Iowa DNR Geological Survey Bureau 109 Trowbridge Hall Iowa City IA 52252-1319
Phone: 319-335-1575 **http://www.igsb.uiowa.edu**

OVERVIEW OF THE BEDROCK GEOLOGY OF NORTHWEST IOWA

by Brian J. Witzke
Iowa Department of Natural Resources
Geological Survey Bureau
May 1997

INTRODUCTION

The region encompassed by the northwest Iowa bedrock geologic map includes the 19-county area generally north of latitude 42° 13' N and west of longitude 93° 58' W. Bedrock across most of the map area is mantled by a cover of Quaternary sediments, primarily glacial till, alluvium, and loess. The Quaternary cover typically ranges in thickness between about 100 to 400 feet (30 to 120 m) across most of the map area, and locally reaches thicknesses in excess of 500 feet (150 m) within the deeper parts of some bedrock channels.

Bedrock exposure is limited to only scattered small areas in the map region. These include Cretaceous exposures scattered along the lower bluffs and adjacent tributaries of the Big Sioux and Missouri River Valleys in western Woodbury and Plymouth counties (e.g., Witzke and Ludvigson, 1987). Small areas of Cretaceous bedrock exposure are also noted at (1) Grant City, southeast Sac County, (2) Camp Quest near LeMars, Plymouth County, and (3) shale outcrop near the margin of the Manson Impact Structure along Lizard Creek in northwestern Webster County (Hartung and Anderson, 1996, p. 33). Significant exposures of Jurassic, Pennsylvanian, and Mississippian strata crop out in portions of the Des Moines River drainage of Webster and Humboldt counties. Economically important Mississippian limestone strata (Gilmore City Formation) are exposed near Gilmore City in eastern Pocahontas County (Woodson, 1989). Exposures of Precambrian Sioux Quartzite are found at and near Gitchie Manitou State Preserve in northwestern Lyon County (Anderson, 1987).

Previous bedrock geologic mapping in the region has been primarily of a generalized or preliminary nature. A series of county geologic maps (1:125,000) published in the Annual Reports of the Iowa Geological Survey between 1896 and 1906 represent the first attempts at synthesizing the bedrock geology of the region, but these must be regarded as pioneering preliminary efforts. A paucity of well control information seriously impeded the accuracy of these county maps. A revised but relatively generalized bedrock geologic map of Webster County was subsequently prepared by Hale (1955). The statewide bedrock geologic map of Hershey (1969), published at 1:500,000, was a major advancement over the previous county maps. Although the Hershey map honored all well data and outcrop information available at that time, its construction did not take into account the configuration of the bedrock surface. For this reason, as well as the acquisition of new data from hundreds of additional wells, a new geologic map was warranted.

More recently, the distribution and thickness of the Cretaceous Dakota Formation were mapped in a 16-county region of northwest Iowa by Munter et al. (1983), published at a scale of 1:500,000 (with supplemental maps of post-Dakota Cretaceous and sub-Cretaceous units presented at more reduced scales). The compilation of Munter et al. (1983) was a major advancement over previous bedrock maps of northwest Iowa, as it utilized an interpretation of the bedrock surface in the region. Nevertheless, it became apparent during the preparation of the

new bedrock map presented herein that new data required significant revision of the bedrock topography and Cretaceous edges originally presented by Munter et al.

The bedrock geologic map presented herein utilized all available geologic information for the region. This included a review and revision of the stratigraphy of available well points and outcrops in the area. In addition, existing coverage of bedrock topography was modified and refined by a systematic review of well penetrations and outcrops for the map area, resulting in a revised bedrock topography (50-foot contour interval) for the area. Structure contours for appropriate stratigraphic datums were intercepted with the revised bedrock surface to produce geologic unit contacts on the new geologic map.

STRATIGRAPHIC SUMMARY

Tertiary

The youngest pre-Quaternary stratigraphic interval present in the northwest Iowa map area is represented by western-sourced (Rocky Mountain) alluvium of probable Tertiary age, including Pliocene and possible Miocene units (Witzke and Ludvigson, 1990). Sub-till units of "salt and pepper" sand, mudstone, and "granite gravel" primarily occupy positions above Cretaceous strata along bedrock topographic highs (ibid.). Unfortunately, without detailed petrographic study of samples from hundreds of well points across the study area, it was not possible to accurately delineate the distribution of these western-sourced sediments. These units were excluded from the bedrock map and included with the Quaternary cover for the following reasons: (1) these sediments are unconsolidated, similar to the Quaternary alluvium and unlike the shale, sandstone, and carbonate lithologies that characterize the bedrock surface across most of the map area; (2) these units are biostratigraphically unconstrained (except for the "granite gravels" at Akron, Plymouth County), and an early Pleistocene age cannot be unequivocally ruled out. It is hoped that further study will enable these western-sourced sub-till alluvial units, which locally provide important groundwater resources, to be included on the next-generation geologic map of the region.

