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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).

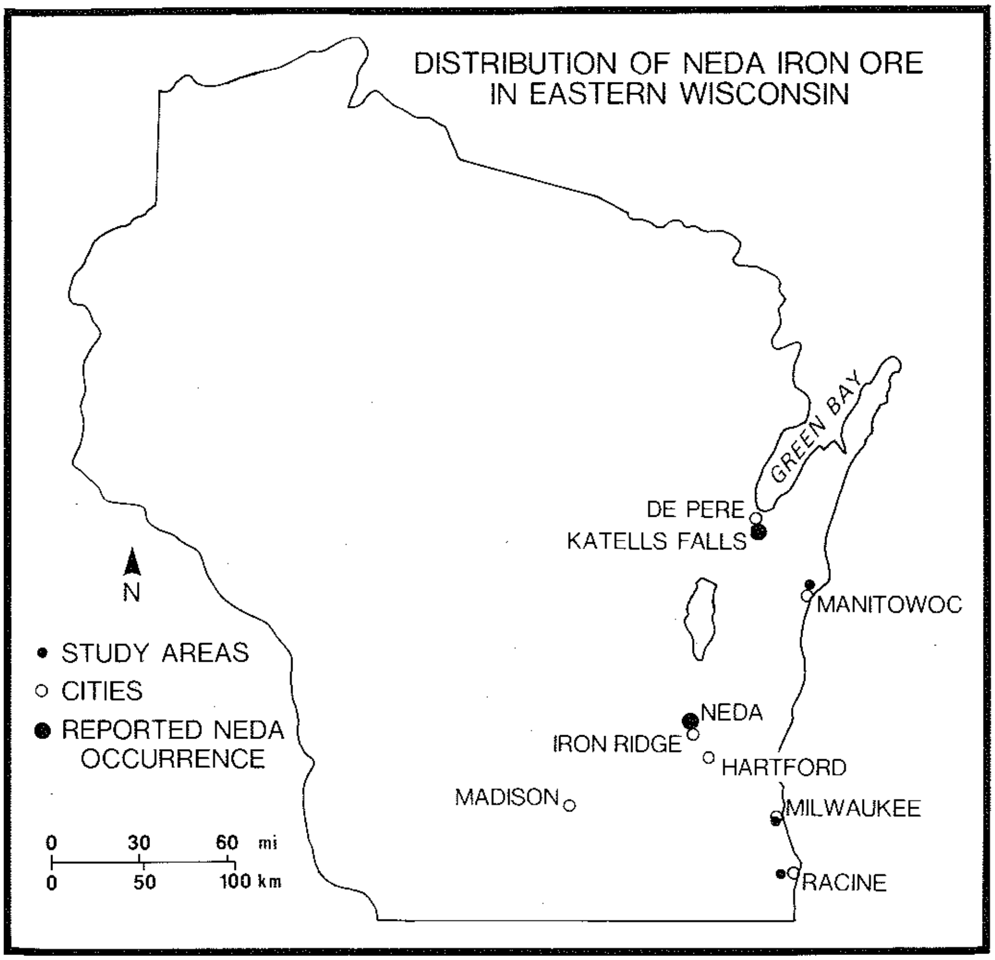

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Figure 1. Study areas and other Neda occurrences.

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.

