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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-

[1]Department of Geology, University of Illinois, 1301 W. Green Str., Urbana, Illinois 61801

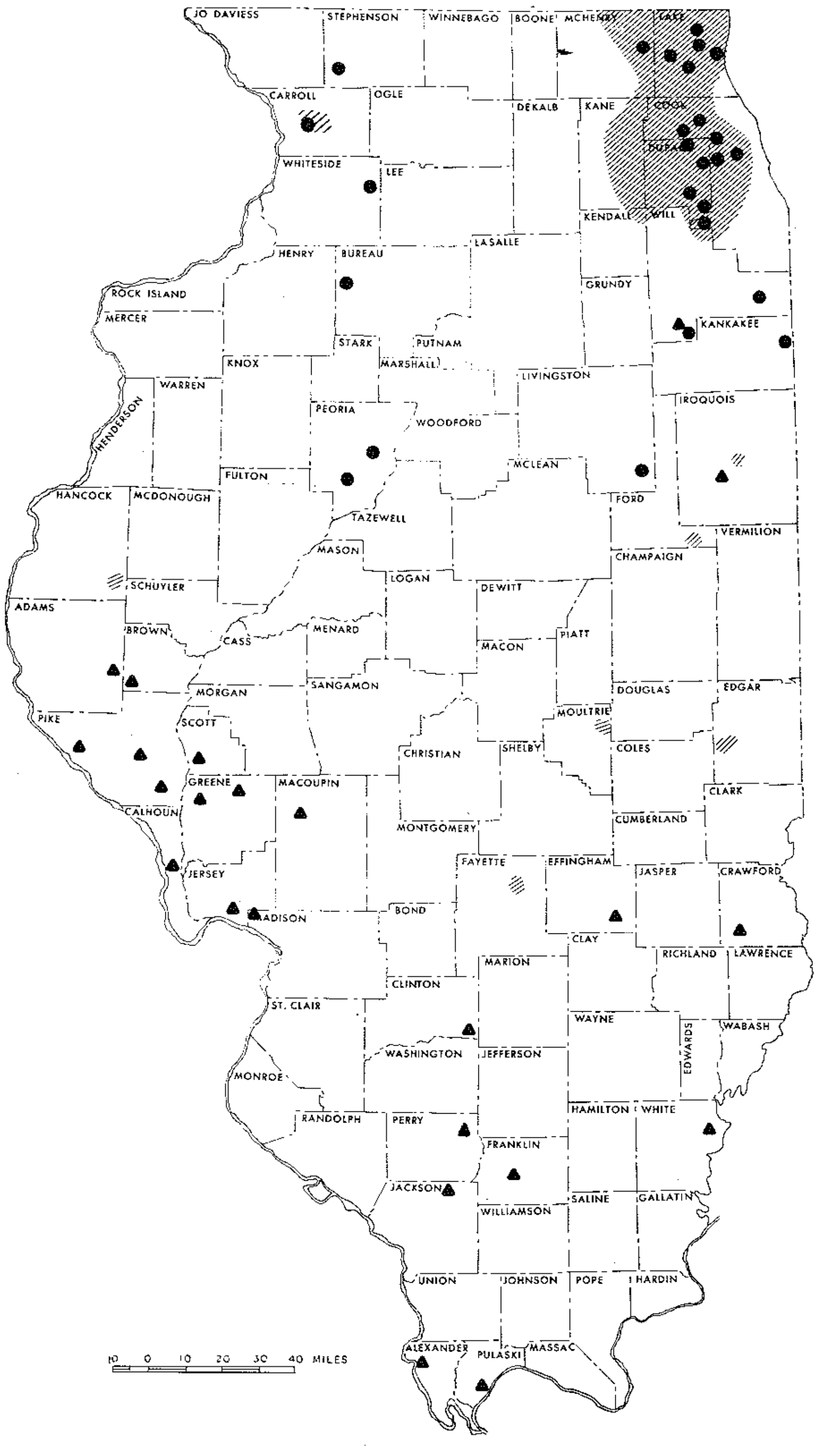

Figure 1. Map showing oolite occurrences at the Ordovician-Silurian boundary in Illinois. Circles - ferruginous oolite (Neda Formation); triangles - calcareous oolite (Noix Oolite); diagonal ruling - red nonoolitic strata, generally mudstone, at the top of the Maquoketa Group. Both calcareous and ferruginous 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.