Cretaceous

The youngest Cretaceous rocks in the map area occur within the Manson Impact Structure, a roughly circular structure with a diameter of about 23 miles (37 km). It is one of the largest impact structures in the United States. Impact-related rocks form the eroded bedrock surface across the extent of the Manson Impact Structure (MIS). The age of the structure has been determined to be about 74 Ma (Izett el al., 1993), a late Campanian date. Recent research drilling has helped clarify the structure and stratigraphic units present within the MIS (Anderson et al., 1996). Three general terranes are recognized in the MIS, each with a distinctive suite of associated rocks (ibid.). An outer "terrace terrane" or "megablock zone" is characterized by a complex faulted region of down-dropped blocks, and includes thick intervals of Cretaceous and Paleozoic strata which locally form the bedrock surface. The down-dropped blocks are primarily covered by a brecciated "overturned flap" of Keweenawan, Paleozoic, and Cretaceous lithologies, which is, in turn, capped by an interval of shaley "Phanerozoic-clast breccia" (see Witzke and Anderson, 1996, for descriptions).

The "central peak" region of the MIS includes a distinctive suite of uplifted brecciated and shock-metamorphosed basement (primarily gneissic) and melt-rock lithologies. A general listing of these lithologies is included on the map key and discussed in Anderson et al. (1996). These central-peak rocks are covered, in part, by "Phanerozoic-clast breccia." Between the terrace terrane and central peak, the bedrock surface across the intervening "crater moat" area is entirely represented by "Phanerozoic-clast breccia" (Witzke and Anderson, 1996).

The major portion of the bedrock surface across the northwest Iowa map area is characterized by strata of mid-Cretaceous age, in ascending order, the Dakota, "Graneros," Greenhorn, Carlile, and Niobrara formations. The youngest Cretaceous strata in Iowa outside of the Manson Impact Structure are represented by subsurface well penetrations of the Niobrara Formation in western Lyon County. Because Niobrara strata are known to crop out a few miles to the west in nearby Lincoln County, South Dakota (Brenner et al., 1981), we had long suspected the presence of Niobrara strata in this area of Lyon County. Recent SEM imaging of well cuttings of the strata in question revealed biostratigraphically-important early Campanian coccoliths known from the Niobrara Formation of Kansas and South Dakota, thereby confirming the presence of Niobrara strata in Iowa (Ludvigson et al., 1997). The calcareous shales and marls of the Niobrara were deposited following a period of regional subaerial erosion on the Carlile Shale surface. Based on biostratigraphic considerations across South Dakota, the Niobrara seas onlapped eastward and did not apparently encroach into Iowa until the late Santonian or early Campanian, significantly later than basal Niobrara deposition farther to the west.

The mid-Cretaceous (late Cenomanian-Turonian) marine shale and marl sequence ("Graneros," Greenhorn, Carlile formations) of northwest Iowa was deposited as the Western Interior sea expanded eastward into the region during the latter stages of the Greenhorn marine cyclothem. These strata comprise the Fort Benton Group, a term first proposed for use in the Missouri River Valley area during the Hayden Survey of the 1850s and 1860s (Meek and Hayden, 1862). This term, however, had fallen into general disuse during subsequent geologic studies in the region, generally replaced with the term "Colorado Group." As originally defined, the Colorado Group encompasses the Graneros, Greenhorn, Carlile, and Niobrara formations. Because a major regional unconformity and sequence boundary separates the Niobrara and Carlile formations in the area, it is more stratigraphically meaningful to not group the Niobrara with the underlying sequence. As such, we have chosen to resurrect the Fort Benton Group as a natural stratigraphic grouping and map unit.

