Stratigraphy and Petrology of the Little Falls Dolostone (Upper Cambrian), East-Central New York

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Stratigraphy and Petrology of the Little Falls Dolostone (Upper Cambrian), East-Central New York[1]

by Donald H. Zenger[2]

ABSTRACT

The main mass of the Little Falls Dolostone extends from Poland on the west to near Randall on the east. The formation thins eastward, largely due to facies replacements, toward Saratoga Springs, where the unit is not recognized. At the type section and along its primary surface occurrence in the Mohawk Valley, the Little Falls is approximately 400 feet (122 m) in thickness, and is well-known for its exquisite quartz crystals ("Herkimer diamonds") and algal stromatolites ("Cryptozoon"). Northward from the Mohawk Valley the formation thins to a feather edge as a result of early Ordovician erosion.

Dolostone is the predominant lithology but sandstones and mixed sandstone-dolostone varieties are common. Medium and thick bedding are characteristic. Shales and limestones are essentially absent and fossils are extremely rare. I recognize four subdivisions, designated as informal "units," in the Mohawk Valley above the nonconformable contact with the underlying Proterozoic gneiss. Unit A, the lowest subdivision, is 90 to 100 feet (28 to 30 m) thick and has thin basal conglomerates and sandstones overlain by generally coarsely crystalline dolostone. Unit B consists of about 200 feet (61 m) of dark, fine- to medium-crystalline dolostone with many vuggy beds; within this unit is a unique sequence of alternating algal stromatolitic dolostone and sandstone. Unit C, 45 to 70 feet (13.7 to 21.3 m) thick, is primarily coarsely crystalline, "glauconitic" dolostone with quartzose intercalations. Unit D, characterized by fine crystalline, laminated dolostone, is 30 to 70 feet (9.1 to 21.3 m) thick, and contains reddish-gray zones and silicified ooids; this unit appears to be overlain conformably and, in places gradationally, by the Tribes Hill Formation (Canadian) in the Mohawk Valley.

Because of the extreme sparsity of fossils, intra- and interformational correlations are tenuous, and are based mainly on lithology, thickness, and stratigraphic position. Northeast from Randall, the lower and middle parts of the Little Falls are represented by the uppermost Potsdam, Galway, and Hoyt. I suggest that the upper Little Falls of the Mohawk Valley may correlate with the lower Gailor Dolostone of the Saratoga Springs region.

Approximately 650 specimens were studied using insoluble residue analysis, density determinations, X-ray diffraction analysis, thin section petrography, electron probe microanalysis, scanning elecron microscopy, and preliminary cathodoluminescence examination.

Dolomite is the dominant mineral and is of replacement origin both in the grains (e.g., intraclasts, ooids, and peloids) and "matrix"; there is significant void-filling secondary dolomite. Quartz, primarily as detrital grains and secondary overgrowths, is second in abundance. Potassium feldspar, as perthite and microcline, and calcite are generally ubiquitous but not common; also significant, but relatively minor, are interstitial

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"glauconite", hematite, and pyrite. The main dolomitization of the carbonate precursors was both preceded and followed by periods of chertification. Secondary quartz overgrowths followed dolomitization. The development of anthraxolite paragenetically overlapped the growth of secondary dolomite rhombs and quartz crystals in vugs. All calcite, as passively precipitated spar or "dedolomite", formed very late in paragenesis, as did the hematitization of pyrite.

Replacement dolomite is generally coarsely crystalline (averaging 110 to 120 μm in greatest dimension) and there is a significant amount of very large crystals characterized by undulatory extinction and low content of ferrous iron. Selected samples have very negative δO^{18} values. Although there may have been some early development of dolomite, possibly in contact with waters of higher than normal salinity, the main dolomite growth occurred later, in the mesogenetic zone, in contact with hydrothermal waters (most likely) or warm formation waters or mixtures of these solutions. Dedolomitization is rare, being represented primarily by epitaxial calcite rims and by calcitic centers of dolomite crystals.

The original sediments accumulated along the inner edge of a wide shelf which lay well to the west of the slope into the Proto-Atlantic Ocean. Pervasive dolomitization and poor lateral continuity of exposure hinder environmental interpretations. Invoking comparative sedimentology and considering the distribution and significance of such features as invertebrate fossils, domal algal stromatolites, algal boundstones, burrowing and bioturbation, intraclasts, peloids, ooids, cross-stratification, ripple marks, channeling, desiccation cracks, quartz sand grains, grain support, and dolostone textures, it can be seen that each stratigraphic unit displays a variety of subtidal and pertidal characteristics; I conclude that tides affected this inner shelf area. Following a relatively rapid transgression, which produced the thin basal conglomeratic sandstones, an aggradational carbonate sequence was developed by a close, but hydrodynamically complex, association of shifting peritidal and adjacent subtidal environments. Eolian-transported quartz sand grains were delivered to the environment and generally were intertidally or subtidally deposited under the influence of tidal currents. The nature and distribution of detrital quartz, the relative abundance of perthite and rutilated quartz, and paleocurrent studies indicate that charnockites (granulite facies) of the present southern Adirondacks were the source of the terrigenous sediments.

INTRODUCTION

OBJECTIVES

The Little Falls Dolostone of east-central New York, popular for its algal stromatolites ("Cryptozoon") and exquisite quartz crystals, has never been studied in detail across its outcrop belt in and near the Mohawk Valley (see Plate 1A); neither has its sedimentary petrology been investigated. The purpose of this program is thus twofold:

1) To attempt to elucidate the stratigraphy of the unit and to consider relations with units above, below and to the east, beyond the limits of the Little Falls proper (Utica through Fonda Quadrangles).
2) To carry out a thorough laboratory study of the petrology of the unit. This includes a consideration of environments of deposition and the nature of dolomitization, in the light of reported Holocene dolostone; in this regard, the Little Falls project is a major component of a continuing investigation of the petrology of dolomitic rocks sponsored initially by the American Chemical Society.

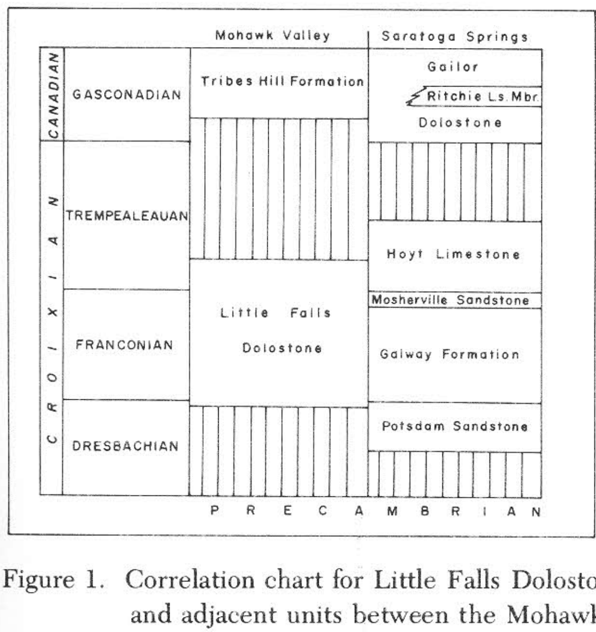

Figure 1. Correlation chart for Little Falls Dolostone and adjacent units between the Mohawk Valley and Saratoga Springs, as illustrated by Fisher (modified from Fisher, 1977).

GENERAL SETTING AND PLAN

Plate 1 shows the outcrop map of the Little Falls Formation in east-central New York. Major areas of exposure are separated by normal faulting. The unit definitely extends from near Poland, in the Utica 15′ Quadrangle on the northwest, to the Fonda 15′ Quadrangle on the southeast. Most exposures are in or near the Mohawk Valley or two of its major tributaries, East and West Canada Creeks; it is primarily about the Little Falls in this area that the report is concerned. However, to the east and north, in the Amsterdam, Broadalbin, Lake Pleasant, and Saratoga 15′ Quadrangles are an attenuated dolostone and other carbonate units that are laterally equivalent to the Little Falls. Although the emphasis will not be on this area, the stratigraphy will be considered briefly. Essentially, then, the area of study lies within the Mohawk Section of the Appalachian Plateau Province (Fenneman, 1938 p. 323) south of the Adirondack Mountains. Although glacial deposits provide considerable cover, outcrop control is better in the western part of the belt, i.e., the Mohawk Valley and its tributaries. Eastward, from the Fonda Quadrangle to the Saratoga Quadrangle, exposures are much more spotty and fragmentary.

First, the stratigraphy of the Little Falls at its type section will be discussed. This will be followed by descriptions of the stratigraphy to the northwest of the type section, that is, along West Canada Creek, and to the southeast, from St. Johnsville through the Randall area. Finally, there is a section on stratigraphic relations in the Amsterdam, Broadalbin, Lake Pleasant, and Saratoga Quadrangles. The aspects of the petrology will be treated in a separate section followed by a discussion of dolomitization and other aspects of diagenesis. The report concludes with a consideration of the environments of deposition of the original mixed terrigenous and carbonate sediments.

METHODS OF STUDY

During the summers of 1967 and 1969, I examined the Little Falls and adjacent units across the outcrop belt. Approximately 130 localities were visited and these are presented in Appendix A. In addition to the surface sections, three drill cores were studied, one from the immediate vicinity of the Middleville quarry (Eastern Rock Products, Inc.; loc. 6A) and two near locality 23 north of Little Falls (James R. Dunn and Associates, loc. 23A).

Although some 15 weeks were spent in the field, the great bulk of the time was spent in the laboratory on the "petrology" phase of the investigation. Some 650 oriented rock specimens were collected and analyzed in various ways. Approximately 50 grams of each sample was crushed and the density determined using a Beckman Air Comparison Pycnometer (#930). This instrument and its geologic application was described by McIntyre, and others (1965) as well as by Zenger (1968) who described a method of determining calcite/dolomite ratios using this non-destructive method. The standard deviation of the density determination is good, being about 0.0028 based on 18 measurements of a sample of Shady Dolomite (Cambrian, Virginia).

Quantitative insoluble residues were determined after acidization with 10% HCl. This concentration does minimal damage to clays but still allows digestion of all the carbonate within a reasonable amount of time. The precision of this method is a standard deviation of 0.14% based on a 30-split sample of dolostone from the Lost Burro Formation (Devonian, east-central California). The residues were retained for qualitative examination. Appendix B contains quantitative data for insoluble residues, density, and dolomite percentages for all Little Falls samples analyzed.

X-ray diffraction briquettes were made of powders of all rock samples and most insoluble residues (see Baird, 1961). The semi-quantitative scans covered a 2θ range of 4° to 40° at a goniometer speed of 1°/minute. A determination of calcite/dolomite ratios was not felt necessary. As will be seen, calcite is a very minor constituent in practically all samples of the Little Falls; furthermore, that present is paragenetically late.

Thin sections were prepared for nearly all of the specimens. All of these were stained in an acidic solution of Alizarin Red S (positive for calcite) and most were also treated with an acidic solution of potassium ferricyanide (positive for ferrous iron).

The electron probe microanalyzer (Phillips Electronic Instruments AMR/3) was used semi-quantitatively to help solve various petrological problems recognized under the petrographic microscope. A description of the operating conditions of the probe was presented by Baird and Zenger (1966).

Dolomite crystal size and quartz grain surfaces were studied to a minor extent using an AMR 1200 Scanning Electron Microscope.

Most computations and statistics were done using an IBM 5100 Portable Computer.

Six samples were analyzed for carbon and oxygen isotopes by the Institute of Geophysics, University of California, Riverside. In this procedure (T. B. Coplen, written communication, 1973), carbonates were reacted with 100% phosphoric acid to evolve carbon dioxide which was analyzed on a double-focusing, double-collecting isotope ratio mass spectrometer for carbon and oxygen isotope composition. Oxygen isotopic composition of the calcite and dolomite were determined using the acid fractionation factors in Sharma and Clayton (1965).

Temperatures of homogenization (T_H) for a few relatively large fluid inclusions in one sample of coarsely crystalline dolostone (NI) were determined by E. R. Olson and J. Freckman, University of California, Riverside, using a heated microscope state.

Very preliminary work on zonation of dolomite crystals was performed employing the principle of cathodoluminescence. Luminoscopes (Nuclide Corporation) at the University of Southern California and Marathon Oil Company's Denver Research Laboratory were used in this study.

ACKNOWLEDGEMENTS

Field work during the summers of 1967 and 1969 was supported by the New York State Geological Survey. Acknowledgement is also made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for much of the support of the laboratory investigations. I am grateful to several former undergraduates—Robin Leggewie, Eugene Pearson, Warren Thomas, and Allen Treiman—for their assistance under this grant and under NSF-URP GE 1038 (Pearson).

Eastern Rock Products, Inc., and James R. Dunn and Associates provided access to diamond drill cores from the Middleville and Little Falls areas (locs. 6A and 23A), respectively. I thank authorities at the various quarries for permission to study sections in the Little Falls or related units, particularly: Eastern Rock Products, Inc., quarry near Middleville (loc. 6); Talarico quarry just west of St. Johnsville (loc. 30A); Pallette Stone Corporation quarry west of Saratoga Springs (loc. 127); and, the old Gailor quarry in the northeastern part of Saratoga Springs (loc. 129).

D. W. Fisher has visited me in the field, has shared some of his extensive background on Cambrian and Ordovician stratigraphy of east-central New York, and has spent much time in reviewing and editing this manuscript. J. G. Broughton also accompanied me in the field. Numerous workers have kindly discussed with me many of the stratigraphic and/or petrologic problems encountered, including: R. G. C. Bathurst, P. W. Choquette, D. H. Craig, J. B. Dunham, J. A. Fagerstrom, J. H. Foster, T. Freeman, L. C. Gerhard, P. W. Goodwin, R. B. Halley, P. F. Hoffman, W. D. Huff, D. H. Krinsley, S. J. Mazzullo, J. McLelland, D. G. McCubbin, E. R. Olson, L. V. Rickard, P. Rothe, B. W. Selleck, D. J. Shearman, E. A. Shinn, D. R. Spearing, S. A. Stonecipher, K. Swett, L. Tedesco, W. Wellendorf, R. J. Weimer, and I. M. West. I am deeply grateful to all of these researchers but must accept sole responsibility for any faulty reasoning or conclusions. L. V. Rickard and W. B. Rogers critically reviewed the manuscript submitted for publication, and I am grateful for their editorial comments.

My wife, Ann, read and helped edit the manuscript, which was typed by Jean MacKay. Gene Hartman and Don Tsusaki assisted with some of the photography.

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PREVIOUS WORK

The present Little Falls Dolostone was embraced in the term "Calciferous Sandrock" as applied by Eaton (1824, p. 32–33; 72–79), who described it as an aggregate of quartzose sand and fine grains of carbonate of lime. He mentioned the occurrence of geodes [vugs] and their contained minerals, especially the doubly terminated quartz crystals known as "Herkimer diamonds".

In his final report on the Third District, Vanuxem (1842, p. 30) considered the "Calciferous group" as comprising, in ascending order: ". . . probably . . . the continuation of the Potsdam sandstone . . ."; a mixture of fine yellow siliceous sand and carbonate of lime which was the "Calciferous Sandrock" of Eaton; a mixture of the calciferous material and of compact limestone to which the term "fucoidal layers" were applied. Observing the "Calciferous Sandrock", Vanuxem (p. 32) noted layers ". . . showing a concretionary structure . . .", siliceous [chert] concretions, oolitic bodies, "anthracite" coating cavities, and the ubiquitous quartz crystals. He appreciated the rarity of fossils in the unit, reporting isolated examples of a lingulid brachiopod and a spiral univalve.

Emmons (1842, p. 102–106) considered the Potsdam Sandstone, and the overlying "Calciferous Sandrock" as constituting the lower two units of his "Champlain group". The "Calciferous Sandrock" was described as a sandy limestone. Its geodiferous character and the inclusion of calcareous spar and quartz crystals were noted.

Hall (1847, p. 5–13, pls. II, III) described fucoids and shells from the "Calciferous Sandstone", but from his description it is quite clear that most of the forms were from the "Fucoidal layers" (Tribes Hill of present usage) which he obviously included in the former unit.

Walcott (1879) described a fauna from a limestone (present Hoyt Limestone) overlying the Potsdam near Saratoga. Originally he referred this limestone to the "Calciferous Sandrock" but, impressed with the Potsdam aspect of the fauna, he regarded it as a facies of that unit (1890, p. 346).

Brainerd and Seely (1890) included about 1800 feet (550 m) of carbonate rock between the Potsdam and Chazy of the Champlain Valley in the "Calciferous Formation". They established five divisions, A–E, in ascending order within the unit.

In a reconnaissance study, Prosser and Cummings (1896, p. 641–644) reported about 190 feet (58 m) of "Calciferous Sandrock" at Flat Creek (Canajoharie quadrangle), which included 95 feet (29 m) of "Fucoidal layers"; they recorded about 500 feet (153 m) at "The Noses" (Fonda quadrangle), including about 40 feet (12 m) of fucoidal beds, the top not being exposed.

Clarke and Schuchert, in their classical nomenclatorial revision of New York State stratigraphy (1899, p. 877), proposed the new unit "Beekmantown Limestone" in which they included the "Califerous Sandrock".

Clarke (1903, p. 16) first formally employed the term "Little Falls dolomite" for the ". . . highly magnesian, sparsely fossiliferous phase of the 'calciferous sandrock' in the Mohawk Valley . . ." No further information was presented regarding the type section.

In the Little Falls area, Cushing (1905, p. 24–29) used "Beekmantown formation" for the 450 feet (138 m) of lowest Paleozoic above the Precambrian gneisses and below the Middle Ordovician Lowville Limestone. He could not separate the Potsdam from the Beekmantown and it is evident that the "Fucoidal layers" were considered as part of the Beekmantown. He was impressed with the abundance of secondary mineralization within the unit, commenting on the presence of "anthracite" as well as quartz in the cavities. He noted the presence of "glauconite". Later (1908, p. 174), he explained the term "Little Falls dolomite" as a local name for the representative of the supposed Beekmantown of the Mohawk Valley. Based partly on some unpublished work of Ulrich he suggested that the Little Falls is older and separable from the type Beekmantown of the Champlain Valley and that it might possibly be the correlative of the Potsdam and Theresa Formation.

Ulrich and Cushing (1910) described the Little Falls or its equivalents between the Mohawk Valley and the southern Champlain Valley. However, they measured only three sections of the unit in the western part of the outcrop belt, at Little Falls, Middleville, and Newport. These are all in the upper part of the Formation. They considered the Beekmantown to lie disconformably above the Little Falls (p. 102–103. At Saratoga (p. 113) they estimated about 250 feet (76 m) of Little Falls, the lower 100 feet (31 m) being assigned to the "Hoyt Limestone Member" which contains ". . . Cryptozoon, trilobites, gastropods, and *Lingulepis* at many horizons . . ." Forty to sixty feet (12.2–18.3 m) of transitional gray calcareous sandstone intervened between the Hoyt Member and the underlying Potsdam. They questioned the correlation of the Little Falls with the five subdivisions of Brainerd and Seely (1890) in the Champlain Valley. They suggested (p. 97–98) that whereas Division A and the lower part of B could be the Little Falls equivalent, the other subdivisions were distinctly younger (Beekmantown).

In the Broadalbin Quadrangle, Miller (1911, p. 31–32 estimated some 200 feet (61 m) of "Little Falls Dolomite" between the underlying Theresa and the overlying Ordovician. He noted a uniform lithology consisting predominantly of fine-grained, dolomitic limestone. He emphasized the occurrence of quartz crystals in cavities and the presence of chert. Except in a few localities, the Tribes Hill "limestone" is absent and the Little Falls-Black River contact is marked by a distinct erosion surface.

Apparently, the first direct mention of the type Little Falls was by Hartnagel (1912, p. 29) who stated that the "... type locality is at the pass in the Mohawk Valley at Little Falls, Herkimer County."

Cushing (in Cushing and Ruedemann, 1914, p. 33, 38–39, 41) considered the 100-foot (31 m) thick fossiliferous Hoyt Limestone in the Saratoga area to be a facies of the upper Theresa, based in part on the similar thickness of Theresa-Hoyt interval in that area and that of the Theresa, alone, to the west where the Hoyt is absent. The Hoyt was described as consisting of alternating beds of dolostone and of fossiliferous limestone, the most common specimens being assigned to *Lingulella acuminata* and *Cryptozoon*. Black oolitic beds were noted. The overlying Little Falls (p. 43–45) was described as a gray dolostone ranging from fine-grained to coarsely crystalline. Although an exact thickness could not be determined, well core data suggested a thickness of from 300 to 400 feet (92–122 m). Gray and black chert were observed. With the exception of the ubiquitous *Cryptozoon*, fossils, primarily *Lingulella acuminata*, are very rare. The overlying Ordovician unit was called the Amsterdam Formation (p. 45–47).

Miller (1916, p. 35–36, 42–43) reported occurrences of Little Falls Dolostone in the outliers at Wells and Hope in the Lake Pleasant Quadrangle. The minimum and maximum thickness figures in the Wells area were 74 and 124 feet (22.6 and 37.8 m) respectively. Quartzose dolostone was noted, as well as some streaks of chert and vugs containing dolomite, clear quartz crystals, and white calcite. A district unconformity was described between the Little Falls and the overlying "Black River limestone," the Beekmantown and Chazy apparently being absent.

In her study of algal barrier reefs, Goldring (1938) described three horizons of Cryptozoon reefs within the Hoyt Limestone of the Saratoga region. She considered the Hoyt to be a more calcareous and fossiliferous phase of the lower portion of the Little Falls Dolostone (p. 8).

Wheeler (1942) postulated a major break between the Little Falls and the overlying Tribes Hill in the western Mohawk Valley as a result of a carbonate wedge thinning westward from Whitehall, New York.

In their revision of the geology in the Saratoga Springs area, Fisher and Hanson (1951) reinstated the term "Galway" (previously introduced by Clarke (1910)) for Theresa to comprise the transitional beds between the Potsdam Sandstone and the overlying Hoyt Limestone. They reported a maximum thickness of 55 feet (17 m) for the Hoyt (p. 802) and apparently believed (p. 804) that its westward termination was not due to a lateral gradation into the Theresa of the Broadalbin area, but rather to truncation by erosion represented by an unconformity increasing in significance to the west. Significant changes in the Hoyt-Amsterdam interval were presented. The name Ritchie was applied to blue-gray calcilutite (about 43 feet (13 m)) apparently unconformably overlying the coarse-grained dolostone of the upper Hoyt (p. 805), although a Late Cambrian or Early Ordovician age could not be determined. Hanson (p. 805) felt that the Ritchie might represent an offshore facies of the sandier Hoyt. The prominent thin sandstone above the Ritchie was named the Mosherville (p. 806) and considered for practical purposes to be the basal Ordovician unit owing in part to "... an unconformity of some magnitude ..." at its base. Discovery of Canadian fossils (p. 807) in dolostone overlying the Mosherville led these workers to the conclusion that these beds were not assignable to the Little Falls Dolostone, as had been assumed previously, but rather to a new unit which they called the Gailor Dolostone. They claimed that the type Little Falls is absent in the Saratoga area but that it is represented by facies equivalents, i.e., the Potsdam Sandstone, Galway Formation, and possibly part of the Hoyt Limestone.

Fisher's excellent work on Canadian stratigraphy of the Mohawk Valley (1954) dealt primarily with units directly above the Little Falls. However, he mentioned (p. 76) the discovery of some Franconian trilobites in a loose block of presumably Little Falls. He also suggested the possibility that the uppermost Little Falls might be Lower Canadian. The presence of the gastropod *Schizopea* in this position is not unequivocal; although the genus is more abundant in Canadian rocks, it is also known from strata of Trempealeauan age. Fisher considered that the Ordovician inference might be supported by intraformational disconformities within the Little Falls, but admitted that the magnitude of these breaks had not been satisfactorily determined.

Dunn and Fisher (1954) described the nature of anthraxolite in the Little Falls and some younger Canadian units. They concluded that this material, similar to anthracite in composition, originated through an increase of viscosity of an initial liquid that had become concentrated in zones of relatively high porosity and permeability. They thought that the parent substance was probably vegetable and might have had a source in *Cryptozoon* material. A Canadian assignment for the uppermost Little Falls was considered a possibility (p. 490). In addition to "major breaks" at the base and top of the unit, two other breaks of an intraformational nature were illustrated.

Fisher (1956, p. 333–336) again claimed that the Little Falls is an offshore carbonate phase of the Upper Cambrian Potsdam and Theresa, the relationship being one of transgression. The lower part of the formation was considered as Franconian on the basis of the presence of *Elvinia*. The presence of this trilobite in both the Little Falls and the Galway of the Saratoga region suggested a correlation of these units. Similar relationships are shown on his Cambrian correlation chart (Fisher, 1962a).

In a detailed study of the Wells outlier, Fisher (1957, p. 11) felt that the cherty, light bluish-gray dolostone represents a northerly occurrence of the Little Falls Dolostone of the Mohawk Valley, but also mentioned the possibility that the dolostone could be Canadian.

Zenger (1971a) urged that the Ritchie be assigned an Ordovician age and be included in the Gailor Formation as a member. His argument was based on the presence of the Canadian cephalopod *Ellesmeroceras* and on the observation of similar limestone sequences in the Gailor at a section near the type Ritchie.

In his work on subsurface Cambrian and Ordovician stratigraphy, based on observation of drill cuttings, Flagler (1966, p. 11) reported on the subsurface Little Falls in central, western, and southern New York. Particularly noteworthy is the thickness information; thinning to a feather edge against the Adirondacks, it reaches its maximum thickness (760 feet; 231.6 m) in the southwestern part of the state. Dolomite and quartz were noted as the essential constituents; calcareous beds were observed, particularly in the upper part of the formation although "... dolomites are generally calcareous ..." He maintained that an oolitic chert zone commonly present near the base is useful in delimiting the gradational Theresa-Little Falls contact. Rickard (1973) utilized gamma-ray logs, supplemented by lithologic data, in an attempt to elucidate the stratigraphy of Cambrian and Ordovician carbonates in the subsurface of New York. He subdivided the Cambrian west and south of the outcrop belt into two units, the Potsdam-Galway, and the Little Falls. He (p. 5) restricted the name Little Falls to only the upper part of the type Little Falls which includes all Cambrian rocks between the Precambrian and overlying Tribes Hill units; he pointed out that the lower part of the type Little Falls unquestionably is equivalent to the Galway and to rocks mapped as "Theresa" between the Mohawk Valley and the Adirondack Precambrian. Rickard recommended that the name Galway be used because the type Theresa north of Watertown is not continuous with the "Theresa" of the subsurface; also, the former is Ordovician whereas the latter is Cambrian.

Zenger (1976) defined the type Little Falls Dolostone, subdividing it into four informal members above the Proterozoic gneiss. The lowest Unit, A, 90 to 100 feet (20 to 30 m) thick, is a coarse crystalline dolostone containing sandstone and conglomerate at its base; Unit B, about 200 feet (61 m) thick is mainly fine to medium-crystalline, commonly vuggy dolostone containing algal stromatolites; Unit C, 25 to 40 feet (7.6 to 12.2 m) thick is mainly coarsely crystalline, "glauconitic" dolostone including quartzose intercalations; the uppermost Unit D is 30 to 40 feet (9.1 to 12.2 m) thick, generally fine crystalline dolostone with reddish zones. He believed the Little Falls-Tribes Hill contact to be conformable in the vicinity of Little Falls.

Fisher (1977), in a revision of his earlier correlation chart for the New York Cambrian (Fisher, 1962a), showed essentially the same age and stratigraphic relations for the Little Falls, which he considered to represent the low intertidal to low energy subtidal part of the shelf environment of the continental margin facies. As in the latest editions of the Geologic Map of New York (Fisher, and others, 1961; Fisher, and others, 1970), the term "Beekmantown" was used to include strata of both Late Cambrian and Early Ordovician age. Figure 1 is modified from his Plate II and shows the temporal relations of the units discussed in this report as Fisher envisions them.

Mazzullo, and others (1978), basing their work primarily on a core at the site of the present Pallette Stone quarry just west of Saratoga Springs, proposed some minor revisions for the stratigraphy in that area. The Mosherville Sandstone was recognized as a member within the upper part of the Galway. The Gailor Formation, the lower part of which was considered as possibly Trempealeauan, contains two limestones which they considered as members—the lower Ritchie and a new upper unit, the Slade Creek.

