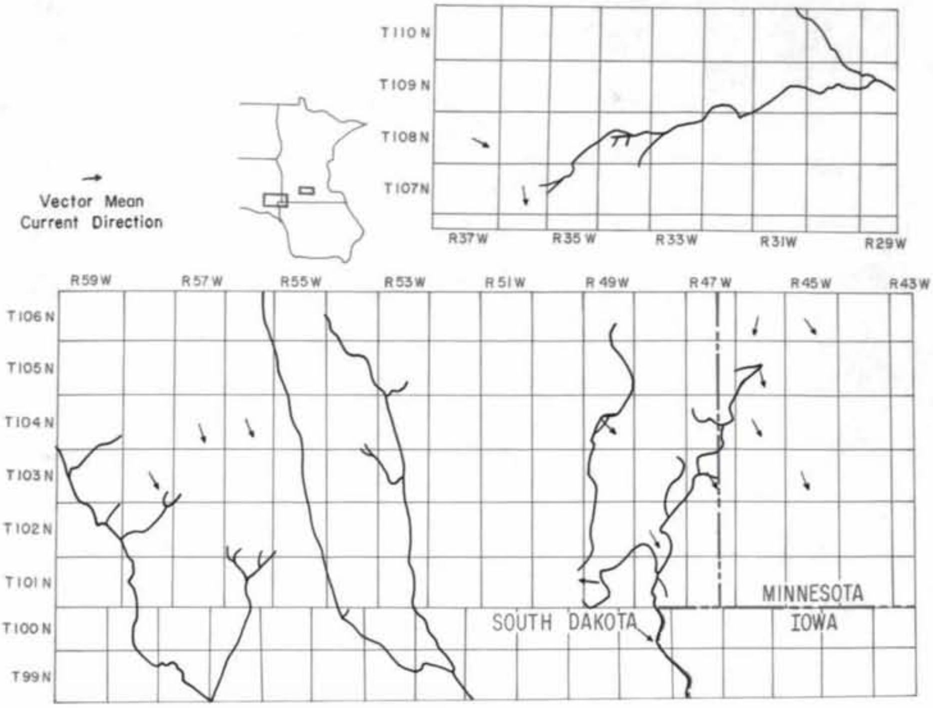


Figure 10. Map showing vector mean of asymmetrical ripple marks by township.

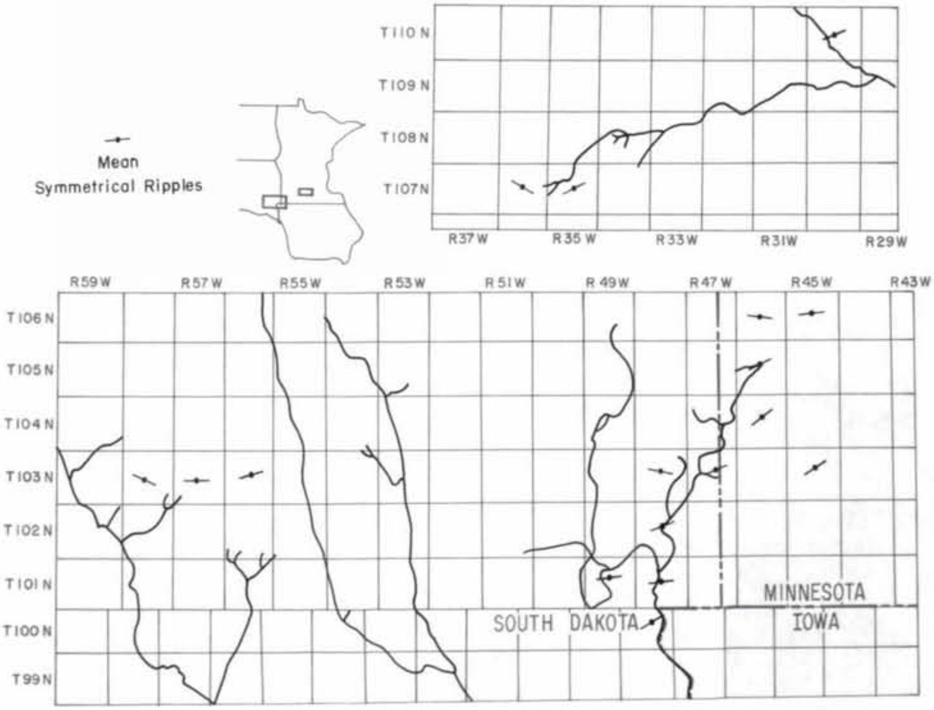


Figure 11. Map showing average trends of symmetrical ripple marks by township.

Table 1. Modal analyses of orthoquartzite in the Sioux Quartzite
[From Weber (1981, p. 147-148). See Figure 1 for sample locations.
T, trace; -, not detected]

Sample	Monocrystalline quartz	Polycrystalline quartz	Chert	Hematitic chert	Quartz cement	Hematite	Opaque minerals	Sericite	Diaspore
102	77	15	1	-	-	-	-	T	7
106	77	15	3	-	2	1	-	1	1
110	89	5	T	T	4	-	-	-	2
112	89	4.5	T	-	2.5	1	-	1	2.5
114	94	5	T	-	0.5	-	-	-	0.5
117C	75	20	0.5	0.5	3	-	0.5	-	0.5
117B	87	6.5	T	-	2.5	T	-	-	4.5
124A	88.5	4.5	T	T	5	T	-	-	1
125	88.5	4	T	T	4	-	-	-	3
130A	91	4.5	1		2	-	-	-	2
137	89	5	T	T	4	-	-	-	2
138	93.5	3	T	T	2.5	-	-	-	1
140	93	2	-	-	3	-	-	-	2.5
155A	93	3	T	T	2.5	-	-	1	T
155B	92	4	T	0.5	2	-	1	-	-
157	91	7	-	-	2	-	-	-	-
164	90.5	3	T	T	2	-	-	3	1
165	94	2	0.5	-	3.5	T	-	-	T
169	85	10	T	-	3	-	-	1	T
172	95	2	T	-	3	-	-	0.5	T
175B	95	3	T	T	1	-	-	-	0.5
179	95	1.5	-	-	2	-	-	1.5	-
181	94	1.5	0.5	-	2.5	-	-	1.5	-
182B	85	3	T	-	3.5	-	3	4.5	-
188A	94	4	T	-	1.5	-	-	-	T
214	82	6	2	0.5	4	T	-	-	4.0
215A	87	5.5	T	-	3	-	-	-	0.5
216B	86	3.5	0.5	-	7	-	-	-	6
218	82	4	3	0.5	10	-	-	-	T
219	77	3	1	-	8	8.5	T	-	-
220	83	6	1.5	-	8	T	1	-	0.5
251	16	65	T	3	15.5	-	2	-	-
252B	76	14	3	1	1	-	0.5	-	5
253	60	26.5	4	0.5	12	-	-	2.4	-
258	72.5	9.3	1	0.5	3.6	-	2	8.6	T

1984) in a matrix of coarse to medium sand and argillaceous material. The conglomerate is coarsest at the base and grades upward into argillaceous orthoquartzite with scattered beds of coarse cobble conglomerate. Quartzite clasts are the most common; they are subrounded to well rounded and range in size from 2 to 16 cm. Clasts of vein quartz and hematitic chert are rounded to subrounded and are about equally abundant. Fragments of red and maroon mudstone predominate in some beds. They are similar in composition to the mudstone within the Sioux and occur as angular, tabular fragments 2 to 6 cm across.

Conglomeratic Orthoquartzite

Beds of conglomeratic orthoquartzite in the Sioux are composed of 1- to 6-cm pebbles and cobbles of vein quartz, quartzite, and hematitic chert, together with sparse clasts of banded iron-formation that are well rounded and well sorted. The conglomeratic beds are clast supported and contain a matrix of coarse sand. Heavy minerals, commonly magnetite and lesser amounts of zircon, are placered in streaks in the conglomeratic layers. No major geographic or stratigraphic changes in mineralogy were observed in the conglomeratic orthoquartzite, except that the percentage of chert and quartzite clasts appears to decrease upward in the section.

Mudstone

All the mudstones observed in thin section, except for the so-called pipestone beds at Pipestone National Monument (Morey, 1983 and

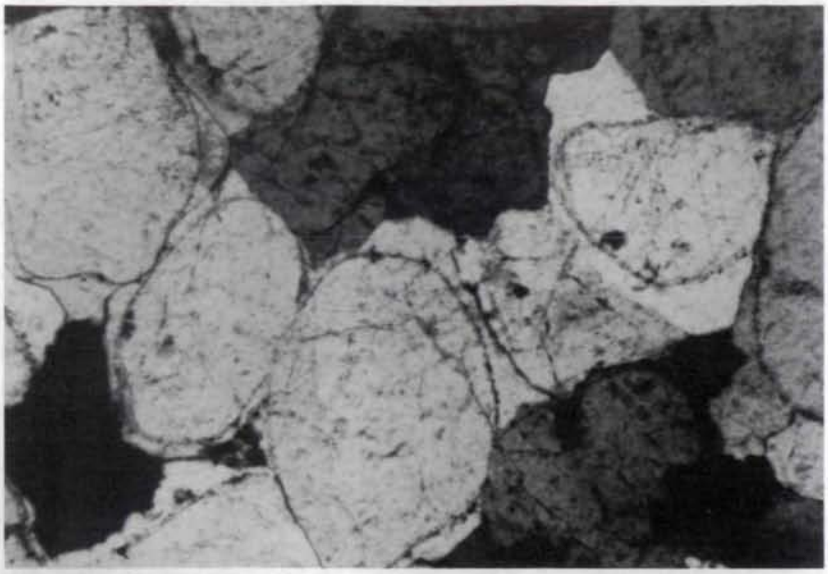


Figure 12. Photomicrograph of orthoquartzite with epitaxial overgrowths of silica. Field of view 2.5 mm wide. Crossed nicols. Sample from sec. 22, T. 104 N., R. 49 W.

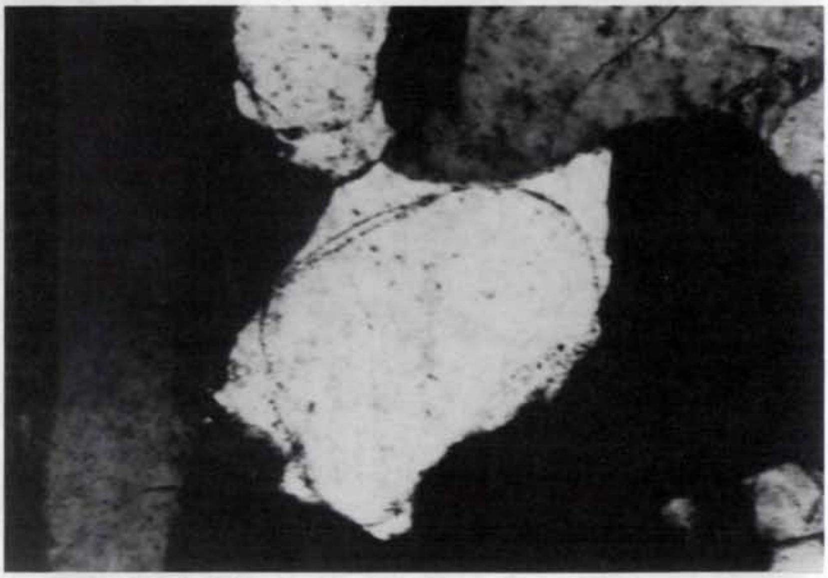


Figure 13. Photomicrograph of multicycle quartz grain with abraided (rounded) silica overgrowth under most recent overgrowth. Minor hematite coats both boundaries. Field of view 1.0 mm wide. Crossed nicols. Sample from sec. 16, T. 104 N., R. 47 W.

Figure 14. Basal conglomerate of the Sioux near New Ulm, Minnesota, in sec. 27, T. 110 N., R. 30 W.

1984, this volume) contain 10 to 25 percent silt-size quartz. At Pipestone, sericite and hematite are abundant, diaspore occurs in some samples, and X-ray diffraction indicates the presence of pyrophyllite. Gundersen (1982; 1984) has conducted detailed studies of the pipestone.

SEDIMENTATION

The basal conglomerates probably are proximal deposits formed in a braided fluvial regime, as indicated by their coarseness, poor sorting, and fining-upward attributes. However, much of the Sioux appears to be similar to the "South Saskatchewan type" model of Miall (1978) or the S_{II} facies assemblages of Rust (1978), in that both represent deposition in a distal, braided river-alluvial plain, sand-dominated river system under dominantly lower flow regime conditions. The ideal cyclicity characteristic of these models was not noted within the Sioux Quartzite. This may be in part because of outcrop sparsity and because the fieldwork for this investigation was accomplished before depositional models were well developed. A generalized facies analysis (after Miall, 1978) shows that the large-scale trough cross-bedding (St), which dominates the sedimentary sequences, is indicative of erosional and depositional processes related to underwater dune formation. The minor planar cross-bedding (Sp) is the result of deposition on bars. Parallel (horizontal) bedding (Sh), with rare parting lineation, represents high-velocity, planar bed flow. Rippled sand (Sr) is common. The conglomeratic orthoquartzites are largely in Miall's Gm facies, with horizontal layers of quartz pebbles representing both deposition on longitudinal bars and lag deposits resulting from washing (winnowing) of pebble-bearing sands. The minor muddy units, some with desiccation cracks, may represent drape deposits (Fm) or waning flood deposits (Fl).

A generally southward paleocurrent pattern with only minor stratigraphic and geographic variations is consistent with deposition in a fluvial regime. The variance of all the cross-bed measurements is 2,668, but if readings from the two anomalous townships were removed, the value would be larger. Long (1978) suggested that variance values of less than 4,000 indicate fluvial deposition, and Potter and Pettijohn (1977) stated that the variance for fluvial deposits is commonly between 4,000 and 6,000.

Structures that can be interpreted as tidal or tidally influenced are the few herringbone cross-beds, the local bimodal-bipolar cross-bedding, and the few bimodal ripple-mark patterns, all in the upper third of the formation (Ojakangas, 1976). An alternative, but less likely explanation is that the herringbone and bimodal-bipolar cross-beds represent lateral accretion on the sides of adjacent bars of a braided fluvial environment.

In summary, we conclude that the Sioux consists largely of fluvial sedimentary rocks with possible marine components in its upper parts. Dott (1983) suggested that "Baraboo interval" quartzites, including the Sioux, were deposited by a combination of braided fluvial and shallow marine processes.

Source Area

The paleocurrent pattern indicates that the source area was located somewhere to the north of the present Sioux outcrop area, as the consistent regional pattern suggests a southward-dipping paleoslope. The monocrystalline quartz could well be first cycle grains, derived from Archean and lower Proterozoic granitoid rocks and Archean gneiss. Some monocrystalline quartz may have come from rhyolites that would be correlative with those that apparently underlie the Baraboo Quartzite in Wisconsin (Smith, 1978). The presence of such rhyolites in the Minnesota-South Dakota-Iowa area is indicated by the presence of rhyolite pebbles in the basal conglomerate west of Pipestone, Minnesota. Lidiak (1971) also reported a rhyolite flow or sill intercalated with the Sioux Quartzite in northwestern Iowa. Dott (1983) also illustrated rhyolite and schist fragments from somewhere in the Sioux Quartzite. However volcanic quartz grains would lack many of their identifying attributes because of the textural maturity of the Sioux and thus would be identified simply as monocrystalline (common) quartz.

Although granitoids, gneiss, and rhyolite were probably important sources of detritus, the presence of pebble-size clasts of quartzite, chert, and iron-formation, together with sand-size grains having abraded quartz overgrowths, indicates that older sedimentary rocks were present in the source area, possibly in substantial quantities. The chert and iron-formation detritus could have been derived from the various lower Proterozoic iron-formations of the Lake Superior region as first suggested by Miller (1961). The only known quartzites north of the Sioux are the lower Proterozoic Pokegama, Mahnomen, and Denham formations of the Animikie and Mille Lacs Groups in northern and east-central Minnesota, but other lower Proterozoic quartzites, including the Sunday, Palms, Ajibik, and Goodrich, are present in Wisconsin and Michigan to the northeast in the Marquette Range Supergroup. All of the above-named formations are relatively thin, and unless they had a much greater extent than they now have, they could not have supplied much of the quartz sand.

The lack of terrestrial vegetation in Precambrian time should have resulted in the rapid maturation, by eolian action, of loose surface material on a deeply weathered, low-lying peneplaned landmass consisting of various rock types. The Archean and Proterozoic granitoids and the Archean gneiss terranes could therefore have supplied much of the quartz in a single cycle of weathering and abrasion.

The accumulation of large quantities of quartz sand, such as are present in the Sioux, poses a problem of whether or not older sandstones were present in the source areas. The Sioux may have covered an area of approximately 50,000 km^2 and may have been 2,000 m thick over much of that area, for a total volume of 100,000 km^3 of quartz sand. This areal estimate may even be conservative, for the coarser, proximal portions of the braided river (and alluvial fan?) complex, which should have formed to the north of the Sioux outcrop belt, apparently have been removed by erosion. Even if this estimate is high by an order of magnitude the volume of quartz sand was still tremendous.

The quartz problem becomes even greater when the Barron and Flambeau, which cover about 6,500 km^2, and the Baraboo, which with related outliers such as the Waterloo Quartzite may cover 4,000 km^2, are considered. If a single basin is assumed, including the recently recognized Washington County quartzite of east-central Iowa (Anderson and Ludvigson, in press), the total area of quartz-rich sedimentary rocks could have been as large as 300,000 km^2. Even if separate smaller basins are assumed, the total volume of quartz sand remains enormous. A low-lying source area of 400,000 km^2, as large as the northern three-fourths of Minnesota, all of North Dakota, and the northern half of South Dakota, would have to have been covered by a residual quartz sand layer 250 m thick to have supplied the quartz sand of the Sioux Quartzite alone.

Tectonic Framework

The apparently great thickness of texturally and mineralogically mature quartz sand requires that the basin of deposition was tectonically unstable and underwent significant subsidence, whereas the source area probably remained relatively stable and low-lying, supplying sediment consisting mainly of quartz and clay minerals. Most of the clay would have been carried through the braided fluvial system and deposited elsewhere to the south of the Sioux outcrop belt. The probable fluvial environment of deposition for most of the sedimentary sequence requires that the basin of deposition was either intracratonic or marginal to a marine environment. The evidence in the upper third of the section indicative of a marine, tidally influenced, environment of deposition is more compatible with a marginal basin.

However, additional evidence, apart from sedimentology, must be available before the tectonic setting of the depositional basin can be ascertained. Several workers, including Dott (1983), Greenberg and Brown (1984), and Anderson and Ludvigson (in press), have synthesized data relevant to the tectonic setting of the red quartzites of the "Baraboo interval."

Dott (1983), on the basis of several lines of evidence including the thicknesses of the quartzites and the presence of marine rocks (black slate, iron-formation, and dolomite) overlying the Baraboo, opted for deposition of the quartzites on a stable, passive, continental margin on the southern edge of a craton. He suggested that the quartzites were subsequently deformed, about 1,615 to 1,630 Ma (Van Schmus and Bickford, 1981), by collision with an island arc or another continent during southward subduction along a suture buried beneath what is now Iowa and Illinois.

Anderson and Ludvigson (in press) generally agree with Dott, but locate the suture farther to the south in order to place the red quartzites recently discovered in the subsurface of Washington County in southeastern Iowa on the same proto-North American continent as the rocks of the Sioux, Baraboo, and Barron Quartzites.

A cratonic (epicontinental) setting was suggested by Greenberg and Brown (1984), with deformation at 1,630 Ma due to anorogenic igneous activity and epeirogenic doming, rather than subduction.

The available information does not allow for a final determination of the tectonic setting. Either a passive continental margin later deformed by subduction, or an epicontinental setting without subduction, would accommodate a depositional setting on the continental margin for the Sioux.

CONCLUSIONS

The pink to red Sioux Quartzite consists of a mature basal conglomerate, a great thickness of trough cross-bedded, silica-cemented, mature orthoquartzite (quartzarenite), and minor amounts of interbedded conglomeratic orthoquartzite and red mudstone. The formation has been subjected to very little metamorphism or deformation. It is present in three major "basins," which may be either depositional or structural. The formation was probably deposited between 1,760 and 1,630 Ma ago, with a mild event causing the metamorphism and slight deformation at about 1,630 Ma.

The Sioux was likely deposited in a braided fluvial-alluvial plain, which was largely a distal environment, as indicated by the conglomerates and conglomeratic quartzites, the sedimentary structures, the unimodal paleocurrent patterns, and the overall low variance. However, some paleocurrent measurements in the upper part of the formation are compatible with a shallow, tidally influenced, marine environment.

The source areas were located to the north of the outcrop area; the paleocurrents transported sediment southward down the paleoslope. Sedimentary rocks composed part of the source terrane, as indicated by quartz grains with overgrowths and by pebbles of quartzite, chert, and iron-formation. However, quartz volume considerations necessitate extensive derivation from felsic plutonic and metamorphic rocks. These probably were deeply weathered and the resultant detritus extensively reworked by eolian action.

We suggest that the Sioux Quartzite was formed in a depositional basin or basins that were probably on a passive continental margin, as suggested by Dott (1983) who placed the other red quartzites of the "Baraboo interval," the Baraboo and Barron, as well as the Sioux, in the same sedimentary-tectonic framework.

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THE SIOUX QUARTZITE AND SUBJACENT REGOLITH IN THE COTTONWOOD COUNTY BASIN, MINNESOTA

By

D.L. Southwick and John H. Mossler

ABSTRACT

Three privately financed diamond core holes were drilled in 1979-1980 through the base of the Sioux Quartzite (inferred age >1,630, <1,760 Ma) in the Cottonwood County basin of southwestern Minnesota. This drilling, in conjunction with careful remapping of surface outcrops, has led to the definition of five provisional stratigraphic subunits within the lowermost 480 m of Sioux Quartzite. It also has revealed a paleo-regolith on the sub-Sioux Archean basement, which is attributed to early Proterozoic subaerial weathering.

The sub-Sioux regolith is characterized by intensive alteration of coarse-grained metamorphic feldspar to fine-grained kaolinite and sericite, and extensive introduction of secondary hematite and silica. The basal 15 m of the Sioux, immediately above the regolith, is a heterogeneous assemblage of interbedded mudstone, siltstone, fine to coarse orthoquartzite, and conglomerate. This interbedding of kaolinitic mudrocks with resistate-dominated conglomerate and grit is evidence that the basal Sioux was derived from a deeply weathered source. Stratigraphically above the basal mixed zone the Sioux is dominantly cross-bedded orthoquartzitic sandstone with relatively minor interbeds of mudstone and shale. Stratigraphic and sedimentological attributes indicate that the Sioux Quartzite of the Cottonwood County basin was deposited from braided streams.

The Cottonwood County basin is interpreted as a northwest-trending, fault-bounded, intracratonic basin having dimensions of about 75 by 150 km. It is one of several en echelon basins that together constitute the east-west outcrop belt of Sioux Quartzite in Minnesota, South Dakota, and adjacent states. The gently southwest-dipping north limb of the basin has been deformed by broad second-order flexures and by two sets of faults.

REGIONAL GEOLOGY

The Sioux Quartzite is a thick unit of generally hard, vitreous, maroon to gray quartzite of early Proterozoic age that occurs in an east-west-trending belt across southwestern Minnesota, southeastern South Dakota, and adjacent areas of Iowa and Nebraska (Fig. 1). It rests unconformably on a complex crystalline basement that is inferred to be dominantly of Archean age in south-central Minnesota; however the basement probably contains rocks of earlier Proterozoic age in extreme southwestern Minnesota and adjacent states. Although the Sioux crops out sparsely, it is extensive in subcrop beneath Cretaceous and Quaternary deposits. Quartzite outcrops are confined to steep-faced stream cuts along the Big Sioux River and its tributaries in southeastern South Dakota, and elsewhere to widely scattered clusters of low, rounded knobs that protrude through the Quaternary glacial deposits on the prairie uplands. The general sparsity of outcrops and lack of stratigraphic control in the vertical dimension have been serious impediments to modern sedimentological study of the Sioux Quartzite, and models for the depositional and tectonic history of the formation remain qualitative and subjective despite some important recent advances (Weber, 1981; Morey, 1983).

Recent drilling in southwestern Minnesota by water well contractors and mineral exploration companies has demonstrated that the Sioux Quartzite covers far less area than it was shown to cover on earlier generations of geologic maps; compare Figure 2 with the map of Austin and others (1970). The east-west-trending "Sioux ridge" or "Sioux arch" is in fact divided into four northwest-trending blocks or basins that contain substantial thicknesses of quartzite; these are separated from each other by positive structural divides where the quartzite is either thin and dissected or absent entirely. The structural divides may reflect differential vertical motion on northwest-trending faults (Fig. 2). Such faulting, which can be inferred from aeromagnetic anomaly patterns and cataclastic

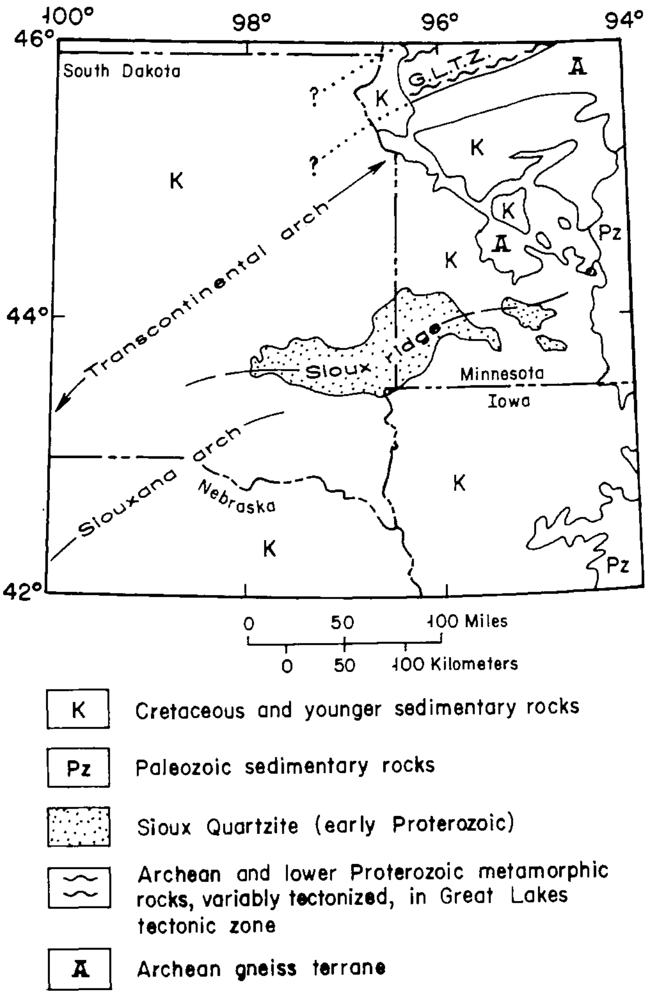

Figure 1. Regional geologic map of southwestern Minnesota, eastern South Dakota, and adjacent parts of Iowa and Nebraska, showing distribution of the Sioux Quartzite.

textures in four bedrock samples along anomaly trends, may have been responsible for individual fault-block basins during the deposition of the Sioux, and faulting may have continued long after deposition and lithification. For convenience of discussion the four subdivisions of the Sioux arch in Minnesota have been termed, from west to east, the Pipestone, Fulda, Cottonwood County, and New Ulm basins (Fig. 2). These "basins" actually are erosional remnants and it is not known to what extent their present map geometry corresponds with that of original depocenters. Basinal structure for the Pipestone basin has been inferred from the map distribution of conglomerate beds which were interpreted as continuous stratigraphic horizons (Baldwin, 1951). This stratigraphic assumption and the derivative conclusion of basinal geometry have been questioned by Morey (1984, this volume). Structural closure cannot be demonstrated for the other basins, although partial closure can be inferred for the Cottonwood County basin, as discussed below.

Medium- to coarse-grained, tightly cemented orthoquartzitic sandstone, typically medium- to thick-bedded and trough cross-laminated, is the dominant lithology of the Sioux Quartzite as seen in outcrop. Weber (1981), judging from outcrop, estimated that the formation as a whole contains about 90 percent orthoquartzite, 8 percent polymict orthoconglomerate, and 2 percent mudstone. Conglomerate beds containing well-rounded pebbles of vein quartz, chert, and quartzite generally are restricted to the lower two-thirds of the section and are most common in the lowermost third; thin beds and partings of mudstone occur throughout the formation, but may be somewhat more abundant toward the top. The basal few meters of the Sioux Quartzite in the New Ulm basin are strongly cross-stratified coarse conglomerate that contains cobbles of vein quartz, chert, ferruginous chert, granular cherty iron-formation, and quartzite, but no fragments larger than sand size of the immediately subjacent Archean granite (Miller, 1961). A similar conglomerate along the west edge of the Pipestone basin, presumably also near the base, contains clasts of rhyolite and welded rhyolite tuff in addition to the pebble types found at New Ulm. Basal beds do not crop out in the Cottonwood County or Fulda basins, but recent core drilling (Fig. 3) has penetrated the basal conglomerate in the Cottonwood County basin and also has revealed a substantial weathered zone in the Archean gneissic rocks beneath it.

The stratigraphic thickness of the Sioux Quartzite is difficult to determine precisely. Baldwin (1951) and Austin (1972) calculated a thickness range of 1,600 to 2,400 m (5,300 to 7,900 ft) for the Sioux in the Pipestone basin, using conglomerate horizons as stratigraphic markers to determine map thickness and assuming an average constant dip of 5° to 7°. This calculated thickness is a minimum because neither the top nor the base of the Sioux is exposed in the Pipestone basin. It is also subject to large probable error because the influences of dip variation and lenticular stratigraphy are not measurable. Despite these uncertainties, however, the Sioux Quartzite clearly is thousands of meters thick and therefore represents a major sedimentological system.