The Fort Benton Group is characterized, in ascending order, by calcareous shale ("Graneros" Shale); marl and calcareous shale with "white specks" and inoceramite limestone lenses (Greenhorn Formation); calcareous shale (lower Carlile, Fairport Member); and noncalcareous shale (upper Carlile, Blue Hill Member). The shales contain scattered septarian calcite concretions and minor siltstone ripples (Ludvigson et al., 1994). A sequence of inoceramids, ammonites, foraminifera, and nannofossils provide biostratigraphic control (ibid.). The lower marine shale interval in Iowa and adjacent Nebraska and South Dakota has been traditionally referred to the Graneros Shale, a name originally applied to an Albian-Cenomanian noncalcareous shale sequence in Colorado. However, as pointed out by Witzke and Ludvigson (1994), this shale interval in the Iowa area is neither a lithostratigraphic or biostratigraphic correlate of the type Graneros interval, and the name is probably inappropriate in Iowa. For this reason, the term is informally used in Iowa ("Graneros") pending further stratigraphic study. In

general, the "Graneros" Shale correlates with the lithologically-similar Hartland Shale Member of the Greenhorn Formation in Colorado-western Kansas. Marine facies of the Fort Benton Group conformably overlie upper Dakota strata over most of the map area, but onlap the Precambrian surface in northwestern Lyon County.

The most widespread lithostratigrahic unit present at the bedrock surface in northwest Iowa is the mid-Cretaceous (late Albian-late Cenomanian) Dakota Formation, whose type locality is in the Sioux City area. The Dakota Formation in Iowa includes a lower sandstone-dominated Nishnabotna Member and an upper mudstone-dominated Woodbury Member (Witzke and Ludvigson, 1994). The Nishnabotna sandstones were aggraded in braided fluvial channels which coalesced to form a general sheet-sand geometry in the area. The Nishnabotna Member includes coarse-grained sandstones and quartzose conglomerates, especially in the lower part. Strata of the Nishnabotna Member do not crop out in the map area, and are best known from exposures to the south in Guthrie County (Witzke and Ludvigson, 1996). Sediments of the overlying Woodbury Member were deposited in the lower coastal plain along the eastern margin of the encroaching Western Interior Seaway, and are dominated by floodbasin mudstones, commonly mottled with paleosol fabrics and interspersed with fine-grained sandstones and lignites.

The Nishnabotna Member is overstepped eastward and northwestward in the map area by strata of the Woodbury Member, where Woodbury strata are known to directly overlie Precambrian (northwest area) and Paleozoic (to the east) rocks (Munter et al., 1983). Unlike the Woodbury Member in the western map area, eastern facies of the Woodbury beyond the Nishnabotna edge include coarse-grained sandstones (best represented by well penetrations in Kossuth County). The fluvial systems that deposited the sediments of the Dakota Formation generally drained towards the west-southwest, with the thickest sections of Nishnabotna sandstones occuring within strike-oriented paleovalleys developed on the deeply-eroded Paleozoic surface. The sub-Cretaceous surface displays approximately 350 feet (105 m) of erosional relief across the map area.

Jurassic

Jurassic strata of the Fort Dodge Formation are entirely restricted in Iowa to Webster County, where they contain important economic deposits of high-quality gypsum. The formation is characterized by a lower gypsum unit and an upper "redbed" interval ("Soldier Creek beds") of mudstone, siltstone, and sandstone (Cody et al., 1996). The gypsum unconformably overlies Pennsylvanian or Mississippian units, although a basal conglomerate locally occurs (ibid.). The "Soldier Creek beds" disconformably to unconformably overlie the gypsum unit over much of the formation's extent. These clastic deposits overstep the gypsum edge to directly overlie Mississippian and Pennsylvanian strata in the northernmost and westernmost outliers of the formation.

The Fort Dodge gypsum beds were variously assigned a Pennsylvanian, Permian, Cretaceous, or Miocene age in earlier reports on the formation. However, palynomorphs recovered from the gypsum indicated a Jurassic age for the formation (Cross, 1966). A Late Jurassic age seems most likely, although a Middle Jurassic age cannot be ruled out (Cody et al., 1996; C. Klug, 1996, pers. comm.). The origin of the Fort Dodge gypsum remains equivocal, and deposition either in a restricted-marine evaporite basin or a nonmarine evaporitive lake remains a possibility. Similar sulfur-isotope values of the gypsum to known Jurassic marine-

derived gypsum support a marine-derived origin. It seems most likely that the Fort Dodge gypsum was deposited marginal to the Late Jurassic Sundance seaway.

