PROCEEDINGS OF THE 10TH SYMPOSIUM ON THE GEOLOGY OF THE BAHAMAS AND OTHER CARBONATE REGIONS

Edited by
Benjamin J. Greenstein and Cindy K. Carney

Production Editor:
Dana Bishop

Gerace Research Center
San Salvador, Bahamas
2001

Front Cover: The reef crest indicator species, *Acropora palmata*, on Gaulin's Reef, San Salvador Island. Gaulin's Reef is a classic bank-barrier reef that has shown remarkable resilience following two significant disturbances: El Niño-induced warming of the sea surface in 1998 and Hurricane Floyd in September, 1999 (see Peckol et al., this volume). Photo by Janet Lauroesch.

Back Cover: The oolite shoals of Joulter's Cay, north of Andros Island, Bahamas, site of the pre-meeting field trip. Photo by Ben Greenstein.

© Copyright 2001 by Gerace Research Center

All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electric or mechanical, including photocopy, recording, or any information storage and retrieval system, without permission in written form.

ISBN 0-935909-69-9

EARLY TIDAL FLAT DOLOMITIZATION IN THE SILURIAN BYRON FORMATION OF THE MICHIGAN BASIN

Katherine A. Hartig and Kathleen Counter Benison
Department of Geology
Central Michigan University
Mt. Pleasant, MI 48859

ABSTRACT

The Silurian Byron Formation (Burnt Bluff Group) of northern Michigan is composed of both limestone and dolostone, but until now its diagenetic history has not been studied in detail. Lithologies, sedimentary structures, and fossils indicate that the Byron Formation was deposited in peritidal environments similar to those of the modern Bahamas. Petrographic study of a core from Alpena, Michigan has focused on evaluating its diagenetic history. In particular, this study characterizes the dolomite and its relationships with depositional features and other diagenetic features.

Four main types of dolomite have been found in the Byron Formation: (1) isolated, randomly-oriented pseudomorphs of displacive dolomite rhombs; (2) massive replacement interlocking dolomite crystal mosaic; (3) isolated small equant replacement dolomite crystals; and (4) equant dolomite cement.

Displacive dolomite pseudomorphs, some associated with displacive anhydrite, are found in mudstone intraclasts and are interpreted as having formed very early in a peritidal environment. The interlocking crystal mosaic dolomite is found only in supratidal mudstone units and as dolomite intraclasts at the base of intertidal and subtidal limestone units, suggesting very early replacement of supratidal lime sediments. Isolated replacement dolomite crystals cross-cut both calcite shells and peloid grain boundaries. The equant dolomite cement fills fractures and displacive dolomite pseudomorphs, and the timing of this cement is difficult to ascertain.

These observations indicate that the majority of the dolomite in the Silurian Byron Formation, including some (if not all) of the replacement dolomite, formed very early in this rock's diagenetic history. Depositional environment, timing, and association with displacive evaporites suggest that evaporated seawater may have been the dolomitizing fluid. This study has shown that dolomite, including replacement dolomite, can form early in supratidal zones in the presence of evaporated seawater.

INTRODUCTION

The formation of dolomite has long been an enigma to sedimentary geologists and geochemists. Dolostones are common in the rock record and serve as important oil and gas reservoirs and lead-zinc deposits. Regardless, conditions of dolomitization are not well understood. Numerous field, petrographic, geochemical, experimental and theoretical studies have led to various models for dolomitization (see Hardie, 1987 and Morrow, 1990 for summaries.) Continuation of basic petrographic descriptions is still important in helping to refine these models and better understand conditions of dolomitization.

The Michigan Basin is famous for its Silurian rocks, especially its Niagaran reefal carbonates and Salina halites (Dellwig, 1955; Soderman and Carozzi, 1963; Sears and Lucia, 1979; Cercone and Lohmann, 1987; Sonnenfeld and Al-Aasm, 1991; Leibold, 1992).

The Michigan Basin also contains Silurian peritidal carbonates that have not received as much attention as their reefal and evaporitic cousins (Harrison, 1985). This paper describes the basic depositional and diagenetic history of the early Middle Silurian Byron Formation of northern Michigan (Fig. 1). Focus on the dolomitization adds new insights to the dolomite problem.

SERIES	GROUP	FORMATION
Cayugan	Salina	St. Ignace Dolomite
		Pointe aux Chenes Shale
Niagaran		Engadine Dolomite
	Manistique	Cordell Dolomite
		Schoolcraft Dolomite
	Burnt Bluff	Hendricks Formation
		Byron Formation
		Lime Island Formation
Alexandrian	Cataract	Moss Lake Formation
		Cabot Head Shale
		Manitoulin Dolomite

Figure 1. Generalized stratigraphic column for the Silurian rocks of northern Michigan. Modified after Ehlers and Kesling, 1957.

GEOLOGICAL BACKGROUND

The Michigan Basin is a large synclinal basin centered on Michigan's Lower Peninsula and composed mostly of Paleozoic sedimentary rocks. The Silurian of the Michigan Basin is composed of carbonates and evaporites. Niagaran reefal limestones and dolostones have been well documented (Sears and Lucia, 1979; Cercone and Lohmann, 1987). Several studies have interpreted paleoenvironment and paleoclimate from Salina halites (Dellwig, 1955; Sonnenfeld and Al-Aasm, 1991; Leibold, 1992; Losey and Benison, 2000). Silurian peritidal carbonates of the Michigan Basin are less well known.

The early Middle Silurian (lower Niagaran Series) Burnt Bluff Group is found in the subsurface of northern lower Michigan and on the surface at the southern edge of the Upper Peninsula. The limited literature on the Burnt Bluff Group focuses on the stratigraphy, depositional environments, and transgression and regressions associated with these rocks (Ehlers and Kesling, 1957; Ells, 1962; Sheldon 1963; Harrison, 1985; Johnson and Sorenson, 1978).

The Burnt Bluff Group consists of three formations: the Lime Island Formation, the Byron Formation, and the Hendricks Formation (Fig 1). All three formations consists of both limestone and dolostone. The Lime Island Formation at the base of the Burnt Bluff Group contains abundant burrows, forams, brachiopods, mollusks, trilobites, corals, and echinoderms (Harrison, 1985). Harrison (1985) interpreted the Lime Island Formation as a subtidal shelf or shoal reef deposit.

