QUATERNARY AND SILURIAN GEOLOGY AT THE MARTIN MARIETTA CEDAR RAPIDS QUARRY, LINN COUNTY, IOWA

edited by Raymond R. Anderson & Richard J. Langel

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cover photograph:
A photograph of the west highwall of the Martin Marietta Cedar Rapids Quarry that contains exposures of Silurian Scotch Grove and Gower Fm. dolomites. Pleistocene Pre-Illinoian pro-glacial sediments and glacial till, which are capped by Wisconsinan Peoria Fm. loess, overlay these dolomites.

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The lowest exposures in the Cedar Rapids Quarry.

Today's field trip will be a short visit to the Martin Marietta Materials, Cedar Rapids Quarry, in southern Linn County, Iowa. Martin Marietta, the nation's second largest aggregate producer, currently operates 32 aggregate quarries, mines, and pits in Iowa. The Cedar Rapids Quarry was first opened in 1959 and produces many grades of stone from the Silurian Gower and Scotch Grove formations. Field trip leaders will discuss depositional and post-depositional structures, rare fossils, and some spectacular mineralization.

The weathered bedrock surface, with over a meter of relief, contains a well developed, iron-rich geest (chemical weathering residual). This surface is overlain by a Quaternary section that displays a wide variety of interesting features. Pro-glacial silts are present as very dark gray layers below or in pods incorporated into one of several Pre-Illinoian tills. The till contains abundant, well-preserved spruce wood and a variety of erratics. The Peoria (Wisconsinan) Loess overlays the till. Leached and unleached facies are present within the loess. Terrestrial snails and kindchen can be found in the loess. Some spectacular pipes are developed in the loess in the west wall of the quarry.

You may collect all of the rocks and other materials that you can carry, so enjoy your visit to the quarry. Remember to wear your hard hat and safety glasses, stay away from dangerous situations, and respect the wishes of our gracious hosts, Martin Marietta Materials.

INTRODUCTION TO THE MARTIN MARIETTA CEDAR RAPIDS QUARRY

Bob Krasniewski
Martin Marietta Aggregates
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Martin Marietta Aggregates is the second largest construction aggregates producer in the United States, supplying the crushed stone, sand, and gravel used to build the roads, sidewalks, and foundations on which we live. Our four divisions are comprised of more than 300 quarries and distribution facilities in 28 states, the Bahamas, and Nova Scotia.

The roots of Martin Marietta date back to Superior Stone, an aggregates company founded in Raleigh, North Carolina in 1939. This company merged with the American-Marietta Corporation, a national producer of construction materials, paints, chemicals and other building products, in 1959. This company merged in 1961 with the Glenn L. Martin Company to form the Martin Marietta Corporation, a leader in aerospace, cement, aggregates, electronics, and chemicals. In 1993, Martin Marietta Materials was incorporated as part of the Martin Marietta Corporation. Iowa Region operations of Martin Marietta Aggregates are a part of the company's Northwest Division. As the largest aggregate producer in Iowa, Martin Marietta operates 32 mines, pits, and quarries across the state and produces sand, gravel, and a variety of crushed stone products.

The Martin Marietta Cedar Rapids Quarry (Fig. 1) has been producing quality crushed aggregate for construction, paving, and municipal customers since 1959. The Cedar Rapids Quarry produces the highest-grade aggregates, with the concrete stone supplied from the quarry rated Class 3i (suitable for interstate highway paving) by the Iowa Department of Transportation.

The section of the quarry you will tour has been in operation since the late 1980s and at its deepest point is more than 140 feet below the surface and approximately 100 feet below the adjacent Cedar River. In order to access the stone, up to 120 feet of loess, glacial till, and other materials must first be stripped.

After blasting, the raw rock material is loaded by a Caterpillar 988G pit loader into a 40-ton haul truck and transported from the pit to the processing plant. The primary crusher, a Cedarapids Model 4350H impact crusher with double spinners, provides initial breakage of the material to a top size of approximately 8 inches. The material is then stockpiled for further processing. After initial screening, secondary crushing is performed by an ANI impact crusher with adjustable curtains and tertiary crushing by a Cedarapids 4026 double roll crusher. Both secondary processing and wash plants are computer controlled.

Crushed material is initially processed on twin Deister 5x16 screens with washed product screened over a single Deister 6x20 inclined screen with spray bars. Concrete Stone is stockpiled using an Assinck computerized stacker that permits mechanical stockpiling without segregation of the material.

This quarry provides between 400,000 and 600,000 tons of finished materials to the Cedar Rapids market annually. Quarry products include Concrete Stone, Clean Asphalt Stone, Washed Chips, Manufactured Sand, Roadstone, and Aglime.

Martin Marietta is pleased to welcome the participants in the Geological Society of Iowa's Spring Field Trip, and we are happy to share our interesting geology with you.

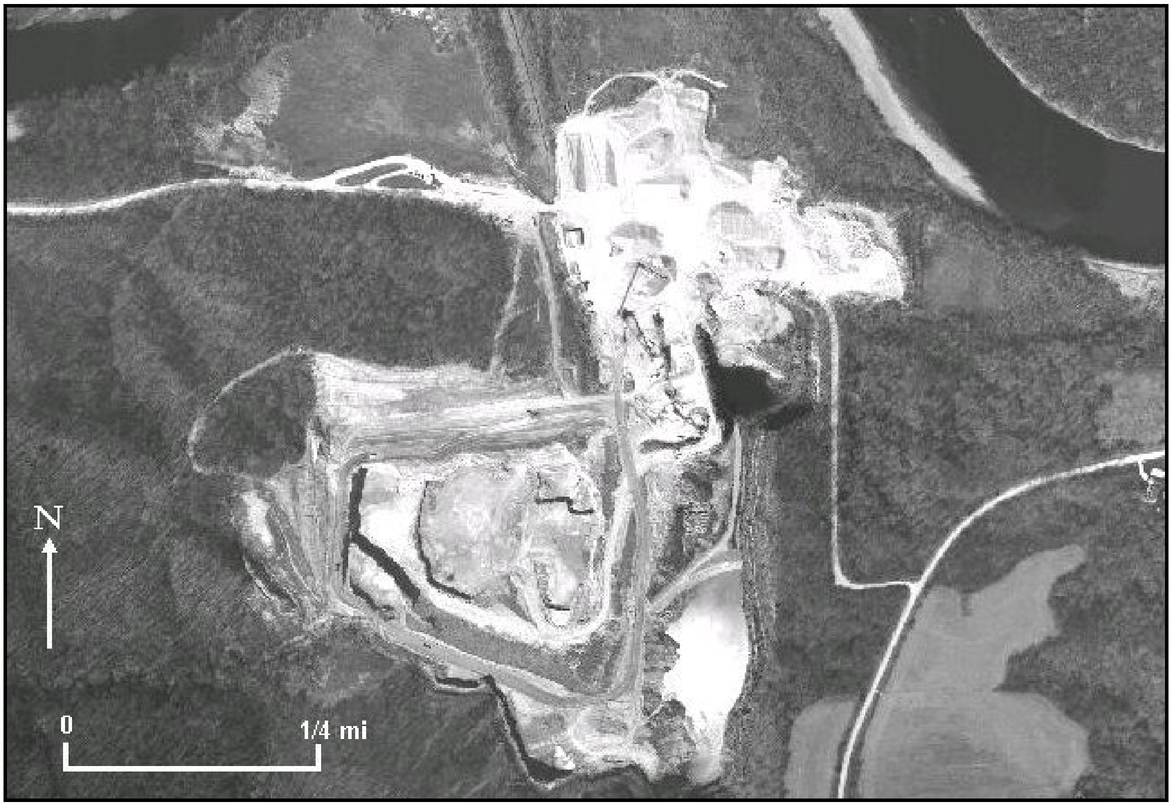

Figure 1. April 2004 aerial photograph of the Martin Marietta Cedar Rapids Quarry.

OVERVIEW OF THE QUATERNARY GEOLOGY OF MARTIN MARIETTA'S CEDAR RAPIDS QUARRY

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INTRODUCTION

A record of continental glaciation extending over the past 2 million years is preserved to varying degrees in the Upper Midwest. The record consists of deposits and weathering horizons formed during several glacial and interglacial intervals. Terrestrial sedimentary records are notoriously incomplete – they are replete with erosional unconformities and diastems marked by paleosols. Martin Marietta's Cedar Rapids Quarry exposes a Quaternary section generally representative of that encountered in the eastern portion of the Southern Iowa Drift Plain near large river valleys. The description of the section and interpretation of the sequence presented here is very rudimentary and meant to stimulate more detailed investigation of what is exposed here.

REGIONAL SETTING

Martin Marietta's Cedar Rapids Quarry is located in the Southern Iowa Drift Plain near its northern border with the Iowan (erosion) Surface (Prior, 1991). The Southern Iowa Drift Plain was glaciated several times during the interval from before 2.2 million to 500 thousand years before present (Hallberg, 1986). Quaternary deposits in this area discontinuously cover an irregular bedrock surface. Since the last Pre-Illinois glaciation of the area, an integrated drainage network has developed by episodic erosion of the landscape. Two Wisconsin Episode loess sheets mantle the landscape; these are differentially preserved as a result of late Wisconsin and Hudson (~Holocene) Episode erosion (Johnson et al., 1997).

The Quaternary record of the Southern Iowa Drift Plain is fragmentary because of multiple periods of both glacial and subaerial erosion. No primary glacial landforms remain, although scattered loess-mantled tabular divides underlain by 'Yarmouth-Sangamon' paleosols are considered to be possible remnants of the youngest Pre-Illinois drift plain (e.g., Kay and Apfel, 1929; Ruhe, 1969). The present landscape is thus dominated by stream dissection and erosional landforms. Across the Southern Iowa Drift Plain, at least four different *sets* of surfaces can be identified: the Yarmouth-Sangamon, Late-Sangamon, Iowan, and Holocene surfaces.

In eastern Iowa, the loess-mantled Yarmouth-Sangamon surface is preserved only on narrow, nearly flat upland divides. This surface is perhaps the remnant of the youngest Pre-Illinois drift plain, which was subject to weathering and local modification until burial by Wisconsin loesses. Generally, a thick gray (poorly drained) buried soil is developed on the Yarmouth-Sangamon surface. This soil was named the Yarmouth-Sangamon Paleosol (Ruhe et al., 1967) because it was presumed to transgress Yarmouth (end of Pre-Illinois Glaciation to first Illinois Episode glaciation) and Sangamon (end of Illinois Episode glaciation to beginning of Wisconsin Episode – last Interglacial) time. Unfortunately, like many other Quaternary buried soils, it was named in the context of time terms rather than independently, as recommended by the present stratigraphic code (NACSN, 1983). In strict terms, the 'Yarmouth-Sangamon Paleosol' is a facies of the Sangamon Geosol because the units that bury and stratigraphically define them are equivalent.

The Late-Sangamon surface is a set of erosion surfaces cut into and inset below the Yarmouth-Sangamon surface of the primary divides. The break between the Yarmouth-Sangamon and Late-Sangamon surfaces is marked by topographic, geomorphic, and pedologic discontinuities (Ruhe et al., 1967; Hallberg et al., 1978b). In eastern Iowa, the Late-Sangamon surfaces generally consist of gently sloping loess-mantled pediments that are now only partially preserved as steps (levels) at about the same elevation on interfluves within a given, relatively small drainage basin. In localized areas, other parts of the Late-Sangamon landscape, from the pediments to the valley-slope fans to the floodplain, are preserved. After, and in part during, the later stages of cutting of the Late-Sangamon erosion surfaces, soil formation processes became dominant over erosion processes, indicating a change to relatively more stable hillslope conditions. Soil formation continued until the rate of Wisconsin Episode loess accumulation exceeded pedogenic mixing rates. The loess-mantled buried soil on the Late-Sangamon paleogeomorphic surface has been called the Late-Sangamon Paleosol in Iowa (e.g., Ruhe et al., 1967; Hallberg et al., 1978b). Compared to the Yarmouth-Sangamon paleosols, Late-Sangamon paleosols are generally less weathered, have thinner sola, and are better drained with generally red to reddish-brown colors (Ruhe, 1969; Hallberg et al., 1978b, 1980a). Late Sangamon paleosols are typically developed in multiple parent materials: 1) an upper unit of "pedisediment," sediment derived from upslope erosion of the pediment; 2) a stone zone or gravel lag that marks the pediment/erosion surface; and 3) underlying glacial deposits (Canfield et al., 1984; Ruhe et al., 1967; Ruhe, 1969). Pedogenesis commonly continued during slow burial by Wisconsin Eposide Pisgah Formation deposits, resulting in upbuilding of the Late-Sangamon Paleosol and "welding" (pedogenic overprinting and joining together) of the Farmdale Geosol, formed in Pisgah Formation loess and colluvium, to the Late Sangamon Soil. In strict terms, the Late-Sangamon Paleosol is also a facies of the Sangamon Geosol because the stratigraphic units that bury and define it are the same as those in the type area of the Sangamon Geosol (Athens Quarry in Menard County, Illinois).

Another set of erosion surfaces, called the Iowan Surface, are inset below the Late-Sangamon surfaces in the Southern Iowa Drift Plain. This set of erosion surfaces has been referred to by various terms in previous literature: the "Iowan surface" (Ruhe et al., 1968; Prior, 1991), the "Iowan Erosion Surface" (Ruhe, 1969; Hallberg et al., 1978b), and the "Early Wisconsin pediment" (Ruhe et al., 1967). The break between the Late-Sangamon and Iowan surfaces is again marked by topographic, geomorphic, and pedologic discontinuities. In eastern Iowa, the Iowan Surface consists of gently sloping, loess-mantled pediments that are generally shorter in length than the Late-Sangamon pediments. Again, only remnants of these pediments are preserved, and they occur as steps or levels down interfluves below Yarmouth-Sangamon and Late-Sangamon surfaces. The Iowan Surface represents a renewed period of relatively rapid downcutting, and it is again marked by a stone zone or gravel lag that is commonly overlain by a thin increment of colluvium formed as the erosion surface developed upslope. The Iowan erosion surfaces were cut just prior to and during the Wisconsin glacial maximum (c.a. 21,000-16,500 B.P.; Bettis and Kemmis, 1992). Regional deposition of Peoria Formation loess began during development of the surfaces: Peoria Loess is thinner on Iowan surfaces than on Yarmouth-Sangamon and Late-Sangamon surfaces upslope, and basal radiocarbon ages of the loess are younger on the Iowan surfaces (Hallberg et al., 1978b; Ruhe et al., 1968). Early increments of Peoria Formation loess accumulated on the relatively "stable" Yarmouth-Sangamon and Late-Sangamon surfaces, but did not accumulate where the Iowan erosion surface was actively being developed. During the later phases of Peoria Formation loess deposition, the Iowan surfaces stabilized and the last increments of loess were deposited on them. No buried soil is present on this surface because it was immediately buried by Peoria Formation loess.