Pennsylvanian

Pennsylvanian strata of the Cherokee Group are located in the southeastern region of the map area, and are best displayed in the DesMoines River Valley of Webster County (Lemish et al., 1981). The Cherokee Group in Iowa is subdivided into four formations, in ascending order, Kilbourn, Kalo, Floris, and Swede Hollow (Ravn et al., 1984). The type locality of the Kalo Formation is in Webster County (ibid.). Sub-Cretaceous erosion has beveled the Cherokee Group across the southern tier of counties in the map area, and upper Cherokee strata (Swede Hollow Fm.) are primarily absent. The Cherokee Group is dominated by dark shales and mudstones, and sandstones are locally prominent (Lemish et al., 1981). The sandstones are commonly fine- to medium-grained, but, unlike Cherokee sandstones of southern Iowa, the northern Iowa occurrences include coarse-grained to pebbly facies (ibid.). Coal beds are typically present, and historic coal mining occurred within the DesMoines River Valley of Webster County. Thin marine limestones are also noted in portions of the Cherokee Group.

The Cherokee Group is of Middle Pennsylvanian age and correlates with portions of the Atokan and Desmoinesian stages. Cherokee deposition was initiated with the infilling of the eroded Mississippian surface by aggrading fluvial systems. Subsequent Cherokee deposition was characterized by alternating episodes of nonmarine, marginal-marine to estuarine, and shallow-marine sedimentation. A period of relatively deep channel incision and sandstone filling, in places into Mississippian strata, is locally recognized in the lower Floris Formation. Except for the lower Swede Hollow Formation, regionally-widespread marine limestones and shales are not characteristic of the Cherokee Group, and fully-developed marine cyclothems, which are well developed in younger Pennsylvanian strata of southern Iowa, are typically not seen. Nevertheless, characteristic alternations between nonmarine and marine sedimentation in the Cherokee Group suggest that cyclic changes in sea-level exerted broad controls over sedimentary patterns.

Mississippian

Mississippian rocks crop out in portions of Webster, Humboldt, and Pocahontas counties, and provide important limestone aggregate resources to the region, especially from the quarries at Humboldt and Gilmore City. Mississippian strata are approximately restricted to the southeastern half of the map area, and are beveled and truncated to the northwest beneath the Cretaceous Dakota Formation. Pennsylvanian units overlie an eroded Mississippian surface across portions of the southern tier of counties in the map area, with up to 150 ft (45 m) of relief developed on this surface. Four Mississippian map units are utilized, in ascending order: (1) Maynes Creek, Chapin, and Prospect Hill formations; (2) Gilmore City Formation; (3) Augusta Group; and (4) Pella and "St. Louis" formations. A confusing array of stratigraphic nomenclature has emerged from various studies in the central and northern Iowa Mississippian outcrop, but existing stratigraphic problems have been partly rectified by Woodson and Bunker (1989) and Witzke et al. (1990).

The youngest Mississippian unit in the area is the Pella Formation, characterized in Webster County by red to green-gray shale and limestone, fossiliferous in part, with minor siltstone and sandstone. The Pella interval was referred to the Ste. Genevieve Formation in some early

reports, but the Pella is lithologically distinct and only correlates with the upper part of the type Ste. Genevieve of Missouri (Witzke et al., 1990). The Pella overlies an interval historically assigned to the "St. Louis" Formation, which consists of dolomite (sandy to cherty in part), sandstone, and minor shale. The "St. Louis" is lithologically distinct from the type St. Louis Formation of Missouri, and is now known to include strata in the upper part that correlates with the lower Ste. Genevieve of Missouri. As such, the term "St. Louis" for this interval is inappropriate, and new formational terminology should be erected. Pending such revision, the term is informally applied in Iowa. The interval has been subdivided into a series of members by Witzke et al. (1990), but the relationships of these members in the Webster County area has not yet been established. The "St. Louis" overlies a major intra-Mississippian erosional surface developed on the Augusta Group, with up to 100 ft (30 m) of erosional relief in the subsurface of northern Iowa.