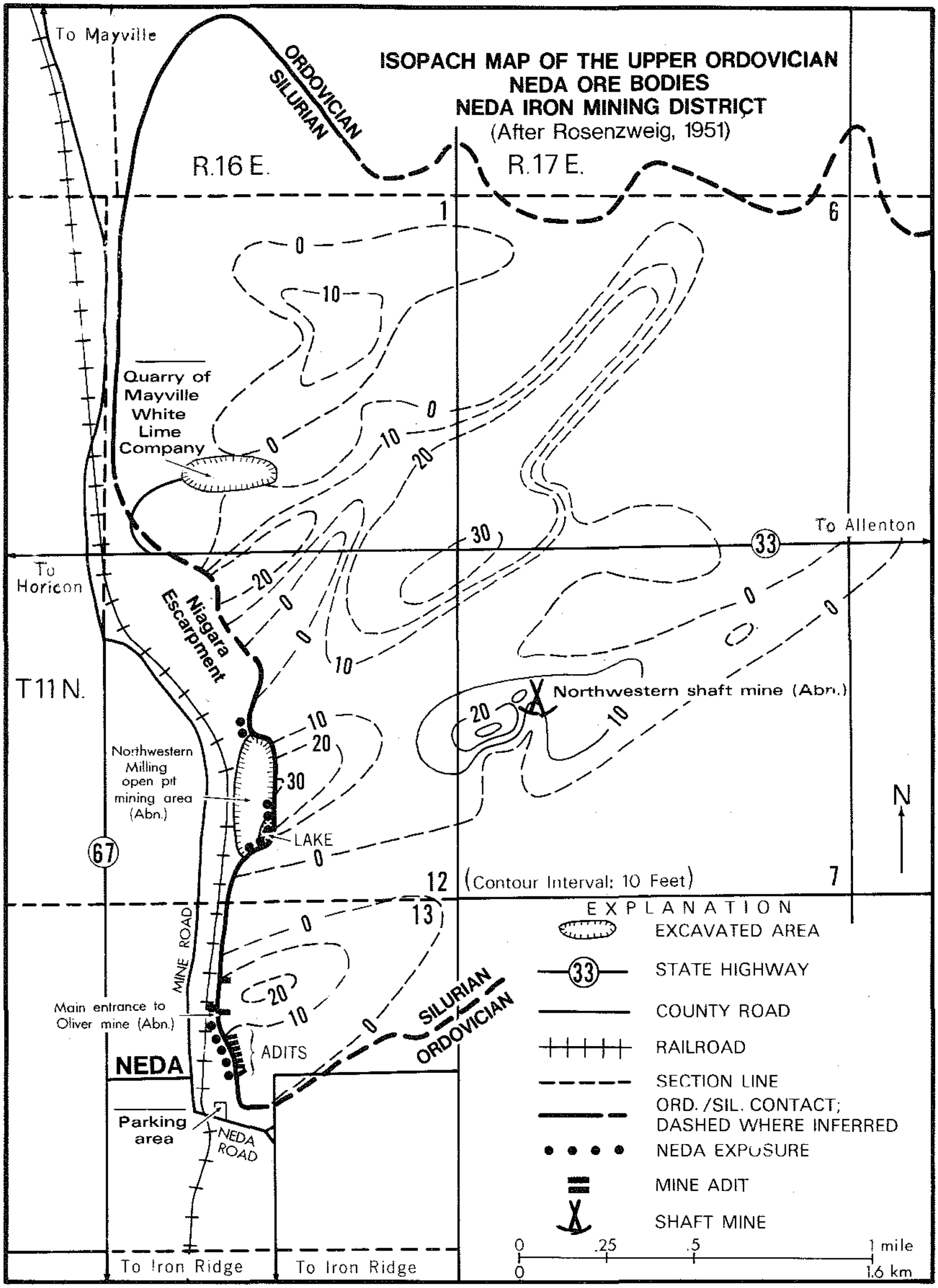


Figure 2. Isopach map of the Neda Formation at the type area near Neda, Wisconsin (modified from Rosenzweig, 1951; and Paull, 1977, p. C-2.

