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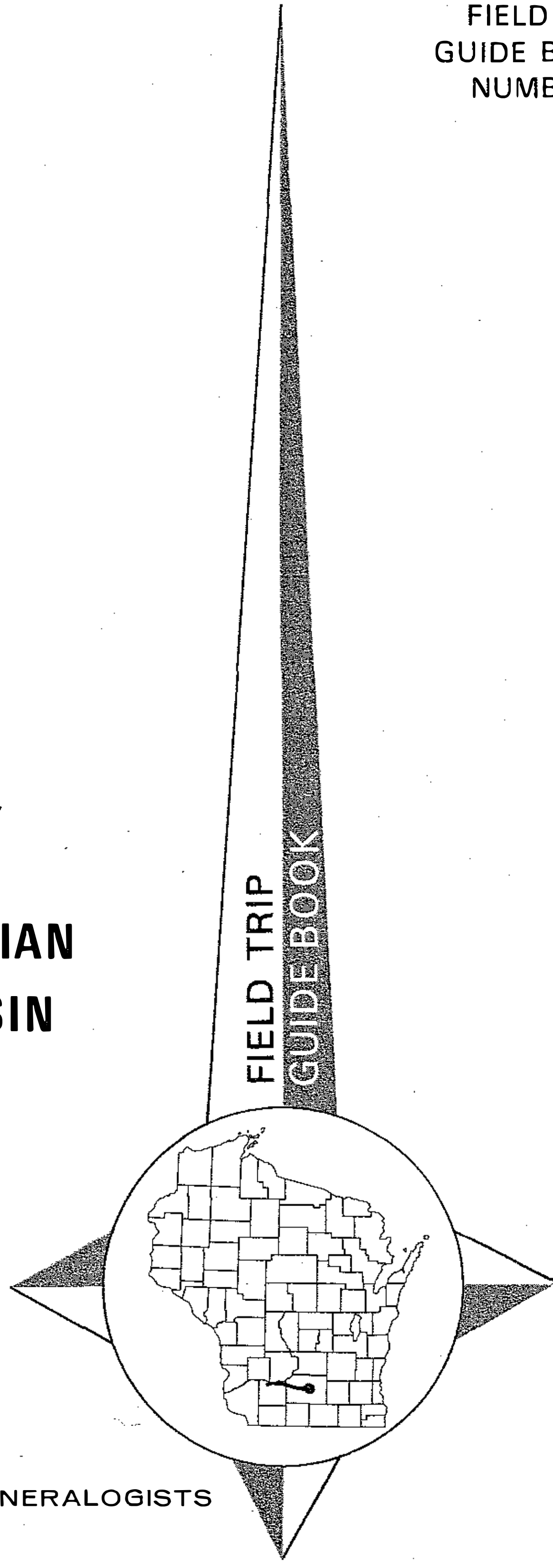
Meredith E. Ostrom, State Geologist and Director

FIELD TRIP
GUIDE BOOK
NUMBER 3
1978

LITHOSTRATIGRAPHY, PETROLOGY, AND SEDIMENTOLOGY OF LATE CAMBRIAN–EARLY ORDOVICIAN ROCKS NEAR MADISON, WISCONSIN

with special papers



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Field Trip Guide Book
Number 3

University of Wisconsin-Extension
GEOLOGICAL AND NATURAL HISTORY SURVEY
M. E. Ostrom, State Geologist

LITHOSTRATIGRAPHY, PETROLOGY, AND SEDIMENTOLOGY OF LATE CAMBRIAN-EARLY ORDOVICIAN ROCKS NEAR MADISON, WISCONSIN

Special Papers

Stratigraphic Relations of Lower Paleozoic Rocks of Wisconsin
Meredith E. Ostrom

Lithostratigraphy, Petrology, and Sedimentology of the Jordan Formation near Madison, Wisconsin
I. Edgar Odom and Meredith E. Ostrom

Mineralogy of Cambrian Sandstones, Upper Mississippi Valley
I. Edgar Odom

Sedimentology of Upper Cambrian Cross-Bedded Sandstone Facies as Exemplified by the Van Oser Sandstone
Robert H. Dott, Jr.

Depositional Environments of Fine-Grained Upper Cambrian Lithofacies
Charles W. Byers

Stratigraphy and Petrology of the Lower Oneota Dolomite (Ordovician), South-Central Wisconsin
Richard L. Adams

Lithostratigraphy and Sedimentology of the Lone Rock and Mazomanie Formations
I. Edgar Odom

Field Trip Committee and Leaders

I. Edgar Odom, Chairman
Meredith E. Ostrom, Robert H. Dott, Jr.
Charles W. Byers, Robert C. Morris, and Richard A. Adams

Prepared for

The Eighth Annual Meeting
Great Lakes Section
Society of Economic Paleontologists and Mineralogists
Madison, Wisconsin
September 30 and October 1, 1978

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1978

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INTRODUCTION

"The seas came in and the seas went out" and "when you've seen one you've seen'em all". Perhaps you have heard these fallacious expressions used (hopefully in jest) by some geologists (even in the presence of students) to describe the "layer cake" lithic units and the depositional processes of the Late Cambrian to Middle Ordovician stratigraphic sequence in the Upper Mississippi Valley. The extensive past literature pertaining to these rocks contains innumerable references to the monotonous quartz sandstones that compose the "entire" St. Croixan Series, to dolomitization of the carbonates that has erased all evidence of primary textures and structures, and to the repetition of pancake-like lithic units that extend for hundreds of miles.

So, What's New? During this field conference you will be privileged to examine, to observe, to ponder and to reflect upon: (1) thick lithic units composed of feldspathic, indeed even arkosic, sandstones sandwiched among thick units of super-mature quartzose sandstones, both of which were derived from the same provenance and deposited hundreds of miles from a possible gneiss, granite or other source, (2) the striking influence of textural properties, especially grain size, on the mineral composition of sandstones, (3) the presence of abundant K-feldspar, a large part of which is authigenic (no plagioclase), (4) build-up-type bar and shoal quartzose sands that intertongue with shoreface and shallow inner shelf glauconitic and feldspathic sands, which in turn intertongue with very fine highly feldspathic sands and shales deposited in only slightly deeper water, (5) possibly tidal-influenced, littoral bar, shoal, and spit deposits juxtapose with (local) subtidal lagoon deposits, (6) tenable solutions to several perplexing stratigraphic problems, (7) littoral, dolomitic sandstones that grade upward into sandy, "oolitic" dolostones, which may represent "oolite" shoals formed around stromatolite mounds, (8) pure dolostones in which the primary textures and structures, including stromatoliths, are remarkably well-preserved, that are believed to represent intertidal hypersaline environments, (9) algal "reef" structures that developed along the trend of a tectonic arch, and (10) myriads of trace fossils, which may or may not be the "infallible key" to the depositional environments. These and other intriguing lithic, sedimentologic, and biogenic features are displayed by the Oneota, Jordan, St. Lawrence, Lone Rock and Mazomanie Formations that crop out in the Madison area. Diverse interpretations are expressed in this guidebook on certain sedimentological and environmental aspects of these formations.

Although prepared for the occasion of the 8th Annual Field Conference of the Great Lakes Section of the Society of Economic Paleontologists and Mineralogists, the guidebook is designed to benefit the many students who annually visit the Baraboo and Madison areas, so that they may gain a more comprehensive understanding of the sedimentary rock record in central Wisconsin. This guide compliments the excellent guidebook on the Geology of the Baraboo Area prepared in 1970 by I.W.D. Dalziel and R.H. Dott, Jr. Under the auspices of the Wisconsin Geological and Natural History Survey, these guides will be available for many years to come.

There has been a "renewed" interest in many aspects of the Cambro-Ordovician stratigraphic sequence in recent years, and there are many important sedimentologic and stratigraphic problems for future investigation. The field trip committee and other contributors to this guidebook will consider their efforts successful if only a few students are inspired to carry the work onward. Caution! In studies of the Cambro-Ordovician of the Upper Mississippi Valley, it is necessary to "study the rocks", preferably on a regional scale. Too often interpretations and "models" are based on local aspects without regard to the regional "picture".

WELCOME TO BADGER COUNTRY!

I. Edgar "Ed" Odom

STRATIGRAPHIC RELATIONSHIPS OF LOWER PALEOZOIC ROCKS OF WISCONSIN

by

Meredith E. Ostrom*

INTRODUCTION

Lower Paleozoic rocks of the Upper Mississippi Valley area have long been recognized as cyclic. In 1964 the author discussed previous work and presented an interpretation based on a repeating pattern of similar lithologies representing different but related marine environments. The following discussion is based primarily on that presentation and is only slightly modified from papers published in 1970 and 1976. It is repeated here to provide a ready reference to one interpretation of the origins and relationships of Lower Paleozoic rocks in the Upper Mississippi Valley area.

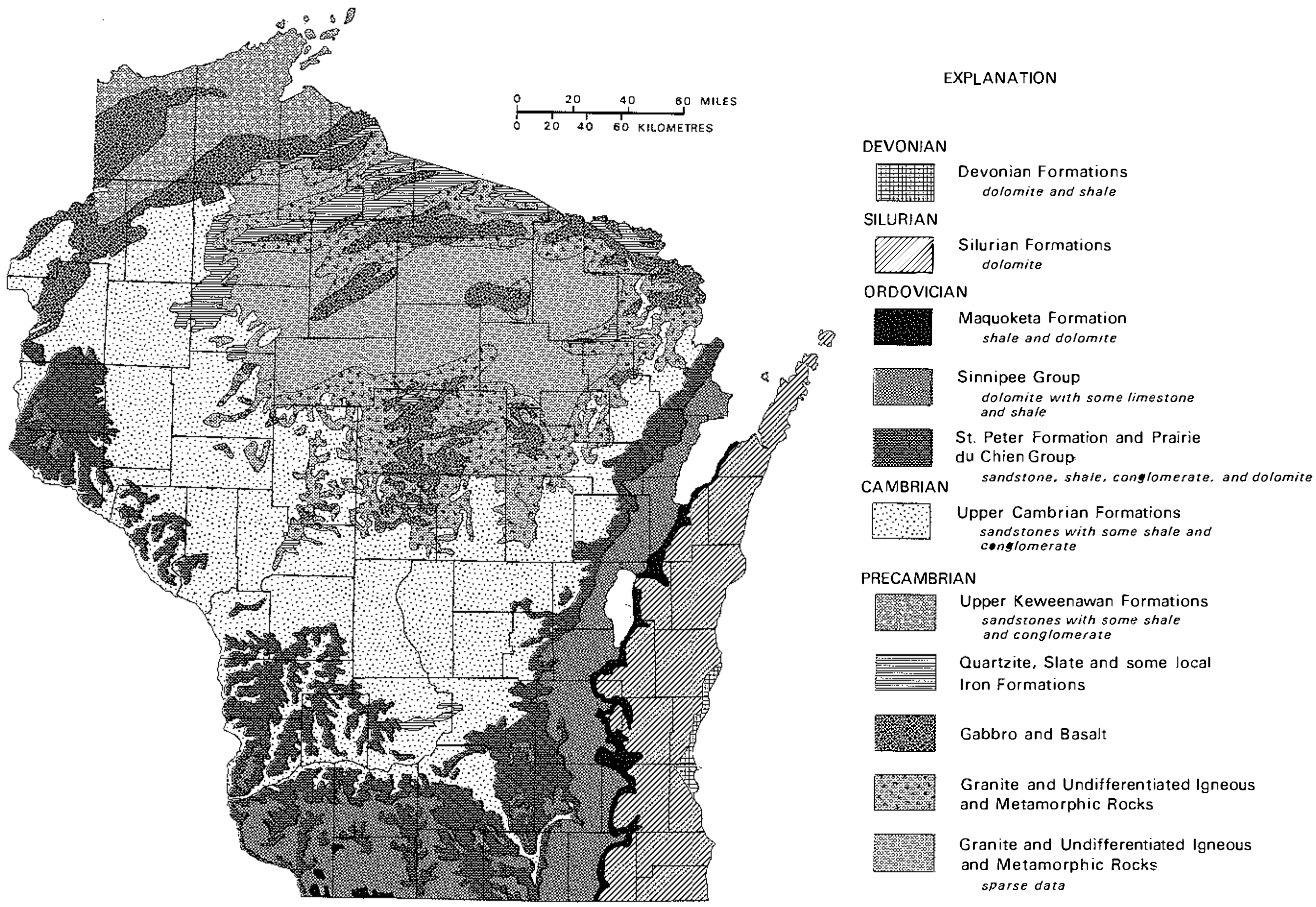

Figure 1. Bedrock geologic map of Wisconsin.

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Sedimentary rocks of Lower Paleozoic age overlie Precambrian rocks in the west, south, and east areas of the State (Fig. 1). They consist of a sequence of alternating clastic and carbonate rocks ranging in age from Late Cambrian to Late Devonian (Fig. 2). The clastic rocks are predominantly quartzose and feldspathic stones with shale in some areas. A notable exception is the Maquoketa Formation which is mainly shale. The carbonate rocks are mainly dolostone; locally some may consist of dolomitic limestone and limestone.

System	Series	Group	Formation	Member
Devonian	Upper		Kenwood	
	Middle		Milwaukee	
			Thiensville	
			Lake Church	
Silurian	Cayugan		Waubakee	
	Niagaran		Racine	
			Manistique	
			Hendricks	
			Byron	
	Alexandrian		Mayville	
Ordovician	Cincinnatian		Neda	
			Maquoketa	
	Champlainian	Sinnipee	Galena	
			Decorah	
			Platteville	
			St. Peter	Glenwood
				Tonti
				Readstown
	Canadian	Prairie du Chien	Shakopee	Willow River
				New Richmond
			Oneota	
Cambrian	St. Croixan	Trempealeau	Jordan	Coon Valley
				Sunset Point
				Van Oser
				Norwalk
			St. Lawrence	Lodi / Black Earth
		Tunnel City	Lone Rock / Mazomanie	Reno
				Tomah
				Birkmose
		Elk Mound	Wonewoc	Ironton
				Galesville
			Bonneterre / Eau Claire	
			Mt. Simon	

Figure 2. Geologic column of Paleozoic rocks in Wisconsin.

Four major lithostromes are present in the Lower Paleozoic rocks of the Upper Mississippi Valley. These are: (1) thick-bedded, medium- to coarse-grained, well-sorted, and cross-bedded quartzose sandstone; (2) medium- to thin-bedded, reworked quartzose sandstone characterized by alternating poorly-sorted sandstone which is commonly burrowed, calcareous, slightly glauconitic and shaly and by well-sorted, medium- to coarse-grained sandstone; (3) shale or argillaceous thin-bedded sandstone that is fine-grained, feldspathic, glauconitic, and shaly with minor carbonate; and (4) carbonate or sandy or silty carbonate or calcareous siltstone. Each lithostrome is interpreted as the manifestation of a different and distinct marine shelf lithotope which has its analogue in recent sediments such as those of the Northwest Gulf of Mexico (Van Andel and Curray, 1960).

Previous investigators recognized the broad cyclic pattern in the Lower Paleozoic rocks of this area and described them as an alternating sequence of carbonates and sandstones but relationships of beds and the implications of these relationships were only poorly known and described. Berg, Nelson, and Bell (1956) recognized four principal lithostromes which occur repeatedly in the Upper Cambrian rocks of Southeastern Minnesota and which coincide approximately with those described in this paper. The major difference between their work and this paper is in interpretation and in expansion to include the Lower and Middle Ordovician rocks of the area.

Berg et al (op. cit.) interpreted the Mt. Simon through Galesville Formations as a record of a "...relatively simple transgressive-regressive cycle of marine sedimentation across an area of moderately low relief." The nearshore deposits of the transgressive and regressive phases of their cycle consist of medium- to coarse-grained quartzose sandstones which are, respectively, the Mt. Simon Formation and the Galesville Member of the Wonewoc Formation. In their opinion the Galesville is topped by a disconformity which they attribute to pre-Franconia erosion and which they, at least in part, believe is responsible for regional thinning of the underlying rocks.

In studies by the author (1964, 1970, 1976) no evidence for disconformity of the Galesville and overlying Ironton Sandstone was found: their contact is transitional. However, the basal contact of the Galesville is clearly one of disconformity which resulted from pre-Galesville erosion. Thus, it is apparent that both the Mt. Simon and Galesville Sandstones are nearshore deposits of transgressive phases of two separate cycles.

In the overlying rock section the quartzose sandstone lithostrome is repeated three more times as the Jordan Sandstone (Van Oser), New Richmond Sandstone, and St. Peter Sandstone. There is a major widely recognized unconformity at the base of the St. Peter (Dapples, 1955) and a minor unconformity at the base of the New Richmond (Ulrich, 1924; Andrews, 1955; Davis, 1970). As for the Jordan Formation, a minor unconformity occurs on and near the Wisconsin Arch between the Van Oser and Norwalk Members or between the Van Oser Member and St. Lawrence Formation where the Norwalk has been eroded (Odom and Ostrom, this guidebook). Studies of well cuttings suggest that in the subsurface of Eastern Wisconsin (Fig. 3) a major unconformity occurs between the Jordan and and St. Lawrence Formations.

These data and the regular and repetitive occurrence of other lithostromes suggested that there might be a broad and predictable cyclical pattern of rock-type occurrence and contact relationships which would reflect a cyclical pattern of sedimentation different than that described by Berg et al (1956). Subsequent examination revealed this to be true (Ostrom, 1964) as shown by the fact that each of the five quartzose sandstones which occur in the Lower Paleozoic section of this area is at least locally unconformable with underlying rocks. Furthermore, each of the quartzose sandstones is separated by a similar sequence of rock units. The close similarity of cycles with regard to contact relationships and arrangement of lithostromes led to the interpretation that they reflect a tectonic and depositional history characterized by repetition of similar tectonic and depositional events. The tectonic events are believed to have been, in the simplest context, slow periodic uplifts and downdrops of the Wisconsin Dome which caused periodic fluctuations in sea level, each one recording the tectonic activity by cyclic deposition of the various lithostromes as the sediment zones migrated over the shelf.

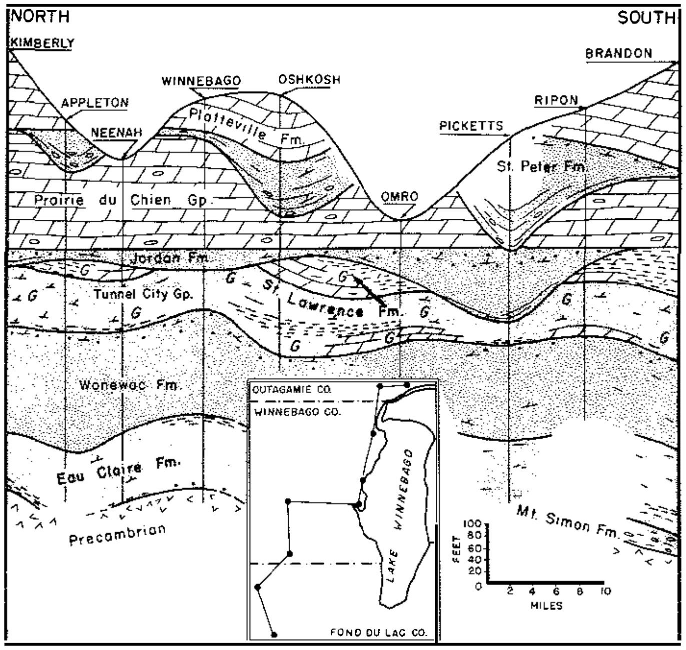


Figure 3. Northeast-southwest cross section of pre-Cincinnatian Paleozoic strata, Kimberly to Brandon.

THE LITHOLOGIC CYCLE AND LITHOSTROMES

Lithologic Cycle

A lithologic cycle is a recurring sequence of strata consisting of several lithostromes arranged in the same order. Lithologic cycles record a definite series of physical conditions (lithotopes) and geologic events which recurred in the same order with only minor variations. In the Cambrian and Ordovician rocks of the Upper Mississippi Valley area the cycles are asymmetrical because the succession of lithostromes in the transgressive order does not match that of the regressive order. Asymmetry here is attributed mainly to post-depositional erosion or variations in the source area and sediment supply or the distribution pattern of reworking and dispersing agents.

A cycle of sediments is formed during a single episode of advance and retreat by the sea. As the sea advances, the land is slowly submerged; and the four sediment zones (lithotopes) shift landward. Sediments deposited in lithotopes located near to and roughly parallel with the shore become buried as those previously deposited in lithotopes farther from shore advance shoreward. In this manner, layers of sediment representing different sediment zones are laid on top of the other and always in the same order.

During retreat of the sea it might be expected that deposits would be formed in reverse order. In some cases this is true (Jordan cycle); but for the majority, at least in Wisconsin, these deposits have been wholly or partly removed by erosion during the retreat phase of a cycle. Maximum retreat of the sea at the close of each cycle is approximately the seaward or southernmost limit of deposits of quartzose sandstone as shown in Figure 4.

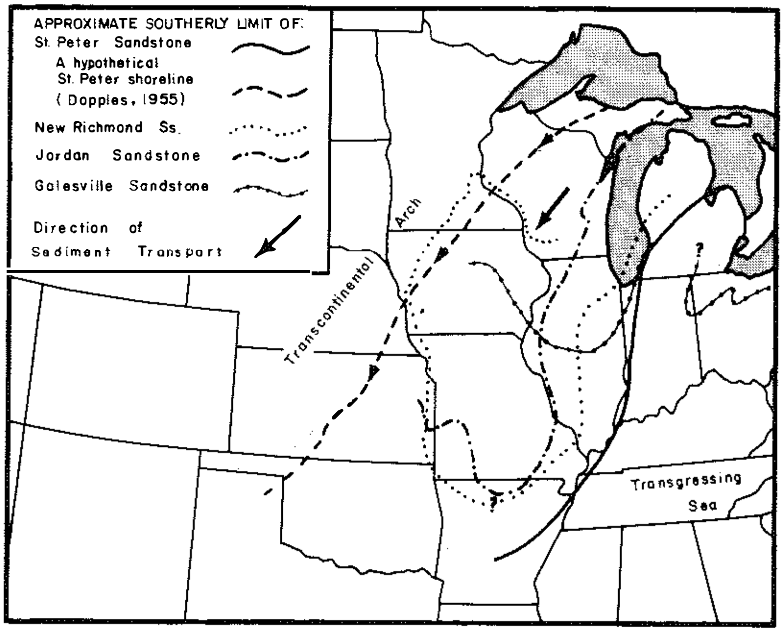


Figure 4. Map of approximate southern limit of occurrence of quartzose sandstone.

Variations in cycles may occur where a particular lithotope did not occur due to differences in sediment source, sediment supply, energy conditions, suitability of receiving area, or distribution pattern of currents and other sediment dispersing agents. Variations may also occur in the last phase of a cycle where one of the normal deposits was removed when the sea retreated and the land was exposed to erosion by streams and wind. A cycle ends with maximum retreat of the sea. In some cases the erosion surface produced during retreat may have a relief of up to 350 feet. However, in most cases relief is small, on the order of several feet, and may be difficult to detect.

Five sedimentary cycles, indicating five successive episodes of advance and retreat by the sea, occur in the Upper Cambrian and Lower and Middle Ordovician rocks of Wisconsin. The rock strata comprising each cycle and their relationships are shown in Figure 5.

Upper Ordovician rocks consist of the Maquoketa Formation which is primarily shale with some thin units of dolomite. The Maquoketa represents a major change in the depositional pattern. There is some evidence to indicate an erosion surface separating the shale from underlying carbonates. In addition, the presence of chlorite-type clay minerals in the shale and their absence in older rocks suggest a different source area such as possibly the then youthful northern Appalachian Mountains. An extensive delta developed westward from the northern Appalachians in Middle and Late Ordovician time, and the shale may be a deposit from that event.

Four major lithostromes which recur in the same sequence in five lithologic cycles, as shown in Figure 5, are recognized in the Upper Cambrian and Lower and Middle Ordovician rocks of the Upper Mississippi Valley area. The four lithotopes are: (1) quartzarenite, (2) reworked quartzarenite, (3) argillaceous sandstone or shale, and (4) carbonate. The lithostromes are believed to have formed in different sediment zones (lithotopes) located on a marine shelf and oriented approximately parallel with the shoreline. The sediment zones are roughly analogous to the zones described by Curray (1960) and Van Andel (1960) for Recent sediments in the Northwest Gulf of Mexico which, in a seaward direction, are the high energy littoral zone of sands, the slow or nondepositional zone of reworked alternating sands and muds, the shelf depositional zone of fine-grained clastics and the biogenic zone of calcareous "reefs".

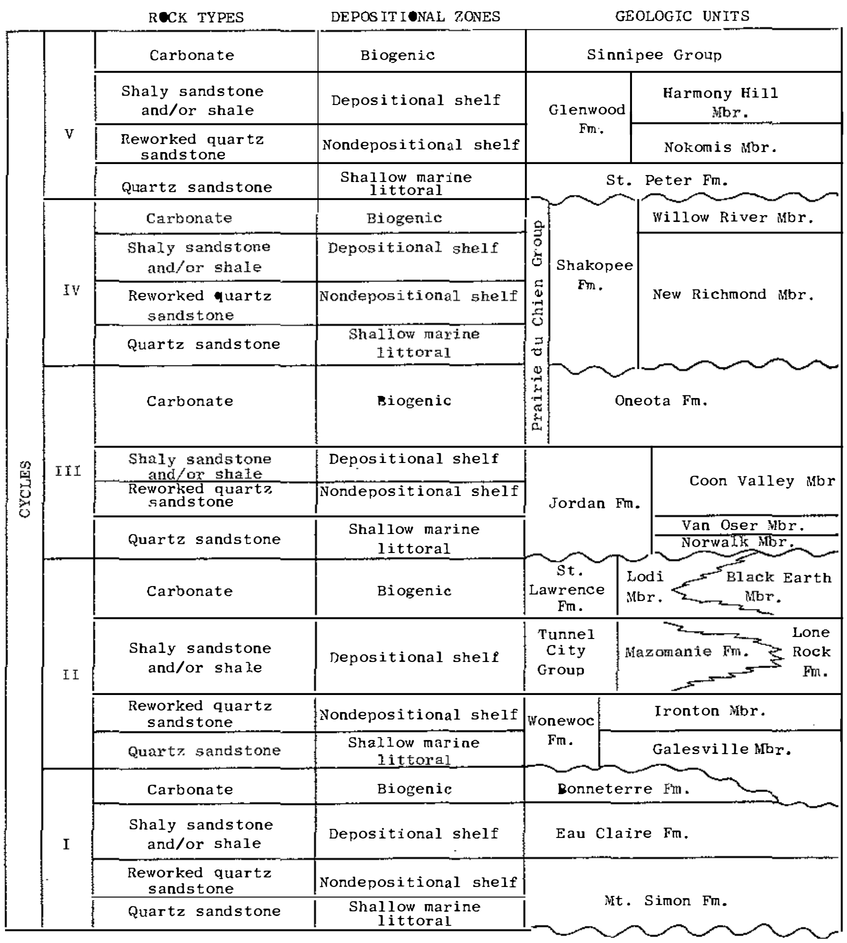


Figure 5. Cycles of sedimentation in Upper Cambrian and Lower and Middle Ordovician in Wisconsin.

The extent to which a deposit in a given sediment zone can develop depends upon the coincidence of many factors, chief among which are sediment source, sediment supply, energy, suitability of receiving area, and sediment distribution pattern. Variations in these factors are reflected in the relationships of the resultant lithotopes.

The littoral lithotope exhibits the greatest stability in terms of energy and location chiefly because current and energy conditions in this zone are consistent and high and because its landward boundary is relatively stable. Distribution and size of the other zones which have lower energy levels is subject to the vagaries of available energy and distribution pattern of reworking and dispersing agents. Where these conditions are stable there is minor shifting of zones, thus little mixing of sediment type. Under fluctuating conditions, deposits of different zones will be intermingled.

Quartzose Sandstone Lithostromes

The quartzose sandstone lithostrome which is the basal unit of each cycle is represented by the Mt. Simon, Galesville, Jordan, New Richmond, and St. Peter Formations. These sandstones are characterized by thick bedding, uniform lithology and mineralogy, and cross bedding. Lithologically, the lithostrome consists mainly of well-sorted, clean, friable, medium- and fine-grained sandstone. The basal few feet may locally contain coarse and very coarse sand, granules, pebbles and cobbles. In the base of the Mt. Simon and St. Peter Sandstones coarse materials may locally be more abundant than in the others.

Mineralogically, these quartzose sandstones consist chiefly of quartz sand grains, although recent studies by Distefano (1973), Odom (1975), and Odom and Ostrom (this guidebook) show that these sandstones locally contain facies which are very fine-grained and highly feldspathic (Waukon and Sunset Point Members of the Jordan). Heavy minerals common to this lithotope are magnetite, ilmenite, leucoxene, zircon, tourmaline, and garnet. The amount of garnet is generally less than 5 percent of the total heavy mineral content.

Fossils are rare or absent in the quartzarenite lithotope. Where present they tend to occur either in the basal few feet or near the top.

The quartzose sandstones occur as blanket deposits which grade into fine-grained shaly sands and carbonates laterally to the south and east across the craton in the direction of the Appalachian Geosyncline as is illustrated in Figure 6. Directional indicators show that current direction at the time and place of deposition of these sandstones was predominantly to the southwest and south (Fig. 4). Locally the quartzose sandstones tend to thicken in basins such as the Illinois Basin and to thin over highs such as the Wisconsin Dome.

The relationship of the quartzose sandstones with underlying beds is locally unconformable in Wisconsin, and may be angular which is interpreted to indicate erosion prior to their deposition. The unconformable relationship at the base of the Mt. Simon, Galesville, Jordan (Van Oser Member), New Richmond, and St. Peter Sandstones can be seen in Figures 7, 8, 9, and 10, respectively.

The contact with the overlying lithostrome is commonly transitional but may locally be sharp and distinct. The upper contact is placed approximately where there is a distinct change from thick bedding to thinner and uniform bedding and/or where there is evidence of reworking of bottom materials.

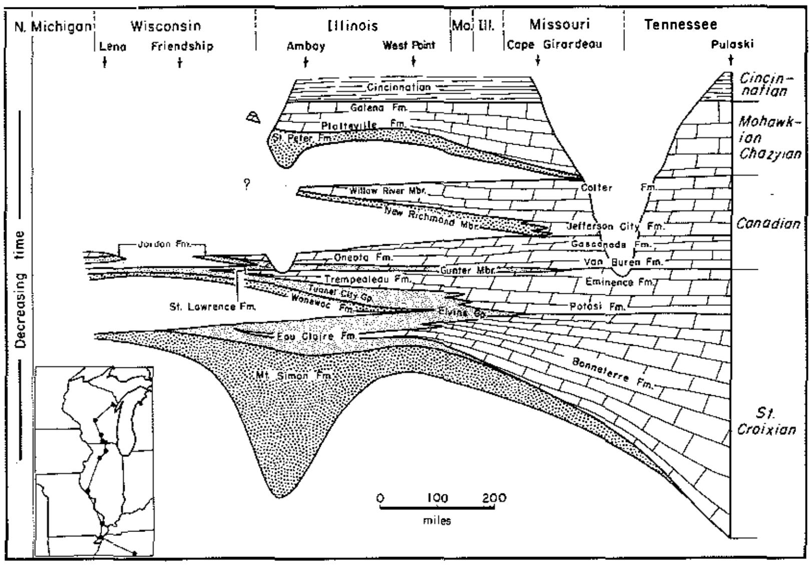


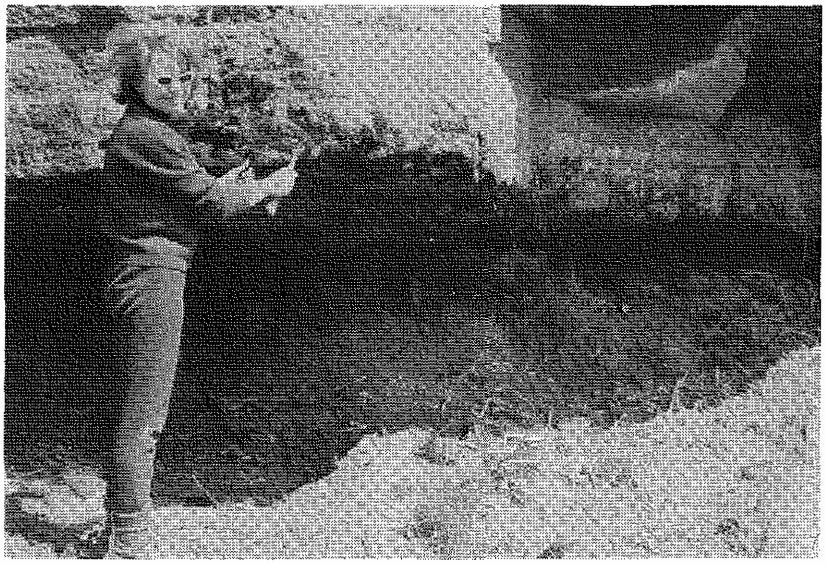
Figure 6. North-south generalized cross section of pre-Cincinnatian Paleozoic strata from Lena, Wisconsin to Pulaski, Tennessee.

The quartzose sandstone lithostromes are believed to have developed in the littoral sediment zone which is defined to include the sediments of the beaches, barriers, spits, and nearshore zone along a coast. A modern analogue to this lithotope is forming in the littoral sediment zone of the Northwest Gulf of Mexico (Van Andel and Curray, 1960).

Formation of these blanket-type deposits of sand is attributed to the coalescing of a continuous series of littoral sands which migrated over a shallow marine shelf during progressive subsidence (Curray, 1960; DuBois, 1945; Dapples, 1955; Freeman, 1949; Calvert, 1962; Ostrom, 1964). Sediment delivered to the sea by rivers, together with sediment eroded from the shore by the transgressing sea, is winnowed and redistributed by waves and currents. The coarser fraction, consisting of sand, is distributed in the littoral zone by waves and longshore currents similar to those of the Northwest Gulf of Mexico which parallel the shoreline. The finer fraction is carried farther out on the shelf and is deposited according to the distributing pattern of marine dispersing agents.

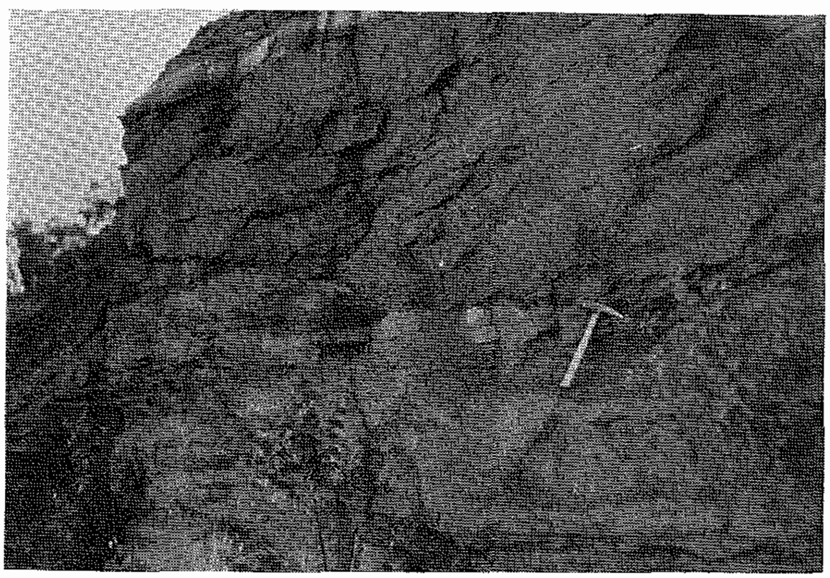
The width of the littoral zone, in a seaward direction, in the present-day Northwest Gulf of Mexico is shown at a maximum of about 10 miles by Van Andel (1960) and includes the high energy surf zone and turbulent zone down to a depth of 6 fathoms off the Texas coast. Movement of sand parallel to the shoreline in the littoral drift system is reported out to depths of 60 to 80 feet (Johnson, 1956).

The seaward limit of deposits of the littoral sediment zone at the time of maximum regression can be mapped and is interpreted to indicate approximately the configuration of the ancient shoreline at that time as is shown in Figure 4.



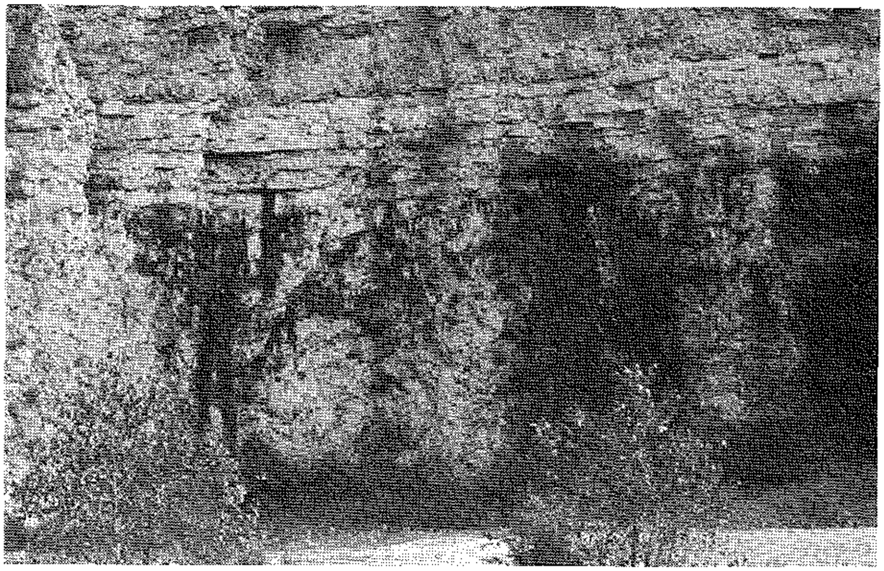
Mt. Simon Ss.
Precambrian

Figure 7. Unconformable contact of Mt. Simon Sandstone with weathered Precambrian gneiss.



Galesville Ss.
Eau Claire Ss.

Figure 8. Unconformable contact of Galesville Sandstone with Eau Claire sandstone.



Shakopee Fm.
Oneota Fm.

Figure 9. Unconformable contact of New Richmond Sandstone with Oneota Dolomite.

St. Peter Ss.
Shakopee Fm.

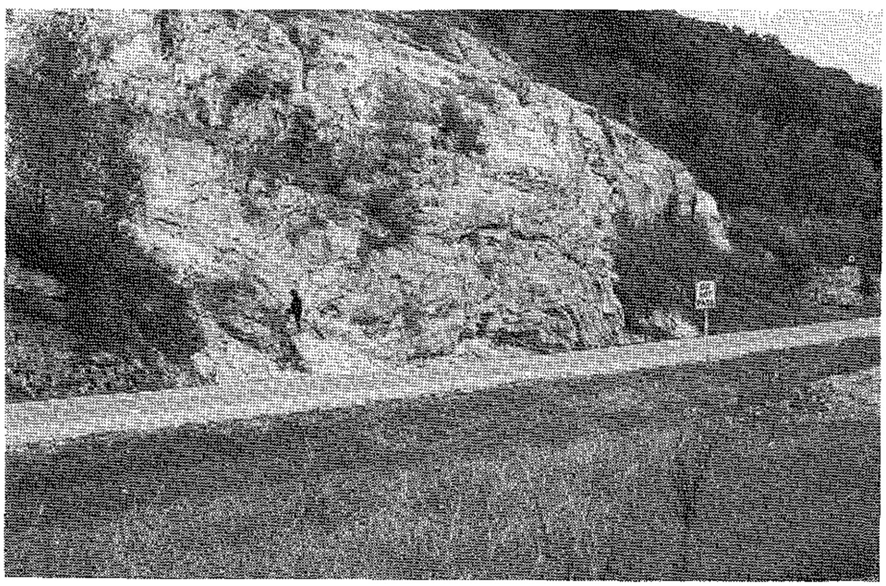


Figure 10. Unconformable contact of St. Peter Sandstone with Shakopee Formation.

Reworked Quartzose Sandstone Lithostromes

The reworked quartzose sandstone lithostromes overlie the quartzose sandstones and are represented in the sequence by the upper 20 to 40 feet of Mt. Simon Sandstone, the Ironton Member, the lower part of the Coon Valley Member, and the lower part of the Glenwood Formation (Nokomis Member). Each is distinct and well-developed except the upper part of the New Richmond Sandstone. This may be explained by the fact that at many places the entire New Richmond is lithologically similar to the reworked quartzose sandstone lithostromes of other cycles which suggests that this lithotope does in fact exist but that it has not been distinguished from the quartzarenite lithotope with which it has been erroneously equated.

The reworked lithostromes are compositionally and texturally transitional with both the overlying and underlying lithostromes, having some of the characteristics of each of them as well as possessing certain unique characteristics. The contacts may be sharp and well defined or transitional and obscure.

The reworked lithotope consists primarily of coarse-grained quartzose sandstones which are commonly interbedded with poorly-sorted strata composed of materials ranging in size from clay to granules or with arenaceous carbonate strata, and beds of very fine-grained highly feldspathic sandstone are locally present in the Mt. Simon and Ironton Sandstones and in the Coon Valley Member of the Jordan. The interbedding is expressed on weathered outcrops as ledges separated by reentrants and reflects differences in texture and cementing character of beds (Fig. 11).

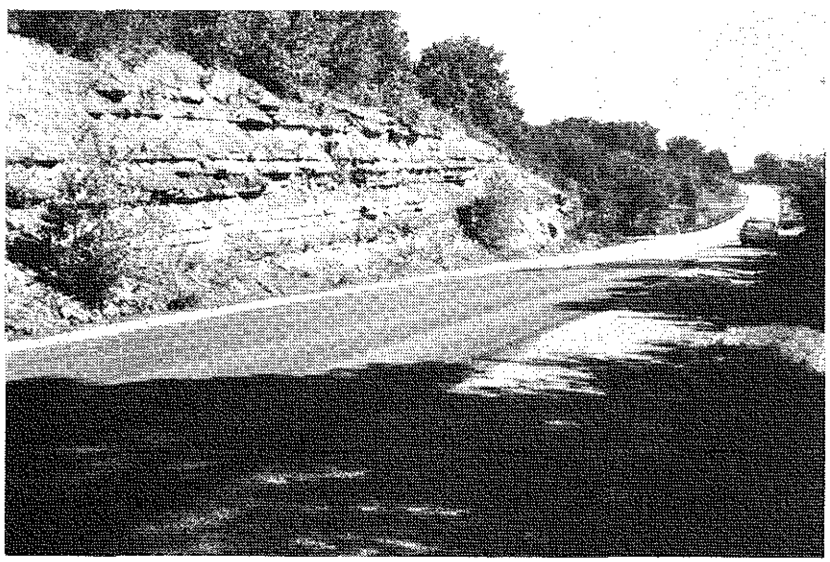


Figure 11. Outcrop characteristics of quartzose sandstone lithostrome as shown by exposure of Ironton Sandstone.

Locally these sandstones contain thin shale laminae and intraclasts. Heavy minerals are essentially the same as those which occur in the underlying quartzose sandstones, although the garnet content is commonly higher. The coarser grained beds are commonly cross-bedded. They may be, at least in part, lag concentrates formed by wave and current removal of fine-grained materials from bottom deposits similar to those of intervening beds which contain particles ranging in size from clay to granules.

The poorly-sorted silty beds are thick and may contain abundant burrows. The mixing, reworking, and burrowing of these beds is thought to have all been done by the same organisms. Ripple marks are most common in finer grained beds. Conglomerates are of limited lateral extent and are commonly composed of intraclasts.

Fossils are locally common, especially in the upper part and in finer grained and poorly-sorted beds. They consist of the burrows already mentioned and of trails, and less commonly of brachiopod shell fragments and of trilobites.

Contact with the underlying quartzose sandstone may be sharp or transitional. The contact is placed at the base of the lowest bed indicating reworking and is generally based on the change upward to coarser grained sandstone that is better sorted in individual beds but may contain materials ranging in size from clay to granules. These strata are generally silty and somewhat calcareous, and may contain ferruginous cement, fossils, glauconite, pyrite, and beds of shale, dolomite, and conglomerate.

The reworked lithostromes are commonly thinnest over positive features such as the Wisconsin Dome and Arch and tend to thicken into intracratonic basin areas. For example, the Ironton Formation shows an increase of from zero feet over the Wisconsin Arch in south-central Wisconsin to about 100 feet basinward in northeastern Illinois (Emrich, 1966; Buschbach, 1960) and 50 feet in western Wisconsin (Emrich, 1966); the lower portion of the Glenwood Formation (Nokomis) increases from zero feet over the Wisconsin Arch to about 8 feet in southwestern Wisconsin (Ostrom, 1969).

Detailed examination of particular units assigned to the reworked quartzose lithostrome indicates that some beds can be traced over broad areas. Certain beds in the Ironton Formation are cited as being laterally persistent and as maintaining an essentially uniform thickness over distances of up to 100 miles in west-central Wisconsin (Emrich, 1966).

The reworked quartzose sandstones developed in a shelf lithostrome that produced vertical variability between beds and lateral persistence of individual units. Vertical lithologic variability is interpreted to mean unstable and frequently changing environmental conditions. Such an area is the shelf zone of slow or no deposition characterized by reworked and alternating beds of sand and finer sediments analogous to that described for the Northwest Gulf of Mexico, by Curray (1960) and Van Andel (1960). In the Northwest Gulf of Mexico burrowing organisms and occasional hurricane waves rework bottom sediments and mix small quantities of newly added clay and biogenous carbonate with the underlying older sands. The result is sands interbedded and mottled with clay or clayey sands. Such mixing penetrates to a depth of up to about 5 feet and may produce a crude graded bedding.

Neighboring lithotopes may encroach into the slow or no deposition zone of reworking in response to a variety of conditions related to changes in sediment supply and available energy and produce an intermingling of deposits of both zones in an alternating pattern. The energy level in the zone of slow or no deposition is erratic and is subject to extremes of energy conditions. At times of low wave and current energy finer materials normally carried to more remote areas of the shelf may be deposited, bottom conditions stabilize, benthonic animals establish themselves, and neighboring environments of lower energy may encroach on the area. At times of high wave and current energy bottom sediment is churned up, finer materials are kept in suspension or removed, coarse materials are left behind, animals adapted to low-energy conditions are displaced or destroyed, and neighboring environments of lower energy are encroached upon.

The zone of slow or no deposition is, thus, seen to expand, contract, and shift position frequently in response to changing energy conditions causing intricate intermixing with deposits characteristic of neighboring environments which may encroach into and retreat from this zone.

Argillaceous Sandstone or Shale Lithostromes

Argillaceous sandstone or shale lithostromes overlie the reworked quartzose sandstone lithostromes and locally, where the latter are missing, rests directly on the quartzose sandstones. Strata assigned to the argillaceous lithostromes are the Eau Claire Sandstone, the Lone Rock Formation, the thin clayey sandstone or shale or calcareous shale in the lower part of the Coon Valley Member, the Blue Earth Siltstone of Minnesota, a thin pale green clayey sandstone and calcareous shale at the top of the New Richmond Sandstone, and the Harmony Hill and Hennepin Members of the Glenwood Formation.

The argillaceous lithostrome is characterized by fine-grained sediments consisting of shale or silty or argillaceous sandstone. The sand grains are predominantly quartz and feldspar. Clay may occur as a green coating on sand grains or it may be present as thin shale partings or in shale beds up to 10 or 12 feet thick; it may also occur in the form of abundant glauconite pellets. Carbonate is common as cementing material or as thin beds. The heavy mineral suite is dominated by garnet (the Lone Rock heavy mineral suite contains up to 90 percent: Driscoll, 1959) with lesser amounts of ilmenite, leucoxene, tourmaline, and zircon.

This lithostrome is essentially uniform in composition on a regional scale. Variations are due chiefly to differences in shale-to-sand ratio and locally in carbonate content.

Fossils commonly consist of fragmented brachiopods, trilobite molds and casts, and abundant burrows and trails.

The argillaceous lithostrome is commonly thin bedded or shaly which distinguishes it from the underlying lithostromes in which bedding ranges from thick to thin and in which shale is rare. Cross-bedding is common and is well developed. Ripple marks and current lineation features are locally abundant. Beds of intraclasts are common and consist chiefly of sandstone clasts in a matrix of fine sand, silt, clay, and glauconite cemented with carbonate.

Regionally the argillaceous lithostromes are transitional laterally with carbonates and tend to thin southward and southeastward in the direction of the Appalachian Geosyncline. They tend to thicken into basin areas and to thin over highs such as the Wisconsin Arch.

The environment of deposition of the argillaceous lithostrome is believed to have been the depositional zone of the shelf located generally seaward from the zone of slow or no deposition (Van Andel, 1960). The uniformity of texture, composition, and thickness of this lithotope over broad areas is interpreted to indicate a stable environment having an essentially constant energy level and a uniform rate of sediment accumulation. Variations in this uniformity are attributed to nearness to neighboring depositional zones or to minor shifts of environmental areas at times of major wave and current activity which would cause intermingling with neighboring depositional zones.

The sediments of this depositional zone consist of the fine clastics winnowed from the river sediments and beaches and deposited farther offshore in accordance with the distribution pattern of marine currents. The amount of sediment which accumulates is a function of sediment supply and of local shelf subsidence.

Present-day deposition of fine sediment on the shelf in the Northwest Gulf of Mexico is limited primarily to the area beyond the littoral zone and occurs mainly in the middle and outer shelf areas. The pattern of dispersion of these sediments appears to be independent of the coarser sand distribution (Van Andel, 1960).

Carbonate Lithostromes

Formations assigned to the carbonate lithostrome include the Bonneterre Dolomite, St. Lawrence Dolomite, upper portion of the Coon Valley Member of the Jordan, Oneota Dolomite, Willow River Dolomite, and Sinnipee Group. What may be Bonneterre Dolomite in this area is limited in distribution to the southern edge of the state near Beloit. It is a persistent carbonate unit which occurs in the upper part of the Eau Claire Formation in the area and which is considered to be the lithostratigraphic equivalent of the Bonneterre Dolomite of Missouri.