The Byron Formation contains a higher percentage of dolomite compared to the Lime Island Formation and Hendricks Formation. It is characterized by alternating layers of muddy limestones and muddy dolostones that contain thin algal laminations, mudcracks, soft sediment deformation, intraclasts, brachiopods, and gastropods. This formation most likely represents alternating intertidal and supratidal complexes (Harrison, 1985).

The uppermost formation of the Burnt Bluff Group is the Hendricks Formation. It contains limestones and dolostones with various fossils such as stromatoporoids, rugose corals, and tabulate corals. Because of the abundance and type of these fossils, it has been speculated that the Hendricks Formation represents a shoal reef complex (Harrison, 1985).

The diagenetic features of the Burnt Bluff Group, until now, have not been documented. The diagenetic history, with particular attention paid to dolomitization, is the focus of this paper.

METHODS

The majority of the research focused on core and thin section petrography of the Byron Formation (70 feet thick) in the Alpena Brown-Snowplow 1-5 well from Alpena County, Michigan (Fig. 2). Depositional and diagenetic features were first described macroscopically in core samples, followed by microscopic study of thin sections. Identifications of various depositional and diagenetic features and the relationships among those features allowed us to establish a diagenetic history for the Byron Formation. Representative thin sections were stained with Alizarin red in order to distinguish between calcite and dolomite and with potassium ferricyanide to determine if iron was present (Friedman, 1959; Dickson, 1966).

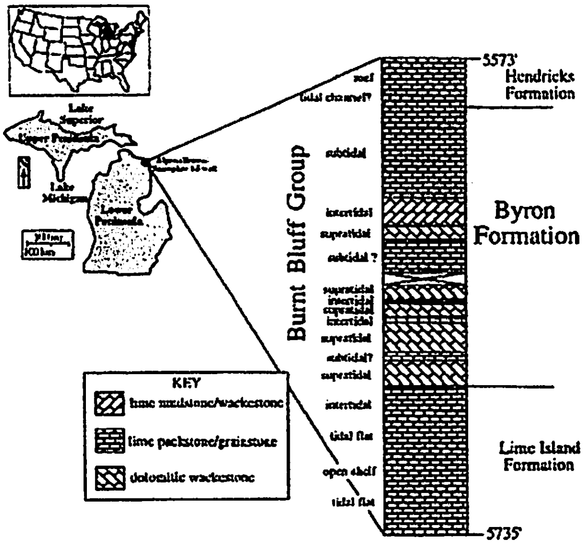

Figure 2. Map showing the location of Alpena Brown-Snowplow 1-5 core in Michigan and the interpreted lithofacies in the core.

Thin sections were examined under cathodoluminescence in order to determine qualitative iron and manganese concentrations and to help correlate various dolomite types. Unfortunately, all samples were dull under cathodoluminescence, so this method could not be used for correlation.

PETROGRAPHIC OBSERVATIONS

We identified three separate lithofacies in the Byron Formation: (1) lime mudstone and wackestone lithofacies, (2) lime packstone and grainstone lithofacies, and (3) dolomitic wackestone lithofacies.

Lime Mudstone and Wackestone Lithofacies

This limestone lithofacies, which makes up less than 10% of the Byron Formation, is dominated by tan to light brown mudstones and wackestones. The mudstones are massive with some barely distinguishable peloids. The wackestones contain rounded mudstone intraclasts and brachiopod- and gastropod-dominated skeletal fragments in a peloidal mud. Slightly wavy and planar thin laminations can be seen throughout this rock, but much of it appears to be massive. Small burrows are also found in these mudstones and wackestones. There is some soft sediment deformation including deformed mudcracks and some mm-scale ball and pillow structures.

Diagenetic features in this unit include displacive anhydrite crystals, two distinctive dolomite types, and some compaction features. Randomly-oriented, euhedral and subhedral crystals of anhydrite are found at the top of one bed of this lime mudstone. Silt-sized, anhedral to euhedral isolated replacement dolomite crystals make up approximately 50% of this peloid-rich mudstone (Fig. 3a). Some of these dolomite crystals cross-cut calcite shell boundaries. In addition, this lithofacies contains fracture- and intergranular pore-filling calcite and dolomite

