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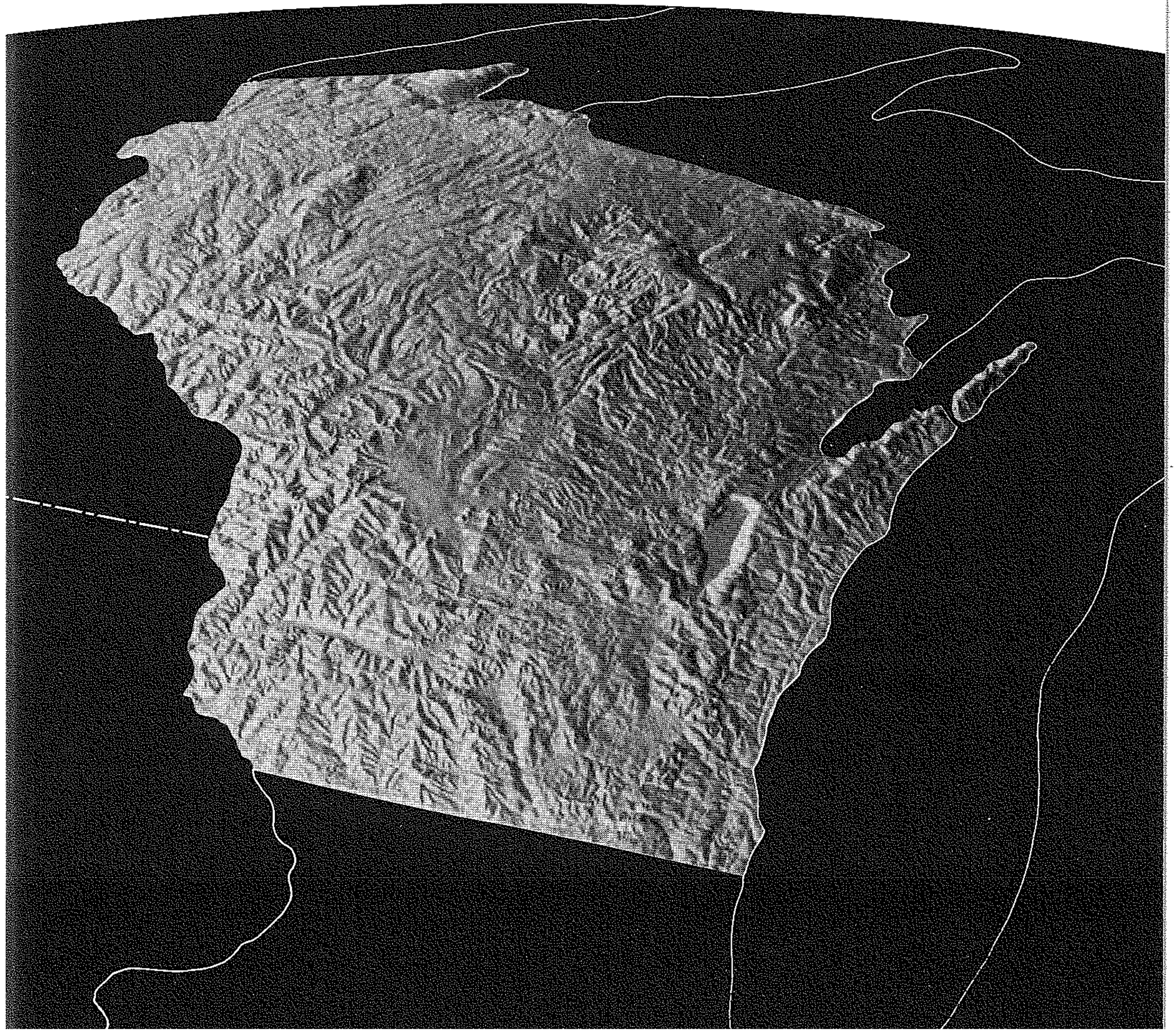
Ordovician–Silurian Boundary of the Neda Formation



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Ordovician–Silurian Boundary of the Neda Formation

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PREFACE

Geoscience Wisconsin is a serial that addresses itself to the geology of Wisconsin — geology in the broadest sense to include rock and rock as related to soil, water, climate, environment, and so forth. It is intended to present timely information from knowledgeable sources and make it accessible via scientific review and publication for the benefit of private citizens, government, scientists, and industry.

Manuscripts are invited from scientists in academic, government, and industrial fields. Once a manuscript has been reviewed and accepted, the authors will submit a revised copy of the paper, and the Wisconsin Geological and Natural History Survey will publish the paper as funds and time permit, distribute copies at nominal cost, and maintain the publication as a part of the Survey list of publications. This will help to ensure that results of research are not lost in the archival systems of large libraries or lost in the musty drawers of an open-file.

In conjunction with the Seventeenth Annual Meeting of the North-Central Section of the Geological Society of America in Madison in late April and early May of 1983, Don Mikulic and Joanne Kluessendorf coordinated a symposium on the description and origin of the Neda Formation and related units at the Ordovician-Silurian boundary. Following the meeting they led a field excursion to eastern Wisconsin.

We encourage submission of manuscripts relating to Wisconsin geology. Special consideration will be given to papers which deal with timely topics, present new ideas, and have regional or statewide implications.

M.G. Mudrey, Jr.
Editor - Geoscience Wisconsin
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Natural History Survey

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FERRUGINOUS AND CALCAREOUS OOLITES AT THE ORDOVICIAN-SILURIAN BOUNDARY IN ILLINOIS

Joanne Kluessendorf[1]

ABSTRACT

The Ordovician-Silurian boundary in Illinois is marked locally by oolitic strata. In the northern part of the state these strata belong to the ferruginous Neda Formation, which is characterized by oblate, concentrically-layered, goethitic ooids scattered through diverse lithologies. In the southern part of the state the Noix Oolite, composed of spherical, concentrically-layered, calcitic ooids, occupies this stratigraphic position. Both units exhibit patchy geographic distribution, and occur in a similar stratigraphic position and lithologic sequence. Oolite at one locality in northeastern Illinois displays a possible transition from calcite ooids at the base to siderite and, finally, goethite ooids at the top. As they show progressive alteration to iron minerals, these ooids assume the oblate shape characteristic of ferruginous ooids in the Neda Formation and some other oolitic ironstones. Preliminary study of this transition suggests that at least some of the Neda Formation may represent a ferruginized calcareous oolite, perhaps related genetically to the Noix Oolite.

INTRODUCTION

Mikulic (1979, 1983) observed that oolites at the Ordovician-Silurian boundary in the central United States could be subdivided geographically according to mineral composition, with ferruginous oolite occurring to the north and calcareous oolite to the south. He suggested that, even though they all may not be synchronous, these oolites possibly were deposited under similar conditions during regressive-transgressive episodes across the underlying uneven Maquoketa surface.

Oolite occurs sporadically at the Ordovician-Silurian boundary in Illinois. Conforming to the regional pattern noted by Mikulic, the ferruginous Neda Formation oolite occurs in the northern part of the state whereas the calcareous Noix Oolite is present to the south (fig. 1). Both oolitic units occupy a similar stratigraphic position and lithologic sequence, succeeding upper Ordovician clastics and preceding lower Silurian carbonates.

The Noix Oolite is typical of calcareous oolites deposited under agitated, shallow-water, normal-marine conditions. The mechanism of formation and the depositional environment of ferruginous oolites (oolitic ironstones) such as the Neda Formation is, in general, controversial. Proposed origins range from authigenesis during lateritic weathering (Nahon, and others, 1980) to eluviation and replacement of normal calcareous oolite (Kimberley, 1979).

The main purpose of this paper is to document and describe the ferrugi-

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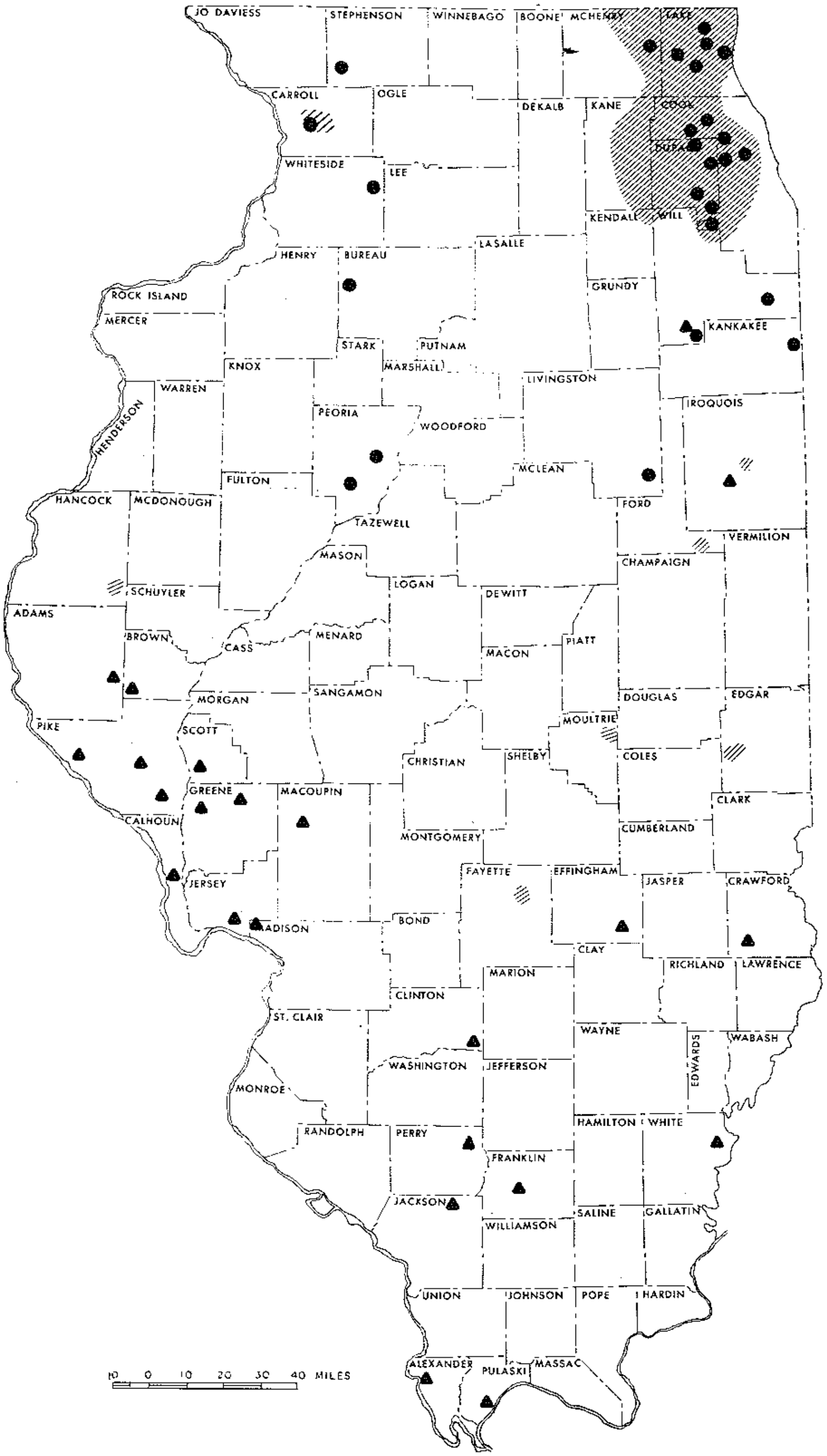

Figure 1. Map showing oolite occurrences at the Ordovician-Silurian boundary in Illinois. Circles - ferruginous oolite (Neda Formation); triangles - calcareous oolite (Noix Oolite); diagonal ruling - red nonoolitic strata, generally mudstone, at the top of the Maquoketa Group. Both calcareous and ferruginous ooids occur in the oolite in southern Will County. A single symbol may represent more than one locality within a small area.

nous and calcareous oolites at the Ordovician-Silurian boundary in Illinois. The possible significance of the transition oolite for the origin of the ferruginous Neda Formation oolite is suggested on the basis of preliminary evidence. The supporting appendices are published separately (Kluessendorf, 1991) as Wisconsin Geological and Natural History Survey Open-file Report WOFR 91-1. Locations of samples examined for this study, both in outcrop and in subsurface, are given in appendix 1; appendix 2 gives stratigraphic and lithologic descriptions of selected Neda Formation outcrops.

NOIX OOLITE

A calcareous oolite occurs at the Ordovician-Silurian boundary in southern Illinois (fig. 1) and adjacent parts of Missouri (Thompson and Satterfield, 1975) and Kentucky (E. Atherton, 1982, personal communication). Keyes (1898) named it the Noix Oolite for Noix Creek near Louisiana, Pike County, Missouri, in the area where it is best exposed. Generally, the unit is less than 3 m thick, of limited lateral extent and discontinuously distributed. In Illinois this oolite crops out only along the Mississippi River in Calhoun, where it was first reported by Worthen in 1870, and Alexander Counties. The oolite also occurs in the subsurface of at least 15 other counties (see Kluessendorf, 1991, appendix 1). Calcareous oolite that may belong to the Noix is present in the subsurface of Iroquois County and crops out in Will County.

Keyes (1898) gave the oolite formation rank, whereas Savage (1913) considered it a part of the Cyrene Member of the Edgewood Formation. Willman and Atherton (1975) referred it to the Noix Oolite Member of the Edgewood Formation. Thompson and Satterfield (1975) returned the unit to formation rank, assigning it to the Noix Limestone of the Edgewood Group in western Illinois and northeastern Missouri. However, they applied the name Leemon Formation to the oolite in extreme southern Illinois because of lithologic differences and geographic separation between these two outcrop areas. Figure 2 shows various stratigraphic schemes for the Noix and contiguous units.

At all known localities the Noix Oolite succeeds upper Ordovician strata, typically clastic sediments. In southern Illinois it unconformably overlies either the Girardeau Limestone or the Orchard Creek Shale of the Maquoketa Group (fig. 2). Girardeau Limestone clasts occur locally at the base of the oolite (Savage, 1908, 1909; Weller and Ekblaw, 1940; Pryor and Ross, 1962). Where present, the Girardeau Limestone is gradational with the underlying Orchard Creek Shale, which although possibly equivalent to the Brainard Shale was considered a member of the older Scales Shale by Willman and Buschbach (1975). Both the Girardeau Limestone and the Orchard Creek Shale have been dated as late Ordovician (Cincinnatian) on the basis of conodonts (*Amorphognathus ordovicicus* and *Prioniodus ferrarius* faunas) (Thompson and Satterfield, 1975); graptolites (*Climacograptus putillus*) (Pryor and Ross, 1962) support this age determination for the Orchard Creek Shale.

In western Illinois the Noix Oolite succeeds upper Ordovician Maquoketa Shale, which is characterized by the late Ordovician conodonts *Amorphognathus ordovicicus* and *Prioniodus ferrarius* faunas (Thompson and Satterfield, 1975). The contact between these two units generally is planar, but may be disconformable (fig. 3); Rogers (1972) reported clasts of Maquoketa mudstone at the base of the oolite.

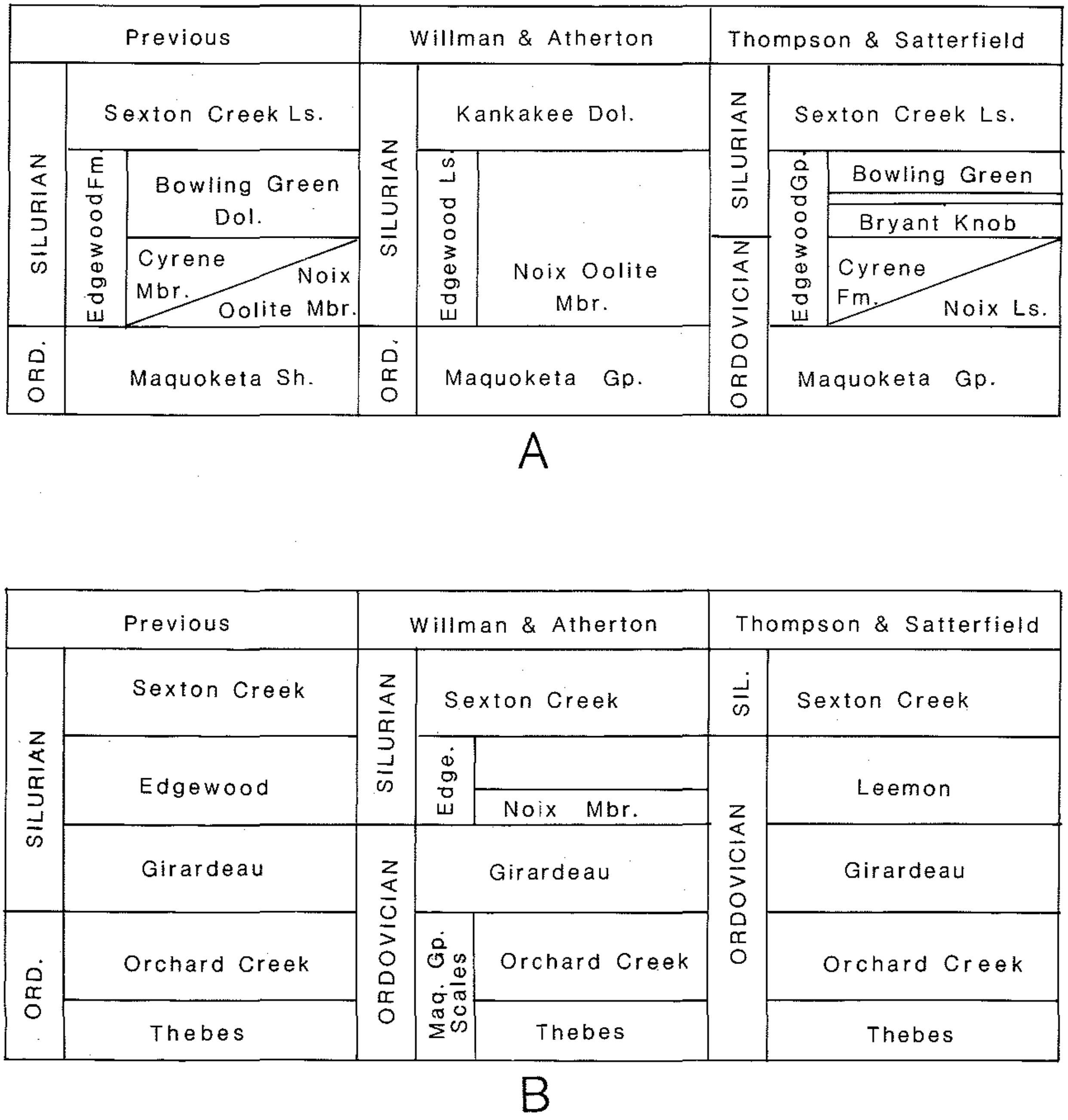

Figure 2. Stratigraphic relationship and nomenclature of strata contiguous to the Ordovician-Silurian boundary in: A - western Illinois and northeastern Missouri and B - southern Illinois and southeastern Missouri. First column gives nomenclature prior to 1975; columns 2 and 3 give Willman and Atherton (1975) and Thompson and Satterfield (1975) nomenclature, respectively. Unit between Bowling Green and Bryant Knob is unnamed limestone.

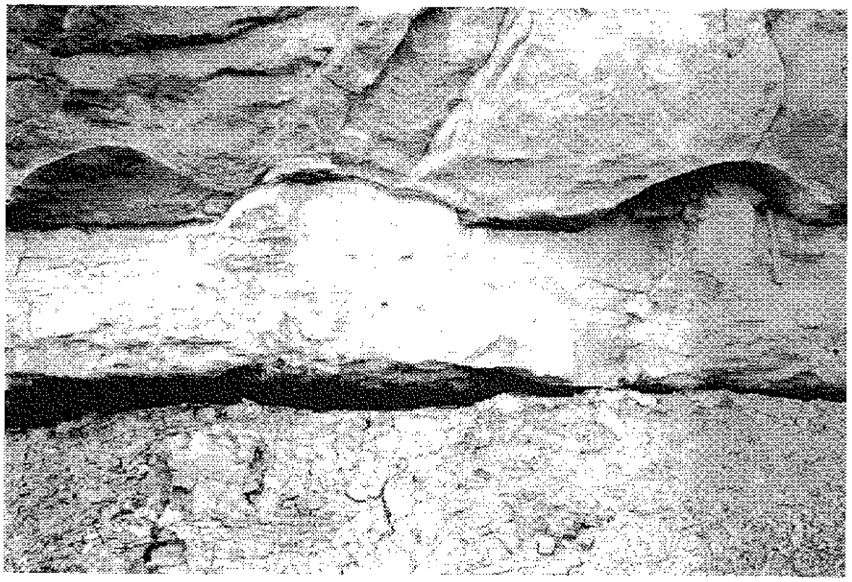

Figure 3. Noix Oolite outcrop, Clarksville roadcut, Pike County, Missouri (see Kluessendorf, 1989 for location). Noix is center unit; observe undulating upper contact with Silurian Bowling Green Dolomite and relatively planar lower contact with Ordovician Maquoketa Shale.

An erosional unconformity separates the oolite in southern Illinois from the overlying lower Silurian Sexton Creek Limestone, which in places lies directly on the Girardeau Limestone. Generally the upper surface of the Noix in western Illinois is planar, but may be locally irregular (fig. 3). In northeastern Missouri the oolite may be succeeded by any of several carbonate units (in ascending stratigraphic order): an unnamed dolomitic limestone member or the Kissinger Member of the Bryant Knob Formation, an unnamed light-gray limestone, or the Bowling Green Dolomite (Thompson and Satterfield, 1975). Thompson and Satterfield (1975) inferred that all three of the lower units were removed almost completely by erosion prior to Bowling Green Dolomite deposition. The Bryant Knob Formation has been dated as early Silurian on the basis of the conodont *Icriodella*? and the graptolites *Medusagraptus* and *Diplospirograptus*; the Bowling Green Dolomite yields an early Silurian *Paltodus dyscritus* conodont fauna (Thompson and Satterfield, 1975). The Sexton Creek Limestone, also characterized by the *Paltodus dyscritus* fauna, overlies the Bowling Green Dolomite in northeastern Missouri (Thompson and Satterfield, 1975). McCracken and Barnes (1982) placed the Bowling Green Dolomite in the early Llandovery on the basis of the conodont *Oulodus*? *nathani*.

Originally the Noix Oolite was assigned to the Silurian (Worthen, 1870; Savage, 1913; Willman and Atherton, 1975); however, several faunal studies have demonstrated that it is late Ordovician instead. Articulate brachiopods in the oolite resemble the late Ashgillian Hirnantian fauna of Europe (Amsden, 1974). Only late Ordovician conodonts (mostly *Prioniodus ferrarius* and *Amorphognathus ordovicicus* faunas) were found in the unit by Thompson and Satterfield, 1975). McCracken and Barnes (1982) assigned the Noix to the Asgillian (late Richmondian) on the basis of the conodonts *Noixodontus girardeauensis* and *Gamachignathus* sp.; they suggested that the simple cones (*Panderodus*, *Pseu-*

doneotodus, *Walliserodus*) that make up about 80% of the overlying Silurian fauna were opportunistic generalized taxa that reoccupied the area following a Llandoverian transgression.