The carbonate lithostrome is the most readily recognized of all the lithostromes as it is characterized by carbonate rocks. In the lower part of each carbonate unit sand and minor amounts of shale and/or glauconite and silt are generally present. Higher in the section these constituents may be totally absent. In other cases, beds of shale and sand can be found throughout the unit. Bedding is commonly medium but varies from thin to thick.

In this lithostrome fossils are more diversified and plentiful than in those of the other three lithotopes. Biohermal reefs are present in all carbonates except the Sinnipee Group.

The carbonate lithostromes maintain a uniform thickness locally and show a regional thickening into basin and geosynclinal areas. In the geosynclinal area (Fig. 6) carbonate sections appear to be continuous and are uninterrupted by intervening beds of sandstone or shale. Exceptions to the local uniformity of thickness occur where erosional unconformity exists between a carbonate and the overlying lithostrome or where an irregular reef surface is buried by sediment characteristic of a neighboring environment, as for example that of the depositional shelf area, the contact is commonly transitional and even. If the carbonate is succeeded by a deposit characteristic of a more remote environment of deposition, for example that of the littoral zone, then the contact is likely to be one of unconformity.

Contact of the carbonate lithostrome with the underlying lithostrome may be sharp or transitional and is most often even. Departure from this condition may occur locally due to variations in bottom topography and energy and to the distribution pattern of marine reworking and dispersing agents. Where the contact is transitional the carbonates may initially contain beds of quartzose sandstone, shale, fine-grained dolomite, stromatolites, intraclasts, or discontinuous thin beds of oolitic white chert indicative of shallow agitated waters as are the upper surfaces of the dolomite beds which may be marked by ripple marks and dessication cracks. The vertical lithologic variability of the transitional beds in the base of certain of the carbonates, such as the Willow River Dolomite and the upper part of the Coon Valley Member of the Jordan, is interpreted to indicate intermingling of deposits of the biogenic carbonate zone with those neighboring depositional zones in response to changes in energy conditions and in the distribution pattern of marine reworking and dispersing agents.

Deposits having these characteristics are found in shallow water shelves, lagoons, and tidal areas behind algal headlands or reefs and differ considerably from those of the open shelf such as banks or platforms which consist almost entirely of carbonate material. Sediment deposited in lagoonal areas may come from four sources: the mainland, the algal headland, non-headland skeletal hard parts, and chemical precipitation. The gradation from algal headland into lagoonal sediments ranges from sharp to indefinite. In a shoreward direction the headland may merge, with indefinite or complex interfingering relations, into lime sands that surround small patch reefs and eventually into lagoon lime sands, evaporites, or clastic sediments (Cloud, 1952).

The amount of terrigenous and calcareous materials that accumulate in a lagoon varies with supply and nearness to the mainland or the reef. In the area of the Great Barrier Reef, terrigenous material commonly exceeds 90 percent near the mainland (Fairbridge, 1950). In the reef vicinity calcareous clastic materials and chemically precipitated lime muds may form 98 percent of the total.

The bulk of carbonate deposition today is taking place in biogenic environments similar to those which occur on the shelf off the east coast of Australia, off the southeast coast of Florida, or in the Northwest Gulf of Mexico (Fairbridge, 1950; Illing, 1954; Ludwick and Walton, 1957). Areas of active reef development in the Northwest Gulf of Mexico are located in water shallower than 30 fathoms (Parker and Curray, 1956; Stetson, 1953) in the zone of slow to no deposition and in areas of stable but unconsolidated bottom where all other requirements for their development exist. Ladd and Hoffmeister (1936) and Cloud (1952) maintain that reefs may develop upward from any stable, preexisting platform in areas where all other requirements for their development exist and that they will continue to develop so long as these requirements are not altered. Carbonate deposition and reef formation seldom if ever occur where bottom conditions are unstable or where there is abundant shifting sediment.

The carbonate lithostromes in Cambrian and Ordovician rocks of the Upper Mississippi Valley area are interpreted to represent a biogenic lithotope of carbonate deposition. The conclusion that these lithostromes probably developed in such a zone seems logically inescapable (Gilluly, Waters, and Woodford, 1951; Cloud, 1952). Studies of the Oneota Dolomite (Starke, 1949) and of the "Trenton" formations (Du Bois, 1945) in the Upper Mississippi Valley indicate that these carbonates were deposited during times of transgression by the sea and that they accumulated in biogenic zones of deposition as a series of coalescing deposits which were spread out as sheetlike bodies shoreward over the shelf as the sea transgressed.

PATTERN OF SEDIMENTATION

Depositional Setting

The area of deposition of Upper Cambrian and Lower and Middle Ordovician sediments in the Upper Mississippi Valley was a craton on which there were active intracratonic basins and scattered arches and domes. A study of dispersal centers of Paleozoic and later clastics of this and adjacent areas indicated to Potter and Pryor (1961) that the southward direction of sediment movement and slope of the craton have persisted through the Paleozoic to the present. They believe that (p. 1229-30):

> "Such uniformity over so long a time and over such a wide area can reflect only major tectonic control. The behavior of basement rocks of the craton provides that control. This underlying tectonic control is the immediate cause of persistent paleoslopes, of recycling, and of the location and orientation of major clastic deposits ultimately derived from distant tectonic lands."

In the Upper Mississippi Valley area direction of sediment transport, especially in the littoral zone, is interpreted to have been parallel to the shoreline, hence approximately parallel to the continental margin, which lay toward the Appalachian Geosyncline to the southeast and south, and perpendicular to the paleoslope, a relationship demonstrated for the St. Peter Sandstone by Dapples (1955).

During the Late Cambrian and Early and Middle Ordovician there existed high areas in the Upper Mississippi Valley referred to as the Wisconsin Dome, the North Huron Dome, a connecting link between these two domes called the Northern Michigan Highland, and the Canadian Shield (Fig. 12). The major intracratonic basin of this time was the Illinois-Michigan Basin. The Ozark area is considered to have subsided during pre-St. Peter time and to have risen before the end of the Cincinnatian (Eardley, 1951; Lee, 1943). Deformation during this interval is believed to have resulted in the development of many arches and other structural features on the craton including the Kanakakee Arch, which separated the Michigan Basin from the Illinois Basin (Ekblaw, 1938), and the Findlay and Waverly arches which bordered these basins along their southeastern margin (Woodward, 1961).

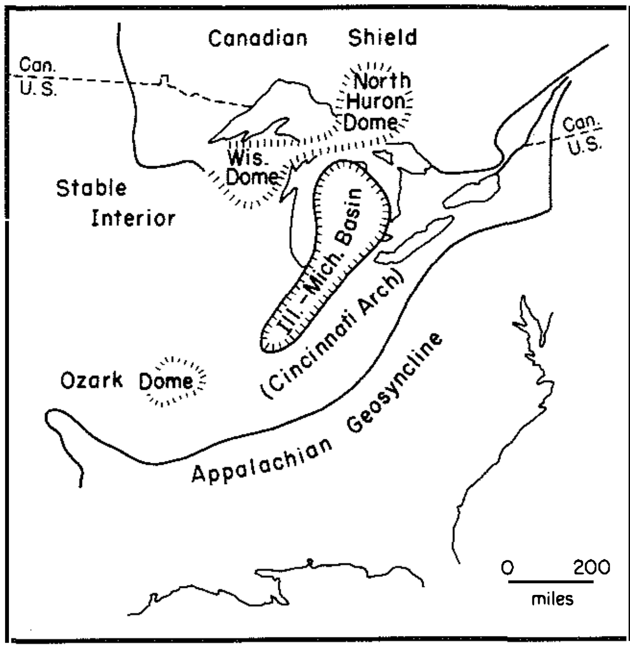


Figure 12. Map of eastern North America indicating areas of pre-Cincinnatian Paleozoic orogenic activity.

DEVELOPMENT OF CYCLES

Distribution of major depositional zones over present-day shelf surfaces is roughly parallel to the coastline. Changes in sea level cause each zone to migrate over the shelf. Lowering of sea level relative to the land causes zones to shift seaward; conversely, a relative rise in sea level results in a shoreward shift. Minor sea level changes, over shallow shelves, may cause broad shifts of the strandline emerging or submerging vast areas and can account for many thin, but widespread, units. Major changes in sea level result in the development of complete cycles which should consist ideally of deposits of both transgressive and regressive phases.

In a somewhat irregular pattern seaward from, and roughly parallel with, the coast one can expect to encounter the high energy littoral zone of well-sorted sand, the slow or no deposition zone of reworked alternating sands and muds, the shelf depositional zone of fine-grained clastics, and the biogenic zone of calcareous "reefs" (Van Andel, 1960; Van Andel and Curray, 1960). Migration of each environment over the shelf results in their being deposited in sheetlike bodies over the shelf surface, one on top of the other.

Deposits of the emergent phase are not as well represented as those of the submergent phase. This is especially true of deposits developed in higher energy environments located in the littoral and inner shelf depositional zones. Regression of the sea exposes these zones and their characteristic deposits to subaerial erosion. Thus, during emergence, deposits of the littoral zone are continually reworked and removed to the retreating shoreline. For this reason they can be expected to be rare unless they are lowered, by local subsidence, beyond reach of erosion in which case they will be preserved.

A continuous sheet of coalescing nearshore beach sands will be deposited over the erosion surface as the sea readvances over the land in the subsequent submergent phase. Deposits of the submergent phase will be separated from those of the preceding emergent phase by a hiatus except in the area defined by the width and breadth of the littoral zone at the time of maximum emergence. The hiatus may be apparent if there is an obvious difference in lithology, an unevenness of the contact surface, or clasts occur in the base of the overlying unit. However, if, on the other hand, the lithologies are similar and the underlying unit is so soft that the erosion surface is not preserved and clasts do not form, then the hiatus may be obscured.

Cycles are likely to develop in nearshore areas because such areas are the most readily affected by minor sea level changes which cause environmental zones to shift widely back and forth. Where there is little change in environmental conditions, and where deposition is continuous from one cycle to the next as can occur in outer shelf areas in which local environmental conditions are unaffected by sea level changes, there may be no discernible cycles.

VARIATIONS IN CYCLES

Lower Paleozoic sedimentary cycles may appear incomplete because of erosional lacunas. A lithotope representing a specific depositional zone will develop only if that zone is present in the area. Thus, deposits of the littoral zone will not occur seaward beyond the area of maximum regression of this environment nor will they occur shoreward beyond the area of maximum transgression of the environment.

Subaerial erosion may produce surfaces with high local relief, such as that at the base of the St. Peter Sandstone, which is the reason for abrupt lateral changes in thickness of the underlying lithotope and often its complete removal. On the other hand, subaerial erosion may not cut deeply and only partially remove the underlying lithotope as in the case of erosion prior to deposition of the New Richmond Sandstone.

Regressive phases are identified in Cambrian cycles in the Upper Mississippi Valley area but are unknown in Ordovician cycles. Presence of a regressive phase in the Eau Claire Formation was described by Ostrom (1964) and a regressive phase for the upper part of the St. Lawrence Formation and the Norwalk Member in western Wisconsin was described by Nelson (1956). It is suggested that active subsidence of the Illinois-Michigan Basin during shelf emergence, at the close of the Mt. Simon and Galesville cycles, caused regressive deposits to be lowered beyond the reach of subsequent erosion and resulted in their preservation. The Jordan and New Richmond cycles of the Lower Ordovician differ from older cycles in that their shale or argillaceous sandstone lithotopes, representing the depositional shelf environment, are poorly developed. Regression prior to development of these cycles was probably less than during previous cycles and did not extend into basin areas; land areas were, thus, low and of low relief and provided only small amounts of clastics, and consequently less sediment accumulated in the depositional shelf environment.

SUMMARY AND CONCLUSIONS

Upper Cambrian and Lower and Middle Ordovician deposits of the Upper Mississippi Valley consist of four recurring lithostromes comprising five sedimentary cycles. The lithostromes and depositional zones are: (1) thick-bedded quartzose sandstones deposited in the littoral zone; (2) thin- to medium-bedded, poorly-sorted, reworked quartzose sandstones, transtional with overlying and underlying lithostromes and formed in the non-depositional shelf zone; (3) shales or argillaceous sandstones formed in the depositional shelf zone; and (4) carbonates formed in the biogenic carbonate zone.

The depositional zone in which each lithostrome developed occupied a position that was roughly parallel to the shoreline and that migrated over the shelf landward in response to submergence and seaward in response to emergence. Each cycle has in its base a quartzose sandstone which marks the environment of the littoral depositional zone. These are overlain, in turn, by deposits developed successively farther out to sea, namely those of the non-depositional shelf zone, depositional shelf zone, and carbonate zone. Deposition during emergence resulted in reversed order of occurrence.

Rock units which comprise the five cycles of sediments, in ascending order, are the: (1) Mt. Simon Sandstone, Eau Claire Sandstone, Bonneterre Dolomite; (2) Galesville Sandstone Member, Ironton Member, Tunnel City Group, St. Lawrence Formation; (3) Jordan Sandstone, Oneota Dolomite; (4) New Richmond Sandstone, Willow River Dolomite; and (5) St. Peter Sandstone, Glenwood Formation, and Sinnipee Group.

The relationships of factors affecting pre-Cincinnatian Paleozoic sedimentation in the Upper Mississippi Valley are summarized in Figure 13.

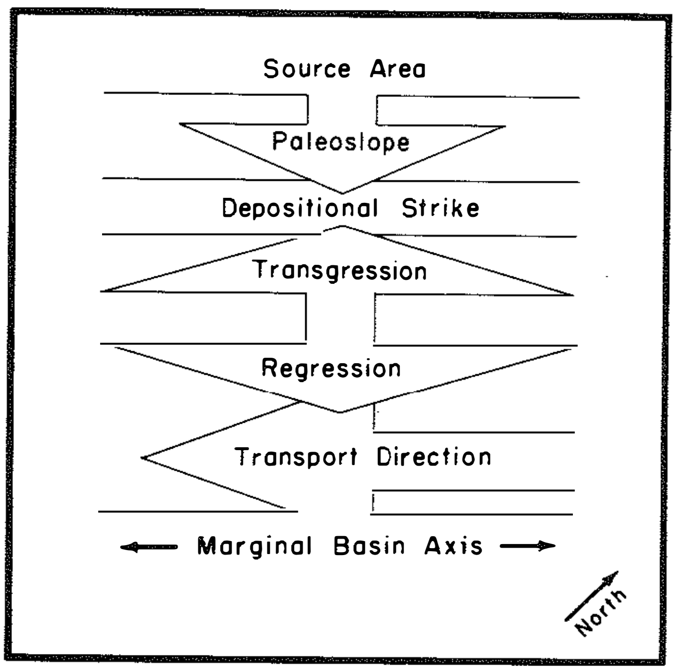


Figure 13. Model summarizing relationships of factors which affected pre-Cincinnatian Paleozoic sedimentation in the Upper Mississippi Valley area.

Deposition of Cambrian and Lower and Middle Ordovician sediments in this area was on the craton which was situated northwest of the Appalachian geosyncline, and on which were located more rapidly subsiding intracratonic basins and essentially stable arches and domes. It is believed that the lithic cycles are the product of repeated emergence, which was caused by rejuvenation of tectonically positive portions of the craton, and submergence, which resulted from subsidence of the geosyncline and of the neighboring shelf area of the craton.

The paleoslope of the area remained constant throughout the time of deposition of these sediments and had a dip to the southeast in the direction of the geosyncline. The dominant direction of sediment transport was to the south and southwest roughly parallel to ancient shorelines.

Regressive phases are identified in Cambrian cycles in the area but are unknown in Ordovician cycles. It is suggested that active subsidence of the Illinois-Michigan Basin during shelf emergence at the close of the Cambrian Mt. Simon, and Galesville cycles allowed deposits developed during regression to be lowered beyond the reach of subsequent erosion.

The Jordan and New Richmond cycles of the Lower Ordovician differ from previous cycles, and from the succeeding St. Peter cycle, in that their shale or argillaceous sandstone lithotopes, representing the depositional shelf zone, are poorly developed. Development of this lithotope in the other cycles is thought to have been caused by coincidence of the depositional shelf zone with the actively subsiding basin area which received large amounts of clastic sediment from a land area of moderate relief during regression. Poor development of the argillaceous lithostrome in the Jordan and New Richmond cycles interpreted to mean that the depositional shelf zone did not regress as far south as the subsiding basin, that the land area exposed to erosion was lower and less extensive than at previous times of regression, and consequently, that less sediment was delivered to the shelf.

The results of this study are the basis of a working hypothesis being used by the Wisconsin Geological and Natural History Survey for interpreting problems of Cambrian and Ordovician stratigraphy and sedimentation. It is not meant to infer that conclusions drawn from this study are final. However, use of the cyclical hypothesis provides a rationale to explain stratigraphic relationships which have hitherto been poorly known on the local and regional scale, as well as to define geologic problems for additional investigation.

LITHOSTRATIGRAPHY, PETROLOGY, SEDIMENTOLOGY, AND DEPOSITIONAL ENVIRONMENTS OF THE JORDAN FORMATION NEAR MADISON, WISCONSIN

by

I. Edgar Odom[1] and Meredith E. Ostrom[2]

INTRODUCTION

The main emphasis of this field conference is on the lithostratigraphy, petrology, sedimentology and depositional environments of the Jordan Formation near Madison, Wisconsin. This and other papers included in the guidebook provide relevant information on the lithic and sedimentologic characteristics of the Jordan and on recent studies and interpretations as a supplement to the outcrop descriptions.

The lithostratigraphy and depositional environments of the Jordan and other Late Cambrian and Early Ordovician formations near Madison have been debated for more than 70 years. A major point of past and present controversy involves the interpretation of the relationship of the Jordan and adjacent formations near Madison to supposedly time equivalent strata in western Wisconsin and eastern Minnesota. Outcrops to be examined during this field conference were selected to clarify salient aspects of past disagreements and to show the basis for new stratigraphic, sedimentologic, and environmental interpretations.

In our study of the Jordan, we have employed comprehensive petrologic (never before done) and textural analyses and field mapping. To better understand the total spectrum of stratigraphic and sedimentological problems, we have included in our study all type sections as well as other sections in the upper Mississippi Valley that have in any way been considered controversial or stratigraphically significant. Many relatively recent exposures provided by quarrying and highway construction were studied, and these were especially helpful in resolving several long standing stratigraphic and sedimentological problems, especially in the Madison area. Although this paper deals primarily with interpretations of the Jordan Formation near Madison, certain aspects of the formation in western Wisconsin, eastern Minnesota and northeastern Iowa are also discussed because to comprehend local stratigraphic and sedimentologic relations and depositional environments it is essential to understand the regional nature of the Jordan Formation.

REVIEW OF PREVIOUS INVESTIGATIONS

Irving (1875) used the name Mendota for a dolomite and dolomitic siltstone and the name Madison for an overlying sandstone exposed in the Madison, Wisconsin area. A year earlier, Winchell (1874) working in the St. Peter (Minnesota) River Valley named the St. Lawrence Dolomite and the sandstone which superceded it the Jordan Sandstone, and later Winchell (1876) correlated the St. Lawrence with the Mendota and the Jordan with the Madison. (Note: Irving intended that the name

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Madison be used for the whole of the Jordan Formation as developed near Madison, Wisconsin, and he recognized that the local quarry stone which later became equated with the name Madison was local in occurrence.) Ulrich (1911) questioned Winchell's correlation and in 1914 Walcott published a columnar section, credited to Ulrich, which indicated that both the Mendota Dolomite and the Madison Sandstone were stratigraphically younger than the Jordan and St. Lawrence Formations. This interpretation was later questioned by several students of the Upper Mississippi Valley Cambrian (Thwaites, 1923; Stauffer, 1925), and by 1934, most workers agreed that the Mendota and St. Lawrence Dolomites were stratigraphically equivalent.

Prior to 1923, the Jordan Formation was generally considered to consist of two unnamed lithic units, a lower very fine-grained sandstone and an upper fine- to medium-grained sandstone. Ulrich (1924) named the lower unit the Norwalk Sandstone. The name Van Oser which is now used for the upper unit was apparently first suggested by Trowbridge and Atwater (1934). From about 1925 to the present, the type Madison (Sunset Point) Sandstone has been considered to be younger than the Jordan, Van Oser Member.

Thwaites (1923) appears to be the first to mention the presence of a Madison Sandstone (Sunset Point) equivalent in western Wisconsin, and he indicates that this was a suggestion of Ulrich. Wanemacher, Twenhofel, and Raasch (1934) briefly mention the occurrence of dolomitic sandstones overlying the Jordan in western Wisconsin, and they also suggested that these sandstones were the lithic and stratigraphic equivalents of the type Madison. The Madison Sandstone and the strata believed to be its equivalent in western Wisconsin were both considered by Raasch (1935, 1939) to be younger than the Jordan (Fig. 14), although Trowbridge and Atwater (1934) earlier expressed the opinion that the Madison was equivalent to the whole of the Jordan Formation exposed nearby rather than being younger. (Note: this same stratigraphic relation was also suggested by Twenhofel and Thwaites, 1935, p. 1711).

In 1951, Raasch (Fig. 14) proposed the name Sunset Point to replace the name Madison to eliminate possible confusion with the Madison Formation of Wyoming and Montana. He suggested that the Sunset Point should have formational rank, and he placed the new formation stratigraphically above the Van Oser Member of the Jordan. Sunset Point is the local name for a hill in Madison, Wisconsin, where the type Sunset Point (Madison) Sandstone is exposed in former quarries (Outcrop no. 1).

In his 1951 paper, Raasch described the gross lithology of sandstones in the Stoddard area of western Wisconsin that he considered to be the lithic equivalent of the type Sunset Point (Madison). A year later, Raasch (1952) also described the superjacent Oneota Formation in the Stoddard area, which he divided into four members (Fig. 14). Raasch considered the Sunset Point Formation in the Stoddard area to consist of predominantly sandstone, to be approximately 20 feet in thickness, and to be overlain unconformably by approximately 20 feet of sandstone and arenaceous dolostones which he named the Hickory Ridge Member of the Oneota. Raasch placed the Cambro-Ordovician boundary at the contact between the Sunset Point Formation and the Hickory Ridge Member of the Oneota. The second Oneota member identified by Raasch is a sequence of dolostones containing abundant "chitons" and algal masses, approximately 13 feet in thickness, which he named the Mound Ridge Member. The Mound Ridge was considered to be overlain by the Genoa and Stoddard Members, respectively (Fig. 14).

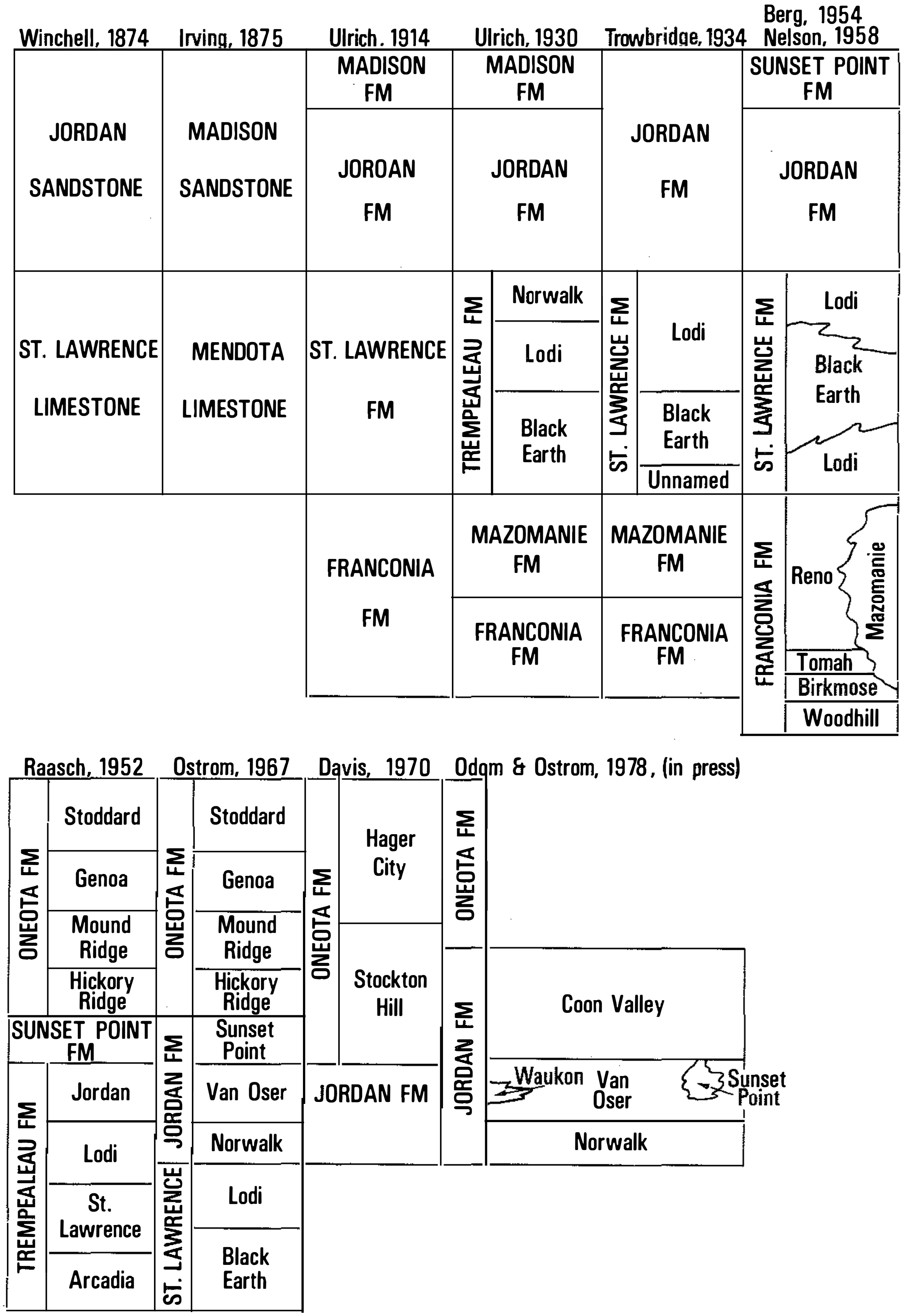

Figure 14 Past and proposed lithostratigraphic subdivisions of the Jordan, St. Lawrence, Lone Rock and Mazomanie Formations.

Other studies of the Sunset Point Sandstone were made by Starke (1949), Boardman (1952), Ahlen (1952), Melby (1967), Davis (1970), and Wegrzyn (1973). Boardman, Ahlen, and Melby concluded that there was a significant gross lithologic difference between the type Sunset Point Sandstone and the sandstones Raasch considered as being lithically equivalent in western Wisconsin. Davis stated that he could not consistently recognize the Sunset Point Sandstone even within western Wisconsin. Wegrzyn's work showed a striking textural and mineralogical difference between the type Sunset Point at Madison and the so-called Sunset Point Sandstone in western Wisconsin.

In 1970, Davis proposed to combine the Sunset Point Formation, the Hickory Ridge Member, and all except the upper few feet of the Mound Ridge Member of the Oneota in western Wisconsin into a single lithostratigraphic unit that he named the Stockton Hill Member of the Oneota Formation (Fig. 14). Davis does not specifically discuss the relation of the type Sunset Point Sandstone at Madison to his Stockton Hill Member, but cross sections in an unpublished report by him suggest that he did not consider them to be lithostratigraphic equivalents.

PROPOSED REVISIONS IN NOMENCLATURE AND CORRELATIONS

Several proposed revisions in the nomenclature and correlations previously applied to the Jordan and the Oneota Formations are shown in Figure 14. The Sunset Point is considered to be a member of the Jordan, and the name is used only for a sequence of very fine-grained, highly feldspathic sandstones which occur in and near Madison, Wisconsin. Based on field relations and mineralogical and textural analyses, we consider the Sunset Point Member to be a local facies laterally equivalent to the Van Oser Member (Fig. 14).

The name Waukon is proposed for a previously unrecognized lithic unit composed of very fine-grained, feldspathic sandstone that occurs locally in southwestern Wisconsin and northeastern Iowa. This sandstone is also considered to be a local facies laterally equivalent to the Van Oser Member (Fig. 14). The Waukon is assigned member status. Although its lithology is similar to that of the Sunset Point Member, a new name is necessary to avoid the possible confusion of its stratigraphic position with those sandstones overlying the Van Oser Member in western Wisconsin that were previously called the Sunset Point Formation by Raasch (1951).

The name Coon Valley is proposed for a sequence of dolomitic sandstones, sandy dolostones, and sandstones containing poorly sorted sand, abundant intraclasts, shale interbeds, some chert, sand-cored "oolites", and minor algal structures which intervene between the underlying Van Oser (locally the Sunset Point) Sandstone and the overlying relatively pure Oneota Dolostone. In western Wisconsin, we include in the Coon Valley Member the strata that Raasch (1951, 1952) called the Sunset Point Formation as well as the overlying Hickory Ridge Member of the Oneota Formation (Fig. 14). The Coon Valley Member is equivalent to the strata that Davis (1970) assigned to the Stockton Hill Member, except that a large part of Raasch's Mound Ridge Member of the Oneota is excluded (Fig. 14). The sand, oolitic (sand-cored), conglomeratic, "glauconitic", dolostones in western Wisconsin that Starke (1949), Ahlen (1952), Melby (1967) and Adams (this guidebook) assigned to the base of the Oneota Formation are placed in the Coon Valley Member.

The name Coon Valley is introduced for four reasons. First, it is necessary to abandon the name Stockton Hill, which Davis (1970) proposed for essentially the same interval, because this name was previously used by McGannon (1960) for a member of the St. Lawrence Formation (same type sections). Although McGannon's Stockton Hill Member has not been used in subsequent stratigraphic descriptions of the St. Lawrence, it appears as an informal name in the Lexicon of Stratigraphic Nomenclature. Second, a revision of the nomenclature pertaining to this stratigraphic interval has a direct bearing on the original work of Raasch (1951, 1952) in the Stoddard Quadrangle of western Wisconsin. Thus, we feel that unless there is a compelling reason to do otherwise, the type section of a new stratigraphic unit formed by combining several of Raasch's stratigraphic units should be in the Stoddard area. Third, the name Sunset Point as previously applied in western Wisconsin to strata we include in the basal part of the Coon Valley Member should be abandoned because textural and mineralogical data show that these beds and the type Sunset Point Sandstone are not lithostratigraphically equivalent. It is subsequently shown in this paper that the Coon Valley Member overlies the Sunset Point Member at the latter's type section in Madison, Wisconsin. Fourth, although McGee (1891) included all of the beds we assign to the Coon Valley Member in his Oneota Formation, as have others in later years, we consider them more akin to the Jordan Formation because of their high sand content throughout western Wisconsin and eastern Minnesota. It is also expedient to exclude the sandy Coon Valley Member from the Oneota because it is economically unsuitable for the same uses as the Oneota. In geological mapping, it is essential to differentiate the highly sandy beds (Coon Valley) from the purer Oneota. This cannot readily be accomplished on the scale of most geological maps because the member is thin and usually crops out on steep slopes.

LITHOLOGY, PETROLOGY, AND THICKNESS

Norwalk Member

The Norwalk Member is typically a very fine-grained, feldspathic (Fig. 15), massively to thinly bedded sandstone, but in northeastern Iowa, strata believed to be equivalent to the Norwalk Member are fine-grained and contain thin beds of medium-grained sand (Fig. 16). Massive beds in the Norwalk are mottled and intensely burrowed and bioturbated (Outcrop 8), but the only fossils are occasional trilobite fragments. Cruziana (prevalent) and Skolithos trace fossil assemblages are present. The mean grain size of the Norwalk Member usually coarsens upward. Trough and some planar-types of cross stratification are occasionally present where the mean size approached 3Ø (fine-grained), usually only in the upper two to three meters (Outcrop 8).

The predominant minerals composing the Norwalk Member are quartz, feldspar, and minor amounts of dolomite (Outcrops 3 and 8 and Fig. 18), although massive beds frequently contain some illitic clay matrix. The feldspar content is distinctive and ranges from 15 to more than 50 percent. Approximately 25 percent of the total feldspar occurs as authigenic overgrowths on detretal feldspar grains (Fig. 15). The enrichment of feldspar in the Norwalk Member, compared to the Van Oser and Coon Valley Members, is related to its very fine grain size (Odom, 1975; Odom, Doe and Dott, 1976).

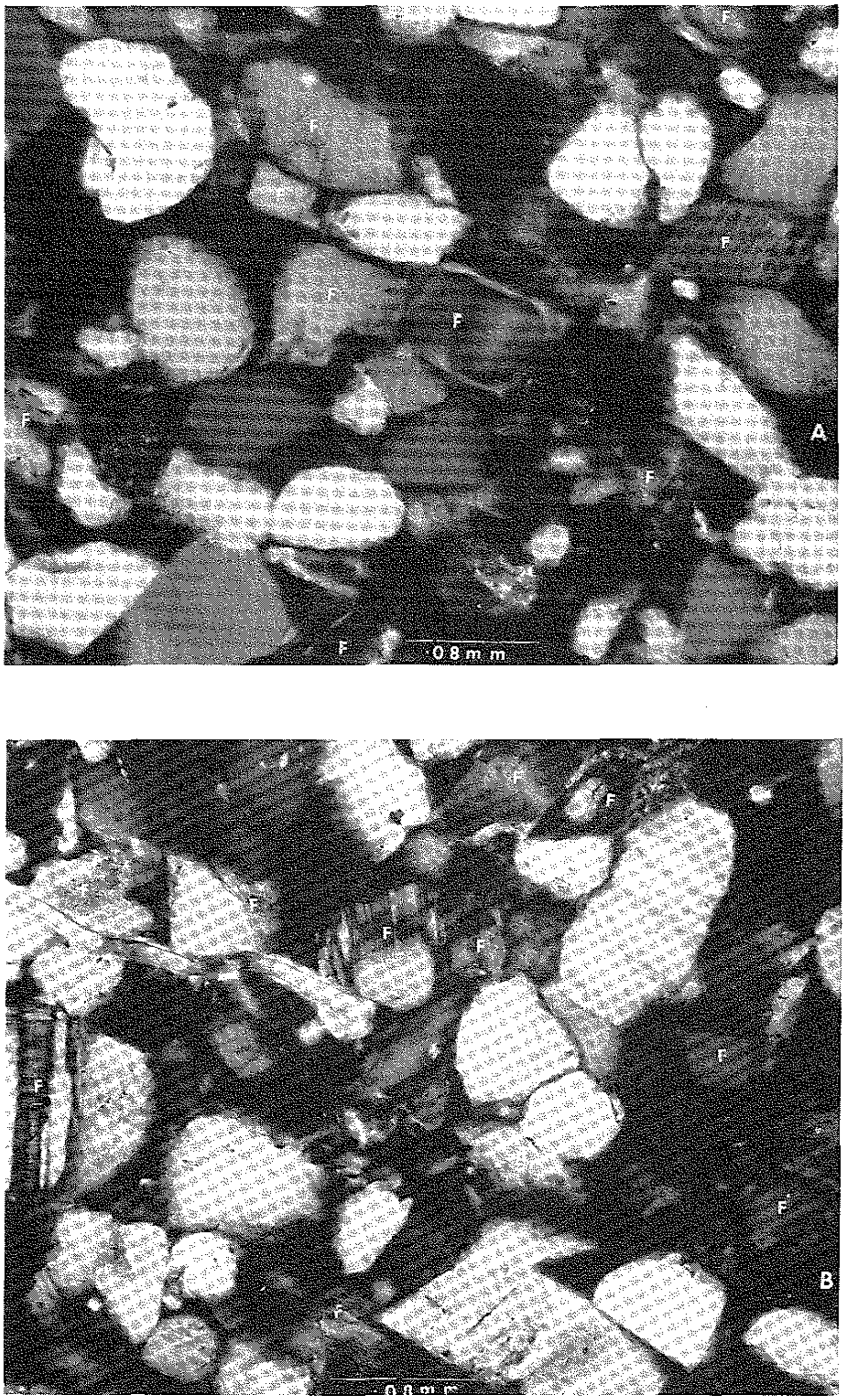

Figure 15 Feldspar (F) in sandstones of the Jordan Formation. A- Norwalk Member B- Sunset Point Member.

The Norwalk Member is present throughout western Wisconsin and eastern Minnesota except locally along the axis of the Wisconsin Arch (Fig. 17), where it apparently was eroded prior to deposition of the overlying Van Oser Member. The coarsening of the Norwalk Member in the northeastern corner of Iowa as well as stratigraphic relations in the subsurface of Iowa suggest that it is absent farther to the south. In western Wisconsin and eastern Minnesota, the Norwalk Member has an average thickness of 6-7 meters.

Van Oser Member

The Van Oser Member of the Jordan is a remarkably uniform, medium- to fine-grained, well- to moderately well-sorted, white to brown, quartzose sandstone. In many sections, the grain size of the Van Oser Member coarsens upward (Outcrops 2, 3, and 8), and the lower portion is better sorted. Skolithos burrows are common. The Van Oser Sandstone is characterized by abundant trough (some wedge and tabular) shaped cross sets. Dott (this guidebook), Dalziel and Dott (1970) and Michelson and Dott (1973) show a dominantly south-southwest transport direction for the Van Oser Member in central and western Wisconsin. A significant sedimentological aspect of the Van Oser Member is the large dispersion of current direction indicators within individual outcrops (Outcrops 3 and 4).

The thickness of the Van Oser Member ranges from a minimum of 6 meters locally in central Wisconsin on the axis of the Wisconsin Arch (Fig. 17) to more than 22 meters locally in the area of the Mississippi River Valley (Fig. 16). Its average thickness is approximately 12 meters. Throughout most of the Upper Mississippi Valley, the Van Oser Sandstone is a single lithic unit, but in extreme southwestern Wisconsin and northeastern Iowa, it is separated into two units (Fig. 16) by the Waukon Member. Also, in and near Madison, Wisconsin, it is locally split by the Sunset Point Member (Outcrop 4 and Fig. 17).

Waukon Member

The name Waukon is proposed for a very fine-grained, feldspathic, slightly dolomitic, massive to thinly bedded, bioturbated sandstone that occurs in Vernon County (southwest), Wisconsin and Allmankee County (northeast), Iowa. The type section for the Member is on the north side of the Upper Iowa River on State Road 26 A, 1.62 km east of State Highway 72 and 16 km north of Waukon, Iowa. The member is present in intermittent outcrops over a distance of 50 km from near Coon Valley, Wisconsin (Fig. 18) southwestward to the type section where it then passes into the subsurface; however, it is not known whether the member is continuous over this distance. Its gross lithology and mineralogy (also trace fossils) are quite similar to that of the Sunset Point Sandstone and also to that of the Norwalk Sandstone. In all outcrops so far observed containing the Waukon Member, it is overlain and underlain by fine- to medium-grained quartzose sandstone (Van Oser Member).

The Waukon Member is 5.5 meters in thickness at its type section, but it thins to only 3.4 meters at Coon Valley, Wisconsin (Fig. 18).

Sunset Point Member

The Sunset Point Member consists of dolomitic and nondolomitic, massive to thinly bedded, highly feldspathic, very fine-grained sandstone. At its type section in Madison, Wisconsin (Outcrop 1), this member is 5.8 meters in thickness and is divided into upper and lower units by a thin bed of medium-grained sandstone. The

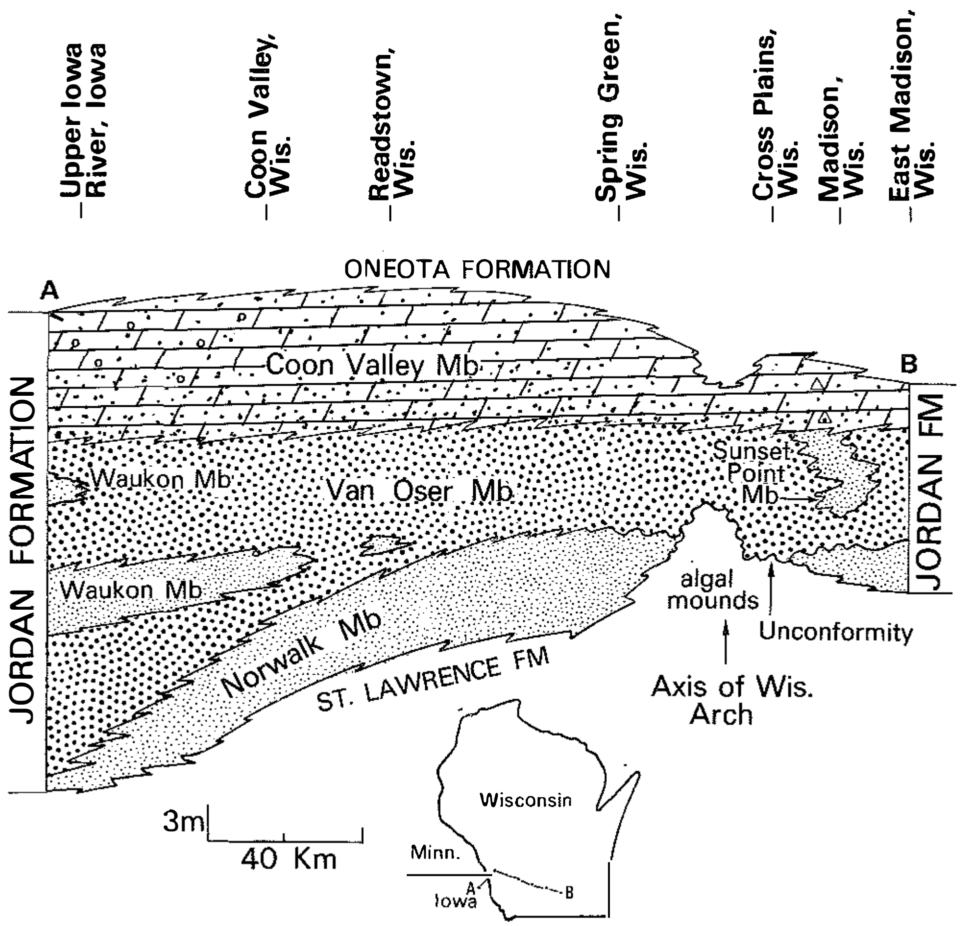

Figure 16 Lithostratigraphy of the Jordan Formation, northeastern Iowa to central Wisconsin.

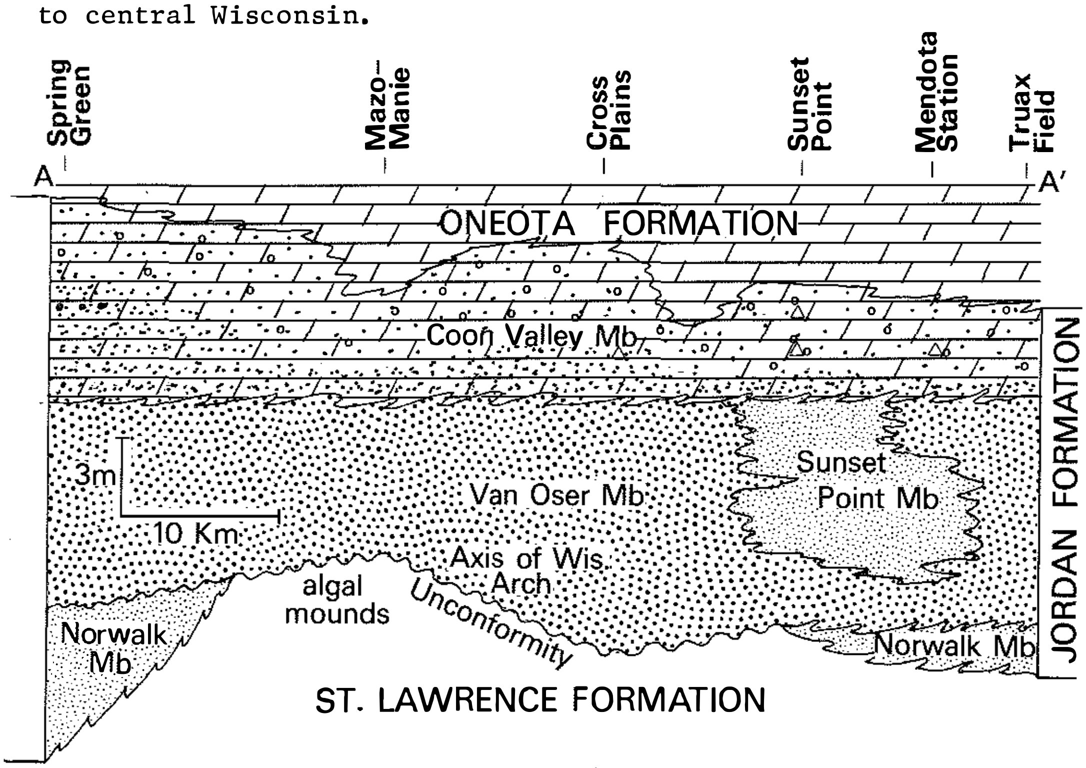

Figure 17 Lithostratigraphy of the Jordan Formation in the vicinity of the Wisconsin Arch.

upper unit is dolomitic and thinly bedded, whereas the lower unit is massive and mostly nondolomitic. Both units contain numerous burrows and other types of trace fossils (Cruziana and Skolithos Ichnofacies). At the type section, the Sunset Point Sandstone is underlain by 1.5 meters (base not exposed) of fine- to medium-grained, quartzose sandstone characterized by trough-shaped cross sets (Van Oser) and overlain by the Coon Valley Member. At Outcrop 4, however, the Sunset Point Sandstone is both overlain and underlain by the Van Oser Sandstone and the Coon Valley Member supersedes the upper unit of the Van Oser.

Coon Valley Member

As previously described, the name Coon Valley (proposed) is applied to a persistent sequence of dolomitic sandstones and sandy dolostones which intervene between the Van Oser Member (locally the Sunset Point Member) and the Oneota Dolostone throughout western Wisconsin, eastern Minnesota, and northeastern Iowa. It extends into the subsurface of Iowa and Illinois and is equivalent in part to the Gunter Formation.

The type section (Fig. 18) chosen for the Coon Valley Member is on the south side of U.S. Highway 14 two miles west of the town of Coon Valley, Vernon County, Wisconsin (NW$\frac{1}{4}$, NE$\frac{1}{4}$, Sec. 11, T. 14 N., R. 6 W.). This exposure is an excellent representation of the regional lithic character of the Coon Valley Member, other members of the Jordan and adjacent formations are well exposed, and most importantly, it is located in the region where Raasch (1951, 1952) described the dolomitic sandstones he correlated with the type Sunset Point Formation (Sunset Point Member) and also divided the Oneota Formation into several members.

The Coon Valley Member is a very heterogeneous lithic unit. The predominant rock types, in order of abundance, are fine- to medium-grained, poorly sorted, dolomitic, quartzose sandstones (Fig. 19); sandy "oolitic" dolostones in which the quartz grains are frequently poorly sorted; quartzose sandstones that are frequently only moderately well sorted; a few thin dolostone (algal) beds; and minor amounts of very fine-grained, feldspathic sandstones. On and east of the Wisconsin Arch, however, sandy dolostones greatly predominate over dolomitic quartz sandstones. Along the Mississippi River Valley, the member becomes more dolomitic toward the south.

Throughout western Wisconsin, eastern Minnesota and northeastern Iowa, poorly sorted, fine- to medium-grained, dolomitic sandstones usually compose the lower one-third to two-thirds of the member, whereas the remainder consists predominantly of interbeds of dolomitic sandstones and sandy dolostones. The lower dolomitic sandstone sequence was correlated with the Sunset Point Member at Madison by Raasch (1951), but comparison of the petrology and texture of these beds (Fig. 18) with that of the Sunset Point Member (Outcrop 1) shows clearly that they are not lithic equivalents.

The Coon Valley Member is also heterogeneous from a sedimentological view point. Striking lithic variations may occur in a short distance, and a wide variety of sedimentary structures are present. Intraclasts composed of rounded to subangular, silty, algal, dolostone and sandy dolostone are exceedingly abundant at many stratigraphic positions in almost all outcrops. In central Wisconsin, the member locally contains lithoclasts and even conglomerates composed of granules and pebbles of Precambrian Baraboo Quartzite. In many sections sandy dolostone beds in the upper part contain abundant sand-cored "oolites" (Fig. 19). Although oolites are also present in the overlying Oneota Dolostone, they are usually not sand-cored. It is probable that a significant percentage

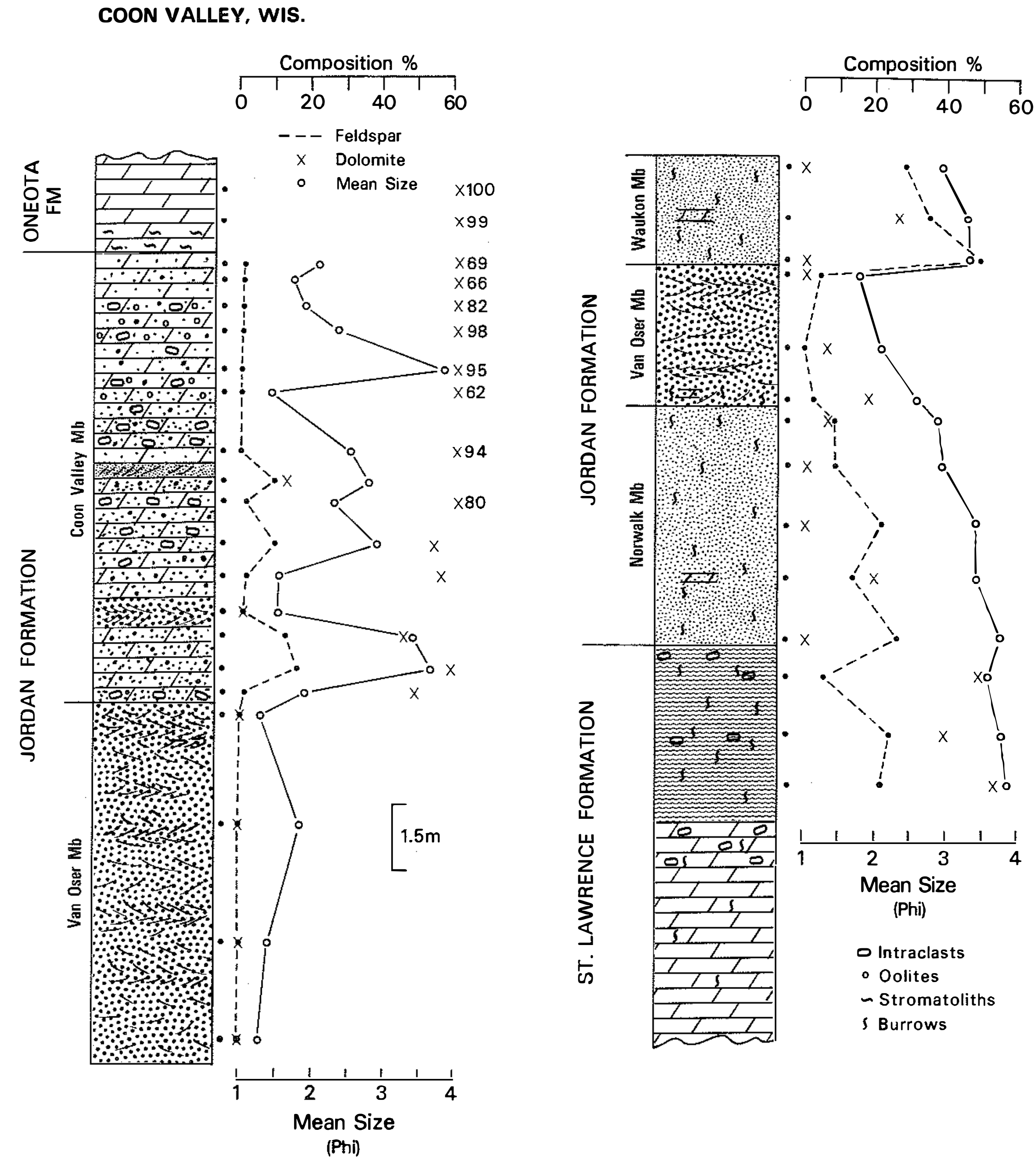

Figure 18 Stratigraphy, petrology and texture of the Jordan Formation at the type section of the Coon Valley Member, Vernon County, Wisconsin.