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-

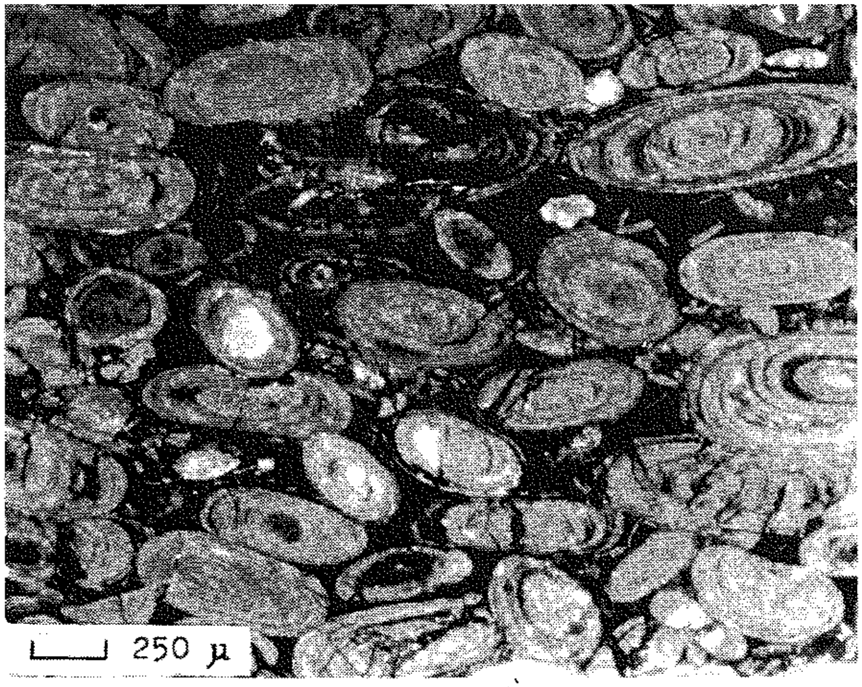


Figure 3. Photomicrograph of the soft, oolitic part of the Neda Formation at the type locality. The highly deformed, often fractured, ooids are oriented sub-parallel to bedding. Thin section is normal to bedding. Uncrossed nicols; white bar is 250 microns.

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

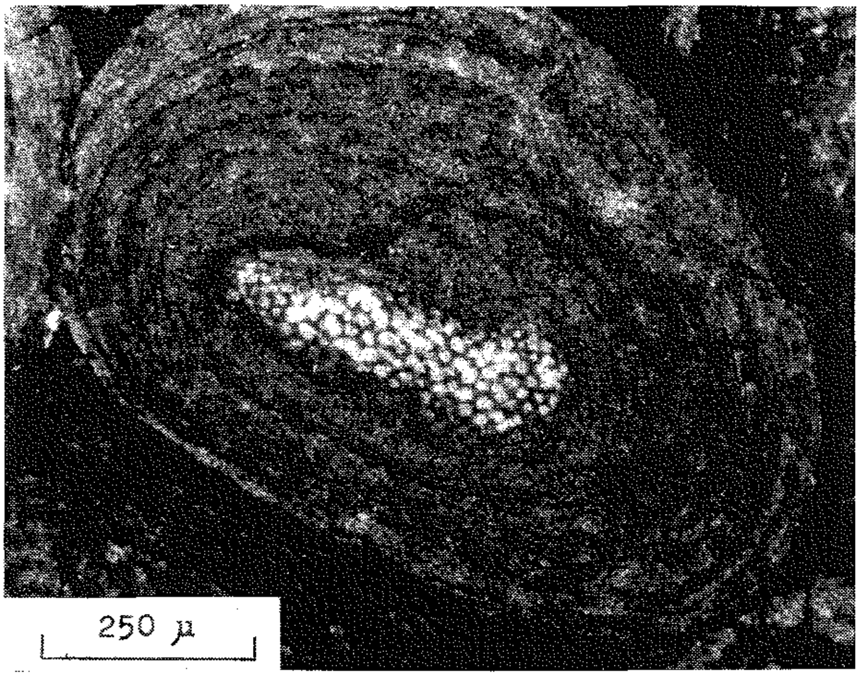


Figure 4. Photomicrograph of an ooid with a ferruginized fossil fragment as a nucleus. Uncrossed nicols; white bar is 250 microns.

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.