The Sioux Quartzite was deposited in a shallow-water, current-dominated regime, as indicated by the presence of several types of cross-stratification, current ripples, oscillation ripples, scour-and-fill phenomena, rip-up mudstone conglomerate horizons, and desiccation cracks (Baldwin, 1951; Miller, 1961; Weber, 1981; Morey, 1983). Previous workers have proposed several different depositional environments for the Sioux, including shallow marine, intratidal, coastal braided stream, and pediment fan-distributary channel settings. Elsewhere in this paper we present sedimentological data from the Cottonwood County basin that appear to fit

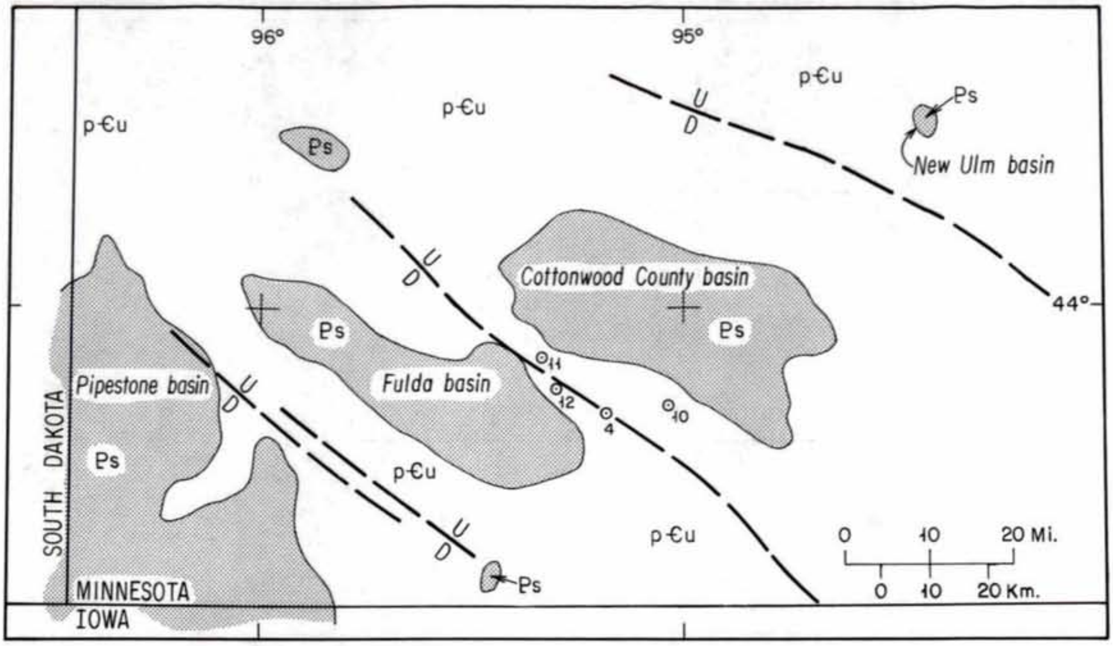

Figure 2. Pre-Paleozoic subcrop map of southwestern Minnesota showing the outlines of the Pipestone, Fulda, Cottonwood County, and New Ulm basins of Sioux Quartzite (Ps) as presently delineated by drilling. The two unnamed patches of Sioux are poorly defined by low-quality drilling data. Heavy dashed lines indicate possible faults in magnetic basement, as inferred from aeromagnetic maps. Basement rocks at sites 4, 10, 11, and 12 have cataclastic textures; the rock at 12 is a refractured blastomylonite.

best with a braided-stream depositional model, and suggest that sedimentation occurred in one or more fault-controlled structural depressions.

THE COTTONWOOD COUNTY BASIN

Structure

Plate 1A is a geologic map of the Sioux Quartzite in Cottonwood County, Minnesota. Master bedding strikes about 110° and dips southwestward at angles of 3° to 14° along "Red Rock Ridge," the principal outcrop area of the Cottonwood County basin, and rotates to a northward strike and an eastward dip in scattered outcrops west and south of Jeffers (Fig. 3). These strikes define the north and west limbs of a gentle basin that trends northwest. The north limb of the basin is deformed by minor flexures with northwest axial trends and by several minor faults. The most prominent transverse flexure is a broad anticline that plunges gently southeastward (about az 130°) across the center of sec. 12, T. 107 N., R. 36 W. (Plate 1) and extends along the strike of its axial surface for several kilometers. Two small faults trend about 130°, nearly parallel to the axial surfaces of the northwest-trending flexures, and probably are related genetically to the shallow flexing of highly brittle quartzite. A second, younger group of faults trends about 065° and delineates a regional fracture zone that extends for several kilometers across the west-central part of the main outcrop belt (Plate 1A). The quartzite near the larger faults in this zone is pervasively crackled by countless small fractures of diverse length and orientation. Many of the fractures in the crackled rock are little faults having displacements of a few centimeters or less, and others are simple joints. Total displacement on the fracture zone cannot be measured accurately because markers are lacking, but it probably is no more than a few tens or hundreds of meters. Slickensides indicate that the latest motion was diagonal-slip with a large left-lateral component.

The northeast-trending fracture zone is colinear with a prominent magnetic lineament in the Archean basement beyond the periphery of the Cottonwood County basin (Philbin and Gilbert, 1966). The magnetic lineament (Fig. 4) is interpreted to define an Archean fault zone that is wholly covered by Sioux, Cretaceous, and Quaternary strata; the fracture zone in the Sioux is thought to record reactivation of the underlying basement fault in post-Sioux time.

The regional paleocurrent study of Weber (1981) has demonstrated that the primary direc-

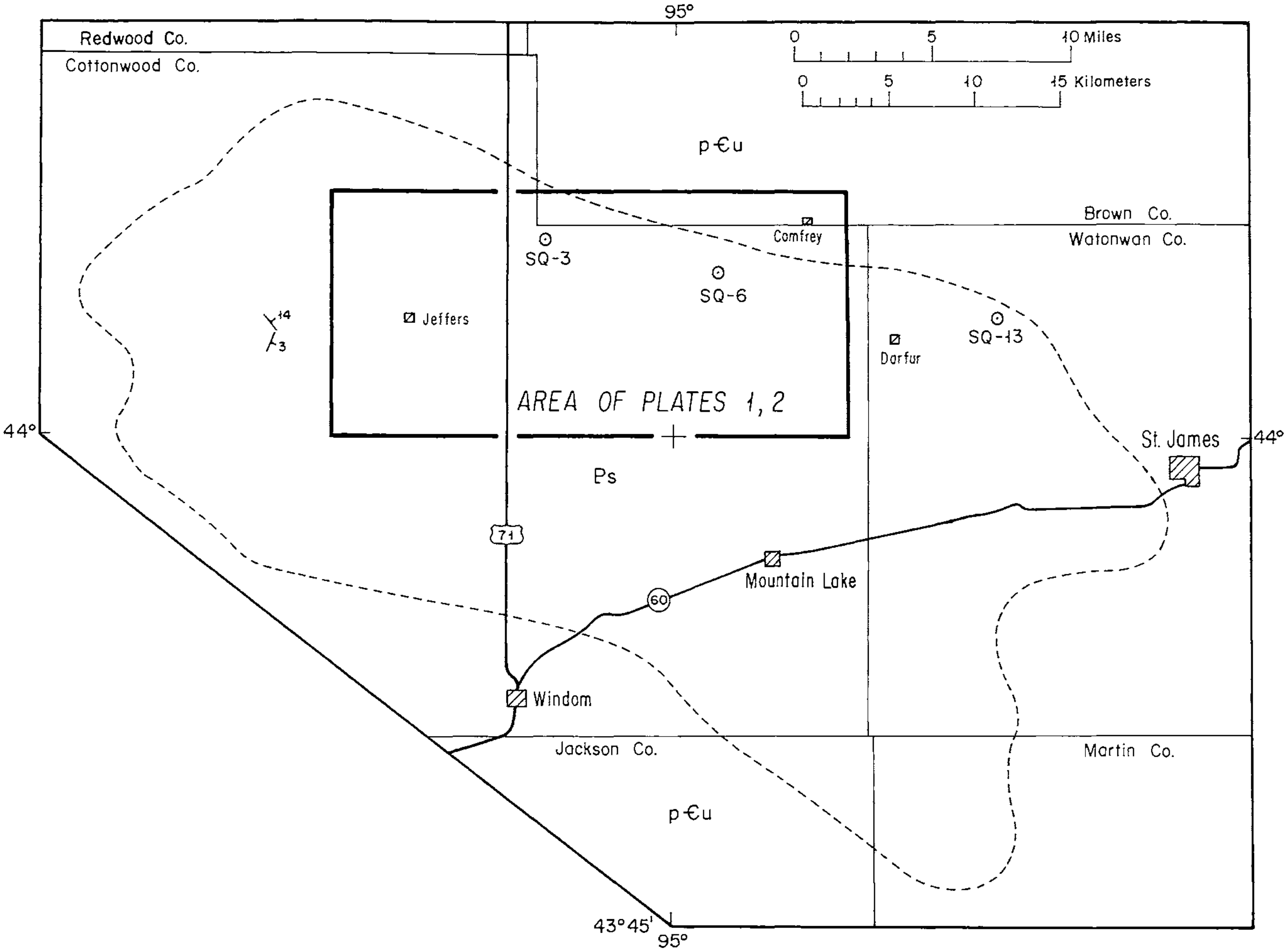

Figure 3. Outline subcrop map of the Cottonwood County basin showing the area on the north limb that is mapped in detail. The structural symbols west of Jeffers are on two isolated outcrops of Sioux Quartzite that are outside the area of detailed study. Drill holes discussed in the text are shown by number. Unit p€u is Precambrian gneiss, undivided.

tion of sediment transport in the Cottonwood County basin was toward the southeast (az 162°) with a subsidiary maximum toward the southwest (also see Plate 1B). Weber noted that the paleoslope corresponds approximately to the present dip direction, and concluded from this correspondence that an undefined component of the present dip is primary. The average dip on master bedding in the north limb of the Cottonwood County basin is about 7°. As we shall argue later from sedimentological reasoning, most of this dip is probably tectonic.

Stratigraphy and Sedimentology

The outcrops of Sioux Quartzite along the north limb of the Cottonwood County basin represent a stratigraphic thickness of about 1,125 m (3,600 ft). Roughly the lowermost two thirds of the exposed section is dominantly medium grained, trough cross-bedded quartzite with many thin interbeds of mudstone. The upper third of the exposed section is dominantly coarse to very coarse quartzite with many thin lenses of grit and orthoconglomerate.

Three recently completed diamond drill holes through the north limb of the Cottonwood County basin penetrate the basal portion of the Sioux Quartzite from the lower part of the exposed section downward through the basal contact, and terminate in the underlying gneiss. The longest transect of the Sioux, about 287 m (942 ft), was drilled at site SQ-3 (Fig. 3 and Plate 1); transects of 104 m (342 ft) and 11.3 m (37 ft) were drilled at sites SQ-6 and SQ-13, respectively. It is clear from the drilling and Plate 1 that the rocks exposed in outcrop are a few hundred meters stratigraphically above the base of the Sioux Quartzite. Throughout the text of this report we will refer to drill holes SQ-3, SQ-6, and SQ-13 simply as holes 3, 6, and 13 for the sake of brevity.

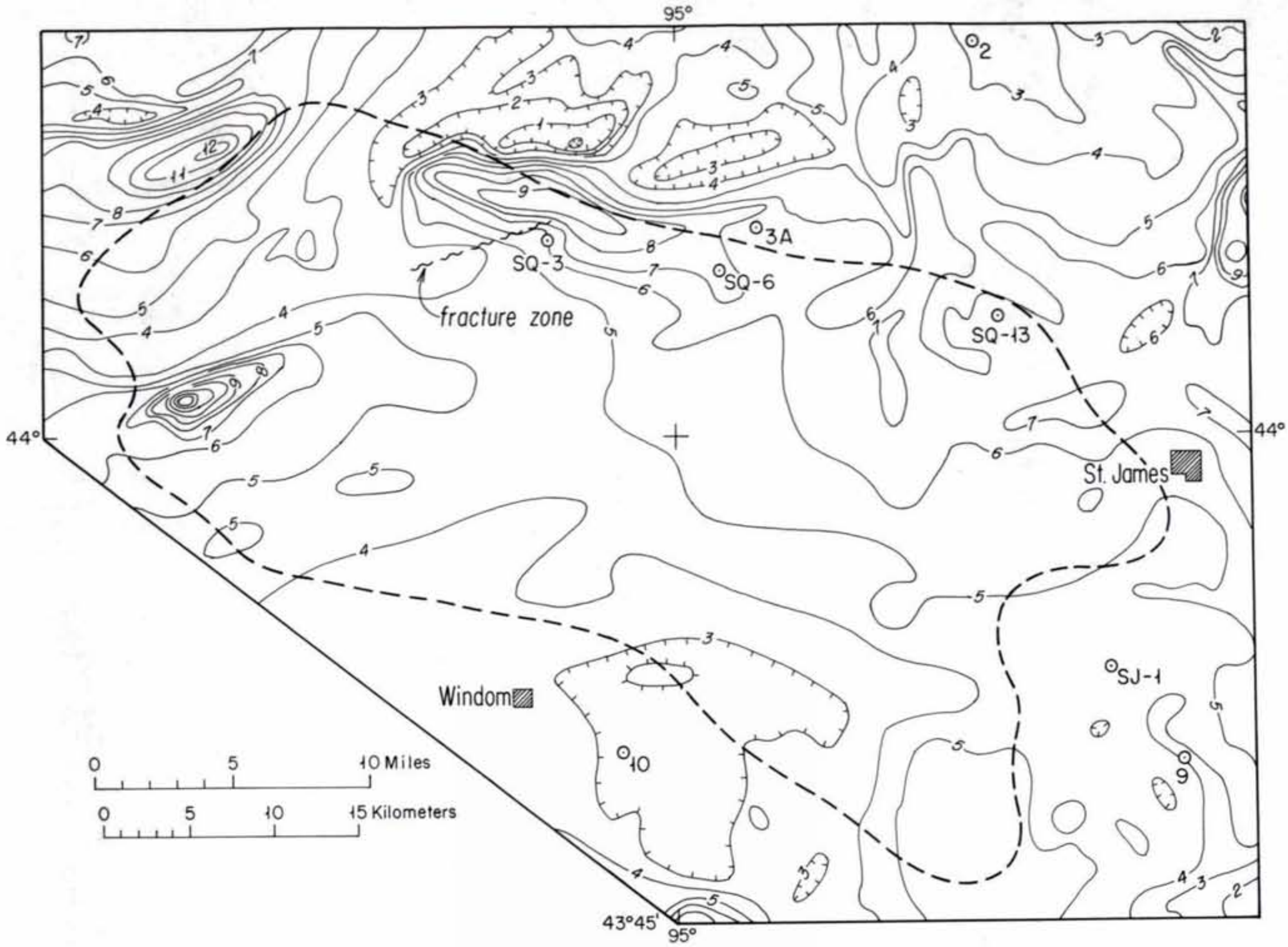

Figure 4. Simplified aeromagnetic map over the Cottonwood County basin, modified from Philbin and Gilbert (1966). Contour interval 100 gammas, relative to an arbitrary datum. The mapped fracture zone in the Sioux Quartzite aligns with a linear magnetic pattern, and is thought to record reactivation of a fault zone in the crystalline basement. Drill holes outside the basin (numbered circles) penetrate gneissic basement.

In a very broad way the lithologic logs of drill holes 3 and 6 (Appendixes A and B) define a stratigraphic succession that fines upward overall, but contains small-scale internal sequences that coarsen upward individually. Pebble-bearing layers are very minor at levels higher than 15 m (50 ft) above the base of the section, but grit beds and granule-bearing coarse sand layers occur throughout the column. Mudstone and quartz-rich siltstone are abundant in the basal few meters of the section where they form medium to thick beds interstratified with very coarse sandstone and conglomerate. At higher levels mudstone and siltstone form thin beds and partings that are interbedded with medium to coarse orthoquartzite.

On the basis of the drilling we have subdivided the lower part of the Sioux Quartzite into five informal units, termed A through E, with unit A at the base. Units D and E, though best recognized and defined in core, are interpreted to include much of the exposed section along the north limb of the Cottonwood County basin. Unit D crops out along the low ridge south of Comfrey, at and near Red Rock Dells in section 36 of Greenwood Township, and in the southwest part of Stately Township (Plate 1). The top of unit E is placed at the base of the massive, very coarse grained orthoquartzite and grit that is sporadically exposed on the south flank of Red Rock Ridge. Unit E crops out extensively along the north flank of Red Rock Ridge. Excellent exposures occur near the mutual corner of sections 4, 5, 8, and 9, Delton Township, and on the broad hillside that occupies most of section 11, also in Delton Township. Informal units A through E appear to persist laterally among the three holes drilled, but it remains to be seen from future drilling whether the stratigraphy recognized here has basin-wide applicability.

Unit A is a heterogeneous basal sequence consisting of mudstone, siltstone, fine to coarse orthoquartzite with grit layers, and conglomerate. It makes up roughly the lowermost 15 m (50 ft) of the Sioux in holes 3 and 6 and all of the short intersect (11 m or 37 ft) in hole 13 (Appendix B). Dark reddish-brown mudstone, brick-red to pink quartzose siltstone, and very fine grained pink to maroon sandstone together account for more than half of the unit. The remainder is mostly coarse to very coarse orthoquartzite and grit. Quartz-pebble conglomerate, which contains minor quantities of chert and granular cherty iron-formation, occurs in thin beds throughout unit A, and forms the basal few meters of section at sites 3 and 6. Boulders of gneiss as large as 20 cm in core intercept occur at the very base of the section in hole 6. Unit A is characterized by the intercalation of thin beds of strongly contrasting grain size and by the rather common occurrence of "floating" larger clasts within beds of all textures. The mudstone beds commonly contain a scattering of dispersed sand grains, the fine sandstone beds contain dispersed coarser sand, granules, and small pebbles, and the very coarse sandstone and grit beds contain a sprinkling of pebbles and cobbles.

The beds in unit A range in thickness from less than a centimeter to about 2 m; most mudstone and siltstone beds are about 2 to 20 cm thick and commonly are laminated internally. Although many beds are essentially uniform in texture, without obvious systematic changes in grain size, two types of upward-fining bedding packets have been recognized in parts of unit A. The more common cycle begins with coarse sand or grit at the base, above a sharp, scoured contact; the basal grit grades upward over a few meters into a medial section of uniform, medium to coarse sand, typically about 0.5 m thick, which grades abruptly through a few centimeters of very fine sand to an upper unit of quartzose siltstone or laminated mudstone. The second type of cycle consists of alternating mudstone and sandstone beds, each on the order of a few centimeters in thickness, that aggregate to a total thickness of a few meters for the cycle. In this type of cycle the basal bed of coarse sandstone rests on a scoured contact, and each successively higher sandstone bed is somewhat finer grained than the one below it. The upper and lower contacts of the intercalated mudstone beds are both gradational except for the top of the topmost mudstone bed, which is scoured.

Mudstone and quartzose siltstone have not been reported previously in the basal part of the Sioux Quartzite. The fine clastic rocks of basal unit A in the Cottonwood County basin probably were derived from the fine-grained constituents of the weathering zone on Archean crystalline rocks that underlies the Sioux (described below). The intimate interbedding of clay- and silt-rich rocks with markedly coarser grit and orthoconglomerate requires a sedimentary regime in which currents of strongly varying competence have operated on a source terrane that contains chemically mature coarse material as well as abundant silt and clay. We tentatively suggest that the depositional environment was a braided fluvial network playing over a surface of decomposed and disintegrated crystalline rock. The pediment-fan environment first suggested by Miller (1961) to explain the attributes of the basal conglomerate near New Ulm (Fig. 2) has considerable merit, and deserves critical reexamination.

The heterogeneous basal sequence defined as unit A is overlain in holes 3 and 6 by a section 12 to 35 m (40 to 115 ft) thick composed dominantly of medium to very coarse orthoquartzite with minor granule-bearing beds, which is defined as unit B. The orthoquartzites of unit B are gray, purplish gray, and maroon in color, are steeply cross-bedded, and show marked grain-size variation from foreset to foreset (cf Ore, 1964). The overall coarseness and highly cross-bedded structure of the unit B orthoquartzites are characteristics of channel sands in modern braided rivers (Ore, 1964; Smith, 1970; Rust, 1972; Miall, 1977; Walker and Cant, 1979), and we tentatively interpret unit B as having been deposited as channel sands in a braided fluvial system. Units A and B together form a gross upward-coarsening sequence about 30 to 45 m (100 to 150 ft) thick.

Unit C, stratigraphically above the coarse, cross-bedded orthoquartzite of unit B, is composed dominantly of medium-grained orthoquartzite with many thin interbeds of brick-red laminated mudstone. Unit C is about 15 m (50 ft) thick. Individual mudstone beds rarely exceed a few centimeters in thickness and commonly are less than 1 cm thick. The associated sandstones are cross-bedded at low angles; individual cross-sets generally are thinner than 0.5 m. Thin upward-coarsening packets of sandstone occur at several horizons within unit C; these commonly are eroded at the top and are overlain by a thin mudstone layer (Fig. 5A). In some layers the mudstone is the base of another upward-coarsening cycle, which passes gradationally upward into fine sandstone. Other mudstone layers have rippled upper surfaces, or have been ripped up into mud-chip conglomerate at the base of an overlying coarse sandstone. The attributes of unit C suggest deposition on mid-channel bars or sand flats in braided fluvial systems (Walker and Cant, 1979); the mudstones are interpreted as the thin and patchy clay-drape laminae that formed on the tops of mid-channel bars.

Unit D, overlying unit C, is steeply cross-stratified, massively bedded, coarse orthoquartzite that is lithologically similar to

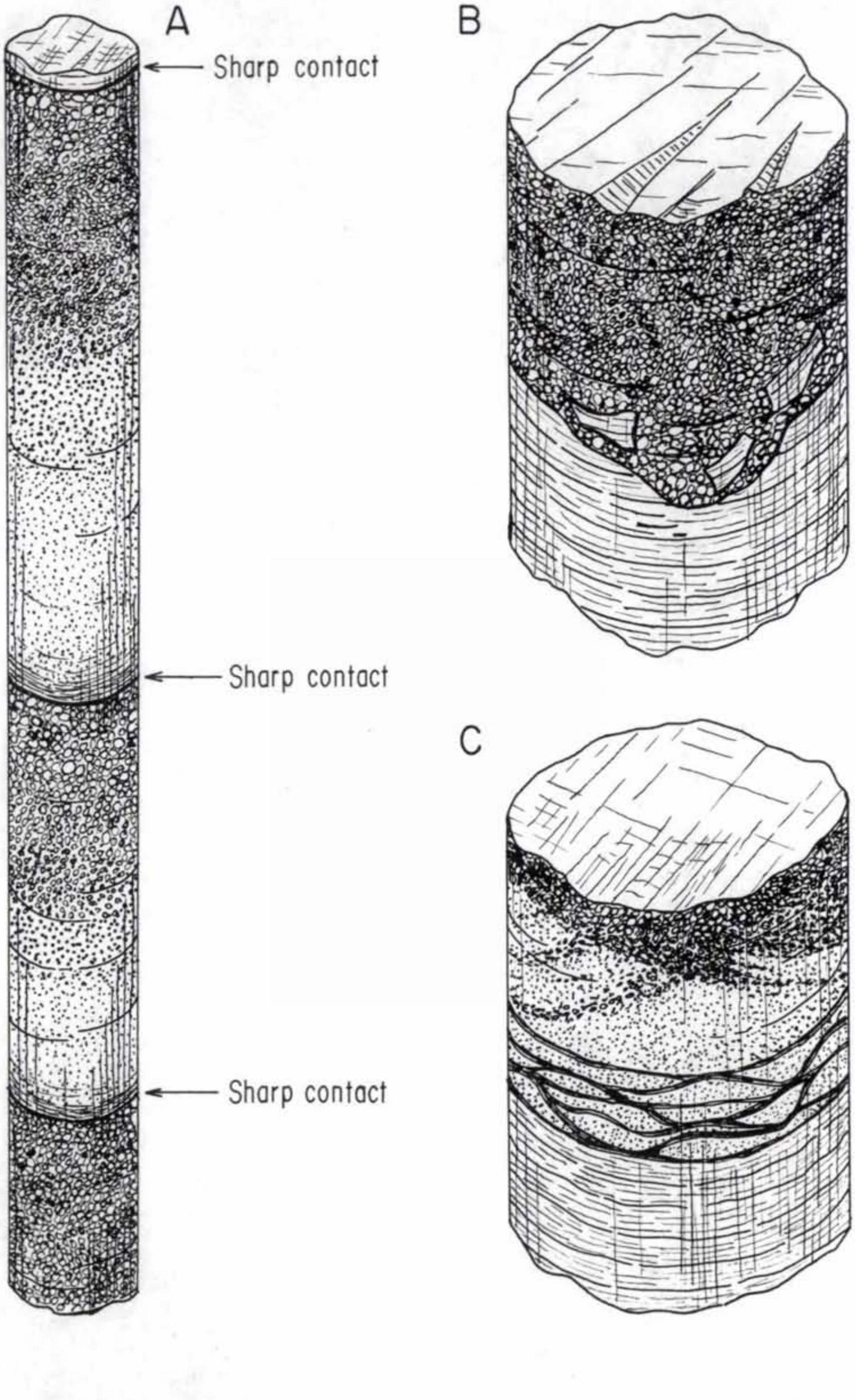

Figure 5. Detailed sketches of drill core. (A): Upward-coarsening mudstone-siltstone-sandstone beds in unit C. (B): Scoured contact between laminated mudstone (below) and coarse sandstone with mud chips (above) in unit E. (C): Planar contact between mudstone (below) and flaser-bedded fine sandstone (above) in unit E. All cores are 5 cm in diameter.

unit B. Mudstone beds and partings are scarce in this interval, which is about 40 m (130 ft) thick. Unit D is entirely a large-scale, upward-coarsening sequence in hole 3 (Appendix B); this large-scale gradation is not obvious in hole 6, but several well-defined, coarsening-upward sequences from a meter to several meters thick were noted near the center of the unit. These begin with fine sand at the base, in scoured contact with subjacent coarser sand, and pass upward into very coarse sand. Unit D is interpreted to be primarily channel sands that were deposited during a period of source-area uplift and basinward progradation of an alluvial apron; the finer rocks of unit C may be the lower part of the same progradational cycle.

Unit E is a thick section dominated by gray to reddish-gray, fine- to medium-grained orthoquartzite, generally medium bedded and cross laminated, that contains a varying small proportion of thin mudstone beds and shale partings. A few shale beds high in the section contain detrital muscovite flakes on bedding surfaces. The lowermost 40 m (132 ft) of the unit is dominantly medium-grained orthoquartzite, with very few shaly interbeds, and the quartzite beds typically range in thickness from 0.6 m to several meters. Thinner sandstone beds, commonly between 20 and 50 cm in thickness, occur in the middle and upper parts of the section where mudstone layers are relatively abundant. Although a few upward-coarsening cycles about 60 to 90 cm thick occur in the sand-dominated basal part of unit E, as do somewhat fewer upward-fining cycles that overlie scoured mudstone surfaces, grain-size trends are generally scarce in this interval. Upward-fining sandstone cycles become prominent in the upper part of the unit where mudstone beds become more common, and typically begin with coarse sand or mud-chip conglomerate above a scoured base (Fig. 5B). Small cycles that begin with laminated mudstone at the base and grade through flaser-bedded siltstone to sandstone also are found in the upper two thirds of unit E (Fig. 5C).

The top of unit E is defined as the base of a massive pebbly quartzite unit that crops out in a map position corresponding to a stratigraphic position about 200 m (650 ft) above the top of hole 3 (Plate 1A). Thus, unit E has a total estimated thickness of about 375 m (1,230 ft). It is interpreted to represent a long period of braided-channel sedimentation during which the system was graded to a more or less constant throughput of detritus. Small cycles representing channel, sand-flat, and "mixed influence" settings in a braided-stream system are superposed in complex order, reflecting local channel migration as a function of time (Fig. 6).

The pebbly quartzite horizon stratigraphically above unit E, sporadically exposed along the south flank of Red Rock Ridge (Plate 1A), is interpreted to be the basal part of another large-scale, grossly upward-fining cycle similar to the one represented by units A through E. It probably represents regional adjustments of stream gradients and sediment supply to uplift of the source area, perhaps related to basin subsidence along normal faults.

Reasoning from outcrop observations, Baldwin (1951) constructed two short but detailed stratigraphic sections of rocks that we now regard as part of unit E and some of the overlying coarse quartzite. The sections were constructed on either side of the transverse structurally disturbed zone centered in sec. 12, T. 107 N., R. 36 W. on the north limb of the Cottonwood County basin. Although they are similar, Baldwin's stratigraphic sections differ in detail, and Baldwin interpreted them to be different stratigraphic levels that had been juxtaposed by motion on intervening faults. Baldwin correlated a thin horizon of mud-chip conglomerate between his two measured sections and thus across the structurally disturbed zone, and concluded from this correlation that the eastern section was somewhat higher stratigraphically than the western (Baldwin, 1951, fig. 6).

Although Baldwin's measured sections on opposite sides of the disturbed zone are substantially correct, and do differ, we consider the differences to have resulted from the locally shifting conditions of deposition in a braided-stream environment, rather than from later structural displacement. In modern braided streams the cross-bedded channel sands and gravels tend to adopt complex lenticular and sinuous forms as the stream channels shift and rework older channel deposits, and they also exhibit abrupt grain-size variations both vertically and laterally (Ore, 1964; Allen, 1965; Smith, 1970; Walker and Cant, 1979). Mud-chip conglomerates might be expected to form repeatedly and locally in braided streams as channels migrate and erode patches of mud from former low-energy sites on mid-channel bars or along the channel margins. Mud-chip horizons are known to occur at several levels within the Sioux Quartzite (Appendix A), and even local correlations based on this lithology therefore are doubtful.