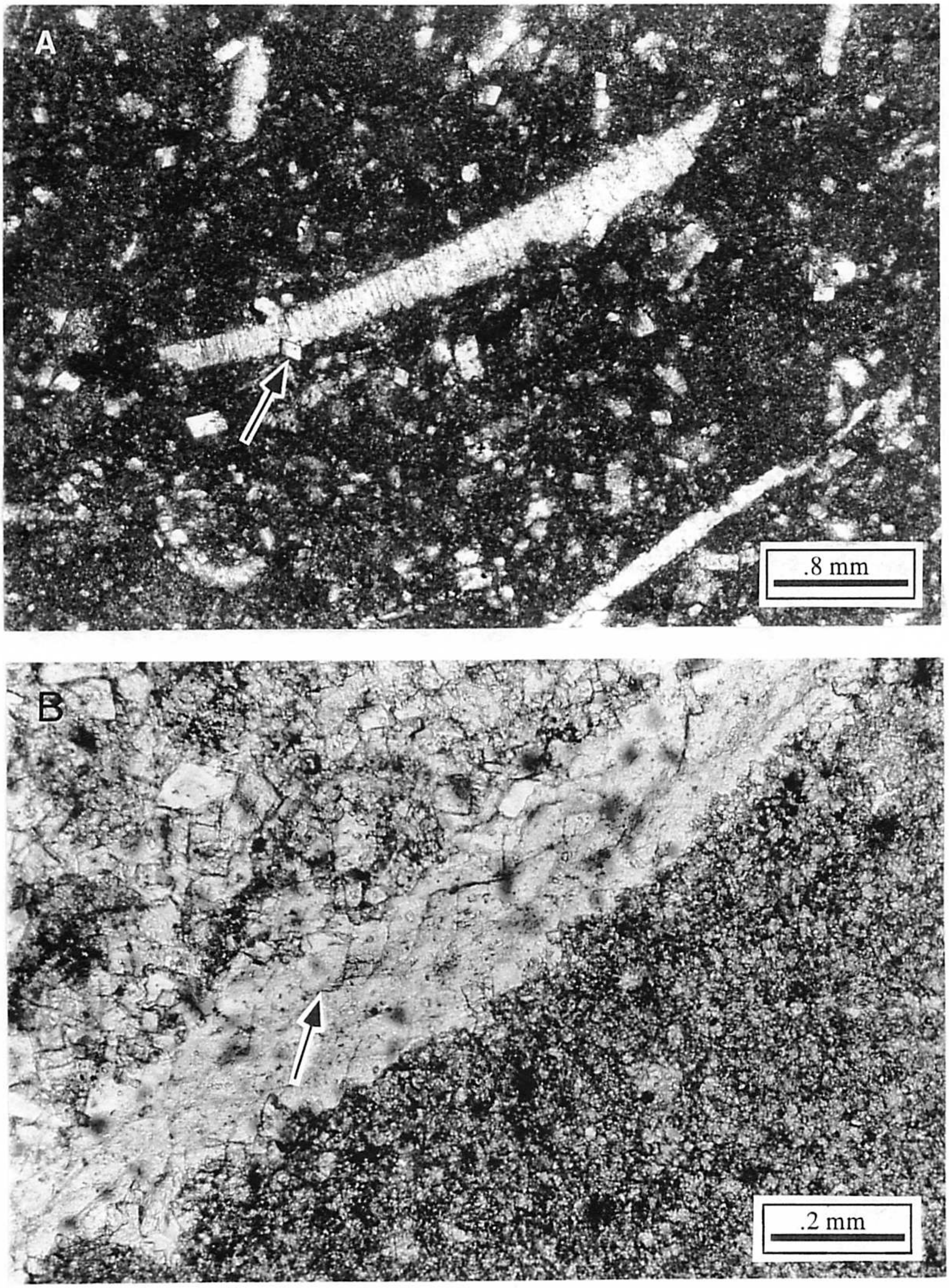

Figure 3. Photomicrographs of isolated replacement dolomite crystals. a) Lime mudstone and wackestone lithofacies contains up to 50% partial replacement dolomite. Note dolomite crystal cross-cutting calcite shell (arrow). b) Detail of calcite shell cross-cut by isolated replacement dolomite crystal (arrow) in lime packstone and grainstone lithofacies.

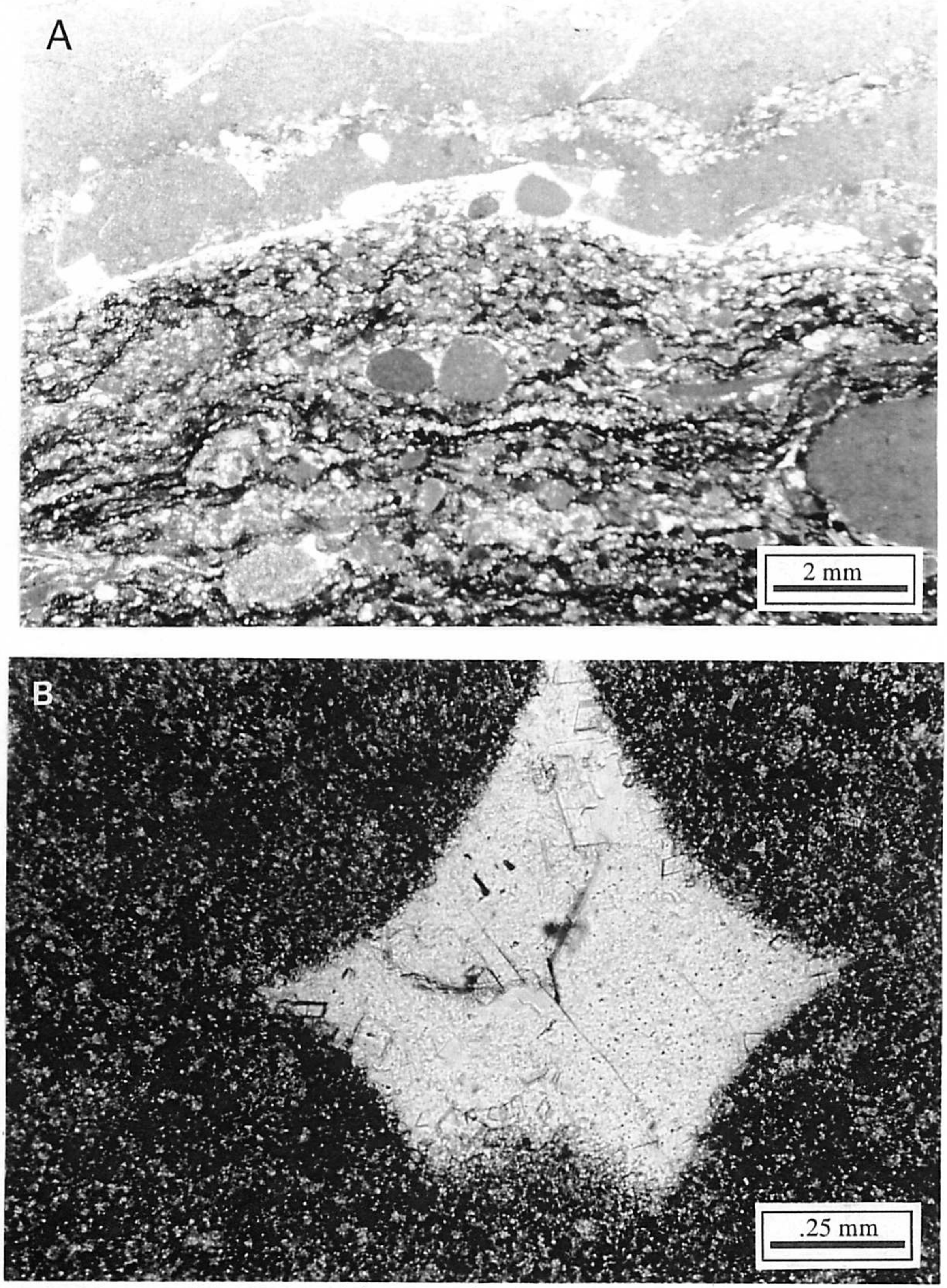

Figure 4. Photomicrographs of lime packstone and grainstone lithofacies. a) Lime mudstone intraclasts and dolomitic mudstone intraclasts cemented byboth dolomite and calcite intergranular cements. b) Displacive dolomite pseudomorph, now filled with dolomite cement. Pseudomorph is in dolomitic intraclast.

cement. Serrated, high amplitude stylolites are found throughout this unit and truncate some of the isolated replacement dolomite crystals.