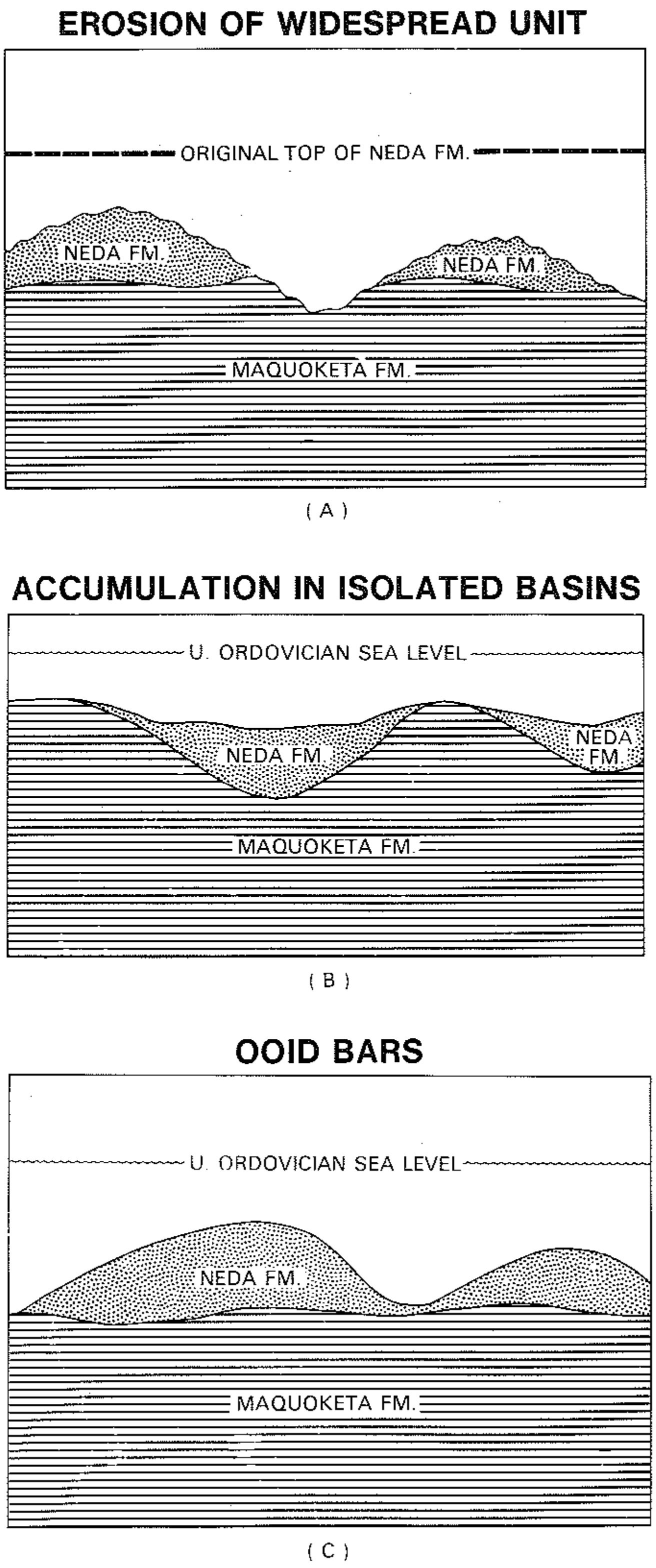
Samples from the Neda and Mayville were slabbed, sectioned, and processed for microfossils. Four kilograms of oolitic Neda were examined for microfossils during this study in an unsuccessful attempt to refine the age of the Neda. The five samples of basal Mayville processed for conodonts yielded only 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.

