ORDOVICIAN
GALENA GROUP
OF THE UPPER MISSISSIPPI VALLEY --

DEPOSITION, DIAGENESIS, AND PALEOECOLOGY

GUIDEBOOK for the

13th ANNUAL FIELD CONFERENCE

September 30 - October 2, 1983

GREAT LAKES SECTION

Society of Economic Paleontologists
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EDITOR'S PREFACE

This year's Great Lakes Section field conference focuses on the Galena Group, a mostly carbonate deposit which was laid down near the peak of the great mid-to-late Ordovician epeiric transgression. This transgression inundated almost the entire North American craton. Galena correlatives, known under such aliases as Montoya, Red River, Trenton, Viola, Kimmswick, and Big Horn, were almost certainly different parts of one contiguous carbonate sheet when deposited. Most of these units share similar depositional and diagenetic characteristics, so examination of the Galena in outcrop should help in understanding (say) Trenton or Red River facies in subsurface. Furthermore, similar facies characteristics and sedimentologic problems recur in Silurian, Devonian, and Mississippian carbonates deposited during similar transgressions. Many of these units are important petroleum reservoirs, so this year's field trip should be practical as well as (we hope) interesting!

Purists will be dismayed at the use of English units in the road log and some papers in this volume. This was done because (1) the abundant stratigraphic literature on the Galena uses English units almost exclusively; (2) English units are still the more familiar units to most of us, and are still in general use in the U.S. petroleum industry, and (3) in the editor's opinion, adoption of metric units lost some urgency with the general availability of the pocket calculator. One of the chief advantages of metric over English was ease of calculation; but calculators don't care.

Many individuals have helped greatly in the production of this guidebook and organization of the field trip. I would here like to record my thanks to:

Curtis Wright and Dick Kellogg, our efficient local arrangements handers;

Frank Adler, Bill Harrison, Tony Ekdale, K. C. Lohmann, Don Zenger, Jack Hayes, Reuben Ross, and Bob Cluff, for the careful and useful reviews they provided of papers in this volume;

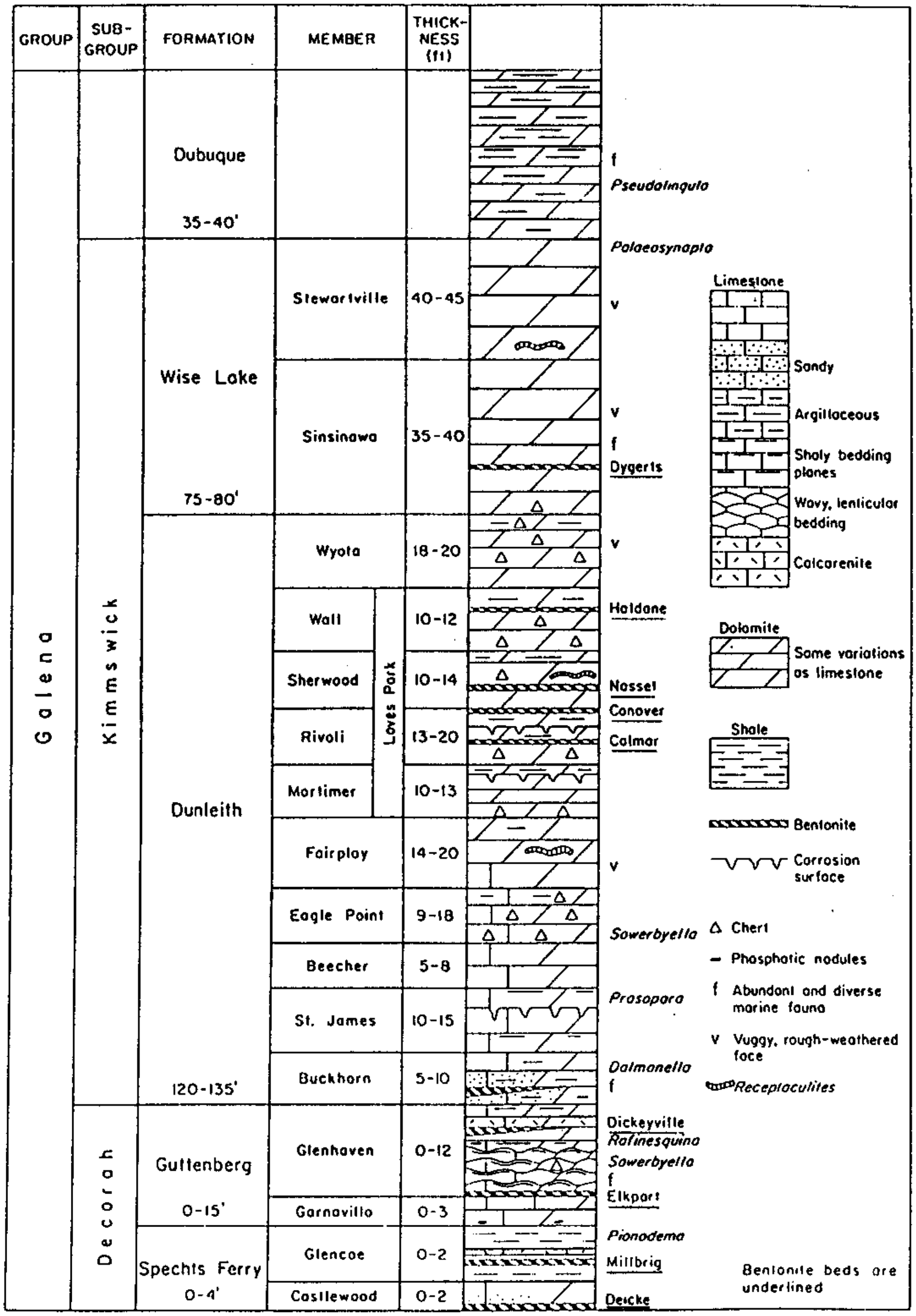
Dennis Kolata, Art Gerk, Calvin Levorson, and Brian Witzke, for assistance with the road log;

The Dubuque Stone Co. and Dan Miller and staff, for their gracious cooperation in making the Sageville Quarry (stop 2) available to us;

Mrs. Mary Romary of Englewood, Colorado, for her cheerful willingness to type long papers at short notice; and

The Phillips Petroleum Company for the financial and material support that made my own contributions to the field conference feasible.

I also want to express my appreciation for the other authors of this guidebook. Their cooperation has been magnificent, and their contributions valuable. I have gained greatly by working with them.



Illinois State Geological Survey classification of the Galena Group. From Willman and Kolata, 1978, fig. 11.

Finally: a recurring theme in the papers on this volume is recognition that the Illinois State Geological Survey's stratigraphic classification is workable, widely useful, and a powerful aid in establishing the close stratigraphic control which is a prerequisite of good sedimentologic and paleoecologic work. A principal author of this scheme is H. B. Willman, who has actively investigated Galena problems for more than 50 years. This guidebook is respectfully dedicated to Bo Willman in recognition of his contributions to Galena studies.

REFERENCE

Willman, H. B.; and Kolata, D. R., 1978, The Platteville and Galena Groups in Northern Illinois: Illinois State Geol. Survey, Circ. 502. 75 p.

Delgado, D. J., ed. (1983), Ordovician Galena
Group of the Upper Mississippi Valley --
Deposition, diagenesis, and paleoecology:
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DEPOSITION AND DIAGENESIS OF THE GALENA GROUP IN THE UPPER MISSISSIPPI VALLEY

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ABSTRACT

The Dunleith, Wise Lake, and Dubuque Formations (Galena Group, Ordovician) of the Upper Mississippi Valley outcrop area display extreme lateral continuity on all scales from named stratigraphic units to very thin beds. Lithologies are dominantly mud-supported bioclastic carbonates with variable but minor clastic content; but include bioclastic grainstones (deposited by storms or as sand waves) and more than eight K-bentonites derived from Appalachian sources. Strata become shalier toward the northwest, suggesting derivation of clastics from the Transcontinental Arch. "Floating" quartz silt occurs in certain beds over wide areas; the silt may be an eolian-marine deposit from a supermature weathered terrane 250 to 500 miles north to west of the outcrop area.

The biota is subtidal, dominantly benthic, and generally stenohaline. It includes algae of dasycladacean affinities, but these are rare at some horizons at some localities. Possible molds of evaporite nodules and crystals are associated with beds of "floating" silt and restricted biotas, suggesting that occasional regressions led to restriction of water circulation and emergence of clastic sources. There is no evidence for emergence or near-emergence within the Galena outcrop during Galena deposition. Deposition occurred subtidally below normal wave base, generally deep within the photic zone.

Early diagenetic processes included submarine dissolution of aragonite; submarine cementation on a spectacular scale to form numerous hardgrounds and lithified nodules; and possibly some submarine dolomitization, chiefly within filled burrows.

Average rates of deposition probably were between 4.1 and 13.9 mm per 1000 years between hiatuses. At typical localities, an estimated 1.2 to 6 million years aggregate was spent on formation of hardgrounds, which represent about 15 to 30% of total Galena time.

Later diagenesis included chertification and silicification of biotics, additional post-chert dolomite mottling, and later regional dolomitization in part of the outcrop area. Regional relationships are consistent with a mixing-zone (Dorag) origin for this regional dolomite, but do not require it. Mixing zones could have been present at the end of Galena time or at the end of Ordovician time, or both.

INTRODUCTION

This paper concerns the sedimentology of the Dunleith, Wise Lake, and Dubuque Formations. These carbonates are the upper three formations of the Ordovician Galena Group in the classification of Templeton and Willman (1963), and account for most of the group's thickness. The stratigraphy is well described by Templeton and Willman (1963), Levorson and Gerk (1972), Willman and Kolata (1978), Levorson et al. (1979), and in this volume by Witzke (1983), Levorson and Gerk (1983), and Stone (1983), among others.

My investigation is based on more than 60 stratigraphic sections measured at a scale of one inch to two feet in a field area measuring roughly 65 by 250 miles in Wisconsin, Illinois, Iowa, and Minnesota. Several hundred polished slabs and thin sections were examined using binocular and petrographic microscopes.

DEPOSITION OF THE GALENA GROUP

Depositional character

The Dunleith, Wise Lake, and Dubuque Formations share many attributes. These characteristics persist laterally throughout most of the Upper Mississippi Valley outcrop area. They include the following:

Extreme lateral continuity

Galena Group strata exhibit extreme lateral continuity on many scales. Facies persist across the outcrop area, with only exceedingly gradual lateral change. Most members may be traced over nearly all of the outcrop area, and vary but little in thickness or depositional characteristics over great distances. Some individual distinctive argillaceous beds may be traced more than 100 miles; at least one grainstone bed, 1" to 3" thick, is traceable over a comparable distance (SCB #7 of Levorson et al., 1979). On exposed faces, bedding is parallel and continuous.

Bioturbate carbonate mud

Over 95% of the thickness of the Galena Group consists of thoroughly bioturbate bioclastic mudstones and wackestones or their dolomitized equivalents. These muds are so thoroughly mixed by biological activity that biogenic structures are virtually the only penetrative primary sedimentary structures preserved. The burrows which are preserved probably represent only the latest stages of burrowing; earlier stages are destroyed by later reworking. The result is thorough mixing and homogenization of beds. Intense sediment mixing was most likely effected mainly by very shallow burrowers, as seen in modern sediments. Rhoads (1967) found that modern shallow subtidal sediments of Buzzards Bay, Massachusetts, were intensively reworked only in their upper 2 - 3 cm., although deep burrows could penetrate to 10 cm. depth. Berger et al. (1979) found a similar pattern in abyssal sediments of the Pacific Ocean: only the upper 5 - 7 cm. was intensively reworked, although burrows could penetrate to depths of

20 to 35 centimeters beneath the sea floor.

Grainstones

Punctuating the prevailing muddy sediments are thin (1 - 13 cm) bioclastic grainstone beds. These rest on sharp scoured surfaces, but generally have gradational upper boundaries. They may show graded bedding, imbrication, cross-bedding or hummocky cross-stratification (Harms et al., 1975, p. 87-88), or parallel lamination.

Most grainstones are composed of bioclasts which may be disarticulated or in some cases broken, but are generally not highly abraded. Some include intraclasts as large as 30 x 27 x 17 mm, indicating deposition by high-energy events; but many of the intraclasts slump into underlying cavities or are transected by burrows, showing that they were cohesive but not lithified at the time of deposition, and thus could not survive long-distance transportation. Bioclasts and intraclast lithologies represent the composition of the underlying bed. Such grainstones most likely formed by resuspension of shelly muds and winnowing out of fines during occasional severe storms.

Lenticular coquinites in the Middle Ordovician Decorah Shale of Minnesota -- in part the stratigraphic equivalent of lower Dunleith carbonates -- (Weiss, 1957, p. 1052-1053), and similar beds in the Upper Ordovician Eden Shale (Anstey and Fowler, 1969) or Kope Fm. (Harrison, 1980; Mahan and Harrison, 1980) -- equivalent to the Wise Lake and perhaps the Dubuque Fms. -- have been interpreted likewise as storm deposits.

The fact that grainstones are interstratified with much larger quantities of shelly muds indicates that reworking and redeposition was due to rare invasions of the bottom environment by high-turbulence events which "punctuated" the normal quiet-water conditions. Each grainstone appears to record one such invasion; therefore, such episodes were much rarer than is suggested by a comparison of aggregate grainstone thickness with wackestone/mudstone thickness. Grainstones constitute less than 5% of the thickness of the Galena Group at typical outcrops, but represent far less than 1% of the total time involved in the accumulation of Galena sediments.

The wide distribution of some Wise Lake and lower Dubuque grainstones (Levorson and Gerk, 1972 and this vol.; Levorson et al., 1979) merely requires that a large storm affected the sea bottom over a large area each time such a bed was deposited. Dunleith grainstones seem more locally distributed, suggesting that either storms were more severe later in Galena time or the sea was somewhat shallower in Wise Lake-lower Dubuque time than in most of Dunleith time.

A few grainstones in the Galena show signs of more extensive transport -- good sorting, rounding, and abrasion; absence of unlithified intraclasts; and absence of aragonitic shells (discussed below). Such grainstones are generally not coarser than coarse sand size; they may be vaguely laminated; and at one exposure they have the form of sand waves up to 10 cm. high. All examples of this type of grainstone which I have seen overlie hardgrounds. Such grainstones may represent small sand waves which moved slowly across hard bottoms. The sand waves were usually dormant, but moved repeatedly during storms, and quite likely in different directions at different times (interpretation suggested by John Harms, oral commun., 1977). Sand waves are known in modern seas below the zone of normal wave action in many parts of the world, and range in amplitude from a few centimenters to many meters, and occur in fields up to tens of miles across (Johnson and Stride, 1969; Kenyon and Stride, 1970; Boggs, 1974).

Some grainstones can be identified in the dolomite facies, where intergranular pores or shell molds are preserved as voids (probably due to incomplete dolomitization, followed by dissolution of undolomitized calcite cement or shells). As seen in partially dolomitized samples, however, grainstones can be dolomitized without such diagnostic porosity preservation, and may be difficult or impossible to recognize. It seems likely that fewer grainstones are recognizable in dolomitized exposures than were actually deposited there.

K-bentonites

At least eight widely traceable K-bentonites and several other more local ones occur in the Galena Group (Mossler and Hayes, 1966; Levorson and Gerk, 1972; Willman and Kolata, 1978; Levorson et al., 1979). These appear to be submarine ash falls sourced by volcanoes in the northern Appalachians. Preservation of the bentonites indicates the general lack of erosion on the sea floor during Galena time.

Clay content

Shales in the Galena Group become thicker towards the northwest; new shale beds are intercalated toward the northwest; and carbonates become increasingly argillaceous towards the northwest. This indicates that clastics were derived from the direction of the Transcontinental Arch (cf. Witzke, this vol., and Stone, this vol.).

Quartz sand

In the western and northern part of the field area, well-rounded medium quartz sand occurs in the Buckhorn and St. James Members of the Dunleith Fm. as disseminated "floating" grains. I have found samples in which burrows in otherwise quartz-poor mudstones are filled with quartz sand. It is not clear how the sand was introduced, but the present "floating" texture is probably due to reworking by burrowers. Basal Dunleith carbonates in subsurface in western Iowa are stratigraphically higher than the St. James, but contain abundant quartz sand (Witzke, this vol.). The source of the sand is not known, but its distribution suggests it may be derived from near the Transcontinental Arch.

Silty beds

Carbonate beds consisting of 5 to 10% exceedingly-well-sorted "floating" angular 20µm - 50µm silt grains occur consistently over wide areas at certain stratigraphic levels, especially in the Dunleith Fm. Some of these can be traced over 100 miles laterally. Within single beds, the silt coarsens very gradually northwestward (or northward or westward?). At any one locality, silt grains in all silty beds tend to be of about the same size. The composition of the silt (99% quartz, 1% microcline) indicates that it was derived from a supermaturely weathered source terrane. The extremely good sorting, very gradual lateral size gradient, and great lateral continuity of silty beds can best be explained by the silt being a windblown dust, eroded and transported by winds from an emergent source area 250 to 500 miles north to west of the study area (although purely subaqueous processes of transportation and deposition cannot be ruled out entirely). Numerous studies have demonstrated the importance of wind transportation over the sea for long distances. For instance, dust blown from North Africa is:

1. the chief non-carbonate pelagic sediment in the subtropical North Atlantic (Delany et al., 1967; Beltagy et al., 1972);
2. the main ingredient of dusts arriving at Barbados (Delany et al., 1967);
3. the chief non-carbonate aerosol at Miami (Prospero, 1979);
4. detectable in snowfields in Central America (Windom, 1975).

Eolian dusts are also significant components of marine sediments far from land in the South Atlantic (Chester et al., 1971), wide areas of the Pacific (Prospero and Bonatti, 1969; Rex et al., 1969; Clayton et al., 1972), and other areas (Fowler, 1978, p. 277).

Despite the proved importance of eolian transport in the deposition of modern fine clastics, almost no attention has been paid to the possibility that some fine silicates in pre-Quaternary offshore marine deposits may have been transported by the wind. Eolian transport may have been an especially important mechanism in early Paleozoic time, due to the lack of land plants to baffle or bind sediments against the wind.

One possible problem with an "eolian" interpretation is that of paleowind direction. If the study area lay in tropical (Dott and Batten, 1976, p. 228) or subtropical (Witzke, 1980, p. 15) southern latitudes, with the paleoequator running roughly NNE - SSW, the prevailing trade winds should not have blown from the north, northwest, or west. The bentonites in the Galena section are evidence that long-distance wind transport occurred from the direction of the Appalachians at times. However, no suitable sources for supermature silt are known in this direction. It must be recognized that "prevailing" winds do not always prevail, as emphasized by two modern examples:

1. The great dust storm of March, 1901, carried dust from a probable source in southern Algeria in a dominantly north-northeastward direction, as far as southern Scandinavia. The direction of "prevailing" trade winds over the source is westward. A similar event occurred in 1903 (Fowler, 1978; Prospero, 1979).
2. The June 12, 1980 eruption of Mt. St. Helens spread ash to the north, west, and south of the volcano, but not in the expected eastward direction of "prevailing" winds (Science News, v. 117, p. 391, June 21, 1980).

Even single storms can deposit significant amounts of sediment. Windom and Chamberlain (1978) showed that a single 1977 dust storm carried 3% to 5% of the normal total annual dust load from North Africa.

In sum, although purely subaqueous transport of silt cannot be ruled out, there is equally no valid reason to reject wind as a possible transporting agent. Eolian transportation of siliciclastic fines has generally (and unjustifiably) been neglected as a depositional mechanism for ancient rocks, despite the utility of eolian silt beds as time markers and possible extremely sensitive indicators of temporary sea level drawdown, and despite the demonstrated importance of this process in modern seas.

Biota

The carbonates of the Galena Group are bioclastic throughout. The biota is diverse and, in most zones, includes echinoderms, trilobites, ostracodes, brachiopods, bryozoans, rugose corals, pelecypods, gastropods, cephalopods, and other animal groups. Algal remains include receptaculitids and the abundant microscopic dasycladacean alga, Vermiporella. Endolithic borings and micrite envelopes occur in most Galena strata; boring morphologies suggest that both boring algae and boring fungi were active. The algal remains vary from very rare to common, suggesting that Galena strata were generally deposited within the photic zone, but possibly near its lower limit at certain times and places.

Certain zones contain a dominantly molluscan biota, plus or minus receptaculitids. Similar biotas in other formations, e.g. the gastropod-cephalopod-dasycladacean algal association characteristic of backreef areas in the Permian Capitan Fm. of West Texas (Lloyd C. Pray, oral commun., 1979), are interpreted as euryhaline. Such zones in the Galena, devoid of definitely stenohaline forms such as trilobites or crinozoans, may have been deposited under conditions of unstable salinity.

Possible evaporite molds

Vugs of equant to elongate shape and consistent sizes, many with internal septa, tend to occur at consistent stratigraphic positions over wide areas. Some of these occurrences are associated with a chiefly molluscan biota at some exposures. Near the Wisconsin Arch, small "floating" slit-like cavities occur in the vuggy zones at some localities (Delgado, 1983); I interpret these as molds of evaporite crystals. The crystal molds are platy and also show fairly common chevron twinning, suggestive of gypsum. The nodule-shaped vugs may well be molds of calcium sulfate nodules which grew displacively within the sediment during times when the overlying water became hypersaline. It is worth repeating that there is no evidence of emergence during Galena deposition. As these presumed evaporite traces are commonly associated with biotic remains, the evaporites must have grown displacively within the sediment some time after deposition of the sediment. Restriction of these presumed evaporite traces to well-defined stratigraphic intervals, and association in some cases with restricted biotas, indicates that the evaporitic intervals occurred not long after deposition of the enclosing sediments.

These postulated evaporite traces are commonly associated with slightly argillaceous intervals containing "floating" silt as described above. This leads to the speculation that, during temporary lowerings of sea level, clastic source areas were exposed to erosion, while simultaneously the vast but thinned sheet of water covering the North American craton could not circulate efficiently, thus permitting patches of hypersaline water to develop.

Not present

Oolites, pisolites, and oncolites; stromatolites; laminites; fenestral fabrics; mud cracks; flaser bedding; ripple marks; and other possible indicators of normal high energy or periodic or occasional emergence are entirely absent from Galena strata. This is strong evidence that Galena deposition was entirely subtidal.

Depositional environment and processes

The great lateral continuity of individual beds, consistent thickness of members over a wide area, preservation of unabraded shells in mud support through 95% of the thickness of the group, general preservation of thin bentonites over large areas, lack of emergence or normal-high-energy indicators, and offshore, quiet-water aspect of the biota, indicates that the Galena Group was deposited in normally quiet water on a highly stable, uniform marine shelf, below normal wave base.

Presence of green algae, micrite rims on bioclasts, and endolithic borings with algal-origin morphology, indicate deposition occurred within the photic zone. Rarity of algal remains and poor development of micrite rims and discrete algal borings at some localities at some horizons suggests that deposition was at times near the lower limit of the photic zone.

Presence of ?euryhaline biotic assemblages in some zones at some localities, in association with possible evaporite molds, suggests the possibility that at times salinity could fluctuate, probably due to poor local circulation. Association in many cases of evaporite molds with silty beds interpreted as possible eolian-marine deposits indicates that hypersaline conditions were most likely to develop during minor regressions which exposed clastic source areas hundreds of miles away.

EARLY DIAGENESIS

Evidence of several submarine diagenetic processes is displayed in Galena strata.

Submarine dissolution of aragonite

The Dunleith and Wise Lake Formations contain abundant evidence that aragonite commonly dissolved not far beneath the sea floor. The best such evidence consists of large molluscan and receptaculitid shells (inferred to have been wholly or largely aragonite) which have been replaced by burrowed bioclastic sediment. The sediment which casts the former shell is distinguished from the matrix in which the shell was embedded by color or texture; the outline of the former shell is clearly preserved in the matrix. This is a very common phenomenon; perhaps 50% of the large molluscs of the Stewartville Member, Wise Lake Fm., are cast by burrowed sediment. The following sequence of events is implied:

1. An aragonite shell is buried shallowly.
2. The enclosing sediment becomes firm and cohesive enough not to collapse

into the void when the shell dissolves;

3. The shell dissolves, leaving a void;
4. The void is filled with bioclastic sediment piped in via a burrow which intersects the void;
5. Burrowing organisms enter the position formerly occupied by the shell, and burrow the sediment which fills up the void which was created when the shell dissolved.

These considerations show that aragonite commonly dissolved while buried less deeply than the base of the zone of active burrowing; hence, under submarine conditions.

Exactly similar burrowed casts occur in carbonate rocks which are sedimentologically similar to, and lateral equivalents of, the Galena Group in Manitoba and Saskatchewan (Kendall, 1977). Kendall estimated that burrowers could penerate vertically through a sediment thickness "probably no greater than a few meters" (p. 497), certainly a generous estimate.

Submarine cementation

Evidence of submarine cementation is spectacularly displayed in the Dunleith Fm. and the lower Wise Lake Fm. The two chief manifestations are hardgrounds and nodules in argillaceous strata.

Hardgrounds

The term "corrosion zone" has long been applied to zones associated with mineralized and pitted bedding surfaces and pebbles at various stratigraphic levels in the Galena Group and subjacent units (Sardeson, 1898, 1914; Weiss, 1954, 1957, 1958; Prokopovich, 1955; Templeton and Willman, 1963; Levorson and Gerk, 1972; Willman and Kolata, 1978). "Corrosion zones" are generally several centimeters thick, and include:

1. "Corrosion surfaces" -- bedding surfaces which may be smooth or irregular, but are commonly pitted and/or dovetailed in vertical section; the underlying bed is more or less permeated with iron minerals, with an intensity which decreases downward, away from the "corrosion surface".
2. "Corrosion conglomerates" -- horizons characterized by clasts, some more than 30 cm. in horizontal measure, which are pitted and iron-mineralized (Sardeson, 1898, 1914).

"Corrosion surfaces" and "corrosion conglomerates" may occur in association with one another or independently (Sardeson, 1914).

In this study, I have identified a minimum of 153 separate stratigraphic levels at which "corrosion surfaces" occur in the combined Dunleith, Wise Lake, and Dubuque Fms. They occur at essentially every exposure of the Dunleith and lower Wise Lake, and are one of the most spectacular, as well as important, petrologic features of the Galena Group.

The "corrosion surfaces" in the Galena are in fact hardgrounds: surfaces which were cemented by submarine processes before deposition of the overlying bed. The clasts of "corrosion conglomerate" may be termed hardground intraclasts;

they show evidence of lithification at the sea floor also, and may or may not in individual instances have been transported from their point of lithification.

There is essentially no evidence that hardground surfaces in the Galena have been sculpted, even in part, by corrosion. Chemical attack would produce "highly intricate sculpture varying with the chemical heterogeneity of the rock" (Bromley, 1978, p. 398). Such sculpture is not seen on Galena hardgrounds; they are therefore not demonstrably "corrosion surfaces" in the strict sense, and should not be referred to as such. The terms "corrosion zone", "corrosion surface", and "corrosion conglomerate" are inappropriate and should be abandoned.

The following features of hardgrounds and hardground intraclasts are evidence that they were cemented before burial:

1. The bed underlying the hardground surface contains bioclasts which are truncated flush with the hardground surface. Thus the bioclast and the hardground surface were of similar hardness at the time of erosion.

2. About 30% of hardgrounds and most hardground intraclasts contain *Trypanites* borings, up to a maximum density of about 80,000 borings per square meter.

3. Many hardgrounds show overhanging sculpture which could not have supported itself unless lithified. Note that this is also evidence for the final sculpting of the hardground after lithification.

4. 20% of the hardground samples examined contain cracks filled with sparry calcite cement which is truncated at the hardground surface. In one case, the cement is bored.

5. Several examples were seen in which hard-substrate epibiota (pelmatozoan holdfasts, bases of ramose bryozoans, and sheet-like encrusting bryozoans) encrust the hardground (see also Sardeson, 1898, p. 319; Palmer and Palmer, 1977).

6. Burrows in the next overlying bed may descend to the hardground; they then run along the hardground, at least until they can descend through the cemented layer via a pre-lithification omission burrow.

That this lithification was submarine is indicated by the following lines of evidence:

1. Galena strata are uniformly marine and contain no evidence of emergence or near-emergence. The sediment in pits in hardgrounds in uniformly marine (Sardeson, 1914).

2. Hardground epibiota required marine conditions.

3. Hardgrounds are present at at least 153 separate stratigraphic levels. 153 separate advances and retreats of the sea during Galena time seem unlikely.

4. Many of the hardgrounds are of very limited lateral extent. Surfaces exposed by withdrawal of the sea would probably be more extensive, especially given the characteristic flat, parallel bedding of most of the Galena.

5. The morphologic and other characteristics of Galena hardgrounds are similar to those of known submarine-cemented hardgrounds, especially those of the Chalk of northwestern Europe, and are dissimilar to those of intertidally-cemented surfaces.

Many previous students of the Upper Mississippi Valley Ordovician have assumed the pits and dovetails in hardgrounds to be the result of chemical erosion (e.g., Weiss, 1954). In fact, as with European Mesozoic hardgrounds (e.g., Bromley, 1975) and modern hardgrounds (e.g. Shinn, 1969), most if not all pits are burrows and borings of the omission suite.

Micrite cement is overwhelmingly the most common cement at Galena hardgrounds. It is presumed to have been Mg-calcite in view of the fact that aragonite commonly dissolved near the sea floor. Galena hardgrounds are preferentially developed on wackestones and mudstones; thus, hardground cement cannot be distinguished optically from the original sediment which it cements. Many Mesozoic and Cenozoic shallow-water hardgrounds are preferentially developed in coarse-grained permeable carbonates, and have various non-aphanitic cement morphologies (e.g., Purser, 1969; Shinn, 1969, p. 129-133; Bathurst, 1971, p. 371; Kaźmierczak, 1974; Kennedy et al., 1977). Hardgrounds on fine-grained substrates, with micrite cement, are found in the northwest European Chalk (Kennedy and Garrison, 1975) and other "deeper-water" occurrences.

Galena hardgrounds are mineralized to variable extent with iron minerals: pyrite, limonite and/or hematite. Pyrite appears to be the original mineral in all cases; hematite and/or limonite are products of weathering of pyrite. Pyrite impregnates the hardground and may form a crust on the surface. Some hardgrounds are also encrusted with collophane; invariably the phosphate overlies or encloses the pyrite, demonstrating that the phosphate postdates the pyrite. Pyrite weathers easily, producing strong acids. Because of this, hardgrounds tend to weather back faster than surrounding beds; in old exposures, the hardgrounds may be hard to find because they have become slots on the exposure face and appear to be mere bedding planes.

Nodules

Hardgrounds represent lithified strata which were exposed to the sea floor. Some hardground intraclasts probably represent discontinuous lithified nodules which were similarly exposed. If nodules lithified but were never exhumed, the diagnostic mineralization and morphology were never imposed. However, if they developed in sufficiently argillaceous strata, they can still be recognized. This is because clay content appears to have inhibited the normal propensity of Galena muds to cement rapidly. Early-cemented nodules in argillaceous strata stand out from their enclosing matrix in several ways: they resisted compaction while the matrix did not. Because of this, the nodules are generally lighter-colored than the surrounding matrix (because insolubles are concentrated in the matrix); nodules are devoid of microstylolitic laminae which are present in the matrix; and molds of aragonitic shells are preserved in the nodules, whereas the matrix was not sufficiently firm to hold the shape of aragonitic bioclasts when they dissolved, and the voids collapsed.

Possible submarine dolomitization

Where Galena strata are limestone, dolomite mottling is common, especially in certain stratigraphic intervals. Where strata are pervasively dolomitized, the mottling is preserved as differences in color, texture, porosity, and/or petrographic character of the dolomite. Dolomitization chiefly follows *Thalassinoides* burrow systems which may be interconnected laterally and vertically over a wide area. Dolomite may also halo burrows, and may occur as disseminated rhombs in lime mud.

Several lines of evidence suggest that some of this dolomite mottling is submarine in origin:

1. Dolomite rhombs just below scoured surfaces and at edges of intraclasts appear to be abraded. The abraded surface may have a hackly appearance due to breakage along intersecting cleavage planes; or the abraded rhomb may protrude slightly from the abraded surface.

2. Dolomite mottles descend from bedding planes. Even where they extend down to the next bedding plane, they are never seen to become increasingly dolomitic downward; but they quite commonly become increasingly dolomitic upward toward the bedding plane from which the host burrows descend.

3. Dolomitized burrows penetrate some cherts. This suggests that (a) the burrows were dolomitized before formation of the chert, and (b) dolomite resisted chertification but limestone did not.

Submarine authigenic dolomite is well-known from depths of several hundred to several thousand feet in the ocean (e.g., Marlowe, 1971; Davies and Supko, 1973; Bartlett and Greggs, 1970; Müller and Fabricius, 1974), but is not well documented from shallower seas under fully marine conditions.

Rate of deposition

The age and duration of Galena Group deposition is not closely known, but probably spanned about 8 million (Odin, 1982) to 20 million (Ross, 1982) years for the Dunleith to Dubuque interval. The aggregate thickness of the Dunleith, Wise Lake, and Dubuque Formations is about 220 to 255 feet (Willman and Kolata, 1978, fig. 11). This gives a net accumulation rate of about 3.5 mm to 9 mm per thousand years.

However, some of Galena time is certainly represented by periods of nondeposition, probably mostly represented in the rock record by hardgrounds. How much time is represented by hardgrounds? An estimate can be made by making two reasonable assumptions:

1. A hardground developed at any surface which was exposed at the sea floor for a significant length of time.

2. Grainstones were deposited at random times.

Granting these assumptions, we may take the proportion of grainstones which overlie hardgrounds as an estimate of the proportion of time hardgrounds were exposed at the surface during Galena time. At different outcrops, this proportion varies from 15% to 30%. Thus we can estimate that hiatuses, represented by hardgrounds, account for 15% to 30% of Galena time, or 1.2 to 6 million years aggregate. The deposits represent the remaining 5.6 to 17 million years, and thus accumulated at an average rate of 4.1 to 13.9 mm per thousand years between hiatuses.

LATER DIAGENESIS

Chertification and silicification

The upper seven members of the Dunleith Fm. and the basal few feet of the Wise Lake Fm. are bariably cherty in the Upper Mississippi Valley outcrop region. Chert nodules occur at specific horizons which are fairly consistent across a single exposure; some chert horizons can be correlated between exposures (Levorson and Gerk, 1972 and this vol.). Silicified brachiopods and corals are common in the cherty zone. Chert and silicified fossils are very rare below the base of the Eagle Point Member and absent above the basal few feet of the Wise Lake Fm.

The chert nodules commonly contain silicified burrows and silicified bioclasts, clearly indicating that the chert formed by diagenetic replacement of carbonate and was not a primary precipitate on the sea floor.

Distribution of chert and silicified fossils is similar in the limestone and dolomite facies of the Galena (see below; cf. also Witzke, this vol.). In the dolomite facies, better preservation of sedimentary textures in chert nodules than in surrounding dolomite, and finer preservation of shell ornamentation on silicified fossils than in dolomitized ones, is strong evidence that chertification and silicification of fossils predated regional dolomitization.

In dolomite-mottled limestone, some dolomite mottles penetrate the chert nodules; other mottles are truncated by chert nodules. This suggests that some dolomite mottles are older, others younger, than chert.

Chert nodules are strongly localized to specific horizons at any one exposure. This suggests some compositional or possibly textural control operated at the time chert was growing. Many cherts preserve siliceous sponge spicules within them. One possibility which cannot be evaluated on the basis of evidence I have seen is that siliceous sponge spicules were concentrated along bedding planes. Intensive sediment-mixing burrowers distributed the spicules within a zone 2 or 3 cm. wide above and below the former bedding plane, but did not have sufficient vertical range to truly homogenize the sediment over larger vertical distances. When conditions became right for diagenesis of biogenic opal, chert nodules grew in the silica-rich bands.

The groundmass of Galena cherts is composed of cryptocrystalline quartz. Fibrous length-fast chalcedony lines original cavities such as open burrows; fibres are perpendicular to the cavity wall. Any remaining space is eventually filled with clear blocky megaquartz cement.

Regional dolomitization

At the northwest end of the outcrop belt in Minnesota and northernmost Iowa, Galena strata are limestone. Farther southeast, equivalent beds have been dolomitized. The Galena is limestone again at the extreme southeast end of the outcrop belt near Morris, Illinois. Facies characteristics and even individual beds continue without change from the limestone into the dolomite lithofacies; this indicates that regional dolomitization was mesogenetic and not related to depositional conditions.

As discussed under chertification, above, regional dolomitization apparently occurred after chertification.

The Galena is part of the type example of "Dorag" dolomitization (Badiozamani, 1973). Under the Dorag hypothesis, dolomitization occurred by reaction of limestone with mixed fresh and marine phreatic water at a time when the Wisconsin Arch was exposed and receiving fresh water recharge.

Dolomitization patterns are similar in all formations of the Galena Group; in general, the limestone/dolomite facies boundary is gently inclined, with dolomite overlying limestone. This boundary is exposed low in the Dunleith Fm. in Grant County, Wis., and Jo Daviess County, Ill., and rises through the Dunleith and Wise Lake in Dubuque and Clayton Counties, Iowa. This geometry is consistent with the Dorag model, but hardly proves it. The Dorag model predicts that a symmetrical facies transition from dolomite to limestone occurs east of the Wisconsin Arch. Such a facies transition is indeed found, but in subsurface in western Michigan (Gregg, 1982). That puts the axis of symmetry near the western edge of Lake Michigan. Perhaps coincidentally, the only locality near the outcrop area where significant erosion of the Galena before Maquoketa deposition can be documented is in the Texas Wisconsin Gas Co. Van Driest #1 stratigraphic test in Sheboygan County, Wis., on the Lake Michigan shore. In this well, about 100 feet of upper Galena strata are cut out below the Maquoketa Group (Moretti, 1971).

In subsurface Iowa (Witzke, this vol.) and in northern Illinois (Kolata and Graese, 1983), areal patterns of dolomitization in Maquoketa carbonates coincide sith those in the Galena to large extent. This suggests that, if dolomitization occurred by a mixing-zone process, the freshwater recharge must have occurred after deposition of much of the Maquoketa Group, probably during the worldwide eustatic drawdown at the end of Ordovician time.

REFERENCES

Anstey, R. L.; and Fowler, M. L., 1969, Lithostratigraphy and depositional environments of the Eden Shale (Ordovician) in the tri-state area of Indiana, Kentucky, and Ohio: Jour. Geology, v. 77, p. 668-682.

Badiozamani, Khosrow, 1973, The dorag dolomitization model, application to the Middle Ordovician of Wisconsin: Jour. Sedimentary Petrology, v. 43, p. 965-984.

Bartlett, G. A.; and Greggs, R. G., 1970, The Mid-Atlantic Ridge near 45° 00' north, VIII. Carbonate lithification on oceanic ridges and seamounts: Can. Jour. Earth Sci., v. 7, p. 257-267.

Bathurst, R. G. C., 1971, Carbonate sediments and their diagenesis. Elsevier, Amsterdam and New York, xx, 620 p.

Beltagy, A. I.; Chester, R.; and Padgham, R. C., 1972, The particle-size distribution of quartz in some North Atlantic deep-sea sediments: Mar. Geol., v. 13, p. 297-310.

Berger, W. H.; Ekdale, A. A.; and Bryant, P. P., 1979, Selective preservation of burrows in deep-sea carbonates: Mar. Geol., v. 32, p. 205-230.

Boggs, Sam, Jr., 1974, Sand-wave fields in Taiwan Strait: Geology, v. 2, p. 251-253.

Bromley, R. G., 1967, Some observations on burrows of thalassinidean Crustacea in Chalk hardgrounds: Quart. Jour. Geol. Soc. London, v. 123, p. 157-182.

Bromley, R. G., 1975, Trace fossils at omission surfaces: in Frey, R. W., ed., The study of trace fossils. New York, Springer-Verlag, p. 399-428.

Bromley, R. G., 1978, Hardground diagenesis: in Fairbridge, R. W.; and Bourgeois, J., eds., The encyclopedia of sedimentology: Encyc. Earth Scis., v. 6, p. 397-400.

Chester, R.; Elderfield, H.; and Griffin, J. J., 1971, Dust transported in the North-east and South-east Trade Winds in the Atlantic Ocean: Nature, v. 233, p. 474-476.

Clayton, R. N.; Rex, R. W.; Syers, J. K.; and Jackson, M. L., 1972, Oxygen isotope abundance in quartz from Pacific pelagic sediments: Jour. Geophys. Res., v. 77, p. 3907-3915.

Davies, T. A.; and Supko, P. R., 1973, Oceanic sediments and their diagenesis: some examples from deep-sea drilling: Jour. Sedimentary Petrology, v. 43, p. 381-390.

Delany, A. C.; Delany, A. C.; Parkin, D. W.; Griffin, J. J.; Goldberg, E. D.; and Reimann, B. E. F., 1967, Airborne dust collected at Barbados: Geochim. Cosmochim. Acta, v. 31, p. 885-909.

Delgado, D. J., 1983, Alternate stop A -- Lower Galena Formation, Okeson Quarry: in Sedimentology of Ordovician carbonates and sandstones in southwestern Wisconsin, North-Central Sec., Geol. Soc. America, April 28-May 1, 1983, p. 43.

Dott, R. H., Jr.; and Batten, R., 1976, Evolution of the earth, second ed. McGraw-Hill, New York, viii, 504p.

Folger, David W., 1978, Eolian dust in marine sediments: in Fairbridge, R. W.; and Bourgeois, J., eds., Encyclopedia of sedimentology: Encyc. Earth Scis., v. 6, p. 276-279.

Gregg, J. M., 1982, The origin of xenotopic dolomite texture: unpub. Ph. D. Diss., Michigan State Univ., x, 151 p.

Harms, J. C.; Southard, J. B.; Spearing, D. R.; and Walker, R. G., 1975, Depositional environments as interpreted from primary sedimentary structures and stratification sequences: Soc. Econ. Paleontologists Mineralogists, Short Course no. 2, 161 p.

Harrison, W. B., 1980, Low diversity benthic faunal communities in the Kope Formation, lower Upper Ordovician, Ohio Valley region as a result of sporadic environmental instability (abstr.): Geol. Soc. America, Abstr. with Prog., v. 12, p. 228.

Johnson, M. A.; and Stride, A. H., 1969, Geological significance of North Sea sand transport rates: Nature, v. 224, p. 1016-1017.

Kaźmierczak, J., 1974, Crustacean associated hiatus concretions and eogenetic cementation in the Upper Jurassic of central Poland: Neues Jb. Geol. Paläont., Abh., v. 147, p. 329-342.

Kendall, A. C., 1977, Origin of dolomite mottling in Ordovician limestones from Saskatchewan and Manitoba: Bull. Canadian Petroleum Geol., v. 25, p. 480-504.

Kennedy, W. J.; and Garrison, R. E., 1975, Morphology and genesis of nodular chalks and hardgrounds in the Upper Cretaceous of southern England: Sedimentology, v. 22, p. 311-386.

Kennedy, W. J.; Lindholm, R. C.; Helmold, K. P.; and Hancock, J. M., 1977, Genesis and diagenesis of hiatus- and breccia-concretions from the mid-Cretaceous of Texas and northern Mexico: Sedimentology, v. 24, p. 833-344.

Kenyon, N. H.; and Stride, A. H., 1970, The tide-swept continental shelf sediments between the Shetland Isles and France: Sedimentology, v. 14, p. 159-173.

Kolata, D. R.; and Graese, Anne M., 1983, Stratigraphy and depositional environments of the Maquoketa Group (Ordovician) in northern Illinois: Illinois State Geol. Surv., Circ. 528, iv, 49 p.

Levorson, C. O.; and Gerk, A. J., 1972, A preliminary stratigraphic study of the Galena Group of Winneshiek County, Iowa: Iowa Acad. Sci., Proc., v. 79, p. 111-122.

Levorson, C. O.; and Gerk, A. J., 1983, Field recognition of stratigraphic position within the Galena Group of northeast Iowa (limestone facies): this volume.

Levorson, C. O.; Gerk, A. J.; and Broadhead, T. W., 1979, Stratigraphy of the Dubuque Formation (Upper Ordovician) in Iowa: Iowa Acad. Sci., Proc., v. 86, p. 57-65.

Lindström, Maurits, 1979, Diagenesis of Lower Ordovician hardgrounds in Sweden: Geologica et Palaeontologica, v. 13, p. 9-30.

Mahan, T. K.; and Harrison, W. B. III, 1980, Depositional environment of lower Cincinnatian Kope Formation and some paleoecologic implications (abstr.): Am. Assoc. Petroleum Geologists Bull., v. 64, p. 744.

Marlowe, J. I., 1971, Dolomite, phosphorite and carbonate diagenesis on a Caribbean seamount: Jour. Sedimentary Petrology, v. 41, p. 809-827.

Moretti, George, Jr., 1971, Reference section for Paleozoic rocks in eastern Wisconsin: Van Driest No. 1, Sheboygan County: unpub. M.S. thesis, University of Wisconsin-Milwaukee, xiv, 137 p.

Mossler, J. H.; and Hayes, J. B., 1966, Ordovician potassium bentonites of Iowa: Jour. Sedimentary Petrology, v. 36, p. 414-427.

Müller, Jens; and Fabricius, Frank, 1974, Magnesian-calcite nodules in the Ionian deep sea: an actualistic model for the formation of some nodular limestones: in Hsu, Kenneth J.; and Jenkyns, Hugh C., eds., Pelagic sediments: on land and under the sea. Intl. Assn. Sedimentologists, spec. publ. 1, p. 235-247.

Odin, Gilles Serge, 1982, The Phanerozoic time scale revisited: Episodes, v. 1982 (3), p. 3-9 (Oct. 1982).

Palmer, T. J.; and Palmer, C. D., 1977, Faunal distribution and colonization strategy in a Middle Ordovician hardground community: Lethaia, v. 10, p. 179-199.

Prokopovich, N., 1955, The nature of corrosion zones in the Middle Ordovician of Minnesota: Jour. Sedimentary Petrology, v. 25, p. 207-215.

Prospero, J. M., 1979, Dust from the Sahara: Natural History, v. 88 (5), p. 54-61, 94-95.

Prospero, J. M.; and Bonatti, E., 1969, Continental dust in the atmosphere of the eastern equatorial Pacific: Jour. Geophys. Res., v. 74, p. 3362-3371.

Purser, B. H, 1969, Syn-sedimentary marine lithification of Middle Jurassic limestones in the Paris Basin: Sedimentology, v. 12, p. 205-230.

Rex, R. W.; Syers, J. K.; Jackson, M. L.; and Clayton, R. N., 1969, Eolian origin of quartz in soils of Hawaiian Islands and in Pacific pelagic sediments: Science, v. 163, p. 277-279.

Rhoads, D. C., 1967, Biogenic reworking of intertidal and subtidal sediments in Barnstable Harbor and Buzzards Bay, Massachusetts: Jour. Geol., v. 75, p. 461-476.

Ross, R. J. Jr., ed., 1982, The Ordovician System in the United States: correlation chart and explanatory notes: International Union of Geological Sciences, Publication no. 12.

Sardeson, F. W., 1898, Intraformational conglomerates in the Galena series: Am. Geologist, v. 22, p. 315-323.

Sardeson, F. W., 1914, Characteristics of a corrosion conglomerate: Geol. Soc. America Bull., v. 25, pp. 265-276.

Shinn, E. A., 1969, Submarine lithification of Holocene carbonate sediments in the Persian Gulf: Sedimentology, v. 12, p. 109-144.

Stone, D. J., 1983, Lithostratigraphy of the upper Dunleith Formation (Ordovician) in southeastern Minnesota: this volume.

Templeton, J. S.; and Willman, H. B., 1963, Champlainian Series (Middle Ordovician) in Illinois: Illinois State Geol. Survey, Bull. 89, 260 p.

Weiss, M. P., 1954, Corrosion zones in carbonate rocks: Ohio Jour. Sci., v. 54, p. 289-293.

Weiss, M. P., 1957, Upper Middle Ordovician stratigraphy of Fillmore County, Minnesota: Geol. Soc. America Bull., v. 68, p. 1027-1062.

Weiss, M. P., 1958, Corrosion zones: a modified hypothesis of their origin: Jour. Sedimentary Petrology, v. 28, p. 486-489.

Willman, H. B.; and Kolata, D. R., 1978, The Platteville and Galena Groups in Northern Illinois: Illinois State Geol. Surv. Circ. 502. 75 p.

Windom, H. L., 1975, Eolian contributions to marine sediments: Jour. Sedimentary Petrology, v. 45, p. 520-529.

Windom, H. L.; and Chamberlain, C. F., 1978, Dust storm transport of sediments to the North Atlantic Ocean: Jour. Sedimentary Petrology, v. 48, p. 385-388.

Witzke, B. J., 1980, Middle and Upper Ordovician paleogeography of the region bordering the Transcontinental Arch: in Fouch, T. D.; and Magathan, E. R., eds., Paleozoic paleogeography of west-central United States, Rocky Mountain Paleogeography Symposium 1, Rocky Mountain Sec., Soc. Econ. Paleontologists and Mineralogists, p. 1-18.

Witzke, B. J., 1983, Ordovician Galena Group in Iowa subsurface: this volume.

Delgado, D. J., ed. (1983), Ordovician Galena
Group of the Upper Mississippi Valley --
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TRACE FOSSILS IN PLATTEVILLE AND GALENA (ORDOVICIAN) CARBONATES OF THE UPPER MISSISSIPPI VALLEY

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ABSTRACT

The strata of the Platteville and Galena Groups display abundant and pervasive burrowing. *Chondrites*, *Planolites*, and *Thalassinoides* are the most common ichnogenera. Hardgrounds are characterized by the boring *Trypanites*. The trace fossil assemblage indicates a laterally extensive epeiric sea environment, with quiet water, a low rate of sedimentation, and frequent intervals of nondeposition.