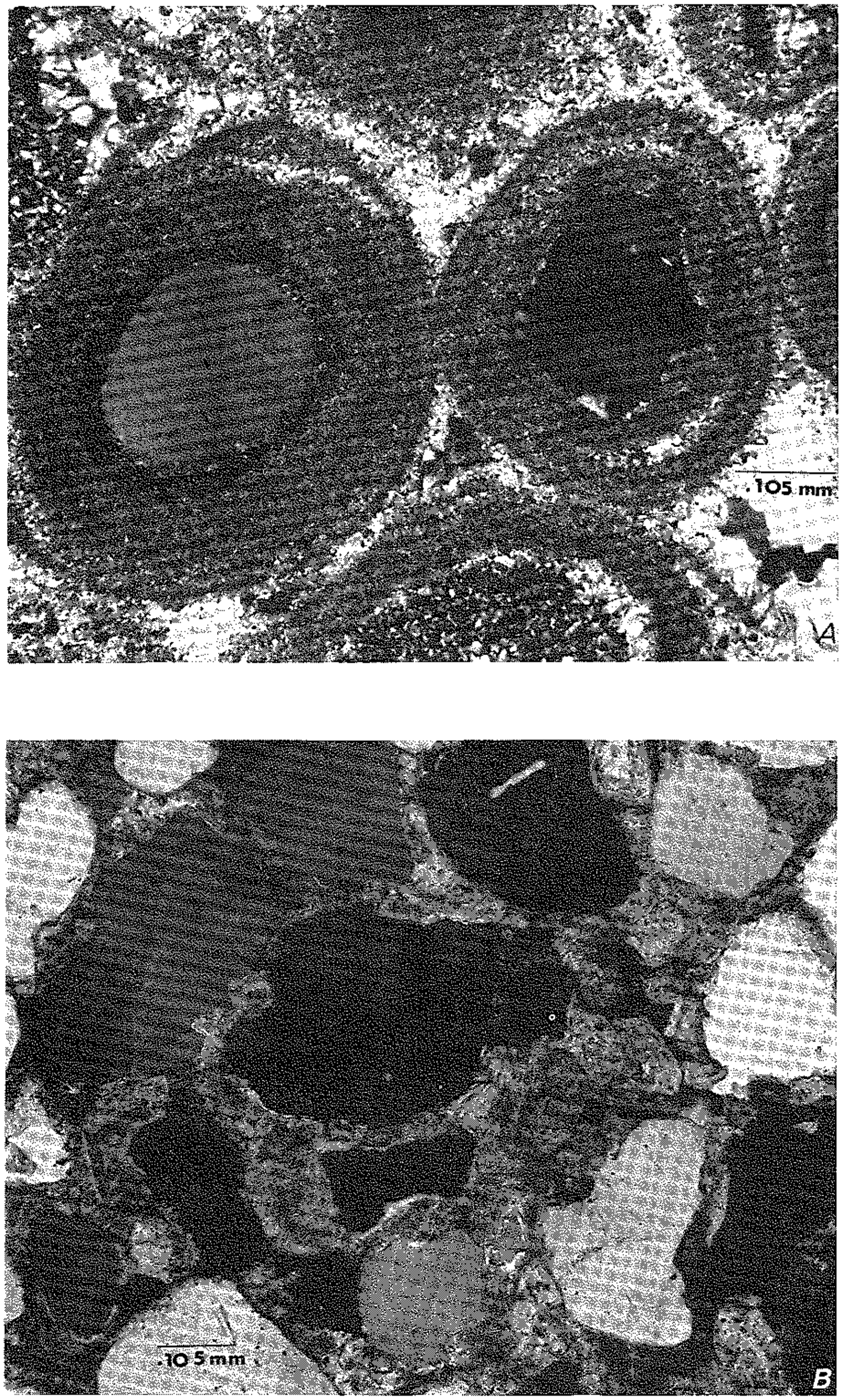

Figure 19 Some lithic characteristics of the Coon Valley Member. A- Sand-cored "oolites", B- Texture of a typical dolomitic sandstone.

of the "oolites" in the Coon Valley Member are of vadose rather than primary origin. A vadose origin is suggested by the fact that the laminated portions are either silica or calcite, and in some the nucleus consists of fine sediment identical to the sediment in which the "oolites" are embedded.

Thin dolostone beds containing algal stromatoliths (see paper by Adams) and oolitic chert occur locally in the Coon Valley Member, especially in the upper portion, but stromatoliths and chert are much more abundant in the lower beds of the Oneota immediately overlying the member. Small scale cut and fill structures and trough and wedge-shaped cross sets are often present in sandstones and dolomitic sandstones. Thin interbeds and streaks of shale and fragments of illitic green clay, previously called glauconite, are often present. A relatively persistent shaly zone occurs above the basal dolomitic sandstones in western Wisconsin and near the base of the sandy dolostones in central Wisconsin. Burrows are frequently present, but the only fossils reported are Ordovician age conodonts (Melby, 1967). Polygonal dessication cracks believed to indicate subaerial exposure are locally present. The dolomite in the Coon Valley Member ranges from finely to coarsely crystalline. Locally, large amounts of secondary calcite has been deposited in dolomitic sandstones near the contact with as well as within the Van Oser Member.

In western Wisconsin and eastern Minnesota, the Coon Valley Member averages 11 meters in thickness (Fig. 16), but it progressively thins eastward to an average of 4 meters in central Wisconsin (Fig. 17). In the vicinity of Shakopee and Jordan, Minnesota, the Coon Valley Member is absent. In that area, the Coon Valley is believed to be stratigraphically equivalent to the Blue Earth Siltstone.

Although we have made extensive use of textural and petrographic analyses to evaluate the lithology and to establish the contacts of the Coon Valley Member, such analyses are not necessary to recognize the contacts or to map this member in the field. Specifically, the lower contact with the Van Oser Member is placed at the first appearance of dolomitic sandstones or occasionally sandy dolostones, both of which usually contain poorly sorted sand and intraclasts. Where the Coon Valley Member overlies the Sunset Point Member in and near Madison, Wisconsin, the lower contact is marked by a distinct change from very fine-grained dolomitic sandstone (Sunset Point) to fine- to medium-grained dolomitic sandstone or sandy dolostone containing intraclasts and locally stromatoliths. The upper contact is everywhere placed at the top of the uppermost bed of conspicuously sandy dolostone. To accurately identify the upper contact requires careful examination of "fresh" rock with a hand lens.

STRATIGRAPHIC RELATIONS RELATED TO SEDIMENTATION AND EROSION

Figures 16 and 17 illustrate interpretations of regional and local stratigraphic relations of the Jordan Formation to adjacent formations and of its members to each other based on detailed petrologic, textural, and outcrop analyses. The cross section shown in Figure 16 is not extended into the subsurface of Iowa or east of Madison because well records are inadequate to resolve stratigraphic relations. The following discussion emphasizes only the stratigraphic relations that in the past have been especially problemmatical or that have been newly discovered.

Jordan and St. Lawrence Formations

The very fine-grained sandstones that characterize the Norwalk Member constitute a transitional sequence between the Lodi Siltstones of the St. Lawrence and the fine- to medium-grained sandstones of the Van Oser Member. There are, however, several areas where they are not transitional due to lithic variations in the St. Lawrence or to erosion of the Norwalk Member prior to deposition of the Van Oser Member. In local outcrops situated on or near the axis of the Wisconsin Arch, the Norwalk Member is absent (Fig. 17) and the Van Oser Member directly overlies the St. Lawrence (Outcrops 6 and 7), yet in outcrops only a few miles distant (also on the Arch) several feet of the Norwalk Sandstone may be present. The patchy distribution of the Norwalk Sandstone as well as variations in the elevation of the base of the Van Oser Sandstone over the Wisconsin Arch indicate that subaerial erosion occurred prior to deposition of the Van Oser Member. This period of erosion is also evident farther west in eastern Crawford and Vernon Counties, Wisconsin where channels of Van Oser Sandstone cut up to 3.5 meters into the underlying Norwalk Member.

Another complex stratigraphic relation between the Norwalk Member and the St. Lawrence Formation related to sedimentation also occurs in the eastern Crawford and western Richland Counties, Wisconsin. Field studies and mineralogical and textural analyses of outcrops west of Richland Center, Wisconsin reveal that the Lodi Member of the St. Lawrence, instead of consisting of siltstone and silty dolostone grades laterally into very fine-grained sandstone. The Norwalk is, however, clearly recognizable in this area (Fig. 20).

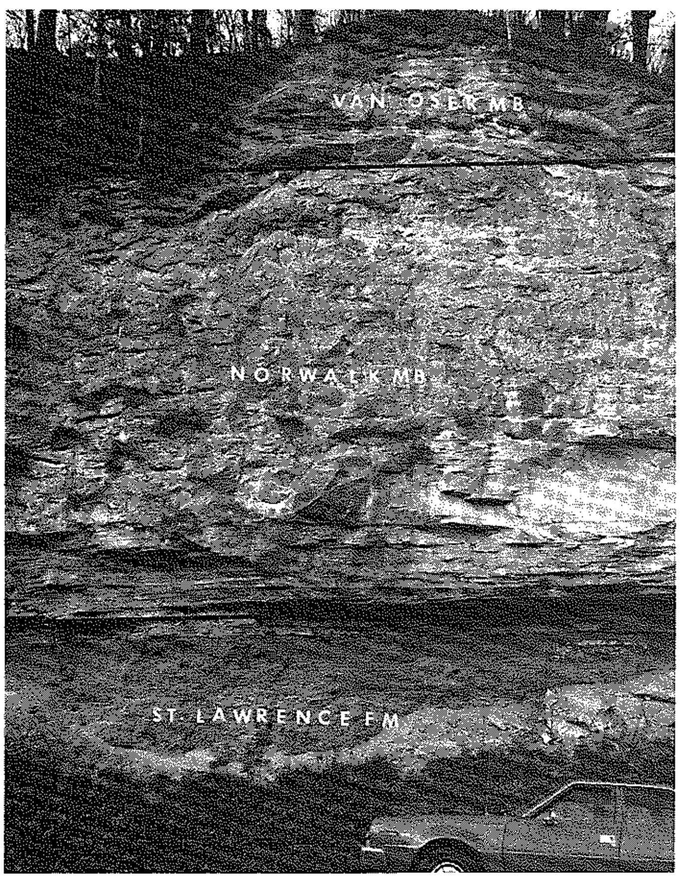

Figure 20 Stratigraphic relations of the Jordan and St. Lawrence Formations on U.S. Highway 14 6.4 km west of Richland Center, Wisconsin.

Near the outcrop limits of the Jordan and St. Lawrence Formations in central Wisconsin (Juneau and Monroe Counties) and in the St. Croix River Valley, the Lodi Siltstone grades laterally into very fine-grained, massive, burrowed Norwalk Sandstone (Twenhofel and Thwaites, 1919; Nelson, 1958). Thus, in more near shore areas part of the Norwalk Member was deposited simultaneously with the Lodi Siltstone and Black Earth Dolostone facies farther south.

The lithology of the Norwalk Member in northeastern Iowa differs in that it is fine rather than very fine-grained, and it also contains thin interbeds of medium-grained sandstone. (We interpret the interbeds of medium-grained sandstone to represent washover fans from nearby Van Oser bars.) This lithic variation and also other subsurface stratigraphic relations suggest that farther to the south and west the Norwalk Member grades into the Van Oser Sandstone.

Norwalk and Van Oser Members

As previously described, the Norwalk Member usually coarsens upward, however, the contact between the Norwalk and Van Oser Members may be abrupt (Outcrop 8) or transitional through an interval of up to 2 meters. As previously described, these members are locally separated by an unconformity along the axis of the Wisconsin Arch south of the Baraboo Syncline and in eastern Crawford County, Wisconsin. The Norwalk Member is believed to grade laterally into the Van Oser Member in northeastern Iowa (Fig. 16).

Van Oser and Waukon Members

In all outcrops in southwestern Wisconsin and northeastern Iowa where the Waukon Member has been observed, it is overlain and underlain by fine- to medium-grained, quartzose sandstone--Van Oser Member (Fig. 16). Field mapping shows that the Waukon Member disappears to the north, east, and south, but because the Late Cambrian and Early Ordovician strata pass into the subsurface its extent toward the west cannot be defined. The Waukon Member may be a local facies enclosed by the Van Oser Member or a tongue that grades southward into sandy dolomite (Eminence Formation).

In the two sections where textural analyses have been made of the Waukon and associated Van Oser Members, the contact with the underlying Van Oser Member is abrupt, the texture of the Waukon Member coarsens upward, and the textural change to the underlying Van Oser Sandstone is gradual (Fig. 18).

Van Oser and Sunset Point Members

Mapping of the Sunset Point Member shows that it is a lens-shaped body which extends from near the south end of Lake Mendota in the City of Madison, Wisconsin northward for about 25 km. The maximum width of the lens is approximately 10 km in the vicinity of Lake Mendota.

The major reason that the Sunset Point Member was previously regarded as being younger than the Van Oser Member (Ulrich, 1911, 1930; Twenhofel and Thwaites, 1923; Raasch, 1935, 1951, and Ostrom, 1967) appears to be the stratigraphic relations at the Sunset Point type section (Outcrop 1), where it is overlain by sandy dolostones (Coon Valley) that were previously assigned to the Oneota. The early workers apparently did not observe the underlying Van Oser Sandstone at the Sunset Point type section since it was not exposed prior to the early 1960's.

Unequivocal evidence that the Sunset Point Member is a local facies laterally equivalent to the Van Oser Member is provided in several outcrops of the Jordan near the Sunset Point type section. The most significant exposure occurs at Mendota Station (Outcrop 4) in a railroad cut located 9 km northeast of the Sunset Point type section. Textural and mineralogical analyses of the Mendota Station section (Outcrop 4) show 13 feet of very fine-grained, massive, burrowed, highly feldspathic sandstone overlain and underlain by highly cross-stratified quartzose sandstone. Previously, all of the sandstone above the lower unit of the Van Oser, was called Sunset Point. We regard the quartzose sandstone overlying the Sunset Point in Outcrop 4 to be a tongue of the Van Oser Member. Especially significant is the fact that this Van Oser tongue is directly overlain by the Coon Valley Member, which is composed of sandy, oolitic (sand-cored), cherty (reddish) dolostones, very similar to the Coon Valley Member at Outcrop 1.

Virtually the entire Jordan Formation is exposed at two other locations in Madison located to the east of the Mendota Station section (near Truax Airport 4.8 km (3 miles) east and near the U.S. 151 - I-90 interchange 8 km (5 miles) east - Outcrop 3), but neither section contains sandstones characteristic of the Sunset Point Member. Another section located 4.8 km (3 miles) southeast of the Sunset Point type section (Outcrop 2) also does not contain the Sunset Point Member. Three miles west of the type section, near Middleton, Wisconsin, are several exposures in which the very fine-grained Sunset Point Sandstone can be observed to grade toward the west into fine- to medium-grained, cross-stratified Van Oser Sandstone.

In summary, field, stratigraphic, textural, and mineralogical data show that the Sunset Point Member is a local facies laterally equivalent to the Van Oser Member. In some areas it is overlain by the Coon Valley Member, whereas in others it is overlain by the Van Oser Member, which is in turn overlain by the Coon Valley Member. The Sunset Point and Van Oser Members can be shown to be gradational into each other.

Van Oser (locally Sunset Point) and Coon Valley Members

The Coon Valley and Van Oser Members are apparently conformable except locally where the Coon Valley Member conformably overlies the Sunset Point Member near Madison, Wisconsin. In the Minnesota River Valley, the dolomitic sandstones and sandy dolostones typical of the Coon Valley Member are replaced by the Blue Earth Siltstone, which intervenes between the Van Oser Member and the Oneota Dolostone. We believe the Blue Earth and possibly part of the Van Oser (Kasota Sandstone) are time equivalent to the Coon Valley in that area.

Figure 16 shows that the Coon Valley Member thins over the Wisconsin Arch, and in a few outcrops along the axis of the arch, the member is represented by as little as .3 to $1\frac{1}{2}$ meters of shaly sandstone or sandy dolostone. In these areas, deposition of nonsandy dolostone appears to have begun sooner than in surrounding areas. There is no field evidence that the Van Oser Sandstone thickens where the Coon Valley is very thin. In fact, the Van Oser and Coon Valley are both quite thin at Outcrop 7.

Based on stratigraphic, textural and mineralogical evidence (Fig. 18), we conclude that the dolomitic sandstones in the lower part of the Coon Valley Member in western Wisconsin, which were previously called the Sunset Point Sandstone, are not lithically equivalent to the type Sunset Point Member at Madison, Wisconsin. The dolomitic sandstones in western Wisconsin are, however, believed to be time equivalent to the upper parts of the Van Oser and Sunset Point Members (Fig. 21) near Madison. It is also probable that the Van Oser Member continued to be deposited in the Baraboo area while parts of the Coon Valley Member were being deposited in the Madison area.

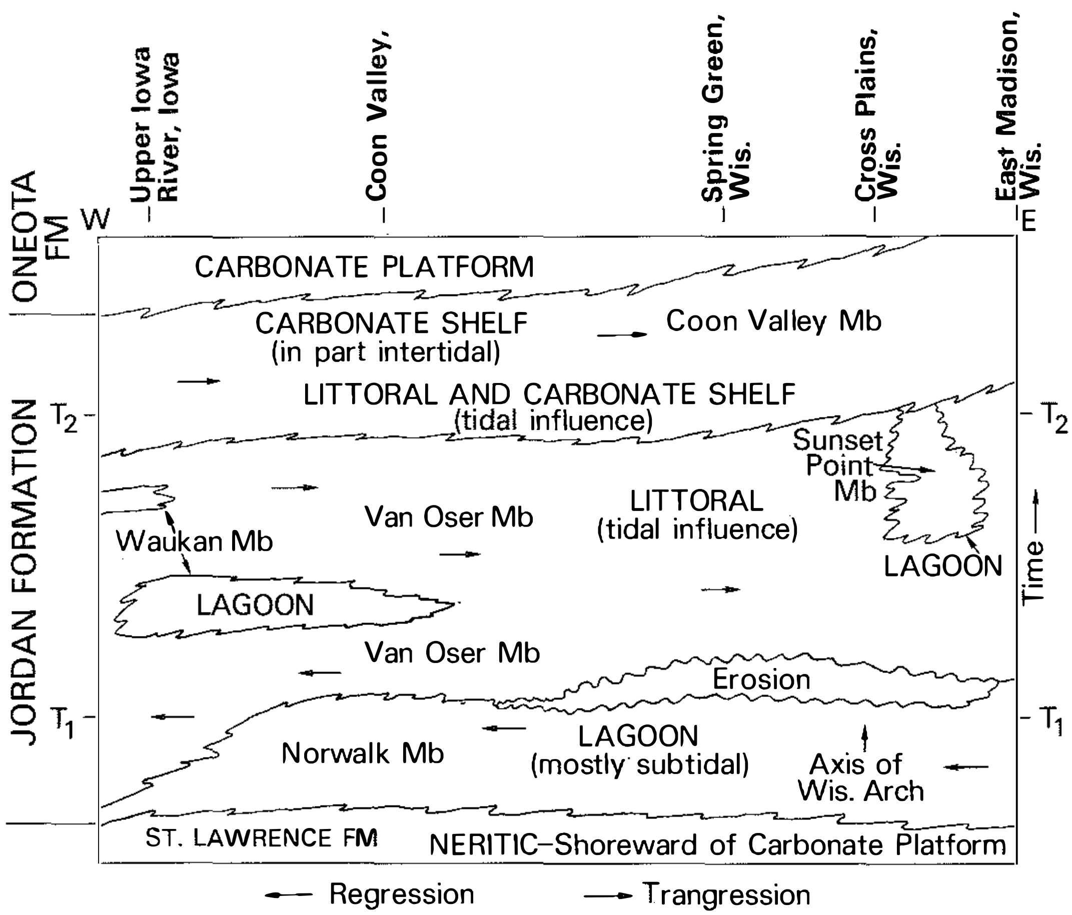

Figure 21 Proposed time-stratigraphic distribution of environments during deposition of the Jordan Formation, northeastern Iowa to central Wisconsin.

Coon Valley Member and Oneota Dolostone

Except in the areas previously mentioned, the Coon Valley Member is transitional through a stratigraphic interval of up to 3 meters with the overlying Oneota Dolostone. As previously indicated, the top of the Coon Valley Member is placed at the top of the uppermost dolostone bed in which fine to coarse quartz sand is conspicuous ($<$ 1-2%). The basal beds of the Oneota are usually massive to laminated, nonsandy dolostones containing stromatolites (honeycomb weathering common), but stromatolitic beds (some honeycomb) also occur interbedded with sandy dolostones near the top of the Coon Valley Member (Outcrop 8). On the axis of the Wisconsin arch, sandy Coon Valley and nonsandy Oneota are juxtaposed (Fig. 17), a relation that is believed to be due to the build-up of local stromatolite mounds.

DEPOSITIONAL ENVIRONMENTS

The Jordan and Oneota Formations represent the third Cambro-Ordovician depositional cycle as defined by Ostrom (this guidebook), however, there are several significant sedimentologic and lithic aspects that are unique to this cycle. First, the Jordan-Oneota cycle contains much more carbonate and much less very fine-grained clastics than the previous two cycles. Second, the basal clastic (Van Oser Member) and upper pure carbonate phases (Oneota Dolostone) are transitional through a relatively thick sequence of mixed clastics and carbonates (Coon Valley Member). Third, a regressive phase (Norwalk Member) is present at the top of the second cycle, whereas in the case of the first cycle a regressive phase is not as evident in Wisconsin. In general, the first two cycles begin with a sequence of littoral and near-shore deposits (some fluvial deposits occur in the Mt. Simon at the base of the first cycle) that are overlain by thick sequences of very fine-grained, sometimes glauconitic and shaly, sandstones, which then grade into carbonates or dolomitic siltstones. In Wisconsin, coincident with the Wisconsin Arch, an unconformity occurs between the first and second cycles, i.e. between the Eau Claire and Wonewoc Formations. As for the third cycle, a local unconformity occurs, also coincident with the Wisconsin Arch, at the base of the Van Oser Member. It is very significant that the third cycle contains very little glauconite, whereas glauconite is very abundant in the fine grain sediments of the first two cycles. Because each cycle as defined by Ostrom begins with transgressive littoral deposits, the regressive Norwalk Member of the Jordan might be considered to be part of the second cycle.

Based on their regional and stratigraphic distributions, lithic characteristics, and sedimentary structures, we interpret that the members of the Jordan Formation were deposited in four types of environments--lagoon, littoral, carbonate shelf, and intertidal. Also, it is believed that the littoral and carbonate shelf environments were influenced by a significant tidal range. The time-stratigraphic distribution of these environments as we envision them is shown in Figure 21.

Lagoon Environments

The Norwalk, Sunset Point and Waukon Members are interpreted to represent dominantly subtidal lagoonal deposits based on their very fine grain size, bioturbated structure, mineralogy and trace fossil assemblages (a Cruziana assemblage dominates). An intertidal environment is not acceptable for these members because they lack sedimentary sequences and structures, such as dessication features, seaward coarsening, tidal channels, or flaser bedding, that are indicative of tidal processes. The only sedimentary structure present in these members that might indicate water movement resulting from tidal currents is the local development of trough axes in the top of the Norwalk and in the lower part of the Sunset Point Members having directional modes 140° to 180° apart. The stratigraphic positions and wide dispersions of current direction indicators in these members is in agreement with our concept of tidal activity in a littoral environment into which these members grade.

The Norwalk Member is most areas is gradational with the dolomitic siltstones and silty dolostones which compose the St. Lawrence (Fig. 18). We interpret that the St. Lawrence Formation in western Wisconsin and eastern Minnesota was deposited in a shallow inner shelf environment, slightly below wave base except during large storms, located immediately landward of a carbonate platform environment. This interpretation is supported by the fact that the St. Lawrence Formation grades into entirely dolostone in south central Minnesota and north central Iowa and into entirely very fine-grained sandstones toward the north. Thus, the spacial distribution of lithic types is difficult to reconcile with tidal depositional models as proposed by Lochman-Balk (1970) or Byers (this guidebook).

On the basis of the thickening of the Van Oser Member and the coarsening as well as thinning of the Norwalk Member in northeastern Iowa, we infer that a littoral bar complex developed in central and northern Iowa soon after the depositon of the St. Lawrence. This inference is supported by the presence of a thick sequence of approximately time equivalent finc- and medium-grained sandstones in the subsurface of eastern Iowa, which thicken toward the south, called the Momence Sandstone by Buschbach (1964). We believe that the Norwalk Member is time equivalent to the Momence Sandstone and perhaps part of the Eminence Formation and was deposited in a broad lagoon situated north of this bar complex and south of a littoral environment in northern Wisconsin. Our concept of the spacial distributions of these environments is shown in Figure 21 at time T_1. The thin beds of medium-grained sandstone in the Norwalk Member in northeastern Iowa (Fig. 16) are considered to represent washover fans from nearby Van Oser bars. The coarsening upward texture of the Norwalk Member is interpreted as evidence of a gradual eustatic lowering of sea level through time. The regional uplift that initiated this regression caused the Norwalk and underlying St. Lawrence Formation to be locally exposed to subaerial erosion across the Wisconsin Arch (Figs. 16 and 17), which accounts for the local unconformity between the Van Oser Member and the St. Lawrence Formation west of Madison, Wisconsin and between the Van Oser and Norwalk Members near Soldiers Grove, Wisconsin.

The Sunset Point and probably the Waukon Members are believed to have been deposited in lagoonal environments more local in distribution. Our stratigraphic analyses indicate that these local lagoons existed at the same time that the Van Oser Member was being deposited nearby. The physical factors responsible for the development of local lagoons within a high energy littoral environment (Van Oser) are not entirely apparent in the case of the Waukon Member (it may be a tongue-shaped unit rather than a lens). The Sunset Point lagoon, however, appears to have developed because of the influence of a nearby island chain (Baraboo) on marine circulation and sand transport. As previously described, mapping shows that the Sunset Point Member is limited to a small area in and near Madison, Wisconsin, and its northern most outcrops occur about 15 miles from the Baraboo Syncline. According to Raasch (1958) and Dalziel and Dott (1970), the Baraboo Quartzite in Cambrian time formed an emergent island complex in the Cambrian seas (Fig. 22).

Paleogeographic reconstructions of thc geography, physiography and dominant wind direction for the Baraboo region in Late Cambrian time by Raasch (1958) and Dalziel and Dott (1970) show that the axis of the Baraboo Syncline was then oriented approximately N. 15° W. rather than east-west as at present. The prevailing wind direction was from the east, and the Madison area was located at approximately 10° south latitude based on present geographic coordinates. Thus, the Sunset Point depositional area in Cambrian time was situated to the southwest of the Baraboo Syncline (Fig. 22).

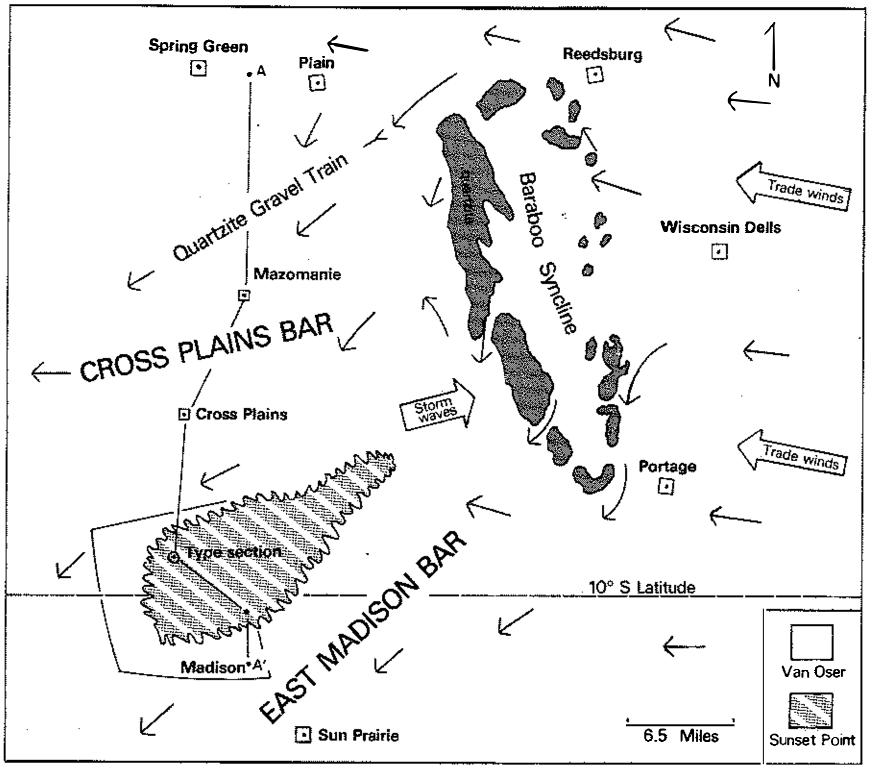

Figure 22 Paleogeographic location of the Sunset Point Lagoon in relation to the Baraboo Islands and the Cross Plains and East Madison Bar complexes in Late Cambrian time.

Raasch (1958) and Dott (1974) have documented the strong influence of the ancient Baraboo Islands on local sedimentation during Late Cambrian and Early Ordovician time (Fig. 31). Field mapping and textural and mineralogical analyses of the Van Oser Member of the Jordan in the Madison, Baraboo, and Cross Plains, Wisconsin areas show that spit and bar complexes projected westward from both ends of the island chain. The Cross Plains Bar (Fig. 22) which projected from the north end extended west and south into Cross Plains area. The East Madison Bar (Fig. 22) which projected from the south end extended southwest into the east and south Madison areas. Granule and often pebble-size grains of Baraboo Quartzite are common in the Van Oser Sandstone composing these bar complexes and demonstrate the influence of the Baraboo Islands on sand transport. Based on the above relations, it is concluded that the very fine-grained, feldspathic Sunset Point was deposited in a small lagoon located leeward of the west of the Baraboo Islands between the Cross Plains and East Madison Bars (Fig. 22).

Thin, fine- and medium-grained sandstone beds which occur locally in the Sunset Point Member (Outcrop 1) are interpreted as washover fans from adjacent bars caused by tropical storms (perhaps hurricanes). Dott (1974) believes that tropical storms were quite frequent and had a strong influence on conglomerate distribution nearer to the Baraboo Islands (Fig. 31). The high feldspar content of the Sunset Point Member as well as the Waukon and Norwalk Members, compared to the quartzose Van Oser Member, is believed to be due to the abrasion and size reduction of feldspar to very fine sand in the surrounding high energy littoral environment followed by sorting and then redeposition in low energy lagoon and other off-shore environments (Odom, 1975).

Littoral and Intertidal Environments

The term littoral is used to indicate marine sedimentation under high to moderately high hydrologic energy related to waves and currents. It includes modern geomorphic environments such as beach, shoal, bar and shallow shelf. The term intertidal is used in its "conventional" sense.

Van Oser Sandstone

For years geologists have been awed by the extensive distribution of certain comparatively thin fine- to medium-grained, texturally and mineralogically mature sandstones that occur in the Cambrian and Ordovician of the Upper Mississippi Valley. Most investigators have concluded that these sandstones are products of the transgression and regression of epicontinental seas onto the edge of a stable craton. The Van Oser Member is one of these super mature sandstones (it sometimes contains up to 3% feldspar), although it is not as extensive as others such as the St. Peter or Wonewoc Sandstones (Fig. 4).

It is envisioned that the Van Oser Sandstone is both time regressive and time transgressive (Fig. 21), but a simple regression-transgression model does not seem to fully account for its widespread distribution, thinness, or high degree of maturity. It is certain that its mineralogical maturity is not related to derivation from a provenance that was mineralogically different than that of the associated feldspathic Norwalk, Sunset Point and Waukon Sandstones, thus an environmental process other than simple marine wave and current activity in near-shore environments seems necessary to account for the above characteristics.

We propose that the widespread distribution and super maturity of the Van Oser Sandstone is a product of high energy within a regressive-transgressive littoral environment influenced by strong tidal currents. Most of the Late Cambrian and Early Ordovician clastics in the Upper Mississippi Valley were deposited in an embayment (Hollendale-Austin, 1970) located between the Wisconsin and Transcontinental Arches and north of an extensive carbonate platform. The tidal range in this embayment may have been 4 to 5 meters, or even greater if the moon was closer to the earth in Cambrian time as has been proposed. Considering that deposition of sediment was very slow and that the paleoslope was very low, it is believed that sand deposited in the littoral zone would be repeatedly reworked and intensely abraded by wave activity, and wave energy would be spread over a very large area (an extensive foreshore) as water depth varied with the ebb and flood of the tides. Currents generated by the tides would tend to move sand in many directions, especially over and around islands, shoals, and bars, and also transport the fine sediments to low energy lagoon and off-shore inner shelf environments.

With a very low paleoslope, a tidal range of just 4-5 meters within a littoral environment would produce simultaneous deposition of a relatively thin stratigraphic unit (like the Van Oser Member) over thousands of square kilometers (see paper by Dott, this guidebook). This situation would also provide a mechanism for mineralogical differentiation, abrasion, sorting and transportation, of feldspar from littoral environments to sites of lower hydrologic energy. The tidal currents might also account for the large dispersion in local current directional indicators, such as occur in the Van Oser Member, yet a mean current direction from cross sets and trough axes would still be apparent (southwest for the Van Oser).

If tides were an important process in the development of the super mature quartzose sandstones of the Upper Mississippi Valley such as the Van Oser Member, as we strongly believe, why do these sandstones not contain the more common textural and structural characteristics indicative of tidal environments? The primary reason, we propose, is that the fine sediments were largely removed causing these sandstones to be relatively uniform in grain size. Thus, textural and structural features such as fining upward sequences and flaser bedding, would not be present. Tidal channels would be difficult to identify in fine- to medium-grained mature sandstones. Mud cracks indicative of subaerial erosion would either not form or seldom be preserved. The intertidal deposits that might have formed in the very near-shore coastal zone have been eroded, but tidal-influenced deposits believed to have been developed in the outermost zone of the foreshore are present in the top of the Mt. Simon Formation, in the base of the Birkmose Member of the Lone Rock Formation, and in the base of the Coon Valley Member (dolomitic sandstones) of the Jordan Formation.

Although this tidal-influenced littoral lithotope hypothesis has not been fully tested, a significant tidal range and its associated currents operating within a dominantly littoral complex of beach, shoal, and bar subenvironments over a long duration would provide a tenable mechanism for the development of the extensive Late Cambrian to Middle Ordovician super mature quartzose sandstones. It would also provide a mechanism to explain how very fine feldspathic sandstones come to be both regionally and stratigraphically closely associated with super mature sandstones. The proposal made by Byers (this guidebook) that the Van Oser and other quartzose sandstones were deposited seaward of the very fine-grained lithofacies seems to be incompatible with regional lithic aspects and is difficult to reconcile with the <u>total</u> stratigraphic and sedimentologic record. Additional details on the sedimentology of the quartzose Van Oser Sandstone are given by Dott (this guidebook).

Coon Valley Member

In almost all cases, Cambro-Ordovician clastic formations in the upper Mississippi Valley above the Mt. Simon grade southward into sandy and silty carbonates, which then grade into pure carbonates. The Coon Valley Member represents a sandy carbonate lithotope which transgressed northward during Early Ordovician time immediately preceeding the carbonate platform lithotope in which the Oneota was deposited (Fig. 21).

The lithic characteristics of the Coon Valley Member as developed in the field conference area indicate subtidal carbonate shelf and local intertidal lithotopes. The Coon Valley Member may be transitional into hypersaline deposits (Adams - this guidebook) represented by the Oneota Formation. Our concept of the spacial distribution of the dominantly littoral phase (dolomitic sandstones) of the Coon Valley Member in relation to the littoral Van Oser lithotope for time T_2 is illustrated in Figure 21.

The Coon Valley Member is sedimentologically very complex, and additional detailed regional study of it and the superjacent Oneota Dolomite is required (currently in progress) before a comprehensive environmental model can be developed. The littoral and carbonate shelf-intertidal lithotopes in which this member is believed to have been deposited produced poor sorting, abundant intra-clasts (conglomerates), possibly local "oolite" banks, thin algal beds (mounds), cut and fill structures, shaly sandstones, and locally "true" mud cracks. These textural and structural properties point to vigorous and local highly variable hydrologic conditions due to storm-generated wave and tidal current activity.

SUMMARY AND CONCLUSIONS

The Jordan Formation in central and western Wisconsin, eastern Minnesota, and northeastern Iowa is differentiated into five lithic members based on textural and mineralogical properties, sedimentary structures, and regional and local stratigraphic relations. The Norwalk, Van Oser, and Coon Valley Members are regional in occurrence, whereas the Sunset Point and probably the Waukon Members are local in distribution. The Sunset Point and Waukon Members are time-stratigraphic equivalents of the Van Oser Member. Although the upper portions of the Van Oser and the Sunset Point Members in the vicinity of Madison, Wisconsin may be time-stratigraphically equivalent to a sequence of dolomitic sandstones that compose the lower part of the Coon Valley Member west of the Wisconsin Arch, the dolomitic sandstones in the lower portion of the Coon Valley are not lithically equivalent to the Sunset Point Sandstone as previously proposed.

A regressional-transgressional depositional model best fits the lithic and stratigraphic characteristics of the Jordan. The thickening of the Van Oser Member and the coarsening of the Norwalk Member in northeastern Iowa and subsurface stratigraphic data suggest that the very fine-grained, feldspathic, intensely bioturbated Norwalk Member was deposited in a dominantly subtidal lagoon situated between a Van Oser-type sand bar and shoal complex located in south central Iowa (Momence Sandstone) and a littoral lithotope in northern Wisconsin. The Norwalk Sandstone usually coarsens upward, which is interpreted to indicate that it was deposited during a regression of the sea.

The very fine-grained, feldspathic and bioturbated Sunset Point and probably the Waukon Sandstones appear to have been deposited in local subtidal lagoons. The Sunset Point lagoon was located leeward (west) of an emergent quartzite island complex (Baraboo Syncline) between Van Oser bars and spits that egressed westward (in Cambrian time) from both ends of the island chain.

The fine- to medium-grained quartzose, cross-stratified Van Oser Sandstone represents a littoral shoal and bar environment influenced by tidal currents. The lower portion of the Van Oser in Western Wisconsin is thought to be regressional, whereas the upper portion is believed to be transgressive based on its coarsening upward texture. A local unconformity occurs as the base of the Van Oser on and near the Wisconsin Arch. The Norwalk Member was locally entirely eroded from the crest of this arch.

Stratigraphic evidence indicates that the littoral lithotope in which the Van Oser Member was deposited existed over many miles perpendicular to the shore concomitant with regression and transgression. It is proposed that the extensive breadth of this lithotope was due to a tidal range of perhaps 3 to 5 meters, which is not unreasonable considering that upper Mississippi Valley Late Cambrian and Early Ordovician sediments were deposited in a broad embayment. The ebb and flood of tides produced a large dispersion in current direction indicators and a mean transport direction that is approximately perpendicular to the probable shore line.

The mineralogical and textural maturity of the Van Oser is believed to be related to energetic hydrologic conditions which selectively abraded feldspar and to the activity of tidal and other marine currents that winnowed and transported the feldspar to low energy environments (lagoon, shoreface, and shallow shelf). This mechanism provides the most amenable explanation currently available to explain the close association of mineralogically mature and immature sandstones, such as the Van Oser and Norwalk, respectively, both of which appear to have been derived from the same provenance. A progradational depositional model appears to be incompatible with the total stratigraphic and sedimentologic record.

Although the exact provenance for Late Cambrian sandstones is not known, they do not appear to have been derived from Keweenawan age arkoses, as previously proposed, because the latter contain appreciable plagioclase, whereas the plagioclase content of Late Cambrian sandstones is minute to say the least. Keweenawan arkoses could have been the source rocks only if plagioclase was removed by abrasion.

The Coon Valley Member of the Jordan is a heterogeneous lithic and sedimentologic unit composed of dolomitic sandstones, sandy dolostones, and minor amounts of algal dolostone and feldspathic sandstone, all of which contain abundant intraclasts. Sand-cored "oolites" and stromatoliths are abundant in the upper part. These lithic characteristics and sedimentary structures suggest that it was deposited in energetic littoral and shallow carbonate shelf environments. The oolite beds, if the oolites are primary rather than vadose in origin, may represent shoals formed by storm-generated and tidal currents around small stromatolite mounds. The local presence of "true" subaerially formed mud cracks substantiates the presence of some intertidal sedimentation.

Acknowledgment: Mineralogical studies of the Jordan Formation were supported by a grant (ERA75-1748) from the Earth Sciences Section, National Science Foundation to I.E. Odom.

MINERALOGY OF LATE CAMBRIAN AND EARLY ORDOVICIAN SANDSTONES, UPPER MISSISSIPPI VALLEY

by

I. Edgar Odom*

The essential detrital minerals composing Late Cambrian and Early Ordovician sandstones in the Upper Mississippi Valley are quartz, K-feldspar, and muscovite. Accessory detrital minerals are zircon, tourmaline, garnet, ilmenite, anatase, and illite. Authigenic minerals include glauconite, dolomite, K-feldspar, illite, kaolinite, smectite, pyrite, alunite, jarosite, and iron oxides. Authigenic glauconite, K-feldspar, and dolomite are major mineral constituents in some stratigraphic units. Recent petrographic studies show that feldspar, glauconite and dolomite are especially significant in stratigraphic and sedimentological interpretations because their abundance and stratigraphic distribution are directly or indirectly related to physical and chemical characteristics of the depositional environments.

Feldspar - Although local occurrences of sizeable amounts of K-feldspar in Cambrian sandstones have been known for many years (Tester and Atwater, 1934; Goldich, 1934; Berg, 1952), its great abundance and restricted stratigraphic occurrence has come to be appreciated only recently (Odom, 1975). It is now known that all very fine-grained Late Cambrian and Early Ordovician sandstones and coarse siltstones in the Upper Mississippi Valley contain large amounts of detrital and authigenic K-feldspar, regardless of stratigraphic position or geographic location. The Cambrian section is, in fact, composed of an altenation of feldspathic and nonfeldspathic sandstones (Fig. 23). This variation in feldspar content is related to the mean grain size of the sandstones. Sandstones classified as quartzose (<10% feldspar) have means greater than 2.75Ø (.149mm). Sandstones having means between 2.75 and 3.25Ø (.149- .105mm) are usually feldspathic (10 to 25% feldspar) unless they contain large amounts of dolomite or glauconite. Sandstones and coarse siltstones with means between 3.25 and 5Ø (.105- .031mm) are usually highly feldspathic (25-65% feldspar). Figure 24 illustrates the close correlation that exists between mean size and feldspar content.

Approximately 25 to 28% of the total feldspar in Cambrian sandstones is authigenic in origin. The secondary feldspar occurs as euhedral overgrowths on rounded detrital K-feldspar grains (Fig. 25) and is itself very rich in potassium (Odom, 1975; Stablein and Dapples, 1977). Because the Tomah Member of the Lone Rock Formation initially contained a large amount of detrital feldspar due to its very fine grain size, it thus contains the largest total amount of authigenic feldspar. Detailed data on the morphology and composition of selected feldspar grains from the Tunnel City and Elk Mound Groups are given by Odom (1975) and Stablein and Dapples (1977). Interestingly, in both of these studies it was concluded that no plagioclase (perhaps a trace) feldspar occurs in the Cambrian of the Upper Mississippi Valley. Its absence is not related to selective leaching but is probably due to abrasion.

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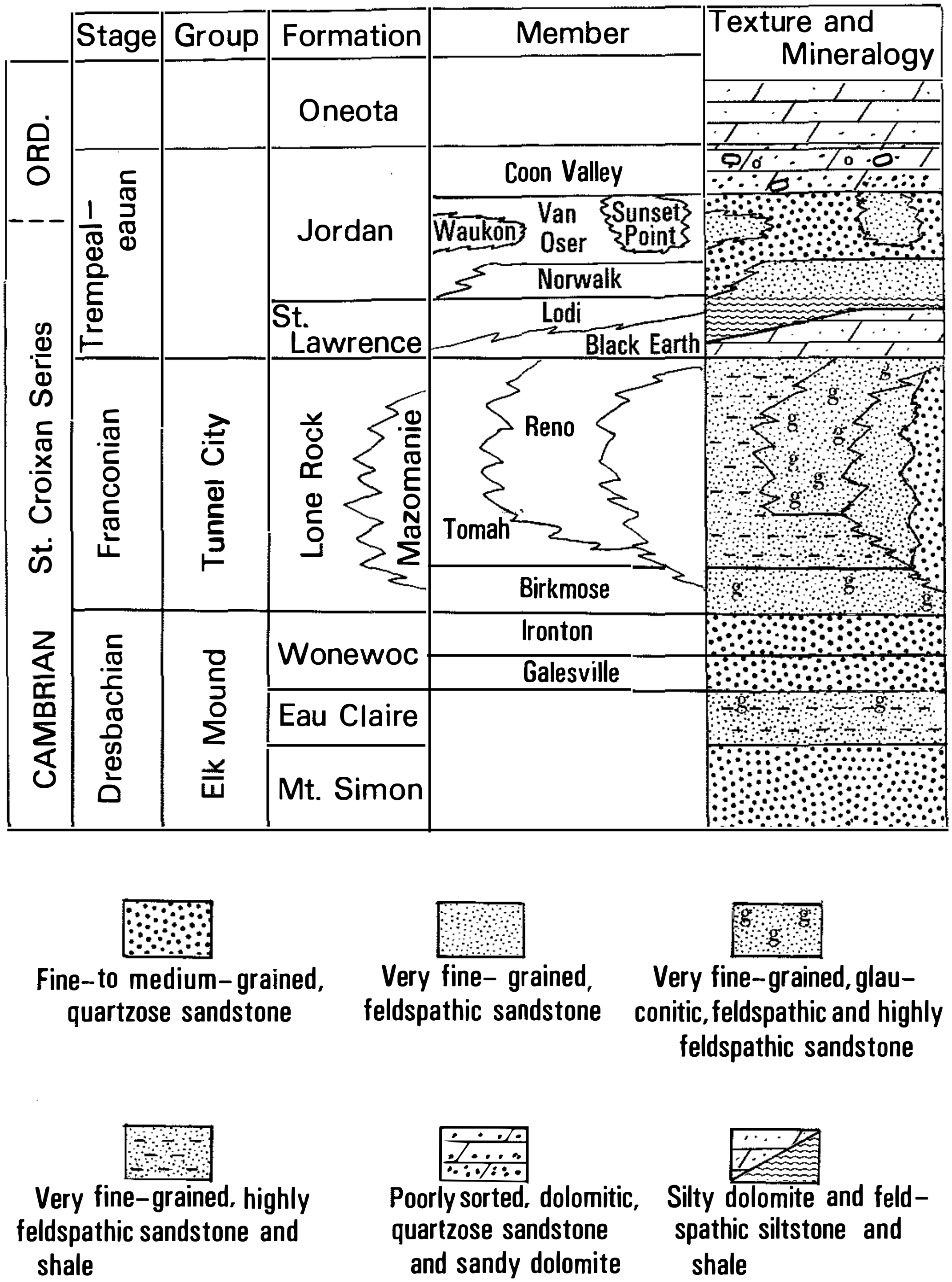

Figure 23 Gross textural and mineralogical characteristics of Late Cambrian and Early Ordovician lithic units in the northern portion of the Upper Mississippi Valley.

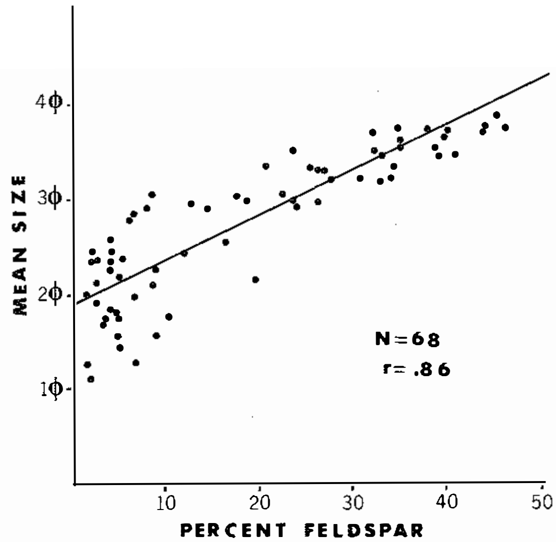

Figure 24 Relationship of feldspar content to mean grain size in some Cambrian sandstones, Upper Mississippi Valley.