The Augusta Group is used here in the sense of Witzke et al. (1990) to include strata of the Burlington, Keokuk, and Warsaw formations. The Augusta was first proposed as a stratigraphic term by Keyes (1893), but the term had fallen into general disuse until recently resurrected (Witzke et al., 1990). The constituent formations of the Augusta Group are all defined from exposures in the Mississippi River Valley, and have long-standing utility in southeast Iowa. The Augusta Group is a particularly appropriate lithostratigraphic grouping in northern Iowa, as correlation and recognition of the constituent formations in the area remain unclear. In addition, it is uncertain whether or not the Burlington Formation is present in northern Iowa as part of the basal Augusta Group, or whether the Burlington correlates with the Gilmore City Formation. Although further biostratigraphic study is needed, Witzke et al. (1990) and Witzke and Bunker (1996) advanced the hypothesis that the Gilmore City Formation is a northern facies equivalent of the Burlington Formation of southeast Iowa. If this proves to be true, the Augusta Group of northern Iowa would then be equivalent to only the Keokuk and Warsaw formations. Regardless of the actual stratigraphic relations with southeast Iowa, the Augusta Group in northern Iowa can be recognized as a discrete lithostratigraphic interval characterized by distinct lithologies. As in southeast Iowa, the Augusta Group of northern Iowa is dominated by cherty dolomite with secondary fossiliferous limestones (crinoidal packstones); these strata are glauconitic in part, especially in the lower half. Traces of quartz druse and chalcedony, in part from geode infillings, are unique to the interval. Unlike the Augusta Group of southeast Iowa, the Augusta in northern Iowa includes a thin interval of "sublithographic" lime mudstones and oolite which subdivides the group into two subequal depositional cycles. The Augusta Group is considered to be entirely within the Middle Mississippian Osagean Series (Witzke et al., 1990).

The Gilmore City Formation is a distinct stratigraphic interval restricted in outcrop to northern Iowa, where it has historically served as the primary source of high-quality limestone aggregate in the region. The formational definition as used here was clarified by Woodson and Bunker (1989). Earlier workers had applied a confusing array of poorly-defined stratigraphic terms to this interval, including the Iowa Falls, Alden, and Humboldt. The Iowa Falls is a dolomitized facies of the Gilmore City. The Humboldt corresponds to the upper part of the Gilmore City interval as represented by quarry exposures near Humboldt. In general, the Gilmore City Formation is characterized by limestone facies over most of its extent, primarily skeletal to oolitic packstones. It is subdivided into two depositional cycles, each capped by peritidal lime mudstone facies, commonly "sublithographic" and locally brecciated to intraclastic. Basal Gilmore City strata contain latest Kinderhookian faunas, but upper strata are

of early Osagean age. Although far from resolved, the Gilmore City may be a northern facies equivalent to part of the Burlington Formation of southeast Iowa (Witzke and Bunker, 1996).

The lowest Mississippian map unit is entirely of Kinderhookian age. This interval primarily encompasses the Maynes Creek Formation (as defined by Woodson and Bunker, 1989), but also includes a thin basal siltstone (Prospect Hill Formation) and a thin skeletal to oolitic limestone facies (Chapin Formation). The interval formerly termed the "Eagle City" is now included within the upper Maynes Creek Formation (ibid.). The Maynes Creek Formation is dominated by cherty dolomite strata. However, an oolitic limestone interval is recognized near the middle of the formation (the "middle oolite" of Woodson and Bunker, 1989), and dense "sublithograpic" peritidal limestones, locally stromatolitic, cap the formation. Although the basal Prospect Hill Siltstone overlies a regional unconformity on Upper Devonian strata, there is little erosional relief developed on this surface.

Devonian

No exposures of Devonian strata are known in the map area, and, where shown on the geologic map, the Devonian units entirely subcrop beneath the Quaternary cover. Middle and Upper Devonian strata onlap to the northwest across Iowa above a major sub-Devonian erosional surface, and Devonian strata are known to overlie Ordovician, Cambrian, and Precambrian units in northwest Iowa. Devonian strata are beveled and truncated to the northwest beneath the Cretaceous Dakota Formation across the map area. Although Middle Devonian strata of the Cedar Valley Group occur in the subsurface in the southeastern part of the map area, all Devonian units present at the bedrock surface are Upper Devonian. These primarily include strata of the Lime Creek Formation, represented in the map area by a relatively thick and monotonous sequence of dolomite, argillaceous in part; minor dolomitic limestone and "sublithographic" limestone are present. Lime Creek strata of northwest Iowa encompass shallow-marine and peritidal carbonate facies. Outside the map area to the south and east, these strata thin and are comprised of shale-dominated subtidal facies, dysoxic in part (Witzke and Bunker, 1996). The Lime Creek Formation forms a disconformity-bounded transgressive-regressive depositional cycle of late Frasnian age.