In Figure 7 the three drill holes on the north limb of the Cottonwood County basin have been projected along strike into a common cross section parallel to dip. This maneuver brings hole 6 roughly 2,200 m (7,200 ft) basinward of hole 13, and hole 3 about 2,400 m (8,000 ft) basinward of hole 6. Despite the projection distances involved and the probable form of rock layers that collectively make up units A through E, it does appear that the lithostratigraphy has some lateral continuity on the basin scale. Moreover, the basin slope deduced from this projection is about 3° to the southwest as compared to an average southwest dip of about 7° measured in outcrop. The slope values obtained by the two methods agree remarkably well, considering

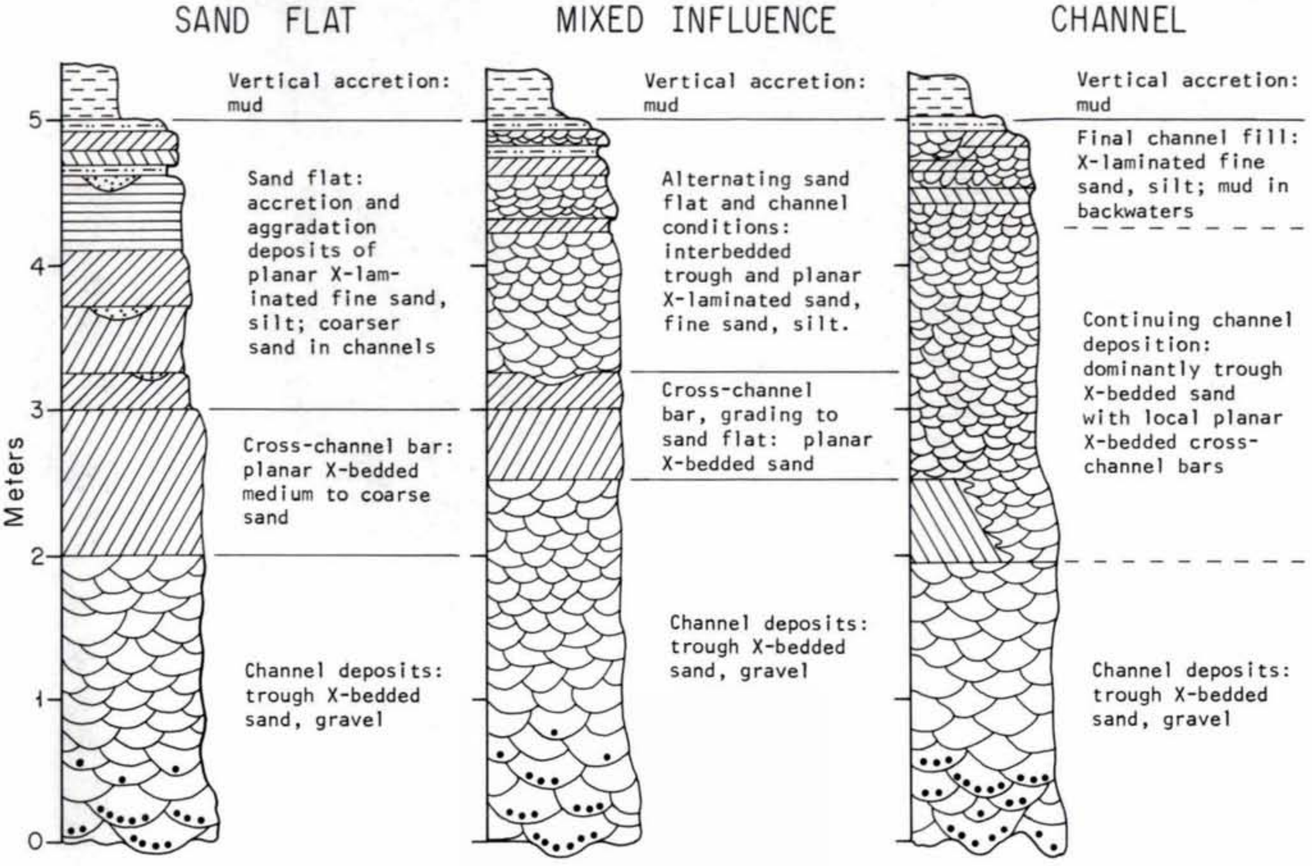

Figure 6. Sequences of lithologies and sedimentary structures observed in sand flat, "mixed influence," and channel subenvironments of the braided Saskatchewan River; modified from Walker and Cant (1979).

the questionable stratigraphic assumptions involved in making long projections parallel to strike.

Diagenetic Phenomena

Previous studies by Berg (1937, 1938), Baldwin (1951), and Weber (1981) have dealt with various aspects of diagenesis in the Sioux Quartzite, including the origin of the red pigmentation, the source of the voluminous silica cement, and the paragenesis of the secondary minerals sericite, pyrophyllite, diaspore, and kaolinite. We present several observations from the core drilling in the Cottonwood County basin that bear on these problems, but we do not attempt to treat the complete diagenetic history of the Sioux.

A long-recognized characteristic of the Sioux Quartzite is its lack of detrital feldspar. This is hard to explain even in a multicycle sedimentary rock that rests directly on quartzofeldspathic gneiss.

Three observations from drilling in Cottonwood County bear on the feldspar problem. First, there is a well-developed regolith on the Archean basement beneath the Sioux (described in more detail below) within which the degradation of feldspar to kaolinite and sericite is common and characteristic. Thus there probably was a relative shortage of sand-size detrital feldspar in the near-surface layers of the source area that supplied sediment to the Sioux. Second, there are small amounts of clastic plagioclase and microcline in basal unit A of the Sioux Quartzite; the feldspar is best preserved in the core from hole 6, but it also occurs in hole 3 where feldspar kernels form the residual nuclei of grains that have been converted largely to secondary clay minerals. Third, many beds widely scattered throughout the Sioux Quartzite contain kaolinite-sericite clots that can be interpreted as pseudomorphs of former feldspar grains. These strongly resemble the clay-mineral pseudomorphs and near-pseudomorphs of feldspar that we have documented in unit A, but we have not been able to find kernels of residual feldspar in them. The rocks containing these clots invariably contain appreciable amounts of interstitial sericite-kaolinite "matrix" as well. We tentatively propose that feldspar may originally have made up several percent of those

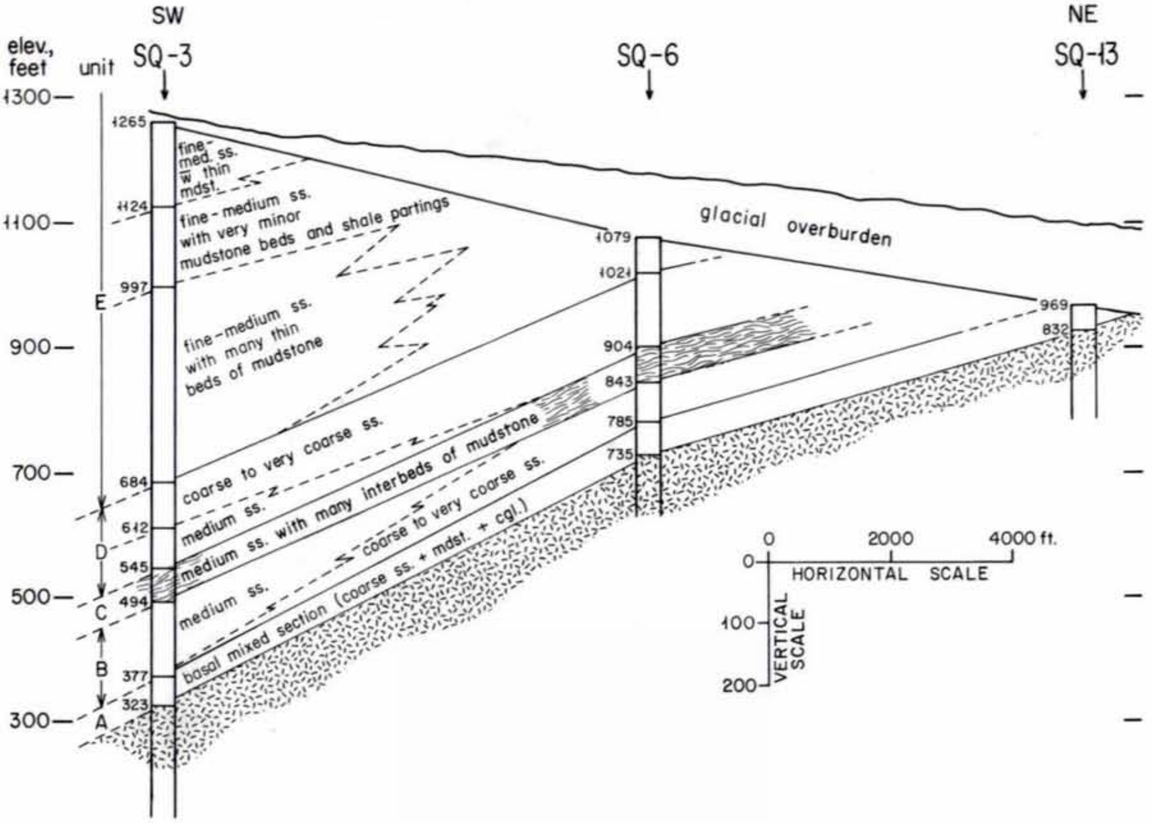

Figure 7. Generalized stratigraphy from drill holes SQ-3, SQ-6, and SQ-13 as projected parallel to strike; the resulting pseudosection is oriented perpendicular to the north edge of the basin and extends basinward about 4.6 km (2.9 mi).

beds throughout the Sioux that now contain phyllosilicate clots and phyllosilicate matrix, and that some of the the matrix is the residue from intrastratal solution of feldspar. Land and Milliken (1981) have presented evidence for massive feldspar dissolution in Oligocene sandstones on the Texas Gulf Coast, and have established order-of-magnitude constraints on the material transfers involved. Land and Milliken show that under conditions where kaolinite is the dominant solid product, intrastratal solution of K-feldspar can produce large amounts of dissolved silica which potentially may reprecipitate as silica cement. We do not propose to account for the total volume of quartz cement in the Sioux by feldspar solution, but suggest that some fraction of it may have come from this source.

Diaspore was first reported in the Sioux Quartzite by Berg (1937, 1938) and was interpreted by Baldwin (1951) and Austin (1970) as a product of late Cretaceous lateritic weathering. However, we find diaspore to a depth of 286 m (938 ft) in drill hole 3, at which depth it is far below the reach of surficial weathering. The diaspore commonly forms single crystals or granular crystalline aggregates in the interstices of quartzite, where it is associated with secondary quartz, kaolinite, and sericite, and it also forms blade-like poikiloblasts in some mudstones. Textural relations indicate that diaspore in the quartzites developed more or less simultaneously with an early generation of well-crystallized kaolinite, and that it was later partly replaced by a second generation of less well formed kaolinite. The textural relations involving diaspore and the early kaolinite are very similar to those reported by Chandler and others (1969) for diaspore and associated phases in the lower Proterozoic Lorrain Formation of Ontario. We tentatively favor a diagenetic origin for the assemblage diaspore + early kaolinite + quartz in the Sioux, as did Chandler and others (1969) for this assemblage in the Lorrain. Detailed mineralogical and geochemical investigations of the diaspore problem are currently underway.

Weathered Zone Beneath the Sioux Quartzite

1. General discussion

Drill holes 3, 6, and 13 all intersect a regolith on Archean gneissic rocks beneath the Sioux Quartzite. The alteration is most severe immediately beneath the basal Sioux contact, and diminishes downward into essentially fresh rock over a thickness ranging from 9.8 m (32 ft) to more than 23 m (>75 ft). Intense hematite staining, widespread kaolinitization of original feldspar, and local silicification are the most obvious characteristics of the altered rock.

The presence of weathered residuum beneath the Sioux is consistent with the chemically mature, resistate-dominated composition of the basal conglomerate at New Ulm (Miller, 1961), and with the peculiar combination of clay-rich mudstone and coarse clastic rocks that occurs in basal unit A in Cottonwood County. Moreover, such regoliths are known beneath other terrestrial arenites of Proterozoic age that rest unconformably on greatly older Archean basement, such as the Mistassini Group of Quebec (Chown and Caty, 1973, 1983), the Athabaska Group of Saskatchewan (Ray, 1977), and various sedimentary sequences in southern Africa (Button and Tyler, 1979). These weathering profiles collectively indicate extended periods of crustal stability and low net erosion in the interior regions of Proterozoic cratons.

Although we interpret the alteration zone beneath the Sioux to be primarily the result of subaerial weathering, we recognize that circulating pore water is an effective leaching and altering agent within, and presumably beneath, thick accumulations of unlithified porous sediment (Walker, 1967; Land and Milliken, 1981; Boles, 1982; Chown and Caty, 1983) Thus the sub-Sioux regolith may record subaerial weathering followed and modified by "diagenetic" processes that affected both the basin fill and its porous, weathered basement.

2. Description of the regolith

The weathered material beneath the Sioux Quartzite at drill sites 3 and 6 consists basically of two lithologies: grus-like microbreccia composed of angular quartz and sericitized feldspar that is variably recemented by secondary hematite and quartz, and partially decomposed gneissic rock that retains some or all of its original metamorphic texture. The microbreccia predominates in the topmost 3 m (10 ft) of the weathering profile of hole 3, and forms scattered thin layers at deeper levels; it occurs only as thin layers in the weathering profile of hole 6. The partially decomposed gneiss is stained with secondary hematite, and varies in hardness in proportion to its degree of conversion to clay minerals. Soft, clay-rich zones within the weathered gneiss decrease downward both in thickness and frequency. No layers of totally decomposed rock comparable to the A or B horizons of modern weathering profiles were found in the drilling. They may never have formed, or they may have been eroded away. In general the weathered material at drill sites 3 and 6 is analogous mechanically to zone III, core stones and matrix, and zone IV, partly weathered bedrock, in the descriptive terminology for weathered rocks proposed by Ruxton and Berry (1957). The weathered profile at site 13 is somewhat different, and is discussed separately below.

The basement rock beneath the Sioux Quartzite is complex, coarse-grained gneiss composed of granitic, tonalitic, granulitic, and amphibolitic layers. The gneiss at each drilled locality differs in detail from that at the other two, but the three have much in common and are viewed as variants within the Archean gneiss terrane of southern Minnesota, which is best known from exposures along the Minnesota River (Lund, 1956; Himmelberg, 1968; Goldich and others, 1970, 1980a, 1980b; Grant, 1972; Bauer, 1980).

At drill site 3 the dominant basement lithology is medium-grained tonalite gneiss composed of about 50 percent plagioclase, 35 percent quartz, and 15 percent biotite. Layers or inclusions of somewhat finer-grained amphibolite make up about 5 percent of the 23 m (75 ft) cored. All of the basement core exhibits some degree of weathering. The principal mineralogical changes during weathering have been (1) replacement of plagioclase by a mixture of kaolinite + sericite; (2) conversion of biotite to vermiculite + hematite + sericite; (3) conversion of hornblende (in amphibolitic layers) to a very fine mixture of pale-green chlorite + sericite; and (4) the introduction or mobilization of secondary hematite throughout the rock as thin wisps along cracks, grain boundaries, and cleavage planes. The uppermost 3 m (10 ft) of basement core, just below the basal Sioux contact, is intensely stained by hematite to a very dark maroon-brown. The remainder of the core is less deeply stained to brick-red and is transected by a network of gradationally bounded, light-greenish-gray to white zones that are enriched in kaolinite and leached of hematite. These bleached zones, typically a few centimeters to about a meter wide, appear to be fracture-controlled and are interpreted to be the product of later alteration by circulating ground water.

The basement gneiss at drill site 6 is mafic hornblende-augite granulite, interlayered on the scale of centimeters to meters with coarse pegmatoid granite. The granulite layers consist of about 40 percent augite, 35 percent hornblende, 18 percent plagioclase, 5 percent apatite, and 2 percent sphene; a few layers contain small amounts of biotite. The granitic layers consist of about 65 percent very coarse microcline microperthite and about 35 percent quartz. Weathering has converted the augite and hornblende of the mafic layers to a very fine mat of chlorite + sericite + granular hematite, and the plagioclase to an intimate mixture of kaolinite + sericite. Sphene and apatite have been concentrated as resistates, and the fact that some weathered samples contain as much as 35 percent apatite, as opposed to about 5 percent in unweathered granulite, is clear evidence for substantial loss of mass through dissolution of the major rock-forming silicates. Iron oxides (dominantly hematite) in the weathered granulite form sigmoidal to highly irregular wisps and seams that physically resemble the solution films and stylolites of carbonate rocks. The oxide seams are interpreted as solution phenomena, and their presence is further evidence for appreciable volume loss during weathering.

The weathering profile at site 13 is different from those at sites 3 and 6, in that secondary hematite and quartz are lacking, kaolinite is much more abundant, and the upper part of the profile is more thoroughly disintegrated mechanically. The unweathered basement rock is tonalite gneiss with minor layers of granite. The tonalite gneiss consists of about 65 percent plagioclase, 25 percent quartz, 7 percent biotite, 3 percent hornblende, and minor K-feldspar, apatite, and sphene, and the granite stringers consist of about 40 percent microcline and 30 percent each of plagioclase and quartz. The uppermost 7 m (22 ft) of the weathering profile is kaolinite-rich, crumbly, greenish-gray to white saprolite. This grades downward through a mottled transition zone about 8 m (26 ft) thick to incipiently weathered rock in which the development of kaolinite and sericite from feldspar and of chlorite from mafic phases can be seen petrographically. This profile is similar both physically and mineralogically to the deeper parts of weathering profiles developed on Archean rocks of the Minnesota River Valley during late Cretaceous time (Goldich, 1938; Parham, 1970), which are known to be as thick as 60 m (200 ft) at various places in southern and central Minnesota. Because the top of the basement at site 13 is capped by only 11 m (37 ft) of Sioux Quartzite, and the thin covering of Sioux Quartzite is itself partly altered to a crumbly, kaolin-rich, creamy white aggregate comparable to the Cretaceous weathering profile at other Sioux localities in Minnesota described by Austin (1970), we interpret the profile at site 13 to be a Cretaceous weathering phenomenon. Whatever evidence there may have been for earlier pre-Sioux weathering has been strongly modified by the Cretaceous weathering process.

ENVIRONMENT OF DEPOSITION FOR THE SIOUX QUARTZITE

Stratigraphic and sedimentological attributes discussed above suggest to us that the Sioux Quartzite of the Cottonwood County basin is an alluvial, braided-channel deposit. Sediment was transported southeastward from a source area of deeply weathered granite, gneiss, quartzite, and ferruginous chert by streams which debouched from low uplands along the sides and at the headward end of a subsiding trough and built up a complex apron of alluvial fan and braided-channel deposits on the trough floor.

The paleocurrent indicator map of the Cottonwood County basin (Plate 1B) illustrates that the sediment dispersal pattern is toward the southeast in the western part of the area and toward the southwest, west, or northwest in the eastern part of the area, and indicates that the basin was a depocenter fed by a crudely centripetal current regime. A significant component of flow was more or less down the long axis of the basin, and a less significant component was more or less perpendicular to the basin axis. These flow directions consistent with deposition from a river system that over time flowed from northwest to southeast down the long axis of a fault-controlled valley, and received some sediment imput from tributaries flowing in from the valley walls.

The second important fact to be extracted from the paleocurrent data is that the current directions deduced from ripples on beds of fine sandstone, siltstone, or mudstone commonly differ significantly from the directions of cross-bedding troughs in medium- to coarse-grained sandstone in the same outcrop (Plate 1B). This divergence of current azimuths is additional evidence for braided-stream deposition. Observations of modern braided streams (Ore, 1964; Smith, 1970; Miall, 1977; Cant and Walker, 1978; Walker and Cant, 1979) have shown that longitudinal bars typically form at the downstream ends of stable sand flats or larger mid-channel islands in areas of flow expansion, and commonly divide a quiet backwater from a faster flowing channel. During low flow, mud accumulates in the backwater and on the backwater side of the bars where rippled bed forms commonly develop. The flow direction across the bar may be at a high angle to that in the main high-velocity channel, and the orientation of the ripples on the surface of the bar records that transverse flow. Although these observations have been made on low-sinuosity braided rivers, not alluvial aprons, analogous sorts of bars, flats, and divides are characteristic of braided distributary systems on alluvial plains and fans (Spearing, 1974; Vos, 1975; Boothroyd and Nummedal, 1978). Moreover, the lower sediment-choked reaches of fan-head valleys typically are braided, and are not known to differ significantly from other types of braided rivers in bed forms or channel parameters. Therefore the braided channel systems associated with alluvial plains and fans ought to show local divergences in current direction similar to those observed in non-fan braided rivers such as the Platte

(Smith, 1970) or the South Saskatchewan (Cant and Walker, 1978; Walker and Cant, 1979).

The Sioux Quartzite is characterized by excellent rounding and sorting (Weber, 1981), unlike Cenozoic to Recent alluvial fans in arid regions which are characterized by angular, poorly sorted detritus deposited by debris flow and sieve infiltration (Bull, 1972). We conclude, therefore, that the Sioux is more likely to have been deposited by purely fluvial processes than by debris flow, and that the morphology of the deposit may have been nearer to that of modern-day glacial outwash fans (Boothroyd and Nummedal, 1978; Hine and Boothroyd, 1978) or inland humid-region deltas (Gole and Chitale, 1966) than to the Basin-and-Range style of alluvial fans. This implies that depositional surface slopes (primary dips) were 1° or less, as is typical of slopes on glacial outwash fans and inland deltas depositing sand (Boothroyd and Nummedal, 1978, table 1, p. 644), rather than slopes of about 3° to 8° that are typical of mountain-front alluvial cones (Hooke, 1968).

We suggest that the landscape at the time of Sioux deposition was of low to moderate relief and was partly mantled by a surface layer of lateritic to grus-like residual soil. The scene may have resembled present-day northwestern Australia or parts of the Canadian Arctic Archipelago, but need not have been either arid or cold. In the absence of vegetation during Proterozoic time to stabilize the surface layer or promote chemical breakdown in the upper soil zone, grus-like residual soils may have been more prevalent in moist, warm climates than they are today.

A broadly distributed surface layer of granular rock debris unprotected by vegetation would be highly susceptible to hillslope erosion, and the abundance of sand-size detritus brought to valley floors by hillslope processes during periods of moderately high runoff would tend to overload the fluvial system. Under these conditions the streams would tend to braid, and the confluence of several braided streams into a topographic depression might be expected to produce bahada-like accumulations of overlapping alluvial deposits.

Although there is no direct evidence to suggest that the Sioux Quartzite was deposited under high-latitude, periglacial conditions, such an environment cannot be ruled out. The Sioux is inferred to be essentially time-correlative with the Baraboo Quartzite of Wisconsin (Dott and Dalziel, 1972), and the Baraboo is inferred to have been deposited between 1,760 and 1,630 Ma ago (Van Schmus and others, 1975). According to the paleolatitude reconstructions of Irving (1979), central North America lay virtually at the pole about 1,650 Ma ago. However, Irving's (1979) data also indicate that central North America lay in near-equatorial latitudes during the period 1,850 to 1,800 Ma ago, prior to deposition of the Sioux, and returned from a near-polar to a near-equatorial position during the interval 1,600 to 1,400 Ma ago. A substantial part of the sub-Sioux regolith may have formed during the first tropical interval, and, depending on the exact depositional age of the Baraboo-Sioux within the age limits of 1,760 to 1,630 Ma, which are imposed by igneous and metamorphic events (Van Schmus and others, 1975), sedimentation could have occurred under climatic conditions ranging between polar and equatorial.

We conclude that subsidence of the Cottonwood County basin probably was fault controlled, even though boundary faults have not been observed directly. This conclusion is based chiefly on analogy with mature red-bed sequences of Phanerozoic age, which typically are found in extensional tectonic regimes, and secondarily on the presence of linear magnetic anomalies, in one case associated with the documented cataclastic rocks, that could mark basinal boundary faults in the Archean basement (Fig. 2). If these inferences are correct, the Cottonwood County basin originally may have been a graben or half-graben about 100 to 200 km long and about half as wide. The axial portion of the depositional trough is not exposed, and therefore its properties are unknown. We tentatively postulate that it contains a high proportion of finer grained and relatively non-resistant alluvial (and lacustrine?) mudstone and siltstone, but this conclusion will remain speculative until further drilling is done. The depositional setting we currently envision is similar to that proposed by Vos (1975) for the Witwatersrand succession in South Africa.

Stratigraphic evidence for vertical tectonism, perhaps related to adjustments on basin boundary faults, is found in the alternation of thick coarsening- and fining-upward sequences, such as combined units C and D (coarsening upward, about 50 m [164 ft] thick) and the upper half of unit E (fining upward, at least 80 m [262 ft] thick). Coarsening-upward sequences of this thickness are consistent with source-area uplift and basinward prograding of alluvial cones, whereas comparably thick fining-upward sequences are consistent with downcutting of a stable source terrane, decreasing stream gradients, and headward regression of the alluvial apron.

The broad-scale tectonic setting of the basin or basins filled by the Sioux Quartzite and its approximate correlatives in Wisconsin has been a matter of recent debate. Dott (1981, 1983a, 1983b) has suggested that the quartzites were deposited on a stable, passive continental margin that lay along the northern edge of a now-consumed Proterozoic ocean basin. In contrast, Greenberg and Brown (1983) have suggested that quartzite deposition occurred in fault-controlled cratonic basins that developed in response to anorogenic uplift following Penokean

($\sim$1,850 Ma) orogenesis and cratonizaton. The scanty evidence available in Minnesota tends to favor the intepretation of Greenberg and Brown. In addition to the stratigraphic, sedimentological, and structural arguments already presented, the clasts of anorogenic rhyolite and welded tuff in conglomerate in the Pipestone basin and the rhyolite interbedded with Sioux Quartzite in northwestern Iowa (Beyer, 1893) are further indications of a cratonic setting.

CONCLUSIONS

Five informal lithostratigraphic units within the Sioux Quartzite (termed units A through E) have been identified from core drilling and outcrop study in the Cottonwood County basin. These units together are about 490 m (1,600 ft) thick; they comprise a section of about 287 m (940 ft) that is stratigraphically beneath the horizons exposed in outcrop and is known only from drilling, and a section of about 200 m (660 ft) that crops out along the north flank of the basin. Sedimentary sequences and primary structures within units A through E are interpreted to indicate deposition from braided streams, probably on an alluvial plain or a plexus of alluvial fans that formed within a subsiding intracratonic trough. The principal direction of sediment transport was toward the south or southeast at the time when unit E was being deposited.

The Cottonwood County basin is a shallow structural depression that appears to have been a primary depocenter prior to slight tectonic warping, and is interpreted to have been fault controlled. The north limb of the basin has been tilted southward and has been deformed by northwest-trending gentle flexures and by two sets of faults. A northeast-trending fracture zone in the quartzite aligns with a pronounced magnetic lineament that extends beyond the basin edge. The fracture zone is interpreted to record reactivation of a concealed fault in the Archean basement.

Residual feldspar grains, intensely altered to kaolinite and sericite, make up less than 5 percent of a few basal sandstone and grit beds cut by the drilling. A few beds higher in the section locally contain kaolinite-sericite clots that resemble feldspar pseudomorphs, and these beds invariably contain some kaolinite-sericite matrix in addition to quartz cement. It appears that some of the phyllosilicate matrix may in fact be an authigenic residue from the diagenetic breakdown of feldspar, but residual feldspar has not been verified in any of the matrix-bearing horizons above unit A. The occurrence of diaspore in the quartzite to a depth of at least 286 m (938 ft) suggests that diaspore is a product of diagenesis rather than surficial weathering. Its origin may also be related to the breakdown of feldspar.

A weathering profile about 15 to 20 m (50 to 65 ft) thick developed on Archean basement gneiss prior to deposition of the Sioux Quartzite. The weathered material is in the form of saprolite and partly decomposed rock; it is characterized by abundant secondary hematite, widespread kaolinitization of feldspar, and significant silicification. It is likely that the regolith in its present state records both pre-Sioux weathering and post-Sioux diagenetic processes.

Late Cretaceous weathering has affected the Sioux Quartzite at shallow levels and has obliterated evidence of pre-Sioux weathering in places such as drill site 13 where the total thickness of Sioux is less than a few tens of meters.

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APPENDIX A. DESCRIPTIVE LOGS OF THE BASAL SIOUX QUARTZITE

This appendix contains descriptive logs of diamond drill holes SQ-3, SQ-6, SQ-13, referred to as holes 3, 6, and 13 in text. The drilling was done by Pan Ocean Oil, Ltd., a subsidiary of Marathon Oil, Inc. The core is retained at the Hibbing offices of the Minnesota Department of Natural Resources, Minerals Division, and is available for public examination.

Explanatory remarks:

The following generalizations and definitions pertain to the lithologic descriptions in the logs:

1. Quartzite refers to a hard, vitreous, very well cemented quartz sandstone, typically an orthoquartzite in the classification of Pettijohn (1957). Most of the quartzite in the Sioux Quartzite consists of well-rounded, well-sorted quartz sand grains, some multicycle, that are cemented by secondary quartz overgrowths. However some quartzite contains variable amounts of phyllosilicate matrix (kaolinite and sericite) and this is noted in the logs where it is prominent.

2. The terms fine-, medium-, coarse- and very coarse grained quartzite refer to the size of the dominant sand-size clasts in the rock. The size limits are those of Wentworth (1922).

3. Granules are sedimentary particles between 2 and 4 mm in diameter. Grit refers to a rock composed dominantly of granules.

4. Cross-bedding is used in the broad, generic sense to describe inclined layering and lamination in the drill core. Most quartzite in the Sioux Quartzite is cross-bedded, and therefore cross-bedding is mentioned in the logs only where it is especially prominent. Units described as massive typically lack cross-bedding.

5. Mudstone refers to a rock composed of clay- and silt-size material that fractures in a blocky manner. Shale is mudstone that has bedding-parallel fissility.