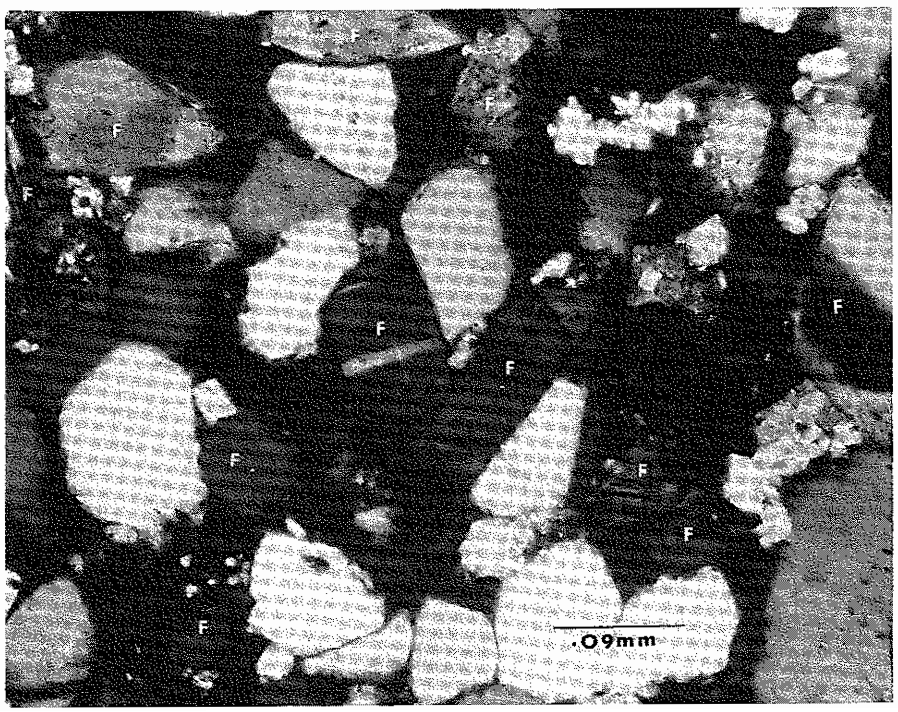

Figure 25 Detrital and Authigenic feldspar (F) in the Norwalk Member of the Jordan Formation near Spring Green, Wisconsin.

Radiometric age determinations indicate that the detrital feldspar was initially derived from rocks of Middle Precambrian age (2.1 B.Y.), however, it is possible that the source rocks for Cambrian sediments were Late Precambrian sediments. The only certainties regarding the age of the authigenic feldspar are that it is younger than authigenic glauconite, with which it is often associated, and that it predates most, but perhaps not all, dolomitization.

The relationship between grain size and feldspar volume is well illustrated by various members of the Jordan, St. Lawrence, Lone Rock, Mazomanie, and Wonewoc Formations which crop out in the Madison, Wisconsin area. The fine to coarse-grained sandstones composing the Wonewoc, the Van Oser Member of the Jordan, and part of the Mazomanie Formations are quartzose (Outcrops 2, 5, 7, and 8). Fine to coarse quartz sand is also the dominant detrital mineral in the dolomitic sandstones and sandy dolostones of the Coon Valley Member of the Jordan (Outcrops 1, 5, and 8). In contrast, large amounts of feldspar (10-40%) are present in the very fine-grained sandstones composing the Norwalk and Sunset Point Members of the Jordan Formation (Outcrops 1, 4, and 8), in the Tomah and Reno Members of the Lone Rock Formation (Outcrop 9), in the very fine-grained sandstones of the Mazomanie Formation (Outcrop 9), and in the Lodi Siltstone of the St. Lawrence Formation.

The large variations in the stratigraphic abundance of feldspar in Cambrian sandstones of the Upper Mississippi Valley are not related to changes in provenance area or to interstitial solution. These conclusions are supported by the following: (1) some stratigraphic units grade laterally from coarse and medium-grained sandstones to very fine-grained, feldspathic sandstones (Fig. 23), (2) local thin beds of very fine-grained, feldspathic sandstone occur within dominantly medium-grained quartzose sandstones, and (3) feldspar is abundant in the very fine grain size fractions of quartzose sandstones. The author (Odom, 1975) has proposed that the enrichment of feldspar in very fine-grained sandstones is a result of sedimentary processes and diagenesis. The detrital feldspar is believed to have been selectively abraded in littoral environments characterized by vigorous and sustained hydrodynamic energy and then sorted and deposited in lower energy environments (inner neritic, shoreface, lagoon and locally intertidal). The total feldspar in very fine-grained sandstones was further increased approximately 27% by authigenic development of feldspar overgrowths from pore fluids.

The concentration of feldspar in very fine-grained sandstones is not unique to the Cambrian of the Upper Mississippi Valley (Odom, Doe and Dott, 1976). It is especially important that sedimentary petrologists recognize the far reaching implications of the relationship when considering the maturity, origin, and provenance of a single sedimentary unit or sequence of units.

<u>Micas</u>-Greenish pellets composed of mineral glauconite are abundant in the Birkmose and Reno Members of the Lone Rock Formation and in the upper part of the Eau Claire Formation. These pellets consist of an aggregation of crystals less than one micron in size, often surrounded by a rim (Fig. 26). Glauconite crystals in the rims (Fig. 26) are partially oriented (Odom, 1976). The glauconite has an ordered 1M-type structure. Although its chemical composition is slightly variable, a typical analysis is $K_{.77}Ca_{.04}$ $(Al_{.26}\ Fe^{+++}_{1.22}\ Fe^{++}_{.27}\ Mg_{.29})$ $(Si_{3.66}\ Al_{.44})\ O_{10}\ (OH)_2$. Both the structure and composition are typical of "mineral" glauconite.

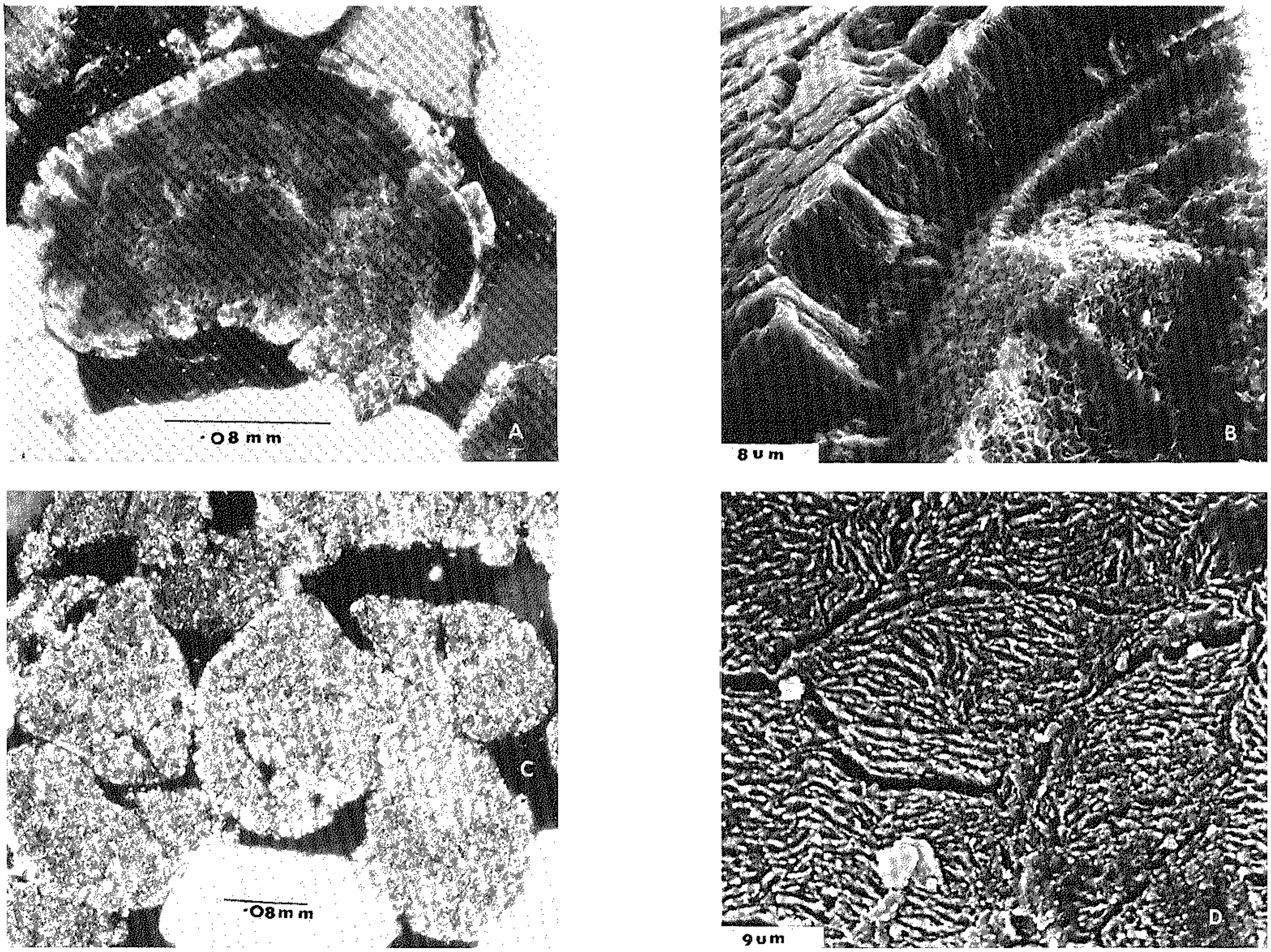

Figure 26 Microstructural characteristics of Cambrian glauconite pellets. A-Photomicrograph of pellet with well-developed rim. B-SEM of rim and core portions of pellet showing oriented and aggregate arrangements of glauconite crystals, respectively. C-Photomicrograph of pellets without rims. D-SEM of the surface of pellet without rim.

Muscovite is moderately abundant in most of the very fine-grained sandstones but is especially abundant in the Tomah Member of the Lone Rock Formation. X-ray data on muscovite from the Tomah Member and the Eau Claire Formation show that it has a $2M_1$-type structure characteristic of muscovite formed at high temperature, thus it is considered to be of detrital origin. Illite present in shale beds and dispersed through bioturbated very fine-grained sandstones has a 1Md (disordered)-type structure and is also considered to be of detrital origin. Small quantities of authigenic illite and kaolinite are occasionally present in fine- and medium-grained sandstones.

Although there have been many studies of "glauconite", its origin, especially the pellet morphologies, is still problematical. Mechanisms previously suggested for the origin of the various morphologies of glauconite and glauconite pellets include: (1) the alteration of detrital clay internal fillings in foraminifera tests, (2) the alteration of detrital clay minerals composing fecal pellets, (3) the transformation of biotite flakes, (4) the agglomeration of clay-sized material, (5) the precipitation on or the alteration of mineral surfaces, and (6) the direct replacement of certain minerals (e.g. amphiboles). Based on studies of the internal structure of Cambrian glauconite in the Upper Mississippi Valley, the author (Odom, 1976) has suggested that these glauconite pellets were formed by concretionary-like growth. It is believed that "glauconite" crystallization was nucleated by decaying organic material in massive bioturbated (Planolites) beds previously called wormstones. The pellets grew rapidly and then underwent some chemical and mineralogical change and were subsequently incorporated in cross-bedded sandstones through reworking of the wormstone beds. The stratigraphic distribution (Figs. 35 and 36) and the origin of glauconite are further discussed in the paper on the lithostratigraphy and sedimentology of the Lone Rock and Mazomanie Formations.

Carbonates- Late Cambrian and Early Ordovician carbonates of the Upper Mississippi Valley are dolostones. In contrast to many dolostones of other ages, which are often mixtures of dolomite and calcite, these dolostones contain entirely dolomite. The dolomite is assumed to have formed diagenetically from calcite. Some secondary calcite occurs in vugs, around sand grains, along fractures, and as a cement in the top of sandstones overlain by dolostones. This secondary calcite is derived from the leaching of the dolostones. Chemically, the dolomite in the Coon Valley Member of the Jordan and in the Oneota Formations of the Madison area is essentially stoichiometric, but some Mg is replaced by Fe. Goethite crystals are often found in vugs where the dolostones are extensively leached.

Acknowledgement: Mineralogical studies of Cambrian sediments supported by Earth Sciences Section, National Science Foundation (Grant ERA 75-1748).

SEDIMENTOLOGY OF UPPER CAMBRIAN CROSS BEDDED SANDSTONE FACIES AS EXEMPLIFIED BY THE VAN OSER SANDSTONE

by

R. H. Dott, Jr.*

INTRODUCTION

The environments and processes of deposition of Paleozoic cross-bedded quartz sandstones of the craton have puzzled at least two generations of geologists. Nearshore eolian, beach, and even fluvial environments have been suggested. Why should it be so difficult to establish definitively the origin of such classic layer-cake formations? First, fauna is very rare in the medium and coarse sandstones; until recently not even trace fossils had been observed in certain units (e.g. the Galesville, Tanck, 1977). Secondly, these "clean" sandstones are so homogeneous both compositionally and texturally (i.e. so antiseptic) that they reveal few physical clues of their genesis other than medium-scale trough cross bedding, which is known to form in several different environments. Ripple marks are only very rarely seen, and shale layers, which in muddier (septic?) clastic sequences can provide many clues, are almost totally lacking. Clearly attention to minute details of vertical sequences of structures, textures and presence or absence of trace fossils is required if environments are to be understood with any sort of sophistication. Fortunately there is now a significant body of detailed data from modern as well as other, less ambiguous, ancient sediments for comparison.

The Van Oser Member of the Jordan Formation, which will be seen on the field trip, is a typical example of the relatively coarse enigmatic cross bedded Lower Paleozoic quartz sandstones. Except for slightly more burrowing, it is essentially identical with the older Galesville Sandstone and younger St. Peter. The Mazomanie Formation of the slightly older Tunnel City Group is also very similar, but it generally contains some glauconite, has more carbonate cement, and is more densely burrowed.

COMPOSITION AND SOURCE

The Van Oser sandstones, like their counterparts, are composed of 98-99 percent quartz. Unstrained grains are about three times as abundant as strained ones, and polycrystalline grains comprise less than one percent. Unlike the very fine-grained sandstones of the Norwalk and Sunset Point Members, which contain 25-35 percent feldspar, the Van Oser has no more than 1 or 2 percent, a significant part of which is authigenic. It is now well established

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that feldspar in such sandstones is controlled strictly by grain size (Odom, and others, 1976). Glauconite also is very minor in the Van Oser Sandstone. Heavy minerals, which total less than 1 percent of the rock, consist of garnet, zircon, tourmaline, and ilmenite-leucoxene in decreasing abundance (Ockerman, 1930; Wanemacher, 1932). This suite is almost identical with that of the Galesville and St. Peter. Scattered sand-cored ooliths occur sporadically in the top meter or so of the Van Oser, especially around Baraboo. A few thin seams of green or red illitic shale 5-10 mm thick and spaced about 10-15 cm apart also occur sporadically in the top meter or so.

By every measure, the sandstones are compositionally very mature and must represent many episodes of purification by abrasion and chemical breakdown before Van Oser time. Their ultimate source is uncertain, again because of their great homogeneity. The simplest appeal is to recycling of grains from already-mature Precambrian quartzites. Baraboo Quartzite, for example, is both mature and near by; however, petrographic details seem to preclude it as a significant sand contributor. First, it contains no garnet or tourmaline, the most abundant heavy species in the Cambro-Ordovician sandstones, yet it possesses several other species not found in the latter (Wanenmacher, 1932). Secondly, grains with deformation lamellae as well as polycrystalline ones would be expected in the medium-grained fraction were the Baraboo a major source. Polycrystalline pink quartzite appears only as granule- and larger-sized clasts. Therefore, I have concluded (in Dalziel and Dott, 1970) that local quartzites contributed only gravel, while the quartz sand was transported from the Lake Superior region where it was recycled from older Cambrian and/or Precambrian sandstones.

CEMENTATION

Van Oser Sandstones like most others have chiefly carbonate cement, although quartz overgrowths are very common and complete silicification occurs locally. The degree of cementation varies greatly, with some localities being so friable that material can be shoveled for sand boxes. In the upper Van Oser, spherical concetretionary carbonate cementation is very distinctive. Such concentrations of cement are akin to sand crystals. On the outcrop surface they weather in relief, producing a characteristic knobby appearance known colloquially as "popcorn rock". We can see this especially well at the Cross Plains west Quarry. Silicification is most common also in the upper Van Oser, particularly near Baraboo. There have been at least two sources of silica. The Baraboo Quartzite apparently yielded that found in quartzite sandstones adjacent to the Precambrian-Cambrian unconformity, whereas leaching of Coon Valley and Oneota cherty dolomites seem to have provided silica to the upper Van Oser over a larger area. There is a complete gradation from scattered grain overgrowths to complete quartzitic silicification.

Typical Van Oser exposures are white to tan colored, but locally they show bright red iron oxide coloration. Most common are areas with red streaks or mottles, however there also are whole outcrops that are uniformly brick-red like typical Permo-Triassic redbeds of the western states. One such exposure can be seen on a secondary road 0.6 mile southeast of the Cross Plains East Quarry stop (SE corner Sec. 11, T. 7 N., R.7E.). University of Wisconsin Professor G. H. Dury interprets most of the red coloration in the various

Lower Paleozoic sandstones as representing the mottled zone of deep, tropical weathering profiles formed during a past warm climatic episode (late Mesozoic or early Cenozoic?). Others suggest instead that iron has been irregularly concentrated from ground water in much later times.

TEXTURE

The Van Oser sand is also texturally very mature. It averages near the fine- to medium-size boundary, that is between about 0.20 and 0.30 mm (Fig. 27A,B). It is well sorted with standard deviation values averaging around 0.50-0.60 (Fig. 27B,C). The size distributions are not strongly skewed, and are about equally positive and negative (Fig. 27 A,C). With exception of locally-derived Baraboo Quartzite granules 2-4 mm in diameter (and larger boulders adjacent to quartzite monadnocks near Baraboo), the coarsest common sand size typically is around 0.8-1.0 mm. There is a tendency for coarsening upward. Besides good sorting, the high degree of rounding, especially of coarser grains, is the most conspicuous textural feature of the Van Oser--again in common with the Galesville and St. Peter. This trait of mature Lower Paleozoic and many Precambrian sandstones has long been noted. Kuenen (1960) made a strong case for high rounding reflecting an important wind history, especially for relatively finer sands because his experiments showed grain impacts in air to be many times more effective at abrasion than those in water. Balsz and Klein (1972), however, have argued that vigorous, frequent and long-continued rolling of grains in tidally-dominated environments might make up for the faster abrasion rate of wind.

Various types of empirical grain-size plots have been made for Van Oser sands, as well as for other formations, as student class projects over the past 15 years. Some of the results are presented in Figure 27. Friedman's (1961) plots of different statistical moments (Fig. 27, A,B,C,) do not provide a unique environmental solution either from sieve or settling tube analyses; about equal numbers of points fall within Friedman's wind, beach and river fields. Does this mean that all three envionments are represented? Probably not. Consider Passega's CM plot of Figure 27D. Somewhat to my surprise we found years ago that this plot tended at first glance to give the least ambiguous result because practically all points for any of the Lower Paleozoic sands treated cluster nicely within the "beach" field. While a river origin seems clearly ruled out by the CM plot, unlike Friedman plots, wind deposits are not distinguished by the former. All that we could expect for wind would be a tendency to shift the field downward and the right toward finer sizes. Sahu's discriminant function analysis technique (1964) produced similar results to the CM diagram. Comparison of size and settling velocity of heavy versus light minerals (Hand, 1967) has not been very helpful (Andrew, 1965). Many cumulative curves also have been plotted over the years a la Visher (1969), but the results also are hopelessly ambiguous. To represent adequately here the range of variation of these would require too much space. I concluded some years ago that none of the empirical grain-size plots are sensitive enough to discriminate unambiguously the environments (or,better, the processes) of deposition of texturally very mature sands.

The size approach to environmental analysis is especially fraught with difficulties for ancient sandstones because of diagenetic alterations of grain

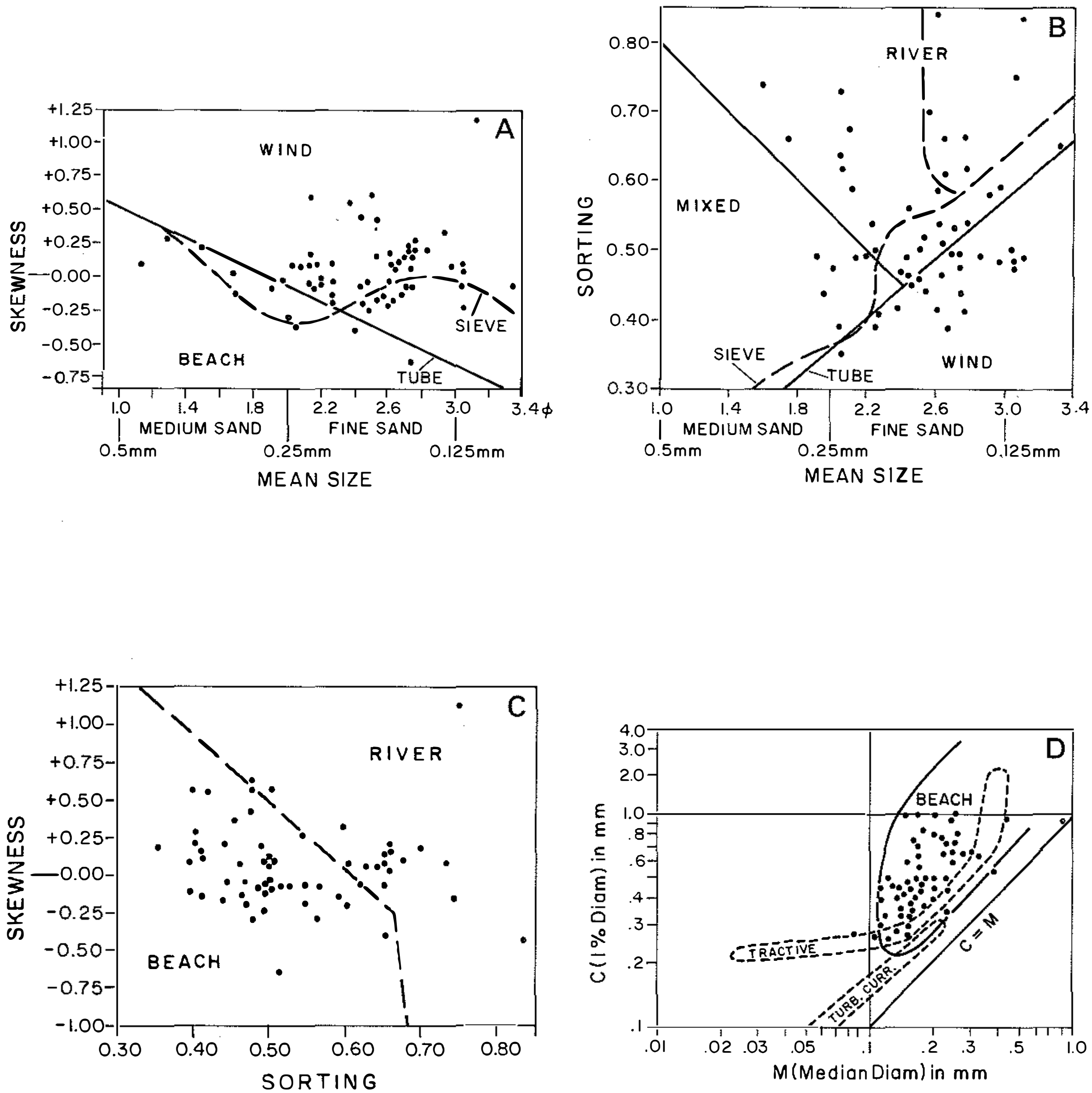

Figure 27. Empirical graphs of various grain-size parameters claimed to be useful for distinguishing sedimentary environments (or processes). Data points are for the Jordan Formation (A, B. and C after Friedman, 1961; D after Passega, 1957).

size. Grain overgrowths are common as noted above, but reduction of size by etching also has been documented (e.g. Andrew, 1965). Although no systematic SEM study has been made of the Jordan Formation, such studies of other formations show that diagenetic changes have so dramatically obscured primary grain surface features as to render this approach essentially useless (see Tanck, 1977-Galesville).

TRACE FOSSILS

The Jordan Formation is well endowed with trace fossils. They are more abundant in the very-fine-grained Norwalk-Sunset Point lithofacies, but the Van Oser tends to have scattered discrete burrowed zones up to 10-15 cm thick. Most common in the Van Oser Sandstone are vertical to oblique *Skolithos* type burrows averaging about 2-3 mm in diameter and 5-10 cm in length. These burrows represent the dwelling places of suspension feeding animals. The *Skolithos* assemblage is generally considered typical of sandy shallow agitated marine environments. Byers' article (this guidebook) and Anstett's recent thesis (1977) provide much fuller discussions of the Cambrian trace fossils.

SEDIMENTARY STRUCTURES

Cross bedding and horizontal planar stratification are the principal sedimentary structures of the Van Oser Member and its kin. Ripple marks, while probably common, are only rarely visible; Tanck (1977) has found some oscillation ripples in the Galesville Sandstone. Cross bedding in the Van Oser Sandstone is almost exclusively of the trough type, occurring in sets with average thicknesses or amplitudes of between 10 and 30 cm. The maximum seen is about 1 m. whereas the Galesville of the Wisconsin Dells area has sets up to 4 or 5 m and the St. Peter southwest of Madison has some sets up to 10 m in amplitude. Trough widths vary considerably, but average between 0.3 and 1.0 m in the Van Oser Sandstone. Some show symmetrical fills, but others are very asymmetrically filled. Truncation surfaces are about equally divided between the horizontal or planar and inclined or wedge types. Some outcrops like that behind Howard Johnson's Motel on the east side of Madison show the very complex festoon character. Low-angle inclined stratification (10°) is very rare in the Van Oser Sandstone, but is present in the underlying Norwalk Member, especially north of Spring Green (see outcrop 8).

PALEOCURRENTS

Regional Pattern

Orientations of cross bedding in the Jordan Formation of south-central and western Wisconsin have been measured extensively by Farkas (1960), Dott (in Dalziel and Dott, 1970), and Michelson (in Michelson and Dott, 1973). Farkas and Dott measured cross lamination dip directions, and Dott and Michelson also measured trough-axis plunge directions. As in other studies, the Jordan results show clearly that trough-axis data, if sufficiently abundant, yield much less dispersed results, and so are the superior paleocurrent indicator. Table 1 summarizes the results.

TABLE 1. CROSS BEDDING ORIENTATION DATA FOR THE JORDAN FORMATION
(After Michelson and Dott, 1973)

Area	Author	No. Obs.	Indicator	Vector Mean	S.D.	r.
South-central	Farkas (1960)	45	Cross lamina dip	199°	±108°	0.17NS
Baraboo-Dells	Dott (1970)	766	Cross lamina dip	250°	±122°	0.11NS
Baraboo Islands*	Dott (1970)	200	Trough axis plunge	157°	±95°	0.25
Baraboo-Dells	Dott (1970)	331	Trough axis plunge	167°	±81°	0.35
West-Central	Michelson (1973)	1467	Trough axis plunge	180°	±65°	0.53

*Localities within 6 km of old monadnocks showing apparent influence of the islands upon paleocurrents. This category is a sub-set of "Baraboo-Dells".
NS Statistically non-significant (i.e. showing no significant orientation).
r Vector magnitude varies from zero (completely random) to 1.0 (perfectly oriented).

Michelson's study showed clearly a north-to-south regional dispersal of Jordan sands (Fig. 28). In fact, the Jordan (Van Oser) has yielded the most consistent data of any formation studied. In the immediate vicinity of the Baraboo Quartzite islands, not surprisingly, the orientations even of trough axes are more dispersed. A number of localities show transport parallel to adjacent island shorelines, and the local mean direction there was 23° east of the regional mean (Table 1). Michelson's regional mean trough-axis plunge direction is nicely verified independently by a fall-out train of readily identifiable red or pink quartzite granules and pebbles extending south from Baraboo for at least 60 km (Raasch, 1958; Dalziel and Dott, 1970; Dott, 1974). We shall see examples of such clasts on the field trip.

Madison Area

University of Wisconsin class projects have provided detailed Van Oser Sandstone orientation data for the Madison area, which is shown in Figure 29. These data typify the extreme complexity of the cross bedding in all of the Lower Paleozoic sandstones of Wisconsin that was documented previously (Dalziel and Dott, 1970; Dott and Roshardt, 1972; Dott, 1973). The data are portrayed in the manner first developed a decade ago for the Baraboo area, where it was desired to compare cross lamination orientation distributions directly with those for trough axes for each locality. One can see that the cross laminae show extreme variability of orientation with unimodal patterns being the exception. Some bimodal localities are present (e.g. Truax), but most are polymodal. Trough-axis distributions, while considerably less noisy than the cross lamination data, nonetheless show their own complexity. Just as was found at Baraboo nearly ten years ago, bimodal trough plunge patterns are common (for

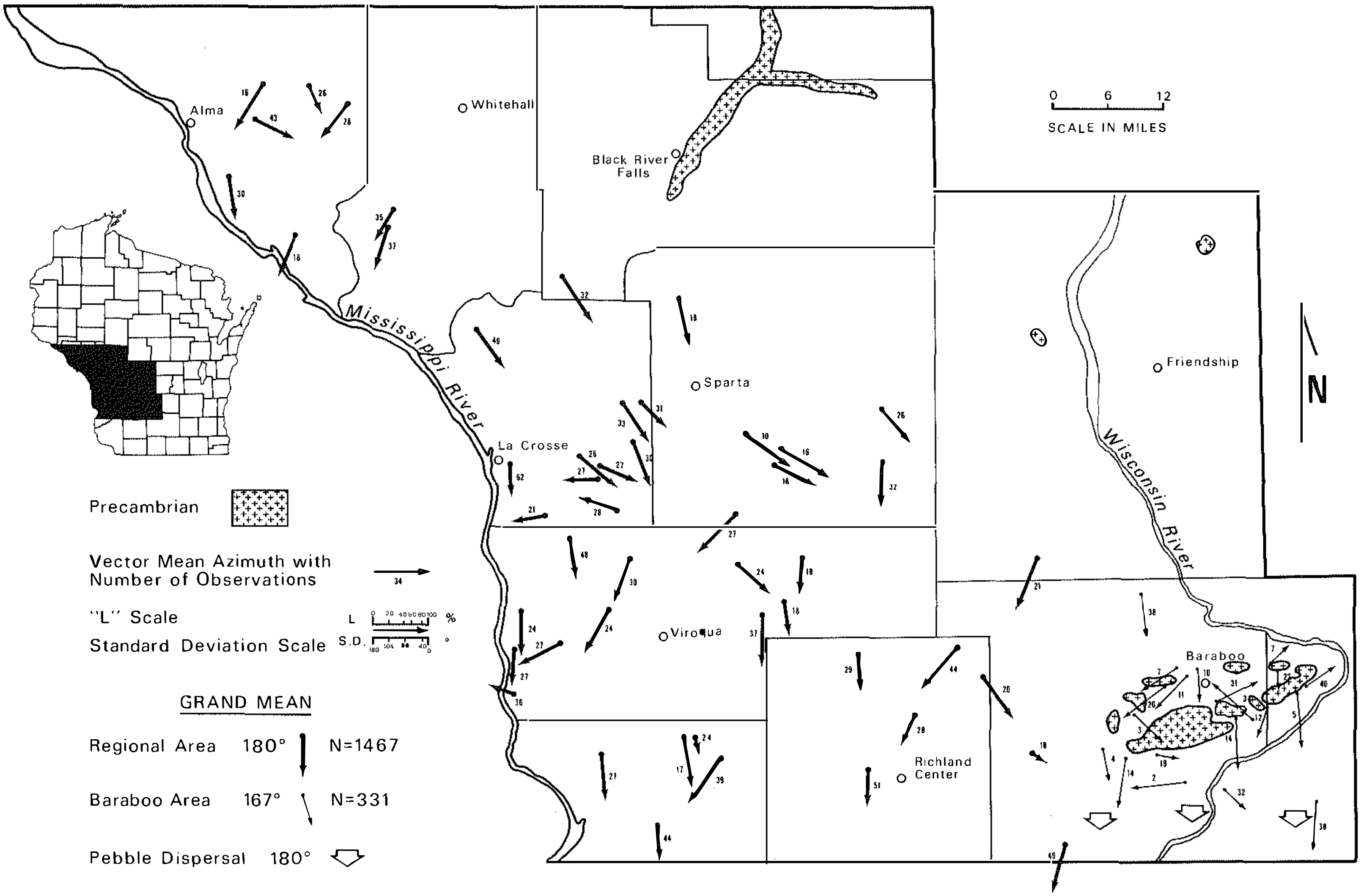

Figure 28. Regional trough-axis-plunge orientations for cross bedding in the Jordan Formation in west-central Wisconsin. Solid-line arrows are vector means whose length varies inversely with dispersion; open arrows in lower right show general dispersal direction of fine Baraboo Quartzite pebbles. (From Michelson and Dott, 1973; compare Table 1).

example Howard Johnson's, Penn Park, and Sunset (Hoyt Park) of Fig. 29). At Howard Johnson's it should be possible to see this relationship for oneself.

What can we conclude, if anything, about Van Oser sand dispersal around Madison? From cross lamination data alone, I myself would not wish to hazard any conclusion, for the total array seems virtually random -- just as did that for medium-scale bedding in the St. Peter Sandstone southwest of Madison (see Dott and Roshardt, 1972). But from trough-axis orientations, it seems clear that the dominant direction of sand transport was toward the south or south-southwest. This is also supported by the data for several localities west of Madison (outcrops 1, 2, 3, 4 and 5). Possible explanations of the northerly trough modes are discussed below.

PALEOENVIRONMENTS AND PALEOHYDRAULICS

Based upon modern concepts of sand transport and deposition, it is possible to reconstruct Late Cambrian environments and some parameters of paleoflow conditions more fully than before. Composition tells us nothing about environment because it is dependent upon grain size. Therefore, we look to texture, sedimentary structures, and fauna for such evidence. Of these, organisms provide by far the most compelling environmental evidence. Because no Cambrian land animals are known, the presence of the *Skolithos* trace fossil assemblage indicates marine environments for most if not all of the Jordan Formation and most of the other sandy units. The only significant exceptions seem to be local portions of the Galesville and perhaps some of the St. Peter, which appear to be coastal eolian dunes (see, for example, Tanck, 1977). Rare body fossils, including arthropods and inarticulate brachipods, also indicate marine conditions for much of the sequence.

Texture already has been shown to be environmentally ambiguous, therefore let us turn to sedimentary structures for further insight. Anytime that the Cambrian sands were moved by water, we can assume that flow was fully turbulent, thus Reynolds Number was relatively high. Stratification provides evidence of paleo-flow regimes, for example, ubiquitous trough cross bedding reflects upper-lower regime dune bedforms, which apparently typified Van Oser time. But the conspicuous planar truncation surfaces, which punctuate this and other similar formations, reflect episodic scouring events that seemingly were widespread. Presumably these were produced by great dynamic energy during storms, which produced scour and temporary upper flow regime (plane-bed) conditions. The occurrences of trace fossils tends to confirm such episodicity, for the most intensely burrowed zones occur just below prominent horizontal truncations, whereas intervening cross stratified intervals tend to have much less burrowing or none at all. It also is significant that the very fine-grained sandstone lithofacies (Norwalk-Sunset Point) tend to be relatively more burrowed than the coarser Van Oser lithofacies. This contrast is especially striking in the Mendota Station railroad cut on the north edge of Madison. Seemingly the typical Van Oser substrate with shifting dune forms was less favorable for suspension feeding animals than was the finer-grained substrate. Apparently only when the bottom was relatively less mobile could the organisms become well established. On the Van Oser substrate, relative quiescence favorable for burrowers seems to have followed some of the major scouring events. Perhaps a moderate amount of time elapsed before lower flow regime dunes could reestablish and migrate again over a given area. During such an interval burrowers moved in. On the other hand, episodic scouring probably destroyed some burrowed zones completely, perhaps making the Van Oser seem less hospitable than it actually was.

Maximum grain sizes can allow some assessment of at least lower limits of velocity during episodic storm events. Shields analysis allows estimate of bed shear velocities necessary to entrain the largest grains (see Blatt, and others, 1972, p. 90-94). For the one-millimeter-size common maximum sand grains, bed shear velocity must have exceeded two cm per second. But to move much rarer--though widespread-quartzite pebbles up to 10 mm diameter, bed shear velocities in excess of 10 cm per second are indicated. We can guess that the velocity above the bottom would have been at least an order of magnitude greater -- probably at least 200-300 cm/sec -- but it is impossible to determine paleo-mean flow velocity precisely. Significantly, the pebbles and coarsest sand tend to be concentrated along horizontal truncation surfaces, thus attesting again to episodic, very dynamic events.

Depth is difficult to establish more precisely than "shallow" for the Lower Paleozoic sandstones. The skolithos assemblage is considered most characteristic of the littoral zone, but it also seems to occur in deposits representing depths of some tens of meters. Only the shallow sea-level limit is firmly fixed, which limit is, of course, seen around the Baraboo islands. Simple projection of initial dips in Cambrian sandstones around those old quartzite islands provides a rough index of maxiumum depth of southern Wisconsin. The dips are seen to flatten from as much as 10° to zero within 1 km of a given island (Dalziel and Dott, 1970). Thus water depth should have been of the order of 40 - 50 meters beyond those distances.

Another approach that seemed a few years ago to be fruitful was to invoke a possible correlation between dune height and water depth following a suggestion by Allen (1970, pp. 77-80). Experimental data had suggested the relation indicated by the equation:

$$H = .086\ D^{1.19}$$

wherein H is dune height and D is water depth. Dott and Roshardt (1972) invoked this relation to suggest a depth of at least 40 m for ten-meter thick cross sets in the St. Peter Sandstone at Monticello, Wisconsin. Truncated cross sets, of course, represent only some fraction of original dune height, thus for cross bedding the equation could only provide a minimum limit for water depth. For the largest cross sets of the Van Oser Sandstone, which approach one member in thickness, the minimum indicated depth would have been about six or seven meters, but if we assume that the original dunes were, say, twice as high as the present truncated cross sets, then depths of about 12 meters would be indicated (see Fig. 4). A few years ago I plotted empirical data from natural dune forms representing a variety of modern environments to test Allen's argument. Figure 30 is the result, and it shows a disturbing degree of scatter of points. Moreover, J. C. Harms (personal communication) has pointed out that for shallow water dunes or sand waves, depth varies as much as 80 - 90 percent over troughs versus crests, and in a tidal regime, depth could vary as much as 100 percent with time.

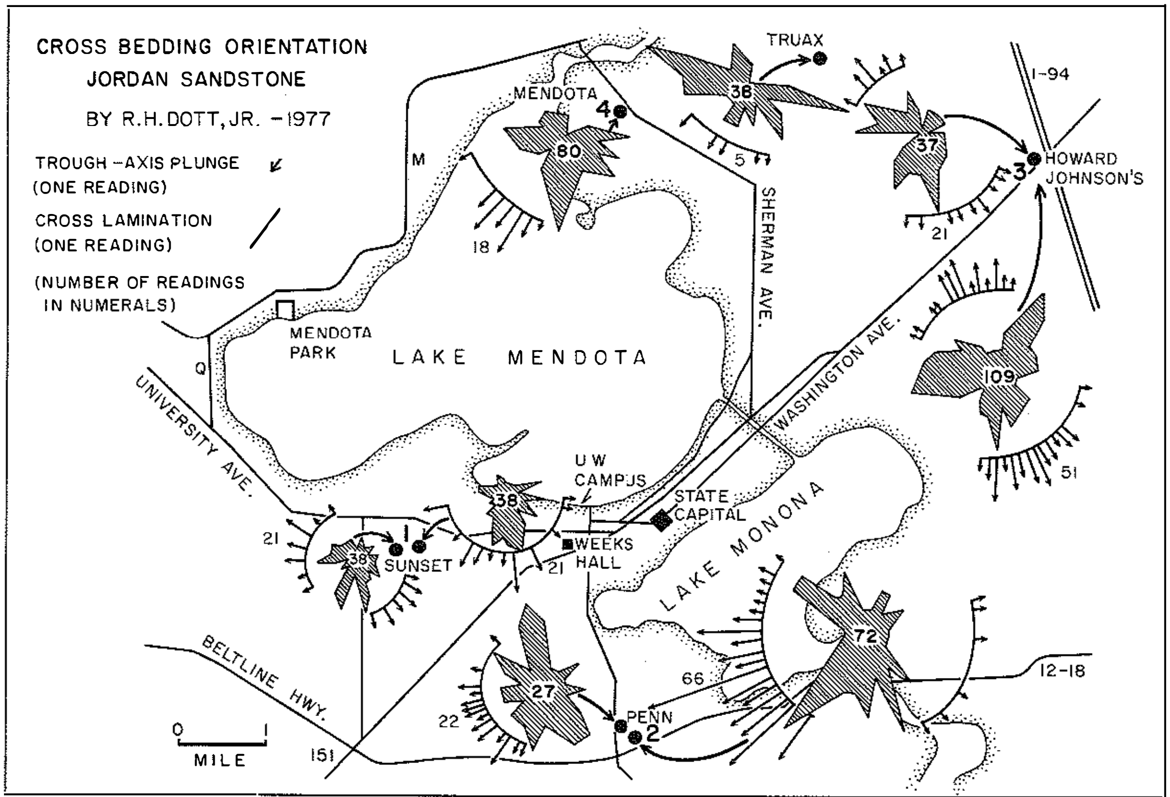

Figure 29. Cross bedding orientation for the Jordan Formation in the Madison area derived from class projects and additional measurements by Dott. Inner polar histograms portray cross lamination dip-direction distributions, whereas outer arcs show the distributions of trough-axis-plunge directions. Note that bimodal and polymodal patterns tend to be the rule, but trough-axis distributions show the greater consistency.

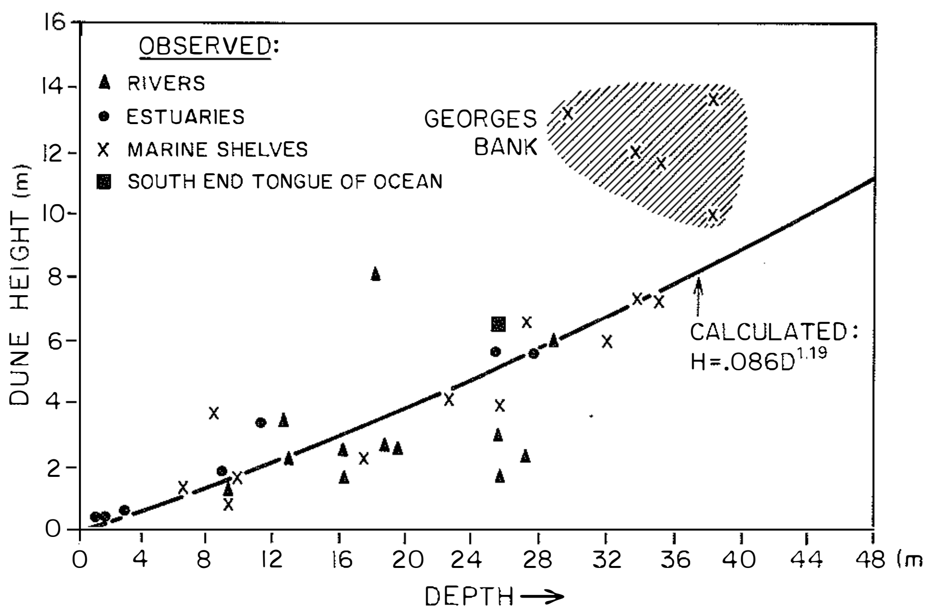

Figure 30. Graphical comparison of dune height with water depth between the curve calculated from experimental results (see Allen 1970) and real-world cases from many environments. See text for discussion.

Even if cross bedding thickness could provide an index of depth, at best the technique would provide, like Skolithos, only a minimum depth indication because dunes of almost any height theoretically could form in deeper water. Thus ripples and small dunes are well known at abyssal depths.

Although Allen's suggestion seems suspect on several grounds, the size and environmental setting of modern subaqueous dune forms deserves our further considerations. The well known sand ridges of the Georges Bank and of the North Sea, Irish Sea, and English Channel long have appealed to me as possible analogues for ancient epeiric sea cross bedded sandstones like those of Wisconsin. In those modern areas, bedforms as high as 10 - 15 meters are common, and have seemed attractive counterparts of certain large-scale Paleozoic cross bed sets of probably marine origin. In Figure 4, however, the Georges Bank sand bodies plot completely above the predictive curve for their depth. When originally confronted with this anomaly, I thought perhaps the bodies were shaped by very abnormal hurricane-force storms and that ordinary processes could not reduce them to their expected heights. I later realized that other possibilities that are at least as plausible include a large, relict preglacial eolian dune complex only slightly modified during Holocene transgression. Moreover, there almost certainly is no single submarine duneform there or in the North Sea-English Channel region that is 10 - 15 meters high. Instead large sand bodies there are almost certainly composites of smaller individual bedforms (in fact, smaller dunes have been documented on the surfaces of some such large bodies). It has also been pointed out to me by Harms and Spearing (personal communications) that illustrations of these modern bodies typically have a misleading exaggeration of vertical scale. While it is well documented that these large bodies are shaped dominantly by strong tidal currents today (Jordan, 1962; Stride, 1963; Houbolt, 1968), it may be possible that they originated as pre-Holocene eolian dune fields that have been modified greatly since transgression.

Associated carbonate rocks possess more environmental clues than do the cross-bedded sandstones themselves, a bitter admission for devotees of these "other" sediments. Directly overlying the Van Oser Member at most localities (except within the limits of Madison) are stromatolitic and oolitic dolomites. These clearly are intertidal to supratidal (Adams, this guidebook). Odom and Ostrom's (this guidebook) Coon Valley Member of the Jordan Formation is clearly a transition from quartz sand to almost entirely carbonate deposition. In Wisconsin parlance, this regionally important change reflects a breakdown of the "sand machine" thus allowing the "carbonate factory" to swing into full production. ("Note: in Illinois parlance, it is the "sand industry" and the "carbonate factory"; ref. Odom). Perhaps this was due to transgressive flooding of the inferred sand source north of Lake Superior and the development of an immense expanse of very shallow, tidally-influenced environments. The Coon Valley Member represents essentially sea level deposition, so by vertical sequence extrapolation downwards, it would seem that the Van Oser Sandstone probably represents a littoral environment. The same style of trough cross bedding so typical of it is very characteristic of the sandy subtidal shoreface environment today and has been documented also for several ancient examples (see Harms, and others, 1975). For the Jordan Formation, no associated definite beach or eolian facies have yet been identified, on the one hand, the finer Sunset Point facies may represent the slightly quieter (presumably deeper) lower shoreface counterpart of the Van Oser facies, on the other hand. Where the latter two lithologies occur in vertical succession today (as at Sunset Point (Hoyt Park) and the Mendota Station railroad cut; Outcrops 1 and 4, respectively, we must invoke Walther's Law and infer that the upper and lower shoreface environments shifted laterally so that the one replaced the other locally. But where very thin, coarser Van Oser lithology intervenes within the finer Sunset Point facies, we probably should appeal merely to instantaneous episodic spreading of coarse sand by storm conditions rather than a significant shift of bottom environments.

PALEOGEOGRAPHIC SUMMARY

All evidence available points to the coarser, cross-bedded Cambro-Ordovician quartz sandstones of the Van Oser type being deposits of the littoral and shallow marine zone. How broad that zone was at any one time is very uncertain, but if it was only of the order of a few Kilometers, it would seem inescapable that such formations must be diachronous because of their widespread blanket-like nature. There may well have been large offshore shoal areas, however, that produced widely scattered deposits with identical littoral characteristics even though located much farther offshore. Maximum depth in the Madison-Baraboo region probably was about 50-60 meters, with the Van Oser Sandstone having formed toward the shallower end of that range and the Norwalk-Sunset Point lithofacies toward the deeper end.

Location of the major regional shoreline is conjectural. Apparently a broad zone of northeast-southwest trending large but low islands marked the Transcontinental arch 600 km to the northwest (in present coordinates). Probably also a low land lay to the north near present Lake Superior. Locally smaller islands such as those around Baraboo persisted into Jordan time, and their influence upon local sedimentation was spectacular. Rounded red boulders up to 1.5 m in diameter and much larger angular ones occur immediately adjacent to the Precambrian-Cambrian unconformity and thin layers of rounded quartzite boulders and cobbles extend out from the old islands for a kilometer or so (Fig. 31). Fine pebbles and granules occur sparingly but widely to the south (present coordinates) as emphasized already.

Coarse Baraboo Quartzite debris was rounded at the bases of sea cliffs by frequent large waves, and some was occasionally dispersed offshore by exceptional storms. Maximum breaker wave heights are estimated mathematically from experimental data to have been at least 7 - 8 meters during those storms; associated bottom water velocities must have been about 600 cm per sec. (Dalziel and Dott, 1970; Dott, 1974). Paleomagnetic data indicate that in Late Cambrian time Baraboo lay at about 10° - 15° South latitude and that the paleo-equator extended across western North America approximately perpendicular to its present trend. This would place Cambrian Wisconsin in the southern trade winds belt and make is susceptible to many tropical storms (Dott, 1974). Furthermore, paleocurrent analysis indicates that the normal, day-to-day shallow marine currents could well have been trade-wind-driven, that is east to west in paleocoordinates (but north-to-south in present coordinates; see Fig. 31).