Lime Packstone and Grainstone Lithofacies

This coarser-grained medium brown to very dark gray limestone makes up approximately 40% of the Byron Formation (Fig. 4a). This lithofacies consists of a framework of shells and shell fragments, peloids, and large rounded mudstone intraclasts with a small amount of mud matrix. The majority of the shell fragments are bivalves and/or brachiopods, and gastropods. Algal laminations appear as dark, thin slightly wavy layers. Some localized compaction resulted in mud lenses bound between algal laminations. Many of the intraclasts contain mudcracks.

This lithofacies contains all four types of dolomite identified in the Byron Formation, as well as some other diagenetic features. Some intraclasts are composed of an interlocking crystal mosaic ferroan dolomite. The dolomite crystal mosaic is truncated by these intraclast grain boundaries; dolomite crystals do not cross-cut the grain boundaries. Randomly-oriented, euhedral and subhedral pseudomorphs of displacive dolomite are found only in the mudstone intraclasts (Fig. 4b). These pseudomorphs of dolomite crystals vary up to 3mm in size. The original dolomite in these pseudomorphs has been dissolved and two generations of dolomite cement have filled in the rhombic pore space (Fig. 4b). Besides the pseudomorph-filling dolomite cement, white, blocky dolomite cement is also present in mudcracks and in fractures (Fig. 5).

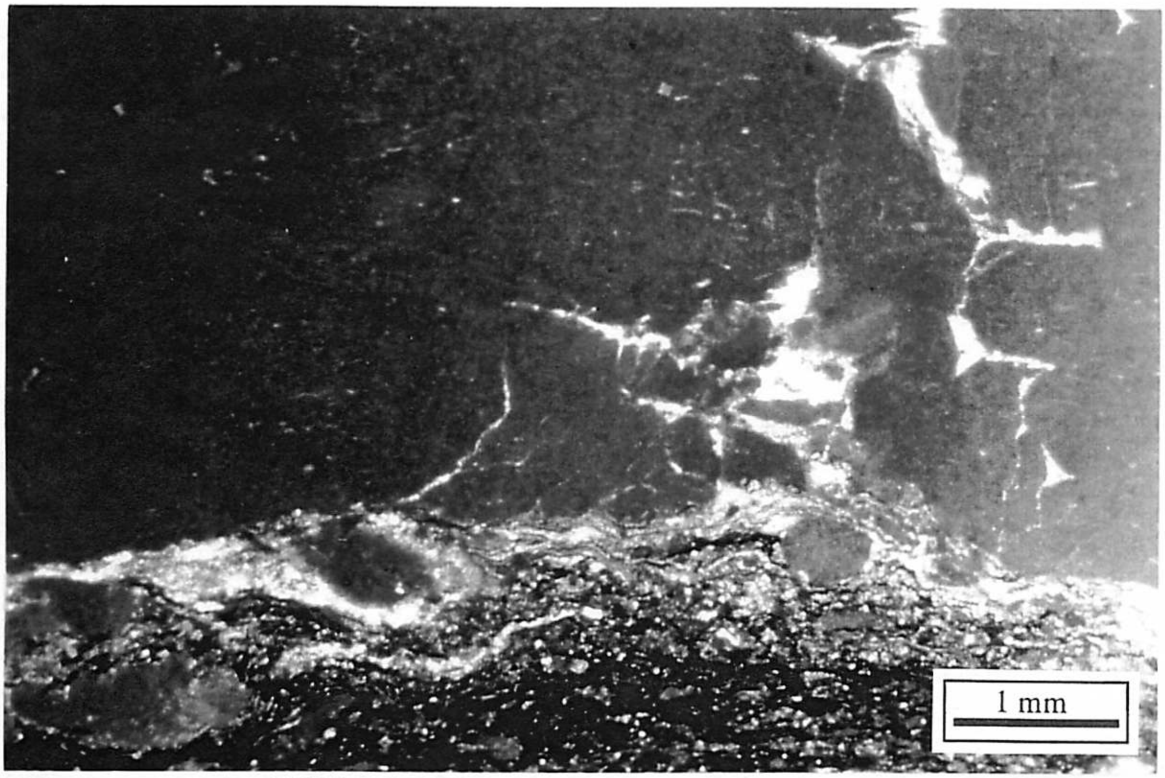

Figure 5. Photomicrograph of fractures filled with dolomite cement in dolomitic intraclast within lime packstone and grainstone lithofacies.