STRATIGRAPHY

GENERAL

A few comments are in order concerning the descriptive stratigraphic terminology. "Bedding" in many of the homogeneous intervals is defined by a physical separation, or parting; consequently, parting terminology is used in many instances, especially where true bedding is difficult to determine. Thin, medium, and thick parting and bedding refer to layers less than 2 inches (5 cm) in thickness, from 2 to 12 inches (5 cm–0.3 m) in thickness, and greater than 12 inches (0.3 m) in thickness, respectively. With regard to textural descriptions for sandstones, the categories fine, medium and coarse grained refer to the lower (2), middle (1), and upper (2) subdivisions of the 1/16 mm to 2 mm scale, respectively. For field description of crystalline rocks I have used very fine crystalline (essentially micritic), fine crystalline (silt sized), medium crystalline (fine and medium sand sized), coarse crystalline (coarse and very coarse sand), and very coarse crystalline (granule size or above). Friedman's scheme (1965a) for crystalline rocks will be used in the petrology portion, but is less practical for hand specimen work. The term orthoquartzite is used here in the sense of Krynine (1948, p. 149–152) and includes friable varieties of sandstone (as does the popular equivalent term, quartz arenite). Feldspar (microcline and perthite) usually contributes 5 percent or less of the grains in sandstones but may reach 10 percent; in these exceptional cases the term orthoquartzite (or quartzite—see Appendix A) is still retained as a practical field term. "Glauconite" is used in this qualified sense for an oxidized-copper green interstitial clay mineral, the composition and X-ray diffraction pattern of which resemble glauconite. Optically, however, it does not appear like typical glauconite and the usage here of "glauconite" also includes illite (see the section on "Petrology" for a more detailed description of this "glauconite"). Colors are taken from the Rock Color Chart of the Geological Society of America (Goddard, and others, 1951).

THE TYPE SECTION

The type section of the Little Falls Dolostone had never been appropriately designated until Zenger's definition (Zenger, 1976). Much of the information in that short paper is presented here for the sake of completeness. Clarke's original usage (1903, p. 16) was very vague. Because there is no one complete section, it is perhaps advisable to consider the general area of Little Falls as a type locality within which there is a composite type section consisting of several partial sections along the north and south sides of the Mohawk Valley (Figs. 2, 3). Glacial deposits are much thicker on the south facing hills; consequently, the better exposures are on the steeper, north facing bluffs on the south side of the Valley. Exposures constituting the type section are in the Little Falls 7½′ Quadrangle (SE/4 Little Falls 15′ Quadrangle).

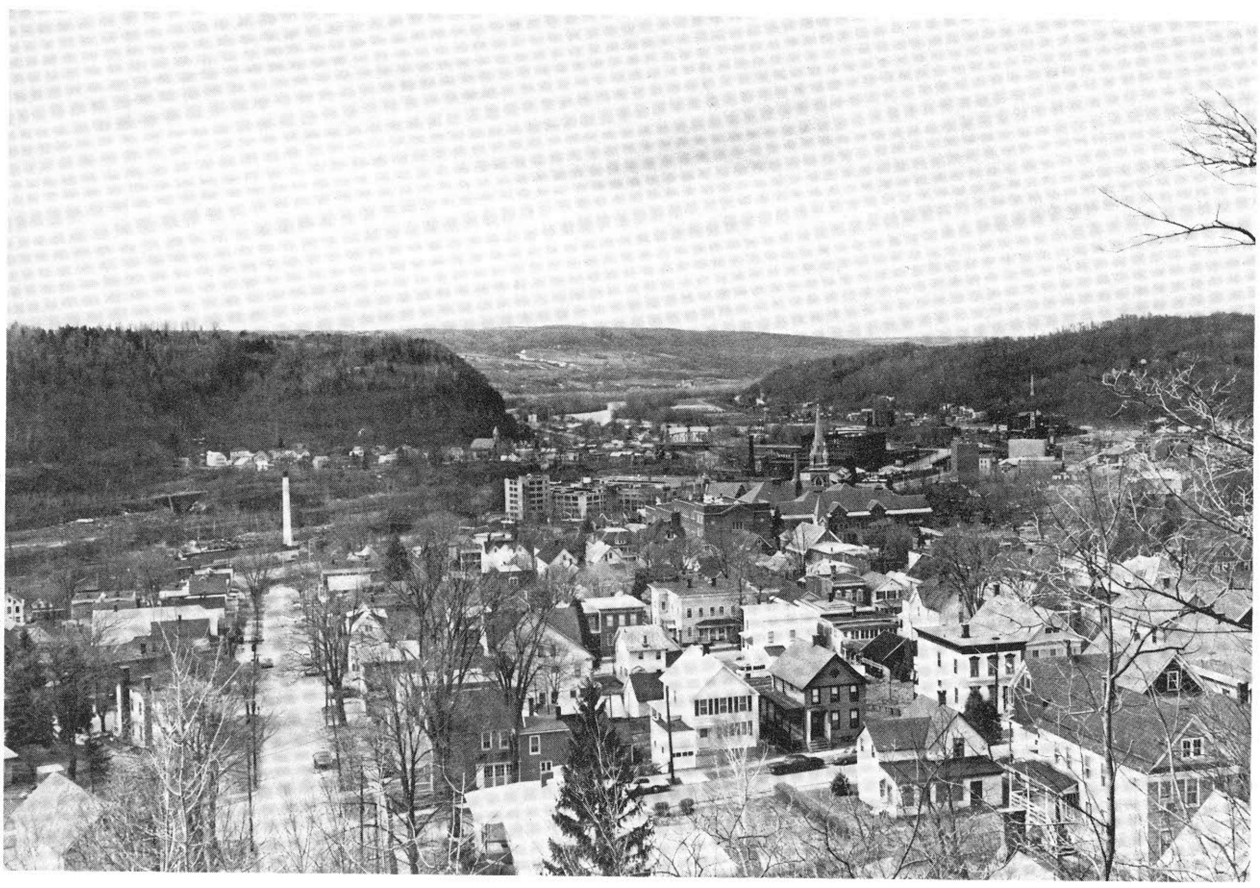

Figure 2. View to west of water gap of Mohawk River at Little Falls. Most continuous sections, comprising main part ot composite type section, are exposed in steep bluffs on south (left) side of River.

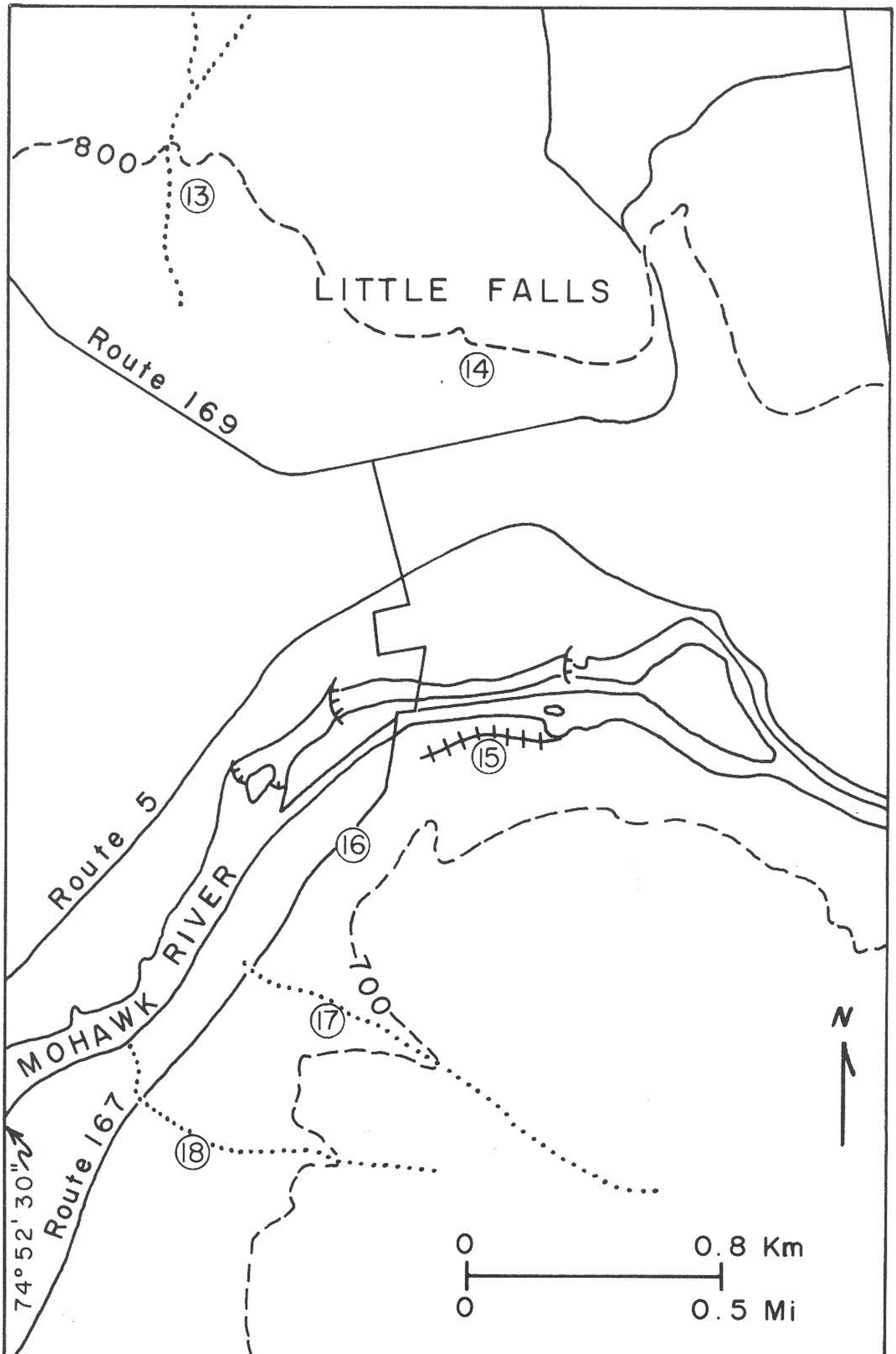

Figure 3. Sketch map showing location of type section at Little Falls. Locality numbers referred to in text. Except for outline of Mohawk River, solid lines are roads; dashed lines are contour lines; dotted lines are streams (from Zenger, 1976, p. 1571).

The composite type section consists of the following:

Loc. 13—Section exposed along south-flowing stream south of Little Falls Reservoir and east of Top Notch Road, in and above Buttermilk Falls; W 1/9 Little Falls 7½′ Quadrangle. Upper 90 feet (29 m) of Little Falls and contact with overlying Tribes Hill Formation (Ordovician) exposed at about 750 foot (230 m) elevation.

Loc. 14—Partly covered section exposed along secondary road (leading to Burrell's Mansion) and along hillside north of road beginning at elevation of about 590 feet (180 m) at northern end of Williams Street; W 1/9 Little Falls 7½′ Quadrangle. Approximately 205 feet (62 m) of section with neither lower nor upper contact exposed.

Loc. 15—Exposures at top of south side of railroad cut just south of old Jefferson Street School* on south side of Mohawk River and Barge Canal; top of cut at about 400 foot (122 m) elevation; northernmost part of SW 1/9 Little Falls 7½′ Quadrangle. Exposed is basal part of Little Falls and nonconformable contact with underlying Proterozoic gneiss.

Loc. 16—Section exposed in steep face just south of New York Route 167, 0.5 mile (0.8 km) east of northwest-flowing tributary at loc. 17 (see below); base of measured section at about 410 foot (125 m) elevation; SW 1/9 Little Falls 7½′ Quadrangle. About 65 feet (20 m) of lower Little Falls exposed.

Loc. 17—Section along northwest-flowing tributary of Mohawk River, directly southwest of steep bluff termed "Rollaway"; measured section begins at 420 foot (129 m) elevation, few hundred feet southeast of Route 167; SW 1/9 Little Falls 7½′ Quadrangle. Nearly 300 feet (92 m) and contact with overlying Tribes Hill exposed.

Loc. 18—Section along another northwest-flowing tributary of Mohawk River, about 1.2 miles (1.9 km) southwest of city hall and 0.5 mile (0.8 km) west of loc. 17; section begins just southeast of New York Route 167 at about 410 foot (125 m) elevation; SW 1/9 Little Falls 7½′ Quadrangle. About 200 feet (61 m) of middle part of formation exposed.

The unit is famous for its exquisite Herkimer "diamonds" (quartz crystals) and "Cryptozoon" structures (algal stromatolites).

Dolostone and sandstone are the main lithologies in the formation, there being a complete range from relatively pure dolostone through mixed dolostone-sandstone varieties (e.g., quartzose dolostone and dolomitic sandstone) to orthoquartzite. If one rock type is most common it undoubtedly is dolostone containing a relatively low quartz and feldspar content (from 10 to 15 percent), but there is really no one representative type. Quartz grains are commonly very well rounded and often frosted. There are no true limestones and calcite is minor (and late, paragenetically—see section on "Petrology"). Shales are essentially absent and although shaly parting is present, it is rare; the argillaceous content of both dolostones and sandstones is extremely low. "Glauconite" is more common in the upper half of the formation although its presence in the lower part precludes its use as a stratigraphic guide. Chert is also more common in the upper half of the formation although it too is present in the lower part where, for example, it has replaced algal stromatolites. The chert is usually light gray to very light gray when occurring as small patches or lenses but ranges from white or very light gray to grayish black in the more massive form. Silicified ooids were thought to be an aspect unique to the Little Falls; however, east of Amsterdam near Hoffman's (loc. 71), chertified ooids were found in an Ordovician unit (possibly Chuctanunda Dolostone) above the measured section. Flagler (1966, p. 11) considered silicified ooids to be useful in delimiting the lower contact of the Little Falls with the Galway in the subsurface; but, they are definitely found at higher horizons in the outcrop. Also, it should be emphasized that unlike Rickard (1970, written communication; 1973, p. 5), who studied mainly subsurface data, I do not consider the Galway to be present at the type section of the Little Falls; the entire interval from the Precambrian to the Tribes Hill at the type section is taken to be Little Falls.

The lithology of the Little Falls is relatively uniform and it is only with a close examination at the type locality that units can be established having certain characteristics which can be used to distinguish them. Contacts between them are gradational and often difficult to place. In addition, many of the characteristics of a particular unit can be found more rarely in the other ones. Medium to thick partings are most common and stratification ranges from laminations to thick beds. Colors are somewhat variable, although medium dark gray to shades of olive gray are most characteristic. Dolostones are most commonly fine to medium crystalline and sandstones usually are medium to coarse grained. Vugs are practically ubiquitous and they host dolomite, calcite, anthraxolite, and the "Herkimer diamonds." With the exception of algal stromatolites, which are of both the LLH and SH types, (Logan, and others, 1964), fossils are extremely rare. I found a lingulid brachiopod (*Lingulepis*?) at three localities in the middle and upper parts of the formation across the outcrop belt, whereas earlier

* The old Jefferson Street School has recently been demolished; its location was adjacent to (immediately west of) the Assembly of God Church.

workers (see Ulrich and Cushing, 1910, p. 121) reported *Lingulepis* from shaly beds near the base of the formation in the Little Falls area.

In the type area it seems feasible to consider the Little Falls as consisting of four subdivisions. Although they can be recognized, with varying degrees of certainty, beyond the type locality, they are given letter designations to connote their informal status. They will be referred to as "units" and are described below in ascending order. Plate 1B consists of columnar sections of localities 13, 15, 16, and 17 (the most important localities in the composite type section) which provide a representative expression of the formation. (In this plate and other columnar sections, the field subunits are given along the left side of each column.)

UNIT A The lowest unit, from 90 to 100 feet (28 to 31 m) in thickness, has a basal interval immediately above the Precambrian (Fig. 4) consisting of three feet (0.9 m) of quartz pebble to boulder conglomerate followed by platy to thinly parted sandstone with minor dolomite content. Above the vertical railroad cut, which was studied with the use of a rope*, there is a six-foot (1.8 m) covered interval. Above the covered interval are 4 feet (1.2 m) of generally low-quartz, light-brownish-gray dolostone with thin to medium parting. The next 11 feet (3.4 m) consist of light grayish-orange to light olive-gray coarse-crystalline to very coarse crystalline, low-quartz, medium to thick-parted dolostone with some quartz grains in the granule range. This section is represented by loc. 15 of the composite type section (see above; Plate 1B). The greater bulk of this unit, however, is exposed at loc. 16 (Fig. 5), as mentioned under the description of the composite type section; 65 feet (20 m) of Little Falls is exposed there (Plate 1B). Although some darker-gray and brownish-gray beds are included, the dominant lithologies are light-gray to light olive-gray, medium- to thick and even-bedded, low-quartz (13.0 percent insoluble, 16 samples), medium- to coarse-crystalline dolostone. Vugs are relatively uncommon and small (measured in millimeters) except for the uppermost beds which are nearly cavernous. No sandstones were noticed, although some beds are very quartzose, the quartz grains generally having a frosted appearance. Vague, darker gray mottles occur in the lower part of the section. Some beds are fine- to very fine-crystalline. Laminations and intraclasts are uncommon.

* Assistance in collecting samples from this nearly inaccessible locality was provided by Kenneth Grainer and is gratefully acknowledged.

Figure 4. Contact (see arrow) of Precambrian charnockitic gneiss (below; massive and jointed) and overlying medium-bedded sandy quartz-pebble conglomerate of Little Falls Dolostone; south side of railroad cut just south of old Jefferson Street school in Little Falls (loc. 15); basal exposed beds of Little Falls 3 feet (about 1 m) thick.

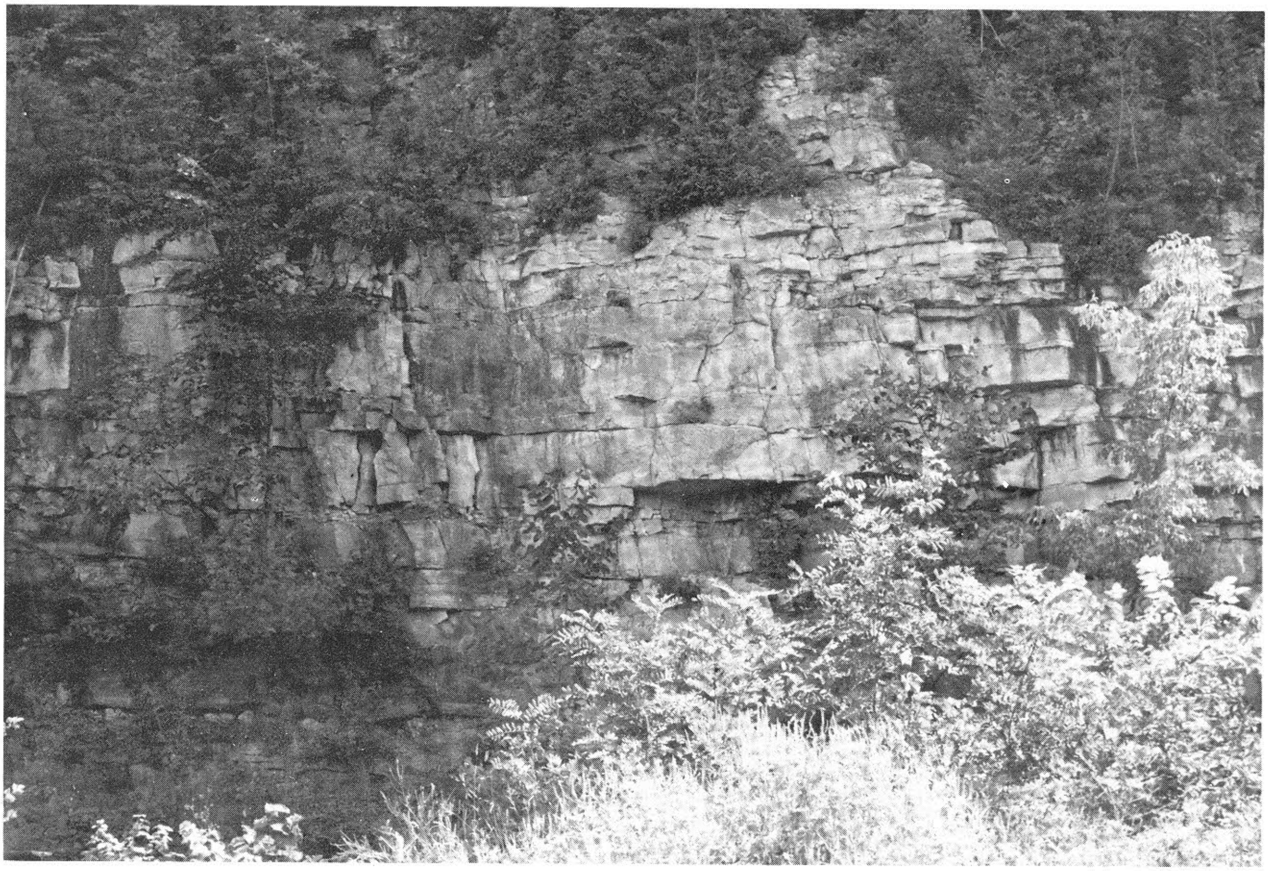

Figure 5. Exposure of part of medium- to thick-bedded Unit A along base of steep bluffs on south side of Mohawk River at Little Falls (loc. 16); about 40 feet (12.2 m) of section exposed.

UNIT B This unit represents about one-half the thickness of the Little Falls. It is seen to best advantage along the stream at loc. 17 where nearly a complete section of some 200 feet (61 m) is found (Plate 1B); another good section is at loc. 18 along the next stream to the west of loc. 17. The "typical" lithology consists of dark-gray to brownish-gray to dark brownish-gray, medium-parted, medium-crystalline, slightly quartzose dolostone. Vuggy beds are much more common than in Unit A. Commonly these are partially to completely filled with associations of secondary calcite, dolomite, and quartz. Fine- and coarse-crystalline dolostone is also present. Dolomitic sandstone and orthoquartzite are relatively common as beds or laminae intercalated with dolostone but they constitute less than 25 percent of the unit. These sandstones range from light gray to grayish black, are fine to coarse grained (most commonly medium-grained), thin- to medium-bedded, in places cross laminated, and contain common, rounded intraclasts of light olive-gray, very fine-crystalline dolostone. Quartz grains, where sufficiently large for observation, appear frosted. Laminations are common, and occur in the following relationships: orthoquartzite with intercalations of dolomitic sandstone; dolostone with more quartzose (including sandstone) intercalations; dolostone of one crystal size alternating with that of a finer or coarser texture. Except for possibly the latter, the other laminations are not likely representative of flat algal structures. In field subunit 34, channeling was observed to truncate laminae. Darker gray to grayish-black mottles are present in several beds; they may be gradational into the main matrix or they appear as sharply delineated spots. Green (oxidized copper green in color) interstitial "glauconite" is present in the upper third of the unit. Stylolites and microstylolites are rare. A bed capped by oolitic chert occurs in field subunit 25. The lower contact with Unit A is not exposed or accessible but I presume it to be conformable. It occurs within a covered interval above the subunits of Unit A in the lower part of the section at loc. 17.

Characteristic of this unit are hemispherical, algal stromatolites primarily of LLH-C and SH-C/LLH-C types (Logan and others, 1964; see Figs. 6, 7). These were observed at four horizons, at about 90 feet (28 m), 115 feet (35 m), 140 feet (43 m), and 190 feet (58 m; the highest bed), respectively, above the base of Unit B. There, typically, the stromatolites consist of dark-gray to dark brownish-gray to light brownish-gray, very fine- to fine-crystalline dolostone including the familiar convex upward laminations. Alternations are distinguished by contrasting lighter and darker

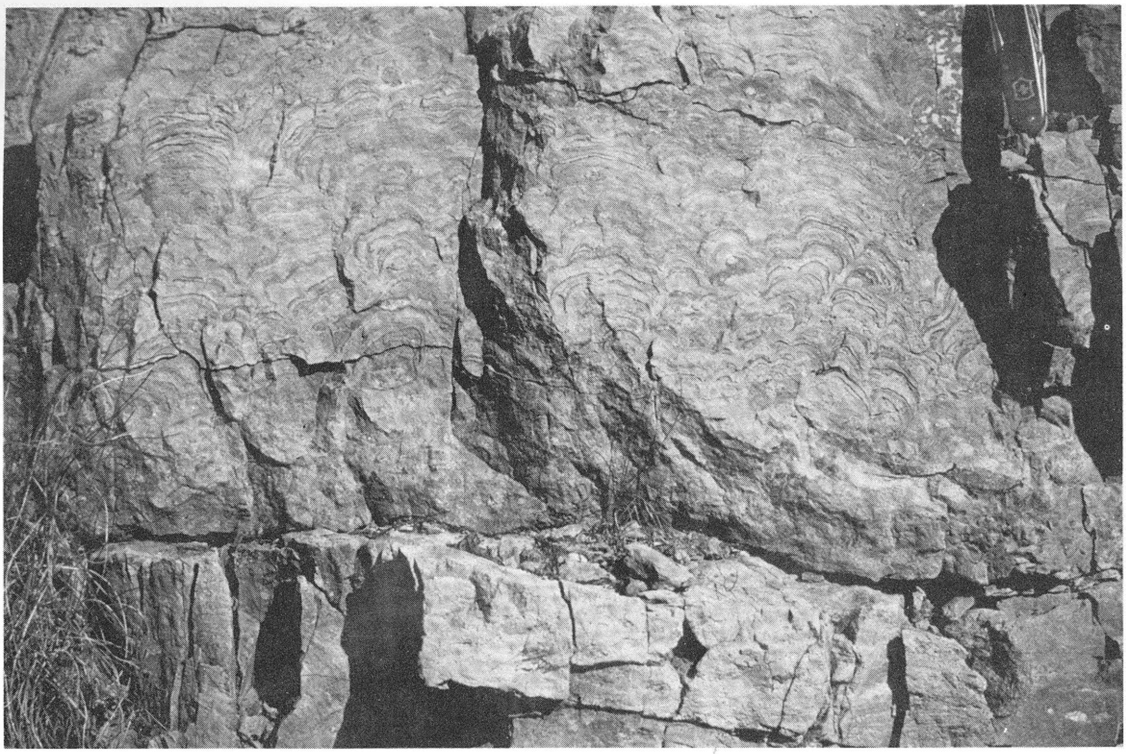

Figure 6. Algal stromatolite of type LLH-C resting on sandstone bed; part of alternating stromatolite-sandstone sequence, Unit B; east side of arterial southwest of Little Falls (loc. 20); note knife (8 cm in length), upper right hand corner of photograph.

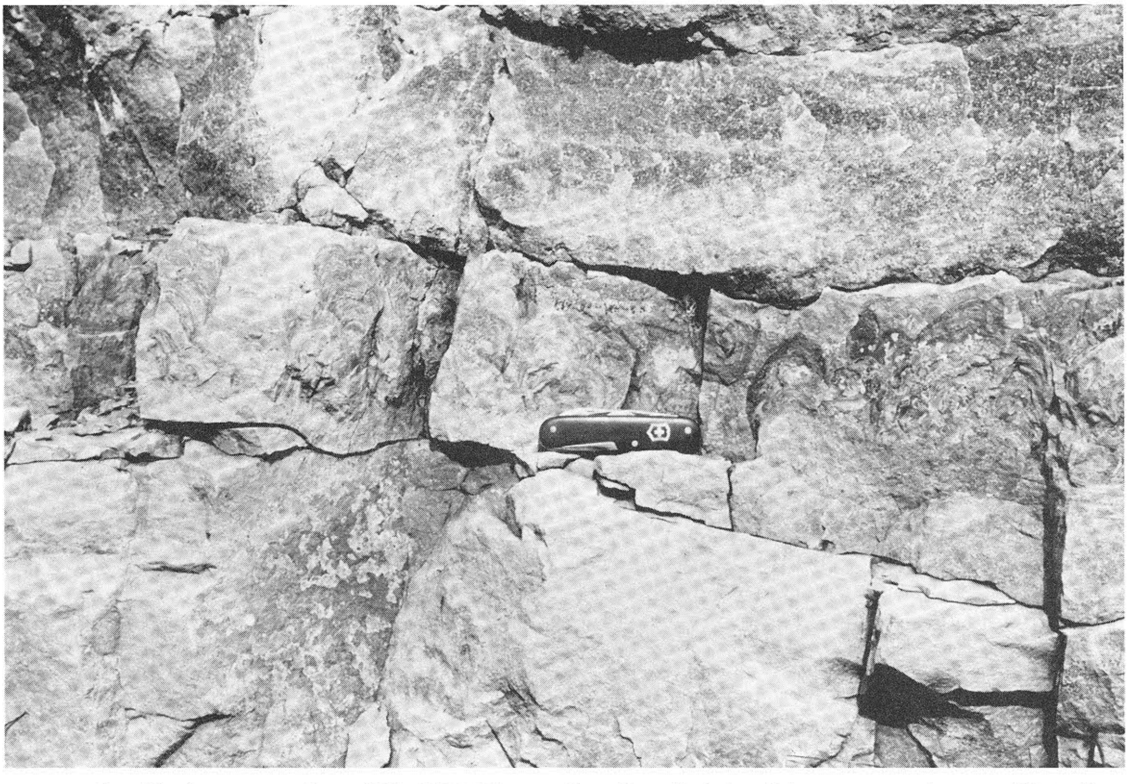

Figure 7. Algal stromatolite (SH-C/LLH) overlain by slightly dolomitic sandstone; Unit B; east side of arterial southwest of Little Falls (loc. 20); knife handle is 8 cm in length.

shades. The algal stromatolites range from less than a foot (0.3 m) to two or three feet (0.6 or 0.9 m) in thickness. At loc. 17 the lowest stromatolite is partially silicified. Vugs are common. Generally the stromatolitic layers are separated in the section.