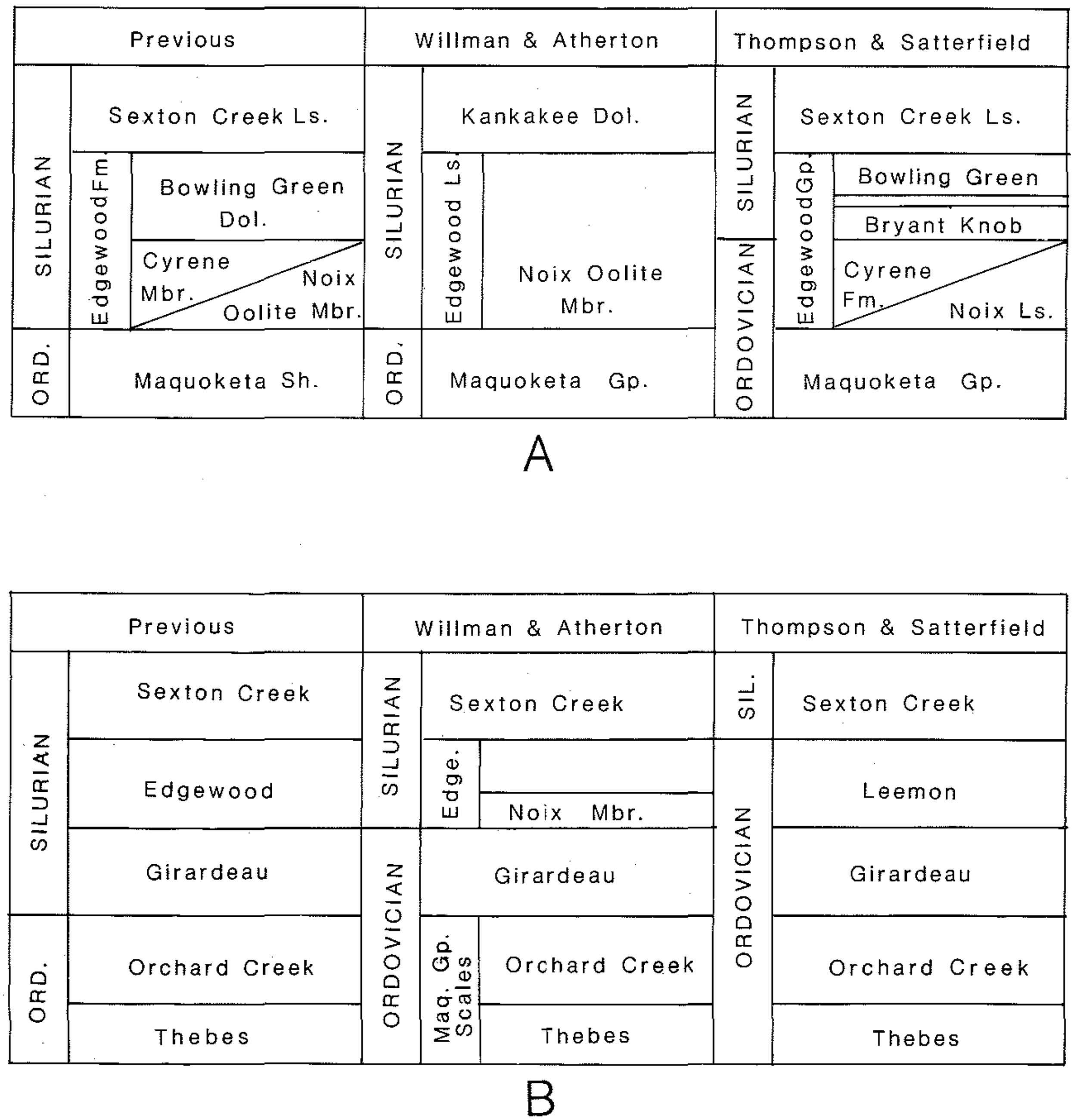

Figure 2. Stratigraphic relationship and nomenclature of strata contiguous to the Ordovician-Silurian boundary in: A - western Illinois and northeastern Missouri and B - southern Illinois and southeastern Missouri. First column gives nomenclature prior to 1975; columns 2 and 3 give Willman and Atherton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