Following an episode of subaerial exposure, a mid Famennian marine transgression flooded the Lime Creek surface across northwest Iowa. Two earlier Famennian transgressive-regressive cycles which occur in southeast Iowa are absent in northwest Iowa (Witzke and Bunker, 1996). Shale-dominated Famennian strata of northwest Iowa comprise a relatively thin (15-55 ft; 4.5-17 m) interval, which includes units variously referred to the "Maple Mill" and Sheffield formations. A fossiliferous dolomite unit (Aplington Formation) locally occurs in the middle of the shale interval and represents a shallowing depositional phase that subdivides two general depositional sequences (ibid.). Devonian seas withdrew from the area during the late Famennian.

Ordovician

Ordovician strata are not exposed in the northwest Iowa map area, but sub-Quaternary Ordovician subcrop is recognized in a few areas, primarily northeast Kossuth County and the deep bedrock channel near Spencer in Clay County. These are Middle and Upper Ordovician strata which include, in ascending order, the St. Peter Sandstone, Glenwood Shale, Platteville Formation, Galena Group, and Maquoketa Formation. Two major erosional surfaces bevel and

truncate Ordovician strata to the northwest in the map area which formed during sub-Devonian and sub-Cretaceous erosional episodes.

Only the lower portion of the Maquoketa Formation, the Elgin Member, is represented in the map area. It is primarily a cherty dolomite, but fossiliferous cherty limestone locally occurs in the upper part. The Maquoketa was deposited during a major deepening event in the continental interior during the Richmondian (Upper Ordovician)(Witzke and Bunker, 1996). The formation is beveled beneath Upper Devonian strata, and truncated by sub-Cretaceous incision to the northwest. The Maquoketa Formation conformably overlies the Galena Group, a Middle to Upper Ordovician (Rocklandian-Maysvillian) interval, in the map area. The Galena varies between about 250 and 275 ft (75-85 m) in thickness in northwest Iowa. The Galena is primarily a carbonate-dominated interval, but is shale-dominated (Decorah Shale) in the lower 40 to 70 ft (12-21 m), thickest near the northwestern sub-Cretaceous edge (Witzke, 1983). Where represented at the bedrock surface in the map area, strata of the Galena Group are primarily characterized by dolomite with secondary dolomitic limestone and limestone, especially in the lower part. Lower Galena carbonates are cherty to varying degrees (Dunleith Formation), but upper Galena carbonates are typically chert-free (Wise Lake and Dubuque formations). Sub-Galena Middle Ordovician strata of the Platteville and Glenwood formations are not found at the bedrock surface in the map area.

The oldest Paleozoic map unit in northwest Iowa is the St. Peter Sandstone, which forms the bedrock surface at a single well point near East Lake Okoboji in Dickinson County. The St. Peter is a relatively pure fine- to medium-grained quartzarenite which overlies an eroded surface of Lower Ordovician and Upper Cambrian strata in northwest Iowa. Thin conodont-bearing shales and pyritic and phosphatic hardgrounds occur in the St. Peter in the western area (Witzke, 1980). The St. Peter was deposited during the early phases of Tippecanoe marine transgression into the continental interior during the late Chazyan (Witzke and Bunker, 1996). Sub-St. Peter Lower Ordovician and Upper Cambrian strata are present across much of northwest Iowa, but are consistently overlain by younger Paleozoic and/or Cretaceous units and are not found at the bedrock surface.

Precambrian

The Precambrian Sioux Quartzite forms the bedrock surface in the northwestern corner of the map area, lapped at its southern edge by Cretaceous rocks of the Fort Benton Group. Surface exposures are seen in and near Gitchie Manitou State Preserve in northwestern Lyon County (Anderson, 1987). The Sioux Quartzite is an incredibly durable quartz-cemented pink to red quartzarenite that has been interpreted by some, but not all, geologists to have been slightly metamorphosed. It locally includes minor argillites (pipestone) and conglomerates, but these facies are not exposed in Iowa. The Sioux Quartzite outcrop is more extensive in adjacent areas of South Dakota and Minnesota, and it is widely used in the region as a high-quality aggregate resource. The formation extends in the subsurface in a general east-to-west trend for about 300 miles (500 km) from south-central Minnesota into central South Dakota (where it is covered by Cretaceous strata). The quartzite is one of the most erosionally resistant rocks found in the region, and it forms a broad bedrock topographic high (the “Sioux Ridge”) that persisted as an important geologic feature throughout the Phanerozoic.