The Noix Oolite varies somewhat lithologically, primarily in siliciclastic content, throughout its geographic extent. In western Illinois it is a moderately- to well-sorted oolitic calcarenite with a micrite matrix or cemented by sparry calcite. To the south the Noix is a silty oolitic calcarenite, containing common subangular quartz and tourmaline grains, with lenses and layers of argillaceous limestone or mudstone. Weller and Ekblaw (1940) reported "coarse, more or less hematitic oolite" in SE, sec. 5, T. 15 S., R. 3 W., near the base of the section, but this is now below the level of the Mississippi River. Amsden (1974) concluded that the oolite in southern Illinois was close to a source area that supplied extra-basinal detritus; however, in White County, north and east of the southernmost outcrop area, the oolite contains even more abundant quartz and tourmaline, suggesting that the source of detritus may have been to the east or southeast.

Phosphatic nodules and glauconite grains are common locally in the Noix Oolite, especially at its base. Rubey (1952) reported that phosphatic "pebbles" occurred where the unit was most oolitic.

The calcite ooids, which range in size from 0.5 to 1.0 mm, possess predominantly concentric cortical layers, although some ooids lack all internal structure because of extensive micritization, especially in the southernmost occurrences. Although most of the ooids are spherical, flattened, broken and composite ooids occur (fig. 4); flattened ooids are particularly noticeable in the White County oolite. Rubey (1952) reported that many ooids lack recognizable nuclei, whereas others possess nuclei of crystalline calcite or glauconitized echinoderm fragments. Other nuclei include ooid fragments, fossil fragments, and phosphate or carbonate grains. Many ooids in the White County occurrence are pyritized.

In places the Noix Oolite is fossiliferous, with brachiopod, gastropod, echinoderm, bivalve, and trilobite bioclasts being most common (Savage, 1908; Rubey, 1952; Amsden, 1974). Condition of brachiopod shells in the southernmost oolite suggested a moderate-energy depositional environment to Amsden (1974). Cross-bedding and oolitic intraclasts indicate moderate- to high-energy conditions for the westernmost occurrence as well.

NEDA FORMATION

The ferruginous oolitic Neda Formation occurs at the Ordovician-Silurian boundary in northern Illinois and surrounding states (fig. 1). It is best exposed in old iron mines at its type locality near Neda, Dodge County, Wisconsin. Limited occurrences have been reported elsewhere in Wisconsin (Rosenzweig, 1951; Synowiec, 1981; Mikulic and Kluessendorf, 1983), northeastern Iowa (Brown and Whitlow, 1960; Whitlow and Brown, 1963; Parker, 1971; Witzke and Heathcoate, 1983), northern Illinois (Workman, 1950; Synowiec, 1981), Indiana (Gray, 1972) and Michigan (Nurmi, 1972).

Throughout the region, the Neda occurs as widespread lenticular bodies of differing lateral extent and thickness. The thickest (16.5 m) Neda was reported from the subsurface of Manitowoc County, Wisconsin (Fuller and San-

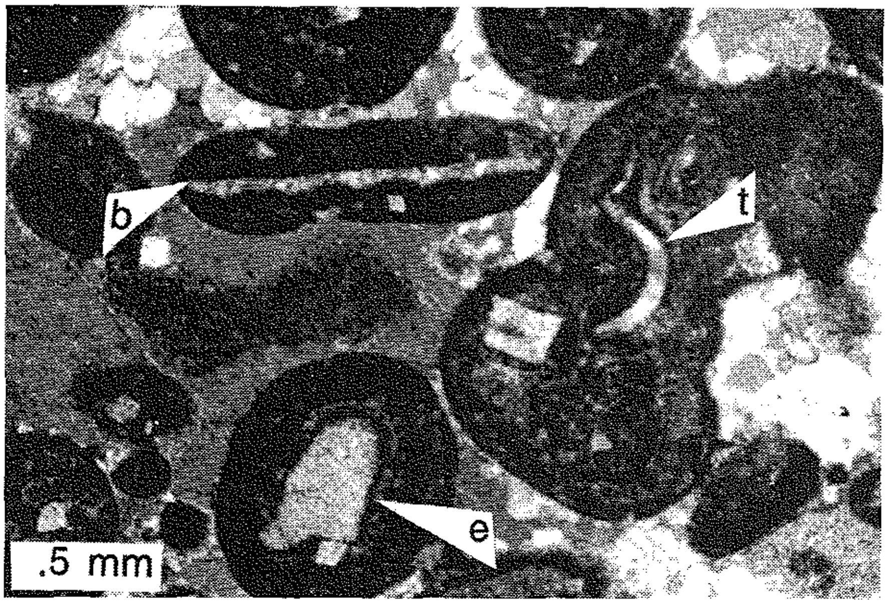

Figure 4. Photomicrograph of the Noix Oolite from the Clarksville Roadcut (see fig. 3). Poorly-sorted calcite ooids with concentric cortical layers in sparry calcite cement. Ooid nuclei include: brachiopod (b) trilobite (t) and echinoderm (e) fragments; however, nuclei are not always apparent. Euhedral dolomite rhombs scattered throughout. Observe nonspherical ooid shapes, large composite ooid on right, and amount of micritization which obscures ooid fabric. Crossed nichols.

ford, 1906; Thwaites, 1923), but the unit is generally much thinner. Although inIllinois it reportedly (Willman and Buschbach, 1975) ranges from zero to 3.0 m in thickness, as much as 9.0 m occurs in the subsurface of Whiteside County.

Contact between the Neda Formation and the underlying upper Ordovician Brainard Shale (fig. 5), typically a greenish gray mudstone, has been interpreted variously as gradational (Synowiec, 1981), conformable but sharp (Willman and Buschbach, 1975) and unconformable (Savage and Ross, 1916). Kolata and Graese (1983) observed a discontinuity in the gamma ray curve between the Brainard and the Neda, with an even greater discontinuity occurring between the Neda and overlying Silurian rocks.

Although the Neda-Brainard contact is relatively planar, evidence for a break in deposition exists. The locally phosphatized, burrowed, irregular surface of the Brainard and common phosphatic nodules at the contact indicate a period of nondeposition. Rarely, a basal conglomerate of iron-encrusted green siltstone pebbles and cobbles occurs just above the contact. In some places, especially in Illinois and Indiana, a greenish mudstone that resembles the Brainard Shale, but which could be Silurian in age, succeeds the Neda Formation.

A prominent unconformity with as much as 0.6 m of relief separates the Neda Formation from overlying lower Silurian carbonate rock, generally beloning to the Kankakee Dolomite (fig. 5). The Kankakee Dolomite is in the Llandoverian upper *Icriodina irregularis* conodont zone (Liebe and Rexroad, 1977). Basal Silurian strata typically are iron-stained, and may contain phosphatic nodules and reworked ferruginous ooids. The earlier Llandoverian (lower *Icriodina irregularis* zone) Wilhelmi and Elwood formations (fig. 5) generally are absent where the Neda Formation is present. A thin sequence of these units was reported overlying the oolite along the Kankakee River (Willman, 1972; Willman and Buschback, 1975). Although these strata are similar lithologically to those units, they may not be coeval. The Wilhelmi and Elwood sediments generally fill low areas on the Maquoketa surface, but the Neda Formation typically occurs only on local Maquoketa highs; the presence of the Wilhelmi and Elwood above the Neda is inconsistent with these facts. Also, Liebe and Rexroad (1977) did not find the lower *Icriodina irregularis* conodont fauna in these strata. The lower Silurian sequence from the base of the Joliet Dolomite down to the top of the Neda in this area is exceptionally thin, probably due to a thicker underlying Maquoketa.

Age of the Neda Formation is not known with certainty. In Wisconsin, where it first was recognized, the Neda originally was considered "Clinton" (middle Silurian) in age because of its lithologic similarity to the oolitic Clinton Iron Ore of New York (Hall, 1851). Chamberlin (1877) collected late Ordovician marine macrofossils from the Neda at Iron Ridge, Dodge County, Wisconsin, but he thought that they had been reworked from underlying Ordovician mudstone and stained with iron. It became apparent that the Neda no longer could be assigned to the "Clinton" after Savage (1916) recognized that overlying strata were "Alexandrian" (early Silurian) and, therefore, older than the Clinton of New York. Savage and Ross

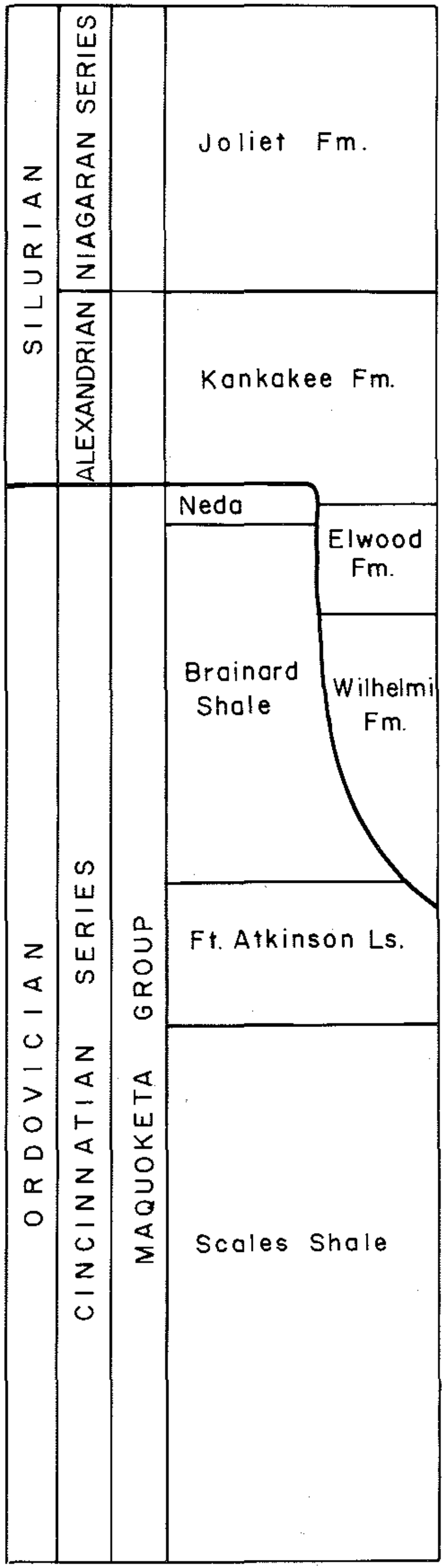

Figure 5. Stratigraphic relationship of strata contiguous to the Ordovician-Silurian boundary in northern Illinois in the area of ferruginous Neda Formation occurrence.

(1916), who named the unit the Neda Iron Ore, found late Ordovician macrofossils at Katell Falls, Dodge County, Wisconsin. Ulrich (1924) assigned the unit to the Maquoketa Group, and it is considered the uppermost Maquoketa unit in Iowa (Brown and Whitlow, 1960; Whitlow and Brown, 1963), Illinois (Templeton and Willman, 1963) and Indiana (Gray, 1972). Athy (1928) correlated the Neda with the Noix Oolite of Missouri because both were oolitic and occurred in the same stratigraphic position. Workman (1950) was the first to correlate the ferruginous oolite in Illinois with the Neda Iron Ore of Wisconsin. He also found that the insoluble residues in the Neda are similar to those of the underlying Ordovician rocks, but differ markedly from those in the overlying Silurian. Nevertheless, Workman assigned the unit to the Silurian because that is the age of the ferruginous oolites in the eastern United States. Ostrom (1967) considered the age of the Neda in Wisconsin as inconclusive.

The Neda Formation is distributed sporadically, both locally and regionally, throughout northern Illinois (fig. 1), cropping out only in southern Will County, where it was first reported by Savage (1916). Although the Neda is present in the subsurface over a wide area of the northern part of the state, most known occurrences are in the northeastern corner, possibly due to a sampling artifact (Kluessendorf, 1989). Workman (1950) thought that the unit had been more widespread but had been eroded prior to "Edgewood" (Silurian) deposition.

The Neda Formation was reported to occur only where the underlying Maquoketa Group is thickest locally and where basal Silurian strata are thin or absent (Brown and Whitlow, 1960; Whitlow and Brown, 1963; Buschbach, 1964). This relationship is generally true, but does not hold for all cases because in closely-spaced wells in Cook and Lake Counties the Neda occurs where the Maquoketa is not at its thickest.

The Neda Formation is lithologically diverse. Basal strata in Illinois typically are blackish red hematitic and dolomitic mudstone containing scattered matrix-supported goethitic ooids. Similar mudstone occurs in Iowa and at the base of the unit in Wisconsin. In Wisconsin, however, several feet of relatively pure grain-supported goethitic oolite overlies this mudstone, but it is not found in thinner sequences elsewhere. Rosenzweig (1951) reported ripple marks, cross-bedding and mudstone intraclasts in the Wisconsin oolite. At the type locality, the oolite is capped by a dense, hard layer of hematite as much as 0.3 m thick, suggesting a laterite to Synowiec (1981). Above the basal mudstone in Illinois the Neda varies lithologically among dolomitic siltstone, mudstone and micrite, which are oolitic and ferruginous to differing degrees. Most of these strata are somewhat silty, containing subangular to angular quartz grains. The clay fraction consists primarily of chlorite and illite. Tourmaline, potassium feldspar and glauconite grains are minor constituents of some strata. Phosphatic nodules are common in places and locally mark both the top of the Neda and the Brainard Shale.

X-ray diffraction analysis reveals that goethite is the dominant iron mineral in both the ooids and matrix of the Neda Formation, imparting the characteristic reddish brown coloration. Hematite is less abundant, and siderite is the major iron mineral at only one locality, although it occurs in minor amounts elsewhere. Chamosite is very rare.

Smooth oblate ferruginous ooids with concentric cortical layers characterize the unit (fig. 6). Ooid shape and size, averaging 0.75 mm in diameter (Workman, 1950), are quite uniform. Some ooids apparently lack nuclei, possi-

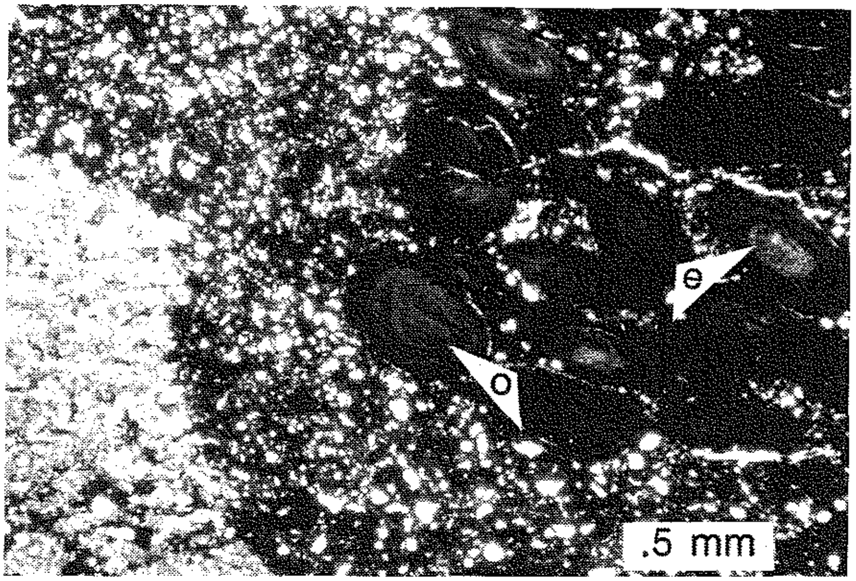

Figure 6. Photomicrograph of the Neda Formation from Chippewa Campground, Kankakee River State Park, Will County, Illinois (see Kuessendorf, 1991). Oblate goethitic ooids in burrow-fill within ferruginous siltstone. Ooids are concentrically layered; nuclei include: broken ooids (o); echinoderm fragments (e) and siltstone grains. Observe that ooids are packed in approximately parallel alignment. Plane light.

bly as a result of complete ferruginization of lithic or fossil nuclei, ferruginization of micritized nuclei, or the angle of cut in the thin section. Other ooids show nuclei of ooid fragments, phosphatic grains, quartz grains, fossil fragments (especially echinoderms and triaxon sponge spicules) and lithic fragments (including volcaniclastics). All originally calcareous fossil nuclei and bioclasts scattered throughout the matrix have been either ferruginized or phosphatized to some degree. Most of the ooids are goethitic, rarely sideritic or calcitic. In places, some of the ooids are reciprocally deformed, and fracturing and spalling of the cortical layers produced rare spastolithic texture. Lithic superficial ooids, typically composed of siltstone, occur. Oomoldic porosity is very common in certain strata. workman (1950) reported that ooids in the upper part of the Neda had lost iron content during pre-Silurian weathering and are preserved as illite.

TRANSITION OOLITE

Synowiec (1981) reported calcite ooids from the Neda Formation in Illinois; however, reexamination of the same outcrops and thin sections showed that these are actually oomoldic pores filled with blocky calcite cement. Calcite ooids do occur, however, at one other locality not examined by Synowiec. At this site most of the exposed Brainard Shale is a typical dolomitic siltstone that has been slightly sideritized; however, the uppermost few inches of Brainard have been strongly sideritized (fig. 7, 8). Phosphate-filled burrows and phosphatic nodules on the Brainard surface enclose spherical, concentrically-layered, calcite ooids, some of which have been incipiently phosphatized

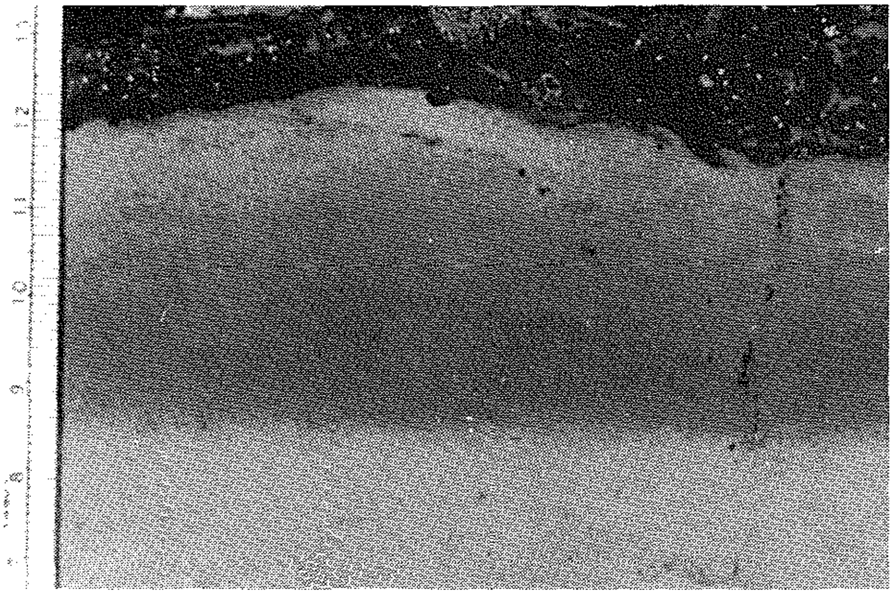

Figure 7. Polished slab from transition oolite (see Kluessendorf, 1989) showing phosphatized Brainard Shale surface (darkest) with calcite ooids in phosphatic nodules and burrow-fills. Rest of Brainard in photo is sideritic siltstone, more weakly sideritized downwards. Scale in mm.

(fig. 8, 9). This surface is overlain by an oolite composed of subspherical, concentrically layered, sideritic ooids that pass upwards into oblate, and even spastolithic, concentrically layered, goethitic ooids typical of the Neda Formation elsewhere (fig. 10). This transition is gradational over a thin stratigraphic interval (25.4 cm).

RED STRATA AT TOP OF THE MAQUOKETA GROUP

In northeastern Illinois the Neda Formation occurs within a broader area where red mudstone is present at, or slightly below, the top of the Maquoketa Group (fig. 1). Workman (1950) observed that this mudstone occurs only where the Maquoketa Group reaches a thickness of 58-76 m. Temporary exposures in 1979-1980 at the Hillside quarry, near Chicago, demonstrated that some of this red-colored strata is otherwise lithologically indistinguishable from contiguous green Brainard Shale (D.G. Mikulic, 1979, oral communication). In this quarry a large semi-elliptical patch of red mudstone along one wall extended down into the typical green Brainard mudstone from just beneath the top of that unit (fig. 11). The boundary of this patch cut sharply across bedding within the Brainard without affecting other characteristics of the unit, indicating that it represented just a difference in color. X-ray diffraction analysis of the red mudstone showed it to be identical in composition to the green mudstone except for very minor hematite content that imparted the reddish coloration.

In the past, any red-colored lithology at the top of the Maquoketa Group was considered part of the Neda Formation, whether or not ooids were present (Buschbach, 1964; Willman and Buschbach, 1975). The Hillside quarry exposure,

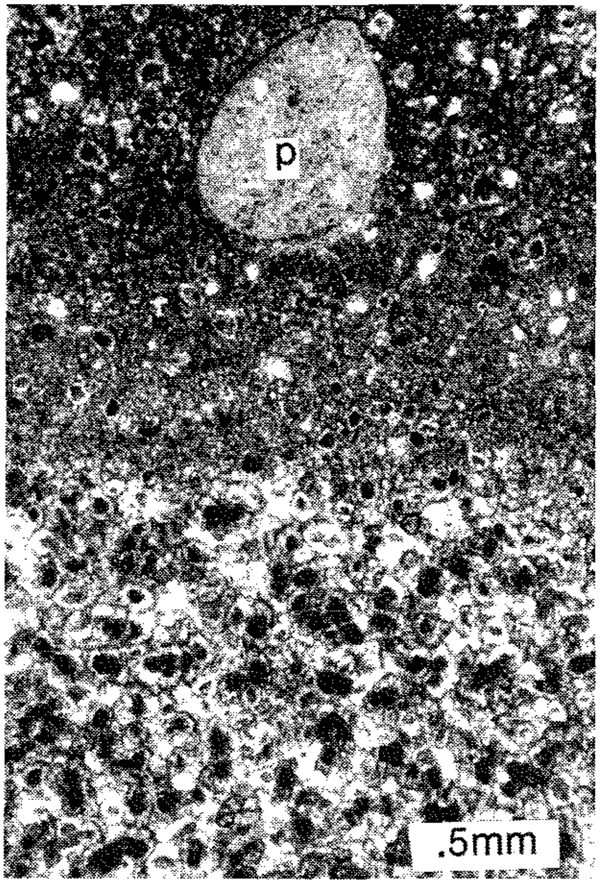

Figure 8. Photomicrograph of the top of the Brainard Shale at the transition oolite showing sideritic siltstone phosphatized in upper half of photo. Phosphatic nodule (P) contains no ooids. Crossed nichols.

however, clearly showed that large areas of the Brainard Shale were stained red post-depositionally, and that these red strata are unrelated depositionally to the Neda Formation. Reddish strata, some nonoolitic, are common in the Neda and, therefore, caution must be exercised when logging cores and well cuttings. Unless stratigraphic relationships are explicit, red strata at the top of the Maquoketa that lack ooids should not be assigned to the Neda in such samples. Nonoolitic red strata occurs at the top of the Ordovician in scattered subsurface localities to the south and west also (fig. 1). Red mudstone in well cuttings from Edgar, Fayette and Moultrie Counties, however, is quite dissimilar to either red Brainard Shale or red Neda Formation, and may have been caved from overlying Carboniferous strata in the well.