6. Elevations, depths, and thicknesses were measured originally in English units and converted to metric equivalents.

7. Color designations are qualitative and subjective.

Drill hole SQ-3, SE¼SE¼NW¼ sec. 6, T. 107 N., R. 35 W.
Log of the Sioux Quartzite and subjacent Archean gneiss

DEPTH		THICKNESS		DESCRIPTION
m	ft	m	ft	
0	0	2.13	7.0	Glacial overburden (record from driller's log only)
				UNCONFORMITY ERODED TOP OF UNIT E, SIOUX QUARTZITE
2.1	7	2.44	8.0	Quartzite, medium-grained, with numerous shale partings less than 1 cm thick.
4.6	15	0.91	3.0	Shale, dark-reddish-brown, laminated.
5.5	18	1.46	4.8	Quartzite, medium-grained, gray to purplish-gray.
7.0	22.8	7.01	23.0	Quartzite, fine- to medium-grained, with numerous interbeds of shale. Shale beds are laminated, dark reddish brown to brick red, and range between 2 and 8 cm in thickness. Numerous "rip-up" shale clasts in quartzite layers. Minor bleaching around pyrite granules.
14.0	45.8	0.30	1.0	Shale, dark-brick-red, with minor laminae of quartzose siltstone and fine quartzite.
14.3	46.8	1.74	5.7	Quartzite, medium-grained, prominently mottled in shades of dusky red and creamy to greenish white. Liesegang banding well developed on fractures.
16.0	52.5	0.46	1.5	Quartzite, medium-grained, purplish-gray.
16.5	54	0.61	2.0	Shale, dark-brick-red, with minor thin beds of quartzose siltstone and fine quartzite.
17.1	56	0.46	1.5	Quartzite, medium- to coarse-grained, with numerous shale clasts.
17.5	57.5	1.07	3.5	Quartzite, fine- to medium-grained, purplish-gray.
18.6	61	0.76	2.5	Quartzite, fine- to medium-grained, with numerous shale partings.
19.4	63.5	2.74	9.0	Quartzite, medium-grained, with dispersed very coarse sand grains and granules.
22.1	72.5	1.37	4.5	Quartzite, medium-grained, with numerous shale partings and
23.5	77	5.12	16.8	Quartzite, medium-grained, with very minor shale partings.
28.6	93.8	0.37	1.2	Shale, brick-red, with interbeds of quartzose siltstone and fine quartzite.
29.0	95	0.24	0.8	Quartzite, coarse-grained with kaolinitic matrix.
29.2	95.8	8.29	27.2	Quartzite, medium- to coarse-grained, purplish-gray; several thin (1-5 cm) beds of red to brick-red shale and mudstone in depth interval 32-35 m; widely scattered shale partings elsewhere.
37.5	123	0.15	0.5	Quartzite, very coarse, with white kaolinitic matrix.
37.7	123.5	2.44	8.0	Quartzite, medium- to coarse-grained, reddish-gray.

DEPTH		THICKNESS		DESCRIPTION
m	ft	m	ft	
40.1	131.5	0.46	1.5	Quartzite, fine- to medium-grained, gray to dark maroon, with interbedded mudstone and shale. Bleaching along fractures; pyrolusite films on fracture surfaces.
40.6	133	9.76	32.0	Quartzite, generally medium grained; pinkish gray to purplish gray.
50.3	165	2.74	9.0	Quartzite, fine- to medium-grained, with partings and thin beds of brick-red shale and laminated quartzose siltstone.
53.1	174	17.68	58.0	Quartzite, generally medium grained, pinkish gray.
70.7	232	3.05	10.0	Quartzite, fine- to medium-grained, maroon to brickred, with numerous interbeds of shale, mudstone, siltstone that range in thickness from 7 to 10 cm.
73.8	242	10.15	33.3	Quartzite, generally medium grained; pinkish gray.
83.9	275.3	0.52	1.7	Quartzite, very coarse, prominently cross-laminated, with abundant small shale chips. Sharp basal contact.
84.4	277	3.51	11.5	Quartzite, coarse-grained, with prominent kaolinitic matrix.
88.0	288.5	5.03	16.5	Quartzite, medium-grained, with minor coarser sections.
93.0	305	35.67	117	Quartzite, medium- to coarse-grained; grain-size changes are gradational. Overall color is in pinkish-gray range; coarser beds are less pink and have visible creamy-white kaolinitic matrix. Interbeds 3 to 6 cm thick of shale, mudstone noted at depths 97.4, 109.7, 111, 112.5, 123.7, and 128.2 m.
128.7	422	0.46	1.5	Quartzite, medium- to coarse-grained, ochre-red, porous, friable. Appears to have been leached by circulating water.
129.1	423.5	17.99	59.0	Quartzite similar to interval 93-128.7 m described above. Shale beds noted at depths 137.1, 140.4, 140.9, and 141 m.
147.1	482.5	5.18	17.0	Quartzite, generally medium grained, dark reddish gray to maroon, with numerous shaly partings.
152.3	499.5	12.04	39.5	Quartzite, similar to interval 93-128.7 m described above.
164.3	539	3.35	11.0	Quartzite, similar to interval 147.1-152.3 m described above.
167.7	550	11.59	38.0	Quartzite, generally medium grained, with interbedded coarse-grained intervals; reddish gray to light pinkish gray. Shale partings sparse.
				TOP OF UNIT D
179.3	588	21.90	71.8	Quartzite, prominently cross-bedded, with gradational grain-size variation from cross-bed to cross-bed. Texture generally in coarse to very coarse sand range with granule horizons as thick as 30 cm. Color variable in shades of pinkish gray, gray, and dusky red; the redder layers in general are the finer grained.
201.2	659.8	6.92	22.7	Quartzite, fine- to medium-grained, light-purplish-gray to dark-reddish-gray, generally cross-bedded, with both grain-size and color variations defining laminae.

DEPTH		THICKNESS		DESCRIPTION
m	ft	m	ft	
209.2	686	4.63	15.2	Quartzite, fine- to medium-grained, cross-bedded as above, with scattered layers of coarse to very coarse sand.
213.8	701.2	0.40	1.3	Laminated quartzose siltstone, pink, with centimeter-thick interbeds of clay-cemented, fine-grained quartzite.
214.2	702.5	7.41	24.3	Quartzite, fine- to medium-grained, pink to gray, prominently cross-laminated.
				TOP OF UNIT C
221.6	726.8	15.82	51.9	Quartzite, fine- to coarse-grained, pink to reddish-gray, thinly cross-bedded, with scattered interbeds of silty shale in thickness range of 1-4 cm. Shale beds are brick red with grayish-white reduction spots; delicately cross-laminated.
				TOP OF UNIT B
237.4	778.7	6.34	20.8	Quartzite, fine- to medium-grained, pinkish-gray to pink.
243.7	799.5	0.30	1.0	Conglomerate, dark-gray; well-rounded clasts of quartz (70%), gray chert (20%), and reddish-gray siltstone (10%) in matrix of coarse to very coarse quartz sand.
244.0	800.5	0.76	2.5	Quartzite, essentially massive, medium- to fine-grained, uniform light-pinkish-gray.
244.8	803	2.74	9.0	Quartzite, fine-grained, laminated on scale of 5-10 mm.
247.6	812	8.23	27.0	Quartzite, medium-grained, light- to dark-pinkish-gray; very minor widely separated shaly partings. Kaolinitic matrix noted in some beds. Cross-bedding prominent in all but topmost meter of unit.
255.8	839	0.30	1.0	Pebbly quartzite with scattered pebbles of quartz, chert, as large as 1 cm.
256.1	840	16.77	55.0	Quartzite, medium- to fine-grained, typically cross-bedded with laminae marked by subtle color variations in tones of gray and grayish purple. Pebbly horizon about 6 cm thick at depth 257.9 m.
				TOP OF UNIT A
272.9	895	11.59	38.0	Quartzite, coarse to very coarse, with numerous layers of granules and pebbles. Prominent conglomeratic horizons, all thinner than 30 cm, at depths 275.3, 277.1, 282, and 282.7 m. Conglomeratic beds contain pebbles of quartz, chert, minor cherty iron-formation.
284.5	933	4.51	14.8	Quartzite, fine- to medium-grained, with numerous dispersed granules and coarse sand grains. Prominent bleaching and kaolinitic matrix in topmost 30 cm and in basal 4 m. Steep slickensided fracture noted at depth 286 m.
289.0	947.8	0.43	1.4	Conglomerate and pebbly quartzite, grayish-white to purple. About 30% of rock consists of pebbles; pebbles as large as 4 cm are dominantly quartz with some gray chert. Lowermost 10 cm has abundant kaolinitic matrix.

DEPTH		THICKNESS		DESCRIPTION
m	ft	m	ft	
				BASE OF SIOUX QUARTZITE UNCONFORMITY
289.4	949.2	3.20	10.5	Granitic gneiss, hard, dark-reddish-brown to dark-gray; extensive secondary silica, hematite. Strongly altered rock.
292.6	959.7	4.66	15.3	Tonalitic gneiss, feebly foliated, medium-grained, hematite-stained to various tints of brick-red. Dip of foliation varies between 0 and 10 degrees. Feldspar grains kaolinized, of chalky appearance. Biotite extensively chloritized. Numerous thin seams, veinlets of chlorite, epidote, clay minerals.
297.3	975	0.30	1.0	Tonalitic gneiss, creamy-white to greenish-white, moderately soft. Abundant kaolin, chlorite.
297.6	976	1.52	5.0	Tonalitic gneiss, brick-red, as in interval 292.6 to 297.3 m.
299.1	981	0.46	1.5	Tonalitic gneiss, creamy-white to greenish-white, speckled with green; heavily kaolinized and moderately soft.
299.5	982.5	1.92	6.3	Tonalitic gneiss, brick-red, as in interval 292.6 to 297.3 m.
301.5	988.8	0.30	1.0	Tonalitic gneiss, light-gray to creamy-white with flecks of brick-red and green; heavily kaolinized and moderately soft.
301.8	989.8	2.50	8.2	Tonalitic gneiss, brick-red as in interval 292.6 to 297.3 m.
304.3	998	0.61	2.0	Mafic schist, biotite-bearing but heavily altered to chlorite, sericite, hematite. Relict hornblende pseudomorphs noted in thin section. Interpreted as mafic layer or inclusion in tonalitic gneiss.
304.9	1000	2.59	8.5	Tonalitic gneiss, medium-grained, biotite-bearing; hematite staining varies irregularly in intensity.
307.5	1008.5	0.61	2.0	Gneiss consisting of alternating thin mafic and granitic layers; mafic layers are essentially biotite and hornblende-biotite schist; granitic layers are somewhat kaolinized, medium- to coarse-grained granite and/or tonalite. Foliation is subhorizontal.
308.1	1010.5	4.42	14.5	Tonalitic gneiss, weakly foliated, medium-grained, biotite-bearing; variably stained with secondary hematite and variably kaolinized, sericitized, Numerous seams, thin veinlets of epidote, chlorite; veinlets increase in frequency toward bottom of interval.
312.5	1025	-	-	END OF HOLE

Drill hole SQ-6, SW¼SW¼NE¼ sec. 7, T. 107 N., R. 34 W.
Log of the Sioux Quartzite and subjacent Archean gneiss

DEPTH		THICKNESS		DESCRIPTION
m	ft	m	ft	
0	0	30.27	99.3	Glacial overburden (record from driller's log only).
				UNCONFORMITY ERODED TOP OF UNIT E, SIOUX QUARTZITE
30.3	99.3	1.52	5.0	Quartzite, fine- to medium-grained, light-gray to pink, somewhat bleached; thin interbeds of bleached, greenish-gray kaolinitic shale.
31.9	104.5	0.15	0.5	Quartzite, fine- to medium-grained, reddish-gray, slightly bleached.
32.0	105	0.34	1.1	Interbedded fine- to medium-grained quartzite and mudstone; variegated gray and red with evidence of bleaching.
32.3	106.1	15.52	50.9	Quartzite, fine- to medium-grained, light-purplish-gray to gray, with numerous irregular bleached zones. Bleached zones spatially related to fractures and zones of pyrite blebs. Pyrite blebs noted at depths 33.5, 35.7, 40.7, 43.9 m. Detrital muscovite noted at depth 36.6 m. Low-angle cross-lamination common.
				TOP OF UNIT D
47.9	157	3.05	10.0	Quartzite, purplish-gray, medium- to coarse-grained.
50.9	167	0.61	2.0	Prominent zone of bleached greenish-gray quartzite with abundant pyrite blebs.
51.5	169	4.48	14.7	Quartzite, fine- to coarse-grained, purplish-gray; grain-size changes are gradational, without sharp bedding planes. Half-inch shale bed at base.
56.0	183.7	1.31	4.3	Quartzite, brick-red, with gradational thin layers of very coarse sand; numerous thin partings of mudstone.
57.3	188	5.03	16.5	Quartzite, fine- to very coarse grained, with prominent thin beds of grit 1 to 20 cm thick.
62.3	204.5	0.76	2.5	Grayish-white bleached zone in coarse-grained quartzite.
63.1	207	2.04	6.7	Quartzite, predominantly very coarse grained, purplish-gray, with kaolinitic matrix.
65.1	213.7	1.10	3.6	Grayish-white bleached zone in very coarse grained quartzite.
66.2	217.3	4.02	13.2	Quartzite, predominantly very coarse grained, purplish-gray, with kaolinitic matrix. Granule bed 7.5 cm thick at base.
70.3	230.5	4.42	14.5	Quartzite, dominantly fine to very fine grained, locally laminated, with prominent centimeter-scale interbeds of very coarse sand and granules. Bleached grayish white; bleaching diminishes toward base. Granule beds contain dispersed pyrite blebs and have kaolinitic matrix.
74.7	245	0.61	2.0	Quartzite, massive, fine- to medium-grained, light-gray to purple.
75.3	247	11.28	27.0	Quartzite with gradationally bounded, fine- to very coarse grained interbeds 1-10 cm thick; purplish gray.

DEPTH		THICKNESS		DESCRIPTION
m	ft	m	ft	
				TOP OF UNIT C
83.6	274	0.15	0.5	Brick-red mudstone, 15 cm thick.
83.7	274.5	2.90	9.5	Quartzite, generally fine to medium grained, with gradationally bounded coarse layers 2-10 cm thick. Gray to purplish gray.
86.6	284	5.15	16.9	Quartzite, very fine to coarse-grained, with numerous shale and mudstone partings less than 1 cm thick. Dark purplish gray to brick red.
89.3	292.9	4.09	13.4	Quartzite with gradationally bounded, fine- to very coarse grained interbeds 1 to 10 cm thick; purplish gray. Red shale beds, 15 cm thick, at depths 91.6 and 93.2 m.
93.4	306.3	8.75	28.7	Complex thin-bedded interval composed dominantly of interstratified very coarse to very fine grained quartzite with numerous partings and thin beds of mudstone and shale. Mudstone layers, less than 15 cm thick, at depths 95.3, 96, 98.2, 98.6, 98.8, and 101.6 m.
				TOP OF UNIT B
102.1	335	12.8	42.0	Quartzite, coarse- to very coarse grained, with numerous thin beds of granules and small pebbles; gray to purplish gray. Prominent conglomerate beds at depths 104.7-105.1, 106.7-107.9, and 108.5-108.8 m. Shale parting at depth 109.5 cm.
114.9	377	4.89	16.0	Quartzite, dominantly medium grained, with some coarse layers; gray to purplish gray. Minor shale partings at depths 117.7, and 119.6 m; conglomeratic quartzite 20 cm thick at base.
				TOP OF UNIT A
119.8	393	0.27	0.9	Silty quartzite with interbedded shale; dark purple.
120.1	393.9	0.27	0.9	Quartzite, fine- to medium-grained, with shale partings; purplish gray.
120.4	394.8	0.09	0.3	Shale and quartzose siltstone; dark purplish gray
120.5	395.1	0.49	1.6	Quartzite, strongly size-graded (fining up); dark purplish gray.
121.0	396.7	0.24	0.8	Shale and quartzose siltstone.
121.2	397.5	0.24	0.8	Quartzite, very coarse grained, with granule layers and shale partings. Kaolinitic matrix.
121.4	398.3	0.61	2.0	Dominantly shale with minor quartzose siltstone, silty quartzite; very dark maroon.
122.0	400.3	0.21	0.7	Quartzite, fine- to medium-grained, with shale partings.
122.3	401	1.68	5.5	Dominantly shale, dark-maroon, with minor thin interbeds of silty quartzite on order of 1-7 cm thick. Soft-sediment sand-injection dikes noted at 123.4 m depth.
123.9	406.5	0.46	1.5	Quartzite, fine- to medium-grained, grayish-purple; 4-cm-thick bed of shale at center.

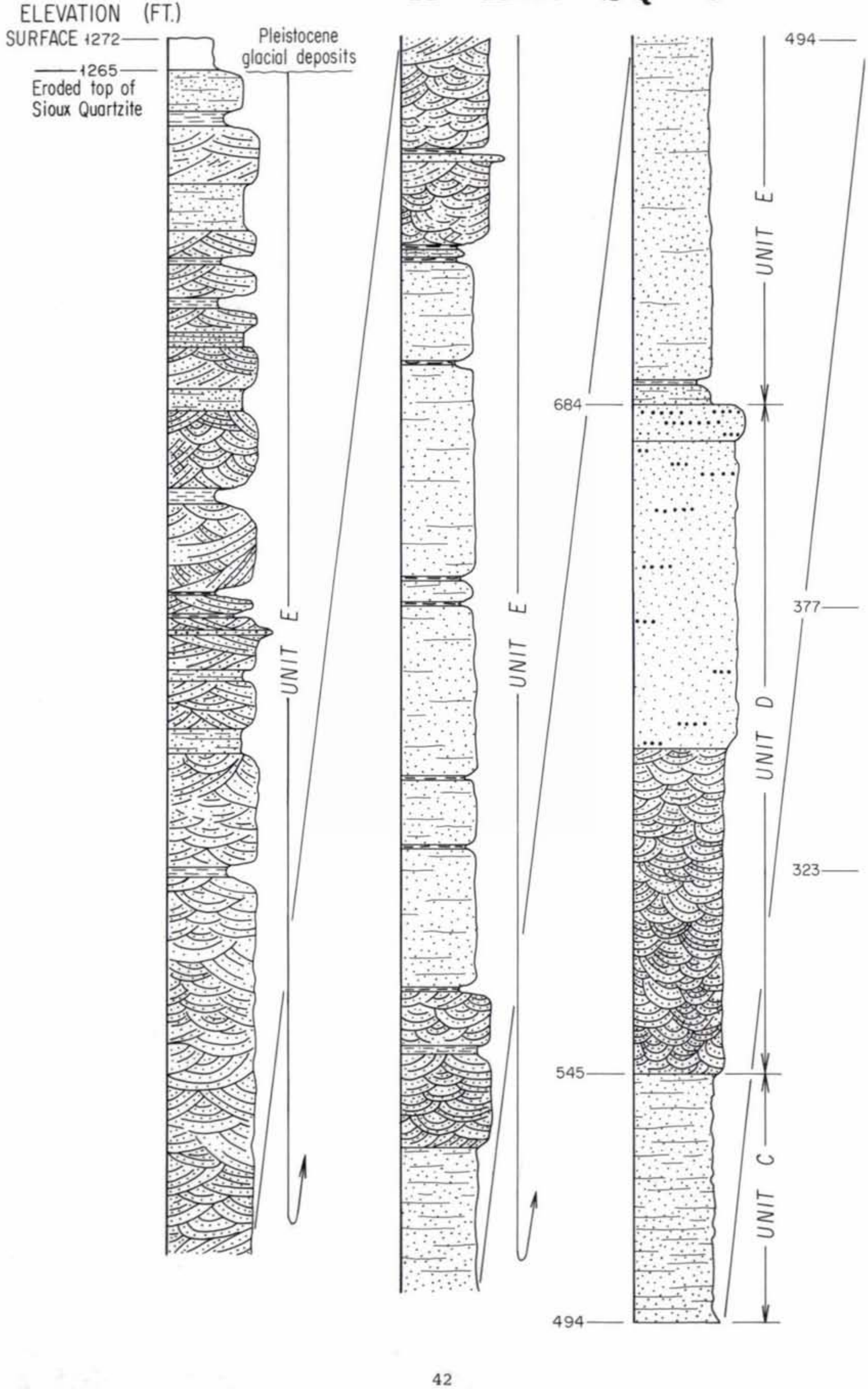
DEPTH		THICKNESS		DESCRIPTION
m	ft	m	ft	
124.4	408	4.73	15.5	Dominantly shale, very dark maroon, with numerous beds of fine quartzite on order of 7-10 cm thick making up 20 percent of total section.
129.1	423.5	0.24	0.8	Quartzite, fine- to medium-grained, with prominent dispersed granules.
129.4	424.3	0.52	1.7	Shale, soft, dark-reddish-brown to maroon, with minor mottling in grayish green. Minor sandy to silty interbeds.
129.9	426	2.59	8.5	Quartzite, very fine to very coarse grained, with vaguely defined thin bedding; purplish gray. Prominent granule bed with kaolinitic matrix, 15 cm thick, at depth 131.7 m.
132.5	434.5	0.09	0.3	Silty shale, dark-maroon.
132.6	434.8	0.09	0.3	Quartzite, medium-grained with dispersed granules; dark gray.
132.7	435.1	0.12	0.4	Conglomerate; small rounded pebbles of vein quartz and angular, flat intraclasts of bleached, greenish-gray, clay-rich shale.
132.8	435.5	0.61	2.0	Quartzite, medium- to coarse-grained, with dispersed granules and small pebbles; minor shale partings. Dark brownish gray.
133.4	437.5	0.09	0.3	Conglomerate; granules, pebbles, and small cobbles of vein quartz in matrix of sand-size quartz and kaolinite. Core badly fractured.
133.5	437.8	1.59	5.2	Conglomerate; cobbles of granitic gneiss as large as 25 cm in diameter together with pebbles and granules of quartz. Much iron staining and extensive development of secondary kaolinite. Core badly fractured, crumbly.
				BASE OF SIOUX QUARTZITE UNCONFORMITY
135.1	443	6.10	20.0	Partly weathered mafic schist and gneiss; varies in texture from fine to medium grained and in foliation from schistose to gneissic; foliation dips 20-25°. Variable, locally intense, hematite staining; extensive development of secondary kaolinite, chlorite; some residual hornblende and biotite. More felsic pale-greenish-gray layers occur at depths 138.1-138.4 and 140.3-140.5 m.
141.2	463	3.66	12.0	Granitic gneiss, subpegmatitic, crudely foliated. Variably altered to kaolinite, chlorite.
144.8	475	3.05	10.0	Essentially fresh granitic gneiss, weakly foliated to massive, with numerous layers, streaks, and clots of mafic composition. Granitic component is very coarse grained with prominent large crystals of reddish-brown microcline; mafic component is dominantly hornblende-clinopyroxene granulite.
147.9	485	-	-	END OF HOLE

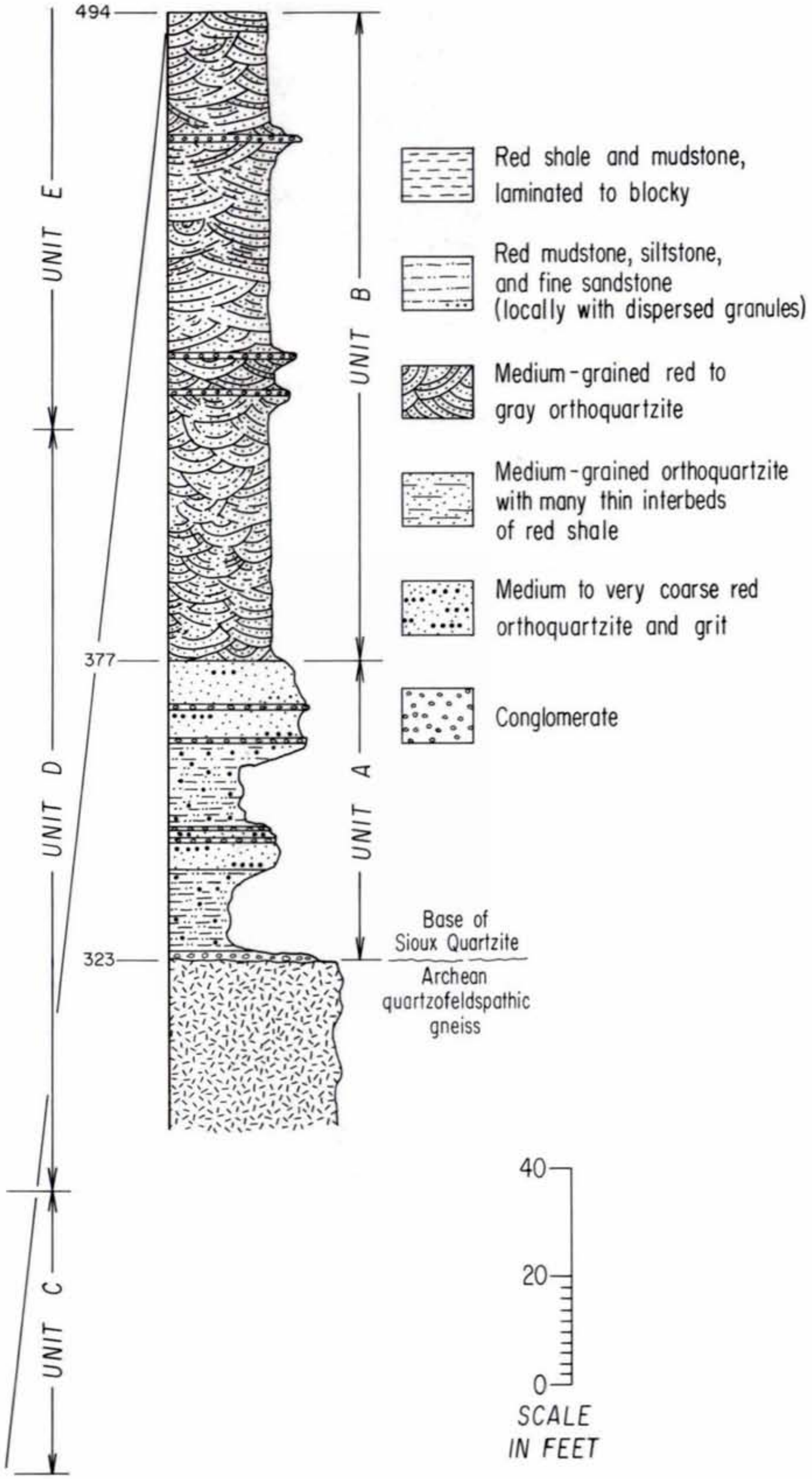
Drill hole SQ-13, NE¼NW¼NE¼ sec. 23, T. 107 N., R. 33 W.
Log of the Sioux Quartzite, the overlying Cretaceous shale, and underlying Archean gneiss

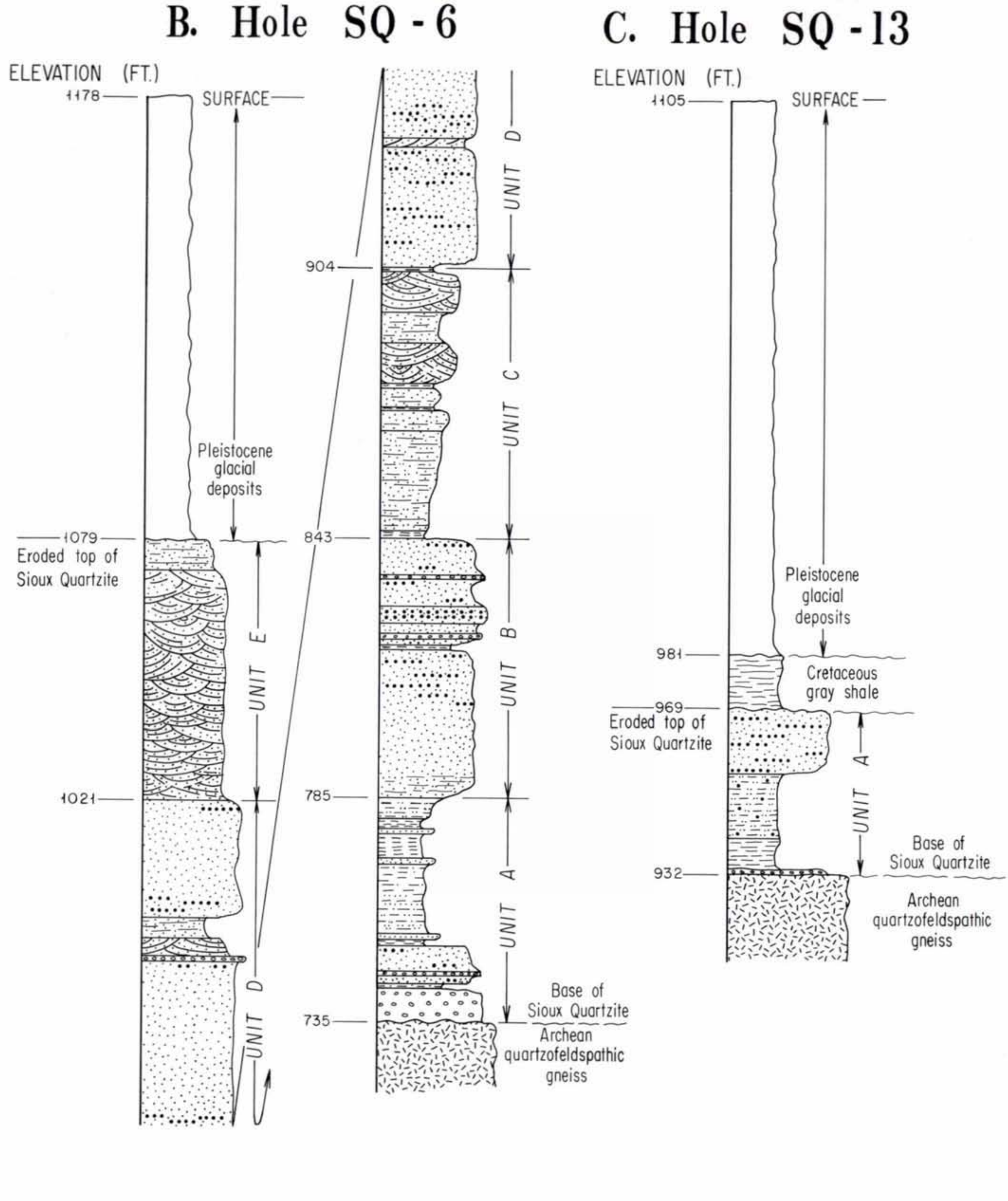
DEPTH		THICKNESS		DESCRIPTION
m	ft	m	ft	
0	0	37.96	124.5	Glacial overburden (record from driller's log only).
				UNCONFORMITY ERODED TOP OF CRETACEOUS STRATA
38.0	124.5	3.51	11.5	Shale, medium-gray, soft, laminated, with scattered lenses of hard, light-brown, well-indurated siltstone.
				UNCONFORMITY ERODED TOP OF UNIT A, SIOUX QUARTZITE
41.5	136	4.36	14.3	Conglomeratic grit and quartzite; streaked and mottled in various shades of brown, reddish brown, and light greenish gray. Vein quartz pebbles as large as 5 cm in a poorly sorted, poorly to moderately well rounded matrix of quartz grains and granules, kaolinized feldspar, and lithic clasts of reddish quartzite and granitic rock. Crude bedding marked by changes in texture. Abundant secondary kaolinite; numerous millimeter-scale veinlets of epidote.
45.8	150.3	0.06	0.2	Shale, dark brick-red.
45.9	150.5	4.42	14.5	Shale, light-greenish-gray to gray, laminated, with dispersed sand- and granule-size grains of quartz.
50.3	165	2.13	7.0	Shale, streaked and mottled in various shades of reddish brown and pale greenish gray. Laminated; clay rich; very uniform fine texture.
52.4	172	0.24	0.8	Poorly sorted, moderately feldspathic quartzite with dispersed granules and pebbles; bleached greenish-gray color. Abundant secondary kaolinite. Millimeter-thick shale parting about 2 cm below top of unit. Sharp basal contact on weathered gneiss.
				BASE OF SIOUX QUARTZITE UNCONFORMITY
52.7	172.8	6.77	22.2	Weathered granitic gneiss; near total decomposition of primary minerals to kaolinite, illite. Color light gray to light grayish green. Foliation preserved.
59.5	195	7.93	26	Transition zone between totally weathered gneiss (above) and essentially fresh rock.
67.4	221	1.22	4	Interlayered tonalitic and granitic gneiss. Tonalitic layers range from gray to brown; consist of quartz, plagioclase, and varying small amounts of biotite, hornblende, and clinopyroxene. Granitic layers are subpegmatitic near center and grade to finer grain size at contacts. Incipient weathering along fractures. Foliation dips 20-25°.
68.6	225	-	-	END OF HOLE