A final period of downcutting and headward extension of the drainage system has occurred during the Hudson Episode (Holocene). These post-Wisconsin Episode erosion surfaces are present on portions of upland slopes and in the upper part of the drainage network as a result of headward stream extension. These surfaces descend to alluvial valleys that consist of a series of multiple, often subtle terraces underlain by deposits of the DeForest Formation (Bettis, 1990; Bettis et al., 1992).

In different parts of the Southern Iowa Drift Plain various surfaces dominate the landscape because of differential preservation (Hallberg et al., 1980; 1978b; Ruhe, 1969). In much of east-central and southern Iowa, the loess-mantled Late-Sangamon surface is best preserved. Martin Marietta's Cedar Rapids Quarry has exposed several cross-sections of a Late-Sangamon interfluve.

WEATHERING ZONES AND WEATHERING ZONE TERMINOLOGY

One of the most obvious features of sediment is its color. Some color variations in Quaternary deposits are the product of distinctive source rocks, such as the reddish tills deposited by glaciers flowing out of the Lake Superior Basin. However, most glacial tills in the Upper Midwest were shades of gray or grayish brown when originally deposited, while loesses were originally yellowish brown. The movement of water, the activity of microbes, and fracture development in the sediments since deposition have altered the original colors, chemistry, and porosity in a systematic fashion below the modern soil profile, as well as beneath now buried soils formed on ancient landscapes. These systematic subsoil alterations are grouped into a series of "weathering zones" that display predictable relationships and can be used to identify stratigraphic breaks and interpret water table history.

Weathering zone terminology refers to the shorthand phrases used to describe weathering-related features of sediments. The terminology is applied only to deposits that are below the solum (A and B horizons – topsoil).

Weathering zones in glacial sediments have been described on the basis of the presence or absence of matrix carbonates, presence or absence of fractures, and interpreted oxidation state as suggested by color and mottling pattern. The standard terminology discussed here concentrates on features that are easily and routinely observed in the field with the use of one's eyes, a Munsell color book, and an acid bottle.

Oxidation Zones

Oxidation in sediments is related to the state of aeration. Oxidized sediments exist in an environment where the oxygen supply is high, or exceeds the biological oxygen demand. Iron is the most commonly oxidized element in midwestern glacial sediments. The oxidation of iron, from the ferrous (FeII) to the ferric (FeIII) state, disrupts the electrical neutrality of the crystal lattice, promoting the formation of an oxide, hematite ($Fe_2 O_3$) or hydrous oxides such as goethite and limonite. These iron minerals impart a brown color to the sediment.

Reduction (deoxidation) occurs in an environment where the oxygen supply is limited or the biological oxygen demand is high. Saturation or near saturation and the presence of organic matter and microbes are prerequisites for this process. In a deoxidized environment, iron is reduced to a mobile ferrous form. Once in this form, iron may be lost through net movement of the groundwater, it may remain in the sediment matrix and react with sulfides, or it may move into fractures, pores, or other small openings in the sediment and be oxidized. Matrix colors in a deoxidized or reduced zone range from gray to greenish gray, a condition reflecting relatively low free iron oxide content. In contrast to the grayish matrix, fractures and pores in the deoxidized zone, where iron has migrated and become oxidized, appear as brown and reddish brown stains, streaks, and mottles.

An unoxidized state occurs when the sediment has not been exposed to oxygen or oxygenated water. Most iron is in the ferrous form in this state, and the sediment matrix is a uniform gray color without the brown or reddish brown stains, streaks, and mottles characteristic of the deoxidized or reduced weathering zone.

Carbonate Status - Leached and Unleached Zones

Most of the glacial tills and all of the loess in the Upper Midwest were originally deposited in a calcareous state – with finely divided carbonate in the sediment matrix. Leaching of sediments commences with the removal of matrix carbonates. This process involves the formation of weak acids as rainwater passes through the atmosphere and the surface soil. These acids react with carbonate minerals to release the highly mobile calcium ion, which then moves with the soil water and groundwater. As calcium ions move downward with infiltrating water into calcareous deposits, or in evaporative situations as water is evaporated, the water carrying the ions may become supersaturated with respect to calcium, and carbonate will precipitate to form coatings, patches, and nodules.

Weathering Zone Terminology

Hallberg et al. (1978) developed shorthand weathering zone terminology that is applicable to unlithified sediments of the Upper Midwest. The descriptive system contains two sets of terminology, one for use with loess and another for till. The choice of which set to use with other kinds of sediments, such as alluvium, is dependent on whether the sediment is more like loess or till. Each weathering zone is defined in terms of a range of moist Munsell colors (if samples are allowed to dry they may change color irreversibly), reaction with dilute (10-15%) HCl, presence or absence of mottles, presence or absence of secondary accumulations of carbonates, and presence or absence of visible fractures.

<u>Loess</u>
<u>First Symbol</u> – color reference
O – oxidized; 60% of matrix has hues of 2.5Y or redder, values of 3 or higher, may have mottles

D – deoxidized; 60% of matrix has hues of 10YR, 2.5Y, and/or 5Y, values of 5 and 6, and chroma of 1 or 2 with segregation of iron (ferric oxides) into mottles, tubules, or nodules

U – unoxidized; matrix has hues of 5Y, 5GY, 5GB, and 5G, values of 4, 5, or 6, and chroma of 1 or less, with no secondary segregation of ferric iron into mottles, tubules, or nodules

<u>Second Symbol</u> – leached or unleached state
U – unleached; matrix reacts vigorously with dilute HCl, primary carbonates present

U2 – unleached; primary carbonates present, has secondary accumulations of carbonate as coatings or nodules

L – leached; no carbonate detectable with dilute HCl

L2 – leached; primary carbonates absent, secondary accumulations of carbonate as coatings or nodules present

<u>Modifier Symbols</u> – when used precede first symbol
M – mottled; refers to zones containing 20-50% contrasting mottles

J – jointed; describes the presence of well-defined subvertical to vertical fractures, these often show oxidized and deoxidized colors and may have coatings of secondary iron oxides, manganese oxides, or other secondary minerals such as calcite or gypsum

<u>Till</u>
<u>First Symbol</u> – color reference
O – oxidized; 60% of matrix has hues redder than 2.5Y, or hues of 2.5Y with values of 5 or higher, may have mottles

R – reduced; 60% of matrix has hues of 2.5Y with values of 3 or less, hues of 2.5Y with values of 4 and chroma of 2 or less, hues of 5Y, N, 5GY, 5G, and 5BG, and values of 4 or higher. Colors in this zone are almost always mixed as diffuse mottles, streaks, and diffuse blends of colors. There may be considerable segregation of secondary iron compounds (with oxidized colors) into mottles, tubules, nodules, or sheets along fractures and other discontinuities.

U – unoxidized; matrix uniform color with hues of 5Y and N, values of 5 or less, 5GY, 5G, or 5BG with values of 6 or less, with no mottles, nodules, etc.

Secondary and modifier symbols are the same as those applied to loess.

Examples

Loess:

OL - oxidized, leached; yellowish brown (10YR5/3) matrix, leached (does not react with weak HCl)

MDU - mottled, deoxidized, unleached; grayish brown (2.5Y5/2) matrix with strong brown (7.5YR5/6) mottles and tubules, unleached (reacts strongly with dilute HCl)

Till:

UU - unoxidized, unleached; uniform very dark gray (5Y3/1) matrix, unleached

JUU - jointed, unoxidized, unleached; uniform dark greenish gray (5G4/1) matrix with few thin vertical fractures that have mottled olive (5Y5/6) and olive gray (5Y5/2) faces with thin discontinuous black (2.5Y2.5/1) patches of manganese oxide accumulation, unleached

MJOL2 - mottled, jointed, oxidized, leached with secondary carbonate accumulation; brownish yellow (10YR6/6) matrix with brown (7.5YR5/3) and grayish brown (2.5Y5/2) mottles, common vertical fractures with almost continuous strong brown (7.5YR4/6) iron segregations and thin discontinuous coatings of secondary carbonate on faces, few small secondary carbonate concretions (nodules), leached matrix

Discussion

Weathering zone boundaries are usually transitional. Oxidation and leaching proceed downward from a land surface in a predictable manner, producing a typical expected vertical sequence of weathering zones. The following table shows complete vertical sequences expected for loess and till.

Loess	Till
solum	solum
OL	OJL
JOL2	MOJL
MJOU	MOJL2
MDU	MOJU
DU	MRJU
UU	RJU
	MUJU
	UJU
	UU

With slight modifications to adjust for regional variations in primary matrix color and carbonate status, this terminology is applicable to most Quaternary continental glacial sequences.

Interpretation of Stratigraphic Breaks

Weathering profiles have predictable vertical sequences progressing downward from a land surface. The progression of weathering zones varies with landscape position, primarily in response to the position of the long-term water table and organic matter content (these factors strongly influence the oxidation state and distribution of iron-oxide compounds). The intensity of leaching, related in large part to macroclimate (seasonal distribution of rainfall, temperature, and thus vegetation composition), controls matrix carbonate status (assuming originally calcareous materials). Weathering zone characteristics, then, can provide reliable information on both macroclimate and local landscape relationships within a sequence of glacial deposits.

The depth to which oxygenated water is able to penetrate the deposits controls the vertical extent of the weathering profile. In continental settings, the percolation of oxygenated waters through matrix-dominated Quaternary glacial sequences is controlled in large part by relief on the landscape. Oxygenated waters penetrate to greater depths, and the oxygenated portion of the weathering profile thickens, as the local and regional drainage network develops and landscape dissection increases. In a general sense, a regional drainage network progressively develops as time passes following a continental glaciation. Since the development of the weathering profile and the evolution of a regional drainage network are linked, the thickness and character of the oxidized portion of the weathering profile beneath paleo-upland positions provides us with a reasonable way to compare the relative rank (interglacial vs. interstadial) of stratigraphic breaks in the glacial record (Bettis, 1998).

Applications in Environmental Geology

Secondary weathering profile properties of Quaternary deposits allow us to infer water-table history, redox conditions, and some hydrogeologic properties that are important considerations in understanding water and contaminant movement in these sediments. Hydraulic conductivity of glacial tills increases from unoxidized (UU) to oxidized (O) to fractured (JO) weathering zones. Fractures in these sequences provide avenues for rapid water movement. There are two categories of hydraulic conductivity in these sediments; primary, or matrix conductivity, and secondary – that associated with the fracture network. The latter is commonly two or three orders of magnitude greater than the primary conductivity.

Fractured tills are also characterized by two specific storage values; intergranular specific storage associated with the sediment matrix and the specific storage associated with the fracture network. During pumping of an underlying aquifer, changes in head are rapidly transmitted from fractures, producing rapid responses in wells whose screened intervals intersect open fractures, while piezometers screened in unfractured till respond much more slowly because their water is released by the much slower process of intergranular consolidation.

Fracture networks, then, are responsible for relatively rapid vertical and lateral movement of water and contaminants through these deposits that have low matrix permeability. Since fracture networks in these deposits become denser, and more interconnected from the unoxidized to the oxidized weathering zones (toward the land surface with which they are associated), recognition and description of weathering profiles in cores and auger samples, often too small or of insufficient quality to permit direct observation of fractures and fracture networks, provides a qualitative measure of fracture networks and the development of secondary hydraulic conductivity and specific storage associated with the fracture network.

Weathering zones also provide information about water-table history and redox conditions. Reduced zones form when oxygen availability is low or biological oxygen demand exceeds oxygen availability. These situations occur under saturated conditions and low eH. The presence of a reduced weathering zone therefore usually indicates a water table within or above that zone and strong reducing conditions. A reduced weathering zone often marks the outer fringes of organic contaminant plumes. If mottles or streaks of oxidized iron are present in a reduced zone, indicating fluctuating eH conditions, caution needs to be taken to ensure that the reduction features reflect present saturated conditions rather than relict saturated conditions of a former period.

THE QUARRY'S QUATERNARY SUCCCESSION

Wisconsin Loess

Two loess units were deposited during the Wisconsin Episode across eastern Iowa (Bettis et al., 2003a). The oldest is a thin sheet that has largely been reworked by colluvial (including periglacial) processes and pedogenically altered. This unit is referred to as the Pisgah Formation. Its stratigraphic position is the same as the Roxana Silt of Illinois and the Gilman Canyon Formation of Nebraska, but its lithologic properties differ. The youngest Wisconsin Episode loess is Peoria Formation loess. In eastern Iowa, this loess is thickest near river-valley sources, such as the Cedar Valley.

Both loess units are present in this exposure. Peoria Formation silt (Peoria Loess) is the uppermost deposit in the section. The quarry's proximal position to the source, the late-glacial Cedar Valley, causes the section to be exceptionally thick in the quarry. Regional relationships indicate that the Peoria Formation began to accumulate on the late glacial landscape about 23,000 B.P. and continued to accumulate until about 11,000 B.P. Deposition was most rapid from about 21,000 to 16,000 years ago during the coldest and driest portion of the late glacial period. Tests of land snails that lived on the late-glacial forest floor are quite prominent in this exposure.

Much thinner Pisgah Formation loess is present beneath the Peoria. The Pisgah is slightly denser, grayer color, leached of carbonates and has occasional pods of transported Farmdale Geosol in its upper part. The Farmdale Geosol was originally formed in the upper part of the Pisgah Formation but was eroded and transported downslope by solifluction during the early part of the full glacial period before the rate of Peoria Loess accumulation was great enough to bury the Pisgah Formation (Bettis et al., 2003b).