The Sioux Quartzite was primaily deposited in fluvial systems that drained the southern region of the paleocontinent during the Early Proterozoic, the so-called “Baraboo interval” of

Dott (1983), likely 1760-1640 Ma. Except for the re-deposited megabreccias of Precambrian crystalline rock in the central peak area of the Manson Impact Structure, the Sioux Quartzite forms the only Precambrian rock at the bedrock surface in Iowa. Elsewhere in the state, Precambrian rocks are buried beneath a cover of Phanerozoic strata. The buried Precambrian rocks of the northwest Iowa map area are varied and complex. These are primarily characterized by metamorphic rocks (especially gneisses), granitic plutons, rhyolite flows, and mafic instrusives varying in age from Archean through Middle Proterozoic. The extensive Middle Proterozoic Keweenawan Midcontinent Rift System trends through the southeastern portion of the northwest Iowa map area. A thick sequence of rift-filling sedimentary rocks, the so-called "Red Clastic" interval, and associated mafic extrusives remain deeply buried. However, blocks and brecciated units derived from the Keweenawan "Red Clastic" sequence locally form the bedrock surface in portions of the terrace terrane of the Manson Impact Structure.

REFERENCES:

Anderson, R.R., 1987, Precambrian Sioux Quartzite at Gitchie Manitou State Preserve, Iowa: Geological Society of America, Centennial Field Guide – North-Central Section, p. 77-80.

Anderson, R.R., Witzke, B.J., and Roddy, D.J., 1996, The drilling of the 1991-1992 Geological Survey Bureau and U.S. Geological Survey Manson impact structure research cores, *in* Koeberl, C., and Anderson, R.R., eds., The Manson Impact Structure, Iowa: Anatomy of an Impact Crater: Geological Society of America Special Paper 302, p. 45-88.

Brenner, R.L., and 7 others, 1981, Cretaceous stratigraphy and sedimentation in northwest Iowa, northeast Nebraska, and southeast South Dakota: Iowa Geological Survey, Guidebook Series no. 4, 172 p.

Cody, R.D., Anderson, R.R., and McKay, R.M., 1996, Geology of the Fort Dodge Formation (Upper Jurassic), Webster County, Iowa: Iowa Dept. Natural Resources, Geological Survey Bureau, Guidebook Series no. 19, 74 p.

Cross, A.T., 1966, Palynologic evidence of mid-Mesozoic age of For Dodge (Iowa) gypsum: Geological Society of America, Special Paper 101, Annual Meeting, Abstract, p. 46.

Dott, R.H., Jr., 1983, The Baraboo interval; a tale of red quartzites: Geological Society of America, Abstracts with Programs, v. 15, p. 209.

Hale, W.E., 1955, Geology and ground-water resources of Webster County, Iowa: Iowa Geological Survey, Water-Supply Bulletin no. 4, 257 p.

Hartung, J.B., and Anderson, R.R., 1996, A brief history on investigations of the Manson impact structure, *in* Koeberl, C., and Anderson, R.R., eds., The Manson Impact Structure, Iowa: Anatomy of an Impact Crater: Geological Society of America Special Paper 302, p. 31-43.

Hershey, H.G., 1969, Geologic Map of Iowa (1:500,000 scale): Iowa Geological Survey.

Izett, G.A., Cobban, W.A., Obradovich, J.D., and Kunk, M.J., 1993, The Manson impact structure: $^{40}Ar/^{39}Ar$ age and its distal impact ejecta in the Pierre Shale of southeastern South Dakota: Science, v. 262, p. 729-732.

Keyes, C.R., 1893, Geology of Lee County, Iowa: Iowa Geological Survey, Annual Report, v. 3, p. 305-409.

Lemish, J., Burggraf, D.R., Jr., and White, H.J., eds., 1981, Cherokee sandstones and related facies of central Iowa; an examination of tectonic setting and depositional environments: Iowa Geological Survey, Guidebook Series no. 5, 95 p.

Ludvigson, G.A., Witzke, B.J., González, L.A., Hammond, R.H., and Plocher, O.W., 1994, Sedimentology and carbonate geochemistry of concretions from the Greenhorn marine cycle (Cenomanian-Turonian), eastern margin of the Western Interior Seaway, *in* Shurr, G.W., Ludvigson, G.A., and Hammond, R.H., eds., Perspectives on the Eastern Margin of the Cretaceous Western Interior Basin: Geological Society of America, Special Paper 287, p. 145-173.