However, the sequence beginning with field subunit 39, about 140 feet (43 m) above the base of the unit, comprises an alternation of five stromatolite beds, consisting of light brownish-gray to dark brownish-gray, very fine crystalline dolostone, with light brownish-gray to medium light-gray, fine- to medium-grained dolomitic sandstone to orthoquartzite and slightly darker quartzose dolostone. The sandstones possess medium parting and cross-laminations. The clastic material fills in the depressions between heads and contains intraclasts of the underlying stromatolitic dolostone. This interesting sequence is found at other localities particularly along the arterial (Route 167) 0.2 to 0.3 mile (0.3 to 4.5 km) north of the intersection with Route 5S in the southeast part of the Herkimer 7½′ Quadrangle (i.e., loc. 20; Fig. 8). These relations will be discussed later. Practically all of Unit B, including the stromatolite-sandstone alternations, is also exposed along the next stream west of loc. 17 (loc. 18).

UNIT C This unit is well represented at loc. 17 and at loc. 14. The unit is also exposed in Buttermilk Falls (loc. 13) above dark dolostone and sandstone of Unit B, but except for the upper portion at the brink of the falls, it is largely inaccessible. The dominant lithology of the 40- to 60-foot (12 to 18.5 m) unit is light-gray to light olive-gray, medium- to coarse- and very coarse-crystalline dolostone. Many beds and laminations are quartzose and there are relatively minor intercalated beds of fine- to medium-grained sandstone. Bedding and parting are predominantly medium to thick. Interstitial "glauconite" is more widespread in this unit than the others although it hardly ever is more than a minor constituent. Porous and vuggy beds are common. In the uppermost part of Unit C at loc. 17 is some massive, medium bluish-black chert containing irregularly shaped patches of a greenish-gray ("glauconitic"?) variety. Blackish pockets and irregular laminae are present but relatively uncommon. No algal stromatolites were noted at loc. 17, but in the section near Burrell's Mansion (loc. 14), what is taken to be the basal field subunit of Unit C has a stromatolitic horizon in its uppermost part. There are very sporadic beds of darker gray and brownish-gray dolostone. Such beds are more characteristic of Unit B but, as mentioned earlier, lithologies most typical of one unit may be found in others. The lower contact with Unit B at loc. 17 is conformable. This contact is within a covered interval near Burrell's Mansion (loc. 14) and at loc. 18.

UNIT D Unit D, the uppermost unit of the Little Falls, crops out continuously along the stream above

Figure 8. Algal stromatolite (type SH-C → LLH-C) overlain by slightly dolomitic sandstone in turn overlain by weathered algal stromatolite, east side of arterial southwest of Little Falls (loc. 20).

Buttermilk Falls (loc. 13; see Plate 1B), where both upper and lower contacts are exposed. A nearly complete section is present at loc. 17. The unit is 35 feet (10.7 m) thick at loc. 13 and 37 feet (11.3 m) thick at loc. 17. The most typical lithology is light-gray and medium-gray, fine- to very fine-crystalline, medium- to thick-bedded, slightly quartzose dolostone. Generally the coarser rounded sand grains decrease markedly upward from Unit C into Unit D. There are, however, numerous other rock types. Pale red dolostone, as mottles or matrix, is found in the upper part of the unit and is not found below in the older units. Intercalated with the fine-grained dolostone is medium-dark-gray to brownish-gray, medium-crystalline dolostone with which is associated thin oolitic chert 19 feet (5.8 m) above the base of the unit at loc. 13; chert pods with silicified ooids occur 15 feet (4.6 m) above the base of the unit at loc. 17. Both of these latter lithologies may also be quartzose. Quartz grains decrease in abundance upward in the unit. Most abundant in the upper part are blackish mottles and irregular seams similar to some textures in the overlying Tribes Hill Formation. Thirteen feet (4 m) below the top of the unit at loc. 13 is a one-foot (0.3 m) thick bed consisting of pale-red to brownish-gray, fine crystalline dolostone with intraclasts of somewhat finer grained blackish dolostone which form a unique edgewise breccia. At loc. 17, at about the same distance from the top, is an intraformational conglomerate consisting of very dark gray matrix with pale red clasts. "Glauconite" is present but rare. Several beds are pyritic. A fragment of a lingulid brachiopod was seen about 7 feet (2.2 m) below the top of the unit above Buttermilk Falls (loc. 14). There, both lower and upper contacts are exposed; both are believed to be gradational. About 9 feet (2.8 m) of medium light-gray to medium-gray, medium-crystalline dolostone separate Units C and D. As the typical medium-gray, fine-crystalline dolostone does not occur below Unit D, this transitional zone, which includes a grayish-black to brownish-gray orthoquartzite and a black and very light-gray chert near the top, is arbitrarily assigned to Unit C. I consider the upper contact with the overlying Lower Ordovician Tribes Hill Formation to be transitional; it is drawn about 13 feet (4 m) above the edgewise conglomerate mentioned above and 12 feet (3.7 m) below the lowest limestone near the middle of the upper falls. This boundary is specifically placed at the base of a four-foot (1.2 m) fucoidal dolostone sequence; the weathered surfaces are conspicuously fretted. It crops out on the west bank of the stream just below the upper waterfall. (It should be mentioned here that several other workers such as Ulrich and Cushing (1910), Wheeler (1942), and Fisher (1975, written communication) consider a break between the Little Falls and Tribes Hill at Little Falls; this point will be discussed further in the summary section on stratigraphy.) The dolostones above the contact are dark gray to olive gray to brownish gray and are fine or medium-crystalline. They contain mottles of pale-red and dark-gray dolostone. The uppermost 3-foot (0.9 m) field subunit of this 12-foot (3.7 m) dolostone sequence is calcareous. Just above this is a 0.2-foot (0.06 m) limestone band marked by a conspicuous reentrant in the waterfall. This is overlain by 5 feet (1.5 m) of dark-gray to olive-gray calcareous dolostone, in turn succeeded by a foot (0.3 m) of fine-crystalline, fucoidal limestone with interlaminae of dolostone. Capping the falls is 1.5 feet (0.5 m) of very fine crystalline limestone with brownish and reddish seams and containing fucoids and fossils, including the gastropod *Liomphalus*. The overlying limestones are exposed several feet back from the falls to the northeast. Placing a systemic boundary in a gradational sequence is always a difficult, and rarely an objective, matter. The Tribes Hill is of undoubted Canadian age, as determined by fossil content, not only at this section, but elsewhere as well. The Little Falls, however, is essentially unfossiliferous. With a lack of physical evidence of a disconformity between the Little Falls and the Tribes Hill, and an apparent lack of such within the upper Little Falls, it is very probable that the Cambro-Ordovician boundary would be somewhere within the upper part of the Little Falls. For practical purposes, lacking faunal control, it can be drawn at the contact between these two units.

These, then, are the four units in the type locality. It might be difficult to place a random sample in a particular unit with any degree of certainty. However, if given the typical lithology of each, or if able to look at several feet of section, one is able to distinguish the units more confidently.

The upper part of the Little Falls is nearly continuously exposed along an east flowing stream and a south flowing tributary (loc. 23) east of School No. 4, about two miles (3.2 km) NNE of the center of Little Falls. From field relations as well as from an inspection of two drill cores (loc. 23A; courtesy of James R. Dunn and Associates), the Little Falls has thinned considerably to about 280 feet (85.3 m). However, some of the reduction is probably related to faulting. In the two drill cores studied there are brecciated zones at the Precambrian-Little Falls contact and also above; both dolostone and crystalline clasts occur in these breccias. Also, the traces of two faults immediately border this location on the east. Exposures of Unit B are separated. Unit C, typically light gray to light olive gray, and in places quartzose, is 44 feet (13.4 m) thick. Included as the uppermost subunit are 11 feet (3.4 m) of white chert and associated brownish-gray dolostone. The parting is thin to massive. The subunit contains "glauconite" in various beds including a pyritic, chert-pebble conglomerate in a reentrant at the top of the subunit. Some oolitic chert is present. Near the base is a possible silicified stromatolite. The subunit crops out from the top of the second of three waterfalls to the middle of the highest falls. Below the chert are 33 feet (10.0 m) of typical Unit C lithology—light-gray to olive-gray, fine- to coarse-crystalline, vuggy low-quartz to quartzose dolostone with some minor associated dark-gray to brownish-gray sandstone and orthoquartzite. "Glauconite" is common and calcite, dolomite, anthraxolite, pyrite, and chalcopyrite occur in vugs. There are darker-gray mottles and seams in a few beds. Below is Unit B, the contact with C being conformable. Some 130 feet (39.6 m) of that unit is discontinuously exposed to a point several hundred feet upstream from an outcrop of Precambrian gneiss. The upper contact with Unit D is conformable;

in fact, it appears as though there may be a facies relationship between the units; the upper part of field subunit 5 beneath the chert interval is a medium-gray, very fine- to fine-crystalline dolostone essentially identical to that in Unit D. It would be most difficult, given the outcrop control, to prove this conclusively. Unit D measures 31 feet (9.4 m) in thickness. Its lower contact with Unit C appears to be gradational although it is placed within a two-foot (0.6 m) covered interval. The dolostone in D is medium gray, very fine crystalline to fine crystalline with medium to thick parting. There are more minor intercalations of coarser, brownish-gray dolostone, especially in the lower half. One of these, just above the upper falls at the wood line, is capped by oolitic chert. Reddish mottles occur in the upper 13 feet (4 m) and in the uppermost subunit are some black pockets. The 9 feet (2.7 m) above the contact within the two-feet (0.6 m) of cover (see immediately above) is itself gradational between the Little Falls and Tribes Hill. It consists of medium dark-gray or light olive-gray, fine- to medium-crystalline dolostone including dark-gray pockets or clasts. Reddish mottling is also present. Although perhaps transitional between the two formations, the subunit is placed in the Tribes Hill Formation by virtue of the presence of fucoids and blackish laminae, which are disrupted in places. The exposure ends along the south flowing tributary just upstream from a wooden bridge. Forty feet (12.1 m) higher, topographically, and along the road to the northwest are outcrops of limestone belonging to the Ordovician Trenton Group.

As indicated previously, I believe that the entire section at the type locality between the Precambrian crystallines below and the Tribes Hill above is most appropriately assigned to the Little Falls. In the subsurface, the Little Falls thins to a feather edge to the northwest. On the northwest side of the Adirondacks, above the Precambrian, are, in ascending order, the Potsdam Sandstone, the Theresa Formation (sandy dolostone and sandstone) and the Ogdensburg Formation (predominantly dolostone). Much of the Theresa is considered to be of Ordovician age (Fisher, 1962b; Rickard, 1973). Fisher and Hanson (1951, p. 802) in the Saratoga Springs region recognized "... sandy dolomite, dolomitic sandstones, and calcareous sandstones lying below the Hoyt and above the Potsdam Sandstone." They felt it inappropriate to extend the name Theresa to this area because it had been poorly defined and because the formation included both Upper Cambrian and Lower Ordovician strata. Accordingly, they recommended that the name Galway Formation, originally introduced by Clarke, (1910, p. 12; original reference not seen; see Fisher and Hanson, 1951, p. 802) be substituted for that interval previously called "Theresa" in east-central New York. In the subsurface to the west, southwest, south, and southeast of the outcrop belt of the Little Falls is a unit judged from logs and sample cuttings to be intermediate between the Potsdam and Little Falls. Rickard (1973, p. 5) applied the name "Galway" to this interval, which previously had been referred to as Theresa, because the type Theresa is not continuous with the subsurface equivalent; furthermore, the type Theresa is Ordovician whereas the subsurface "Theresa" is Cambrian. Rickard's (1973, p. 5) distinction between the Little Falls and Galway in the subsurface is based on gamma-ray logs as well as sample data. According to Rickard (op. cit.), "it [the Little Falls] differs from the Little Falls of the type locality in the Mohawk Valley where this formation has included all dolostones between the Precambrian and Tribes Hill. Yet the lower portion of this type Little Falls unquestionably is equivalent to the Galway ... As used in this report, the name Little Falls is restricted to the upper portion of the type section. The Little Falls and its equivalents attain a maximum thickness of 300 feet [91.4 m] in southeastern New York."

Rickard (1970 and 1975, written communication) would also favor the application of "Galway" to approximately the lower half of the type Little Falls; I oppose this, however. I do not intend to dispute the persistence of features on gamma-ray logs. Perhaps it is feasible to distinguish between the two units in the subsurface. But, I can see no lithologic distinction in the field at the type locality. A considerable amount of quartz and sandstone should be typical of the Galway but in none of the sections at Little Falls is the Galway equivalent more quartzose than the upper, restricted Little Falls of Rickard. Furthermore, insoluble residue studies show the lack of a correlation between terrigenous content and the lower (or Galway equivalent) as contrasted with the upper part of the Little Falls. Twenty-three samples from the Galway equivalent at loc. 17 average 19.5 percent insoluble, whereas the restricted Little Falls above averages even higher, 20.3 percent for 31 samples. At loc. 18 much the same was found; twenty-three samples from the Galway equivalent average 24.6 percent insoluble, whereas the upper part averages a bit less, 23.1 percent. Furthermore, Rickard (1970, written communication) would include algal stromatolites as a characteristic of the restricted Little Falls. Generally, stromatolites are most common in the middle of the Little Falls; this portion would be within the Little Falls as used by Rickard. But, although rare, stromatolites do occur within the Galway equivalent. Exactly what the persistent peaks on the gamma-ray logs indicate is not known (Rickard, 1973, p. 4). However, I do not believe that a distinction is valid at the type locality and consider only one formation, the Little Falls, to represent the Precambrian-Tribes Hill interval.

WEST CANADA CREEK-SPRUCE LAKE AREA

This area includes the northwestern part of the outcrop belt of the Little Falls which extends across the Newport 7½′ Quadrangle (NE/4 Utica 15′ Quadrangle) and the Middleville and Salisbury 7½′ Quadrangles (NW/4 and NE/4 of Little Falls 15′ Quadrangle, respectively; see Plate 1A). The most continuous exposures are found in the Middleville Quadrangle although there is no complete section available. On the east bank of West Canada Creek at the northern margin of the village of Middleville is an outcrop of Precambrian crystallines, but the lower part of the Little Falls is covered on both sides of the valley. The most continuous sections are in the quarry of Eastern Rock Products, Inc., a short distance north of Middleville along Route 28 (loc. 6), on Wolf Hollow Creek (loc. 5), and along an east-flowing tributary of West Canada Creek opposite Middleville (loc. 11). The Little Falls is attenuated and pinches out completely northward near Poland in the Newport 7½′ Quadrangle. The upper half of the formation crops out along the two stream sections (locs. 5 and 11), whereas the central part of the Little Falls is exposed in the quarry. Plate 1C consists of columnar sections of the formation for localities 6 and 11. As measured in a diamond drill core (Eastern Rock Products, Inc.; loc. 6A) located just east of the quarry (loc. 6), the Little Falls is about 230 feet (70.1 m) thick. The rate of thinning continues northward as the outcrops near Poland are the northernmost ones and the formation must pinch out a very short distance to the north of that town.

About 90 feet (28 m) of Little Falls were exposed in the quarry north of Middleville in 1969 (Fig. 9; see Plate 1C). A covered interval of 15–20 feet (4.6–6.1 m) separates this main exposure from an outcrop of 10 feet (3 m) of Little Falls near the office of Eastern Rock Products, Inc., opposite the quarry, on the west side of Route 28. The sequence consists of dolostone and sandstone, as usual, although sandstone and the quartz content of quartzose dolostones are more significant here than in the exposures at Little Falls; the average (52 samples) insoluble is 34.1 percent. Using parameters and features such as color, texture, bedding, laminations, mottles, vugs, and basic lithology (e.g., orthoquartzite, dolomitic sandstone, quartzose dolostone) I was able to discern some 25 rock types. The most common dolostone is medium dark gray to slightly brownish gray, fine to medium crystalline, medium- to thick bedded, low-quartz to quartzose, and commonly vuggy. A prevalent sandstone type is light olive gray to pale yellowish brown, medium grained, medium bedded, and dolomitic. Slight variations on these major themes represent the lower 65 feet (19.8 m) in the quarry. Laminations are common, consisting

Figure 9. Northeast face of Eastern Rock Products quarry just north of Middleville (loc. 6); uppermost part of main face and lower part of ledge in background consists of alternating algal stromatolite-sandstone sequence of Unit B.

of quartzose laminations in dolostone beds or of dolostone distinguishable in color and/or crystal size from the main dolostone mass. Mottling is not uncommon toward the middle of the section. "Glauconite" is rare and occurs primarily as interstitial material but also as a parting, particularly in the sandstone-stromatolite unit to be described below. Vugs contain secondary crystals of dolomite, quartz, and calcite, which apparently formed in that order, and anthraxolite. A lingulid brachiopod was found about 10 feet (3 m) above the lowest quarry floor (in 1967). A sandstone bed contains darker quartzite and chert. Some of the interstitial "glauconite" is cherty. Stylolites are rare. The most interesting part of the section is the upper 33 feet (10 m), or field subunits 19, 20, and 22. Subunit 19 consists of 8 feet (2.4 m) of a cyclic sequence of 3 couplets of sandstone and dolostone whose lithologies are as described above. Sandstones contain intraclasts of the underlying dolostone. The 15 feet (4.6 m) of overlying subunit 20 is also cyclic, consisting of couplets (7) of algal stromatolitic dolostone and sandstone or very quartzose dolostone. The dolostone is laminated (convex up), dark gray to pale yellowish brown, very fine crystalline, commonly vuggy, and low in quartz. The stromatolites generally consist of laterally linked heads (LLH) and stacked heads (SH). Each stromatolitic dolostone is overlain by dark-gray to light olive-gray, medium-grained dolomitic sandstone to quartzose dolostone. Intraclasts of stromatolitic dolostone occur in the more clastic beds above. Cross-laminations are common. Two of the cycles show relict ooids in the clastic material draped over and between stromatolite heads. At the uppermost exposures, separated from subunit 20 by 2 feet (0.6 m) of dolostone (subunit 21), is subunit 22, 10 feet (3 m) thick, consisting predominantly of light-gray to light brownish-gray, medium- to coarse-grained, medium-parted, cross-laminated dolomitic sandstone and orthoquartzite (Fig. 10) with minor intercalations of fine-crystalline dolostone. Two feet (0.6 m) above the base of the subunit is a blackish sandstone in contact with the underlying dolostone. The uppermost bed contains dolomitic laminae and intraclasts. Some beds are very porous and ripple marks are present. The cross-laminations dip to the southwest, south, and southeast.

The preponderance of quartz in this sandstone subunit, as well as in the remainder of the section, has a frosted appearance. Although the fraction of quartz is noticeably higher here, the section can be considered equivalent to Unit B at the type locality. On the basis of comparison of this field section and the drill core (loc. 6A) from higher on the hill to the north, it is estimated that there are about 50 feet (15.2 m) of covered Little Falls between the Precambrian and the lowest exposure near the Company office and about 65 feet (20 m) of Little Falls above the quarry section and beneath the Lowville Limestone higher on the hill. Apparently the equivalent of this part of the sequence is exposed along Wolf Hollow Creek approximately 0.9 mile (1.5 km) to the northwest.

There, a 95-foot (29 m) section, with few covered zones, occurs from West Canada Creek eastward for about 0.4 mile (0.65 km) to the contact with the Lowville Limestone under the bridge at Old City. Once again a notable feature is the amount of terrigenous material; the average insoluble residue (26 samples) is 32.1 percent, nearly that at the quarry. The dominant rock types in the lower 70 feet (21.5 m) are medium dark-gray to brownish-gray, thin- to thick-bedded, fine to medium-crystalline, low-quartz to quartzose dolostone, commonly vuggy, and medium light-gray to medium dark-gray, to brownish-gray, very even- and me-

Figure 10. Cross-stratified orthoquartzites (with approximately southerly azimuth), Unit B, near top of section (field subunit 22) at Eastern Rock Products quarry just north of Middleville (loc. 6).

dium-bedded, fine-to predominantly medium-grained dolomitic sandstone. On a small scale, lithologies may be interlaminated. In the lowest field subunit are blackish quartzites interbedded with the dolostone. Three algal stromatolites consist of medium dark-gray, with grayish-orange laminae, medium- to thick-bedded, fine-crystalline dolostone; these are intercalated with medium dark-gray, medium-grained sandstones and quartzose dolostones. Ooids(?) are associated with the uppermost thick stromatolite capping a falls. As this 8-foot (2.4 m) interval occurs roughly 60 feet (18.3 m) below the contact with the Lowville, I suggest that this unit, in part, is equivalent to subunit 20 (alternating stromatolites and dolostone) at the Middleville quarry. In the upper 25 feet (7.6 m) are light-gray to medium light-gray to medium-gray, generally thin- to medium-bedded, normally quartzose, fine- to coarse-crystalline dolostones with very quartzose dolostone or dolomitic sandstone intercalations; a stromatolite horizon occurs in field subunit 10, about 13 feet (4 m) below the Lowville contact. Some beds have considerable "glauconite" as small patches. The uppermost 8 feet (2.4 m) consist of generally medium-gray to medium dark-gray, medium- to thick- and even-bedded orthoquartzite and dolomitic sandstone which become light gray to greenish gray in the uppermost two feet (0.6 m). The dolostones in this upper 25-foot (7.6 m) interval are quite similar to those in Unit C at Little Falls, being a bit darker and having more intercalated sandstone. I suggest that based largely on stratigraphic position, this portion is equivalent to C although the entire section is assigned to Unit B. The Tribes Hill Formation is absent here as well as elsewhere in the area.

The basal five feet (1.5 m) of Lowville Limestone consists of light greenish-gray to greenish-gray, medium- to thick-bedded, very quartzose limestone. In this unit are ubiquitous, elongate, white, calcite-filled bodies which are smaller and less regularly distributed than the "birdseye" structure of the typical medium-gray weathering micrite of the Lowville which immediately overlies this lower subunit. The Little Falls-Lowville contact is placed at the shaly-bedded quartzose limestone at the base of the high waterfalls just east of the bridge.

The upper half of the Little Falls, as it occurs in the Middleville area, is also exposed along the stream at loc. 11 (Plate 1C). Including about 20 feet (6.1 m) of covered intervals, the section is about 120 feet (36.5 m) thick. Basically, the lithologies are much like those at the quarry (loc. 6) and Wolf Hollow Creek (loc. 5), consisting of dolostone and sandstone intercalations on a scale ranging from bedding to laminations. Chert laminae are present. Sandstones and orthoquartzites may contain dolomitic intraclasts and commonly are cross-laminated; where it was possible to determine true dip directions, the azimuths are primarily to the southeast. Approximately midway in the section is a 14-foot (4.3 m) sequence consisting of five couplets of alternating stromatolitic dolostone and overlying laminated and cross-laminated quartzose dolomite and dolomitic sandstone. This familiar sequence is believed to be equivalent to subunit 20 at the Middleville quarry and, possibly, to subunit 3 at Wolf Hollow Creek. The stratigraphic distances of these cyclic subunits beneath the Little Falls-Lowville contact are approximately 75 feet (23 m) at the quarry, 55 feet (16.8 m) at Wolf Hollow Creek, and 60 feet (18.3 m) at loc. 11. Vugs, partly filled with secondary minerals, are more common in the lower part of the section. "Glauconite" is relatively widespread but always minor. Chert, in places "glauconitic," occurs at a couple of horizons in the upper half of the section. One dolostone, associated with intercalated sandstone and orthoquartzite, is essentially a breccia containing angular clasts of quartzite. The uppermost exposed subunit of Little Falls consists of light olive-gray to very light brownish-gray "glauconitic" dolostone, capped by medium-grained, friable, slightly "glauconitic" sandstone; a five to 10-foot (1.5 to 3 m) covered interval separates this exposure from the lowest outcrop of gray, sandy, fine-crystalline Lowville Limestone. The uppermost five feet (1.5 m) of Little Falls is somewhat similar to the light-colored dolostone of Unit C at the type locality and may represent the equivalent of that unit but the entire section is assigned to Unit B.

The Little Falls is also exposed here and there along west-flowing tributaries of West Canada Creek. The most significant one of these exposures is along the southern branch of Maltanner Creek and along adjacent Route 29 near the bridge (loc. 9). Approximately 80 feet (24.5 m) are exposed from the base of the waterfall to the top of the rapids above the main falls and at the edge of the pasture; the upper part of this sequence is capped by 3 feet (0.9 m) of cherty dolostone. Above this, only portions of the uppermost 40 feet (12.1 m) crop out along the stream. Directly north of the farmhouse is a medium-gray, irregularly bedded very fine-crystalline dolostone very reminiscent of the lithology of Unit D at the type locality. At this locality one can examine the contact with the basal Lowville, a light medium-gray to light greenish-gray, quartzose limestone. In a thick bed just above the basal Lowville are large (measured in inches or centimeters), somewhat elongate clasts of dolostone of Little Falls lithology (Fig. 11); these are oriented roughly east-west. Above, the more typical micrite of the Lowville is exposed in the face of an abandoned quarry south of the stream and in turn is overlain by the Kirkfield Limestone (Trenton group), which holds up a waterfall.

There are a few separated outcrops of the upper half of the Little Falls along the steep portion of the smaller, southwest-flowing northern tributary of Maltanner Creek (loc. 7) north of loc. 9. Exposed

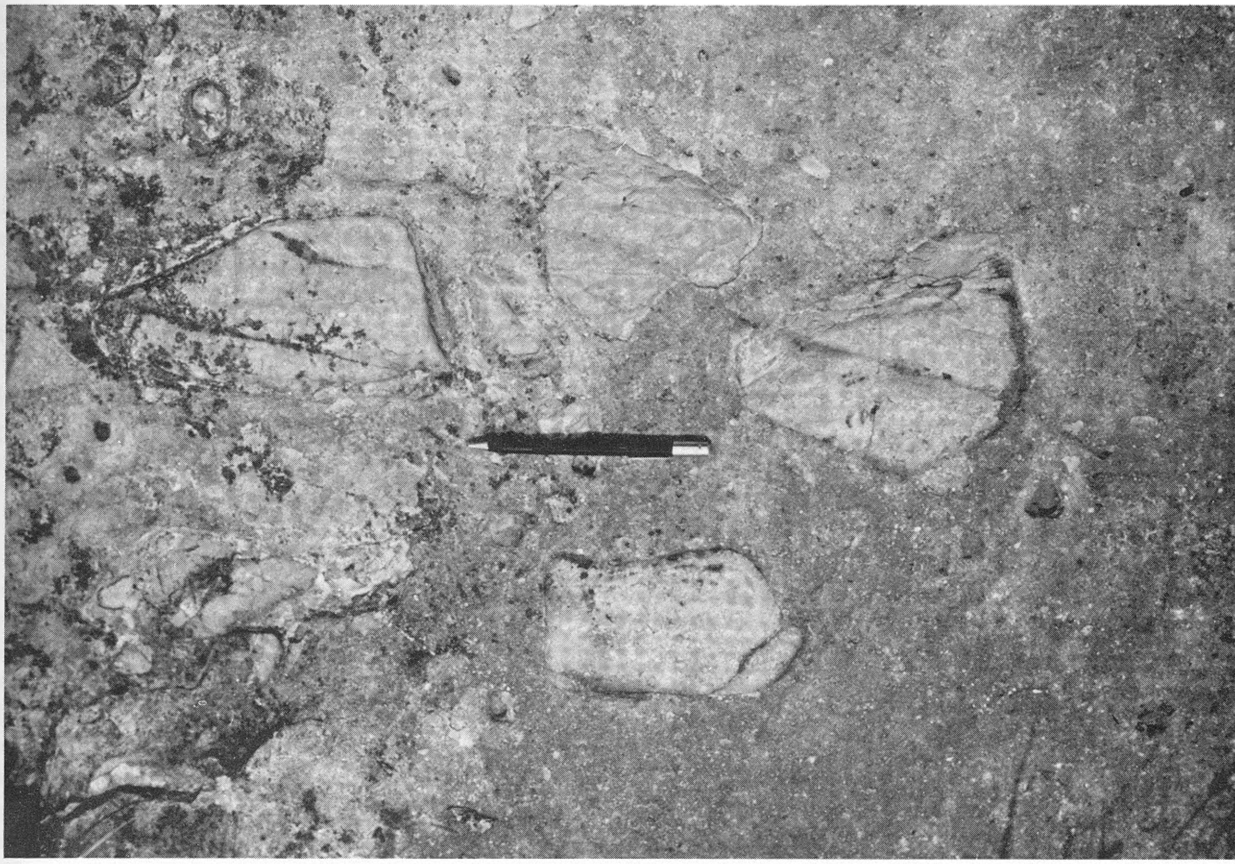

Figure 11. Clasts of fine-crystalline dolostone of Unit D in lower Lowville (Middle Ordovician), south branch of Multanner Creek just east of Middleville (loc. 9); pencil is 5 inches (about 13 cm) in length.

there is an association of algal stromatolites and cross-laminated dolomitic sandstones. At the point where the stream gradient lessens (at about the 780-foot (240 m) elevation) is a reddish weathering bed overlain by irregularly bedded breccia with dark-gray to blackish clasts within a very pyritic matrix; I suspect this is a fault breccia. (Locally folded and brecciated dolomite along Route 29 at loc. 9 may also be tectonic.) A loose fragment of "glauconitic" dolostone containing oolitic chert was found above the breccia at loc. 7.