In the Platteville and Galena Groups the sedimentary fabric is almost everywhere bioturbated. The only obvious primary physical sedimentary structures other than bedding are thin coquina layers, some of which display grading, planar lamination, hummocky stratification, or cross-stratification. They apparently indicate episodic rapid depositional events (storms?). Except for these layers, the sedimentation rate was low; the extensively bioturbated fabric implies that the burrowers had a sufficiently long time to rework the muds thoroughly.

The trace fossils are mostly infaunal deposit-feeder burrows and dwelling tunnels. Vertical burrows such as *Skolithos* or *Diplocraterion* are absent. Surface trails rarely are seen. A few specimens of *Cruziana* were collected by Stasko in his study of the Platteville (Byers and Stasko, 1978). Surface trails have also been reported from bedding plane exposures of hardgrounds in the Galena (Palmer, 1978; Delgado, Pers. Comm.). Rarity of surface trails is probably due to the paucity of bedding plane exposures and the uniformity of the micritic sediment -- surface traces in mud generally are not preserved well unless cast by a contrasting grain size. Dominance of the ichnofauna by infaunal traces also may reflect the fact that infaunal burrowers are the last organisms to move through the muds. Even if surface traces were being made at the sediment-water interface, they could be obliterated by the deep infauna after burial. Such is the situation in much of the deep-sea today, where complex grazing traces are visible on the surface but are absent in cores, having been obscured by infauna (Ekdale, 1977). What we see in the rock record is simply the "last imprint" of the benthic community.

The trace fossil taxa most abundant in the Platteville and Galena strata (*Chondrites*, *Planolites*, *Thalassinoides* (or *Spongeliomorpha*, cf. Fürsich, 1973), and *Zoophycos*) are not restriced to a particular depth range. *Chondrites*, *Planolites*, and *Zoophycos* are notorious for occurring at practically all depths, from the shallow shelf to the deep ocean. Seilacher's original classification of these traces as "intermediate depth" has been shown to be too restrictive (Byers, 1982). What these traces do indicate are 1) quiet water conditions, 2) sediment with sufficient organic matter for deposit-feeding, and 3) a soft substrate. The clear definition of the burrows suggests that the muds were firm enough to deform plastically, and therefore were not extremely fluid, at least not in the zone several centimeters down in the sediment where the burrowing took place (Rhoads, 1970).

The only trace indicative of a hard substrate in the Middle and Upper Ordovician carbonates is the boring *Trypanites* (Byers and Stasko, 1978; Palmer, 1978); commonly it is associated with hardground surfaces. These surfaces are rare in the Platteville but very common in the Galena. Borings are a few millimeters in diameter and a few centimeters long, have sharp margins, and can be found truncating shells and early cement crystals. Delgado (Pers. Comm.) has also recorded *Trypanites* in bryozoans and in bored nodules from hardgrounds. Kobluk and Nemcsok (1982) studied many specimens of *Trypanites* from bryozoan colonies in the Middle Ordovician of Ontario. The presence of scolecodonts in the boring fills suggests that the borer was a polychaete. *Thalassinoides* was a dwelling burrow; it displays a ramifying network extending many centimeters below the sediment-water interface. In Cretaceous and Cenozoic strata, *Thalassinoides* has been interpreted to be the abode of a bottom-living decapod crustacean, akin to the modern shrimp *Callianassa* (Bromley, 1975). Fossil callianassides are known from the Late Jurassic to Recent. Similar burrows in Triassic rocks may have been made by taxonomically-related decapods (glypheoids). However, no fossil decapods are known from rocks older than Permian (Glaessner, 1969); Paleozoic burrow networks resembling *Thalassinoides* have been called *Balanoglossites* and ascribed to enteropneusts (see discussion in Palmer, 1978). Nonetheless, the abundant burrow networks in the Galena have the earmarks of true *Thalassinoides*: horizontal, inclined, and vertical tubes 1-2 cm in diameter, with multiple branches — some interconnecting, others blind. Burrow depths of 22 cm have been recorded (Delgado, Written Comm.). Tunnels display widenings, especially at branch points, as do Mesozoic *Thalassinoides* and modern *Callianasssa* burrows. *Thalassinoides* has also been recognized in the Ordovician of Sweden (Lindström, 1979).

As a dwelling tunnel, *Thalassinoides* descends from distinct bedding planes (the former sea floor). During times of slow deposition, the sediment-water interface can become riddled with burrows. If reduction in the sedimentation rate is accompanied by submarine cementation, the burrow networks will be petrified; thus hardgrounds commonly are intensively burrowed (as well as bored) horizons (Bromley, 1975). This situation is very common in the Galena. In the areas where the Galena is only partly dolomitized, the *Thalassinoides* network is affected preferentially. Delgado (1980) reported that dolomite is commonly restricted to the burrow fill, probably because of greater permeability and/or bacterially-mediated precipitation. Similar differential dolomitization of burrow fills occurs in the Platteville (Byers and Stasko, 1978; Dathe and Weiss, 1983). It has also been reported from other Ordovician sequences, in Manitoba (Kendall, 1977) and in the Canadian Arctic (Morrow, 1978). Brown and Farrow (1978) dredged dolomitized crustacean burrows from modern marine muds, demonstrating that synsedimentary dolomitization is occurring on the seafloor, as deduced by Delgado (1980) for *Thalassinoides* in the Galena.

Another possible dwelling tunnel is _Palaeophycus_. Clear distinction between _Palaeophycus_ and _Planolites_, with criteria for recognizing them, has been made only recently. Pemberton and Frey (1982) specify that _Palaeophycus_ is a dwelling tunnel, filled passively by sedimentation, whereas _Planolites_ is a feeding burrow, backfilled by the organism. Stasko (Byers and Stasko, 1978) collected horizontal burrows from the Platteville, but did not designate between _Palaeophycus_ and _Planolites_. Similarly, Delgado (Pers. Comm.) reports that _Planolites_ is definitely present in the Galena, but _Palaeophycus_ is questionable.

The assemblage of traces in the Platteville-Galena carbonates is essentially identical with that in Cretaceous chalk. Chalk is also a thoroughly bioturbated lithology, with abundant _Chondrites_ and _Zoophycos_ penetrating the micrite, and numerous hardgrounds with borings and _Thalassinoides_. Chalk also resembles the Platteville-Galena strata in terms of the following features:

1) a flat sea floor with very laterally extensive beds,
2) a low rate of deposition and many surfaces of nondeposition,
3) nearly pure carbonate lithology sedimented in a layer cake fashion,
4) zones of abundant chert nodules,
5) deposition below fair-weather wave base on a cratonic platform at a time of maximum worldwide transgression.

Can we use the chalk analogy as a depth indicator for the Middle Ordovician deposition? Depth of deposition of the Cretaceous chalk has been variously estimated: Garrison and Kennedy (1977) cited estimates in the range of 50-300 m for European chalk. Hattin (1982) suggested values of 150-300 m for the Niobrara Chalk of the Interior Cretaceous of North America. The presence of dasycladaean algae in the Galena (Delgado, 1979) implies deposition in the photic zone, suggesting that Galena deposition took place in the shallow end of the range for chalk deposition, probably at a depth of less than 90 m.

REFERENCES

Bromley, R. G., 1975, Trace fossils at omission surfaces: _in_ Frey, R. W. (ed.), The study of trace fossils. Springer-Verlag, Berlin, p. 399-428.

Brown, B. J.; and Farrow, G. E., 1978, Recent dolomitic concretions of crustacean burrow origin from Loch Sunart, west coast of Scotland: Journal of Sedimentary Petrology, v. 48, p. 825-834.

Byers, C. W., 1982, Geological significance of marine biogenic sedimentary structures: _in_ McCall, P. L.; and Tevesz, M.J.S. (eds.), Animal-sediment relations. Plenum Press, New York, p. 221-256.

Byers, C. W; and Stasko, L. E., 1978, Trace fossils and sedimentologic interpretation -- McGregor Member of Platteville Formation (Ordovician) of Wisconsin: Journal of Sedimentary Petrology, v. 48, p. 1303-1310.

Dathe, D. B; and Weiss, M. P., 1983, The origin of mottled dolomitic limestones in the Platteville Group (Ordovician) of northern Illinois (abstr.): Geological Society of America Abstracts with Programs, v. 15, p. 255.

Delgado, D. J., 1979, Sedimentation and submarine diagenesis of Middle Ordovician Kimmswick Strata (Galena Group) in the Upper Mississippi Valley (abstr.): Geological Society of America Abstracts with Programs, v. 11, p. 228.

Delgado, D. J., 1980, Submarine diagenesis (aragonite dissolution, cementation calcite, and dolomitization) in Ordovician Galena Group, Upper Mississippi Valley (abstr.): AAPG Bulletin, v. 64, p. 697.

Ekdale, A. A., 1977, Abyssal trace fossils in worldwide Deep Sea Drilling Project cores: in Crimes, T. P.; and Harper, J. C. (eds.), Trace fossils 2: Seel House Press, Liverpool, p. 163-182.

Fürsich, F. T., 1973, A revision of the trace fossils Spongeliomorpha, Ophiomorpha, and Thalassinoides: Neues Jahrb. Geol. Paläont. Mh., 1973, p. 719-735.

Garrison, R. E.; and Kennedy, W. J., 1977, Origin of solution seams and flaser structure in Upper Cretaceous chalks of southern England: Sedim. Geol., v. 19, p. 107-137.

Glaessner, M. F., 1969, Decapoda: in Moore, R. C. (ed.), Treatise on invertebrate paleontology, Part R, Arthropoda 4, v. 2. University of Kansas Press, Lawrence, Kansas, p. R400-R651.

Hattin, D. E., 1982, Stratigraphy and depositional environment of Smoky Hill Chalk Member, Niobrara Chalk (Upper Cretaceous) of the type area, western Kansas: Kansas Geological Survey Bulletin 225, 108 p.

Kendall, A. C., 1977, Origin of dolomite mottling in Ordovician limestones from Saskatchewan and Manitoba: Bull. Canadian Petroleum Geol., v. 25, p. 480-504.

Kobluk, D. R.; and Nemcsok, S., 1982, The macroboring ichnofossil Trypanites in colonies of the Middle Ordovician bryozoan Prasopora: population behavior and reaction to environmental influences: Can. J. Earth Sci., v. 19, p. 679-688.

Lindström, M., 1979, Diagenesis of Lower Ordovician hardgrounds in Sweden: Geologica et Paleontologica, v. 13, p. 9-30.

Morrow, D. W., 1978, Dolomitization of Lower Paleozoic burrow-fillings: Journal of Sedimentary Petrology, v. 48, p. 295-306.

Palmer, T. J., 1978, Burrows at certain omission surfaces in the Middle Ordovician of the Upper Mississippi Valley: Journal of Paleontology, v. 52, p. 109-117.

Pemberton, S. G.; and Frey, R. W., 1982, Trace fossil nomenclature and the Planolites-Palaeophycus dilemma: Journal of Paleontology, v. 56, p. 843-881.

Rhoads, D. C., 1970, Mass properties, stability, and ecology of marine muds related to burrowing activity: in Crimes, T. P.; and Harper, J. C. (eds.), Trace fossils. Seel House Press, Liverpool, p. 391-406.

Delgado, D. J., ed. (1983), Ordovician Galena
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FIELD RECOGNITION OF STRATIGRAPHIC POSITION WITHIN THE GALENA GROUP OF NORTHEAST IOWA (LIMESTONE FACIES)

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ABSTRACT

The Galena Group as defined in Illinois includes eleven stratigraphic subdivisions above the Decorah shales which can be recognized throughout the limestone facies in northeastern Iowa. A procedure for recognizing stratigraphic position in outcrops of these strata is presented. Major criteria are: presence or absence of chert; stratigraphic thickness exposed; argillaceousness; bedding thickness and style; and index fossils and key beds. At least eight bentonites are recognized. Areally-persistent zones of distinctive hardgrounds are also helpful in correlation. Receptaculites, Ischadites, crinoid zones, Maclurites, and Paleosynapta aid in defining stratigraphic position.

The shaly "marker bed" at the base of the Dubuque Formation, and two thick and widely traceable, distinctive shale beds within the Dubuque permit the formation to be subdivided informally into three units. Bedding thickness, geometry of bedding planes, argillaceous content, and diagenetic mineralization are used to differentiate these subdivisions.

A flow chart and a general section of the Galena Group in Winneshiek County are presented to assist in recognition of stratigraphic position.

INTRODUCTION

In 1970 the authors began an intensive study of the stratigraphy of the Galena Group of Winneshiek County, Iowa, in order to precisely position stratigraphically the abundant crinoid calices we had collected. In the then-current Iowa usage, the "Galena Formation" included Prosser, Stewartville and Dubuque Members. In Illinois, Templeton and Willman (1963) had recently subdivided the same interval into the Dunleith Formation (with eight members recognizable in Winneshiek County, Iowa), the Wise Lake Formation (two members), and the Dubuque Formation (not subdivided). The Illinois classification, with its finer subdivisions, made precise stratigraphic control possible. We found that all of the Illinois members could be recognized in the field, but frequently an arbitrary decision was necessary to determine an exact member contact. However, a sufficient number of persistent features, useful as correlation tools, was located to overcome the problem of locating member contacts (Levorson and Gerk, 1972, 1975; Gerk and Levorson, 1972; Levorson et al., 1979).

PROCEDURE FOR STRATIGRAPHIC POSITIONING

The following is a simplified approach for stratigraphic positioning within the Galena Group. It is summarized on the accompanying flow chart (fig. 1). Finer positioning may be achieved by reference to our General Section (fig. 2).

The first question to be answered at any exposure is: Does chert occur anywhere in the exposed sequence? In the Galena outcrop in Iowa, chert occurs only in parts of the Dunleith Formation and the lower portion of the Sinsinawa Member of the Wise Lake Formation. Non-cherty intervals in the Dunleith in Iowa do not exceed twenty feet in thickness. Thus, a non-cherty exposure more than twenty feet thick is in the Wise Lake and/or Dubuque Formations. A non-cherty sequence less than twenty feet thick may represent either a chert-free interval of the Dunleith, or portions of the Wise Lake and/or Dubuque Formations. (In Minnesota, chert-free intervals more than twenty feet thick do occur in the Dunleith, so the above criterion is not valid north of the Iowa-Minnesota line).

Non-cherty exposures

In the Wise Lake-Dubuque interval, the stratigraphic position of a given exposure may be defined as follows:

1. Exposures consisting of alternating pure carbonate and shale beds are middle or upper Dubuque.
2. If an exposure is entirely carbonate, search for either the widely-traceable "marker bed" (Levorson et al., 1979), or for Receptaculites.
    a. Presence of Receptaculites indicates upper Sinsinawa or lower Stewartville strata.
    b. The "marker bed" is generally easy to recognize; it marks the Wise Lake/Dubuque contact. See further discussion below.
    c. If neither the "marker bed" nor Receptaculites is found, search for continuous sparry calcarenite bands (SCB's: Levorson and Gerk, 1972). Continuous SCB's indicate Stewartville strata.
    d. Where continuous SCB's are absent, Stewartville strata are typically thick-bedded and dolomite-mottled beds of pure carbonate. Sinsinawa strata are generally thinner-bedded, although the uppermost ten to fifteen feet of the Sinsinawa may resemble the Stewartville. Dubuque strata are distinctive due to their argillaceous content, which increases upward.

A non-cherty sequence less than 20' thick could also be in the Dunleith. Non-cherty strata can be found in the Dunleith principally within the Beecher, Fairplay, Rivoli, Wall, and lower Wyota Members.

The Beecher Member is recognizable by its thick bedding, with numerous SCB's of short lateral extent. In addition, many exposures of the Beecher will exhibit the contact with the Decorah Formation, which typically is more shaly than any part of the Dunleith, Wise Lake, or Dubuque Formations. The entire Fairplay Member is commonly non-cherty in Winneshiek County, with rare scattered nodular chert bands in the upper portion. The Fairplay becomes increasingly cherty to the southeast; e.g., at the first U.S. 52 road cut north of Guttenberg (SW¼ SW¼ Sec. 5, T92N-R2W), the bottom portion of the Fairplay has 6 nodular chert bands. Fairplay rock is recognizable for its thin, crinkly, heavily mottled beds with hardgrounds which are virtually hidden by the crinkly bedding and mottling. Within the Rivoli and lower Sherwood Member in Winneshiek County, another chert-free sequence is seen. The rocks of the Rivoli can be recognized by their argillaceousness; this is shown on the face of the explosure as thin to hairline streaks. No other non-cherty sequence exhibits this type of rock. Another non-cherty sequence includes the Wall and lower Wyota Members. This interval is purer and more massively bedded than most of the underlying Dunleith.

Cherty exposures

Chert in the Galena increases to the southeast in Iowa and decreases and eventually becomes absent northwestward into Minnesota. In the limestone facies of the Galena in Iowa, chert is confined to four distinct zones in the Dunleith Formation and two or three bands of widely spaced nodules in the lower part of the Sinsinawa Member of the Wise Lake Formation. Chert generally is represented on the face of the exposure as a 1" to 3" thick band of oblate spheroids of chert, although occasionally chert is found as individually situated nodules.

The chert sequences are as follows: Eagle Point-lower Fairplay (Chert Seq. 1); Mortimer-lower Rivoli (Chert Seq. 2); Sherwood-lower Wall (Chert Seq. 3); and Wyota-lower Sinsinawa (Chert Seq.4). Regardless of the vertical height of the explosure being examined, it is possible to identify the cherty sequence by lithologic association. The Eagle Point chert consists of 7 or more nodular bands enclosed in a matrix of dolomite mottled limestone. The Mortimer chert sequence normally has the thickest nodules (up to 6"), and is associated with argillaceous rock. The Sherwood chert sequence is enclosed in a matrix of calcarenitic limestone, commonly highly fossiliferous. Ischadites are normally associated with this sequence. The Wyota sequence is associated with thick bedded strata. The Wyota chert bands are typically clustered in an argillaceous zone. In southeastern Minnesota the bands are fewer and more widely spaced.

Other correlation tools

Bentonites

If gross positioning has not yet been achieved in a specific exposure, other correlation tools may be used. Bentonites are useful for positioning. The Calmar, Conover and Nasset Bentonites are very distinctive (especially when wet); they consist of bright orange and grey "greasy" clay. In dry seasons they withdraw into the parting; in this event, they can be located by digging into a likely parting. We have not found the Haldane Bentonite within Winneshiek County nor in Southern Minnesota; but, if present, it would likely be positioned between Units 31 and 32 of the General Section (fig. 2). The Dygerts Bentonite is present within the Decorah area and in southern Minnesota. In both areas the bentonite is not the typical "greasy" clay of the Dunleith bentonites, but is represented by a feldspathized shale instead (Weiss, 1954). Within the southeastern area of exposure of the Galena in Iowa, it is present and resembles the Dunleith bentonites. The authors have not observed bentonites within the Dubuque in Iowa except in the extreme northwest corner of Winneshiek County. However, within southern Minnesota four bentonies have been observed. Weiss (1954 p. 270, 1957, p. 1040) observed two of these. Mossler and Hayes (1966) designated the lower of these as "I-8". Levorson et al. (1979, p. 61) described the stratigraphic position of 4 presumed bentonites; these were not subjected to x-ray diffraction, but they did have the typical field appearance of bentonites. All of these bentonites are present at the Kapper Construction Company quarry (NW¼ SW¼ Sec. 3, T103N-R13W, Fillmore County, Minnesota). The approximate stratigraphic positions of the three "presumed" bentonites have been plotted in the margins of Fig. 2 (Units 57, 58, and 59). These bentonites are not widespread but should be the subject of future investigation.

Hardgrounds

Hardgrounds (CS's -- Levorson and Gerk, 1972) are another key resource for positioning. However, they are most useful for precise positioning when making a detailed section. Refer to Fig. 2 for the position of a particular hardground. Hardgrounds within the Dunleith have concentrations of pyrite or marcasite; weathered hardgrounds may be oxidized to limonite. They commonly appear as very grey or dark black with a distinctive "dovetailed" pattern upon the face of lighter rock. By contrast, within the Sinsinawa Member, the surface is more commonly limonitic, and may appear as a faint, ocherous brown color upon the face of a buff-colored rock. We want to emphasize that, although hardgrounds have a distinctive pattern when weathered, field experience may be needed before they are recognized.

The Rivoli hardgrounds are very distinctive, being dark and commonly in clusters of five or six closely spaced surfaces (see fig. 2, Units 19 and 20). The Wall Member has a number of very dark, strong hardgrounds; however, in contrast to the Rivoli hardgrounds, they occur in thick-bedded strata. The Sinsinawa hardgrounds are likewise useful as correlation tools; e.g. in the Decorah area, there are eleven hardgrounds within the lower Sinsinawa (fig. 2, Units 40-41-42). These same eleven hardgrounds may be seen at almost the same stratigraphic positions at Rifle Hill, Minnesota (NW¼ NE¼ Sec. 35, T102N-R12W).

Biota

The biotic content of the rock is of some value for gross positioning. Fossils in the Galena commonly are embedded in the rock and consequently are not readily seen; also, the biota has not been studied extensively. However, several biotic zones are extremely useful for stratigraphic purposes:

There are three Receptaculites zones (Templeton and Willman, 1963). In Winneshiek County the lower zone is primarily in the Fairplay Member. Receptaculites occur here in large numbers in a crinkly bedded, mottled limestone (Fig 2, Units 10-11-12-13). The middle zone is almost non-existent in Winneshiek County -- only sparse specimens can be found. To the southeast, e.g. at the Guttenberg north road cut described above, the middle and lower zones come together. The upper Receptaculites zone is almost completely restricted to the upper Sinsinawa and lowest Stewartville Members.

Ischadites are to all practical purposes restricted to the upper Rivoli and lower Sherwood Members.

Crinoids can be found sparingly in much of the Galena, but are quite common at two horizons. At these horizons typical crinoid "nests" have been found. Crinoid Horizon No. 1 is in the lower Sinsinawa Member (fig. 2, Unit 40). Crinoid Horizon No. 2 is in the middle to upper Sherwood (fig. 2, Unit 28).

Maclurites, although not common, are useful as an indicator of Stewartville rock; rarely are they found in any but this member.

Weiss (1954) described the supposed holothurian trace Paleosynapta flaccida, and reported observing it in the upper Stewartville in Minnesota. P. flaccida, while not abundant, is by no means rare; we have observed the range of the species through a zone only 2' to 8' thick at any one locality. However, this zone may be found at levels from sixteen feet below to four feet above the "marker bed" (Levorson et al, 1979, fig. 3D) (in Units 52-56 on fig. 2).

DUBUQUE FORMATION

While recognizing the Dubuque in the field is not difficult, it does present some problems:

Basal contact

Most writers in the past have used the lowest shaly bed as the base of the Dubuque (Kay 1935). Past usage of the lowest shaly bed as the base of the Dubuque, however, has not proven satisfactory because of the lack of broad lateral continuity of the shale partings within the lower 15' of the Dubuque. Here the need for other correlation tools is demonstrated. Levorson and Gerk (1972) put the base of the Dubuque 19' 9" below the base of the Maquoketa. Subsequent investigations of Dubuque rocks in Illinois, Iowa and Minnesota made it apparent that using the widely traceable "marker bed" (Templeton and Willman, p. 239; Levorson and Gerk, 1975; Levorson et al., 1979) as the base of the Dubuque would eliminate confusion about the lowest shaly bed and the transition zone. This bed is readily traced from Galena, Illinois, to Stewartville, Minnesota.

Continuous shale beds

There are three shale beds within the Dubuque, as so defined, that appear to be laterally continuous from Galena to southern Minnesota.

The lowermost continuous shale bed includes two partings at the top and bottom of the "marker bed". Rarely, the "marker bed" is so argillaceous that weathering reduces it to a prominent reentrant. In other exposures the "marker bed" consists of several nodular shaly interbeds, or of shale overlain by up to 4" of dolomitic limestone with a weak parting at the top, or of a nodular to thick dolomitic shale bed. The "marker bed" is not readily recognizable at some new exposures. However, regardless of the characteristics displayed at any exposure, it normally has a slight shale parting at both the top and bottom of the bed. This is more noticeable in weathered exposures; where it is argillaceous it commonly weathers to a reentrant. The only other bed in this stratigraphic interval with which it could be confused is a 3" to 4" thick, slightly shaly bed that occurs at some exposures approximately 5' below the "marker bed". The presence of P. flaccida and of shales in the strata above this bed can confirm recognition of the "marker bed" where necessary. This is an example of the way various correlation tools can be used together in identifying stratigraphic position in the Galena Group.

The middle shale bed is approximately 11 feet above the "marker bed" -- at the top of the transition beds of previous usage. This shale is normally 2½" to 4" thick, but at the Kapper Construction Co. quarry, 4.6 miles north of Spring Valley, Minnesota, it is 12" thick and has a 2" bentonite at the top. This is also the lowest shale parting exposed at the floor level of the parking lot at the Dubuque type section. It is also the 2½" parting used by Levorson and Gerk (1972) as the Dubuque - Stewartville contact in Winneshiek County.

The third or upper shale bed occurs approximately 10' to 12' below the Dubuque-Maquoketa contact, except in Fillmore County, Minnesota, where it may be as much as 19' below the contact. The increased thickness in Minnesota is due to intercalation of additional shale beds as well as to the thickening of the shale beds between carbonate beds (Levorson et al., 1979, fig. 2). This upper shale bed ranges from 12" to 14" thick between Spring Valley, Minnesota, and Littleport, Iowa. To the southeast it thins to an average 3", and can be confused with a 7" shale bed that occurs approximately 7' below the upper shale bed.

Sparry calcarenite beds

Additional correlation tools useful in Winneshiek and northern Clayton Counties are two widely traceable SCB's (fig. 2, Units 56 and 57). They maintain a relatively stable stratigraphic position from Decorah to St. Olaf, Iowa (Johnson quarry: NE¼ SE¼. Sec. 25, T94N-R5W).

Informal subdivisions of the Dubuque

On the basis of bedding characteristics, the authors suggested an informal subdivision of the Dubuque into three divisions -- in ascending order the Frankville, Luana and Littleport beds (Levorson et al., 1979).

Frankville beds

The "marker bed" is the base of the Frankville beds. This division is composed of beds 6" to 30" thick, which become generally thinner and more argillaceous upwards. They show planar to slightly undulose surfaces, and have prominent to weak shale partings.

Luana beds

The Luana beds are 6" to 24" thick, but more commonly range from 8" to 12", with 1" shale partings between the beds with few exceptions. They exhibit planar to very slightly undulose bedding. Common in the upper 5' to 6' are marcasite concretions and small ¼" to ½" disseminated clusters of pyrite crystals. At the top of the Luana beds is a 7" to 12" thick distinctive shale bed. Within Iowa this bed is reddish brown, distinctively laminated, silty shale, with fossils preserved as molds and casts. It weathers to a light grey with a reentrant at the top.

Littleport beds

The Littleport beds have strongly undulose bedding surfaces. Individual undulations may be up to 3' in length and have a relief of 5". There are prominent shale partings from southern Minnesota to Littleport, Iowa. From here to the southeast, bedding is undulose; beds thicken but weather to thin laminae. This unit bears 3" calcite-filled vugs and small pyrite concentrations that oxidize to rusty stains.

ADDITIONAL CONSIDERATIONS

The above should suffice for gross positioning within the Galena Group. To obtain precise stratigraphic control, sections should be drawn at a scale of a minimum of ¼" to the foot for comparison with the General Section. This point cannot be over-emphasized; it enforces attention to detail. In the preparation of detailed sections, it should be cautioned that some features may have short lateral continuity at some exposures. For instance, the authors found many times in correlating beds of definite stratigraphic equivalence, that a particular chert was not present at all localities. When this occurs the locality lacking a chert will have a hardground, an SCB or a bedding plane where the chert should be.

As an example of this, at the Landsgaard Quarry north of St. Olaf, Iowa, (NW¼ NW¼ Sec. 24, T97N-R5W) an SCB, a chert band, and a hardground were found at the same precise stratigraphic position at different points within this quarry. In tracing this position around the quarry, a point was observed where all three were seen -- as a chert band and an SCB overlying a hardground.

REFERENCES

Gerk, A. J.; and Levorson, C. O., 1972, Revision of Galena stratigraphy: [Guidebook for] Geological Society of Iowa field trip, May 6, 1972. 10 p.

Kay, G. M., 1935, Ordovician Stewartville-Dubuque problems: Jour. Geology, v. 43, p. 561-590.

Levorson, C. O.; and Gerk, A. J., 1972, A preliminary stratigraphic study of the Galena Group of Winneshiek County, Iowa: Proc. Iowa Acad. Sci., v. 79, p. 111-122.

Levorson, C.O.; and Gerk, A. J., 1975, Field recognition of subdivision of the Galena Group within Winneshiek Co.: Fall gathering of Iowa, Minnesota, and Wisconsin Academies of Science, Saturday October 4, 1975: Geological field trip [guidebook]. 17 p.

Levorson, C. O.; Gerk, A. J.; and Broadhead, T. W., 1979, Stratigraphy of the Dubuque Formation (Upper Ordovician) in Iowa: Proc. Iowa Acad. Sci., v. 86, p. 57-65.

Mossler, J. H.; and Hayes, J. B., 1966, Ordovician potassium bentonites of Iowa: Jour. Sedimentary Petrology, v. 36, p. 414-427.

Templeton, J. S.; and Willman, H. B., 1963, Champlainian Series (Middle Ordovician) in Illinois: Illinois State Geological Surv. Bull. 89. 260 p.

Weiss, M. P., 1954, Feldspathized shales from Minnesota: Jour. Sedimentary Petrology, v. 24, p. 270-274.

Weiss, M. P., 1957, Upper Middle Ordovician stratigraphy of Fillmore County, Minnesota: Geol. Society America Bull., v. 68, p. 1027-1062.

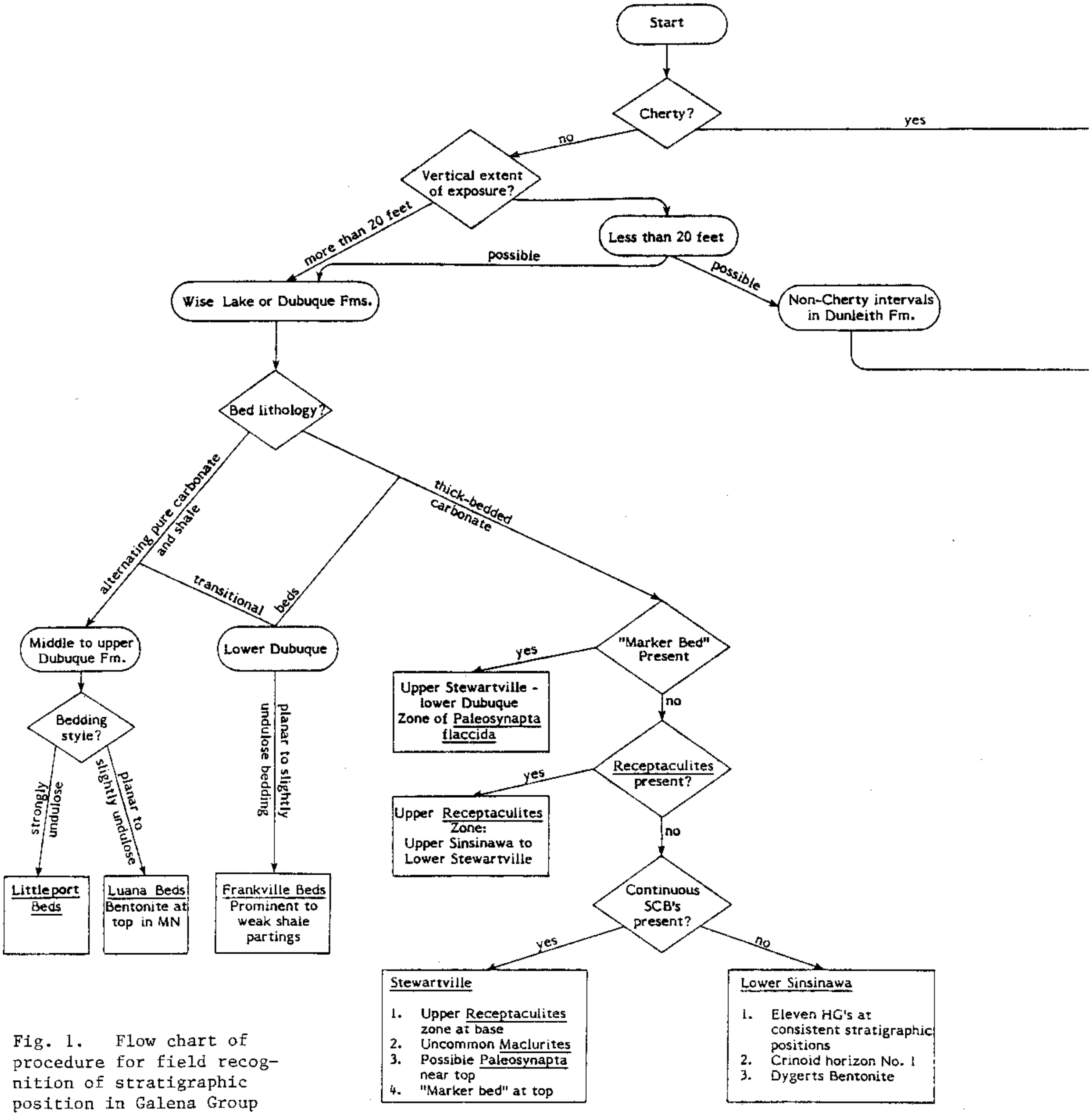


Fig. 1. Flow chart of procedure for field recognition of stratigraphic position in Galena Group limestone facies, northeast Iowa outcrop area.

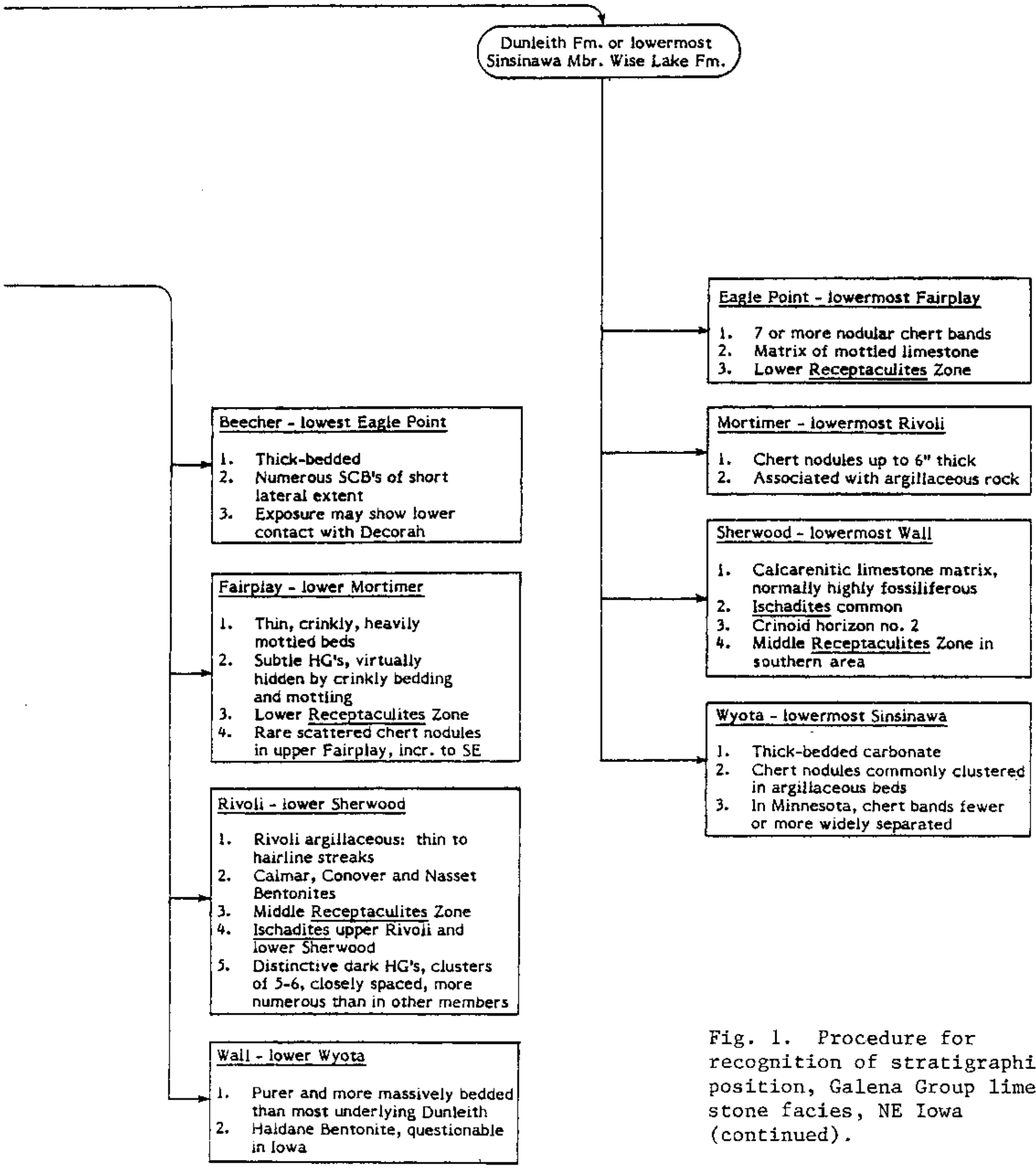


Fig. 1. Procedure for recognition of stratigraphic position, Galena Group limestone facies, NE Iowa (continued).

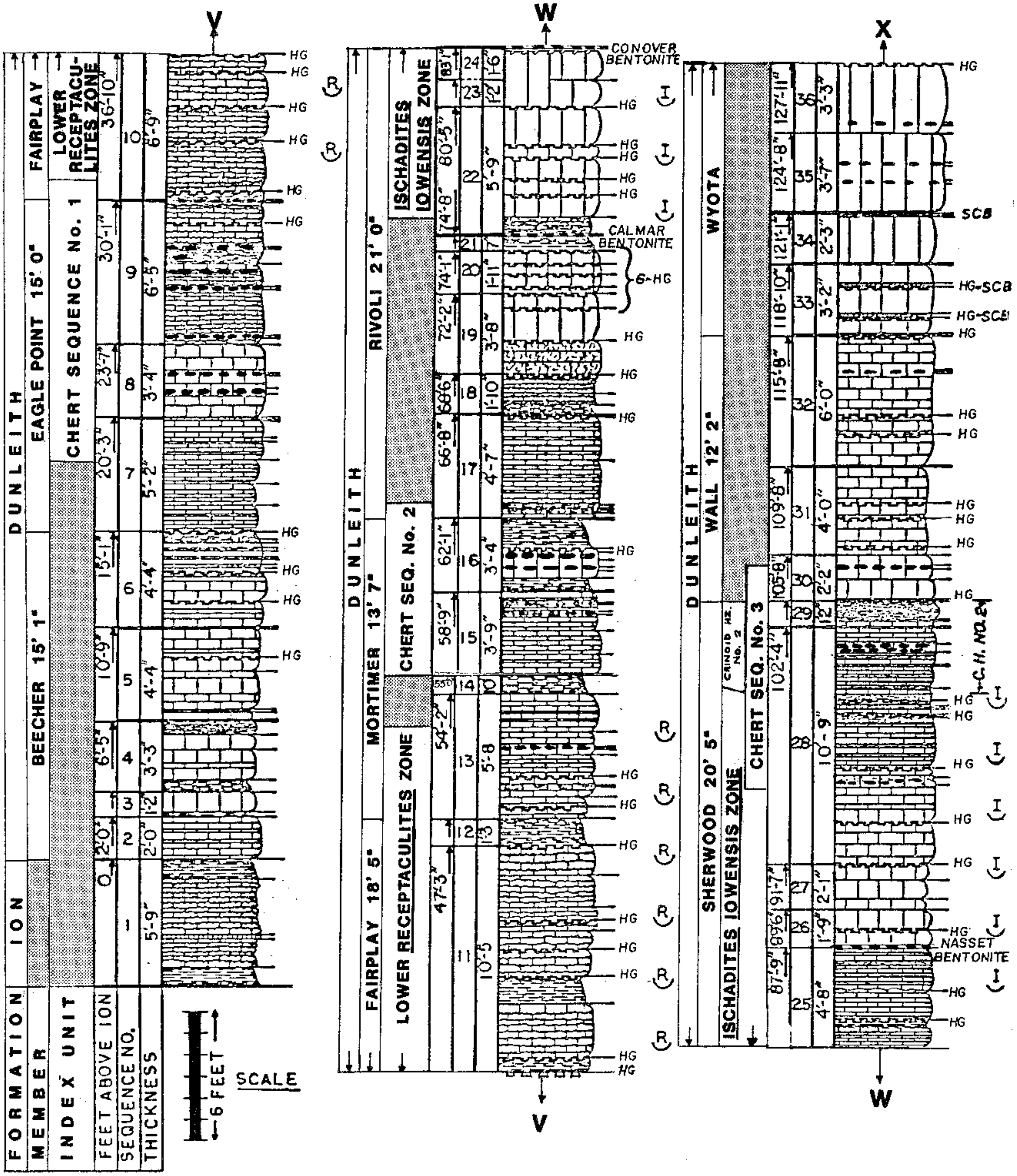
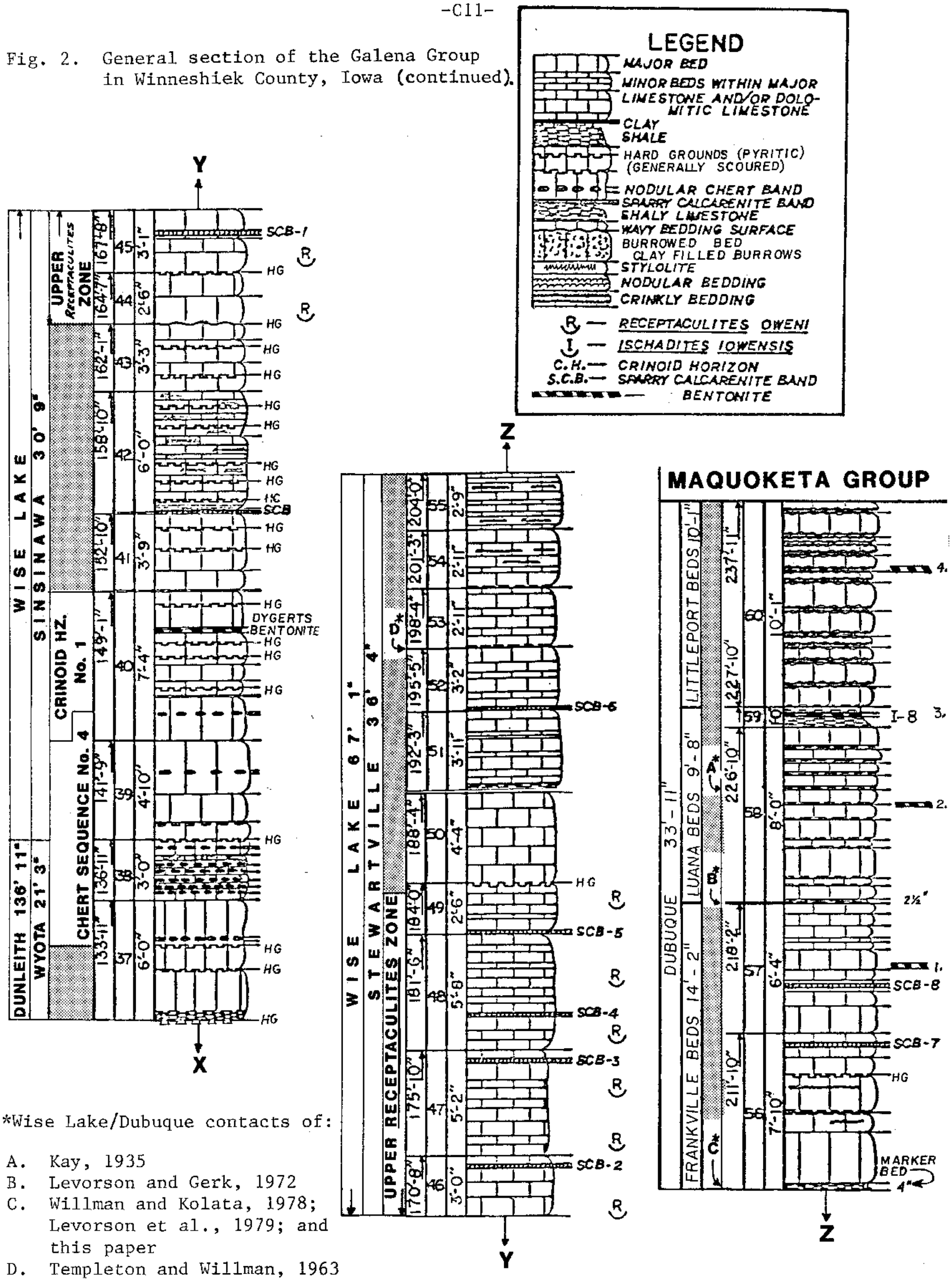


Fig. 2. General section of the Galena Group in Winneshiek County, Iowa (modified after Levorson and Gerk, 1972).

Fig. 2. General section of the Galena Group in Winneshiek County, Iowa (continued).



*Wise Lake/Dubuque contacts of:

A. Kay, 1935
B. Levorson and Gerk, 1972
C. Willman and Kolata, 1978; Levorson et al., 1979; and this paper
D. Templeton and Willman, 1963

Delgado, D. J., ed. (1983), Ordovician Galena
Group of the Upper Mississippi Valley --
Deposition, diagenesis, and paleoecology:
Guidebook for the 13th Annual Field Conference,
September 30 - October 2, 1983, p. D1 - D26.

ORDOVICIAN GALENA GROUP IN IOWA SUBSURFACE

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ABSTRACT

The Middle and Upper Ordovician Galena Group in Iowa is subdivided, in ascending order, into the Decorah, Dunleith, Wise Lake, and Dubuque formations. The Decorah becomes progressively more shaly to the northwest in Iowa, in the direction of probable detrital source terranes on the Transcontinental Arch. The Decorah includes sandstone and sandy carbonates in southwest Iowa. The Dunleith-Decorah contact is broadly diachronous across the state, and is drawn where shale-dominated or interbedded shale/carbonate facies are overlain by an interval of cherty carbonate. As the Dunleith becomes sandier and more argillaceous to the west and north, it includes progressively less chert. The Wise Lake carbonate interval is generally non-cherty, except in its basal portion, across eastern Iowa, but it is variably cherty in western Iowa. The Dubuque contains interbedded shale in northeast Iowa; elsewhere in the state it is characterized by crinoidal carbonates containing "cinnamon specks." The Wise Lake-Dubuque contact is difficult to distinguish in western Iowa. Shale and carbonate of the Maquoketa Formation conformably overlie the Dubuque in Iowa. Some workers have equated the carbonate and cherty carbonate interval (variably termed the "Viola," Kimmswick," or "Galena") above the Decorah and below Maquoketa shales with Galena Group strata of the Upper Mississippi Valley. However, a significant portion of this interval correlates lithostratigraphically to lower and middle Maquoketa carbonate strata.

The geographic distribution of limestone and dolomite facies within the Galena Group of Iowa is plotted for the Dunleith, Wise Lake, and Dubuque Formations. The distribution of major carbonate facies is compared to regional thickness patterns and paleostructure in an effort to constrain speculations on the paleohydrologic setting for regional dolomitization within the Galena Group. The maximum geographic extent of limestones in the Galena of Iowa occurs within the Decorah Formation. The geographic extent of pervasively dolomitized sequences successively increases for each overlying formation in the Galena Group. However, the transition zone separating limestone-dominated strata from pervasively dolomitized sequences within each formation is stratigraphically complex; dolomite content does not increase uniformly within the transition zone of each formation. Limestone-dominated facies within the Galena Group are best developed in northeast Iowa, where the group is thickest. In southwest Iowa, where the Galena Group is thinnest, the Dunleith, Wise Lake, and Dubuque are pervasively dolomitized. No single dolomitization model adequately explains the distribution of dolomite facies in the Galena Group of Iowa. However, mixing zone and brine reflux models may explain some aspects of dolomitization in the group.

INTRODUCTION

The general purpose of this report is to document major lithofacies trends within the upper Middle and lower Upper Ordovician Galena Group in the Iowa subsurface. Adoption of Templeton and Willman's (1963) Illinois Galena Group stratigraphic nomenclature for use in Iowa is recommended, with some modification. The utility of their refined stratigraphic subdivisions has been demonstrated within the Iowa Galena Group outcrop belt (e.g., Levorson and Gerk, 1972), although practical recognition of members within the Iowa subsurface has proved difficult. In addition, formational boundaries are not consistently recognizable in regions of the Iowa subsurface. For this report the Galena Group is subdivided, in ascending order, into the following formations: Decorah, Dunleith, Wise Lake, and Dubuque. Although the Decorah was assigned subgroup status by Templeton and Willman (1963), it is assigned formational status in Iowa because the constituent "formations" within the "Decorah Subgroup" are not distinguishable over large areas of the state.