Pre-Illinoian Sequence

Pre-Illinoian glacial deposits of Iowa are monotonously similar; where unweathered, the diamictons (glacial tills) are all gray and have similar loam textures. As a consequence, regional stratigraphic differentiation has been made using laboratory data rather than field properties. Further, the stratigraphic units are differentially preserved beneath different paleogeomorphic surfaces that have developed as the regional drainage system evolved following the last Pre-Illinois glaciation. A definitive stratigraphic sequence was constructed only after an exhaustive regional drilling program that included transects across the different surfaces and across bedrock valleys where the thickest and often most complete stratigraphic sequences were preserved (Hallberg, 1980a, b).

Pre-Illinoian deposits have been lithostratigraphically classified into the Alburnett Formation and younger Wolf Creek Formation (Hallberg, 1980a). Both formations are predominantly glacial diamictons (largely basal tills), but include other deposits as well. The formations and their members are differentiated by various physical and mineralogical characteristics, but clay mineralogy is the main property used to distinguish between deposits at the formation level (Hallberg, 1980a, b). Whereas some lithostratigraphic units, such as the Wedron and Glasford formations of Illinois, may also correspond to diachronic intervals (Johnson et al., 1997), the Wolf Creek and Alburnett formations do not; each formation consists of multiple depositional units and paleosols, and includes deposits of several glacial and interglacial episodes. The Wolf Creek and Alburnett formations, therefore, are not correlative in any way to the former concepts of 'Kansan' and 'Nebraskan' glaciations, outdated concepts based on inadequate stratigraphic data (Hallberg, 1986; Boellstorff, 1978). In western Iowa, where thicker sequences are preserved, stratigraphic units correlative to the Wolf Creek and Alburnett formations overlie still older glacial deposits (Hallberg, 1986). In the absence of radiocarbon dating, absolute ages for the different Pre-Illinois stages are unknown, although fission-track ages on volcanic ashes buried within the western Iowa sequence provide some time control (e.g., Boellstorff, 1978; Hallberg, 1986). The oldest Pre-Illinois glacial deposit in western Iowa underlies a volcanic ash with a fission-track age of 2.2 million years B.P., and the youngest Pre-Illinois glacial deposit overlies a volcanic ash dated at about 610,000 years B.P., and is estimated to be about 500,000 years old (Hallberg, 1986). Paleomagnetic study of the detrital remnant magnetism (DRM) of tills at Conklin Quarry in Iowa City indicates that deposits of the Alburnett Formation have reversed polarity, and are thus interpreted to be older than 790,000 years ago (the Bruhnes reversed/Matuyama normal boundary; Johnson, 1982), whereas deposits of the Wolf Creek Formation have normal polarity, and are younger than 790,000 years old (Baker, 1985; Baker and Stewart, 1984). At Conklin Quarry, the Bruhnes/Matuyama boundary occurs within sub-Wolf Creek Formation slopewash and alluvium that the Westburg Geosol is formed in (Charles Rovey and E.A. Bettis III, unpublished data).

The Wolf Creek Formation is dominated by massive, texturally and compositionally uniform basal tills, and is subdivided into members based on lithologic differences (calcite/dolomite ratio and sandfraction lithology) between these tills. Diamicton units within the Alburnett Formation, however, have virtually identical properties; as yet there is no way to differentiate or correlate Alburnett Formation deposits on a regional scale.

Because we have not yet undertaken clay mineral or other laboratory analyses of the deposits exposed in the Martin Marietta Cedar Rapids Quarry, we refer to the glacial diamictons and associated deposits here as "Pre-Illinoian undifferentiated." The sequence exposed along the quarry's west face consists of at least three glacial diamictons distinguished on the basis of weathering profiles and deformed zones (glacially tectonized). The uppermost diamicton (diamicton 3) has the Sangamon Geosol (Late Sangamon paleosol) formed in its upper part, and is modified by the development of a weathering profile related to that soil. This unit is truncated by a subareal erosion surface (the late Sangamon Paleogeomorphic surface) on the south end of the exposure (Figure 1). Diamicton 3 rests unconformably on diamicton 2. The upper part of diamicton 2 has cobbles lodged in it and contains abundant sheared

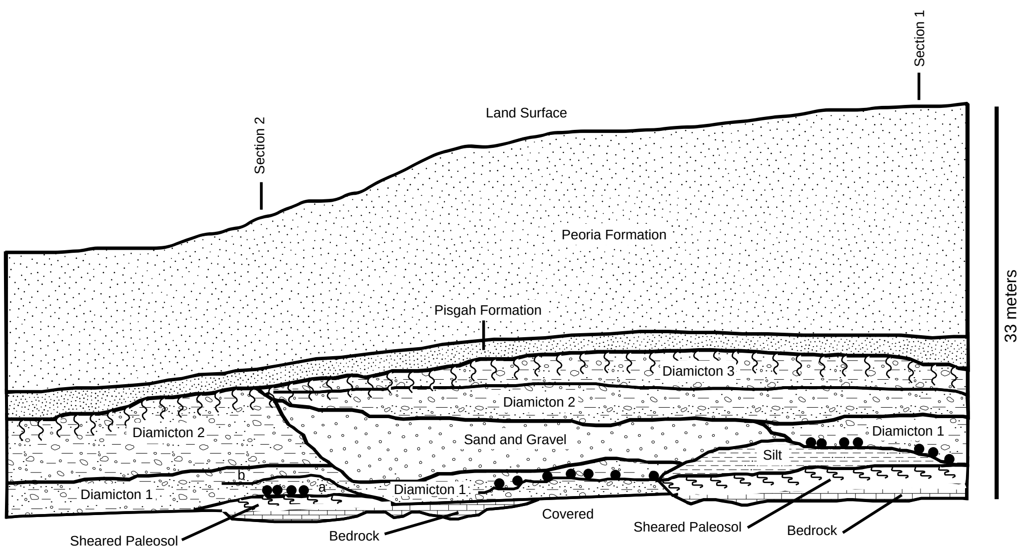

Figure 1. Sketch of Quaternary section exposed along north quarry wall on April 7, 2005. Vertical exaggeration is approximately 3X.

sand and silt bodies that grade downward into pervasively sheared loamy diamicton (Figure 2). Diamicton 2 unconformably overlies a truncated weathering profile formed in diamicton 1 (Figure 3). On the north end of the exposure, the contact appears as an abrupt transition from the MRU weathering zone formed in the lower part of diamicton 2 to unweathered (UU) diamicton 1, while on the south end of the exposure the contact is marked by a sheared zone and cobble concentration (stone pavement?) at the top of diamicton 1. A large sand and gravel body that occurs beneath diamicton 2, and that buries diamicton 1, may represent proglacial outwash or subglacial sand and gravel associated with diamicton 2. Diamicton 1 ranges from massive to pervasively sheared and contains common coniferous wood (many stumps and logs) at its base. On the north end of the exposure, diamicton 1 buries deformed organic-rich silt that may represent proglacial sediments in which a coniferous forest grew before the glacier that deposited diamicton 1 overrode it.

Basal Paleosol Formed in Weathered Limestone

A deformed paleosol occurs beneath the Quaternary deposits exposed in the west face (Table 1, Figure 1). The paleosol is eroded at its top, silt loam to silty clay loam texture, and has undergone extensive shear deformation. The sheared paleosol rests abruptly on a silica-cemented chert nodule layer in weathered Silurian limestone bedrock. This paleosol is a rather unique occurrence, in nearly all sections the authors have observed in eastern Iowa Pre-Illinoian glacial deposits rest on a glacial erosion

Figure 2. Faulted and folded stratified sand and silt beneath diamicton 2 just north of measured section 2. Knife is approximately 20cm long. Photo by A. Haj.

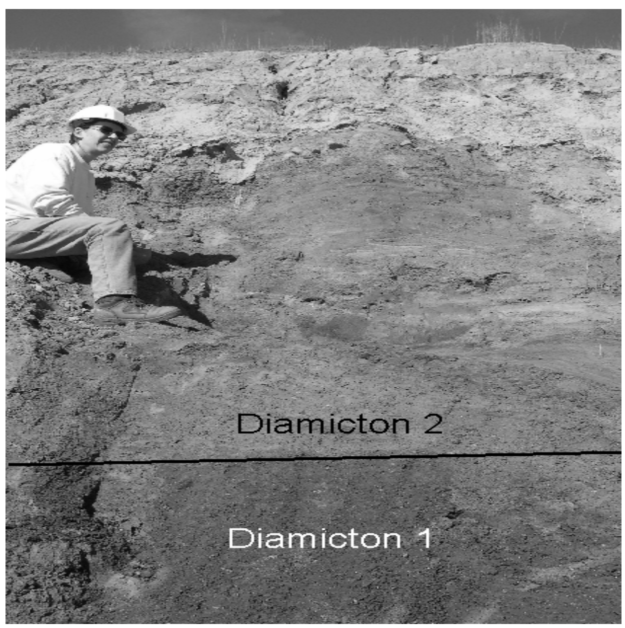

Figure 3. Contact between diamicton 2 and diamicton 1 in the northern part of the exposure. The contact is marked by an abrupt and relatively flat transition from the MOU-MRU (lighter colored) weathering zone formed in diamicton 2 to the UU weathering zone (darker color) in diamicton 1. Close examination of the exposure indicates that the upper part of diamicton 1 is sheared and is denser than the overlying diamicton 2. Photo by A. Haj.

surface developed on the bedrock surface. The age of this paleosol is unknown – it may represent pre-Quaternary weathering or weathering of an exposed rock surface during the Quaternary. Upper parts of the paleosol were deformed during advance of the first Pre-Illinoian glacier to deposit till at this locality.

Table 1. Measured sections 1 and 2, west quarry face

Section 1

Depth (m)	weathering zone	Description
		Peoria Formation silt facies
0-1.75	OL	Brown silt loam loess with surface soil developed in upper 1.2m
1.75-5.25	MOU	Brown silt loam loess with few large gastropod shells, weakly to moderately calcareous
5.25-7.83	MOU	Weakly bedded brown silt loam loess, few small gastropod shells, calcareous
7.83-9.68	MOL	Brown silt loam loess, few to common small gastropod shells, very weakly calcareous to noncalcareous
9.68-20.98	MOU-MDU	Brown silt loam calcareous loess with common gray and yellowish brown (iron) streaks, common gastropod shells, moderately calcareous
		Pisgah Formation loess
20.98-22.59	DL-MOL	Gray to brown silt loam loess with common iron streaks and mottles, very few pods of organic-rich loess in upper 15cm – these are soliflucted remnants of the Farmdale Geosol, noncalcareous
		Sangamon Geosol (Late Sangamon paleosol) formed in undifferentiated Pre-Illinoian glacial diamicton
22.59-23.49	paleosol	Approximately 30 cm of stone-poor pedisediment overlying a diffuse stone zone, profile is truncated and consists of a 40cm thick strong brown Bt horizon grading downward into a brown BC horizon, all noncalcareous
		Undifferentiated Pre-Illinoian glacial diamicton (diamicton 3)
23.49-25.24	RJL	Grayish brown fractured glacial diamicton, deformed sandy loam pod at top of zone
		(diamicton 2)
25.24-26.04	MOU-MRU	Sandy and silty diamicton with lodged cobbles in upper surface, strongly calcareous
26.04-27.34	MOU-MRU	Sheared loamy diamicton, strongly calcareous

		(diamicton 1)
27.34-30.74	UU	Loamy diamicton, strongly calcareous, upper contact is abrupt
		Proglacial? silts
30.74-31.94	UU	Sheared organic-rich silt with occasional conifer wood (stumps), top of the unit defines a broad folded zone, occasional pyrite
		Unnamed Paleosol formed in weathered limestone
31.94-32.54	paleosol	Deformed and sheared silt loam and silty clay loam, common iron staining, noncalcareous, rests on weathered, silica-cemented chert nodule zone in weathered Silurian bedrock

<u>Section 2</u>

Depth (m)	weathering zone	Description
		Peoria Formation **silt facies**
0-0.45	Surface soil	Surface soil formed in silt loam loess, noncalcareous
0.45-7.95	MOU	Brown silt loam loess, very few gastropod shells, moderately calcareous
7.95-13.2	MOU	Brown silt loam loess, common gastropod shells, few hard carbonate nodules, moderately to strongly calcareous
		Pisgah Formation loess
13.2-15.05	DL	Gray silt loam loess with iron mottles, noncalcareous
		Sangamon Geosol (Late Sangamon paleosol) formed in undifferentiated Pre-Illinoian glacial diamicton
15.05-16.0	Paleosol	Strong brown weathered glacial diamicton, soil surface is truncated, diffuse stone zone over 55cm thick Bt horizon grading downward to BC horizon, noncalcareous
		Undifferentiated Pre-Illinoian glacial diamicton (diamicton 2)
16.0-17.75	MOL	Brown loamy glacial diamicton overlying faulted and folded stratified fine to medium sand and silt, noncalcareous
17.75-21.95	UU	Dark grayish brown glacial diamicton, strongly calcareous
		(diamicton 1b)
21.95-23.2	UU	Sheared dark grayish brown glacial diamicton with streaks of reddish brown silt loam defining shear planes, concentration of cobbles at top of horizon, strongly calcareous

		(diamicton 1a)
23.2-23.35	UU	Sheared dark grayish brown diamicton with streaks and pods of underlying paleosol, common sheared silt loam and wood traceable to proglacial silts and wood to north, strongly calcareous
		Unnamed paleosol formed in weathered limestone
23.35-24.3	paleosol	Sheared silty clay loam paleosol formed on weathered rock, noncalcareous

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SILURIAN GEOLOGY AT THE MARTIN MARIETTA CEDAR RAPIDS QUARRY

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INTRODUCTION

The rocks seen at the Martin Marietta Cedar Rapids Quarry (MMQ) were deposited about 425 million years ago during the Silurian Period. During the middle Silurian, this area lay in the southern tropics, beneath the warm, shallow waters of a vast seaway that covered much of the interior of North America. This environment was very conducive for the proliferation of marine organisms that utilized lime ($CaCO_3$) in their shells and skeletal structure.