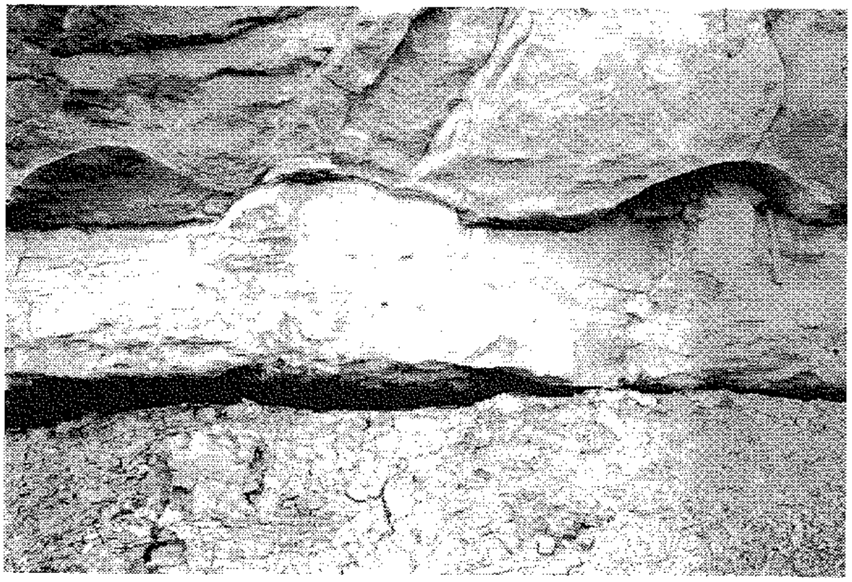

Figure 3. Noix Oolite outcrop, Clarksville roadcut, Pike County, Missouri (see Kluessendorf, 1989 for location). Noix is center unit; observe undulating upper contact with Silurian Bowling Green Dolomite and relatively planar lower contact with Ordovician Maquoketa Shale.

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-

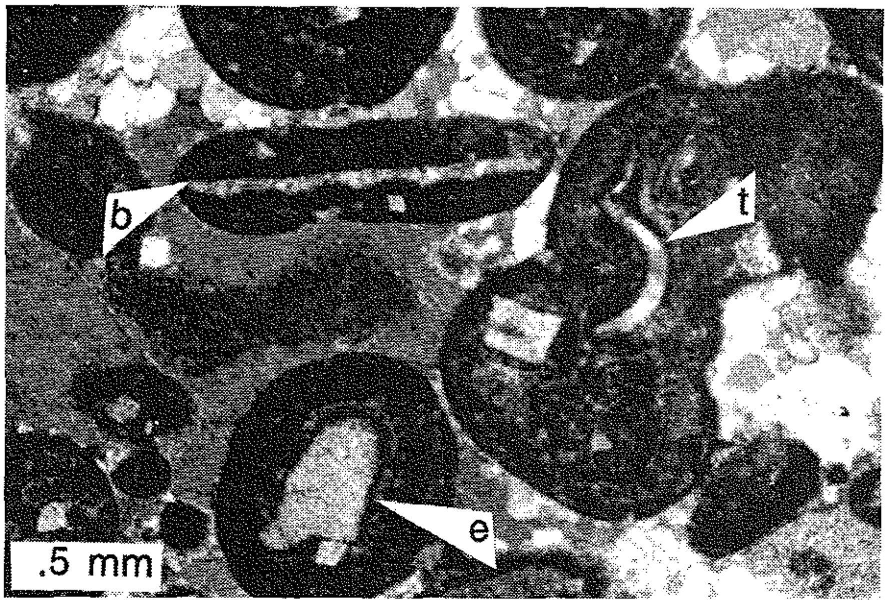

Figure 4. Photomicrograph of the Noix Oolite from the Clarksville Roadcut (see fig. 3). Poorly-sorted calcite ooids with concentric cortical layers in sparry calcite cement. Ooid nuclei include: brachiopod (b) trilobite (t) and echinoderm (e) fragments; however, nuclei are not always apparent. Euhedral 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