The northwesternmost outcrop is in an abandoned quarry immediately west of Buck Hill Road just north of its intersection with the Poland-Cold Brook Road (loc. 1). Dark brownish-gray to dark-gray dolomitic sandstone and quartzose dolostone with medium parting is unconformably overlain by the Lowville Limestone. Only one foot (0.3 m) below this unconformity is a stromatolitic horizon which is overlain by coarse-grained, dolomitic sandstone. The lithology is similar to that in Unit B at the type locality.

Thus, the Little Falls thins northward, from about 400 feet (122 m) at the type locality, to slightly more than 200 feet (61 m) at Middleville, to the very attenuated section near Poland. It pinches out completely a short distance north of Poland. Although neither the basal contact with the Precambrian nor the lower part of the Little Falls is exposed in the Middleville-Poland area, it seems that the thinning is due primarily to a loss from the upper part. Except at loc. 9, where it appears that Unit D is present, most sections show either characteristic Unit B or beds assignable to that unit but bearing a slight resemblance to Unit C, and probably a lateral equivalent of that unit, immediately below the disconformable contact with the overlying Lowville. This is further supported by the absence of the Tribes Hill Formation, which overlies the Little Falls at the type locality. It is unlikely that the stratigraphic gap results from nondeposition alone, especially in view of the clasts of Little Falls in the basal Lowville at loc. 9 east of Middleville. I suggest that Early Ordovician erosion was the main cause of the disconformity; thus, a considerably greater thickness of Little Falls than now exists was present in this area.

Outcrops are very fragmentary along Spruce and East Canada Creeks in the vicinity of Salisbury (locs. 25–29). The formation has again thinned northward from the Mohawk Valley, but a thickness cannot be determined because nowhere in this area is there a complete section. The most accessible section is in an abandoned quarry about 0.4 mile (0.65 km) northwest of Salisbury (loc. 25); some 25 feet (7.6 m) of Little

Falls are exposed there. The predominant lithology is brownish-gray to light olive-gray to yellowish-gray, fine- to medium-crystalline, commonly vuggy dolostone. Some beds are quartzose and there are interlaminations of quartzose dolostone with the low-quartz variety. Some "glauconite" is present and anthraxolite and secondary dolomite rhombs occur in the vugs. Cross-laminations were noted in one bed of quartzose dolostone. Relict ooids were noted in the uppermost part of a very vuggy bed about 8 feet (2.4 m) below the top of the quarry. The section is tentatively assigned to Unit B although the upper part resembles the lithology of Unit C and is probably a facies equivalent.

Outcrops along an easterly flowing tributary of Spruce Lake (loc. 28) provide a relatively good section of 34 feet (10.3 m), parts of which are covered. Dolomitic sandstones are as common as dolostones and quartzose dolostone. Dark brownish-gray, fine- to medium crystalline dolostone and sandstone are intercalated with light olive-gray beds somewhat similar to Unit C. A stromatolitic bed occurs about 11 feet (3.4 m) above the base of the section and directly above this is a 6-foot (1.8 m) subunit of dolomitic sandstone to quartzose dolostone containing rounded (oolitic?) "glauconitic" bodies. About 15 feet to 20 feet (4.6 to 6.1 m) stratigraphically above the uppermost exposure of Little Falls, and just east of the north-south road, are beds of fossil-fragmental, pelmatozoan-rich, gray limestone of the Trenton Group.

The Precambrian-Little Falls contact is exposed along the west bank of Spruce Creek immediately south of the bridge at Diamond Hill (loc. 26); it consists of siliciclastic Little Falls overlying Precambrian gneiss and quartzite. The contact dips conspicuously to the south. The poor quality of lateral continuity of outcrop makes it difficult to distinguish between the possibility of initial dip vs. later uplift to the north but it appears that there was some relief on the Precambrian surface here. The contact and the nature of the basal part of the Little Falls is very similar to the exposure along the railroad cut at Little Falls (loc. 15). At Diamond Hill, the lower three feet (0.9 m) of Little Falls above the Precambrian consists of dark-gray, mostly thin-bedded, medium- to coarse-grained orthoquartzites to dolomitic sandstones containing some quartzite granules and cobbles. The dolomite crystals are very coarse. This basal subunit is overlain by 1.5 feet (0.4 m) of dark-gray, medium-bedded, very dolomitic, coarse-grained pyritic sandstone to quartz pebble conglomerate; the quartzite clasts are more conspicuous than in the basal units. There follow several feet of thin partings of brownish-gray, quartzose dolostones and light olive-gray to very-pale orange, coarse-crystalline, quartzose dolostone to dolomitic sandstone; orthoquartzitic intercalations occur within this interval as well as quartz pebbles to cobbles (15 mm greatest dimension noted). The occurrence of these clasts 4 to 7 feet (1.2 to 2.2 m) above the basal conglomeratic beds suggests at least some relief on local Precambrian sources during early Little Falls deposition. "Glauconite" is present but rare. Near the top of the bank (along the main waterfall) and separated from the lower beds by a short covered interval are some beds of coarse-crystalline, low-quartz to quartzose oolitic dolostone.

The upper contact with the Ordovician (presumably Lowville) is not exposed in the Salisbury-Spruce Creek region. The exposures at Diamond Hill can be assigned to the basal part of Unit A. The other short sections belong to Unit B. Thus it would again appear that the decrease in thickness is due primarily to the upper disconformity.

EAST CANADA CREEK-ST. JOHNSVILLE-CANAJOHARIE AREA

This area extends from the lower reaches of East Canada Creek (north of its junction with the Mohawk River) on the west, through the vicinity of St. Johnsville to Canajoharie on the east (locs. 30–40). Several good sections are available but they are all in the middle or upper part of the formation; the Precambrian-Little Falls contact is covered everywhere by the alluvium of the Mohawk Valley and is not exposed. Columnar sections at East Canada Creek (loc. 30) and St. Johnsville (loc. 31) are presented in Plate 1D.

The most complete section in this area is along Timmerman Creek (= Klock Creek on highway sign; loc. 31) which enters the Mohawk in the western part of St. Johnsville. About 245 feet (74 m) were measured, which may be slightly high owing to the difficulties caused by a combination of the presence of covered intervals and the fact that the stream often flows essentially down the slight dip slope. The section presents a somewhat different picture than that at the type locality. Presumably Unit A and part of Unit B are covered. However, there is less of the lithology of Unit B, that is, the darker gray and brownish-gray dolostone, in its stratigraphic position based on the sections at Little Falls (from about 100 feet (31 m) to 300 feet (92 m) above its base). On the other hand, Unit D has thickened considerably (assuming no repetition due to the problems discussed above, or due to tectonism), although the division between Units C and D is transitional and difficult to place. There are intercalations of the light olive-gray to medium light-gray, fine- to coarse-crystalline dolostone of Unit C with dolostone similar to Unit B (medium dark-gray to brownish-gray, fine- to coarse-crystalline, low-quartz to quartzose, commonly vuggy, dolostone). Stromatolitic horizons are relatively common; one of these intervals, field subunit 13C, consists of 7 feet (2.2 m) of the familiar alternation of algal stromatolitic and cross-laminated quartzose strata. The cross laminations are directed to the NW in the lower part of the sequence and to the SE in the higher portion. Sandstones overlying the stromatolites include clasts of the latter. There is much more chert in this section than in any other section visited; several of the stromatolitic layers are silicified. The chert varies in appearance; it may take the form of silicified stromatolite heads or the finer grained laminae of these structures (field subunits 11, 16, 17, 18A); it may occur as lenses or irregular seams associated with coarse-crystalline dolostone and dark orthoquartzites (field subunits 16, 24); it may exist as conglomerate or breccia (field subunits 13, 18A); it may be in the form of cherty "orthoquartzite"; it may occur as relatively massive beds (field subunits 33, 37). At three horizons (field subunits 13, 37, 43) the chert is oolitic. The color of the various cherts is generally very light gray or blackish. Dolomite rhombs or dolomolds can be seen in some cherts, which in places are pyritic.

Another difference is the relatively low amount of dolomitic sandstone and quartzite in the section (there are numerous laminae, seams, and beds of quartzose dolostone). Whereas the amount of chert has increased measurably, sandstones are much less abundant than at other localities. Of the 47 field subunits established, only two were sufficiently quartzose to warrant the name "sandstone."

Nonsilicified relict ooids are found in field subunits 18B, 18D, and 19. "Glauconite," never abundant at any horizon, occurs more or less throughout the section. Laminated dolostone, other than stromatolites, is not as common as elsewhere and mottling is rare except in the uppermost part of the section. Some luster-mottling, represented by large crystals of poikilotopic calcite, occurs low in the section. Incomplete mud cracks occur in field subunit 33. Anthraxolite and dolomite rhombs are the usual occupants of vugs.

The upper 20 feet (6.1 m) of section measured is equivalent to Unit D at the type locality, although there is proportionally less of the medium-gray, fine- to very fine-crystalline dolostone. Pale-red laminations, beds, and mottles are common in this interval and there are darker gray pockets as well. Ten feet (3.1 m) below the top of the measured section is a grayish-orange to medium-gray to light greenish-gray dolostone containing elongate clasts of blackish dolostone, some of which lie at high angles to the stratification and form an edgewise conglomerate; this is similar to the edgewise conglomerate above Buttermilk Falls in Little Falls (loc. 13, field subunit 10). Above this "marker" bed are laminated and mottled dolostones that appear to be transitional to the Tribes Hill. However, above this point (at about 780 feet (240 m) behind a red house) the stream gradient becomes very low and less than the dip slope; it was considered impractical to continue the section. A discontinuous section occurs along Mill Road roughly parallel to and immediately west of Timmerman Creek. Seven measurements of cross laminations showed a range of azimuths in the SW, SE, and NE quadrants with six of these being in the southerly quadrants.

Zimmerman Creek is parallel to Timmerman Creek and about 0.75 mile (1.2 km) to the east. There are relatively few exposures along the stream but in and immediately above the high waterfall (known locally as Scudder's Falls) are exposed about 100 feet (31 m) of Little Falls. The lower 60 feet (18.2 m) consist primarily of brownish-gray, fine-crystalline dolostone with interbedded quartzose dolomite and dolomitic sandstone. Orthoquartzites are uncommon. Bedding ranges from laminations to thick bedding. Two algal stromatolitic horizons and several strata with cross laminations were observed. Vuggy and porous beds are common and there is at least one instance of quartzose dolostone filling desiccation cracks in a very fine-crystalline dolostone. "Glauconite" is present but rare. The sequence is followed by 12 feet (3.7 m) of alternating stromatolitic dolostone and quartzose dolostone to orthoquartzite with cross laminations. The upper 30 feet (9.2 m) studied consists predominantly of brownish-gray, fine-crystalline dolostone with some quartzose dolostone and dolomitic sandstone. Unsilicified ooids are present in a bed near the top of the falls. Also observed in this uppermost interval are mottles, fucoids, and a sandstone with dolomitic clasts. Several measurements (11) were made of cross laminations, both along the road to the base of the falls and along the falls proper. Four had azimuths to the southeast, three to both the northeast and southwest, and but one to the northwest. At the very top of the section are current ripples striking N53°E with the lee side to the southeast.

The equivalent of the lower part of the succession along Timmerman Creek is exposed in the Talarico quarry on the north side of Route 5 in West St. Johnsville (loc. 30A) and less than one-half mile (0.8 km) west of Timmerman Creek. Of the 15 field subunits established only two are classed as sandstone. This operation began in 1968; consequently when I studied the section in 1969 only 37 feet (11.3 m) of Little Falls was exposed. The quarry has since been enlarged considerably with perhaps 50 feet (15 m) being exposed in 1977.

In this area, there are several excellent exposures of the upper part of the Little Falls and its contact with the overlying Tribes Hill Formation. The uppermost 67 feet (21 m) of Little Falls is exposed in the streambed and walls along East Canada Creek north of the Beardslee Power Station and south of the dam (loc. 30; see Plate 1D); this location is slightly more than 2 miles (3.2 km) west-northwest of the Talarico quarry

(loc. 30A). Outstanding examples of potholes are exhibited along this portion of East Canada Creek (Fig. 12). At the base of the section is a 15-foot (4.6 m) subunit or predominantly light yellowish-gray to olive-gray, fine- to mostly very coarse-crystalline, low-quartz to quartzose, "glauconitic," vuggy dolostone. The subunit has intercalations of darker weathering dolostone. There are some thin, dark quartzites in the middle part of the subunit, which is assigned to Unit C. The overlying 9 feet (2.8 m) (3 field subunits) are also considered part of Unit C although they are probably transitional to Unit D. The lower 6 feet (1.8 m) consist of medium light-gray to light brownish-gray, irregularly bedded, commonly very coarse-crystalline dolostone with "glauconite" and greenish to black chert, often brecciated, in the lower half. Some of the chert fragments contain silicified ooids. The upper part is vuggy with secondary mineralization consisting of dolomite, quartz, and calcite in that order of formation. The upper three feet (0.9 m) consist of olive-gray, irregularly bedded, "glauconitic" and cherty sandstone associated with olive-gray to medium-gray, "glauconitic" dolostone. Oolitic chert occurs in the uppermost part. Partings are very "glauconitic." Thin wavy laminations may represent flat algal laminae.

The overlying 41 feet (12.5 m) are considered to represent Unit D. The most common lithology is the light-gray to medium light-gray to medium-gray, fine to very fine-crystalline, generally low-quartz dolostone that is characteristic of that unit. Interbedded with this is medium dark-gray to brownish-gray, fine- to coarse-crystalline, generally low-quartz dolostone. Parting is medium to thick and commonly irregular and uneven. Approximately 23 feet (7 m) and 27 feet (8.3 m) below the upper contact with the Tribes Hill are zones of oolitic chert as elongate pods parallel with the bedding (Fig. 13). Pale red mottles and pockets are common in this uppermost Little Falls. Wavy to convolute laminations occur about 17 feet (5.2 m) and 24 feet (7.3 m) below the upper contact; these may represent algal laminations (Fig. 14) which may be somewhat deformed. On the other hand, there are also even laminations usually consisting of alternations of finer and coarser dolostone. Each of these laminated intervals is capped by edgewise breccias consisting of thin, blackish clasts in a matrix of medium-gray to olive-gray dolostone. Such dolostones are more quartzose owing to a considerable proportion of quartz in the blackish clasts. Also present are intraclasts of fine-crystalline dolostone and, in one subunit (9) of "glauconitic" dolo-

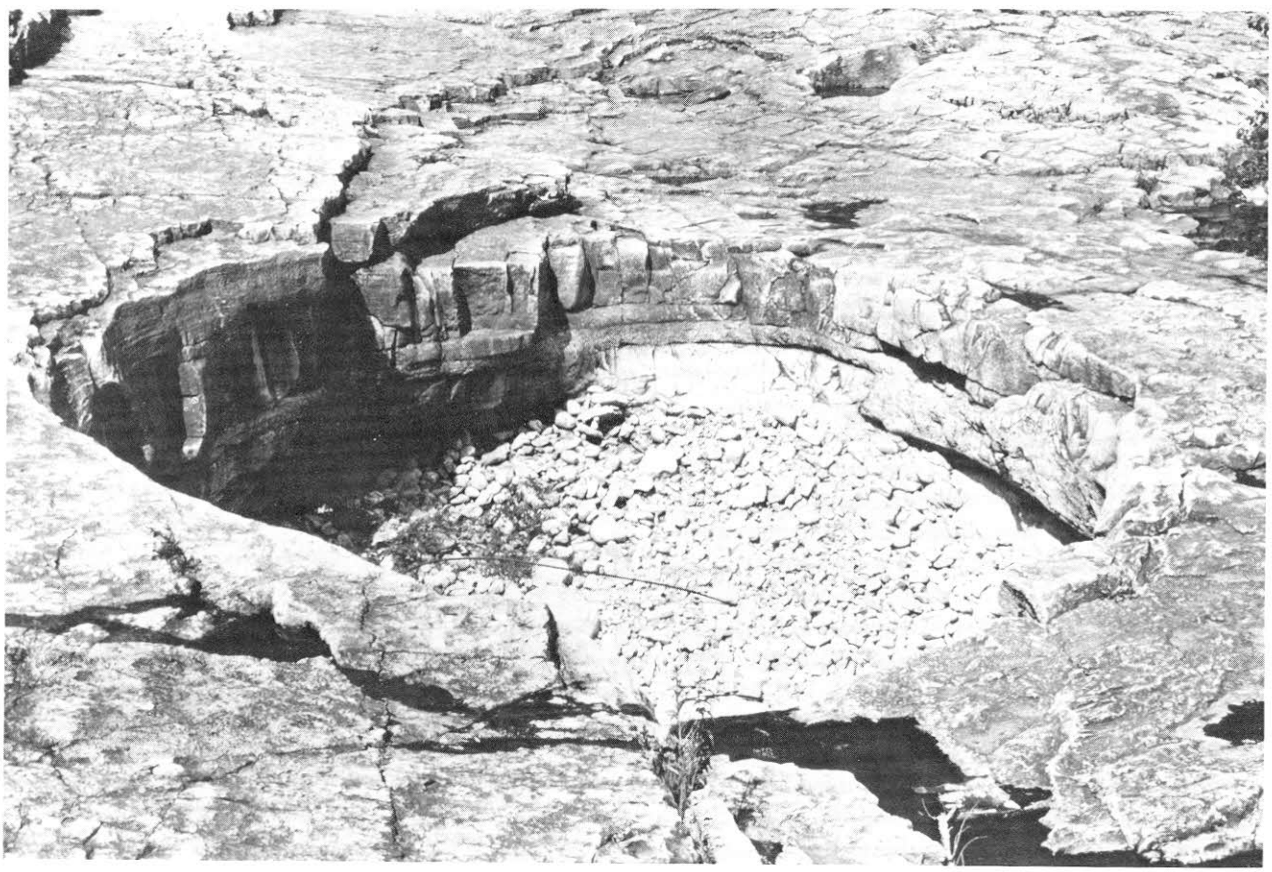

Figure 12. Pothole (about 10 feet (3.1 m) deep) in Unit D of Little Falls Dolostone, East Canada Creek just north of Beardslee Power Station (loc. 30).

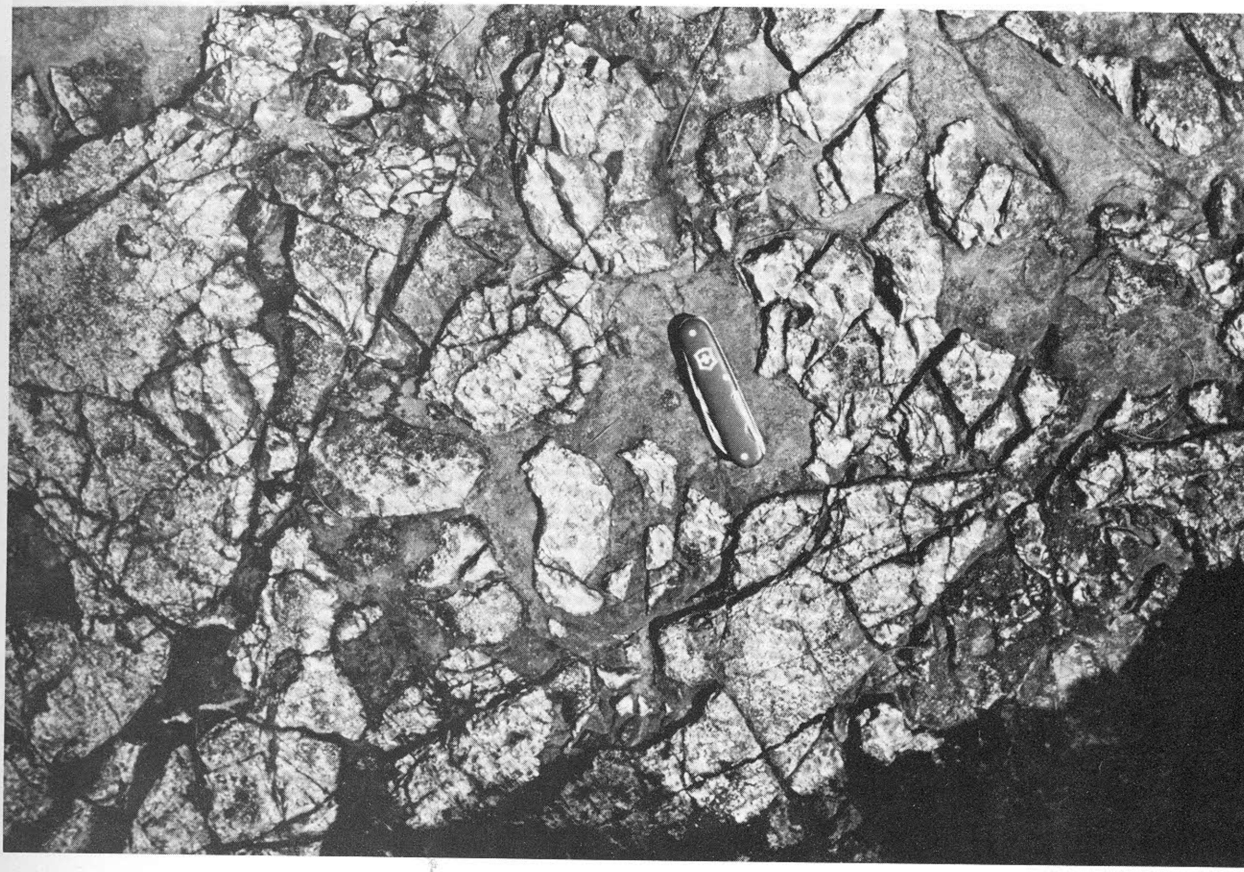

Figure 13. Pods of oolitic chert (light) on bedding surface; field subunit 9, East Canada Creek north of Beardslee Power Station (loc. 30).

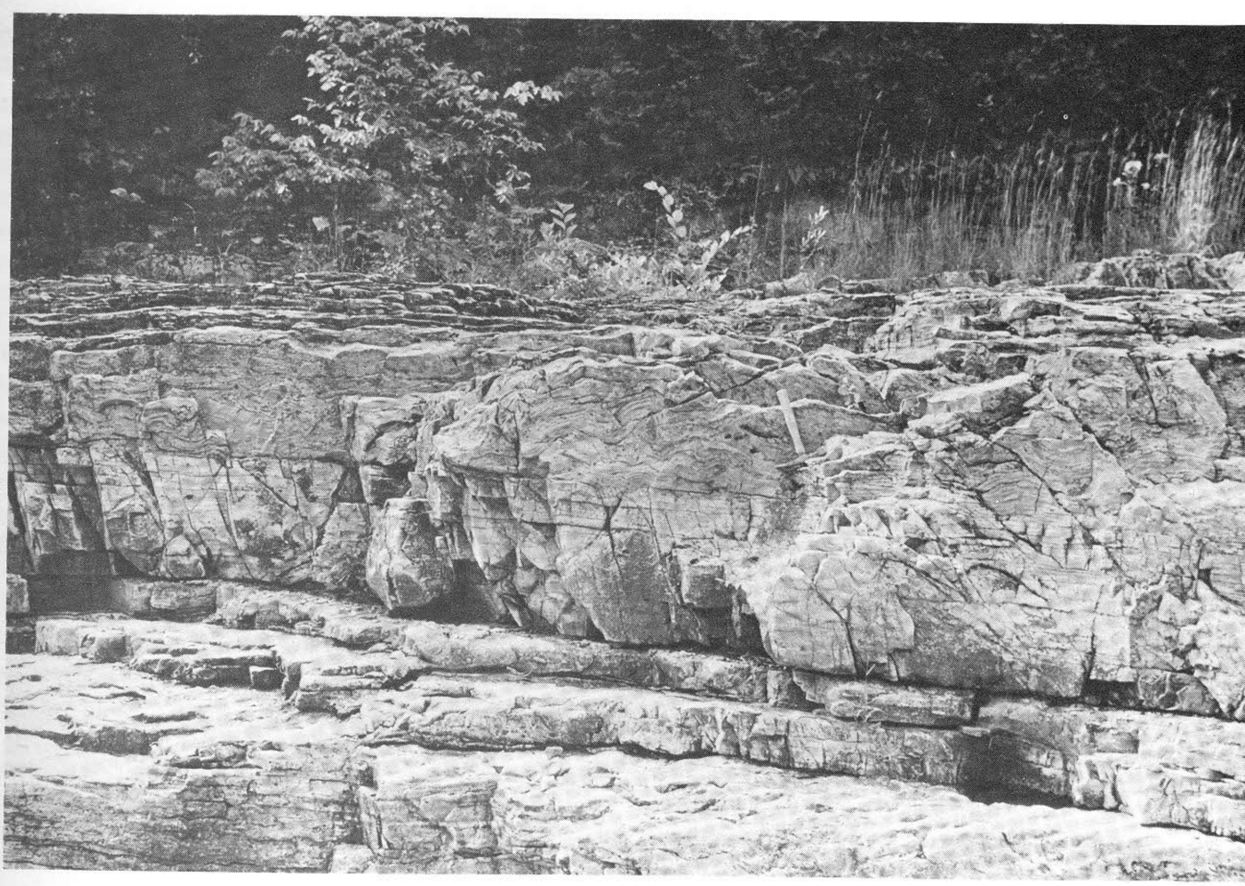

Figure 14. Upper zone (field subunit 13, Unit D) of undulatory, laminated dolostone (algal laminated?) underlain by flat laminated dolostone; East Canada Creek just north of Beardslee Power Station (loc. 30); note hammer for scale.

stone, which are parallel to the bedding or in an edgewise situation (Fig. 15). Two fucoidal zones were observed, 24 feet (7.3 m) and 38 feet (11.6 m) below the upper contact. Darker-gray mottles and seams are relatively common in the upper part. Vuggy intervals occur throughout the section; not surprisingly anthraxolite, dolomite, quartz, and calcite are the secondary materials in the vugs.

The contact with the overlying Palatine Bridge Member of the Tribes Hill Formation appears to be conformable. The uppermost Little Falls (field subunit 17) consists of pale yellowish-brown to light brownish-gray, coarse-crystalline, porous to vuggy, low-quartz dolostone including clasts and laminae of finer crystalline grayish-orange weathering dolostone. There are some pale red areas. The overlying base of the Tribes Hill is dark-gray, fine-crystalline, medium-bedded, resistant dolostone which forms a protruding ledge over the uppermost Little Falls on the east wall (Fig. 16). This basal dolostone is overlain by either more dolostone or, as is most often the case, by light-gray weathering, thin-parted, micritic limestone with dolomitic seams. The limestone is in turn, overlain by mottled dolostones—grayish orange and grayish black—and including some pale red mottling. Fucoids, many appearing as incomplete mud crack fillings(?), are prominent and there is some intraformational conglomerate. Strong development of fucoids and the presence of limestone are two guides setting off the Tribes Hill from the Little Falls.

The uppermost 22 feet (6.7 m) of Little Falls, as well as its contact with the Tribes Hill, are exposed in the easterly of two cuts along the Thruway (Route 90) south of St. Johnsville (loc. 33); the sequence dips to the west and is located on the downthrown side of a north-south normal fault immediately to the east. The

Figure 15. Edgewise breccia in Unit D (field subunit 9) at top of falls along East Canada Creek (west bank) just north of Beardslee Power Station (loc. 30): note dark oolitic chert pods near top of photograph.

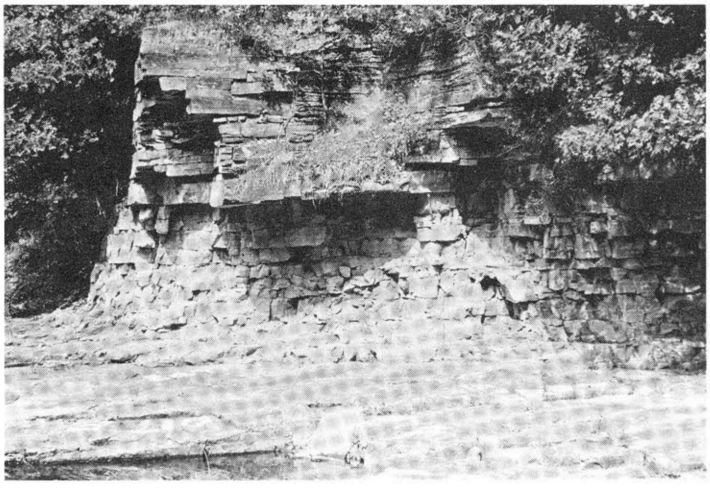

Figure 16. Contact between Unit D of Little Falls Dolostone (below) and overlying Palatine Bridge Member(?) of Tribes Hill Formation; hammer head at overhang marks contact; East Canada Creek north of Beardslee Power Station (loc. 30).

lower 7 field units, totaling about 22 feet (6.7 m), are Little Falls in assignment. However, even these seem to be in a broad sense transitional to the Tribes Hill. The lowest field subunit is medium-gray to medium light-gray, fine-crystalline dolostone typical of Unit D to the west. This lithology interfingers with pale red laminae in field subunit 5. Except for field subunit 3, which is very light-gray to yellowish-gray, the other dolostones are generally medium-gray to dark-gray, medium-parted, fine-crystalline dolomite with pale red mottles or seams, at least some of which probably represent bioturbation. Pods and lenses of oolitic chert occur in the upper 10 feet (3.1 m) of this sequence. Blackish chert, in dark pockets or as seams parallel with the bedding, occur in field subunit 2 and a "tranquil" chert breccia occurs in 5. Several subunits are vuggy.