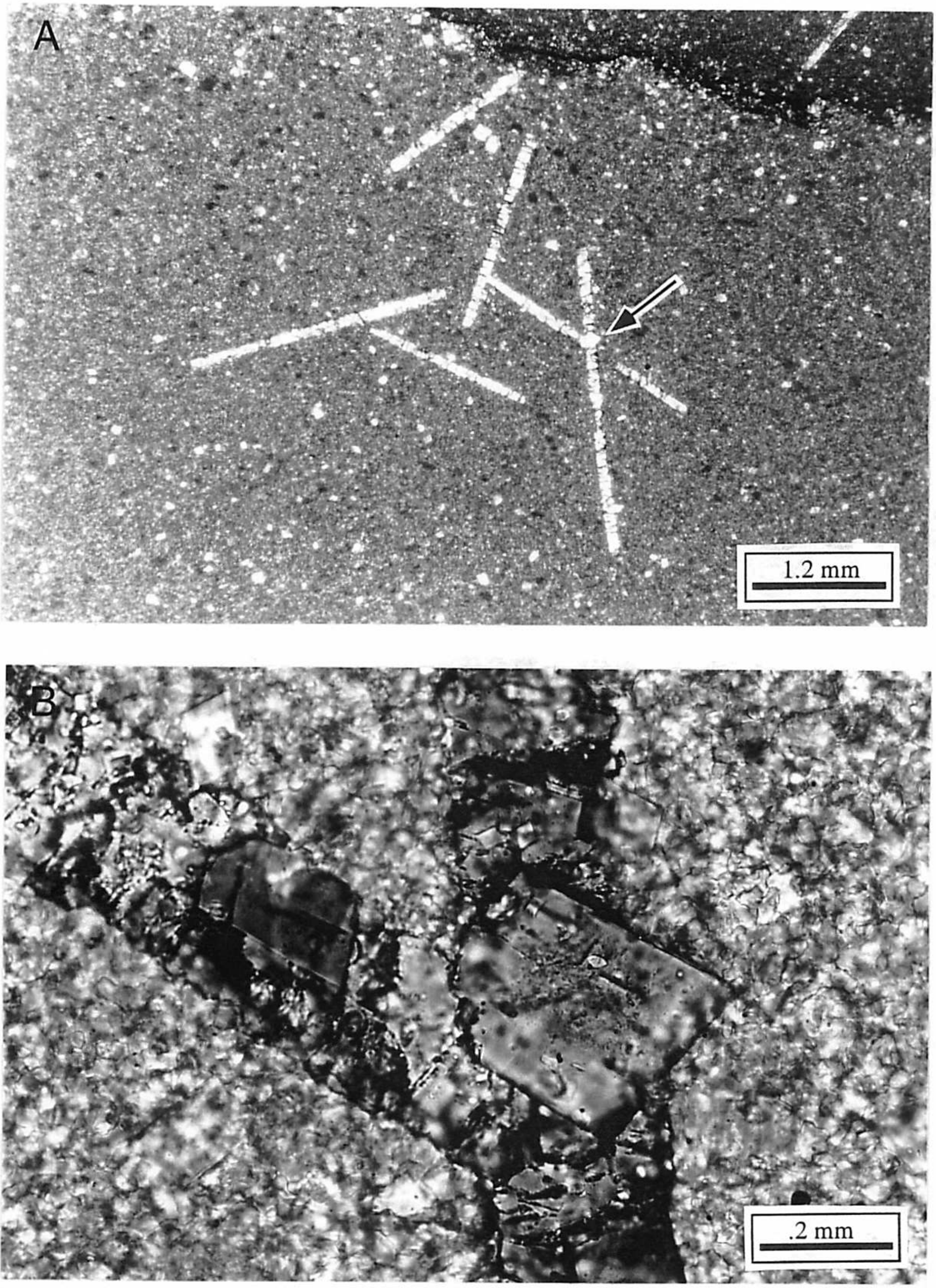

Figure 6. Photomicrographs of displacive anhydrite. a) Displacive anhydrite laths in lime mudstone and wackestone lithofacies. b) Close-up view of 5a (see arrow), showing isolated replacement dolomite crystal cross-cutting displacive anhydrite crystals.

Some displacive anhydrite laths are found in association with some of the isolated replacement dolomite crystals (Fig. 6a). In many cases, the anhydrite laths and calcite shell fragments are cross-cut by isolated replacement dolomite crystals (Fig. 6b). Some calcite and dolomite cement is also found in this lithofacies as intergranular cement between intraclasts, as well as vug-filling cement. Stylolites are present throughout this unit and cross-cut displacive anhydrite crystals. The stylolites in this unit vary from low amplitude, serrated to gently undulating.

Dolomitic Wackestone Lithofacies

The third lithofacies is the most abundant, making up nearly 50% of the formation. It is a very fine-grained light tan peloidal dolomite with rare brachiopod and gastropod shells and shell fragments and rare mudstone intraclasts. Very thin laminations and both small mudcracks and large prism cracks dominate this lithofacies. Both undeformed and slightly compacted mudcracks exist, but are markedly different than the deformed mudcracks in the limestone lithofacies. An interlocking crystal mosaic ferroan dolomite has replaced all grains and sedimentary structures in this lithofacies, including peloids, shell fragments, and mudcracks. However, some intercrystalline dolomite cement is found in areas of the coarsest replacement dolomite (Fig. 7).

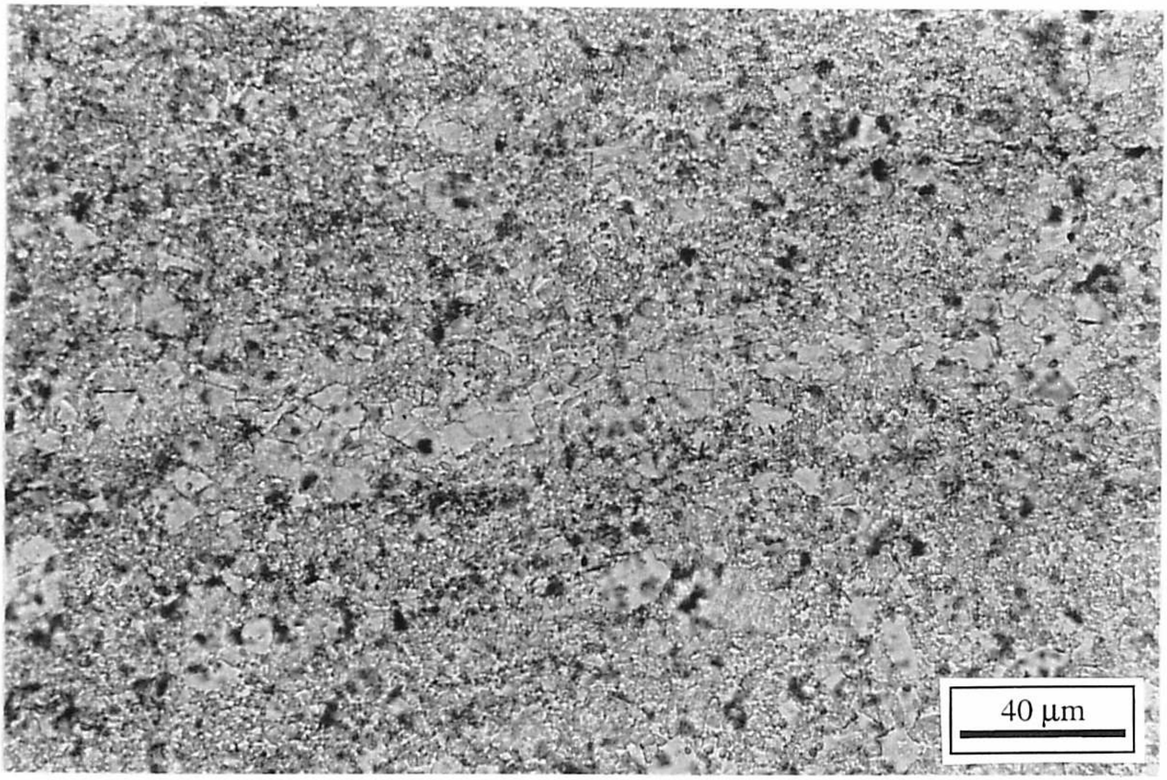

Figure 7. Photomicrographs of interlocking crystal mosaic dolomite that makes up the dolomitic wackestone lithofacies. Some intercrystalline dolomite cement is found only in the coarsest parts of this replacement dolomite

DISCUSSION

Depositional Environments

The Byron Formation consists of abundant mudcracks and planar to slightly wavy thin laminations along with some massive mudstone, algal laminations, intraclasts, peloids, gastropods, brachiopods, and bivalves. In addition, there is evidence of displacive anhydrite, displacive dolomite, and soft sediment deformation. These features are characteristic of many modern tidal flats, and, therefore, the Byron Formation was most likely deposited in a tidal flat setting during the Silurian. More specifically, the dolomitic wackestone lithofacies was deposited in a supratidal zone, while the lime mud-stone/wackestone and lime pack-stone/grainstone deposits probably formed in intertidal and subtidal zones, respectively. Our interpretations of tidal flat depositional environments agree with those of Harrison (1985), who found evidence of intertidal and supratidal deposits in the Byron Formation in other cores from northern Michigan.