DEPOSITIONAL ENVIRONMENTS

During the Ordovician and Silurian Illinois was situated in the interior of the Laurentian continental plate, and was located at low southern (10-20°) latitudes (Ziegler and others, 1979). Warm shallow seas covered much of the area, and arid conditions prevailed at about 20° north and south latitudes during the Ordovician. The eastern border of Laurentia was tectonically active for some of that time (Taconic Orogeny)(Bambach and others, 1980), and may have

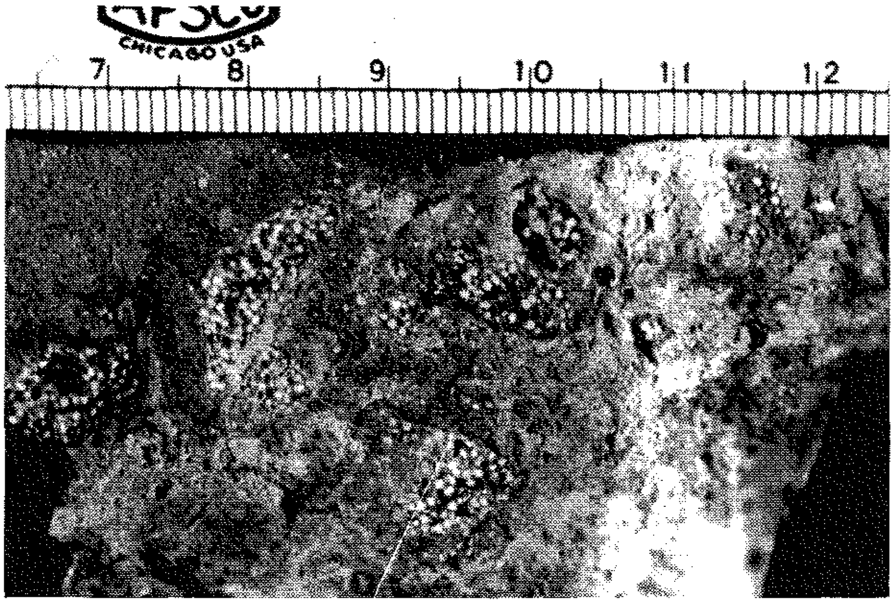

Figure 9. Slab from top of the Brainard Shale at the transition oolite showing spherical calcite ooids (white) and oomoldic pores (black) concentrated in phosphatic nodules and phosphatized burrow-fills. Scale in mm.

been the source of some fine-grained detritus to the Illinois area. Beginning in the middle Ordovician, the Gondwanan continental plate, which was located near the South Pole, underwent glaciation (Ziegler and others, 1979). A major transgression followed the melting of the Gondwana ice cap during the Llandoverian (Sheehan, 1973).

The Maquoketa surface in northeastern Illinois is deeply dissected, probably as a result of emergence and erosion following the major Ashgillian regression. Topographic relief on this surface is as much as 45 m (Kolata and Graese, 1983), and, in general, the Neda Formation occurs only where the Maquoketa is thickest locally (Workman, 1950; Buschbach, 1964). It is uncertain whether the Neda is related depositionally to these topographic highs, or whether it was deposited prior to the erosion that dissected the Maquoketa surface and only remnants of the Neda are preserved. Such relief can promote shoaling conditions that favor oolite development; however, Harris (1979) observed that calcareous oolite forming in the Bahamas today may occur as extensive lateral deposits, not just as banks and bars. The lenticular nature of the Neda Formation deposits suggests either accumulation on shoals or in hollows or erosional remnants of once more extensive deposits.

Little is known about the Maquoketa topography or morphology of the Noix Oolite deposits in southern Illinois, although the oolite appears to occur primarily as lenticular bodies. D.G. Mikulic (1983, oral communication) observed that the Noix generally is succeeded by pure carbonates, but where the Noix is absent the Maquoketa is overlain by argillaceous carbonates. This relationship suggests that the sub-oolite topography in southern Illinois resembles that of northern Illinois where the thinner sequences of Maquoketa (eroded valleys) are overlain by argillaceous carbonate, but the Neda oolite, located on Maquoketa highs, is overlain by pure carbonate.

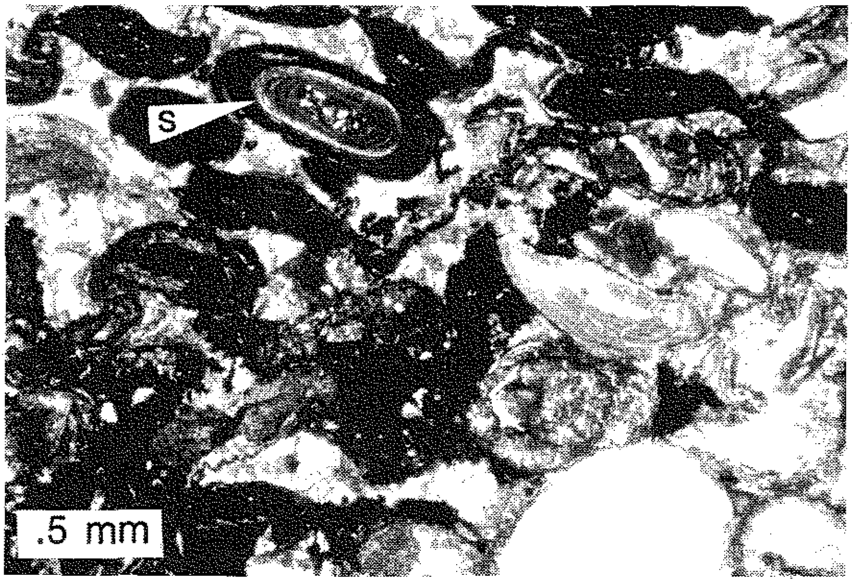

Figure 10. Photomicrograph of transition oolite showing sideritic (lighter colored, generally subspherical) ooids at lower right and oblate to spastolithic ooids at upper left. Best-formed goethitic ooid has a siltstone nucleus (s). Plane light; thin section cut somewhat thicker than normal.

Figure 11. Large semi-elliptical patch of red mudstone within typical green mudstone near the top of the Brainard Shale formerly exposed in the Hillside quarry near Chicago, Cook County, Illinois. Red color is imparted by minor amount of hematite. Observe that red coloration cuts sharply across bedding in normal green (lighter) mudstone and that the red mudstone patch is overlain by thin interval of normal Brainard. Bulldozer at left for scale. Photo courtesy of D.G. Mikulic, 1979.

The Noix Oolite is thought to have formed under normal-marine, shallow-water, moderate-energy conditions (Amsden, 1974), but the depositional environment of the Neda Formation, and oolitic ironstones in general, is controversial. DuBois (1945) and Synowiec (1981) suggested that the Neda Formation is a residual, probably lateritic, deposit of Maquoketa sediment. Athy (1928) invoked alteration of an originally calcareous oolite by a solution of silica, iron and aluminum hydroxide in a littoral setting; he inferred that the underlying impervious mudstone favored such a reaction with groundwater. Paleomagnetic studies of the Neda demonstrated a Permian paleopole position, which was attributed to Permian tectonism (Kean, 1981). Kean (1981) suggested that the Neda formed in two stages with the ooids forming first and later being incorporated into iron-rich muds.

Ferruginous ooids in the Neda Formation appear to have been transported and mixed with other sediments as suggested by the diversity of lithologies through which they are scattered. Some mixing may have been accomplished by bioturbation as many strata are bioturbated and commonly burrows are filled with ooids (fig. 6). In Illinois the oolite is relatively matrix-free at only one locality, and nowhere in Illinois or Iowa does a pure grain-supported oolite occur like the one at the type locality in Wisconsin. The Wisconsin oolite may represent a shoaling environment in which the oolite developed, whereas most other Neda occurrences represent allochthonous ooid deposits. The abundantly oolitic deposits may represent shoals near the paleoshoreline as they occur as lenticular bodies with a patchy distribution and are located near the Wisconsin uplands, which may have been emergent some of that time.

Dreesen (1982) reported ferruginous ooids from the Devonian of Belgium that had been transported offshore from high-energy shoals by storm waves. These allochthonous ooids occur in a variety of red-colored sediments at several stratigraphic levels, often above hardgrounds. Dreesen inferred that during periods of emergence, iron minerals replaced the original calcareous ooids; this interpretation is supported by ferruginization of associated calcareous bioclasts. Harris (1979) reported that modern calcareous ooids can become mixed with other sediments by bioturbation. Petranek (1969) attributed the Early Paleozoic oolitic ironstones to deposition in a shallow-marine environment, citing as evidence the lenticular shape of the deposits, paleogeographic position near to shorelines, lack of stratificiation within the oolites (implying constant agitation and reworking by currents) and the presence of broken ooids as nuclei.

The transitional calcite-siderite-goethite oolite suggests a possible link between the calcareous Noix Oolite and the ferruginous Neda Formation oolite, and may provide insight into the origin of oolitic ironstone. The compositional transition of this oolite may be a result of environmental fluctuations related to sea level changes. The uppermost Brainard Shale is strongly sideritized and phosphatized indicative of reducing conditions. Reducing conditions, restricted circulation, and presence of abundant organic matter during periods of nondeposition favor phosphate formation in shallow marine environments (Bromley, 1967; Bentor, 1980; Odin and Letolle, 1980; Birch, 1979). Mud solutions in hollows between shoals are especially rich in dissolved phosphates (Bushinski, 1964), and phosphatization typically originates in burrow-fills or on a calcite framework (Pedley and Benent, 1985). The Brainard-oolite contact at this locality is marked by a phosphatic zone, including phosphatic burrow-fills and nodules that enclose calcite ooids. Some of the ooids are incipiently phosphatized and may have acted as a framework for phosphatization. Calcite ooids preserved in the phosphatic nodules and burrows are concentrically layered and spherical, which suggests they were deposited as part of a normal-marine calcareous oolite, perhaps formed during a major transgressive episode. These ooids may have been transported intermittently from nearby shoals into this area. As ooid accumulation continued, phosphatization was inhibited. Subsequent reducing conditions caused sideritization of the oolite not protected by phosphatization. Later, the uppermost oolite was oxidized and ooids were altered to goethite. Ooid distortion must have accompanied alteration to iron minerals, eventually resulting in the oblate shape characteristic of ferruginous ooids like those in the Neda Formation. Following a period of erosion, an early Silurian marine transgression deposited relatively pure carbonates over the oolite.

Source of the iron in the Neda Formation and the transition oolite is unknown. Templeton and Willman (1963) suggested that the Queenston Delta to the east supplied the iron. Hawley and Beavan (1934) and Kean (1981) invoked the weathered Precambrian granitic terrain to the northwest as the source.

SUMMARY

The calcareous and ferruginous oolites at the Ordovician-Silurian boundary in Illinois correspond to the geographic distribution pattern observed by Mikulic (1979, 1983) in the central United States. Despite the mineralogical differences, both oolite types share similar characteristics: patchy geographic distribution, lenticular deposits, stratigraphic position, lithologic sequence, marine fauna, and possibly age.

A transition oolite occurs in northeastern Illinois at a geographic position somewhat intermediate between the two main oolite types. Spherical concentrically layered calcite ooids, similar to those in the Noix Oolite, are preserved in phosphatic nodules and burrow-fills at the base of the oolite. As ooids accumulated and environmental conditions changed, calcareous ooids not preserved in phosphate were altered to siderite and goethite, taking on the oblate shape of ferruginous ooids in the Neda Formation. Because study of this transition oolite is still in a preliminary stage, the possibility that these calcite and siderite ooids are replaced chamositic ooids cannot yet be totally discounted.

The transition in mineralogic composition and shape of the ooids in this oolite suggests that at least some of the oolitic ironstones, such as the Neda Formation, may be ferruginized calcareous oolite. Evidence that suggests the Neda may represent replaced calcareous sediments include: ferruginized originally calcareous marine fossils; type of nuclei and internal ooid structure comparable to the calcareous Noix Oolite; sedimentary structures such as cross-bedding and ripple marks; lithoclastic superficial ooids; lenticular shape of deposits; type of bioturbation; and grain-supported texture of some of the occurrences where transportation is not indicated. These features agree in part with the eluviation-replacement model for the origin of oolitic ironstones proposed by Kimberley (1979), although the overlying leached muds necessary for iron replacment are not present.

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GENESIS OF THE UPPER ORDOVICIAN NEDA FORMATION IN EASTERN WISCONSIN

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ABSTRACT

The Upper Ordovician Neda Formation is a hematitic oolite which occurs sporadically at the Ordovician-Silurian boundary in eastern Wisconsin and adjacent areas. The only surface exposures of the formation in Wisconsin are near the Village of Neda, Wisconsin and at Katells Falls, near De Pere, Wisconsin, and both were studied during this project.

Interbedding of the Neda with the underlying Upper Ordovician Maquoketa indicates that initial accumulation of Neda ooids was concurrent with final stages of Maquoketa deposition. Ooid formation began on local shoal areas in response to latest Ordovician glacioeustatic lowering of sea level.

An Late Ordovician age assignment for the Neda is supported by a new fossil collection from Katells Falls. The ferruginized fossils are well preserved, and even the most fragile forms show no evidence of reworking.

Previous investigations provide hypotheses for the genesis of the Neda Formation. These include: (1) in-situ formation of ferruginous pisoids within a paleosol, (2) direct precipitation of iron-rich ooids from seawater, (3) replacement of calcareous ooids by iron compounds, and (4) mechanical accretion of iron minerals to form primary ferruginous ooids.

The tangential-concentric microstructure of Neda ooids, as disclosed by the scanning electron microscope, is different from that of bauxite/-laterite pisoids, and indicates they did not grow in-situ within a paleosol. Direct precipitation of iron ooids is not geochemically feasible.

The deposition and subsequent leaching of iron-rich silt and clay overlying the Neda Formation could result in ferruginization of an underlying calcareous oolite. Our analysis, however, failed to establish the existence of appropriate sediment of suitable thickness in eastern Wisconsin during latest Ordovician-earliest Silurian time. The occurrence of calcareous oolites at about the same stratigraphic position elsewhere in the Midcontinent and ferruginized macrofossils suggests an original calcareous deposit was replaced by iron. Although the mechanical accretion of iron minerals is not ruled out, we consider it a less attractive theory than replacement. Hence, the mechanism and timing of replacement remains unresolved.

Localized accumulation of ferruginous silt and clay resulted in the formation of a thin, dense, iron-rich layer at the top of the Neda Formation at the type area. Transgression of the Early Silurian sea over an irregular Ordovician surface resulted in deposition of the Mayville Dolomite prior to

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complete lithification of the Neda. Following lithification of the Mayville, gentle structural warping exaggerated irregularities on the Neda surface.

INTRODUCTION

The Upper Ordovician Neda Formation (or Member of the Maquoketa Shale in adjacent states) is a hematitic oolite, which occurs sporadically at the Ordovician-Silurian boundary in eastern Wisconsin, northern Illinois, eastern Iowa, northern Indiana, and in the subsurface of southern Michigan, northwestern Missouri, and southeastern Nebraska. In Wisconsin, the Neda is reported from only six surface and subsurface localities (Percival, 1855; Chamberlin, 1883; Thwaites, 1914, 1923; Alden, 1918; Rosenzweig, 1951) (fig. 1). Mikulic (1979) and Mikulic and Kluessendorf (1983) suggested that hematitic oolite-bearing red shale at several subsurface localities in Milwaukee and Racine counties occupy the stratigraphic position of the Neda (fig. 1). If subsequent work substantiates this interpretation, Michael G. Mudrey, Jr. (verbal communication, 1987) indicated that additional occurrences are present in wells from Racine County.

Surface exposures in Wisconsin are currently limited to a complete section at Katells Falls near De Pere and an incomplete sequence at the type area of the formation in an abandoned mine pit near Neda. Although both exposures were studied by a number of geologists during the past 136 years, uncertainty still exists regarding the age, depositional environment and stratigraphic relations of the Neda. New information from field and laboratory investigations based on the two surface exposures is used to reinterpret the depositional environment of the Neda Formation in eastern Wisconsin, and to clarify stratigraphic relations with the underlying Upper Ordovician Maquoketa Shale and the overlying Lower Silurian Mayville Dolomite.

PREVIOUS INVESTIGATIONS

Nomenclature and Age

The first reference to strata now called Neda in Wisconsin was made by James Hall in 1851. Lithologic similarity of these to the Middle Silurian Clinton iron ore of New York led Hall, and subsequently Whittlesey (1852) and Hall and Whitney (1862), to assume equivalency in age and nomenclature. Later workers accepted this conclusion (Chamberlin, 1878, 1883; Thwaites, 1914; Alden, 1918) until Savage and Ross (1916) discovered Late Ordovician (Richmondian) ferruginized fossils at Katells Falls from the unit they termed the Neda iron ore. This name was subsequently modified to Neda Formation by Thwaites (1923), and it is probable that Thwaites considered the Neda as a formation within the Richmond Group (Maquoketa).

Ulrich (1924) also recognized a genetic relationship between the Maquoketa Shale and the Neda in Wisconsin, and he clearly assigned the latter as a formation at the top of the Maquoketa Group. A similar approach was followed by Whitlow and Brown (1960) in eastern Iowa, and Willman and others (1975) in northern Illinois. Ostrom (1967) also assigned formational status to the Neda in Wisconsin, but he did not include it as part of the Maquoketa. The formation was assigned an uncertain age of Late Ordovician or Early Silurian (Ostrom, 1967).

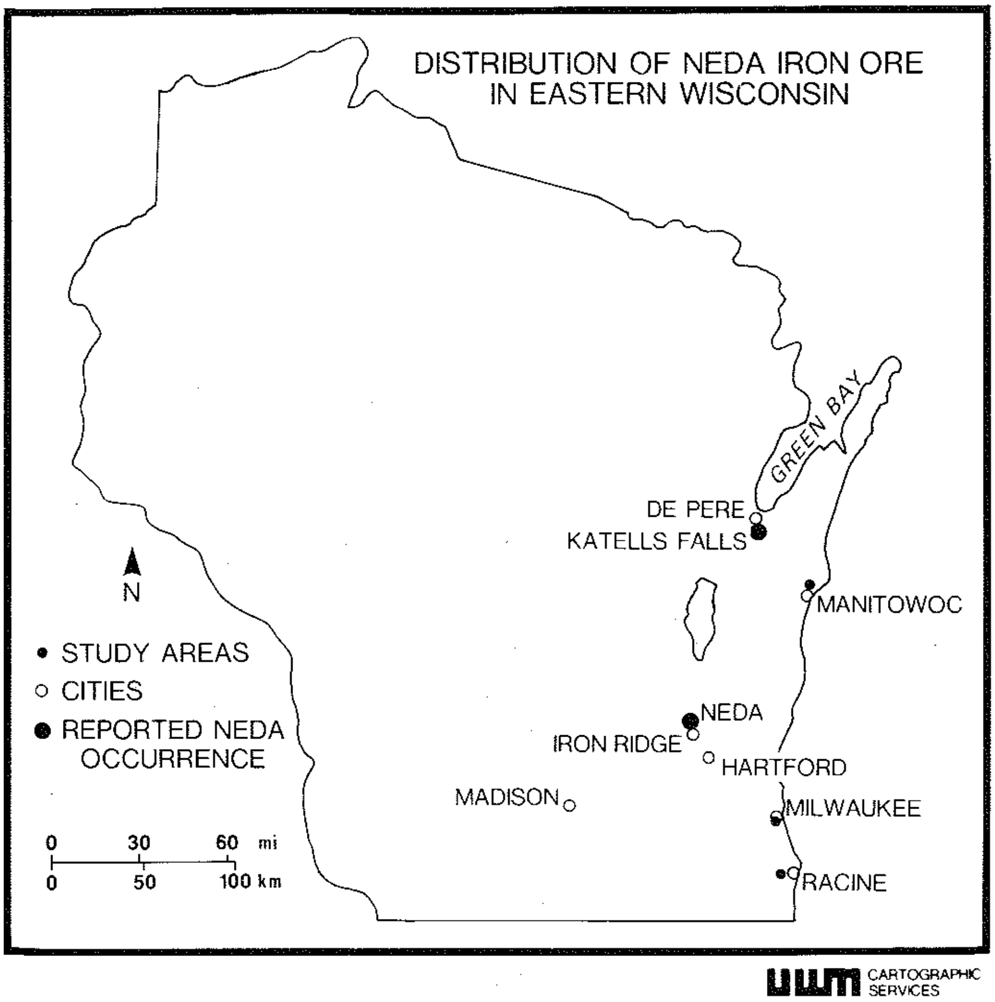


Figure 1. Study areas and other Neda occurrences.

Distribution and Thickness

The maximum reported thickness for the Neda is 16.7 m in the subsurface at Manitowoc, Wisconsin (Thwaites, 1914). Approximately 6.4 m is present in the abandoned Northwestern Milling Company open pit mine near Neda, although the lower 3 m is now covered. Exposures adjacent to the open pit are discontinuous, but persist for about 2 km to the south. At Katells Falls, 1.8 m of Neda is present, and the lateral extent of the exposure is limited to about 9.1 m .

The Neda is characterized by abrupt changes in thickness over extremely short distances. Figure 2 is an isopach map of this unit based on mining company information in the vicinity of, and including, the abandoned open pit mine near Neda. As shown, the formation consists of several northeasterly trending bodies of limited extent with a maximum thickness of 11.2 m (Rosenzweig, 1951).

The Neda area was mined from 1849 to 1928; initially by removing the Silurian dolomite escarpment, later by underground workings (now closed), and finally at the flooded pit that exists today. Mikulic (1979) and Mikulic and Kluessendorf (1983) provided a detailed summary of mining activity.