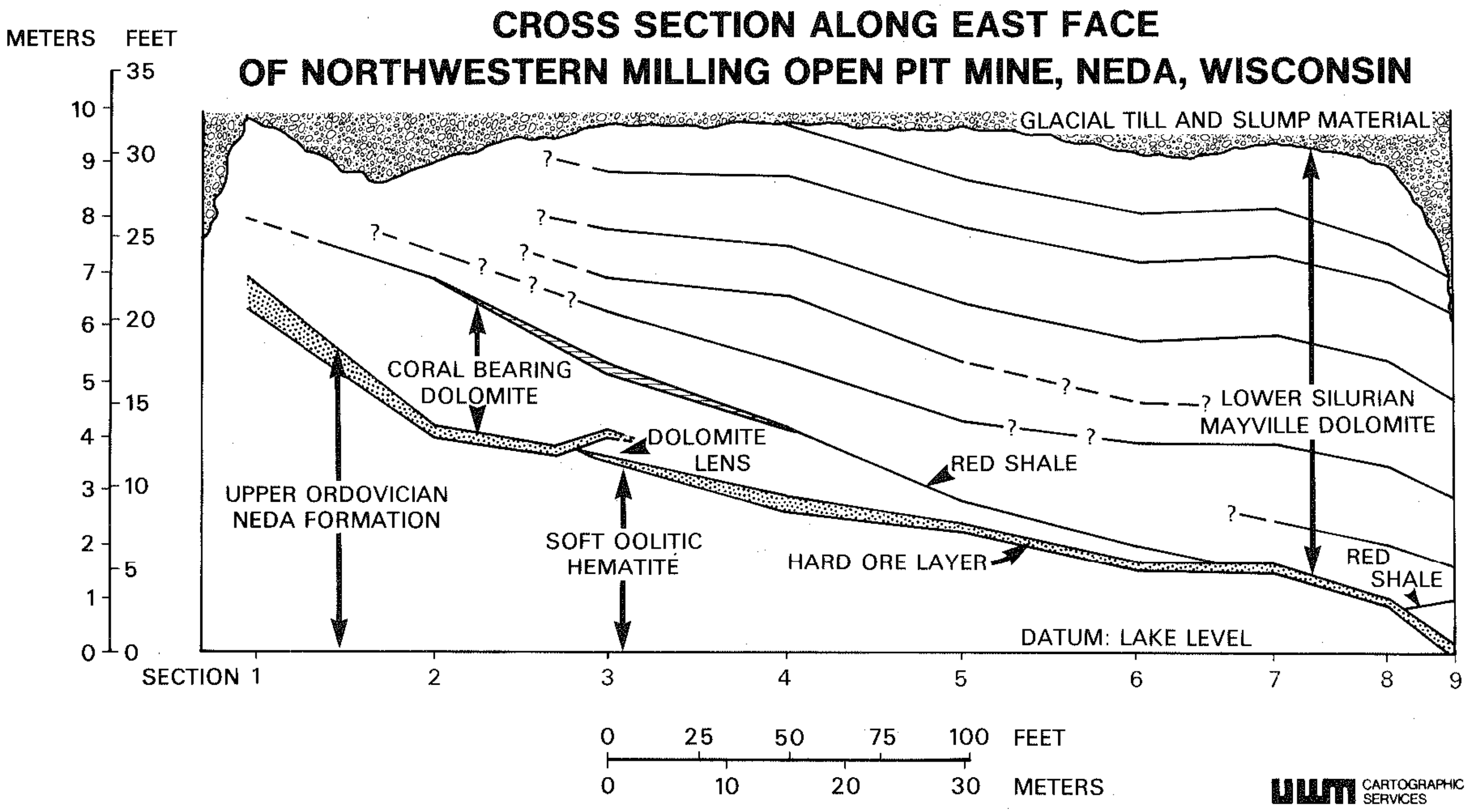


Figure 6. Cross section displaying nine closely spaced measured sections of the upper part of the Neda Formation and the lower part of the Mayville Dolomite at the open pit mine near Neda, Wisconsin. Higher beds in the Mayville generally maintain thickness while rising over what may be a mound on the 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.