APPENDIX B. STRATIGRAPHIC COLUMNS FOR DRILL HOLES SQ-3, SQ-6, AND SQ-13
[See Appendix A for more complete descriptive logs]

A. Hole SQ - 3




494
377
323
UNIT E
UNIT D
UNIT C
UNIT B
UNIT A
Red shale and mudstone, laminated to blocky
Red mudstone, siltstone, and fine sandstone (locally with dispersed granules)
Medium-grained red to gray orthoquartzite
Medium-grained orthoquartzite with many thin interbeds of red shale
Medium to very coarse red orthoquartzite and grit
Conglomerate
Base of Sioux Quartzite
Archean quartzofeldspathic gneiss
40
20
0
SCALE IN FEET



B. Hole SQ-6

C. Hole SQ-13

HYDROGEOCHEMICAL ANOMALIES ASSOCIATED WITH THE BASAL CONTACT OF THE SIOUX QUARTZITE ALONG THE NORTH MARGIN OF THE COTTONWOOD COUNTY BASIN

By

D.L. Southwick and R.S. Lively

ABSTRACT

Dissolved uranium, helium, and oxygen, radon activity, alkalinity, and specific conductivity vary regionally and systematically in ground water of the Sanborn-Jeffers area in southwestern Minnesota. Ground water from wells in areas of quartzite bedrock is characterized by lower contents of dissolved uranium and helium, higher contents of dissolved oxygen, regionally higher radon activity, and regionally lower alkalinity and specific conductivity than ground water from wells in areas where the first bedrock is Cretaceous shale. The quartzite-shale contact corresponds closely to the subcrop position of the basal contact of Sioux Quartzite on Archean gneissic basement, and also marks the place where Quaternary glacial overburden changes from thin (over quartzite) to thick (over shale). The areal variation in ground-water chemistry reflects the influence of bedrock lithology, and also the variations in overburden composition and thickness.

INTRODUCTION

Ground-water samples from domestic and farm wells in the Sanborn-Jeffers area of southwestern Minnesota (Figs. 1 and 2) were analyzed for uranium, radon, and helium during a federally sponsored effort to evaluate the uranium resource potential of the New Ulm NTMS quadrangle (Southwick and others, 1982). Total dissolved oxygen, specific conductivity, and alkalinity also were determined for most of the water samples. Although no economically significant amounts of uranium were found, the research did reveal an unexpectedly good correlation between the measured geochemical variables and the buried bedrock geology of the area, which straddles the basal contact of the Sioux Quartzite on the north margin of the Cottonwood County basin (Southwick and Mossler, 1984). In this brief note we present contoured geochemical maps of the Sanborn-Jeffers area and interpret the geochemical patterns in terms of the bedrock and surficial geology. The data base consists of 118 analyzed samples of ground water (Table 1) collected within an area of approximately 837 km^2 (323 mi^2).

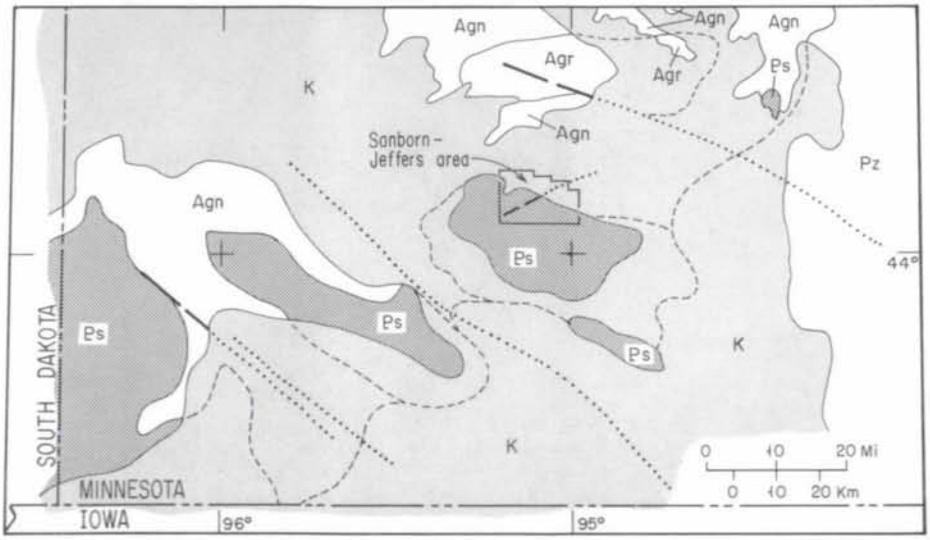
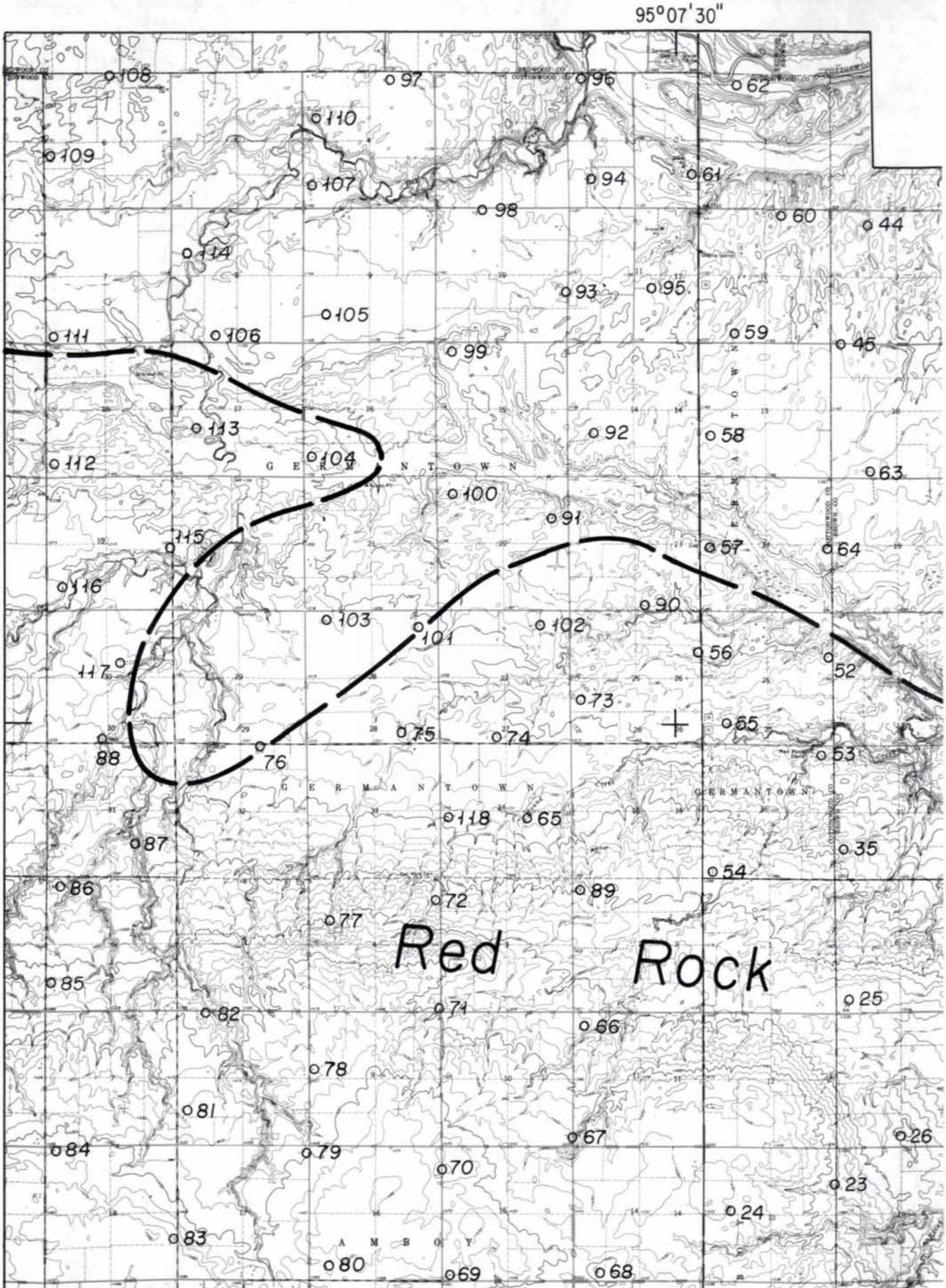


Figure 1. Regional geologic setting of the Sanborn-Jeffers area (bedrock geology). Agn = Archean gneiss; Agr = Archean granitic rocks; Ps = Sioux Quartzite; Pz = Paleozoic sedimentary rocks; K = Cretaceous sedimentary rocks. Sub-Cretaceous contacts shown by short-dashed lines. Faults shown as heavy lines, dotted where concealed by younger rocks. Data from Morey and others (1982) and files of the Minnesota Geological Survey.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Red Rock
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AMBOY
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68

Figure 2. Map of the Sanborn-Jeffers study area showing the locations of water wells sampled. The sample numbers apply to Table 1. Heavy line marks the inferred contact of Cretaceous sedimentary rocks against Sioux Quartzite. Base modified from U.S. Geological Survey, Comfrey, Jeffers, Sanborn, Sanborn Northeast, Sanborn Southeast, and Springfield 1:24,000, 1967.

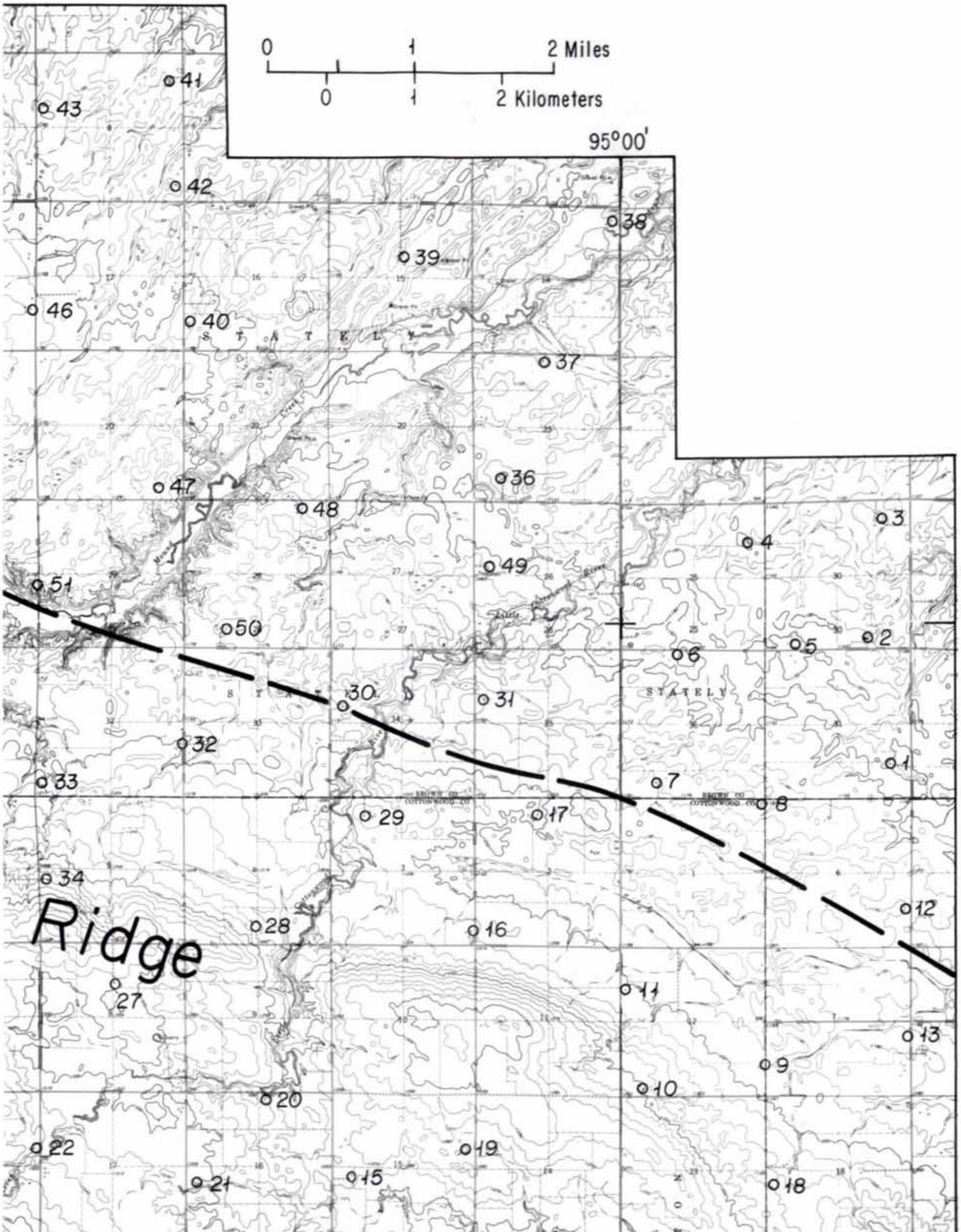

Table 1. Hydrogeochemical data, Sanborn-Jeffers area

Station	U	Rn	He	Sp. cond.	Alk.	Diss. O_2
	(See notes at end of table for units)					
MFG - 1	0.1	160	51.	1237	423	0.7
2	15	1000	-0.2	1306	478	0.7
3	9	580	-0.09	1237	400	1.9
4	14	680	-0.28	n.d.	n.d.	n.d.
5	6	580	-0.15	1083	330	2.8
6	5	180	-0.20	1819	500	0.9
7	4	460	0.11	711	314	3.7
8	3	620	0.00	893	378	0.8
9	0.1	240	-0.11	458	260	4.1
10	0.1	2400	-0.056	345	118	4.9
11	0.1	260	-0.056	n.d.	n.d.	n.d.
12	5.	1600	0.22	467	286	1.0
13	0.1	350	0.034	360	239	0.6
14	2.	2100	0.00	515	245	2.7
15	16.	1900	-0.056	910	379	2.4
16	0.1	400	-0.056	521	257	0.3
17	4.	6300	-0.11	847	325	4.1
18	2.	4300	-0.034	n.d.	n.d.	n.d.
19	0.1	530	n.d.	288	104	6.2
20	2.	380	-0.056	730	303	2.2
21	0.1	58	0.11	925	372	0.8
22	4.	16000	-0.056	666	264	3.9
23	3.	14000	-0.090	539	255	8.5
24	4.	910	0.056	804	339	1.5
25	0.1	860	-0.056	652	362	4.2
26	4.	2300	-0.17	n.d.	n.d.	n.d.
27	0.1	470	-0.15	488	162	6.0
28	2.	2100	-0.09	699	266	5.9
29	1.	610	-0.034	n.d.	n.d.	n.d.
30	0.1	900	0.11	791	317	0.4
31	0.1	250	0.15	1069	366	0.1
32	10.	250	-0.17	n.d.	n.d.	n.d.
33	7.	160	-0.11	911	310	1.8
34	0.1	6000	-0.15	342	155	8.8
35	2.	7900	-0.090	820	299	8.0
36	20.	540	-0.23	n.d.	n.d.	n.d.
37	0.1	250	10.	958	346	0.2
38	0.1	240	4.1	n.d.	n.d.	n.d.
39	0.1	350	0.79	851	470	0.1
40	0.1	4500	19.	810	326	0.0
41	0.1	160	0.17	n.d.	n.d.	n.d.
42	2.	170	-0.056	n.d.	n.d.	n.d.
43	0.1	700	0.090	n.d.	n.d.	n.d.
44	4.	320	-0.11	887	474	0.3
45	4.	180	-0.11	888	360	5.5
46	0.1	340	4.5	1188	504	0.3
47	0.1	740	1.1	1167	388	0.1
48	0.1	220	0.034	1236	536	1.9
49	0.1	770	0.90	n.d.	n.d.	n.d.
50	0.1	320	0.34	852	374	0.2
51	0.1	240	1.5	912	342	0.2
52	0.1	660	0.56	825	461	0.9
53	3.	1400	-0.11	n.d.	n.d.	n.d.
54	4.	5500	-0.11	862	381	8.0
55	1.	360	-0.11	n.d.	n.d.	n.d.
56	0.1	310	0.90	n.d.	n.d.	n.d.
57	0.1	390	0.45	1174	387	0.9
58	0.1	330	0.090	1343	345	0.8
59	2.	260	0.37	n.d.	n.d.	n.d.
60	0.1	150	20.	583	253	0.4
61	0.1	160	38.	570	200	0.1

62	0.1	92	11.	1088	388	0.8
63	0.1	770	4.6	888	420	2.1
64	0.1	830	98.	808	280	0.5
65	3.	1800	0.034	654	278	7.2
66	5.	6500	0.034	726	232	0.3
67	1.	330	0.034	1388	336	0.5
68	1.	460	0.20	1305	266	2.3
69	0.1	6	0.034	960	450	2.6
70	8.	1600	-0.056	1086	315	4.4
71	4.	n.d.	-0.090	n.d.	n.d.	n.d.
72	2.	3700	0.0	660	233	9.2
73	0.1	1300	0.9	740	284	0.5
74	2.0	550	-0.034	n.d.	n.d.	n.d.
75	0.1	280	0.15	827	480	0.7
76	9.	280	-0.20	1259	478	0.2
77	1.	6500	-0.056	705	196	7.0
78	5.	2700	-0.034	1069	310	2.8
79	2.	590	-0.11	n.d.	n.d.	n.d.
80	1.	320	-0.034	1472	373	0.4
81	2.	390	0.20	1415	400	0.6
82	7.	9100	-0.034	1089	377	5.9
83	2.	500	-0.056	1325	387	0.7
84	1.	290	0.056	1235	400	0.5
85	8.	1500	n.d.	1070	362	0.4
86	5.	1200	-0.090	1324	418	0.2
87	2.	3800	-0.090	939	300	2.1
88	5.	920	0.11	1077	360	0.8
89	6.	5200	0.0	1361	292	6.0
90	0.1	230	9.6	n.d.	n.d.	n.d.
91	0.1	310	2.4	880	352	0.5
92	5.	570	-0.090	1224	362	7.0
93	0.1	190	5.1	1035	387	0.3
94	2.	230	0.056	565	342	7.9
95	0.1	330	10.	n.d.	n.d.	n.d.
96	0.1	170	0.034	813	418	0.0
97	0.1	220	16.	n.d.	n.d.	n.d.
98	0.1	310	1.6	1041	413	0.5
99	0.1	240	0.20	n.d.	n.d.	n.d.
100	0.1	230	1.5	1319	345	0.7
101	0.1	220	1.3	683	441	1.2
102	2.	490	0.96	n.d.	n.d.	n.d.
103	14.	730	-0.17	n.d.	n.d.	n.d.
104	0.1	360	1.6	887	374	0.1
105	0.1	140	2.4	1113	433	0.6
106	0.1	150	4.5	n.d.	n.d.	n.d.
107	20.	680	-0.17	1143	365	1.2
108	0.1	690	2.6	1153	400	0.5
109	0.1	290	5.7	1234	384	1.9
110	0.1	1000	18.	1211	415	1.0
111	8.	560	0.0	n.d.	n.d.	n.d.
112	0.1	230	1.1	n.d.	n.d.	n.d.
113	4.	270	1.9	879	370	0.6
114	0.1	110	2.7	1216	385	0.2
115	6.	380	0.0	753	327	0.6
116	0.1	320	0.39	n.d.	n.d.	n.d.
117	1.	360	0.0	n.d.	n.d.	n.d.
118	4.	5000	0.056	818	314	6.6

NOTES:

The data are in the following units:

U: ppb U_3O_8

Rn: picoCuries per liter

He: ppm in gas phase above (below) concentration in standard air

Specific conductivity: micromhos

Alkalinity: ppm bicarbonate equivalent

Dissolved oxygen: ppm

The entry n.d. means not determined. See Figure 2 for station locations.

OUTLINE OF GEOLOGY AND HYDROGEOLOGY

The oldest rocks in the Sanborn-Jeffers area are complex quartzofeldspathic and granulitic gneisses of Archean age. The gneisses do not crop out but are known in the subsurface from three diamond drill holes in and near the geochemical study area (Southwick and Mossler, 1984, fig. 2 and plate 1). The gneisses are lithologically similar to rocks exposed in the Minnesota River Valley some 50 km (30 mi) to the north (see descriptions in Lund, 1956; Himmelberg, 1968; Goldich and others, 1980a; 1980b) and are presumed to be correlative with them. Unconformably overlying the gneissic basement is the Sioux Quartzite of late early Proterozoic age. The Sioux is dominantly a hard, vitreous, very well cemented orthoquartzitic sandstone that contains greatly subordinate interbeds of red shale, red mudstone, and quartz-pebble conglomerate. It is characterized by many kinds of shallow-water sedimentary structures (Weber, 1981) and is interpreted to be a braided-river and alluvial-plain deposit that accumulated in one or more fault-controlled, grabenlike basins (Morey, 1983; Greenberg and Brown, 1983; Southwick and Mossler, 1984). Many outcrops of Sioux Quartzite occur along Red Rock Ridge in the Sanborn-Jeffers area (Fig. 2), but the basal contact of the formation is not exposed.

Both the Sioux Quartzite and the subjacent gneiss are overlain unconformably by a discontinuous cover of Upper Cretaceous laminated gray shale, fine sandstone, and siltstone, all dominantly of marine origin. This shale-dominated sedimentary sequence is thin, having been deposited near the strandline of the highest Zuni transgression (Sloss, 1963), and it may never have covered the higher knobs of erosionally resistant Sioux Quartzite (Shurr, 1981). The Cretaceous rocks are soft and erode easily; therefore they have been variably removed by post-Cretaceous stream erosion and by Quaternary glaciation.

A nearly continuous blanket of Quaternary glacial deposits covers all of the older rocks in the Sanborn-Jeffers area. These deposits range in thickness from a meter or less along portions of Red Rock Ridge to more than 50 m in the valley of the Little Cottonwood River. The uppermost layer of drift was deposited from the Des Moines lobe of the Wisconsinan continental glacier (Hobbs and Goebel, 1982), which advanced over the area from the northwest. Several older drifts of diverse provenance are known in the subsurface (Matsch, 1972).

Within the Sanborn-Jeffers area the regional flow of ground water is toward the north-northeast; major recharge occurs in the southwesternmost part of the outlined study area and in adjacent parts of the broad upland surrounding the town of Jeffers (Broussard and others, 1973; Anderson and others, 1974; Fig. 3). Data are inadequate to characterize the three-dimensional flow of ground water in detail. However, in areas where the Sioux Quartzite is shallow, such as along Red Rock Ridge (Fig. 2), the flow pattern is strongly influenced by the local hydraulic properties of the quartzite. In such areas there are ephemeral springs and seeps where shallow ground water is forced to the surface by a barrier of impermeable quartzite beneath; these typically flow only during spring runoff or during periods of excessive rainfall. In general, reliable supplies of ground water in the shallow quartzite areas can be obtained only from secondary fracture systems. Vertical

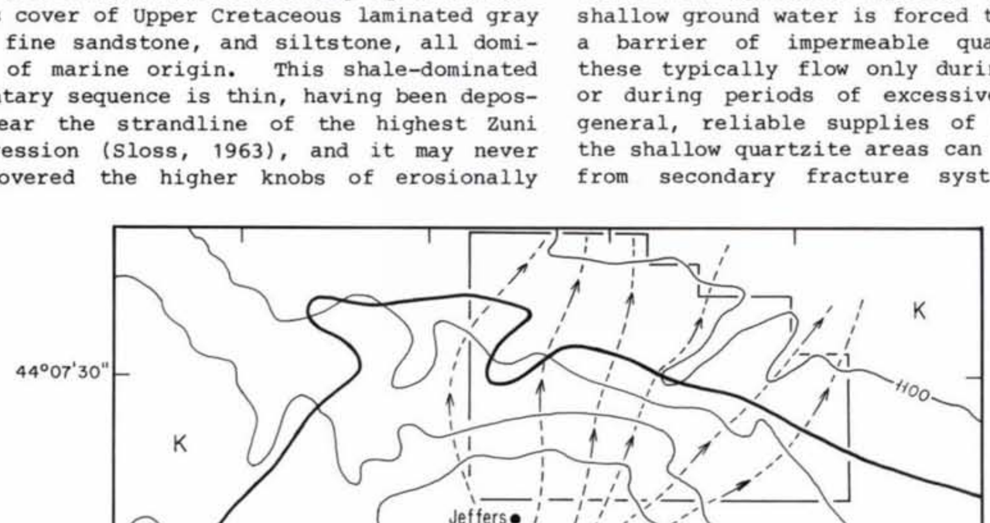

Figure 3. Map showing water-table contours (solid lines) and schematic ground-water flow paths (short-dashed arrows) in the vicinity of the Sanborn-Jeffers study area. Heavy line marks the inferred contact of Cretaceous sedimentary rocks against Sioux Quartzite. Water-table contours are in feet above sea level. Data modified from Broussard and others (1973); Anderson and others (1974).

joints, oriented on north-northwest and east-northeast trends, and subhorizontal joints, chiefly with dips of a few degrees to the south, are both exploited for water.

Many wells away from Red Rock Ridge obtain water from layers of gravel and sand within the Quaternary glacial drift, and somewhat fewer, in the northern part of the area, obtain water from permeable zones in the underlying Cretaceous strata. As a general rule we do not know which wells north of the basal Sioux contact are finished in glacial deposits and which are finished in Cretaceous rocks, because most of the wells in this long-established farming community were drilled before it became common practice to keep detailed drilling records. However, the relatively small amount of recent drilling in the area indicates that most wells shallower than 45 m (150 ft) probably obtain water from Quaternary aquifers; some wells deeper than 60 m (200 ft) may be drawing water from Cretaceous strata.

An important consideration, from the standpoint of interpreting ground-water chemistry, is the degree of hydraulic interconnection among waters in the quartzite, shale, and glacial drift aquifers. Unfortunately, data on this point are virtually lacking in the Sanborn-Jeffers area. The hydraulic connection between drift and quartzite may be relatively direct in areas where the drift is thin (on the order of 15 m [50 ft] or less), although even under these conditions there could be extensive lateral flow if parts of the drift section are impermeable. There is no clear evidence for a simple, direct hydraulic connection among quartzite, shale, and drift in areas where the drift section is thick and consists of several alternating permeable and impermeable layers.

CHEMICAL CHARACTERISTICS OF THE GEOLOGIC UNITS

The Archean crystalline basement of the Sanborn-Jeffers area is mostly tonalitic and granitic gneiss that encloses less abundant layers of amphibolite and granulite gneiss (Southwick and Mossler, 1984). Although no chemical analyses of gneisses from the study area are available, these rocks are so similar petrographically to exposed gneisses in the Minnesota River Valley that their major chemical attributes may be reasonably inferred from published analyses of Minnesota River Valley rocks (Goldich and others, 1980a, 1980b; Wooden and others, 1980). In general the gneissic basement is composed of ordinary silicate rocks that are not readily soluble in ground water. If these rocks were present alone in the ground-water environment, they would contribute small amounts (parts per million range) of dissolved Na, K, Ca, Mg, and Si to the water, and trace amounts (parts per billion range) of a long list of other chemical elements, including uranium (Davis and De Wiest, 1966, p. 112 and 134-137).