Ludvigson, G.A., Witzke, B.J., Liu, P.H., and Pope, J.P., 1997, Outlier of Cretaceous Niobrara Formation in Lyon County, Iowa: Iowa Academy of Science, Program Abstracts, 109th Session, Abstract no. 108.

Meek, F.B., and Hayden, F.V., 1862, Descriptions of Lower Silurian (Primordial), Jurassic, Cretaceous, and Tertiary fossils, collected in Nebraska by the exploring expedition under the command of Capt. Wm F. Reynolds, U.S. Top. Engineers, with some remarks on the rocks from which they were obtained: Philadelphia Academy of Natural Science Proceedings, v. 13, p. 415-447.

Munter, J.A., Ludvigson, G.A., and Bunker, B.J., 1983, Hydrogeology and stratigraphy of the Dakota Formation in northwest Iowa: Iowa Geological Survey, Water-Supply Bulletin no. 13, 55 p.

Ravn, R.L., Swade, J.W., Howes, M.R., Gregory, J.L., Anderson, R.R., and Van Dorpe, P.E., 1984, Stratigraphy of the Cherokee Group and revision of Pennsylvanian stratigraphic nomenclature in Iowa: Iowa Geological Survey, Technical Information Series, no. 12, 76 p.

Witzke, B.J., 1980, Middle and Upper Ordovician paleogeography of the region bordering the Transcontinental Arch, *in* Fouch, T.D., and Magathan, E.R., eds., Paleozoic paleogeography of the west-central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, p. 1-18.

Witzke, B.J., 1983, Ordovician Galena Group in Iowa subsurface, *in* Delgado, D.J., ed., Ordovician Galena Group of the Upper Mississippi Valley – Deposition, diagenesis, and paleoecology: Society of Economic Paleontologists and Mineralosists, Great Lakes Section, 13th Annual Field Conference Guidebook, p. D1-D26.

Witzke, B.J., and Anderson, R.R., 1996, Sedimentary-clast breccias of the Manson impact structure, *in* Koeberl, C., and Anderson, R.R., eds., The Manson Impact Structure, Iowa: Anatomy of an Impact Crater: Geological Society of America Special Paper 302, p. 115-144.

Witzke, B.J., and Bunker, B.J., 1996, Relative sea-level changes during Middle Ordovician through Mississippian deposition in the Iowa area, North American craton, *in* Witzke, B.J., Ludvigson, G.A., and Day, J.E., eds., Paleozoic Sequence Stratigraphy: Views from the North American Craton: Geological Society of America, Special Paper 306, p. 307-330.

Witzke, B.J., and Ludvigson, G.A., 1987, Cretaceous exposures, Big Sioux River Valley north of Sioux City, Iowa: Geological Society of America, Centennial Field Guide – North-Central Section, p. 97-102.

Witzke, B.J., and Ludvigson, G.A., 1990, Petrographic and stratigraphic comparisons of sub-till and inter-till alluvial units in western Iowa: implications for development of the Missouri River drainage, in Bettis, E.A., III, leader, Holocene Alluvial Stratigraphy and Selected Aspects of the Quaternary History of Western Iowa: Midwest Friends of Pleistocene, 37th Field Conference, p. 119-143.

Witzke, B.J., and Ludvigson, G.A., 1994, The Dakota Formation in Iowa and the type area, *in* Shurr, G.W., Ludvigson, G.A., and Hammond, R.H., eds., Perspectives on the Eastern Margin of the Cretaceous Western Interior Basin: Geological Society of America, Special Paper 287, p. 43-78.

Witzke, B.J., and Ludvigson, G.A., 1996, Mid-Cretaceous fluvial deposits of the eastern margin, Western Interior Basin: Nishnabotna Member, Dakota Formation; A field guide to the Cretaceous of Guthrie County: Iowa Dept. Natural Resources, Geological Survey Bureau, Guidebook Series no. 17, 75 p.

Woodson, F.J., 1989, An excursion to the historic Gilmore City quarries: Geological Society of Iowa, Guidebook 50, 41 p.

Woodson, F.J., and Bunker, B.J., 1989, Lithostratigraphic framework of Kinderhookian and early Osagean (Mississippian) strata, north-central Iowa: Geological Society of Iowa, Guidebook 50, p. 3-17.