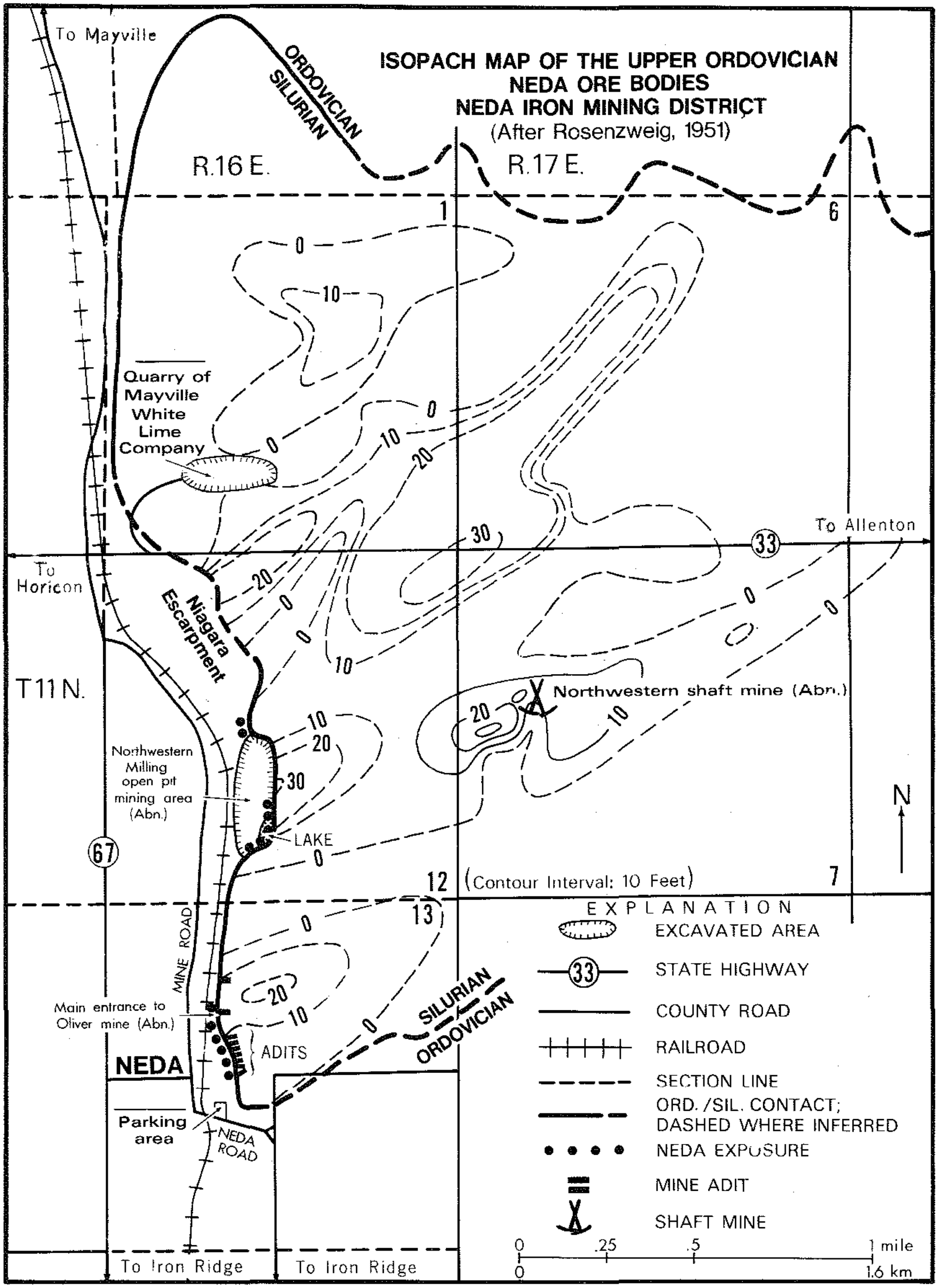


Figure 2. Isopach map of the Neda Formation at the type area near Neda, Wisconsin (modified from Rosenzweig, 1951; and Paull, 1977, p. C-2.

Stratigraphic Relations

Early acceptance of a Middle Silurian age for strata now known as Neda required that an unconformity be placed at the base of the formation to separate it from the Upper Ordovician Maquoketa Shale (Hall, 1851). Furthermore, conformable relations with the overlying Mayville Dolomite were favored by this age assignment.

Although the recovery of Late Ordovician fossils from the Neda resolved some stratigraphic relations, the nature of the upper and lower contacts was still open to interpretation. Savage and Ross (1916) placed an unconformity at the top of the ore body to account for the newly recognized time gap. They also put an unconformity at the base of the Neda because the formation rested on different levels of the Maquoketa. This relationship was previously described by Chamberlin (1878, p. 327) when he noted that the Maquoketa "...mingles somewhat with the lower layers of the iron deposit, the ore 'takes on' layers at the bottom...". In the study area, the Maquoketa is a grayish-olive, fissile shale with a concentration of invertebrate fossils within thin, interbedded limestones.

Rosenzweig (1951) recognized gradational relations between the Neda and the Maquoketa, but he also reported reworked Maquoketa Shale fragments within the basal Neda Formation. He concluded that: (1) the sporadic distribution of the Neda resulted from accumulation in localized basins on the Maquoketa surface, and (2) the Neda-Mayville contact was unconformable.

The Lower Silurian Mayville Dolomite within the study area is a grayish orange, massive- to thin-bedded dolomite with minor amounts of nodular chert. The Mayville commonly has a vuggy texture and contains a sparse fauna. The lowermost 0 to 2.7 m of Mayville at the type locality of the Neda, however, contains *Favosites sp.*, *Halysites sp.*, zaphrentid corals, trilobites, conodonts, and variable amounts of fossil debris in association with stromatolitic structures. Earlier workers referred to this local unit as "nodular," "conglomeratic," or "reefal" Mayville (Ulrich, 1914, unpublished field notes; Shrock, 1930, unpublished field notes).

Lithologic Character

The dominant Neda lithology consists of poorly indurated hematite- and goethite- rich ooids within a matrix of hematitic silt (fig. 3). Many ooids are deformed into oblate spheroids or oblate ellipsoids oriented parallel and subparallel to bedding. Fractured ooids are also common. Spherical and nearly spherical ooids are present, but in less abundance than deformed ooids. The ooids have a varnished appearance that suggested polishing during transport by waves or currents (Paull, 1977). We attribute the shiny appearance to a concentration of crystalline apatite at the outer surface. Concentric laminae within the ooids consist of hematite, goethite, and clay minerals (Hawley and Beavan, 1934; Synowiec, 1981). Ooid nuclei are often unrecognizable, fine-grained, hematite replacements, but others consist of quartz grains, ferruginized fragments of broken ooids, or fossil fragments (fig. 4).

Rosenzweig (1951) studied the entire Neda sequence in the type area. He reported that the lowermost 0.9 m of the Neda differed from the overlying soft oolitic ore in that it consisted of brownish shale with shiny iron-stained pebbles containing flattened ooids. He also observed an upward in-

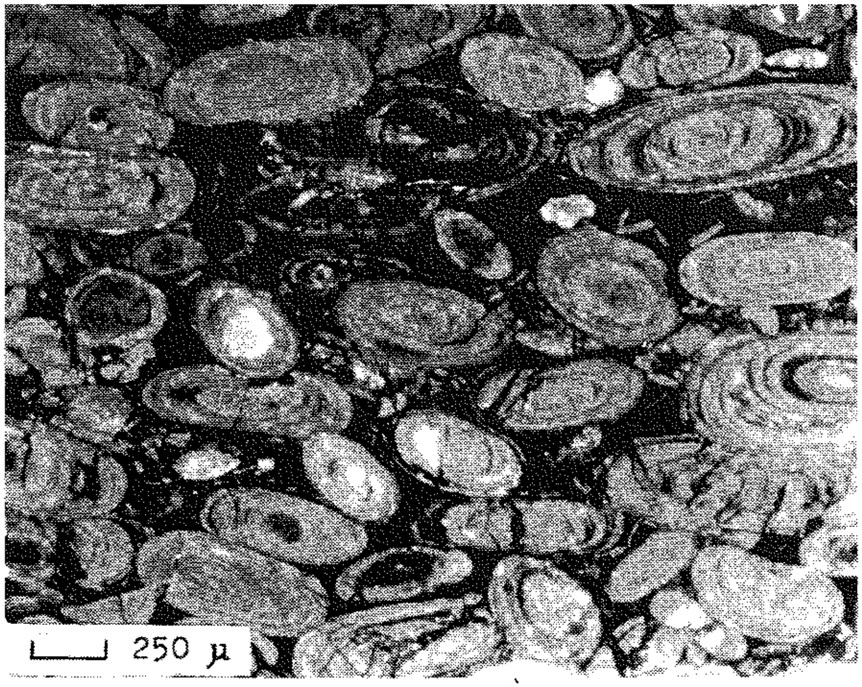


Figure 3. Photomicrograph of the soft, oolitic part of the Neda Formation at the type locality. The highly deformed, often fractured, ooids are oriented sub-parallel to bedding. Thin section is normal to bedding. Uncrossed nicols; white bar is 250 microns.

crease in the abundance of ooids from their first appearance along bedding planes in the uppermost Maquoketa. At the type locality, the uppermost 15 to 30 cm of the Neda is composed of dense hematite containing few ooids.

At Katells Falls, the Neda is generally similar in lithology to the type locality with some important differences. These are described in a following section.

Depositional Environment

Several different interpretations were proposed to explain the localized distribution of the Neda and the genesis of the ferruginous ooids, but most can be assigned to one of three basic mechanisms. The first model envisions the Neda as a widespread deposit with subsequent erosion causing limited distribution (fig. 5A). Alden (1918) proposed this interpretation, but it attracted few other adherents in Wisconsin.

A second interpretation involves the accumulation of ooids in isolated basins on an irregular Maquoketa surface (fig. 5B). Ooids either formed in the basins, or were transported from higher energy areas considered more suitable for ooid formation. Chamberlin (1878) first suggested this possibility, but he believed ooid deposition occurred during the Silurian transgression. Savage and Ross (1916), Alden (1918), Hawley and Beaven (1934), and Rosenzweig (1951) favored Chamberlin's (1878) concept of Neda deposition, but not necessarily his timing.

The formation of ooid bars in favorable areas as the Maquoketa sea shoaled is another possible explanation for the Neda (fig. 5C). Paull (1977) suggested that ooid formation was probably concurrent with deposition of the

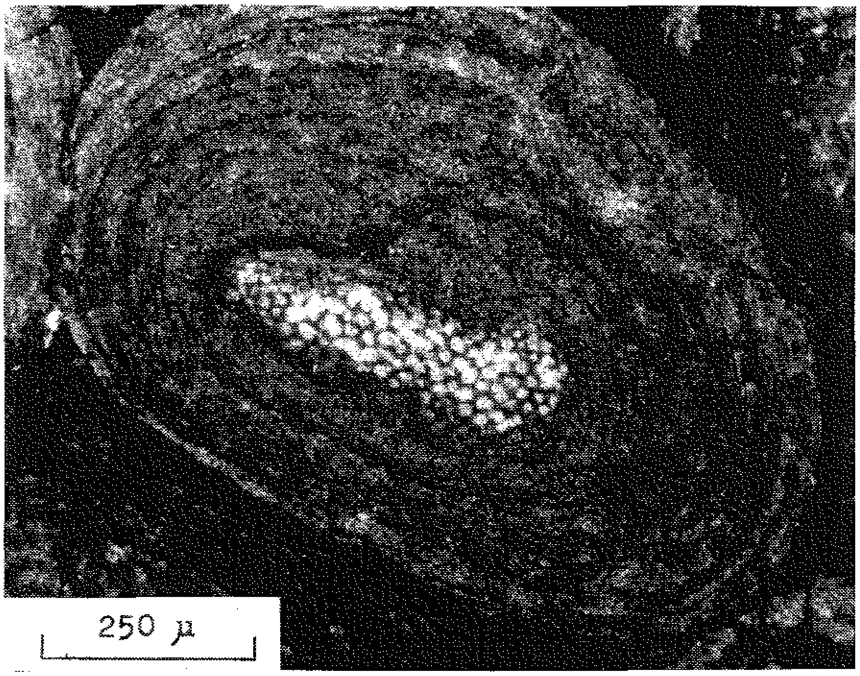


Figure 4. Photomicrograph of an ooid with a ferruginized fossil fragment as a nucleus. Uncrossed nicols; white bar is 250 microns.

Maquoketa, with bars eventually rising above the level of Maquoketa deposition. This would account for the transitional base reported by Chamberlin (1878) and Rosenzweig (1951). On Rosenzweig's isopach map (fig. 2), the Neda is shown as a group of elongate, northeasterly trending bodies. It cannot be determined whether these lenses have the form of channels or bars since Rosenzweig's (1951) thickness information was not related to a stratigraphic datum above or below the Neda.

In addition to concerns about the physical setting for Neda deposition, there are uncertainties regarding the source of iron and the mechanism for genesis of the ferruginous ooids. Chamberlin (1883) proposed that the iron oxide ooids were primary deposits. Later workers generally agreed with this view (Savage and Ross, 1916; Alden, 1918; Hawley and Beaven, 1934; Rosenzweig, 1951). Grabau (1913), however, maintained that oolitic ironstones like the Neda originated as calcareous oolite deposits, which were later replaced by iron minerals. Paull (1977), Kean (1981), and Synowiec (1981) endorsed this concept for the Neda.

The source for iron in the Neda was first addressed by Chamberlin (1883, p. 181) who suggested "...iron bearing waters coming from the low, flat land adjacent", while "...the more distant ferruginous rocks of the Archaean..." were considered a less likely source. The Queenston delta of the Appalachians was suggested as a source of iron for the Neda by Willman and others (1975), Kean (1981), and Synowiec (1981). Kean (1981) also suggested the Transcontinental arch to the west was a contributing source.

METHODS

The Neda Formation at Katells Falls and the type area was measured, described, and sampled. Specific locality information and selected descriptions of measured sections are included in the Appendix 1. A single stratigraphic section was measured at Katells Falls due to the limited exposure. At the type locality, twelve stratigraphic sections were measured with a Jacobs staff, Brunton compass, and tape measure. Eleven of these sections were spaced at approximately 15 m intervals across the east face of the open pit mine, and nine of these are illustrated in figure 6. The final section describes the base of the Neda at the northwest edge of the flooded open pit mine.

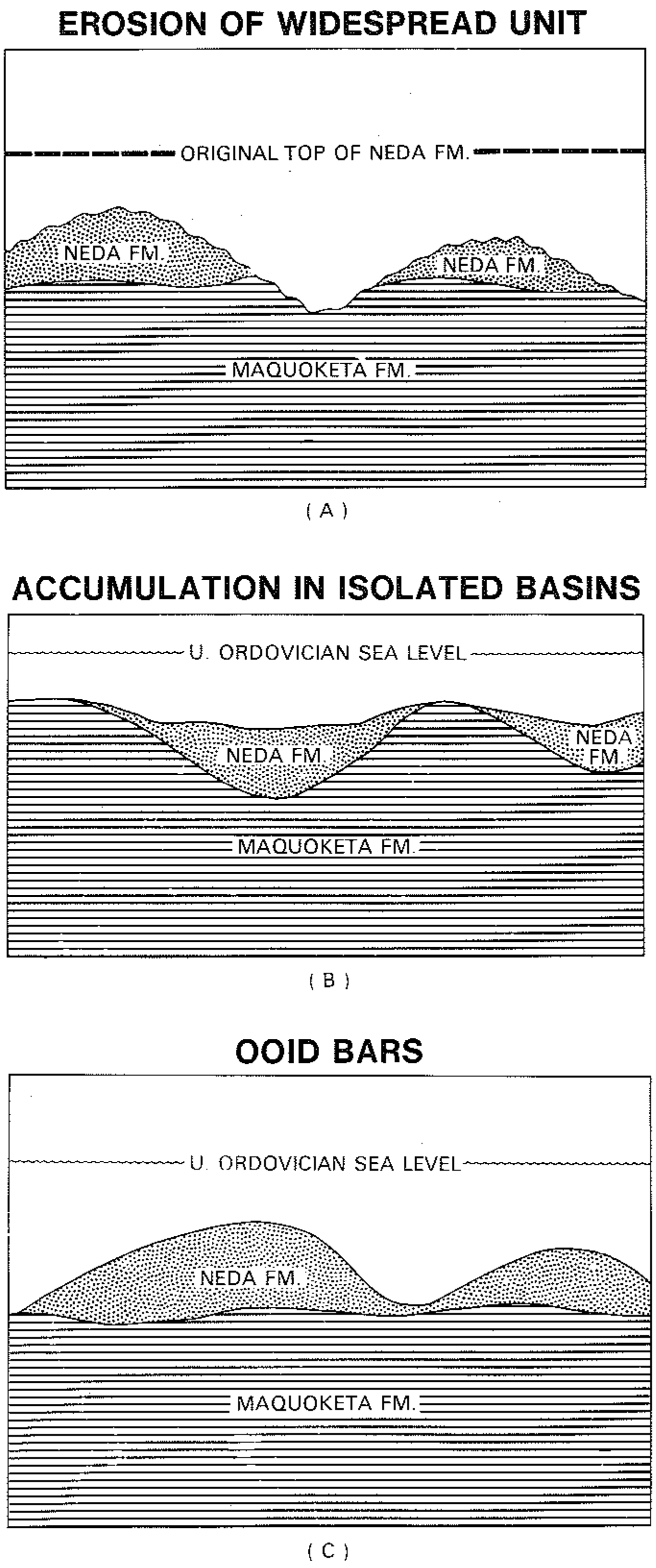
Samples from the Neda and Mayville were slabbed, sectioned, and processed for microfossils. Four kilograms of oolitic Neda were examined for microfossils during this study in an unsuccessful attempt to refine the age of the Neda. The five samples of basal Mayville processed for conodonts yielded only four specimens of the wide-ranging genus *Panderodus* (Ordovician to Devonian).

The scanning electron microscope (SEM) defined ooid microstructure, and X-ray diffraction determined mineralogy of fine-grained samples when conventional petrographic examination was inconclusive. Analyses were also performed to determine chemical composition. Colors for rock description were determined from wet samples using the GSA Rock Color Chart.

MEASURED SECTIONS

Katells Falls

Figure 7 is the Neda section at Katells Falls near De Pere, Wisconsin (see Appendix 1). Here, the Brainard Member of the Upper Ordovician Maquoketa Shale grades abruptly upward into the Neda, wheras the upper contact with the Lower Silurian Mayville is sharp


EROSION OF WIDESPREAD UNIT

ACCUMULATION IN ISOLATED BASINS

OOID BARS

Figure 5. Schematic diagrams of proposed depositional settings for the Neda Formation. Vertical exaggeration is about 6.25X.

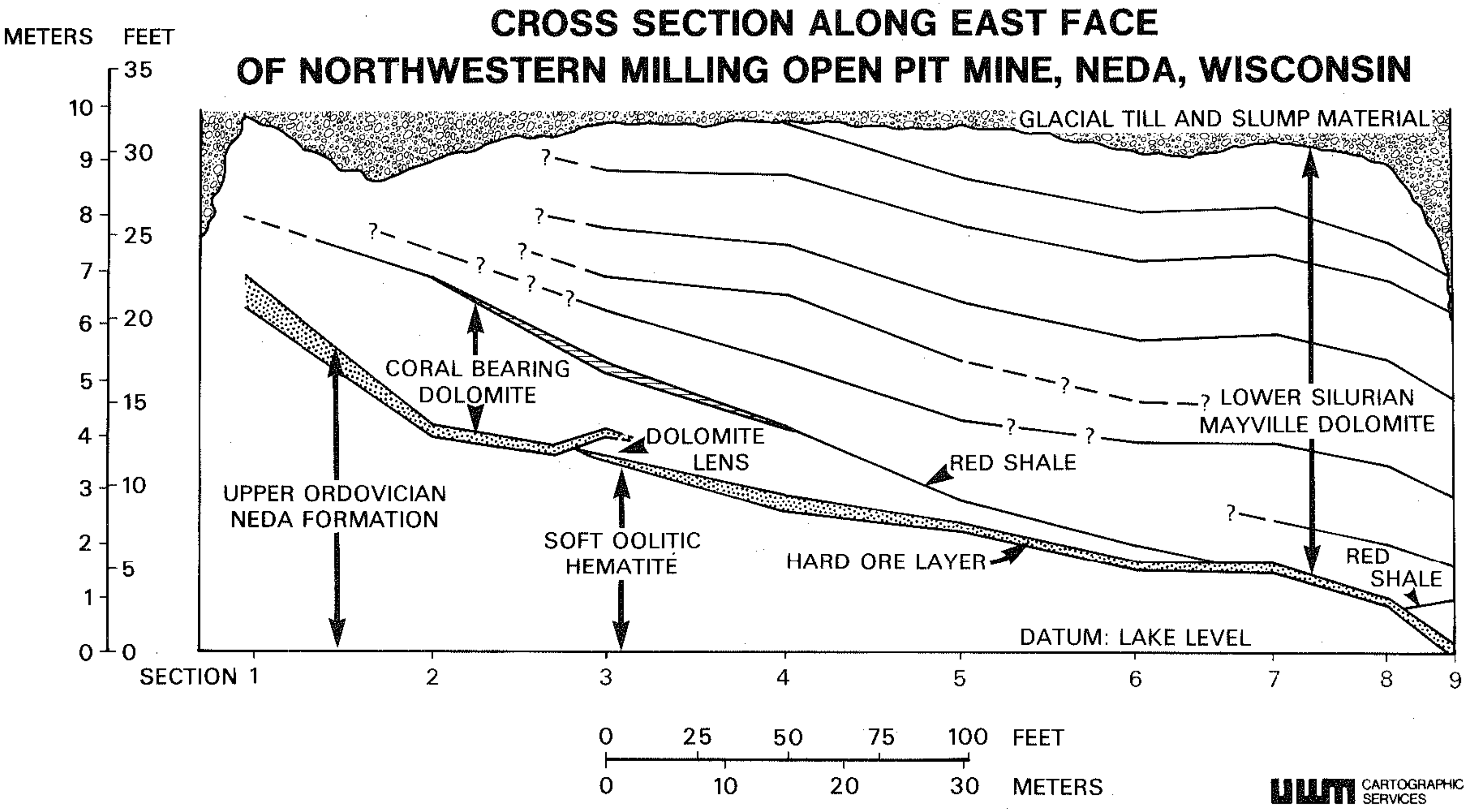
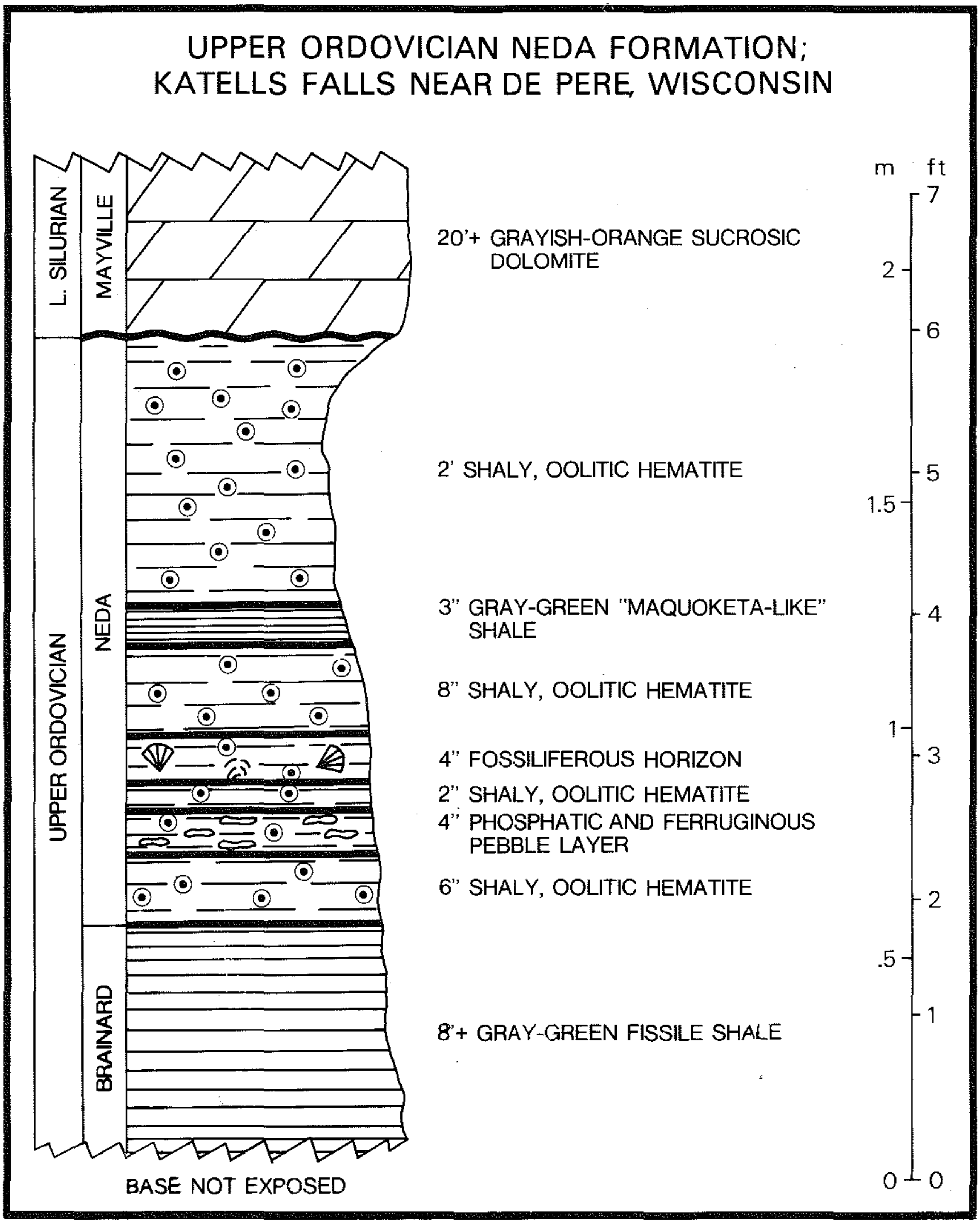


Figure 6. Cross section displaying nine closely spaced measured sections of the upper part of the Neda Formation and the lower part of the Mayville Dolomite at the open pit mine near Neda, Wisconsin. Higher beds in the Mayville generally maintain thickness while rising over what may be a mound on the top of the Neda. The diagonally lined area is a thicker part of a red shale bed in the Mayville. Datum is lake level in the flooded pit.