Downcutting of the Cedar River in this area has exposed an instructive and picturesque array of Silurian rocks, revealing an ancient reef-like accumulation of mounded carbonate sediments. Such mounded features are widely distributed in Silurian strata of North America and particularly well known in the Great Lakes area from Ohio to Wisconsin. Of all the many exposures of these features known in the Midwestern United States, those at nearby Palisades-Kepler State Park (PKSP) and in this quarry provide among the best and most complete portrayals of these mounded reef-like accumulations available for geologic study.

The Silurian exposures in this region, especially at PKSP, have been the subject of numerous geologic studies. Norton (1895, p. 129) noted the exposures "front the river in vertical cliffs locally called the Palisades," which reach a maximum height of 89 feet. Philcox (1970, 1971, 1972) was the first to study the exposures at PKSP in detail, describing them as a coalesced complex of mounds. He interpreted the mounds to have been largely constructed of carbonate (lime) mud with an abundance of crinoid (sea lilies) debris and locally common corals. Philcox recognized these crinoidal mud mounds were succeeded in time by a second stage of mound growth typified by an abundance of brachiopod shells and an absence of crinoid material. Mikulic (1979) identified local "pockets" within the crinoidal mounds containing remarkable accumulations of trilobite and nautiloid fossils, probably within depressions or fissures developed within the lithified mound. Witzke (1981a,b, 1983, 1985, 1987a, 1992; Witzke and Johnson, 1999) studied the stratigraphy and paleontology of the mounded complex at PKSP. He included the crinoidal mud mounds in the upper Scotch Grove Formation (Figs. 1, 2) and he defined a new member to include these strata, the Palisades-Kepler Member, whose name derives from the state park (the type locality). Witzke included the succeeding generation of brachiopod-rich mound deposits within the Gower Formation, Brady Member.

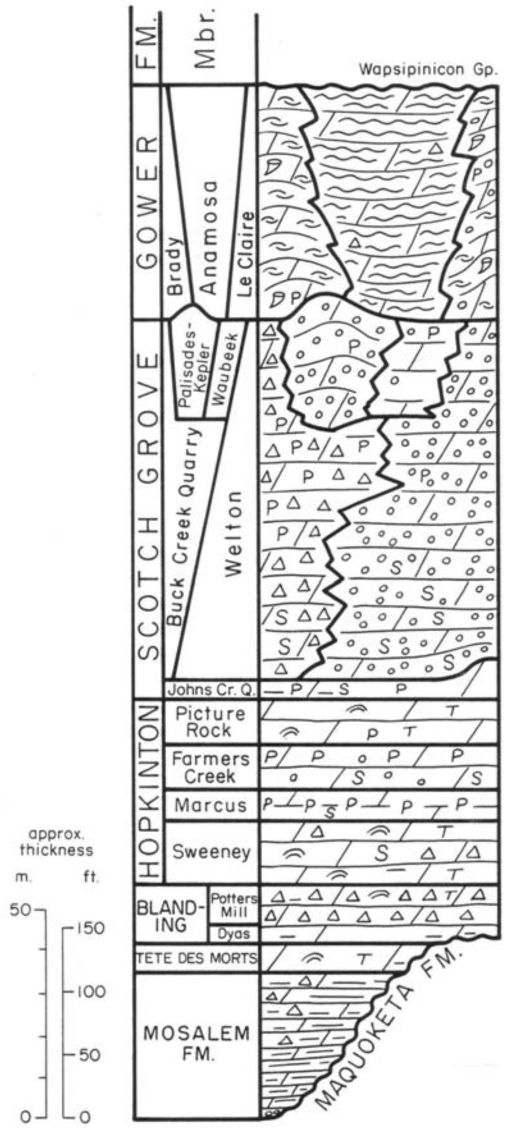

Figure 1. Generalized stratigraphic column of the Silurian System for eastern Iowa (Witzke, 1992).

SILURIAN UNITS AT THE MMQ

Two of the uppermost formations in the Silurian succession of Iowa, the Gower Formation and underlying Scotch Grove Formation (Fig. 1), are exposed at the MMQ. Both units are composed of members that are dominated by carbonate mounds and inter-mound members.

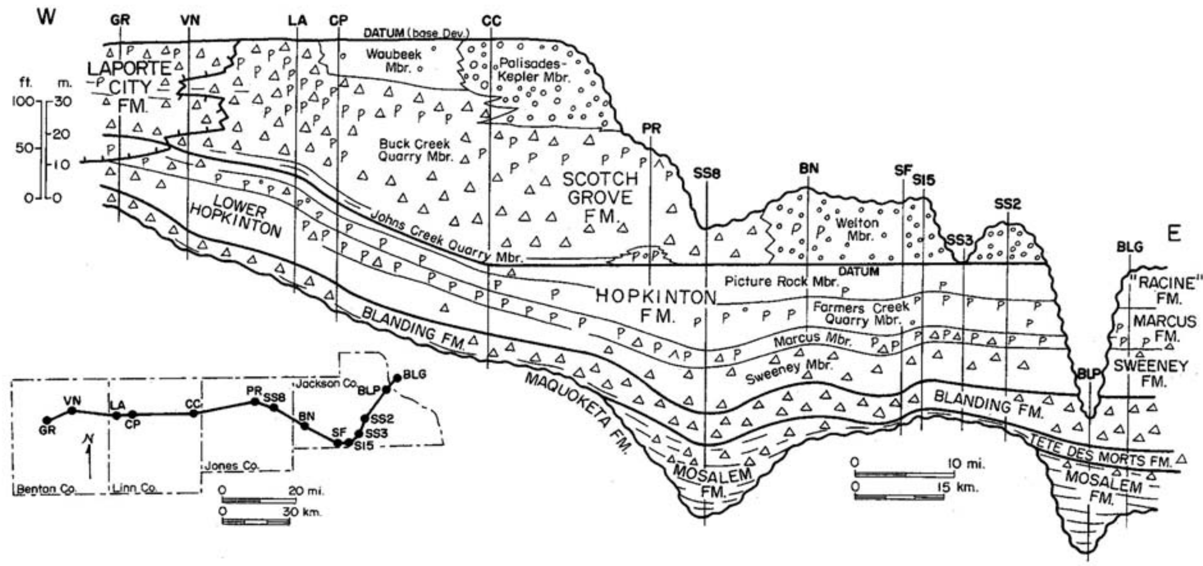

Figure 2. Stratigraphic cross-section of Silurian dolomite units, eastern Iowa. The LaPorte City Fm. is a western limestone facies. Control points include both core and outcrop sections. Datum shifts from base of Devonian in the west to base of Scotch Grove Fm. in eastern outcrops. See Figure 3 for lithologic symbols.

Gower Formation

The Gower Formation, the youngest Silurian formation recognized in Iowa, is subdivided into two distinct phases in Linn, Johnson, Cedar, and Jones counties. The regionally dominant inter-mound phase is characterized by finely laminated, horizontally-bedded strata assigned to the Anamosa Member. The brachiopod-rich mounded phase is known as the Brady Member. A third phase, the LeClaire Member, is recognized in the Quad Cities area of Scott and Muscatine counties (Witzke, 1992).

As seen in the MMQ/PKSP area, the Gower Formation is generally conformable above the Scotch Grove Formation. The formational contact is abruptly marked by a shift to laminated dolomite strata in the inter-mound areas. Above the mounded Palisades-Kepler Member, Brady strata also are apparently conformable in most areas of the mound complex, and the contact can be generally marked at the base of the first brachiopod-rich debris flow. However, the top 1 to 3 meters of the underlying Palisades-Kepler Member illustrates a degree gradation into the overlying Gower beds, commonly showing a general upward decrease in the abundance and size of crinoidal material. Strata of the Gower Formation entirely lack crinoid debris. Philcox (1972) suggested some of the crinoidal mound crests were locally and temporarily exposed to subaerial erosion prior to their burial by Gower sediments (a possible erosional surface separates Scotch Grove and Gower strata at the old quarry workings at the south end of the dam at the Palisades-Natural area).

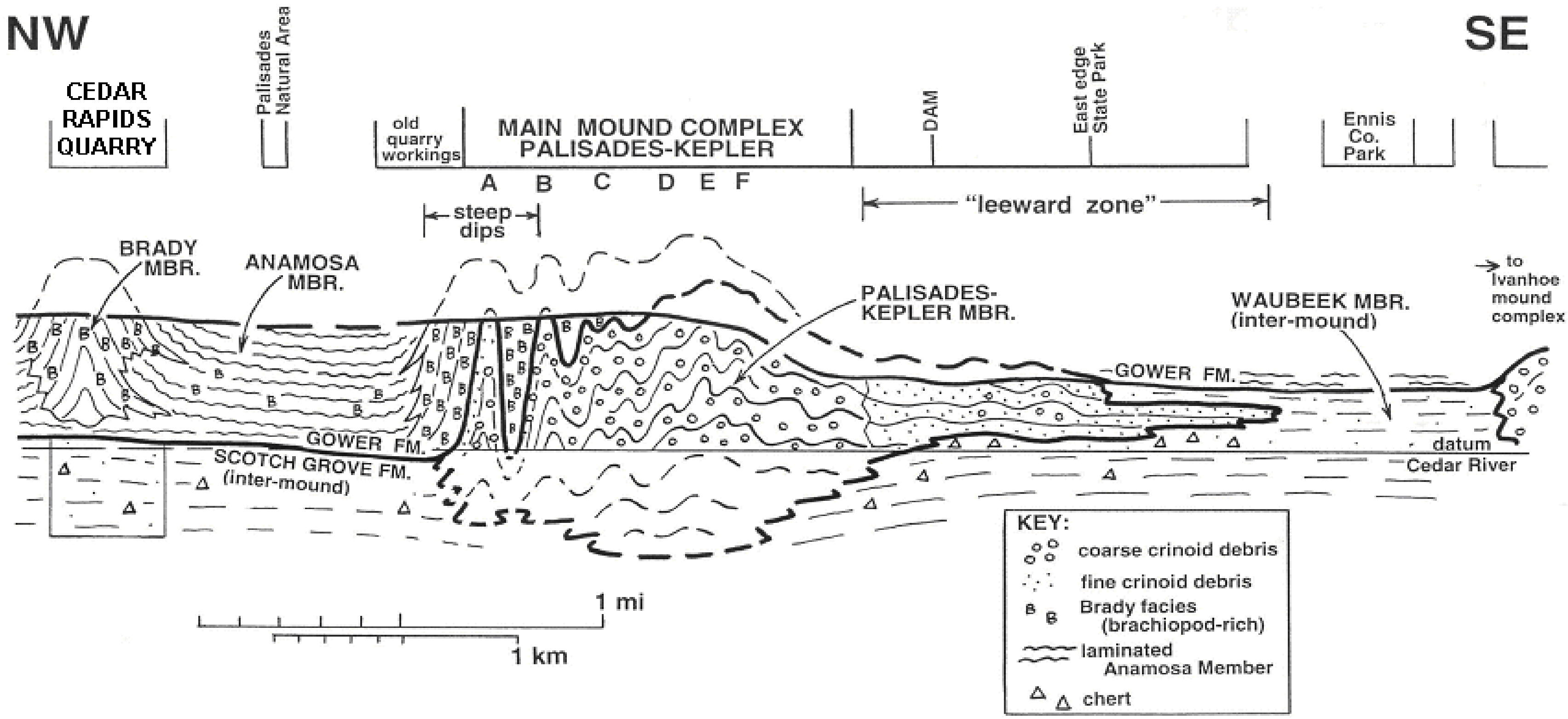

Figure 3. Schematic cross-section of upper Scotch Grove and Gower strata along the Cedar River, at the Cedar Rapids Quarry, Palisades-Kepler State Park, and surrounding area. Extent of exposures are bracketed at top of figure. Relationships of Brady and Palisades-Kepler mounds are dashed where inferred. Figure is vertically exaggerated. Modified from Witzke, 1999, Figure 4.

Anamosa Member

The Anamosa Member. (named for the rocks exposed in the quarries at Stone City west of Anamosa), are characterized by thin (mm scale) crinkly to planar laminations. The only fossils preserved in the Anamosa facies are the stromatolites that produce the crinkly laminations and the enigmatic "rods" found on bedding surfaces (Fig. 4). A well developed Brady mound was documented in the southeast corner of the MMQ by Witzke (1981a, 1981b). He described the interfingering of the flat-lying Anamosa facies (Fig. 3) with the mounded, non-laminated Brady facies, and the increasing content of fossils and skeletal grains towards the core of the mound. These fossils included a great abundance of brachiopods (rhynchonellids and *Protathyris*) and near the mound core, tabulate corals, brachiopods (*Harpidium*, *Trimerella*, and others), and more rarely solitary corals, gastropods, nautiloids, and echinoderm debris. However, the laminated dolomites of the Anamosa Member generally lack skeletal fossils and burrowing (laminae are well preserved), suggesting that the bottom conditions during deposition were largely unsuitable for animal life. Witzke (1992) proposed the bottom waters were strongly hypersaline and possibly low in oxygen.

Figure 4. Enigmatic fossils know as "rods" cover the bedding surface of this sample of Anamosa Member dolomite from the MMQ.

Brady Member

Dolomite strata of the Brady Member are well displayed in the northern part of PKSP, just east of the MMQ, where mounded and dipping Brady strata are observed to flank and bury the older crinoidal mounds of the Palisades-Kepler Member. An isolated Brady mound is clearly displayed in the MMQ (Figs. 5, 6, 7), but this Brady mound occurs above inter-mound upper Scotch Grove strata and not above the crinoidal mounds as seen in the PKSP.

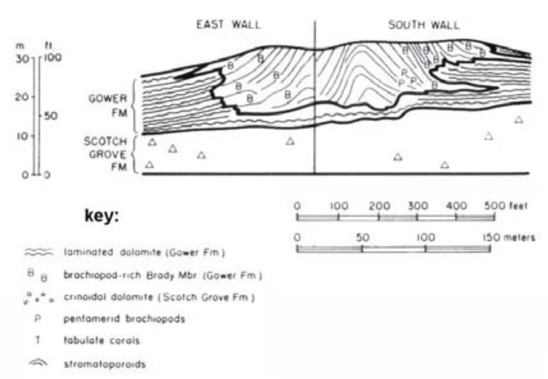

Figure 5. Brady Mbr. mound on the southeast corner of the MMQ (modified from Witzke, 1992, 1999).