The historical development of Galena Group stratigraphic nomenclature in the Upper Mississippi Valley region, which includes the northeast Iowa outcrop belt, is summarized by Agnew et al. (1956), Weiss (1957), Templeton and Willman (1963), and Willman and Kolata (1978). Agnew (1955) was the first to investigate subsurface Galena stratigraphy in Iowa; his "Cherty unit" is approximately equivalent to the Dunleith Formation of Templeton and Willman (1963). However, the "Cherty unit" of Agnew (1955) may include the basal portion of the Wise Lake Formation. Templeton and Willman (1963, p. 237) noted that the basal Wise Lake in northeast Iowa contains chert. The top of the "Cherty unit" apparently "climbs up and down section across Iowa" (Witzke, 1980, p. 9). Therefore, the Dunleith Formation and "Cherty unit" may not be exact equivalents. The "Non-cherty unit" of Agnew (1955), which forms the upper portion of the Galena sequence in the Iowa subsurface, is approximately equivalent to the Wise Lake and Dubuque Formations of Templeton and Willman (1963). The Wise Lake-Dubuque contact in the Iowa subsurface is unclear in many well sections, and, in many respects, the "Non-cherty unit" of Agnew (1955) remains the most practical upper Galena subdivision for general subsurface stratigraphic work across much of the state. Nevertheless, an attempt to recognize the upper Galena subdivisions of Templeton and Willman (1963) in the Iowa subsurface has been made in this report, and recognition criteria and inherent difficulties are discussed for each unit in subsequent stratigraphic sections.

SUBSURFACE DATA

Rock cuttings derived from water well penetrations form the primary data base for investigating Iowa subsurface Galena Group stratigraphy. Well cuttings samples (mostly rotary bit, some cable tool) were generally taken every 5 feet. In most cases, sample recovery was good to excellent. Although certain problems are inherent in the study of well cuttings, any well point with apparent recirculation or caving problems was not used for detailed mapping. Oil tests and gas storage stratigraphic tests provided additional subsurface data in Iowa, primarily well cuttings (5 to 10 foot sample interval) and some borehole geophysical logs. In addition, partial to complete rock core penetrations of the Galena Group have been used for more detailed subsurface control (1 to 5 inch diameter cores; primarily mineral exploration, stratigraphic, or engineering test cores). Galena Group core is available from localities in the following counties (fig. 1): Cerro Gordo, Cherokee, Clayton, Dallas, Des Moines, Dubuque, Jackson, Jones, Lee, Louisa, Plymouth, Washington, and Webster. In addition, complete core penetrations of Galena strata from near the Iowa-Nebraska line in Sarpy County, Nebraska, and from north of the Iowa line in

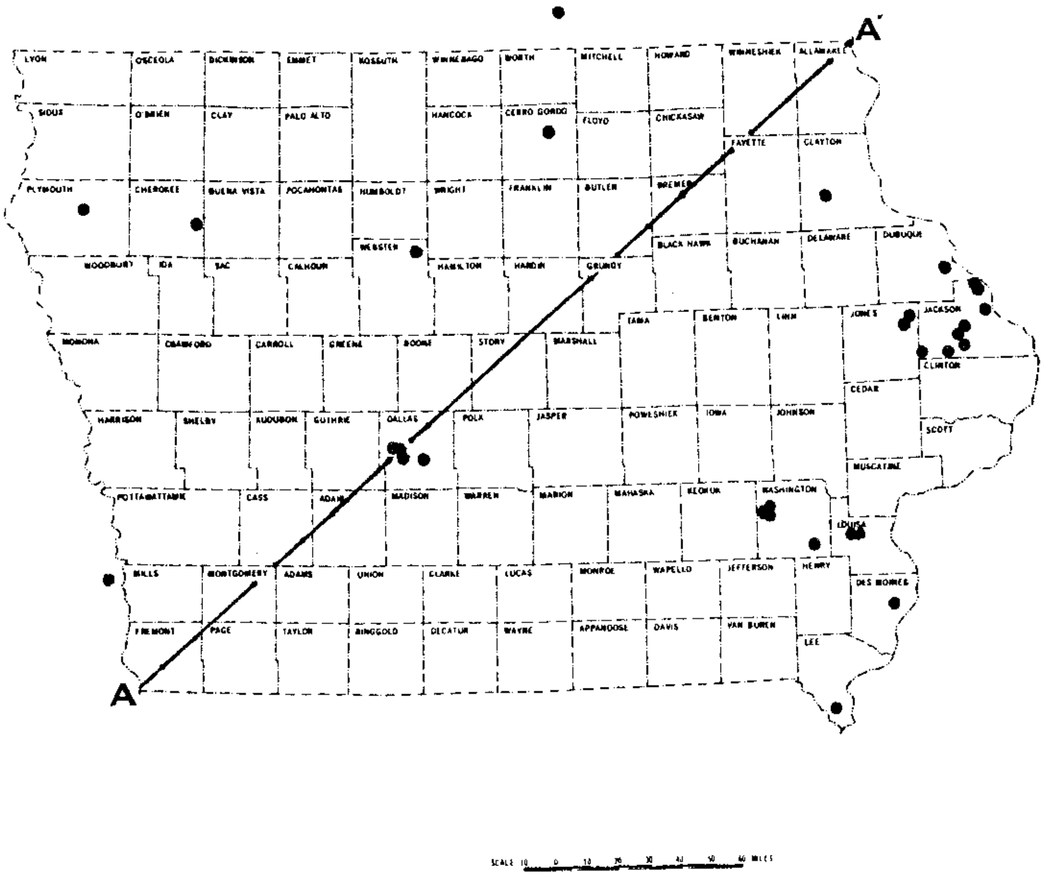


Fig. 1. Locations of partial to complete Galena Group core penetrations in Iowa (stored at Iowa Geological Survey). Locations of nearby core in Nebraska and Minnesota also shown. AA' is cross-section line for figure 6.

Freeborn County, Minnesota (Austin, 1970), provide additional detailed state-line control. All Iowa subsurface materials (well cuttings and rock core) are stored at the Iowa Geological Survey. Except for a few industry cores in temporary confidential status, all are available for further study by interested geologists.

Because a number of different people logged well cuttings through the years at the Iowa Survey, evaluating standardization of descriptions and logging techniques became a problem for this study. However, the bulk of the Galena Group descriptive well logs were constructed by only two people--Dick Northup and Allen Agnew. Descriptive consistency of the various well loggers was checked by re-examining cuttings from certain key well points and comparing the descriptions of different well loggers. I also examined unstudied well cuttings and rock core, but all well points were not re-studied. Stratigraphic contacts within the Galena Group were redefined for each well point, since there was little stratigraphic consistency between well loggers. However, there was found to be a high degree of descriptive consistency of well cuttings between the different well loggers. Mapping consistency provided additional confirmation of general trends. Nevertheless, the maps presented in this report are certainly subject to detailed revision, and greater precision of limestone/

dolomite percents could be achieved by using new analytical techniques. Therefore, the lithofacies maps (figs. 7-9) are merely presented as geographic approximations of major lithofacies trends.

Relative percentages of limestone and dolomite within individual 5 foot cuttings samples were visually estimated using a binocular microscope and a degree of error was undoubtedly introduced (probably ± 20%). Representative cuttings were immersed in a 15% solution of cold HCl; vigorous reaction was characteristic limestone, slow reaction of dolomite, and intermediate reactions characteristic of dolomitic limestones or calcitic dolomites. Many limestones contain scattered dolomite rhombs that are of considerable diagenetic interest, although volumetrically insignificant. Shale percents were more difficult to evaluate in individual well samples, primarily because shale cuttings may be pulverized by the rotary bit and washed out by the drilling fluids.

GALENA GROUP ISOPACH MAP AND STRUCTURAL RELATIONS

The Iowa Galena Group isopach map (fig. 2) was constructed in an effort to identify gross structural patterns developed during Galena Group deposition. The Galena Group was not contoured in extreme northwestern Iowa where it is beveled beneath Cretaceous strata, in southeast Iowa where it is beveled beneath Middle Devonian strata, or within the eroded outcrop belt. Thicknesses in those areas primarily reflect post-Ordovician erosional events. The Galena Group was only isopached where it is covered by the Maquoketa Formation. Major Ordovician and Silurian paleostructural features in the central midcontinent are illustrated in figure 3.

In general, the Galena Group significantly thickens from southwest to northeast Iowa. As suggested by Agnew (1955, p. 1722), the Galena sequence in southwest Iowa was not erosionally thinned, but a thinner conformable Galena sequence was apparently deposited in that area. The thinning of the Galena Group into southwest Iowa occurs in the vicinity of a prominent Middle Ordovician paleostructural high termed the Southeast Nebraska Arch (Lee, 1943, 1957; Witzke, 1980; Bunker, 1981). Platteville and Galena Group thinning within the present-day Forest City Basin area may indicate that the Southeast Nebraska Arch area remained structurally elevated with respect to areas to the north, south, and east during the Middle Ordovician. The arch had apparently subsided by the Late Ordovician, and the thickest sections of the Maquoketa Formation in Iowa occur in the southwestern part of the state (Parker, 1970). This reversal of structural trends in southwest Iowa (and adjacent areas of Missouri, Kansas, Nebraska) during the Middle or Late Ordovician marked the destruction of the Southeast Nebraska Arch and the initial development of the North Kansas Basin (Lee, 1943, 1957). The North Kansas Basin remained a prominent structural basin throughout much of the mid-Paleozoic (Bunker, 1981.

The pronounced thickening of the Galena Group in northern Iowa and southern Minnesota suggest that a shallow cratonic basin developed in that area during Galena deposition. This paleobasin is presently transected by the Galena outcrop belt in Iowa and Minnesota. The northward thickening of the Galena Group into southern Minnesota occurs within a structural depression commonly termed the Hollandale Embayment. However, the Hollandale Embayment was best developed during Sauk Sequence deposition (U. Cambrian-L. Ordovician), when general *southward* thickening along the axis of the Hollandale Embayment was apparently disrupted during the Middle Ordovician, probably coincident with the initiation of uplift along the Ozark Dome-Northeast Missouri Arch trend. However, the northern axis of the Hollandale Embayment apparently remained a prominent

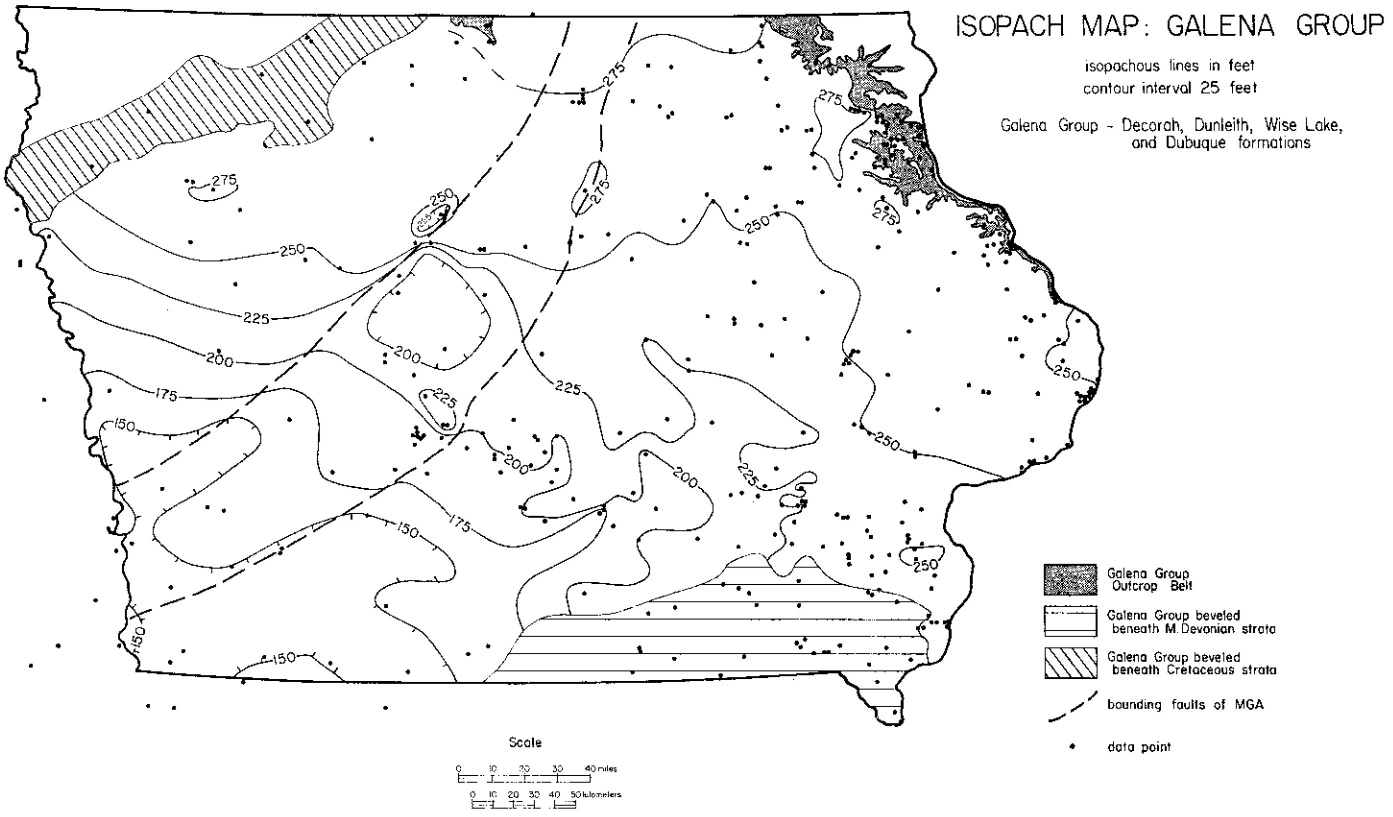
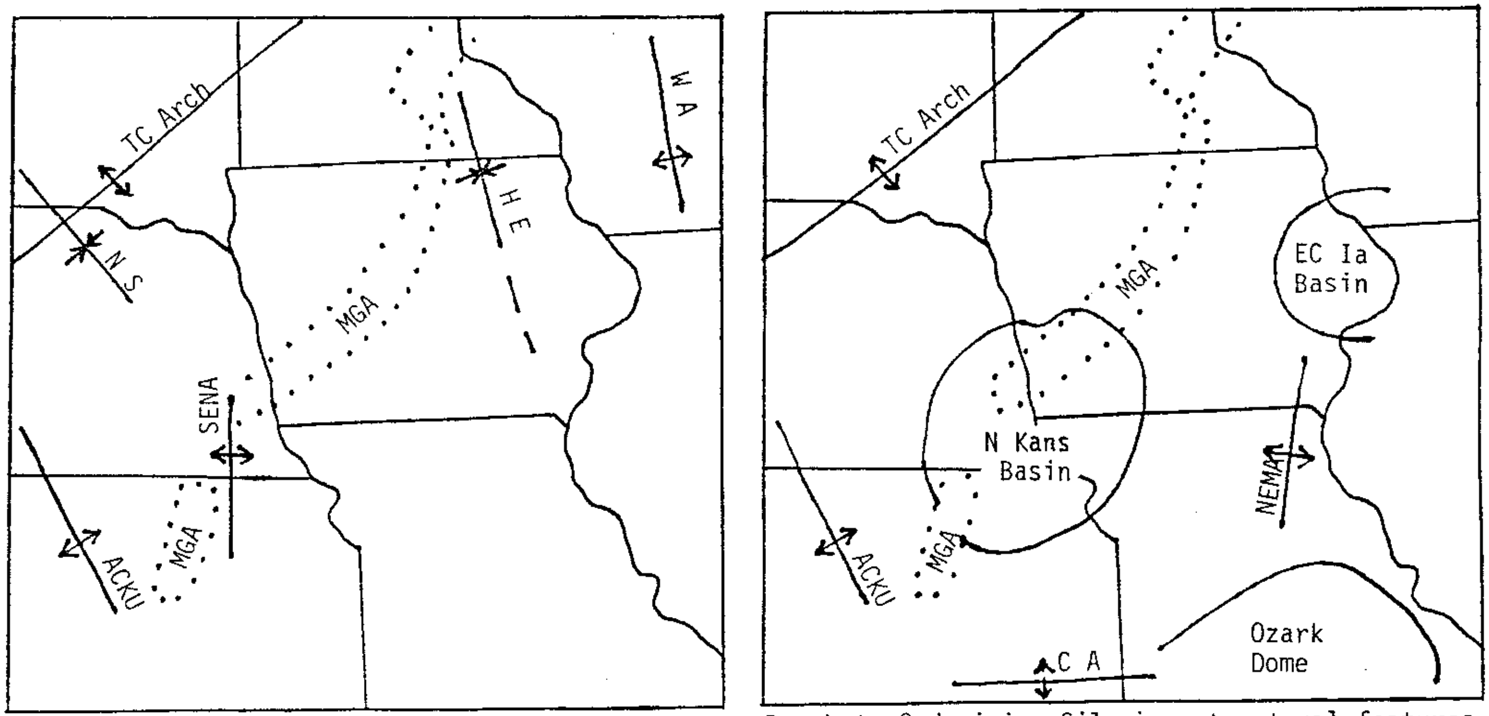


Fig. 2. Isopach map of Iowa Galena Group. Some data points used on figures 5, 7, 8, and 9.



A. Pre-Middle Ordovician structural features.

B. Late Ordovician-Silurian structural features.

Fig. 3. Major Ordovician-Silurian structural features in the central midcontinent. Adapted from Lee (1943, 1946, 1957) and Bunker (1981). TC Arch--Transcontinental Arch; ACKU--Ancestral Central Kansas Uplift; MGA--Midcontinent Geophysical Anomaly (dotted boundary is central horst of the Central North American Rift System); SENA--Southeast Nebraska Arch; HE--Hollandale Embayment; NS--Nebraska Sag; WA--Wisconsin Arch; N Kans Basin--North Kansas Basin; EC Ia Basin--East-Central Iowa Basin; CA--Chautauqua Arch; NEMA--Northeast Missouri Arch.

structural depression during Galena deposition. Erosional truncation of Galena strata beneath mid-Maysvillian Maquoketa strata around the Ozark Dome indicates that major uplift of the Ozark Dome and its associated arches was, in part, coincident with the Galena Group deposition away from the dome (Templeton and Willman, 1963, p. 137; Witzke, 1980).

Thick Galena sections are also noted in northwest Iowa, although no basinal precursors in that area have been identified. The thick Galena trend from northwest Iowa into southeast Minnesota roughly parallels the trend of the Transcontinental Arch along its southeast margin. The Transcontinental Arch was a broad positive structural feature that profoundly influenced Galena Group depositional patterns (Witzke, 1980). Disruption of isopach lines along the trend of the Midcontinent Geophysical Anomaly (MGA), an area of failed Late Precambrian continental rifting (Central North American Rift System), suggests that differential crustal movements along the MGA infuenced Galena Group deposition.

The Galena Group also thickens eastward into east-central Iowa. The southeastward deflection of the 250-foot contour in eastern Iowa (fig. 2) roughly delineates the southwestern margin of a Silurian-Middle Devonian paleobasin termed the East-Central Iowa Basin (Bunker, 1981; see fig. 3). Thickening trends suggest that the East-Central Iowa Basin began to develop as a shallow basin area during the Galena deposition. Maximum subsidence within this basin apparently occurred during the Silurian.

DECORAH FORMATION

The Decorah is the basal formation of the Galena Group in Iowa. Over much of the eastern Iowa subsurface it can be subdivided into three membrs, which in ascending order are: 1) Spechts Ferry Shale Member (primarily gray-green shale with minor carbonate interbeds; generally 5 to 10 feet [1.5 to 3 m] thick), 2) Guttenberg Member (dominantly limestone with minor brown and green shale partings; generally 10 to 20 feet [3 to 6 m] thick), and 3) Ion Member (primarily interbedded limestone and shale; ranges from about 0 to 30 feet [9 m] in thickness). Across much of northern and western Iowa the entire Decorah interval is dominated by gray-green calcareous shales with varying numbers of carbonate interbeds. In those areas the three members cannot be distinguished in the subsurface.

The basal contact of the Decorah is readily picked in subsurface sections where the Spechts Ferry Shale overlies Platteville carbonates. However, the Platteville-Decorah contact in the western Iowa subsurface is more difficult to identify. In western Iowa, as well as Nebraska, northwest Missouri, and Kansas, these formations are commonly combined by well loggers as "Decorah-Platteville undifferentiated." Difficulties in distinguishing the formational contact are due in part to the increasing shale content of the Platteville northwestward in Iowa. In addition, core studies indicate that the Platteville significantly thins in western Iowa (ranges 15 to 30 feet; 4.5 to 9 m) where it consists primarily of light brown dolomite, light to dark brown shale, and gray-green shale. For this study, the Platteville-Decorah contact in western Iowa was consistently picked above a thin Platteville brown shale/dolomite interval and below the characteristic thick green calcareous shale and argillaceous carbonate interval of the Decorah.

The Decorah-Dunleith contact is broadly diachronous across Iowa, ascending stratigraphically to the north and west across the state. Templeton and Willman (1963) recognized that the basal Dunleith in northern Illinois (Buckhorn and St. James Members) is equivalent to upper Decorah strata in northeast Iowa (Ion Member). Likewise, the Ion Member is replaced by basal Dunleith carbonates in east-central and southeast Iowa. The Decorah reaches thicknesses in excess of 90 feet (27 m) in northwest Iowa. Lithostratigraphic relations suggest that the top of the Decorah in northwest Iowa correlates to the middle portion of the Dunleith (approximately Mortimer Member) in eastern Iowa and northern Illinois (see fig. 4). In general, the interbedded shales and carbonates of the Ion Member in Iowa and the Cummingsville Member in Minnesota represent a transitional facies separating shale-dominated facies of the Decorah to the northwest from carbonate-dominated facies of the Dunleith Formation to the southeast.

An isolith map shows total shale thicknesses in the Decorah Formation of Iowa (fig. 5). However, poor recovery of shale cuttings made interpretations difficult in some areas, particularly western Iowa where isolith contours are dashed

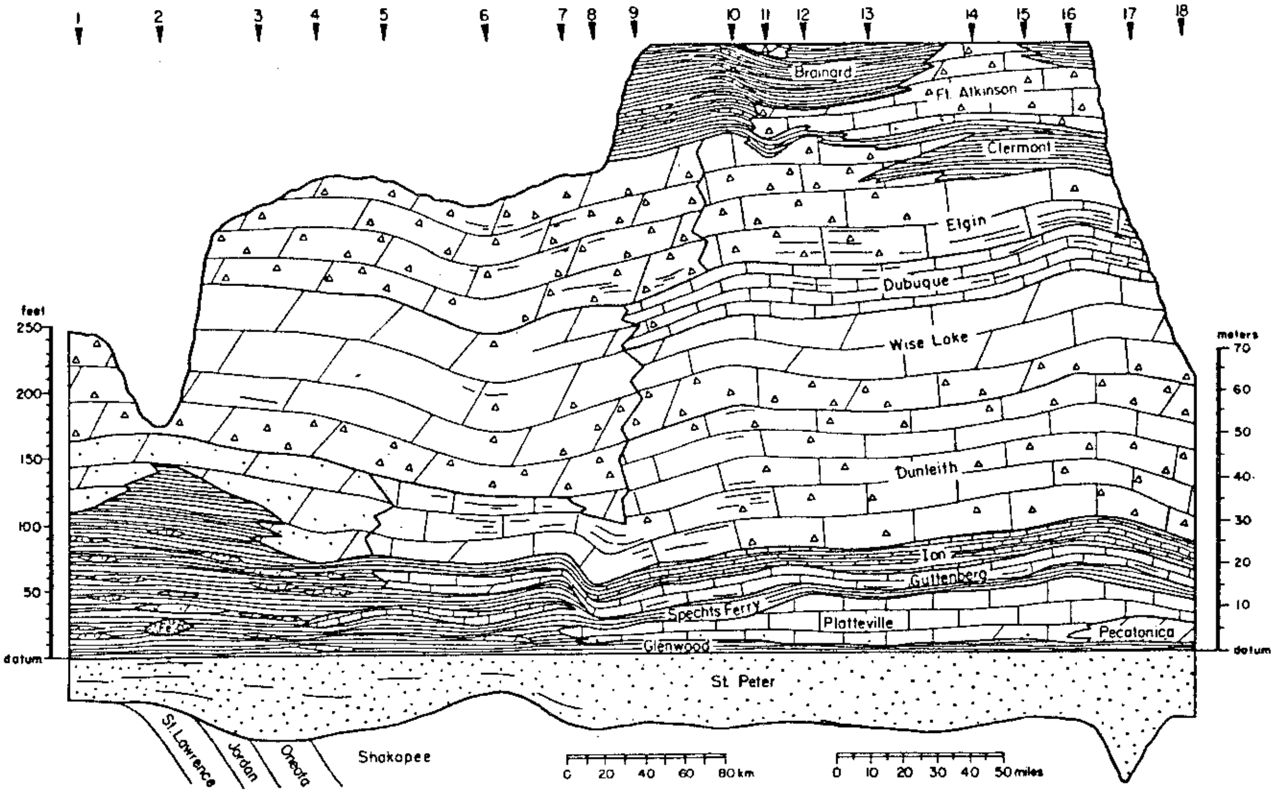
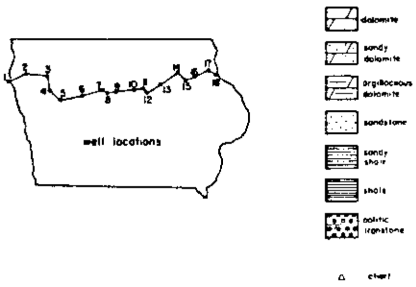


Fig. 4. East-west stratigraphic cross-section of Middle and Upper Ordovician strata across northern Iowa. Upper Decorah shales of northwest Iowa apparently correlate with Dunleith carbonates to the east. Subsurface localities (core and well cuttings) listed in Witzke (1980).



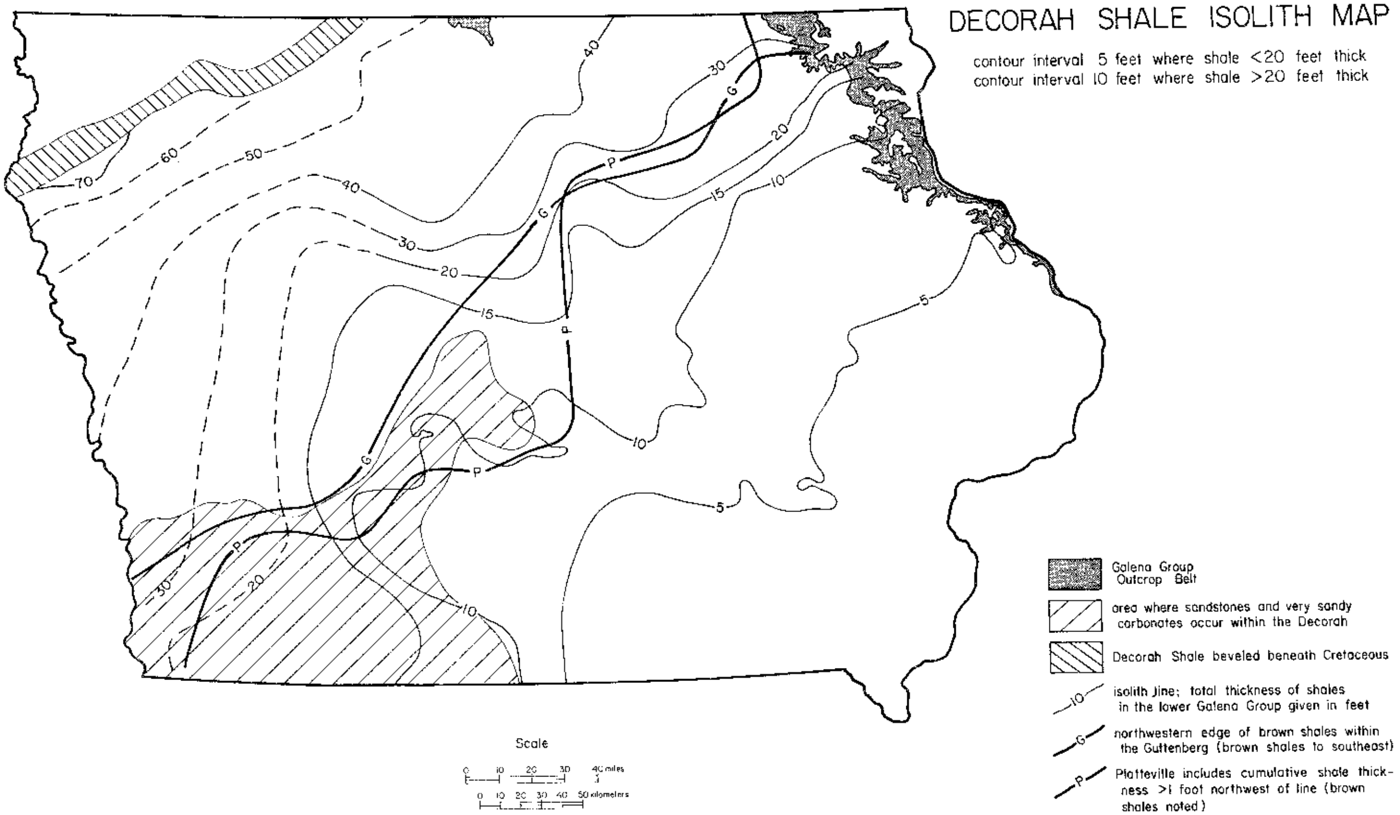


Fig. 5. Decorah Shale isolith map. Contours dashed in western Iowa to reflect uncertainty.

to reflect uncertainty. Cored intervals of the Decorah provided more accurate shale isolith control, and cuttings samples were compared to nearby core points in order to evalaute consistency of sampling. Over most of Iowa, recovery of shale cuttings was generally good, and the interpreted shale thicknesses from well point to well point were generally consistent with regional thickness trends. The interpreted shale isolith lines show that Decorah shale content progressively increases to the north and west in Iowa. Thickness patterns and clay mineral facies within the Decorah suggest that shale source areas were present along the Transcontinental Arch (Parham and Austin, 1969, p. 6; Witzke, 1980). The Decorah Formation correlates to the upper portion of the Winnipeg Formation on the opposite side of the Transcontinental Arch in the Williston Basin area. Upper Winnipeg sandstone facies spread off the arch in northwestern Minnesota and Manitoba, indicating that Transcontinental Arch source terranes supplied clastic sediments to both sides of the arch (Witzke, 1980). Inundation of Transcontinental Arch source areas during the late Middle Ordovician progressively cut off shale influx to the Galena seaway, allowing relatively pure carbonate sediments to accumulate over a vast area of the midcontinent epeiric sea by the Edenian.

The Guttenberg Member is recognizable across the southeastern half of Iowa and is the most clastic-free unit in the Decorah. Brown, organic-rich shale interbeds, containing up to 20% total organic carbon, are noted at most localities where the Guttenberg is present. These brown shales are best developed in southeast Iowa (northwestern edge of Guttenberg brown shale distribution shown on fig. 5). Similar brown shales are noted within the Platteville of northwestern Iowa (southeastern edge of Platteville brown shale distribution shown on fig. 5). Regional deposition of Guttenberg organic-rich shales suggests periodic bottom anoxia in the Guttenberg depositional environments. Guttenberg carbonate well cuttings commonly include small (less than 0.5 mm) reddish-brown organic blebs termed "cinnamon specks" by most Iowa well loggers. Some of the specks are recognizable as algal megaspores. Although limestone-dolomite lithofacies patterns within the Decorah have not been plotted, limestones in the Galena Group achieve their widest geographic extent in the Decorah.

The Decorah of central to southwestern Iowa is notably sandy and includes fine- to medium-grained sandstone, sandy shale, and sandy dolomite (figs. 5, 6). Underlying Platteville strata in the same general area also include sandstones and sandy dolomite. The Decorah-Platteville sand is dominantly rounded quartz sand of the "St. Peter type." Agnew (1955, p. 1727-1729) identified sandy Ion and Guttenberg strata in central and southwest Iowa, and Lee (1943, p. 33) noted sandy Decorah strata in northeast Kansas, northwest Missouri, and southeast Nebraska. Although not recognized by Agnew, the interval here assigned to the Spechts Ferry in southwest Iowa also includes sandstone. Sandy Decorah strata are best developed in the general area where the Galena Group is thin (fig. 2), and Decorah sand deposition was apparently most pronounced in the vicinity of the structural high that roughly corresponds to the Southeast Nebraska Arch.

Although Decorah shale source terranes were apparently along the trend to the Transcontinental Arch, the Decorah sandstones of southwest Iowa are replaced to the north (toward the arch) by a shale-dominated sequence with little or no sand. Likewise, Lee (1957, p. 34) recognized that Decorah sandstones in northeast Kansas (which he assigned to the Platteville) are replaced to the northwest (i.e., toward the arch) by green shales. These geographic relationships are especially perplexing, since the coarsest clastic facies are usually developed closest to source areas, with finer-grained clastic sediments deposited farther offshore. The Decorah sandstones may have been derived from

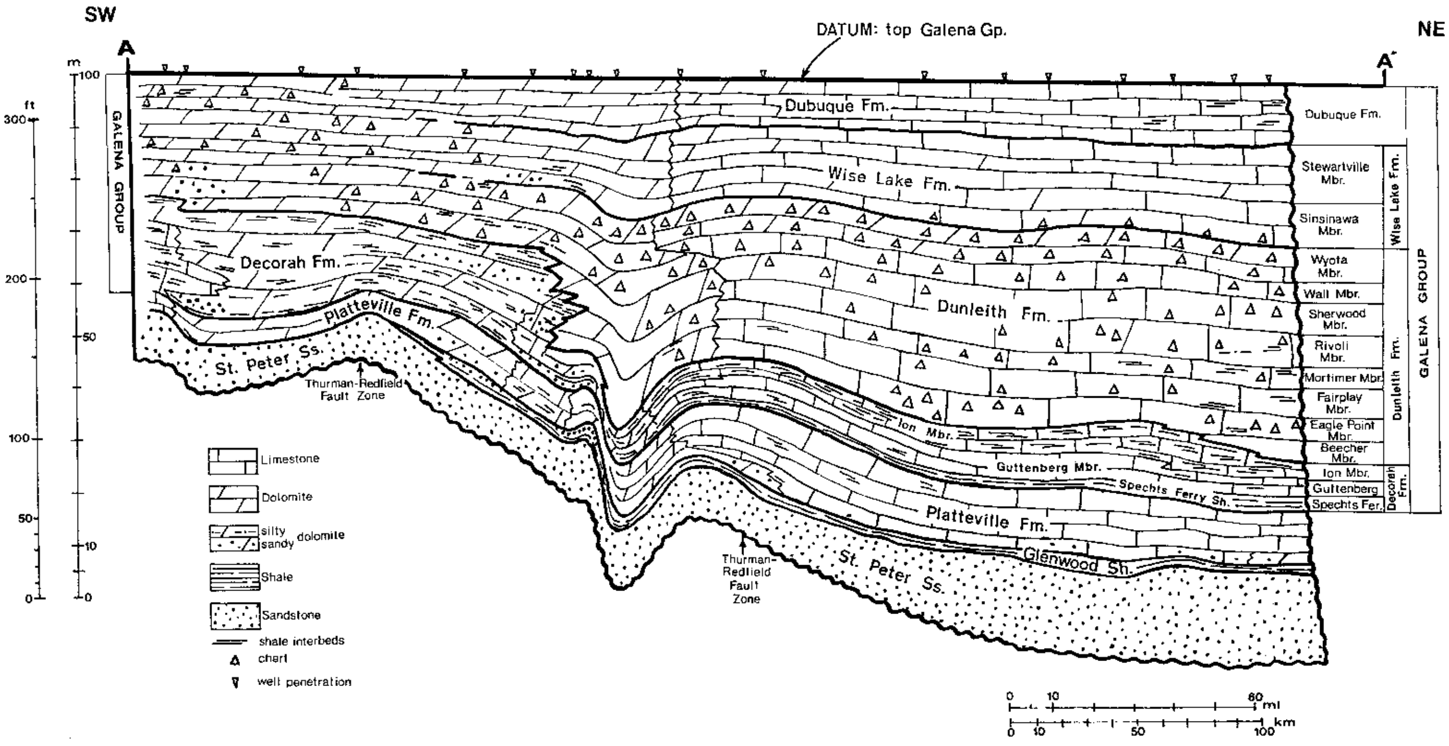


Fig. 6. Northeast-southwest stratigraphic cross-section of the Galena Group in Iowa. Location of line AA' shown in figure 1. Galena Group stratigraphic nomenclature used in northeast Iowa outcrop belt shown along right margin.

source terranes farther to the west, possibly the Transcontinental Arch in Nebraska or the northward extension of the Ancestral Central Kansas Uplift (fig. 3). Alternatively, the Decorah sandstones may have been derived from northern Transcontinental Arch source terranes but were deposited in an off-shore position as submarine sand bodies. Further studies are needed.

Although the Decorah in northwest Iowa is generally non-sandy, the overlying basal Dunleith carbonates are characteristically sandy to very sandy. This, again, runs contrary to general facies concepts; in most vertical/lateral facies transitions, a sandstone-shale-carbonate sequence is expected (not shale-sandstone-carbonate). Ion strata in portions of east-central Iowa and Cummingsville strata in southeast Minnesota are locally very sandy (Austin, 1970). Basal Dunleith strata (Buckhorn-St. James Members) as far east as northwest Illinois may also be slightly sandy (Templeton and Willman, 1963). In general, the Decorah-Dunleith transition is commonly sandy to varying degrees, although the sandy zone is apparently broadly diachronous from southeast to northwest across Iowa. Until Ordovician eustatic or epeirogenic changes in the midcontinent seaway are more adequately evaluated, and additional paleontologic and petrographic studies are completed, the Decorah-Dunleith transition remains poorly understood.

DUNLEITH FORMATION

As discussed in the introduction, the "Cherty unit" of Agnew (1955) and the Dunlieth Formation are approximately equivalent, although probably not identical, stratigraphic units. For the purposes of this report, the approximate top of the Dunleith is drawn at the boundary separating cherty carbonates from overlying non-cherty carbonates. As recognized in the outcrop belt of northeast Iowa, chert nodules occur up to 8 feet (2.4 m) above the top of the Dunleith. However, cherty carbonate strata occur within various positions of the upper Galena sequence in western Iowa (see fig. 6), and the Dunleith-Wise Lake boundary cannot be identified easily. Fortunately, the Galena carbonate sequence in western Iowa is entirely dolomite, and, therefore, identification of exact formational boundaries is not essential for accurate mapping of limestone/dolomite facies within individual formations.

In general, the members of the Dunleith defined by Templeton and Willman (1963) are not identifiable in the subsurface using well cuttings. The Dunleith of Iowa displays lateral shale and carbonate facies variations. The Dunleith of southeast Iowa is primarily a cherty carbonate interval with only minor argillaceous impurities. However, the Dunleith becomes progressively shalier, especially in the lower portion, towards the northwest. Prominent shale interbeds occur within Dunlieth strata in western Iowa, and these shaly Dunleith intervals have been termed "False Decorah" by some well loggers (Agnew, 1955, p. 1721). Interbedded limestones and shales in southeast Minnesota that correlate to Dunleith strata to the south have been termed the Cummingsville Member (Weiss, 1957).

The Dunleith Formation thins to the northwest, primarily due to lithofacies change from carbonate to shale in the lower Dunleith-Decorah interval. The Dunleith thins to the southwest where the entire Galena Group is also thinner. The Dunleith in eastern Iowa ranges from 95 to 145 feet (29 to 44 m) in thickness, but it thins in western Iowa, varying from about 30 to 100 feet (9 to 30 m) in thickness. As noted by Agnew (1955), the lower Galena dolomite interval (i.e Dunleith) in northwest Iowa becomes very sandy. In general, as the lower Dunleith becomes shalier and sandier to the west and north, both in outcrop and subsurface, it includes progressively less chert.

The carbonate rocks within the Dunleith Formation across major portions of southern and western Iowa, as well as part of east-central Iowa, are predominantly dolomite (fig. 7); minor sparry calcite void fillings are the only additional carbonate material noted in the dolomite sequences. However, the Dunleith includes varying quantities of limestone and dolomite over much of the northeastern one-third of the state (fig. 7). Regions where the Dunleith is dominantly a limestone unit are separated from Dunleith dolomite sequences to the east, west, and south across a broad limestone/dolomite transition zone. The transition between Dunleith limestones and dolomites is accessible within the northeast Iowa Galena outcrop belt. Willman and Kolata (1978, p. 46) recognized a "northern limestone facies" within the Dunleith (i.e., northeast Iowa, southeast Minnesota) that lies to the north and west of the Dunleith dolomite facies in Wisconsin and northern Illinois. Although the "northern limestones facies is more shaly and argillaceous than the dolomite facies," the transition between limestone and dolomite is not directly related to argillaceous content (ibid).

The transition from limestone-dominated to dolomite-dominated facies in the Dunleith is stratigraphically complex, and dolomite/limestone content is not homogeneous throughout the Dunleith sequence at individual localities. As one proceeds from limestone- to dolomite-dominated facies, the dolomite content does not increase uniformly within the Dunleith, but certain stratigraphic intervals were favored sites of dolomitization. Where significant amounts of dolomite are noted within limestone-dominated Dunleith sequences, the dolomite commonly occurs at two general stratigraphic positions: 1) top 10 to 30 feet (3 to 9 m; probably equivalent to Wyota and Wall Members), and 2) a 5 to 30 foot (1.5 to 9 m) zone centered below the middle of the Dunleith sequence (probably includes Fairplay and Mortimer Members). In general, as dolomite content increases within Dunleith sequences, the dolomite-bearing intervals in the upper and middle parts of the formation progressively thicken. Observations in the Iowa Galena outcrop belt show a similar dolomite distribution pattern within limestone-dominated sequences; from north to south the Wyota is characteristically the first member to be dolomitized pervasively, where the Fairplay is also typically more dolomitic than surrounding Dunleith strata. Proceeding into dolomite-dominated Dunleith facies that still contain some limestones, similar patterns are commonly observed. The basal Dunleith is usually the last portion of the formation to be dolomitized pervasively (probably up to Beecher Member), and limestones are commonly retained in dolomite-dominated Dunleith sections at a general position above the middle of the sequence (probably Sherwood Member).

The stratigraphic distribution of limestone and dolomite within the Dunleith sequence, as described in the previous paragraph, generally holds true within limestone/dolomite transition facies across northern, central, and east-central Iowa. However, limestone/dolomite distributions within the Dunleith sequence of southeast and south-central Iowa apparently do not follow any clear stratigraphic patterns; limestone content increases upward in the sequence at some localities, while at other localities dolomite content increases upward. The reasons for these apparent anomalies are not clear.

Since the bulk of limestone/dolomite distributional information used for this study was derived from well cuttings, megascopic information on the mode of occurrence of dolomite in the sequence is lacking at most localities. However, rock core and outcrop information suggests that dolomite burrow-mottling accounts for a substantial portion of the dolomite contained in mixed limestone/dolomite sequences. In limestone-dominated sequences, dolomite is generally limited to burrow mottlings and as scattered euhedra within the micritic

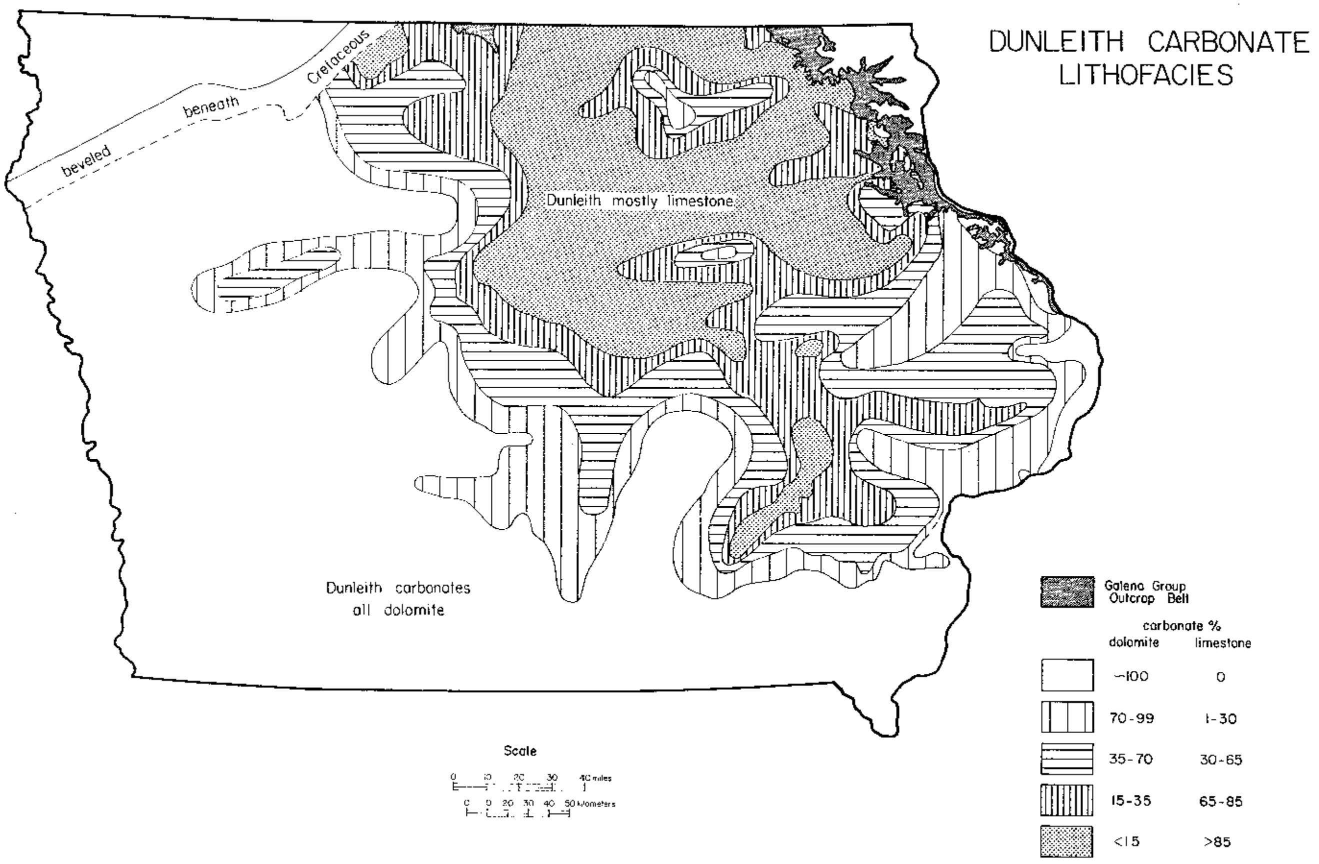


Fig. 7. Distribution of limestone/dolomite in Dunleith Formation of Iowa.

matrix. However, as overall dolomite content increases, bedded intervals within the sequence become dolomitized pervasively.

WISE LAKE FORMATION

The Wise Lake Formation can be roughly equated with the lower portion of Agnew's (1955) "Non-cherty unit" over much of the Iowa subsurface, although probable Wise Lake strata are locally cherty in portions of western Iowa. The Wise Lake-Dubuque contact occurs within the "Non-cherty unit," but the exact position of the contact cannot be picked in the subsurface at many localities. In general, the base of the Dubuque was chosen at the lowest occurrence of shale interbeds and/or "cinnamon specks" within the "Non-cherty unit," but these criteria are not always evident at some localities. The Wise Lake-Dubuque contact in western Iowa cannot be identified consistently. Fortunately, since the Galena carbonate sequence is entirely dolomite in that area, the exact position of the contact is not needed for mapping gross carbonate lithofacies at the formational level. Criteria for recognizing the Wise Lake-Dubuque contact in the northeast Iowa outcrop belt are given by Willman and Kolata (1978) and Levorson et al. (1979). The two members of the Wise Lake, the Sinsinawa and Stewartville, are not readily differentiated in the Iowa subsurface. The Wise Lake displays thickness variations across Iowa: 55 to 90 feet (17 to 27 m) in east-central and northeast Iowa; 30 to 70 feet (9 to 21 m) in southest and south-central Iowa; about 20 to 55 feet (6 to 17 m) in central to southwest Iowa.

The Wise Lake across Iowa is notably less argillaceous than the Dunleith, although thin shales and argillaceous partings are noted within cores from northwest and north-central Iowa. This suggests that local source terranes on the Transcontinental Arch may have supplied some clay to the adjacent seaway. However, the noted decrease in clastic content between the Dunleith and Wise Lake also suggests that much of the Arch was probabaly inundated during Wise Lake deposition.

The distribution of limestone and dolomite within the Wise Lake (fig. 8) closely resembles distributional patterns in the Dunleith with two notable differences: 1) the Wise Lake dolomite facies is slightly more expanded geographically, and 2) the region where limestone dominates is correspondingly reduced. The expansion of dolomite facies in east-central Iowa is especially noteworthy. As with the Dunleith, dolomite in Wise Lake limestone sequences appears first in burrow-mottlings, and, as overall dolomite content increases, bedded intervals within the Wise Lake are dolomitized pervasively. Within limestone/dolomite transition facies in central, northeast, and north-central Iowa, the dolomite content commonly decreases upward in the Wise Lake sequence. However, no consistent pattern was recognized in Wise Lake sequences within transitional facies in east-central and southeast Iowa, where dolomite variably increases or decreases upward in the sequence at different localities.