The Sioux Quartzite is a highly mature rock consisting predominantly of quartz with lesser quantities of kaolinite, sericite, hematite, and diaspore. The high-silica, high-alumina minerals making up the Sioux are virtually insoluble in ground water of normal acidity, and the quartzite, if present alone in the ground-water environment, would contribute only miniscule amounts of dissolved silica and very minor amounts of colloidal Fe-oxides to the water. Ground water that has come into contact only with Sioux Quartzite should be of high chemical quality, essentially similar to rain water. However, because infiltration occurs through open fractures, the chemistry of ground water in areas of shallow quartzite is strongly influenced by the composition of the thin overburden and by residues of agricultural chemicals. Thus, although ground waters in the Sioux Quartzite generally contain less than 700 ppm total dissolved solids (TDS) (Minnesota Department of Natural Resources, 1976), TDS levels in excess of 2,000 ppm are not uncommon (R. Kanivetsky, oral communication).

The shale-rich Cretaceous section of southwestern Minnesota contains thin layers of impure limestone and calcareous mudstone, and also contains carbonaceous layers rich in disseminated to nodular iron sulfide (Sloan, 1964). These layers contribute substantial loads of Ca^{+2}, HCO_3^-, SO_4^{-2}, and colloidal Fe-oxides to the associated ground waters, which typically are a mixture of the Ca-Mg bicarbonate and Ca-Mg sulfate types (Broussard and others, 1973). Data tabulated in the report of the Oak Ridge Gaseous Diffusion Plant (1979) and unpublished data in Minnesota Geological Survey files indicate that water in Cretaceous aquifers within and near the Sanborn-Jeffers area is dominantly the Ca-Mg sulfate type, and typically contains more than 1,500 ppm TDS.

The uppermost layers of glacial drift in the Sanborn-Jeffers area are dark-gray clay tills rich in comminuted shale (mainly from nearby Cretaceous deposits) and carbonate (mainly from Paleozoic strata in eastern North Dakota). Similar shale- and carbonate-rich tills also occur among the deeper drift sheets in the area and record earlier ice advances from northwesterly source areas (Matsch, 1972). The chemistry of water from wells finished in the glacial deposits strongly reflects the proportions of carbonate and shale; waters typically range from hard to very hard (120 to >180 mg/l equivalent $CaCO_3$) and also may be rich in SO_4^{-2} and colloidal Fe-oxides in places where the drift has incorporated a high proportion of sulfide-bearing shale (Broussard and others, 1973; Anderson and others, 1974; Oak Ridge Gaseous Diffusion Plant, 1979). The content of dissolved solids fluctuates widely in response to local availability of soluble constituents in the drift and to the varying hydraulic characteristics of the specific aquifers being utilized. TDS values as high as 3,000 ppm are not uncommon (Broussard and others, 1973).

None of the geologic formations in the New Ulm NTMS quadrangle, which includes the Sanborn-Jeffers area, is known to contain anomalous amounts of uranium. However, all bedrock units in the area do contain trace amounts of uranium (Table 2), and therefore the ground water also contains traces of uranium and certain of the daughter elements derived from uranium by radioactive decay. Further data on the content of uranium and selected other minor elements in stream sediments and ground waters of the New Ulm quadrangle are tabulated in the report of the Oak Ridge Gaseous Diffusion Plant (1979).

HYDROGEOCHEMISTRY OF URANIUM, HELIUM, AND RADON

Uranium, though a relatively rare element, is widely distributed as a trace constituent of most common rocks. Uranium is readily water soluble under oxidizing conditions, and therefore oxidizing ground water that circulates through uranium-bearing rock typically dissolves a little uranium from the rock and transports it in solution. However uranium is very insoluble under reducing conditions. If uranium-bearing ground water encounters a reducing environment, such as a layer of organic matter, a zone rich in sulfide, or a graphitic schist, the uranium tends to precipitate from solution and accumulate as uranium minerals in pore spaces or veins in the rock. Clearly, therefore, the quantity of dissolved uranium in a ground-water sample is not necessarily proportional to the quantity of uranium in the rock at the site where the water sample was taken. The hydrogeochemical distribution of uranium is the end product of complex interactions among circulating ground water, the host rock, and the factors that govern oxidation state.

Uranium and several intermediate daughter products decay radioactively by the emission of alpha particles from their nuclei. Because alpha particles are actually helium atoms, the natural radioactive decay of uranium and its daughters produces helium. Helium that is produced in this way may dissolve in and be transported by flowing ground water; furthermore, because it is a light, inert gas and has no half-life limitation (it is nonradioactive), helium may also migrate through ground water by diffusion. As a result, helium may accumulate in ground water to levels above the levels that result from normal dissolution in water of ordinary air. It follows that the concentrations of dissolved helium and uranium should positively correlate under circumstances where neither nuclide is lost, and dissolved helium anomalies therefore have some value to explorationists as

Table 2. U_3O_8 in pre-Quaternary bedrock units of the New Ulm NTMS quadrangle
[Results in parts per million]

Rock unit(s)	Mean[1]	Median[2]	85th percentile	High	N_t	N_b
*Archean gneissic complex						
Morton Gneiss	3.71	2.40	5.60	17	75	12
Other migmatitic gneiss, including the Montevideo	3.60	3.10	6.30	21	68	5
Amphibolite	1.89	1.82	3.20	8	34	6
Aluminous gneiss	2.69	1.88	4.40	8	17	4
Archean granitic plutons						
Sacred Heart Granite	9.16	5.30	13.5	95	69	2
Fort Ridgely Granite and unnamed granite masses	7.25	5.00	16.0	18	8	0
Minor Proterozoic intrusions, Minnesota River Valley						
Postorogenic plugs	2.68	2.57	4.35	8	42	1
Diabase dikes	2.40	2.0	3.80	5	14	4
*Sioux Quartzite	2.64	1.09	3.37	7	42	20
Paleozoic sedimentary rocks	1.75	2.00	-	2	6	2
*Pre-Cretaceous regolith on Precambrian rocks	3.57	3.45	7.00	8	37	2
*Cretaceous sandstone	2.57	2.44	4.90	6	28	5
*Cretaceous shale	5.19	4.85	9.80	15	42	0

*Rock units present in Sanborn-Jeffers area

[1] Arithmetic mean of values above the detection limit (>1ppm)

[2] Derived from log-normal cumulative curve

N_t = total number of samples analyzed

N_b = number of samples with U_3O_8 below detection limit (<1 ppm)

Table modified from Southwick and others (1982, table 2).

possible indicators of anomalous concentrations of uranium.

Radon, a radioactive but chemically inert gas, is an intermediate nuclide in the uranium decay series. Of the three naturally occurring isotopes of radon, only ^{222}Rn, a member of the ^{238}U decay series, survives for a significant length of time (half-life = 3.8 days), and for all practical purposes the radon dissolved in natural water may be considered as entirely ^{222}Rn. The immediate parent isotope of ^{222}Rn in the ^{238}U decay series is the radium isotope ^{226}Ra. This isotope has a long half-life of 1,700 years; its abundance and chemical properties and hence its geochemical behavior are quite different from uranium, and thus ^{226}Ra and ^{238}U commonly become separated in the near-surface geochemical environment. Because ^{222}Rn has a short half-life relative to ^{226}Ra, its immediate radioactive parent, the distribution of ^{222}Rn in nature is linked much more closely to the distribution of radium than to the distribution of uranium (see Lively and Southwick, 1981, for further radiochemical details).

Uranium and radium are readily adsorbed from solution onto both iron and manganese oxides. Therefore, if ground water that contains both ^{238}U and ^{226}Ra in solution should pass through fractures lined with iron or manganese oxide, both nuclides would tend to accumulate on the fracture walls. Fractures coated with iron or manganese oxides are common in the Sioux Quartzite and in the regolith developed on Archean gneiss just beneath the basal Sioux contact (Southwick and Mossler, 1984). We suggest that the observed distributions of dissolved U, Rn, and He in the Sanborn-Jeffers area (Figs. 4, 5, and 6) are related to the selective adsorption of ^{238}U and ^{226}Ra near the basal contact of the Sioux Quartzite, as discussed more fully below, but we have not been able to measure directly the activities of Ra or U at this stratigraphic position.

INTERPRETATION OF THE HYDROGEOCHEMICAL MAPS

The maps in Figures 4, 5, and 6 clearly show that the distributions of U, Rn, and He are spatially related to the contact of Cretaceous materials against the Sioux Quartzite. This contact approximately coincides with the subsurface location of the basal contact of the Sioux Quartzite against Archean gneiss (Fig. 1), and it also marks the place where the glacial deposits thicken markedly toward the north. The maps also show that Rn and He are inversely related;

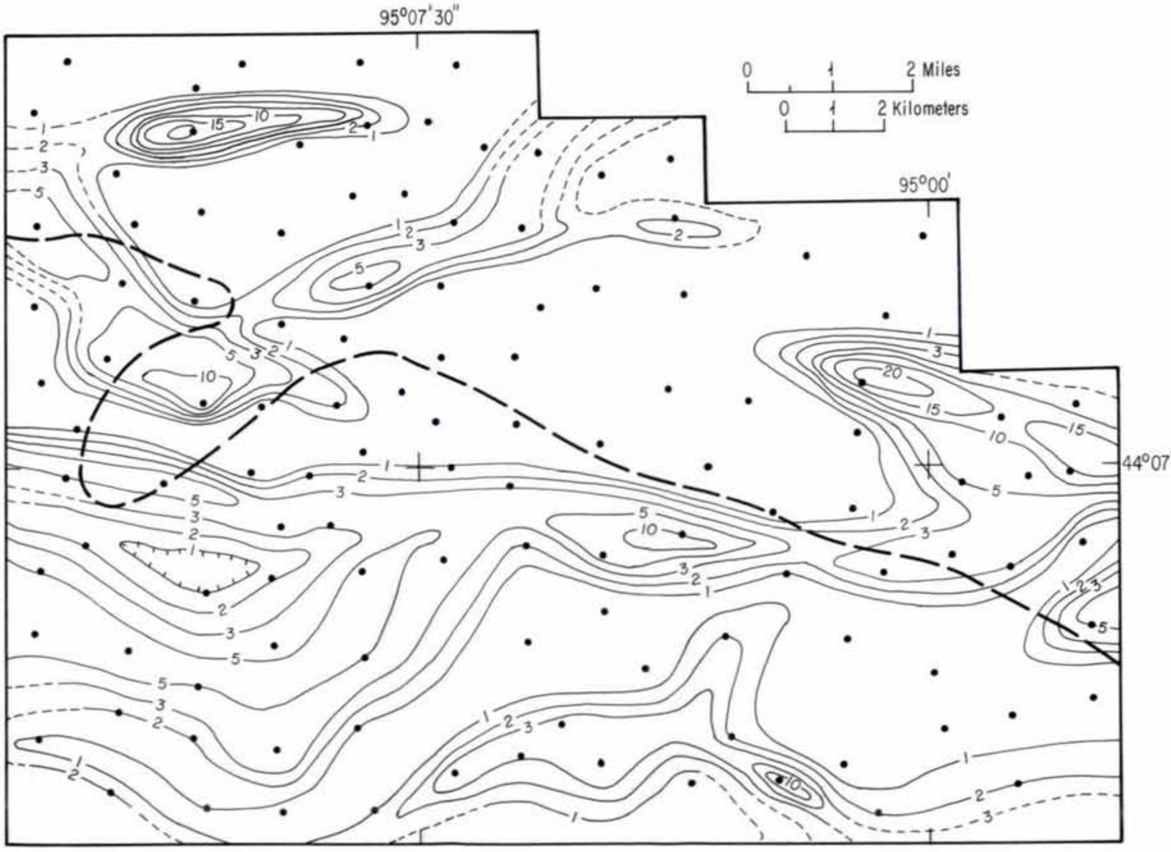

Figure 4. Dissolved uranium in ground water; data in parts per billion U_3O_8. Contours: 1, 2, 3, 5, 10, 15, 20 ppb; 118 analyses. Heavy line is subcrop contact between Sioux Quartzite (on south) and undivided Cretaceous sedimentary rocks (on north).

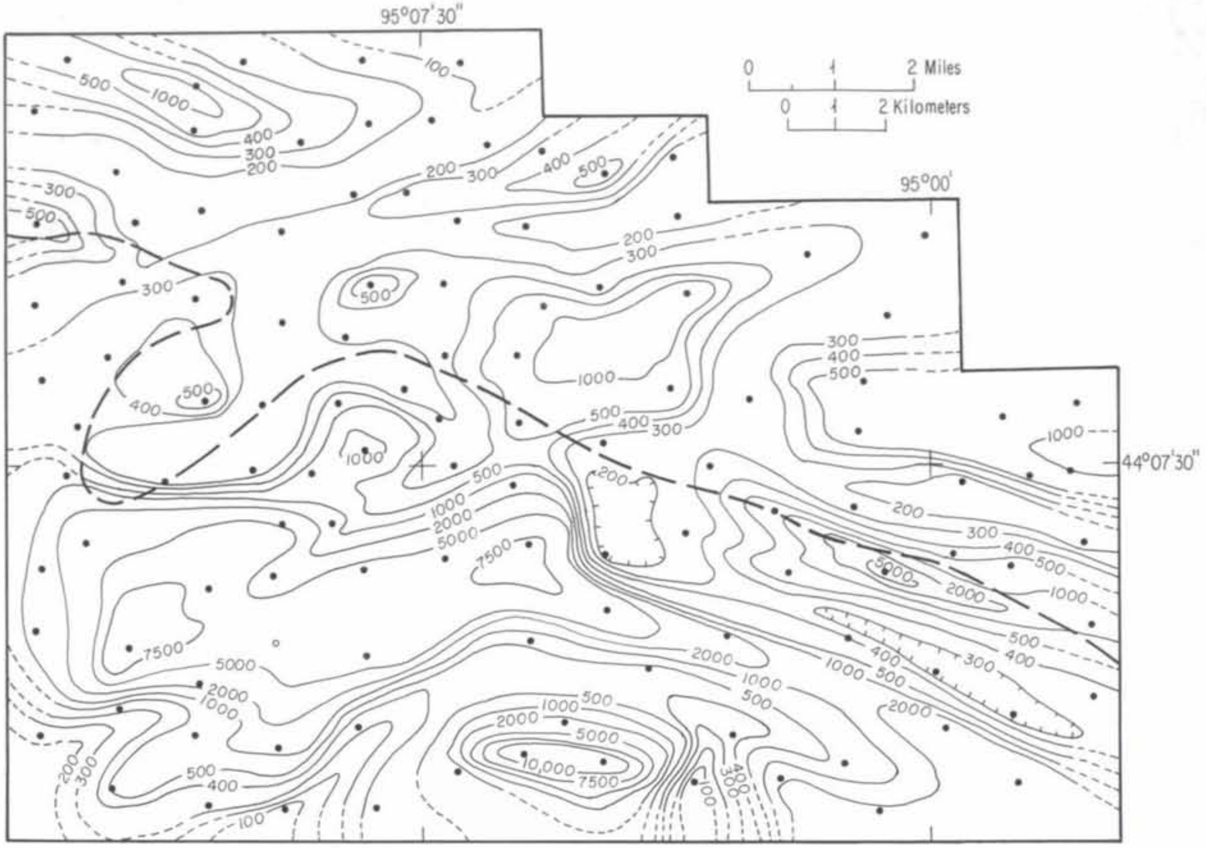

Figure 5. Radon activity in ground water; data in picoCuries per liter. Contours: 100, 200, 300, 400, 500, 1000, 2000, 5000, 7500, 10,000 pCi/l; 117 analyses.

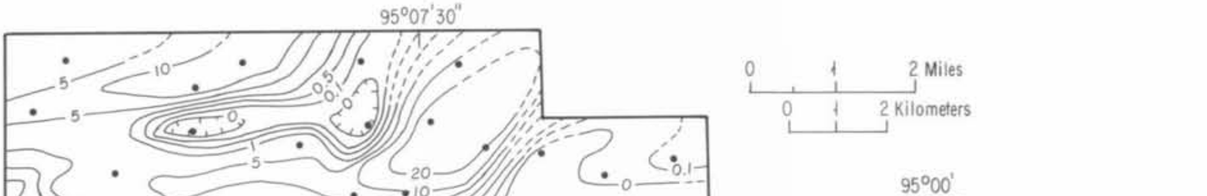

Figure 6. Helium anomaly in ground water; data in parts per million helium above the atmospheric value in dissolved gas phase. Contours: 0, 0.1, 0.5, 1, 5, 10, 20, 50 ppm; 116 analyses.

where Rn is high, He is low, and vice versa. Given the northward flow of ground water in this area (Fig. 3), the high Rn/He ratio over the Sioux Quartzite outcrop belt on the south, and the low Rn/He ratio north of the projected basal contact of the Sioux (cf Figs. 5 and 6), we conclude that uranium and radium have been, and are being, captured by oxide films at and above the basal Sioux contact, whereas the much more mobile He is continuing to migrate along the hydraulic gradient (Fig. 7). The ultimate source of uranium in the system may be one or more unconformity-related vein-breccia concentrations localized by the sub-Sioux erosion surface (Ojakangas, 1976; Mathews, 1978; Kalliokoski and others, 1978). However we emphasize that the postulated uranium concentrations have not been demonstrated in the Sanborn-Jeffers area by this or any other study; the hydrogeochemical data require a uranium source in the area, but it need not be a major concentration of economic or even subeconomic grade.

The maps in Figures 8, 9, and 10 show that the distribution patterns for dissolved oxygen content, alkalinity, and specific conductivity of ground water also are spatially related to the distribution of the Sioux Quartzite. In general, the dissolved oxygen content of ground water is high in areas where the quartzite is at or close to the land surface and wells are drawing water from fissures in the rock; the alkalinity and specific conductivity of ground water in the same areas tend to be low, but the spatial correlations are not as strong. We interpret the high values of dissolved O_2 to indicate direct or nearly direct infiltration of well-oxygenated surface water into the high-standing recharge area underlain by Sioux Quartzite; the cover of soil and glacial material is thin, the infiltration path is relatively short, and little oxygen is consumed by organic layers. The low alkalinity and specific conductivity of the water are consistent with this hydrological setting. These parameters are related closely to the concentrations of HCO_3^- and total dissolved solids. In places where glacial drift and Cretaceous beds are thin and patchy, as on the upland supported by Sioux Quartzite, recharging ground water has only limited access to HCO_3^- and other soluble constituents, and therefore contains relatively little of them.

The lower terrain north of the basal Sioux contact is underlain by much greater thicknesses of Quaternary and Cretaceous deposits, and these materials exert a predictable influence on ground-water chemistry. Dissolved O_2 is relatively low in this region, whereas alkalinity and specific conductivity tend to be high. Ground water infiltrating through or circulating within calcareous, shale-rich glacial drift will tend to become deoxygenated through contact with organic matter and iron sulfide, especially at low velocities of flow, and also will tend to accumulate HCO_3^- and other soluble constituents from comminuted carbonate and other lithic debris.

CONCLUSIONS

Six hydrogeochemical parameters correlate spatially with the margin of the Sioux Quartzite along the north edge of the Cottonwood County basin in southwestern Minnesota. The distributions of U, Rn, and He in ground water are interpreted to be bedrock controlled. Dissolved uranium and radium are thought to precipitate selectively on oxide-coated fracture surfaces near the base of the Sioux Quartzite; radioactive decay of the captured nuclides leads to high radon activity in shallow wells above the basal contact zone. Dissolved helium is not captured on fracture surfaces and continues to migrate down

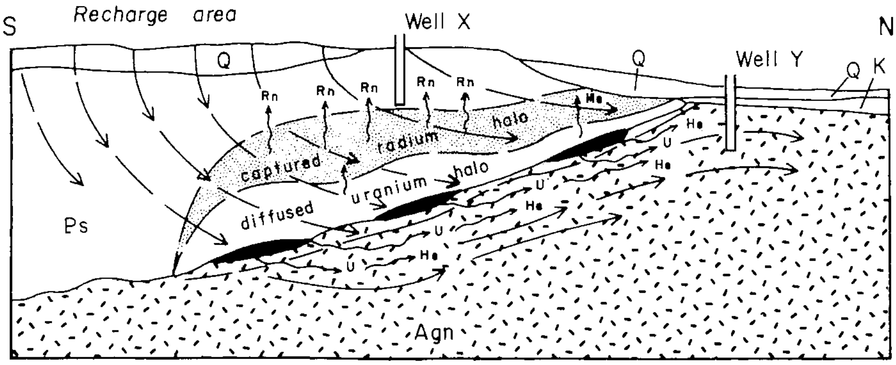

Figure 7. Schematic section (not to scale) along long. 95°07'30" showing possible migration paths of dissolved U, He, and Rn away from hypothetical uranium concentrations (black) near the basal unconformity of the Sioux Quartzite. Ground-water flow paths are indicated by smooth arrows. Well X, hydrologically upgradient from the Sioux unconformity, draws ground water impoverished in U but containing Rn and He generated from U and Ra capture on Fe-oxide films near the unconformity; water in well Y, down the hydraulic gradient, contains U and He from the unconformity zone but is poor in the short-lived Rn, which decays within a short distance of the captured Ra halo. Q, Quaternary glacial deposits; K, Cretaceous sedimentary rocks; Ps, Sioux Quartzite; Agn, Archean gneiss.

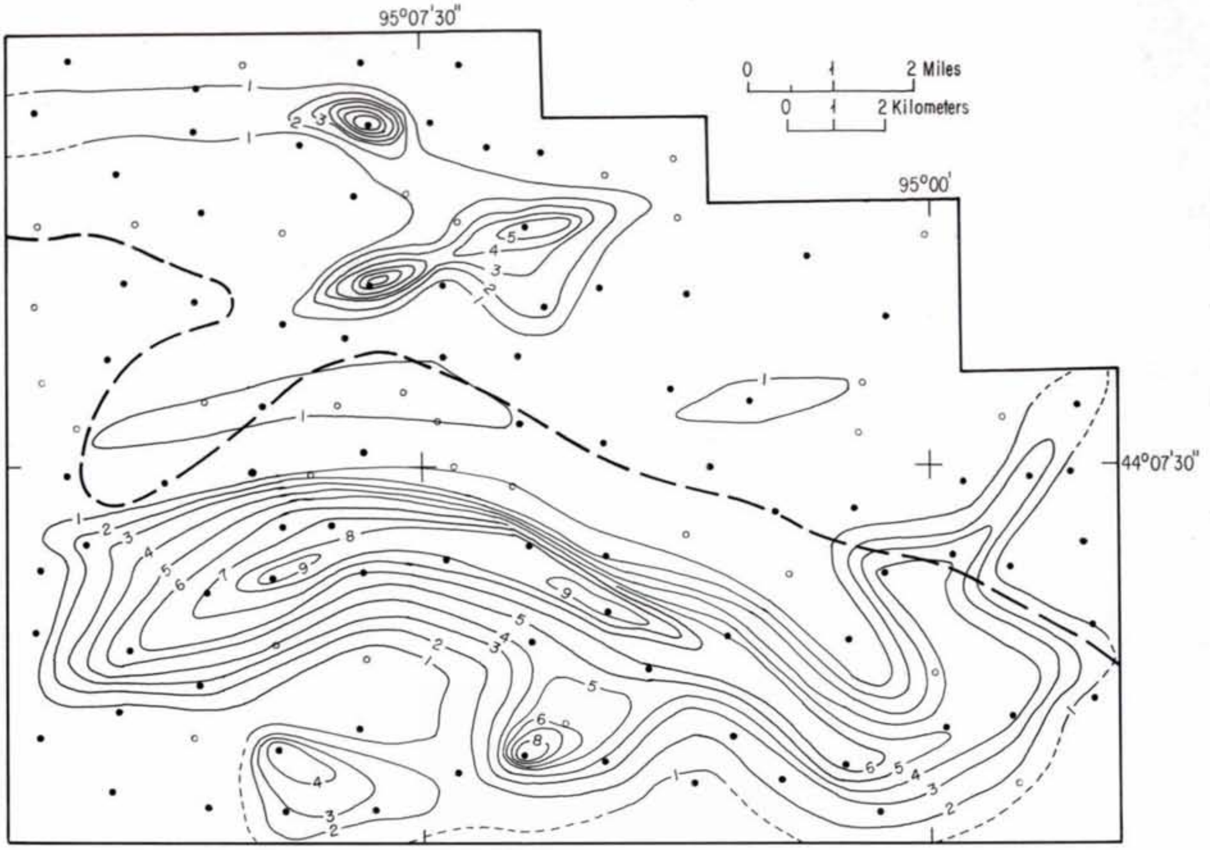

Figure 8. Dissolved oxygen in ground water; data in parts per million. Contour interval, 1 ppm; 88 analyses.

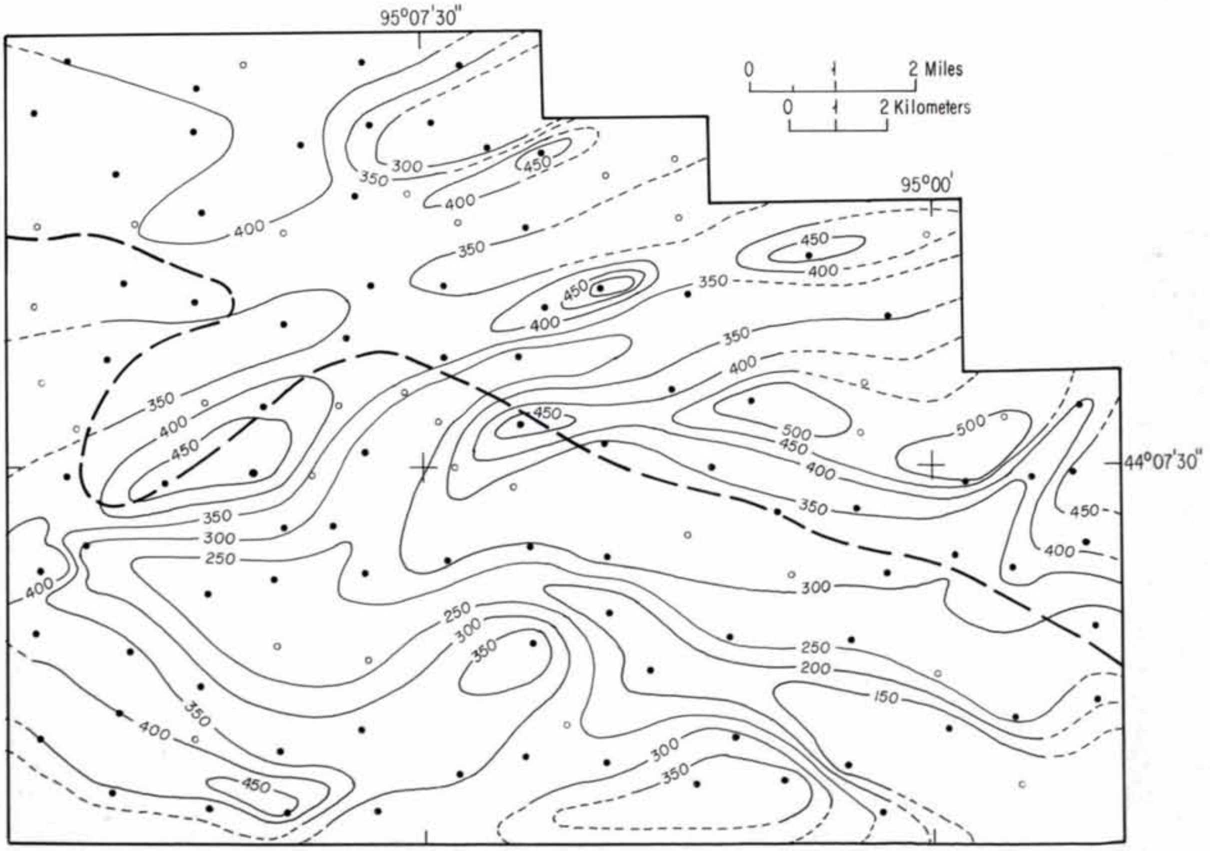

Figure 9. Ground-water alkalinity; data in parts per million bicarbonate equivalent. Contour interval, 50 ppm; 88 analyses.

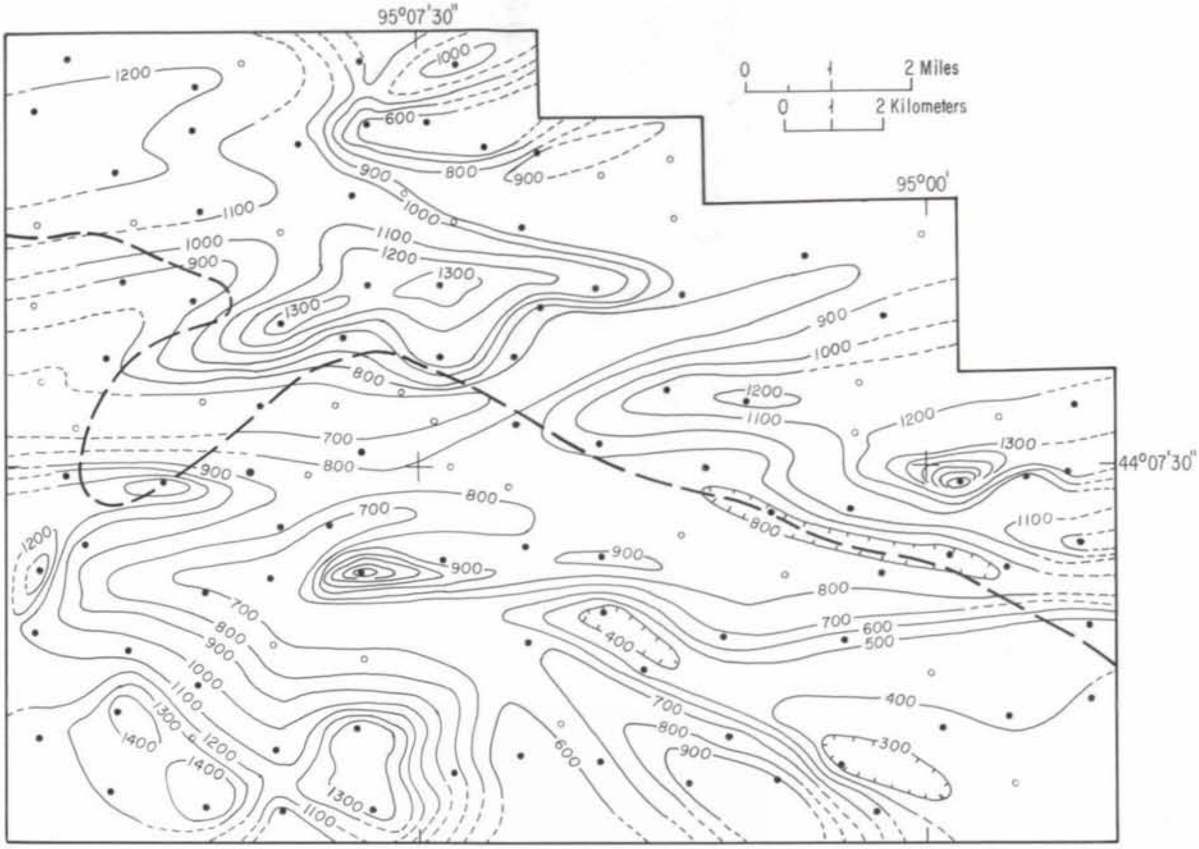

Figure 10. Specific conductivity of ground water; data in micromhos. Contour interval 100 micromhos; 88 analyses.

the hydraulic gradient; it comes within reach of shallow wells in the lower country north of the basal contact of the Sioux.