UWM CARTOGRAPHIC SERVICES

Figure 7. Neda Formation at Katells Falls near De Pere, Wisconsin. The heavier lines define the limits of each unit described.

with little local relief. The Neda is predominantly a shaly, oolitic hematitic unit with ooids commonly concentrated in pockets and stringers within a silty dark yellowish brown (10 YR 4/2) to moderate-brown (5 YR 3/4) shaly matrix. The ooids are both flattened and ellipsoidal, with lesser amounts of spherical, non-deformed ooids. Flattened ooids at this locality, unlike the type area, have no preferred orientation with respect to bedding.

A concentration of ferruginous and phosphatic dolomite pebbles are present about 15 cm above the Neda-Brainard contact. These pebbles, which occur in a wide range of shapes and degrees of rounding, range in maximum width from a few millimeters to approximately 5 cm. Many are disc-like or slab-like in appearance, and some are bored. All are characterized by a polished or varnished appearance, and most are oriented parallel or sub-parallel to bedding.

A fossiliferous horizon 10 cm thick lies 0.3 m above the basal contact with the Brainard. The fauna in this zone consists of ferruginous brachiopods, pelecypods, bryozoans, gastropods, conulariids, and trilobites. In addition to the Upper Ordovician fauna described from this horizon by Savage and Ross (1916), Upper Ordovician conulariids of the genus *Climaconus* and *Paraconularia* and dalmanitid (?) trilobite fragments were recognized. All specimens are generally well preserved, and even the most fragile forms show little evidence of reworking.

Another interesting feature at Katells Falls is a thin bed of "Maquoketa-like" shale about 0.6m below the top of the Neda. Maquoketa-like interbeds within strata with Neda affinities (hematitic oolite-bearing red shale in the stratigraphic position of the Neda) were reported by Mikulic (1977, 1979) from the subsurface in Racine and Milwaukee counties, Wisconsin. According to Michael G. Mudrey Jr. (verbal communication, 1987), the Wisconsin Geological and Natural History Survey has records of seven wells in Racine County that penetrated similar strata. Our interpretation is that these occurrences should be considered Neda, but additional work is required to substantiate this belief.

The uppermost 0.6 m of shaly, oolitic hematite at Katells Falls is characterized by an upward increase in the percent of ooids. Scattered, well-rounded, phosphatic pebbles are also present at the top of this unit, and the contact with the overlying Mayville is abrupt.

The lowermost 0.3 m of the Mayville contains significant amounts of massive pyrite, occasional phosphatic ooids, and black phosphatic pebbles less than 0.5 cm in diameter. The contact of this basal unit with overlying beds of the Mayville is abrupt. Rosenzweig (1951) suggested this unit was equivalent to the dense hematite layer at Neda. Synowiec (1981) believed the uppermost layer at Neda and the pyritic layer at Katells Falls reflected oxidizing and reducing environments, respectively, at the top of the Neda. It is our opinion, however, that the pyritic layer at Katells Falls is not part of the Neda, but is post-depositionally altered Neda material that was reworked during the Silurian transgression.

Neda Area

Low water levels at the flooded open pit mine near Neda in the fall of 1982 and a excavation along the northwest shoreline exposed the Neda-Brainard contact. The contact at this locality was previously described by Shrock in 1930 (unpublished field notes). This contact, which we trenched laterally for 3 m, is abruptly gradational from gray-green shale of the Brainard member of the Maquoketa Shale (fig. 8 and App. 1). The basal 0.3 m of the Neda consists of shaly, oolitic hematite, lenses of gray-green shale, and an abundance of hematitic and phosphatic pebbles up to 8 cm in maximum diameter. These pebbles are highly polished, generally sub- to well-rounded, intensely bored, and some contain significant amounts of ostracodes, sponge spicules, and deformed ferruginous ooids (fig. 9).

The conglomerate is similar to the unit described from the basal part of the Neda at Katells Falls, and both may have resulted from wave destruction of carbonate hardgrounds. The presence of ooids within pebbles in the basal conglomerate and the interbedding of Neda and Maquoketa lithologies also indicate that ooid genesis was concurrent with deposition of the uppermost Maquoketa.

The Neda-Mayville contact at the open pit mine ranges from abrupt and horizontal to highly irregular and undulatory, and includes interfingering of Neda and Mayville lithologies. As shown in figure 10, a tongue of Lower Silurian Mayville Dolomite projects into the upper "hard ore" layer of the Neda over a distance of approximately 0.75 m. This relation indicates the uppermost Neda was unlithified when basal Mayville carbonates were deposited.

Additional evidence for unconsolidation at the top of the Neda during onset of Mayville deposition is suggested by prominent load casts on the lower surface of the "hard ore" layer of the Neda Formation (fig. 11 and App. 1). These compaction features are present wherever this surface is well exposed. Ooids within the "hard ore" bed are also more highly deformed and stretched (spastolithic texture) than those in the underlying oolitic unit. Irregular features documenting compaction prior to lithification are also present on the upper surface of the oolitic part of the Neda. Figure 12 shows a small-scale intrusive mound of ooids projecting through "hard ore" into the overlying Mayville Dolomite.

In contrast, the abrupt nature of the upper contact of the Neda is illustrated in figure 13. No evidence of reworked "hard ore" is present in the basal few centimeters of the Mayville at this locality.

Shrock (1930) described basal Mayville beds filling low areas between Neda mounds at the open pit, while "reefal" Mayville accumulated on the higher surfaces and thinned rapidly away from the crests. He also reported overlying Mayville beds terminated against the "reefal" unit. Similar carbonate buildups over Neda mounds were described by Ulrich (1914, unpublished field notes) from the south wall of the open pit mine before it flooded. Our observations partly support these views.

A coral-bearing basal unit of the Mayville is shown in sections 1 and 2 in figure 6 overlying an apparent mound on the Neda surface. This bed thins and becomes unfossiliferous when traced laterally, while the thickness of the overlying Mayville bed is inversely proportional. Bed by bed correlation shows that higher beds maintain essentially equal thickness across the exposure. This indicates compensation for "reefal" development is confined to lowest Mayville beds, and upper units maintain thickness over the "reef" (fig. 6). Hence, some of the apparent relief on the surface of the Neda at

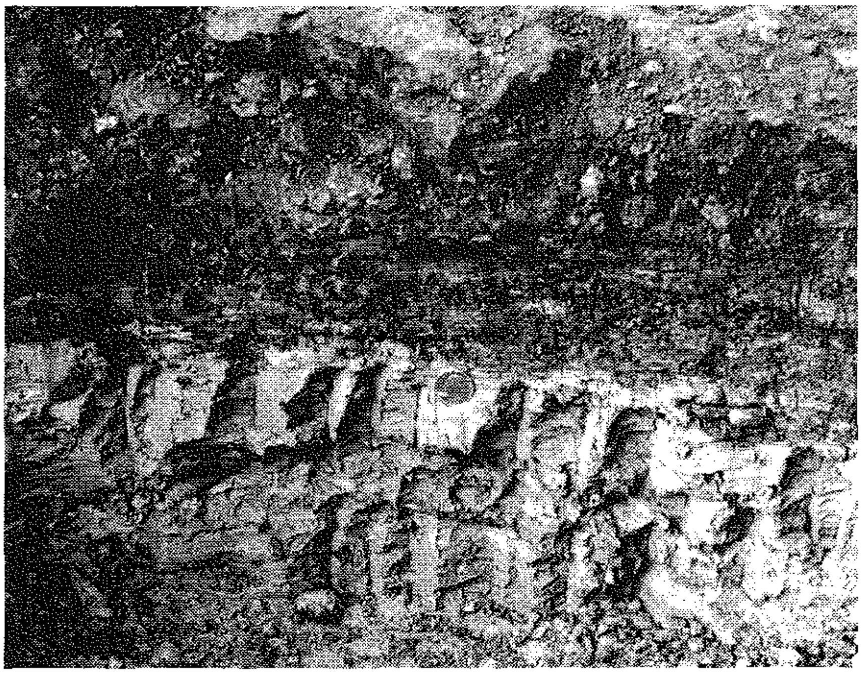


Figure 8. Neda-Brainard contact along the northwestern shoreline of the flooded open pit mine near Neda, Wisconsin. The basal Neda consists of a 0.3 m gradational interval with abundant ferruginous and phosphatic pebbles. A quarter of a dollar immediately underlies the contact, and provides scale.

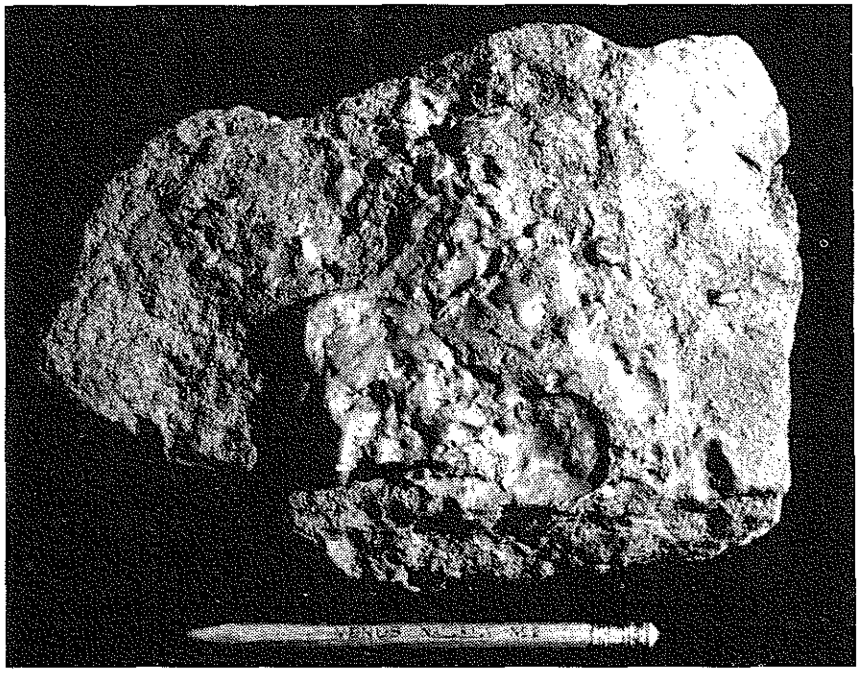


Figure 9. Highly polished, intensely burrowed, hematitic and phosphatic pebbles in a matrix of ferruginous ooids are characteristic of the basal Neda shown in figure 8.

Figure 10. Lower Silurian Mayville Dolomite reentrant into the "hard ore" layer at the top of the Neda. This "tongue" of dolomite (arrow) is approximately 0.3 m thick.

Figure 11. Load casts on the lower surface of the "hard ore" layer of the Neda Formation. A quarter of a dollar provides scale.

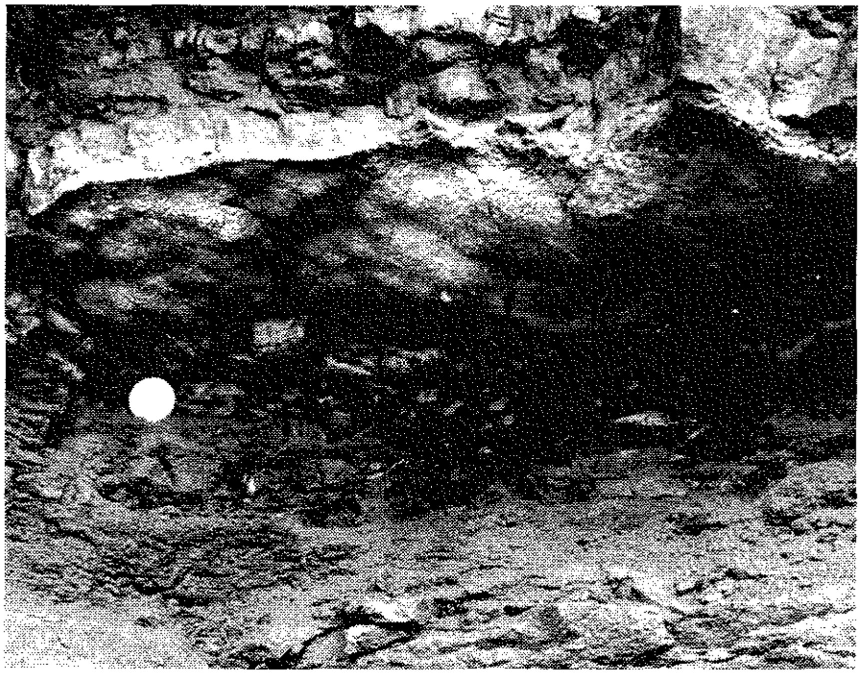


Figure 12. This small mound of ferruginous ooids intrudes the "hard ore" layer at the top of the Neda, and appears to deform the overlying Mayville Dolomite.

Figure 13. Sharp, almost horizontal, upper contact of the "hard ore" member of the Neda with the overlying Mayville Dolomite. Hammer provides scale.

this locality results from structural warping after lithification of the Silurian sediments (Paull and Paull, 1977, p. 48).

FORMATION OF FERRUGINOUS NEDA OOLITES

Paleogeographic Setting

Extrapolation from maps provided by Scotese and others (1979) indicates the study area was located about 15° to 20° south of the equator during accumulation of the Neda. This assignment is supported by paleomagnetic investigations by Kean (1981, 1983) and studies of lithic paleoclimatic indicators by Witzke (1980).

Depositional environments of the uppermost Maquoketa in eastern Wisconsin fluctuated between a normal open marine setting, restricted basins with poorly oxygenated waters, and intertidal mud flats behind barrier islands. These conditions resulted in alternations of thin, relatively pure, fossiliferous limestone, unfossiliferous gray-green shale, and stromatolitic carbonate. A general retreat of the Late Ordovician sea in response to a glacioeustatic fall in sea level resulted in shoaling conditions (Berry and Boucot, 1973; Sheehan, 1973). Formation of calcareous ooids on subtle highs during final retreat of the Maquoketa sea was proposed by Paull (1977), Mikulic (1979), and Synowiec (1981) to explain the discontinuous distribution and oolitic character of the Neda Formation.

Latest Ordovician lowering of sea level is documented by a prominent unconformity at the Ordovician-Silurian boundary in much of the Midcontinent east of the Transcontinental arch (Witzke, 1980). Lower Silurian carbonate deposition (Mayville) occurred on a broad shallow shelf during transgression when the input of terrigenous sediment was low.

Iron Transportation

Sources of iron for ferruginous sedimentary deposits were reviewed by Taylor (1949), James (1966), Hallam (1975), and Maynard (1983). James (1966) concluded that iron is transported in natural water: (1) in true solution, (2) in colloidal suspension, or (3) associated with clastic particles (adsorption and chelation).

The solubility of iron under normal marine conditions seldom exceeds 0.003 parts per million (James, 1966). Maynard (1983) maintained that such low concentrations of iron are insufficient to produce oolitic ironstones. Organic matter, however, stabilizes colloidal ferric hydroxide, and allows higher concentrations of iron to be transported (Moore and Maynard, 1929). More recently, Boyle and others (1977) established that the bulk of iron in rivers is carried as mixed iron oxide-organic matter colloids.

The majority of workers investigating the formation of oolitic ironstone favored the transportation of iron in colloidal suspension (Kimberley (1979). Maynard (1983) and Kimberley (1979) reviewed other suggested iron transport mechanisms. These include: (1) groundwater leaching from iron-rich mud (Sorby, 1856; Kimberley, 1979), (2) submarine springs (James, 1966), (3) upwelling of oxygen-deficient waters onto fresh or brackish water shelves (Borchert, 1960), and (4) upward diffusion from underlying organic- rich sediments (Aldinger, 1957; Kolbe, 1970). After evaluating these mechanisms, Maynard (1983) concluded that only upwelling of basinal waters and fluvial transport of clastic and colloidal iron were quantitatively adequate to produce significant ferruginous deposits. Maynard (1983) also stated that upwelling basinal waters did not apply to ironstones like the Neda that were deposited in shallow marine waters.

Genesis of Oolitic Ironstones

The association of iron minerals (which form in relatively low energy, oxygen deficient environments) with ooids (which generally form in high energy, oxygenated environments) complicates interpretation of the origin of oolitic ironstones. Furthermore, their variable mineralogy (chamositic, sideritic, hematitic, and goethitic) seems to preclude a universally applicable mechanism for formation. Consequently, numerous theories of genesis are proposed, but most can be grouped into four categories. These are: (1) formation of primary calcareous ooids accompanied by penecontemporaneous or later replacement by iron minerals, (2) direct precipitation of ferrous ooids from seawater under conditions of relatively low energy and minimal detrital input, (3) in-situ, iron- rich "ooid" or pisoid formation within a soil at an unconformity, and (4) mechanical accretion of ferrous ooids in moderately, but not strongly, agitated marine waters. Each of these theories is weakened by numerous contrary examples.

The replacement of calcareous ooids by iron requires significant amounts of ferruginous silt and clay overlying the oolite, and subsequent leaching by groundwater (Kimberly, 1979). The absence of thick deposits of fine clastics above most oolitic ironstone sequences and the general lack of partially replaced ooids flaw this hypothesis.

Direct precipitation of iron-rich ooids from seawater (Borchert, 1960) is considered unlikely because the quantity of iron minerals that could form is significantly less than the amount necessary to produce the average ironstone (James, 1966). Agnew (1955) and Nahon and others (1980) suggested lateritic weathering could generate ferruginous "ooids" or pisoids. In the Neda, cross bedding, ferruginized marine fossils, and ooid nuclei belie in-situ weathering. The microstructural studies discussed below also confirm this conclusion.

Iron-rich ooid formation through mechanical accretion of particulate iron from waters of low to moderate agitation was proposed by Knox (1970), James (1966), and James and Van Houten (1979) to explain the genesis of chamosite ooids. This theory, however, may not be applicable to hematite- or goethite-rich ooids.

Oolith Microstructure

Bhattacharyya and Kakimoto (1982) used the scanning electron microscope to study the internal fabrics of ferruginous pisoids from two localities, and ironstone ooids from seven occurrences ranging in age from Cambrian to Eocene. All the ironstones were deposited in shallow marine environments in association with detrital or carbonate sediments.

This study established that ferruginous ooids were characterized by tangential-concentric fabric, whereas the iron minerals in pisoids had a radial-concentric arrangement (Bhattacharyya and Kakimoto, 1982). Radial concentric grain orientation in pisoids reflects crystal growth outward from a nucleus during in-situ dissolution and reprecipitation or direct precipitation (Bhattacharyya and Kakimoto, 1982). Conversely, Bhattacharyya and Kakimoto (1982) attributed the tangential-concentric fabric of ironstone ooids to mechanical accretion of hydrated iron oxides and detrital clay minerals in moderately, but not necessarily strongly, agitated marine waters.

Representative ooids from the Neda Formation at the type locality exhibit tangential-concentric internal fabric when examined with the SEM (Figs. 14 and 15). These results suggest Neda ooids formed through mechanical accretion of iron-rich materials, and not through ferruginization of calcareous ooids. More importantly, the internal structure of the ooids eliminates the hypothesis of lateritic weathering as a mechanism for generation of "ooids" in the Neda as suggested by Kolata and Graese (1983).

It is uncertain if the tangential-concentric structure of Neda ooids condemns the replacement theory. Almost all Holocene marine ooids are composed of aragonite crystals oriented parallel to grain exteriors, while the majority of ancient marine ooids are composed of calcite oriented normal to grain exteriors (Wilkinson, 1982, p. 200). The preferred alignment of aragonite is destroyed during recrystalization to calcite (Wilkinson, 1982), but the effect of ferruginous replacement on the orientation of calcium carbonate crystals is unknown.

Interpretation

This study establishes two mechanisms of ooid genesis as the most plausible explanations for the Neda oolitic ironstone in eastern Wisconsin. These are: (1) replacement of primary calcareous ooids by iron minerals, and (2) mechanical accretion of hydrated iron oxides and clay minerals to form ooids.

As previously described, latest Ordovician sedimentation in the study area was characterized by waning detrital input during progressive shoaling of the Maquoketa sea. This condition would have been favorable for the formation of calcareous or ferruginous ooids. There is no evidence, however, to suggest an increase in the availability of iron at this time to facilitate either replacement or the mechanical accretion of hydrated iron oxides and particulate matter.

A replacement mechanism for the Neda is supported by the: (1) presence of ferruginized macrofossils and fossil fragments within ooids in the Neda Formation at Katells Falls and at the type area, respectively, (2) occurrence of carbonate oolites at approximately the same stratigraphic horizon elsewhere in the Midcontinent (Mikulic, 1979), and (3) lack of large amounts of detrital material within the ooid laminae, which would not be the case with mechanically accreted iron minerals.