Storm effects are most obvious around the old islands, but they also can be inferred in the offshore deposits. Horizontally scoured cross bed sets in the Van Oser Sandstone also reflect such storms, especially where burrowed zones are also truncated or lag concentrations of coarse sand or quartzite

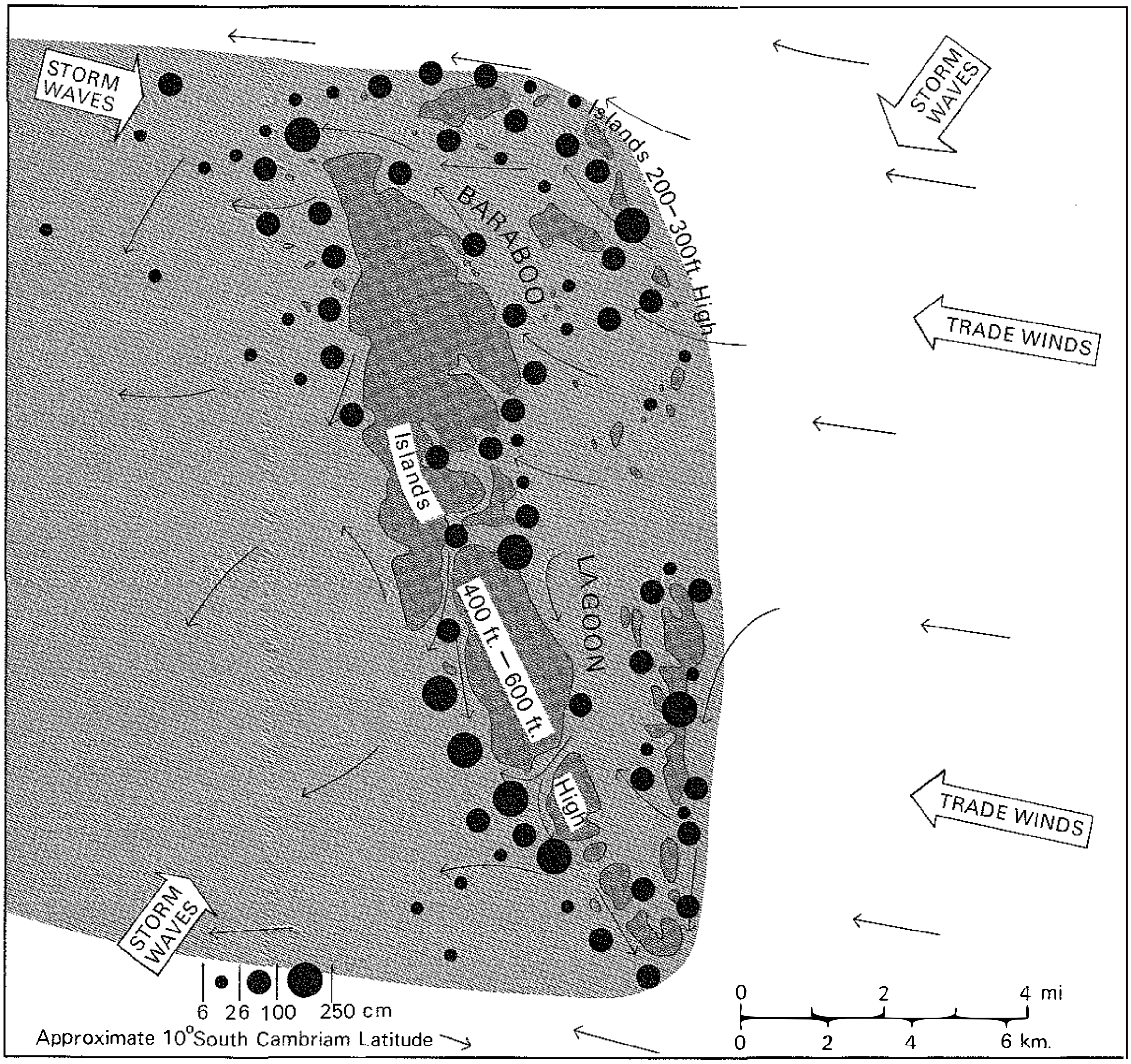

Figure 31. Late Cambrian paleogeography of the Baraboo district incorporating paleomagnetic evidence for location within the southern trade winds belt. Dots show distribution of coarse conglomerate clasts; shaded area extending to left from islands is the fallout area of fine quartzite pebbles and granules carried at least as far as 60 km. (From Dott, 1974).

granules occur. In the finer lithofacies, prominent flat-pebble intraclast (rip-up) conglomerate and coarser sand zones provide additional evidence of exceptional scouring of the sea bottom. Even the carbonate rocks show evidence of episodic violence in the form of brecciated stromatolite layers, intraclast conglomerates, and thin quartz sand layers (as in my backyard at Sunset Point in Madison, Outcrop 1). I have even found four or five quartzite granules in dolomite as far as 60 km south of Baraboo (including my backyard).

It is provocative to speculate about the probable frequency of Cambrian storm events; that is, to ask "how rare was the rare event?" Applying the average modern frequency of hurricanes experienced around the Gulf of Mexico (roughly one per century for most localities on its perimeter), the Madison-Baraboo region might have experienced 250,000 tropical storms during the approximately 25 m.y. of Late Cambrian time (Dalziel and Dott, 1970; Dott,1974). This is hardly rare even on the geologic time scale! Consider next that in the Baraboo area many outcrops consist of at least fifty percent of thin conglomerate layers separated by normal cross-bedded sandstone. Farther from Baraboo, laterally-persistent horizontal truncation surfaces punctuate most outcrop sequences with moderate frequency, much as the conglomerate layers do at Baraboo. These relationships lead one to wonder if the preserved record of presumably normal, day-to-day Cambrian sedimentation -- the cross bedded sandstones -- or the rate event scour surfaces and conglomerate layers actually account for more total time? I would bet my money on the proposition that every horizontal bedding plane in the local section is a minor unconformity and that their cumulative time equivalence exceeds that of the preserved rock.

But what of tidal influences? Where we have identified paleoshorelines at Baraboo and have postulated littoral sand deposits over a large region, we should expect important tidal influences if there was, in fact, a significant Cambrian tidal fluctuation here. Byers (this guidebook) discusses strong evidence for important tidal impact in some of the finer-grained clastic facies, and tidal influences are well established for the carbonate rocks (Adams, this guidebook). Therefore, I feel compelled to believe that tides operated during deposition of the coarser lithofacies as well. The extreme paucity of fine, argillaceous sediments within this facies makes it very difficult to recognize definite tidal effects, although in the Galesville Sandstone clayey silt laminae only one millimeter thick show sand-filled polygonal cracks in a few localities. Perhaps the bimodal cross bed trough-axis distributions reflect tidal currents. In 1970 I attributed these simply to oscillatory flow due chiefly to wave agitation of the bottom to produce ill-defined elongate dunes and depressions like some that had been produced in oscillatory flume experiments (see Dalziel and Dott, 1970, p. 63). It now seems more probable to me that tidal currents may have played a considerable role in producing the bimodal troughs. If so, then the very prominent bimodality at localities such as Howard Johnson's (Outcrop 4) and Sunset (Hoyt Park, Outcrop 1) in Madison (Fig. 29) may reflect offshore shoal conditions with stronger bottom shear by tidal currents here than elsewhere. Such an interpretation for Howard Johnson's may be consistent with the Odom-Ostrom sand bar hypothesis for that area (Fig. 22). In any case, as I have argued before, bimodal and polymodal orientations seem to be the rule in many cratonic sandstones. Therefore, very careful orientation analysis on a zone-by-zone basis together with more attention to subtle vertical sequence changes may help us eventually to understand the genesis of such enigmatic deposits more fully.

CHALLENGES FOR THE FUTURE

Many questions remain concerning the genesis of cratonic blanket deposits of cross bedded quartz sandstones, which are well represented in other areas and other parts of the stratigraphic column as well as in Wisconsin. How important were tidal currents? Specifically, what was their magnitude? If they were important, how can we tell? How can we make better bathymetric evaluations for such deposits? What is the maximum possible height of submarine sand waves? How can we establish the degree of diachroneity within the formations in a region lacking long, continuous exposures like those of the arid west? How can we document precisely the relative magnitude of unconformities within such strata? Have there, in fact, been many (perhaps eustatic) transgressions and regressions? And is there differential preservation of the transgressive versus regressive phases? Finally, where _is_ that simple overstudied layer-cake geology we have heard so much about?

DEPOSITIONAL ENVIRONMENTS OF FINE-GRAINED UPPER CAMBRIAN LITHOFACIES

by

Charles W. Byers*

INTRODUCTION

The type St. Croixan strata in Wisconsin can be divided into two generalized facies: 1. coarse and medium sands dominated by high angle cross bedding, and 2. very fine sands dominated by low angle or planar bedding. The coarser facies is discussed by Dott (this Guidebook); the finer facies will be discussed here in terms of its paleontology and distinctive sedimentary structures. A depositional model which encompasses these features will be advanced, and its implications for the traditional transgressive-regressive stratigraphic model will be commented on.

It has long been recognized that there is a repetition of lithofacies types in the St. Croixan rocks (see Ostrom, 1970, for a review of earlier theories of cyclicity and an explanation of the most recent depositional model). Current stratigraphic usage emphasizes lithostratigraphic terminology; the St. Croixan Series comprises several formations that apparently lie in simple superposition. Laterally the formations maintain their thicknesses and overall lithologic character, and boundaries between formations are usually easily recognized. These facts tend to accustom stratigraphers into emphasizing separation and nomenclature ("splitting"), and it is easy to see how Ulrich and his followers managed to cling to a Wernerian viewpoint ("layer-cake" stratigraphy) into the Twentieth Century, as they traced out and minutely subdivided these strata. The average St. Croixan formation is only tens of meters thick, and can be followed laterally for scores, even hundreds, of kilometers. The insistence on formational nomenclature, which is erected mainly on the basis of grain size and mineralogy, tends to obscure the similarities among formations; these similarities are more apparent when the rocks are viewed as lithofacies, that is, when sedimentary structures and trace fossils are taken into account. For example, the same bedding styles and trace fossils are to be found in sands and carbonates, and in glauconite-rich and glauconite-poor sands. The "lumper" approach will be employed in this paper, for I have become convinced that the structures and fossils in these rocks reflect the depositional environments more directly than does the mineralogy. My basic premise in this paper is to suggest that similar environments recurred throughout the Late Cambrian in Wisconsin, and that the processes in those environments were not concerned with the mineralogic composition of the grains that happened to be present at any given time or place. Indeed, on the field trip I invite the participants to don mentally a pair of special eyeglasses, which render carbonate and glauconite invisible, thus allowing one to concentrate on the sedimentary structures, which of a certainty reflect depositional processes.

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FINE-GRAINED LITHFACIES

The units dominated by fine-grained sands are, in ascending order, the Eau Claire Formation, the Tunnel City Group, the St. Lawrence Formation, and the Norwalk and Sunset Point Members of the Jordan Formation. In each, at least part of the unit is characterized by planar lamination and low-angle cross-bedding. The lower three units are all shaley and glauconitic to various degrees, whereas the Norwalk and Sunset Point Members are nearly pure, very fine sand and contain no glauconite. All the units contain trace fossils and at least an occasional body fossil, indicating that all are marine in origin. Only the St. Lawrence contains an appreciable amount of carbonate, the Black Earth Member, and even here the carbonate is sporadic in distribution and very impure; the Black Earth Member is actually a silty dolomite or dolomitic siltstone interstratified with siltstone and very fine sandstone. Not every outcrop of the St. Lawrence contains carbonate beds; in some places the entire interval is composed of clastic sediment.

Rather than itemize the lithologic units one-by-one, I will discuss the features which bear on environmental interpretation. The individual formations do display differences, but the general statements here apply to all the fine-grained units. The specific data upon which these generalities are based were collected by myself and a series of Masters students at the University of Wisconsin: Huber (1975), Anstett (1977), James (1977), Byers (1978), Porter (1978), Schwartz (1978). Table 2 lists diagnostic sedimentary structures for specific lithologic units. Although we will not see the Eau Claire Formation on the field trip, it will be discussed here, for it is perhaps the least enigmatic, and has served as a local model for tentative reinterpretation of the rest of the section.

Body Fossils

Body fossils in the type St. Croixan rocks are generally rare. Only in the Eau Claire are fossils readily apparent in outcrop. Parts of the Tunnel City contain as much fossil debris as the Eau Claire, but, owing to poorer preservation, fossils may not be recognized easily. The other formations contain fossils only in scattered patches; for example, in Porter's study of the Norwalk Member, only a single fossiliferous locality was found in a total of 19 measured sections.

The rarity of fossils is accompanied by a lack of species diversity. All the St. Croixan assemblages are dominated by trilobites, inarticulate brachiopods, and hyolithids. Very occasionally a representative of another higher taxon appears, such as the St. Lawrence merostomes, but as a rule the Upper Cambrian communities contained only the three faunal elements noted above. Missing are representatives from the sponges, articulate brachiopods, gastropods, and echinoderms.

The fossils are always preserved in the same fashion, as concentrations of shell molds occurring in discrete layers in the sandstones (coquinites, Fig. 32a). Coquinites are usually found along bedding planes or cross-bedding surfaces, and the coquina layer itself may contain hundreds or thousands of fossils packed tightly together. Typically all shell material has been dissolved, although inarticulate brachiopods may retain some part of their shells.

Coquinites nearly always are composed of disarticulated and fragmented shells. Trilobites are always broken into separate cephalons and pygidia, and often the free cheeks and spines are separated as well. Brachiopods are almost never preserved with valves together, and the valves themselves may be broken, as are hyolithid shells. Hyolithids are sometimes preserved parallel to each other on a bedding plane, indicating orientation by currents. Although the faunal elements may be mixed, it is common to find a single species dominating a coquinite, again probably indicating current activity, i.e. sorting of shells. No fossils have been found in what could be interpreted as life position; all fossils appear to have been transported.

The single exception to the discussion above occurs not in the faunal realm but in the floral. Within the sporadic development of carbonate facies in the St. Lawrence Formation, algal stromatolites are sometimes observed. Owing to dolomitization the internal structures of the algal mounds are not well preserved, but typically the characteristic concentric banding is present. The stromatolites vary from horizontal mats to low (30 cm high, Fig. 32b) hemispheroids to a spectacular columnar development (at two localities) with columns 1.3 m high. The stromatolites are clearly in growth position and are probably the single best environmental indicator in the entire fine-grained lithofacies.

Trace Fossils

Whereas body fossils give no clear indication of *in situ* benthic animal life, trace fossils in the fine-grained lithofacies demonstrate that the environments were inhabited. As noted by Dott (this Guidebook), the coarse-grained, cross-bedded lithofacies is dominated by the trace fossil *Skolithos*. This trace also occurs in the fine-grained planar-bedded lithofacies, although not usually in profusion, and here it is accompanied by other traces (Fig. 32c). Whereas *Skolithos* is thought to be the dwelling burrow of a suspension-feeding animal, the other traces in the fine-grained lithofacies indicate deposit-feeding and/or surface scavenging. These feeding modes produce burrows parallel to or inclined to the sediment-water interface, as opposed to the vertical orientation of the dwelling burrow *Skolithos*.

Two main types of horizontal burrows prevail in the fine-grained strata: (1) sinuous sediment-filled cylindrical burrows within beds (Planolites, Fig. 32d), and (2) scratches and grooves on bedding planes, probably made by trilobites walking and digging at the sediment-water interface (*Cruziana*, *Rusophycus*, *Monomorphichnus*, Fig. 32e).

Planolites bioturbation is common in all the fine-grained formations; typically burrows are present only in restricted zones that alternate with adjacent well laminated zones undisturbed by burrowing. Burrowed horizons alternating with laminated sediments are especially common in the Tunnel City, the Norwalk and the Sunset Point, and excellent examples will be observed on the field trip.

Trilobite traces are less common and less well preserved. They are usually found on the bases of sandstone beds (hypichnial traces). Apparently the traces were made as scratches in cohesive muds, and later cast in sand as the next bed was deposited. In the Eau Claire, where sand and shale are interbedded, traces are delicately preserved, and ichnospecies of Cruziana can be identified (Byers, 1977). Where shales are lacking, as in most of the other formations, the traces were dug in sand, and the resulting casts are ill-defined. In addition, all the St. Croixan rocks are poorly consolidated, and traces, as well as physical sedimentary structures, tend to be quickly weathered into oblivion.

In Seilacher's (1967) original environmental classification of trace fossil facies, the Skolithos assemblage was assigned to a very shallow water (littoral) zone, whereas the Cruziana assemblage was thought to represent slightly deeper (subtidal shelf) conditions. As noted previously, Skolithos burrows in the local section are present even in strata dominated by Cruziana and Planolites. Thus although the coarse-grained facies may be a "pure" Skolithos habitat, it is clear that the fine-grained facies represents an adjacent depositional environment in which the Skolithos-animal occasionally lived. None of the fine-grained formations contain traces such as Zoophycos, taken to mean intermediate depth by Seilacher; and, as might be expected, there are no grazing traces of the Nereites facies, which would indicate very deep water. It should be noted that although Seilacher labelled his facies as corresponding to depth zonation, they actually refer to degree of water agitation in the environment, which is often, but not exclusively, inversely correlated with depth. The suspension-feeding Skolithos-animal was not concerned with living in shallow water per se, but in a relatively high-energy environment. The trilobites which made Cruziana and Rusophycus required a quieter water habitat, but not necessarily a deeper one. It is my contention (Byers, 1977) that linking the simple presence of a trace fossil to a very specific depth is probably erroneous, particularly for the St. Croixan section in which the Skolithos and Cruziana facies integrade. I suspect that local energy levels controlled the distribution of the various trace makers, and, given a fluctuating energy regime, no great depth variations are signalled by the changes in traces from bed to bed or even formation to formation.

Sedimentary Structures

The fine-grained facies contains a number of sedimentary structures that indicate current activity in the depositional environment. Commonly there are indications of fluctuating energy levels as well, and in some instances structures are present that apparently formed in very shallow water or even by subaerial exposure.

The most common sedimentary structure is horizontal lamination in fine and very fine sandstone (Fig. 32f). In the older literature these laminae were taken as evidence of quiet-water deposition in an offshore environment (Ostrom, 1970) or perhaps in a protected lagoon (Berg, 1954). In accordance with modern sedimentologic concepts, it seems better to interpret these sands as products of an energetic environment dominated by currents of the upper plane-bed flow regime. As shown in flume studies (see Southard, 1975, for example), the fine and very-fine sand grades do not form dune bedforms. Instead, the bedform changes from no sediment involvement to ripples to upper plane bed as flow velocity is increased. In other words, no large-scale high-angle cross-stratification is produced even at high current velocities. The flume-study graphs in Southard (1975) give flow velocities of 60-150+ cm/sec for transport of 0.1 mm sand in the upper plane bed regime.

James (1977) listed several criteria which substantiate that horizontal bedding in the Tunnel City sands is due to energetic current flow:

1.) the occurrence of occasional broad, low-angle cross-laminae within planar-bedded sands (Fig. 32f).

2.) the occurrence of parting lineation in planar-bedded sands,

3.) the occurrence of coquinites of transported fossil debris on the bedding planes.

The Norwalk and Sunset Point Members of the Jordan Formation are dominated by low angle trough cross-stratification. This bedding is certainly the result of an energetic sedimentary environment, although the current velocity cannot be determined unambiguously; for a given grain size, bedform geometry is the result both of flow depth and flow velocity (Southard, 1975), and neither variable is known for the Cambrian sands. However, it is clear that whatever the flow depth, velocity must have been in the range of tens of centimeters per second.

All the units in the fine-grained facies display evidence of episodic alternations in energy. In the Eau Claire Formation and Tunnel City Group (especially in the Tomah Member) fine sand beds alternate with thin shale horizons, forming a variety of bedding types. Much of this alternation can be called <u>coarsely interlayered bedding</u> (Reineck and Singh, 1973). The shales are extremely thin, only one or two millimeters thick, whereas the sandy layers are several centimeters thick. In places the sand beds are rippled, and the bedding style becomes true flaser bedding (Fig. 32g). Where shales are rare or absent, especially in the Norwalk and Sunset Point Members, there is little evidence of such a rapid alternation of current velocity. Apparently these latter units were subjected to nearly continuous sifting and winnowing, and their alternating zones of bioturbate and laminated sediment probably represent periodicity on a scale of weeks or months, as opposed to the hours or days involved in generating the couplets of coarsely interlayered bedding in the other formations. In any event, the fine-grained lithofacies was characterized by either constant agitation or continual alternation between agitation and quiet water. I suggest that both of these modes are best developed in very shallow water. Other evidence of alternation in energy level includes:

1.) the presence of rip-up conglomerates, especially well developed in the Tunnel City Group and St. Lawrence Formation,

2.) the juxtaposition of trilobite traces, indicating the environment was habitable, with fossil coquinites, indicating considerable post-mortem transport and destruction,

3.) apparent herringbone cross-stratification in the Tunnel City Group (Reno Member), indicative of varying current orientations,

4.) interference ripple marks, also produced by shifts in current orientation (Fig. 32h).

Perhaps the best evidence for a specific depositional environment is to be found in the suite of structures indicating extremely shallow (centimeters in depth) or emergent conditions. Most important here are polygonal mud cracks and mudchip conglomerates, which are especially prevalent in the Eau Claire and Tunnel City units, and would seem to be very strong evidence of periodic subaerial exposure and desiccation (Fig. 32i,j). It is known that mud cracks can form subaqueously by dewatering of clays (see Huber, 1975 for a review of pertinent literature), but cracks formed thus, both in nature and in laboratory experiments, require large changes in salinity. Experimentally-produced synaeresis cracks involve deposition and dewatering of clays in water only a few centimeters deep; in nature such shallow depths would probably be necessary for the generation of appropriate salinity changes. Reineck and Singh (1973) suggested that synaeresis cracks might be important features in hypersaline lagoons and sabkhas, environments which are ruled out for the St. Croixan rocks by the presence of trilobite traces and Planolites. Reineck and Singh also noted that experimentally-produced synaeresis cracks are rather narrow and rarely v-shaped in section, and tend not to form polygons. Cracks in the Eau Claire Formation and Tunnel City Group form meter-size fields of polygons. I suggest that the simplest interpretation of these features is that they were produced by subaerial desiccation; to call on synaeresis seems to be special pleading, as emphasized by Blatt and others (1972, p. 193), "it has been demonstrated that mud may crack underwater in the laboratory but, in nature, mud cracks appear to be a relatively reliable indicator of emergence".

Also produced in extremely shallow water are flat-topped ripples (Fig. 32k) and wrinkle marks (Fig. 32l) which have been observed in the Eau Claire and Tunnel City units. Both of these features are modifications of a sediment surface only barely awash. Flat-topped ripples result from the planing action of very small waves in water only a few centimeters deep; wrinkle marks are essentially microripples produced by a thin film of water moving by wind pressure across the sediment surface. Both structures have been well-documented in modern sediments (Reineck and Singh, 1973).

Environments of Deposition

The fine-grained lithofacies appears to encompass several specific environments within a larger depositional setting dominated by tidal sedimentation. I interpret the shalier units - Eau Claire, Tunnel City, St. Lawrence - as tidal flats, based on a complex of evidence, including the suite of sedimentary structures and trace fossils, and the taxonomic composition and mode of formation of the fossil assemblages. These data and their implications are compared with modern tidal flat features in Table 1. There are fewer diagnostic features in the Norwalk and Sunset Point Members, and my interpretation of these units is more tentative. Although I am here suggesting that they represent subtidal and lower intertidal regions of a large tidal flat, other interpretations are possible and are discussed below.

Tidal sedimentation has been extensively discussed in the literature in recent years, and summaries of studies of both modern and ancient tidal flats are available (Reineck, 1972; Ginsburg, 1975; Klein, 1977 a, b). Modern tidal flats form in shallow water where sediment is available and strong wave action is not present: in estuaries, lagoons, bays, behind barrier bars, or facing the open sea where a wide subtidal zone damps wave action (Reineck and Singh, 1973). The dominant transport mechanisms are wind-waves in very shallow water

TABLE 2 - Occurrence of Tidal Features in the Fine-Grained Lithofacies

(categories modified from Klein, 1977a)

Sedimentary Features	Lithostratigraphic Unit	Depositional Process
Cross-strata with sharp set boundaries	E.C., T.C., N., S.P.	Tidal current phases with nearly equal flow velocity
Parallel laminae	E.C., T.C., St.L., N., S.P.	
Herringbone cross-stratification	T.C.	
Supermature rounding of quartz grains	(in adjacent coarse-grained lithofacies)	
Interference ripples	E.C., T.C.	Late-stage emergence runoff producing changes in flow direction
Flaser bedding	E.C., T.C., St.L.	Alternation of tidal current bedload sediment transport with mud suspension deposition during slack water
Mud cracks	E.C., T.C., St.L., N.	Exposure
Wrinkle marks	E.C., T.C.	
Flat-topped ripples	E.C., T.C.	
Mud chip conglomerates	E.C., T.C., St.L.	
Stromatolites	St.L.	
Fossil coquinas in washout bases	E.C.	Tidal scour
Cruziana-facies	E.C., T.C., St.L., N., S.P.	Feeding and crawling burrows
Skolithos-facies	E.C., T.C., N., S.P.	Dwelling burrows

E.C. = Eau Claire Fm., T.C. = Tunnel City Gp., St.L. = St. Lawrence Fm., N = Norwalk Member , S.P. = Sunset Point Member and tidal currents, which are characteristically variable across the locale and over short time periods (hours). Currents change orientation and strength constantly in response to water level differences, wind direction, and local topography. Thus tidal flat sediments generally show cyclic alternations in grain size in a given section and contain few beds which are laterally extensive. Both of these characteristics are paramount in the St. Croixan rocks: sands and shales are intimately interbedded and thin beds can be seen to pinch out within the space of a few meters. I suggest that this variability is best accounted for by deposition in very shallow water, in the fluctuating current regime of a tidal flat.

Variability in current orientation is also shown by the presence of interference ripple marks and the diversity of cross-bedding orientations in the fine-grained facies. Dott (Michelson and Dott, 1973 and this guidebook) has shown that there is considerable variability in cross-bedding orientation in several of the St. Croixan sandstones. Although an overall southerly direction of flow can be deduced for the Van Oser and Galesville sands (coarse-grained lithofacies) there is no discernible pattern to orientations in the Tunnel City sands. Dott previously attibuted this to poorer exposures of the fine-grained lithofacies, and to the possible presence of doubly-plunging trough cross-sets. However, if the fine-grained sediments were deposited in a tidal regime, perhaps the lack of a single nonrandom mean in Dott's Tunnel City measurements reflects variability produced by reversing flow.

Also common in tidal sedimentation are the structures indicative of subaerial exposure, mud cracks and mudchip conglomerates; and of extremely shallow (and variable) water, flat-top ripples and wrinkle marks. Tidal flats are constantly being exposed to the air and then resubmerged, so structures formed at high water are modified as depths diminish, and eventually the surface is subjected to desiccation.

The presence of *Skolithos* has been used by many authors to infer very shallow marine conditions, especially tidal flat sedimentation (see Klein, 1977a, and references therein), and recently patterns in distribution and morphology of *Skolithos* have been used to map sub-environments within a tidal flat complex (Goodwind and Anderson, 1977). As noted previously, the mixture of traces indicating lower energy (*Cruziana*, *Planolites*) with *Skolithos* suggists the fluctuations in energy diagnostic of tidal sedimentation. On a modern tidal flat, energy is variable, with currents in the lower intertidal and subtidal, and more intermittent currents and quieter water in the higher intertidal.

Thus a relatively small area can contain both bioturbate muds (*Planolites*) and cross-laminated sands (*Skolithos*). It should be noted that on the fine depth scale of a tidal flat, the usual depth-energy correlation breaks down; the shallowest water is also the quietest, so the application of a strict model of trace fossil depth zonation would be erroneous. I suggest that the prevalent *Cruziana* and *Planolites* burrows in the St. Croixan rocks simply indicate somewhat quieter conditions than are represented in the *Skolithos*-bearing sediments, and that there was no appreciable depth differential between the two ichnofacies. Indeed, I suspect that the *Skolithos*-bearing sands were slightly deeper than the *Cruziana-Planolites* muddy sands, in accordance with the modern tidal flat configuration. Seilacher (1977) recently came to a similar conclusion. In a brief discussion of traces in tidal flat environments he figured a specimen of Cruziana from an Upper Cambrian (?) sandstone with large mud cracks. The cracks cut across the trilobite trace, suggesting that the depositional environment was alternately submerged and dessicated; clearly, the Cruziana-zone involved water only a few centimeters or decimeters deep.

Modern flats are rigorous environments; the stress of continually changing current velocity, temperature, and salinity, and the possibility of desiccation, restricts the number of taxa that can inhabit the environment. Stressful habitats are populated by physiologic "generalists", which can endure physical fluctuations, and by mobile animals which can retreat into deeper water or into the sediment for protection (Emery and others, 1957; Parker, 1975; Rhoads, 1975). Attached epifaunal benthic animals are rare. Modern tidal flats are dominated by a low-diversity assemblage of arthropods, gastropods, polychaetes, and bivalves (Frey and Howard, 1969; Schafer, 1972). In terms of preservable species, the Cambrian trilobite-inarticulate brachiopod-hyolithid assemblage seems a reasonable analog (Runnegar and others, 1975). The absence of other phyla, especially epifaunal suspension feeding types such as echinoderms and articulate brachiopods, argues against a subtidal interpretation for these rocks.

The mode of formation of the Cambrian fossil assemblages is also consonant with modern tidal flats. Continuous reworking of the sediments by currents aggregates shells into discrete layers. Shells are buried and exhumed and may be moved back and forth by oscillating currents. Although net transportation may be minor, the shells are liable to much abrasion and fragmentation during their preburial exposure time. The resulting coquinas contain species which live in the immediate habitat, but none of the shells records the life position of the animal. Schafer (1972) discussed the various modes of shell accumulation in the North Sea and its adjacent tidal flats. He stressed that shells were transported both by waves and tidal currents, the latter confined to depths less than 30-40 m. In the intertidal zone, a shell coquina can be produced by storm erosion of the tidal flat and redeposition of shells in a single layer above the normal high tide mark. Shells can also accumulate as lag gravels in the bases of laterally migrating tidal channels. The stratigraphic result of channel sedimentation is a cross-bedded sand erosionally overlying muddy sand, with a shell coquina along the contact. This kind of vertical sequence is common in the Eau Claire Formation, in which trilobite-brachiopod-hyolithid coquinas occur at the sharp bases of cross-laminated sandstones.

In the North Sea subtidal zone, shells will accumulate in the bottoms of deep tidal channels. They also are abundant on the flat sea floor where they may be moved about and abraded by storm waves. Schafer (1972) stated that shells of the open sea floor do not accumulate, since there are few depressions, but instead they occur embedded in the sandy or muddy sediments. The shells may form pavements but are rarely thick deposits or imbricated stacks.

The previously dicussed depth zonation on modern flats may explain the specific differences between formations of the fine-grained lithofacies. The principal difference between the Eau Claire Formation, Tunnel City Group, and St. Lawrence Formation on one hand, and the Norwalk and Sunset Point Members of the Jordan Formation on the other, is the near total absence of shale in the latter units. The most diagnostic features of tidal sedimentation: mud cracks, flasers, trace fossils, depend on the presence of muddy layers. Although true shale formations do not occur in the type St. Croixan, shale may be thought of as an enhancing agent, allowing more specific interpretations to be made regarding the sandstones which compose most of the stratigraphic thickness. As Dott has noted (this guidebook), the pure sandstones contain clearly visible and even spectacular structures whose genesis is unfortunately ambiguous; within the fine-grained facies the Norwalk and Sunset Point Members fall into the ambiguous catagory. The interstratification of the very similar Norwalk and Sunset Point Members with the coarse-grained Van Oser Member would seem to link all three units in terms of genesis. That is, any lithotope postulated for the two fine-grained sands must be compatible with a nearby Van Oser lithotope. Unfortunately, the Van Oser Sandstone itself is not well understood, so the constraints are few. One possible model for the Norwalk-Van Oser sequence is a prograding shoreface - foreshore, in which sands increase in grain size upward and biogenic structures decrease in abundance relative to cross-stratification (see Howard, 1972; Ryer, 1977). This interpretation would place the Van Oser Sandstone in the shallowest and most agitated environment, more or less as in Ostrom's (1970) model. The main difficulty with this interpretation is the <u>lack</u> of wave-produced stratification in the Van Oser Sandstone; instead, it <u>is</u> dominated by current-produced trough cross-beds, which are not typical of the beach foreshore.

In terms of the tidal flat model, the Norwalk and Sunset Point Members might be assigned to the upper subtidal zone in which submergence and current action are continuous, so that mud is "never" able to settle out of suspension and burrowing communities are repeatedly destroyed by erosion or sedimentation events. Reineck and Singh (1973; and many references therein to Reineck's previous publications) refer to this zone as the Sand Flat. Slightly higher, in the intertidal, sand is mixed with mud as a consequence of fluctuating tidal flow (Mixed Flat) and burrowers are more common. True Mud Flats, usually strongly bioturbate, are found in the high intertidal zone. The shaley formations in the St. Croixan should probably be assigned to the Mixed Flat zone, because sands are universally present and typically dominant.

DISCUSSION

There are several aspects of the problem of the fine-grained lithofacies which require further comment: the relationship of clastics to carbonates in the section, the relationship of the fine-grained to the coarse-grained lithofacies, the implications of the tidal model for the cyclic depositional model. These topics go beyond the scope of this paper, and in fact are not yet fully understood, but a few remarks will be made here.

Carbonate

The St. Croixan section lacks significant carbonate development, in strong contrast to the overlying Ordovician, which is dominated by carbonate units hundreds of meters in aggregate thickness. Carbonate in the St. Croixan is confined to cements in some of the sandstones (especially notable are layers of dolomitic cement in the Tunnel City Group), and to the silty dolomites of the Black Earth Member of the St. Lawrence Formation. Usage of the term "formation" rather than "dolomite" for the St. Lawrence is strongly recommended, for this unit has an appreciable content of silt and sand even where the carbonate is best developed. Glauconite is present as well. In terms of fossils, traces, and sedimentary structures, the St. Lawrence is very similar to the underlying Tunnel City Group; in fact it is not always easy to distinquish the contact between the formations.

Overall, the St. Lawrence is fine-grained, with more silt than any other St. Croixan unit. This fine grain size and the presence of carbonate have led to the interpretation that the St. Lawrence was deposited in a quiet water, offshore environment (Ostrom, 1970). However, the presence of features indicative of tidal flat sedimentation, most especially the stromatolites, argues that the quiet environment was extremely shallow; perhaps the discontinuous areas of stromatolitic Black Earth Dolomite development represent the high intertidal or even supratidal Mud Flat environment. The lack of continuity of the carbonate and the significant terrigenous clastic fraction of the lithology suggest that carbonate sedimentation barely got started even in the one so-called "Dolomite" in the St. Croixan. The Black Earth Dolostone is emphatically not the sort of blanket carbonate we find in the Middle Ordovician (Platteville Formation, Galena Formation), and it is misleading to think of it as such. A better image of the Black Earth Dolostone is that of an occasional small carbonate "overprint" onto a widespread shallow marine clastic lithotope at one point in time when the sand deposition rate was even lower than normal (cf. Swett and others, 1971, p. 412-413; Klein, 1977a, p. 10). Parenthetically, it should be noted that tidal flats have extremely rapid "instantaneous" rates of sedimentation, on the order of centimeters per hour (Kukal, 1971), but that net accumulation may be small because of equally rapid instantaneous rates of erosion. Thus a tidal flat may persist for a long time essentially at local baselevel with little vertical accretion (Reineck, 1972). As Dott has emphasized (this guidebook), the St. Croixan section is extremely thin in comparison to the long span of Late Cambrian time; this fact, plus the super-maturity of much of the sandy sediment, and the virtual absence of shale, suggests to me that sediment supply from the land (wherever that was in Late Cambrian time) and rate of subsidence of the craton were both extremely low in comparison to the rates of depositional and erosional processes in action. I suspect that for long periods of time the Cambrian epeiric seafloor was near a state of equilibrium: lots of sediment moving around and being deposited but very likely to be removed during the next diurnal or lunar tidal cycle, or the next tropical storm, or the next regional shift in tidal currents. Again, Dott calls our attention to the disparity between human and terrestrial time scales (Dott and Batten, 1976; Dott, this guidebook) and to the significance of the "rare" event in the generation of the stratigraphic record. Ager's (1973) memorable phrase, "long periods of boredom and short periods of terror" seems especially applicable to St. Croixan section, as does Ager's contention that it is not the processes of deposition that are paramount but the overall "geophysical environment" of preservation.

Walther's Law in the St. Croixan

The concept of a carbonate "overprint" upon a pre-existing depositional environment forces a re-evaluation of the traditional transgressive model for the St. Croixan section. If changes in relative sea level were not necessary for the initiation of carbonate deposition, then we may wonder whether sand-shale-carbonate onlap actually occurred; that is, if the fine-grained facies in general, and carbonates in particular, did not form in an "offshore" position, then a transgressing sea cannot explain the observed fining-upward vertical sequences. I suggest that the transgressive onlap model probably has too strong a hold on our imaginations; we tend to look for lithotopes that "ought" to be present, given the assumption of transgression. This assumption is largely a biostratigraphic concept, originally invoked to bring in new stocks of trilobites, although it was later modified by Ostrom to explain the lithostratigraphic realities of the St. Croixan. Our purpose now should be to interpret each unit sedimentologically and <u>then</u> let the stratigraphic relations between lithotopes dictate the overall model. It thus becomes crucial to decipher the paleoenvironmental relationship between the coarse-grained and fine-grained lithofacies. Dott (this guidebook) has emphasized the difficulty of establishing water depths for the coarse-grained facies, and has concluded that "littoral" could have encompassed depths of tens of meters; he also has noted the lack of true beach stratification in the coarse-grained facies. Might we not postulate that, in accordance with modern tidally-dominated environments, the coarse-grained facies represents <u>deeper</u> water than the fine-grained facies? That is, in water a few meters or tens of meters deep, strong tidal currents produced migrating dune fields of pure sand, whereas in the shallower (intertidal) areas, variable and overall quieter conditions led to the deposition of "muddy" finer sands. If this were the case, then the St. Croixan fining-upward cycles could easily be explained as tidal flats prograding laterally over subtidal sand shoals. A shift in the other direction, placing the higher energy lithotope over the lower energy lithotope, would probably involve erosion, as stronger currents cut into the fine-grained lithofacies. In fact we typically find a disconformity at such contacts in the St. Croixan section (sub-Galesville, sub-Van Oser). These surfaces have been considered to mark times of actual withdrawal of the sea (Berg and others, 1956; Ostrom, 1970). Instead, I suggest that the erosion may have taken place within the shallow marine environment as a consequence of shifting depositional regimes. One possible modern analog would be the development of <u>ravinement</u> surfaces by the process of inlet migration and/or shoreface retreat. In recent years, a number of authors (Fischer, 1961; Swift, 1968; LeFournier and Friedman, 1974; Stahl and others, 1974; Sanders and Kumar, 1975; Ryer, 1977) have shown that the sedimentary result of shoreline retreat is likely to be an erosion surface covered by subtidal deposits, rather than an onlapping sequence comprising non-marine, marginal marine, and beach lithotopes. Ryer (1977), in particular, has emphasized the asymmetry of transgression-regression cycles in Cretaceous rocks, noting that the shoreline retreat is usually marked only by a disconformity, whereas the shoreline advance is recorded by a progradational wedge. According to Ryer, onlapping sequences are exceptional in the Western Cretaceous section, long considered to be a definitive example of such sequences.

A case of asymmetric transgression-regression cyclicity involving tidal deposits was discussed by Beukes (1977), who documented a vertical sequence of prograding tidal flat wedges in Precambrian rocks in South Africa. The inferred transgressions are represented only by erosional surfaces, whereas the regressions are shown by complete fining-upward sequenees. (cf. a series of papers by Klein, listed and discussed in Klein, 1977b).

Cyclicity

The transgressive-regressive model leads naturally to the concept of repeated inundations and retreats of the sea to explain the recurrent lithologies in the St. Croixan section. Ostrom (1970) generalized the model sufficiently to include the Lower and Middle Ordovician rocks as well. As noted previously, I think there is a profound difference between the St. Croixan strata and the Middle Ordovician carbonates. The intervening Lower Ordovician rocks are also carbonate but seem similar to the inferred Cambrian environments; they contain much evidence of shallow water deposition (see papers by Adams and by Odom and Ostrom, this guidebook). The Lower and Middle Ordovician carbonates are separated by the regional Sauk-Tippecanoe sequence unconformity and the St. Peter Sandstone, an erosional-depositional event of craton-wide magnitude. I suggest that the shallow conditions which prevailed throughout the St. Croixan and into Early Ordovician came to an end with the Prairie du Chien carbonates, and when the seas returned in the Middle Ordovician analogous environments did not occur. Based on my limited work with the Middle Ordovician carbonates, I suppose the depth of their environments to be significantly greater than anything in the St. Croixan, i.e., tens to perhaps hundreds of meters. Studies of the Middle Ordovician by University of Wisconsin Masters students have shown that both trace fossil and body fossil assemblages indicate open-marine quiet-water conditions (Stasko, 1974; Gavlin, 1976; Hopper, 1978). Conodonts are very abundant in the Middle Ordovician strata, both in terms of species and individuals, whereas they are quite rare in both the Cambrian sands and Lower Ordovician dolomites (Clark, 1971).

Restricting ourselves to the Cambrian and Early Ordovician then, it is clear that cyclicity exists. It was Ostrom's admirable insight that the St. Croixan column of formational names can be understood in terms of only a few recurrent lithotopes. In this paper I have advocated a somewhat more extreme approach, that really there are only two grand lithofacies in the Cambrian of Wisconsin, coarser cross-bedded and finer planar-bedded, representing lithotopes of subtidal and intertidal depth, respectively. Within these lithotopes there were small differences in current regime which account for the variations in grain size, shale, and carbonate content.

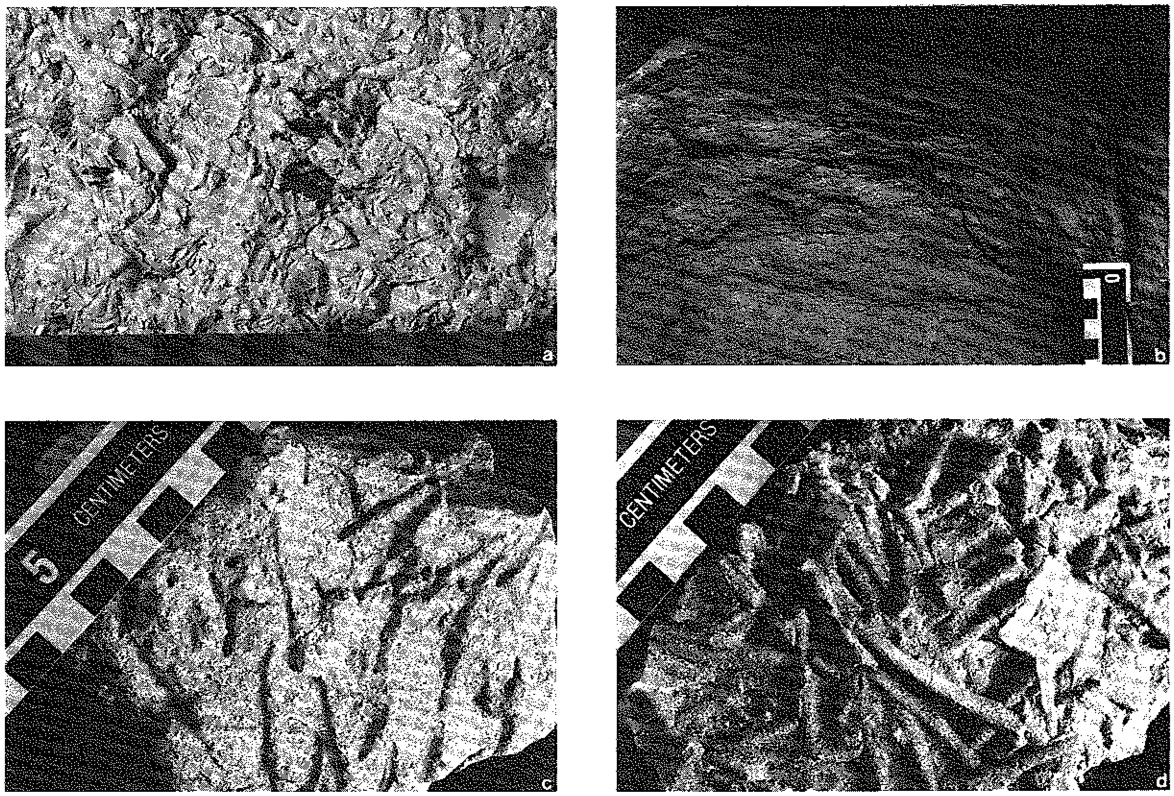

Figure 32. Fossils and Sedimentary Structures of the Fine-Grained Lithofacies (Scale in centimeters).

a. Fossil coquina composed of trilobites, inarticulate brachiopods, and hyolithids from Eau Claire Fm.
b. Hemispherical stromatolite head from Black Earth Dolomite of St. Lawrence Fm.
c. Skolithos in sandstone of Tunnel City Gp.
d. Planolites in bedding plane exposure of Norwalk Member of Fordan Fm.
e. Cruziana in bedding plane exposure of Eau Claire Fm.
f. Planar stratification and low-angle cross-stratification in sandstone in Eau Claire Fm.
g. Coarsely interlayered bedding and flaser bedding in Tomah Member of Tunnel City 6 p.
h. Interference ripple marks in Eau Claire Fm.
i. Mudcracks in Eau Claire Fm.
j. Mud chips in sandstone in Tunnel City 6 p.
k. Flat-topped ripple marks in Eau Claire Fm.
l. Wrinkle marks in Eau Claire Fm.

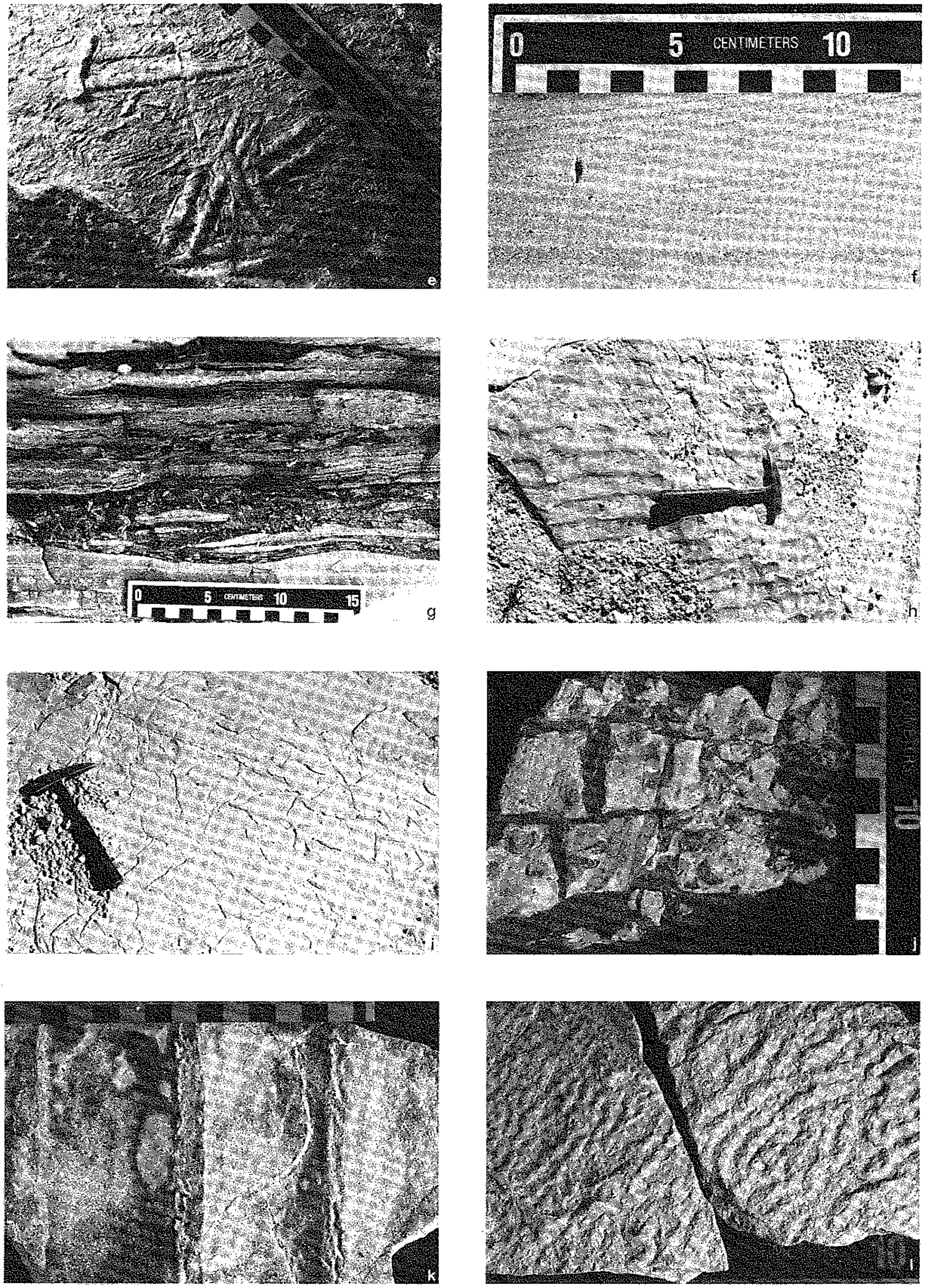

Figure 32 (continued)

STRATIGRAPHY AND PETROLOGY OF THE LOWER ONEOTA DOLOMITE (ORDOVICIAN) - SOUTH-CENTRAL WISCONSIN

by

Richard L. Adams*

ABSTRACT

Field study of eight outcrop sections in the Madison, Wisconsin area, and binocular microscope analysis of polished slabs were used to interpret carbonate facies in the lower Oneota Dolomite across Dane County.