DUBUQUE FORMATION

The Dubuque Formation is distinguished in outcrop from underlying Wise Lake strata by the presence of distinctive thin shale partings between parallel beds; argillaceous content generally increases upward in the Dubuque. However, thin shale beds are not consistently recognizable in well cuttings, and the base of the Dubuque is difficult to pick at many subsuface localities. In addition, although shale partings are well developed within Dubuque sequences

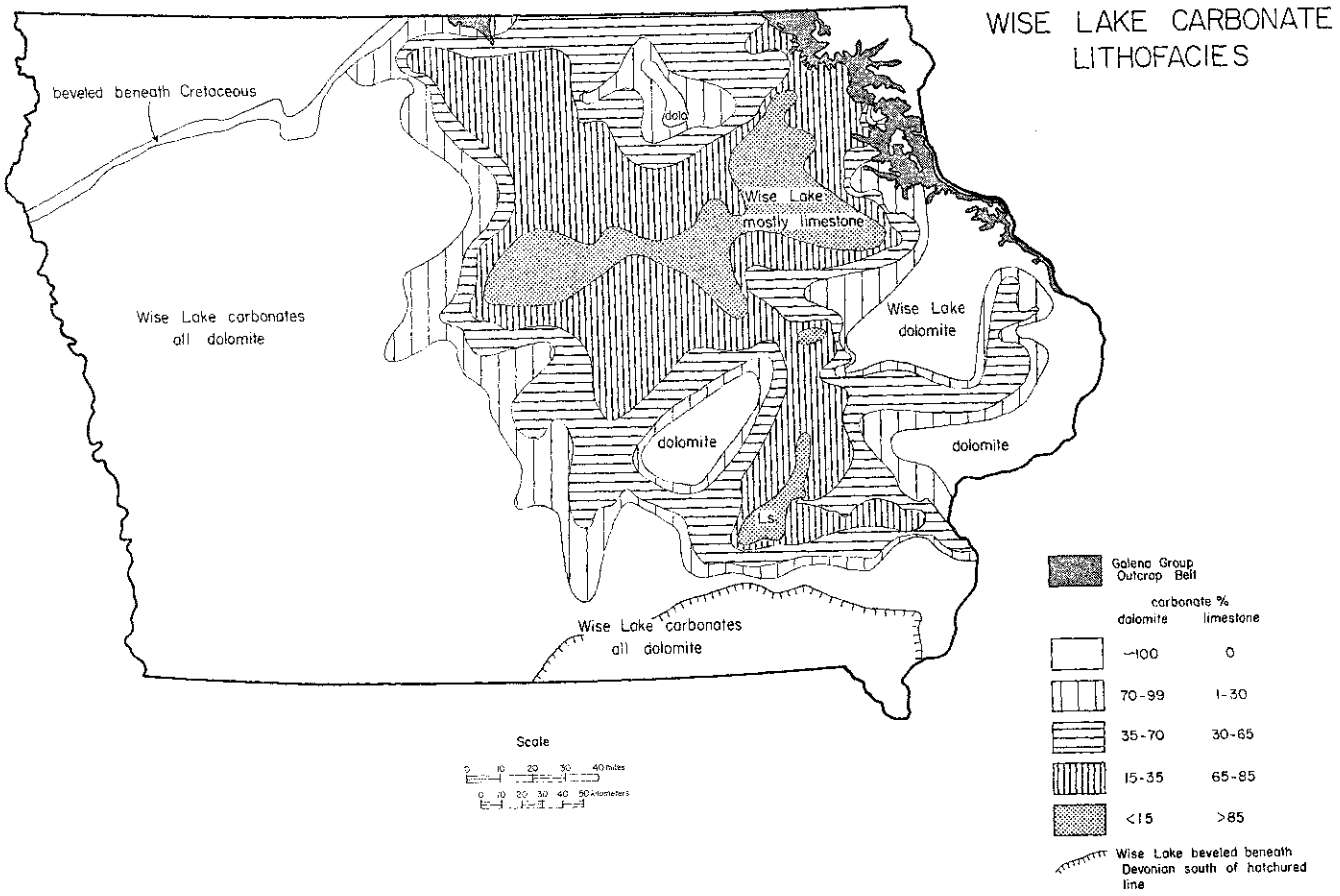


Fig. 8. Distribution of limestone/dolomite in Wise Lake Formation of Iowa.

in east-central and especially northeast Iowa, the Dubuque lacks prominent shale partings at many localities in central and western Iowa. The pronounced northward thickening of Dubuque shale beds within the outcrop belt from northwest Illinois into southeastern Minnesota, as documented by Levorson et al. (1979), suggests that the bulk of the Dubuque clastics may have been derived from northern sources on the Transcontinental Arch (Witzke, 1980). However, close to the Transcontinental Arch in northwest Iowa, the Dubuque is only slightly argillaceous and lacks shale interbeds. This may further suggest that major source areas were only locally present along the trend of the Arch. The great influx of Maquoketa shales following Dubuque deposition in east-central and southeast Iowa apparently originated from eastern clastic sources, probably Taconic source terranes. The general upward increase in argillaceous content in the Dubuque of northwest Illinois and east-central Iowa may also be, in part, related to the Maquoketa clastic influx. Perhaps some of the Dubuque clastics may represent the distal clays of a prograding Maquoketa shale wedge. However, lower Maquoketa shale content decreases northward in the Iowa outcrop belt, whereas Dubuque shale content increases in the same direction; this suggests generally different sources and/or transport directions for the Dubuque and Maquoketa shales in eastern Iowa.

Because Dubuque shales are not consistently recognizable in well cuttings (thin and easily washed out) and, in addition, are not present everywhere across Iowa, other criteria for recognizing the Dubuque in the subsurface had to be employed. Carbonate well cuttings from the upper 20 to 40 feet (6 to 12 m) of the Galena Group commonly display "cinnamon specks" similar to those noted in the Guttenberg, and the lowest occurrence of these "specks" was used to tentatively mark the base of the Dubuque in some wells. In addition, the Dubuque is notably more crinoidal than the underlying Wise Lake, and the lowest occurrence of very crinoidal carbonates in the upper Galena was also used to mark the approximate base of the Dubuque for this study. However, the Dubuque-Wise Lake contact remains a difficult one to identify objectively in most subsurface sections.

The Dubuque-Maquoketa contact is generally much easier to pick in subsurface sequences. The contact in southeast and east-central Iowa can be picked consistently at the contact between the basal Maquoketa brown organic-rich shale sequence (commonly with phosphorites) and the Galena carbonates. In northeastern and north-central Iowa, the basal Maquoketa is a non-crinoidal argillaceous carbonate unit (Elgin Mbr.) that lacks the "cinnamon specks" of the underlying Dubuque. Across most of the central and western Iowa the Dubuque-Maquoketa contact is drawn above the Galena carbonate sequence and below an unnamed extremely cherty lower Maquoketa dolomite interval. Agnew (1955, p. 1721) suggested that the Galena-Maquoketa contact in western Iowa occurs within this very cherty interval, rather than below it. Although the Dubuque is slighty cherty at some localities in western Iowa, Maquoketa lithofacies analysis generally confirms that the overlying very cherty interval is best considered the basal stratigraphic unit of the Maquoketa across the area (e.g., Parker, 1970). The Dubuque-Maquoketa contact across central and western Iowa and southeastern Minnesota is apparently conformable, but a diastemic hardground is present at the contact in eastern Iowa and Illinois. The Dubuque Formation, as recognized for this study, ranges from 15 to 45 feet (4.6 to 13.7 m) in thickness and is thinnest in south-central to west-central Iowa.

Limestone/dolomite facies within the Dubuque of Iowa are shown in figure 9. In general, gross carbonate lithofacies resemble those of the Dunleith and Wise Lake. However, in comparison to the two underlying formations, the Dubuque

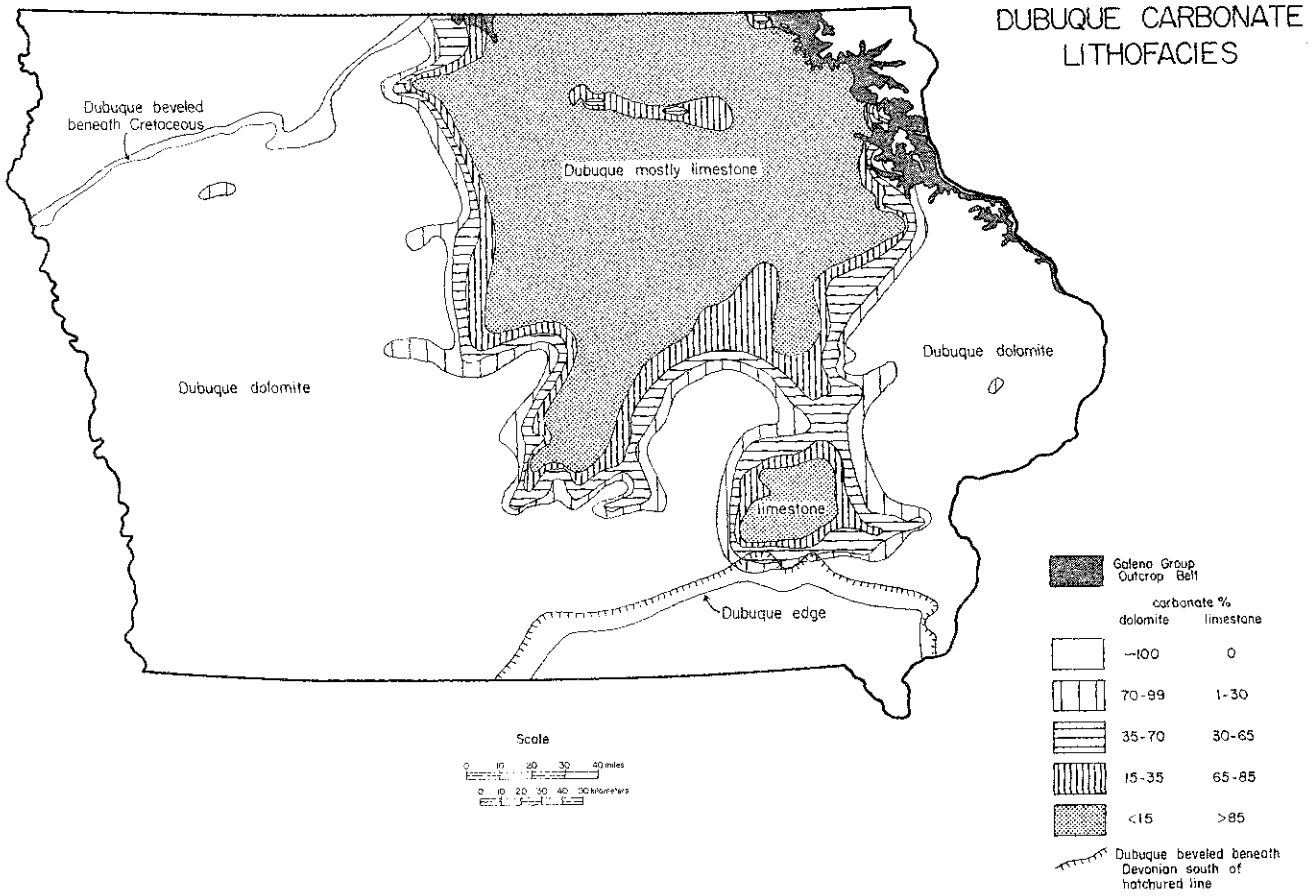


Fig. 9. Distribution of limestone/dolomite in Dubuque Formation of Iowa.

displays a further expansion of the dolomite facies, particularly in east-central Iowa. In contrast to the Wise Lake, the Dubuque also displays a general expansion of the limestone-dominated facies. Correspondingly, the width of the transition zone of mixed dolomite/limestone that separates regions on either side dominated by limestone or dolomite is substantially reduced. Within this transition zone, dolomite content generally increases upward in the Dubuque sequence of southeast Iowa, whereas limestone content generally increases upward in the transitional sequences in northeast and north-central Iowa.

REGIONAL CONSIDERATIONS

Recognition of gross limestone and dolomite facies on a regional scale in the central midcontinent is hampered by lack of uniformity in stratigraphic nomenclature and by general imprecision of correlations within the Middle and Upper Ordovician carbonate sequences. In general, the Galena Group carbonate sequence of eastern Iowa is bounded by prominent shale units--Decorah shales below and Maquoketa shales above. Subsurface workers in Nebraska, northern Missouri, and Kansas also observed a thick Ordovician carbonate and cherty carbonate sequence bounded by shale units--the "Decorah-Platteville" or "Simpson" below and the "Maquoketa" or "Sylvan" above. As such, the carbonate sequence, termed "Viola" in Kansas and "Kimmswick" in northwestern Missouri, generally has been equated with the Galena Group sequence of the Upper Mississippi Valley. However, subsurface cross-sections across Iowa between the Upper Mississippi Valley section and the western subsurface sequence indicate that only the lower portion of the "Viola" and "Kimmswick" in the Forest City Basin area equates with the Galena Group carbonates. The Maquoketa Formation (or Group) progressively changes from a shale-dominated sequence in eastern Iowa to a carbonate-dominated sequence in southwestern Iowa (fig. 10). Although the shale-carbonate boundary has commonly been used to mark the Galena-Maquoketa contact, this boundary is a broadly diachronous facies transition.

Carlson (1969) tentatively correlated the thick Middle and Upper Ordovician carbonate sequence in eastern Nebraska with the "Galena Formation" of Iowa, although much of this sequence apparently correlates to Maquoketa carbonates of western Iowa. If similar relations hold true in northwestern Missouri, then the so-called "Kimmswick" in that area is not an exact lithostratigraphic equivalent of type Kimmswick strata in eastern Missouri. Likewise, the term "Viola" has achieved widespread use in the Kansas subsurface. The "Viola" in Kansas has yielded Late Ordovician conodonts similar to those noted in the "Fernvale" of Oklahoma, whereas the type Viola in Oklahoma has only produced Middle Ordovician conodonts (Sweet, 1979, p. 48). The Kansas "Viola" and the type Viola sequences are physically separated by the Chautauqua Arch. The conodont evidence strongy suggests relating the "Viola" carbonates of Kansas with the upper Galena and Maquoketa carbonates of western Iowa. The "Viola" of Kansas, the "Kimmswick" of northwest Missouri, and the "Galena" of Nebraska are not apparently exact lithostratigraphic equivalents of the Galena carbonate sequence in the Upper Mississippi Valley. Substantial portions of these sequences are apparently younger than the type Galena sequence.

Although precise Ordovician correlations are not yet clarified in the central midcontinent, some gross carbonate lithofacies patterns can nevertheless be recognized. Galena and Maquoketa carbonates in Nebraska are essentially all within a major dolomite facies. However, Lee (1943, p. 36) recognized that the lower "Kimmswick" (or "Viola") sequence in eastern Kansas and northern Missouri generally changes from dolomite in the north to limestone in the south. The

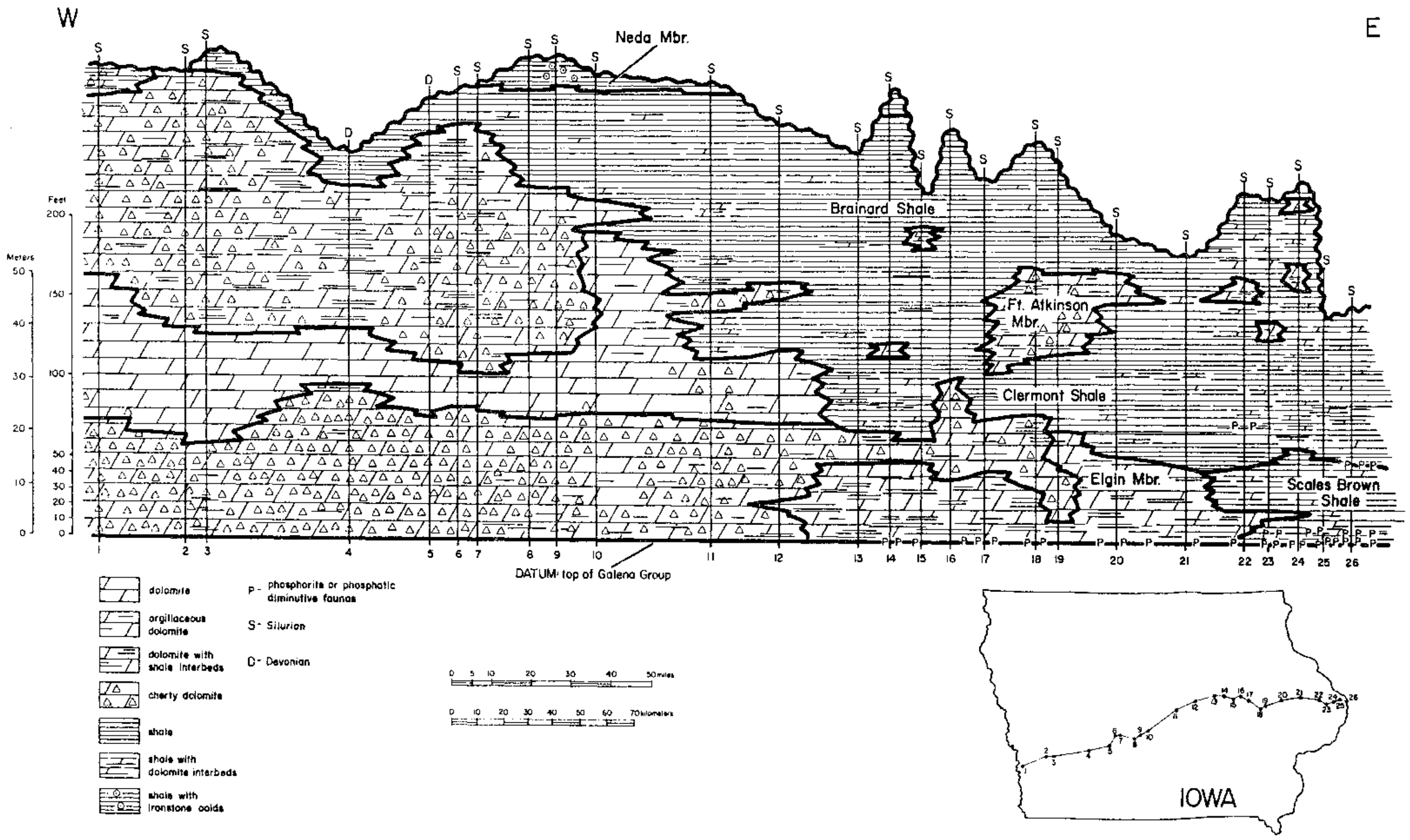


Fig. 10. East-west stratigraphic cross section of the Maquoketa Formation in Iowa. General position of members shown for eastern Iowa sequence; members unnamed in western Iowa. The boundary separating eastern shale-dominated and western carbonate-dominated facies is broadly diachronous across the state, although this boundary has been used to define the top of the "Kimmswick" or "Viola" in the Forest City Basin area. Well logs on file at Iowa Geological Survey.

"Viola" is "mostly limestone in northeastern and eastern Kansas," but it includes progressively more dolomite to the west; towards the Nebraska line the "Viola is almost all dolomite" (Cole, 1975, p. 11). Likewise, the Galena Group in Illinois is primarily dolomite in the north, but Galena carbonates are included in the "southern limestone facies" across the southern two-thirds of Illinois and adjacent Missouri (Templeton and Willman, 1963). These regional relationships suggest that the Galena Group can be divided into several major geographic realms in the central midcontinent based on limestone and dolomite distributions. 1) A "northern limestone facies" occupies areas of southeastern Minnesota and eastern and northern Iowa. 2) A central dolomite facies occupies the region across Wisconson, northern Illinois, southernmost and western Iowa, northwest Missouri, northeast corner of Kansas, and Nebraska. 3) A "southern limestone facies" occupies a broad area across central and southern Illinois, much of Missouri, and into eastern and central Kansas.

DOLOMITIZATION OF THE GALENA GROUP

A comparison of limestone/dolomite distribution patterns in Iowa (figs. 7-9) with Galena Group isopachs (fig. 2) suggests some general relationships between carbonate facies and paleostructure on a gross regional scale. In general, Galena limestones in Iowa are best developed where the Galena Group is thickest (i.e., in northern and eastern Iowa). However, there certainly is not a one-for-one correspondence between thickness and limestone distribution, suggesting that additional relationships also need to be investigated. The general geographic expansion of dolomite-dominated facies upward in the Iowa Galena Group sequence is noteworthy. Maximum extent of limestones occurs within the Decorah Formation, whereas maximum geographic distribution of dolomite-dominated facies occurs within the Dubuque Formation. Although not elaborated here, a further expansion of dolomite facies is seen in the lower Maquoketa Formation (with Elgin limestones restricted to the same general area as the "northern limestone facies" of the Galena Group; see fig. 4 cross section). The vertical and lateral distribution of limestone/dolomite facies (forming a "limestone pyramid") in the Middle and Upper Ordovician carbonate sequence in Iowa may suggest a genetic relationship between dolomitization of the various formations. The gross geographic and stratigraphic variations in dolomite content within the Galena Group of Iowa provide some general constraints on dolomitization models applied to the sequence.

Various syndepositinal (or penecontemporaneous) dolomitization models have been proposed, but the applicability of many of these to Galena Group dolomitization is limited. Modern precipitation of non-stoichiometric dolomite, commonly as thin crusts at or near the surface, is documented for sabkha, supratidal, and shallow evaporitic environments, but the Galena Group rocks share few analogies with these sediments. The great lateral extent of individual members within the Galena suggests general uniformity of conditions over broad expanses of the epeiric sea, for the most part probably subtidal. Likewise, fossil representatives of groups generally regarded as stenohaline (e.g., echinoderm and trilobite debris) are found through most of the Galena sequence, both in dolomite and limestone facies, suggesting that hypersaline environments were generally absent across Iowa during most of Galena deposition. The dolomites of the Iowa Galena Group are primarily, if not entirely, replacement products of calcium carbonate. Syndepositional dolomite, if present, must be volumetrically insignificant in comparison to the vast quantity of metasomatic dolomite present in the widespread Galena Group dolomite facies, which presumably formed by later diagenetic processes.

Two additional dolomitization models deserve closer attention: 1) brine reflux and 2) mixing zone. In general, brine reflux dolomitization is a process in which hypersaline dolomitizing brines, originating from evaporitic basins or lagoons, descend through the sedimentary sequence, following local or regional flow paths. Carbonate strata in Manitoba (Red River Formation) that are equivalent to the Galena Group incude dolomitized burrow-mottled patterns closely similar to those noted in the Upper Mississippi Valley sequences. Kendall (1977) investigated the Manitoba carbonates and discussed the possible role of brine reflux on the dolomitization of the burrow-mottlings.

Athough it may be tempting to invoke a brine reflux model to explain burrow-mottled dolomitization patterns in the Iowa Galena, several outstanding questions remain. 1) When, if ever, did dolomitizing brines move through the sequence? 2) Did dolomitization of burrow-mottlings precede or accompany pervasive regional dolomitization? 3) Where and how did the hypothesized brines originate? 4) How did they flow? (a paleohydrologic problem). 5) Can a brine reflux model adequately explain regional dolomitizatin patterns? The origin of the hypothetical brines needed for brine reflux dolomitization is not readily apparent. No evidence for hypersaline or evaporitic depositional environments has been identified in the Middle and Upper Ordovician sequence in Iowa, although probable evaporite crystal molds are noted in the Galena Group of Wisconsin (Delgado, this volume). Generating significant volumes of hypersaline brine at any time during Galena or Maquoketa deposition in Iowa becomes an important problem. Brine flow would theoretically proceed down-dip, or basinward, as the denser brines displaced connate fresh or marine water, following flow paths consistent with regional or local structure. The stratigraphic and geographic distributions of limestone/dolomite facies in the Iowa Galena Group are not readily explained in terms of a brine reflux model. Even if brine reflux was responsible for some dolomitization in the sequence, such as burrow-mottled dolomite patterns, it seems inadequate to account for the pervasive dolomitization of the widespread dolomite facies.

Hanshaw et al. (1971, p. 722) suggested that dolomitization may occur in the groundwater system in the zone of "mixing of saline with potable water." This model was termed "meteoric dolomitization" by Land (1973) and "Dorag dolomitization" by Badiozamani (1973). I will subsequently refer to this as the mixing zone dolomitization model. Mixing zone diagenetic environments apparently migrate through the groundwater system during marine regressions, as freshwater phreatic environments progressively move seaward. Dolomitization in the mixing zone is thermodynamically possible where the pore fluids are undersaturated with respect to calcium carbonate but supersaturated with respect to dolomite, and dolomitization proceeds as a solution-precipitation process. In general, there should be a close association of paleo-structural highs with areas of dolomitization if mixing zone environments were responsible for the dolomitization.

Badiozamani (1973) suggested that dolomitization of Platteville and Galena strata in the Upper Mississippi Valley area occurred within mixing zone environments associated with periodic emergence of the Wisconsin Arch. Although the Ordovician sequence is pervasively dolomitized along the trend of the Wisconsin Arch, pervasively dolomitized Galena sequences in Iowa cannot be consistently related to paleo-structural highs. If a mixing zone dolomitization model is applied to the Galena sequence in Iowa, then some paleohydrologic questions need to be evaluated. When, if ever, did mixing zone environments migrate through the Iowa Galena sequence? The migration of mixing zone environments proceeds as freshwater phreatic lenses progressively displace marine phreatic environments. Areas of freshwater recharge are needed to drive the system, and emergent conditions are required somewhere in the area. There is no evidence of emergent conditions in Iowa until the withdrawal of the seas at the close of Maquoketa deposition. Therefore, if the Galena was pervasively dolomitized in mixing zone environments, such environments would not be reasonably expected to have occurred in Iowa until the latest Ordovician. Therefore, paleostructural patterns present at the close of the Ordovician may be more relevant to Galena dolomitization than the paleo-structure reflected on the Galena isopach map.

What flow paths would migrating freshwater phreatic and mixing zone environments reasonably follow? If dolomitization occurred in a mixing zone, the distribution of limestone/dolomite should reflect paleoflow. Dolomite facies should occupy a position up-head from the limestone facies, and flow directions should be generally towards the limestone facies. Mixing zone dolomitization would extend only as far as the limits to freshwater groundwater movement. Can the regional distribution of Galena limestone and dolomite facies be explained in terms of mixing zone dolomitization? Perhaps, although many problems are apparent. Why weren't the Galena carbonates of the "northern limestone facies" pervasively dolomitized as they were to the east, south, and west? Mixing zone environments should have migrated through northeast Iowa during the Late Ordovician offlap, just as they did in other areas. Why are some structural highs dolomitized (e.g., Wisconsin Arch), but other prominent highs were not (e.g., limestones in Missouri adjacent to Ozark Uplift)? Although mixing zone models are intriguing, many questions remain.

Galena Group stratigraphic considerations place additional constraints on dolomitization models. The distribution of dolomite within the various Galena Group formations is not uniform; within transition facies certain stratigraphic intervals are preferentially dolomitized over others. This suggests that lateral movement of dolomitizing fluids was more easily facilitated within certain stratigraphic intervals, probably those with increased permeability. The general geographic expansion of dolomite facies upward in the Galena-lower Maquoketa sequence in Iowa can probably be interpreted in several ways. If brine reflux models are invoked, the downward descent of dolomitizing brines through the sequence would probably result in an upward increase in the degree of dolomitization within the sequence (Kendall, 1977, p. 500). If mixing zone models are preferred, the upward increase in dolomite would presumably be related to the migration of freshwater and mixing zone phreatic environments through the sequence, with migration rates progressively impeded with depth.

The precipitation of large quantities of stoichiometric dolomite, as in the Galena dolomite facies, is presumably not a rapid process, and kinetic factors need to be considered carefully in any dolomitization model. For example, how do rates of brine reflux or mixing zone residence times affect dolomitization? Although dolomitization conditions may be thermodynamically achieved in mixing zone environments, pervasive dolomitization would certainly not occur if such environments only resided in a particular area for a very short period of time. Evaluation of specific dolomitization models is further complicated by introducing such kinetic considerations.

At present, no single existing dolomitization model seems adequate to account for all geographic and stratigraphic observations within the Galena Group. Perhaps more than one model applies, and dolomitization may have occurred at more than one time. Additional studies are needed to evaluate regional trends in limestone, dolomite, and silica diagenesis. For example, regional oxygen isotopic studies may help clarify some outstanding problems. Subsurface information needs to be incorporated into such studies.

SUMMARY

1. Adoption of Templeton and Willman's (1963) Galena Group stratigraphic nomenclature is recommended for use in Iowa, although the Decorah is retained in formational status. Members within the Dunleith and Wise Lake Formations are recognizable in the Iowa outcrop belt but are difficult to distinguish in the subsurface.

2. The Galena Group in Iowa is thickest in northern and eastern Iowa. The Galena significantly thins in southwest Iowa, reflecting the proximity of the Southeast Nebraska Arch.

3. The Decorah Formation increases in thickness northwestward across Iowa, and shale content progressively increases in the direction of probable source areas on the Transcontinental Arch. The Decorah-Dunleith contact is broadly diachronous across Iowa, becoming younger to the north and west. Decorah sandstones and sandy carbonates are well developed in southwest Iowa and nearby areas of other states. Maximum geographic extent of limestones in the Galena Group occurs within the Decorah.

4. The Dunleith Formation approximately correlates with the "Cherty unit" of Agnew (1955), although the top of the cherty interval in the Galena is not a consistent datum in western Iowa. The Dunleith becomes progressively shalier to the northwest in Iowa. Dunleith limestones are best developed in northeast Iowa, although mixed dolomite/limestone sequences are more widespread in the state. Dunleith dolomites within mixed sequences are usually best developed in the middle and upper part of the sequence.

5. The Wise Lake Formation is locally cherty in western Iowa; the Wise Lake-Dubuque contact cannot be picked precisely across most of Iowa. Wise Lake dolomite/limestone facies patterns are similar to those in the Dunleith, although the Wise Lake dolomite-dominated facies is expanded geographically.

6. Pervasively dolomitized Galena Group carbonate facies achieve their greatest geographic extent in the Dubuque Formation. Dubuque shale source areas were probably on the Transcontinental Arch, although eastern Taconic sources cannot be ruled out. The Dubuque-Maquoketa contact is apparently conformable across much of Iowa, but a submarine diastemic hardground marks the contact in eastern Iowa.

7. The top of the "Galena," "Viola," and "Kimmswick" sequence in western Iowa and adjacent states has commonly been picked at the contact between the carbonate-dominated sequence below and the shale-dominated sequence above. However, the shale-carbonate contact is a broadly diachronous facies transition. As a result, the "Viola" or "Kimmswick" of the Forest City Basin area probably includes carbonate strata equivalent to a portion of the Maquoketa sequence in Iowa.

8. The northern limestone facies of the Galena generally occupies northeast Iowa and southeast Minnesota. A central dolomite facies extends across much of Wisconsin, northern Illinois, Iowa, and Nebraska. The southern limestone facies extends generally across the southern two-thirds of Illinois, much of Missouri, and into portions of Kansas.

9. In general, Galena limetones in Iowa are best developed where the Galena Group is thickest. No single dolomitization model adequately explains the distribution of dolomite facies in the Galena Group of Iowa. However, mixing zone

and brine reflux models may explain some aspects of dolomitization in the Iowa Galena Group.

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REFERENCES

Agnew, A.F., 1955, Facies of Middle and Upper Ordovician rocks of Iowa: Am. Assoc. Petroleum Geologists Bull., v. 39, p. 1703-1753.

Agnew, A.F.; Heyl, A.V., Jr.; and Lyons, E.J., 1956, Stratigraphy of Middle Ordovician rocks in the zinc-lead district of Wisconsin, Illinois, and Iowa: U.S. Geol. Survey, Prof. Paper 274-K, p. 251-312.

Austin, G.S., 1970, Deep stratigraphic test well near Hollandale, Minnesota: Minn. Geol. Surv., Rept. Inves. 12, 52 p.

Badiozamani, K., 1973, The Dorag dolomitization model--application to the Middle Ordovician of Wisconsin: Jour. Sed. Petrol., v. 43, p. 965-984.

Bunker, B.J., 1981, The tectonic history of the Transcontinental Arch and Nemaha Uplift and their relationship to the Cretaceous rocks of the central midcontinent region: Iowa Geol. Surv., Guidebook Ser. 4, p. 1-23.

Carlson, M.P., 1969, Stratigraphic framework of Precambrian and Lower and Middle Paleozoic rocks in the subsurface in Nebraska: unpubl. Ph.D. thesis, Univ. Nebr., 66 p., 4 pl.

Cole, V.B., 1975, Subsurface Ordovician-Cambrian rocks in Kansas: Kans. State Geol. Surv. Subsurf. Geol. Ser. 2, 18 p.

Hanshaw, B.B.; Back, W.; and Deike, R.G., 1971, A geochemical hypothesis for dolomitization by ground water: Econ. Geol., v. 66, p. 710-724.

Kendall, A.C., 1977, Origin of dolomite mottling in Ordovician limestones from Saskatchewan and Manitoba: Bull. Canad. Petrol. Geol., v. 25, p. 480-504.

Land, L.S., 1973, Holocene meteoric dolomitization of Pleistocene limestones, North Jamaica: Sedimentol., v. 20, p. 411-424.

Lee, W., 1943, The stratigraphy and structural development of the Forest City Basin in Kansas: Kans. State Geol. Surv. Bull. 51, 142 p.

Lee, W., 1946, Structural development of the Forest City Basin of Missouri, Kansas, Iowa, and Nebraska: U.S. Geol. Surv., Oil and Gas Inves., Prelim. Map 48, 7 sheets.

Lee, W., 1957, Stratigraphy and structural development of the Salina Basin area: Kansas Geol. Surv., Bull. 121, 167 p.

Levorson, C.O.; Gerk, A.J., 1972, A preliminary stratigraphic study of the Galena Group in Winneshiek County, Iowa: Proc. Iowa Acad. Sci., v. 79, p. 111-122.

Levorson, C.O.; Gerk, A.J.; and Broadhead, T.W., 1979, Stratigraphy of the Dubuque Formation (Upper Ordovician) in Iowa: Proc. Iowa Acad. Sci., v. 86, p. 57-65.

Parham, W.E.; and Austin, G.S., 1969, Clay mineralogy, fabric, and industrial uses of the shale of the Decorah Formation, southeastern Minnesota: Minn. Geol. Surv., Rept. Inv. 10, 32 p.

Parker, M.C., 1970, The Maquoketa Formation (Upper Ordovician) in Iowa: Iowa Geol. Surv., Misc. Map Ser. 1.

Sweet, W.C., 1979, Late Ordovician conodonts and biostratigraphy of the western midcontinent province: Brigham Young Univ. Geol. Studies, v. 26, pt. 3, p. 45-85.

Templeton, J.S.; and Willman, H.B., 1963, Champlanian Series (Middle Ordovician) in Illinois: Ill. State Geol. Surv., Bull. 89, 260 p.

Weiss, M.P., 1957, Upper Middle Ordovician stratigraphy of Fillmore County, Minnesota: Geol. Soc. America Bull., v. 68, p. 1027-1062.

Willman, H.B.; and Kolata, D.R., 1978, The Platteville and Galena Groups in northern Illinois: Ill. State Geol. Survey., Circ. 502, 75 p.

Witzke, B.J., 1980, Middle and Upper Ordovician paleogeography of the region bordering the Transcontinental Arch: *in* Fouch, T.D.; and Magathan, E.R. (eds.), Paleozoic Paleogeography of the West-Central United States: Soc. Econ. Paleon. Mineral., Rocky Mtn. Sec., Denver, p. 1-18.

Delgado, D. J., ed. (1983), Ordovician Galena
Group of the Upper Mississippi Valley --
Deposition, diagenesis, and paleoecology:
Guidebook for the 13th Annual Field Conference,
September 30 - October 2, 1983, p. E1 - E6.

LITHOSTRATIGRAPHY OF THE UPPER DUNLEITH FORMATION (ORDOVICIAN) IN SOUTHEASTERN MINNESOTA

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ABSTRACT

The upper four members of the Dunleith Formation, Galena Group (Ordovician) of the Illinois classification can be recognized in southeastern Minnesota. These members correspond approximately to the Prosser Member of the Galena Formation in the Minnesota classification.

The Rivoli, Sherwood, Wall, and Wyota Members are composed primarily of micrite, increasing in argillaceous and/or dolomitic content towards the northwest. Argillaceous zones, hardgrounds, cherty zones, and marker beds are areally persistent, and aid in defining member contacts across the study area.

Four bentonite beds are present within the upper Dunleith Formation in Minnesota: The Calmar, Conover, Nasset, and Haldane K-Bentonites. Heavy mineral assemblages in three of these bentonites consist predominantly of zircon and apatite. The Nasset K-Bentonite has a distinctive heavy mineral composition dominated by zircon and hornblende.

INTRODUCTION

In a large area of southeastern Minnesota, quarries and road cuts expose carbonates of upper Middle Ordovician age. At most exposures, these rocks include portions of the Prosser Member of the Galena Formation in the official Minnesota terminology (Weiss, 1955; Austin, 1970). Commonly, neither the top nor the base of the Prosser is exposed. This makes it difficult to define precise stratigraphic position of specific horizons and zones of interest.

The equivalent interval in Illinois is divided into the four upper members of the Dunleith Formation (fig. 1). Several studies have shown that the Illinois subdivisions can be recognized from north-central Illinois to northeastern Iowa (Templeton and Willman, 1963, Gerk and Levorson, 1972; Levorson and Gerk, 1972, Willman and Kolata, 1978).

During the summer of 1979 I studied this interval extensively in southeastern Minnesota and the adjacent edge of northeastern Iowa (figs. 2, 3). An important conclusion was that the Illinois stratigraphic subdivisions can be recognized consistently in Minnesota (fig. 4). At least one Illinois member contact is recognizable at nearly every exposure; therefore, it is easy to define the precise stratigraphic location of lithologic and biostratigraphic zones of interest, and to correlate them between exposures.

Another important result of this study is recognition of four bentonite beds previously identified in exposures in Illinois and Iowa (Mossler and Hayes, 1966; Levorson and Gerk, 1972; Willman and Kolata, 1978). This extends westward and northward the known areas of deposition of several Ordovician K-bentonites, and identifies potential new tools for correlation in this area. Additionally, I confirmed that the Nasset K-Bentonite has a distinctive heavy mineral assemblage.

The following discussion summarizes field and laboratory observations on the four members of the upper Dunleith Formation in Minnesota.

RIVOLI MEMBER

The lowest member of the upper Dunleith Formation studied, the Rivoli, generally averages 12 to 14 feet in thickness, thinner than the 17 to 20 feet recorded near Decorah, Iowa (Gerk and Levorson, 1972). The dominantly limestone Rivoli Member is readily discernible from the underlying Mortimer Member which consists of alternating beds of limestone and shale. The Mortimer is the upper part of Weiss' (1955) "sawtooth zone" (Templeton and Willman, 1963).

The Rivoli is a biomicrite with a detrital content of approximately 20 percent. The clastic material within the Rivoli Member occurs predominantly in the lower 5 feet, but increases throughout the section northwestward. Weathered Rivoli outcrops usually appear nodular as a result of weathering of the clastic material.

Two bentonite beds are commonly present in the Rivoli. The Calmar K-Bentonite (Willman and Kolata, 1978) is 4 to 7 feet above the base of the member. The Conover K-Bentonite (Willman and Kolata, 1978) is located at the Rivoli-Sherwood contact. Mineralogically the two bentonites are similar. Abundant euhedral zircon and apatite grains are the prevalent heavy mineralogical constituents, with minor amounts of pyroxene and hornblende. Traces of biotite, tourmaline, and collophane were also found, and may indicate some contamination of the bentonite beds after deposition. Heavy mineral assemblages of euhedral apatite and zircon were not present in non-bentonite Dunleith shales and clays.

Chert nodules are not present in the Rivoli except at a location near Greenleafton, Fillmore County, Minnesota (Locality 3, fig. 3), where chert is found in the upper two feet of the member.

The Minnesota Geological Survey places the Cummingsville-Prosser contact 7 to 10 feet above the base of the Rivoli Member (fig. 1). Lithologically, the upper 3 to 5 feet of the Rivoli Member resembles the overlying Sherwood Member, with no distinct lithological change at the contact between the two members in Fillmore County. In Goodhue County, Minnesota, the Rivoli-Sherwood contact is distinguished by a distinct 6 inch shale horizon. Elsewhere a prominent 1 to 2 foot argillaceous zone occurs at the boundary between the two members (fig. 4).

SHERWOOD MEMBER

The Sherwood Member of the upper Dunleith Formation ranges in thickness from 16 to 22 feet, as compared to 14 feet at the type section in East Dubuque, Illinois. The Sherwood is thicker bedded (1 to 3 feet), lighter colored and less silty than the Rivoli Member.

In southern Minnesota, the Sherwood Member is a biomicrite containing fossil allochems predominantly of crinoids and brachiopods, comprising 3 to

30 percent of the lithologic constituents. These fossil assemblages, which are prominent throughout the upper Dunleith Formation, indicate normal marine conditions existed during deposition of upper Dunleith strata.

Detrital material, dominantly quartz and clay, comprises approximately 5 to 10 percent of the Sherwood Member, increasing northwestward into Olmsted and Goodhue Counties (fig. 3). The northwestward increase in terrigenous clastics in the Rivoli and Sherwood Members probably indicates that the Transcontinental Arch (fig. 2) supplied much of this detritus material.

Chert nodules are common within the Sherwood Member in Fillmore and southern Olmsted Counties, but disappear north of Rochester, Minnesota (Locality 10, fig. 3). At some localities a bentonite bed (Nasset K-Bentonite, Willman and Kolata, 1978) occurs approximately 4 to 6 feet above the base of the Sherwood Member. Nasset K-Bentonite heavy minerals include abundant zircon and hornblende grains, with some zircon grains containing inclusions elongated parallel to the c-axis. The abundance of hornblende distinguishes the Nasset K-Bentonite from other bentonites studied.

The contact between the Sherwood Member and the overlying Wall Member of the upper Dunleith Formation lies at the top of a distinct yellow-brown, thinly bedded, argillaceous zone. In Fillmore and Olmsted Counties, a distinct, commonly oxidized hardground is present at the top of the Sherwood Member. The occurrence of bedded chert nodules 5 to 7 feet below the top of the Sherwood Member in Fillmore and southern Olmsted Counties can be useful in placing the Sherwood-Wall contact.

WALL MEMBER

The Wall Member in southern Minnesota varies in thickness from 8 to 14 feet, approximately the same thickness as at the type section near East Dubuque, Illinois. The Wall Member is noncherty and more dolomitic than the underlying Sherwood Member. In Fillmore County, Minnesota, the Haldane K-Bentonite (Willman and Kolata, 1978) may be present within the middle of the Wall Member. Mineralogically the Haldane K-Bentonite is similar to the Calmar and Conover K-Bentonites. The source area for all bentonites in the upper Dunleith Formation is believed to be the northern Appalachian Mobile Belt, with the volcanic ash being carried by the southeast trade winds (Dott and Batten, 1976).

The contact of the Wall Member with the overlying Wyota Member is not sharply defined in southern Minnesota. An approximate contact can be placed at the top of a one-foot argillaceous zone which commonly weathers recessively.

WYOTA MEMBER

THe Wyota Member ranges in thickness from 21 feet in northern Iowa (Levorson and Gerk, 1972) to 15 feet northward in Olmsted County. Many localities do not have the total thickness of the Wyota exposed since it is missing as a result of present erosion. Lithologically the Wyota is a tan-colored, medium bedded biomicrite, increasing in dolomitic content in Olmsted and Goodhue Counties. Chert nodules similar to those in the Sherwood Member are present in central and southern Fillmore County, but disappear in Olmsted and Goodhue Counties.

The contact of the Wyota Member with the overlying Sinsinawa Member of the Wise Lake Formation is not sharply defined, but lithological and sedimentological features of the Sinsinawa permit an arbitrary contact to be chosen. The Wyota-Sinsinawa contact is the same as the Prosser-Stewartville contact as described by the Minnesota Geological Survey (fig. 1). Sinsinawa strata in Minnesota are dolomite-mottled limestones containing abundant Receptaculities specimens from approximately 10 feet above the base of the member upwards.

REFERENCES:

Austin, G.S., 1970b, Deep stratigraphic test well near Hollandale, Minnesota: Minnesota Geological Survey Report Inv. 12, 52p.

Dott, R.H. Jr., and Batten, R.L., Evolution of the Earth, 2nd ed. New York: McGraw-Hill Book Company, 1971.

Gerk, A.J., and Levorson, C.O., 1972, Field trip guide to the Galena stratigraphy of Winneshiek County, Iowa, 10p.

Levorson, C.O., and Gerk, A.J., 1972, A preliminary stratigraphic study of the Galena Group of Winneshiek County, Iowa: Iowa Academy of Science Proceedings, v. 79, p. 111-112.

Mossler, J.H., and Hayes, J.B., 1966, Ordovician Bentonites of Iowa: Journal of Sedimentary Petrology, v. 56, p. 414-427.

Stone, D.J., 1980, The Geology of the Upper Dunleith Formation (Prosser Member Galena Formation) of Middle Ordovican Age in Southeastern Minnesota: unpublished masters thesis, University of Minnesota.

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

Weiss, M.P., 1955, The Stratigraphy and Stratigraphic Paleontology of Upper Ordovician rocks of Fillmore County, Minnesota: University of Minnesota, unpublished doctoral dissertation.

Willman, H.B. and Kolata, D.R., 1978, The Platteville and Galena Groups in Northern Illinois: Illinois State Geological Survey Circular 502, 75p.

FIGURES

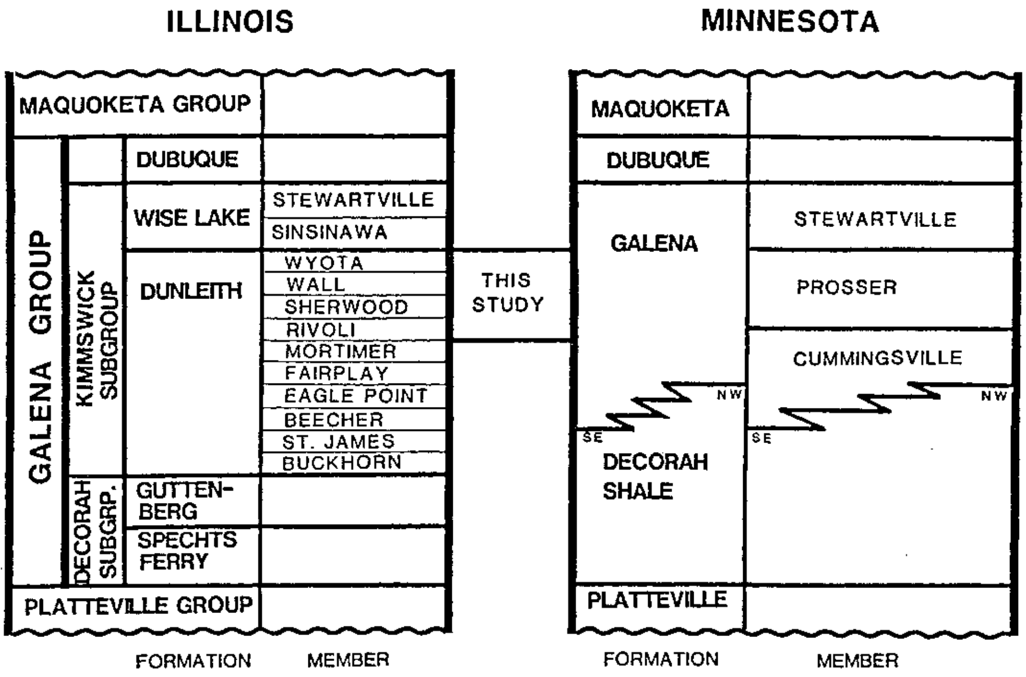

Figure 1-- Correlation of Galena stratigraphy of Illinois and Minnesota (Weiss, 1955; Austin, 1970; Templeton and Willman, 1963).

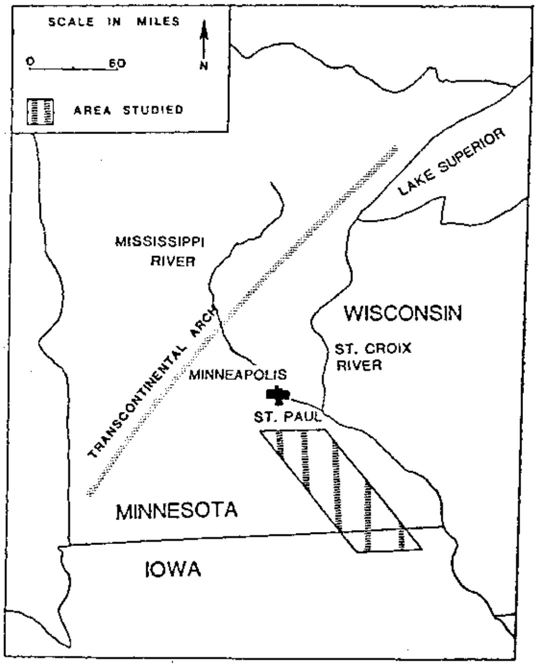

Figure 2-- Location map of study area and location of the Transcontinental Arch.

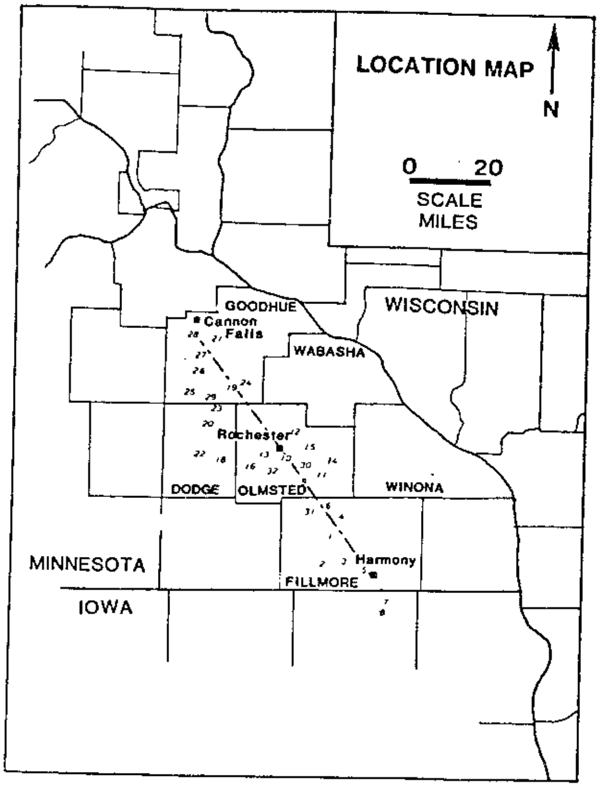

Figure 3-- Location map showing studied Dunleith exposures in southeastern Minnesota. Numbers refer to localities described by Stone (1980).