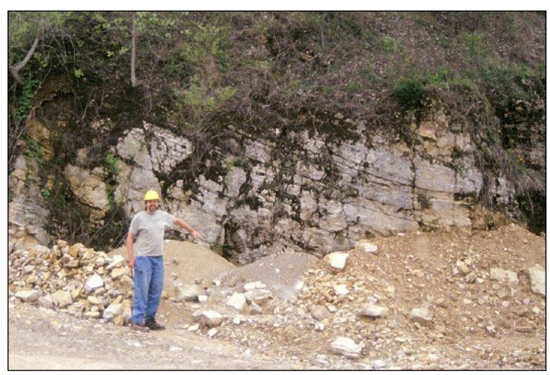

Figure 6. Author Brian Witzke shows the bed dips on the flanks of the Brady Mbr. mound, southeast end MMQ.

The Brady Member is characterized by dense dolomite lithologies in the central mounds, commonly only sparsely fossiliferous. This suggests that the bulk of the Brady mounds were originally composed of carbonate mud, although brachiopods, corals, and other fossils are present (*Harpidium*-*Trimerella* Community of Witzke and Johnson, 1999, described from central mound at MMQ). Fossils are scattered in these mounds, but the dipping flanking strata commonly concentrate many of the fossils in graded debris flows, and literally millions of brachiopod molds characterize these deposits. The brachiopod-rich flanking strata form the bulk of the Brady Member exposure at the MMQ, with fossils typically preserved as ovoid molds creating Swiss-cheese porosity.The brachiopod-rich flanking strata dip at varying angles away from the mounds, generally paralleling the underlying mound geometries of the crinoidal Palisades-Kepler Member. These beds achieve their steepest dips of about 30 to 40º at PKSP, but dips of 10 to 30º are more typical over much of the remaining Brady outcrop. Brachiopods are concentrated along the base of graded beds, but variations in thickness and shell concentration have been noted. Many localities show an upward steepening of the dipping strata, a feature also seen in older crinoidal mounds. This upward-steepening most likely reflects the progressive upward growth of the adjacent mounds.

The flanking Brady debris flows are seen to flatten out down-dip, merging into flat-lying laminated Anamosa strata in the MMQ and at the northern end of the old quarry workings at PKSP. Tongues of brachiopod-rich Brady lithologies locally extend considerable distances into inter-mound areas of laminated Anamosa strata. Brachiopod-bearing Brady interbeds and stringers within the Anamosa Member at the old quarry adjacent to the Palisades-Natural area occur over 2000 feet (600 m) from the nearest recognized Brady Member mounds.

Scotch Grove Formation

The basal unit in the MMQ is the Scotch Grove Formation Like the Gower, the Scotch Grove displays a flat-lying facies (Buck Creek Quarry and Waubeek Mbrs.) and a mounded facies (Palisades-Kepler Member) The Buck Creek Quarry Member is a dense to vuggy, bedded, cherty dolomite. Fossils are sparse, limited to scattered molds of small echinoderm debris, cup corals, brachiopods, and bryozans. The Buck Creek Quarry facies grades into the Scotch Grove mound facies, named the Palisades-Kepler Member for the spectacular mounds developed at the nearby PKSP. The south wall of the MMQ displays a well developed Palisades-Kepler mound (Fig. 7). The lowest unit seen in the MMQ belongs to the Palisades-Kepler and Waubeek Member of the Scotch Grove, encountered in the northeast corner of the new quarry.

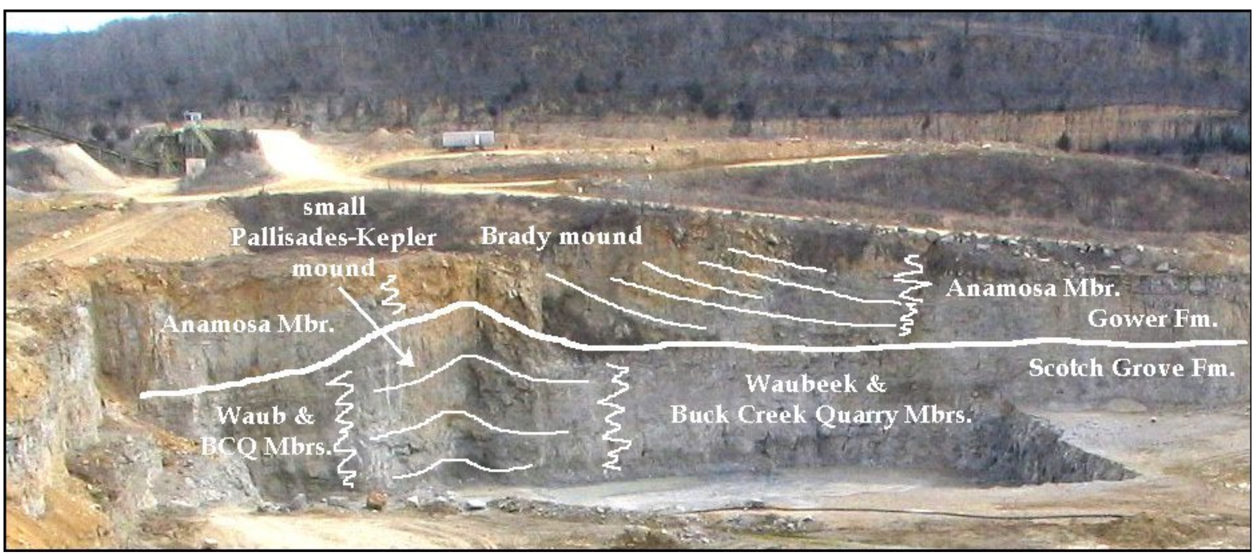

Figure 7. View of the east wall of the MMQ with the Brady Mbr and Palisades-Kepler mounds and other stratigraphy highlighted.

Palisades-Kepler Member

Palisades-Kepler Member mounds are spectacularly exposed in the northern area of PKSP. This area, known as the main mound complex (Fig. 3), is marked by a coalesced series of haystack-shaped mounded features, whose crests were given letter designations A through F by Philcox (1970). This complex is characterized internally by weakly stratified beds (commonly 20 cm to 2 m thick) that define the general geometry of the mounds. The beds contained within the bulk of the mound complex dip at varying attitudes, generally at angles less than 20º. Across much of the area the strata appear to be roughly subhorizontal (0-5º), although the beds can be seen to swale and roll across the exposure faces at low angles (5-10º, locally to 20º). In places, stratification is difficult to identify, where the bedding style is more massive. Irregular bedding breaks within the mound complex are generally marked along concentrations of fossil debris; the lower portions of individual beds are commonly more fossil rich than their upper parts, although exceptions are noted. Much of the complex resembles a large platform mound, steepest at the northern margin, but with a relatively flat rolling surface across much of the central region.

The beds along the northern end of the complex locally achieve notably steeper dips. Steeply dipping flanking strata achieve dips of up to 40º, and the dips are observed to steepen upward within the exposure faces. The dipping flank beds represent debris flows off the tops of the mounds, and many show wedge-shaped geometries thickening up-dip. In addition, individual beds show clear grading internally, with the coarsest material at the base (packed concentrations of coarse crinoid material, sometimes with stem segments oriented either perpendicular or parallel to dip). The upper parts of individual beds are typically less fossiliferous and contain more muddy matrix material. The upward steepening aspect of these successions of debris flows demonstrates that the mounds were actively growing upward, with episodic debris flows triggered by sediment movement off the mound tops. One mound is disjunct from the main complex, where it exists surrounded and buried by younger strata of the Brady Member. Remnants of Brady Member strata are seen to locally cap swales near the tops of other mounds, indicating that the full thickness of the upper Scotch Grove mound complex is locally preserved. However, the mound crests are erosionally truncated beneath the cover of Quaternary sediments (primarily loess) across most of the complex. The true vertical dimensions of the complex can only be inferred.

Corals and stromatoporoids are present in some mounds, but they comprise no more than a few percent of the sediment volume in those areas. Internal sediment fills, including trilobite and nautiloid-rich pockets as well as unfossiliferous mud fillings, have been identified. Fracturing and brecciation is locally apparent in the central portions of several mounds.

The mound complex at PKSP is highly asymmetric, as first recognized by Philcox (1970). He labeled the southeastern exposures in the park the “leeward zone” of the complex. This leeward zone of the complex contrasts significantly from the main mound complex in two important ways. First, the strata in this area are mostly horizontal to sub-horizontal, contrasting with the more notable dips in the northern part of the complex. However, several small-scale mounded features do occur within the leeward zone, primarily in the eastern series of exposures in the park. Second, the rocks in the leeward zone are more finely porous, and much of the crinoidal material is represented by small molds of individual stem columnals (most less than 2 mm in diameter). This contrasts notably with the much larger crinoid stems seen in the main part of the mound complex. Some coarser crinoid material is locally associated with the smaller mounds in the eastern part of the leeward zone.

The northwestern portion of the leeward zone near its interface with the main mound complex, which can be seen in a series of exposures upstream from the dam at PKSP, contains some unique lithologies not seen elsewhere in the park. Rounded and reworked carbonate clasts (most 1 to 5 mm) merge into the finely porous crinoidal lithologies, and even larger clasts (1-2 cm) are seen near the base of some of these intraclastic intervals. The origin of these intraclastic rocks is unclear, but their occurrence near the margins of the main mound complex suggests derivation from down-dip movement of lithified material from the higher portions of the complex.

The porous and finely crinoidal leeward zone thins eastward (especially eastward from the park boundary) and interfingers with denser and more sparsely fossiliferous inter-mound rocks. Immediately downstream from the dam in PKSP, the lower porous crinoidal leeward-zone rocks merge with cherty inter-mound strata along their lower boundary. In a general sense, the leeward zone of Philcox (1970) represents a transitional belt that separates the main mounded complex from their flat-lying inter-mound equivalents to the southeast. The gradual transition of more-or-less horizontally-bedded strata in this belt contrasts markedly with the northwestern portion of the complex, where steeply dipping flanking strata abruptly mark the margin of the complex.

Fossiliferous strata included in the Palisades-Kepler Member can be seen in the sump area of the MMQ. Beds with abundant crinoidal debris are noteworthy, and articulated crinoid cups have been collected (*Eucalyptocrinites*, *Dimerocrinites*). Additional fossils observed include bryozoans (especially fenestellids), brachiopods (gypidulinid, *Atrypa*, *Protomegastophia*, *Rhynchotreta*, *Hedeina*, etc,), nautiloids, gastropods, corals (*Favosites*, cup coral), and trilobites (*Bumastus*).

Buck Creek and Waubeek Members

Denser and more sparsely fossiliferous horizontally-bedded dolomite strata characterize the inter-mound equivalents of the Palisades-Kepler mounds. These strata were deposited adjacent to, and between the mound complexes, and were thereby deposited in slightly deeper-water environments than those which characterized the mounds themselves. These inter-mound strata, which comprise the bulk of the upper Scotch Grove Formation in eastern Iowa, are variably included within two named members within the formation (Witzke, 1992). Where chert is a prominent constituent (Fig. 8) of the dolomite lithologies, the strata are assigned to the upper part of the Buck Creek Quarry Member. Where chert is sparse or absent, the strata are included in the Waubeek Member. Both members are present at the MMQ. Inter-mound strata in the MMQ are slightly cherty. Therefore, assignment to the Buck Creek Quarry Member seems reasonable. However, chert is only sparsely represented in these strata. Inter-mound exposures a short distance down the Cedar River at Ennis County Preserve lack chert. The general paucity of chert in that area probably makes assignment to the Waubeek Member a better choice. In general, these inter-mound strata display scattered chert nodules, and inclusion in an undifferentiated Waubeek-Buck Creek Quarry Member seems appropriate.

Figure 8. A Buck Creek Mbr. chert nodule (arrows) cut and displaced by a chert-filled fracture.

The inter-mound strata in the MMQ are dense well-bedded dolomites with scattered to common molds of small fossils (especially fine crinoid debris). Vugs are locally present. A different association of fossils (*Hedeina*-Gypidulid Community) contrasts with the coarse crinoid and coral fossils seen in the contemporaneous mounds. The inter-mound strata of the upper Scotch Grove are generally overlain by flat-lying laminated dolomites of the Anamosa Member, Gower Formation. By contrast, the upper Scotch Grove mound complexes are overlain and flanked by dipping brachiopod-rich strata of the Brady Member, Gower Formation.

MINERALIZATION IN THE MMQ

Well developed sulfide and related mineralization have been found in solution enlarged, high-angle fractures in Gower and Scotch Grove dolomites in the MMQ (Fig. 9). Minerals that can be found include sphalerite (Zn, Fe)S, marcasite (FeS_2), associated calcite ($CaCO_3$), and quartz (SiO_2). Although such minerals are commonly associated with the Upper Mississippi Valley Zinc-Lead district, at the MMQ they may instead be associated with the development of Pennsylvanian paleokarst (Garvin and Ludvigson, 1993). Sinkholes and related karst topography developed in exposed carbonate rocks during the period between the end of Mississippian carbonate deposition and the beginning of Pennsylvanian deposition (about 335 to 315 million years ago). Many of the solutional voids filled with mineral-rich marine and estuarine shales. Compaction of the shales by the weight of subsequent, overlying sediments drove the mineralizing fluids from the shales allowing them to precipitate in fractures and voids. A much more detailed discussion of this mineralization by Garvin (2005) can be found beginning on page 29 of this guidebook.

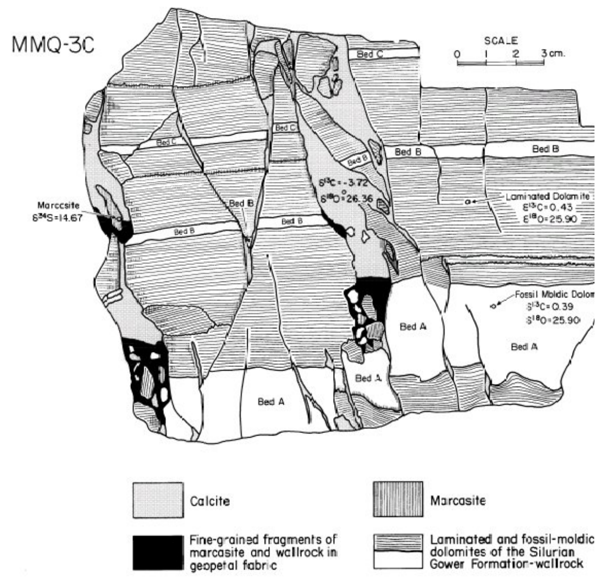

Figure 9. Drawing of slab of mineralized rock, Gower Formation, MMQ (Witzke, 1992, 1999).