It seems that the three subunits (8, 9, 10) overlying the 22 feet (6.7 m) described above, are really transitional between the Little Falls and Tribes Hill. About 6 feet (1.8 m) intervene between uppermost definite Little Falls and lowermost definite Fort Johnson Member of the Tribes Hill Formation (see Fisher, 1954, p. 78). The interval consists primarily of fine- to coarse-crystalline, medium dark-gray to dark-gray dolostone. Immediately above the shaly parting above definite Little Falls is yellowish-orange, coarse-crystalline dolostone with finer crystalline, dark-gray seams. Fucoids occur in the upper five feet (1.5 m). Field subunit 10 has a profusion of *Lingulepis*(?) on one bedding plane. Pale red laminations are present. In places laminations are broken into clast-like segments that locally form an edgewise conglomerate. This subunit appears to thicken to the east; the uppermost bed grades westward to the lowest limestone. The lowest unequivocal Tribes Hill consists of medium dark-gray, fine-crystalline, dolomitic, platy, and fucoidal limestone with intraclasts in the upper part. One-half foot (0.15 m) of dolostone separates this from an overlying 25 feet (7.6 m) of limestone, similar to that below, with an associated irregular network of yellowish-brown dolostone. The presence of pale red zones and *Lingulepis*(?) suggest a Little Falls assignment. However, the presence of fucoids and fretted surfaces and a higher feldspar content (based on X-ray data) in the gradational interval suggest Tribes Hill, as does the fact that the uppermost dolostone in the transitional sequence apparently grades to Tribes Hill limestone. The lower yellowish-orange dolostone with darker gray seams resembles the lower Tribes Hill as seen at Little Falls. This point, coupled with the minor facies change and the presence of fucoids compels me to place the subjective formational boundary at the base of the transitional sequence (base of field subunit 8). D. W. Fisher and L. V. Rickard (1970, written communication) preferred to draw the boundary at the base of the lowest limestone (subunit 11).

Nearly an equivalent section is exposed in the abandoned quarry south of Route 5S on the eastern outskirts of Canajoharie. The uppermost Little Falls, 25 feet (7.6 m) thick, is apparently in gradational contact with the overlying Fort Johnson Member, which consists of a basal two feet (0.6 m) of fine crystalline, mottled and fucoidal dolostone followed by 18 feet (5.5 m) of light-gray weathering, fine- to very-crystalline limestone (Fig. 17). The sequence of Little Falls is assigned to Unit D. It is primarily a medium-gray to medium dark-gray to dark-gray, fine- to very fine-crystalline dolostone with medium to thick partings, Pale red dolostone is very common as mottles, as laminations, or blended with gray. The fine-crystalline dolostone is very light weathering. Desiccation cracks occur in very light-gray, very fine-crystalline dolostone; these are

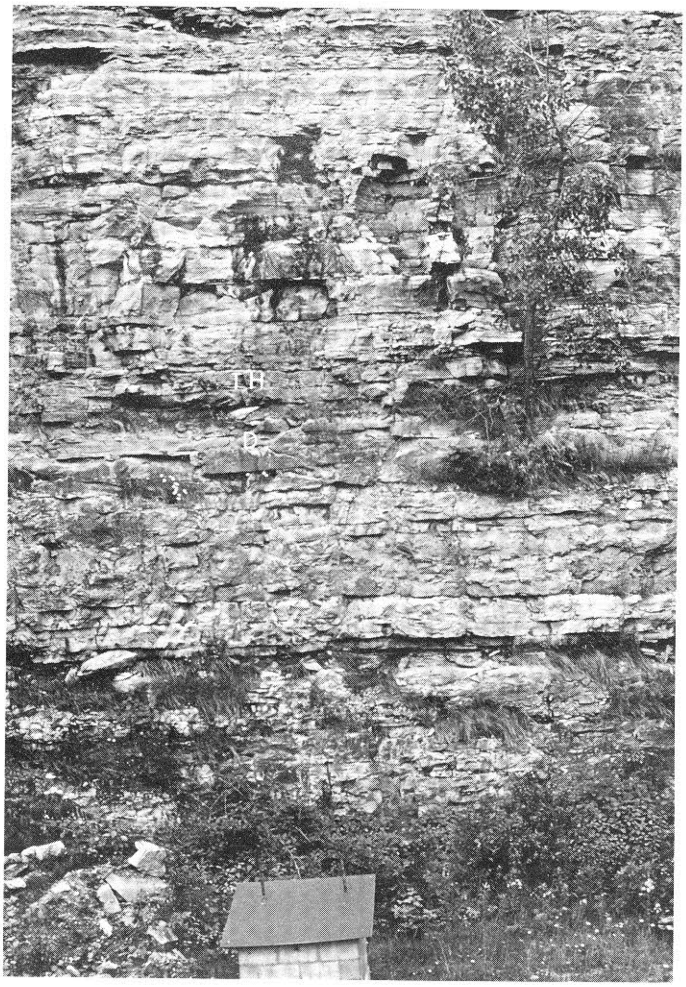

Figure 17. Section of uppermost Little Falls Dolostone (Unit D) and overlying Tribes Hill Formation (contact at about base of 15-foot (4.6 m) tree on right); abandoned quarry just east of Canajoharie (loc. 39); D = Unit D; TH = Tribes Hill.

filled with reddish dolostone from overlying layers. Five feet (1.5 m) below the top of the formation is a horizon of chert pods parallel to the bedding; some of the chert is oolitic. Eleven feet (3.4 m) above the base is a 6-inch (0.15 m), laminated bed of medium-gray chert which is considerably different in appearance than chert elsewhere in the Little Falls. The Little Falls-Tribes Hill contact occurs about three-fifths of the way up the quarry wall.

About 150 feet (45 m) of the upper Little Falls, as well as the overlying Tribes Hill, is exposed in the section along Flat Creek near Sprakers (loc. 40). The lower 30 feet (9.1 m) is similar to the lithology of Unit B at Little Falls. Overlying this are about 40 feet (12.2 m; field subunits 9 and 10) of pale yellowish-brown to light olive-gray, generally coarse-crystalline "glauconitic" dolostone similar to Unit C at the type locality. Quartzose beds are relatively minor. Vugs are abundant, particularly in the lower part and include orangish dolomite rhombs and clear calcite. In the upper part are some intercalations of light-gray to medium light-gray dolostone; light and dark chert occur as discontinuous lenses. The overlying 35 feet (10.7 m) consist of interbeds of Unit C lithology and a predominantly medium-gray to medium dark-gray, fine-to very fine-crystalline dolostone, in places laminated, which strongly resembles Unit D at Little Falls. The lower part is vuggy and the upper dolostone includes some quartzose laminations, intraformational conglomerate to edgewise breccia, "glauconite," and chert pods. The uppermost 52 feet (15.8 m) are typical of Unit D. The fine- to very fine-crystalline dolostone is commonly laminated with thin to thick partings. Pale reddish mottles and seams occur in several of the field subunits. Vugs contain anthraxolite, quartz, and calcite. Midway through the unit is a subunit that consists, atypically, of coarser crystalline dolostone containing nodules and fragments of oolitic chert. The uppermost subunit is somewhat fucoidal and grades into the more strongly fucoidal Tribes Hill above. The 35-foot (10.7 m) transitional sequence between Units C and D is placed somewhat arbitrarily in Unit D as the lithology similar to that unit is more common than that of Unit C. Thus, Unit D is considered to be about 80 feet (24.2 m) in thickness at Flat Creek. Gradationally overlying the Little Falls is a 4-foot (1.2 m) unit of olive-gray to medium-gray, coarse-crystalline dolostone with intraclasts, darker gray shaly partings and mottles, and with conspicuous fretted surfaces. This basal unit of the Tribes Hill (Fort Johnson Member) grades upward into the main part, 20 feet (6.1 m) thick, consisting of mainly fine crystalline, intraclastic limestone, the lower bed of which grades laterally to fucoidal dolostone. About 48 feet (14.7 m) of Palatine Bridge Member, are exposed in the main waterfall. Above that, the Wolf Hollow Member caps the high waterfall.

RANDALL-KECKS CENTER AREA

This area marks the eastern limit of decent exposure of the Little Falls and that of my main focus of attention. In this area, represented primarily by the Peck Lake and Randall 7½′ Quadrangles, the outcrops are generally small and scattered. The continuous, although largely inaccessible, exposures at Big Nose and Little Nose (Fig. 18), are just east of the Flat Creek section (loc. 40). I was able to negotiate the steep north facing slope of Little Nose and measure nearly a complete section (loc. 52) of the lower 320 feet (97.5 m) of Little Falls, including a 30-foot (9.1 m) interval low in the unit that may represent an intertonguing of Galway or Potsdam. The uppermost Little Falls crops out along Lasher Creek and its tributaries (loc. 49); together with the section in the face of Little Nose, the whole of the formation is practically exposed and the sections at these two localities are presented in Plate 1E.

Cropping out on the south side of the West Shore Railroad tracks, about 100 yards (91 m) east of the main section up Little Nose, are two feet (0.6 m) of brownish-gray, medium- to coarse-grained orthoquartzite just above Precambrian gneiss. A short stratigraphic distance above are the ledges exposed to the west along the railroad, at the base of the escarpment. The lower portion of the Little Falls differs from that at the type locality (locs. 15 and 16) where lighter-gray, commonly coarse-crystalline dolostone dominates above the basal conglomeratic portion. The lowest 13 feet (4 m) here consist predominantly of darker gray, fine- to medium-crystalline, mostly low-quartz dolostone; however, some seams of orthoquartzite and quartzose dolostone are present. Just above the very base of the escarpment is a stromatolitic bed. Ordinary laminations are relatively common. Shales (exceedingly rare in the Little Falls) occur in the uppermost part of this sequence. There follows a 31-foot (9.5 m) succession (field subunit 9) of predominantly light-gray to pale-orange orthoquartzites, dolomitic sandstone, and quartzose dolostone (Fig. 19). The quartz grains are commonly in the fine to medium range. Cross-stratification is common and parting is thin to thick. Some of the more dolomitic beds show desiccation cracks filled with sand from the overlying strata. Bioturbation is expressed by irregular distribution of quartz. Small sandstone dikes were observed, Dolostone and sandstone alternations represent cyclical sedimentation. The 31-foot (9.5 m) interval is the thickest continuous sequence primarily of sandstone that I have found in the Little Falls. Here again, D. W. Fisher and L. V. Rickard (1970, written communication) suggest that the section discussed thus far, as well as the following 85 feet (26 m) (through field subunits 49), be considered Galway. It is very probable that subunit 9 does represent a tongue of the Galway or, possibly,

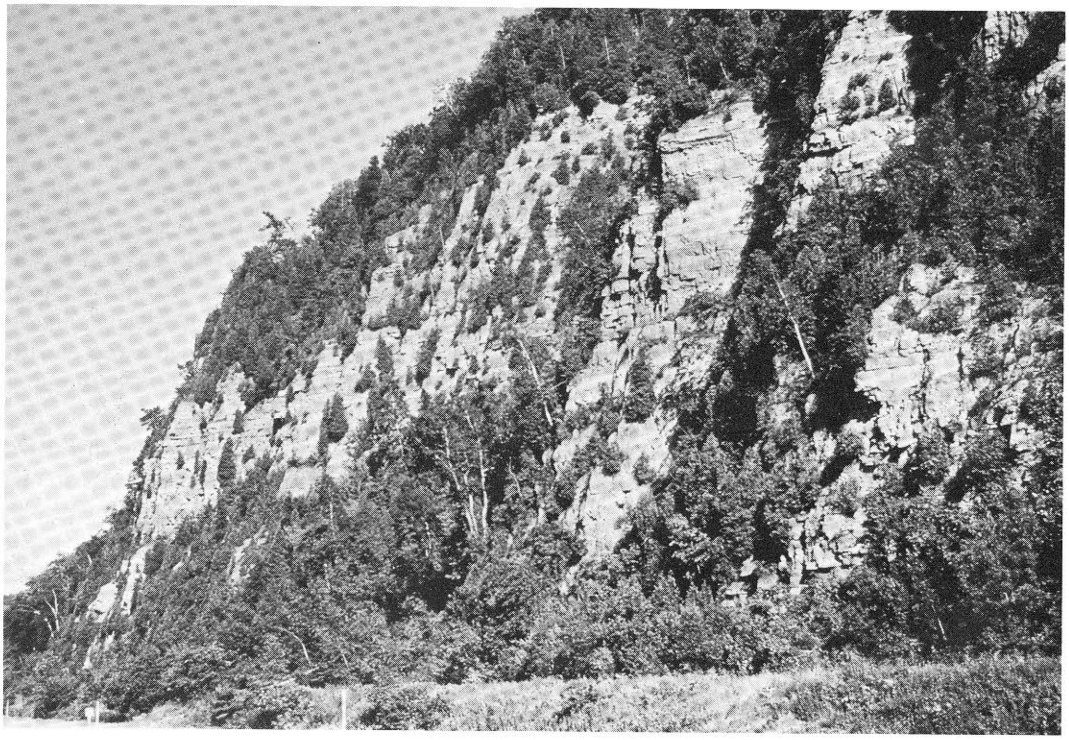

Figure 18. Section of Little Falls Dolostone exposed at Little Nose (loc. 52).

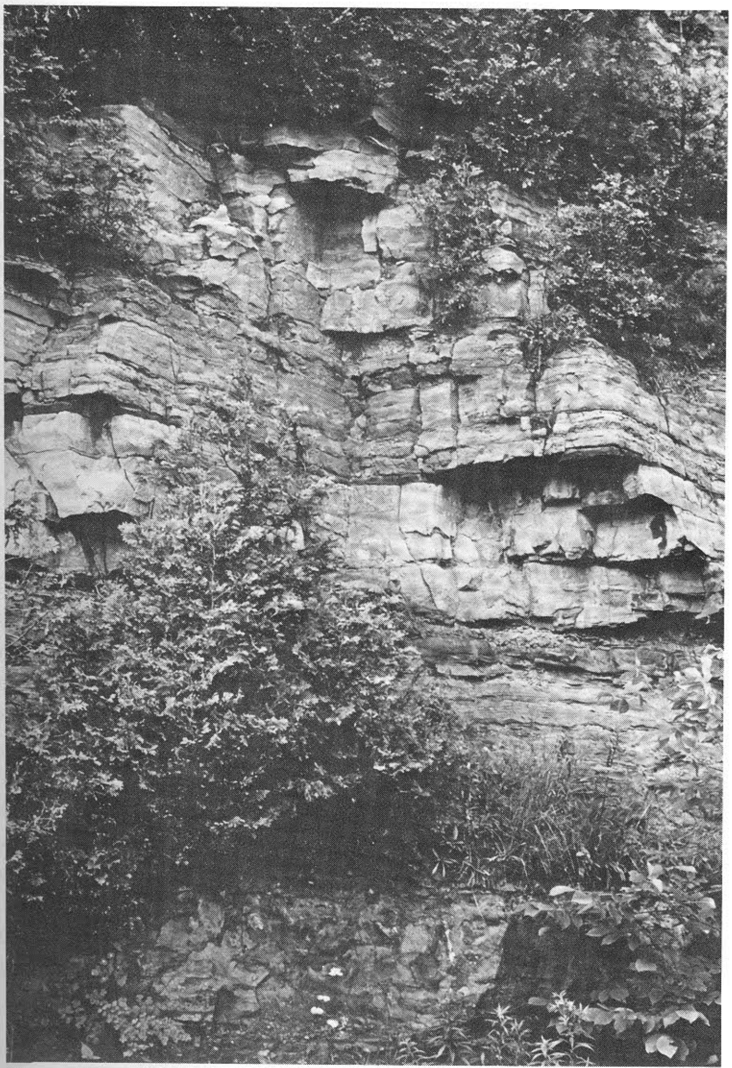

Figure 19. Middle part of Unit A exposed in lower part of escarpment, Little Nose (loc. 52); note laminated dolostone (field subunit 8) one-third of way up section and partly concealed by shrub and overlain by lower half of sandstones and dolomitic sand stones of unit 9 which may represent a tongue of Galway or Potsdam; about 30 feet (10.1 m) of section shown in photograph.

Potsdam. The average insoluble content of this unit (7 samples) is 47.3 percent, which is significantly higher than the average for the formation (including subunit 9) of 22.6 percent. With the exception of Unit 9, the lower half of the Little Falls (Fisher and Rickard's "Galway") averages 22.5 percent vs. the upper half which averages 19.3. I do not consider this a significant factor and hardly an appropriate measure for field classification. Furthermore, the color of the sandstone and quartzose dolostones even in subunit 9 are much lighter than the typically darker Galway to the east.

Intercalated in the upper part of Unit 9 and continuing on through the next 15 feet (4.6 m) of section (field subunits 10–12) are light-gray to yellowish-gray coarse- to very coarse-crystalline dolostone and more minor, quartzose dolostone. Quartzose pods parallel the bedding and a thin zone of intraclasts occurs 4 feet (1.2 m) above the base of the subunit. These dolostones resemble those in Unit A at Little Falls and are assigned to that unit.

Above these dolostones the sequence is not amenable to subdivision for the next 200 feet (61 m); this interval is equivalent to Unit B. Generally, the dolostone ranges from medium gray to medium dark gray to brownish gray and is fine to medium crystalline although there are some very fine- and coarse-crystalline layers. Ten horizons of algal stromatolites were observed and although discrete heads occur, they are predominantly laterally linked as best as can be determined from the limited exposure. The sequence discribed to the west, consisting of alternations of stromatolites and sandstones, apparently is absent here. Stromatolitic laminae are commonly dark brownish gray and fine to very fine crystalline. Unit B consists of approximately 70 field subunits. Of these, 17 are laminated, as determined in the field. In many instances the laminae are very even and probably represent normal deposition. On the other hand, a few may represent flat algal laminations. Mottling is much rarer, having been found in less than 10 subunits. Dolomitic sandstones are commonly light gray to medium gray to light olive gray and fine to predominantly medium grained. Orthoquartzites intercalated with these sandstones, or with dolostone, weather white and are conspicuous. Numerous sandy beds are cross-laminated. Sand fills desiccation(?) cracks in some intercalated layers of dolostone. Channeling the dolostones was noted at two horizons and these are filled with dolomitic sandstone. Intraclasts, normally dolomitic, were recorded at 6 different stratigraphic levels. Seven chert zones were noted, all in the upper half of Unit B. They occur mainly as elongate nodules or pods parallel with the bedding or as a replacement of stromatolitic heads. Silicified ooids are present in two of the chert occurrences. As usual, vugs are common; one third of the subunits are vuggy, calcite and dolomite being the important secondary minerals within the voids. "Glauconite" is very rare. Anthraxolite is present in vugs and is also associated with chert.

The main lithology in the upper 60 feet (18.2 m) exposed on the escarpment (subunits 80–100) consists primarily of the light-gray to light olive-gray dolostone characteristic of Unit C at the type section. Medium to thick parting are characteristic and the texture is predominantly fine crystalline although the range is from very fine to very coarse crystalline. Although there are some quartzose intercalations within some of the dolostones, none of the field subunits is classed as sandstones and quartz content is comparatively low (mean insoluble residue content = 20.4%; median = 4.1%). There are three occurrences of bedded to massive chert. One of these (subunit 95, 3–4 feet (0.9 –1.2 m) thick) is light gray, dolomoldic, and includes some very irregular laminae that may represent stromatolites. Thin chert horizons occur in the dolostones just above and below. Chert pods were observed in the uppermost unit. Laminations are present in a few subunits; cross-stratification is less common than below. Mottling is rare. A porous and vuggy zone of some 15 feet (4.6 m) occurs in the lower half of the sequence.

The lowest 20 feet (6.1 m) of the 60-foot (18.2 m) sequence (field subunits 80–89) is considered transitional between Units B and C; more or less arbitrarily it is placed in Unit B. The dolostone is a shade darker than that above and ranges in texture from very fine crystalline to coarse crystalline. Flat laminae stand out on weathered surfaces and a few beds are mottled. Vugs containing secondary minerals are common at certain horizons. A chert zone occurs about 5 feet (1.5 m) from the top of the unit.

The upper part of the Little Falls was examined along a northeast-flowing tributary of Lasher Creek and along the upper part of Lasher Creek itself (loc. 49; see Plate 1E). About 100 yards (91 m) downstream from the continuous section along the tributary is a massive chert bed exposed on the east side of the creek. The chert is laminated (stromatolitic?) and oolitic; it becomes lighter in color upward. Underlying the chert are a couple of feet of light-olive-gray, coarse-crystalline dolostone similar to that in Unit C; it may be that this massive bed of chert is equivalent to the chert in field subunit 95 in the upper part of Unit C at Little Nose (loc. 52). Along this tributary the uppermost Little Falls can be observed, including what I take to be the transitional contact with the overlying Tribes Hill. Although there are some sporadic quartzose seams, none of the field subunits can be designated as sandstone. The dominant lithology is that of Unit D—a medium light-gray very fine-crystalline, low-quartz to very slightly quartzose dolostone which frequently shows laminations which are probably not stromatolitic. This dolostone is associated with another which is darker (medium dark-gray to brownish-gray) and more coarsely crystalline; this coarser dolostone occurs as pockets and more commonly as intact or disrupted laminae. Becoming more common toward the top are very dark-gray to grayish-black laminae and mottles which are very similar to transitional beds between the Little Falls and Tribes Hill at Little Falls. Thirty feet (9 m) above the base of the section (in field subunit 11) is a cherty horizon. The chert, in places oolitic, is commonly in the form of nodules and matrix and is associated in this 2.5 foot (0.8 m) bed with pebbles and angular fragments of dolostone. Some of the beds have reddish splotches. Mudcracks were observed in field subunit 9. Parting is predominantly thin to medium. Vugs are very rare.

What can be recognized as definite Tribes Hill occurs as the uppermost exposure at the wood line where the gradient of the tributary decreases markedly. Six feet (1.8 m) of medium dark-gray to brownish-gray, very coarse-crystalline, low-quartz dolostone possesses medium parting in its lower part; above this the parting is thin and the dolostone is olive-gray and includes darker gray mottles which produce a fretted weathering surface. The gastropod *Ophileta levata* (identified by D. W. Fisher, written communication, 1969) was found on the fretted bedding surface. Some 65 feet (20 m) of Unit D are present.

There are some interesting but puzzling relationships along the main creek at this stratigraphic level. Dolostone similar to the basal Tribes Hill crops out in the western stream bank, laterally adjacent to dark-gray calcisiltites and calcarenites. It is suspected that this abrupt lateral change is due to a fault. Some 100 feet (31 m) of dolostone are exposed above Route 162. There is some difference of opinion regarding the assignment of this sequence. D. W. Fisher and L. V. Rickard (1970, written communication) would place only the upper 32 feet (9.5 m; field subunits 44–47) in the Tribes Hill; all of these subunits are exposed in the waterfalls immediately north of Route 162. Certainly the sequence below subunit 44 seems to be intermediate in character between the Little Falls and Tribes Hill; it is similar to the transitional lithologies but, of course, much thicker. An assignment of this 70-foot (21 m) interval to either the Little Falls or Tribes Hill would result in a thicker-than-normal section for both. Somewhat arbitrarily, but in part because there is no similar sequence beneath the *Ophileta* bed along the tributary described above, I choose to assign the 70 feet (21 m) of dolostone between the fault and subunit 44 to the Tribes Hill; such action would measurably thicken the Fort Johnson Member. More will be said in this regard later in the part concerning stratigraphic relations between Saratoga Springs and the Mohawk Valley.

Most other exposures are smaller and more fragmentary, except for Big Nose itself which is practically inaccessible. There is an interesting outcrop along and above the West Shore Railroad tracks immediately south of the Thruway and Route 5S, east of Big Nose, south of Yosts and about 0.8 mile (1.3 km) southwest of the main road junction in Randall (loc. 56). At the northeast end of the cut is a major fault setting the Little Falls on the west against the Middle Ordovician Canajoharie Shale on the down dropped block to the east. At the southwest end of the exposure, the Little Falls overlies Precambrian gneiss having a foliation striking N80°W and dipping 37° to the north. The bedding in the Little Falls strikes N25°E and dips to the northwest at 45°, although this attitude is somewhat variable along the outcrop. The impressive feature both immediately east of the Precambrian exposure and at the higher level, is the very coarse "polymict" breccia above the reentrant marking the Precambrian contact (Fig. 20). The clasts range from millimeter-sized to blocks 4 feet (1.2 m) in greatest dimension. These blocks are quite diverse and include stromatolitic dolostone, fine-crystalline dolostone, coarse-crystalline dolostone, and cross-laminated dolomitic sandstone (Fig. 21). Northeastward, in this exposure along the tracks, the better bedded Little Falls consists of brownish-gray and medium dark-gray, in places oolitic, dolostone. This is followed by a stromatolite horizon topped by a "glauconitic" vuggy zone with secondary dolomite crystals. Farther north the dolostone is olive gray and coarser. Zones of breccia are still found toward the north; they are intercalated with the bedded dolostone. The upper exposure is actually more conglomeratic but less coarse. At the southwest end there is an association of "intact" Little Falls and brecciated zones. The "intact" portion includes oolitic chert and the medium light-gray, fine-crystalline dolostone typical of Unit D at Little Falls. Some of the clasts contain reddish mottles.

Several attempts have been made to explain this outcrop, in particular the breccia. I observed other similar breccias in Little Falls and Tribes Hill dolostones. Some of these occur along known faults. The facts that, at loc. 56, the blocks increase in size and number toward the Precambrian contact, the blocks show some stratigraphic range, and the intact stratigraphy is that of the upper part of the Little Falls lead me to suspect a fault between the gneiss and the dolostone. The breccia may be tectonic but I cannot discount the possibility that it resulted from collapse above a cavern system in dissolved carbonates. This

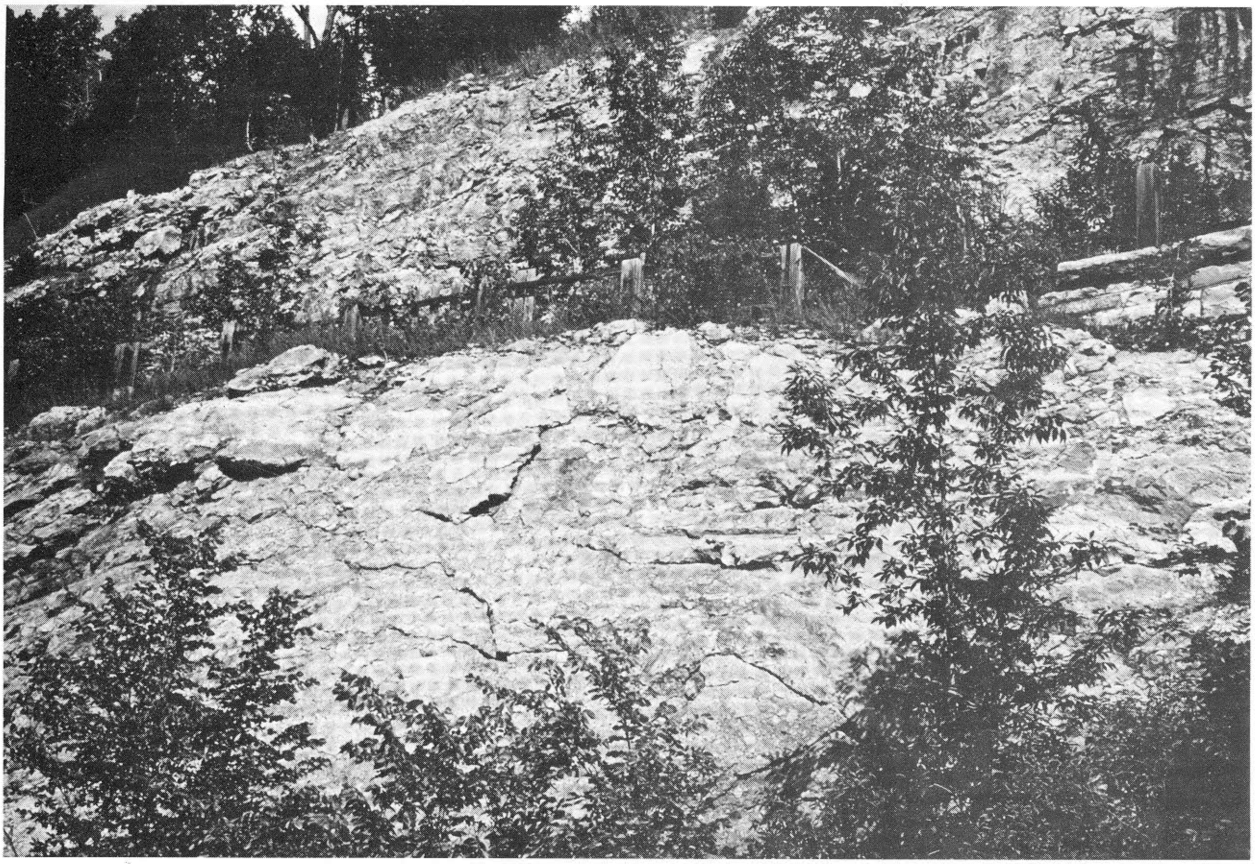

Figure 20. Coarse (tectonic?; solution collapse?) breccia in Little Falls Dolostone, West Shore Railroad cut, just west-southwest of Randall (loc. 56); largest blocks at top of lower cut are four feet (1.2 m) in greatest dimension.