Anomalies observed in the distribution of dissolved oxygen, alkalinity, and specific conductivity have more to do with hydrologic recharge patterns, glacial drift thickness, and glacial drift composition than with intrinsic chemical properties of the bedrock units. The Sioux Quartzite holds up high ground on which the glacial drift is thin; the high ground is also a major area of recharge. Consequently the surface water that enters the Sioux is in contact with glacial drift only for a short distance; it therefore tends to retain high levels of dissolved O_2 and generally does not acquire a heavy charge of dissolved solids. North of the Sioux contact, on the other hand, the glacial drift is much thicker. Ground water in this area infiltrates through, and flows within, calcareous shale-rich glacial debris from which it picks up higher concentrations of dissolved solids (reflected in higher levels of alkalinity and specific conductivity) and to which it yields dissolved oxygen.

ACKNOWLEDGMENTS

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SEDIMENTOLOGY OF THE SIOUX QUARTZITE IN THE FULDA BASIN, PIPESTONE COUNTY, SOUTHWESTERN MINNESOTA

By

G.B. Morey

ABSTRACT

The Sioux Quartzite is a thick unit of generally hard, vitreous, maroon to gray quartzite of early Proterozoic age that underlies much of southwestern Minnesota. In Pipestone County the quartzitic strata crop out as a series of low ridges that extend northward for about 4 km (2.5 mi) from the city of Pipestone. In these outcrops the sequence strikes to the north, dips to the east at angles of 5° to 10°, and contains in addition to quartzite, lesser amounts of quartz-rich siltstone, clayey siltstone, silty mudstone, and claystone (catlinite). The rocks contain a variety of sedimentary structures indicative of sedimentation by fluvial processes associated with a braided-stream system that flowed down a paleoslope inclined to the south-southeast. It is inferred that the sandy and silty units formed as channel and nearly filled channel deposits, whereas the claystone beds formed as vertical accretion deposits during periods of major flooding.

Neither the top nor the bottom of the Sioux Quartzite is exposed north of Pipestone. However the presence of pyrophyllite implies that the rocks were once deeply buried and consequently that a considerable thickness of strata was removed by post-Sioux erosion. This is consistent with the hypothesis that the outcrops are on the upthrown side of a northwest-trending fault system that defines the southwest edge of the Fulda basin of Southwick and Mossler.

INTRODUCTION

The Sioux Quartzite in southwestern Minnesota is a thick unit of generally hard, vitreous, maroon to gray quartzite of early Proterozoic age that crops out as part of an east-trending belt that extends into adjacent parts of South Dakota and Iowa (see Southwick and Mossler, 1984, fig. 1). Although the Sioux is distributed fairly widely in the subsurface beneath a cover of Quaternary glacial and postglacial materials, it crops out only at relatively few places. Most outcrops occur along steep-faced walls of river valleys or as low knobs that protrude a few meters above the Quaternary deposits. This sparsity of exposures and the general lack of a three-dimensional view has hindered the development of a comprehensive sedimentologic model for the sequence.

The estimated thickness of the Sioux Quartzite of 1,000 to 3,000 m (3,300 to 9,900 ft) (e.g., Baldwin, 1951) has led to several qualitative and subjective sedimentologic models that involve deposition in a shallow, nearshore, marine environment whose source area was somewhere to the north of the outcrops, even though many sedimentary structures had been recognized as possibly indicative of fluvial-alluvial deposition. Thus while Baldwin (1951) held open the possibility that some of the Sioux could have been laid down by nonmarine processes, he proposed that much of it formed in a marine environment on a slowly sinking shelf characterized by shifting currents. Miller (1961) also believed that the basal Sioux was partly nonmarine in origin and suggested that it may represent a sediment-fan assemblage of fluvial sediments that was slowly inundated and reworked by a transgressing marine sea. More recently Weber (1981) proposed that the lower two-thirds of the formation was deposited either in a braided fluvial environment or in a high-energy shallow marine environment, and the upper third in a shallow marine intertidal environment.

The question of a marine versus a nonmarine or a mixed marine/nonmarine origin is not trivial. From a practical standpoint, Ojakangas (1976) proposed that the unconformity beneath the Sioux may be a favorable place for the development of uranium mineralization of the unconformity-related vein-breccia type (Mathews, 1978a), and Cheney (1981) proposed that the basal part of the Sioux Quartzite in South Dakota could contain a "giant" uranium deposit. However, an unconformity-related uranium deposit cannot be present beneath the Sioux unless a substantial part of the Sioux is of terrestrial origin (Mathews, 1978b). The question of origin also is important in terms of Proterozoic crustal evolution in the region. Dott (1983) proposed that the Sioux Quartzite and its approximate correlatives in Wisconsin, the Barron, Baraboo, and Waterloo Quartzites, were deposited on a stable passive continental margin that lay along the northern edge of a now-consumed Proterozoic ocean basin. In contrast, Greenberg and Brown (1984) suggested that the quartzites, or at least those in Wisconsin, were deposited, at least in part in fault-controlled cratonic basins. Obviously the merits of both positions are strongly dependent on the sedimentologic models that are inferred for these rocks.

A serious impediment to any sedimentologic study of the Sioux Quartzite in Minnesota has been a general lack of marker beds that place the outcrops into a stratigraphic framework. One of the few locations where such a framework can be established is a north-trending ridge that extends for about 4 km (2.5 mi) north of the city of Pipestone in Townships 106 and 107 N. in southwestern Pipestone County (Fig. 1). This outcrop area includes Pipestone National Monument where approximately 30 m (100 ft) of strata are intermittently exposed. The natural exposures have been augmented by several shallow drilling programs in the Monument in 1979 and 1980 which penetrated an additional 15 to 23 m (50 to 75 ft) of section. The strata include exposures of thick claystone (catlinite) beds that have been penetrated in the subsurface and make useful marker beds for local stratigraphic reconstruction. Although the stratigraphic section that has been studied in and around Pipestone National Monument represents a very small part of the total Sioux Quartzite, the three dimensionality of the section is ideal for a detailed sedimentologic study.

STRUCTURAL ATTRIBUTES

In this volume, Southwick and Mossler (1984) propose that substantial thicknesses of Sioux Quartzite occur in four northwest-trending basins, which they have named from west to east, the Pipestone, Fulda, Cottonwood County, and New Ulm basins. These basins are separated from each other by positive structural areas where the quartzite is either thin and dissected or absent entirely (Fig. 2). Southwick and Mossler (1984) suggest that the structural divides may reflect differential vertical motion on northwest-trending faults. They emphasize that the four basins are erosional remnants and that the extent to which their present map geometry corresponds to the geometry of the original depocenters is unknown.

The present map geometry in the Pipestone basin in Rock and southwestern Pipestone Counties defines a doubly plunging syncline that Baldwin (1951) called the "Rock County structural basin." The structural basin is defined by inward-facing dips that are generally less than 10°, except along the southwestern edge where dips of as much as 20° occur (Fig. 3). As mapped by Baldwin (1951), the long axis of the Rock County basin trends in a north-northwest direction at a fairly acute angle to the trends of the faults inferred by Southwick and Mossler (1984) to separate the Pipestone and Fulda depositional basins.

The Sioux outcrops north of the city of Pipestone have master bedding planes that generally strike to the north and dip to the east at angles of 5° to 10°, and lineaments having the same trend as master bedding are readily apparent on aerial photographs of the National Monument area. These are defined on the ground by subdued ridges and valleys that have a topographic relief of a meter or less, and are in-

Figure 1. Generalized geologic map of a part of Pipestone County north of the city of Pipestone. The distribution of Sioux outcrops is shown by selected strike and dip data. For details on the geology within and around Pipestone National Monument see Figures 4-7 and Morey (1983). (Base modified from U.S. Geological Survey Pipestone North 7½-minute quadrangle, 1967.)

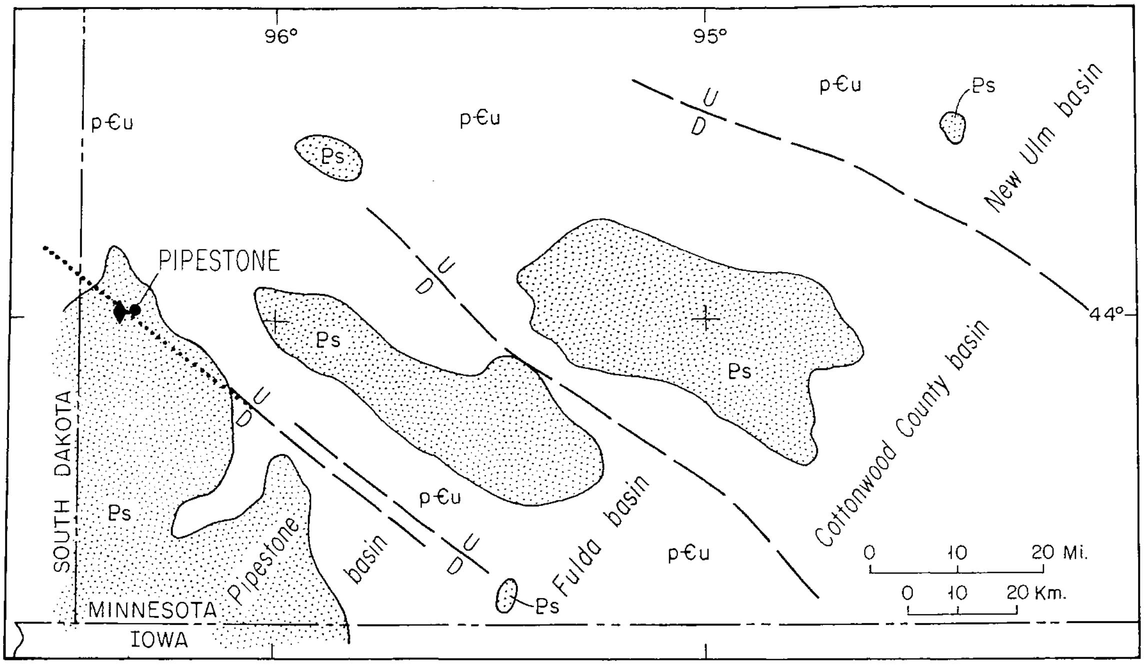


Figure 2. Pre-Paleozoic subcrop map of southwestern Minnesota (modified from Southwick and Mossler, 1984, fig. 2). The dotted extension of Southwick and Mossler's fault defines the proposed southwest edge of the Fulda basin. The inferred epicenter of the 1964 earthquake mentioned in the text is shown as a diamond.

terpreted as strike-controlled bedrock ridges masked by a thin cover of glacial deposits. Although Baldwin (1951) mapped these outcrops as part of the Rock County structural basin, he recognized that the north-trending bedding attitudes were difficult to reconcile with east-trending bedding attitudes in outcrops only 6.5 km (4 mi) to the south. This diversity in bedding attitudes implies that the two outcrop areas are separated by a fault. Because the trace of this probable fault corresponds to the trace of the fault proposed by Southwick and Mossler (1984) to separate their Pipestone and Fulda basins, the outcrops north of Pipestone are considered part of the Fulda basin. Interestingly, the trace of the probable fault also passes close to the epicenter of a 3.4-magnitude earthquake that occurred near Pipestone in 1964 (Mooney and Morey, 1981).

PETROLOGIC ATTRIBUTES

Various aspects of the petrology of the Sioux Quartzite, including the origin of the red pigmentation, the source of the silica cement, and the paragenesis of the secondary minerals sericite, pyrophyllite, diaspore, and kaolinite have been described by Berg (1937, 1938), Baldwin (1951), Miller (1961), Weber (1981), and Vander Horck (1984). Many problems are as yet unresolved, and an understanding of the post-depositional history of these rocks is still of considerable sedimentologic importance. Therefore some observations that bear on these petrologic problems are summarized below, mainly as a contribution for future more detailed studies.

Quartz-Rich Rocks

The quartzitic rocks throughout the study area are characteristically medium pink in color, but beds vary from light pink to deep red. The lighter colors result from finely disseminated hematite around the edges of quartz grains, whereas the deep red colors result from a hematite-stained matrix. Thus the Sioux Quartzite is a red-bed sequence, but it differs from many Phanerozoic red-bed sequences in its extreme compositional and textural maturity.

Much of the quartzite, and particularly that along the ridge on the east side of Pipestone National Monument, has a simple mineral composition. In general these rocks consist of 91 to 98 percent framework grains and 2 to 9 percent cement and other interstitial material (Morey, 1983). The framework grains typically range in size from medium to fine sand and are well sorted, although several samples are bimodal, consisting of rounded grains 1.0 to 1.5

mm in diameter surrounded by subangular grains 0.5 mm in diameter. Quartz predominates, but trace to minor amounts of polycrystalline chert, cherty iron-formation, and metamorphic quartzite are also present. Many of the larger quartz grains have abraded authigenic quartz overgrowths indicative of several cycles of deposition and erosion. Opaque minerals present in trace amounts include magnetite, hematite, and rutile. Other heavy minerals such as zircon and tourmaline also can be recognized.

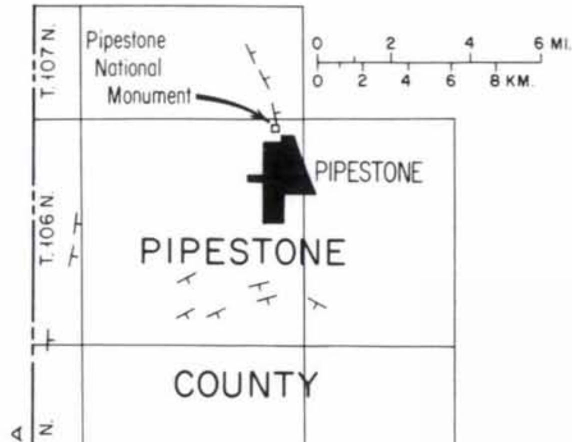


Figure 3. Geologic sketch map of southwestern Pipestone and northwestern Rock Counties showing the strike and dip evidence for the Rock County structural basin (modified from Baldwin, 1951, fig. 4). The inferred axis of this basin is shown by the syncline symbol.

The framework grains and their overgrowths are cemented by either an epitaxial quartz cement or a matrix of admixed sericite, very fine grained quartz, and finely disseminated hematite. Inasmuch as the epitaxial quartz cement fills void spaces between framework grains, it must have formed early in the history of the rock. After cementation, the quartzite was subjected to a period of stress, as shown by the strain shadows and deformation lamellae that cross boundaries between quartz grains and quartz cement. The strained quartz grains, their overgrowths, and the epitaxial cement are in turn replaced by the sericite-quartz-hematite matrix. In a few samples, small grains of diaspore, kaolinite, and pyrophyllite are intergrown with the matrix material. Textural relationships preclude accurate determination of the paragenetic relationships between the individual aluminum-rich minerals and their collective place in the postdepositional history of the rock.

Much of the quartzite surrounding the major claystone (catlinite) beds in Pipestone National Monument is similar to that described above. However, some quartz-rich beds near quarried catlinite units are distinctly finer grained, less well sorted, and contain as much as 35 percent matrix material. Samples having abundant matrix material also appear to lack the epitaxial quartz cement and the evidence of subsequent stress. This implies that the matrix material formed prior to the development of the epitaxial quartz cement. This in turn implies that the matrix material formed from a clayey protolith that was deposited contemporaneously with the framework grains, and was recrystallized later in the history of the rock.

There is a more or less continuous textural and mineralogic gradation from quartzite to quartz-rich siltstone to silty mudstone to mudstone. The quartz-rich siltstone differs from the fine-grained quartzite only in having a finer grain size and in containing somewhat more matrix material, which consists of sericite, very fine grained quartz, and hematite. The silty mudstone beds consist predominantly of sericite, quartz, and hematite. Silt-size quartz grains that are typically angular to subangular in shape and fairly well sorted in size occur in thin laminae that give the rock a distinctly shaly fabric, or as dispersed grains that impart a structureless fabric.

Claystone (Catlinite)

Beds of claystone contrast markedly with the quartz-rich rock types, even with those that are very fine grained and muddy. For the most part the claystone lacks quartz, is typically deep red to pale orange in color, and is generally structureless except for a few shaly parting planes parallel to the bedding.

The claystone beds consist of various proportions of very fine grained sericite, hematite, and diaspore, together with smaller amounts of kaolinite, chlorite, and possibly rutile. Sericite may or may not be present (Berg, 1938; Gundersen, 1982). Pyrophyllite occurs also in these beds, either as small white flakes or as lenses as much as 10 cm (4 inches) long and 5 cm (2 inches) thick that lie more or less parallel to bedding. Most of the thick claystone beds have gradational contacts with underlying and overlying strata, and the gradational intervals are marked by scattered grains of silt-size quartz that tend to become larger and more abundant toward the exterior. Some thin clayey beds must be classified as mudstone because they have quartz grains dispersed throughout.

Postconsolidation Phenomena

All of the quartz-rich rock types have been somewhat recrystallized as shown by the presence of sericite in the matrix. Textural evidence implies that the matrix recrystallized late in the history of the rock from some clay-size protolith that was deposited interstitially to the framework grains. Unfortunately the original composition of the protolith cannot be established from the suite of samples. Nonetheless, the fact that sericite occurs implies either that the protolith originally contained potassium or that potassium was introduced when the protolith was recrystallized. Inasmuch as there is no evidence that the potassium was introduced, it seems likely that the sericite formed from a potassium-rich clay, possibly illite.

Other evidence of postdepositional recrystallization includes the presence of trace to small quantities of the aluminum-rich phases kaolinite, diaspore, and pyrophyllite. Kaolinite and diaspore were first recognized by Berg (1938) who suggested that they formed near the bedrock surface during a period of intense chemical weathering in early Cretaceous time about 100 Ma ago (see also Baldwin, 1951; Austin, 1970, 1971). Although some of the kaolinite and diaspore may have formed in this way, both minerals occur in other parts of the Sioux terrane at depths inferred to be considerably below the extent of Cretaceous surficial weathering processes (Southwick and Mossler, 1984). In those places it appears that the assemblage diaspore + kaolinite + quartz (as the epitaxial quartz cement) formed by diagenetic processes involving the postdepositional dissolution of potassium-rich feldspar, as has been documented in the Lorrain Quartzite of Canada (Chandler and others, 1969). These processes also may have occurred in the rocks north of Pipestone, and they could be responsible for some of the potassium now associated with sericite in the matrix. However, if these diagenetic reactions did occur, they must have occurred prior to the final recrystallization of the clayey matrix.

The presence of pyrophyllite also bears on this problem. Berg (1938) suggested that the pyrophyllite formed by a metamorphic reaction involving sericite, quartz, and water, and the concurrent release of some potassium. Alternatively it could have formed by metamorphic reactions involving either kaolinite or diaspore or both--reactions involving neither the release nor consumption of potassium. Regardless of the specific reactions involved, the presence of pyrophyllite and sericite implies that the rocks now exposed north of Pipestone were subjected to temperatures and/or pressures above those normally associated with diagenesis.

SEDIMENTOLOGIC ATTRIBUTES

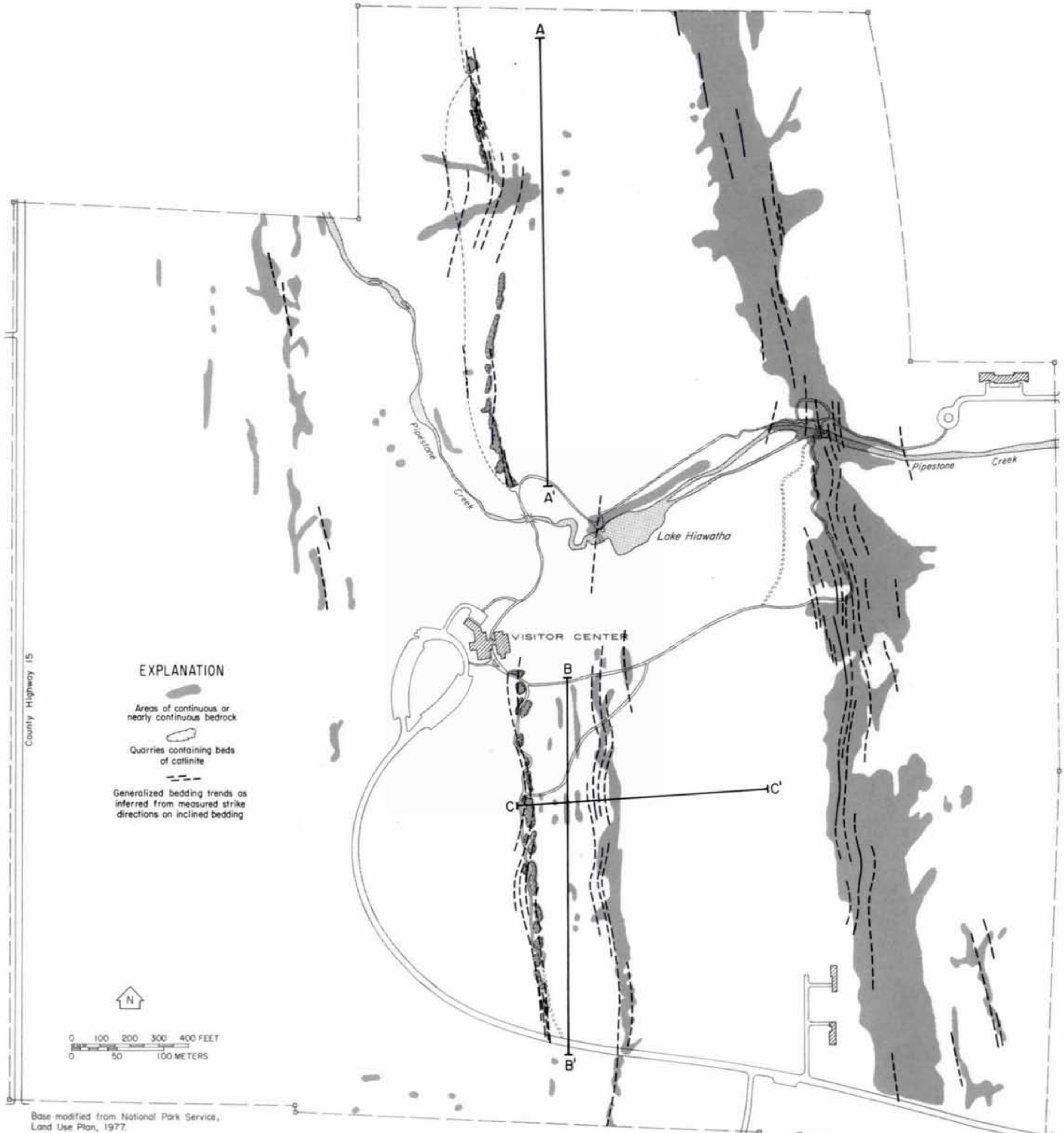
The Sioux Quartzite north of the city of Pipestone and especially within the Pipestone National Monument (Morey, 1983) contains a variety of sedimentary structures including scour and fill deposits, trough and planar cross-bedded sands, horizontally laminated and cross-laminated sands, ripple marks, mud cracks, mud chips, and lag deposits. However, of these sedimentary structures, trough cross-bedding, especially of the festoon type, is by far the most common, and its ubiquitous presence complicates the recognition of master bedding surfaces. The orientations of presumed master bedding surfaces shown on the geologic map in Figure 4 were derived from measurements made on thick claystone beds and on thin siltstone or mudstone beds whose upper surfaces are ripple marked or mud cracked.

Figure 4 shows that although the master bedding has a generally consistent strike to the north and dip to the east, there is considerable local variability. These data imply that even the master bedding does not have a simple planar orientation, but rather is characterized by numerous gentle rolls or warps of somewhat diverse size and orientation (Fig. 5).

The rolls or warps on Figure 5 could conceivably reflect gentle folding about east-trending axes, but the lack of any systematic geometric arrangement implies a nontectonic origin. Therefore it seems more likely that the rolls or warps are the local manifestations of curvilinear master bedding surfaces that separate large lenticular bodies of strata. Because the outcrops are limited in size and distribution, it is difficult to demonstrate conclusively that the quartzitic beds occur within large, lenticular bodies. Nonetheless a detailed subsurface study in the Pipestone National Monument (Morey, 1983) has shown that the thick claystone beds have a concave-upward,

Base modified from National Park Service, Land Use Plan, 1977.

Figure 4. Outcrop map of the Sioux Quartzite in Pipestone National Monument showing major structural features.



Base modified from National Park Service, Land Use Plan, 1977.

Figure 5. Trend lines of master bedding planes in the Sioux Quartzite as inferred from the structural data of Figure 4. Note also the curvilinear rather than planar nature of these structures. See Figure 6 for cross sections A-A' and B-B' and Figure 7 for cross section C-C'.

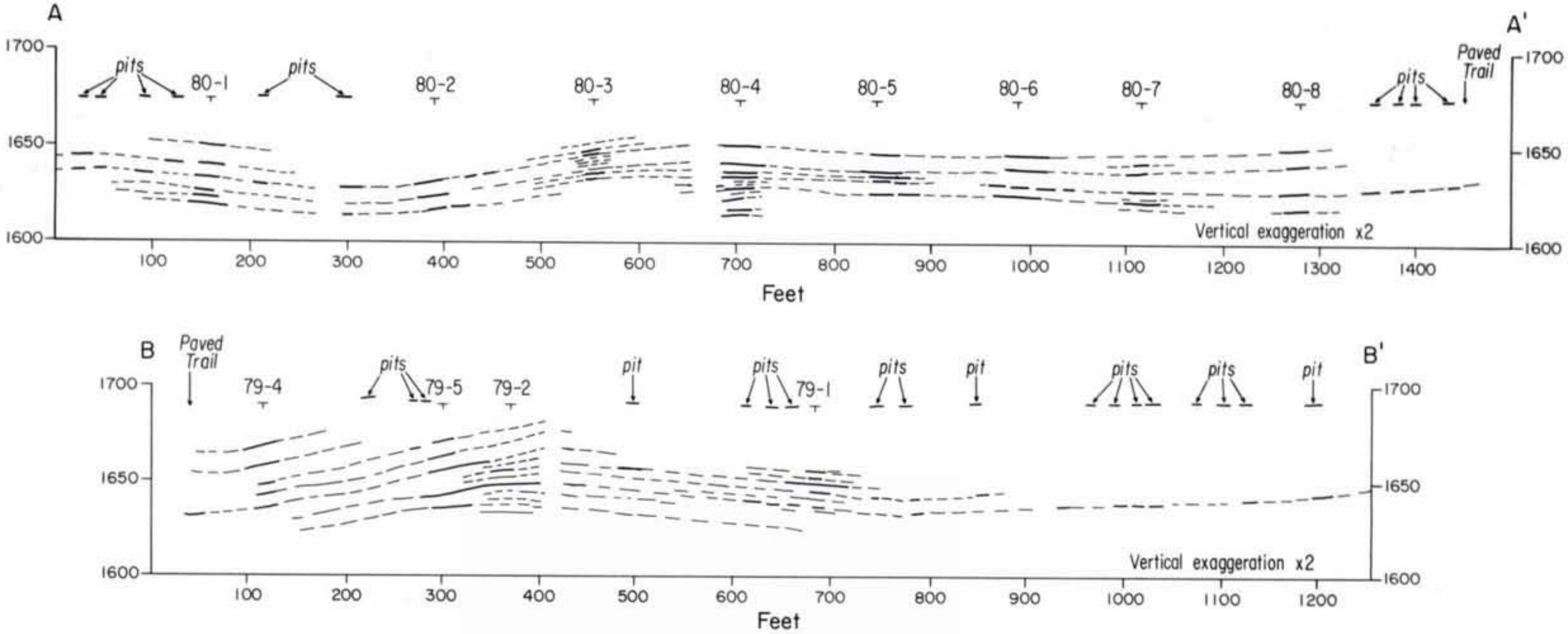


Figure 6. Longitudinal cross sections showing the distribution of claystone (catlinite) beds along a trend generally parallel to the strike of bedding in the northern (A) and southern (B) parts of Pipestone National Monument. Although individual data points were projected to the cross sections along lines not everywhere parallel to the master bedding directions, the cross sections illustrate the irregular distribution and lenticular shape of the claystone units in the strike direction. See Figure 5 for locations of cross sections.