Conversely, evidence suggesting the Neda ferruginous ooids are products of primary accretation includes: (1) paucity of identifiable ooid nuclei, which are commonly present in carbonate ooids, (2) presence of minor amounts of clay minerals within ooids, (3) relatively poor sorting of both ooids and matrix, suggesting moderate, but not strong, agitation during deposition, (4) deformed Neda ooids are unlike most calcareous ooids, and (5) presence of ferruginous ooids within phosphatized Maquoketa rip-up clasts sug-

Figure 14. SEM photograph of an equatorial section of an ooid from the soft, oolitic part of the Neda at the type locality. Oblique view, (80 X). Refer to figure 15 for magnified view of the area marked "X".

gests primary formation or penecontemporaneous replacement at the latest.

Additional support for primary mechanical accretion of ironstone ooids was provided by Knox (1970), James and Van Houten (1979), and Bhattacharyya and Kakimoto (1982). All three studies involved oolitic ironstones from predominantly clastic associations, which contained either chamosite or polymineralic ooids composed of chamosite/goethite, chamosite/hematite, or mixtures of these types. Since Neda ooids are hematite/goethite in association with shallow marine carbonates and fine clastics, a direct comparison with the work of Knox (1970), James and Van Houten (1979) and Bhattacharyya and Kakimoto (1982) is not possible. Although the process of mechanical accretion resolves some uncertainties about the origin of the Neda, it fails to account for replacement evidence cited above.

Synowiec (1981) endorsed the replacement theory of ferruginous ooid genesis described by Kimberley (1979) to explain the Neda Formation. The process she proposed involved: (1) formation of calcareous ooid bars in shoaling marine waters followed by deposition of iron-rich muds and clays, (2) uplift and weathering to allow a leachate to ferruginize the calcareous deposit, (3) compaction during replacement to deform the ooids, (4) removal of previously leached muds and clays during subaerial exposure, (5) development of a laterite on top of the oolite, (6) partial erosion of the laterite and, locally, the underlying oolitic deposit, (7) Early Silurian transgression and deposition of the Mayville Dolomite, and (8) additional compaction with some fracturing of ooids.

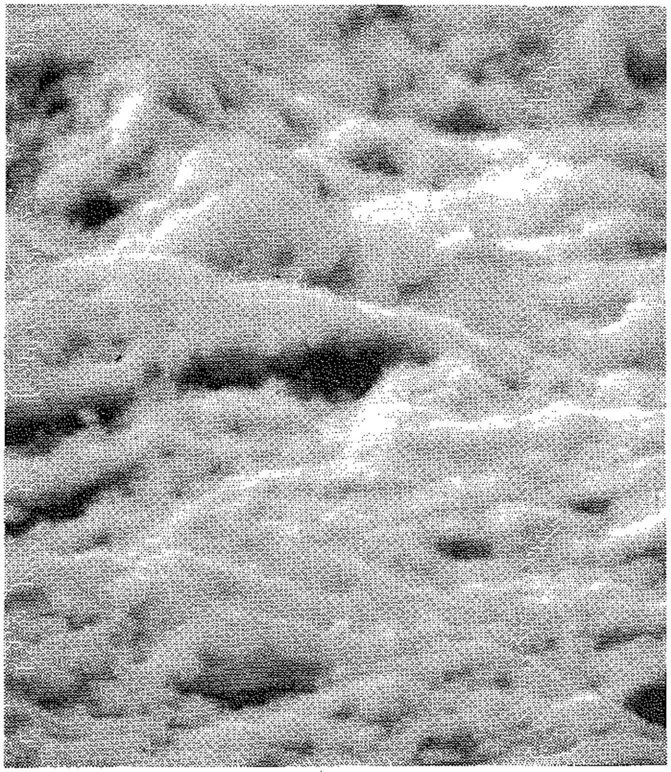


Figure 15. Enlarged part of figure 14 displays tangential-concentric internal fabric typical of Neda ooids (1500 X).

Our study contradicts some aspects of the genetic model proposed by Synowiec (1981). For example, the Neda at Katells Falls contains significant amounts of shaly bedded, fine-grained ferruginous sediment that should not exist in the high energy environment of an ooid bar.

A more important objection concerns the conceptual sequence of overlying silts and clays that are required to provide iron for the Kimberley (1979) model, as endorsed by Synowiec (1981). The Neda locally exceeds 11 m in thickness, and contains up to 45% iron. Since the iron content of representative red clays is 6.7% and the average shale is 5.5% (Garrels and MacKenzie, 1971), ferruginization of thick Neda oolite lenses would require about one hundred meters of latest Ordovician-earliest Silurian sediments (Kimberley, 1980). The Synowiec (1981) hypothesis also requires that these sediments, once leached, were completely eroded away.

Previous workers suggested that the sediments required to ferruginize the Neda were derived from the Queenston delta to the east (Willman and others, 1975; Kean, 1981; Synowiec, 1981), or the Transcontinental arch to the northwest (Kean, 1981). Although red beds related to the Queenston delta do not extend into eastern Wisconsin, the iron content of the greenish Maquoketa Shale is similar. Regardless, non-oolitic red beds or Maquoketa-like shale do not overlie the Neda Formation within the study area.

Additional problems are encountered if Precambrian rocks in the northeastern part of the Transcontinental arch are considered the source of the iron-bearing sediments overlying the Neda. This would require a drastic reversal in sedimentary transport direction in Late Ordovician time from easterly to westerly. In addition, the Wisconsin arch is located between the Neda depositional area and the Transcontinental arch. The effect of this feature, which may have been mildly positive in Late Ordovician time, would also seem to preclude sediment transport from the west.

The fortuitous combination of deposition-erosion of a thick sequence of post-Neda and pre-Mayville sediments challenges the imagination, but it also denies the geologic considerations described above. If one accepts our conclusion that no volume of suitable sediments was deposited above the Neda, the replacement model of Kimberley (1979) is unacceptable.

The timing and mechanism of ooid deformation in the Neda is an unresolved problem. The preferential alignment of elongate ooids subparallel to bedding at Neda could result from either deposition or compaction. If post-depositional compaction is accepted, the absence of ooid orientation at Katells Falls would require redeposition. Furthermore, the presence of spastolithic iron-rich ooids within phosphatic pebbles at the base of the Neda indicates deformation and ferruginization occurred prior to deposition.

Microstructural analysis of ooids from the "hard ore" at the top of the Neda eliminates the possibility that this bed is an in-situ lateritic soil deposit. Field evidence supporting this conclusion is the nongradational contact between the "hard ore" and the underlying oolitic unit. The mechanism for enriching the uppermost layer to about 60% iron remains an enigma.

As previously noted, inclusion of ferruginous material in the lowermost Mayville Dolomite and interfingering of Neda and Mayville lithologies (fig. 10) indicate Lower Silurian carbonate deposition began prior to lithification of the "hard ore" layer. Compaction features (Figs. 11 and 12) at the base of this unit also suggest unconsolidation when Mayville deposition began.

CONCLUSIONS

Conclusions documented by this study are:

1. The Neda Formation is Upper Ordovician (Richmondian) in age, conformable and gradational with the underlying Upper Ordovician Maquoketa Shale, and unconformable with the overlying Lower Silurian Mayville Dolomite.

2. The ferruginous ooids of the Neda may have formed by the mechanical accretion of particulate iron-rich minerals or through replacement of calcareous ooids. The concepts of in-situ formation within a paleosol or direct precipitation of iron-rich ooids from marine waters are ruled out.

3. Although there is support for each of the two favored hypotheses, we believe the replacement theory best accounts for the Neda. The mechanism and timing of ferruginization, however, is uncertain.

4. If replacement is accepted, the genesis of the Neda oolitic ironstone began with the deposition of calcareous ooids in a shoaling Late Ordo-

vician sea as deposition of Maquoketa mud and carbonate waned.

5. Deposition of a thin layer of ferruginous silt and clay resulted in the "hard ore" at the top of the Neda Formation in the type area. Lithification of this unit was incomplete when the Early Silurian sea transgressed the area.

6. Reefal deposits developed in the basal Mayville Dolomite over higher areas on the Neda surface during the Early Silurian transgression.

7. Post-Mayville folding emphasized irregularities on the Neda surface in the type area.

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APPENDIX 1: MEASURED STRATIGRAPHIC SECTIONS OF THE NEDA FORMATION NEAR NEDA AND AT KATELLS FALLS, WISCONSIN

Twelve stratigraphic sections in the vicinity of Neda, Wisconsin were measured as part of this study. All are located in NE 1/4, SW 1/4, sec. 12, T. 11 N., R. 16 E., Horicon quadrangle, Dodge County. Eleven of the sections were measured at about 15 m intervals along the east wall of the flooded open pit mine. Sections 1 through 9 are shown on figure 6. Two other locations are along the pit wall north of the cross section, but these are separated by a covered interval that prohibits physical correlation. Section 12 is located at water level at the northwest corner of the lake.

Sections 4 and 12 were selected for inclusion in this Appendix. Section 4 is included because it contains a representative "hard ore" layer at the top of the Neda, and the basal contact is described in section 12.

The section at Katells Falls, Wisconsin is located under a waterfall 8.5 km east of De Pere and 0.8 km west of Kolbs Corner in SE 1/4, NE 1/4, sec. 32, T. 23 N., R. 21 E., Bellevue guadrangle, Brown County.

Neda Area Section 4	Thickness (Meters)	
Lower Silurian Mayville Dolomite (Top not exposed):		
5. Dolomite, dark yellowish brown (10 YR 6/6), massive, vuggy, vugs partially filled with ferruginous mudstone, stromatolites near base.	4.5	
4. Dolomite, grayish orange (10 YR 7/4) nodular, less resistant than units above and below.	0.45	
3. Dolomite, moderate yellowish brown (10 YR 5/4) to dark-yellowish-orange (10 YR 6/6); ferruginous shale layer 2.5 cm thick at base.	1.05	
2. Dolomite, dark yellowish gray (5 Y 6/2), dense, massive, vuggy; discontinuous dark-reddish-brown (10 R 3/4) shale layer at base.	0.75	
1. Dolomite, same as unit 2, with concentrations of poorly preserved fossil hash (including *Favosites* fragments).	0.45	
Contact with Neda Formation is abrupt.		
Total thickness of exposed Mayville Dolomite:		7.2
Upper Ordovician Neda Formation (Base not exposed):		
2. Hematite, blackish red (5 R 3/2) to grayish red (5 R 4/2), dense, blocky, contains scattered ooids. Prominent compaction features on basal surface.	0.3	
1. Hematite, grayish red (5 R 4/2) to moderate brown (5 YR 3.5/4), oolitic, thin limonitic clay layer at top.	0.75	
Total thickness of exposed Neda Formation:		1.05

Neda Area Section 12	Thickness (Meters)
Upper Ordovician Neda Formation (Top not exposed):	
3. Shale, moderate brown (5 R 3.5/4) to grayish red (5 R 4/2), generally contains less than 10% oblate spheroidal and oblate ellipsoidal hematitic ooids oriented randomly with respect to bedding, but locally concentrated in pockets and stringers. Contact with unit 2 is abrupt.	0.3
2. Hematite, moderate brown (5 R 3.5/4) to grayish red (5 R 4/2), oolitic, with abundant flattened, bored and highly polished pebbles of hematitic and phosphatic dolomite. Pebbles range in maximum diameter from a few mm to 6 cm, and also vary in shape and degree of rounding. Contact with unit 1 is abrupt.	0.05
1. Shale, moderate brown (5 YR 3.5/4) to grayish red (5 R 4/2), hematitic ooids concentrated in lenses and stringers, but oriented randomly with respect to bedding. Clasts of grayish-olive (10 Y 4/2) shale and ferruginous pebbles in basal 2.5 cm layer.	0.09
Contact with Maquoketa Shale is abruptly gradational with interbedding of Neda and Maquoketa lithologies.	
Total thickness of exposed Neda Formation:	0.44
Upper Ordovician Maquoketa Shale; Brainard Member (Base not exposed):	
1. Shale, grayish olive (10 Y 4/2), fissile.	0.3
Total thickness of exposed Brainard Member:	0.3

Katells Falls Section

Lower Silurian Mayville Dolomite (Top not exposed):	
5. Not described (sheer cliff, inaccessible). -------	4.5
4. Dolomite, grayish-orange (10 YR 7/4), massive, vuggy, scattered pyrite blebs and scattered chert nodules. --	0.9
3. Dolomite, moderate-yellowish-brown (10 Y 5/4), massive, vuggy, weathers to sandy texture. -------	0.49
2. Dolomite, grayish-orange (10 YR 7/4), resistant, scattered pyrite, contact with unit 1 is abrupt with thin light-reddish-brown (10 R 2.5/4) clay layer at base. --------------------	0.19
1. Dolomite, dark-grayish-olive (10 Y 5/2), with abundant masses of pyrite and well-rounded black phosphatic pebbles up to 1.25 cm in maximum diameter, hard, blocky fracture, discontinuous black phosphatic pebble layer at base. --	0.3
Contact with Neda Formation is abrupt	
Total thickness of exposed Mayville Dolomite:	6.38

	Thickness (Meters)	
Upper Ordovician Neda Formation		
3. Hematite, dark yellowish-brown (10 YR 4/2) to moderate brown (5 Y 3/4), oolitic, with oblate spheroidal and oblate ellipsoidal hematitic ooids randomly oriented with respect to bedding, matrix of silty, hematitic shale. Concentration of ooids increases upward in this unit. Contact with unit 2 is abrupt.	0.6	
2. Shale, grayish olive (10 Y 4/2), thin-bedded, no ooids, locally very similar to Brainard shale lithology.	0.08	
1. Hematite, dark yellowish brown (10 YR 4/2) to moderate brown (5 YR 3/4), oolitic, shaly, ooids as in unit 3, but concentrated in pockets and stringers with random orientation to bedding, scattered discoidal, well-rounded phosphatic shale pebbles, with a localized concentration .3 m from the base of unit. Bryozoans, brachiopods, pelecypods, conulariids, and trilobite fragments also occur at this horizon.	0.6	
Abruptly gradational contact with underlying Maquoketa Shale.		
Total thickness of exposed Neda Formation:		1.28
Upper Ordovician Maquoketa Shale; Brainard Member (Base not exposed):		
1. Shale, grayish olive (10 Y 4/2), fissile, occasional iron staining	2.4	
Total thickness of exposed Brainard Member:		2.4

	Thickness (Meters)	
Upper Ordovician Neda Formation		
3. Hematite, dark yellowish-brown (10 YR 4/2) to moderate brown (5 Y 3/4), oolitic, with oblate spheroidal and oblate ellipsoidal hematitic ooids randomly oriented with respect to bedding, matrix of silty, hematitic shale. Concentration of ooids increases upward in this unit. Contact with unit 2 is abrupt.	0.6	
2. Shale, grayish olive (10 Y 4/2), thin-bedded, no ooids, locally very similar to Brainard shale lithology.	0.08	
1. Hematite, dark yellowish brown (10 YR 4/2) to moderate brown (5 YR 3/4), oolitic, shaly, ooids as in unit 3, but concentrated in pockets and stringers with random orientation to bedding, scattered discoidal, well-rounded phosphatic shale pebbles, with a localized concentration .3 m from the base of unit. Bryozoans, brachiopods, pelecypods, conulariids, and trilobite fragments also occur at this horizon.	0.6	
Abruptly gradational contact with underlying Maquoketa Shale.		
Total thickness of exposed Neda Formation:		1.28
Upper Ordovician Maquoketa Shale; Brainard Member (Base not exposed):		
1. Shale, grayish olive (10 Y 4/2), fissile, occasional iron staining	2.4	
Total thickness of exposed Brainard Member:		2.4

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PALEOMAGNETIC STUDIES OF ROCK AT THE ORDOVICIAN-SILURIAN BOUNDARY IN WISCONSIN

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ABSTRACT

The paleomagnetism of 64 samples of shale, oolitic iron ore, and dolomite from 10 sites in the Wisconsin area was investigated. The formations studied were the Maquoketa Shale (Late Ordovician), the Neda Iron Ore (latest Ordovician) and the Mayville Dolomite (Early Silurian). The shale and dolomite showed good paleopole directions after thermal demagnetization to 300 °C or AF demagnetization to 50 mT. The Maquoketa Shale produced a reversed pole at 29.3° S., 116° E. (a_{95} = 15.3°). The pole for the Mayville was also reversed and located at 36.7° N., 122.2° E. (a_{95} = 7.60°). Both of these poles are consistent with published Ordovician-Silurian poles of North America.

Thermal demagnetization of the Neda iron ore indicated that its remanence is in the matrix rather than the oolites. The paleopole for the Neda is reversed and located at 45.4° N., 132°E. (a_{95} = 16°). This pole is similar to early Permian poles of North America. This suggests that the hematite in the ore is not original but was produced from the dehydration of goethite through time, possibly during the formation of the Wisconsin Arch. There are no major differences in the magnetic characteristics of the Neda from Iowa, Illinois, and Wisconsin.

INTRODUCTION

This paper is a compilation and review of studies by Kean (1980, 1981) and Voltz (1983) of Ordovician and Silurian age sedimentary rock in Wisconsin and neighboring states. The main objective of these studies was to investigate the paleomagnetism of the Maquoketa Shale (Late Ordovician), Neda Iron Ore (latest Ordovician), and Mayville Dolomite (Early Silurian) (fig. 1). The study is of particular interest for several reasons: (1) Most paleomagnetic results for Ordovician and Silurian time are derived from studies of folded Appalachian rock which contains considerable secondary magnetization. It was considered that a cleaner paleomagnetic record could be obtained from undeformed cratonic rock; (2) If variation in the magnetic characteristics through the Lower Silurian rock could be found, it could be a useful aid in stratigraphic correlation of Lower Silurian rock in eastern Wisconsin; (3) There is a major problem in obtaining original paleopole positions from Ordovician and Silurian age red sedimentary rock. Most results show a pole position of Permian age, or a Permian-age secondary overprint which dominates the magnetization. It was hoped that the Neda Iron Ore would provide some new information for this old problem; and (4) Templeton and Willman (1963) suggested that the Neda ore may be related to the Queenstone Shale of western New York. A comparison of the paleomagnetic directions from the Neda and the Queenstone Shale might add some credence to this idea.

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GEOLOGY

Paleozoic rock of eastern Wisconsin dips gently to the east toward the Michigan Basin. The resistant Silurian dolomite forms a north-northeast trending escarpment which is the result of more rapid erosion of the underlying Maquoketa Shale. Due to its non-resistant nature, exposure of the Maquoketa Shale is of limited thickness in Wisconsin. Samples obtained for this study were limited to the Brainard Shale, the uppermost member of the Maquoketa Formation (Ostrom, 1967). The Brainard is a greenish-gray, fossiliferous, thin-bedded shale interbedded with dolomitic shale.

Lower Silurian rock forms the base of the Silurian escarpment in Wisconsin, and are currently included in one formation, called the Mayville Dolomite (Steiglitz and Allen, 1980). The Mayville is a gray-buff, thick-bedded, cherty, medium-to-coarse-grained dolomite.

The Neda Iron Ore is a hematite-goethite-oolitic formation, which is found locally between the Maquoketa and Mayville. The Neda was originally assigned a Silurian age, but is currently interpreted as having formed during shoaling of the regressing sea in Late Ordovician time (Paull, 1977).

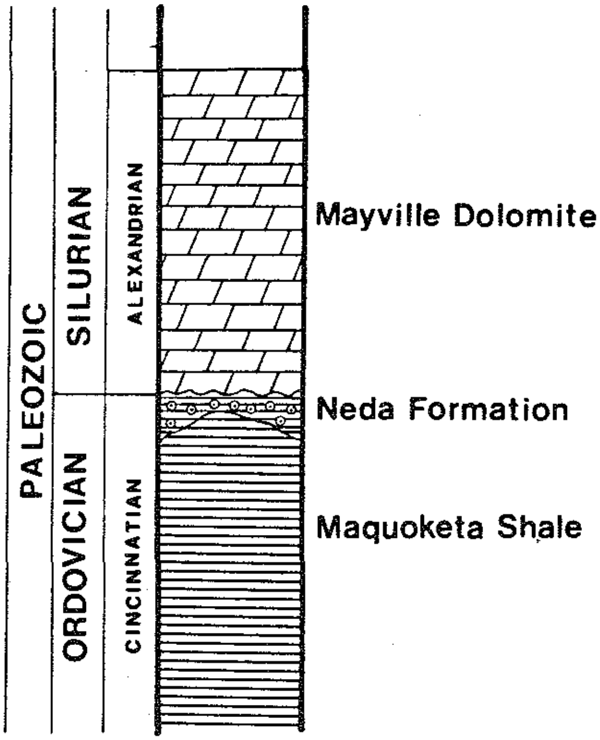


Figure 1. Stratigraphic relationships of Upper Ordovician and Lower Silurian rock in eastern Wisconsin (modified from Nelson and Lasca, 1970).

RESULTS - MAQUOKETA SHALE AND MAYVILLE DOLOMITE

Samples were collected from the Upper Ordovician Maquoketa Shale and Lower Silurian Mayville Dolomite at ten sites in eastern Wisconsin (fig. 2). Sample and specimen totals for each location are given in table 1. A greater number of sampling sites would have been desirable, but good exposures are very limited, particularly for the Maquoketa Shale.

Pilot samples from each location were subjected to detailed alternating field (AF) and thermal demagnetization (McElhinny, 1973). A two axis SCT Cryogenic magnetometer was used to measure the magnetization. Most samples contain a secondary component which could be removed by AF demagnetization at 35-50 mT or by thermal demagnetization at 250 °C. The optimum method and level of demagnetization for each site was determined by studying Zijderveld diagrams for each pilot sample.

A Zijderveld diagram (1967) depicts the change in magnetic inclination and declination as a function of progressive demagnetization. When the curve shows a linear trend toward the origin, the magnetization is decreasing in intensity, but it is maintaining a consistent direction. This direction is considered to be the stable direction and may represent the original magnetization of the sample. Figures 3 and 4 are Zijderveld diagrams for AF-demagnetized samples of Maquoketa Shale and Mayville Dolomite. Linear trends, depicting stable magnetization, are seen at demagnetization levels above 20 mT. The method and level of demagnetization which results in stable magnetization is used to demagnetize the remaining suite of samples for each site. The optimum demagnetization levels are given in table 2. Samples which are located in close proximity to the Neda Formation generally yield inconsistent results, and were not used in the analysis.

Magnetic directions for all samples are statistically combined (Fisher, 1953) to obtain formation mean directions of magnetization andvirtual geomagnetic poles (McElhinny, 1973).