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MINERAL DIAGENESIS IN CARBONATE ROCKS EXPOSED AT THE MARTIN MARIETTA QUARRY

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The rocks exposed at the Martin Marietta Quarry (MMQ) preserve a record of complex diagenetic events and processes. These include dissolution, fracturing, mineral replacements, and open-space linings and fillings of carbonate rocks. Some mineralizing processes appear to have operated on a local scale, while others were likely of regional extent.

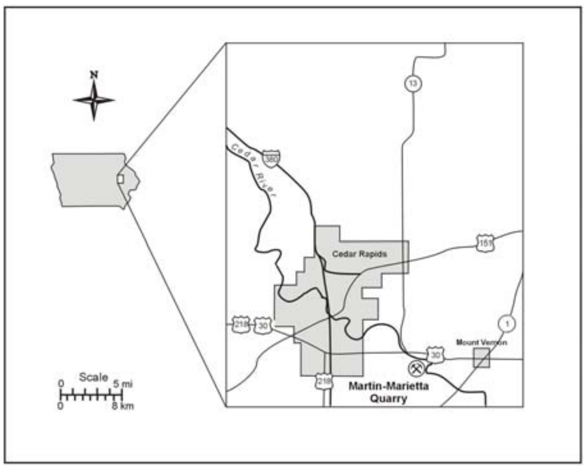


Figure 1. Location of Martin Marietta Quarry.

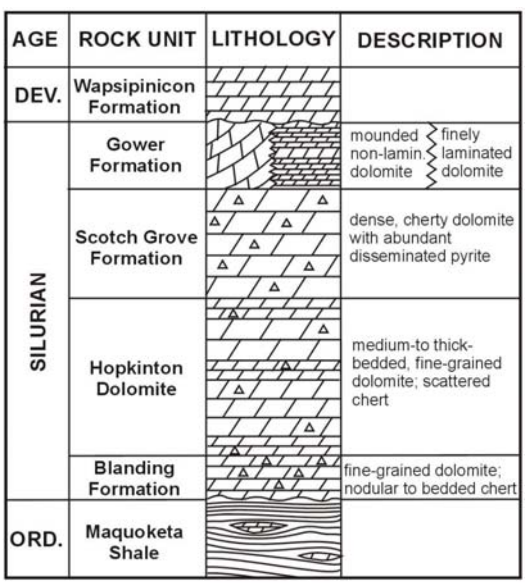


Figure 2. Generalized stratigraphic section of Silurian rocks in eastern Iowa.

STRATIGRAPHY AND PETROLOGY

Rocks exposed at the MMQ are early Silurian (early-middle Wenlockian) (Fig. 2). The Scotch Grove Formation is exposed in the lower levels of the quarry. It consists of dense, light-brownish gray to medium-dark gray, finely crystalline fossiliferous dolostone with intercalated thin beds and nodules of tan to black chert (Bunker et al., 1985). It is quite porous; vugs up to a few centimeters across occur locally. The dark gray coloration of the dolostone is due to the presence of abundant disseminated pyrite (identified by x-ray powder diffraction analysis of HCl-insoluble residue).

The Gower Formation is exposed in the upper levels of the quarry. Two facies are present: the Anamosa and the Brady. The Anamosa consists of finely-laminated, very light gray to medium dark gray, finely crystalline non-fossiliferous dolostone. It interfingers with the Brady, which consists of biohermal mounds containing medium-bedded, yellowish gray to medium gray, finely crystalline brachiopod-rich dolostone. Flank beds on mounds are variably inclined (dips up to 40^{o}). Bedding in the Anamosa has been interrupted locally by wedging and slump folding (Bunker et al., 1985).

STRUCTURAL GEOLOGY

The Martin Marietta Quarry is located in an area of regional and local structural significance (Fig. 3). It lies on the west flank of the Silurian East-Central Iowa

Basin (Bunker et al., 1985). Approximately 2 km west of the quarry is the Svor-Hartl structure, first reported by Dow and Metler (1962), which consists of northeast-trending, low-amplitude folds. The Plum River Fault Zone (PRFZ) passes through the Skvor-Hartl structure and just north of the quarry (Bunker et al., 1985; Ludvigson and Witzke, 1997). Within the quarry itself, high-angle fractures can be observed in the quarry walls, most notably in the Anamosa. These occur in two sets, one with an average strike of N 35° E (range N 30° to 40° E), the other with an average strike of N 77° W (range N 60° to 90° W) (Garvin, 1984). Accurate strikes of the fractures were difficult to obtain in some places because of dissolution enlargement. Minor fault displacement (a few centimeters) was observed along some fractures. Breccia clasts, some rotated out of original horizontal position, were also observed (Fig. 4A, 4B). Whether the rotation was a result of tectonic movement or dissolution of carbonate rock is not known.

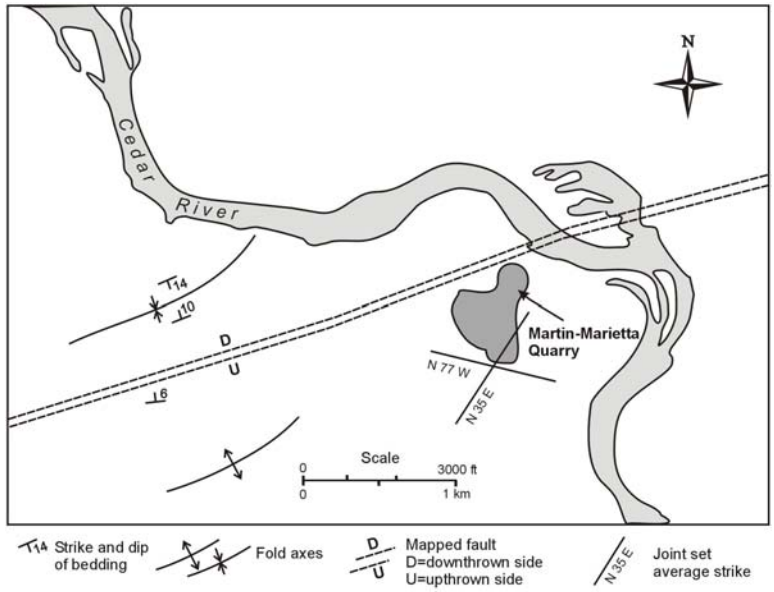


Figure 3. Structural features in the vicinity of the Martin Marietta Quarry.

MINERALIZATION

Silicification

Diagenetic quartz occurs in a variety of physical and chemical settings in the rocks exposed in the quarry. It occurs as: nodular replacements of Scotch Grove (Q1), and Gower (Q2) carbonate; pseudomorphic replacements of brecciated carbonate (Q3) and travertine (Q4) in the Gower, and linings of open vugs in the Scotch Grove (Q5).

Q1. Nodular replacement of Scotch Grove carbonate rock. Nodular chertification is a regional characteristic of the Scotch Grove Formation (Bunker et al., 1985). Chert nodules and lenses are abundant at MMQ. Lenses range up to 15 cm in thickness, and are typically elongated parallel to bedding planes. They exhibit diffuse color bands, with colors ranging from tan to black. Black coloration is likely due to the presence of finely-divided iron sulfide, which is locally abundant in the surrounding dolomite (Garvin, 1984). The boundary between the chert and the enclosing rock is very irregular, and the chert is commonly porous and chalky, due to replacement by dolomite. It is also devoid of iron sulfide (Fig. 5A). These textural and mineralogical characteristics, plus the preservation of fine-scale fossil structures in the chert, indicate that the emplacement of both chert and iron sulfide preceded dolomitization.

Q2. Nodular replacement of Gower carbonate rock. Chert nodules occur locally in the Gower Formation at MMQ. These nodules are morphologically quite different from those contained in the underlying Scotch Grove Formation. They are typically ellipsoidal to spheroidal in shape. Some are nearly perfect spheres (Fig. 5B). The enclosing host rock dolomite is megascopically isotropic, which supports the belief that the rate of nodule growth was equal in all directions. The nodules are variably altered. Some exhibit very thin chalky rinds, indicating minor replacement by dolomite. Others are altered to the point of crumbling. Some nodules have been partially to completely dissolved, and the resulting cavities have been subsequently filled pseudomorphically with sparry calcite (Fig. 5C). Locally nodules exhibit a "cut and fill" texture, suggesting more than one episode of chertification.

Q3. Pseudomorphic replacement of brecciated Gower carbonate rock. Near the south end of the quarry, rocks of the Brady Member are brecciated, with clasts ranging up a meter across (Fig. 5D). Locally, clasts and matrix have been pseudomorphically replaced by tan to dark brown, microcrystalline to macrocrystalline quartz (Fig. 5E). Coarse-grained, dark brown quartz replaced the clasts; fine-grained, tan quartz, the matrix. Incipient replacement of quartz by subhedral to euhedral dolomite rhombs, which is evident in thin section, indicates that regional dolomitization occurred after brecciation and silicification, or that a second episode of dolomitization occurred.

Q4. Pseudomorphic replacement of travertine in the Gower. What appears to have been travertine calcite has been replaced by brown microcrystalline quartz. The travertine lined small, irregular-shaped cavities in the carbonate rock. Original depositional banding is preserved in the quartz. Q4 and Q3 quartz are very similar in color.

Q5. Lining of open vugs in Scotch Grove carbonate rock. Small vugs (up to 10 cm in maximum dimension) in the Scotch Grove are lined with white, drusy quartz. Crystal lengths do not exceed half a centimeter.

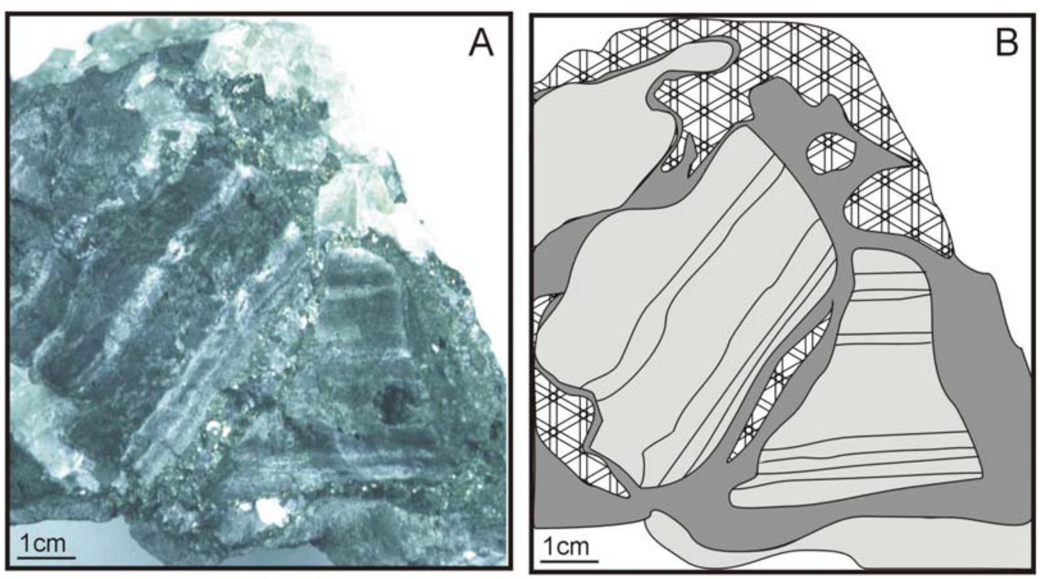
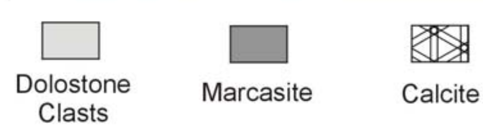


Figure 4. Rotated clasts of Anamosa dolostone, cemented with marcasite and calcite. From vertical fissure. **A.** photograph; **B.** drawing for clarification.



Calcification

Diagenetic calcite is widely distributed as open-space fillings in Scotch Grove and Gower host rocks. The types are: C1: linings of cavities in the Gower with travertine, C2: linings of small vugs in the Scotch Grove, C3: filling of voids produced by dissolution of chert nodules in the Gower, and C4: linings and fillings of dissolution-enlarged high-angle fractures in the Gower and the Scotch Grove.

C1. Lining of cavities in the Gower with travertine. Though travertine was not actually observed at the quarry, the morphology of the quartz pseudomorph (Q4) strongly suggests its former existence.

C2. Linings of small vugs in the Scotch Grove. Calcite is of two types: a) amber to chocolate brown crystals, exhibiting acute scalenohedral and obtuse rhombohedral forms, the rhombohedral faces commonly curved. This variety fluoresces dull violet to dull pink in long-wave ultraviolet light (356 nm); b) aggregates of medium to light gray crystals in subparallel alignment. This variety exhibits acute rhombohedral forms and is not UV-fluorescent. Locally, 1b crystals are perched on etched 1a crystals.

C3. Filling of voids produced by dissolution of chert nodules (Q2) in the Gower. The calcite is colorless, non-UV fluorescent spar (Fig. 5C).

C4. This type will be discussed in conjunction to the sulfidization in the Gower, with which it is believed to be cogenetic.

Sulfidization

Diagenetic mineral sulfides is of three types: S1: disseminations of fine-grained pyrite in Scotch Grove and Gower host rocks, S2: disseminations of marcasite in Gower host rock, and S3: cavity linings in Gower host rock.

S1. Microscopic grains of pyrite are abundant in some carbonate rock horizons, particularly in the Scotch Grove, where they impart a dark gray to nearly black color to the carbonate rock and to contained chert nodules (Fig. 5F). Pyrite in the Scotch Grove is a regional characteristic (Bunker et al., 1985).

S2. Microscopic subhedral crystals of marcasite are disseminated in rocks of the Gower Formation. They are confined to within a few centimeters of contacts with high-angle fissure walls.