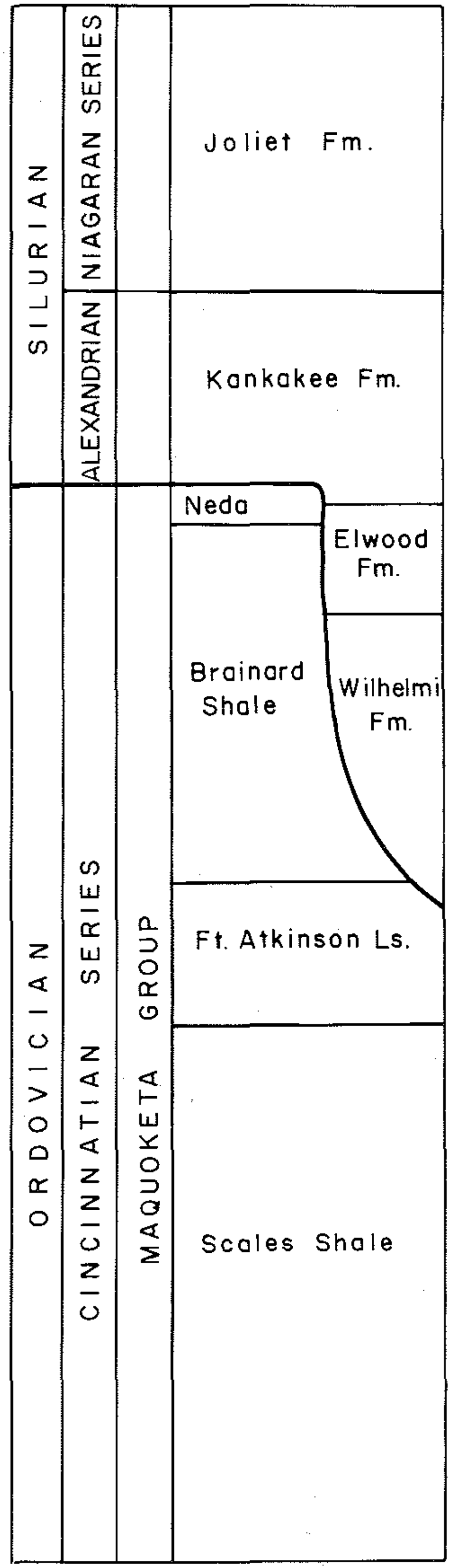

Figure 5. Stratigraphic relationship of strata contiguous to the Ordovician-Silurian boundary in northern Illinois in the area of ferruginous Neda Formation occurrence.

(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-

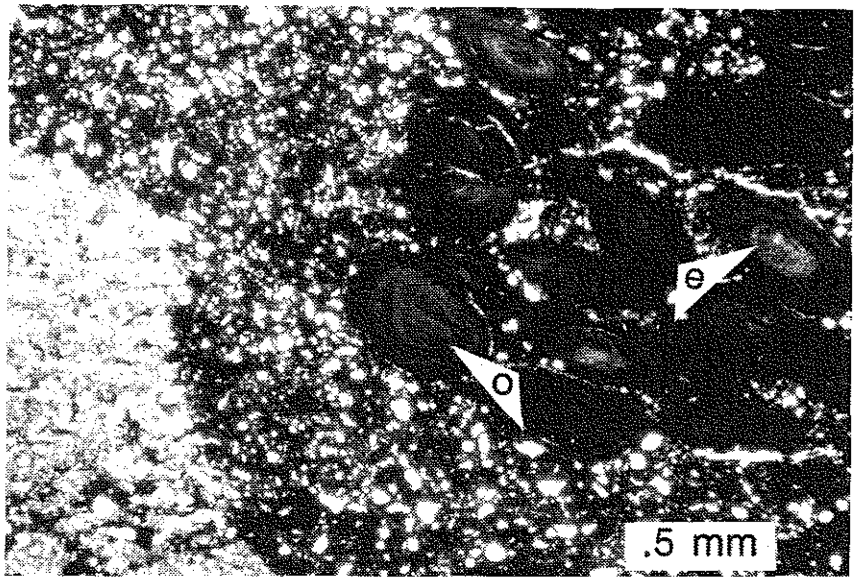

Figure 6. Photomicrograph of the Neda Formation from Chippewa Campground, Kankakee River State Park, Will County, Illinois (see Kuessendorf, 1991). Oblate goethitic ooids in burrow-fill within ferruginous siltstone. Ooids are concentrically layered; nuclei include: broken ooids (o); echinoderm fragments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

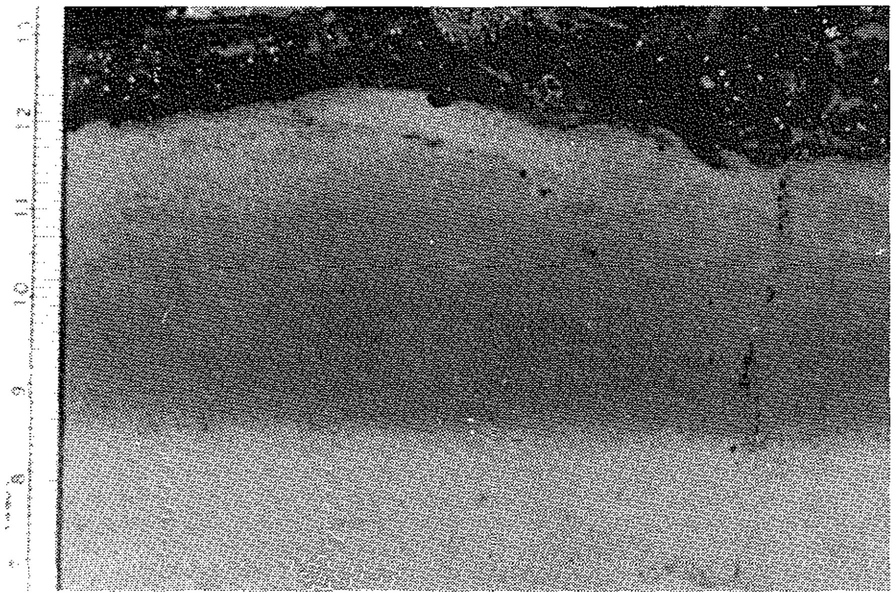

Figure 7. Polished slab from transition oolite (see Kluessendorf, 1989) showing phosphatized Brainard Shale surface (darkest) with calcite ooids in phosphatic nodules and burrow-fills. Rest of Brainard in photo is sideritic siltstone, more weakly sideritized downwards. Scale in mm.