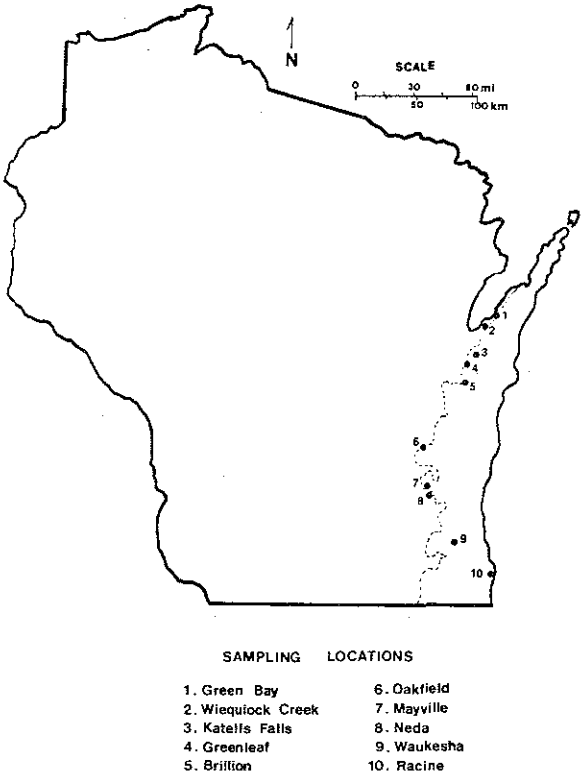


Figure 2. Map of Wisconsin showing sampling locations 1. Green Bay, 2. Wiequiock Creek, 3. Katells Falls, 4. Greenleaf, 5. Brillion, 6. Oakfield, 7. Mayville, 8. Neda, 9. Waukesha, 10. Racine. Dashed line is the Ordovician-Silurian boundary

For the Maquoketa Shale, 22 specimens from 10 samples from six horizons yield a mean inclination and declination of 18.8 and 158.1 respectively (K = 20, $a_{95} = 15.3^{\circ}$); the paleomagnetic pole is located at 29.3° S., 63.2° W. (North pole at 29.3° N., 116.8° E.).

For the Mayville Dolomite, 137 specimens from 29 samples from 11 horizons yield a formation mean direction of $I = 9.8^{\circ}$, $D = 156.1$ (K = 38.5, $a_{95} = 7.5^{\circ}$); the paleomagnetic pole is located at 36.7° S., 57.8° W. (North Pole at 36.7° N., 122.2° E.). These results are in general agreement with those of other Ordovician-Silurian studies (fig. 5). Further discussion is presented later.

As was mentioned earlier, stratigraphic correlation of members of Lower Silurian rock in Wisconsin is difficult because of relatively few thick exposures. The most extensive exposure of the Mayville Dolomite which starts at the contact with the Brainard Shale (uppermost member of the Maquoketa Formation) is located at the Waukesha Lime and Stone Company Quarry (location 9, fig. 2). A cursory study through the 30 m exposure was made to see if there were any significant variations in magnetic characteristics or magnetic directions, which could be used as stratigraphic markers.

Table 1. Sample and specimen totals for each sampling location.

Sampling location hand samples	Number of hand samples	Number of
Maquoketa Shale		
Wiequiock Creek	16	29
Katells Falls	6	8
Oakfield	6	18
Total	28	55
Lower Silurian Dolomite		
Wiequiock Creek	4	14
Green Bay	4	21
Katells Falls	2	16
Greenleaf	4	25
Brillion	4	13
Mayville	4	19
Neda	6	20
Waukesha	16	101
Racine	15	10
Total	59	239

One hundred one specimens from 16 hand samples were measured for demagnetization characteristics and magnetic directions. The optimum demagnetization levels did not change much (table 2), nor were the variations in magnetic directions statistically significant (fig. 6).

AF and thermal demagnetization characteristics are not always sufficient to determine the magnetic mineralogy of rock samples. Therefore, saturation magnetization studies and remanence coercivities studies were also performed.

The remanence acquisition for the Maquoketa Shale shows saturation at 100-200 mT. The remanence coercivity value is approximately 50 mT (Voltz, 1983). Both of these values indicate a spinel phase mineral such as magnetite. The Mayville Dolomite shows a two component remanent acquisition curve; saturation of a spinel phase mineral is indicated at 100-200 mT and the acquisition of significant remanence at 200-1000 mT suggests the presence of hematite. The remanence coercivity study also shows a two component remanence. One value at 38 mT and the other at 453 mt (Voltz, 1983). The results are reasonable for a spinel phase such as magnetite and for hematite respectively.

From these results and AF and thermal demagnetization studies, we conclude that the magnetic carrier for both the Maquoketa Shale and the Mayville Dolomite is a spinel phase iron oxide such as magnetite. We have assumed this to be primary, although recent studies by McCabe and others. (1983) indicate that magnetite can be produced by diagenetic processes as well.

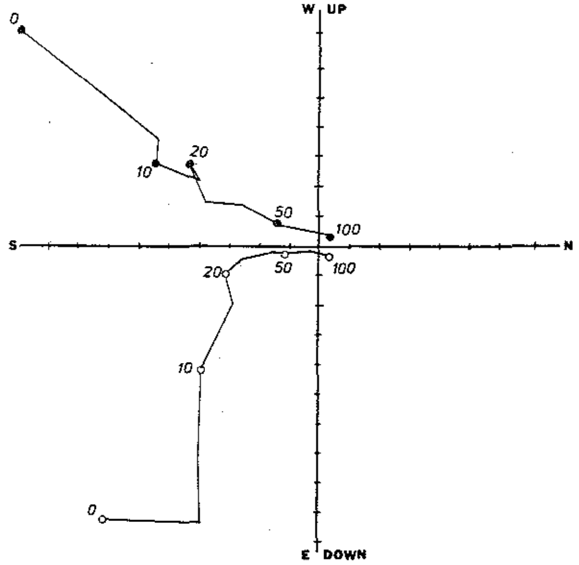


Figure 3. Zijderveld diagram for AF demagnetization of Maquoketa Shale. Numbers along the curve indicate the level of demagnetization in mT. Solid circles are declination, open circles are inclinations. Units along the axes are 10^{-5} Am^{-1}.

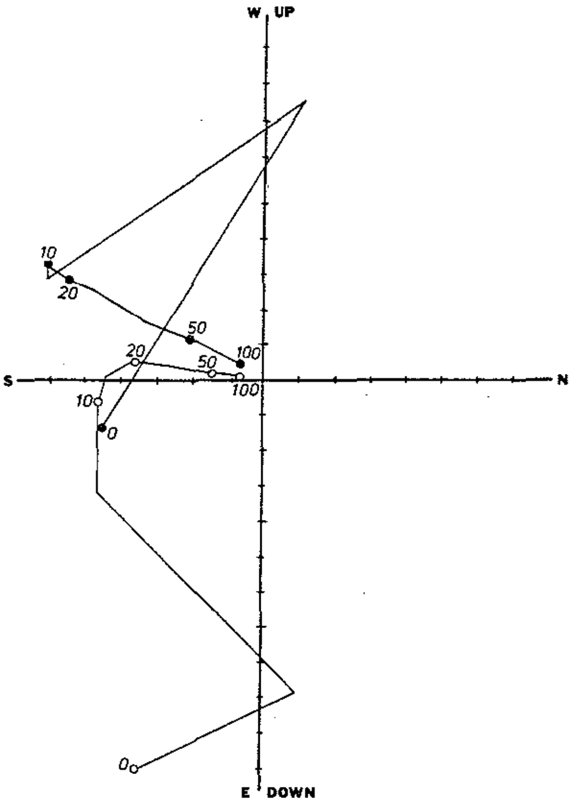


Figure 4. Zijderveld diagram for AF demagnetization of Mayville Dolomite. Numbers along curve are demagnetization level in mT. Solid circles are declination, open circles are inclination. Units along the axes are 10^{-5} Am^{-1}.

RESULTS - NEDA FORMATION

Samples of Neda Iron Ore were collected from locations at Neda, Wisconsin, Dubuque, Iowa, and Kankakee, Illinois (fig. 7). These three sites represent almost all the exposures in the midwest. All samples are from the soft ore or areas rich in oolites.

AF demagnetization of samples from each site show no changes in magnetization direction or intensity. Thermal demagnetization results (figure 8) indicate the dominant magnetic carrier is hematite.

Chemical demagnetization was performed on several samples from Illinois. This is a process in which a sample is placed in an HCl solution for progressively longer periods of time; magnetization is measured after each interval. Chemical demagnetization is effective in removing chemical remanence, which is carried by coatings on grains or secondary pore deposits. Chemical demagnetization of the Neda results in removal of the matrix; eventually

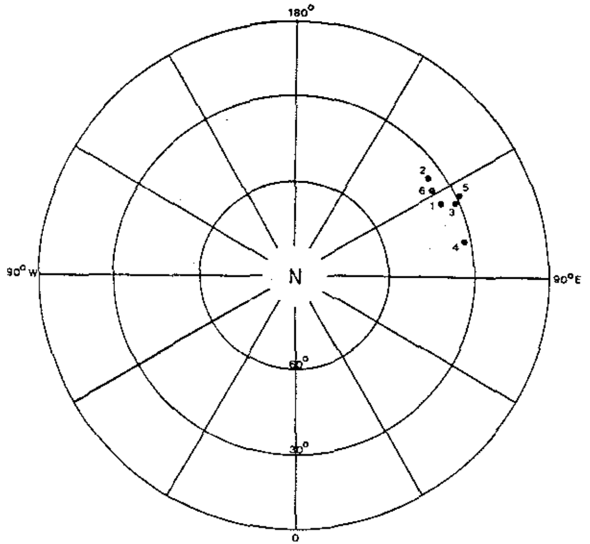
Table 2. Demagnetization scheme chosen for each site based on results of graphic analyses.

Sampling location	Demagnetization technique	Demagnetization level
Maquoketa Shale		
Wiequiock Creek	thermal	300 °C
Katells Falls	----	---
Oakfield	AF	50.0 mT
Lower Silurian Dolomite		
Green Bay	AF	35.0 mT
Wiequiock Creek	----	---
Katells Falls	thermal	250 °C
Greenleaf	thermal	250 °C
Brillion	----	---
Mayville	AF	35.0 mT
Neda	thermal	300 °C
Racine	----	---
Waukesha		
(level above shale in meters)		
3.05	AF	30.0 mT
6.10	AF	30.0 mT
9.14	AF	75.0 mT
12.19	AF	30.0 mT
15.24	AF	20.0 mT
18.29	AF	30.0 mT
21.34	thermal	300 °C
24.38	AF	50.0 mT
30.48	AF	50.0 mT
32.00	AF	50.0 mT

only loose sediment and oolites remain. A Zijderveld plot of the results (fig. 9) shows a linear trend toward the origin, which indicates the magnetization is carried by the matrix material rather than by the oolites (Kean, 1981). X-ray diffraction analysis (Synowiec, 1980) shows that the dominant iron ore in the Neda Formation is goethite.

Paleomagnetic results for the Neda Formation (table 3) are as follows: $I = -12^{\circ}$, $D = 152^{\circ}$, $K = 200$, $a_{95} = 16^{\circ}$. The reversed paleomagnetic pole is located at 45.5 °S., 48° W. (North pole at 45.4° N., 132° E.).

A comparison of results for the Maquoketa Shale, Neda Formation, and Mayville Dolomite shows that, with 95 percent confidence, the magnetization of the Neda is significantly different than that of the Maquoketa or Mayville (fig. 10). The paleomagnetic pole for the Neda is consistent with published results for Permian time. In addition, the paleopole is similar to results obtained from the Queenstone Shale, that is inclination = -10°, declination = 160°, $a_{95} = 10^{\circ}$. The paleomagnetic pole is located at 42°S, 44°W (North pole at 42°N, 136°E) (Kean, 1980).



Explanation

Pole	Age	Source
1.	Middle Ordovician	McElhinny and Opdyke, 1973
2.	Late Ordovician	Proko and Hargraves, 1973
3.	Late Ordovician	Van der Voo and French, 1977
4.	Late Silurian	Roy, et al., 1967
5.	Late Ordovician	this study
6.	Early Silurian	this study

Figure 5. Polar stereographic projection comparing paleomagnetic North pole positions of this study with published Ordovician-Silurian paleomagnetic poles.

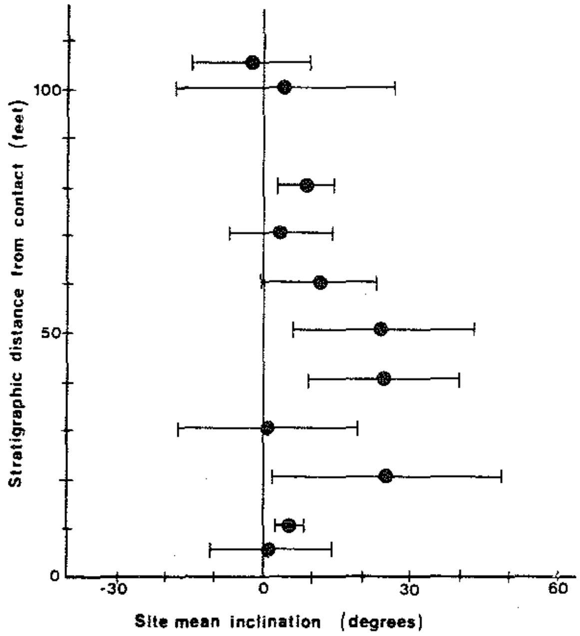


Figure 6. Site mean inclination versus stratigraphic position for Lower Silurian Dolomite. Brackets indicate limits of 95 percent confidence.

DISCUSSION

Obtaining reliable paleopole positions from undeformed sedimentary rock is a tenuous business from the very beginning, because there is never a guarantee that the magnetic minerals are primary or that the magnetism is primary. The usual criteria for the reliability of directions from undeformed sedimentary rock has been, the composition of the magnetic minerals, the internal consistency of the results, and the agreement or near agreement with published paleopoles from similar aged igneous rock or from folded sedimentary strata in which the magnetism exhibit a positive fold test (Graham, 1949).

There is also a question as to the reliability of pole positions from folded sedimentary strata which have secondary components. The Ordovician-Devonian folded sedimentary rock from the eastern United States are a good example, because most of the sedimentary rock contains a significant secondary magnetization overprint which is usually obtained during or after folding (see Van der Voo and French, 1977 as an example). Although it appears that the secondary magnetization can be removed, there is always a question as to the effect of a small residual secondary component on the final pole positions. Therefore, it would not be improbable to find the pole positions displaced slightly from each other. However, if the two pole positions are statistically similar, then one's confidence in the pole position is enhanced.

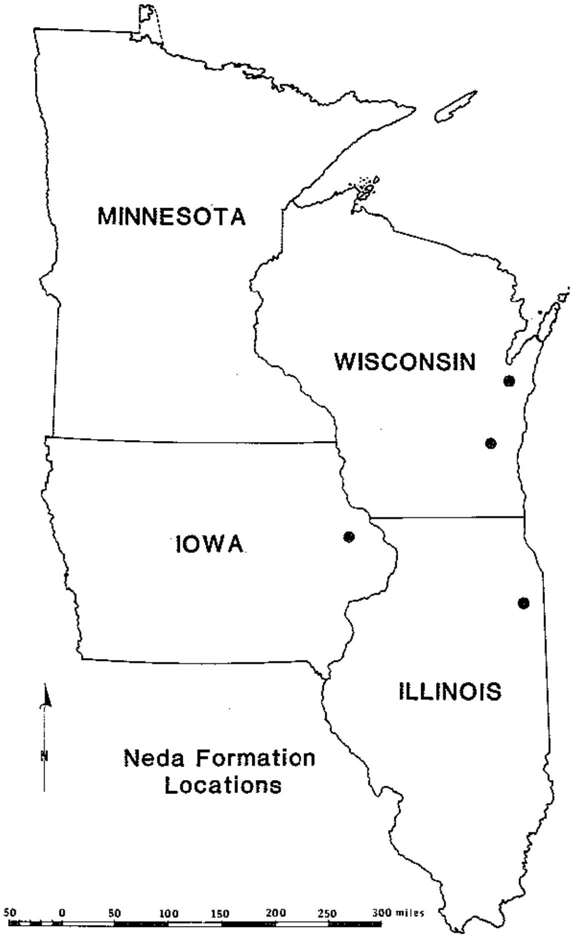


Figure 7. Location map for Neda ore samples: Neda, Wisconsin, (44.16° N, 88.08° W); Dubuque, Iowa (42.5° N, 90.75° W); Kankakee, Illinois, (41.1° N, 87.8° W).

For the formations studied in this report, the results from the Maquoketa Shale are probably the most reliable. The paleolatitude and longitude of the pole position (29.3°N, 116°E) is closer to other published Ordovician poles. In addition, the magnetic mineralogy is a single, spinel phase mineral which is probably magnetite. The Mayville Dolomite is somewhat less reliable because it does contain two phases of magnetic minerals, hematite and probably magnetite. In addition, the pole position is higher in latitude (36.7 °N) than most published Silurian poles. It is tending toward a Permian direction, which is most likely the result of a secondary overprint from the hematite.

Finally, there is little doubt that the magnetic direction for the Neda Iron Ore is a secondary one, and is considered Permian in age, caused by the chemical change of hydrous iron oxides to hematite (Kean, 1981). More recent studies by Perroud and Van der Voo (1983) on the Silurian Red Mountain Formation, Alabama, and by Hodych and others (1983) on the hematite ore of Birmingham, Alabama, have come to the same conclusion for those formations.

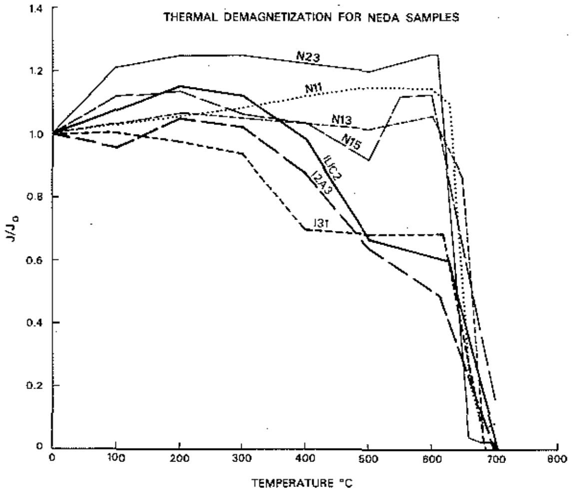


Figure 8. Thermal demagnetization curves for Neda samples from Wisconsin, Iowa and Illinois.

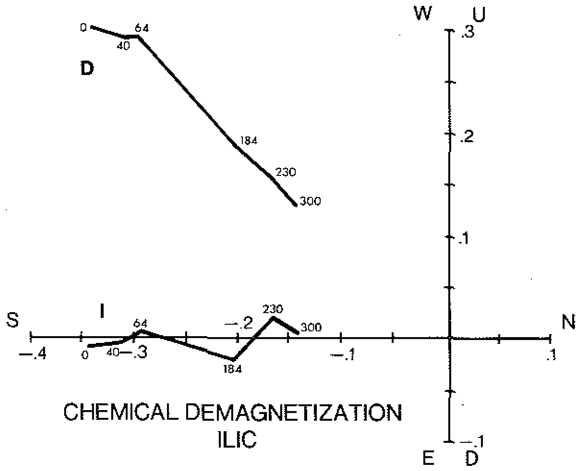


Figure 9. Zijderveld plot of chemical demagnetization for sample ILIC from Kankakee, Illinois.

CONCLUSIONS

The following conclusions may be drawn from the paleomagnetic results.

1. The Maquoketa Shale and Mayville Dolomite appear to record an original Ordovician-Silurian magnetization which is carried by spinel-phase iron oxide. Paleopole results are consistent with published Ordovician-Silurian results.

2. Preliminary studies suggest that neither magnetic characteristics nor magnetic directions can be used for stratigraphic correlation in the Lower Silurian Dolomite of Wisconsin.

3. The magnetization in the Neda is Permian in age, probably produced by dehydration of goethite to hematite as a result of minor uplift during Late Mississippian or Permian time.

4. We cannot determine from the magnetic data whether the Illinois and Wisconsin ooitic ores differ from the Iowa ores, nor can a relationship be drawn between the Neda and the Queenstone Shale. However, data from all areas show chemical magnetization acquired during Permian time, probably by

conversion of goethite or other hydrous iron oxides to hematite. The hematite is not primary at any of the sites.

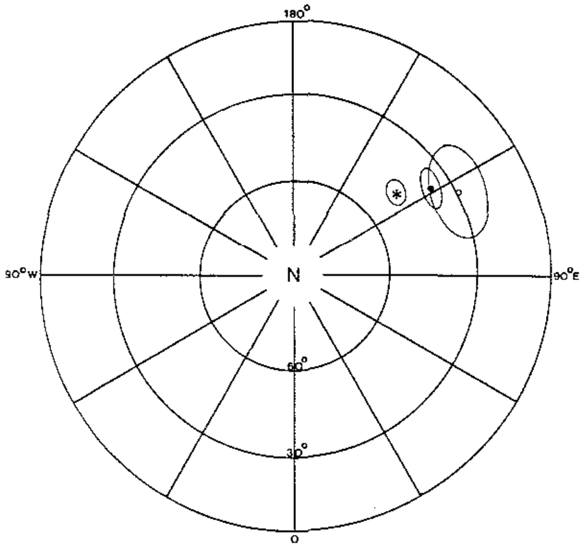


Figure 10. Polar stereographic projection of paleomagnetic north poles for Upper Ordovician Maquoketa Shale (open circle), Neda Formation (Kean, 1981) (asterisk), and Lower Silurian Dolomite (solid circle), including ovals of 95 percent confidence.

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Table 3. Paleopole positions for the three Neda ore sites.

Location	N	Dec	Inc	a_{95}	k	VGP	
		in degrees				Lat	Long
Neda, Wisconsin	12	162	-6.7	5.3	67	46.8 S.	52 W.
Dubuque, Iowa	7	146	-18	5.6	120	46 S.	38 W.
Kankakee, Illinois	6	148	-11	20	45	43 S.	34 W.
Average of three sites		152	-12	16°	200	45.4 S.	48 W.

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DISTRIBUTION AND AGE OF DOLOMITIC AND HEMATITIC OOLITES NEAR THE ORDOVICIAN-SILURIAN BOUNDARY IN NEBRASKA AND KANSAS

Marvin P. Carlson[1]

ABSTRACT

The upper Maquoketa (Late Ordovician) of Kansas is characteristically a greenish gray dolomitic shale which grades northward across Nebraska into a light gray granular dolomite. In southeastern Nebraska and adjacent areas of Kansas a red shale with oolitic hematite concretions commonly occurs at the top of the Maquoketa and is considered equivalent to the Neda of Iowa. The Silurian consists of dolomite with varied amounts of chert and commonly contains dolomitic oolites near its base. This lower unit is present throughout northeastern Kansas but appears to be overlapped by younger Silurian rocks northward across Nebraska. This oolitic interval has been equated with the Noix (Missouri) and Keel (Oklahoma) oolites which are considered to be Late Ordovician. However in Nebraska the dolomitic oolites are associated with an early late Llandovery fauna (Silurian).