S3. Macroscopic cavity-lining crusts and breccia cements of pyrite, marcasite, and sphalerite and cogenetic calcite, associated with high-angle fissures in the Gower. The setting for S3 will be discussed in detail in the following paragraphs.

The mineralization associated with the S3 setting has been described in detail by Garvin (1984). It is confined essentially to dissolution-enlarged, high-angle fractures. These occur throughout the quarry, but they are most conspicuous in the upper walls of the southern part of the quarry, where their presence is marked by iron oxide stains in the adjacent carbonate rock. Minerals occur as fissure linings and fillings (Fig. 4A, 4B, 6A). Euhedral crystal terminations indicate that some fissures remained open throughout the period of mineral deposition. Individual fissure widths range from less than a centimeter to almost a half meter, with marked changes over short distances vertically and horizontally. Locally, S3 mineralization extends from fissure walls up to a few centimeters into wallrock along bedding plane and transverse fractures (Fig. 6A).

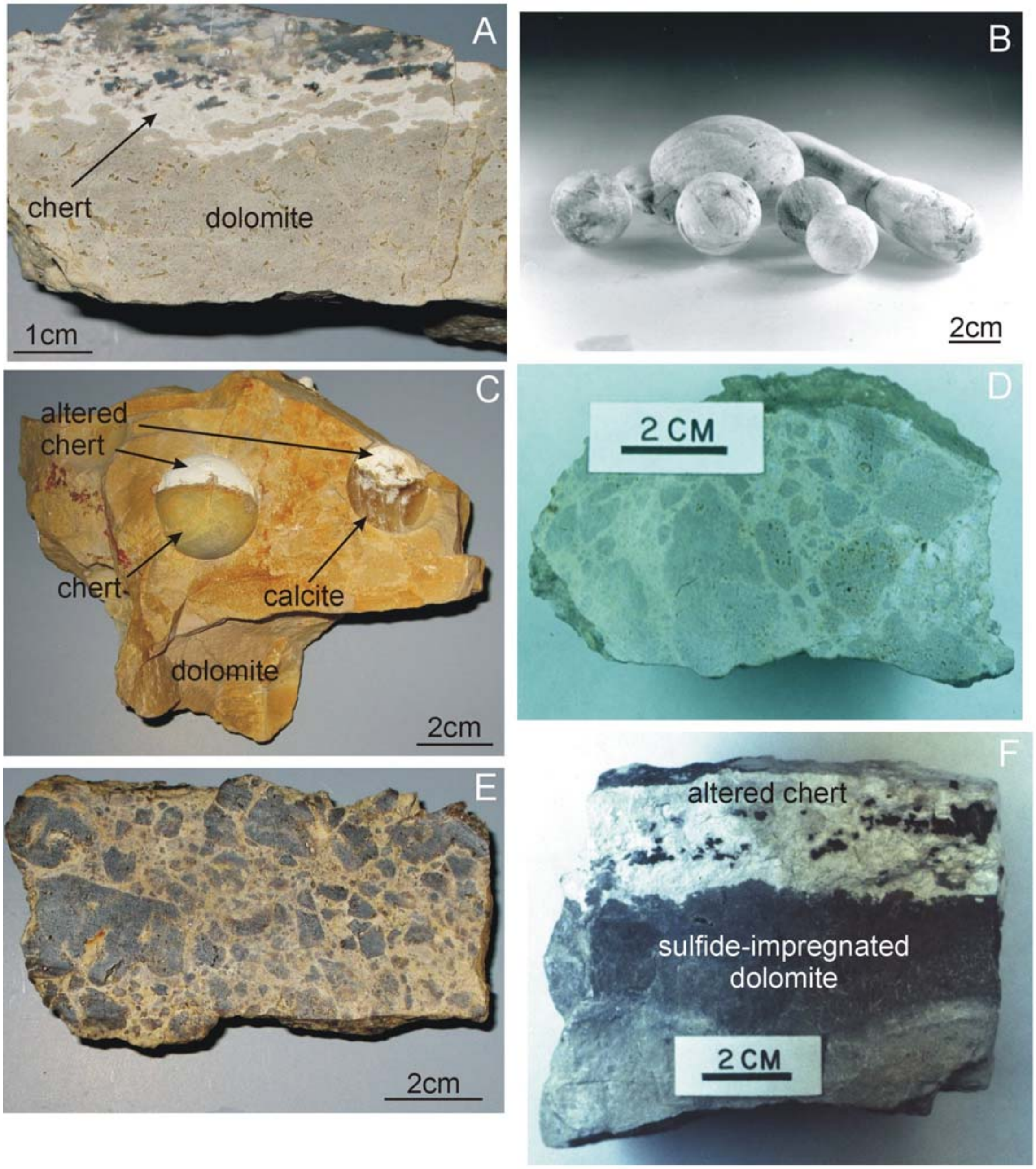


Figure 5. Examples of mineral diagenesis, Martin Marietta Quarry. 5A. chert, partially replaced by dolomite; 5B. spheroidal chert nodules in Gower Formation; 5C. altered and replaced 5C chert nodules; 5D. dolomite breccia in Gower Formation; 5E. replacement of dolomite breccia by silica; Note: both clasts and matrix are replaced by silica; 5F. altered chert and sulfide-impregnated dolomite, Scotch Grove Formation.

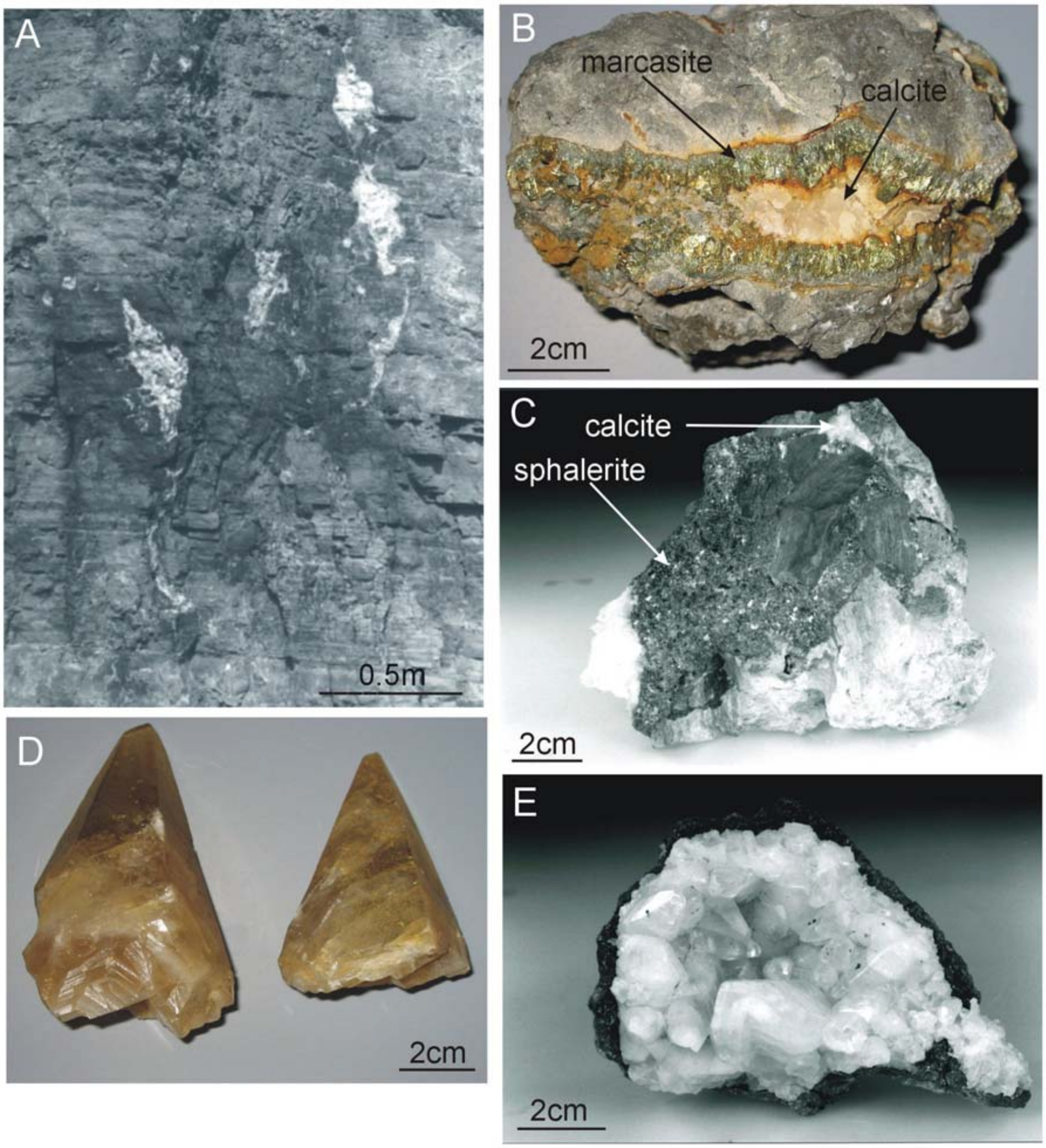


Figure 6. S3-type mineralization, Martin Marietta Quarry. 6A. mineralized fissures. Note darkening of wall rock near fissures, due to iron sulfide impregnation; 6B. fissure-filling marcasite and calcite; 6C. fissure-filling sphalerite and calcite; 6D. large amber calcite crystals; 6E. vug-lining white calcite crystals.

Mineralogy

Marcasite (FeS_2). Marcasite appears as well-formed single blades up to a half centimeter in length, and as aggregates of simple and polysynthetic twins. Crystals line fractures in crusts up to 6 cm thick. Microscopic crystals occur as inclusions in calcite. Note: S2 marcasite disseminations in, and replacements of, the dolostone host may be coeval with S3 marcasite (Fig. 6B).

Pyrite (FeS_2). Pyrite occurs as cubes up to a half millimeter across, which are modified by octahedron and pyritohedron. It is most commonly observed upon and beneath crusts of marcasite. Microscopic pyrite also occurs as inclusions in calcite.

Sphalerite (ZnS). Sphalerite occurs as aggregations of anhedral, brown to yellow-brown crystals. Locally, crystals are zoned with dark-colored cores and light-colored rims, suggesting a decrease in Fe content during crystal growth. Sphalerite crusts are as much as 2 cm thick. It is most abundant in the southern part of the quarry, where it locally makes up as much as 10 to 15% of the total volume of the rock (Fig. 6C).

Calcite ($CaCO_3$). Calcite occurs as aggregations of anhedral to euhedral crystals that are perched on marcasite or sphalerite. Individual crystals up to 10 cm in length have been observed. The dominant crystal form is the acute scalenohedron, which is variably modified by acute and obtuse rhombohedra, obtuse scalenohedron and hexagonal prism. Simple rhombohedral twins and polysynthetic twins were observed locally. Calcite color ranges from colorless to amber. White varieties fluoresce bright pink in long-wave UV; amber varieties fluoresce dull violet to dull pink. Reduced intensity of fluorescence in amber calcite may be due to the quenching effect of Fe^{2+}. Zoning is common and is accentuated by dustings of microscopic iron sulfide crystals on interior growth surfaces (Figs. 6D, 6E).

CHRONOLOGY OF MINERAL DIAGENESIS

The relative chronology of mineral diagenesis is illustrated in Figure 7. Lack of contact between Q minerals in Scotch Grove and Gower host rocks prevents assigning some minerals with certainty. From a study of the diagram and the foregoing descriptions the following general statements can be made.

1. Silicification (types QI and Q2) preceded all other observed diagenetic events.
2. Sulfidization (S1) preceded regional dolomitization.
3. Silicification (Q3) followed regional dolomitization.
4. The events in sulfidization type S3 began with iron sulfides, continued with sphalerite, and ended with calcite.
5. Two separate fracturing events occurred: 1) major fracturing resulting in high-angle fissures that were subsequently mineralized, 2) minor fracturing during the S3 event, after sphalerite and before calcite, resulting in fracturing and dislocation of early sulfides and engulfing by late calcite.

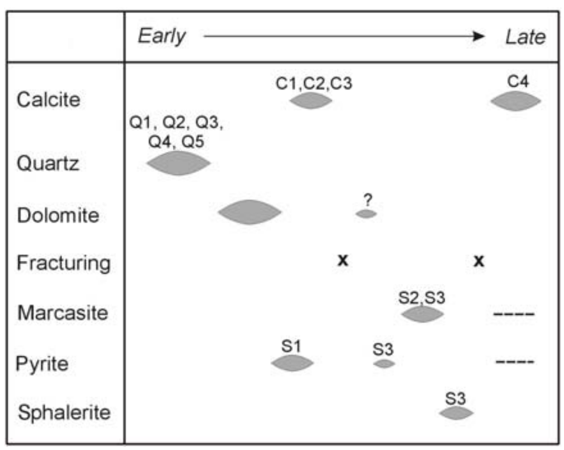


Figure 7. Paragenetic sequence of diagenetic mineralization, Martin Marietta Quarry.

MINERAL-FORMING ENVIRONMENTS

With the possible exception of the process that produced C1 (travertine), all mineralization appears to have occurred under phreatic conditions (below the groundwater table). Evidences for this interpretation are: 1) presence of mineral sulfides throughout diagenesis (early S1 to late S3). Sulfides form only under conditions of low oxygen activity, which normally does not occur under subsurface vadose conditions; 2) concentric banding in chert nodules, indicating outward growth in all directions; 3) inward growth of cavity-lining minerals from all surfaces. Geopetal deposition of minerals in cavities was not observed; 4) large, euhedral crystals of calcite, which are generally considered to form only under phreatic conditions (Jennings, 1985; Ford, 1988). Dripstone and flowstone varieties of calcite have not been observed at MMQ (except C1).

Silicification of type Q3 has been observed elsewhere in eastern Iowa. Float blocks found in a small abandoned rock quarry in the upper Palisades-Kepler State Park contain abundant quartz, which is similar in color and texture to that found at MMQ. Extensive silicification occurs at the Ferguson Quarry near the Pleasant Hill outlier east of Olin in Jones County. All of these occurrences of silicified carbonate are located in close proximity to the Plum River Fault Zone (PRFZ).