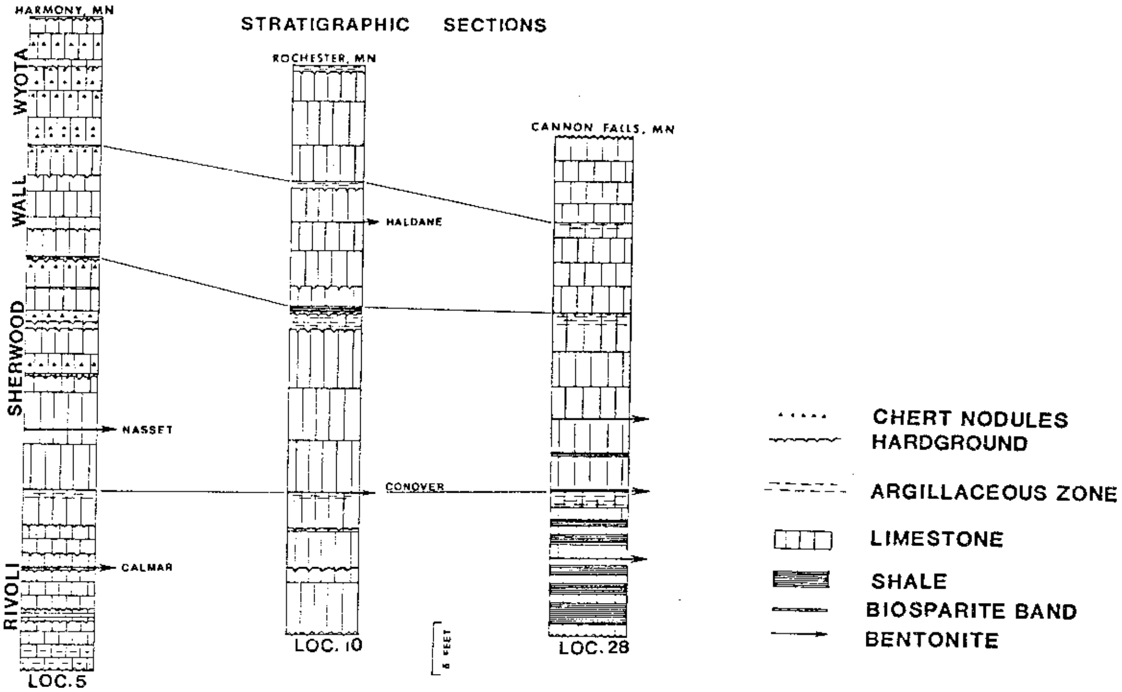

Figure 4-- Stratigraphic correlation of upper Dunleith strata from Harmony (loc. 5) to Cannon Falls (loc. 28), Minnesota. Line of section shown on fig. 3.

Delgado, D. J., ed. (1983), Ordovician Galena
Group of the Upper Mississippi Valley --
Deposition, diagenesis, and paleoecology:
Guidebook for the 13th Annual Field Conference,
September 30 - October 2, 1983, p. F1 - F15.

CORRELATION OF K-BENTONITES IN THE DECORAH SUBGROUP OF THE MISSISSIPPI VALLEY BY CHEMICAL FINGERPRINTING

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ABSTRACT

The Decorah Subgroup (Galena Group; Champlainian Series; Middle Ordovician) of the Mississippi Valley region contains four altered volcanic ash beds called, in ascending order, the Deicke, Millbrig, Elkport, and Dickeyville K-bentonite Beds. Chemical (instrumental neutron activation and X-ray fluorescence) and statistical (step-wise discriminant analysis) analyses indicate that each K-bentonite bed has a distinct chemical fingerprint that can be identified with a high degree of confidence. The most important elements, listed in order of their ability to discriminate between beds are Co, Dy, Na, Sm, As, and Cr.

The Deicke and Millbrig K-bentonites are the thickest, most persistent and widespread K-bentonites in the Mississippi Valley. Their diagnostic trace-element composition can be recognized from southeastern Minnesota to eastern Missouri, a distance of about 800 kilometers. The Elkport and Dickeyville K-bentonites are known from relatively few localities in northwestern Illinois, southwestern Wisconsin, and northeastern Iowa. All four K-bentonites provide time stratigraphic marker beds that should facilitate correlation studies of the Decorah Subgroup and equivalent strata.

INTRODUCTION

The Ordovician rocks of eastern North America contain numerous, widespread beds of potassium bentonite (altered volcanic ash) that record a long period of volcanic activity in the Appalachian mobile belt. Their volcanic origin is indicated by the presence of biotite, sanidine, hornblende, euhedral apatite, euhedral zircon, and relic shard structures. The ash presumably originated from volcanoes situated in an island arc system that extended from Alabama to maritime Canada. Paleowinds from the east-northeast (in terms of present geographic coordinates) apparently carried the ash over the Midcontinent. It fell into widespread epeiric seas and accumulated in environments where marine carbonates and terrigenous clastics were being deposited. At least 17 different ash falls reached the present Mississippi Valley area, and one has been reported as far west as northwestern Iowa (Witzke, 1980). In outcrop and subsurface, Ordovician K-bentonites are distributed over approximately 1.3 million square kilometers (500,000 square miles) of eastern North America (Fig. 1).

K-bentonites consist principally of regularly interstratified illite/smectite with illite the dominant component (Weaver, 1953; Reynolds and

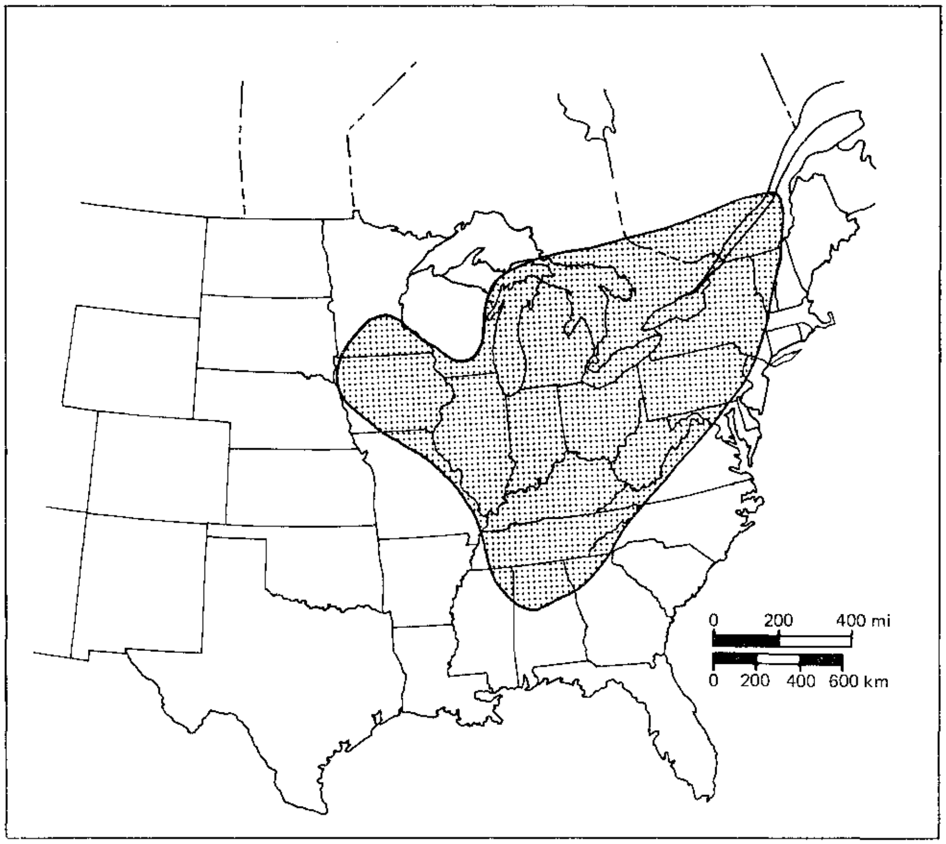

Figure 1. Distribution of K-bentonites in Middle Ordovician rocks in outcrop and subsurface of eastern North America. Stippled area encloses all reported occurrences of K-bentonites; it is not a paleogeographic map.

Hower, 1970). These beds also contain small amounts of quartz, feldspar and various heavy minerals. Certain Ordovician K-bentonite beds in the Mississippi Valley region, which have been feldspathized, consist mainly of authigenic orthoclase (Weiss, 1954).

K-bentonites are of stratigraphic importance because they represent ash falls that occurred in very brief intervals of time over wide areas and are preserved in rocks with complex facies relationships. If a single K-bentonite bed, or a series of beds, can be identified in different stratigraphic sections, then the contemporaneity of these sections is established.

Although K-bentonites have been used in correlations of Ordovician rocks for over 60 years, most stratigraphic studies have been limited to local areas because of the difficulty in recognizing a particular ash fall in widely separated localities. Mineralogic and petrologic studies provide few criteria for distinguishing K-bentonite beds.

Recently, chemical fingerprinting has proved useful for recognizing individual Ordovician K-bentonites (Günal, 1979; Günal and Huff, 1978; Huff, 1981; Huff, in press). Chemical analyses of certain K-bentonites from Champlainian rocks of Ohio, Kentucky, and Tennessee show that quantities of selected major and trace elements are unique for individual beds and uniform over wide areas.

We have found chemical fingerprinting to be very useful in correlating K-bentonites in the Champlainian Decorah Subgroup (Galena Group) in the Mississippi Valley region (Huff et al., 1983). In this paper, we discuss the methods and report the results of our on-going investigation.

Stratigraphy of the Decorah Subgroup

The Decorah Subgroup (Templeton and Willman, 1963; Willman and Kolata, 1978), assigned to the Rocklandian Stage (Ross et al., 1982), consists of shale and shaly carbonate formations at the base of the Galena Group. These are, in ascending order, the Spechts Ferry, Kings Lake, and Guttenberg Formations (Fig. 2). In southeastern Minnesota, northeastern Iowa, and parts of southwestern Wisconsin, the Decorah also includes shaly strata (Ion Member) above the Guttenberg Formation (Kay, 1929). The Ion grades southward to carbonate (Buckhorn and St. James Members of the Dunleith Formation) which is only slightly shaly (Fig. 3). Consequently, south of the general vicinity of McGregor, Clayton County, Iowa, the top of the Decorah is dropped, by vertical cutoff, to the top of the Guttenberg Formation.

The Decorah is nearly 20 meters thick in parts of Minnesota. In south-central Wisconsin and north-central Illinois, the Spechts Ferry pinches out, the Guttenberg thins greatly, and the Decorah Subgroup--represented by the Guttenberg Formation--is only 0.3 to 1.2 meters thick or locally absent (Fig. 4). The Decorah Subgroup extends southward in western Illinois and east central Missouri, where it is also particularly well developed.

Spechts Ferry Formation: The Spechts Ferry Formation is dominantly shale containing thin layers of limestone, particularly in the lower part. The Spechts Ferry was long considered to be the uppermost member of the Platteville Formation (Kay, 1935). However, its close association with the overlying Decorah was shown by Herbert (1949), and its Rocklandian ("Trentonian") age has been supported by faunal studies (Perry, 1962; De Mott, 1963).

Templeton and Willman (1963) and Willman and Kolata (1978) recognized two members in the Spechts Ferry Formation: the Castlewood and Glencoe in ascending order. In its type area of east central Missouri the Castlewood is a limestone up to 2.5 meters thick and is similar lithologically to the underlying Platteville Group, from which it is separated by the Deicke K-bentonite Bed. The Castlewood thins northward; in some places it is absent.

A limestone unit up to 2 meters thick named the Carimona Member by Weiss (1955) occurs in southeastern Minnesota, parts of northeastern Iowa, and southwestern Wisconsin at approximately the same stratigraphic position as the Castlewood. The Carimona is similar lithologically and faunally to the limestone interbedded with the shale of the overlying Spechts Ferry; however, Weiss (1955) assigned the member to the underlying Platteville Formation because of its dominant limestone lithology. The Deicke K-bentonite

("Carimona bentonite") lies at the base of the Carimona Limestone, except in parts of southeastern Minnesota where it is underlain by up to 2.4 meters of Carimona strata (Weiss and Bell, 1956). The Carimona is more argillaceous and somewhat coarser grained than the Castlewood. Additionally, the Carimona, unlike the Castlewood, has smooth to broadly rippled bedding planes separated by relatively thick shaly partings. Because of these differences we prefer to restrict the Castlewood to eastern Missouri and western Illinois, and retain the Carimona as the basal member of the Spechts Ferry Formation in the northern outcrop area.

The Glencoe Member is the dominantly shaly upper part of the Spechts Ferry--the major part. The Glencoe has been identified as far south as Ste. Genevieve, Missouri, and as far north as Decorah, Iowa. North of Decorah, the Guttenberg Formation, which is the upper boundary of the Spechts Ferry Formation, grades to shale; and it becomes impractical to differentiate the Glencoe from the Decorah Shale. The Millbrig K-bentonite Bed ("Spechts Ferry bentonite") occurs in the Glencoe Member.

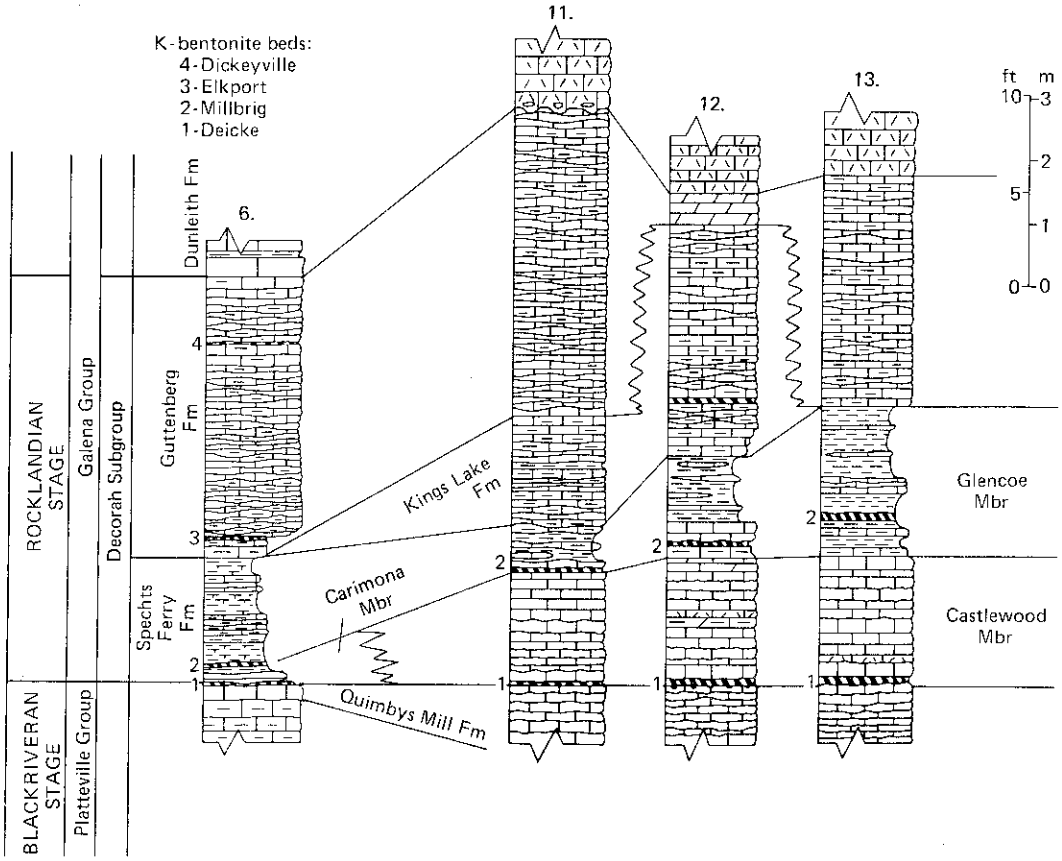

Figure 2. Correlation of the Decorah Subgroup from Dickeyville, Wisconsin, to Barnhart, Missouri, showing stratgraphic relations of the Kings Lake Formation. No horizontal scale.

The Deicke and Millbrig K-bentonite Beds (Willman and Kolata, 1978), which correspond respectively to I-1 and I-2 of Mossler and Hayes (1966) and A and B of Bell (1954), are the most persistent and widespread K-bentonites in the Ordovician rocks of the Mississippi Valley area. The Deicke type section is at the Mincke Section (Templeton and Willman, 1963, p. 235); that of the Millbrig is at the Millbrig Southeast Section (Willman and Kolata, 1978; p. 59) near Galena, Jo Daviess County, Illinois. These K-bentonites, which generally range from 3 to 12 centimeters thick are characteristically light gray (N7) to grayish orange (10 YR 7/4) and plastic when wet.

Kings Lake Formation: In eastern Missouri and western Illinois, lying above the Spechts Ferry Formation and below the Guttenberg Formation, is an argillaceous, very silty, dolomitic limestone described by Herbert (1949) and named by Templeton and Willman (1963): the Kings Lake Formation. Generally 1.5 to 3 meters thick, it has a maximum thickness of 4.5 meters and pinches out to the north in the subsurface. The Kings Lake contains both grayish green and reddish brown shale partings; thus it appears to be transitional in lithology between the Spechts Ferry and Guttenberg Formations. It probably represents a local facies of the upper part of the Glencoe Member of the Spechts Ferry and the basal part of the Guttenberg Formation. Templeton and Willman (1963) described a persistent 1 to 5 centimeter thick K-bentonite bed in the lower part of the Kings Lake that they believed was not present in the northern outcrop area of the Mississippi Valley. It is also possible that this K-bentonite represents the same ash fall as either the Elkport or Dickeyville K-bentonite Beds in the Guttenberg Formation of the northern outcrop area. Chemical fingerprinting may provide the correct correlation.

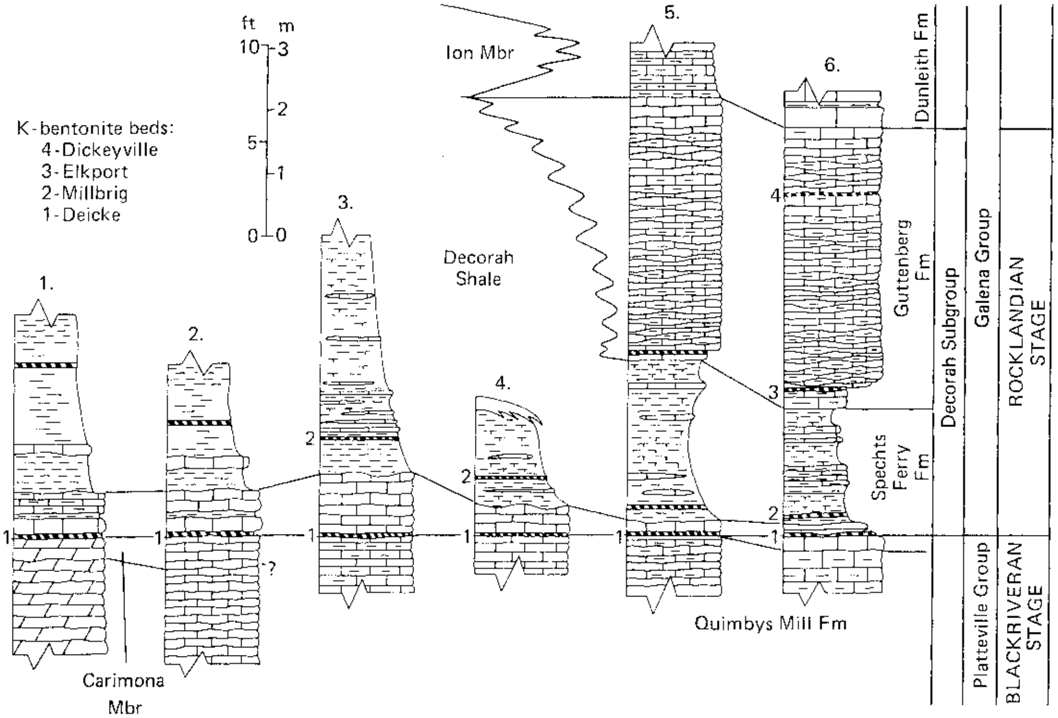

Figure 3. Correlation of the Decorah Subgroup from St. Paul, Minnesota, to Dickeyville, Wisconsin. No horizontal scale.

Guttenberg Formation: The Guttenberg consists of very fine-grained to lithographic, very fossiliferous, limestone or dolomite in wavy beds 5 to 10 centimeters thick that are separated by thin beds of very dusky red (10 R 2/2) shale that may be as much as 2 centimeters thick but mostly less than 0.5 centimeters. The formation is a distinct unit through a large part of the Mississippi Valley from near Foley, Missouri, to McGregor, Iowa. North of the McGregor area, it grades to greenish gray (5 G 6/1) shale and is not a useful rock-stratigraphic unit. The Guttenberg has been identified in the subsurface as far east as Chicago (Buschbach, 1964).

The formation is separated into two members (Templeton and Willman, 1963; Willman and Kolata, 1978)--the lower Garnavillo and the upper and major part of the formation, the Glenhaven. The Garnavillo generally is 45 centimeters thick and has thicker (up to 25 cm), more even layers than the overlying Glenhaven. The Glenhaven forms the bulk of the formation in all areas. Where the Garnavillo is absent, the Guttenberg consists solely of the Glenhaven. The Glenhaven contains two K-bentonite beds, the Elkport at the base and the Dickeyville in the upper part (corresponding to I-3 and I-4 of Mossler and Hayes, 1966). The type section for the Elkport is in the Guttenberg North Section; that of the Dickeyville is in the Dickeyville Northwest Section (Willman and Kolata, 1978, p. 57). Both K-bentonites range from 1 to 4 centimeters thick.

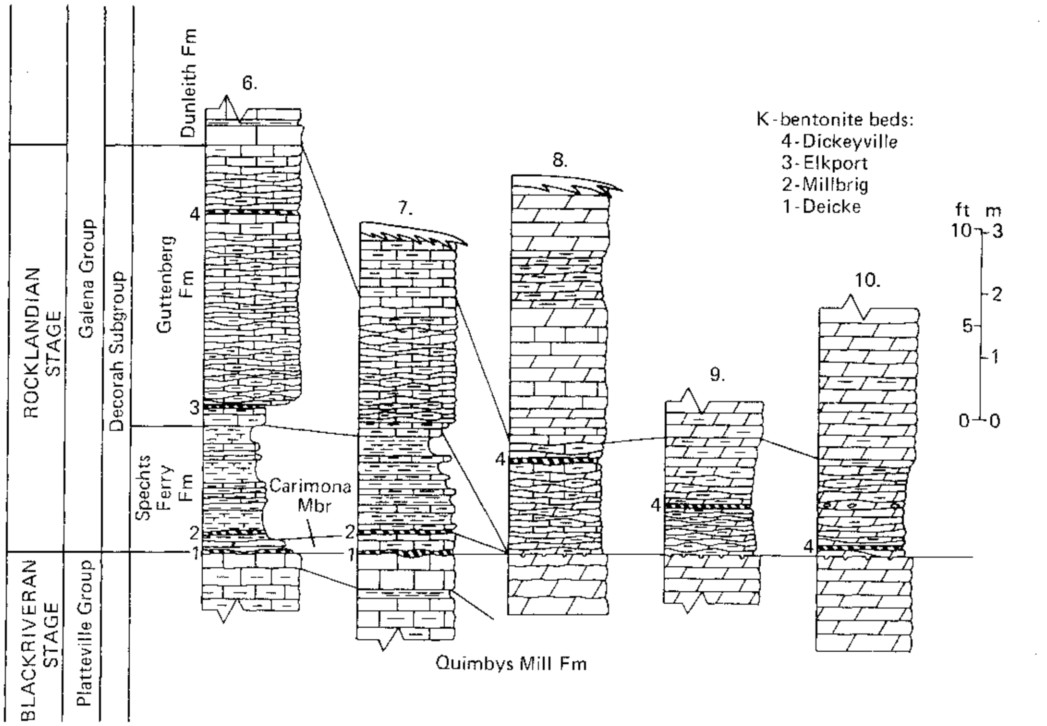

Figure 4. Correlation of the Decorah Subgroup from Dickeyville, Wisconsin, to Polo, Illinois, showing the overlap of Decorah strata on the Quimbys Mill Formation from west to east. No horizontal scale.

METHODS

In the Ordovician rocks of the Mississippi Valley, the largest concentration of K-bentonites occur in the Galena Group. Eleven beds were noted by Willman and Kolata (1978) below the Dubuque Formation and four K-bentonites have been observed by Levorson et al. (1979) within the Dubuque in Minnesota. Of these 15 K-bentonites, the Deicke, Millbrig, Elkport, and Dickeyville of the Decorah Subgroup were chosen for chemical analyses because they are relatively thick, widespread, and persistent in the Mississippi Valley. In addition, they are easily identified because of the distinct lithologies of the formations containing them. The Deicke and Millbrig are particularly useful because they are exposed at numerous localities throughout the outcrop areas. Because these K-bentonites occur near the Blackriveran-Rocklandian boundary, which is easily recognized throughout much of eastern North America, there is an added advantage, potentially the same K-bentonites can be recognized in other areas.

The four Decorah K-bentonites were sampled at selected localities in a limited area of southwestern Wisconsin, northeastern Iowa, and southeastern Minnesota (Fig. 5). Within this area stratigraphic control of the K-bentonites is considered to be very good. Samples were collected from 14 different localities including 11 from the Deicke, 11 from the Millbrig, 2 from the Elkport, and 1 from the Dickeyville. These constitute a reference suite for an initial test of chemical variability. They were analyzed by instrumental neutron activation analysis and wavelength dispersive X-ray fluorescence spectroscopy for Na, K, Sc, Ti, Cr, Mn, Fe, Co, Zn, Ga, As, Rb, Zr, Sb, Cs, La, Ce, Sm, Eu, Tb, Dy, Yb, Lu, Hf, Ta, and Th. The data were statistically evaluated to determine whether each K-bentonite bed has a distinct, consistent chemical signature. A one-way analysis of variance was used to assess within-bed and between-bed variations. Each element was evaluated independently for the probability, at the 95% confidence level, that differences between beds are greater than differences within beds. The elements most likely to serve as good discriminators were selected on this basis. Next, step-wise discriminant analysis was used to establish the ability of all elements together to distinguish between beds.

RESULTS AND DISCUSSIONS

Table 1 summarizes the results of discriminant analysis, listing the functions calculated and their associated eigenvalues and canonical correlation coefficients. The first function accounts for most of the variance in composition between the four beds and the second and third account for the remaining portion. These functions serve as the basis for matching unknown samples with one of the four Decorah K-bentonites. The associated eigenvalues are a measure of the relative importance of each function, and the canonical correlation coefficients express the strength of the association between the individual functions and the group variables. Clearly, the first two functions account for most of the variance among the groups and thus constitute a powerful tool for classification. The analyses show that (1) each of the four K-bentonite beds has a distinct chemical fingerprint and (2) each sample tested can be classified, with 100% confidence, as belonging to one of the four beds. The most powerful discriminators are, in decreasing order, Co, Dy, Na, Sm, As and Cr. These six elements account for most of the variance, and discrimination of the four K-bentonite beds is good using these elements alone.

Table 2 lists mean abundances for these six elements. It should be noted that although the abundance of certain elements in Table 2 do not appear to be significantly different between K-bentonite beds, the discrimination is based on statistical analyses of all elements combined.

Following the successful fingerprinting of the first group of samples, a second group of 24 samples from the same four K-bentonite beds collected over a long distance of the Mississippi Valley (Fig. 5) was then analyzed. The chemical signature for each of these 24 samples clearly matched one of the four reference beds. The stratigraphic position of each sample, as observed in the field, was consistent with its identification by chemical fingerprinting.

Correlations of Decorah K-bentonites at a few localities in the Mississippi Valley are shown in Figures 2 to 4. Those K-bentonites that have been collected, analyzed, and correlated are marked by numbers 1 through 4, corresponding to the Deicke, Millbrig, Elkport, and Dickeyville K-bentonite Beds, respectively. The Dickeyville Northwest Section (locality 6) was chosen as the main reference section because it is the only known locality in the Mississippi Valley where all four K-bentonite beds occur together. Generally, one to three beds occur at a given locality.

Table 1

Canonical discriminant functions

Function	Eigenvalue	Percent of variance	Cumulative percent	Canonical correlation
1	74.08470	91.34	91.34	0.9933185
2	5.16783	6.37	97.71	0.9153516
3	1.85367	2.29	100.00	0.8059618

Table 2

Mean abundances for the six best discriminators in the four Decorah K-bentonites

Bed	Co (ppm)	Dy (ppm)	Na (%)	Sm (ppm)	As (ppm)	Cr (ppm)
Deicke	2.05	2.21	0.02	1.85	7.09	11.78
Millbrig	3.35	1.38	0.03	1.12	5.24	5.93
Elkport	16.50	4.35	0.08	1.70	13.00	12.50
Dickeyville	0.60	3.60	0.03	1.40	9.90	2.00

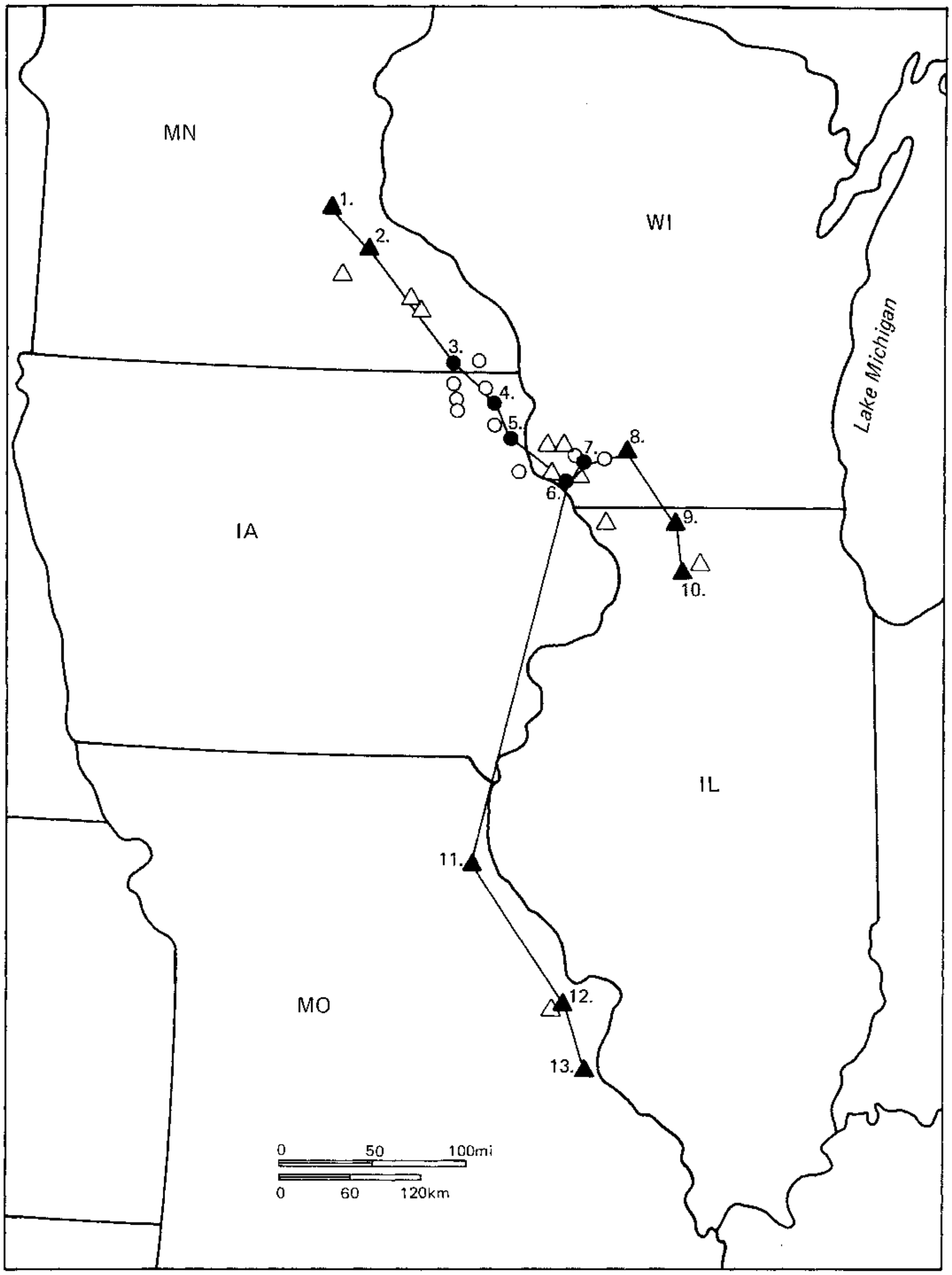

Figure 5. Localities in the Mississippi Valley where K-bentonites were collected from the Decorah Subgroup. Circles are the localities of K-bentonites used in the initial test. Triangles represent localities containing K-bentonites analyzed in the second group. Lines drawn between numbered localities (darkened circles and triangles) correspond to stratigraphic sections in Figures 2-4.

Deicke K-bentonite Bed

The Deicke K-bentonite has a consistent and diagnostic trace-element composition that can be recognized from St. Paul, Minnesota, to at least as far south as Barnhart, Missouri, a distance of about 800 kilometers. Chemical analyses of samples collected in this area, including the Deicke type section in St. Louis County, Missouri, confirm the correlation proposed by Willman and Kolata (1978) based primarily on stratigraphic position.

The Deicke rests on the Quimbys Mill Formation at the Dickeyville and Annaton Sections (Fig. 4; localities 6 and 7) but pinches out east of the Grant-Lafayette County line in Wisconsin and corresponding parts of northern Illinois. It is locally absent in the Mississippi River bluffs from Guttenberg to Dubuque, Iowa. North and west of Grant County, the Quimbys Mill pinches out and the Deicke rests on the Grand Detour Formation (McGregor Limestone).

Chemical analyses of samples from St. Paul, Sogn, and Mabel, Minnesota, indicate that the Deicke occurs within the Carimona Limestone (Fig. 3; localities 1, 2, and 3). This is not in agreement with Templeton and Willman (1963, p. 107), who thought that the K-bentonite in the Carimona was the Millbrig K-bentonite ("Spechts Ferry bentonite") and that the Deicke was absent. Actually, both the Deicke and Millbrig are widespread in the Decorah of Minnesota as shown by Bell (1954) and Weiss and Bell (1956, p. 63). Furthermore, Templeton and Willman (1963, p. 107) judged that the "Castlewood Limestone Member is equivalent to only the basal unit of the Carimona Limestone in the type area [southern Minnesota], but where the upper unit is absent, which is common south of Decorah, Iowa, the Carimona is equivalent to the Castlewood." As correlated in this paper, all Carimona strata below the Deicke are older than the Castlewood, whereas the upper part of the Carimona is approximately equivalent in age to the Castlewood.

The Deicke is consistently present in outcrops of eastern Missouri and western Illinois where it typically forms a prominent reentrant between the limestones of the Platteville Group and the Castlewood Member of the Spechts Ferry Formation. It is at least 3 to 5 centimeters thicker in Missouri than in the northern outcrop area. The interval of strata between the Deicke and the overlying Millbrig K-bentonite Bed (primarily Castlewood limestone) thickens southward from about 2 meters at New London to nearly 3 meters at Barnhart (Fig. 2), which corresponds to the Decorah and Platteville strata thickening toward their depocenters in southernmost Illinois.

Millbrig K-bentonite Bed

Like the Deicke, the Millbrig has a diagnostic trace element composition that is consistent in both the southern and northern outcrop areas. Only a limited number of samples have been collected and analyzed at this time so the geographic extent of the Millbrig, has not yet been determined using trace element chemistry.

At the Dickeyville Section (locality 6), the Millbrig is 4 centimeters thick and separated from the Deicke by 25 centimeters of greenish gray shale and argillaceous limestone. At Annaton (locality 7) the two K-bentonites are separated by 25 centimeters of Carimona Limestone. The Millbrig has been chemically identified as far east as Mineral Point, Wisconsin, thus it extends about 25 kilometers beyond the eastern limit of the Deicke. A K-bentonite in the same stratigraphic position as the Millbrig has been identified by Mossler and Hayes (1966) at McGregor, Clayton County, Iowa; but it was unavailable for our study. At Hanover, Iowa, and Mabel, Minnesota, the Millbrig occurs 0.8 and 1.5 meters, respectively, above the Deicke. No Millbrig samples were obtained north of Mabel, but a K-bentonite thought to be the Millbrig has been traced as far north as St. Paul (Bell, 1954; Weiss and Bell, 1956). The northwest divergence of the Deicke and Millbrig, from southwestern Wisconsin to St.Paul, Minnesota, is caused in part by an increase in shaly strata within the interval, perhaps reflecting nearness to the probable source area, the Transcontinental Arch.

In the southern outcrop area, the Millbrig is 2 to 6 centimeters thicker than in the north, and it lies either on the Castlewood Limestone or 0.35 meters or more above it (Fig. 2). The Millbrig is very persistent in the Missouri outcrops from New London southward, at least as far as Barnhart. It and the Deicke are particularly well exposed in I-55 roadcuts between mile markers 181 and 184.

Elkport K-bentonite Bed

The Elkport is not as thick or persistent as other K-bentonites in the Decorah. Occurrences supported by chemical fingerprinting are restricted to the northern outcrops. At the Dickeyville Northwest Section (locality 6), the Elkport is about 1 centimeter thick and situated 2.3 meters above the Millbrig K-bentonite. The only other confirmed locality for the Elkport is at the Guttenberg North Section (Templeton and Willman, 1963, p. 236) where it is up to 3 centimeters thick and 2.4 meters above the Millbrig.

Other probable occurrences are near McGregor, Bluffton, and Decorah, Iowa (Mossler and Hayes, 1966), and near Galena, Illinois (Willman and Kolata, 1978, p. 59). At several localities in Missouri, Templeton and Willman (1963, p. 104) noted the occurrence of a K-bentonite situated 2 to 3 meters above the Millbrig. Chemical data are not yet available to confirm whether it is the Elkport.

Dickeyville K-bentonite Bed

The Dickeyville K-bentonite is known only from a few localities in northern Illinois and southern Wisconsin. At the Dickeyville Northwest Section, it is 3 centimeters thick and lies 3 meters above the Quimbys Mill Formation (Fig. 4). East of the Dickeyville Section, the Spechts Ferry Formation pinches out and the Guttenberg Formation gradually decreases in thickness from the base up. At the Dodgeville Section (locality 8) the K-bentonite is 1.5 meters above the Quimbys Mill. Farther southeast at Rock City and Polo, Illinois (localities 9 and 10), this interval decreases to 0.8 and 0.09 meters, respectively. Near Rochelle, Illinois, all of the Decorah Subgroup is absent, and the Dunleith Formation rests on the Quimbys Mill.

The gradual decrease in the interval between the Dickeyville K-bentonite and the Quimbys Mill clearly shows the onlapping nature of Decorah strata from west to east. Thinning of the Decorah in south-central Wisconsin and north-central Illinois appears to be the result of uplift on the Wisconsin Arch during Rocklandian time.

SUMMARY AND CONCLUSIONS

1. The Galena Group of the Mississippi Valley area contains at least 15 different altered volcanic ash beds (potassium bentonites or K-bentonites). Four are contained in the Decorah Subgroup and are named in ascending order, the Deicke, Millbrig, Elkport, and Dickeyville K-bentonite Beds. Mineralogically, these K-bentonites are nearly identical; they are dominated by mixed layer illite/smectite clay. Generally they can be recognized in the field by the distinctive lithologies of the formations containing them.

2. Chemical fingerprinting is an effective method for identifying the Decorah K-bentonites. Chemical (instrumental neutron activation and X-ray fluorescence) and statistical (step-wise discriminant analysis) analyses indicate that all four K-bentonite beds can be distinguished at the 100.00 percent confidence level based on a priority ordering of elements. Chemical characterization of each K-bentonite can be made at an acceptable level of confidence on the relative quantities of just a few elements including Co, Dy, Na, Sm, As and Cr. The fingerprinting technique should be useful for identifying other K-bentonites in the Galena Group.

3. Because of their regional extent and distinctive trace element content, the Decorah K-bentonites provide valuable time-stratigraphic marker beds that should facilitiate correlation studies of the Decorah Subgroup and equivalent strata.

ACKNOWLEDGMENTS

We thank H. D. Glass and R. E. Hughes of the Illinois State Geological Survey for analyzing the clay minerals by X-ray diffraction.

LOCALITY REGISTER (For outcrops in Figs. 2-5)

1. St. Paul, MN - Outcrops along bluffs of Mississippi River at west end of Summit Avenue in St. Paul, Ramsey Co., (SE SE NW 5-28N-23W; St. Paul West 7.5' Quad.)

2. Sogn, MN - Roadcut at intersection of county roads 14 and 44 approximately 8 kilometers south of Sogn, Goodhue Co., (SW 1-110N-8W; Kenyon 7.5' Quad.).

3. Mabel, MN - Quarry on north side of county road 0.4 kilometers west of Minnesota State Route 43 and 2 kilometers north of Mabel, Fillmore Co. (SE SW SE 15-101N-8W; Mabel 7.5' Quad.).

4. Hanover, IA - Quarry on east side of county road, 2 kilometer east of Hanover, Allamakee Co., (NW NW SE 25-99N-6W; Waukon 7.5' Quad.).

5. McGregor, IA - Quarry on east side of State Route 340, 1.2 kilometers south of intersection of Highways 340 and 18 in McGregor, Clayton Co., (SW SW SE 27-95N-3W; Prairie du Chien 15' Quad.).

6. Dickeyville, WI - Quarry and roadcuts along U.S. Highway 61, 6.4 kilometers northwest of Dickeyville, Grant Co., (NE NE SW 7 and S 1/2 NW 7-2N-2W; Potosi 7.5' Quad.). Mossler and Hayes (1966) locality 13; Willman and Kolata (1978) locality 1.

7. Annaton, WI - Quarry on west side of county road 6 kilometers south of Annaton, Grant Co., (SE SW SE 25-5N-2W; Ellenboro 7.5' Quad.).

8. Dodgeville, WI - Roadcut on north side of new U.S. Highway 18-151, 5 kilometers east of intersection of new U.S. highways 18-151 and Wisconsin Highway 23 in Dodgeville, Iowa Co., (NE NW SW 19-6N-4E; Jonesdale 7.5' Quad.).

9. Rock City, IL - Quarry 0.4 kilometers south of State Route 75, 0.8 kilometers east of Rock City, Stephenson Co., (SE SW NW 22-28N-9E; Pecatonica 15' Quad.). Willman and Kolata (1978) locality 26.

10. Polo, IL - Quarry along the Burlington Northern Railroad 1.6 kilometer west of Polo, Ogle Co., (SE NE NE 18-23N-8E; Sterling 15' Quad.). Willman and Kolata (1978) locality 45.

11. New London, MO - Roadcut on U.S. Route 61, 6.4 kilometers southeast of New London, Ralls Co., (SE NE SE 21-55N-4W; Hannibal 15' Quad.).

12. Mincke Hollow, MO - Exposure in south bluff of Meramec River along the St. Louis-San Francisco Railroad, 0.4 kilometers southwest of Tyson, St. Louis Co., (E1/2 SE SE 21-44N-4E; Manchester 7.5' Quad.).

13. Barnhart, MO - Roadcut on Interstate 55 (mile marker 183.1) 3.2 kilometers south of I-55 bridge over Glaize Creek in Barnhart, Jefferson Co., (N1/2 SW NW 6-41N-6E; Herculaneum 7.5' Quad.).

REFERENCES

Bell, W. C., 1954, Upper Mississippi Valley Middle Ordovician bentonites (abstr.): Geological Society of American Bulletin, v. 65, p. 1230-1231.

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

DeMott, L. L., 1963, Middle Ordovician trilobites of the Upper Mississippi Valley: Ph.D. dissertation, Harvard University, Cambridge, Massachusetts, 236 p.

Günal, A., 1979, Clay mineralogy, petrology, chemical composition and stratigraphic correlation of some Middle Ordovician K-bentonites in the eastern midcontinent: Ph.D. dissertation, University of Cincinnati, 237 p.

Günal, A.; and Huff, W. D., 1978, Elemental variation of Ordovician K-bentonites: 6th International Clay Conference Abstract Vol., Oxford, p. 312.

Herbert, Paul, Jr., 1949, Stratigraphy of the Decorah Formation in western Illinois: Ph.D. dissertation, University of Chicago: Illinois Geological Survey unpublished manuscript PH-1.

Huff, W. D., 1981, Use of chemical fingerprinting in the stratigraphic correlation of Ordovician K-bentonites (abstr.): Geological Society of America Abstracts with Programs 13, p. 477.

Huff, W. D., (in press), Correlation of Middle Ordovician K-bentonites based on chemical fingerprinting: Journal of Geology.

Huff, W. D.; Kolata, D. R.; and Frost, J. K., 1983, Correlation of Middle Ordovician K-bentonites in the Mississippi Valley region by chemical fingerprinting (abstr.): Geological Society of America, North-Central Section, Abstracts with Programs, v. 15, p. 256.

Kay, Marshall, 1929, Stratigraphy of the Decorah Formation, Journal of Geology, v. 37, p. 639-671.

Kay, Marshall, 1935, Ordovician System in the Upper Mississippi Valley: in Kansas Geological Society; 9th Annual Field Conference Guidebook, p. 281-295.

Levorson, C. O.; Gerk, A. L.; and Broadhead, T. W., 1979, Stratigraphy of the Dubuque Formation (Upper Ordovician) in Iowa: Iowa Academy of Science Proceedings, v. 86, no. 2, p. 57-65.

Mossler, J. H.; and Hayes, J. B., 1966, Ordovician potassium bentonites of Iowa: Journal of Sedimentary Petrology, v. 36, p. 414-427.

Perry, T. G., 1962, Spechts Ferry (Middle Ordovician) bryozoan fauna from Illinois, Wisconsin, and Iowa: Illinois State Geological Survey Circular 326, 36 p.

Reynolds, R. C.; and Hower, John, 1970, The nature of interlayering in mixed-layer illite-montmorillonites: Clays and Clay Minerals, v. 18, p. 25-36.

Ross, R. J., Jr.; and others, 1982, The Ordovician System in the United States: International Union of Geological Sciences Publication 12, 73 p.

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

Weaver, C. E., 1953, Mineralogy and petrology of some Ordovician K-bentonites and related limestones: Geological Society of America Bulletin, v. 64, p. 921-943.

Weiss, M. P., 1954, Feldspathized shales from Minnesota: Journal of Sedimentary Petrology, v. 24, p. 270-274.

Weiss, M. P., 1955, Some Ordovician brachiopods from Minnesota and their stratigraphic relations: Journal of Paleontology, v. 29, p. 759-774.

Weiss, M. P.; and Bell, W. C., 1956, Middle Ordovician rocks of Minnesota and their lateral relations: in Geological Society of America, Guidebook Field Trip No. 2, Minneapolis Meeting, 1956, p. 55-73.

Willman, H. B.; and Kolata, D. R., 1978, The Platteville and Galena Groups in Northern Illinois: Illinois State Geological Survey Circular 502, 75 p.

Witzke, B. J., 1980, Middle and Upper Ordovician paleogeography of the region bordering the Transcontinental Arch: in Fouch, T. D.; and Magathan, E. R. (eds.), Paleozoic Paleogeography of the West-Central United States; Rocky Mountain Paleogeography Symposium 1: Rocky Mountain Section of the Society of Economic Paleontologists and Mineralogists, P. 1-18.

Delgado, D. J., ed. (1983), Ordovician Galena
Group of the Upper Mississippi Valley --
Deposition, diagenesis, and paleoecology:
Guidebook for the 13th Annual Field Conference,
September 30 - October 2, 1983, p. G1 - G15.

XENOTOPIC DOLOMITE TEXTURE--IMPLICATIONS FOR DOLOMITE NEOMORPHISM AND LATE DIAGENETIC DOLOMITIZATION IN THE GALENA GROUP (ORDOVICIAN), WISCONSIN AND IOWA

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ABSTRACT

Xenotopic dolomite texture is observed in the Galena Group (Ordovician), Wisconsin and Iowa, in scattered patches from a few centimeters to meters in size replacing limestone biomicrites and idiotopic dolomites. Xenotopic dolomite texture is characterized by anhedral crystals with curved, lobate, serrated or otherwise irregular intercrystalline boundaries and undulatory extinction. This contrasts with idiotopic dolomite texture which has mostly euhedral to subhedral crystals with straight, smooth compromise boundaries.

Crystal growth theory predicts that crystal morphology is a function of temperature. We hypothesize that xenotopic dolomite in the Galena Group was produced by both late diagenetic replacement of limestone and by neomorphic recrystallization of a pre-existing dolomite. This hypothesis is supported by petrography, stable isotopes and some fluid inclusion data as well as implication of crystal growth theory. Petrographic recognition of xenotopic dolomite provides a quick and easy way to recognize a dolomite produced during late diagenesis at elevated temperature.

INTRODUCTION

The discussion presented here is part of a much larger study investigating the effects of temperature on carbonate textures, neomorphism in dolomites and xenotopic dolomite texture (Gregg and Sibley, 1982; Gregg, 1982; and Gregg and Sibley, in press). We will try to demonstrate the importance of textural criteria in postulating late diagenetic dolomitization and neomorphism of a pre-existing dolomite using the Galena Group (Ordovician) dolomites of Wisconsin and Iowa as an example.

The Galena Group limestones are mudstones, wackestones and a few packstones and grainstones deposited on a stable, uniform, low energy sea bottom; in most cases below wave base (Delgado, 1979; Delgado, this volume). A dorag or mixing zone model for dolomitization was postulated by Badiozamani (1972, 1973). This mixing zone was to have existed during the uplift of the Wisconsin arch. The dolomite is localized along the crest of the arch, becoming limestone toward the flanks (Badiozamani, 1972).