Correlation of these carbonate facies indicate that carbonate deposition commenced early west of Cross Plains and east of Middleton while sand was still being deposited in the area between Middleton and Cross Plains. Sand influx from the north, near the Baraboo hills, fed sand deposition near Sauk City and between Middleton and Cross Plains while only a few miles east (at Middleton and at the Northwest Stone Company Quarry) and west (at the Capitol Stone Company Quarry) carbonate deposition had commenced.

Away from this bar the lower thirty feet of the Oneota Dolomite represents a regressive sequence starting at the top of the Jordan Sandstone (Van Oser or Sunset Point) and progressing upward through the following facies: oolite, vertical honeycomb, large scale LLH stromatolites, and evaporite solution breccia. This regressive sequence is thought to have occurred due to the rate of sedimentation exceeding the rate of subsidence. Lateral variations in this sequence, due to slight variations in bottom topography, allowed islands to form and coalesce. It was around these islands that the large LLH stromatolites acted as breakwaters, and on which the supratidal laminated mudstones and wackestones and evaporite breccias formed.

The sand present in the section near Sauk City and at Miller's Curve is inferred to represent one or perhaps several sand bars down current from a presumed source to the present day north. Some of the sandy dolomites and dolomitic sands in the lower Oneota (called the Coon Valley Member by Odom and Ostrom) are time equivalent to this sand bar(s) and time lines would correlate facies on opposite sides of the bar(s).

For these reasons it is the author's opinion that the sandy dolomite and dolomitic sandstones that Odom and Ostrom (this guidebook) propose to call the Coon Valley Member of the Jordan Formation should remain a part of the Oneota. However, this author's study has been limited to the area near Madison and does not include all of the outcrop area of the Jordan and Oneota.

INTRODUCTION

Study of the lower fifty feet of the Oneota Dolomite was undertaken as part of the requirements for a master's degree at the University of Wisconsin-Madison during 1974 and 1975. This study included nearly two hundred slabs

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from eight outcrops. The slabs were cut vertically from samples collected from each bed and had one face polished enough to remove saw marks. A coating of mineral oil was put on the slabs just before examination under a binocular microscope to facilitate recognition of grains and textures.

The intent of that study was to show the carbonate facies present in the lower Oneota and to use the lateral and vertical relations of those facies to interpret the depositional environments of the lower Oneota in the Madison area. The choice of several outcrops in a small area permitted detailed correlation of carbonate facies from outcrop to outcrop and reconstruction of the depositional environments of the sandy dolomites and dolomitic sandstones of the lower Oneota.

Carbonate microfacies were found to be correlatable and a depositional history was constructed relating the sand deposition around the Baraboo Islands, inferred wind patterns, and the initiation of carbonate deposition leeward of those islands (Figs. 22 and 31).

CARBONATE ROCK TYPES

For the description of carbonate rock types in the lower Oneota, the carbonate classification of Dunham (1962) is used. Dunham divides carbonates on the basis of their depositional texture. Dolomitized equivalents of all of the major rock types in Dunham's classification are present in the lower Oneota. Textural features of cements, though now dolomite, are recognizable. Several stages of cementation are recognizable after both silicification and dolomitization.

Micrite matrix is preserved as a yellow to yellow tan dense dolomite with an average crystal size of 0.01 - 0.03 mm. Evidence of the micritic origin of this very fine grained dolomite is its crystal size, its intergranular position and its support of grains in wackestones.

The most common grains present are ooliths, pellets, intraclasts, and quartz sand grains. Ooliths and quartz sands comprise the highest percentage of grains recognized. They are most common in the lower twenty feet of the carbonate section. The ooliths are from 1/4 to 1 mm in diameter. Most ooliths have quartz sand grains for nuclei and rinds from one layer thick up to rinds that are 4/5 of the grain bulk. Quartz sand grains are 1/8 to 1 mm in diameter and angular to well-rounded. Although a few thin sandstone beds are present quartz sand grains make up less than 25% of most samples examined.

Pellets and intraclasts are common grains in the lower Oneota but are rare as constituents in grainstones. Most of the recognizable pellets are 0.4 - 1.5 mm round grains of yellow-brown dolomite with an average crystal size of 0.05 mm. Nearly all are rounded to ellipsoidal in shape. The inferred origin is fecal pellets from benthic organisms as described by Purdy (1963) in the lee of Andros Island, Bahamas. Perhaps the pellets did not have the strong internal structure often needed to withstand high energy conditions in environments that produce mud-free carbonates. The intraclasts are mostly subangular to angular pieces of algal stromatolites from 1/2 to 10 centimeters in length. Internal structures are similar to those of stacked hemispheroid SH-V, and LLH mat stromatolites of the classification of Logan, et al. (1964). The angularity of the clasts indicates little transportation and at least partial lithification prior to erosion and redeposition.

The algal boundstones are classified according to the classification of Logan, and others (1964) who describes algal columns and mats as being from shallow subtidal to intertidal water depth. Stromatolitic forms in the Oneota are grouped as follows:

1. Large, partially silicified LLH-C heads
2. LLH-C and LLH-S laminated mats forming six inch to two foot beds
3. Layers of SH-V columns
4. One to two foot thick layers with mixtures of LLH-C and SH-V
5. Vertical honeycomb structures

The large, partially silicified LLH-C heads range in size from four to eight inches across up to nearly six feet across and eighteen inches high and have up to 30-40% silica. Locally the chert appears to be in the form of large breccia fragments. Some chert beds are microbreccias (I. E. Odom pers. comm.). In some layers the chert replaces large parts of the LLH-C heads. Most of the dolomite in these LLH-C heads is either yellow dolomite with an average crystal size of 0.01-0.03 mm or yellow brown dolomite with an average crystal size of 0.04-0.1 mm. Both are considered to be dolomitization products of an original carbonate mud. These beds form the datum for Figure 1.

At some localities, possible evaporite molds are found associated with these algal heads. These molds consist of angular 0.1 - 1.0 cm blade shaped pores with right angle reentrants similar in shape to anhydrite blades, and 0.3 - 1.0 cm lobate pores shaped like anhydrite growth nodules. These pores may be a substantiation of the intertidal to supratidal origin of the stromatolites. The brecciated appearance of the interhead area may be a collapse feature due to dissolution of deposits above the LLH heads.

Stromatolite mats form from 1-2 cm individual heads of LLH-C and LLH-S stromatolites. They are composed of 0.01 - 0.03 yellow dolomite and 0.05 - .1 yellow brown dolomite. These two dolomites form couplets 1-2 mm thick. This rock type commonly is seen as intraclasts in conglomeratic beds.

Large SH-V columns form beds up to 18 inches thick with minor LLH-S laminae cutting across tying columns together. Individual columns are 5-6 cm in diameter with an internal lamination showing upward convexity. Original fabric is inferred to have been carbonate muds, silts, and sands trapped and bound by blue-green algae. The interfingering of these columns with the LLH-C and LLH-S mats described above may be explained as an exposed intertidal mud flat with the SH-V columns forming a type of barrier partially protecting a mat covered area behind the columns.

Vertical Honeycomb (VH) is a distinctive rock type in the lower Oneota near Madison that has not been previously well described and defined. It occurs as one-half to two foot thick layers of vertically mottled dolomite. It consists of dense columns of 0.1 - 0.15 mm grey white dolomite (60%) with a porous intercolumnal area of 0.05 - 0.1 mm yellow brown dolomite (40%). The lateral correlatability and constant appearance of the VH in the Madison area argue for it having a primary sedimentary origin. Its consistent composition and stratigraphic relation both vertically and horizontally to other facies, as well as its lateral continuity are not weathering related. VH is found laterally interfingering with LLH at one locality (S-20). This horizontal relation of VH with LLH stromatolites suggests a possible algal origin for the VH. The different growth form may reflect a slight difference in environmental parameters in the depositional regime.

The vertically associated facies found with the VH rock type are also indicative that it is a primary sedimentary facies and not a random diagenetic feature. The rock types found associated with VH and their relationship to the VH are summarized in Table 3 (below).

TABLE 3.	Number of times facies is found above VH	Number of times facies is found below VH
Intraclastic and solution breccias and conglomerates	5	10
Oolites	6	6
LLH stromatolites	6	0
Carbonate mud	0	1

Oolites are found both above and below the VH in nearly equal amounts, indicating a close affinity between the oolites and VH. Intraclastic breccias and conglomerates (especially with clasts of algal stromatolite) are found both above and below but more often below the VH. This shows a strong relationship between the VH and well agitated relatively shallow water conductive to the formation of intraformational conglomerates. The presence of a significant relationship with overlying LLH stromatolites is suggestive of an intertidal depth. On the basis of this data, I infer a very shallow subtidal to low intertidal "algal" origin for the VH rock type. It may be the preservation of an originally algal skeletal structure comparable to modern Goniolithon.

DEPOSITIONAL ENVIRONMENTS

Jordan sand deposition was taking place in western Dane County at the same time that Oneota carbonate (sandy phase) deposition was taking place both to the east and west. This is demonstrated in Figure 33. Localities near Sauk City and at Miller's Curve show a much thinner carbonate section than those localities further east or west. This is inferred to represent the last sand influx into Dane County and is laterally equivalent to Oneota carbonates (sandy phase). Wave and current action spread sand laterally away from this bar. This is the origin of the small sandstone beds and lenses as well as the disseminated sand grains in the lower Oneota. Cessation of sand influx due either to covering of the source area by a slight sea level rise or deflection of the sands to some other area allowed carbonate deposition to take over all of Dane County. The abundant quartz sand grains present in the area were ideal to form the nuclei of oolites.

Correlation of facies in the lower Oneota (both sandy and nonsandy phases) suggest that the bed of large LLH-C stromatolites is the most consistent bed in the lower Oneota and thus it is used as the datum for the E-W stratigraphic cross-section (Fig. 33). Several points should be noted about the quality of correlation possible in the lower Oneota. They are:

1. On a local scale between Sunset Point and Shorewood (about 1 mile) it is almost possible to correlate bed for bed.

2. On a regional scale (across Dane County) zones of sediment types such as boundstone layers (silicified LLH-C layers) and zones of VH plus LLH can be easily correlated.

3. Lateral pinch outs and interfingering of facies can be observed.

Vertically, both small and large scale facies sequences can be seen. On a small scale, bed 4 (Fig. 33) at Shorewood quarry demonstrates an upward transition from a pelletal quartz sand to an oolite grainstone. This may represent sand being transported into a zone of active carbonate precipitation and becoming oolitically coated. Alternatively, it may represent migration of oolite shoals into a region where pelletal quartz sands were being deposited.

On a large scale, the lower thirty feet of the carbonate demonstrates a regressive sequence. That sequence is:

5. Evaporite molds in solution breccias (top)
4. Large scale silicified LLH-C heads
3. Vertical Honeycomb
2. Oolite
1. Jordan quartz sands (base)

Above the Jordan Sandstone is a zone of thick, predominantly oolite beds. The oolites represent a shallow, agitated subtidal environment. A depth of two to ten feet would be consistent with modern oolite bank development. Odom and Ostrom (this guidebook) ascribe the sands of the Van Oser to litteral bars downcurrent from the islands in the Baraboo area. The only difference between these two environments is carbonate precipitation and the development of oolites around the quartz grains. As carbonate precipitation continued, the oolites filled up the topographic lows and brought the area to near sea level. As some areas became higher they were periodically exposed at high tide. At such times, stabilization of the oolite shoals began as the VH and LLH and SH stromatolites grew and spread over the bottom. Large LLH-C stromatolites formed on exposed intertidal mud flats and protected the mat-covered mud flats behind the stromatolitic barrier. As the islands grew larger, the sea was forced to retreat and the water remaining became more and more saline. This hypersaline water led to the formation of evaporite beds over the islands. As some of the more massive beds of evaporites were later dissolved the overlying beds collapsed forming the solution breccias now seen. The evaporite breccias show pores similar in shape to gypsum and anhydrite crystals as well as anhydrite growth nodules. The evaporite breccias have large angular clasts of

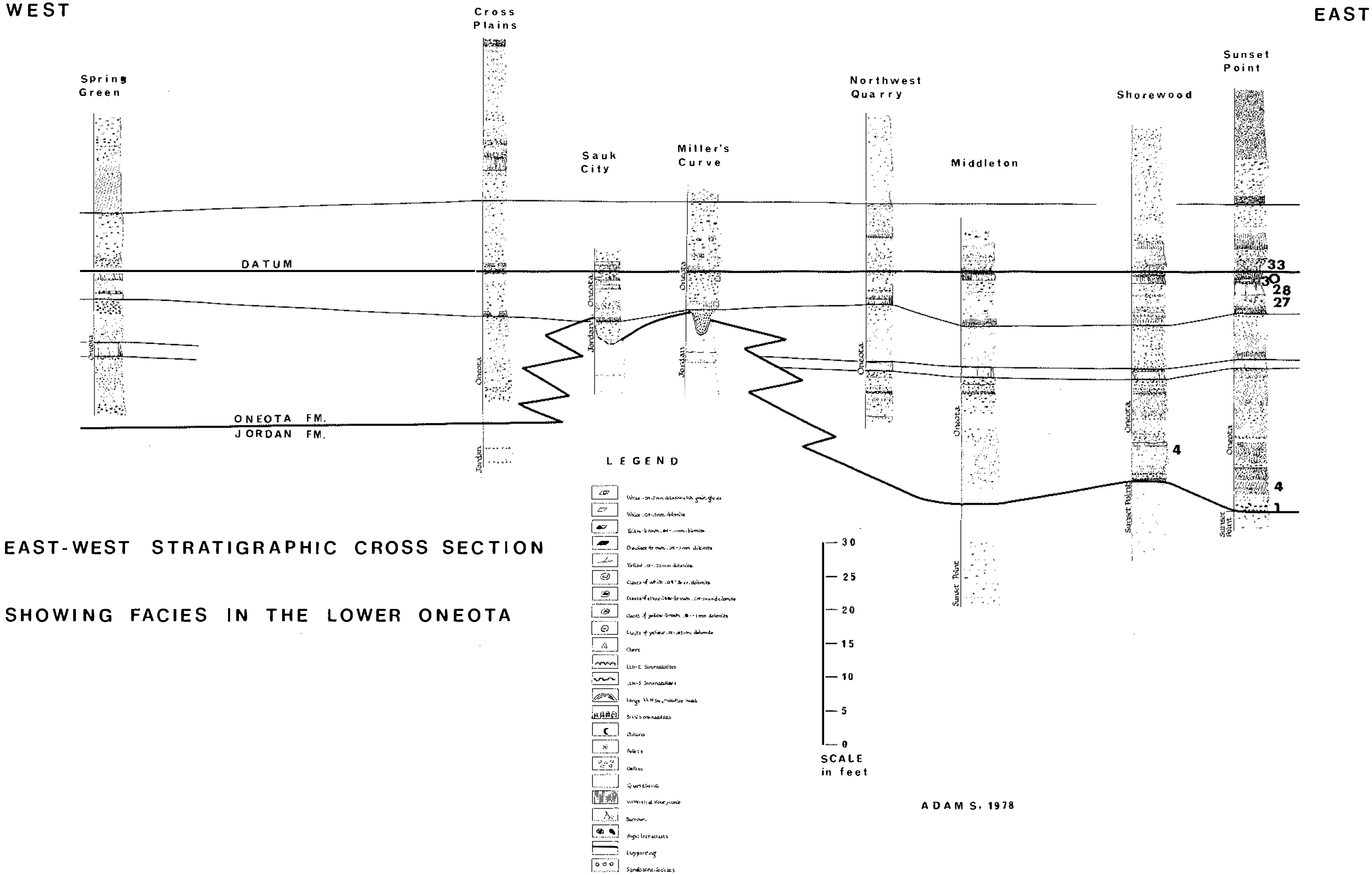

Figure 33 East-west stratigraphic cross section showing facies in the lower Oneota.

dolomite set in a finer background of smaller dolomite grains and clasts. Within the large clasts, pores similar to evaporite crystal shapes give the clue to the origin of the breccias.

The Sunset Point section (outcrop 1) is a good example of this sequence. From the base of the section up to bed SP-1 (Fig. 33) is Jordan Sandstone. SP-4 through SP-27 (Fig. 33) is mostly oolite with two minor VH to stromatolite transitions. SP-28 to SP-30 is mostly VH and SP-31 to SP-32 is large LLH-C stromatolites. SP-33 (Fig. 33) contains minor evaporite molds.

These data suggest deposition in shallow subtidal agitated marine waters that ranged in salinity from near normal marine to hypersaline. Evidence of evaporite deposition indicates an arid to semi-arid climate. A ring of islands was present to the present-day north from the Madison area (Figs. 34 and 22). Data from Dalziel and Dott (1970) suggest that the Baraboo hills which are currently almost due north of Madison were almost due East of Madison during Jordan deposition. The Baraboo hills were inferred to be at about 10° south latitude and the prevailing winds were from the east. In present day directions that means winds blowing from the Baraboo hills toward Madison with a very rocky agitated coast line around the Baraboo hills. After the bulk of oolite deposition had taken place the depositional surface was very nearly flat. The formation and coalescence of islands on the very shallow bottom made the concept of distance from shoreline meaningless in the lower Oneota. Islands were present as a response to local hydrodynamic parameters, and the channels present attest to the effects of storms on bottom topography. Burrowing organisms disrupted the laminated supratidal sediments in some areas (Cross Plains section - Outcrop 5).

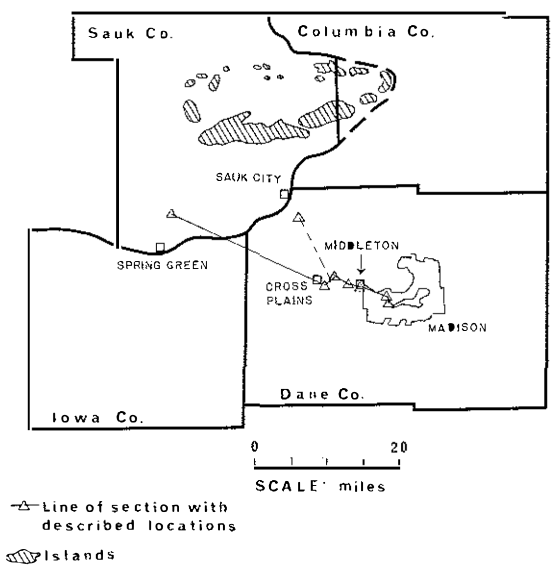

Figure 34 Location map showing the line of section in Figure 33 with described sections and Baraboo hills.

Logan (1961) described algal stromatolites from Shark Bay, Australia that compare favorably with those in the lower Oneota. Large club-shaped columnal stromatolites (SH) act as a breakwater to protect domed structures mixed with flat mat sediments. These types of stromatolites are found together in the lower Oneota. Logan (op cit) claims that tropical to subtropical temperatures are necessary for interstitial aragonite precipitation to cement the algal masses into a wave-resistant "reef".

SUMMARY

A study of facies in the lower Oneota suggests that sand and carbonate deposition took place simultaneously in the Dane County area. Sand deposition was still taking place near Sauk City and between Cross Plains and Middleton while only a few miles east and west carbonate deposition had already commenced. Those carbonate facies include the dolomitized equivalents of mudstones, wackestones, packstones, grainstones, and boundstones.

Grain types observed in the mechanically deposited carbonates include ooliths, pellets, intraclasts and quartz sand grains. The ooliths and quartz sand grains are the most common and are most often seen in the grainstones while the pellets and intraclasts are more common in the lower energy packstones and wackestones. Quartz sand grains are common centers for the ooliths. Most intraclasts are composed of pieces of algal stromatolite or of micrite. Boundstones include large laterally-linked hemispheriods (partly silicified), mats of small laterally linked hemispheroids, stacked hemispheroids, and a peculiar rock type inferred to be an algal boundstone herein called "vertical honeycomb".

Vertical honeycomb is a field name for a laterally correlatable, vuggy, porous, crumbly dolomite in the lower Oneota. It is composed of porous columns 1-3 cm in diameter alternating with less porous intercolumnal areas. This rock type forms beds six inches to two feet thick with sharp bases and sharp to gradational upper surfaces. Vertical honeycomb is found laterally and vertically associated with LLH and SH stromatolites, oolites, breccias, and conglomerate beds. It is inferred to be an algal skeletal or stromatolitic development. The facies sequences indicate a regressive pattern upward from littoral sand bar(s) to intertidal algal stromatolites and supratidal evaporites and laminated dolomites. Sand grains present in the lower Oneota as thin sandstone beds and disseminated quartz grains are ascribed to lateral transport away from this sand bar(s) between Middleton and Cross Plains. Time lines would go through this sand bar(s) and correlate with facies bands in the laterally equivalent carbonates.

Because of the lithologic similarity of the section studied with the overlying pure dolomites in the Madison area it is the author's opinion that the sandy dolomites and dolomitic sandstones of the lower Oneota should remain a part of the Oneota. However, this study has been limited to the Madison area and this opinion does not reflect data from the rest of the outcrop area of the Jordan and Oneota.

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Dr. Lloyd Pray originally brought to my attention the need for study on the Oneota and guided the study. Dr. R. H. Dott, Jr., Dr. C. W. Byers, and Dr. M. E. Ostrom all gave freely of their time and thoughts to aid in the completion of the thesis.

Exxon Company, U.S.A. gave assistance with the drafting and typing of the paper and permission for its publication.

LITHOSTRATIGRAPHY AND SEDIMENTOLOGY OF THE LONE ROCK AND MAZOMANIE FORMATIONS, UPPER MISSISSIPPI VALLEY

by

I. Edgar Odom*

INTRODUCTION

The following synthesis of the lithostratigraphy and sedimentology of the Lone Rock and Mazomanie Formations is based largely on published stratigraphic studies by Berg (1954), Ostrom (1966, 1967), Lockman-Balk (1970), and previously unpublished stratigraphic and petrologic studies by the author. Numerous contributions by other investigators must be omitted for the sake of brevity, however, an excellent bibliography of the literature prior to 1966 is provided by Ostrom.

Essentially the identical stratigraphic sequence that is now divided into the Lone Rock and Mazomanie Formation by the Wisconsin Geological and Natural History Survey was called the Franconia Formation before 1966. Berg divided the Franconia Formation into four lithic members (Birkmose, Tomah, Reno, and Mazomanie). In addition he included in the Franconia the poorly sorted sandstone usually occurring below the Birkmose Member, now called the Ironton Sandstone, and renamed it the Woodhill Member.

Ostrom (1966) suggested that because the name Franconia had come to be used for nonequivalent lithostratigraphic and biostratigraphic units it should be abandoned. He proposed to group Berg's Birkmose, Tomah, and Reno members in a new formation which he named the Lone Rock, to raise the Mazomanie to formational rank due to its thickness and extensive distribution, and to reinstate the term Ironton in place of Woodhill since the former name had precedence. Based on lithic similarities and stratigraphic relations, Ostrom assigned the Ironton and underlying Galesville Sandstones member status and named them the Wonewoc Formation. Although locally quite thin, the Ironton Member of the Wonewoc Formation underlies the Lone Rock and Mazomanie Formations in the field conference area.

According to present usage, the Lone Rock and Mazomanie Formations constitute the Tunnel City Group of the Late Cambrian St. Croixan Series. This group consists of three major lithologies (facies): (1) glauconitic, dolomitic, feldspathic (10-25%), fine-to very fine-grained sandstone, (2) shaly, micaceous, highly feldspathic (25-60%), very fine-grained sandstone, and (3) nonglauconitic (<5%), locally dolomitic, feldspathic to quartzose, fine- to coarse-grained sandstone. These lithologies (facies) occur in an intertonguing relationship (Fig. 35). Within the field conference area, there are numerous outcrops that show the intertonguing of the glauconitic sandstone facies with the nonglauconitic sandstone facies, however, the major area where the glauconitic sandstone facies intertongues with the shaly sandstone facies is confined to the subsurface of southern Minnesota and central Iowa (Fig. 35).

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LITHIC CHARACTERISTICS

In western Wisconsin and eastern Minnesota, the Lone Rock Formation contains three lithic members which can be traced over thousands of square miles (Fig. 35). The basal Birkmose Member consists of glauconitic sandstone, sandy dolostone, and flat pebble conglomerate. In the field conference area this member is thin and is mostly sandy dolostone and conglomerate (Outcrop 9). The succeeding Tomah Member represents the shaly sandstone facies and is composed of thin beds of very fine-grained, highly feldspathic (Odom, 1975), micaceous sandstone with shale interbeds (Outcrop 9). The lithic nature of the Tomah Member is remarkably uniform throughout western Wisconsin and eastern Minnesota. The Reno Member of the Lone Rock Formation is similar to the Birkmose Member in that it consists of glauconitic, dolomitic, feldspathic, fine- to very fine-grained sandstone and flat pebble conglomerate, but it contains much less sandy dolostone. In western Wisconsin, the Reno lithology, which is more than 30 meters in thickness, composes most of the Lone Rock Formation (Fig. 35).

Sedimentary structures characteristic of the Lone Rock Formation include low angle trough and some planar types of cross bedding, symmetrical and asymmetrical ripple marks, current lineations, and dessication (mud?) cracks. Burrows and tracks constitute the primary trace fossils. Tribolite carapaces are most common in the Tomah member.

Of special sedimentological interest are beds of massive, argillaceous, glauconitic, burrowed sandstone which are common in the Birkmose and Reno Members. These beds, which range from a few centimeters up to 4 meters in thickness, have previously been called "wormstone". The upper tongue of the Reno Member in the Lone Rock section (Outcrop 9) is a typical example of a "wormstone" bed. The absence of stratification has previously been attributed to bioturbation. Although burrows are prominent, these beds also contain large randomly oriented shale fragments, whose presence casts suspicion on bioturbation as the sole cause of the massive structure. Another possible cause for the lack of stratification is soft sediment deformation. This deformation possibly occurred during early compaction and dewatering because the very argillaceous, fine sand probably had a very high initial water content.

The Mazomanie Formation consists of nonglauconitic, very fine- to medium-grained, feldspathic and quartzose sandstone and sandy dolostone. Sandy dolostone is especially abundant in the Mazomanie immediately south of the Baraboo Syncline, suggesting that the emergent Baraboo Islands (See papers by Dott, and Odom and Ostrom - this guidebook) influenced sand transport in this area. Some sandy dolostone beds are reddish due primarily to hematite stain from glauconite alteration.

Locally the Mazomanie contains abundant inclined and straight burrows (Skolithos) and low to rather high angle trough and planar-types of cross bedding (Outcrop 7). Intraclasts are common in some dolomitic units.

STRATIGRAPHY

Figure 35 shows the regional stratigraphy of the Lone Rock and Mazomanie Formations as presently understood. It is apparent that in central Wisconsin the Mazomanie Formation is limited in geographic distribution to the vicinity of the Wisconsin Arch and that it intertongues to the west, south and east with

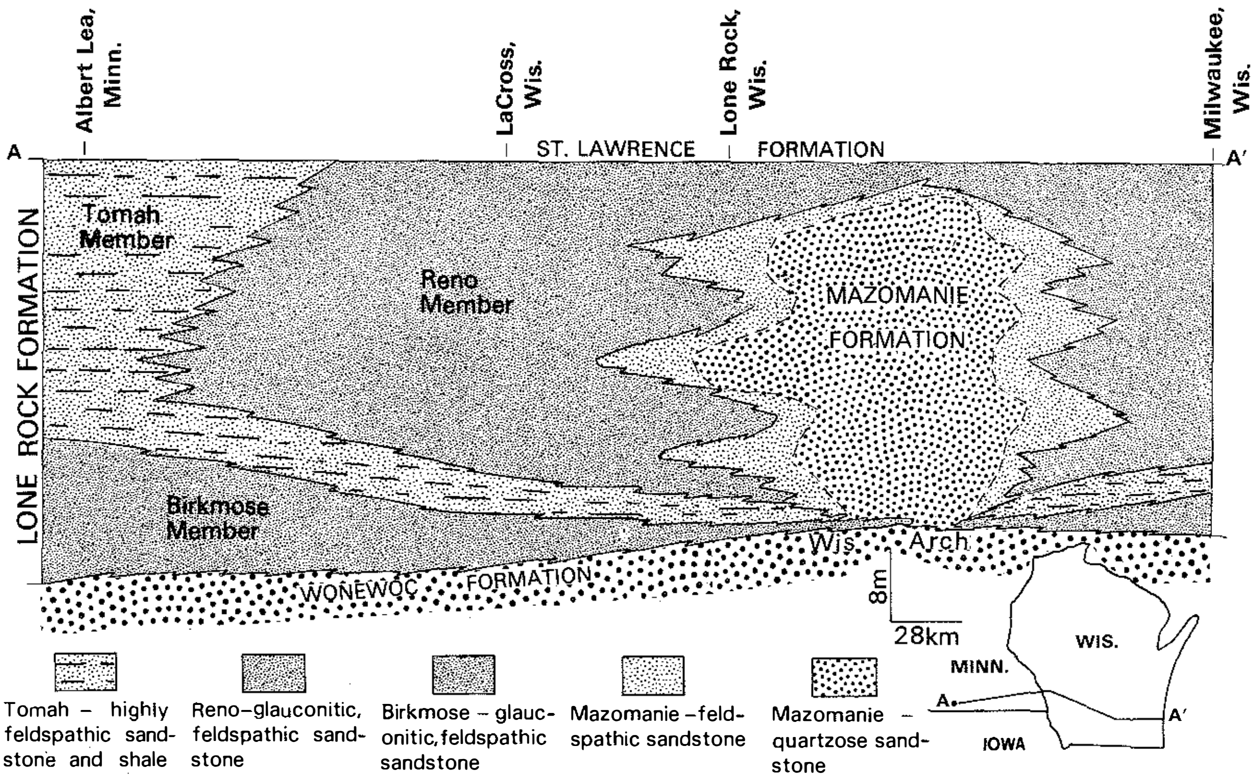


Figure 35 Lithostratigraphy and petrology of the Mazomanie and Lone Rock Formations in central and western Wisconsin and eastern Minnesota.

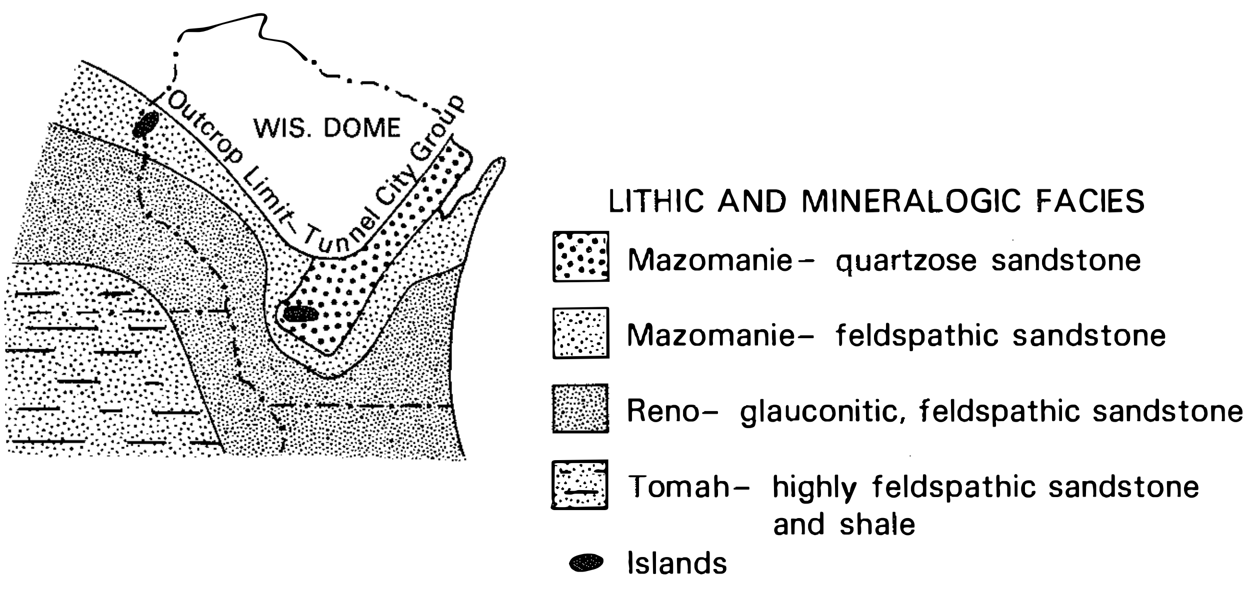


Figure 36 Lithic and petrologic facies of the Mazomanie and Lone Rock Formations, Upper Mississippi Valley.

members of the Lone Rock Formation, especially the Reno Member. In the subsurface near Madison, Wisconsin, the Mazomanie rests on the Wonewoc Formation (Ostrom, 1970, p. 28), but it is usually enclosed by the Lone Rock. In the outcrop area west of Madison, such as at Ferry Bluff on the Wisconsin River north of Mazomanie, Wisconsin, the Mazomanie Formation, which is 36 meters in thickness, overlies the Birkmose Member and is in turn overlain by the Reno Member. In the School House Bluff exposure (Outcrop 7) at the town of Mazomanie, the base of the Mazomanie Formation is not exposed, but it is overlain by more than 4.5 meters of the Reno Member. At Lone Rock, Wisconsin (Outcrop 9), the Reno Member overlies the Tomah Member, above which there is an alternating sequence of Reno and Mazomanie lithologies. Thin tongues of the Mazomanie are known to extend westward to beyond Richland Center, Wisconsin.

The regional textural and mineralogical characteristics of the Mazomanie Formation are of considerable sedimentological significance. Over the crest of the Wisconsin Arch, the Mazomanie consists of fine- to course-grained, quartzose sandstones and sandy dolostones (Outcrop 7), however, toward the west it becomes fine- to very fine-grained and feldspathic (Fig. 35 and Outcrop 9). Farther west, the feldspathic Mazomanie sandstones are entirely replaced by the glauconitic, feldspathic sandstones of the Reno Member (Lone Rock Formation, Fig. 35 and 36).

In western Wisconsin, where the three members of the Lone Rock Formation are best developed, the Birkmose Member is 6-7 meters in thickness, but it thickens to as much as 14 meters in the subsurface of southern Minnesota. The The Tomah Member in central and western Wisconsin ranges from 3 to 8 meters in thickness, but in southern Minnesota and northcentral Iowa it completely replaces the Reno Member and is more than 30 meters in thickness (Fig. 35). Regional studies by the author show that the thickest development of the glauconitic Reno Member is confined to an arcuate band extending from central Minnesota through western Wisconsin and extreme northeastern Iowa into northern Illinois thence northward into eastern Wisconsin (Fig. 36). Farther to the south in central Illinois and northern Missouri, the Tomah Member facies into shale and dolomite called the Davis Formation.

SEDIMENTOLOGY AND DEPOSITIONAL ENVIRONMENTS

The Lone Rock Formation is interpreted to represent part of an overall marine transgressive cycle of sedimentation possibly interrupted by a slight regression (middle part of Mazomanie Formation). The initial deposits of this transgression were the Galesville and Ironton Sandstones of the Wonewoc Formation. The lithic and sedimentary characteristics and mineralogic maturity of Wonewoc Sandstones demonstrate that they were deposited under vigorous hydrologic conditions characteristic of a beach and near-shore (littoral) depositional environment. This littoral environment slowly transgressed northward over the Upper Mississippi Valley, and as this transgression occurred more off-shore lithotopes representing less vigorous yet still quite shallow environments (very shallow inner neritic) then migrated into central Minnesota and western and central Wisconsin. Fine and very fine sand, glauconite, and locally sandy carbonate mud first accumulated in this environment to form the Birkmose Member of the Lone Rock Formation. The presence of abundant cross stratification, ripple marks, and intraclasts provide evidence that the environment of Birkmose deposition was sufficiently shallow for currents and storm waves to scour the bottom, and local areas may have been temporarily emergent. The abundance of glauconite also indicates that the Eh in local areas ranged from slightly reducing to only slightly oxidizing. The glauconite is considered by this author to be a crystallization product, nucleated by and around decaying organic material after which it grew to form silt and sand size pellets (See Odom's paper on mineralogy, this guidebook). The pellet growth process was rapid because the pellets were transported by currents and locally formed lag deposits in the same manner that heavy minerals are concentrated.

The Birkmose lithotope also migrated slowly northward over most of the Upper Mississippi Valley, except for local areas along the axis of the Wisconsin Arch where initial deposits of the Mazomanie Formation had begun to accumulate. As transgression continued, yet another somewhat lower energy lithotope migrated into central Minnesota and central and western Wisconsin. This lithotope was characterized by the deposition of very fine sand with shale interbeds (Tomah Member), and is considered to represent the most seaward environment that existed in western Wisconsin during the deposition of the Tunnel City Group. This environment was not as shallow as that of the Birkmose, but some cross bedding and ripple marks in the Tomah Sandstones indicate weak current activity.

The shaly sandstone (Tomah) lithotope was displaced southward by a eustatic sea level change before any great thickness accumulated in central and western Wisconsin. This regressive pulse caused glauconitic, fine- and very fine-grained sand (Reno Member) to again be deposited primarily in an arcuate band as shown in Figure 36. On the shoreward side of this zone of glauconitic sand deposition, the Mazomanie Sandstone accumulated, whereas to the southwest the Tomah Sandstone and Shale continued to be deposited (Fig. 36).

In central Wisconsin the physical environment of Mazomanie Sandstone deposition was dominantly a shoal area situated along the trend of the Wisconsin Arch. The fact that the Mazomanie varies from fine- to coarse-grained, quartzose sandstone over the crest of the arch to very fine-grained, feldspathic sandstone laterally shows that a strong hydrologic gradient existed across this shoal. This regional variation in mineralogy illustrates the role that environmental energy may have on the selective abrasion, the hydrologic sorting, and the eventual concentration of feldspar in very fine-grained sandstones. It also illustrates that mineralogically mature or immature sandstones may be a product of environmental processes rather than solely related to the mineralogy of the source sediments. This relation has recently been documented in sandstones of other ages (Odom, Doe and Dott, 1976), even some modern sands (Field and Pilkey, 1969). Although some osciliation of lithotopes is apparent from the intertonguing of the Mazomanie Formation with the Reno Member and the Reno Member with the Tomah Member, the spacial distribution of the Mazomanie, Reno and Tomah lithotopes remained remarkably stationary for a long duration considering that deposition was undoubtedly slow.

Near the close of the Franconian Stage, northward migration of the Reno (glauconitic sandstone) lithotope terminated deposition of the Mazomanie along the axis of the Wisconsin Arch. In all complete sections the author has seen located on the crest of the arch, the Reno Member overlies the Mazomanie Formation. In central Wisconsin and in the Mississippi and St. Croix River Valleys, the Reno glauconitic sandstone was superseded by deposition of fine sand and silt inter-bedded with shale and dolostone that is stratigraphically assigned to the St. Lawrence Formation. The siltstones and very fine-grained sandstones in the St. Lawrence show many attributes of the Tomah Member.

Lochman-Balk (1970) proposed that the Tomah and perhaps other members of the Lone Rock Formation were deposited in tidal-dominated environments. During the decade that the author and his students have investigated the mineralogical and lithic characteristics of Upper Mississippi Valley Cambrian sediments, careful attention has been given to collection of stratigraphic and physical evidence necessary for environmental interpretations. Although local evidence exists for some tidal activity, as indeed should be the case in shallow epeiric seas, the regional lithic characteristics and the spacial distribution of time equivalent lithic units deposited during the Franconian Stage do not support the presence of tidal environments 900 by 600 km that would be necessary to validate the Lockman-Balk model or the model proposed by Byers (this guidebook). The broad development of lithic units and most internal sedimentary structures, including trace fossils, indicate that these Cambrian sediments were deposited in littoral, shoreface, and shallow inner neritic environments. The writer believes that because of a low paleoslope and the presence of an off-shore carbonate platform, tidal activity in the northern Upper Mississippi Valley was confined largely to the beach and near-shore littoral environment (see paper by Odom and Ostrom, this guidebook). The flat pebble conglomerates that occur sporatically in the Birkmose and Reno Members have been the most commonly cited evidence for tidal current activity. Many of these conglomerates constitute single beds of relatively uniform thickness over many square miles. They were more likely formed by tropical storms at times of low tide rather than by tidal currents.

SUMMARY

The regional lithic characteristics and stratigraphic relations of the Lone Rock and Mazomanie Formations appear to indicate a special distribution of environments ranging from beach and near-shore (littoral) to shallow inner neritic. The Mazomanie Formation represents the littoral facies. The southward extension of the Mazomanie in central Wisconsin marks the location of a shoal paralleling the axis of the Wisconsin Arch. The Birkmose and Reno Members of the Lone Rock Formation accumulated immediately seaward of the littoral zone where slow deposition, organic material and favorable Eh conditions permitted the development of abundant glauconite. Still further seaward in a shallow inner neritic environment, very fine sand and shale accumulated to form the Tomah Member of the Lone Rock Formation. The fine and very fine-grained sandstones of the Mazomanie Formation and the Reno, Tomah, and Birkmose Members of the Lone Rock Formation were enriched in feldspar through the abrasion and sorting of this mineral from littoral environments.

Acknowledgement: Mineralogical studies of Cambrian sediments supported by Earth Sciences Section, National Science Foundation (Grant ERA 75-1748).

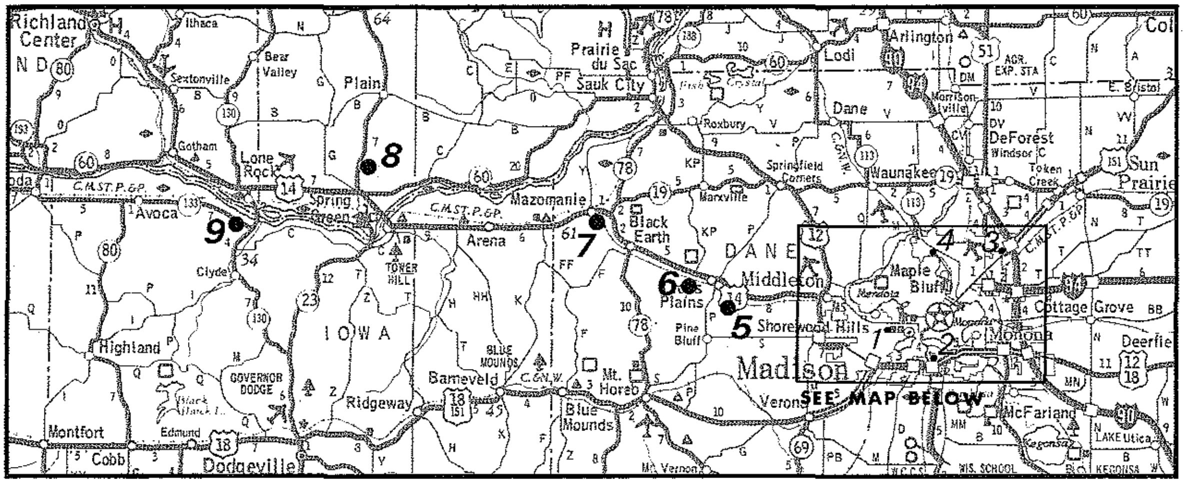


Figure 37. Regional map showing location of Outcrops.

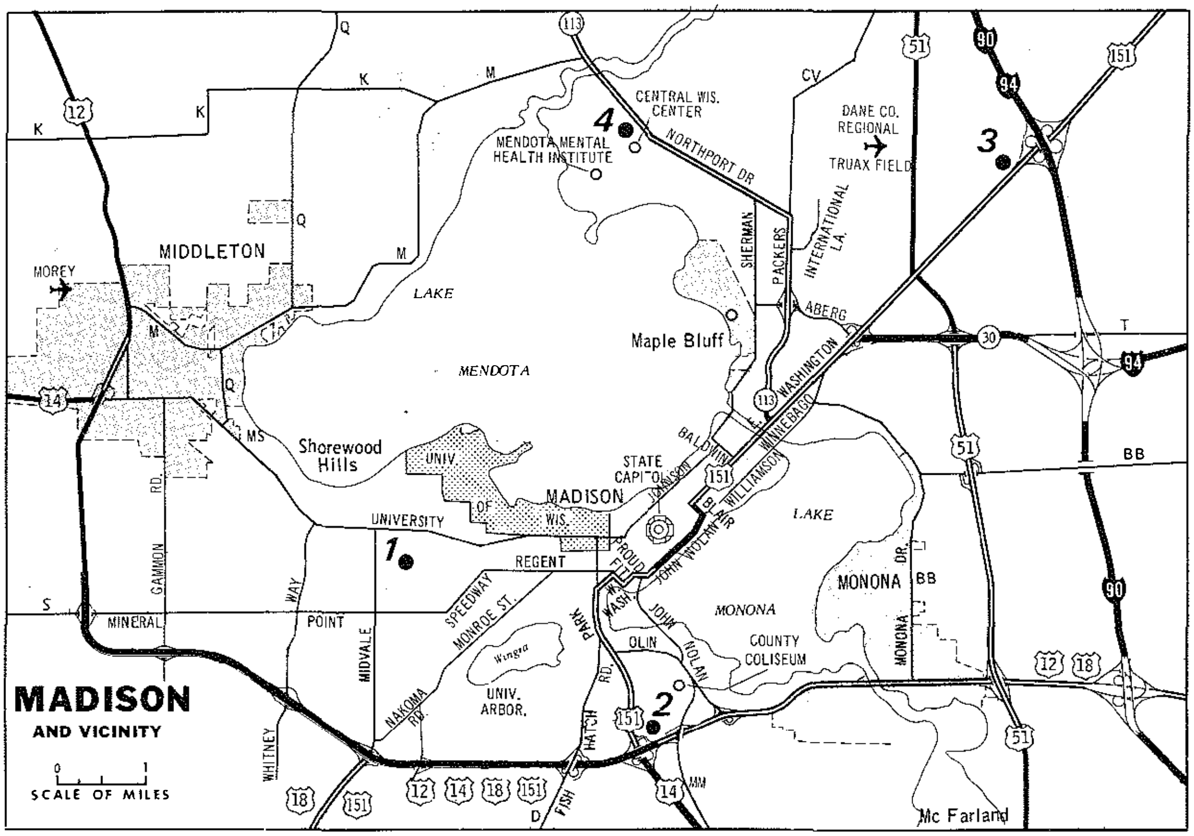


Figure 38. Generalized Madison city map showing location of Outcrop numbers 1 through 4.

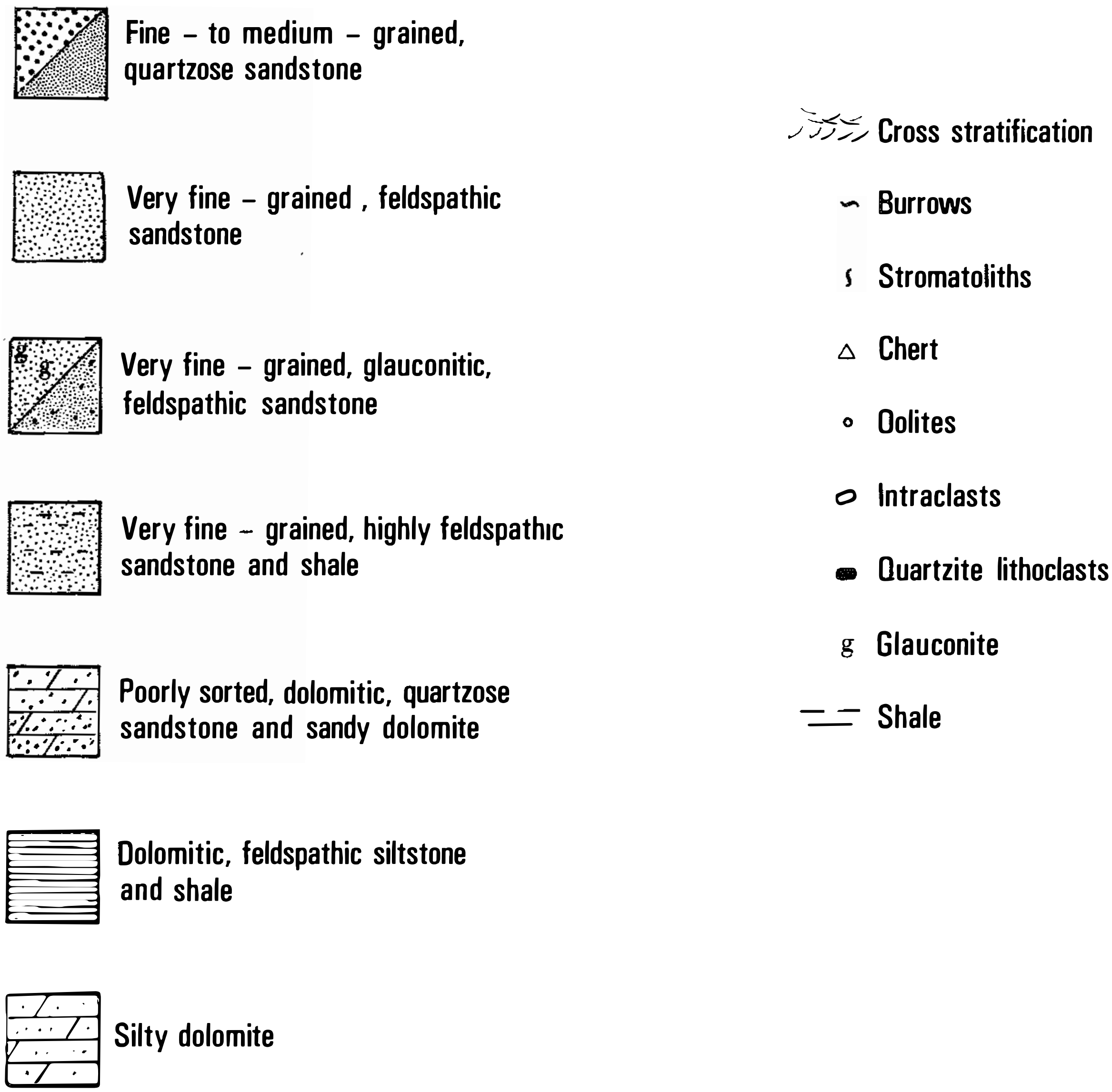


Figure 39. Index to lithologic symbols used in Outcrop descriptions.