Paragenetic Sequence

The Byron Formation contains a variety of diagenetic features including displacive dolomite and anhydrite, two types of replacement dolomite, calcite and dolomite cements, dissolution features, and stylolites.
Many of the diagenetic features we observed in the Byron Formation formed early in its history (Fig. 8). Mudcrack formation and soft sediment compaction features were some of the earliest events after deposition. Mudcracks can be seen cross-cutting laminations, and many of these mudcracks are deformed by soft sediment deformation.

Much of the dolomite also formed early in the paragenetic sequence. Displacive dolomite and anhydrite crystals may have formed early while sediment was soft. Very early displacive growth in a soft sediment is suggested by: (1) relatively large size compared to the host sediment; (2) euhedral crystal shapes; (3) random orientation in host mudstone; and (4) cross-cutting by a mudcrack. Furthermore, displacive dolomite crystals are only found in mudstone intraclasts at the base of subtidal lithofacies. This also suggests early formation of displacive dolomite prior to intraclast transport and deposition.

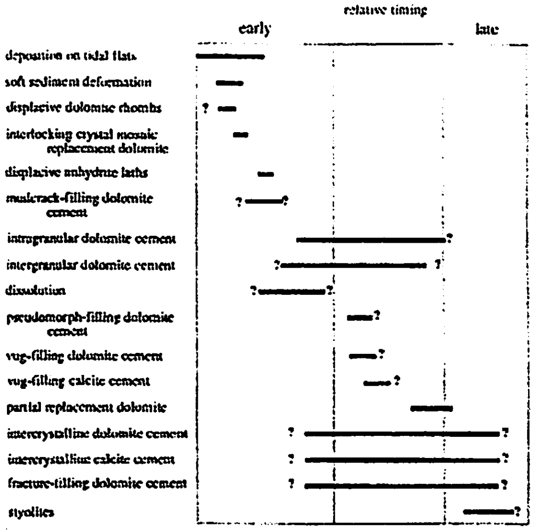

Figure 8. Paragenetic sequence for the Silurian Byron Formation.

Intraclasts and the immediately underlying mudcracked mudstones are composed of the interlocking crystal mosaic dolomite. This dolomite type is interpreted as a replacement phase because the dolomite crystals cross-cut peloid and shell grain boundaries. This dolomite replacement occurred very early, as evidenced by: (1) truncation of the dolomite crystal mosaic at intraclast grain boundaries; (2) cementation of some intraclasts by later-stage calcite and dolomite crystals; and (3) localization of dolomite crystal mosaic in specific lithofacies and grain types. This dolomite type is not pervasive throughout the Byron Formation, another suggestion that this replacement dolomite did not form late in the history of these rocks.

Dissolution occurred to some dolomite and limestone. Displacive dolomite crystals are now pseudomorphs filled with dolomite cement, indicating that the original displacive dolomite was dissolved sometime before the dolomite cementation. In addition, rare irregularly-shaped vugs exist in the limestone lithofacies and are filled with both dolomite and calcite cement.

Isolated replacement dolomite crystals are found throughout the limestone lithofacies. We also interpret this dolomite as a replacement phase. These euhedaral-subhedral dolomite crystals cross-cut shells and peloids, as well as displacive anhydrite crystals and some intergranular calcite cement. These isolated replacement dolomite crystals are a different generation of dolomite than the previously-discussed interlocking mosaic dolomite because: (1) the isolated replacement dolomite crystals are non-ferroan and the interlocking crystal mosaic dolomite is ferroan; and (2) the isolated replacement dolomite crystals are not as specific to lithofacies or grain type as is the interlocking crystal mosaic dolomite. We have observed some isolated replacement dolomite crystals truncated by stylolites, indicating that they formed prior to the compaction of the Byron Formation. Although it is difficult to ascertain the timing of this dolomitization, it was not the earliest nor the latest diagenetic event to occur in the Byron Formation. These isolated dolomite crystals seem to imply partial replacement and may be the beginning stage of the complete dolomite replacement process.

Timing and correlation of the various dolomite and calcite cements has proven to be somewhat difficult to ascertain because of the lack of cross-cutting relationships, and the homogeneity of cathodoluminescent properties. However, some general conclusions can be drawn from the relationships that do exist. Dolomite cement can be seen filling fractures, intergranular and intragranular pores, and displacive dolomite pseudomorphs. Some replacement dolomite crystals seem to act as both replacement phase and cement where a single crystal cross-cuts a peloid or shell grain and grew into pore space. The dolomite cements came after the dissolution of the displacive dolomite crystals and after the replacement interlocking dolomite mosaic. Some calcite cement is found with dolomite cement in vugs and in intergranular pores. In places where the dolomite and calcite cement exist together, it is difficult to determine which formed first. At least some calcite cement formed before the isolated partial replacement dolomite crystals because this dolomite type cross-cuts some intergranular calcite cement. A final dolomite cement type that most likely formed late is fracture-filling dolomite (Fig. 5).

Stylolites are present throughout the Byron Formation and most likely occurred late. The only cross-cutting relationships we observed, in regards to stylolites, were that of a stylolite cross-cutting a partial replacement dolomite crystal and an anhydrite lath. This relationship tells us that the stylolites came after the early formation of the displacive anhydrite laths as well as after the partial replacement dolomite formed. We saw no features that truncated the stylolites, suggesting that solution compaction was among the last of the diagenetic events to occur. However, fractures filled with dolomite cement are not truncated by any other features, indicating that fracture-filling cements also occurred relatively late in the history of these rocks.