(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,

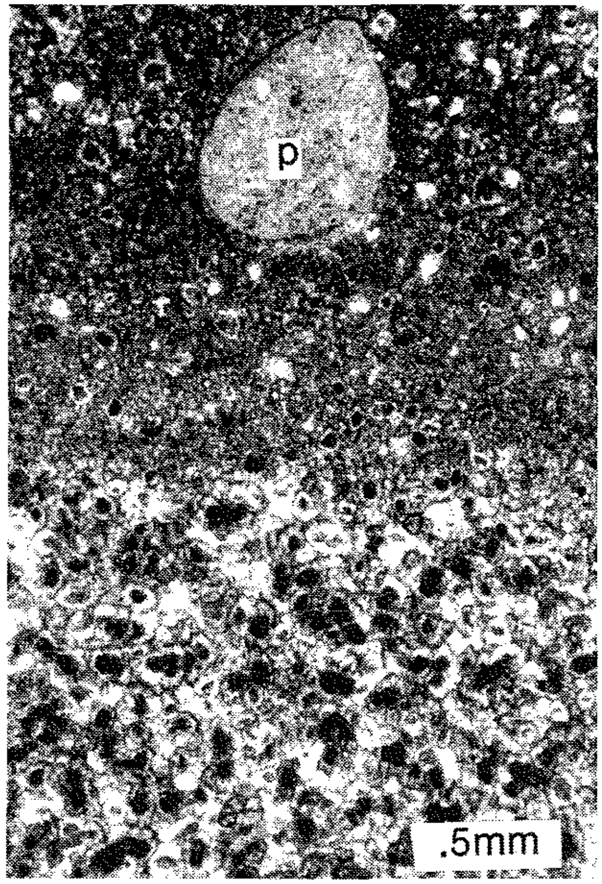

Figure 8. Photomicrograph of the top of the Brainard Shale at the transition oolite showing sideritic siltstone phosphatized in upper half of photo. Phosphatic nodule (P) contains no ooids. Crossed nichols.

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^{o}) latitudes (Ziegler and others, 1979). Warm shallow seas covered much of the area, and arid conditions prevailed at about 20^{o} 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

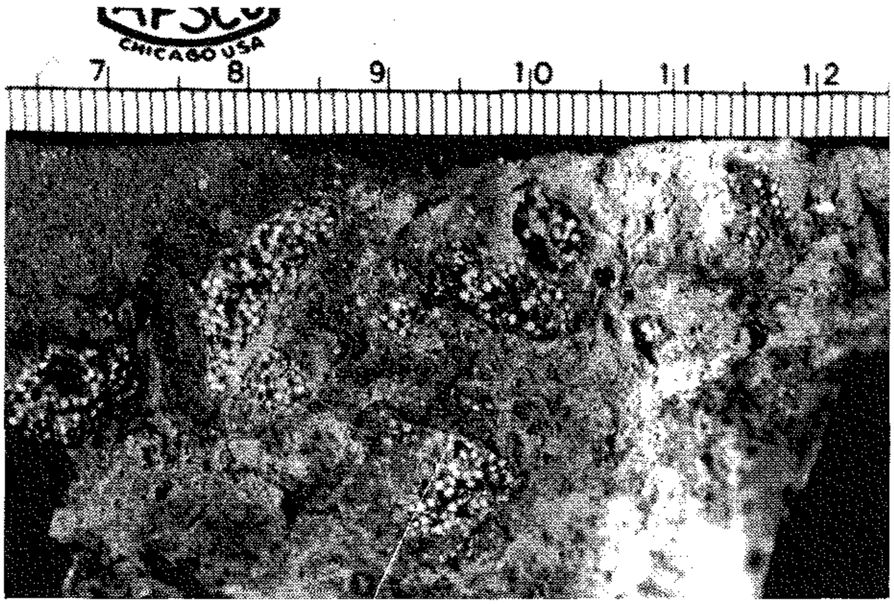

Figure 9. Slab from top of the Brainard Shale at the transition oolite showing spherical calcite ooids (white) and oomoldic pores (black) concentrated in phosphatic nodules and phosphatized burrow-fills. Scale in mm.