The source of silica for mineral diagenesis in cratonic environments is a matter of continuing debate. Sponge spicules are considered by many researchers to be the most likely source for cavity-filling and replacement quartz. A few researchers have invoked ash from the eruption of super volcanoes (Pabian and Zarins, 1994). Another possible source is terrigenous clastic sediment in carbonate rocks, which consists of clay-to-sand-sized quartz and clay minerals. The average limestone contains about 7% silicate detritus (Pettijohn, 1957), most of which is clay-sized in Iowa rocks. Dissolution is enhanced by large surface-area-to-volume ratios in clay-sized grains. Diagenetic alteration of clay minerals can release soluble silica. Leaching of a small percentage of this material would have provided an ample supply for silicification at MMQ. Silica for type Q4 (white, drusy quartz) might have been supplied by the chalky rinds of altered chert nodules which occur in close spatial proximity to the drusy quartz. The nearness of Q3-type silica to the PRFZ suggests that the fault might have been a locus for movement of some silica-bearing fluids.

Alternations between carbonate mineral-forming and quartz-forming events are puzzling, especially where pseudomorphic replacements occur (i.e. Q3, Q4 and C3). In C3, remnants of chalky chert are engulfed by sparry calcite. Dissolution and removal of chert occurred without any observable disturbance of the spherical mold in the enclosing dolomite. These changes in mineralogy reflect alternations from oversaturated to undersaturated fluids with respect to carbonates and silica. The process driving these changes is not known.

There is evidence that the fissure-filling mineral deposition (S3) occurred at temperatures higher than that for normal groundwater. Homogenization temperatures were obtained from primary fluid inclusions by Coveney and Goebel in conjunction with a regional fluid inclusion survey of minor sulfide-bearing mineral occurrences in the mid-continent region (Coveney and Goebel, 1983). Homogenization temperatures range from 85^{o} to 99^{o}C for sphalerite, and from 69^{o} to 82^{o}C for calcite at MMQ. It is widely recognized that the temperatures of Mississippi Valley-type hydrothermal fluids decrease from early to late stages of mineralization. Thus, pyrite and marcasite, which appear early in the paragenetic sequence at MMQ, might have formed at temperatures higher than that for sphalerite. In any case, these preliminary results indicate that temperatures of S3 mineralization at MMQ lie well within the established limits for hydrothermal mineralization. More fluid inclusion research is needed to constrain further the temperatures of mineralizing fluids at MMQ.

MMQ S3 deposits and Upper Mississippi Valley Zn-Pb deposits (UMV) were compared in order to determine similarities and differences with UMV deposits, which are universally considered to be hydrothermal. Comparisons were based on: 1) presence, absence and abundance of specific minerals, 2) paragenesis, and 3) fluid inclusion geothermometry. The similarities are:

1. All MMQ minerals occur in UMV.
2. Marcasite dominates over pyrite in both deposits.
3. The paragenetic sequence pyrite-marcasite-sphalerite-calcite is the same for both deposits.
4. Vertical fissure fills are common in UMV, especially in the western part of the district.
5. Sphalerite formed at a higher temperature than calcite in both deposits.
6. Silicification precedes sulfidization in both deposits
7. Hydrothermal dolomite (characterized by zoned, euhedral crystals) precedes sulfidization at UMV. Zoned euhedral dolomite, though not abundant at MMQ, also appears to precede sulfidization.

The differences are:

1. Galena and barite, which are present in major amounts at UMV have not been reported at MMQ.
2. UMV calcites occur in habits that alternate between acute scalenohedral and obtuse rhombohedral. MMQ calcites are all acute scalenohedral.
3. A majority of UMV deposits are structurally of the pitch-flat type, which does not occur at MMQ.
4. Hydrothermal dolomite is abundant at UMV, but uncommon at MMQ.

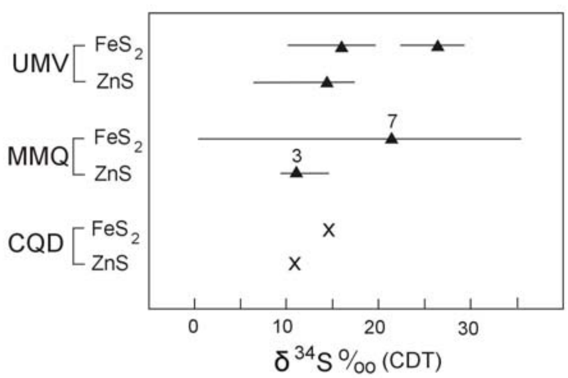


Figure 8. Sulfur isotopic compositions of iron sulfide minerals and sphalerite. UMV = Upper Mississippi Valley Zn-Pb District; MMQ = Martin Marietta Quarry; CQD = Conklin Quarry, Davenport Host. Data from McLimans (1977) and Garvin and Ludvigson (1993).

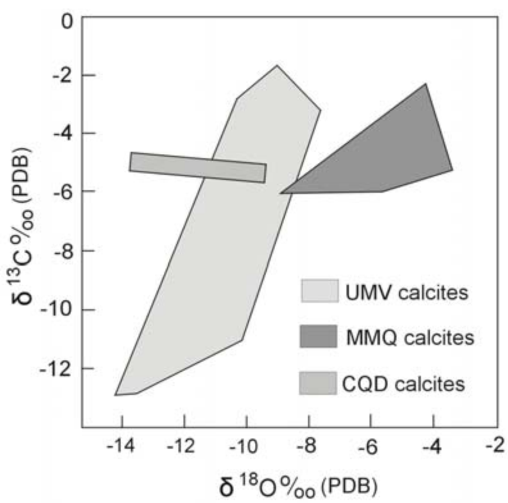


Figure 9. Bivariate plots of carbon and oxygen isotopic compositions of fracture-filling calcites. UMV = Upper Mississippi Valley Zn-Pb District; MMQ = Martin Marietta Quarry; CQD = Conklin Quarry, Davenport Host. Modified from Garvin and Ludvigson (1993).

Sulfur isotopic compositions of UMV and MMQ deposits were compared (Garvin et al., 1987; Garvin and Ludvigson, 1993) (Fig. 9). The δ34 S o/oo values for MMQ sphalerite correspond well to those for UMV sphalerite. For marcasite, the range for MMQ extends above and below the range for UMV, and the average lies slightly above the upper limit for UMV, but some MMQ values lie within the UMV range. A comparison of carbon and oxygen isotopic ratios (Fig. 9) shows that MMQ values fall within the range for carbon, but outside the range for oxygen. In general, MMQ sulfides are more like UMV sulfides and MMQ calcite is more unlike UMV calcite. It should be noted the published isotopic compositions for UMV are for pitch-flat deposits (McLimans, 1977). Sulfur, carbon and oxygen isotopic data are not available for high-angle fracture (gash vein) deposits, which are structurally more like the mineral deposits at MMQ.

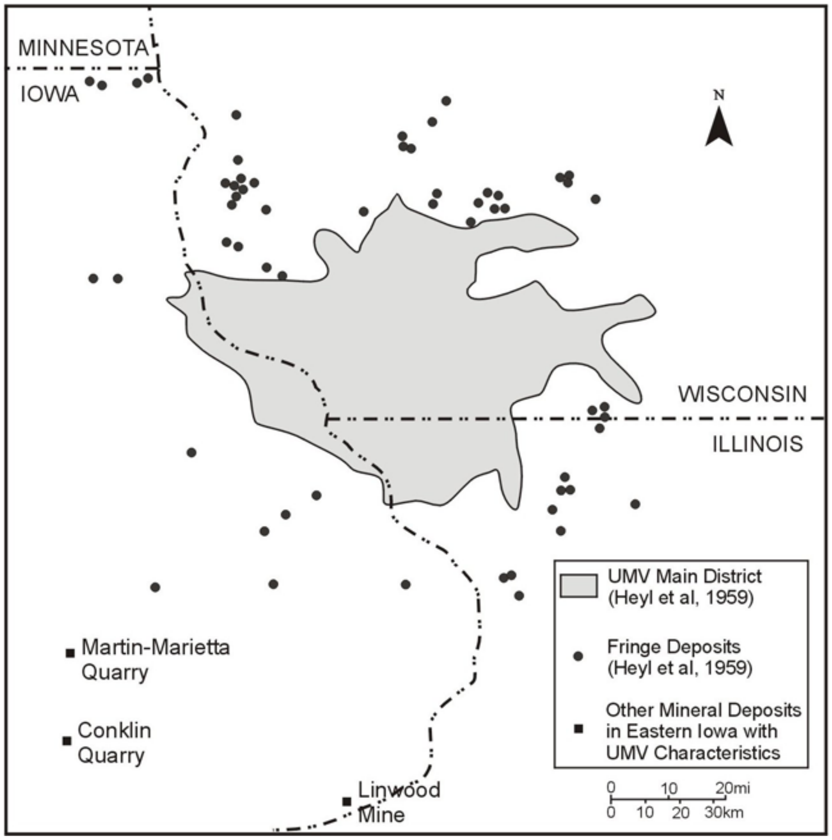


Figure 10. Locations of Upper Mississippi Valley Zn-Pb main district, fringe deposits (described by Heyl et al., [1959]) and mineral deposits in eastern Iowa exhibiting UMV-type characteristics.

The UMV Main District is fringed with a large number of subeconomic sulfide mineral occurrences (Heyl et al., 1959) (Fig. 10), which exhibit varying degrees of similarity to, and difference from, the deposits of the main district. The vast majority of these minor accumulations are geographically closer to the main district than MMQ. Since the landmark study by Heyl et al. (1959), two other UMV-like deposits have been discovered in eastern Iowa: 1) a fracture-fill mineral deposit at the Conklin Quarry at Coralville, and 2) a paleokarst-associated deposit at the Linwood Mine near Davenport (Fig. 10). Striking similarities between minerals, parageneses, and sulfur, carbon and oxygen isotopic compositions of minerals hosted by the Davenport Limestone at Conklin and UMV deposits support a cogenetic relationship (Fig. 9) (Garvin et al., 1987; Garvin and Ludvigson, 1993). At Linwood, although stable isotopic analyses have not been performed, mineralogy and paragenesis show strong resemblance to UMV deposits (Garvin, 1995). The UMV-like character of these three deposits suggests that the mineral-forming processes, which resulted in the large economic concentrations of zinc and lead in the main district, operated on a scale that extended considerably beyond the limits established by earlier research.

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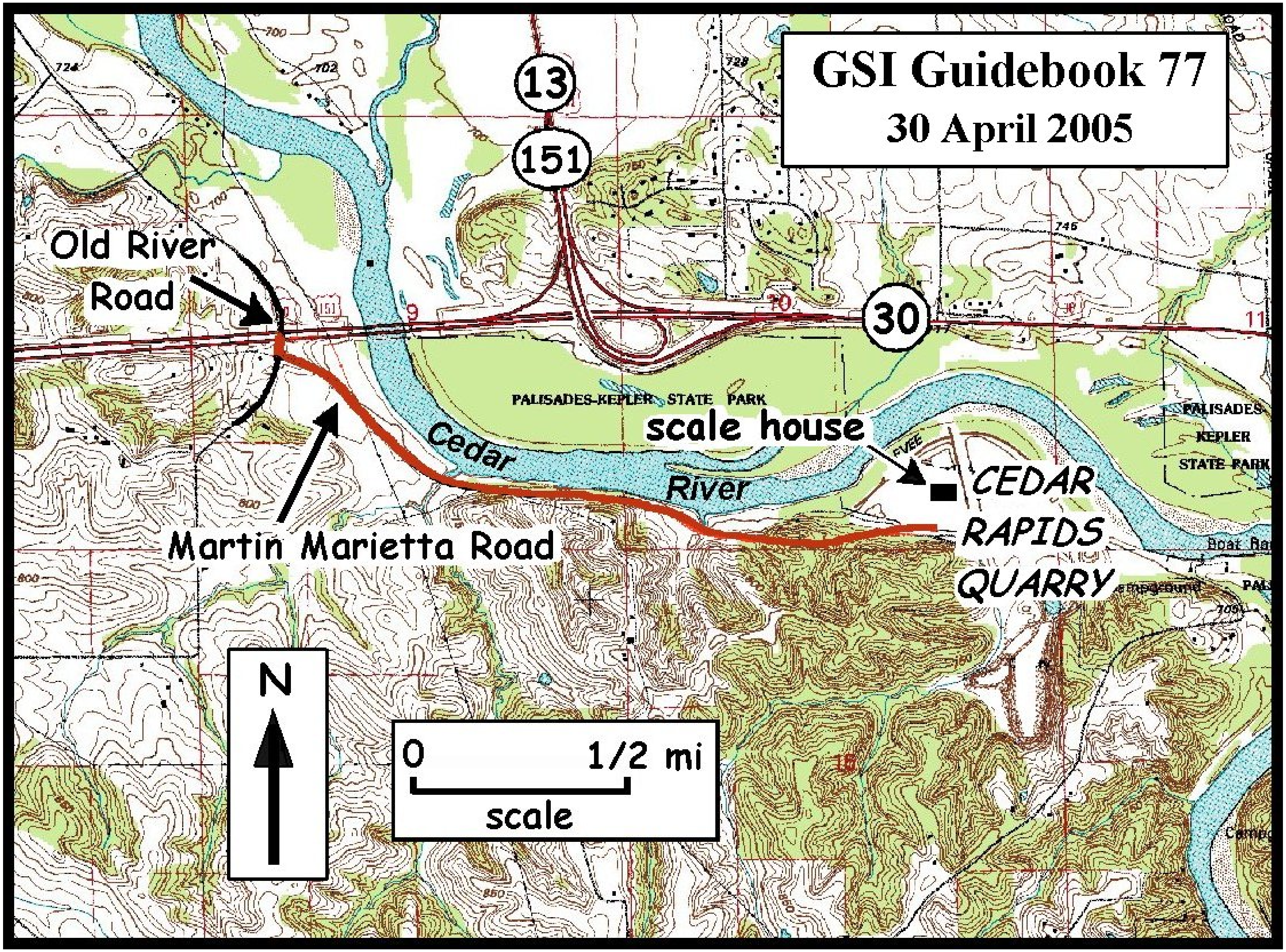
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