Facies-Dolomite Relationships

The lime mudstone and wackestone lithofacies and the dolomitic wackestone lithofacies formed in supratidal-intertidal systems. Both contain a large amount of replacement or partial replacement dolomite. Dolomite and calcite cements are found in these lithofacies. Displacive anhydrite laths exist only in the lime mudstone and wackestone lithofacies.

The lime packstone and grainstone lithofacies probably represents a subtidal environment. Pseudomorphs of displacive dolomite rhombs are only present in this lithofacies, but only in mudstone intraclasts, indicating that the displacive dolomite probably formed in a mudstone in a supratidal or intertidal environment before mudcrack-initiated intraclasts were eroded and deposited in this subtidal zone. Partial replacement dolomite also exists in this subtidal lithofacies. Dolomite and calcite cements are slightly more abundant in this subtidal lithofacies than in the supratidal-intertidal lithofacies.

Dolomitization Model for Displacive Dolomite and Replacement Dolomite

A Case for Early Tidal Flat Dolomitization.

Much of the dolomite that is present in this rock formed early. Petrographic evidence shows that displacive dolomite crystals and interlocking crystal mosaic replacement dolomite formed very early in supratidal flats. These early dolomites probably formed from evaporated seawater. Support for this is found in the displacive anhydrite rhombs as well as the depositional environment. These rocks were formed in a tidal flat complex and were exposed to large amounts of seawater. The presence of anhydrite also suggests evaporative conditions. Modern supratidal zones in arid climates commonly contain seawater with elevated salinities and often result in evaporite minerals as well as some rare dolomite (Shinn, 1983).

Although dolomite has been reported forming relatively early in arid tidal flats, it is usually in the form of displacive rhombs, cements, or surface crusts. Modern replacement dolomite is rare and poorly-ordered. Were conditions during the Silurian more favorable than today for making dolomite?

Silurian seawater temperatures in Michigan were approximately the same as modern seawater temperatures on arid, tropical tidal flats. These temperatures were high for surface water temperatures, ranging from 20°C to 40°C (Losey and Bension, 2000). This temperature range would account for high evaporation rates and result in elevated salinities.

It has been suggested recently that the seawater chemistry during Silurian time was very different than modern seawater (Brennan et al., 2000a and 2000b). Silurian seawater had higher calcium and potassium and lower magnesium and sulfate than modern seawater. Brennan et al. (2000a and b) have calculated that the Mg:Ca ratio of Silurian seawater was 1:1 to 2:1, compared to today's 3:1 Mg:Ca ratio. It would seem that this lower Mg would make it even more difficult to make early dolomite during Silurian time. However, evaporation leading to precipitation of gypsum and/or anhydrite would increase the Mg:Ca ratio, leading to possible dolomite formation.

Many examples of modern dolomite formation in supratidal environments have been described (see Shinn, 1983; Lasemi et al., 1989 for example). These supratidal dolomites are limited to displacive dolomite crystals, dolomite cements, and dolomitic crusts, as well as aeolian dolomite dust. Recent work on Tertiary and Quaternary dolomites has documented various dolomite types, including dolomite cements and partial replacement dolomite, forming in both subtidal sediments (ie., Mazzullo et al., 1998; Swart and Melim, 2000; Teal et al., 2000). Normal salinity seawater, elevated salinity seawater, and biogeochemical processes have all been called upon to explain early dolomitization in modern and recent carbonate settings. Therefore, it is reasonable that some of the Byron Formation's dolomite, even its significant amount of replacement dolomite, may have formed very early in its diagenetic history.

A Case Against Burial Dolomitization.

Most replacement dolomite has traditionally been explained as "burial dolomite". Perhaps this is due to the fact that many replacement dolomites are pervasive and are closely associated with stylolites. But, in some cases, the heat, pressure, and time that have acted on carbonates that are buried deeply simply are attractive conditions to explain dolomitization.

Deep burial was probably not the cause of the majority of the dolomite present in the Byron Formation. The timing, along with relationship with evaporites and specific depositional features, suggests that the displacive dolomite and replacement dolomite formed long before these rocks were buried to any extent.

The maximum burial depth of the Paleozoic rocks of the Michigan Basin has been a difficult question to answer, as it is not well documented in the literature. Through computer modeling, it has been estimated that the maximum burial depth of the Burnt Bluff Group was 2 km in the center of the basin (Everham et al., 1999). However, at the edges of the basin, where these samples were located, the maximum burial depth would have probably been less that 2 km. Regardless, the temperatures generated by the maximum burial depth may not have been sufficient to form "burial" dolomite, which has typically been described as forming at temperatures of at least 90°C (see Aulstead and Spencer, 1985 and Shelton et al., 1992). If a geothermal gradient of 30°C/km is assumed (there is no evidence of hydrothermal influence), the temperature at the center of the basin would be near 60°C and less than 60°C at the edge of the basin. Therefore, it can be tentatively assumed that the section of the Byron Formation used in this study from the edge of the basin was not sufficiently heated to make typical burial replacement dolomite.

Dolomite Cement and Partial Replacement Dolomite: Problematic Dolomitization

The two remaining dolomite types in the Byron Formation (dolomite cements and the partial replacement of dolomite) are difficult to interpret. Dolomite cements are all nonferroan and noncathodoluminescent. This makes it difficult to evaluate any possible relationships among the pseudomorph-, intergranular-, intragranular-, intercrystalline-, vug-, and fracture-filling dolomite cements. Furthermore, some of the dolomite cement is closely associated, and perhaps contemporaneous, with some vug-filling calcite cement.

Isolated dolomite rhombs interpreted as partial replacement dolomite also present problems in interpreting their timing and formation. Unlike the previously-described intercrystalline dolomite crystal mosaic, this partial replacement dolomite is not specific to any one facies. These dolomite crystals partially replace depositional grains as well as some diagenetic features such as calcite cement.

Thus, petrographic study alone is not sufficient to interpret the origin of the dolomite cement or the partial replacement dolomite. However, these dolomite types probably were not formed early or influenced by depositional conditions. Likewise, there is no good evidence that these dolomites were late-stage or burial dolomites, either.

CONCLUSIONS

The majority of the dolomite in the Silurian Byron Formation, including a significant amount of replacement dolomite, formed very early in the rock's diagenetic history. Depositional environment, timing, and association with displacive evaporites suggest that evaporated seawater may have been the dolomitizing fluid. This study has shown that dolomite, including replacement dolomite, can form early in supratidal zones in the presence of evaporated seawater.