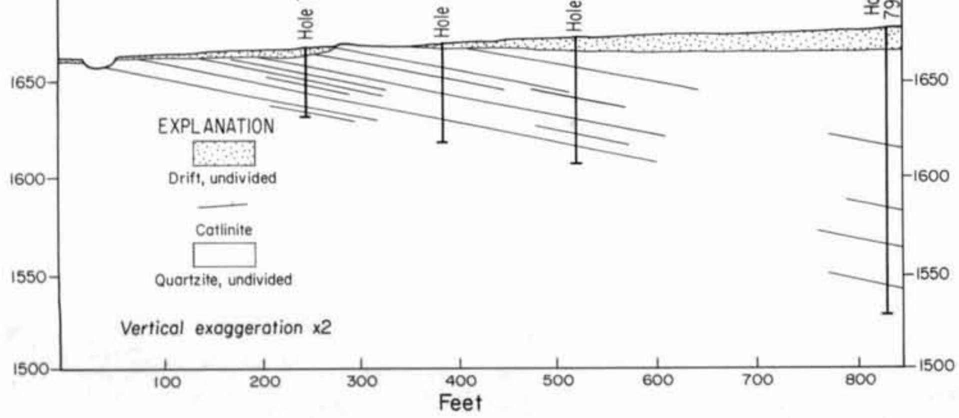


Figure 7. Generalized east-west cross section through the southern part of the Pipestone National Monument (Morey, 1983). See Figure 5 for the location of the cross section.

curvilinear shape in the strike direction (Fig. 6). This geometry is similar to that inferred from the master bedding data and is consistent with the presence of lens-shaped bodies of quartzite.

The geometry of the master bedding surfaces in the direction parallel to dip is somewhat more difficult to evaluate, mainly because data are limited. The subsurface data from within the Pipestone National Monument imply that the thinner claystone layers are discontinuous over distances of several tens of meters (Fig. 7), whereas the thicker layers are discontinuous over distances of more than 150 m (500 ft). Collectively the subsurface data imply that the claystone occurs as discontinuous beds between lenses of quartzite that have strike lengths of 60 m to more than 240 m (200 to 800 ft) and widths of near zero to as much as 150 m. These quartzite lenses appear to have long axes oriented in a south-southeast to southeast direction (Morey, 1983).

As noted previously, trough cross-bedding is by far the most prevalent sedimentary structure; it occurs in every rock type exposed in Pipestone National Monument except the thick beds of claystone. Trough cross-bedded strata occur rarely as solitary scoops; most are sets of mutually crosscutting multistory units. Individual sets in these multistory accumulations are generally 5 to 10 cm (2 to 4 inches) thick and occur in lens-shaped bodies 0.5 to 2 m (1 to 6 ft) wide and 3 to 4 m (10 to 15 ft) long. Stratigraphic intervals as much as 10 m (30 ft) thick may consist almost exclusively of trough cross-bedded strata, but bear little evidence of an erosional relationship to underlying strata. Other cross-bedded units rest on scoured surfaces that are concave downward by several centimeters to several decimeters and range in width from less than 0.3 m to more than 1 m (1 to 3 ft). One channel about 1.5 m (5 ft) deep and 10 m (30 ft) wide could be traced along strike for at least 45 m (150 ft). Other channels could be traced for 2 to 3 m (6 to 9 ft) to 15 m (50 ft).

The scoured surface beneath the larger channels is overlain by a thin structureless unit which in places has scattered granule-size quartz grains or mud chips dispersed through a somewhat finer grained sand-size matrix. These intraclast-strewn structureless units are not particularly abundant, and they always give way upward rather abruptly to units of trough cross-bedded strata.

Planar cross-bedded strata are not particularly abundant but they do occur at several places. These strata have sharply defined, flat to slightly scoured bases and tops. They occur as single entities 2 to 10 cm (1 to 4 inches) thick, but typically they are superimposed multi-story accumulations as much as 1 m (3 ft) thick and lack internal reactivation surfaces.

Beds of quartz-rich siltstone or silty mudstone a few centimeters (1 to 2 inches) thick are horizontally laminated at several places, but laminated beds that are ripple marked, either as solitary trains or as climbing ripples, are more common. The ripples have wavelengths of 2.5 cm to 5 cm (1 to 2 inches) and amplitudes of as much as 0.5 cm (0.2 inch).

Fine-grained silty mudstone and mudstone typically occur as thin, nearly planar beds or laminae a few centimeters thick that seem to unconformably overlie other kinds of sedimentary structures. Many of these muddy beds have upper surfaces that are ripple marked. The ripple marks are mostly of the symmetrical type and have amplitudes of only a few millimeters. Mudstone beds also occur as patchy deposits a few millimeters thick that drape over underlying irregularities.

The thick claystone units are much more widespread than the patchy mudstone beds. They are generally structureless to vaguely laminated, and where there are sufficient data there seems to be a vertical and a lateral gradation from claystone to silty claystone to clayey siltstone and ultimately to argillaceous quartzite. The upper surfaces of the claystone units commonly are marked by sets of asymmetrical and symmetrical ripple marks and mud cracks.

Many of the sedimentary structures described above occur in sequential combinations of two or three, and these combinations recur over various stratigraphic intervals. Although there is no evidence of cyclicity, the various recurring combinations of structures can be interrelated so as to define an idealized composite vertical profile (Fig. 8). Although such a composite profile has not been seen in its entirety nor been proven to exist by statistical methods, it seems to consist of: (1) A scoured surface overlain by (2) a structureless intraclast-strewn sandstone, abruptly overlain by (3) thick beds of trough cross-bedded strata; these appear to be overlain by (4) planar cross-bedded strata, which in turn are overlain by (5) beds of horizontally laminated and/or (6) ripple cross-laminated fine-sand-size beds. The laminated sandy beds are overlain by (7) horizontally laminated muddy units with symmetrical ripple marks on their upper surfaces or by (8) thin drape deposits.

In general the size of the sedimentary structures in the composite profile decreases upward. The profile also is a fining-upward sequence in that the intraclast-strewn sandstone is typically coarser grained than the cross-bedded strata, which in turn are typically coarser grained than the laminated strata. The upward decrease in size of both structures and grains implies that sedimentation was episodic and that it took place in an environment of waning flow. In short, as discussed in more

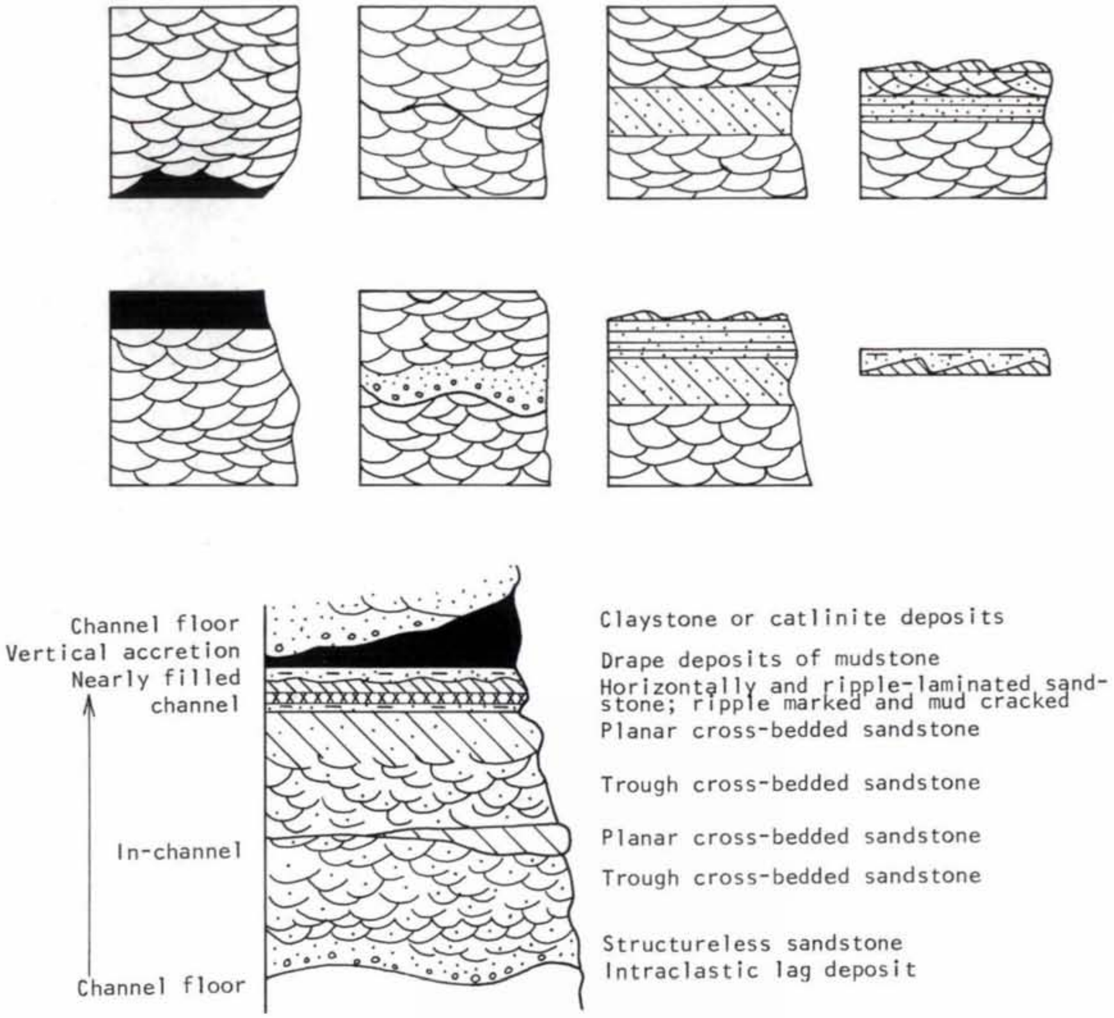


Figure 8. Observed combinations of sedimentary structures in the Sioux Quartzite as exposed in and around Pipestone National Monument and a composite vertical profile inferred from them. See text for discussion.

detail below, the attributes of the idealized vertical profile are very similar to those identified with braided fluvial systems in both modern and geologic times (e.g., Allen, 1965; Smith, 1970; Miall, 1977).

PALEOCURRENT DIRECTIONS

The azimuths of current directions associated with trough cross-bedding were measured at several places. Because in this type of cross-bedding only one direction--the trough axis--is parallel to the current flow, and because it was not always possible to measure this attribute directly, many of the measured values deviate somewhat from the true trough axis and the current direction (Fig. 9A). Regardless, the results indicate a predominantly southward to south-southeastward paleocurrent direction--a direction consistent with the regional paleocurrent patterns suggested by Pettijohn (1957) and documented by Weber (1981).

The azimuths of other current-direction indicators have diverse orientations. For example, azimuths measured from planar cross-beds lack a strong central tendency but nonetheless indicate a generally southward current flow (Fig. 9B). The asymmetrical ripple marks yield even more diverse orientations and some yield azimuths that indicate current flow directions nearly 90° to those measured from immediately subjacent trough cross-beds (Fig. 9C).

PALEOENVIRONMENTAL SYNTHESIS

The stratigraphic and sedimentologic data summarized above imply that the Sioux Quartzite north of Pipestone consists dominantly of intercalated bodies of lenticular strata. The large lenses in turn consist of somewhat smaller lenses, many of which are of outcrop or smaller size. Although fine-grained muddy and clayey units of limited size occur within lenses of all sizes, the thick claystone layers appear to occur as discontinuous beds between larger lenses of quartz-rich strata.

The lenticular nature of the quartz-rich strata, the extensive development of trough cross-bedding, the general lack of silt- and clay-size detritus, and the presence of repetitive fining-upward sequences, imply that the Sioux Quartzite north of Pipestone was deposited by the fluvial processes associated with a braided-stream system. There are a wide variety of modern braided stream systems (Miall, 1977). In general, however, they all may be characterized as consisting of a number of channels of low sinuosity (Moody-Stuart, 1966) that separate and coalesce in a complex manner (Fig. 10). Modern braided-stream deposits also are characterized by a dominance of sand-size, in-channel deposits and a minimum of silt- and clay-size vertical accretion deposits (Leopold and others, 1964). Thus four major lithotopes can be recognized in modern braided-stream systems (Allen, 1965): channel-floor lag deposits, in-channel deposits, nearly filled channel deposits, and vertical accretion deposits. These lithotopes represent flood cycle deposits formed by the superimposition of bedforms deposited at progressively decreasing energy levels.

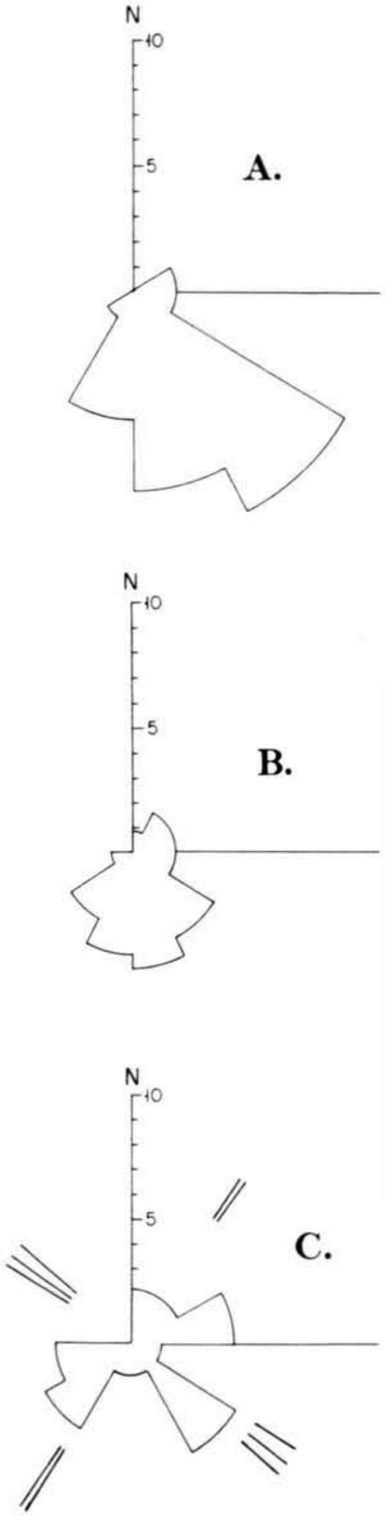


Figure 9. Number frequency paleocurrent plots for directional sedimentary structures in the Sioux Quartzite. A, trough cross-beds (N = 26; X = 156°). B, planar cross-beds (N = 26; X = 137°). C, asymmetrical ripple marks (N = 23); the heavy solid lines are the azimuths of crests and troughs on symmetrical ripple marks.

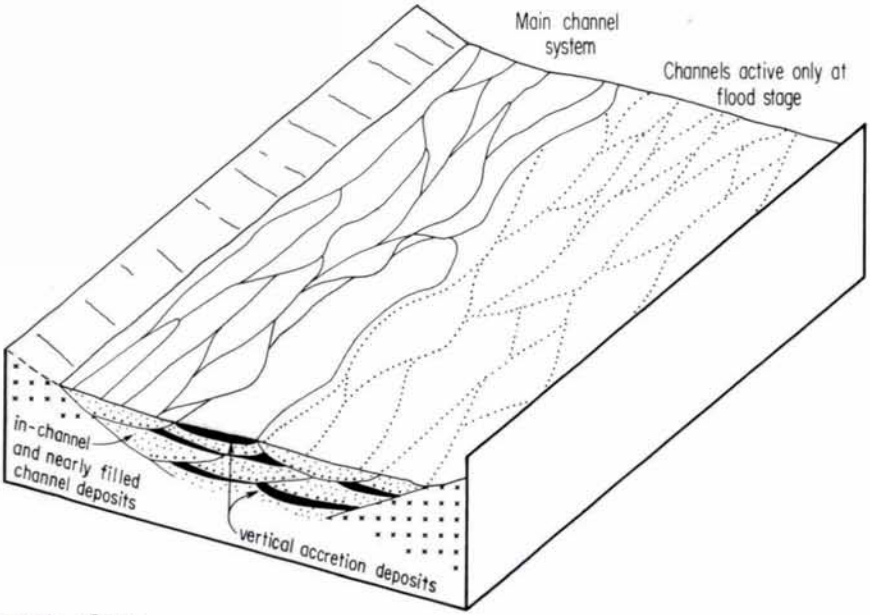


Figure 10. Block diagram showing the major sedimentologic attributes of a braided-stream system (modified from Allen, 1965). Note the lenticular nature of the sandy (quartz-rich) sediments and the irregular distribution of the claystone deposits formed by vertical accretion.

The same four lithotopes can be recognized in the repetitive vertical sequences of the Sioux Quartzite. The presence of a structureless, intraclast-strewn sandstone above a scoured surface implies deposition within a preexisting channel that most likely formed by erosion during an earlier high-water or flood stage. In modern braided-stream systems the topographic relief in and around a channel influences the sedimentary processes that occur within the channel. Once a channel has formed, it tends to persist until it is filled with sediments or is abandoned. Thus the general lack of well-defined scoured surfaces in the Sioux Quartzite implies that little if any topographic relief existed within the channel system, and this in turn implies the existence of many rapidly migrating subchannels and their associated bed-load deposits (Fig. 11). Given that kind of a situation in Sioux time, any channel and its bed-load deposits would have been obscured or destroyed by dissection and redeposition during subsequent changes in the course of individual shallow channels.

Trough and large-scale planar cross-bedded units in braided-stream systems collectively form within channels during high water or floods as a variety of migrating bedforms at a variety of scales. The abundance of trough cross-bedded units implies that the bed-load deposits in the Sioux were mostly transported as linguoid dunes or sand bars that migrated in a downstream direction. This form of sediment transport gives rise to cross-bedding with azimuths that are subparallel to the dominant paleoslope direction.

The planar cross-bedded deposits associated with the trough cross-bedded units typically form as bar avalanche deposits on the slopes that mark the leading edges of the migrating dunes or sand bars. In this situation the configuration and topographic relief of the upper dune surface controls the orientation of the planar cross-beds. Planar cross-bedded strata also may form in shallow water toward the edges of the channels, in channels nearly filled with sediments, or in interchannel areas that receive deposits only during periods of high water. In these situations the current directions are not entirely constrained by the original channel geometry, and the cross-beds may be the result of widely divergent paleocurrent directions. Therefore, the measured azimuths of planar cross-bedded strata formed in any of these situations will be scattered at high angles around the dominant paleoslope direction.

In an ideal situation a variety of low-water accretion structures can form on the tops of the various dune or bar deposits. Although the potential for their preservation is small, they may include thin ripple cross-laminated units that were deposited as small bedforms migrating on the tops of the larger bed-forms. These structures form in fairly shallow water, most likely in the upper part of a channel after much of the channel has been filled (Cant and Walker, 1976). Bar-top deposits also may include laminae of very fine silt and clay, and asymmetrical ripple trains formed as silt- and clay-size material migrates across a bar surface during periods of very low water. The orientation of these structures reflects the topographic relief of the bar surface rather than the topography of the channel itself. Therefore, as often as not, they can reflect currents that flowed at nearly right angles to the main channel direction.

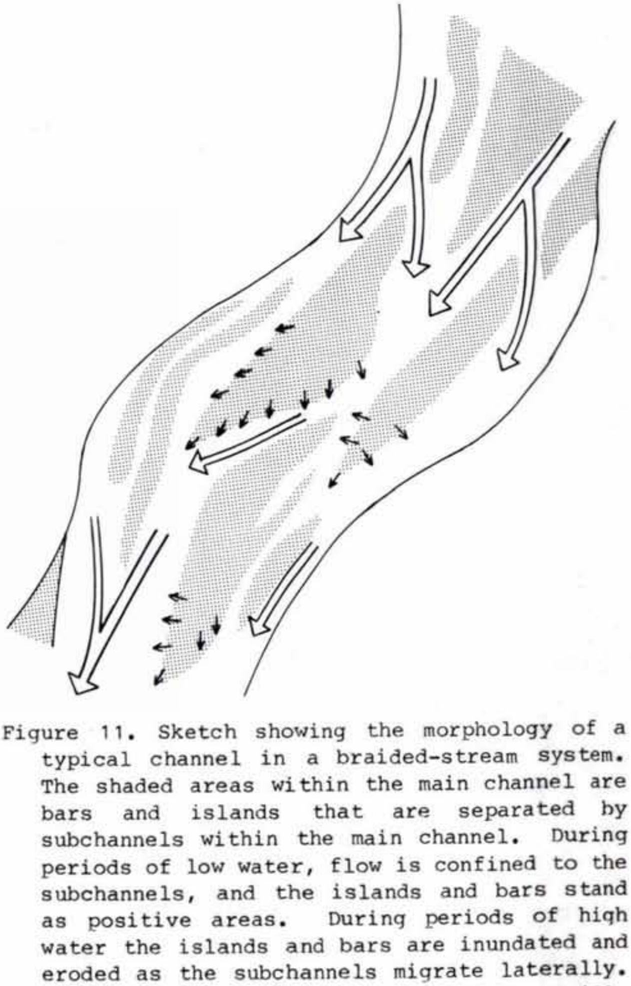


Figure 11. Sketch showing the morphology of a typical channel in a braided-stream system. The shaded areas within the main channel are bars and islands that are separated by subchannels within the main channel. During periods of low water, flow is confined to the subchannels, and the islands and bars stand as positive areas. During periods of high water the islands and bars are inundated and eroded as the subchannels migrate laterally. During major floods, the water also spills beyond the limits of the main channel and subsequently lays down fine-grained vertical accretion deposits. As the water recedes, the topography of the channel system controls the orientation of sedimentary transport phenomena within the channels (large arrows) and on top of the bars and islands (small arrows). No scale is intended, but subchannel widths may be on the order of several hundred or more meters.

Two kinds of vertical accretion deposits can be recognized in the Sioux Quartzite. The first kind consists of layers a few millimeters thick of structureless, muddy material that drapes over underlying beds and masks their irregularities. This deposit most likely forms at times of very low water when fine silt and mud settle out in pools of standing water left behind in low places within abandoned channels. Ultimately some of this material will become desiccated and mud cracked. The potential for preservation of any of this material is very low.

The thick claystone deposits of this area also appear to have formed by vertical accretion. However, deposits of such size could form only during major floods when the river spills from its main channel system onto the surrounding flood plains. During the waning stages of the flood cycle, the river reverts back into the main channels leaving layers of very fine detritus that may be ripple marked and that ultimately may become desiccated and mud cracked. Vertical accretion deposits of this type are uncommon features in a braided-stream system for several reasons. First, most fine-grained material, such as silt and clay, is transported through individual channels in braided-stream systems without significant accumulation. Second, these deposits tend to be quickly eroded by migrating channels during the next flood stage. Consequently any that persist will tend to have a patchy and irregular distribution.

CONCLUSIONS AND SOME SPECULATIONS

The Sioux Quartzite north of Pipestone strikes to the north, and dips to the east at angles of 5° to 10°. It consists predominantly of orthoquartzite with lesser amounts of quartz-rich siltstone, silty mudstone, mudstone, and claystone. These rocks contain a variety of sedimentary structures indicative of sedimentation by the fluvial processes associated with braided-stream systems. It is inferred that the sandy and silty units formed as channel deposits under varied hydrologic flow conditions, whereas the thick claystone beds formed as vertical accretion deposits only during floods. Braided-stream systems are dynamic environments and the likelihood that the smaller sedimentary structures, such as deposits in nearly filled channels, would be destroyed by subsequent events is very great. Thus in braided-stream systems there is a bias toward the preservation of larger sedimentary structures and this bias may explain why the Sioux Quartzite is dominated by units of trough cross-bedded strata.

Southwick and Mossler (1984) have developed a model suggesting that the landscape at the time of Sioux deposition was partly mantled by a surface layer of lateritic to grus-like residual soil. Such a surface layer of granular rock debris, unprotected by vegetation, would be highly susceptible to hillslope erosion. Detritus brought to valley floors by hillslope processes during periods of moderately high runoff would tend to overload the fluvial system and produce conditions leading to a braided-stream system. The lack of incised channel structures in such a situation is not surprising, because braided channels in sandy, cohesionless material tend to shift readily and rework older channel and vertical accretion deposits (Matthews, 1974, p. 159).

The possibility that the grus-like detritus was moved down the hillslopes by alluvial processes, as suggested by Miller (1961), cannot be entirely excluded for the Sioux Quartzite in general, because braided-stream systems are commonly associated with alluvial plains and fans (Steel, 1974). However, angular, poorly sorted material characteristic of debris flow and sieve infiltration processes (Bull, 1972) in alluvial fans has not been recognized in the Sioux Quartzite north of Pipestone. This implies that paleoslopes within the basin were gently inclined and that the immediate surrounding area was probably at low relief.

Neither the top nor the bottom of the Sioux Quartzite is exposed in the immediate area. Consequently there are no data regarding the stratigraphic position of the strata under discussion. However the presence of pyrophyllite, a mineral presumably formed by burial metamorphic processes (Vander Horck, 1984), is consistent with the hypothesis that the outcrops are on the upthrown side of a northwest-trending fault that separates the Fulda and Pipestone basins of Southwick and Mossler (1984). This hypothesis in turn implies that a considerable thickness of strata was removed from this area by post-Sioux erosion, and that the stratigraphic section may be near the base of the sedimentary pile.

Although there is considerable divergence in measured azimuths, which in itself is additional evidence for a fluvial environment, the paleocurrent evidence implies that the braided-stream system was graded to the south-southeast. The general coincidence between the inferred orientation of the paleoslope and the orientation of the fault-bounded Fulda basin implies sedimentation by longitudinal rather than transverse flow. The apparent dominance of a longitudinal braided-stream system in the Fulda basin is consistent with the tectonic setting proposed by Southwick and Mossler (1984). It is unlikely that permanent streams flowing transverse to the longitudinal axis of a fault-bounded basin would be developed to any great extent in relatively narrow basins that are only 40 to 65 km (25 to 40 mi) wide. Consequently a very careful analysis of the paleocurrent directions is required to define the existence of transverse streams. To date such an analysis has been completed only in the Cottonwood County basin where two dominant paleocurrent directions seem to be present (Southwick and Mossler, 1984).

It may be presumptuous to suggest that conclusions drawn from the study of approximately 45 m (150 ft) of isolated strata in southern Pipestone County can be extrapolated to questions of subcontinental-scale tectonic processes. Nonetheless the limited data summarized above are more consistent with Greenberg and Brown's (1984) interpretation that sedimentation during the Sioux-Baraboo interval occurred in fault-controlled cratonic basins, than with Dott's (1983) proposal of a stable passive continental margin.

Without fossils, it is difficult to prove either marine sedimentation on a shelf edge or nonmarine sedimentation in a temporary basin, and the marine or modified-marine model has been favored mainly because, as Dott (1983, p. 138) states, "the great thickness of the Sioux and Baraboo seem[s] to preclude an intracratonic setting." However, extensive thicknesses do not in themselves negate the possibility of a nonmarine origin, inasmuch as 6,000 m (20,000 ft) of alluvial-fluvial strata of Cenozoic age have been reported in the literature (e.g., Johnson, 1984).

Finally, it is worthwhile to examine the evidence for a great thickness in Minnesota. A thickness of 1,000 to 3,000 m (3,000 to 10,000 ft) was calculated by Baldwin (1951) who proposed a stratigraphic reconstruction of the Rock County structural basin on the basis of several conglomeratic intervals as marker beds. Baldwin's (1951) map clearly shows that the outcrops of conglomerate are small and for the most part widely distributed along the eastern side of the structural basin (Fig. 12). Indeed only three conglomerate outcrops define Baldwin's innermost or third conglomerate, which is inferred to extend for a strike distance of 22 km (14 mi). Thus it seems clear that Baldwin's stratigraphic interpretation was premised on a marine depositional model, where a unique lithology, such as a conglomerate, would plausibly be part of a continuous unit that could serve as a stratigraphic marker bed. However, if these conglomerates were deposited in some other environment, such as an alluvial-fan system like that proposed for the conglomeratic unit at New Ulm (Miller, 1961), they would have little correlative value. Until these questions are resolved, any conclusion regarding the thickness of the Sioux Quartzite in Rock and Pipestone Counties must be considered speculative.

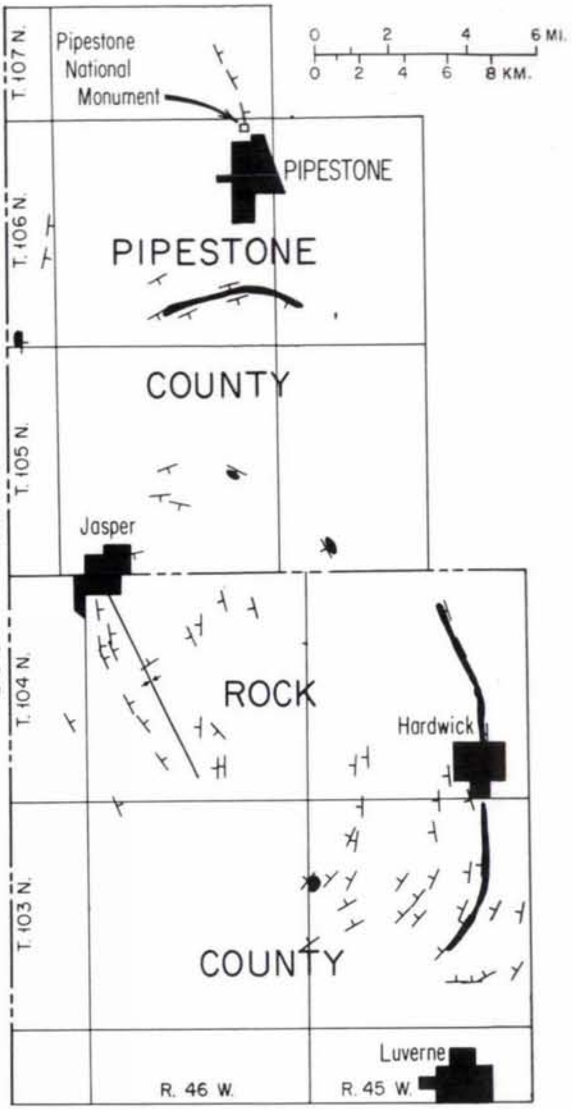


Figure 12. Geologic sketch map of southwestern Pipestone and northwestern Rock Counties showing the distribution of conglomeratic outcrops used by Baldwin (1951) to calculate the thickness of the Sioux Quartzite in the Rock County structural basin.

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