Figure 21. Close-up photograph of breccia (see also Fig. 20) exposed along West Shore railroad tracks just west of Randall (loc 56); note cross-stratified sandstone above knife and block of algal stromatolite in left center of photograph.

problem is discussed more fully in the section on "Dolomitization."

Small outcrops of both Little Falls and Tribes Hill dolostones (locs. 42–48) occur in the east-central part of the Canajoharie 7½′ Quadrangle. More interesting stratigraphic aspects, especially regarding the lower part of the section, are represented by some of the exposures in the northwestern part of the Randall 7½′ Quadrangle (locs. 57–61) and in the southwestern part of the Peck Lake 7½′ Quadrangle (locs. 62–65). At loc. 59, west of Berryville, the Potsdam Sandstone can be distinguished as a unit; it is exposed at the eastern edge of the woods, capping a falls. The lower part of the falls is underlain by 8 feet (2.4 m) of brownish-gray, slightly quartzose dolostone with some intercalations of sandstone; some beds are slightly calcitic and luster mottled. Approximately 15 feet (4.6 m) of Potsdam caps the falls including 4 feet (1.2 m) of dolomitic beds intercalated with white orthoquartzite more typical of the Potsdam. About 300 yards (275 m) below the falls along the lower gradient stream course are some outcrops of Precambrian gneiss. Overlying the Potsdam is a discontinuous sequence of dark-gray and brownish-gray, low-quartz to quartzose dolostone, some beds possessing a slight calcite content predominantly in the form of luster mottling. This sequence is assigned to the Little Falls, although there is the possibility that it could be Galway.

A nearly continuous section of some 51 feet (15.5 m) of Potsdam Sandstone crops out on the small hill 1.4 miles (2.2 km) SW of Sammonsville (loc. 60). The uppermost 14 feet (4.3 m) typical of the Potsdam, consists of thin-bedded to laminated (although weathering more massively) orthoquartzite which grades from grayish orange to pinkish gray in its lower part upward to white to yellowish, including a zone of dusky brown pockets of oxidized iron 5 feet (1.5 m) from the top. Some cross-laminations are present. This field subunit is underlain by 15 feet (4.6 m) of pale yellowish-brown, very fine-crystalline dolostone with thin sandstone intercalations. Parting is medium and luster mottling is common. A 7-foot (2.2 m) covered interval separates this from the basal subunit which consists of medium light-gray to medium-gray, fine-crystalline, partly quartzose dolostone with intercalated gray and brown sandstones commonly possessing luster mottling. Precambrian gneiss occurs in the south flank of the hill not far below the lowest Potsdam exposures; the exact contact is not exposed.

A thinner sequence of 16 feet (4.9 m) of Potsdam is exposed along the sharp bend in the secondary road 1.5 miles (2.4 km) west of Sammonsville, just north of the Fulton County-Montgomery County line (loc. 61). The Potsdam ranges from predominantly grayish-orange, medium-crystalline, dolomitic and calcitic sandstone to the whitish orthoquartzite more characteristic of the formation. Some cross-stratification is present. Just above the basal one-foot (0.3 m) thick bed of sandstone is grayish-orange quartzose and calcitic dolostone with gray quartzose intercalations. The Precambrian gneiss is exposed below a two-foot (0.6 m) covered interval; apparently this particular point represents a Precambrian high as the gneiss slopes off to the east and south. This, coupled with the observation that the top of the Potsdam ledge remains at about 860 feet (262 m), indicates a thickening of Potsdam to the southeast.

Potsdam and Precambrian relationships are shown in the Peck Lake 7½′ Quadrangle just north of the Village of Kecks Center. Along the road about 0.5 mile (0.8 km) north of Keck Center, is an exposure of gneiss; ten yards (9.1 m) to the west, just into the woods, is the white to light-gray to light brownish-gray orthoquartzite of the Potsdam. This is shown on the Geologic Map of New York (Fisher, and others, 1970) as a fault contact. About 0.1 mile (0.2 km) closer to Keck Center, also on the west side of the road, are exposed about 18 feet (5.5 m) of Potsdam, the upper two-thirds being fine- to medium-grained white orthoquartzite grading downward to a grayish orange with dusky-brown patches. Bedding is mainly medium to thick but parting is thinner. Some cross-laminations were noted.

A 35-foot (10.7 m) section with discontinuous outcrops above is exposed immediately north of Kecks Center along Kecks Center Creek (loc. 63) near the power line. The waterfall beneath the power line is capped by white orthoquartzite of the Potsdam. In the falls below are dolostone and dolomitic sandstone with medium parting and calcite content primarily in the form of luster mottling. The intercalated orthoquartzites in this interval are darker than the typical light orthoquartzite of the Potsdam. Above the falls are predominantly sandstones and orthoquartzites with some intercalated dark-gray dolostones. I take these beds to represent the Galway. The Precambrian is not exposed along the stream proper but gneiss crops out as ledges on the hillside adjacent to and west of the main falls. If no structure is involved there was considerable relief on the Precambrian surface on which the Potsdam was deposited.

Thus, in the Randall-Keck Center area we have the westernmost exposures of Galway and Potsdam. These formations become more significant to the east in the Broadalbin-Saratoga Springs Quadrangle. In addition, this area marks the easternmost exposures of the "traceable" Little Falls. Beyond this there are more widely separated outcrops of a lithology similar to that of the formation. Furthermore, there is a geographic gap of some 15 miles (22 km) from these easternmost exposures near the Mohawk Valley to those near Sacandaga Reservoir farther northeast. Although the main outcrop belt of the laterally continuous Little Falls has been considered, comments follow regarding stratigraphic relations in the quadrangles to the north and east (Amsterdam, Broadalbin, Lake Pleasant, and Saratoga 15′ Quadrangles).

COMMENTS ON STRATIGRAPHY IN AMSTERDAM, BROADALBIN, LAKE PLEASANT, AND SARATOGA 15′ QUADRANGLES

To the east and northeast of the occurrence of the Little Falls at Randall, the position of the lower part of the unit is represented by the uppermost(?) Potsdam Sandstone and the Galway Formation, which is sandier than the typical Little Falls and which, in the Saratoga region, contains Franconian and Trempealeauan trilobites (Fisher and Hanson, 1951). Overlying the Galway west of the Saratoga Quadrangle, are dolostones that represent the upper part of the Little Falls. Owing to a relative paucity of continuous exposures, it is very difficult to ascertain stratigraphic relations.

At the nearest outcrops (locs. 68, 81) to the Randall-Kecks Center area on the east side of Route 30 about 1.5 miles (2.2 km; loc. 68) and 2.0 miles (3.2 km; loc. 81) north-northeast of Mayfield are two short sections of what are considered Little Falls and Galway, respectively. At the exposure nearest Mayfield (and the higher, stratigraphically) are about 18 feet (5.5 m) of medium-gray to brownish-gray to olive-gray, fine- to coarse-crystalline dolostone. LLH- and SH-type algal stromatolites occur at two horizons, 4 feet (1.2 m) and 10 feet (3.1 m) from the top, respectively. The uppermost 4-foot (1.2 m) unit is a cross-laminated, dolomitic sandstone. Small sandstone dikes are present. Because of the dominance of dolostone, the sequence is considered to belong to the Little Falls. The subunits measured at the northern end of the exposure grade south to a polymict breccia. The matrix is brownish black and very sandy. Clasts include stromatolitic dolostone, cross-laminated sandstone, laminated dolostone, and fine- and medium-crystalline dolostone. The breccia is probably due to solution collapse but could also be due to faulting (see discussion under "Dolomitization").

To the north, the other road exposure (beneath the power line) includes about 35 feet (10.7 m) of Galway; it is assigned to that formation by virtue of the impressive amount of sandstone, half of the field subunits being so designated. Eleven samples have an average insoluble residue of 42.7 percent. Many of the sandstones are blackish or very dark gray, more so than those in the type Little Falls. Toward the top of the section are oolitic and intraclastic dolostones. The uppermost 6 feet (1.8 m) consist largely of stromatolitic dolostone (commonly discrete heads below becoming laterally linked higher). Vugs are common in the more dolomitic subunits and, as usual, they are partially to completely filled with secondary calcite, dolomite, and quartz. Cross-laminations occur in the sandstones and there are sandy fillings of mudcracks in the dolostones. One bed of sandstone 5 feet (1.5 m) from the top is fucoidal.

There are some small exposures of dolostone that resemble the Little Falls in Gifford Valley along the west side of Woodward Lake in the northwestern part of the Northville 7½′ Quadrangle (locs. 84–86). In a ledge immediately west of the road next to the Winne home there occur three feet (0.9 m) of slightly dolomitic sandstone overlain by 4.5 feet (1.4 m) of massive, cross-laminated orthoquartzite, which is considered to be the Mosherville of Fisher and Hanson (1951, p. 806). Above the Mosherville are 1.5 feet (0.5 m) of dark-gray, dolomitic sandstone with olive-gray fucoids (probably *Planolites*) overlain by medium light-gray to gray, fine- to medium-crystalline dolostone. On the basis of stratigraphic position, this upper part is Little Falls; however, there is no reliable evidence to distinguish this short interval from Canadian dolostones. It does appear that some 35 feet (10.7 m) of what can be called Little Falls crop out along a small stream unmarked on the Northville 7½′ Quadrangle, just to the west of the "V" in the name "Gifford Valley." The lowest exposures are about 200 feet (61 m) west of the road and consist predominantly of gray, sandy dolostone. A one-foot (0.3 m) bed of orthoquartzite is exposed at the base of a small falls. Chert is common on the south side of the lip of the falls; five feet (1.5 m) of quartzose dolostone contain three 4- to 6-inch (0.1 to 0.15 m) beds of nearly pure chert, much of which is oolitic and some of which may be stromatolitic. Above a covered interval are about 9 feet (2.8 m) of medium light-gray, fine-crystalline, laminated, pale yellowish-brown weathering dolostone, some being mottled with red. Beyond a 50-foot (15.5 m) covered interval is a 4-foot (1.2 m) bed of massive, white to light-gray chert. Here, as well as at almost every relatively complete section of the upper part of the Little Falls, are silicified ooids. On the other hand, as will be shown later, silicified ooids also are found in the Canadian dolostones. If the sequence is really Little Falls, then it is impossible to assign it to any particular unit. The reddish coloration is suggestive of the upper part of the formation but, on the other hand, chert is much more common here than is usually the case in this interval. At loc. 86, along a small unmarked stream near the "e" in the word "Gifford Valley" on the map, are numerous pieces of float of fine-crystalline dolostone as well as mottled dolostones similar to the lower Tribes Hill (Fort Johnson Member) or to the Little Falls-Tribes Hill transition of the Mohawk Valley. Also, there are light-gray weathering blocks of Lowville Limestone.

Several miles to the north, in the Lake Pleasant 15′ Quadrangle, are two relatively small areas of fault-bounded outliers which include fragmentary exposures of what appears to be Little Falls lithology overlying the "Theresa" which in turn overlies the Potsdam. Miller (1916, p. 34–36) estimated the thickness of Little Falls to be about 100 feet (31 m). Fisher (1957, p. 11) described a tentative assignment to the Little Falls of "... cherty light bluish-gray (5B 7/1) dolomite which is widely exposed near the cemetery east of New York Route 30 in the Village of Wells ..."

I examined exposures on the hillside in the area east and northeast of the cemetery in the Village of Wells (loc. 69). A traverse was made along the dirt road leading northeast from the cemetery to the elevation of about 1160 feet (359 m) and the proximity of the fault bounding the Wells outlier. Directly east of the cemetery are ledges and slumped blocks of predominantly white orthoquartzite. This lithology is followed by perhaps 40 to 50 feet (12.2 to 15.5 m) of white sandstones and less resistant and more friable sandy dolostone. Quartz grains commonly are frosted and either small sandstone dikes or more likely sand filled desiccation cracks are present. The lower orthoquartzites are thought to represent the Potsdam and the overlying alternating orthoquartzites and sandy dolostones probably represent the Galway. Above the Galway there are sporadic outcrops from about 1040 to 1160 feet (320 to 359 m). The lower beds are sandstones and quartzose dolostones together with some low-quartz dolostones, including a 10-inch (0.3 m) algal stromatolite horizon capped by dolomitic sandstone. In the upper part of this interval is gray and brownish-gray, low-quartz dolostone, some being "glauconitic." Vugs containing secondary minerals are prevalent. Between 1130 and 1150 feet (344–351 m) are some *in situ* ledges as well as some loose blocks which contain silicified stromatolites and oolitic chert. The easternmost outcrops along the road west of the fault consist of finer crystalline, medium light-gray, laminated dolostone with reddish splotches so characteristic of the upper Little Falls of the Mohawk Valley. These characters seem to indicate a Little Falls assignment; the thickness does appear to be at least 100 feet (31 m).

About 5 miles (8 km) to the south of Wells, and a mile (1.6 km) north of Doig Creek west of Route 30 in the Town of Hope (loc. 70), are ledges exposed at the top and in a small west-facing escarpment on the east side of the Sacandaga River. Fragmentary outcrops representing about 20 feet (6.1 m) of section show grayish-orange weathering, very fine-crystalline, medium-gray dolostone with some reddish mottling associated with some coarser-crystalline dolostone containing oolitic chert. Farther to the west along the escarpment is more of the fine-crystalline dolostone underlain by medium-gray dolostone with yellowish-brown pockets and blackish seams with some fretted surfaces; much of this dolostone is brecciated. Underlying the dolostone, in apparant fault contact with it, is primarily micritic limestone containing pelmatozoan columnals and other fossil fragments. Pods of black chert are present. Interesting secondary calcite crystals with curved faces occur as void fillings. It is concluded that the limestone is in fault contact with the dolostones which are tentatively placed in the Little Falls, rather than the Tribes Hill, on admittedly meager evidence.

Far to the south, at the base of the very large roadcut on the north side of Route 5 just west of Hoffmans (loc. 21) in the Pattersonville 7½′ Quadrangle, is a thick sequence, provisionally designated as Little Falls, beneath a thick section of Tribes Hill with possibly Chuctanunda Dolostone at the very top. The main reason for the inclusion of the lower 30 feet (9.1 m) in the Little Falls is the presence near the top of chert pods (8 feet (2.4 m) from the top) and a black chert bed (7 feet (2.2 m) from the top), both of which contain chertified ooids. Also present are beds of light weathering, fine- to very fine-crystalline dolostone similar to that of the upper Little Falls to the west. Aside from these characters, the sequence resembles as much Tribes Hill as Little Falls. Laminations, light-gray seams, grayish-orange mottles, yellowish-gray intraclasts, and lingulid brachiopods (20 feet (6.1 m) above base) are present. Quartzose interlaminations occur toward the bottom. The contact with the overlying Tribes Hill (Fort Johnson Member) is taken at the base of a fine-crystalline dolostone bed which is conspicuous by virtue of its laminations (subunit 11).

Until examining this section I had thought that chertified ooids were a lithologic guide to the Little Falls. However, at this exposure, a loose block of silicified ooids was found well above the Little Falls; this was traced to an *in situ* occurrence nearly at the top of the succession in what must be Wolf Hollow or Chuctanunda. Subsequently, S. J. Mazzullo (written communication, 1975) has informed me that silicified oolite lenses have also been discovered in the Gailor Dolostone and in the uppermost Galway.

Other than two small outcrops (locs. 72, 79), most of the dolostone outcrops in the Pattersonville Quadrangle, particularly those along Route 67, are of Canadian age. The latest edition of the Geologic Map of New York (Fisher, and others, 1970) shows a narrow belt of Little Falls transecting Route 67 in the vicinity of Blue Corners; this is in contrast with the earlier edition (Fisher and others, 1961) where all of these exposures along 67 were assigned to the Little Falls.

Localities 74–78 occur along a 2.5 mile (4 km) east-west stretch centered on the longitude of Blue Corners, the eastern end (loc. 78) being on the top of the east-facing grade of a fault escarpment. From the smallest outcrop (loc. 74, about 5 feet (1.5 m) in thickness) to the largest (loc. 77, 23 feet (7 m) in thickness) the rock type seems to be that of Canadian Beekmantown dolostones (Fort Johnson or Gailor), as contrasted with that of the Little Falls. Some characteristics of all of these occurrences include mottled effects, medium light-gray to medium dark-gray colors, commonly weathering to shades of yellowish gray, laminations, medium to thick parting, slight calcite content (sometimes associated with luster mottling), sporadic small stylolites, and fractures and vugs containing whitish, orangish, and blackish calcite rhombs, commonly with curved faces of aggregates of crystals. The breccias at the east end of loc. 77 and particularly at loc. 78 are possibly attributable to faulting.

In the Broadalbin and Edinburg 7½′ Quadrangles there are only widely separated and small exposures of dolostones, most of which seem to be of closer affinity to the Ordovician Beekmantown. Locality 90, an abandoned quarry just north of Lakeside Drive east of Mayfield, exposes a 32-foot (9.8 m) section of Tribes Hill; just north of the quarry are some ledges of Lowville. Near Edinburg (locs. 95 and 96) are exposures of Potsdam, the one at Latcher's Falls (loc. 96) being especially continuous for about 50 feet (15.3 m). In addition to the typical Potsdam white orthoquartzites, there is considerable dolostone as intercalated beds of dolomitic sandstone and dolostone. About 1.3 miles (2.1 km) south of Edinburg (loc. 97), along an easterly flowing stream, are a few beds of medium light-gray to medium dark-gray fine-crystalline dolostone; a loose block of dolostone contains angular chert fragments. The outcrop is too small for definite placement in the Little Falls.

In the southern part of the Galway 7½′ Quadrangle are numerous, usually small, exposures of Galway, possible Little Falls, and Ordovician Beekmantown. Two of the better sections of Galway are along Route 29 on the north side of Foster Hill (loc. 108) and just east of Kimball Corners (loc. 109; Fig. 22). The latter section comprises 17 feet (5 m) of conglomeratic sandstone with some interbedded dolostone; the average insoluble residue (4 samples) is 24.7 percent. A short distance eastward, on the north side of Route 29, is the Precambrian-Potsdam contact. Locality 108 ex-

Figure 22. Section of lower Galway Formation exposed on north side of Route 29, 1.5 miles (2.4 km) west of Mosherville (loc. 109); lower, dark-weathering unit (field subunit 1) consists of iron-oxide stained sandstone and conglomerate; note hammer (middle of photograph) for scale.

poses some 27 feet (8.2 m) of Galway which is characterized by sandstone (including orthoquartzites) and dolostone beds. The sandstones are commonly dark weathering and include bioturbation effects, cross-stratification, and intraclasts of dolostone. The dolostones commonly are fine-crystalline and also are dark weathering. Field subunit 4 is strongly mottled and may represent thrombolitic structures. Vugs are common in the dolostones. Insoluble residues (6 samples) average 24.5 percent.

To place the generally small and separated exposures in the southern part of the Galway 7½′ Quadrangle in the Galway, Little Falls, and Beekmantown is not an easy matter. As did Miller (1911, p. 29) and Fisher (Fisher and Hanson, 1951, p. 806), I took the persistent 4 to 7 foot (1.2 to 2.2 m) orthoquartzite, designated Mosherville Sandstone by Fisher (*op. cit.*), to occur immediately above the Galway. The Mosherville is recognized as far west as Gifford Valley west of Northville (loc. 84). Without subsurface information, it is tenuous to attempt to carry this unit westward into the Mohawk Valley. The Mosherville crops out at several localities in the Galway area (locs. 102, 103, 106, 112, and 114). It is usually a white to light-gray to yellowish-gray, medium-grained homogeneous, unfossiliferous orthoquartzite having cross-laminations and medium to thick parting (Fig. 23); there is only very minor dolomite content at most localities. Lithologically, it differs little, if at all, from the Potsdam Sandstone or from orthoquartzitic beds in the Galway and Little Falls. It is distinguished from the Potsdam by virtue of a different stratigraphic position and by the greater thickness of the latter. Orthoquartzites interbedded with dolostones of the Galway and Little Falls are thinner.

At most of these localities where the Mosherville occurs, there are very short sections of dolostone above. On the basis of stratigraphic position alone, these dolostones could be tentatively placed in the Little Falls. However, the rock type, including common fucoids, seems to be intermediate between Little Falls and Ordovician Beekmantown. (Mazzullo and others (1978, p. 101, 102) consider the existence of about 18 feet (5.5 m) of Galway above the Mosherville at Saratoga Springs to the east—see subsequent discussion of the Mosherville). At locality 102, just east of Bunn Corners, beneath 6 feet (1.8 m) of Mosherville are about 7 feet (2.2 m) of Galway with linguloids in the basal subunit. Above the Mosherville is 1.1 feet (0.3 m) of grayish-black and yellowish-brown, medium-crystalline fucoidal dolostone; again, by stratigraphic position this dolostone would be equivalent to the Little Falls.

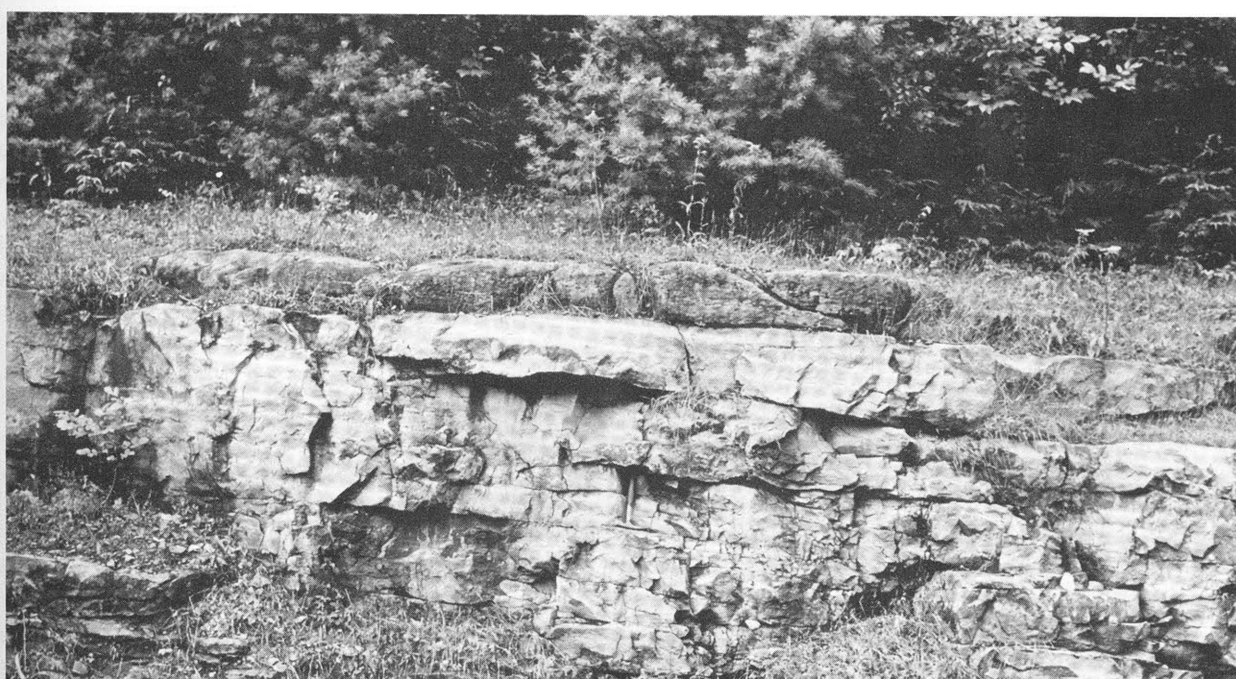

Figure 23. Exposure of Mosherville Sandstone (light) capped by darker weathering bed of Little Falls Dolostone?; 0.3 mile (0.5 km) east of Bunn Corners, Galway 71/2″ Quadrangle (loc. 102).

About 0.8 mile (1.3 km) to the north, at locality 103, along an east-facing ledge, are 5 feet (1.5 m) of dolostone, divisible into 5 field subunits, overlying 5 feet (1.5 m) of Mosherville. These dolostones range in color from dark gray to olive gray to dusky brown and contain ooids and fucoids in the lowest subunit. Some beds are quartzose and there is a thin 0.5 foot (0.2 m) thick bed of dolomitic sandstone. At locality 106, along the west side of the road just south of Cummings Corners, is a discontinuous section on the east-facing slope. Brownish dolostones assigned to the Galway occur below a 15-foot (4.6 m) covered interval above which is the fine- to medium-grained, cross-laminated Mosherville. In a ledge 3 feet (0.9 m) higher are 2 feet (0.6 m) of olive-gray, fucoidal dolostone very similar to that immediately above the Mosherville just east of Bunn Corners (loc. 102). Fifteen feet (4.6 m) above this are 3.5 feet (1.1 m) of irregularly bedded, medium dark-gray, fine-crystalline dolostone with silica, sometimes as chalcedonic rims lining vugs; there are intercalated quartzose laminae. In the stratigraphic position of the Little Falls, these beds once again appear to be intermediate between Little Falls and Beekmantown. The Mosherville crops out at locality 114, along Glowegee Creek 0.25 mile (0.4 km) southeast of Parkis Mills. Upstream and along the road at loc. 113 are medium-gray to olive-gray to medium dark-gray, vuggy, fine-crystalline dolostones. The lowest accessible beds are oolitic. These are mottled and include pods and laminae of chert in the waterfalls. Frosted quartz grains were observed in the sequence along the road and the upper part is very fine crystalline. The combined outcrop totals about 20 feet (6.1 m) and could possibly be Little Falls.

To illustrate the difficulty where the Mosherville is not exposed. I refer to loc. 98 along North Chuctanunda Creek about 0.65 mile (1 km) north of the four corners in West Galway. There, on the north side of the creek and driveway, are exposed about 19 feet (5.8 m) of primarily dolostone with 5 feet (1.5 m) of associated sandstone and orthoquartzite. Mottling, usually consisting of medium-gray to olive-gray mottles in a grayish-orange matrix, is common. Some beds of dolostone, as well as of orthoquartzite, are cross-laminated. An appreciable amount of calcite is present locally as evidenced by luster mottling. Based on geographic and topographic position, and barring any structure between this locality and those (locs. 99 and 100) less than a mile (1.6 km) to the east and southeast, respectively, the exposure should represent the upper Galway. However, the sequence is less quartzose than the typical Galway. Yet, the sandstone beds are not characteristic of the Ordovician Beekmantown. Whereas the sandstone/dolostone ratio is more typical of the Little Falls, the overall character of the dolostone seems to be intermediate between that of the Little Falls and the Beekmantown.

West of the bend in the secondary road just south of the outcrop of Mosherville in Glowegee Creek (loc. 114) are beds about 60 feet (18.2 m) higher, stratigraphically (loc. 115). These are dolostones apparently intermediate between Little Falls and Beekmantown. About 15 feet (4.6 m) are continuously exposed and the dolostone is primarily fine crystalline. Mottling of dark gray and olive gray is present in the middle; in the upper field subunit (3) is a three-inch (0.1 m) band of algal stromatolites (SH →LLH). The lowest subunit is vuggy with secondary dolomite, quartz and calcite in the vugs. Olive-gray and medium light-gray, fine-crystalline dolostone that is similar to the upper Little Falls in the type area crops out a short distance downslope (north).

Of the 11 surface localities in the Saratoga 15′ Quadrangle (locs. 119–129) only one (loc. 121), a small exposure on the north side of Route 29 about 3 miles (4.8 km) east of East Galway, might possibly represent the Little Falls; on the other hand the outcrop is too small for definitive placement in either the Little Falls or Galway. Olive-gray to darker gray dolostones dominate but there is some intercalated slightly dolomitic sandstone. Algal stromatolites of LLH-type structure, close to "*Cryptozoon undulatum*" (Goldring, 1938, p. 10), are exposed near the base of the 3.5 foot (1.1 m) "section." Goldring interpreted this outcrop as basal Little Falls but recognized that it was close to the Galway-Little Falls boundary. Although others (for example Cushing and Ruedemann, 1914, p. 43–45; Goldring, 1938, p. 10; Mazzullo and Friedman, 1975) have referred to Little Falls in the Saratoga Quadrangle, I remain skeptical whether there is any present. In addition, this area has been fraught with several local stratigraphic problems.