ACKNOWLEDGMENTS

This study is part of Katherine Hartig's senior thesis at Central Michigan University. We thank Bill Harrison of Western Michigan University for his encouragement and help in accessing core samples. Duncan Sibley of Michigan State University is gratefully acknowledged for lending his cathodoluminoscope and his expertise. David Matty of CMU allowed us to use his microscope. Cindy Carney and Ben Greenstein are thanked for reviewing, editing, and handling this manuscript. Logistical and financial support from CMU's Department of Geology, College of Science and Technology, and Office of Research and Sponsored Programs made this project possible.

REFERENCES

Aulstead, K.G. and Spencer, R.J., 1985, Diagenisis of the Keg River Formation, northwestern Alberta: Fluid inclusion evidence: Bulletin of Canadian Petroleum Geology, v. 33, p. 167-183.

Brennan, S.T., Lowenstein, T.K., and Hardie, L.A., 2000a, Chemistry of Silurian seawater: Program with Abstracts, Geological Society of America Annual Meeting, Reno, Nevada.

Brennan, S.T., Lowenstein, T.K., Timofeeff, M.N., and Hardie, L.A., 2000b, Chemical compositions of Silurian seawater: Preliminary results from ESEM-EDS analyses of fluid inclusions in marine halites: Proceedings of the Annual Goldschmidt Geochemistry Conference, Boston, Massachusetts.

Cercone, K.R., and Lohmann, K.C., 1987, Late burial diagenesis of Niagaran Middle Silurian Pinnacle reefs in the Michigan Basin: American Association of Petroleum Geologists Bulletin, v. 71, p. 3-35.

Dellwig, L., 1955, Origin of the Salina Salt of Michigan: Journal of Sedimentary Petrology, v. 25, p. 83-110.

Dickson, J.A.D., 1966, Carbonate identification and genesis as revealed by staining: Journal of Sedimentary Petrology, v. 36, p. 491-505.

Ehlers, G.M., and Kesling, R.V., 1957, Silurian Rocks of the northern peninsula of Michigan: Michigan Geological Society, 62 p.

Ells, G.D., 1962, Silurian rocks in the subsurface of southern Michigan, *in* Silurian rocks of the southern Michigan Lake area, Michigan Basin Geological Society Annual Field Conference: Michigan Basin Geological Society, p. 39-49.

Everham, W.D., Huntoon, J.E., and Merriam, D.F., 1999, Thermal history of a deep well in the Michigan Basin: Implications for a complex burial history: Geothermics in Basin Analysis, p. 177-202.

Friedman, G.M., 1959, Identification of carbonate minerals by staining methods: Journal of Sedimentary Petrology, v. 29, p. 87-97.

Hardie, L.A, 1987, Perspectives: Dolomitization: A critical view of some current views: Journal of Sedimentary Petrology, v. 57, n. 1, p. 166-183.

Harrison, W.B., 1985, Lithofacies and depositional environments of the Burnt Bluff

Group in the Michigan Basin, *in* Cercone, K.R. and Budai, J.M. eds., Ordovician and Silurian rocks of the Michigan Basin Geologic Society, Special Paper No. 4, p. 95-106.

Johnson, A., and Sorenson, H., 1978, Drill core investigation of the Fiborn Limestone member in Schoolcraft County, Mackinac and Chippewa Counties, Michigan: Michigan Department of Natural Resources, Geological Survey Division, Report of Investigation 18, 51 p.

Lasemi, Z., Boardmen, M.R., and Sandberg, P.A., 1989, Cement origin of supratidal dolomite, Andros Island Bahamas: Journal of Sedimentary Petrology, v. 59, p. 249-257.

Leibold, A., 1992, Sedimentary and geochemical constraints on Niagara/Salina deposition, Michigan Basin [Ph. D. Dissertation]: University of Michigan, 280 p.

Losey, A., and Benison, K.C., 2000, Silurian paleoclimate data through fluid inclusions in the Salina Formation halite of the Michigan Basin: Carbonates and Evaporites , v. 15, n. 1, p. 28-36.

Mazullo, S.J., Teal, C.S., and Bischoff, W.D., 1998, Syndepositional, subtidal dolomitization model for the formation of some Paleozoic reservoirs in the Permian Basin: Program with Abstracts, American Association of Petroleum Geologists Southwest Section Meeting, v. 81, n. 5, p. 868.

Morrow, D.W., 1990, Dolomite- Part 1: The Chemistry of Dolomitization and Dolomite Precipitation, *in,* Mcllreath, A., and Morrow, D.W. eds., Diagenesis, Geosciences Canada Reprint Series 4, p. 113-124.

Sears, S.O., and Lucia., F.J., 1979, reef-growth model for Silurian pinnacle reefs, northern Michigan reef trend: Geology, v. 7, p. 299-302.

Sheldon, F.D., 1963, Transgressive marginal lithotopes in Niagran (Silurian) of Northern Michigan Basin: American Association of Petroleum Geologist Bulletin, v. 47, p. 129-149.

Shelton, K.L., Bauer, R.M., and Gregg, J.M., 1992, Fluid-inclusion studies of regionally-extensive epigenetic dolomites, Bonneterre (Cambrian) southeast Missouri: Evidence of multiple fluids during dolomitization and lead-zinc mineralization: Geological Society of America Bulletin, v. 104, p. 675-683.

Shinn, E. A., 1983, Tidal flat environment, *in,* Scholle, P.A., Bebout, D.G., and Moore, C.H. eds., Carbonate Depositional Environments: American Association of Petroleum Geologists Memoir 33, p. 172-210.

Soderman, J.W., and Carozzi, A.V., 1963, Petrography of algal bioherms in Burnt Bluff Group (Silurian), Wisconsin: American Association of Petroleum Geologists Bulletin, v. 47, p. 1682-1708.

Sonnenfeld, P., and Al-Aasm, I., 1991, The Salina evaporites in the Michigan Basin: Geological Society of America Special Papers, v. 256, p. 139-154.

Swart, P.K., and Melim, L.A., 2000, The origin of dolomites in Tertiary sediments from the margin of the Great Bahama

Bank: Journal of Sedimentary Research, v. 70, p. 738-748.

Teal, C.S., Mazzullo, S.J., and Bischoff, W.D., 2000, Dolomitization of Holocene shallow-marine deposits mediated by sulfate reduction and methanogenesis in normal-salinity seawater, northern Belize: Journal of Sedimentary Research, v. 70, p. 649-663.