INTRODUCTION

Two stratigraphic intervals in the subsurface of eastern Nebraska and Kansas contain material which has been characterized as oolitic. The upper interval has been correlated as Silurian and consists of clusters of dolomitic oolites in a dolomite matrix. The lower interval has been correlated as uppermost Ordovician and consists of oolitic hematite concretions in a red to greenish gray shale matrix. Both intervals have been described in a number of wells and seem to have regional stratigraphic significance. Deposition in this region during much of the Middle Paleozoic was centered in southeastern Nebraska and northeastern Kansas in what has been termed the North Kansas Basin. The Basin is defined by depositional thickening of major and minor subdivisions of Middle Ordovician through Mississippian rock. However, regional facies changes in some units suggest that variations occurred in the rate of basin sinking or sediment accumulation which masked the depocenter or both. The configuration of the North Kansas Basin has been obscured by later tectonic activity and erosion of Middle Paleozoic rocks. Current thicknesses of the upper part of the Ordovician rocks in Nebraska and Kansas are illustrated in figure 1. This interval consists of rock termed Maquoketa Formation in the subsurface of these states, but the Maquoketa Formation of Iowa apparently encompasses a thicker stratigraphic interval (Carlson and Berry, 1969). The Maquoketa of Nebraska-Kansas contains both shale and dolomite (fig. 2). In Kansas Lee (1956, p. 42) wrote that "the shales of the Maquoketa range from dark gray and greenish gray to dark green. Most of the shales are dolomitic.... The Maquoketa dolomite is gray to dark gray, grainy, composed of fine crystals set in an argillaceous or silty matrix." The dominant lithology in northern Kansas is greenish gray dolomitic shale. This lithology extends into Nebraska but grades northward into a light to medium gray, dense to granular,

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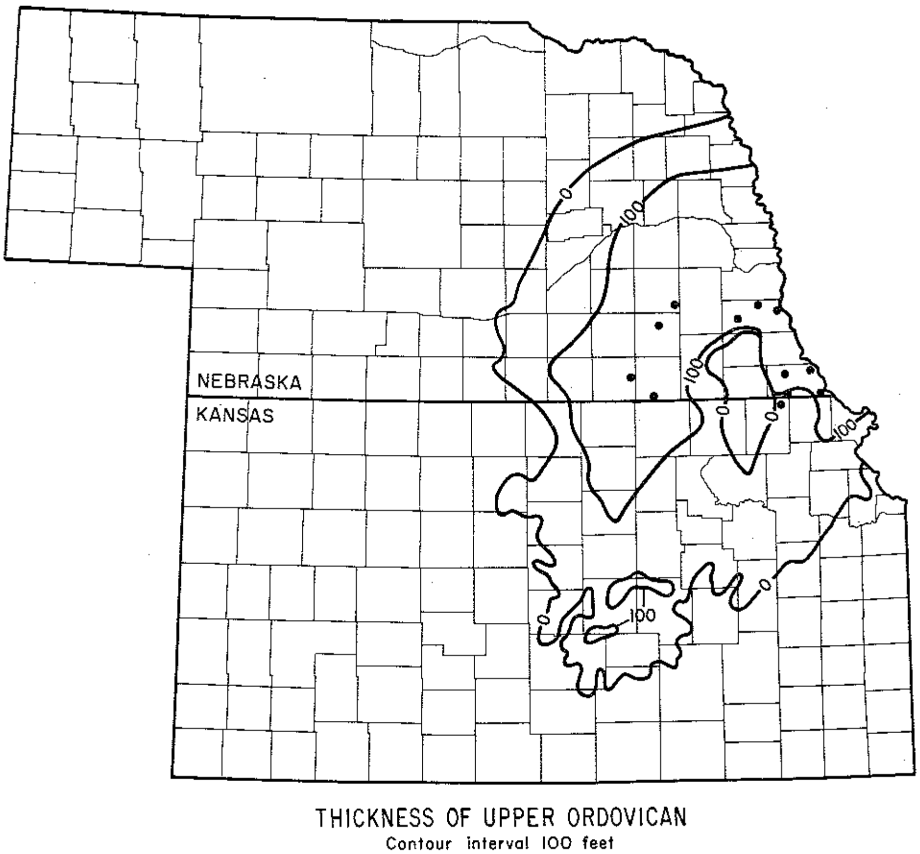

Figure 1. Distribution and thickness of upper Ordovician (Maquoketa) of Nebraska and Kansas. Dots indicate location of selected wells penetrating shale containing oolitic hematite in the top of the Maquoketa. 100 feet equals approximately 30 m.

argillaceous dolomite (Carlson, 1969, p. 29). The Maquoketa (fig. 1) is as much as 40 m thick; current thickness was strongly influenced by erosion. In southeastern Nebraska and adjacent areas of neighboring states a dark maroon to red shale containing oolitic hematite concretions commonly occurs in the top of the Maquoketa. Selected wells where these concretions have been described in Nebraska are noted on fig. 1. Published sample descriptions from Kansas and Missouri have not noted this zone, but inspection of available samples indicates that traces of hematite are present in areas adjacent to Nebraska. The shale matrix and flattened hematite concretions (fig. 3) are considered to be equivalent to the Neda as recognized in Iowa. As has been suggested in other areas, this upper Maquoketa unit probably represents a final regressive phase of the Ordovician and may originally have been more widely distributed. Silurian dolomite overlies the Maquoketa in much of this two--state area (fig. 4). The thickening of Silurian rocks to over 175 m reflects the depocenter of the North Kansas Basin; current edges reflect erosion prior to Devonian and during Pennsylvanian time. The dominant lithology in both Kansas and Nebraska is dolomite containing varying amounts of chert (fig. 5). Throughout northeastern Kansas and adjacent areas of Nebraska, the lowermost Silurian is characterized by a crystalline dolomite containing clusters of oolites resembling miniature golf balls (fig. 6). This zone was described by Lee (1956, p. 49) as "the first or oolitic zone, which overlies the Maquoketa, [and] is everywhere composed of sucrose or fine-grained dolomite characterized by dolomitized oolites." The oolites are composed of sucrose dolomite, and their surfaces are roughened by minute crystals of dolomite. In some samples the oolites are touching without matrix. In others they are embedded in the

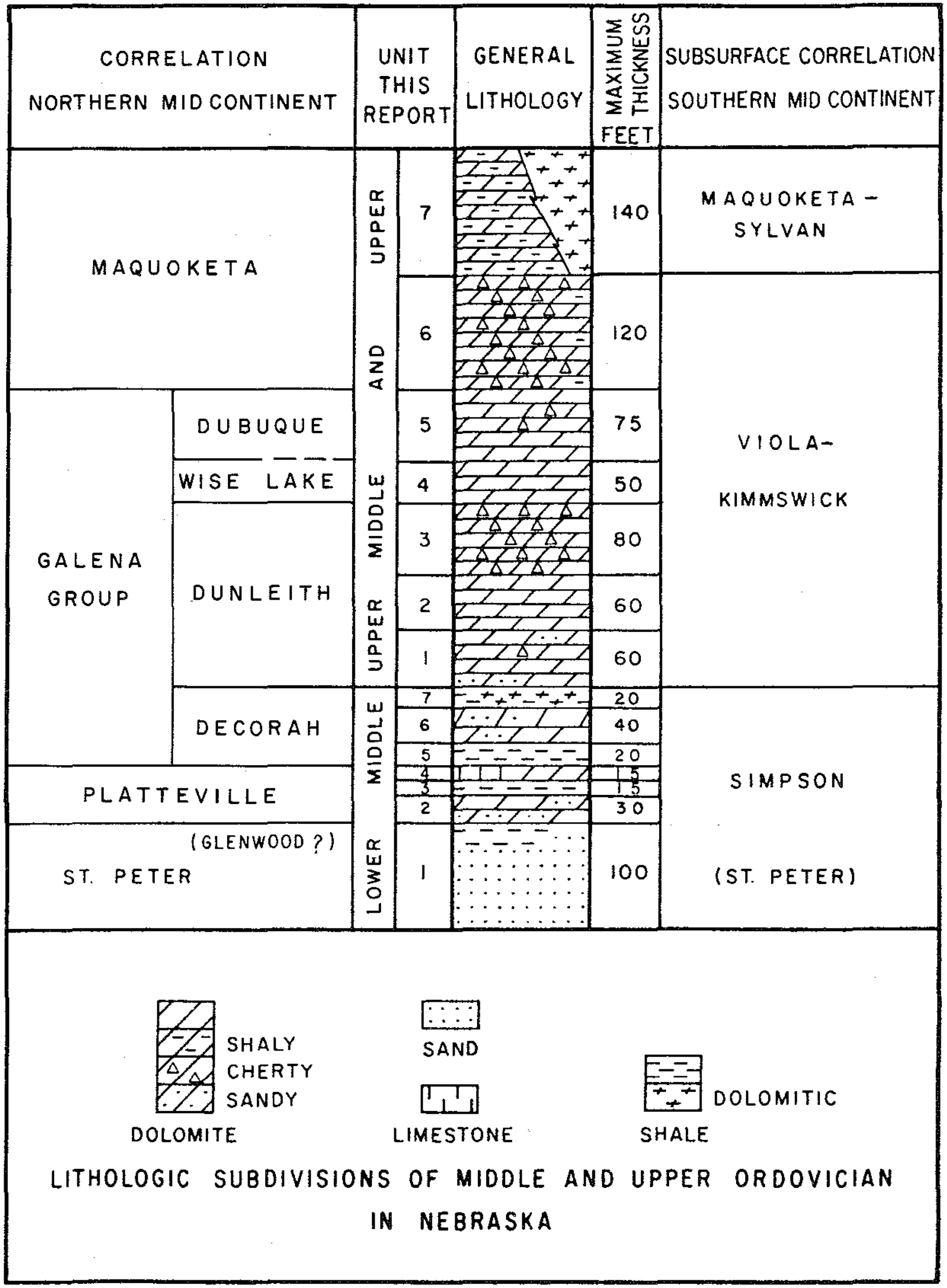

Figure 2. Lithology and correlation of the Middle and Upper Ordovician of Nebraska. 10 feet equals approximately 3 m.

Figure 3. Oolitic hematite in the Maquoketa shale from a well in sec., 14 T. 1 N., R. 16 E. Richardson County, Nebraska.

matrix, which in some places displays voids left by the removal of fossil fragments. In some wells the oolites resemble grains of soft dolomite worn to roundish surfaces in drilling. The abundance of the oolite is variable, and the variation in thickness of the zone may be due either to poor preservation of the oolites or to their irregular distribution." A core from a well in southeastern Nebraska (sec. 2, T. 2 N., R. 16 E.) contains the oolites (fig. 7) in association with an early late Llandovery fauna (Carlson and Boucot, 1967). This lower Silurian unit was correlated by them with the Kankakee of Iowa but is now (fig. 5) considered equivalent to part of the Hopkinton as described by Bunker and others (1985). The distribution of this oolitic interval in Kansas has been described by Lee (1956, p. 50):, Except for local areas where it is absent, the oolitic zone is coextensive with the Silurian. It reaches its greatest thickness of 60 feet in the northern part of the area (Kansas Salina Basin). The zone thins irregularly toward the south, where it is commonly less than five feet thick or absent. The apparent restriction of the zone in Nebraska (fig. 4) indicates that this lower Silurian unit is overlapped by younger Silurian northward across Nebraska (Carlson and Boucot 1967). A similar overlap was noted in the upper Hopkinton of eastern Iowa by Bunker and others (1985). Both the Ordovician oolitic hematite and the Silurian oolitic dolomites (fig. 8) are present in a sample interval spanning the boundary between the two units from a well in sec. 31, T. 9 N., R. 14 E. Similar occurrences of both units have been noted in wells in sec. 14 and 24, T. 1 N., R.14 E. and sec. 5 and 30, T. 1 N., R. 15 E. These rock units probably were probably formed in a shallow marine environment although post-depositional diagenesis has modified the original structure and mineralogy. The lithology and texture of the hematitic shale in the upper Maquoketa suggest correlation with the Neda and a development over a large area of this shale unit. Time-equivalent, shallow marine environments may have produced the Noix and Keel oolites in the Upper Ordovician carbonate facies to the south in Oklahoma and Missouri. The initial Silurian deposits are also of shallow marine origin including deposition of carbonate oolites in Nebraska and Kansas. The distribution of this basal zone suggests some restriction of initial Silurian deposition. Further Silurian transgression overlapped these basal oolites. The association of these dolomitic oolites with Silurian fauna indicate that this unit is younger than the carbonate oolites of the Noix and Keel.

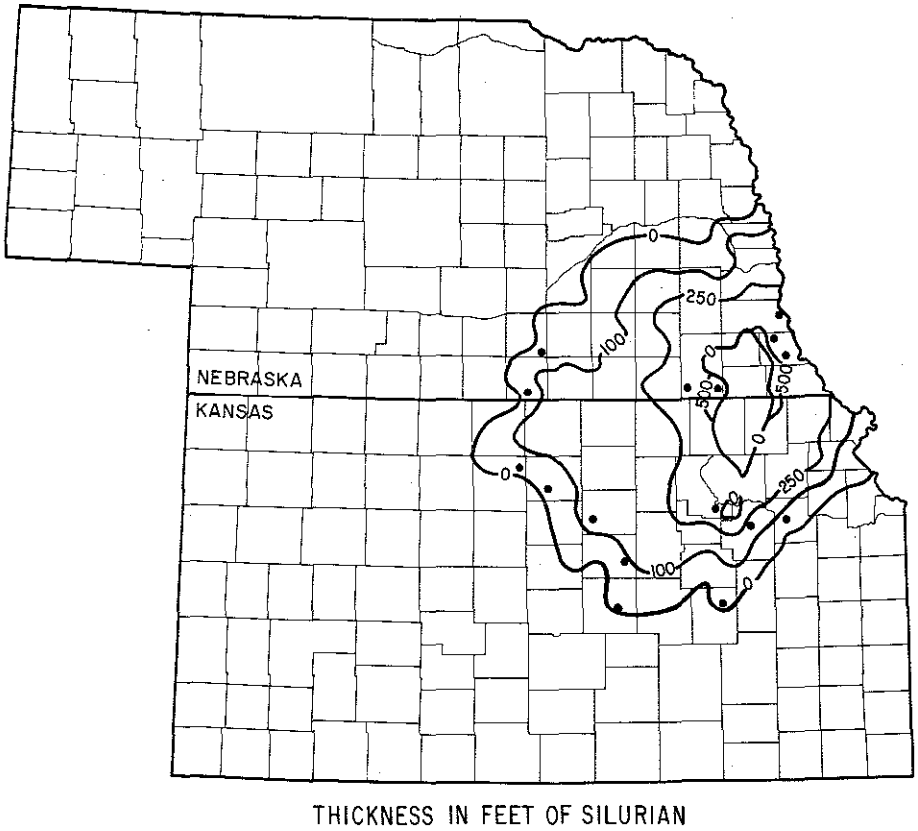

Figure 4. Distribution and thickness of Silurian rock in Nebraska and Kansas. Dots indicate location of selected wells penetrating the zone of oolitic dolomite. 100 feet equals approximately 30 m.

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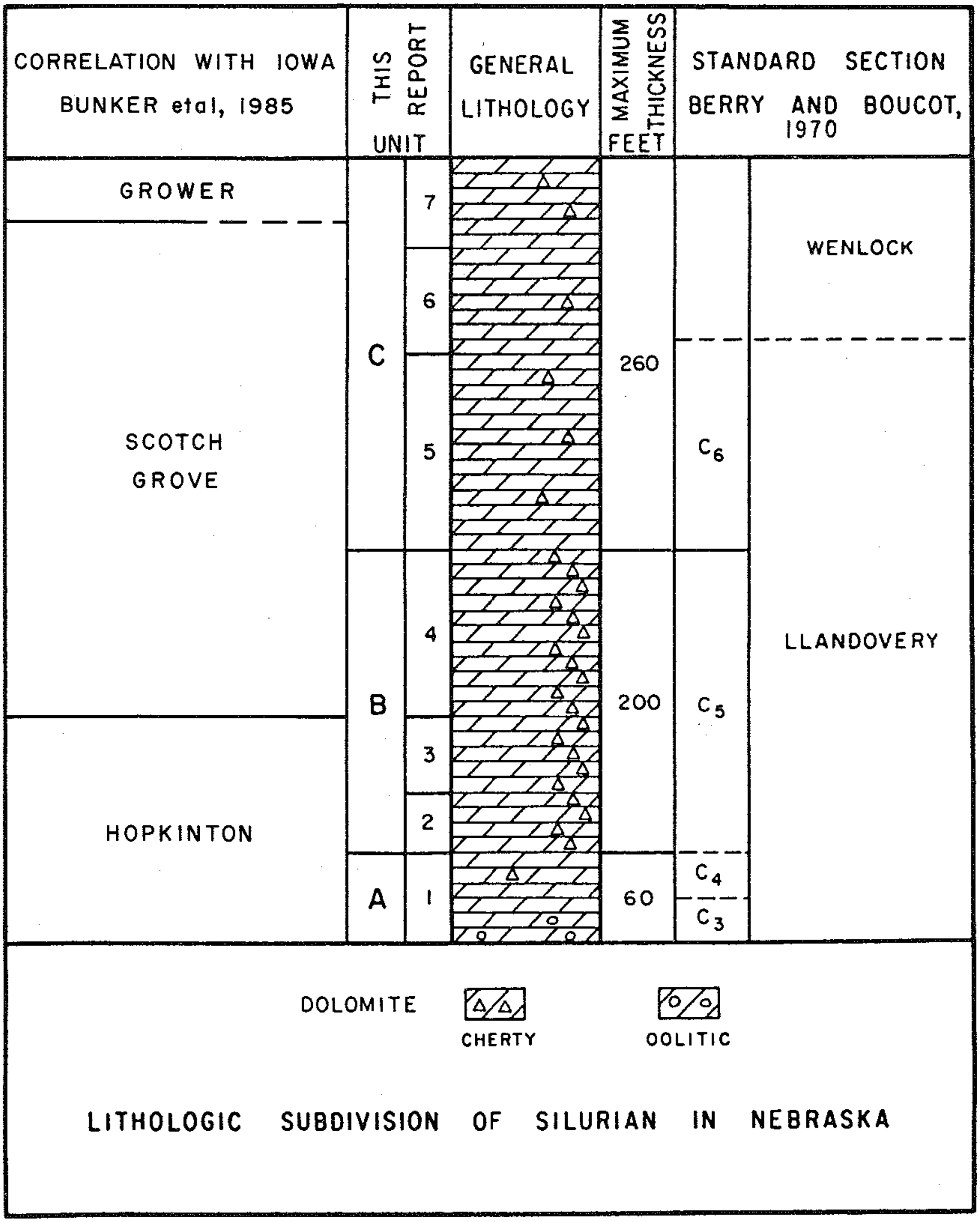

Figure 5. Lithology and correlation of the Silurian in Nebraska. 10 feet equals approximately 3 m.

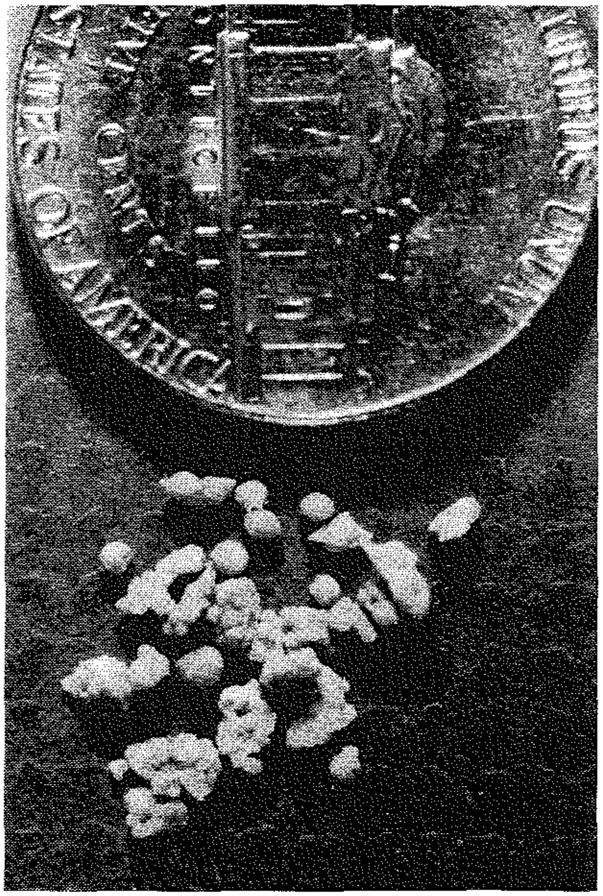

Figure 6. Oolitic dolomite in the Silurian from a well in sec. 14, T. 1 N., R. 6 E. Gage County, Nebraska.

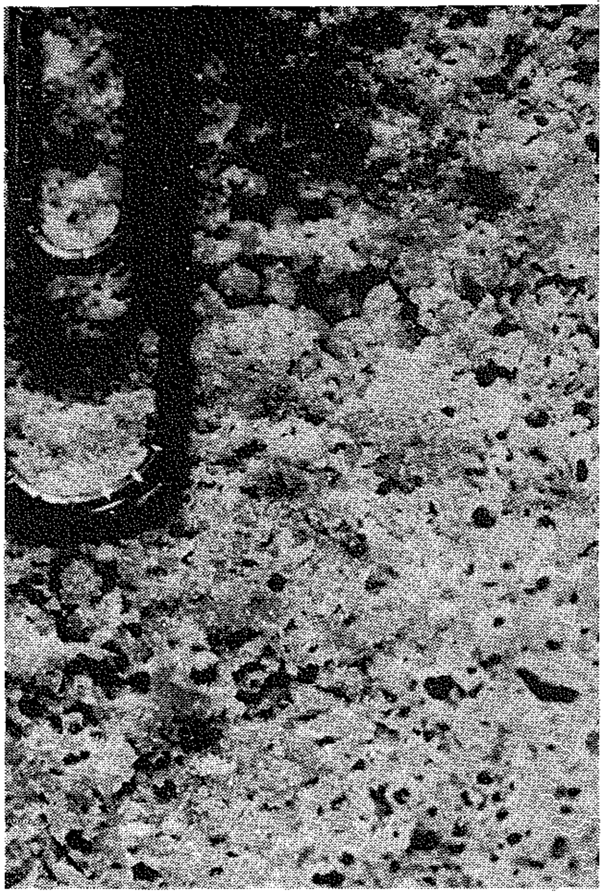

Figure 7. Oolitic dolomite in the Silurian from a cored well in sec. 2, T. 2 N., R. 16 E. Richardson County, Nebraska.

Figure 8. Oolitic hematite and oolitic dolomite from a sample interval including Maquoketa shale and Silurian dolomite from a well in sec. 31, T. 9 N., R. 14 E. Otoe County, Nebraska.

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Papers should be no longer than 25 pages, including all figures, reference, abstracts, and so forth. Manuscripts exceeding 25 pages must have the approval of the editor before submission to "Geoscience Wisconsin." Draft copies for review should be double spaced with ample margins; this includes references cited. For final publication, camera-ready copy of all papers will be prepared by the Wisconsin Geological and Natural History Survey. Originals or photographs of all illustrations will be submitted at this time. Photocopies (xerographies) will not be accepted for printing. General style follows that of the U.S. Geological Survey and Geological Society of America. Manuscripts not meeting style will be returned to the authors without review. There are no page charges.

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