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.

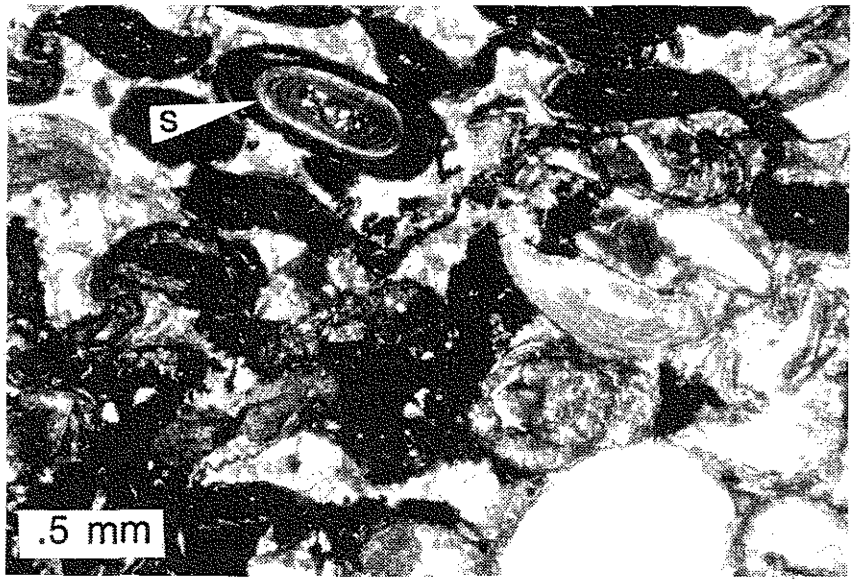

Figure 10. Photomicrograph of transition oolite showing sideritic (lighter colored, generally subspherical) ooids at lower right and oblate to spastolithic ooids at upper left. Best-formed goethitic ooid has a siltstone nucleus (s). Plane light; thin section cut somewhat thicker than normal.

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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REFERENCES CITED

Amsden, T.W., 1974, Late Ordovician and early Silurian articulate brachiopods from Oklahoma, southwestern Illinois, and eastern Missouri: Oklahoma Geological Survey Bulletin 119, 154 p.

Athy, L.F., 1928, Geology and mineral resources of the Herscher quadrangle: Illinois State Geological Survey Bulletin 55, 120 p.

Bambach, R.K., Scotese, C.R., and Ziegler, A.M., 1980, Before Pangea: The geographies of the Paleozoic world: American Scientist, v. 68, p. 26-38.

Bentor, Y.K., 1980, Phosphorites--the unsolved problems: *in* Marine phosphorites, Y.K. Bentor, ed;, Society of Economic Paleontologists and Mineralogists Special Publication No. 29, p. 3-18.

Berry, W.B.N., and Boucot, A.J., 1973, Glacio-eustatic control of late Ordovician-early Silurian platform sedimentation and faunal changes. Geological Society of America Bulletin, v. 84, p. 275-284.

Birch, G.F., 1979, Phosphorite pellets and rocks from the western continental margin and adjacent coastal terrace of South Africa: Marine Geology, v. 33, p. 91-116.

Bromley, R.G., 1967, Marine phosphorites as depth indicators: Marine Geology, v. 5, p. 503-309.

Brown, C.E., and Whitlow, J.W., 1960, Geology of the Dubuque South quadrangle Iowa-Illinois, geology of parts of the Upper Mississippi Valley lead-zinc district: United States Geological Survey Bulletin 1123A, 93 p.

Buschbach, T.C., 1964, Cambrian and Ordovician strata of northeastern Illinois. Illinois State Geological Survey Report of Investigations 218, 90 p.

Bushinski, G.I., 1964, On shallow-water origin of phosphorite sediments: *in* Deltaic and shallow marine deposits, L.M.J.U. van Straaten, ed., Developments in Sedimentology, v. 1, Elsevier, Amsterdam, p. 62-70.

Chamberlin, T.C., 1877, Geology of eastern Wisconsin: *in* Geology of Wisconsin, survey of 1873-1877, T.C. Chamberlin, ed., v. 2, pt. 2, p. 91-405.

Dreesen, Roland, 1982, Storm-generated oolitic ironstones of the Famennian (Falb-Fa2a) in the Vesdre and Dinanta Synclinoria (Upper Devonian, Belgium). Annales de la Societe Geologique de Belgique, v. 105, p. 105-129.

DuBois, E.P., 1945, Subsurface relations of the Maquoketa and "Trenton" formations in Illinois: Illinois State Geological Survey Report of Investigations 105, p. 1-34.

Fuller, M.L., and Sanford, S., 1906, Record of deep-well drilling for 1905: United States Geological Survey Bulletin 298, p. 299.