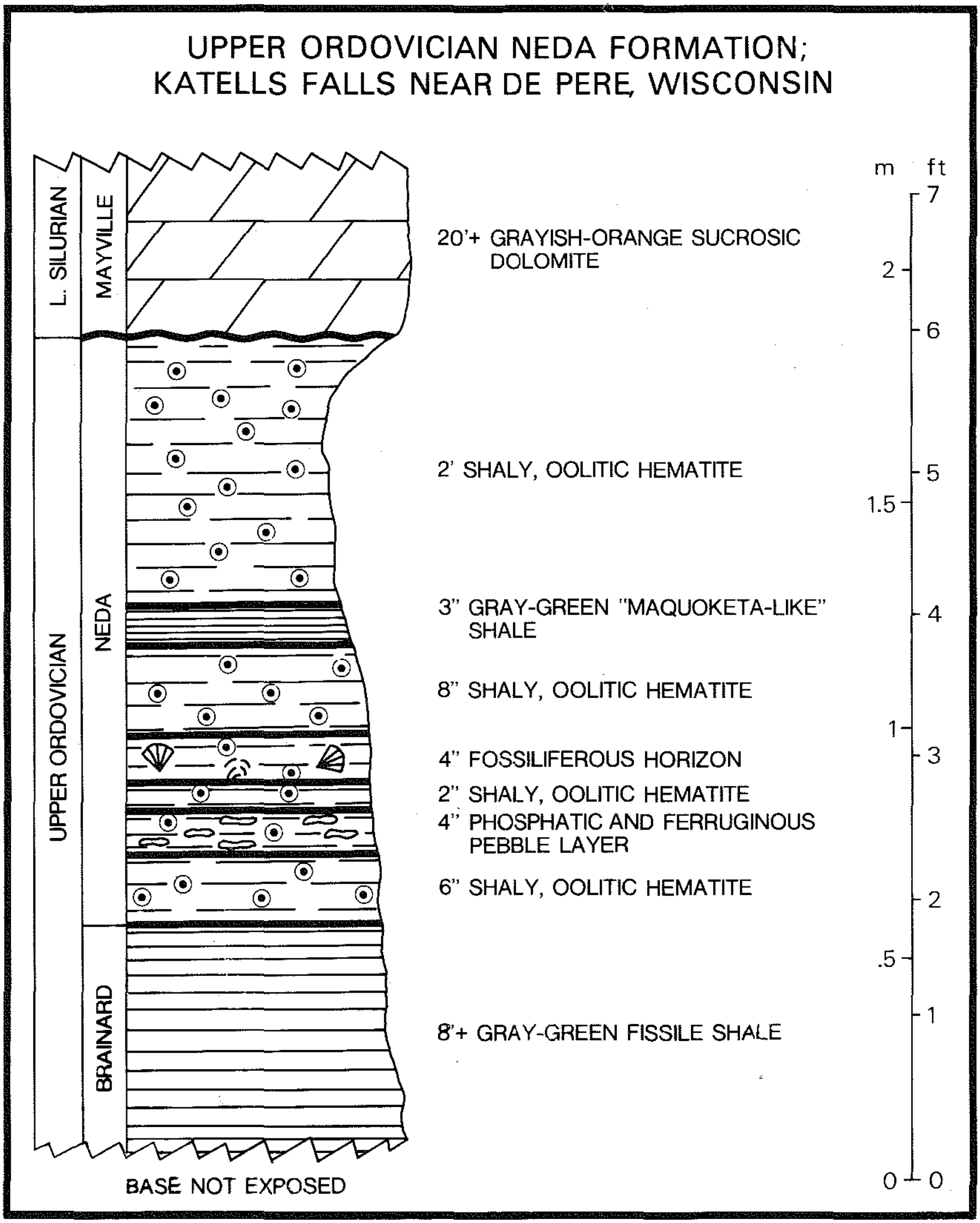


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Figure 7. Neda Formation at Katells Falls near De Pere, Wisconsin. The heavier lines define the limits of each unit described.