After initial, early diagenetic dolomitization, the Galena Group was subjected to low-temperature hydrothermal events resulting in the emplacement of sulfide ores of the Upper Mississippi Valley zinc-lead district (Fig. 1) (Heyl et al., 1959; Heyl and West, 1982). The temperatures of these events, estimated from fluid inclusions, ranged from 80°C to 120°C (Bailey and Cameron, 1951) or to as high as 227°C (McLimans, 1977). Hall and Friedman (1969) corroborate these temperatures with stable oxygen isotope ratios ($\delta^{18}O = -10.6$ per mil. PDB) for dolomite associated with ores.

CLASSIFICATION OF DOLOMITE TEXTURES

The textural classification system used in this study (Fig. 2) uses some of the terminology of Friedman (1965). Unlike Friedman's classification it was designed to distinguish between dolomites with smooth, straight compromise intercrystalline boundaries and those with curved or irregular boundaries. This distinction has considerable genetic importance.

A dolomite is 1) idiotopic if crystals have straight compromise boundaries and/or tend to be euhedral; or 2) xenotopic if crystals have irregular intercrystalline boundaries. Subcategories added to the two main categories accommodate variations caused by porosity, matrix and dolomite cements. This dolomite textural classification system is discussed in detail in Gregg (1982) and Gregg and Sibley (in press).

THEORETICAL EFFECTS OF TEMPERATURE ON DOLOMITE TEXTURE

A statistical mechanical model for crystal growth proposed by Jackson (1958) explains the occurrence of interlocking anhedral crystal mosaics, such as xenotopic dolomite, and relates them to temperature. The model predicts that crystal growth at low temperature proceeds by the addition of atoms, layer by layer, on a crystal surface. This kind of growth requires surface nucleation sites, such as dislocations. It results in the development of smooth crystal facets and euhedral to subhedral crystal mosaics. Above a "critical roughening temperature" (CRT), surface nucleation does not require dislocations and atoms are added randomly to the crystal surface. The surface becomes rough, grows rapidly and crystal facets do not form. This kind of growth can produce a mosaic of interlocking anhedral crystals such as are observed in metal castings and xenotopic dolomite. Jackson's (1958) model has been supported by subsequent theoretical and experimental work (Brice, 1973; Lewis, 1975) and has been used to explain crystal morphologies

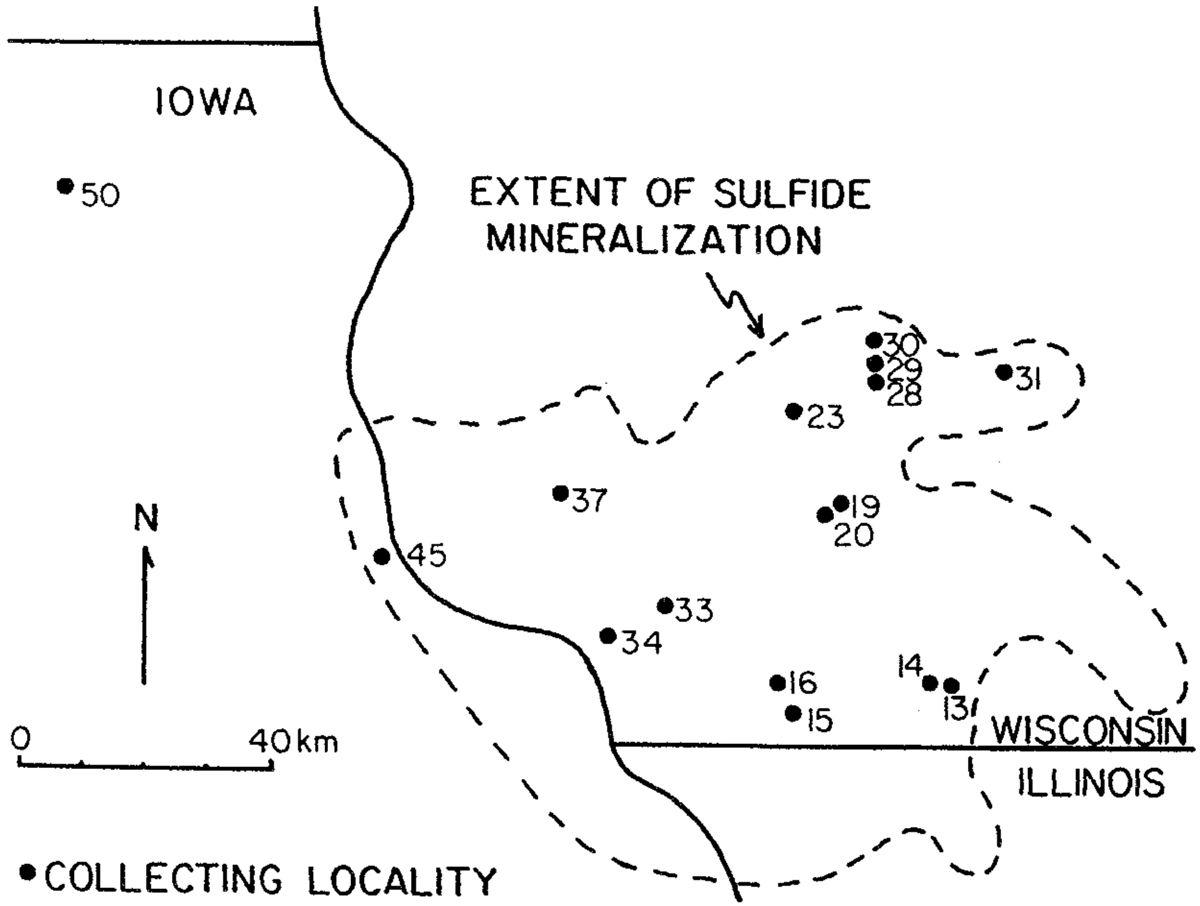
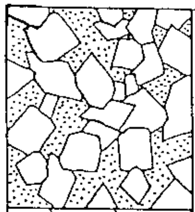
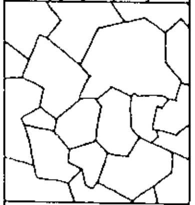
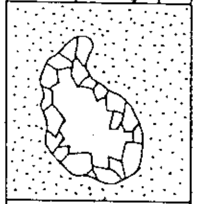
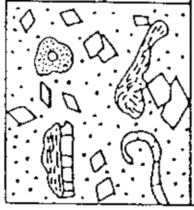


Fig. 1.- Upper Mississippi Valley zinc-lead district showing collecting localities within the Galena Group.

Idiotopic Dolomite- Rhombic shaped euhedral to subhedral crystals.

	Idiotopic-E (Euhedral), almost all dolomite crystals are euhedral rhombs; grain supported with intercrystalline area filled by another mineral or comprised of porosity (as in sucrose texture).
	Idiotopic-S (Subhedral), subhedral to anhedral dolomite crystals with low porosity and/or low intercrystalline matrix; straight compromise boundaries are common and many of the crystals have preserved crystal face junctions.
	Idiotopic-C (Cement), euhedral dolomite crystals lining large pores and vugs or surrounding patches of another mineral such as gypsum or calcite.
	Idiotopic-P (Porphyrotopic), euhedral dolomite crystals floating in a limestone matrix. Matrix supported rather than grain supported.

Xenotopic Dolomite- Non-rhombic, usually anhedral crystals.

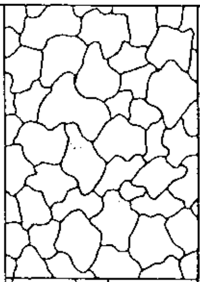
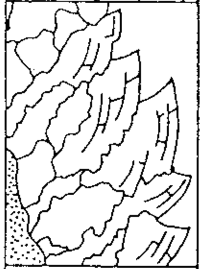
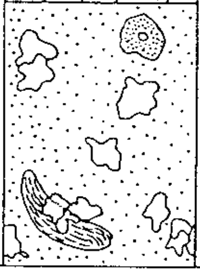
	Xenotopic-A (Anhedral), tightly packed anhedral dolomite crystals with mostly curved, lobate, serrated, indistinct or otherwise irregular intercrystalline boundaries. Preserved crystal face junctions are rare and crystals often have undulatory extinction in cross polarized light.
	Xenotopic-C (Cement), pore lining saddle shaped or baroque dolomite crystals characterized by scimitar-like terminations, when observed in thin section, and sweeping extinction in cross polarized light.
	Xenotopic-P (Porphyrotopic), single anhedral dolomite crystals or patches of anhedral dolomite crystals floating in a limestone matrix. The dolomite crystals usually have undulatory extinction in cross polarized light.

Fig. 2.— Dolomite textural classification system; the term "crystal face junction refers to the angle made by the joining of two crystal faces when preserved in a compromise boundary.

in igneous rocks (Kirkpatrick, 1981).

We hypothesize that a CRT exists for dolomite between 50°C and 100°C. Xenotopic dolomite textures are therefore produced by the replacement of limestone and/or neomorphism of dolomite at elevated temperature after burial. Idiotopic dolomites are generally produced below the CRT by near surface dolomitization processes. Idiotopic dolomite is sometimes produced above the CRT when crystal facets are stabilized adjacent to porosity due to differences in crystal growth mechanics when growing into a bulk solution, or by inhibiting effects of impurities such as organic material and clay minerals (Gregg, 1982, p. 94-96). Xenotopic dolomite cannot be produced below CRT so its occurrence in dolomite indicates dolomitization or neomorphism at temperatures above 50°C. Full discussion of the implications of crystal growth theory to carbonate textures are presented in Gregg (1982) and Gregg and Sibley (in press).

METHODS

Samples collected from the Galena Group (130 samples from 16 localities shown on Figure 1) were made into standard petrographic thin and polished sections and examined using conventional petrography, cathodoluminescence petrography and heating stage for two-phase fluid inclusion studies. Samples were also examined using scanning electron microscope (SEM) equipped with a backscattered electron detector. Analyses were made for stable oxygen and carbon isotopes. Samples analyzed for stable isotopes were also examined using x-ray diffraction to make sure dolomite was the only carbonate present.

RESULTS

Petrology

Where the Galena Group is primarily limestone in southwestern Wisconsin and eastern Iowa (localities 37, 45 and 50 on Fig. 1) it is characteristically biomicrite with some biosparites. The limestones contain chert nodules and a small amount (estimated to be less than 1%) of subrounded silt sized quartz. Occasionally silicified fossils can be found in dolomitized portions of the Galena Group (at, for instance, localities 28 and 30, Fig. 1) and vuggy porosity, interpreted to be fossil molds, is common throughout the dolomitized facies.

Idiotopic-E and P dolomite (crystal sizes from 0.01mm to 0.2mm) is found preferentially replacing micrite (Fig. 3), as burrow fillings and is sometimes associated with lithologic contacts at localities 37, 45 and 50 (Fig. 1). At other localities, composed of 100 percent dolomite, idiotopic-S and E dolomite was observed as a fine grained (0.05 to 0.22mm) to coarse grained (up to 0.5mm) fabric, replacing the precurser limestone (Fig. 4). Some of the coarse crystalline idiotopic-E dolomite has pronounced inclusion zoning. The coarse crystalline

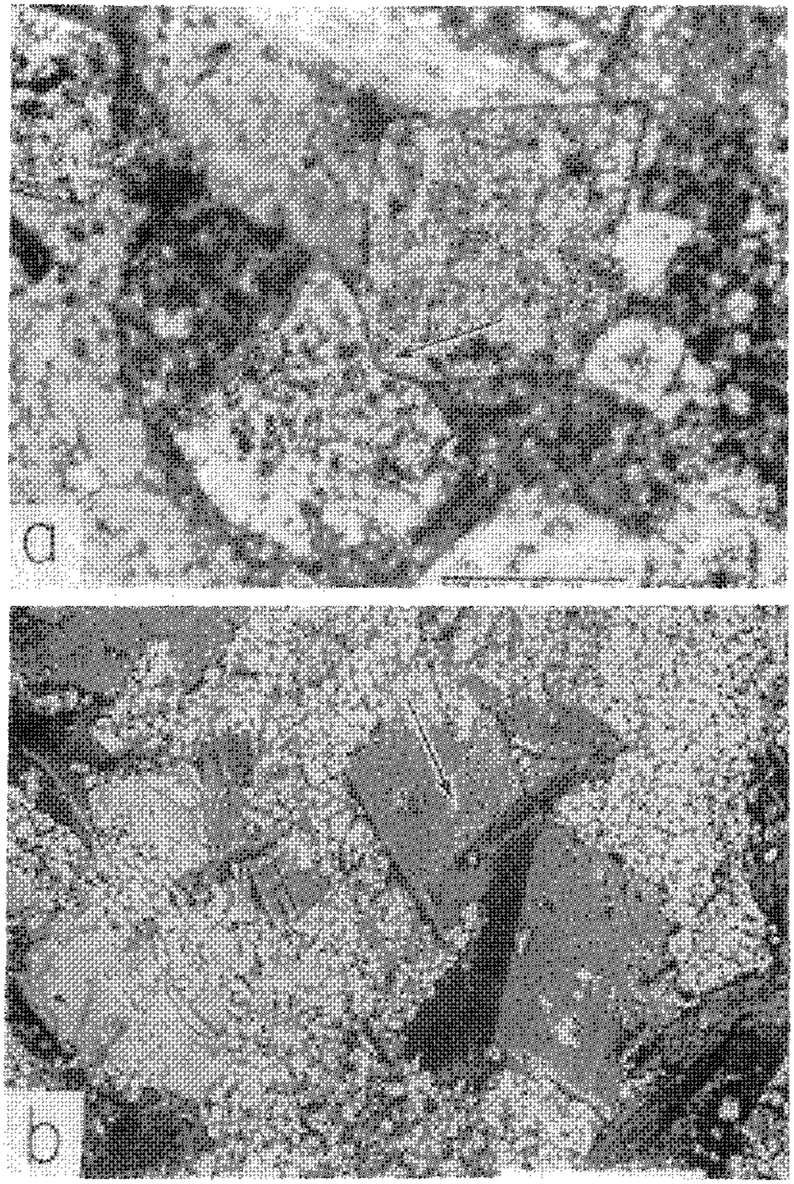


Fig. 3.— Idiotopic-P dolomite replacing limestone micrite (locality 45). a) Note the preservation of a crystal face junction (arrow) in the compromise boundary formed where the two crystals join. Plain polarized light, scale bar = 0.1 mm. b) Note the groove in the large crystal (arrow) created by the crystal face junction of an adjoining crystal which was removed when the sample was mounted. SEM backscattered electron image, scale bar = 0.1 mm.

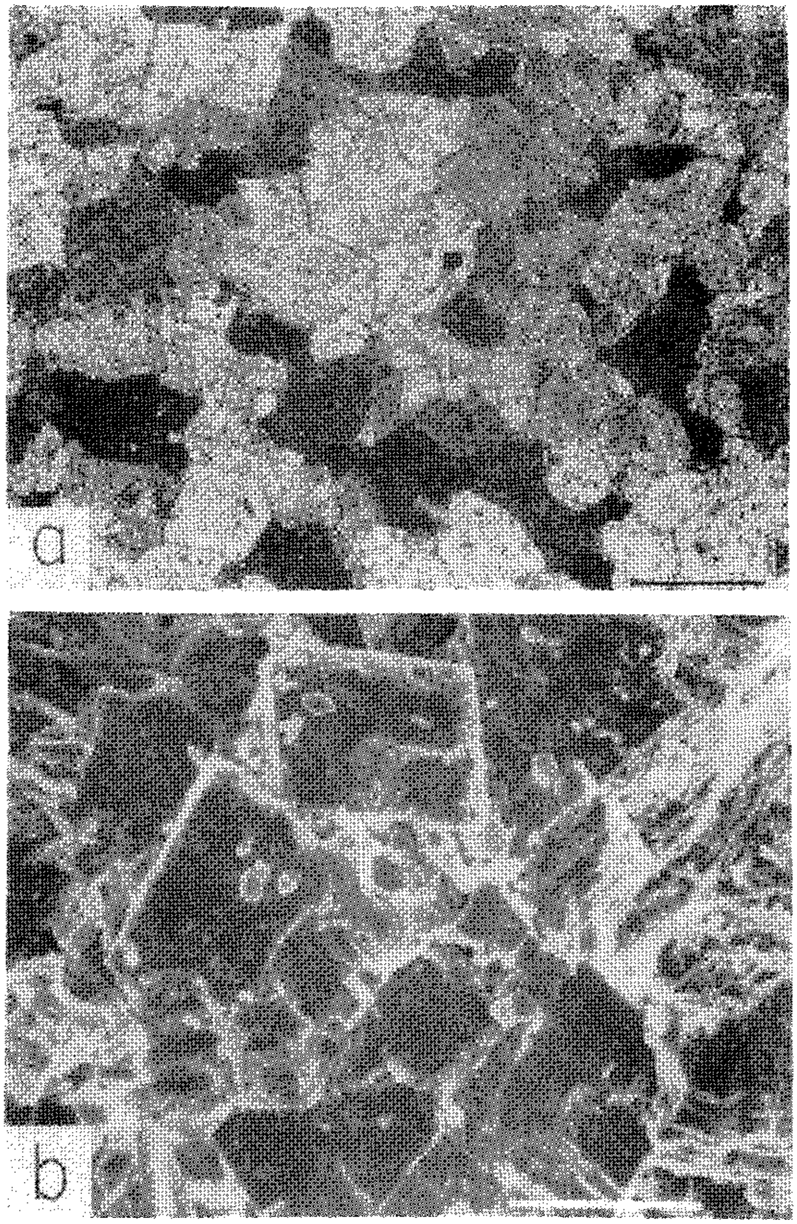


Fig. 4.— Idiotopic-S dolomite from locality 20. a) Note the straight intercrystalline boundaries and the large number of crystal face junctions. Partially crossed polars, scale bar = 0.05 mm. b) Note the rhombic shape of many of the crystals. SEM, scale bar = 0.05 mm.

idiotopic-E dolomite often has undulatory extinction and slightly curved crystal faces where adjacent to porosity (Fig. 5). This dolomite texture is usually found associated with xenotopic dolomite. In the more porous rocks, intercrystalline pore space is often filled with translucent brown to black opaque material which coats the surface of the crystals. This intergranular material is probably mostly amorphous organics, iron sulfide, sphalerite and clay minerals judging from its appearance in reflected light.

Areas of xenotopic-A dolomite in the Galena Group vary in size from scattered patches of one to several centimeters across mixed with idiotopic dolomite; to large portions of outcrops, several meters in width and height. No outcrops were sampled that are made up entirely of xenotopic dolomite; however, at localities 13, 15, 19, 29 and 31 (Fig. 1) it is the dominant textural type. At locality 45, just south of Guttenburg, Iowa, patches of xenotopic-P dolomite replace micrite along horizontal and vertical fractures (Fig. 6). This contrasts with patches and individual porphyrotopes of idiotopic dolomite found at the same outcrop (Fig. 3).

Xenotopic-A dolomites are characterized by curved, irregular intercrystalline boundaries and usually have undulatory extinction (Fig. 7a). The crystals range in size from 0.05 to 0.5mm, averaging about 0.2mm. Rarely, clear-rim cloudy-center zoning is observed in the anhedra. This kind of zoning is most often seen in the coarse grained idiotopic dolomites described above. Both idiotopic and xenotopic dolomites that were examined for this study have the same bright orange, non-zoned cathodoluminescent properties. SEM examination of xenotopic-A dolomite shows the very rough surface texture of the crystals, irregular intercrystalline boundaries and few rhombic shaped crystals (Figs. 6b and 7b). This contrasts with the smooth compromise boundaries and tendency toward a rhombic shape in the idiotopic dolomites (Figs. 3b and 4b).

Two phase fluid inclusions (liquid with vapor bubble) were observed in xenotopic-A dolomite from localities 16, 19 and 28. Most of these inclusions were very small (<5μm) and homogenization temperatures were unobtainable. The presence of a vapor bubble in a small fluid inclusion is consistent with a filling temperature of >60°C due to the difficulty of nucleating the bubble unless the inclusion is cooled considerably below the filling temperature (Roedder, 1981). Homogenization temperatures were obtained for four of the larger (between 5 and 10mm) inclusions in xenotopic-A dolomite from locality 28 (Fig. 1). These temperatures range between 60°C and 93°C. The temperatures were not pressure corrected. It is not known whether these inclusions are primary or secondary and what effects, if any, further diagenesis has had on them. Therefore they may not accurately represent filling temperatures. The fluid inclusion data are, however, consistent with the view that this dolomite texture formed at above 50°C.

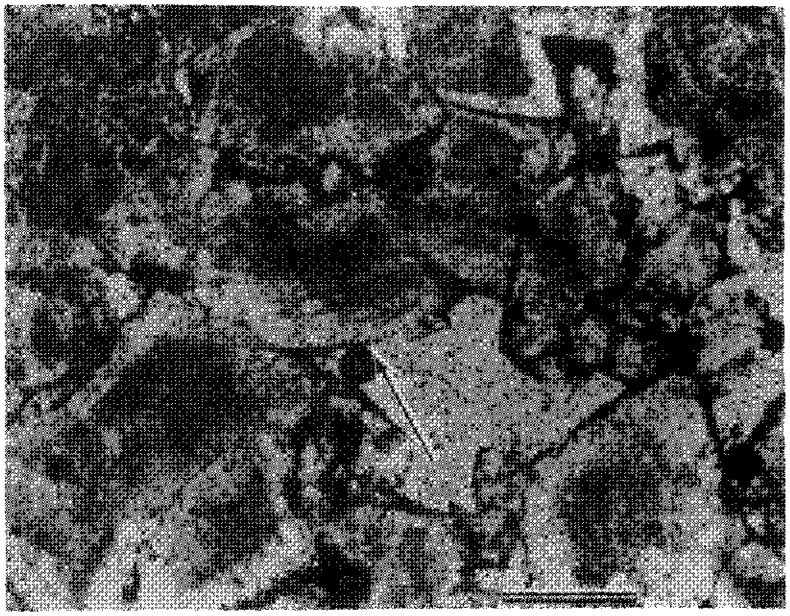


Fig. 5.— Idiotopic-E dolomite from locality 28. Some of the crystals have curved edges adjacent to porosity (arrow). Note the intercrystalline opaque material. Plain polarized light, scale bar = 0.1 mm.

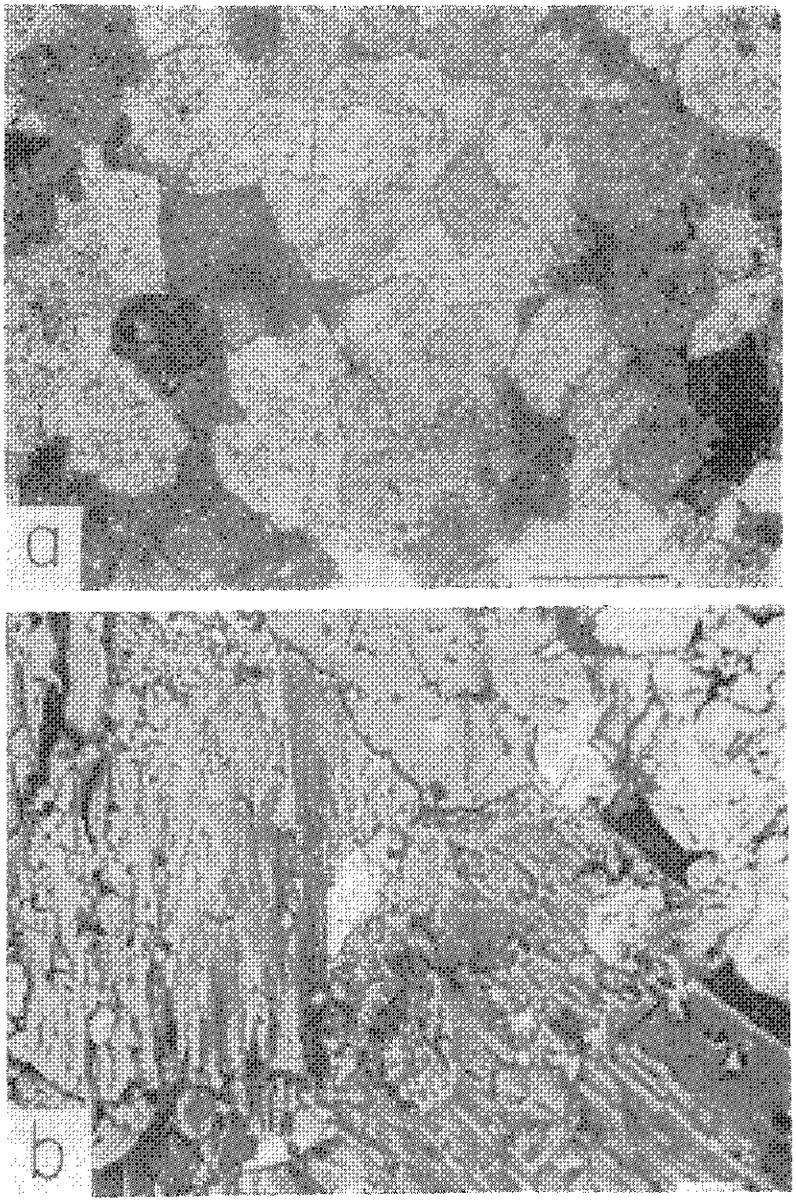


Fig. 6.— Xenotopic-A dolomite from locality 45. a) Replacing a micrite (not shown). The few rhombic shaped crystals may represent an earlier idiotopic dolomite which is also found at this outcrop (Fig. 3a). Partially crossed polars, scale bar = 0.1 mm. b) Xenotopic-P dolomite (dark) replacing calcite (light). Note the irregular intercrystalline boundaries as compared to the idiotopic-P dolomite collected a few feet away (Fig. 3b). SEM backscattered electron image, scale bar = 0.01 mm.

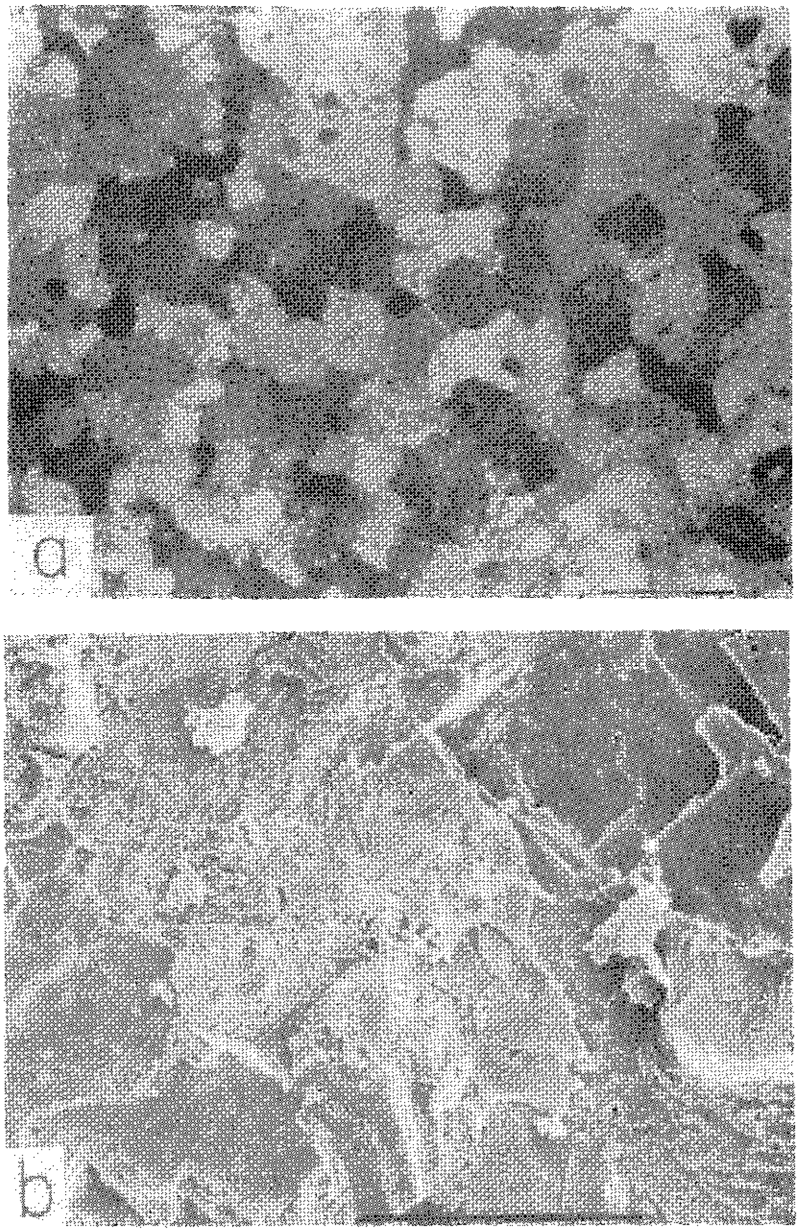


Fig. 7.— Xenotopic-A dolomite from locality 19. a) The dolomite is composed of mostly anhedral crystals with irregular intercrystalline boundaries. Partially crossed polars, scale bar = 0.5 mm. b) Note the irregular intercrystalline boundaries and anhedral crystals. SEM, scale bar = 0.1 mm.

Stable isotopes

Stable oxygen and carbon isotope values were obtained for 20 dolomite samples from the Galena Group. The dolomite samples were grouped into 11 pairs consisting of an idiotopic dolomite matched with a xenotopic dolomite. Some samples were used in more than one pair. The two samples in each pair were collected in close proximity. In all but two cases, pairs were collected from the same outcrop and, in two cases, from the same hand sample.

Oxygen isotope values ranged between $\delta^{18}O = -6.32$ and -2.90 per mil. (PDB) averaging -4.83 per mil. (PDB). In eight pairs, $\delta^{18}O$ values for the xenotopic dolomite were lower by an average of 1.09 per mil. In two pairs, a corase crystalline, porous idiotopic-E dolomite had a slightly lower $\delta^{18}O$ value than the xenotopic-A dolomite. One coarse crystalline idiotopic-S dolomite was found with a lower $\delta^{18}O$ value than its paired xenotopic-A dolomite.

The stable carbon isotope values ranged between $\delta^{13}C = -0.90$ and $+0.79$ per mil. (PDB) with a mean of -0.14 per mil. No relationships were observed between dolomite texture and stable carbon isotope values.

DISCUSSION AND CONCLUSION

Regional dolomitization of the Galena Group probably occurred at low temperature at shallow burial, probably during Ordovician time as suggested by Badiozamani (1972). We interpret most of the xenotopic dolomites in the Galena Group as having been produced by neomorphism of this precursor dolomite at elevated temperature, possibly during the epigenetic events associated with sulfide ore genesis in this area. This interpretation is consistent with the fluid inclusion data presented above and is supported by isotope as well as petrographic evidence.

Small differences in $\delta^{18}O$ were observed between idiotopic and xenotopic dolomite samples (averaging about 1 per mil.) with xenotopic dolomite having more negative values. This is consistent with a neomorphic origin of the xenotopic dolomite at elevated temperature if a closed or only partially open (rock-dominated) system is presumed (see Gregg, 1982; Gregg and Sibley, in press).

Idiotopic-E dolomite with undulatory extinction (Fig. 5) has some of the lowest $\delta^{18}O$ values. These are from areas of high porosity and are interpreted as having equilibriated in a system more open with respect to hot water. Sverjensky (1981) showed theoretically that $\delta^{18}O$ depletion of carbonates near ore bodies in the Upper Mississippi Valley could best be explained by increased porosity near the ore bodies rather than by a temperature gradient.

Much of the xenotopic-A dolomite in the Galena Group is patchy in distribution and mixed with idiotopic-S dolomite. The idiotopic dolomite in many cases probably represents the precursor low temperature texture which was later recrystallized (compare Figure 4 with Figure 7). A patchy distribution of the xenotopic dolomite would be expected in a partially neomorphosed idiotopic dolomite. This is one of the petrograhpic criteria discussed by Bathurst (1975) as evidence for neomorphism in limestone.

Neomorphism would be expected to destroy zoning in the dolomite undergoing recrystallization. Xenotopic-A dolomite in the Galena Group is rarely zoned, and when it is, does not have as well developed a zoning patterns as some of the idiotopic dolomites. Possible subtle changes in chemical conditions during neomorphism might result in a zoned dolomite product (Fairchild, 1980); however, neomorphism would normally be expected to have a homogenizing effect in a chemically closed system.

Xenotopic-P dolomite at the roadcut south of Guttenberg (locality 45) was observed directly replacing limestone (Fig. 6). This dolomite has a $\delta^{18}O$ depletion of almost 2 per mil. below that of the idiotopic dolomite collected at the same locality (Fig. 3). This is consistent with a replacement origin for the xenotopic dolomite at a temperature about 40°C higher than that of the coexisting idiotopic dolomite, assuming similar water compositions. The textural similarity between xenotopic dolomite of replacement origin (Fig. 6) and that of probable neomorphic origin (Fig. 7) illustrates the difficulty in distinguishing between their two origins based on texture alone.

Petrographic recognition of xenotopic dolomite texture may provide a quick and easy way to recognize a dolomite produced by replacement or neomorphism during late diagenesis at elevated temperature. However, other criteria than texture are needed to distinguish between a neomorphic and a replacement origin. More work is needed to verify the relationship between crystal morphology and temperature. In the Galena Group, as well as other ancient dolomites, careful fluid inclusion and isotope work may help to test the hypothesis. Transmission electron microscopy may be useful in further investigating the crystal growth hypothesis discussed here.

ACKNOWLEDGMENTS

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REFERENCES

Badiozamani, K., 1972, The dorag dolomitization model--application to the Middle Ordovician of Wisconsin [unpublished Ph.D. dissertation]: Northwestern University, 95 p.

Badiozamani, K., 1973, The dorag dolomitization model--application to the Middle Ordovician of Wisconsin: Jour. Sed. Petrology, v. 43, p. 965-984.

Bailey, S. W.; and Cameron, E. N., 1951, Temperature of mineral formation in bottom-run lead-zinc deposits of the Upper Mississippi Valley, as indicated by liquid inclusions: Economic Geology, v. 46, p. 626-651.

Bathurst, R. G. C., 1975, Carbonate sediments and their diagenesis, 2nd ed.: Elsevier Scientific Publishing Co., New York, 658 p.

Brice, J. C., 1973, The growth of crystals from liquids: American Elsevier, New York, 379 p.

Delgado, D. J., 1979, Sedimentation and submarine diagenesis of Middle Ordovician Kimmswick strata (Galena Group) in Upper Mississippi Valley: Geol. Soc. America, North Central Section Abstracts with Program, v. 11, n. 5, p. 228.

Delgado, D. J., 1983, Deposition and diagenesis of the Galena Group in the Upper Mississippi Valley: in Delgado, D. J. (ed.), Ordovician Galena Group deposition, submarine and later diagenesis, and paleoecology, 13th Annual Field Conference Guidebook, Soc. Econ. Paleontologists Mineralogists Great Lakes Section, This volume.

Fairchild, I. J., 1980, Stages in a Precambrian dolomitization, Scotland: cementing verses replacement textures: Sedimentology, v. 27, p. 631-650.

Friedman, G. M., 1965, Terminology of crystallization textures and fabrics in sedimentary rocks: Jour. Sed. Petrology, v. 35, p. 643-655.

Gregg, J. M., 1982, The origin of xenotopic dolomite texture [unpublished Ph.D. dissertation]: Michigan State University, 151 p.

Gregg, J. M.; and Sibley, D. F., 1982, The effect of temperature on dolomite replacement textures: Abstracts of Papers, International Association of Sedimentologists, Eleventh International Congress on Sedimentology, Hamilton, Ontario, Canada, p. 124.

Gregg, J. M.; and Sibley, D. F., in press, Epigenetic dolomitization and the origin of xenotopic dolomite texture: Jour. Sed. Petrology.

Hall, W. E.; and Friedman, I., 1969, Oxygen and carbon isotopic composition of ore and host rock of selected Mississippi Valley deposits: U. S. Geol. Survey Prof. Paper 650-C, p. C140-C148.

Heyl, A. V., Jr.; Agnew, A. F.; Lyons, E. J.; and Behre, C. H., Jr., 1959, The geology of the Upper Mississippi Valley zinc-lead district: U. S. Geol. Survey Prof. Paper 309, 310 p.

Heyl, A. V.; and West, W. S., 1982, Outlying mineral occurrences related to the Upper Mississippi Valley mineral district, Wisconsin, Iowa, Illinois, and Minnesota: Economic Geology, v. 77, p. 1803-1817.

Jackson, K. A., 1958, Mechanisms of growth: Liquid metals and solidification, American Society of Metals, Cleveland, Ohio, p. 174-186.

Kirkpatrick, R. J., 1981, Kinetics of crystallization of igneous rocks: in Lasage, A. C.; and Kirkpatrick, R. J. (eds.), Kinetics of geochemical processes, Reviews in Mineralogy, v. 8, Mineralogical Society of America, p. 321-397.

Lewis, B., 1975, Nucleation and growth theory: in Pamplin, B. R. (ed.), Crystal growth, Pergamon Press, New York, p. 12-39.

McLimans, R. K., 1977, Geological, fluid inclusion, and isotope studies of the Upper Mississippi Valley zinc-lead district, southwest Wisconsin [unpublished Ph.D. dissertation]: The Pennsylvania State University, 187 p.

Roedder, E., 1981, Origin of fluid inclusions and changes that occur after trapping: in Hollister, L. S.; and Crawford, M. L. (eds.), Fluid inclusions: applications to petrology, Mineralogical Association of Canada Short Course, v. 6, p. 101-137.

Sverjensky, D. A., 1981, Isotopic alteration of carbonate host rocks as a function of water to rock ratio--An example from the Upper Mississippi Valley zinc-lead district: Economic Geology, v. 76, p. 154-157.

ROAD LOG, DUBUQUE TO DECORAH, 1 OCTOBER 1983

DAVID J. DELGADO, Phillips Petroleum Company, 8055 East Tufts
Avenue Parkway, Denver, Colorado 80237

Assemble in the parking lot behind the Best Western Dubuque Inn, 3434 Dodge Street (U. S. Highway 20). Hard hats will be available for purchase in the parking lot before 8 a.m. HARD HATS ARE REQUIRED AT STOP 2.

Please stay in caravan if possible (this will be difficult in Dubuque). However, we have a long day ahead, so the trip will not wait for stragglers. Please obey speed limits and traffic rules and drive safely and sensibly, to make this an enjoyable trip for all.

MILEAGE		
Point to point	Cumulative	
0	0	Leave Dubuque Inn parking lot via south exit (behind motel). Turn left onto Mercer Drive.
0.1	0.1	Turn left at first corner.
0.3	0.4	Turn left at first corner onto Cedar Cross Road.
0.1	0.5	Continue straight across U. S. 20, then make immediate right onto frontage road (University Avenue). Stay on University Avenue.
1.4	1.9	Loras Blvd. branches off to left ahead; turn onto Loras Blvd.
0.2	2.1	Grandview Avenue stop light. Continue straight on Loras.
0.45	2.55	Loras College ahead on left. Imposing 5-story brick building is Keane Hall.
0.15	2.7	Turn left onto Cox Street, then immediately left again into parking lot. This is Stop 1.

STOP 1. DUBUQUE FORMATION TYPE SECTION, LORAS COLLEGE CAMPUS.
SW 24, 89N-2E, Dubuque North 7.5" Quadrangle.

This parking lot and the athletic field immediately to the east were constructed in the abandoned "Fourteenth Street Quarries" which Sardeson (1907) designated as the type section of the Dubuque Formation. The former Fourteenth St. is now Loras Boulevard. Although weathered, most of the Dubuque is still exposed, and this is a good place to see the Dubuque where it is comparatively low in argillaceous content and in the dolomite lithofacies. At Stop 5, we will see the same interval where it is limestone and much shalier.

Key to symbols used in stratigraphic sections

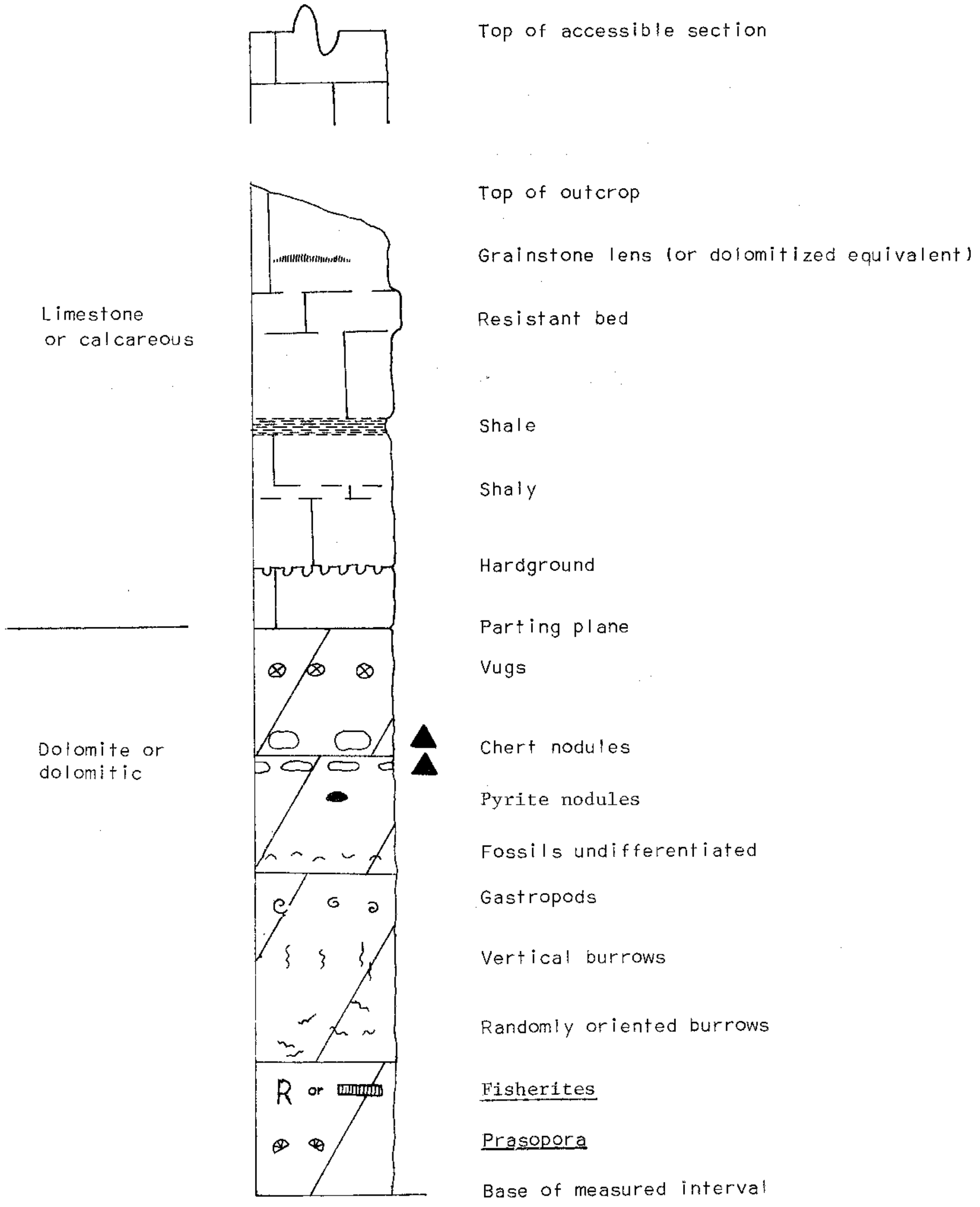
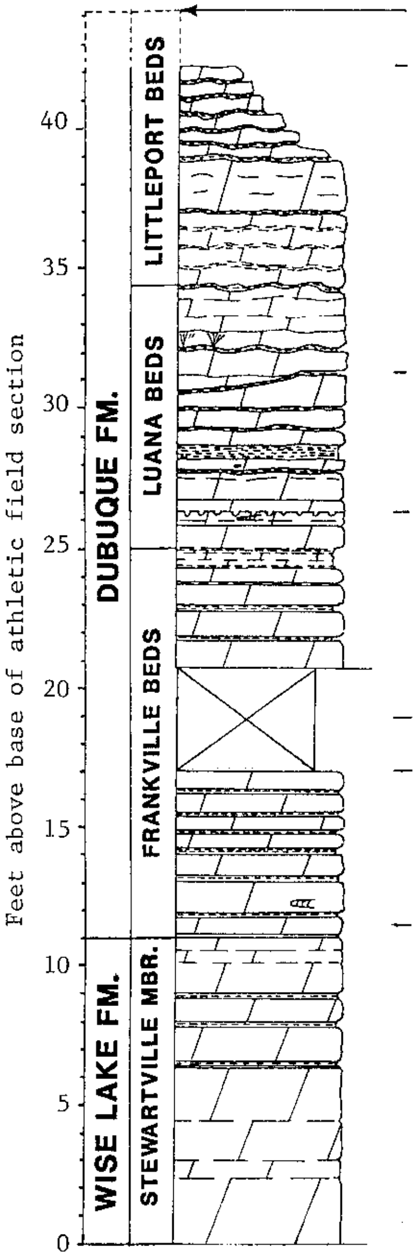


Figure 1.

STOP 1: Dubuque Fm. type section, Loras College campus.



Approximate Dubuque/Maquoketa contact

Top of parking lot exposure

Note channel or scour depression on convex salient of parking lot wall.

Possible hardground

Base of parking lot exposure

Approximately 3' 8" covered

Top of athletic field exposure

"Marker Bed"?

Base of athletic field exposure

Figure 2.

Stop 1 -- continued

Athletic field exposure: The athletic fields directly east of Cox Street occupy the lower of the two old quarries. Two remnants of the original quarry wall are present on the west side of the fields, directly under Cox St. These expose 17 feet of lower Dubuque (Frankville beds of Levorson et al., 1979; cf. Levorson and Gerk, this vol.) and upper Stewartville Mbr. Wise Lake Fm. These two old, small exposures of in-place rock are surrounded by a man-made wall of dimension stone quarried locally from about the same stratigraphic interval.

The west wall exposure is weathered; placement of the Wise Lake/Dubuque contact is uncertain. I tentatively identify the four-inch-thick dolomite bed, bounded by thin shales, six feet below the top of the exposure, as the widespread "Marker Bed" (cf. Levorson and Gerk, this vol.). The "Marker Bed" is the basal bed of the Dubuque Fm. Note the even, flat bedding of the uppermost Stewartville and lower Dubuque beds exposed here, and the apparent shaliness of many bed partings. Weathering accentuates the shaly character.

Parking lot exposure: West of Cox Street, the L-shaped parking lot occupies the upper of the two old quarries. Exposed in the walls are the uppermost Frankville beds, the entire Luana beds, and all but about two feet of the Littleport beds (Levorson et al., 1979; cf. Levorson and Gerk, this vol.). Calvin Levorson and Art Gerk have confirmed this by digging out the Dubuque/Maquoketa contact in the covered interval just above this exposure (C. O. Levorson, written commun., 1983).

About 3' 8" of section are covered between the top of the athletic field exposure and the base of the parking lot exposure.

The Luana beds are transitional in character between the underlying Frankville and overlying Littleport beds. In general, the Frankville and basal Luana beds are thicker and lower in argillaceous content, with flat bed partings. Upper Luana beds and Littleport beds are increasingly argillaceous upward, become wavier and even lumpy-bedded upward, and are thinner. Note the occasional round rusty stains in the upper half of the Luana beds. These are due to the weathering of large pyrite concretions, very characteristic of upper Luana beds throughout the outcrop belt. Pseudolingula iowensis, a large infaunal lingulid with a distinctive bluish-white phosphatic shell, is common in the Dubuque; a few specimens can be found here in life position. Moldic molluscs, especially cephalopods, are also present.

Unique at this exposure is the large depression, more than 12 feet wide and eight inches deep, seen on the out-jutting corner of the wall about ten feet above the base. I interpret it as a scour; this is by far the largest and deepest scour depression known to me anywhere in the Galena outcrop. Its origins are not clear; adjacent beds appear to have the typical quiet-water aspect of the Dubuque.

The upward increase in waviness of bedding is characteristic of the upper Dubuque throughout its outcrop, but the causes are not clear. Some evidence suggests soft-sediment deformation may have contributed.