Gray, H.H., 1972, Lithostratigraphy of the Maquoketa Group (Ordovician) in Indiana: Indiana Geological Survey Special Report 7, 31 p.

Hall, James, 1851, Upper Silurian and Devonian series: *in* Report on the geology of the Lake Superior land district, pt. 2, J.W. Foster and J.D. Whitney, eds., United States 32nd Congress, Special Session, Senate Executive Document No. 4, p. 152-166.

Harris, P.M., 1979, Facies anatomy and diagenesis of a Bahamian ooid shoal: Sedimenta VII, Rosenthiel School of Marine and Atmospheric Sciences, Miami, 163 p.

Hawley, J.E., and Beavan, A.P., 1934, Mineralogy and genesis of the Mayville iron ore of Wisconsin: American Mineralogist, v. 19, p. 493-514.

Kean, W.F., 1981, Paleomagnetism of the late Ordovician Neda Iron Ore from Wisconsin, Iowa and Illinois: Geophysical Research Letters, v. 8, p. 880-882

Keyes, C.R., 1898, Some geological formations of the Cap-au-Gres uplift: Iowa Academy of Sciences Proceedings, v. 5, p. 58-63.

Kimberley, M.M., 1979, Origin of oolitic iron formations: Journal of Sedimentary Petrology, v. 49, p. 111-132.

Kolata, D.R., and Graese, A.M., 1983, Lithostratigraphy and depositional environments of the Maquoketa Group (Ordovician) in Illinois: Illinois State Geological Survey Circular 528, 49 p.

Kluessendorf, Joanne, 1991, Location of Noix Oolite and Neda Formatioon outcrops and subsurface samples: Wisconsin Geological and Natural History Survey Open-file Report 91-1, 24 p.

Liebe, R.M., and Rexroad, C.B., 1977, Conodonts from Alexandrian and early Niagaran rocks in the Joliet, Illinois, area: Journal of Paleontology, v. 51, p. 844-857.

McCracken, A.D., and Barnes, C.R., 1982, Restudy of conodonts (late Ordovician-early Silurian) from the Edgewood Group, Clarksville, Missouri: Canadian Journal of Earth Sciences, v. 19, p. 1474-1485.

McKerrow, W.S., 1979, Ordovician and Silurian changes in sealevel: Geological Society of London Journal, v. 136, p. 137-145.

Mikulic, D.G., 1979, The paleoecology of Silurian trilobites, with a section on the Silurian stratigraphy of southeastern Wisconsin: Corvallis, Oregon State University, Ph.D. thesis, 864 p.

Mikulic, D.G., 1983, Calcareous and hematitic oolites at the Ordovician-Silurian boundary of the central United States: Geological Society of America Abstracts with Program (North Central Section, 17th Annual Meeting (Madison)) v. 15, no. XX, p. 222.

Mikulic, D.G., and Kluessendorf, Joanne, 1983, The oolitic Neda Iron Ore (upper Ordovician?) of eastern Wisconsin: Geological Society of America North Central Section, 17th Annual Meeting (Madison), Field Trip Guidebook, , 54 p.

Nahon, D., Carozzi, A.V., and Parron, C., 1980, Lateritic weathering as a mechanism for generation of ferruginous ooids: Journal of Sedimentary Petrology, v. 50, p. 1287-1298.

Nurmi, R.D., 1972, Upper Ordovician stratigraphy of the Lower Peninsula of Michigan: M.S. thesis (Geology), Michigan State University, Kalamazoo.

Odin, G.S., and Letolle, R., 1980, Glauconitization and phosphatization environments: a tentative comparison, *in* Y.K. Bentor, ed., Marine phosphorites: Society of Economic Paleontologists and Mineralogists Special Publication No. 29, p. 227-237.

Ostrom, M.E., 1967, Paleozoic stratigraphic nomenclature for Wisconsin: Wisconsin Geological and Natural History Survey Information Circular No. 8.

Parker, M.C., 1971, The Maquoketa Formation (upper Ordovician) in Iowa: Iowa Geological Survey Miscellaneous Map Series No. 1.

Pedley, H.M., and Bennett, S.M., 1985, Phosphorites, hardgrounds and syndepositional solution subsidence: a paleoenvironmental model from the Miocene of the Maltese Islands: Sedimentary Geology, v. 45, p. 1-34.

Petranek, J., 1964, Shallow-water origin of early Paleozoic oolitic iron ores, *in* L.M.J.U. van Straaten, ed., Deltaic and shallow marine deposits, Developments in Sedimentology Vol. 1: Amsterdam, Elsevier, p. 319-322.