OUTCROP 1

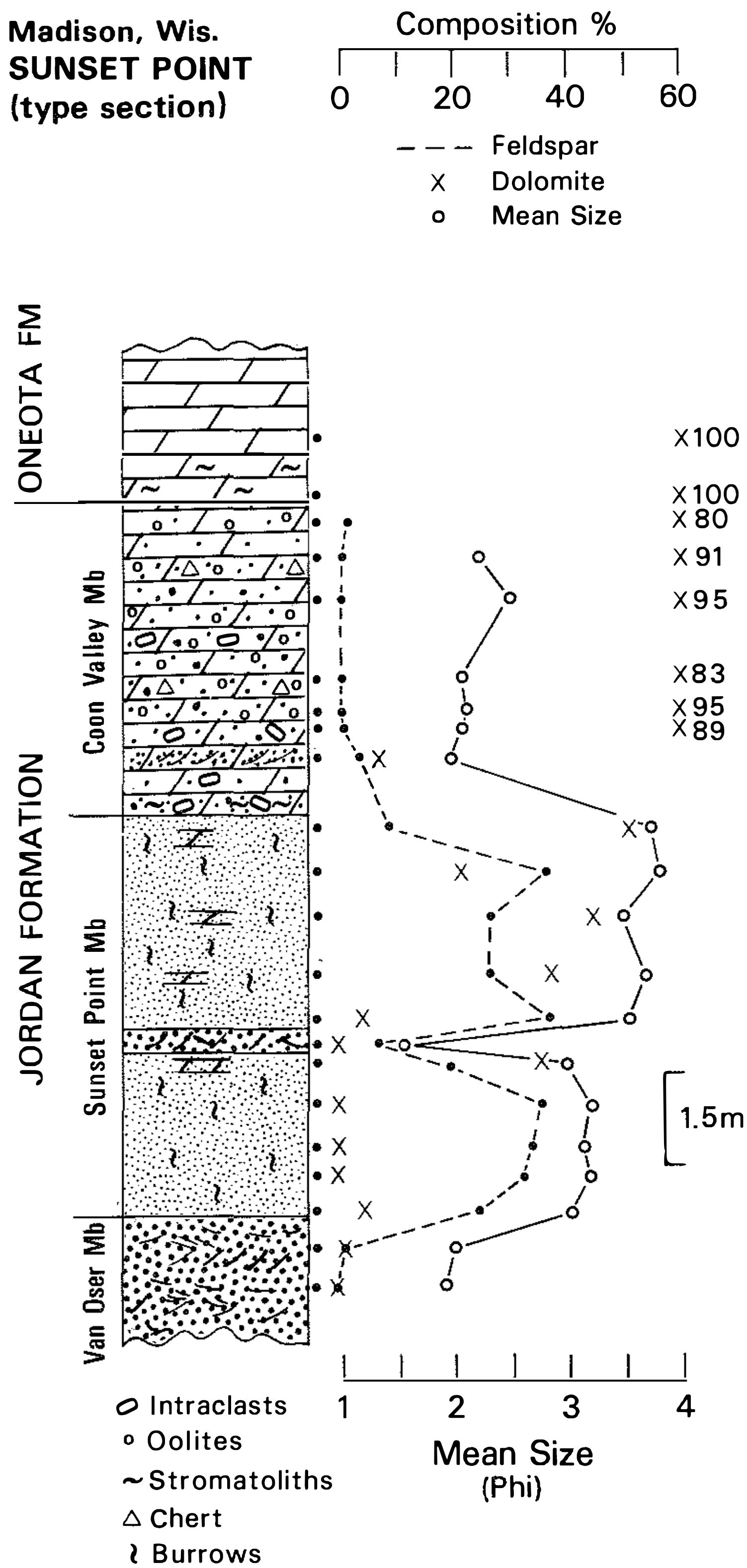
Title: Madison-Hoyt Park

Location: Near Intersection of Bluff Street and Du Rose Terrace, Madison, Wisconsin in the SE$\frac{1}{4}$,SE$\frac{1}{4}$, NE$\frac{1}{4}$, Sec. 20, T.7N., R.9E., Dane County (Madison West 7.5 minute topographic quadrangle, 1974).

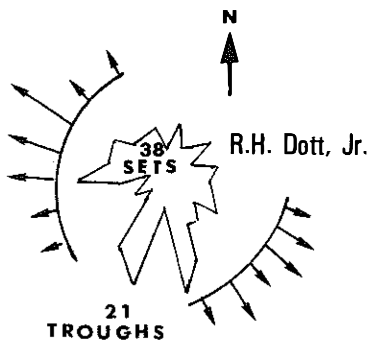
Author: I. E. Odom

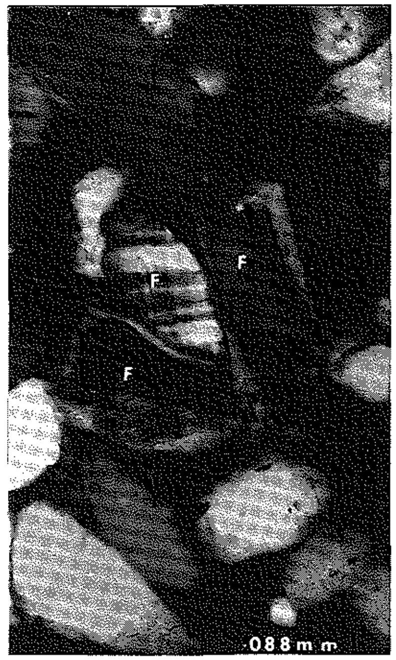
Description: The section above is a composite of exposures along Bluff Street and in an abandoned quarry just (above) south of the Bluff Street outcrop in Hoyt Park (do not tresspass on private property and please do not mutilate the outcrops). This is the type section of the Sunset Point Sandstone Member of the Jordan Formation as currently defined (formerly the Madison Sandstone). The upper part of the Sunset Point was first described by Irvin in 1875, however, the lower 3 meters and the underlying Van Oser Sandstone apparently were not exposed prior to about 1960.

The petrologic and textural data for the Sunset Point Member show that it is a highly feldspathic, very fine-grained sandstone. The upper part is thinly bedded and dolomitic and was previously quarried for building stone (used in several building on the UWM Campus). The lithology of the lower unit of the



Madison, Wis.
SUNSET POINT
(type section)
Composition %
0
20
40
60
Feldspar
X Dolomite
o Mean Size
ONEOTA FM
JORDAN FORMATION
Coon Valley Mb
Sunset Point Mb
Van Oser Mb
X100
X100
X 80
X 91
X95
X83
X95
X89
1.5m
1
2
3
4
Mean Size
(Phi)
Intraclasts
Oolites
Stromatoliths
Chert
Burrows





(Above) Current directional data, Sunset Point Member.

(Right) Authigenic and detrital feldspar (F) in lower unit of Sunset Point Sandstone.

Sunset Point differs from the upper unit only in that it is less dolomitic, more massive, and contains scattered medium size grains. The thin bed of cross-stratified, medium-grained, quartzose sandstone that separates the upper and lower units of the Sunset Point Sandstone varies in thickness over the full outcrop from a few centimeters up to .3 meters. Ostrom (1964) reported a thin quartz granule "conglomerate" in the base of the upper Sunset Point unit. The contact of the Sunset Point Sandstone with the overlying Coon Valley Member was thought by Ulrich (1924) to be a major uncomformity separating the Cambrian from his Ozarkian System.

Note the pinkish color of several of the massive beds of the Sunset Point Sandstone. This color is a reflection of their high K-feldspar content. Both units of the Sunset Point Sandstone are bioturbated and contain burrows and other trace fossils. The walls of buildings on the UWM Campus constructed of this stone are an excellent place to study the trace fossils. Fossils collected from the Sunset Point Member by G. O. Raasch are identified as Cambrian in age and include Tellurina and Saukia. Skolithos burrows are common in the lower unit, whereas a Cruizana assemblage dominates the upper unit.

At the base of the Sunset Point Sandstone is a fine- to medium-grained, quartzose sandstone assigned to the Van Oser Member. A much greater thickness of the Van Oser was at one time exposed at the intersection of Bluff Street and Du Rose Terrace.

The upper beds of the Sunset Point Sandstone and the Coon Valley Member are exposed in the abandoned quarry. The Coon Valley Member consists of 5 meters of dolomitic, conglomeratic sandstones and sandy, oolitic dolostones (see paper by Adams, this guidebook), the base of which contains a prominent bed of very sandy, conglomeratic, algal dolostone. The Coon Valley Member is in turn overlain by nonsandy algal and oolitic dolostones, the lower portion of which locally weathers with a honeycomb appearance, that are assigned to the Oneota Formation. Many more meters of the Oneota are exposed elsewhere in Hoyt Park.

To fully comprehend the stratigraphic sequences in subsequent outcrops to be examined, it is necessary to thoroughly study the lithic characteristics of the Sunset Point and Coon Valley Members of the Jordan and the basal beds of the Oneota Formation at these outcrops. The lithic nature of the Van Oser Sandstone can better be observed at Outcrop 2. Also, more accessible exposures of the Oneota are present at Outcrops 5 and 6.

Interpretations: The Sunset Point Sandstone is believed to be a local lithic unit that is time-stratigraphically equivalent to part of the Van Oser Member rather than being younger than the Van Oser as was previously thought (Odom and Ostrom, this guidebook). The Sunset Point can be traced northward in a narrow belt to near Dane, Wisconsin, a distance of about 15 miles. It can be shown to grade laterally toward the west into fine- to medium-grained, quartzose sandstones of the Van Oser Member, and it also disappears laterally in all other directions. Also, at Outcrop 4 the Sunset Point Member is overlain by the Van Oser Member.

Based on its lithic properties, sedimentary structures, and stratigraphic and geographic patterns of occurrence, the Sunset Point Sandstone is interpreted to represent a lagoonal environment. It is envisioned that this local lagoon was situated between the Cross Plains and East Madison Bar complexes and leeward of the Baraboo Islands (Fig. 22). The medium-grained sandstone that separates the upper and lower units of the Sunset Point Member is believed to be a washover fan from a nearby Van Oser bar caused by one or more storms. A part of the East Madison Bar complex was located as close as 5 km to the southeast. Note the bimodal distribution of current direction indicators.

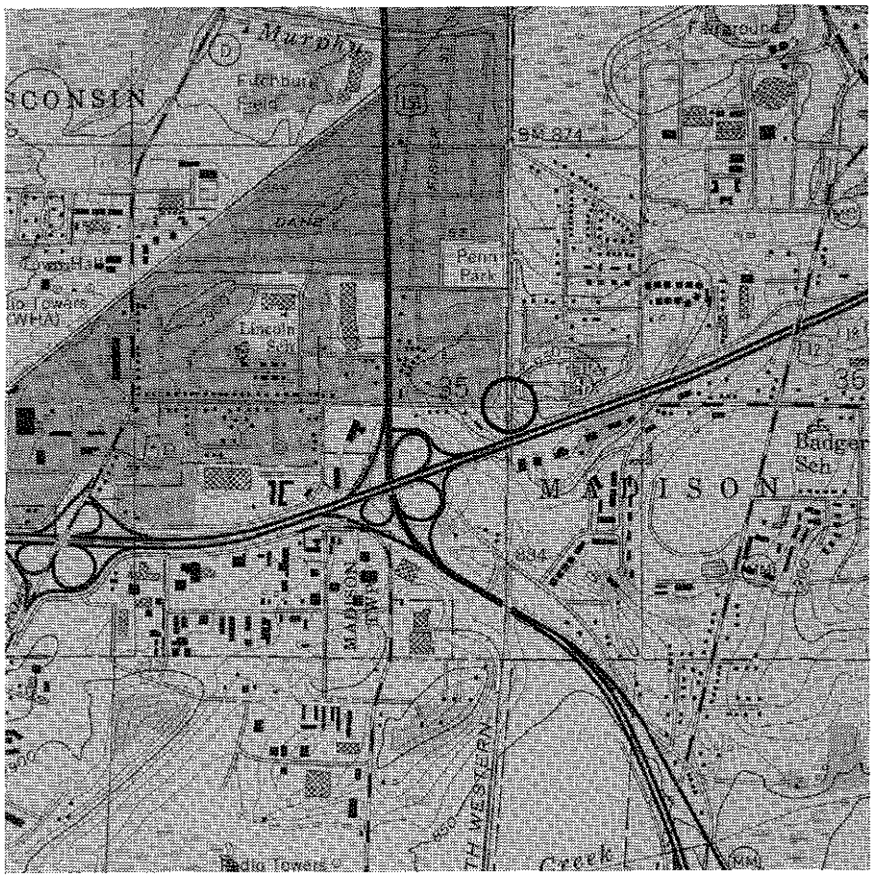
Although the Sunset Point Sandstone is overlain here and at the Shorewood Quarry, one mile north, by the Coon Valley Member, at Outcrop 4 it is overlain by the Van Oser Member. These stratigraphic relations and the fact that the Sunset Point disappears laterally in all directions are the primary evidences for the interpretation that the Sunset Point is a local facies and time-stratigraphically equivalent to the Van Oser Member.

The lithic characteristics of the lower portion of the Coon Valley Member suggest deposition primarily in littoral and shallow carbonate shelf (subtidal) environments with strong wave and current activities. Adams (this guidebook) concludes that the upper part of the Coon Valley Member was deposited in an intertidal environment that slowly changed to a supratidal, hypersaline environment (Oneota Formation). It is possible that the upper Coon Valley represents coalescing sandy oolite shoals resulting from the interplay between storm-generated and tidal currents around small algal mounds, however, I am suspect that some (perhaps most) of the oolites may be vadose in origin.

Outcrop 2

Title: Madison - Penn Park

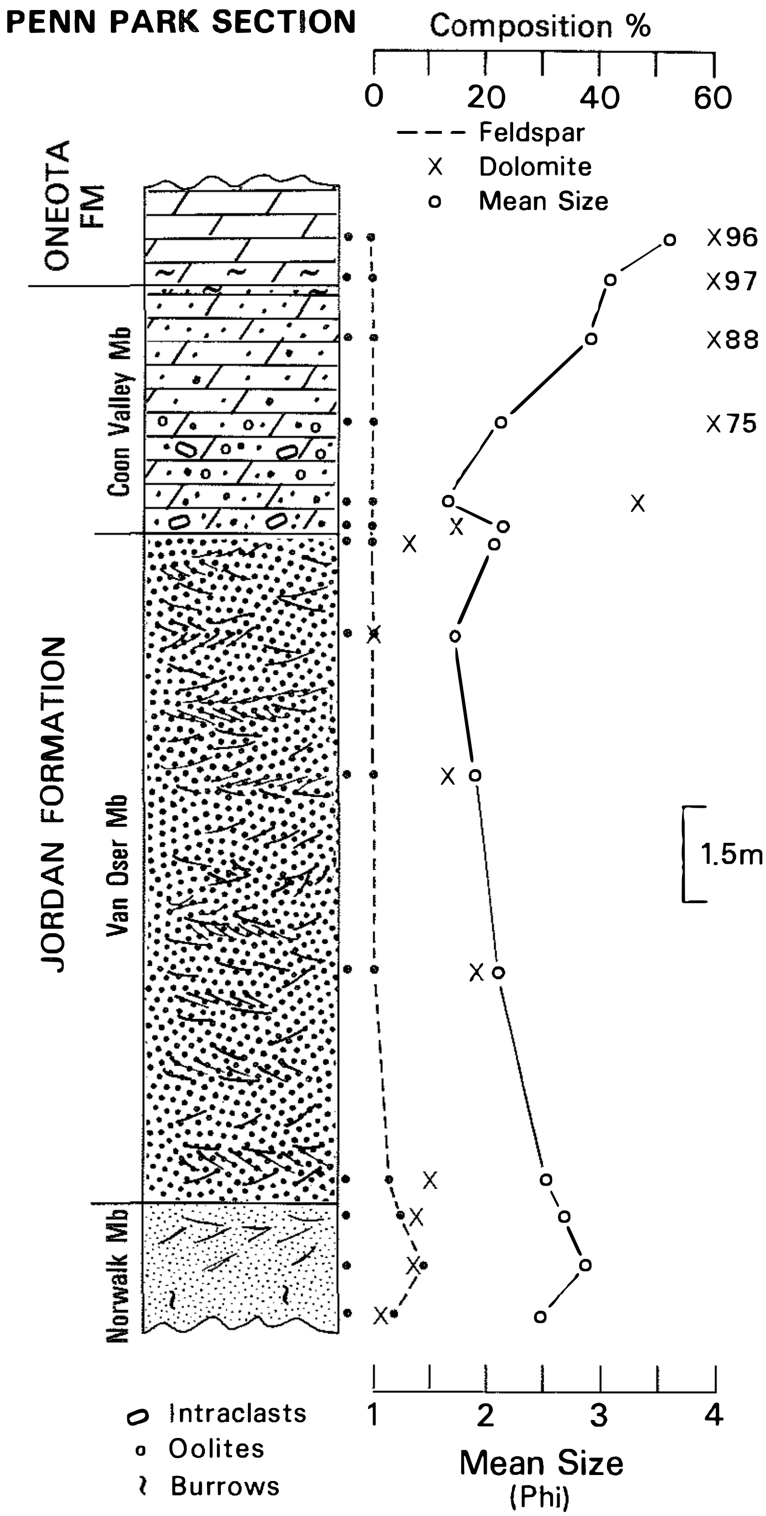
Location: Chicago and Northwestern Riilroad Cut at Badger Road east and south of Penn Park in the SE corner, SW$\frac{1}{4}$, NE$\frac{1}{4}$, Sec. 35, T. 7N., R. 9E., Dane County. (Madison West 7.5-minute topographic quadrangle, 1974).



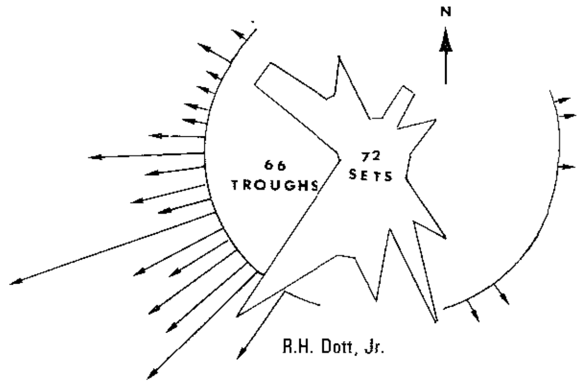
Author: I. E. Odom

Description: This outcrop of the Jordan Formation is very significant because no sandstones characteristic of the Sunset Point Member are present, yet the outcrop is just 5.5 km (3.4 miles) southeast of the Sunset Point type section. The lower two meters of fine-grained, slightly feldspathic sandstone is assigned to the Norwalk Member because its texture and mineralogy are typical of beds that are frequently transitional between the Norwalk and Van Oser Members (Outcrop 3). According to Twenhofel, Raasch, and Thwaites (1935), the Lodi Siltstone was once exposed in this cut.

Note that the stratigraphic interval where the Sunset Point Sandstone might be expected to occur is entirely fine to medium-grained, highly cross-stratified sandstone (Van Oser) which coarsens upward. Although it contains dispersed



PENN PARK SECTION
Composition %
0
20
40
60
Feldspar
Dolomite
Mean Size
X96
X97
X88
X75
ONEOTA FM
JORDAN FORMATION
Coon Valley Mb
Van Oser Mb
Norwalk Mb
1.5m
Intraclasts
Oolites
Burrows
1
2
3
4
Mean Size
(Phi)



Paleocurrent directional data for the Van Oser Member.

dolomite crystals, the overall mineralogy, texture and structure of this sandstone unit (10.5 m) are very similar to the Van Oser Member exposed elsewhere in the Madison area.

The Van Oser Member is here overlain by "oolitic", sandy dolostones and dolomitic sandstones (Coon Valley Member) very similar to those overlying the Sunset Point at its type section, and the lower beds of the Oneota Dolostone supersede the Coon Valley. More accessible outcrops of the upper part of the Coon Valley Member and of the lower beds (algae) of Oneota Dolomite are present along Badger Road south of the bridge.

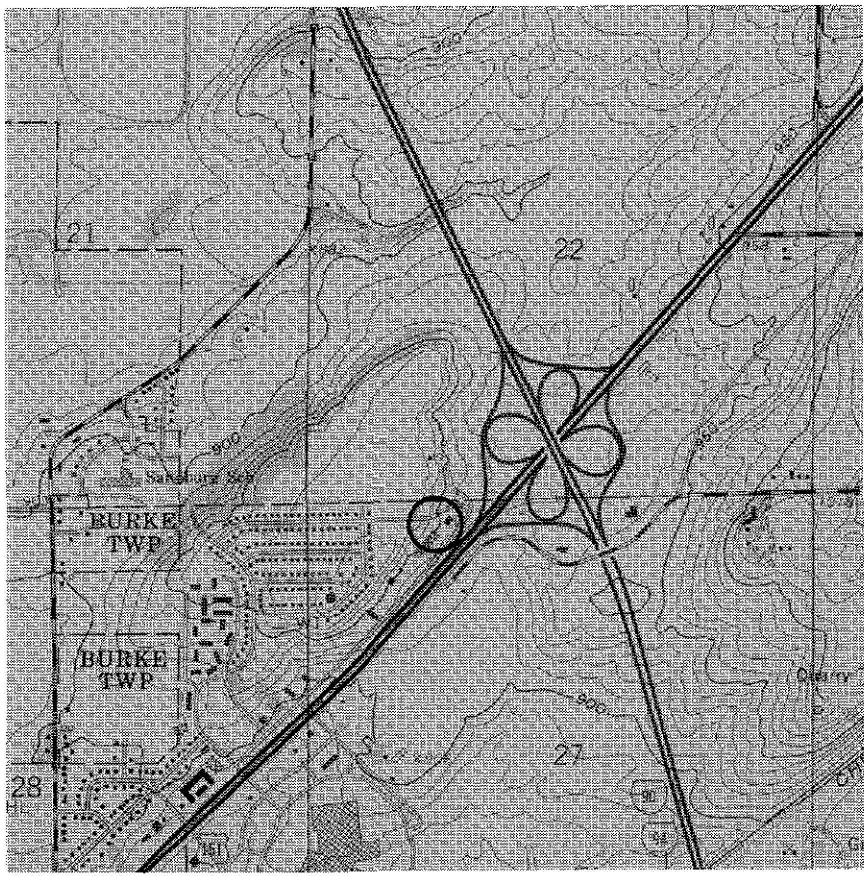
Interpretations: The Van Oser Sandstone at this locality is interpreted to be part of the East Madison Bar complex (Fig. 26), and the local lagoon in which the Sunset Point Sandstone was simultaneously being deposited was located to the northeast. The dominant current directions were to the south and west (Dott, 1977) in agreement with the proposed model that the Sunset Point lagoon was surrounded by Van Oser bars which egressed from the ends of the Baraboo Islands (Fig. 22).

The lithic characteristics of The Coon Valley Member again suggest that it was deposited in a dominantly subtidal carbonate shelf lithotope influenced by strong wave and current activities. The Oneota Dolostone contains the same types of algal structures as at Outcrop 1, which Adams (this guidebook) interprets to be indicative of a supratidal environment.

Outcrop 3

Title: Madison - Howard Johnson East

Location: Rear of Howard Johnson Motel near U.S. 151 and I-90 Interchange in the $NE\frac{1}{4}$, $NW\frac{1}{4}$, $NW\frac{1}{4}$, Sec. 27, T. 8N., R.10E., Dane County. (DeForest 7.5 topographic quadrangle, 1974).

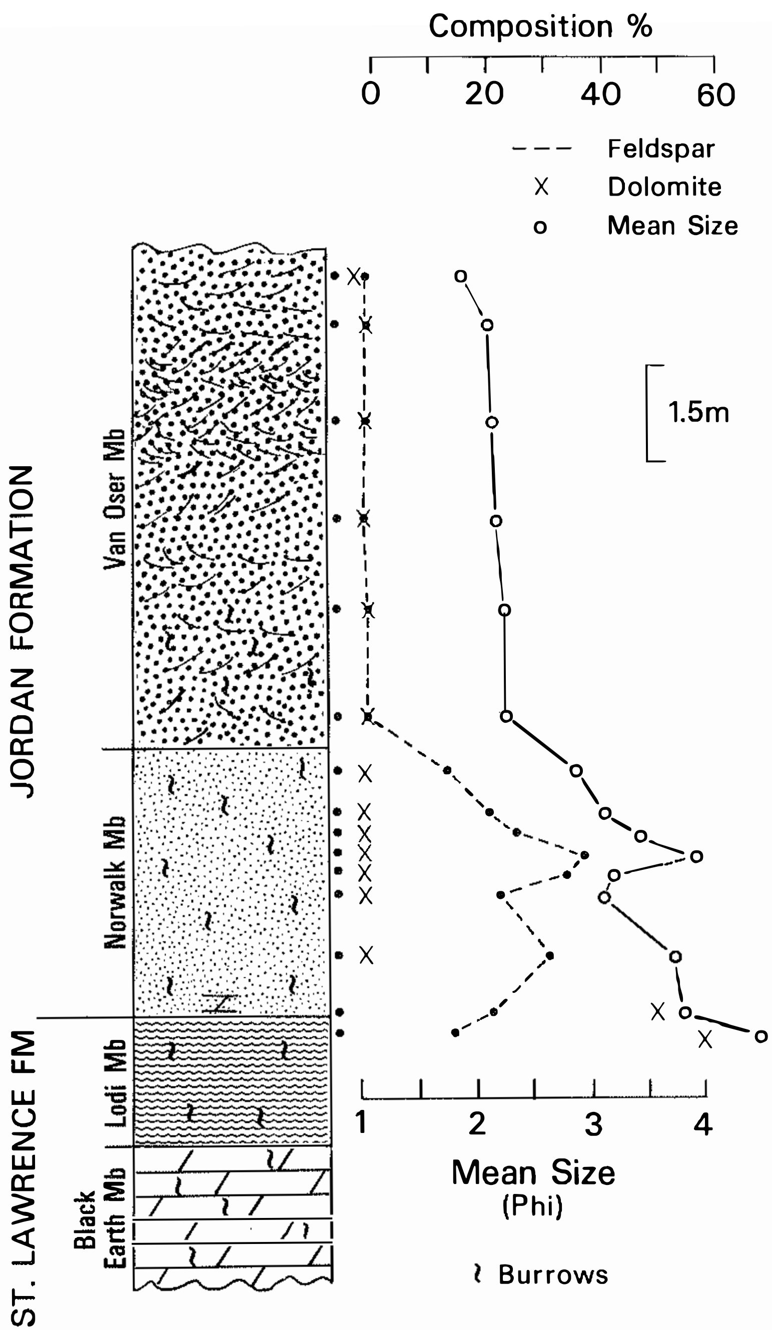


Author: I. E. Odom

Description: This section was measured in 1976 and is a composite of exposures at the rear of and in the driveway to the Howard Johnson Motel and at the rear of Barnaby's Restaurant. Unfortunately, the Lodi Siltstone and Norwalk Sandstone Members, once exposed behind Barnaby's, have been covered to prevent mass wasting and damage to property at the top of the cut. The upper few feet of the Norwalk Member, however, are still exposed behind the Road Star Motel a few hundred meters to the southwest. To further illustrate the bedrock succession in this area of Madison, a section is included of an exposure on Messerschmidt Road northeast of Truax Air Field (4 km - 2.5 miles to the northwest).

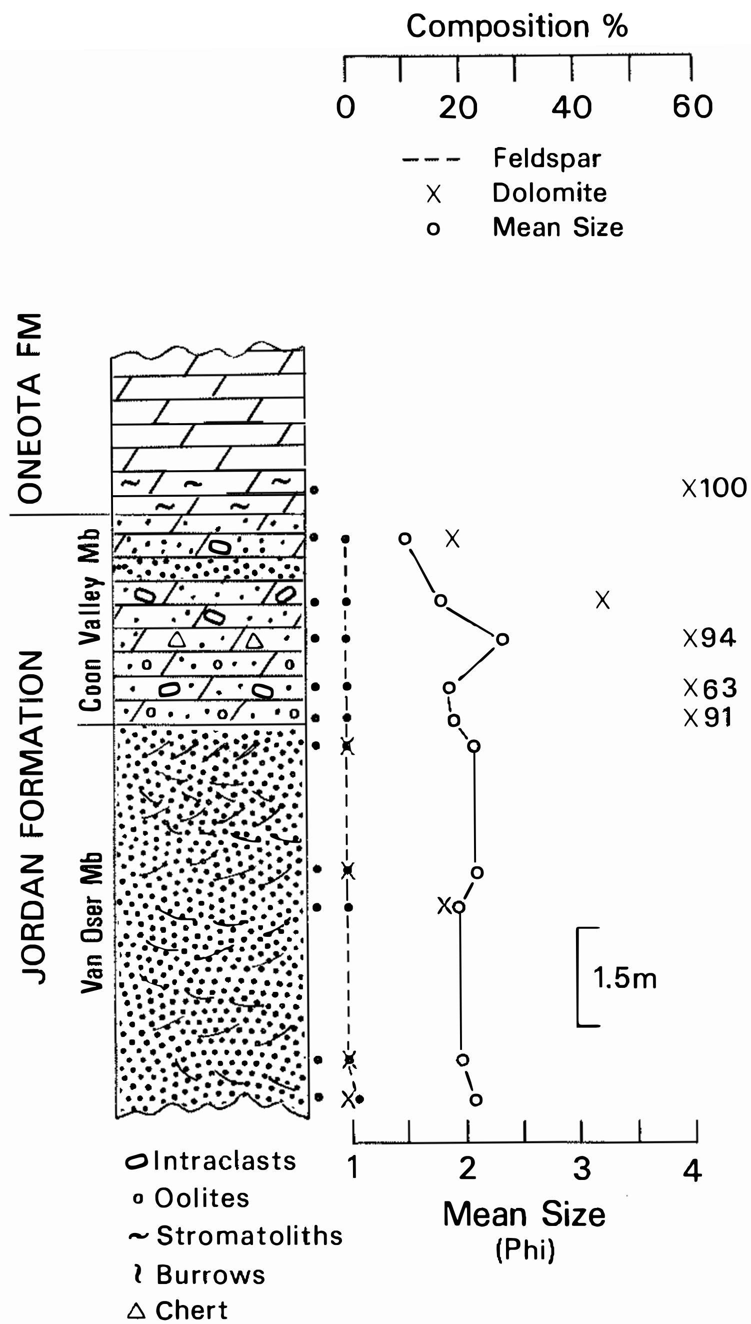
The bedrock exposed in the northeastern part of Madison includes the St. Lawrence, the Jordan, and the lower part of the Oneota Formations. The Norwalk, Madison, Wis.

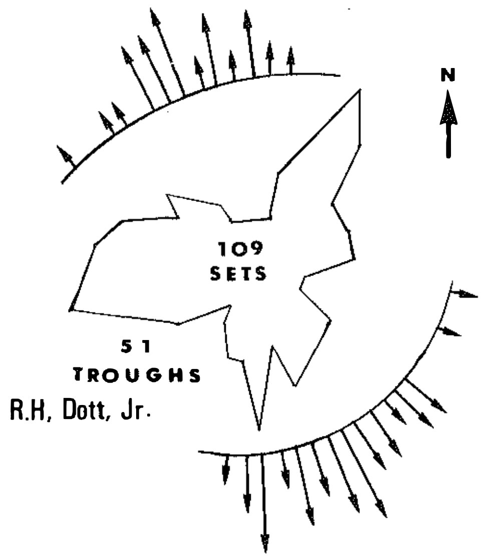
HOWARD JOHNSON MOTEL

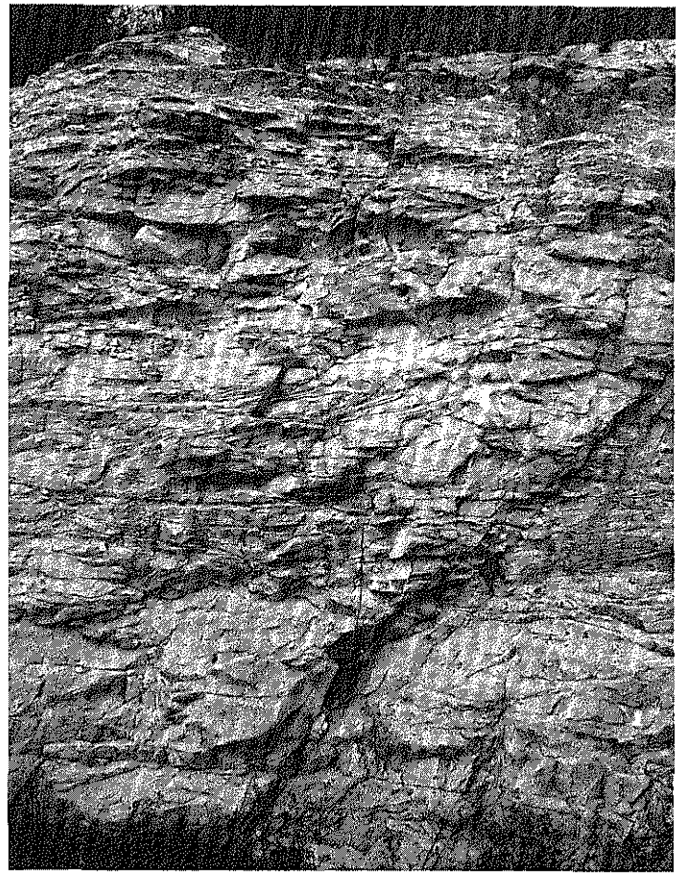


Madison, Wis.

TRUAX AIRPORT SECTION







(Left) Current directional data based on the plunge of trough axes and dip of cross sets in the Van Oser Sandstone, Howard Johnson Motel.

(Right) Cross stratification in the Van Oser Sandstone, Howard Johnson Motel.

Van Oser and Coon Valley Members of the Jordan are represented, with the Van Oser being by far the thickest. These members and the adjacent formations are stratigraphically transitional. It is important to note that the Sunset Point Sandstone is again not present in this area.

An additional point of interest at this locality is the local highly cross-stratified nature of the Van Oser Member. Note that current directional data for this outcrop (shown on page 109 and in Fig. 28), both the plunge of trough axes and the dip of cross sets compiled by R. H. Dott, Jr., show two modes nearly 180° apart. Directional data for the Truax Section, however, show a generally southwest transport (Fig. 28).

Interpretations - Based on the regional lithic nature and occurrence of the St. Lawrence Formation, it is considered to have been deposited in an inner neritic environment immediately shoreward of a carbonate platform. Local conglomeratic beds and algal mounds (note present here) suggests very shallow water. The algal structures and conglomerates have been previously interpreted to indicate intertidal or supratidal conditions (see Outcrop 7). The Black Earth Dolostone is transitional with the feldspathic Lodi Siltstone, which is in turn transitional into the very fine-grained, highly feldspathic Norwalk Sandstone of the Jordan Formation. The very fine grain size and bioturbated nature of the Norwalk Sandstone are interpreted to be indicative of a lagoonal environment (Odom and Ostrom, this guidebook). The textural and structural properties of the Van Oser Sandstone indicate a hydrologic regime characteristic of a littoral environment referred to herein as the East Madison Bar complex. The ebb and flow of tidal currents within this bar complex is a possible explanation for the bimodal nature of the current direction indicators in the Van Oser Sandstone of this area (Fig. 28). The lithic and structural characteristics and thickness of the Coon Valley Member in this area are similar to the Coon Valley at Outcrops 1 and 2.

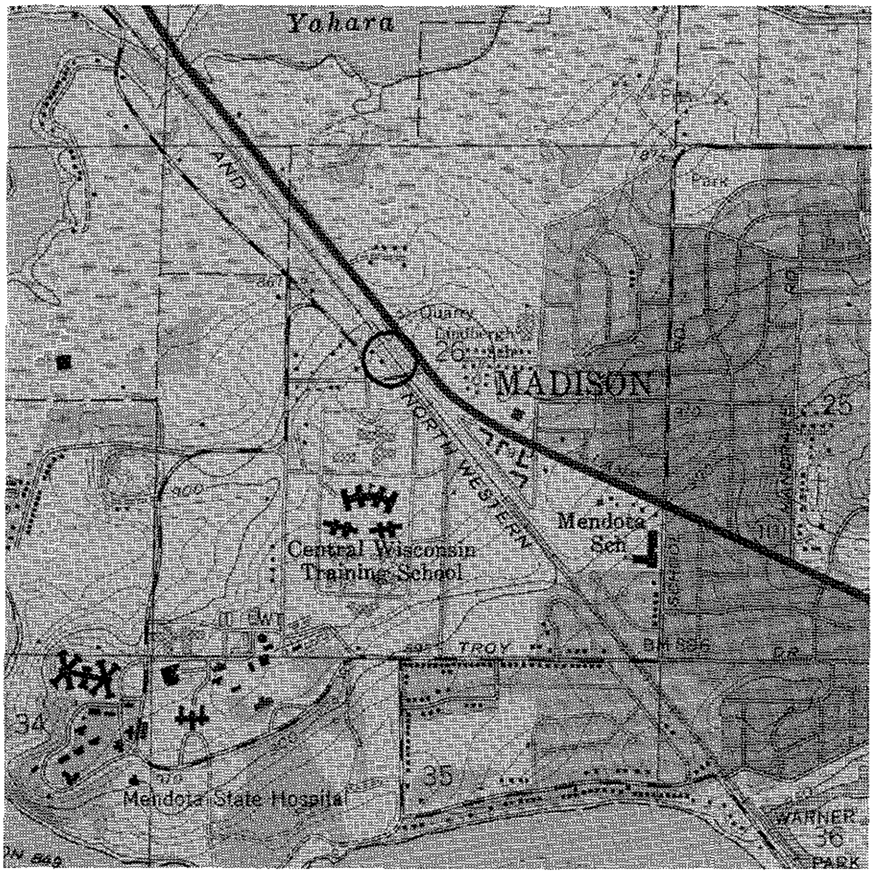
Remarks on Geologic Structure of the Madison Area. Disrupted bedding toward the west end of the Howard Johnson Motel cut suggests that a small fault may be present. During my studies of the bedrock of the Madison area, I identified three significant faults, and I am suspect that many others exist. Structurally, the Howard Johnson exposure is situated on a horst bounded by northeast-southwest trending faults. The northwest bounding fault passes beneath Truax Air Field, whereas the southeast bounding fault passes through the village of Burke. These faults have vertical displacements of at least 20 to 25 meters (60-80 feet). The stratigraphic relations in the East Madison area were initially confusing but became crystal clear when the presence of these faults was recognized.

The third clearly recognizable fault is located near Cross Plains, and it is discussed in the description of Outcrop 5. Open file reports and recently acquired well data in the files of the Wisconsin Geological and Natural History Survey indicate that other faults, some perhaps with displacements greater than 30 meters, occur in the area.

OUTCROP 4

Title: Madison-Mendota Station

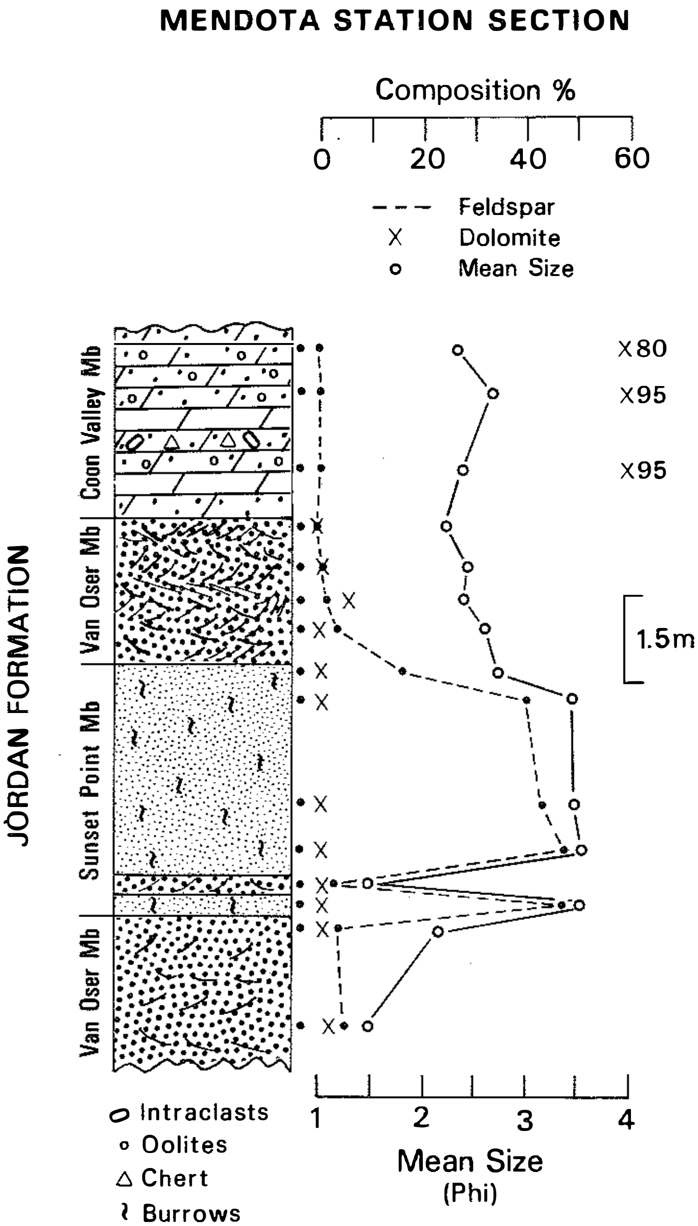
Location: Chicago and Northwestern Railroad Cut at Mendota Station in the SE¼, SE¼, NW¼, Sec. 26, T.8N., R.9E., Dane County (Waunakee 7.5 minute topographic quadrangle, 1974).

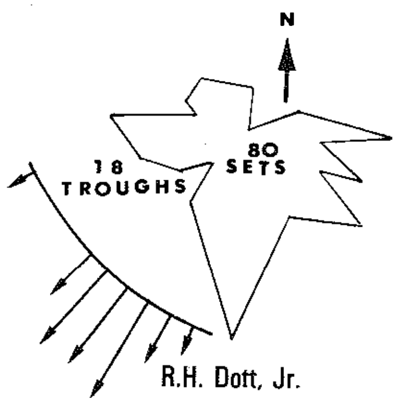


Author: I. E. Odom

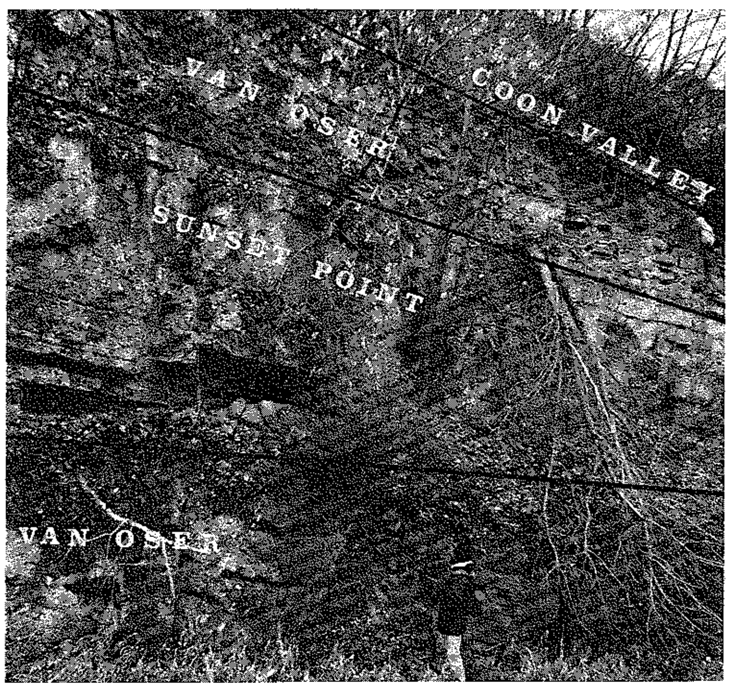
Description: The Mendota Station section is highly important relative to the stratigraphic position of the Sunset Point Member, and to the physical nature of sedimentation during the time that the Jordan Formation was deposited in central Wisconsin. This section has figured prominantly in past controversy regarding the stratigraphy and sedimentology of the St. Lawrence and Jordan Formations since E. O. Ulrich first described it in 1911, yet the lithic succession prior to 1976 was poorly understood. Past literature records this section as containing only the Van Oser Sandstone (at the base), the Sunset Point Sandstone and the Oneota Dolomite.

Recent studies of the lithology and sedimentary structures of this section, especially the texture and mineralogy, show that the very fine-grained, feldspathic





Orientation of cross sets and plunge direction of trough axes in upper unit of the Van Oser Sandstone.



Stratigraphic relations in the Mendota Station Railroad cut.

Sunset Point Sandstone is both overlain and underlain by fine- to medium-grained, quartzose Van Oser Sandstone. The upper unit of the Van Oser Sandstone is in turn overlain by sandy dolostones and dolomitic sandstones (Coon Valley Member). The Sunset Point Sandstone is somewhat thinner, more massive and less dolomitic than at its type section. Between the lower Van Oser Sandstone and the Sunset Point Sandstone is a mixed zone of very fine-grained, feldspathic sandstone and medium-grained, quartzose sandstone. The contact of this zone with the underlying Van Oser Member rises in the section from the south toward the north end of the cut, but this is not considered to indicate an unconformable relationship. The Sunset Point Sandstone is gradational into the upper unit of the Van Oser Sandstone.

While the lower unit of the Van Oser Sandstone is only moderately cross stratified, the upper unit is highly cross stratified, especially on the east side of the cut. Dott shows a southwest current direction for the upper Van Oser unit based on the plunge of trough axes, while cross sets show more divergent current directions.

The Coon Valley Member crops out sporatically in the brushy area at the top of the outcrop and directly overlies the Van Oser. The sandy, "oolitic" dolostones and dolomitic sandstones contain reddish, conglomeratic, chert bands identical to those in the Coon Valley Member at the Sunset Point type section. The basal conglomeratic algal bed present at the base of the Coon Valley at the Sunset Point type section has not been observed in this outcrop.

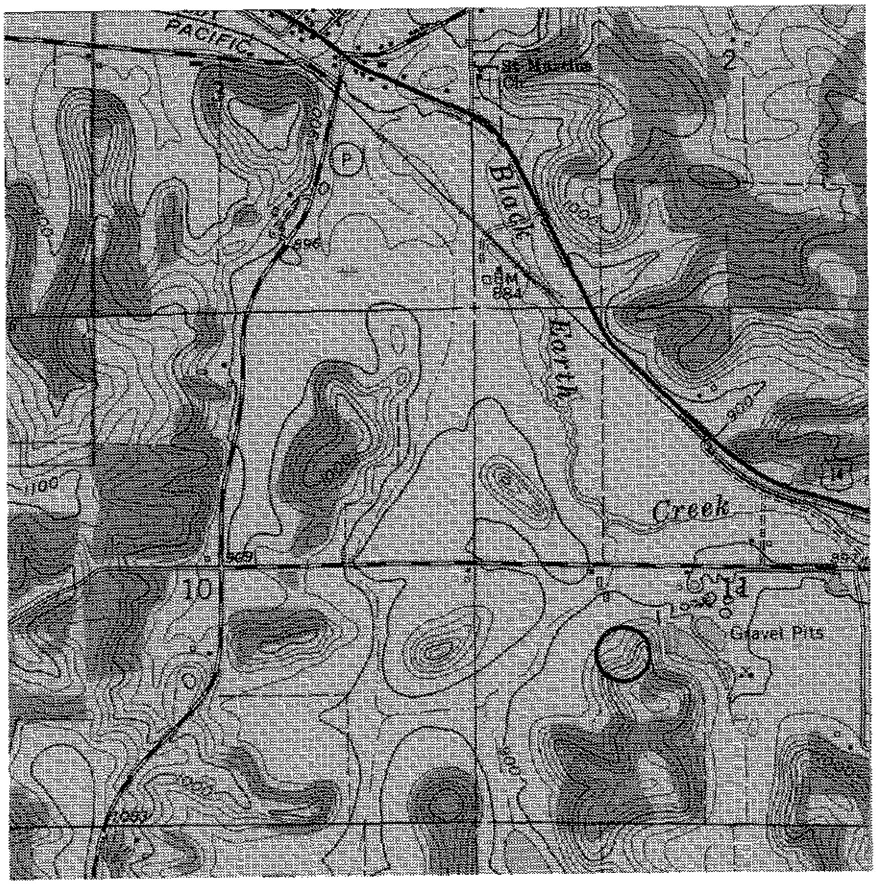
Interpretations: The stratigraphic relations in this exposure and the fact that the Sunset Point Sandstone is not traceable beyond a local area in and north of Madison are the primary evidence for the interpretation that the Sunset Point Sandstone is a local lithic facies of the Van Oser Sandstone. This interpretation is further supported by the regional occurrence and the physical sedimentology of the Van Oser Sandstone.

Based on the fact that the Sunset Point Sandstone is absent only a few miles east of this outcrop, it is concluded that this area was near the eastern side (south side in Cambrian time) of the lagoon in which the Sunset Point Sandstone was deposited (Fig. 22). The lower unit of the Van Oser Sandstone represents a littoral environment existing prior to the development of the Sunset Point lagoon. The upper unit of the Van Oser Sandstone records a shift of the East Madison Bar complex (Fig. 22) into the margin of the Sunset Point lagoon. At this location, the sandy, "oolitic" dolomites of the Coon Valley Member were deposited on the Van Oser Sandstone rather than on the Sunset Point Sandstone. This stratigraphic relation does not imply that deposition of the Coon Valley Member necessarily began earlier at the Sunset Point type section.

Outcrop 5

Title: Cross Plains East

Location: Capitol Stone Quarry, 2 km east of Cross Plains, Wisconsin in the SW$\frac{1}{4}$, NW$\frac{1}{4}$, SW$\frac{1}{4}$, Sec. 11, T. 7N., R. 7E., Dane County. (Cross Plains 7.5 minute topographic quadrangle, 1962).