Fisher and Hanson (1951) and Fisher (1962a; 1962b) presented the more modern versions of the section in the Saratoga Springs region. A compilation of these sources shows the following section up through the Canadian:

Canadian (Lower Ordovician)	Gailor Dolostone Mosherville Sandstone
Croixian (Upper Cambrian)	Ritchie Limestone Hoyt Limestone Galway Formation Potsdam Sandstone

More recent work (Zenger, 1971a; Mazzullo, and others, 1978) repositioned these units as follows:

Gailor Dolostone including Ritchie Member
Hoyt Limestone
Galway Formation with Mosherville Sandstone Member at top
Potsdam Sandstone

Fisher's (1977) correlation chart (see my Fig. 1) also shows these relationships.

Potsdam Sandstone

The Potsdam Sandstone is rarely exposed in the Saratoga Quadrangle (Fisher and Hanson, 1951, p. 802). With the possible exception of the lower part of the dolomitic sandstone and orthoquartzite sequence along Baptist Hill south of East Galway (loc. 120), the Potsdam in the Saratoga area was not studied. Cushing and Ruedemann (1914, p. 34–35) gave an average thickness of 100 feet (31 m) for the Potsdam but they pointed out that the range of thickness varies owing to an irregular Precambrian surface and a gradational boundary with the overlying Galway Formation.

Galway Formation

Exposures of the Galway Formation (locs. 119, 120, 121?) are mostly small and separated. The best available section (loc. 128), also studied by Fisher and Hanson (1951, p. 810), is a composite section in a roadcut along Route 9N and a railroad cut (Adirondack Railroad) west of the crossing over 9N; these are located about 5 miles (8 km) northwest of the center of Saratoga Springs. The section measures about 65 feet (20 m) stratigraphically but includes a 30-foot (9.1 m) covered interval. The sequence shows the combination of sandstone and dolostone which is supposed to be the characteristic of the unit. Dolomitic sandstone and orthoquartzite dominate in the lower 18 feet (5.5 m) of the section, or that part exposed along the highway. The orthoquartzites range from most commonly whitish or light-gray to darker gray; the dolomitic sandstones and sandy dolostones are medium gray to commonly dark gray and in places grayish black. Parting is thin to thick and the orthoquartzites are cross-laminated. It was impossible to obtain the true azimuth and dip of the cross laminations with only one face exposed; however, in subunit 5, a general dip to the south was observed. Trilobite fragments of *Elvinia ruedemanni*, *Camaraspis* sp., and *Berkeia saratogensis* were noted in several of these units; according to Fisher and Hanson (1951, p. 802, 810), these belong to the *Elvinia* Zone, of lower Franconian age. The zone is some 25 feet (7.6 m) above the base of the Galway. Above the 30-foot (9.1 m) covered interval and along the railroad cut to the west the upper 17 feet (5.2 m) of the succession are composed primarily of quartzose dolostone with relatively minor intercalated dolomitic sandstone. The dolostone ranges in color from olive gray through medium gray to brownish gray; there are local moderate yellowish brown beds and splotches which are weathering phenomena. The texture is medium and coarse crystalline. Intraclasts and relict ooids are found in several of the subunits. Lingulids occur in subunit 11 and also in subunit 13, together with trilobite fragments. Quartzose dolostone fills desiccation cracks in subunit 18, 4–5 feet (1.2–1.5 m) from the top of the exposed section. Algal stromatolites occur 7–8 feet (2.2–2.4 m) below the top. Vugs are present in a few of the subunits (e.g.; 18, 19, 21). According to Fisher and Hanson (1951, p. 810), the trilobite fragments in my subunit 13 (their 14) belong to *Plethometopus*. Consequently the Galway Formation is considered by Fisher (1977) to be entirely Franconian in age. The average insoluble residue of 17 samples of Galway at this section is 29.5 percent.

Mazzullo, and others (1978) measured 157 feet (47.6 m) of Galway in the core from the Pallette quarry. These workers reported zones of silicified ooids and vuggy dolostone similar to the Little Falls, as well as to the Gailor and Whitehall Formations. They believed the Mosherville Sandstone to be a member in the upper Galway.

Hoyt Limestone

The Hoyt fauna was originally discussed by Walcott (1879) but the definition and description of the unit is owed to Ulrich and Cushing (1910, p. 101) and to Cushing and Ruedemann (1914, p. 38–42), particularly the latter. Assigned by Ulrich and Cushing (1910) to the basal part of the Little Falls, the Hoyt was considered by Cushing and Ruedemann (1914, p. 36, 38), to be part of the upper Theresa (= Galway) and to measure about 100 feet (30 m) in thickness. Goldring (1938, p. 9) considered the Hoyt as the "basal phase" of the Little Falls Dolostone. Fisher and Hanson (1951, p. 802), claiming that the lower part of the Hoyt is lithologically similar to the Galway and should be considered as such, were left with about 55 feet (17 m) of Hoyt as a separate unit. However, in 1970, Rickard and Fisher (written communication) included the Hoyt in the Little Falls as its basal member. Mazzullo and Friedman (1975) apparently considered it a separate formation as did Fisher and Mazzullo (1976) who showed the Hoyt to be younger than the Little Falls. Fisher (1977) showed the Hoyt as partly equivalent to the upper Little Falls (see Fig. 1). There has been considerable reference to the Hoyt flora and fauna (for example, Walcott, 1879; Goldring, 1938; Halley, 1971a), and several have published on the physical aspects of the unit. Cushing and Ruedemann (1914, p. 38–42) presented field descriptions and Halley (1971b) has given a sound analysis of the Hoyt lithology and petrology. Owens (1973) compared modern algal sediments in the Red Sea with algal limestones of the Hoyt. None of the exposures which I have studied show a complete section of the unit: the railroad cut near Greenfield, where 16.3 feet (5 m) of Hoyt, including the upper contact with the overlying Mosherville(?) or Gailor are exposed (loc. 123); the combined road and abandoned quarry (old Hoyt quarry) where about 28 feet (8.6 m) of Hoyt crop out (loc. 124); and, the well-exposed but stratigraphically limited section in the "Petrified Sea Gardens" (loc. 125). By referring to Goldring (1938) and to Halley (1971b, p. 13–21) one can find thorough descriptions of the algal stromatolites in the Hoyt in the "Petrified Sea Gardens" (Figs. 24, 25). Goldring applied binomial nomenclature (e.g. *Cryptozoon proliferum*, *C. ruedemanni*, and *C. undulatum*) to these "calcareous algae" whereas Halley discusses them in the light of more recent developments in the study of algal stromatolites. Fisher and Hanson (1951, p. 804) were able to use the three "algal reefs" (*Cryptozoon proliferum*, *C. ruedemanni*, and *C.* cf. *undulatum*) in mapping owing to their being "... reliable horizon markers." The first two "algae" are restricted to the Hoyt (Goldring, 1938, p. 10) whereas *C. undulatum*, or related forms, are known from the Galway (Fisher and Hanson, *op. cit.*) as well as from the Little Falls and Hoyt (Goldring, *op. cit.*).

At the type section (loc. 124) in the old Hoyt quarry and along the adjacent roadside to the east, the Hoyt is seen to consist primarily of limestone with significant interbedded dolostone. The limestones are generally medium dark gray to dark gray (but lighter weathering), and fine crystalline; however, coarser oolitic and fossil fragmental (primarily trilobites and gastropods) zones are present. There are two horizons (subunits 6 and 12) of algal stromatolites (there is also a bed of "Cryptozoon proliferum" in Lester Park just to the east across the road; this is stratigraphically below the measured section). Carbonaceous partings are relatively common as are patches and interlaminations of olive-gray dolostone. However, the color of the dolostone is medium dark gray to dark gray, the texture is generally fine crystalline, and the beds are calcitic; the dolostones, some bearing lingulids, do not resemble those in the Little Falls. Small-scale facies changes are evidenced by field subunit 6. At the north end of the roadcut there is dark-gray very fine-crystalline, stromatolitic (SH and LLH), very dolomitic limestone. This is covered and infilled (between the heads) by olive-gray dolostone. Traced to the south the stromatolitic structures become less impressive. It passes into medium dark-gray, very fine-crystalline, evenly laminated dolostone which is in places overlain by an intraformational conglomerate consisting of clasts of dark-gray, fine-crystalline limestone in a matrix of dolostone. The average insoluble residue of 11 samples is 12.6 percent; the calcitic dolostones (7) average 10.0 percent insoluble whereas the dolomitic limestones (4) average 16.0 percent. (One bed of very dolomitic limestone—subunit 4—is noticeably sandy and contained 41.2 percent insoluble material.)

The lithology in the nearby Petrified Sea Gardens (loc. 125) is much the same as in the quarry and along the road. At locality 123, the railroad cut east of the road crossing at Greenfield, 16.3 feet (5 m) of interbedded calcareous dolostone and dolomitic limestone are considered to represent the Hoyt, this sequence is overlain by a 4-foot (1.2 m) subunit (8) of medium-gray to light-gray to brownish-gray, fine- to medium-grained, cross-laminated, very dolomitic sandstone which resembles the Mosherville, except for its high dolomite content (about 45 percent); for reasons given under discussion of the Mosherville (see later), it may be best to tentatively assign this sandstone to the base of the Gailor here and to consider it younger than the Mosherville. The uppermost 6.7 feet (2.1 m) of the section consists of calcitic and quartzose dolostones, including a zone of edgewise breccia, and dolomitic sandstone. The lower 7 field subunits, considered as Hoyt, bear a resemblance to the type Hoyt in consisting of mixed carbonates, particularly the dark-gray, fine crystalline carbonates. Algal stromatolites (both LLH and SH types) are present as are zones with trilobite and lingulid fragments. Field subunit 2, which is also stromatolitic and consists primarily of very light-

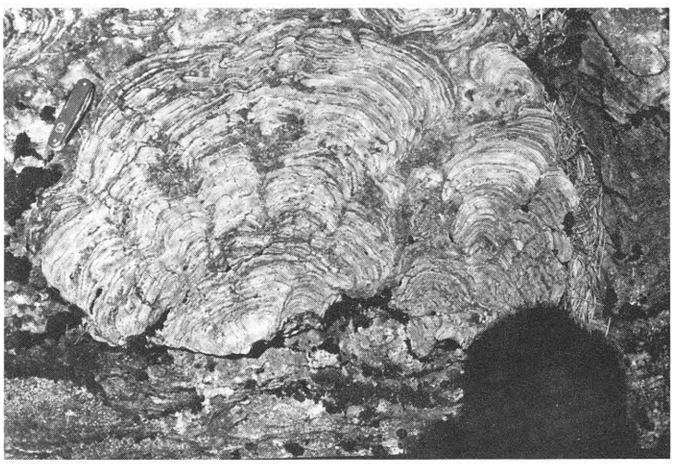

Figure 24. Large colony of "*Cryptozoon proliferum*" (type SH/LLH), Hoyt Limestone, Petrified Sea Gardens (loc. 125): knife handle 8 cm in length.

Figure 25. "*Cryptozoon undulatum*" in Hoyt Limestone; loose, display specimen, Petrified Sea Gardens west of Saratoga Springs (loc. 125); type LLH-C→ SH-C/LLH-C→ LLH-C; knife handle about 8 cm in length.

gray weathering, very fine to fine-crystalline, slightly dolomitic, stylolitic, in places fossil-fragmental limestone, seems rather atypical and at least superficially resembles dolomitic limestones within the Gailor. However, a Croixian trilobite fauna including *Dikellocephalus*, *Prosaukia*, and *Plethopeltis* discovered by D. W. Fisher (1975, written communication) insures the Hoyt assignment. Mazzullo, and others (1978, p. 102–103) described 39 feet (11.8 m) of Hoyt in the Pallette core.

Gailor Dolostone

The Gailor Dolostone was named by Fisher and Hanson (1951, p. 797, 807–808) as follows: "As *Ophileta*, *Helicotoma(?) uniangulata*, and *Ectenoceras* are exclusive Canadian index fossils, the latter two indicative of the Lower Canadian, the age of the cherty dolomite above the Mosherville sandstone is established as lowermost Ordovician. The name Little Falls for these beds (as used by Cushing and Ruedemann (1914, p. 42–45)) is unquestionably in error, and the name Skene dolomite (Wheeler, 1942, p. 522) is similarly not applicable because it was defined as Upper Cambrian. The senior author proposes the name Gailor dolomite for these beds from the Gailor quarry (my loc. 129) which is situated at the northern edge of the city of Saratoga Springs just west of U.S. Highway 9. While no complete section is available, the quarry is designated as the type locality, for it is likely to prove an excellent exposure for years to come ... The Gailor dolomite varies from about 80 feet (24.2 m) in thickness in the northern portion of the Amsterdam quadrangle to about 150 feet (46 m) in the Saratoga region." Mention is made of a massive chert bed, locally containing *Cryptozoon*, that caps the Gailor at several localities. The only lithologic descriptions of the unit are found in the part of their paper dealing with stratigraphic sections at the Gailor quarry (Fisher and Hanson, 1951, p. 811–812; my loc. 129) and at Rock City Falls, about 6 miles (9.6 km) west of Saratoga Springs (*op. cit.*, p. 812–813; my loc. 122). At the type section, the Gailor, about 34 feet (10.3 m) thick, was described as a light- to dark-gray, crystalline, vuggy dolostone, in its lower part, overlain by a light-gray, crystalline dolostone with dark-gray to black chert at the top. At Rock City Falls, the upper 12 feet (3.7 m) of Gailor exposed was described as a blue-gray, fine- to medium-grained, cherty dolostone.

Not available to Fisher and Hanson in 1951 was the quarry, operated by the Pallette Stone Corporation, about 2.6 miles (4.2 km) west of Saratoga Springs, just north of Route 29 (loc. 127). Some 148 feet (45 m) of Gailor are exposed there, including the upper contact with the overlying Middle Ordovician Amsterdam Limestone. Mazzullo, and others (1978, p. 103) measured 256 feet (77.6 m) of Gailor in the core from the Pallette quarry which penetrated the base but not the top of the unit. Dolostones, ranging from light gray to medium light gray to medium gray to dark gray and even grayish-black, constitute the bulk of the formation. They are primarily fine-crystalline, but very fine- and medium-crystalline dolostones are also present. Laminations and mottling are common and the mottling is often very conspicuous—laminations in field subunit 26 may represent flat algal laminae. Partings are commonly even and carbonaceous. "Microscouring" was observed in some beds as were stylolites. Chert was noted only near the top of the section. Vugs containing secondary minerals are relatively uncommon. Many beds contain quartzose laminae but terrigenous material is generally rare. The average insoluble of six carbonate samples is 16.2 percent. Two subunits (3 and 5) near the base of the section are light-gray to medium dark-gray to olive-gray, cross-laminated, dolomitic sandstone. Perhaps one of the more distinguishing features of the dolostones, compared to those of the Little Falls, is the considerable calcite content; most dolostones range from slightly calcitic to very calcitic. Not surprisingly, considering the generally equivalent Tribes Hill of the Mohawk Valley, there are intercalated very fine-crystalline to calcarenitic, dolomitic limestones (4 subunits—12, 14, 16, and 21), all but one being in the lower 57 feet (17.5 m). These limestones include pockets of grayish-orange weathering dolostone and carbonaceous partings. Most weather light-gray, except the very interesting subunit 12 which is conspicuously darker weathering than those dolostones above and below. This subunit, 6.5 feet (2 m) in thickness as exposed in the northern wall of the quarry, is fossiliferous, containing lower Canadian brachiopods, gastropods, nautiloids, and trilobites. The following fauna, identified by D. W. Fisher (1969, written communication) was collected from this subunit:

Brachiopods:	*Finkelnburgia wemplei*
	Lingula clelandi
Gastropod:	*Ophileta* sp.
Nautiloids:	*Clarkeoceras* sp.
	Ellesmeroceras sp.
Trilobite:	*Hystricurus ellipticus*

At Rock City Falls (loc. 122) the Gailor has noticeable fretted ("fucoidal") weathering surfaces caused by mottling (dark-gray dolostone forms the positive relief elements of the fretwork, olive-gray dolostone the negative). Several beds are strongly laminated. At the old Gailor quarry (loc. 129) the Gailor lithology resembles that at the other two localities described but is much more cherty.

Ritchie Limestone

The "Ritchie Limestone" was proposed by Fisher and Hanson (1951, p. 804–806) for a 43-foot (13.1 m) thick limestone cropping out over a very limited area in the immediate vicinity of the type section just south of the Petrified Sea Gardens (loc. 126), about 3 miles (4.8 km) west of Saratoga Springs and 0.9 mile (1.5 km) north of Route 29. The following section, slightly abbreviated here, was presented by Fisher and Hanson (1951, p. 811):

Gailor Dolostone	
Separated exposures of gray-blue, sandy dolostone on hill	30′ (9.1 m)
Mosherville Sandstone	
Cobble conglomerate; grades laterally into coarse sandstone	2–7′ (0.6–2.1 m)
Ritchie Limestone	
Massive, very thick-bedded, ash-white weathering gray-blue calcilutite; *Rhachopea*(?)	43′ (13.1 m)
Hoyt Limestone	
Non-cherty, dark-gray dolomite	8′ (2.4 m)

The only fossils found by Fisher and Hanson, poorly preserved specimens of a gastropod allied to *Rhachopea*, are not diagnostic; although the Hoyt below contains Upper Cambrian trilobites and the succeeding dolostones were reported as containing a Lower Ordovician fauna, the Ritchie could not be definitely assigned a Late Cambrian or an Early Ordovician age. Hanson (Fisher and Hanson, 1951, p. 805–806) theorized that the Ritchie might represent an offshore facies of a portion of the sandier and more fossiliferous Hoyt. In his earlier correlation chart for the New York Cambrian, Fisher (1962a) again mentioned the uncertainty of the age of Ritchie.

I have presented earlier (1971a) a brief summary of my findings and conclusions regarding the Ritchie. The type section is a composite one, consisting of a few isolated ledges immediately east of the north-south road, two abandoned quarries just west of this road, and ledges along the hill above the quarries. The following section, beginning with ledges exposed east of the road, has its base at about 400 feet (122 m):

Unit		Thickness in feet (m)
7	Dolostone, very similar to that in unit 6 but having grayish-orange irregular seams and being more calcitic upward; exposed as separated ledges (see also comments at end of this description).	about 15 (4.6 m)
6	Dolostone, medium light-gray to medium-gray, fine-grained, smooth weathering; slightly quartzose, vaguely laminated; some secondary calcite; at top of lower quarry.	3.8 (1.2 m)
5	Dolomite, calcitic, coarse-crystalline; rough weathered surface; light-gray to medium light-gray; some grayish-orange splotches; sharp contact with overlying; stylolites; secondary calcite.	0–1.5 (0–0.5 m)
4	Limestone, micritic as in underlying, but with irregular seams and mottles of grayish-orange dolostone; thins and thickens in inverse relation to overlying unit.	1–3 (0.3–0.9 m)
3	Limestone, predominantly very fine crystalline, very light-gray weathering, medium-gray on fresh surface; numerous microstylolites; zone of dark-gray chert nodules about 7 feet (2.2 m) above base; mainly thick to massive; zone 9 feet (2.8 m) above base has very closely spaced microstylolites; some zones of very small intraclasts; several cross sections of the orthocone *Ellesmeroceras*.	11 (3.4 m)
NOTE:	Units 3–6 measured in lower quarry immediately west of road, unit 1 in ledges just east of road.	
2	Covered	5 (1.5 m)
1	Dolostone, dark-gray and light-gray, very fine-crystalline, practically non-calcitic, associated with medium-gray dolostone containing brownish splotches of coarser grained (coarse decimicron-sized to fine centimicron-sized), calcitic dolostone; quartzose; secondary calcite, many carbonaceous partings.	5 (1.5 m)

Units 3 and 4, or 12 to 15 feet (3.6 to 4.6 m) of limestone, are assigned to the "Ritchie." The approximately 15 feet (4.6 m) of dolostone of unit 7, when traced 50 to 100 feet (15 to 31 m) to the north across a covered area, appear to pass into limestone which crops out in another quarry topographically higher than the one mentioned in the section. This limestone, about 17 feet (5.2 m) in thickness, is very fine-crystalline and very similar to that in unit 3, and includes stylolites, cephalopods, and chert; the uppermost part seems to be somewhat disrupted and is more or less a "tranquil" breccia. Overlying this unit at the south end is a 2.5 foot (0.8 m) unit of very fine-crystalline limestone with grayish-orange, coarser crystalline mottles of dolostone. When the upper 8 feet (2.4 m) of these limestones are traced to the quarry face at the north end, they become a very coarse conglomerate or breccia (many clasts are very angular); this conglomerate is exposed mainly along a fracture surface.

I conclude that the apparent abrupt passage from the dolostone of unit 7 into the limestone of the upper quarry is a result of a fault between the quarries; the section there is interpreted as essentially a repeat of that in the lower quarry. Thus, the thickness of the Ritchie is between 17 and 19 feet (5.2 m and 5.8 m) including cover, less than half that reported by Fisher and Hanson; these workers (p. 805) did mention the possibility of a small tear fault between the quarries which would result in an excessive thickness.

The discovery of the orthocone *Ellesmeroceras* in the "Ritchie" (identified by D. W. Fisher, 1969, written communication) conclusively demonstrates an Early Ordovician age for the unit, settling one controversy. Fisher (Fisher and Hanson, 1951, p. 805, 811) believed the conglomerate, or breccia, above the typical Ritchie in the upper quarry, to be Mosherville. The lithology of the conglomerate-breccia is very different from the typical orthoquartzitic Mosherville and I observed no such lithology at this location; this unit is not Mosherville but rather a very locally developed "tectonic" breccia associated with the faulting.

I would like to suggest a new relationship based in large part on a section at the quarry of the Pallette Stone Corporation (loc. 127), unavailable to Fisher and Hanson in 1951. As described above, intercalated with the non-fossiliferous laminated and mottled dolostones, which constitute the main bulk of the Gailor, are several limestone units, the thickest being 7.5 feet (2.3 m). Of the accessible limestone units in the Pallette quarry, two grade laterally to dolostone within a short distance. The limestones are light-gray weathering and very fine crystalline, although calcarenitic beds and pockets are present. The lowest of the limestone subunits contains a Lower Canadian faunal assemblage already presented. Higher limestone units are much less fossiliferous but some specimens of *Ellesmeroceras* were observed. This locality is separated from the type section of the Ritchie by faulting (Fisher and Hanson, 1951, p. 799), precluding the possibility of stratigraphic tracing.

There is a striking similarity between the "Ritchie" and the limestone intercalations in the Gailor in the Pallette quarry. On the other hand, the typical Hoyt shows significant differences. Lithologic and petrographic comparisons are much more meaningful. As observed in the field, the "Ritchie" and the limestone intercalations in the Gailor consist primarily of very fine crystalline limestone; some zones at the Pallette quarry are more fossiliferous. The Hoyt, in contrast, is coarser, darker, generally more fossiliferous, and more dolomitic. As seen in acetate peels, the "Ritchie" and limestone intercalations in the Gailor consist largely of micritic material which takes in places the form of peloidal bodies separated by decimicron-sized spar. Such peloids may represent poorly sorted intraclasts formed through organic disruption (dismicrite?). Quartz is minimal and the relatively low amount of dolostone is in the form of euhedral to subhedral, fine to medium centimicron-sized crystals centered mainly in seams or pockets of secondary spar. A specimen of Hoyt shows a much greater proportion of allochems (fossil fragments and peloids) with some oolitic overgrowths and a considerably coarser matrix in the decimicron-sized range. Micrite is present only in the peloidal bodies. Fine-grained, subrounded quartz is noticeable. The nature of the "late" diagenetic dolomitization appears similar to that in the "Ritchie" and Gailor.

Fisher and Hanson (1951, p. 811) considered the dolostone beneath the type Ritchie to be Hoyt and that above the Mosherville to be Gailor. I propose that the entire sequence at the type "Ritchie" locality is Gailor and that the "Ritchie" itself is one of several intercalated limestones in the Gailor. If such a relationship is the case, and the evidence certainly appears to support the contention, the name "Ritchie" is best used for a member within the Gailor. Such a relation is shown in the most recent correlation chart for the Ordovician of New York (Fisher, 1977).

Mazzullo, and others (1978, p. 103) observed two limestone units, a lower one 33.8 feet (10.3 m) thick and an upper one 62 feet (18.8 m) thick, within the Gailor. On the basis of approximate stratigraphic position, they considered the lower limestone to be Ritchie and the upper one, the Slade Creek Member, a new unit.

Mosherville Sandstone

The Mosherville Sandstone (Fisher and Hanson, 1951, p. 806) as a lithologic unit has been previously discussed. Comments on its questionable stratigraphic position are in order in the light of recent developments. In defining the unit, Fisher and Hanson (1951, p. 806) considered it as "... the basal member of the cherty aranaceous dolomite with a lower Ordovician fauna (Gailor dolomite)." They considered Mosherville to unconformably overlie the Hoyt in the Saratoga Springs area, and to truncate the older Galway.

The Mosherville is widely exposed in the Broadalbin 15′ Quadrangle where it demarcates the top of the

Galway (see also Miller, 1911, p. 29). In the Saratoga Quadrangle the unit is much more elusive—I noted it questionably at only two localities (locs. 119, 123). As mentioned earlier in the discussion of the type "Ritchie" (loc. 126), Fisher's (Fisher and Hanson, 1951, p. 805) interpretation of the carbonate conglomerate is considered here to be in error. About 1.5 miles (2.2 km) south of East Galway, 4 feet (1.2 m) of fine- to medium-grained orthoquartzite with medium to thick parting rest on a 10.5 foot (3.2 m) sequence of alternating sandstones and dolostones judged to be upper Galway. Whether the orthoquartzite is in the exact position of the Mosherville, however, as contrasted with another orthoquartzite subunit high in the Galway cannot be determined.

Fisher and Hanson (1951, p. 806) referred to an exposure of Mosherville "... half a mile north-northeast of South Greenfield ..." which probably is locality 123 of this study. In my initial study of that section, I considered the possibility that subunit 8 is Mosherville. It consists of 4 feet (1.2 m) of light-gray to brownish-gray, fine- to medium-grained, cross-laminated, very dolomitic sandstone; included are thin, discontinuous pale yellowish-gray weathering seams of dolostone containing sandstone-filled mudcracks. This subunit has a dolomite content of about 45 percent; normally the Mosherville is orthoquartzite. The underlying subunits seem to belong to the Hoyt.

There is a problem regarding the true stratigraphic position of the Mosherville in the Saratoga Quadrangle. Recent work (Mazzullo and Friedman, 1975; S. J. Mazzullo, 1975, written communication; D. W. Fisher, 1975, written communication) suggested that the Mosherville lies at the top of the Galway and *beneath* the Hoyt. Mazzullo (1975, written communication) claims to have Mosherville *below* algal stromatolites of the Hoyt Limestone at Lester Park (opposite my loc. 124) near Saratoga. In a core from the Pallette quarry (loc. 127) about 5.5 feet (1.7 m) below the relatively indistinct base of the Hoyt, are a few feet of dolomitic sandstone which Mazzullo and others (1978, p. 102) assign to the Mosherville; these beds are unlike typical Mosherville, according to a more detailed description by Mazzullo (1975, written communication).

Working farther east, in Washington County, Fisher and Mazzullo (1976) consider as probably Mosherville, a sandstone above the Ticonderoga and beneath the Hoyt fauna within the Whitehall. After examining the section in the railroad cut near Greenfield (loc. 123), Fisher is now convinced that the 4-foot (1.2 m) dolomitic sandstone (subunit 8) between the Hoyt below and the Gailor above is *not* Mosherville. If we adopt the ideas of Fisher and Mazzullo, which are based on the little data available in the Saratoga area itself, coupled with the stratigraphic position of a sandstone taken to be the eastern extension of the Mosherville in Washington County, the Mosherville would be placed near the top of the Galway, beneath the Hoyt.

The stratigraphic level of the Mosherville would be in a stratigraphic position equivalent to the middle part of the Little Falls Dolostone of the Mohawk Valley. However, I have not distinguished that unit there. Although there are numerous sandstones in the middle of the Little Falls in the nearly complete section at Little Nose (loc. 52), none closely resemble the type Mosherville.