Pryor, W.A., and Ross, C.A., 1962, Geology of the Illinois parts of the Cairo, LaCenter and Thebes quadrangles: Illinois State Geological Survey Circular 332, 39 p.

Rogers, J.E., Jr., 1972, Silurian and lower Devonian stratigraphy and paleobasin development: Illinois Basin-central United States: Urbana-Champaign, University of Illinois, Ph.D. thesis 144 p.

Rosenzweig, A., 1951, Neda Iron Ore of eastern Wisconsin: Madison, University of Wisconsin, M.S. thesis, 57 p.

Rubey, W.W., 1952, Geology and mineral resources of the Hardin and Brussels quadrangles (in Illinois): United States Geological Survey Professional Paper 218, 179 p.

Savage, T.E., 1908, On the lower Paleozoic stratigraphy of southeastern Illinois: American Journal of Science, series 4, v. 25, p. 431-443.

Savage, T.E., 1909, The Ordovician and Silurian formations in Alexander County, Illinois: American Journal of Science, series 4, v. 28, p. 509-519.

Savage, T.E., 1913, Alexandrian Series in Missouri and Illinois: Geological Society of America Bulletin, v. 24, p. 351-376.

Savage, T.E., 1916, Alexandrian rocks in northeastern Illinois and eastern Wisconsin: Geological Society of America Bulletin, v. 27, p. 305-324.

Savage, T.E., and Ross, C.S., 1916, The age of the iron ore in eastern Wisconsin: American Journal of Science, series 4, v. 41, p. 187-193.

Sheehan, P.M., 1973, The relation of late Ordovician glaciation to the Ordovician-Silurian changeover in North American brachiopod faunas: Lethaia, v. 6, p. 147-155.

Synowiec, K.A., 1981, Stratigraphy of the Neda Formation in eastern Wisconsin, northern Illinois, and eastern Iowa: University of Wisconsin-Milwaukee, M.S. thesis, 115 p.

Templeton, J.S., and Willman, H.B., 1963, Champlainian Series (middle Ordovician) in Illinois: Illinois State Geological Survey Bulletin, v. 89, 260 p.

Thwaites, F.T., 1923, The Paleozoic rocks found in deep wells in Wisconsin and northern Illinois: Journal of Geology, v. 31, p. 529-555.

Thompson, T.L., and Satterfield, I.R., 1975, Stratigraphy and conodont biostratigraphy of strata contiguous to Ordovician-Silurian boundary in eastern Missouri: Missouri Geological Survey, studies in Stratigraphy No. 5, Report of Investigations 57, pt. 2, p. 61-108.

Ulrich, E.O., 1924, Notes on new names in table of formations and on physical evidence of breaks between Paleozoic systems in Wisconsin: Wisconsin Academy of Sciences, Arts and Letters Transactions, v. 21, p. 71-107.

Weller, J.M., and Ekblaw, G.E., 1940, Preliminary geologic map of parts of the Alto Pass, Jonesboro and Thebes quadrangles: Illinois State Geological Survey Report of Investigations 70, 26 p.

Whitlow, J.W., and Brown, C.E., 1963, The Ordovician-Silurian contact in Dubuque County, Iowa: United States Geological Survey Professional Paper 475C, p. C11-C13.

Willman, H.B., 1973, Rock stratigraphy of the Silurian System in northeastern and northwestern Illinois: Illinois State Geological Survey Circular 479, 55 p.

Willman, H.B., and Atherton, Elwood, 1975, Silurian System, *in* H.B. Willman, and others, eds., Handbook of Illinois stratigraphy, Illinois State Geological Survey Bulletin, v. 95, p. 87-104.

Willman, H.B., and Buschbach, T.C., 1975 Ordovician System: *in* H.B. Willman, and others, eds., Handbook of Illinois stratigraphy: Illinois State Geological Survey Bulletin, v. 95, P. 47-87.

Witzke, B.J., and Heathcoate, R.C., 1983, The distribution, composition and deposition of the upper Ordovician Neda Member in Iowa: Geological Society of America Abstracts with Program (North Central Section, 17th Annual Meeting (Madison)) v. 15, no. XX, p. 222.

Workman, L.E., 1950, The Neda Formation in northeastern Illinois: Illinois Academy of Sciences Transactions, v. 43, p. 176-182.

Worthen, A.H., 1870, Geology of Calhoun County: *in* Geological Survey of Illinois, A.H. Worthen, ed., v. IV, Geology and paleontology, p. 1-23.

Ziegler, A.M., Scotese, C.R., McKerrow, W.S., Johnson, M.E., and Bambach, R.K., 1979, Paleozoic paleogeography: Annual Review of Earth and Planetary Sciences, v. 7, p. 473-502.