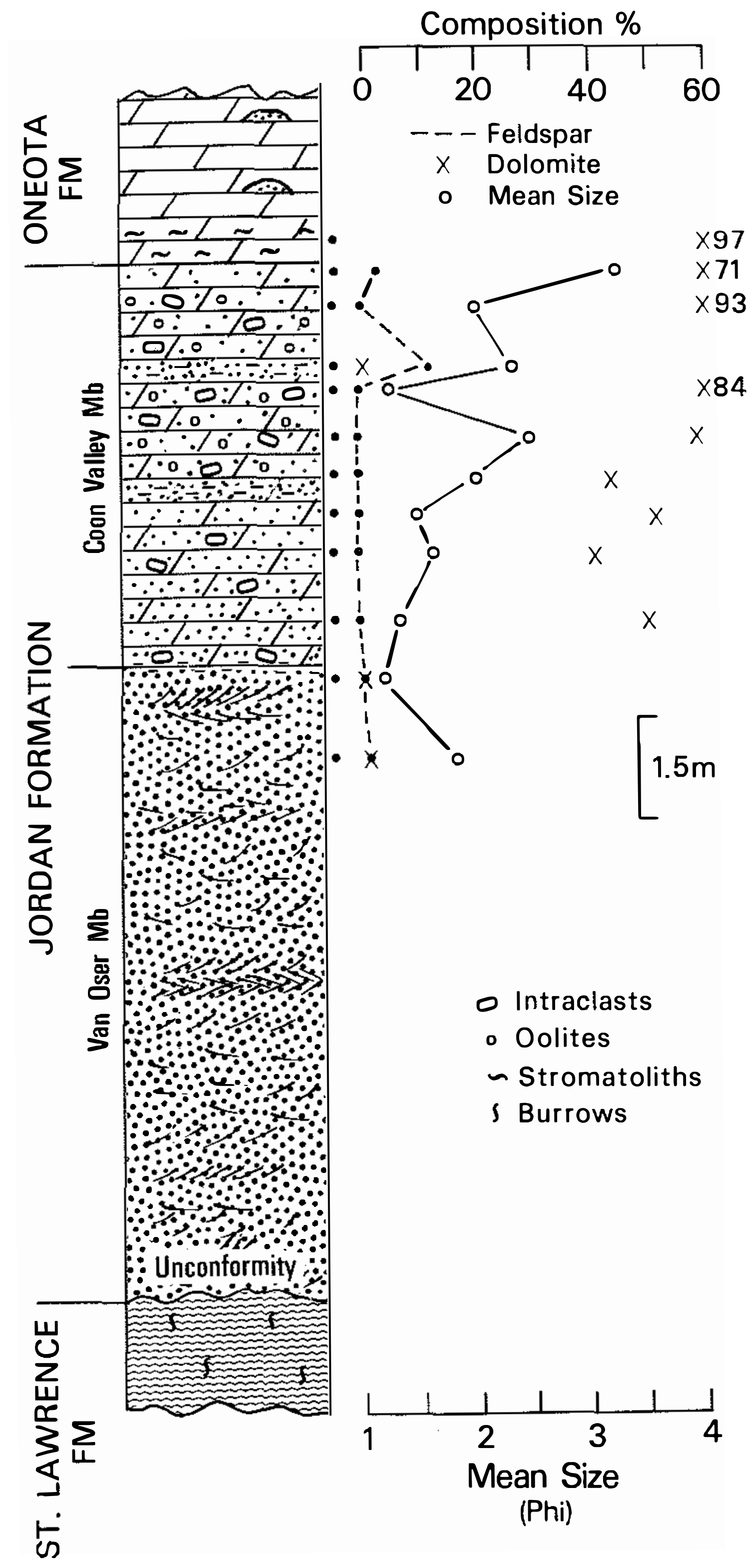


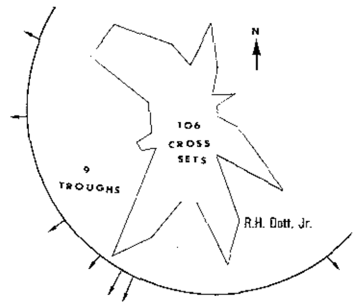
Author: I. E. Odom

Description: The Oneota, Jordan, St. Lawrence and the top of the Lone Rock Formations are exposed in the quarry and in the hillside below (The Lone Rock is not included in the above section because it may have been recently covered by fill for a new quarry road). The Norwalk Member of the Jordan is absent and the Van Oser Member rests unconformably on the St. Lawrence. This same stratigraphic relation can also be seen on U. S. Highway 14 north of the quarry. The Van Oser Member is transitional with the Coon Valley Member, which is in turn transitional into the Oneota Dolostone.

This exposure and others nearby (Outcrops 6 and 7) provide unequivical proof that a local unconformity (disconformity) exits on the axis of the Wisconsin Arch between the Jordan (Van Oser) and St. Lawrence Formations. The unconformity migrates up section toward the west, and at Soldiers Grove, Wisconsin, it is present between the Van Oser and Norwalk Members.

CROSS PLAINS, WIS.





Paleocurrent directional data for the Van Oser Member.

Parts of the Van Oser Member are highly cross-stratified. Current directional data (shown above) by R. H. Dott, Jr. show a dominantly southwest transport. Grains of Baraboo Quartzite have been found near the top of the Van Oser and in the base of the overlying Coon Valley Members, which demonstrates sand transport from the direction of the Baraboo Islands (Figs. 22 and 31).

The Coon Valley Member is represented by dolomitic sandstones and sandy, "oolitic" dolostones which contain abundant intraclasts. The upper contact of the Coon Valley is placed at the top of the sandy dolostones and below the prominent algal dolostone bed that occurs at the base of the Oneota. Although the Oneota is not sandy, two thin sandstone lenses occur a few feet above the contact. This is the only locality where sandstone has been found interbedded with nonsandy Oneota. See Figure 33 for further data on the petrology of the Coon Valley Member and the Oneota Dolostone at this quarry.

Along the axis of the Wisconsin Arch, the thickness of the Coon Valley is locally more variable than elsewhere in the Upper Mississippi Valley (Figs. 16 and 17). Although it is slightly more than 4 meters at this location, in several nearby outcrops the Coon Valley is approximately 1 1/2 meters in thickness, and in one outcrop near Sauk City, Wisconsin, it is represented by just .3 meters of shaly sandstone.

Interpretations - The Jordan-St. Lawrence stratigraphic relationships indicate that following deposition of the Norwalk Member (several feet of the Norwalk is present in nearby outcrops) regional uplift occurred, especially in the area of the Wisconsin Arch. This uplift resulted in a short interval of subaerial erosion which locally entirely removed the Norwalk and variable amounts of the St. Lawrence Formation. The Van Oser Sandstone was deposited in this area over an irregular surface and is considered to be part of the Cross Plains Bar complex, which in Cambrian time is believed to have extended westward from the north end of the Baraboo Islands (Fig. 22). The lithoclasts of Baraboo Quartzite attest to the direction of sediment transport.

No Sunset Point Sandstone is known in this area. The western most outcrop of what is interpreted to be the Sunset Point Sandstone occurs at Middleton, 11 km east; thus it is inferred that the margin of the Sunset Point lagoon during deposition of part of the Van Oser in the Cross Plains area was located near Middleton. The lithic nature of the Coon Valley Member at this location records a transition from a littoral to a carbonate shelf environment. Adams (this guidebook) concludes that the Oneota Formation and perhaps the upper part of the Coon Valley Member in this area were deposited in a supratidal environment.

As previously indicated, the Coon Valley Member is variable in thickness over the axis of the Wisconsin Arch. Several geologists and students, especially Starke (1949) and Melby (1967), have concluded that up to 12 meters (40 feet) of the Oneota Formation are missing at the Miller's Curve Section located to the east on U. S. 14 about half way between Outcrop 5 and Middleton. (Note: both Starke and Melby included the strata presently assigned to the Coon Valley Member in the Oneota). This interpretation was largely based on the thickness of strata occurring between the Van Oser Member and an algal bed that is supposedly continuous from western Wisconsin to this area (Note: the "marker bed" is believed to be the algal bed occurring at the base of the Oneota here and at Outcrops 1 and 8).

Ostrom (1964) concluded that the apparently missing Oneota could be a product of transgression so that dolomitic sandstones in western Wisconsin previously placed in the lower Oneota(now part of the Coon Valley Member) are equivalent in time to portions of the Van Oser Sandstone developed in near-shore areas (Fig. 21). Adams (this guidebook) proposes that a small bar of Van Oser-type sand was present between Cross Plains and Middleton during the time that the Coon Valley Member was being deposited in nearby areas such as at the Capitol Quarry and the Sunset Point type sections. Odom and Ostrom (Fig. 16) show that the Coon Valley Member progressively thins toward the east from an average of 10.5 meters along the Mississippi River to an average 3.5 meters in central Wisconsin. Thus, the problem of the missing Oneota is largely related to the thinning and irregular deposition of the Coon Valley over the Wisconsin Arch. Ostrom's earlier interpretation is correct in that dolomitic sandstones in the lower part of the Coon Valley Member were being deposited in western Wisconsin while the upper portion of the Van Oser Sandstone was still accumulating on the Wisconsin Arch. The stratigraphic interpretation relative to the Miller's Curve bar by Adams (Fig. 33) is tenuous because it is doubtful that the algal "marker bed" used by Starke, Melby, and Adams as a datum is exactly time-equivalent even in the Madison area and certainly not over a distance of 160 km. Also, field relations do not show that a prominent bar of Van Oser Sandstone existed in the area of Miller's Curve at the same time that the Coon Valley was being deposited at the Capitol Quarry and to the east at Hoyt Park. I believe that the variations in the thickness of the Coon Valley Member on the Wisconsin Arch are related to local stromatolite development. Stromatolites "bloomed" whenever sand was in short supply. Also, stromatolite mounds tended to hinder the movement of sand waves.

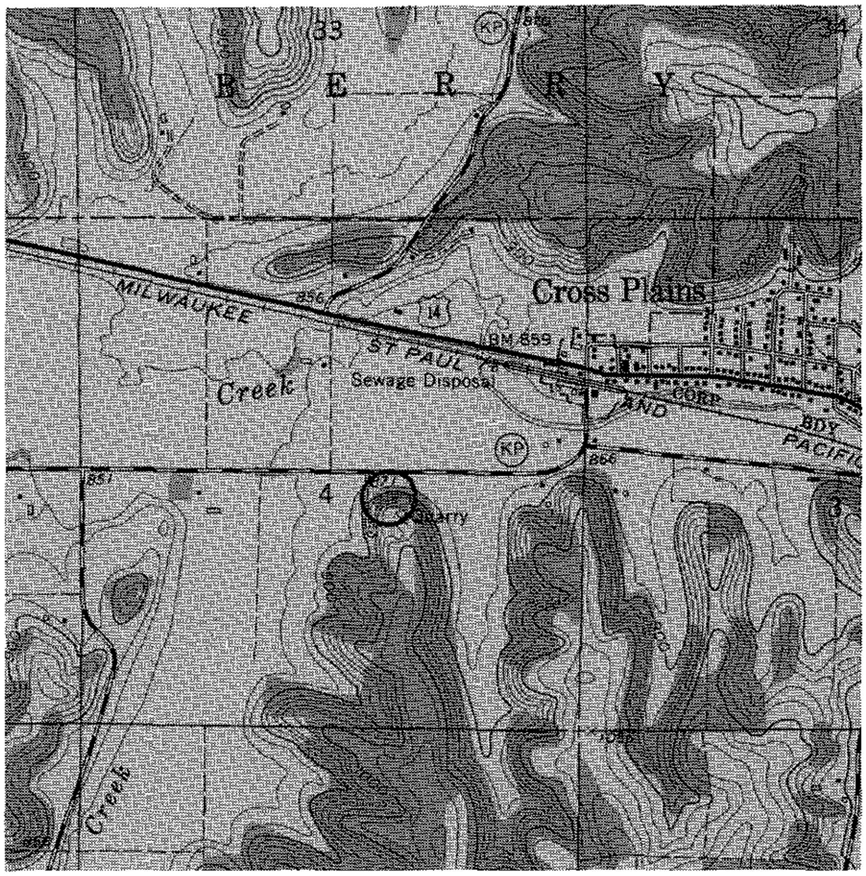
<u>Remarks on Geologic Structure</u> - The elevation of formational contacts at the Capitol Stone Quarry compared to the elevation of equivalent contacts in outcrops to the north along U. S. Highway 14 differ by 35 to 40 feet. The top of the Lone Rock Formation crops out on the hillside below the quarry, whereas the St. Lawrence-Jordan contact occurs at a slightly lower elevation on U. S. 14. This stratigraphic displacement is caused by a small east-west trending fault located in the valley between U.S. 14 and the quarry. The presence of this fault is further substantiated by stratigraphic relations nearer to Cross Plains and by fractured Jordan Sandstone in a road cut about one mile to the west. Rocks on the south side of the faults are up thrown. The stratigraphic displacement is about 12 meters (40 feet). The "stable" craton is not as "faultless" has has been previously thought. Because the displacement on most of these faults is small, detailed mapping is required to identify them.

Note: Permission to enter the Capitol Stone Quarry must be obtained at office.

OUTCROP 6

Title: Cross Plains West

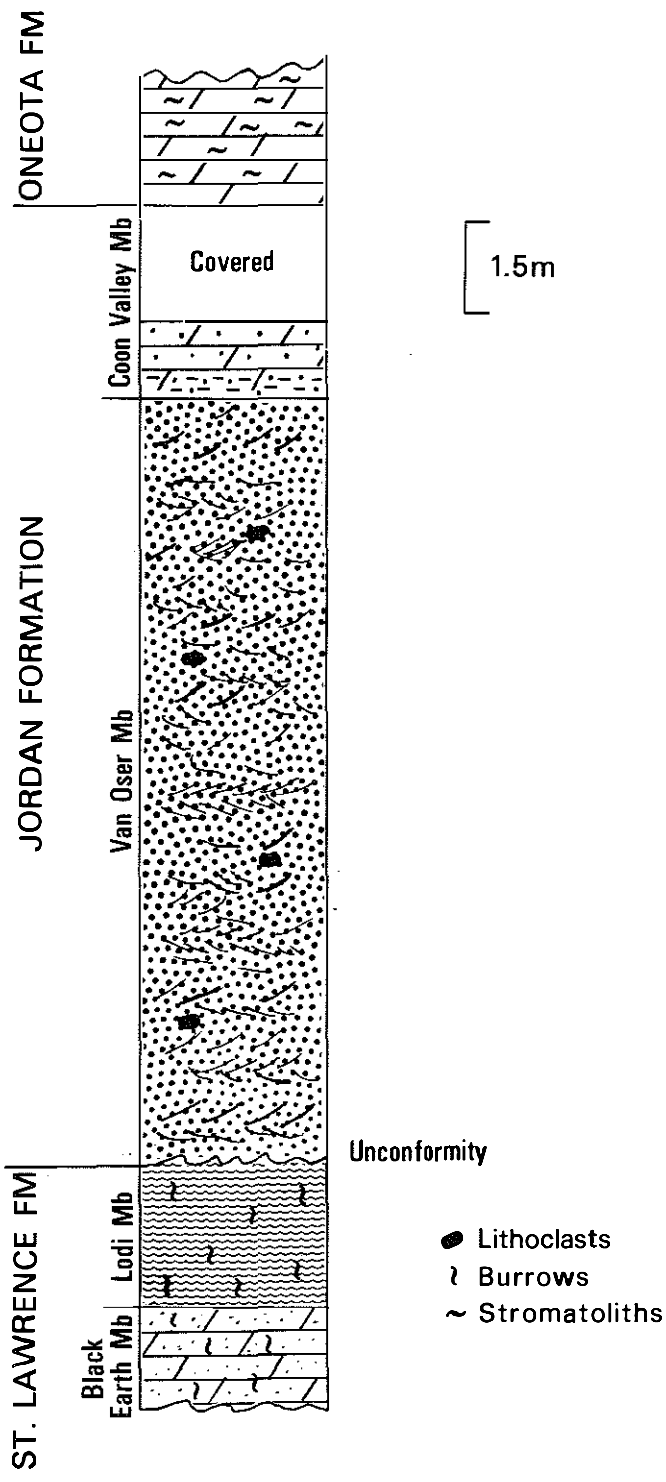
Location: Quarry south of County Highway KP, .7 km southwest of Cross Plains, Wisconsin in the NW¼, NW¼, SE¼, Sec. 4, T.7N., R.7E., Dane County (Cross Plains 7.5 minute topographic quadrangle, 1962).



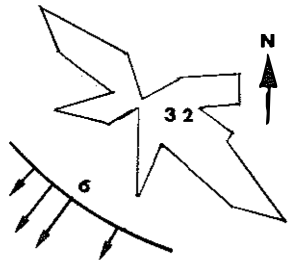
Author: I. E. Odom

Description: This exposure is significant because the disconformable contact between the Jordan (Van Oser Member) and the St. Lawrence Formations is well exposed. The Lodi Siltstone and underlying Black Earth Dolostone are both reddish, a local coloration developed along the axis of the Wisconsin Arch. At this location, the Black Earth is very silty, and both it and the Lodi are intensely bioturbated. At the type section of the Black Earth Member located 4.5 km west on U.S. 14, there is a thick sequence of dolostone containing algal structures. Algal structures are common in the Black Earth Dolostone only in the vicinity of the Wisconsin Arch and around the Baraboo Syncline.

CROSS PLAINS (WEST), WIS.



U.S. 14 near
Festge Park



R.H. Dott, Jr.

Paleocurrent directional data for the Van Oser Member.

Neither the Coon Valley Member nor its contact with the overlying Oneota Formation are well exposed. Baraboo Quartzite lithoclasts are moderately abundant in the Van Oser Sandstone. The upper part of the Van Oser Sandstone is cemented by calcite (popcorn concretions).

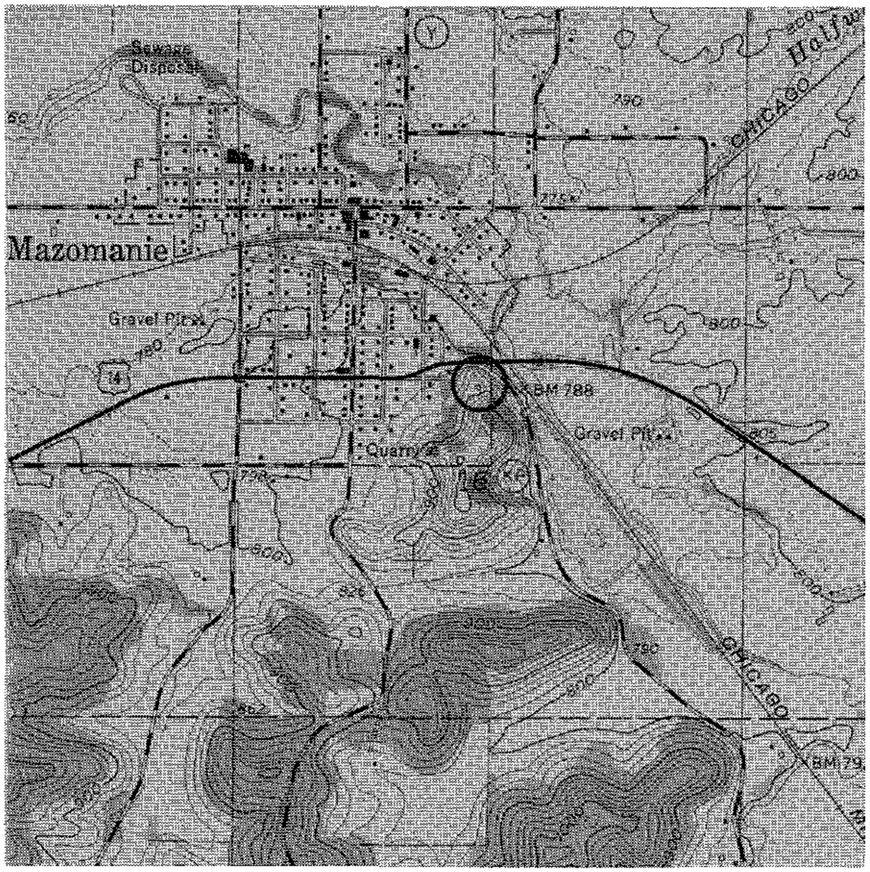
Interpretations: What is the age of the oxidation of iron in the St. Lawrence? Is it due to pre-Van Oser subaerial weathering? Is there evidence in the Van Oser that suggests the oxidation might be recent in age? See description accompanying Outcrop 7 for further discussion of the sedimentology of the St. Lawrence Formation. For additional information on the regional lithology of the St. Lawrence Formation see Ph.D. thesis by McGannon (1960) and Nelson (1956).

Note: Permission must be obtained to enter this quarry. The present owner lives in the first house on the north side of Highway KP toward Cross Plains.

OUTCROP 7

Title: Mazomanie (School House) Bluff

Location: South of U.S. Highway 14 at east edge of Mazomanie, Wisconsin in the NE¼, SE¼, NW¼, Sec. 16, T.8N., R.6E., Dane County (Mazomanie 7.5 minute topographic quadrangle, 1962).

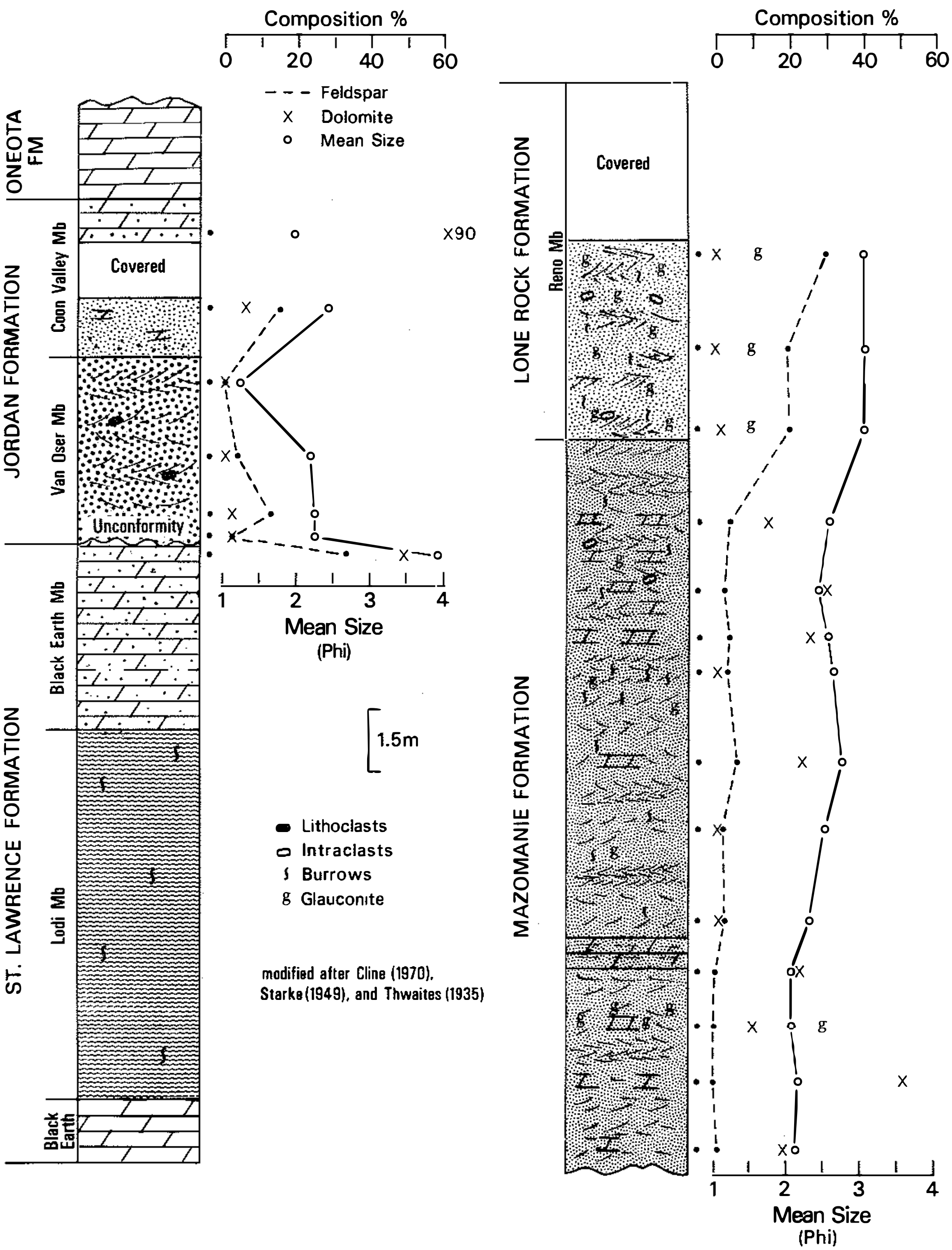


Author: I. E. Odom

Description: School House Bluff is considered to be the type section of the Mazomanie Formation, and it is a magnificent exposure for the total stratigraphic section is the most complete in central Wisconsin. Most of the Oneota, the Jordan, the St. Lawrence and large parts of the Lone Rock and Mazomanie Formations are well exposed. The main purpose for examination of this section is to observe the effects of the Wisconsin Arch on the local sedimentation of the Jordan, St. Lawrence, and Mazomanie Formations.

The Wisconsin Arch was definitely a positive area during the deposition of the Mazomanie, Jordan, and perhaps to a lesser extent the St. Lawrence Formations. The Norwalk Member of the Jordan is entirely absent (eroded). The Van Oser Member thins to 5.5 meters, the minimum thickness observed in Wisconsin, and it is disconformable with the Black Earth Dolomite. The Coon

MAZOMANIE, WIS.



Valley Member of the Jordan is also thin. Transportation of sand from the direction of the Baraboo Islands is shown by lithoclasts of Baraboo Quartzite in the Van Oser Member, some of which are up to one centimeter in diameter. The famous Dikelocephalus fauna has been collected at this locality from the middle of the Lodi Member.

Based on mineralogical and textural analyses, the upper 4.5 meters of the Tunnel City Group is assigned to the Reno Member of the Lone Rock Formation and the lower 15 meters to the Mazomanie Formation. These analyses show that the Reno Member is a glauconitic, feldspathic, very fine-grained sandstone, whereas the Mazomanie at this location is essentially a fine-grained quartzose sandstone, although it contains thin zones in which glauconite is moderately abundant. Both the Mazomanie and the Reno Member are locally intensely burrowed (Skolithos assemblage), dolomitic at certain horizons, and contain intraclasts. Trough and some planar-shaped cross stratification are present, especially in the Mazomanie.

Interpretations: This outcrop further documents that the Wisconsin Arch influenced local sedimentation in Late Cambrian and Early Ordovician time, and that uplift and local erosion occurred prior to deposition of the Van Oser Sandstone. It is interpreted that the absence of the Norwalk Member is due to erosion rather than to nondeposition because several feet of the Norwalk lithology can be identified in nearby outcrops where it was not completely eroded. The local thickening of the St. Lawrence might also indicate that the Wisconsin Arch was a factor in its deposition. The abundance of algal mounds in the St. Lawrence only along the crest of the arch (McGannon, 1960) possibly indicates a type of "reef" development with the algal mats serving to trap and hold sediment. The "reef" dolostones were more resistant to erosion, as they are at the present time, because they formed hills of low relief on the pre-Van Oser erosional surface. Variations in the elevation of the base and increase in the thickness of the Van Oser Member nearby suggest that it was possibly being deposited in surrounding areas before its deposition at this locality; however, no specific beach deposits or lithoclasts of the St. Lawrence have been identified in the Van Oser Sandstone.

The presence of bioturbation, thin bedding and lamination in the Lodi Siltstone, algal structures in the Black Earth Dolostone, some mottling, and possibly dessication cracks (?) have prompted speculations that the St. Lawrence Formation was deposited in intertidal and perhaps supratidal environments. Although such sedimentary structures might form in tidal environments, as well as in other environments, the regional stratigraphy and sedimentology of the St. Lawrence and overlying and underlying lithic units make a tidal interpretation for the entire St. Lawrence highly dubious. More diagnostic indicators of tidal environments such as fining upward sequences, seaward-coarsening, tidal channels, and true flaser bedding, which would be necessary to show water movement, are absent in the St. Lawrence. The thin, scattered conglomerate beds that occur locally in the St. Lawrence, previously suggested to reflect tidal processes, could easily have been formed by hurricane-force storms (see paper by Dott, this guidebook). A shallow subtidal environment seems more probable for most of the St. Lawrence, but the algal mounds along the arch possibly formed in a tidal environment.

The probable nature of the regional and local depositional environments of the Mazomanie Formation and Reno Member of the Lone Rock Formation is discussed by Odom (this guidebook). The quartzose sandstones that compose the Mazomanie at this location are interpreted to have accumulated on a littoral shoal paralleling the Wisconsin Arch (Fig. 35). The quartzose Mazomanie accumulated simultaneously with the feldspathic Mazomanie and with the glauconitic Reno Member in off-shore areas to the west, south and east (Figs. 35 and 36). The Reno facies migrated over the arch with the transgression that occurred in late Franconian time (Fig. 35).

Outcrop 8

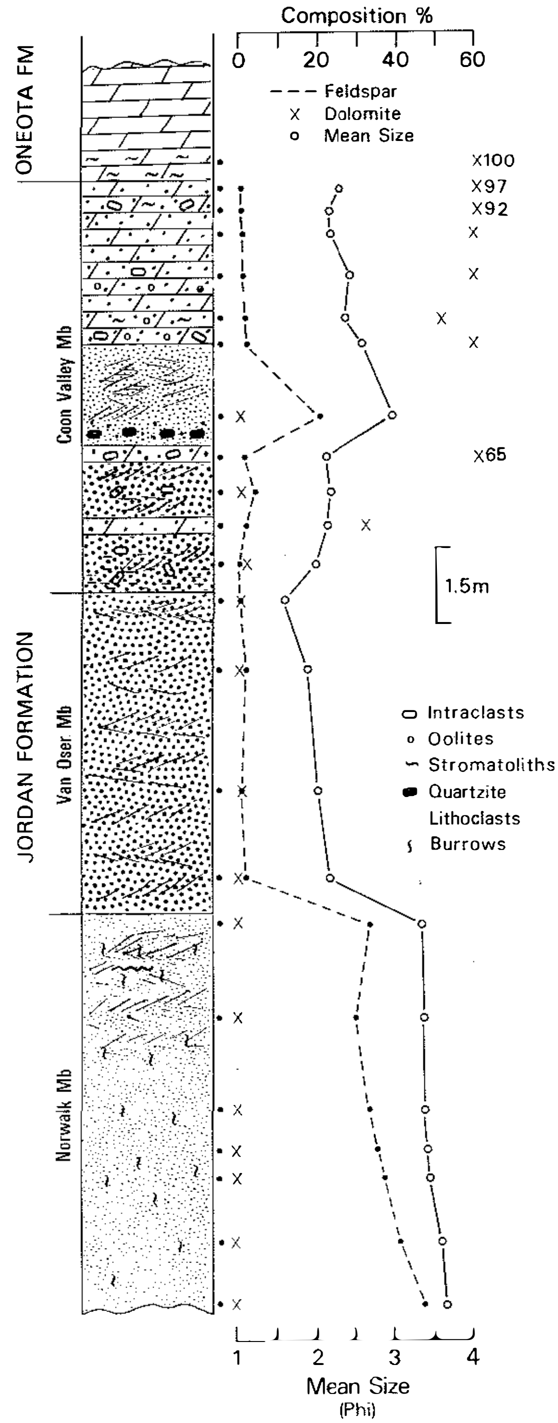
Title: Spring Green

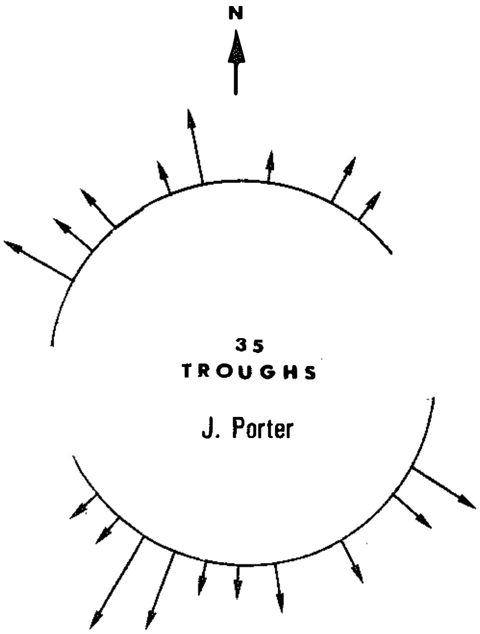
Location: East Side of Wisconsin Highway 23, 4 miles north of Spring Green, Wisconsin in the NW$\frac{1}{4}$, SW$\frac{1}{4}$, SW$\frac{1}{4}$, Sec. 30,T. 9N., R. 4E., Sauk County. (Spring Green 15-minute topographic quadrangle, 1960).

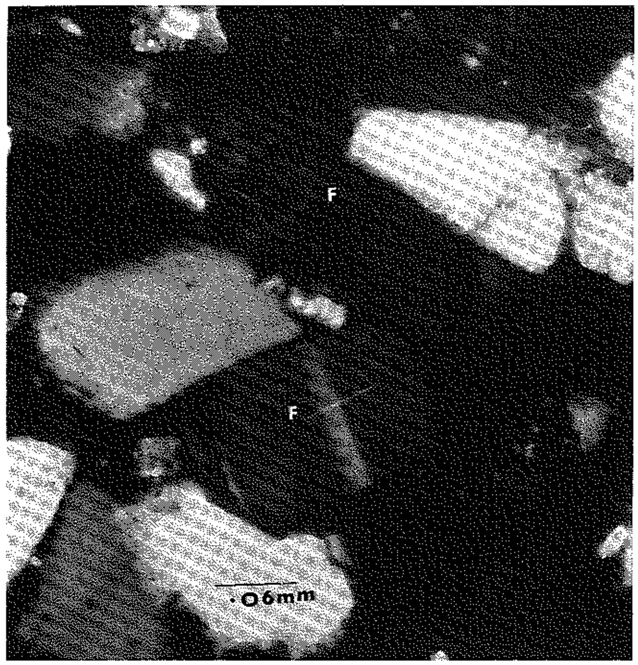
Author: I. E. Odom

Description: This exposure is significant because it illustrates the approximate lithic nature of the Jordan Formation in western Wisconsin, eastern Minnesota, and northeastern Iowa. It also shows the frequent transitional nature of the Jordan and St. LawrenceFormations. Typical of its character elsewhere, here the Norwalk Member is a very feldspathic, very fine-grained sandstone. At this location the Norwalk Member ranges from massive to thinly bedded, and cross stratification is present in the upper 3 to 4 meters, although in other areas it is often entirely massive. Some beds are highly burrowed, which also is a typical characteristic. The plunge of trough axes in the top of the Norwalk Member, determined by Jane Porter (1978) shows two modes approximately 180° apart. No distinct contact between the Norwalk Member and the St. Lawrence Formation is identifiable in the exposure.

SPRING GREEN, WIS.







(Left) Plunge directions of trough axes in the upper portion of the Norwalk Member.

(Right) Detrital feldspar (F) with authigenic overgrowths in the Norwalk Member.

The feldspathic Norwalk Member is in sharp contact with the overlying fine-grained quartzose Van Oser Sandstone, and the Van Oser Sandstone coarsens upward. In many areas a coarsening-upward texture is characteristic of both the Norwalk and Van Oser Members, and the two members are often transitional through an interval of approximately one meter.

The Coon Valley Member,which is 9 meters in thickness, contains approximately 2/3 dolomitic sandstones and 1/3 sandy dolostones, and the upper sandy dolostones are in sharp contact with the overlying nonsandy Oneota Dolostone containing stromatoliths. Note that a thin, sandy dolostone bed containing stromatoliths also occurs near the top of the Coon Valley Member. Stromatoliths are almost always present in the basal beds of the Oneota Dolostone, and it has previously been suggested that stromatoliths might be used to mark the base of the Oneota. Thin, sandy beds containing algal structures are very common in the Coon Valley Member elsewhere in western Wisconsin, thus it would be tenuous to use algal beds for marking the contact between the Jordan and Oneota Formations. On the contrary, if sandy content is used the contact can be easily picked with the aid of a hammer and hand lens.

Note that a prominent zone of Baraboo Quartzite lithoclasts (granules and pebbles) occurs about 3.5 meter above the base of the Coon Valley Member. These attest to the fact that some part of the Baraboo Islands or associated conglomerates were still being eroded during the deposition of this member.

The lower 4.5 meters of dolomitic sandstones in the Coon Valley Member were previously called the Sunset Point Formation or Member. Based on your evaluation of the texture, mineralogy and sedimentary structures, would you consider these dolomitic sandstones to be the lithic equivalent of the type Sunset Point Sandstone at Madison? Although the Coon Valley Member is divisible into two fairly distinct lithic types at this outcrop, this differentiation is quite often not this straight foward, and it is for this reason that the dolomitic sandstones and sandy dolostones which intervene between the Van Oser Sandstone and the non-sandy Oneota Dolomite are combined into a single lithostratigraphic unit. In this context, the Coon Valley Member averages 10.5 meters in thickness and is traceable in outcrop throughout western Wisconsin, eastern Minnesota and northeastern Iowa and also into the subsurface to the south. Note that it is primarily the interval of dolomitic sandstones composing the lower 2/3 of the Coon Valley Member at this outcrop which are not well represented over the Wisconsin Arch.

Interpretations - Odom and Ostrom (this guidebook) and Odom, Wegrzyn and Ostrom (in press) interpret the very fine-grained, feldspathic Norwalk Member to have been deposited in the broad lagoon situated between an off-shore shoal and bar complex to the southwest (Iowa) and a near shore littoral zone to the north (Fig. 21). The current directional data for the Norwalk at this outcrop suggest that tidal processes possibly produced the cross stratification in the upper part. If the bimodal plunge of trough axes is related to the ebb and flood of tides, it would support the model suggested by Odom and Ostrom (this guidebook), which supposes that a significant tidal range was involved in the deposition of the overlying Van Oser Member. The variation of sea level caused by a significant tidal range is also believed to in part account for the widespread distribution of the Van Oser Sandstone.

A sedimentological mechanism is also necessary to explain the distinct stratigraphic differentiation of feldspar in very fine Cambrian sandstones such as the Norwalk. A tenable mechanism for the enrichment of feldspar in very fine sands and its removal from fine and medium sands is that feldspar was selectively reduced in grain size by abrasion in extensive high energy littoral environments, such as the Van Oser Sandstone, then sorted and transported to off-shore and lagoon (Norwalk) environments by currents that were at least partly related to the ebb and flood of tides over the littoral environments.

The sharp contact between the Norwalk and Van Oser Members suggests that they may be disconformable, since these members often are transitional. A minor unconformity is recognizable at this stratigraphic position farther west.

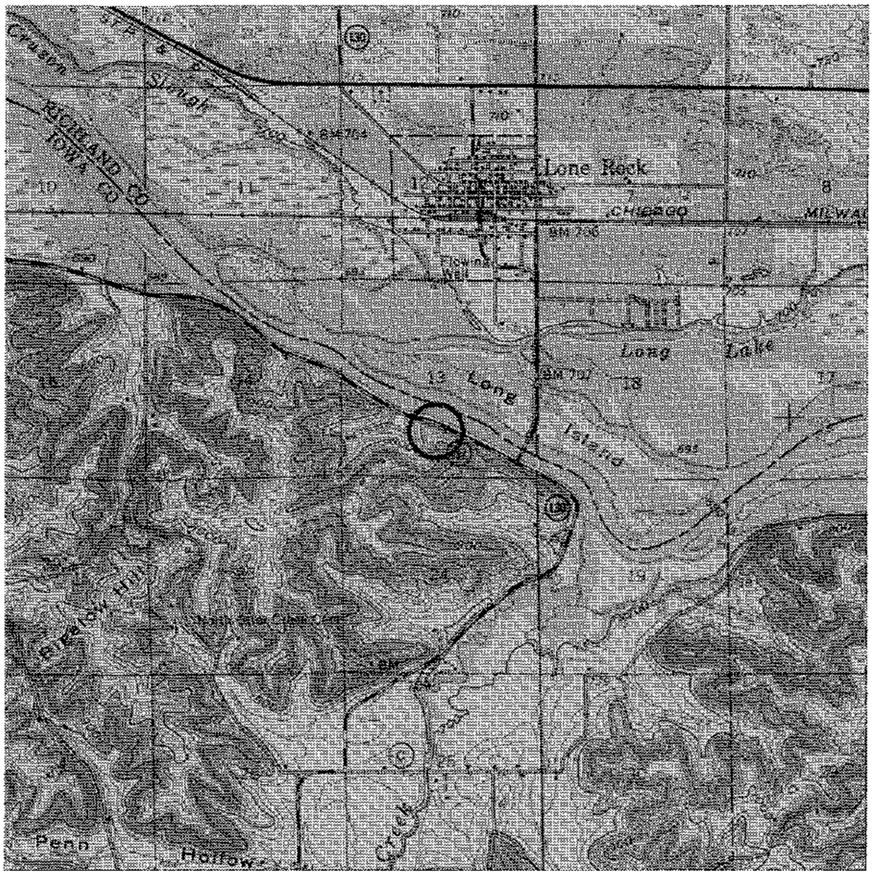
The Coon Valley Member appears to represent several types of comparatively high energy environments ranging from littoral to carbonate shelf. Tidal currents may also have been operative during deposition of some lithic types. Mud cracks are sometimes found which strongly suggest local subaerial exposure, thus local intertidal conditions.

Melby (1967) reported Ordovician age conodonts from shaly beds now considered part of the Coon Valley Member. Where then is the Cambro-Ordovician systemic boundary? The best position if based on physical criteria would be at the base of the Van Oser Member.

OUTCROP 9

Title: Lone Rock

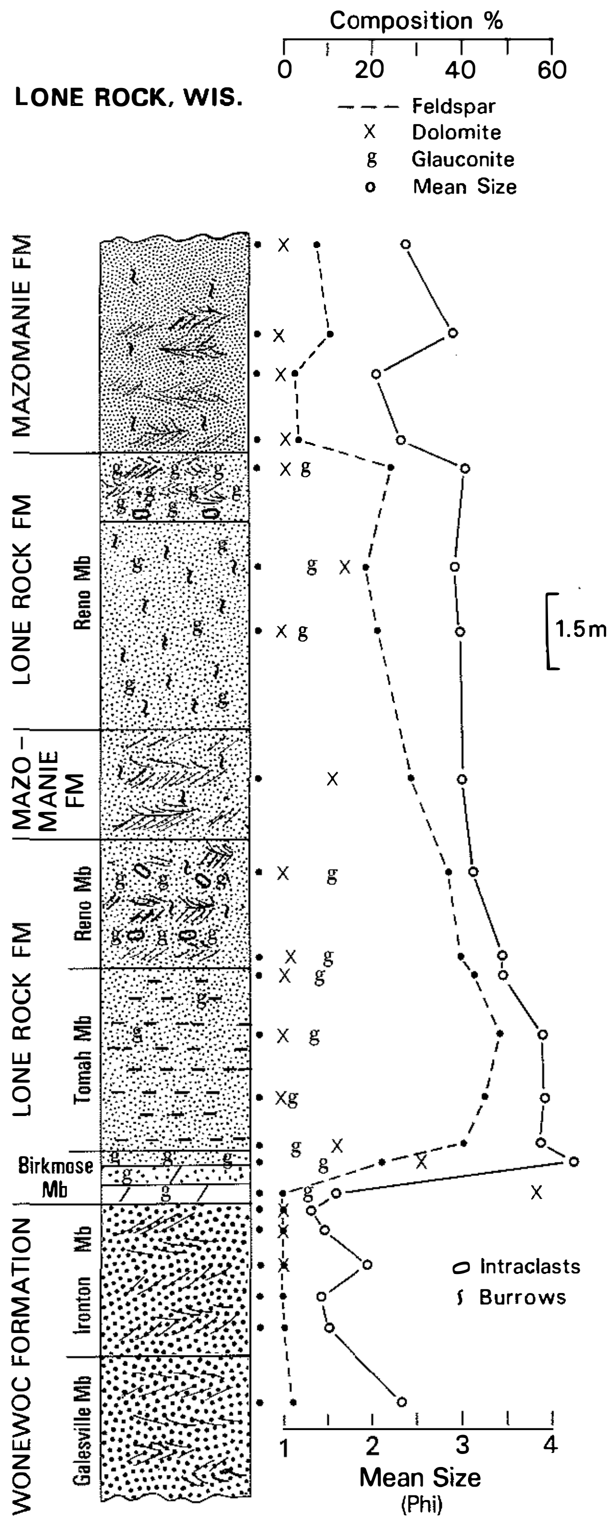
Location: Road Cut on Wisconsin Highway 133, south side of Wisconsin River, 3.2Km south of Lone Rock, Wisconsin in the NW$\frac{1}{4}$, SW$\frac{1}{4}$, SE$\frac{1}{4}$, Sec. 13, T.8N., R.2E., Iowa County (Spring Green 15-minute topographic quadrangle, 1960).



Author: I. E. Odom

Description: This outcrop is an excellent representation of the lithic and sedimentologic characteristics and of the stratigraphic relations of the Lone Rock, Mazomanie, and Wonewoc Formations adjacent to the Wisconsin Arch. Ostrom (1966) chose this outcrop for the type section of the Lone Rock Formation (part of the Tunnel City Group), and except for the Birkmose Member it is a good example of the lithic characteristics of the formation.

The lower 6 meters of the road cut and the bluff down to river level are composed of medium to fine-grained, quartzose, well and moderately well-sorted Galesville and possibly the Ironton Sandstones of the Wonewoc Formation. Generally, the Ironton Sandstone is slightly coarser than the Galesville, and it often contains thin beds that are poorly sorted. These lithic characteristics are not too evident at this outcrop, thus the Ironton may actually be


LONE ROCK, WIS.
Composition %
0
20
40
60
Feldspar
X Dolomite
g Glauconite
o Mean Size
MAZOMANIE FM
LONE ROCK FM
Reno Mb
MAZO-MANIE FM
LONE ROCK FM
Reno Mb
Tomah Mb
Birkmose Mb
WONEWOC FORMATION
Ironton Mb
Galesville Mb
1.5m
Intraclasts
Burrows
1
2
3
4
Mean Size
(Phi)

absent (Ostrom, 1966).

The Birkmose Member of the Lone Rock Formation is thin and contains appreciable reddish dolostone and flat pebble conglomerate throughout this area of Wisconsin. Toward the west, it thickens and more dolomitic and glauconitic sandstones are present (Fig. 35). The very fine-grained sandstones with shale interbeds that succeed the glauconitic sandstone at the top of the Birkmose are assigned to the Tomah Member. This lithology is typical of the Tomah over thousands of square miles in western Wisconsin and eastern Minnesota. As shown in Figure 35, the Tomah thickens west of the Mississippi River, and in southern Minnesota and north central Iowa it composes the entire Lone Rock Formation above the Birkmose Member.

The Tomah Sandstones almost always contain more than 35% K-feldspar, unless they are very dolomitic, and some coarse siltstone beds locally contain 70% feldspar. This high feldspar content is related to the Tomah's exceedingly fine grain size, good sorting, and very leptokurtic kurtosis. The Tomah contains Cruziana and possibly Zoophycos trace fossil assemblages. (Note to petrology instructors -- A suite of thin sections from this outcrop is ideal for use in sedimentary petrology classes to show the strong relationship of feldspar content to grain size that is typical of all Cambrian sandstones in the Upper Mississippi Valley as well as the nature of feldspar overgrowths, the effects of environments on mineralogical sorting, and the principle that mineralogical maturity is not always related to the mineralogy of the source rocks).

The Tomah Member is usually transitional through approximately 1 meter with the overlying Reno Member. The Reno Sandstone is slightly coarser than the Tomah, usually cross-stratified, and very glauconitic. It too contains appreciable feldspar. The enrichment of glauconite in thin bands is related to reworking by currents; the glauconite bands are analogous to heavy mineral concentrations. Note that intraclasts frequently occur near the base as well as within the highly glauconitic beds, and that scour marks occur in the top of the underlying beds. The Reno Member as well as the Mazomanie Formation contains trough and some wedge and tabular-shaped cross sets. Numerous other bed forms and biogenic marks, especially burrows and trails, (Skolithos and Cruziana assemblages) are also present.

The upper part of the Lone Rock section shows the repetition of the glauconitic Reno Member with the sparingly glauconitic Mazomanie Formation. The lower portion of the upper Reno tongue is composed of the rock type that Berg (1954) and others called "wormstone" (see p.92 for description). Note that the lower tongue of the Mazomanie Formation is very fine-grained and feldspathic, whereas the upper tongue contains both quartzose and feldspathic sandstones. Quartzose Mazomanie Sandstone does not extend westward far beyond this outcrop, however, feldspathic Mazomanie Sandstone is present westward to beyond Richland Center, Wisconsin. The regional facies relations of the Lone Rock and Mazomanie Formations are shown in Figures 35 and 36 and are discussed in the paper by Odom (this guidebook).

Interpretations: Quite different interpretations of the depositional environments of the formations (Tunnel City Group) present here are presented by Odom (this guidebook) and by Byers (this guidebook). Readers are referred to these papers, however, I advise against the suggestion made by Byers that before you ponder the depositional environments you don special "eyeglasses" for the purpose of making "glauconite" invisible (see Fig. 36).

It is suggested that the origin of the massive, argillaceous "wormstone" beds in the Reno Member (beds of this nature are more numerous and thicker farther west) is related in part to bioturbation and in part to soft sediment deformation (see paper by Odom, this guidebook). This opinion is based largely on the presence of ramdomly oriented clasts that are always present. What other sedimentological processes might form this type of structure? The possibility that the "wormstones" represent tidal channel deposits has been considered, but this origin appears to be ruled out because individual beds often can be traced for many miles.

During investigations of the mineralogical and chemical nature of glauconite in the Cambrian of this area, considerable effort was made to identify the environment where the pellets initially formed. The author has hypothesized (Odom, 1976) that the pellets initially formed in the "wormstones" beds and were subsequently widely distributed in the cross-stratified sandstones by currents that reworked the "wormstones". This major evidences supporting this view are the frequent heavy concentrations of glauconite in sandstones immediately above the wormstones and the presence of scour and cut-and-fill structures in the top of the "wormstone" beds.

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NUMBER 3

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