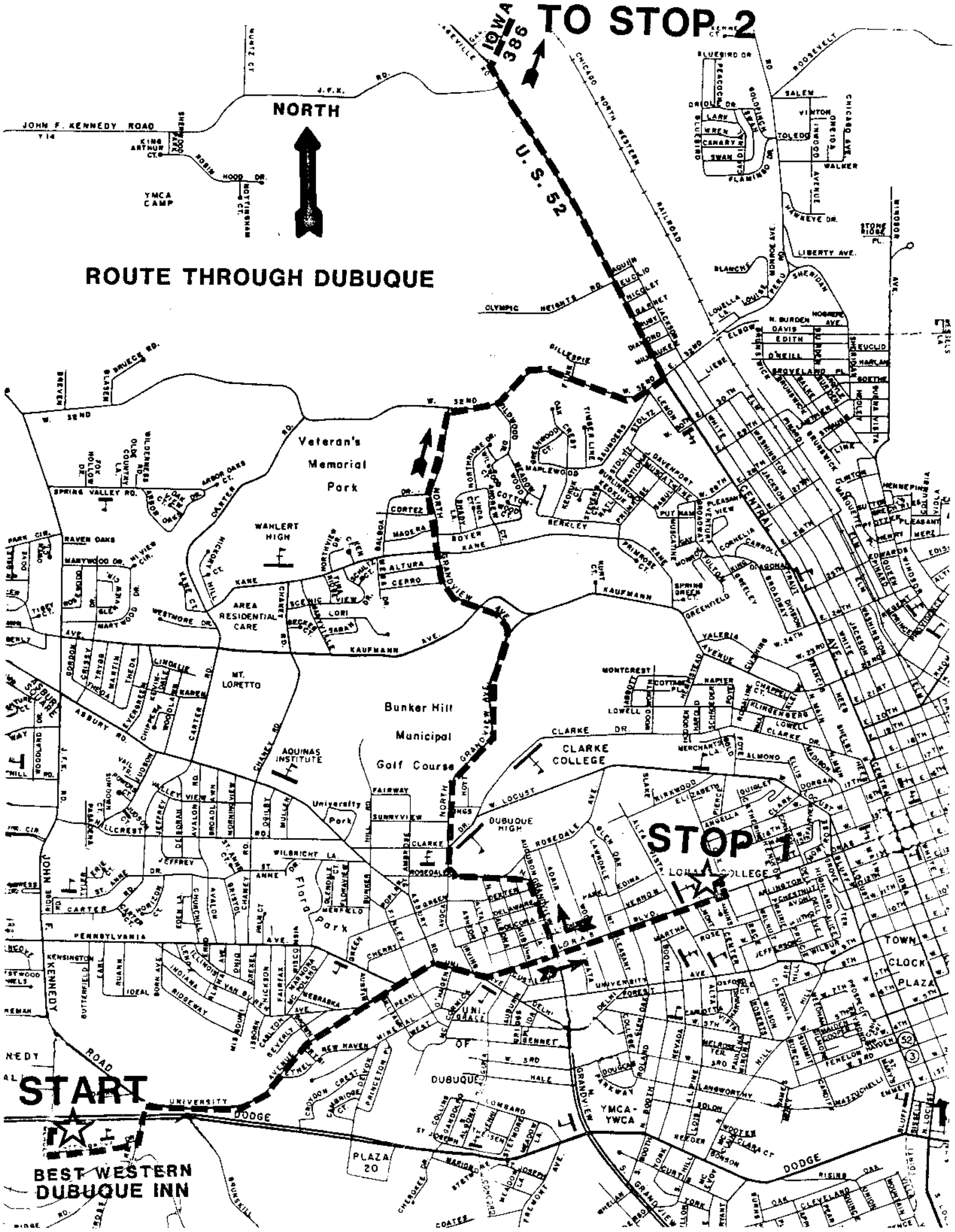

TO STOP 2
IOWA 386
U.S. 52
NORTH
ROUTE THROUGH DUBUQUE
Veteran's Memorial Park
WAHLERT HIGH
AREA RESIDENTIAL CARE
MT. LORETTO
Bunker Hill Municipal Golf Course
AQUINAS INSTITUTE
University Park
Flora Park
CLARKE COLLEGE
DUBUQUE HIGH
STOP 1
LORAS COLLEGE
TOWN CLOCK PLAZA
UNIVERSITY OF DUBUQUE
YMCA-YWCA
PLAZA 20
YMCA CAMP
START
BEST WESTERN DUBUQUE INN
JOHN F. KENNEDY ROAD
GRANDVIEW AVE.
UNIVERSITY
DODGE
CENTRAL AVE.

Figure 3.

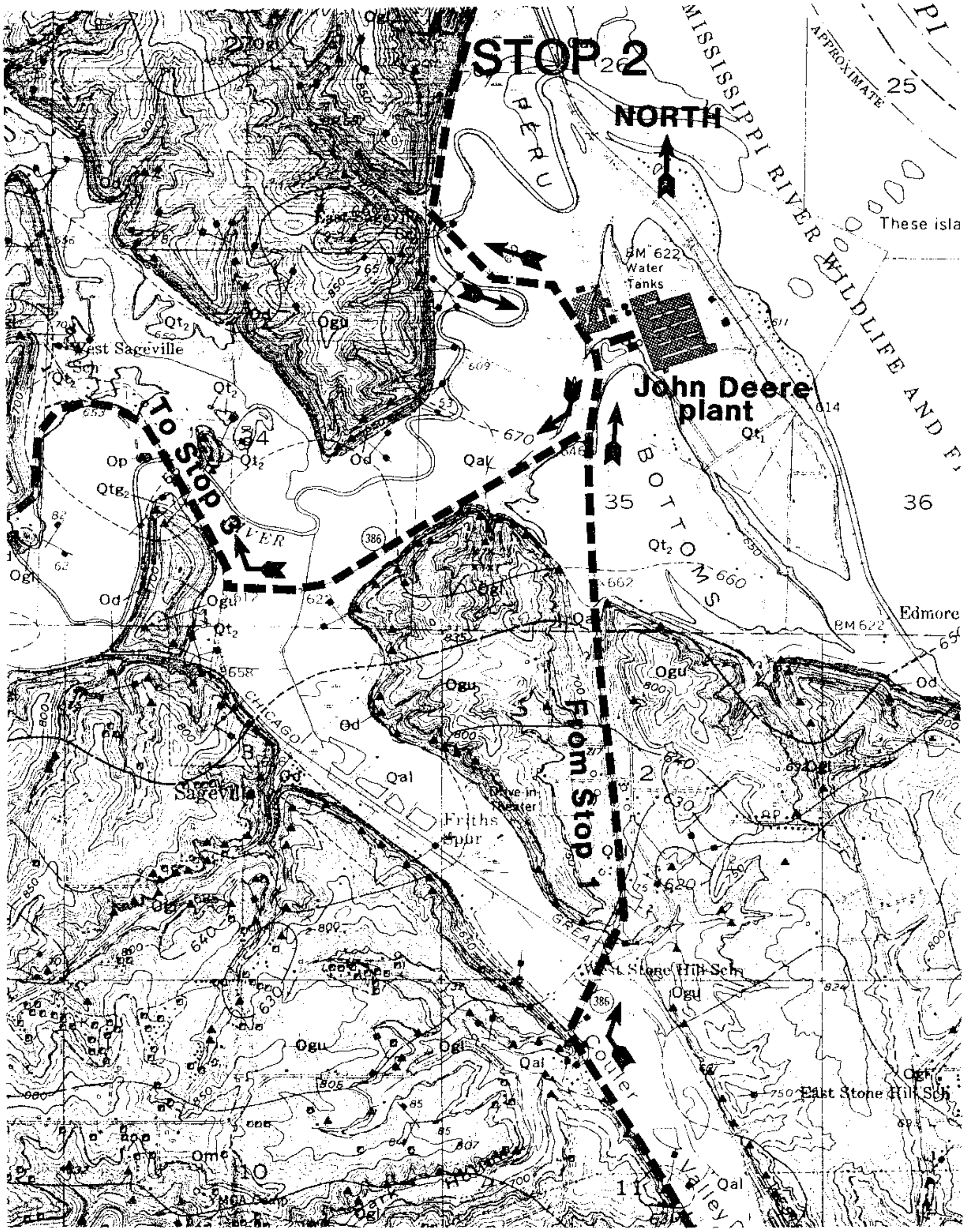


Figure 4. Route to and from Stop 2.

MILEAGE Point to point	Cumulative	
0	2.7	Return to cars. Leave parking lot, turn right on Cox St. and immediately right again onto Loras Boulevard.
0.6	3.3	Stop light. Turn right onto Grandview Avenue.
0.2	3.5	Sharp left bend; stay on Grandview Avenue.
0.3	3.8	Clarke St. intersection, stop sign. Clarke College on right. Continue straight on Grandview Avenue.
0.85	4.65	Fork in road; take left fork up hill (still Grandview Ave.).
0.15	4.8	Stop sign, Kaufmann Avenue. BE CAREFUL! Continue straight across on Grandview Ave. Dubuque Fm. in excavation on right short way past intersection.
0.2	5.0	Stop sign, Kane St. Continue straight on Grandview Ave.
0.5	5.5	Tee intersection. Turn right on West 32nd Street.
0.8	6.3	Stop light, Central Avenue (U.S. 52, Iowa 3). Turn left onto Central Avenue. Next 1.2 miles we will be in Couler Valley, the abandoned valley of the Little Maquoketa River. Stream piracy cut off this part of the river and diverted the mouth of the river to Peru Bottoms near Stop 2 (fig. 4).
1.0	7.3	Dunleith Fm. exposed on left. Leave Dubuque.
0.2	7.5	Second stop light, Iowa Highway 386. Turn right onto 386.
0.9	8.4	Concentration of houses.
0.8	9.2	Large John Deere plant on right. Do not follow 386 around hairpin turn to left; instead, stay straight on local road. These flats are Peru Bottoms.
0.7	9.9	One lane bridge. Give quarry and construction trucks the right-of-way. Follow paved road around corner to right.
0.5	10.4	Sageville Quarry. This is Stop 2.

STOP 2. DUBUQUE STONE COMPANY SAGEVILLE QUARRY.
SW NW 26, 90N-2E, Dubuque North 7.5" Quadrangle.

IMPORTANT: ALL FIELD TRIP PARTICIPANTS MUST SIGN A RELEASE FORM AND MUST WEAR HARD HATS. This is an active quarry; use good sense.

Stop 2 -- continued

> Portions of the walls may be unstable. When on upper ledges, stay away from the edge, especially if cracks are present in the floor. Be careful not to knock stone down on someone else. STAY CLEAR OF ANY WIRES -- they might be connected to unexploded blasting materials!

This quarry is one of the most important Galena Group exposures in the dolomite facies. About 118 feet of the Dunleith Formation (all but the lowermost Buckhorn Member and one or two basal beds of the St. James Member) and about half of the Wise Lake Formation are exposed. Access to the face is gained at four levels: the floor and three benches. The benches are located stratigraphically at the top of the Fairplay Member of the Dunleith Fm. (Bench #1), low in the Rivoli Member of the Dunleith (Bench #2), and just above the basal cherty beds of the Sinsinawa Member of the Wise Lake Fm. (Bench #3). A larger interval of the Dunleith Formation is exposed here than at the type section of the Dunleith in the river bluffs at East Dubuque, Illinois (Templeton and Willman, 1963). In addition, the section here is fresher and more accessible. The entire Dunleith and more of the Wise Lake are exposed at the abandoned Eagle Point Quarry in northeastern Dubuque, but the face is sheer and has been inaccessible for many years.

St. James Member

The St. James Member of the Dunleith Fm. is easily accessible at the floor level in the older part of the quarry. St. James strata are the most argillaceous exposed in the quarry. Much of the argillaceous material is in the form of green shale partings and burrow fills. As this argillaceous content is undesirable for many uses of crushed stone, the quarry operators no longer mine the lower half of the St. James, leading to the higher floor in the newer part of the quarry. Towards the northwest, the St. James becomes more and more argillaceous; north of Guttenberg, it is considered the upper part of the Ion Shale Member of the Decorah Formation (cf. Levorson and Gerk, this vol., fig. 2). Also characteristic of the St. James are well-developed, ferruginized hardgrounds. As the St. James becomes shalier when traced to the northwest, the hardgrounds tend to disappear.

Carbonized dendroid graptolites are common in the upper St. James in this quarry. Similar dendroids occur at precisely the same stratigraphic position at a quarry in western Dane County, Wisconsin (Delgado, 1983). No other occurrences are known to me.

Prasopora zonule

The St. James/Beecher contact can be reached easily at the inner end of the quarry. This contact is marked over most of the Upper Mississippi Valley by a thin zone rich in the hemispherical bryozoan *Prasopora*. The "*Prasopora* zonule" is hard to find in this quarry, but sparse molds of small *Prasopora*, mostly less than 3/4" across, can be found in a 2" argillaceous bed overlying a hardground (top bed of the St. James Member) and in the basal 2" of the next overlying, less argillaceous dolomite bed (basal bed of the Beecher Member). Occurrence of the *Prasopora* zonule within the base of the Beecher is fairly common but has not previously been documented in the literature.

Stop 2 -- continued

Beecher Member

The Beecher Member is chert-free, thick-bedded, and distinctly less argillaceous than the St. James; it contains sparse bryozoans and paper-thin green shale partings. In these characteristics it is entirely characteristic of the Beecher in the dolomite lithofacies and as far north as Guttenberg. Unusual here is the inconspicuousness of the hardgrounds; at many localities, particularly in south-central Wisconsin, the Beecher contains numerous, well-developed, closely-spaced hardgrounds.

Northwest of Guttenberg, Beecher and overlying Eagle Point strata increase in argillaceous content and tend to split into thin, rubbly beds. Northwest of Decorah, these members shale out, and are included in the Decorah Shale in Minnesota (Stone, this vol., fig. 1).

Eagle Point Member

The Eagle Point Member can be reached for close examination only with difficulty, by climbing rubble piles which may be unstable. From a distance, the Eagle Point is characterized by its numerous, closely-spaced bands of chert nodules set in massive dolomite with few or no parting planes. This character persists across southern Wisconsin and northern Illinois, and northward past Guttenberg. Farther northwest, the Eagle Point becomes increasingly argillaceous, like the Beecher.

Lower Receptaculites Zone

The giant green alga Fisherites (renamed by Finney and Nitecki, 1979) (formerly Receptaculites oweni) occurs in all parts of the Galena Group from the Guttenberg Fm. to the Dubuque Fm. inclusive, but is common only in three zones, the Lower, Middle, and Upper Receptaculites Zones. (Although I have adopted the new taxonomic nomenclature for the fossil, the old zonal name is retained as a long-established and familiar stratigraphic term). Areally, the upper and lower boundaries of each zone vary somewhat. The Lower Receptaculites Zone is centered on the Fairplay Member and may include parts of the Eagle Point and Mortimer Members as it does in this quarry. In the dolomite lithofacies, Fisherites are preserved as molds of the aragonite skeleton originally secreted by the alga.

The factors which control the abundance of Fisherites are not clear. The other two common green algae of the Galena Group are Ischadites and the microscopic dasycladacean Vermiporella. Abundance of each seems to vary independently of the other two.

Fairplay Member

The Fairplay is less cherty than the Eagle Point, is more distinctly mottled, and has strong bedding planes at 2-to-3-foot intervals. Fairplay carbonate is commonly the purest in the Dunleith Fm. and is prized by quarry operators, especially where it is free of chert. The first bench provides access to the upper Fairplay just above the lower cherty zone. As at most Fairplay exposures, several resistant, slightly argillaceous beds containing numerous aligned vugs occur at and near the top of the member.

Mortimer Member

The Mortimer commonly is strongly dolomite-mottled, like the Fairplay. It contains distinctive thick, white chert nodules. Where the Fairplay is also cherty, commonly the two members are difficult to distinguish unless the argillaceous zone at the top of the Fairplay is well-developed. A resistant bed with stratigraphically aligned vugs caps the member; this bed may be recognized at least 100 miles laterally.

Rivoli Member

The Rivoli is slightly more argillaceous than adjacent parts of the Dunleith Fm., and contains several strongly ferruginous hardgrounds. In this quarry, the Middle *Receptaculites* Zone is very narrow. Note the resistant, thick bed atop the Rivoli. The second bench provides access to the upper Rivoli.

Sherwood, Wall, and Wyota Members

The lower Sherwood is accessible from the second bench. The member is more cherty and less argillaceous than the underlying Rivoli. The upper Sherwood, Wall, and Wyota Members are not accessible at present and are difficult to distinguish at the distance of the second bench. The entire section seems cherty. The highest chert beds in the quarry face are in the basal Sinsinawa Member of the Wise Lake Fm.

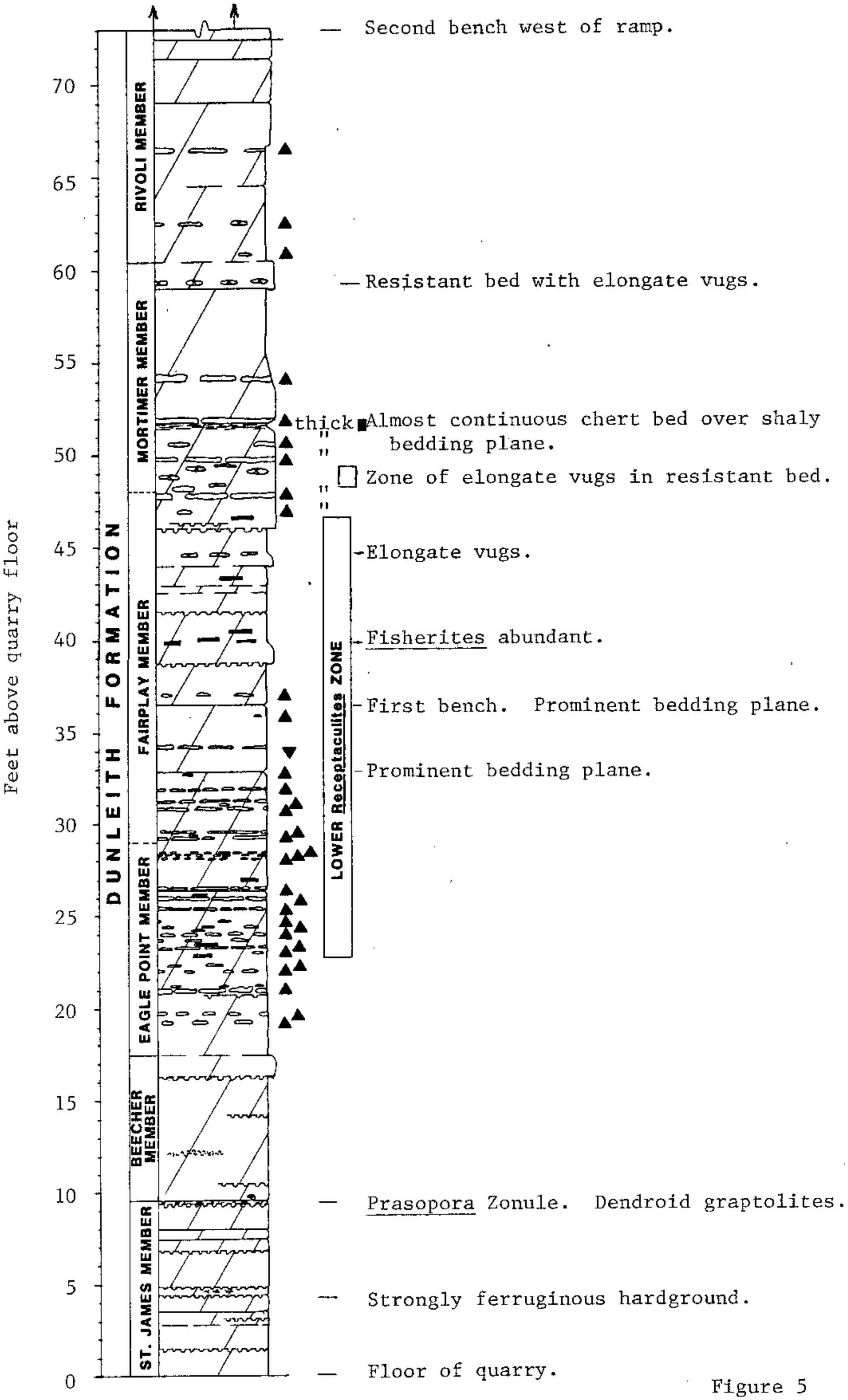
Sinsinawa Member

The third bench is just above the highest chert beds; these occur in the basal eight feet of the Sinsinawa Member of the Wise Lake Fm. The accessible part of the Sinsinawa includes a zone in the middle Sinsinawa characterized by several closely-spaced hardgrounds (at least 5 in this quarry). This zone is very widespread; we will see it again at stops 3 and 4.

The third bench was located so as to obtain chert-free stone; chert is unsuitable in some applications of crushed dolomite (including concrete aggregate). Presence of abundant *Fisherites* in riprap on the third bench indicates that the Upper *Receptaculites* Zone is present high in the inaccessible face above. This zone spans the Sinsinawa/Stewartville member contact.

STOP 2: Dubuque Stone Co. Sageville Quarry

Section continued on following page.



— Second bench west of ramp.

— Resistant bed with elongate vugs.

thick ■ Almost continuous chert bed over shaly bedding plane.

☐ Zone of elongate vugs in resistant bed.

- Elongate vugs.

- *Fisherites* abundant.

- First bench. Prominent bedding plane.

- Prominent bedding plane.

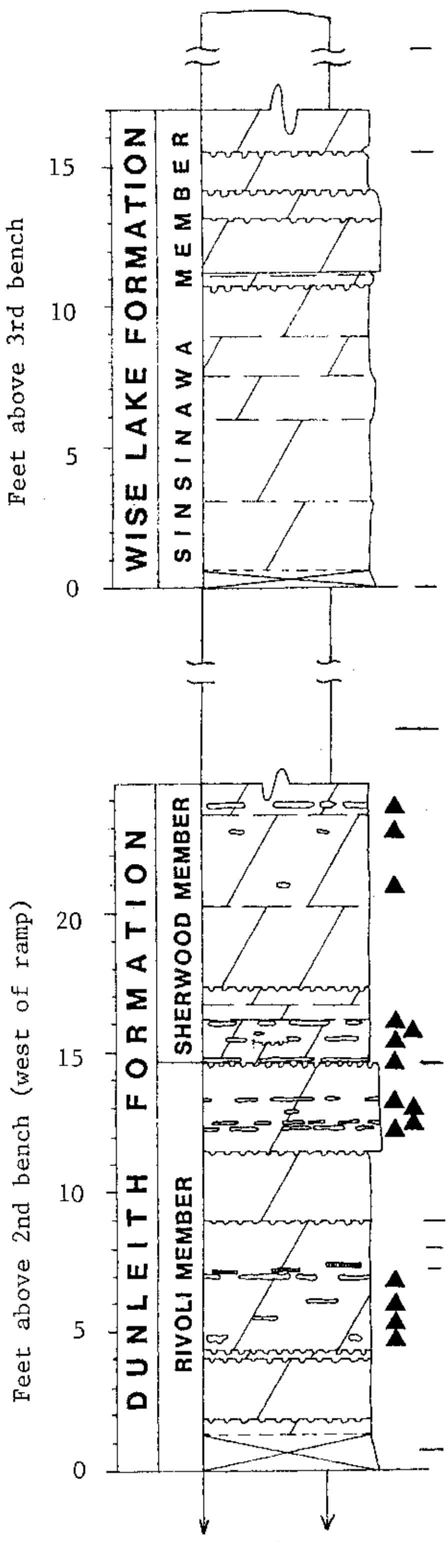
— *Prasopora* Zonule. Dendroid graptolites.

— Strongly ferruginous hardground.

— Floor of quarry.

Figure 5

STOP 2: Sageville Quarry (continued)



About 30' pure mottled dolomite, inaccessible, to top of quarry face; upper Sinsinawa and lower Stewartville Mbrs. Wise Lake Fm.

Major bedding plane visible throughout qy.

Third bench. 6" atop bench covered with rubble; rubble contains abundant *Fisherites* from Upper *Receptaculites* Zone.

About 30' cherty dolomite to 3d bench, inaccessible. Upper Sherwood, Wall & Wyota Mbrs. Dunleith Fm. and lowest 8' Sinsinawa Mbr. Wise Lake Fm.

Strongly ferruginous hardground, nearly continuous chert bed atop.

Second bench east of ramp.

Middle *Receptaculites* Zone.

1.5' covered.
Second bench west of ramp.

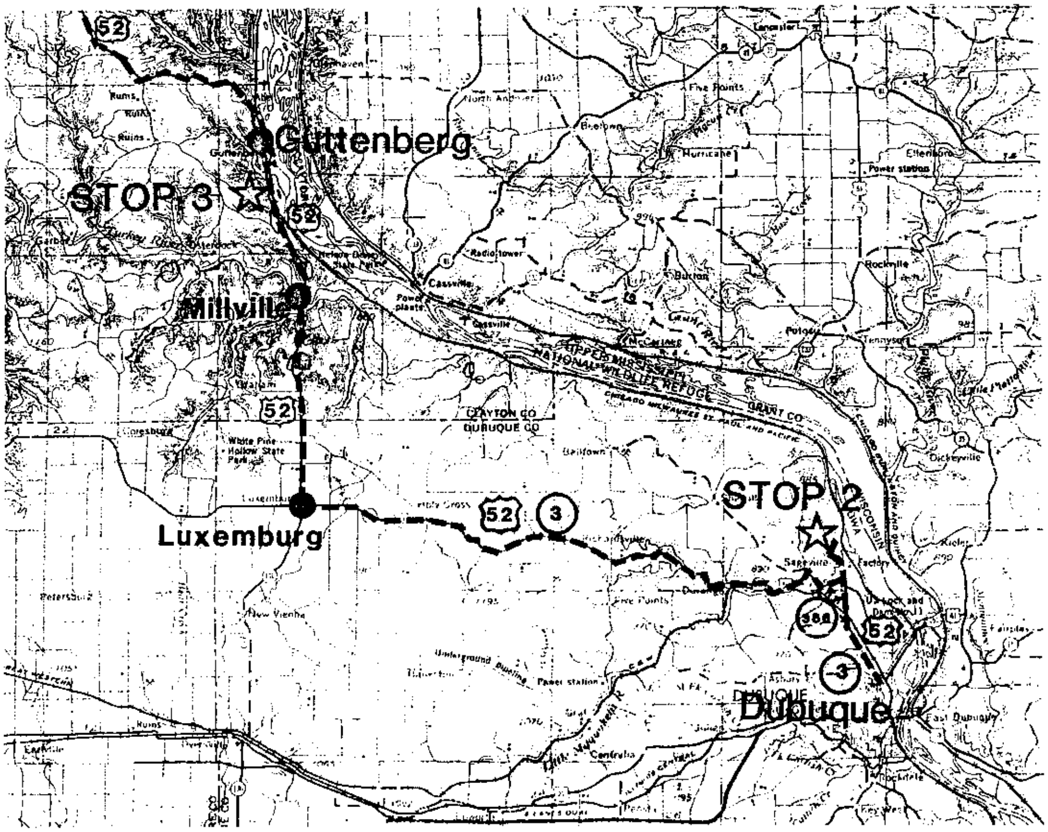


Fig. 6. Dubuque to Guttenberg route.

MILEAGE

Point to point	Cumulative	
0	10.4	Return to cars. Retrace same route used entering quarry.
0.5	10.9	Junction with local road. Turn left, following pavement over one-lane bridge.
0.7	11.6	Junction with Iowa Hwy. 386 in front of John Deere plant. Turn right onto 386.
1.0	12.6	Tee intersection at U. S. 52. Turn right onto U. S. 52. Dunleith Fm. present ahead in bluff.
0.7	13.3	Poorly-marked county road branches off to right just before Ioco gas station. This road leads to Sherrill and Balltown, both located atop Silurian outliers. From Sherrill, a branch road also leads to the type section of the Spechts Ferry Shale. We will skip these interesting localities today, however, so stay on 52.

MILEAGE		
Point to point	Cumu-lative	
1.8	15.1	Dunleith Fm. intermittently exposed on right, next 1.4 miles.
1.4	16.5	Durango, Iowa.
0.4	16.9	Dunleith intermittently exposed on right, next 1.4 miles.
1.9	18.8	Beginning of long but weathered road cut which ascends from the middle Dunleith to the middle Dubuque Fm. Lack of shoulder and heavy traffic make this a very dangerous place to do geology, however.
0.6	19.4	We have climbed above the top of the resistant Galena dolomite and are now in typical rolling open topography developed upon the Maquoketa shales. The main Silurian escarpment is visible in the distance to the left. The heights ahead to the right are two Silurian outliers, Sherrill Mound and the larger Balltown Ridge.
2.4	21.8	Enter Rickardsville.
1.3	23.1	Ascending Silurian escarpment.
6.85	29.95	Holy Cross on side road to right.
3.9	33.85	Enter Luxemburg.
0.15	34.0	Follow U.S. 52 northbound branch around curve to right.
0.2	34.2	Stop sign. Turn right (north).
4.8	39.0	Silurian Hopkinton Dolomite in road cut next 0.3 mile. Note small internal truncation of beds by overlying beds near top of cut. The Hopkinton is a similar facies to the Dunleith and Wise Lake and can be confused with them by observers at a distance. However, it lacks the early diagenetic features such as hardgrounds which are so characteristic of the Galena Group. Tabulate corals are abundant in the Hopkinton, extremely rare in the Galena, providing another criterion useful upon close examination of the rock.
0.5	39.5	The riprap on the slope to the right is Silurian dolomite placed upon a road cut in the soft, easily eroded Brainard shale Member of the Maquoketa by the highway department to control erosion.
0.3	39.8	Small exposure of lower Maquoketa on right.
0.3	40.1	Road cut in Dubuque Fm.

MILEAGE		
Point to point	Cumulative	
0.1	40.2	Road cut in Wise Lake Fm.
0.3	40.5	Begin three closely-spaced road cuts in Dunleith Fm. By contrast with the exposure seen at stop 2, the Dunleith here is limestone except for the Wyota Member. However, 6 miles to the east at North Buena Vista, only the basal Buckhorn Member of the Dunleith is undolomitized. Note dolomitization along joint on left side of road.
0.1	40.6	Dunleith on right.
0.2	40.8	Dunleith on left.
0.1	40.9	Side road on right leads to North Buena Vista and new privately operated car ferry to Cassville, Wisconsin.
0.5	41.4	Millville on left.
0.3	41.7	Bridge over Turkey River.
0.6	42.3	Road cut on left, Dunleith Fm.
0.15	42.45	Begin long road cut on right side, ascending from Wall Member Dunleith Fm. up into Wise Lake Fm. (Stewartville Member?). The Wise Lake and the upper 14 feet of the Dunleith are dolomitized; the underlying part of the Dunleith is limestone. Note heavy calcite mineralization along bedding planes and fractures at the high end of the cut.
0.5	42.95	Wise Lake in road cut on left.
0.15	43.1	Wise Lake in road cut on right.
0.1	43.2	Wise Lake in road cut on left.
0.1	43.3	Wise Lake in road cut on left.
1.4	44.7	A few ledges of the Dubuque Fm. exposed on left.
0.1	44.8	Stewartville Mbr. Wise Lake exposed along driveway on right. Just beyond is the beginning of the long, magnificent road cut on the left side which exposes nearly the entire Galena Group, and a splendid view of the Mississippi River below on the right. This is Stop 3.

STOP 3. GUTTENBERG SOUTH ROAD CUT. SW 28, 92N-2W (Guttenberg and Turkey River 7.5' Quadrangles).

This magnificent road cut, constructed in 1975, is the most nearly complete exposure of the Galena Group. The Spechts Ferry Shale and about the basal two feet of the Guttenberg Fm. are covered at the base, and about twenty feet of the Dubuque Fm. are missing at the top (C. O. Levorson and A. J. Gerk, unpublished stratigraphic section, 1975). The intervening parts of the Guttenberg and Dubuque Fms., and the entire Dunleith and Wise Lake Fms., are exposed without break, with access at road level to the Dunleith and lower Wise Lake. Upper Wise Lake and Dubuque strata must be reached with ladders but can be examined by intrepid sedimentologists with sufficient motivation. The cut is fresh and illustrates most of the characteristics and sedimentological problems associated with the Galena Group. The following notes are merely a brief introduction to the riches available here.

GUTTENBERG FM.

Note the typical nodular bedding of the Guttenberg. The nodular to wavy bedding style and red-brown shale partings reappear in the upper part of the Dubuque Fm.; do these features imply the return of similar depositional conditions? The causes of this bedding style are not understood.

Note the hardgrounds at 3' 7" and at the top of the formation. The Guttenberg/Dunleith contact is easy to pick here; at many localities, however, the upper five or so feet of the Guttenberg is transitional in lithology to the basal Buckhorn Member of the Dunleith, and location of the contact is arbitrary.

DUNLEITH FM.
Buckhorn Mbr.

Note the blackened and bored limestone nodules in several of the shale beds. Some appear to be bored from both top and bottom; if this is indeed the case, the nodules would have had to have flipped over at some point in their history, probably due to nudging by burrowers.

The limestone beds are very argillaceous. Some contain carbonate nodules which are lighter-colored and less clayey than the surrounding shaly limestone. Compaction has deformed laminae around these nodules, indicating that the nodules formed before compaction. Other evidence suggests that compaction was early. Only in the nodules is there evidence of preservation of voids (empty dwelling burrows and voids caused by dissolution of aragonite shells); apparently the surrounding matrix was too soft to bridge over a void at the time the cavities appeared.

St. James Mbr.

The intensely blackened double hardground 1' 7" above the base of the member is cracked. Some of these cracks are filled with sparry calcite cement which is truncated at the hardground surface and punctured by some of the many Trypanites borings which perforate the hardground. Either the sparry cement or some dia-

Stop 3 -- continued

genetic precursor was already in place when the hardground was colonized by the borers.

At 24' 10" above the base of the cut, a hardground contains deep pits which are probably Thalassinoides, a large dwelling burrow characteristic of the prelithification omission suite (see Byers, this vol.). At some places, the sediment directly overlying the hardground is a bioclastic grainstone, but green clayey dolomite is preserved in the pits. Here the only record of an episode of sedimentation (deposition of the green sediment) is that preserved in the pits within the hardground; had early lithification not preserved the intricate pitted structure of the hardground, the open cavities would not have been available and the green sediment would have been completely eroded. This is the lowest dolomite at this exposure.

Prasopora Zonule

The highly fossiliferous Prasopora Zonule includes the upper foot of the St. James and the basal few inches of the overlying Beecher Member. The zonule is thicker and much better developed here than at stop 2. Note that many Prasopora show signs of tilting and upending -- by burrowers?

Beecher Member

Eight hardgrounds occur in the eleven-foot-thick Beecher here. The lowest of these lacks the customary flat upper surface; the hardground at 36' 5" also is flattened only on its highest projections. Two alternative explanations can be proposed:

1. The flat surface represents the original bedding plane. These hardgrounds are so eroded (burrowing? subsolution?) that only traces of the original bedding plane are left.
2. These two hardgrounds represent the primitive condition. In most cases, subsequent scouring has planed off the upper irregularities; these surfaces fortuitously were buried before a scouring event occurred.

For several reasons, I prefer the second explanation. Evidence of scouring is abundant at many hardgrounds and will be seen at stop 6. Such evidence includes truncation of bioclasts at the hardground surface, unroofing of burrows, and preferential removal of the pyritic stain from the top of the hardground compared to the halo around the pits.

Eagle Point Member

Closely-spaced layers of chert nodules and nearly massive host rock with dolomite mottling are the hallmarks of this member. Note the similarity between the limestone Eagle Point here and its dolomite counterpart at stop 2.

Three well-developed grainstone beds are present. The lowest is graded, whereas the middle one shows cross-bedding. Each has a sharp base and an upper boundary which is either gradational, obscured by burrowing, or diagenetically imposed (the hardground atop the upper grainstone). All these characteristics are consistent with the grainstones being storm deposits, but the exact depositional mechanism(s) are not clear. Grainstones generally comprise one to five percent of the total thickness of the Galena Group, but appear to represent much less than one percent of the depositional time. Many rest atop hardgrounds, suggesting that (if grainstone deposition occurred at random times) hardgrounds may represent a considerable portion of the total time which elapsed during Galena deposition.

Chert nodules at 49' and 52' contain dolomitized burrows. Other cherts include chertified burrows and bioclasts. This is evidence that (a) the chert is replacive; and (b) at least some dolomitization of burrows occurred before the formation of chert nodules. Evidence from cherts in the dolomite facies indicates that chert formed before the general dolomitization of Galena strata; thus, some burrow dolomitization may have occurred at a distinct time before the general dolomitization of the dolomite facies. There is reason to believe that at least some of this burrow dolomite may be submarine (Delgado, 1980 and this volume).

Fairplay Member

Dolomite mottling is much more pronounced in the Fairplay than in underlying strata. Mottles chiefly follow dwelling burrow networks (*Thalassinoides* chiefly). Note how dolomitization decreases in intensity downward from bedding planes. Even where dolomitized burrow networks extend down to the next underlying bedding plane, dolomitization never seems to increase in intensity downward, as would be expected if the dolomitization were due to dolomitizing fluids penetrating along bedding planes. This is another bit of evidence which may support the notion of synsedimentary dolomitization on the sea floor.

Alan Kendall (1983, oral commun.) has suggested that biotic restriction may be associated with dolomite-mottled intervals. This is a point which merits careful attention from the paleontologically-inclined members of the field party, because if true it would suggest that dolomite-mottled intervals may have been deposited in somewhat abnormal waters.

The uppermost bed of the Fairplay is dolomite and is slightly argillaceous. This dolomite tongue can be traced more than 50 miles (A. J. Gerk, oral commun., 1983) in outcrop; in subsurface, the Fairplay/Mortimer contact appears to be a locus of preferential dolomitization across much of Iowa (Witzke, this vol.). Is this due to preferential penetration of dolomitizing fluids into this interval at the time that regional dolomitization took place? Or was this interval dolomitized at an earlier time, and, if so, under what conditions? Numerous vugs, here filled with sparry calcite, are present in this bed. In the dolomite facies (e.g. stop 2), this bed is one of several which are characteristically slightly argillaceous and silty and contain vugs, often found aligned along a particular stratigraphic horizon within the bed. So far, no evidence has surfaced concerning the origin of these vugs. Crystal molds have been found in the similar bed atop the Mortimer Member in Wisconsin. Could the vugs be molds of evaporite nodules?

Mortimer Member

Dolomite mottling in the Mortimer is similar to that in the Fairplay. Two horizons of thick white chert nodules are present; such thick white nodules are

Stop 3 -- continued

typical of the Mortimer.

At the top of the member, a hardground is overlain by several discontinuous grainstone bodies which appear to be asymmetrical dunes or sand waves. Each has a steep face toward the south, and a very gently inclined face toward the north. This geometry suggests that these grainstones may have been formed as small piles of bioclastic lime sand which migrated southward across an extensive hardground surface. A 2" bed of gray shale drapes over the sand waves, and rests on the hardground surface where the grainstone bodies are not present.

Rivoli Member

The Rivoli is more strongly argillaceous here than at stop 2; typically it is the most argillaceous part of the Dunleith above the St. James. The well-developed hardgrounds seen here are also a characteristic feature of the Rivoli.

Sherwood Member

The Nasset K-bentonite, eight feet above the base of the member, consists of two inches of orange plastic clay. Samples from this locality have been confirmed to consist of mixed-layer clay by X-ray diffraction analysis (Mossler and Hayes, 1966). The bentonites were presumably windblown from the Appalachians, probably the northern Appalachians, over distances of 1000 miles or more. Until recently, chemical criteria have not existed which could be used to distinguish the various Ordovician K-bentonites. Recent work using minor element geochemistry promises to change this, however, and may permit tracing Galena Group bentonites back into other basins closer to the Appalachian sources (Kolata et al., this volume). In addition, the Nasset has recently been shown to have a distinctive heavy mineral assemblage in Minnesota and Iowa (Stone, this vol.; Mossler and Hayes, 1966). The bed underlying the Nasset has been silicified to a depth of as much as 2" below the bentonite, and the overlying bed has been silicified about ½"; however, this silicification is easily overlooked, as the appearance of the rock is unchanged.

Wall Member

A grainstone and a 1" shale bed overlying the grainstone are the top of the limestone facies at this outcrop. Strata above the 1" shale are dolomite. Below the 1" shale, the grainstone has largely escaped dolomitization, but the underlying two to three feet of wackestone have become partially dolomitized. A horizontal boundary between overlying dolomite and underlying limestone is present in the Dunleith at several exposures north of Guttenberg, at Millville, and at North Buena Vista; in each case the facies boundary is at a different stratigraphic level. Individual beds maintain their distinctive character across the facies boundary from outcrop to outcrop. Dolomite-mottled limestone beds in the limestone facies become mottled dolomite beds in the dolomite facies. All of this indicates that regional dolomitization of the Galena Group was not synsedimentary and did not reflect depositional conditions.

Stop 3 -- continued

Wyota Member

Note several resistant (slightly argillaceous) beds, two of which are vuggy. The Wyota is characteristically cherty. Note the general similarity of these beds to the dolomite facies at stop 2.

WISE LAKE FM.
Sinsinawa Member

The Sinsinawa is most easily accessible on the small cut across a gully to the south of the main road cut. Unfortunately, much of the face of the small cut is obscured by flowstone. Note the zone of at least six hardgrounds beginning about 13 feet above the base of the member. The same zone was seen at stop 2 and will be seen again at stop 4.

The upper Sinsinawa and overlying units are not accessible from road level, and will be seen at the next stop.

MILEAGE

Point to point	Cumulative	
0	44.8	Return to cars. We will proceed into Guttenberg for lunch.
0.6	45.4	Base of road cut.
0.1	45.5	Platteville Fm. in road cut on left.
1.1	46.6	Platteville Fm. in road cuts on left.
0.3	46.9	Turn right at Koerner St. (just before the Guttenberg Motel) and follow Great River Road signs.
0.1	47.0	Railroad crossing. DANGER! FREQUENT TRAINS!
0.15	47.15	Tee intersection, River Park Drive. Turn left, continuing to follow Great River Road signs.
0.65	47.8	Lock & Dam No. 10.
0.15	47.95	South end of River Park. Washrooms on right. Lunch stop.

LUNCH

0	47.95	Return to cars; continue north on River Park Drive.
0.35	48.3	Turn left at Hayden Street.
0.5	48.8	Railroad crossing. Frequent trains as before.

STOP 3: Guttenberg South road cut

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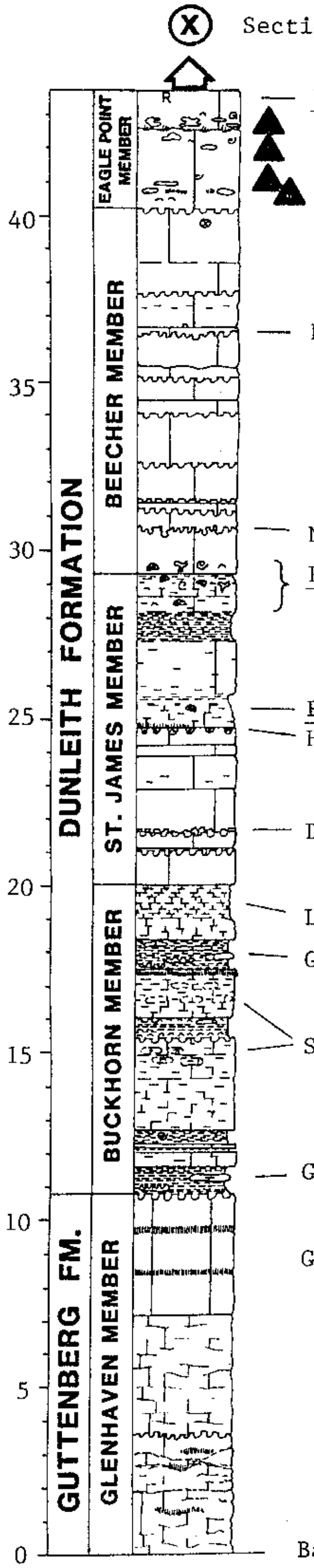


Fisherites. Base of Lower Receptaculites Zone.

Hardground scoured only on highest projections.

Non-scoured, strongly blackened hardground.

Prasopora Zonule. Abundant Prasopora, other bryozoans, and other biota. Note that zonule includes basal Beecher as well as uppermost St. James.

Prasopora.

Hardground; strongly blackened. Pits (omission suite burrows) filled with green clayey dolomite.

Double hardground, intensely blackened and bored. Some borings transect early sparry calcite cement which fills cracks.

Limestone, very shaly.

Green shale, with nodules of micrite and of packstone/grainstone; some of former are blackened and bored.

Shaly limestone beds with micrite nodules. Compaction has deformed laminae around undeformed nodules.

Green shale with limestone nodules. Some nodules blackened and intensely bored (up to 80,000 borings per sq. meter!)

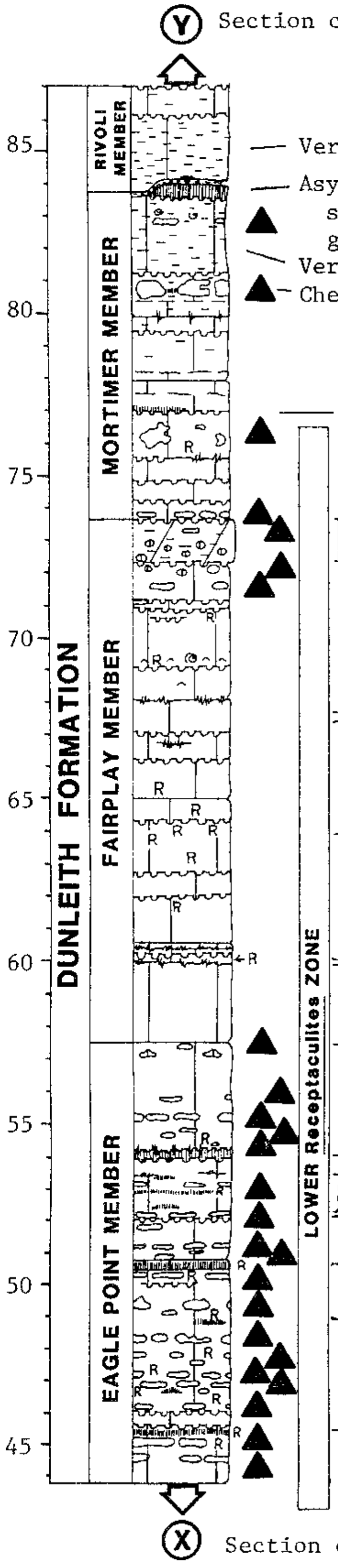
Guttenberg Limestone characterized by wavy to lenticular bedding, discontinuous grainstones, and red-brown shale partings. Typically pinkish on freshly broken surface, white where weathered.

Base of section.

Figure 6.

STOP 3: Guttenberg South road cut (continued)

Section continued on following page.



— Very argillaceous limestone.

— Asymmetrical "sand waves" of grainstone, steep face toward south, up to 6" thick. Overlie hardground; draped by 2" gray shale.

Very argillaceous limestone.

— Chert; typical thick white nodules of Mortimer Mbr.

Strongly blackened hardground. Overlying strata are less strongly dolomite-mottled than underlying.

Abundant chert nodules rest directly upon very strongly ferruginous hardground. Underlying bed is dolomite and is traceable approx. 50 miles laterally (A. J. Gerk, oral commun.). Dolomite bed contains abundant vugs filled with sparry calcite; are these evaporite molds?

Stylolites.

—Giant *Fisherites*.

Stylolites.

—Major bedding plane. Small ledge at road level. Underlying bed has small vugs filled with sparry calcite.

—Grainstone bed; hardgrounds atop and below.

Several minor grainstones.

—Chert nodules riddled with dolomitized burrows.

—Grainstone bed, many intraclasts and large shells; major bedding plane above.

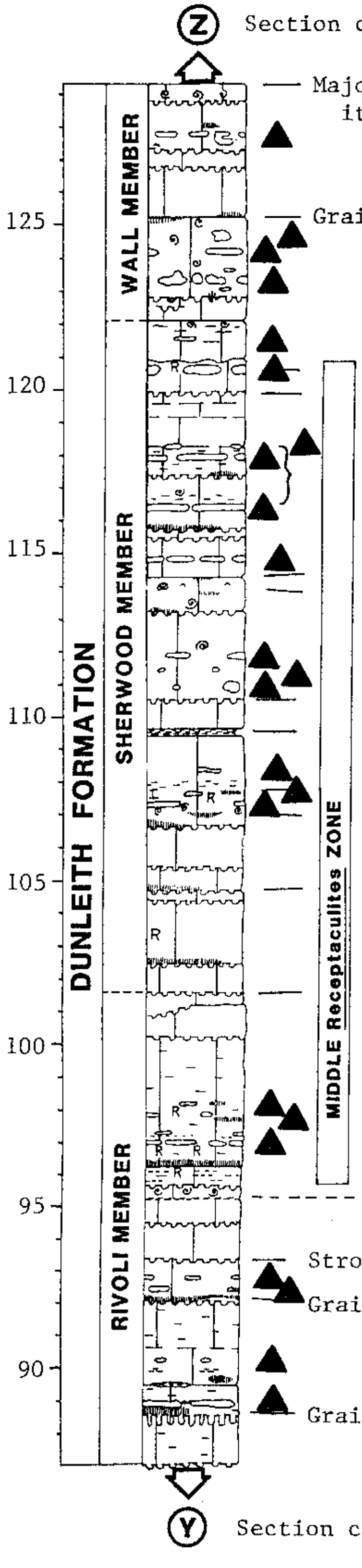
—Chert nodules riddled with dolomitized burrows.

—Grainstone; graded bedding; sharp base and gradational upper boundary.

Section continued from previous page.

STOP 3: Guttenberg South road cut (continued)

Section continued on following page.



Major bedding plane; possible position of Haldane K-bentonite (missing here).

Grainstones above and below bedding plane.

Giant Fisherites.

Prominent, laterally persistent hardground.

2' slightly argillaceous zone.

Major bedding plane, small bench.

Prasopora.

Unusually planar hardground.

Nasset K-bentonite, 2". Adjacent strata silicified up to ½" above and 2" below.

Ischadites iowensis.

Small scour or channel filled with grainstone.

Grainstone, persistent laterally, burrowed.

Strongly blackened, bored hardground; position of Conover K-bentonite (missing here).

Approx. position of Calmar K-bentonite (missing here).

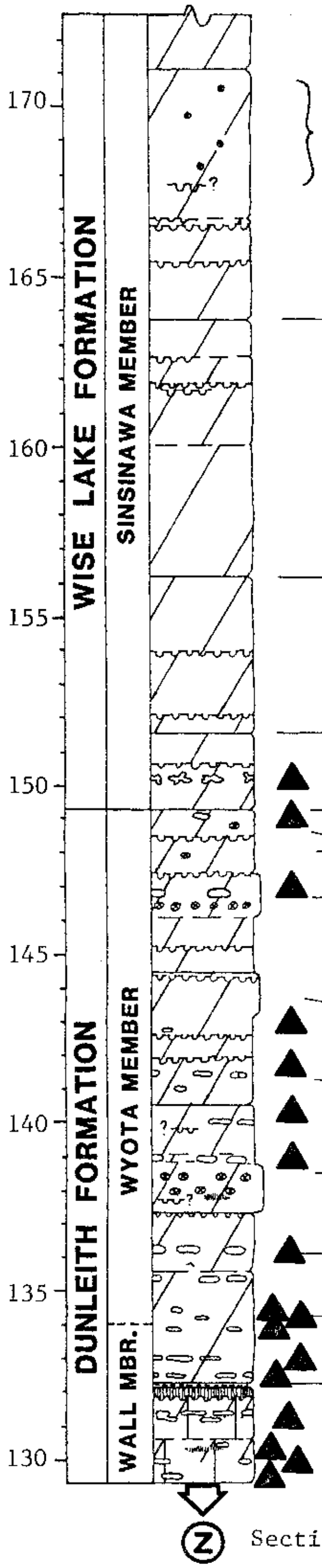
Strongly blackened hardground, visible across entire road cut.