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

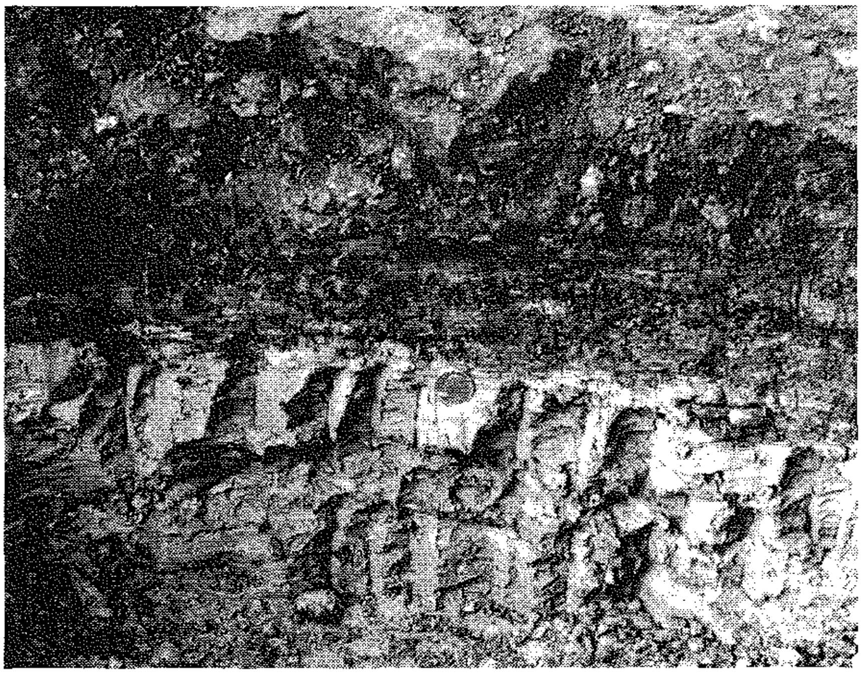

Figure 8. Neda-Brainard contact along the northwestern shoreline of the flooded open pit mine near Neda, Wisconsin. The basal Neda consists of a 0.3 m gradational interval with abundant ferruginous and phosphatic pebbles. A quarter of a dollar immediately underlies the contact, and provides scale.

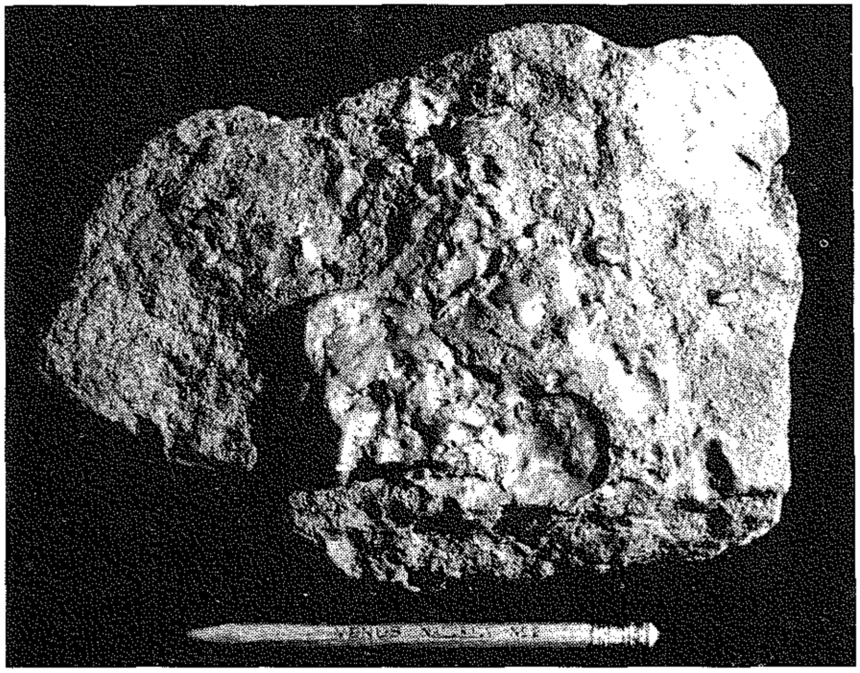

Figure 9. Highly polished, intensely burrowed, hematitic and phosphatic pebbles in a matrix of ferruginous ooids are characteristic of the basal Neda shown in figure 8.

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.

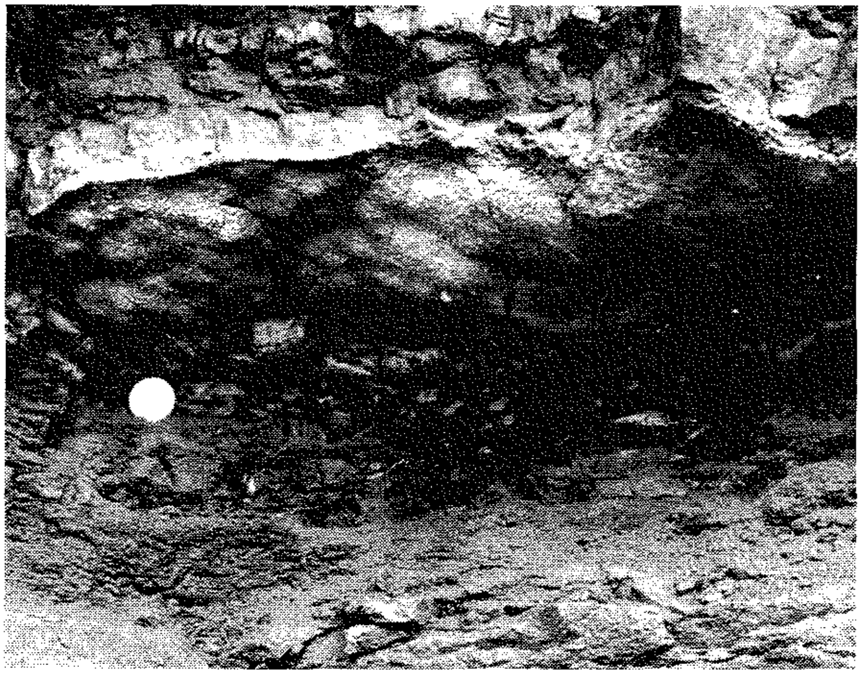

Figure 12. This small mound of ferruginous ooids intrudes the "hard ore" layer at the top of the Neda, and appears to deform the overlying Mayville Dolomite.

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.

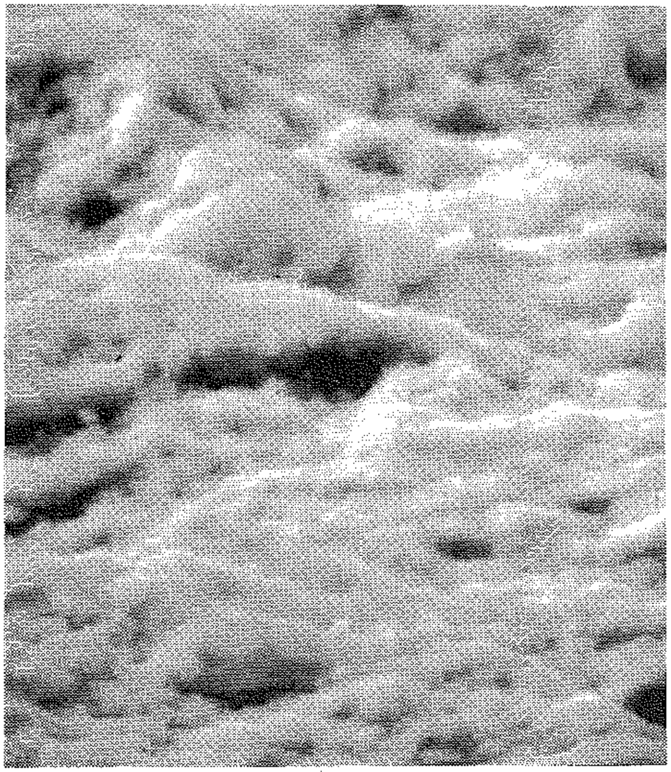

Figure 15. Enlarged part of figure 14 displays tangential-concentric internal fabric typical of Neda ooids (1500 X).

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