Grainstone upon hardground.

Grainstone upon hardground.

Section continued from previous page.

STOP 3: Guttenberg South road cut (continued)



Highest easy access. Additional 9' Sinsinawa, 44' Stewartville, and 13' Dubuque exposed above.

Irregular vugs, no preferential concentration along definite horizons, mostly ½" diameter.

Major bedding plane.

Major bedding plane.

First major bench along main roadcut.

Major bedding plane.

Vugs

Resistant bed with abundant vugs filled with sparry calcite cement.

Resistant bed.

Some vugs, filled with sparry calcite cement.

Resistant bed with ½" diameter open vugs at two horizons.

Chert riddled with burrows.

Chert nodules and chert breccia.

1" shale separates dolomitized strata above from limestone below. Laminated grainstone just below has resisted dolomitization better than the 2' to 3' of partially dolomitized wackestone beneath the grainstone.

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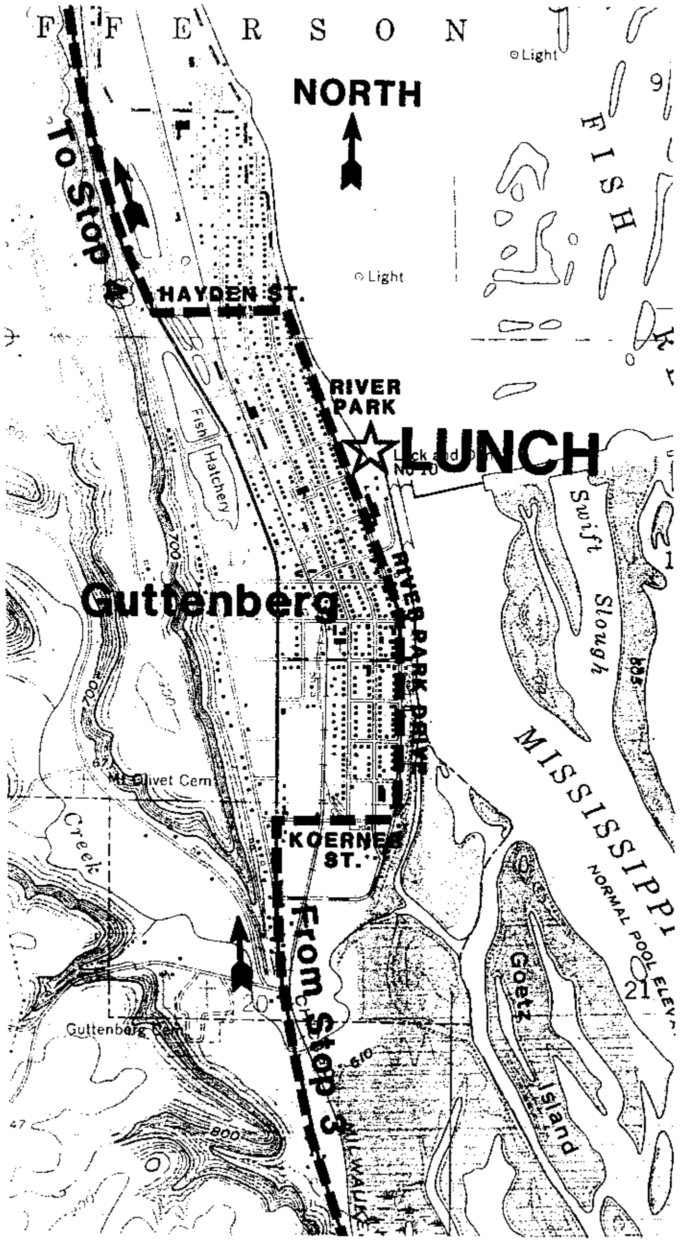


Fig. 8. Trip route through Guttenberg.

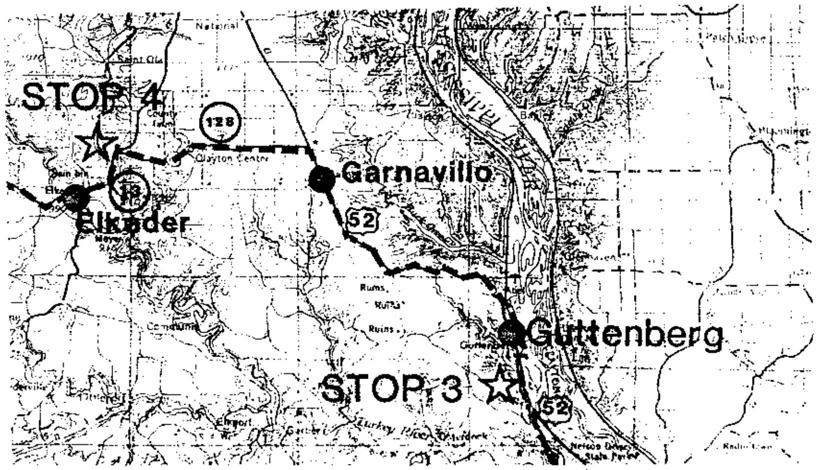


Fig. 9. Trip route, Guttenberg to Elkader.

MILEAGE

Point to point	Cumulative	
0.15	48.95	Turn right on U.S. 52, head up hill. We are driving past the famous Guttenberg North road cut. This is the type section of the Guttenberg Fm. The road cut exposes a continuous section from the St. Peter Sandstone up into the Sinsinawa Member of the Wise Lake Fm. Templeton and Willman (1963) give the following section:

27. Guttenberg North Section

Roadcut of U. S. Highway 52 where it ascends to the upland from the Mississippi River bottomland on the northwest side of Guttenberg, Clayton County, Iowa (SW SW 5, 92N-2W, Elkader Quad.). Type sections of Glenhaven and Garnavillo Members of Guttenberg Formation.

Galena Group

Wise Lake Formation

Sinsinawa Member

Dolomite, pure, vuggy, in 2-4′ beds; a few beds moderately dense with thin argillaceous streaks; scattered small chert nodules in lower part; prominent reentrant at base	27′

Dunleith Formation (138′)

Wyota Member (16′7″)

Dolomite, slightly argillaceous, dense, very cherty	6′ 8″
Dolomite, mostly pure and vuggy alternating with dense and slightly argillaceous beds; contains thin argillaceous-flecked beds, many bands of chert nodules, and 6 corrosion surfaces	9′11″

Wall Member (11′1″)

Dolomite and limestone interbedded, cherty; many thin shale partings	2′ 4″
Limestone, dolomite mottled, dense, cherty	3′ 9″
Bentonite; makes reentrant	0-½″
Limestone, lithographic to medium grained; cherty bands in lower part; prominent corrosion surface at base	5′

Sherwood Member (20′1″)

Limestone, lithographic, gray speckled; black shale partings	1′
Limestone, as above, cherty; red-brown shale partings	1′
Limestone, lithographic, calcarenitic; red-brown chert; few shale partings; corrosion zone in middle and scour surface at base	2′
Limestone, lithographic, gray; argillaceous-flecked beds; many wavy red-brown shale partings	2′ 4″
Limestone, pure, medium and very fine grained, cherty, massive; *Receptaculites*	8′ 2″
Bentonite	2″
Limestone, lithographic, thin bedded, shaly	1′ 1″
Limestone, pure, lithographic, fucoidal; several corrosion surfaces; prominent bedding reentrant at base may contain a bentonite	4′ 4″

Rivoli Member (18′1″)

Limestone, pure, calcarenitic, fine to coarse grained; corrosion surface near bottom; *Receptaculites*	1′11″
Limestone, argillaceous, in 7-13″ beds with thick shale partings; lower part cherty; *Receptaculites* abundant	3′ 7″
Calcarenite, dark gray	4-6″
Shale, gray	2″
Limestone, dolomite mottled, pure, in 4-12″ beds; chert in middle; lower 3″ argillaceous-flecked	7′ 1″
Limestone, very shaly, cherty	7″
Limestone, dolomite mottled, pure, massive	4′ 3″

Mortimer Member (11′3″)

Calcarenite, fine grained; thin shale partings	1′ 1″
Calcarenite, pure, medium grained, massive	2′
Limestone, dolomite mottled, slightly argillaceous, cherty	4′ 3″
Limestone, shaly, prominent reentrant	2″
Limestone, argillaceous, cherty	3′ 9″

Fairplay Member (20′2″)

Limestone, argillaceous; prominent corrosion surface at base	1′ 1″
Limestone, pure, vuggy; chert near top; *Receptaculites* abundant	5′ 5″
Limestone, dolomite mottled; shale partings	5″
Limestone, pure, massive	2′
Bentonite, thin; makes reentrant	
Limestone, pure, dolomite mottled; thick bedded; chert bands in lower half; *Receptaculites* abundant	11′ 3″

Eagle Point Member (13′1″)

Limestone, slightly argillaceous, dolomite mottled, cherty; *Receptaculites*	2′ 3″
Limestone, pure, dolomite mottled, in 1-6″ beds; many bands of chert nodules; *Receptaculites*, *Prasopora*	10′10″

Beecher Member (7′10″)

Limestone, pure, massive	1′ 6″
Limestone, shaly; corrosion surface at top	3″
Limestone, pure, massive	1′ 4″
Limestone, shaly	2″
Limestone, pure, fossiliferous, in 1-5″ beds with shaly partings; lower 1′ vuggy	4′ 7″

St. James Member (top of Ion) (9′4″)

Shale, green; large *Prasopora*	4″
Limestone, pure, gray, massive; argillaceous at base	1′
Shale and limestone interbedded; small *Prasopora*	1′ 1″
Limestone, slightly argillaceous, massive	6″
Shale and limestone interbedded; corrosion surface at base	1′ 1″
Limestone, pure to slightly argillaceous, vuggy at base, slightly shaly in middle; corrosion surface 1′6″ above base	5′ 4″

Buckhorn Member (10′6″)

Limestone and shale interbedded	8″
Calcarenite, dark gray; *Dalmanella* abundant	2″
Limestone, argillaceous	7″
Shale, green	7″
Limestone, calcarenitic	6″
Shale, green; limestone nodules and lenses	1′
Limestone, argillaceous, and shale, green, interbedded	2′ 5″
Limestone, shaly	2′ 2″
Shale, green; contains a thin gray clay bed, possibly bentonite	4″
Limestone, calcarenitic; strong corrosion surface at base	1″
Limestone, massive	1′
Shale, green; grades to shaly limestone	1′

Decorah Subgroup

Guttenberg Formation (16′6″)

Glenhaven Member (14′10″)

Limestone, light brown, weathering whitish, dolomite mottled, very fine grained, in relatively regular beds with major bedding planes 8-13″ apart and minor planes 1-2″ apart; red-brown shale partings; much fossil debris and calcarenite streaks	6′
Limestone, as above but argillaceous, lithographic, more shaly, with thicker red-brown shale beds, more wavy bedding and whiter weathering	8′10″
Bentonite	½-1½″

Garnavillo Member (1′8″)

Limestone, argillaceous, brownish gray	7″
Shale, green	4″
Limestone, argillaceous, massive; abundant small black phosphatic nodules in basal 2″; lower part grades laterally to green shale	9″

Spechts Ferry Formation (6′4″)

Shale, green; contains several thin beds of coquina and beds of nodules of argillaceous limestone	1′ 4″
Limestone, argillaceous, interbedded with coquina	2-3″
Shale, green; lenses of dark gray calcarenite	4-5″
Coquina, dark gray	1″
Shale, green; lenses of argillaceous limestone	1-2″
Limestone, argillaceous, interbedded with coquina	4-6″
Shale, dark gray-green	5″
Shale, dark brownish and dark greenish gray, fossiliferous	2′ 3″
Dolomite, very argillaceous and silty, light brownish gray, massive; weathers platy; *Pionodema* abundant	3″
Bentonite, orange	¼-1″
Shale, green	3″
Shale, dark greenish gray; abundant *Pionodema*	7″

Section at Guttenberg North road cut (Templeton and Willman, 1963), continued:

Platteville Group	
Grand Detour Formation (17′)	
Forreston Member (9′9″)	
Limestone, dark purplish gray, red flecked, dolomite mottled, very fine grained	1-2″
Limestone, silty, argillaceous, gray, black flecked; lower 1″ dolomite mottled; calcarenite at base	1′11″
Limestone, dolomite mottled, gray, very fine grained, fucoidal; corrosion surface above thin calcarenite 2″ above base	1′
Limestone, as above, with prominent brownish gray argillaceous partings; several beds of calcarenite; weathers thin bedded	6′ 8″
Clement Member (4″)	
Calcarenite, dark purplish gray, medium grained	2-5″
Stillman Member (4′11″)	
Limestone, gray, lithographic, thin bedded, shaly; ½″ orange clay at top may be bentonite	1′ 3″
Limestone, lithographic, nodular	8″
Limestone, gray, fine to medium grained; corrosion surface 4″ below top	1′ 2″
Limestone, white, lithographic; corrosion surface at top; lower half locally replaced by calcarenite	4″
Limestone, gray, lithographic, thin bedded, shaly	1′ 6″
Walgreen Member	
Limestone, dolomite mottled, gray, weathering white, lithographic, in 2-5″ beds	1′
Dement Member	
Limestone, as above, but massive	1′
Mifflin Formation (16′10″)	
Briton Member (7′4″)	
Limestone, gray, weathering white, lithographic, thin bedded	1′10″
Limestone, as above but has thick shale partings	5′ 6″
Hazelwood Member	
Limestone, as above but massive	1′
Establishment Member	
Limestone, as above but has thick shale partings	5′
Brickeys Member	
Limestone, as above but in 1-4″ beds with thin shale partings	3′ 1″
Blomeyer Member	
Limestone, gray, lithographic, and shale, calcareous, green to buff	5″
Pecatonica Formation	
Medusa Member (5′2″)	
Dolomite, buff, fine grained, massive; contains red fucoids; strongly pitted ferruginous top surface	10″
Dolomite, pure, gray to buff, medium grained, in 8-24″ beds	4′ 4″
New Glarus Member	
Dolomite, pure, massive	2′ 1″
Dane Member	
Dolomite, argillaceous, gray to buff, fine grained, in 2-6″ beds	3′ 3″
Covered	5′
Ancell Group	
Glenwood Formation	
Harmony Hill Member	
Shale, green, mostly covered	5′ 3″
St. Peter Formation	
Sandstone, white, fine grained, friable, ferruginous and quartzitic at top; base concealed	5′

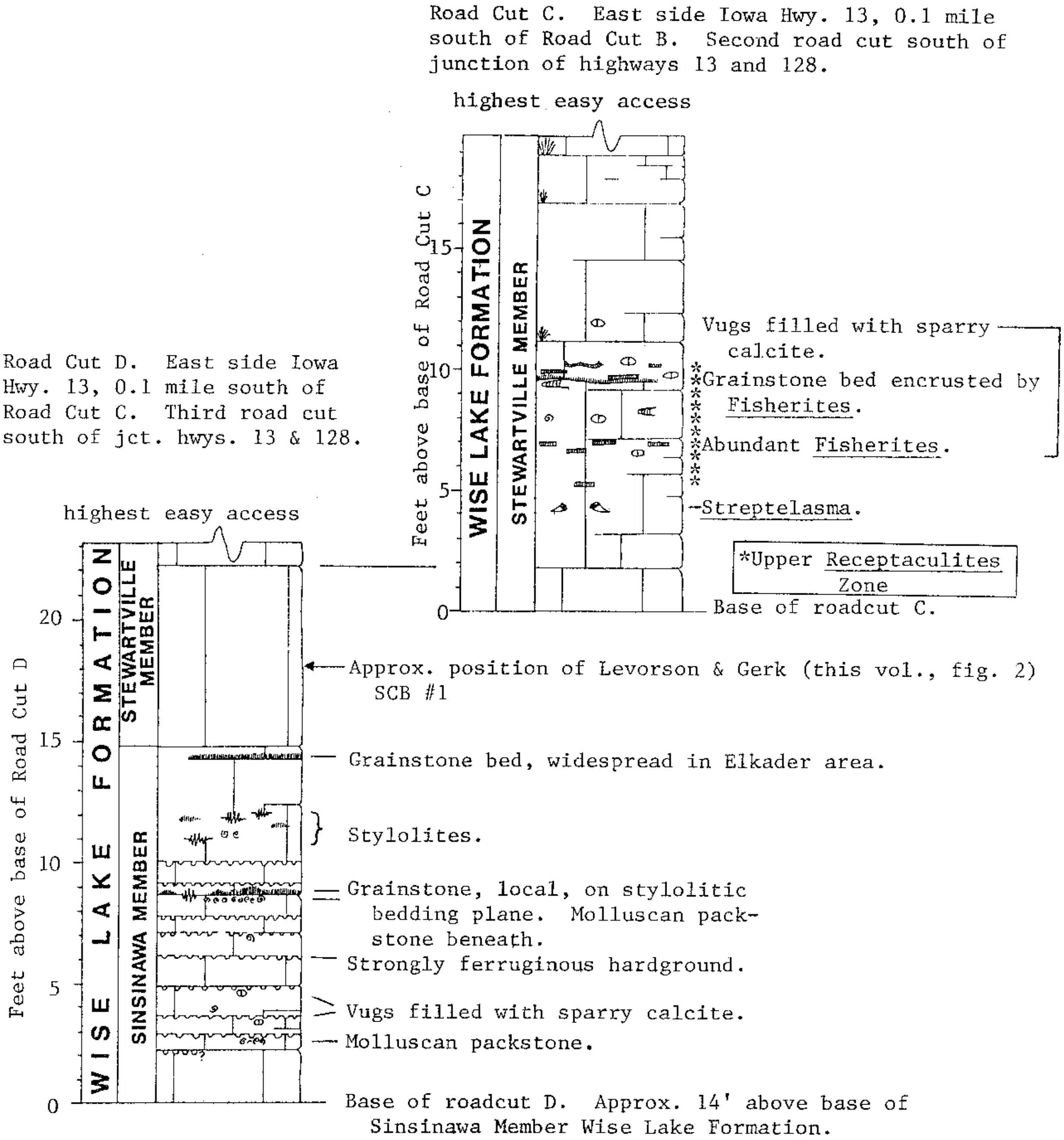
MILEAGE

Point to point	Cumulative	
9.45	58.4	Enter Garnavillo.
0.4	58.8	Leave Garnavillo.
1.2	60.0	Turn left on Iowa Hwy. 128.
3.95	63.95	Clayton Center, Iowa.
3.0	66.95	Road cut on right side in Dubuque Fm. This is Stop 4.

STOP 4. ROAD CUTS NORTHEAST OF ELKADER. SE SW and NW SE 12, 93N-5W (Farmersburg and St. Olaf 7.5' Quadrangles).

At this stop we will examine briefly four road cuts (designated A, B, C, and D; see fig. 10) which expose most of the Wise Lake and lower Dubuque section which was inaccessible at Guttenberg. Details are noted on the graphic sections. A fifth cut, south of D, is old, weathered, and dangerous to examine due to lack of a shoulder on busy Hwy. 13; it duplicates upper Dunleith strata seen at stop 3.

STOP 4: Road cuts northeast of Elkader



Road Cut C. East side Iowa Hwy. 13, 0.1 mile south of Road Cut B. Second road cut south of junction of highways 13 and 128.

Road Cut D. East side Iowa Hwy. 13, 0.1 mile south of Road Cut C. Third road cut south of jct. hwys. 13 & 128.

Vugs filled with sparry calcite.

*Grainstone bed encrusted by *Fisherites*.

*Abundant *Fisherites*.

Streptelasma.

*Upper *Receptaculites* Zone

Base of roadcut C.

Approx. position of Levorson & Gerk (this vol., fig. 2) SCB #1

Grainstone bed, widespread in Elkader area.

Stylolites.

Grainstone, local, on stylolitic bedding plane. Molluscan packstone beneath.

Strongly ferruginous hardground.

Vugs filled with sparry calcite.

Molluscan packstone.

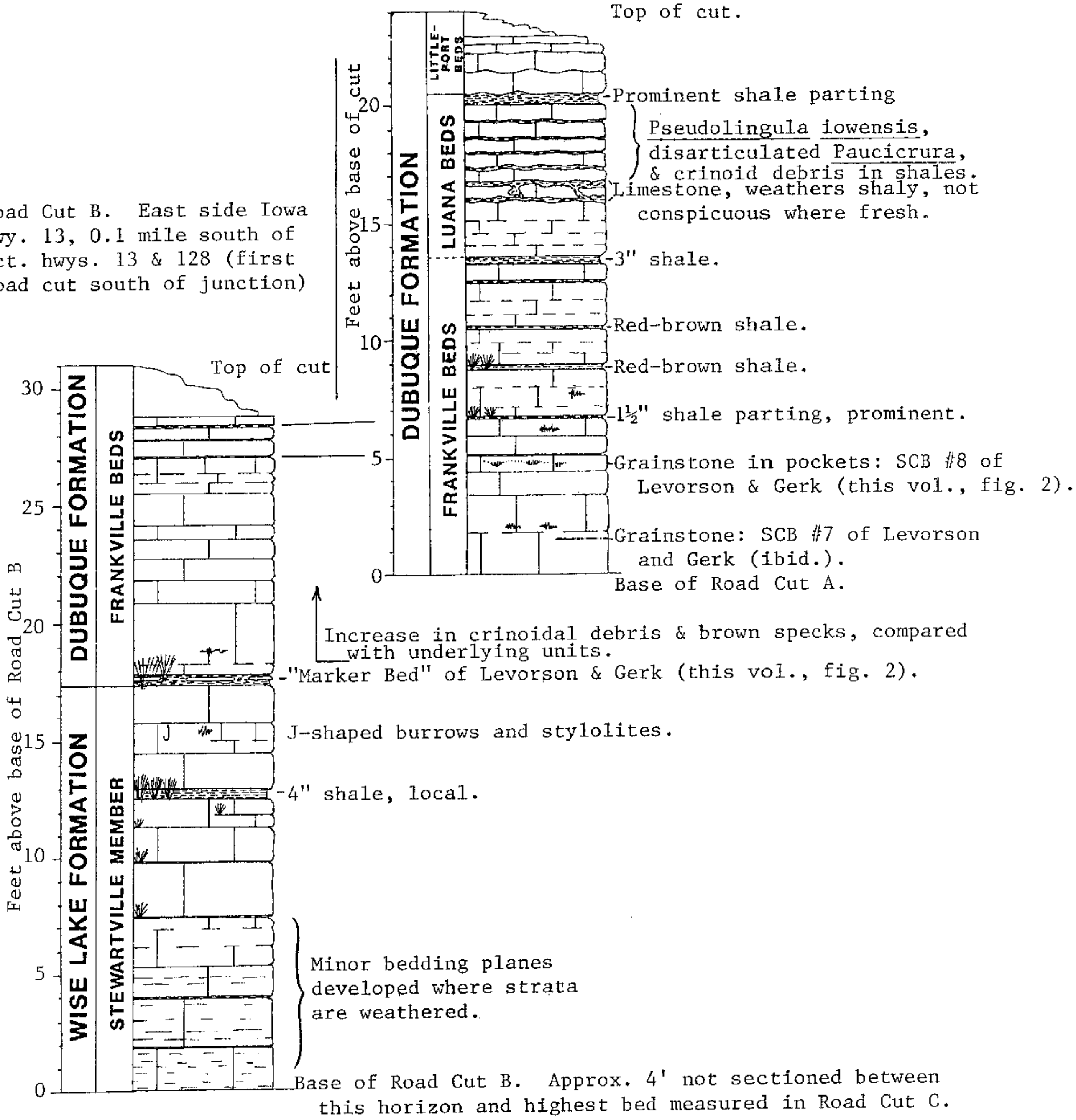
Base of roadcut D. Approx. 14' above base of Sinsinawa Member Wise Lake Formation.

Figure 10.

STOP 4: Road cuts northeast of Elkader (continued)

Road Cut A. North side of Iowa Highway 128 at junction with Iowa Highway 13.

Road Cut B. East side Iowa Hwy. 13, 0.1 mile south of jct. hwys. 13 & 128 (first road cut south of junction)



Top of cut.

-Prominent shale parting

Pseudolingula iowensis, disarticulated Paucicrura, & crinoid debris in shales.

Limestone, weathers shaly, not conspicuous where fresh.

-3" shale.

-Red-brown shale.

-Red-brown shale.

-1½" shale parting, prominent.

-Grainstone in pockets: SCB #8 of Levorson & Gerk (this vol., fig. 2).

-Grainstone: SCB #7 of Levorson and Gerk (ibid.).

Base of Road Cut A.

Top of cut

Increase in crinoidal debris & brown specks, compared with underlying units.

-"Marker Bed" of Levorson & Gerk (this vol., fig. 2).

J-shaped burrows and stylolites.

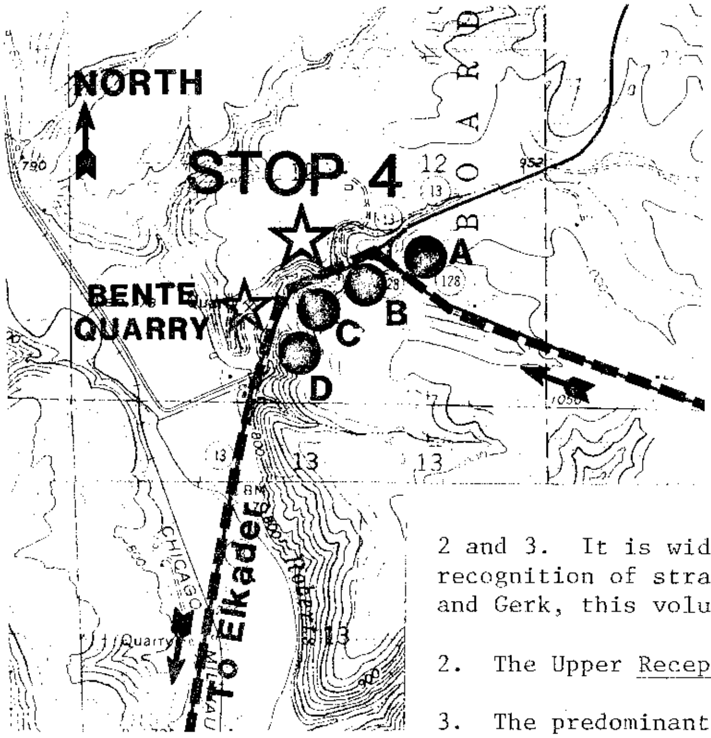
-4" shale, local.

Minor bedding planes developed where strata are weathered.

Base of Road Cut B. Approx. 4' not sectioned between this horizon and highest bed measured in Road Cut C.

Stop 4 -- continued

Fig. 11. Road cuts at Stop 4.



The Bente Quarry on the west side of Highway 13 displays the same section as seen in these road cuts. Correlations and member contacts in the graphic sections were located with considerable help from an unpublished stratigraphic section of the Bente Quarry kindly provided me by Calvin Levorson and Arthur Gerk.

Note:

1. The zone containing at least nine closely-spaced hardgrounds in the Sinsinawa Member of the Wise Lake. This zone was also seen at stops 2 and 3. It is widespread and useful for field recognition of stratigraphic position (Levorson and Gerk, this volume).

2. The Upper *Receptaculites* Zone.

3. The predominantly molluscan fauna in much of the Wise Lake and lower Dubuque.

4. J-shaped burrows, not hitherto described in the literature, which are very characteristic of the zone near the Wise Lake/Dubuque boundary.

5. The continuous grainstone beds (SCB's #7 and #8 of Levorson and Gerk, 1972 and this vol.). The grainstones of the Dunleith do not persist laterally, but at least eight in the Wise Lake and lower Dubuque can be traced miles laterally. SCB #7 has been traced over 100 miles (Levorson et al., 1979).

MILEAGE

Point to point	Cumulative	
0	66.95	Return to cars. Turn left onto busy Hwy. 13 (watch for traffic!).
0.7	67.95	Road cuts in Galena Group both sides.
1.3	68.95	Road cut, Galena Group.
0.45	69.4	Turn right on Iowa Hwy. 56, follow 56 through Elkader.
0.55	69.95	Old stone arch bridge over Turkey River; downtown Elkader.
0.2	70.15	Stay on 56 around right turn onto North Second Street.

MILEAGE

Point to point	Cumulative	
0.3	70.45	Road cut, Wise Lake Fm.?
0.5	70.95	Leave Elkader. Still on Hwy. 56.
6.0	76.95	Long views north and south intermittently for next mile.
5.4	82.35	Turn right onto county road W51 toward Elgin.
3.9	86.25	Enter Elgin. We are low in the Maquoketa section here, and

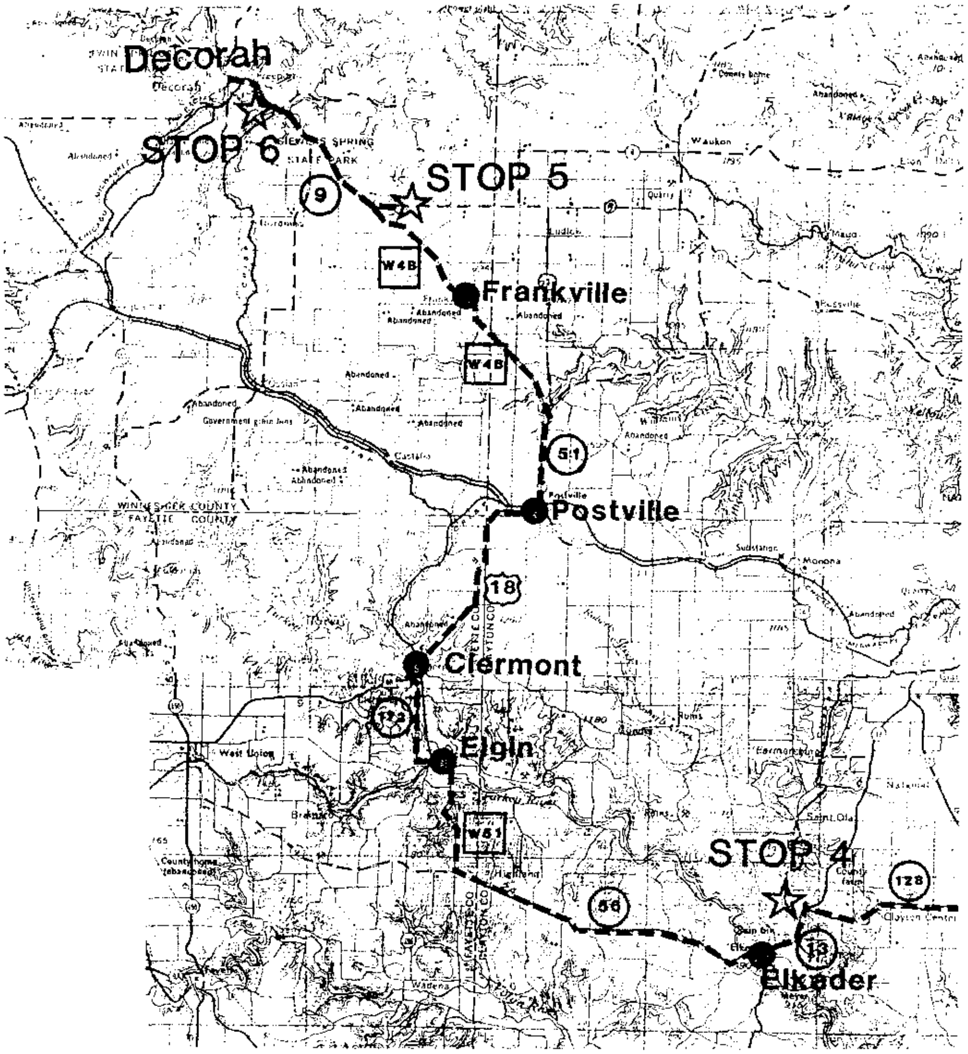


Fig. 12. Trip route from Elkader to Decorah.

MILEAGE		
Point to point	Cumulative	
		several famous collecting localities in the *Vogdesia* and *Isotelus* Zones are in the vicinity.
0.3	86.55	Cross narrow bridge, then take *immediate* left at north end of bridge onto Main St. Stay on Main St. through town.
1.1	87.65	Leave Elgin.
1.6	89.25	Bridge over Turkey River.
1.0	90.25	Cemetery on right. Enter Clermont.
0.6	90.85	Turn right onto Mill Street (U.S. 18). Note the prevalent brick construction of the old buildings in Clermont. The bricks were made locally from Maquoketa shale.
0.6	91.45	Road cut both sides in Fort Atkinson Dolomite, part of the Maquoketa Group. Note abundant chert.
0.3	91.75	Silurian dolomite on both sides of road at top of hill.
6.75	98.5	Jct. U.S. 18 and U.S. 52. Stay straight on U.S. 18 into Postville.
0.2	98.7	Enter Postville.
0.9	99.6	Turn left onto Lawler St. (Iowa Hwy. 51 north).
0.2	99.8	Railroad crossing; very rough! go slowly.
2.3	102.1	Road cut both sides, probably upper Elgin Fm., Maquoketa Gp. (A. J. Gerk, written commun., 1983).
0.5	102.6	Road cut on left is practically a complete exposure of the Dubuque Fm. SCB's #7 and #8 are present in the Frankville beds. The quarry on the right duplicates the road cut section, and additionally has underlying strata of the Stewartville Member of the Wise Lake Fm. Art Gerk has been keeping tabs on activity in this quarry; if recent work has exposed the Dubuque/Maquoketa contact and if we are ahead of schedule, we may make a brief stop here.
0.4	103.0	Road cuts both sides, Stewartville Mbr. Wise Lake Fm. About 10' of Upper *Receptaculites* Zone present at base. SCB's #2, #3, and #4 are present (A. J. Gerk, written commun., 1983).
0.8	103.8	Series of small road cuts, Wise Lake Fm.

MILEAGE

Point to point	Cumu-lative	
0.15	103.95	Turn left onto county road W4B (road to Frankville).
3.65	107.6	Frankville.
4.3	111.9	Quarry on right, not examined.
1.6	113.5	Turn right on Iowa Hwy. 9.
0.3	113.8	Road cut both sides exposing complete Dubuque Fm. This is Stop 5.

STOP 5. DUBUQUE FORMATION REFERENCE SECTION. SW SW and SE SE 4, and NW NW and NE NE 9, 97N-7W (Postville NW 7.5' Quadrangle).

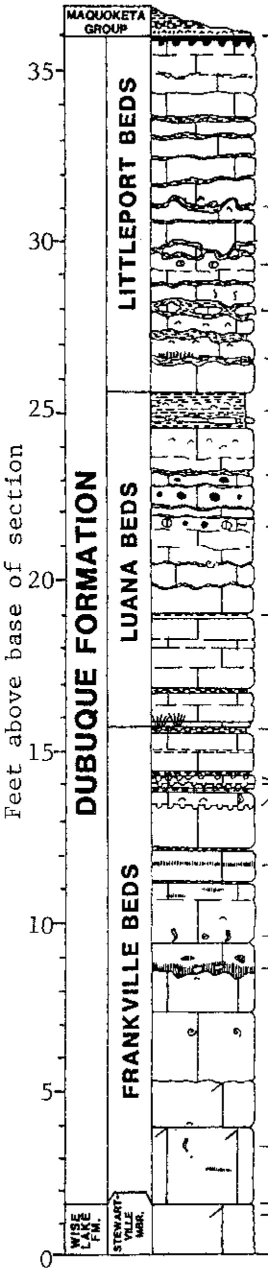
Road cuts at the top of the hill on both sides of the road on both the east and the west sides of the valley together expose the complete Dubuque Fm. and its contacts with the underlying Wise Lake Fm. and the overlying Maquoketa Gp. The graphic section is a composite section; strata below the Luana/Littleport contact were measured north of the highway on the west side of the valley; strata of the Littleport beds were measured on the north side of the highway on the east side of the valley.

Details are noted on the graphic section. Note:

1. Position of the "Marker Bed". This is one of the anomalous localities where the "Marker Bed" is difficult to recognize.
2. Paleosynapta flaccida, the problematic index fossil of the upper Stewartville/lower Dubuque (see discussion by Levorson and Gerk, this vol.). It may be either a mold of a soft-bodied organism or a trace fossil.
3. Heavy dolomite mottling at the base of the cut. Argillaceous content increases and dolomite mottling decreases upward in the section.
4. Grainstones, SCB's #7 and #8 of Levorson and Gerk (1972 and this vol.). Note the irregular base of #7, which can be traced over 100 miles laterally.
5. Zone of heavy pyrite development in the upper Luana beds. This feature is characteristic of the upper Luana beds at least as far as Mineral Point, Wisconsin, about 85 miles east of here.
6. Increasingly wavy bedding planes upward in the section starting in the upper Luana beds. Several features are suggestive of soft-sediment deformation (e.g. apparent folding of packstone layers at 26' 7").
7. A tabular backfilled feeding burrow, tentatively ascribed to Zoophycus, is

STOP 5: Dubuque Fm. Reference Section

Composite section measured on north side Iowa Highway 9 at road cuts in SW SW 4, SE SE 4, SW SW 9, and SE SE 9, 97N-7W



Top of cut.

Diastemic hardground, strongly ferruginized, plated with phosphatic crust. Overlying hardground is basal Maquoketa phosphatized "Depauperate fauna" and phosphate nodules in zone 1" thick; this is overlain by unfossiliferous gray shale.

Bedding plane with 6" relief. Pseudolingula iowensis.

Vugs with sparry calcite filling.

Nodules of burrowed micrite (sedimentary boudinage?)

Crinoidal packstone, apparent soft-sediment deformation.

12" shale.

Zone of pyrite nodules, pyritic feeding burrows, and vugs with pyrite haloes and sparry calcite filling.

Upper limit of dolomite mottling. Increasingly argillaceous above.

Prominent 1" to 3" shale bed, vegetated.

3 hardgrounds, local, faint.

Grainstone: SCB #8 of Levorson & Gerk (this vol., fig. 2).

Paleosynapta flaccida WEISS.

Grainstone, up to 3" thick, with intraclasts: SCB #7 of Levorson and Gerk (ibid.). Pseudolingula iowensis below.

Molluscan fauna characteristic of lower part of cut.

Heavily dolomite-mottled to base.

Paleosynapta flaccida.

Position of "Marker Bed" of Levorson and Gerk (this vol.).

Base of cut.

Figure 13.

Stop 5 -- continued

abundant in the Littleport beds. Commonly it can only be recognized on sawed and polished sections.

8. The Dubuque/Maquoketa contact is exposed on the north side of the east cut. The basal Maquoketa phosphatic zone and the "Depauperate fauna" are present. Although the contact zone displays many signs of being a condensed section (e.g., hardground development, phosphatization), there is essentially no sign of stratigraphic cut-out at this contact in the Upper Mississippi Valley outcrop area (Levorson et al., 1979). In Minnesota, this contact is a normal conformable formation contact without hardground development, phosphatization, or development of the "Depauperate fauna". However, near the Ozark Dome (Templeton and Willman, 1963), and in the Texas-Wisconsin Gas Van Driest #1 well in Sheboygan County, eastern Wisconsin (Moretti, 1971), more than 100 feet of Dubuque, Wise Lake, and upper Dunleith strata are cut out beneath the basal Maquoketa.

MILEAGE

Point to point	Cumulative	
0	113.8	Return to cars. All vehicles will make U-turns; it may be necessary to proceed east to the first side road for turning. Traffic moves very fast on Hwy. 9, especially large trucks. Head west on Hwy. 9.
0.3	114.1	Jct. with W4B on left. Continue straight on 9.
3.7	117.8	Begin series of road cuts on alternating sides of highway descending through the section from Wise Lake to the base of the Dunleith. These are localities 8, 8A, 8B, etc., of Levorson and Gerk, 1972.
0.5	118.3	Stop opposite the next-to-last road cut on the left side of the road, across the gully. The road cut has two benches. This is Stop 6.

STOP 6. EXPOSED HARDGROUND SURFACE, RIVOLI MEMBER. NE NE 26, 98N-8W (Freeport 7.5' Quadrangle).

This road cut is locality 8-B of Levorson and Gerk (1972), and was described in detail by Gerk and Levorson (1972). The stratigraphic section is essentially that of the general section for Winneshiek County of Levorson and Gerk (this vol., fig. 2). Our objective is the second bench on this road cut; it is perhaps the finest exposed hardground surface in the United States. The paleoecology has been described by Palmer and Palmer (1977) and Palmer (1978).

Note here:

1. <u>Thalassinoides</u> omission-suite burrows in the hardground. They are filled with dolomite, although the matrix is limestone. Scouring has unroofed

Stop 6 -- continued

some. Scouring has lowered the bedding surface by three to five inches at least at this locality; it is not certain how much of this erosion occurred before lithification and how much after.

2. The odd "railroad track" trace fossil, *Scalaridomus flexuosus* PALMER 1978. Palmer believes it to be a burrow consisting of two parallel tunnels, connected by cross-tunnels at approximately 8-inch intervals. The burrow complex, in this interpretation, has been unroofed by subsequent scour. Palmer asserts that, at various places on the hardground, the trace can be seen to descend below the present bed surface. This is a critical contention, for if verified it would clinch the case for *Scalaridomus* being a burrow. Otherwise one might advance the alternative suggestion that *Scalaridomus* is a track, perhaps grooves dug by genal spines of *Eoharpes*, *Ceraurus*, or *Isotelus*. In the latter case, scouring would largely predate formation of *Scalaridomus*; this would indicate that most scouring occurred before lithification of the surface. By this interpretation, Palmer's (1978) "cross-tunnels" at 8-inch intervals would be fortuitous intersections of the post-scour trail with pre-scour unroofed burrows. Which interpretation best fits your observations?

3. *Trypanites*, the small cylindrical polychaete (Kobluk and Nemcsok, 1982) boring, is concentrated on mounds which rise above the general level of the hardground. What is the origin of the mounds? Did the *Trypanites* animals baffle their immediate neighborhood against scour, thus producing the mounds as erosional remnants? Or did *Trypanites* animals preferentially colonize preexisting mounds?

4. The hardground surface is cracked in places. Some cracks are filled with cemented sediment, or overgrown by bryozoan colonies; thus, the cracks were present in Dunleith time.

5. Encrusting bryozoan colonies and echinoderm holdfasts can be seen at several places. In addition, some brachiopods appear to be cemented in place above the hardground. These represent the "post-omission" suite.

6. At least two truncated orthoconic cephalopods can be seen embedded in the hardground surface. These large nautiloids were members of the "pre-omission" suite, and their shells were buried before cessation of sedimentation and development of the hardground surface. Scouring has removed the top half of each shell, laying bare an approximately axial section. These fossils are probably molds of the original aragonite cephalopod shell, as aragonite generally dissolved just beneath the Galena sea floor (Delgado, 1980).

This concludes the formal field trip. For those planning on staying overnight in Decorah, the Super 8 and Cliff House motels are ahead on Hwy. 9.

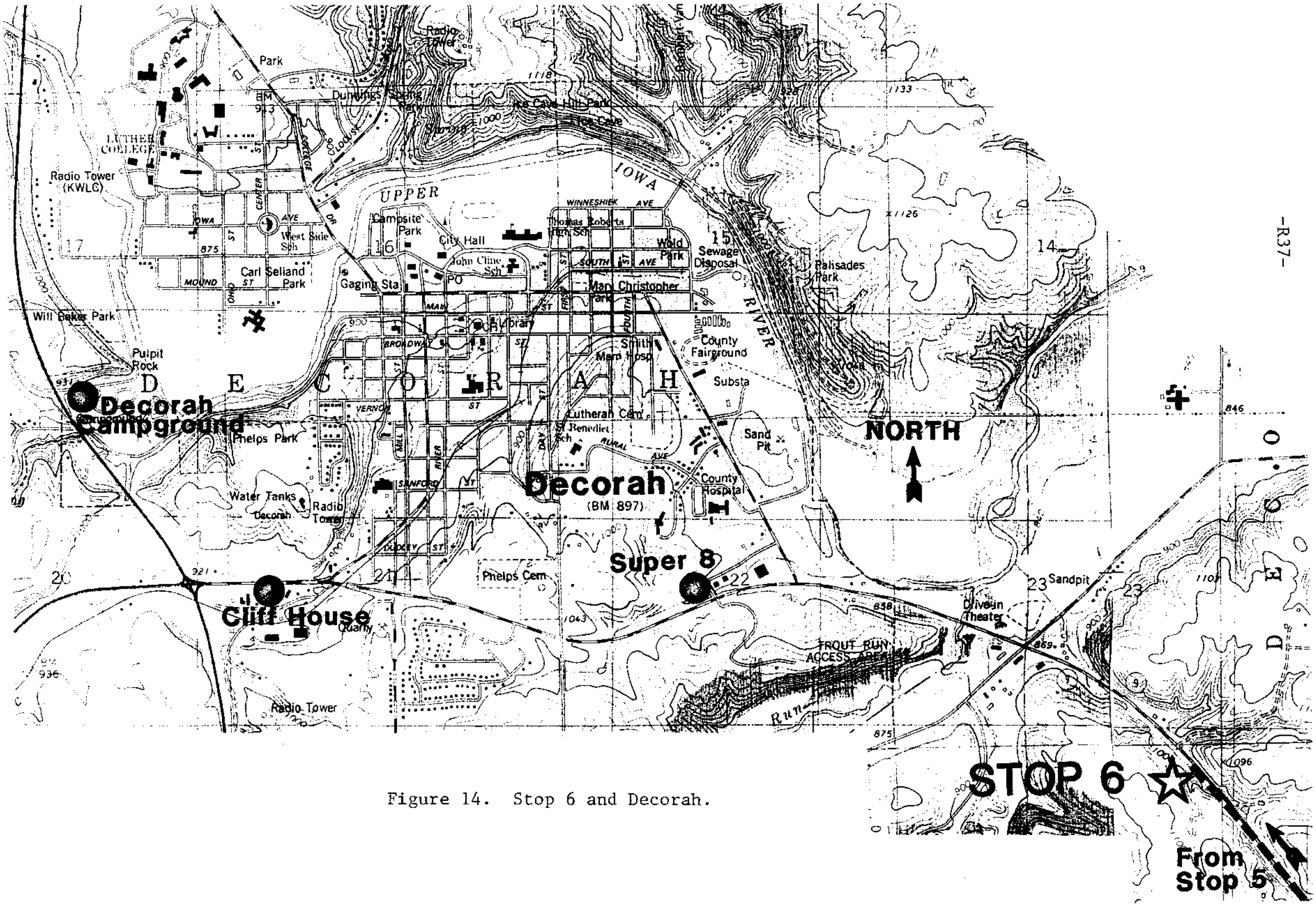


Figure 14. Stop 6 and Decorah.

REFERENCES

Delgado, D. J., 1980, Submarine diagenesis (aragonite dissolution, cementation by calcite, and dolomitization) in Ordovician Galena Group, Upper Mississippi Valley (abstr.): Am. Assoc. Petroleum Geologists Bull., v. 64, p. 697.

Delgado, D. J., 1983, Ringgenberg Quarry: in Sedimentology of Ordovician carbonates and sandstones, southwestern Wisconsin: Guidebook prepared for the 17th annual meeting, North Central Section, Geol. Soc. America, Univ. of Wisconsin-Madison, Madison, Wis., April 28-May 1, 1983.

Finney, S. C.; and Nitecki, M. H., 1979. Fisherites n. gen. reticulatus (Owen, 1844), a new name for Receptaculites oweni Hall, 1861: Jour. Paleont., v. 53, p. 750-753.

Gerk, A. J.; and Levorson, C. O., 1972, Revision of Galena stratigraphy: Guidebook for Geological Society of Iowa field trip, May 6, 1972. 10 p.

Kobluk, D. R.; and Nemcsok, S., 1982, The microboring ichnofossil Trypanites in colonies of the Middle Ordovician bryozoan Prasopora: population behavior and reaction to environmental influences: Can. Jour. Earth Sci., v. 19, p. 679-688.

Levorson, C. O.; and Gerk, A. J., 1972, A preliminary stratigraphic study of the Galena Group of Winneshiek County, Iowa: Proc. Iowa Acad. Sci., v. 79, p. 111-122.

Levorson, C. O.; Gerk, A. J.; and Broadhead, T. W., 1979, Stratigraphy of the Dubuque Formation (Upper Ordovician) in Iowa: Proc. Iowa Acad. Sci., v. 86, p. 57-65.

Moretti, G., Jr., 1971, Reference section for Paleozoic rocks in eastern Wisconsin: Van Driest #1, Sheboygan County: Unpub. M.S. thesis, Univ. of Wisconsin-Milwaukee, 138 p.

Mossler, J. H.; and Hayes, J. B., 1966, Ordovician potassium bentonites of Iowa: Jour. Sedimentary Petrology, v. 36, p. 414-427.

Palmer, T. J., 1978, Burrows at certain omission surfaces in the Middle Ordovician of the Upper Mississippi Valley: Jour. Paleont., v. 52, p. 109-117.

Palmer, T. J.; and Palmer, C. D., 1977, Faunal distribution and colonization strategy in a Middle Ordovician hardground community: Lethaia, v. 10, p. 179-199.

Sardeson, F. W., 1907, The Galena Series: Geol. Soc. America Bull., v. 18, p. 179-194.

Templeton, J. S.; and Willman, H. B., 1963, Champlainian Series (Middle Ordovician) in Illinois: Illinois State Geol. Survey Bull. 89, 260 p.