SUMMARY AND CONCLUDING REMARKS ON STRATIGRAPHY

The Little Falls Dolostone in the type locality at Little Falls in the western Mohawk Valley is about 400 feet (122 m) thick. Its lower contact with the Precambrian gneiss is nonconformable. I consider the upper contact with the overlying Canadian Tribes Hill Formation to be conformable. The Little Falls is subdivided into 4 units, informally designated, from oldest to youngest, A–D. Unit A, from 90 to 100 feet (27 to 30 m) in thickness, has a basal interval of about 3 feet (0.9 m) of coarse-grained sandstone to quartz pebble conglomerate immediately overlain by quartzose and low-quartz, medium- to coarse-crystalline dolostone. The remainder of the unit is primarily light-gray (with some darker and brownish-gray beds) dolostone with medium to thick and even parting, relatively minor quartz, and a coarser texture than that in the overlying unit (B). Laminations and intraclasts are common. Unit B, about 200 feet (61 m) thick, is primarily dark-gray to brownish-gray to dark brownish-gray, often quartzose dolostone. Intercalated sandstones are relatively common. Vuggy intervals are ubiquitous. Algal stromatolites of both LLH and SH types are distributed through the unit, although an interesting sequence of alternating stromatolites and sandstones occurs near the middle. Mainly fine to medium crystalline, the dolostone also occurs as very fine-crystalline, light-weathering strata; such beds, as well as fine-crystalline, stromatolitic dolostone, provide clasts for intraformational conglomerates. "Glauconite" is present but not abundant. Some chert occurs, mainly as silicified stromatolites. Unit C, ranging between 40 and 60 feet (12 and 18 m) in thickness, is mainly light-gray to light olive-gray, medium- to coarse-crystalline, low-quartz to quartzose dolostone weathering distinctly lighter than the bulk of the underlying unit. Medium to thick bedding and parting predominate. Vugs are common and "glauconite" is characteristic. Some chert is present. The uppermost unit, D, is about 35 feet (10.7 m) thick, is typified by very fine- to fine-crystalline low-quartz dolostone. Coarser dolostone may include lenses and thin beds of chert, commonly oolitic. The upper part of the unit is often mottled with grayish red. Edgewise breccia is present and the uppermost part, near the contact with the overlying Tribes Hill, is in places mottled.

I noted the most impressive occurrences of anthraxolite in the upper Little Falls, especially near the contact with the overlying Tribes Hill (and also in the basal, fucoidal Tribes Hill). Dunn and Fisher (1954, p. 490) have contended that anthraxolite in the Little Falls occurs in 3 zones, each beneath a "major break." I have found no evidence for these disconformities.

I consider the passage from Little Falls to the Tribes Hill in the Little Falls area to be not only conformable but, at least in places, gradational. Fucoidal and mottled dolostone occur in an interval that appears to be transitional between the two formations. Placing the contact at the lowest limestone is not appropriate; sequences of fucoidal dolostone would commonly occur below. Since the time of Vanuxem, many workers have considered the "fucoidal" beds as separable from the Little Falls and they are now generally assigned to the Tribes Hill. Furthermore, where limestones do occur low in the Tribes Hill, they grade laterally to dolostone at certain localities.

Others have reported that an unconformity exists between the Little Falls and the Tribes Hill at Little Falls. Ulrich and Cushing (1910, p. 121–122) considered their subunit 12, including a conglomerate with blackish clasts that locally are "... disturbed and may stand on edge," to represent the base of the Tribes Hill. They believed that the Little Falls-Tribes Hill contact represented an unconformity of considerable significance (Ulrich and Cushing, 1910, p. 136, 139). This conglomerate horizon is most certainly the edgewise breccia of my subunit 10 of the section above Buttermilk Falls (loc. 13) at Little Falls. I do not believe this edgewise breccia is anything more significant than an intraformational structure, perhaps due to a storm. I have drawn the Little Falls-Tribes Hill contact some 13 feet (4 m) above this breccia; such placement would result in the inclusion of some reddish mottling within the uppermost Little Falls. Above the base of the Tribes Hill, drawn at the base of a 4-foot (1.2 m) bed of fretted, fucoidal dolostone (subunit 15), are about 12 feet (3.6 m) of dolostone, some with reddish mottles, beneath the lowest limestone horizon.

Wheeler (1942, p. 519–520) referred to the "major unconformity" between the Little Falls and Tribes Hill in the western Mohawk Valley described by Ulrich and Cushing who traced the unconformity into the Champlain Valley. Wheeler (1942, p. 521–522) claimed that the 160-foot (49 m) thick light dolostone above the Hoyt at Whitehall, New York, formed part of a westerly thinning wedge which "... disappears west of Little Falls so that the Tribes Hill Formation rests with a pronounced erosion surface upon the Little Falls dolostone."

Fisher (1975, written communication) now also subscribes to the theory of a Little Falls-Tribes Hill break. Certainly the Cambrian-Lower Ordovician section at Little Falls is thinner than the equivalent succession in Washington County, east of Saratoga Springs. Such an unconformity is shown in a correlation chart of Fisher and Mazzullo (1976, p. 1447) dealing primarily with the Lower Ordovician Great Meadows Formation in eastern New York, and in Fisher's correlation chart (1977, Plate 2). Fisher (1975, written communication) interprets the red-stained dolostone in the uppermost Little Falls as reflecting iron-oxide leached soil permeating the upper Little Falls prior to the deposition of the Tribes Hill; the Hoyt or Hoyt equivalent is missing from the Mohawk Valley.

I would argue that Fisher places too much emphasis on the reddish mottling. As will be mentioned further under the section on petrology, the reddish coloration is due to small hematitic grains within dolomite crystals. There is good petrographic evidence that much of the hematite in the Little Falls has replaced pyrite and that it is relatively late in the paragenetic sequence. Intracrystalline as well as interstitial hematite is relatively ubiquitous in the Little Falls although the intracrystalline variety is most abundant where the rock appears reddish. However, since the hematite abundance is undoubtedly related to original pyrite abundance, I question whether the mechanism proposed by Fisher—that is, that the red results through oxidation by iron-oxide leached soil at an unconformity—is valid. There is no other evidence of a paleosol or disconformity. Furthermore, as just mentioned, as I have drawn the Little Falls-Tribes Hill contact, there are locally reddish beds in the lower Tribes Hill *above* what I conclude is a transitional contact. The reddish coloration could result from oxidation of the pyrite at a much later date. I suggest, as did Fisher much earlier (1954, p. 76), that the uppermost Little Falls may be Canadian. Owing to the absence of megafossils, a search for conodonts in residues of several selected samples of the upper Little Falls was made in the hopes of shedding light on the Cambro-Ordovician boundary. Unfortunately, none were recovered (P. W. Goodwin, 1973, written communication).

The suggested stratigraphic relations of the Little Falls and its units outward from the type section toward Poland to the northwest and Randall to the east are shown in Fig. 26.

North of the type section, but south of Middleville, the Tribes Hill has pinched out and the Little Falls is overlain unconformably by the Lowville Limestone (Black Riveran). Furthermore, the Little Falls is attenuated, the reduction coming primarily at the expense of the upper part of the formation. At Middleville the Little Falls is approximately 230 feet (70 m) in thick-

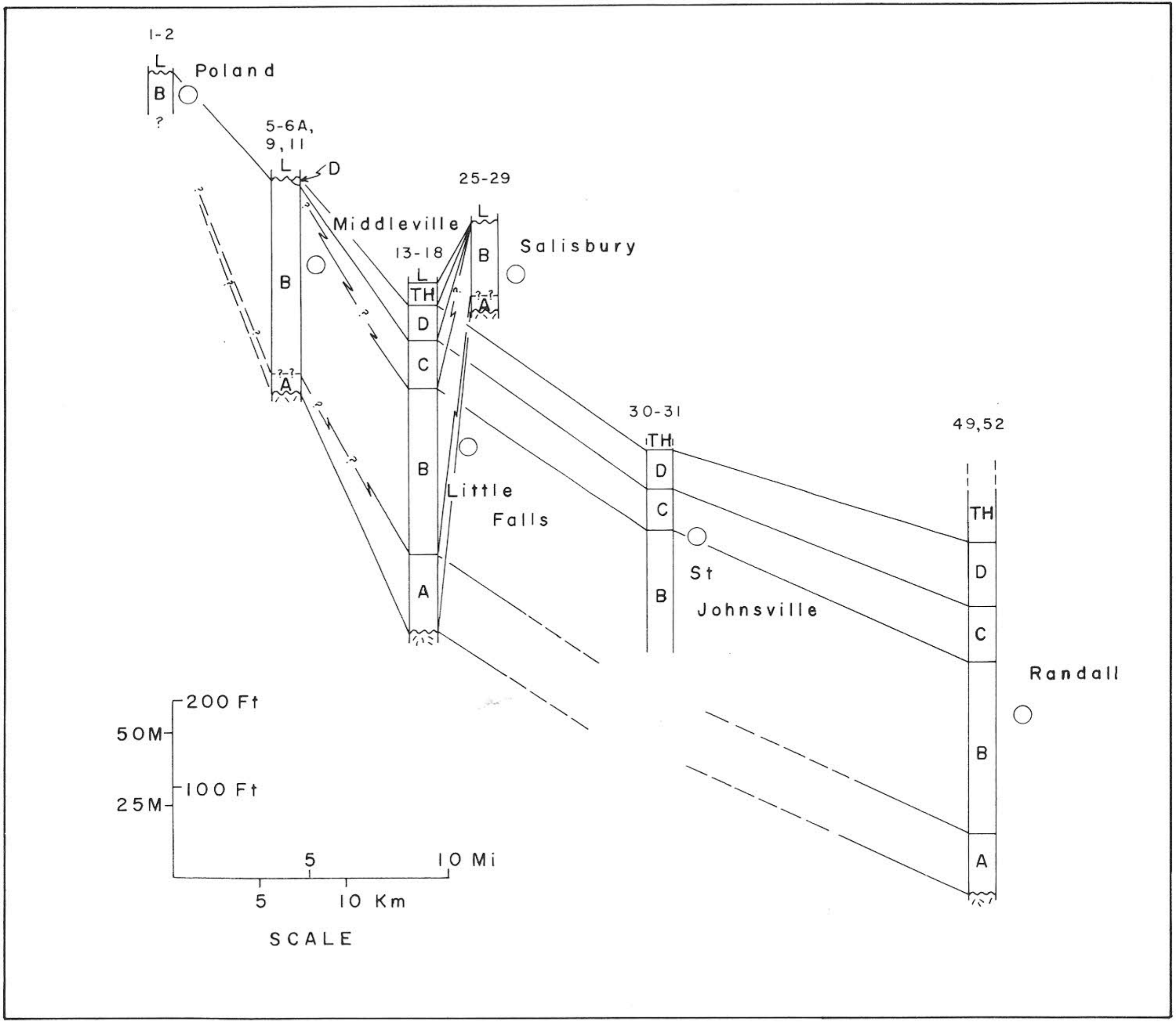

Figure 26. Stratigraphic relations of units of Little Falls Dolostone between Poland and Randall; sections composite, based on the localities designated at top of each column; short-lined pattern, Precambrian; A-D, units of Little Falls; TH, Tribes Hill; L, Lowville.

ness and completely pinches out a short distance north of Poland. A corresponding thinning and wedging out northward is exhibited 7–8 miles (2.2–2.4 km) to the east along Spruce Lake and Spruce Creek north of Salisbury.

The Little Falls maintains the approximate 400-foot (122 m) thickness eastward along the Mohawk Valley to the vicinity of Yosts east of which the outcrop belt trends to the northeast. There, the lower contact of the formation is nonconformable on the underlying gneiss. A 31-foot (9.4 m) subunit (9, loc. 52) of dolomitic sandstone and light-gray orthoquartzite may represent a tongue of Galway. The four units established at Little Falls can be recognized, with some difficulty, in this area. I would again submit that the upper contact with the Tribes Hill is gradational; it is exposed along that part of Lasher Creek northeast of Route 162 (loc. 49). As discussed earlier, there is some question of the assignment of some 70 feet (22 m) of dolostone between a fault and definite Tribes Hill just north of the road. I conclude these dolostones are also Tribes Hill, probably a thicker-than-normal Fort Johnson. They occur stratigraphically above a dolostone containing *Ophileta* along a tributary (see loc. 49).

From this point northeastward there is a geographic gap of some 15 miles (24 km) with no exposures of the Little Falls, Galway or Potsdam until reaching the Broadalbin 15′ quadrangle. The problem of generally small, spotty exposures in this area has been emphasized. The Little Falls is very attenuated, much of its position being represented by the thickened Galway and possibly uppermost Potsdam, probably in a manner similar to that illustrated by Fisher (1962a; 1977). There is, however, little direct evidence in surface outcrops that reveals the exact nature of this facies change. Part of the problem lies in the poor exposures in the geographic zone of transition between Randall and Gloversville.

Another difficulty is the fact that even the "typical" lithologies of the Potsdam, Galway and Little Falls possess some characteristics which are intermediate between the others. Take, for example, the 31-foot (9.4 m) sandy subunit 9 in the lower part of the Little Falls section at Little Nose (loc. 52) just referred to above; this sequence almost certainly reflects a transition from the Little Falls to Galway, or less likely Potsdam, but which unit is not really apparent. North of Randall, in the immediate vicinity of Kecks Center, are several exposures of Potsdam, many consisting of the white orthoquartzite which is typical of the unit. The Potsdam rests nonconformably on Precambrian gneiss. Stratigraphically above the Potsdam are isolated outcrops that probably represent the Galway although in view of the poor exposures available, it is impossible to make a definite assignment. Thus, the rapid lateral transition from the lower part of the Little Falls on the west to the uppermost Potsdam(?) and Galway on the east is evidenced as much by thinning of the Little Falls and by stratigraphic position of the equivalent units above the basement as by direct evidence of the facies change itself. The Little Falls-Tribes Hill boundary was not observed directly but the nature of the lithology leads me to suspect that the thin Little Falls grades into an overlying mass of dolostone that should be classed as Tribes Hill or Gailor. Many of the road cut exposures along Route 67 in the northern part of the Amsterdam 15′ Quadrangle, (Pattersonville 7½′ Quadrangle) once assigned to the Little Falls (Fisher, and others, 1961), are now considered as Lower Ordovician (Fisher, and others, 1970). I believe that all the exposures that I examined along Route 67 in the Pattersonville Quadrangle (locs. 74–78) are in either Fort Johnson (Tribes Hill) or Gailor. I believe, as Fisher illustrated (1962b, 1977) that the Fort Johnson Member grades eastward into the Gailor of the Saratoga region. The dolostone above the Little Falls in the Broadalbin 15′ Quadrangle probably is transitional between the Fort Johnson and Gailor and perhaps deserves a new stratigraphic designation; however, I feel this should be decided by other workers concentrating on the Canadian in that area. More work in this area, despite the poor outcrop control, is definitely called for.

I am unconvinced that the Little Falls Dolostone exists in the Saratoga Quadrangle and in his latest correlation charts, Fisher (1977) seems to agree. I believe it is represented by equivalents, from bottom to top, the uppermost Potsdam, Galway, Mosherville, and Hoyt, and probably the lowest part of the Gailor. The base of the Potsdam no doubt is older than the base of the Little Falls in its type area. Most others would concur in a lateral relationship between the lower and middle part of the Little Falls to the west, with the uppermost Potsdam and Galway (for example, see Fisher, 1962a, 1977). The tentative correlation with the lowermost Gailor assumes there is no break between the Hoyt and Gailor. Mazzullo and others (1978, p. 101, 103) considered the possibility that the lowermost Gailor could be Trempealeauan and considered the Hoyt-Gailor contact to be gradational; the Gailor is substantially thicker than previously estimated by Fisher and Hanson (1951).

According to Goldring (1938, p. 8) "The Hoyt limestone is a more calcareous and more fossiliferous phase of the lower portion of the Little Falls dolomite ..." Wheeler (1942, p. 522–523), referring to the Whitehall area, considered the base of the Whitehall to coincide with the contact between the "Little Falls" and the overlying Hoyt; the Hoyt was redefined as a lower member of the Whitehall Formation.

Fisher (1962a) depicted the Hoyt near Saratoga to be partly equivalent to the upper Little Falls to the west and partly to a Little Falls-Tribes Hill disconformity. His ideas (1975, written communication; 1977) remain much the same—he feels that the type Little Falls is Franconian and that overlying disconformity represents the Trempealeauan (i.e., Hoyt), which is missing in the Mohawk Valley. Fisher and Mazzullo (1976) showed the Hoyt to lie on a dolostone equivalent to the upper Little Falls in the Mohawk Valley, but, in his most recent correlation chart, Fisher (1977) showed only the Mosherville between the Galway and Hoyt.

Taylor and Halley (1974, p. 6, 9), using primarily trilobites, assigned the lower part of the Whitehall to the *Saukiella serotina* Subzone of the Late Cambrian *Saukia* Zone, whereas the upper part was assigned to the earliest Ordovician *Missisquoia* Zone. They claimed that, although the Hoyt fauna is Trempealeauan, it was not possible to document, on paleontological data, which parts of the Hoyt and lower Whitehall are synchronous. Apparently the Hoyt was not considered as a lithologic part of the Whitehall.

Despite some similarities between the Hoyt and the Little Falls, there is a particularly striking distinction—a considerable part of the Hoyt is undolomitized; lithologically it is justifiably treated as a separate unit regardless of its temporal relations with the Little Falls. Stratigraphic position, common algal stromatolites, and similarities in their petrology strongly suggest a very rough correlation between the upper part of Unit B of the Little Falls at the type section and the Hoyt; no diagnostic fossils have been found in the former unit.

Despite the majority opinion to the contrary, I do not subscribe to the idea of a significant break between the Little Falls and the Tribes Hill in the western Mohawk Valley. Despite the lack of any definitive fossil evidence, I suspect the uppermost Little Falls could be correlative with the lowest Gailor near Saratoga and the lowest Whitehall, above the Hoyt fauna, in Washington County. Consequently, the Mosherville would also be equivalent to some parts of the middle Little Falls but its exact position is uncertain. Knotty problems in the stratigraphy of the Saratoga region have been, and will continue to be, clarified by analyses of stratigraphic relations with units in Washington County to the east.

Figure 27 presents my conception of the generalized relations of the Little Falls and associated units between Poland and Little Falls. This arrangement is based primarily on physical lithology, thickness, and stratigraphic position. I am well aware of the weaknesses in employing such criteria, as well as the difficulties involved in correlating with little biostratigraphic control. Although the relations between the main part (i.e., lower and middle) of the Little Falls Dolostone and lateral units are similar to those illustrated by Fisher (1977), I envision a much closer relation between the upper Little Falls and overlying Tribes Hill strata in the Mohawk Valley and a possible correlation with the lower Gailor to the east. Although

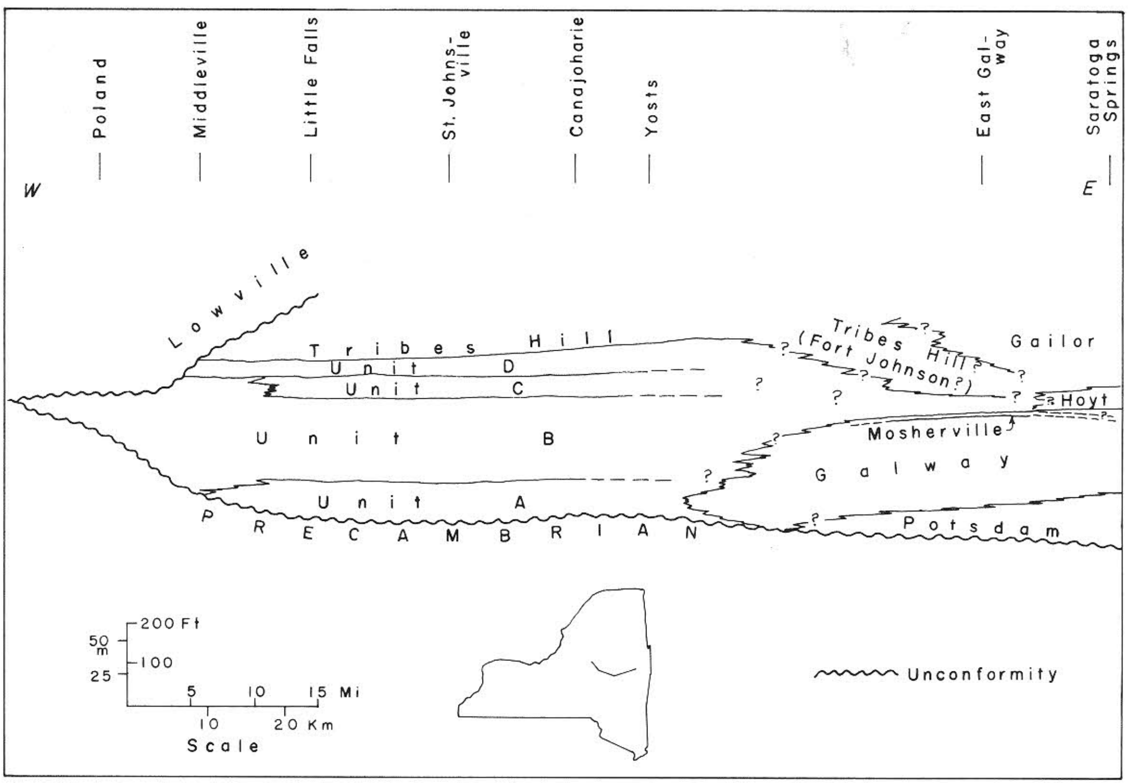

Figure 27. Generalized stratigraphic relations of Little Falls, and its units, from Poland to Saratoga Springs (note line of section on small map of New York State at bottom center).

TABLE 1 - Analytical Data for Subdivisions of Little Falls and for Adjacent Units

Unit	Insoluble Residue (%)	Density (g/cm^3)	Dolomite (% of total carbonate)
Little Falls			
Unit A	$\bar{x}$ = 28.4 Md = 21.8 (n = 48) SD	$\bar{x}$ = 2.804 Md = 2.826 (n = 47) SD	$\bar{x}$ = 96 Md = 97.2 (n = 45) SC,D
Unit B	$\bar{x}$ = 26.0 Md = 15.4 (n = 257)	$\bar{x}$ = 2.805 Md = 2.823 (n = 254) SD	$\bar{x}$ = 94.4 Md = 96.4 (n = 247) SD
Unit C	$\bar{x}$ = 25.4 Md = 9.7 (n = 42)	$\bar{x}$ = 2.803 Md = 2.831 (n = 42) SD	$\bar{x}$ = 93.8 Md = 94.4 (n = 39) SA,D
Unit D	$\bar{x}$ = 19.9 Md = 15.9 (n = 69) SA	$\bar{x}$ = 2.826 Md = 2.835 (n = 69) SA,B,C	$\bar{x}$ = 98.0 Md = 98.3 (n = 70) SA,B,C
Galway	$\bar{x}$ = 30.8 Md = 22.8 (n = 37)	$\bar{x}$ = 2.806 Md = 2.830 (n = 37)	$\bar{x}$ = 99.4 Md = 100 (n = 36)
Gailor	$\bar{x}$ = 25.2 Md = 12.0 (n = 17)	$\bar{x}$ = 2.771 Md = 2.787 (n = 17)	$\bar{x}$ = 65.8 Md = 78.7 (n = 14)
Hoyt	$\bar{x}$ = 14.3 Md = 10.8 (n = 19)	$\bar{x}$ = 2.781 Md = 2.775 (n = 19)	$\bar{x}$ = 57.9 Md = 58.2 (n = 19)
Potsdam	$\bar{x}$ = 69.1 Md = 77.7 (n = 18)	$\bar{x}$ = 2.718 Md = 2.705 (n = 18)	$\bar{x}$ = 81.9 Md = 91.5 (n = 13) (excluding samples > 99% insol.)
Tribes Hill	$\bar{x}$ = 19.9 Md = 15.3 (n = 53)	$\bar{x}$ = 2.794 Md = 2.794 (n = 53)	$\bar{x}$ = 75.9 Md = 87.7 (n = 53)

$\bar{x}$ = mean Md = Median n = no. of samples SD = Significant difference at 95% confidence level with the mean of another designated unit in the Little Falls, for example Unit D.

my views undoubtedly represent a departure from the consensus, I do suggest that more work be done in the Gloversville, Amsterdam, and Broadalbin Quadrangles in order to determine whether there is any merit in the proposal.

PETROLOGY

GENERAL

As discussed under "Methods of Study," the petrology phase of the investigation included various kinds of examination: insoluble residue analysis; density determinations (including calculation of calcite/dolomite ratios); analyses of the mineral composition of "whole rock" samples and of insoluble residues by X-ray diffraction; thin section petrography; electron probe microanalysis; determination of carbon and oxygen isotopes of a few selected samples; minor scanning electron microscopy; and preliminary cathodoluminescence study.

Table 1 summarizes the general statistical data for the subdivisions of the Little Falls and for adjacent units. If there is a significant difference (at the 95 percent confidence level), between the mean of a particular unit in the Little Falls and another unit within that formation, it is indicated by the designation "S" followed by the letter of the unit(s) which are differentiated from that particular unit (based on "t" test). Data for individual samples are presented in Appendix B.

QUALITATIVE INSOLUBLE RESIDUE ANALYSIS

That there is a sizable terrigenous content in the Little Falls, as well as in adjacent units, is indicated in Table 1. Figures for the mean and median are given; a relatively low median, as compared to the mean, reflects the fact that the greater bulk of samples are dolostones or quartzose dolostones containing less than 20 percent insoluble material. Alternatively, the higher mean results from the presence of sandstones, including orthoquartzites. Actually, there are relatively few "pure" dolostones—only about 7 percent of the samples contain less than 3 percent terrigenous matter. The mean of the percentage of insoluble residue for Unit D is conspicuously lower than that for the other three units (see Table 1), reflecting not so much a lower terrigenous content within the dolostones (note the medians) but rather of the paucity of sandstones. Unit C, on the other hand, includes substantial sandstone but the insoluble content of the dolostone is lower. It should be pointed out that both averages for Unit A are high owing in large part to the inclusion of 7 samples from field subunit 9 at Little Noses (loc. 52) which, although included in A, may well represent a westerly directed tongue of Potsdam or Galway, or, more likely, an eastward transition to these units. Unit B, as exposed in the Middleville area, consists of more impure dolostone that at Little Falls. For example, at localities 5 and 6 the mean terrigenous content is 32 percent and 34 percent, respectively, as contrasted with 20 percent and 24 percent at localities 17 and 18 at the composite type section. It is clear that it is practically impossible to assign any one sample to a particular unit of the Little Falls based on its insoluble content.

It can be seen that there are some distinctions between the adjacent stratigraphic units and those of the Little Falls. Although there is a surprisingly appreciable carbonate content in the Potsdam Sandstone, it is basically a terrigenous unit. Figures support field observations that there is a considerable sand content in the Galway, both in the form of sandstones and relatively high sand content in the dolostones. Analyses of 19 samples of Hoyt Limestone show a significantly lower terrigenous content as compared with the subdivisions of the Little Falls. The figures for the lower Tribes Hill and Unit D of the Little Falls are essentially identical, further suggesting a closeness of the stratigraphy between the two units which I feel does exist in the western Mohawk Valley. The Gailor is not significantly different than the "average" Little Falls.

The qualitative nature of the residues was determined by X-ray diffraction and will be discussed below.

X-RAY DIFFRACTION ANALYSIS

"Whole rock" analyses by X-ray diffraction show that for all units of the Little Falls the most common mineral is dolomite, followed by quartz (Fig. 28). Based on the peak positions and shapes, the dolomite is well ordered and stoichiometric. The main dolomite reflection {211} lies between 2θ values of 30.92° and 30.98°. Considering that some of the dolomite is very slightly ferroan, it is certain that it is not calcium-rich. Generally present in the sandy dolostones and sandstones is microcline (most commonly as perthite—see further comments under "Petrography") with its distinctive reflection at $2\theta = 27.4°$. Normally this feldspar is much less common than quartz but very rarely may be nearly equal in abundance. With an instrument setting of 500 counts per second, the only other minerals recognized in the "whole rock" runs are calcite, "glauconite" and pyrite, the latter two being undetected in most of the specimens and very minor when present. The nature of the "glauconite" will be considered in the section on thin section petrography; it is represented by an X-ray pattern similar to that of muscovite and illite except for the greater relative intensity of the reflection at $2\theta = 34.7°$ and the slightly lower angle of the reflection from {020} (Fig. 29).

Calcite is present in about half of the "whole rock" analyses but usually in minor quantities; there are essentially no limestones and only a few specimens qualify as "calcareous" (i.e., more than 10 percent calcite). Occasionally calcite is more abundant than microcline but normally, in decreasing order, the minerals are dolomite, quartz, microcline, and calcite.

X-ray scans were also run on the insoluble residues in order to gain a better knowledge of the nature of the terrigenous content. Minerals not showing up in the "whole rock" analyses commonly appear in the scans of the residues (Fig. 29). Chlorite occurs in very small amounts in a low percentage of the samples. The terrigenous components, in general order of decreasing presence and abundance are quartz (by far the commonest), microcline, "glauconite," pyrite, and chlorite. There seems to be no significant stratigraphic distribution of these minerals, with the possible exception of the common presence of pyrite in the residues of Unit D.

There are few mineralogical differences between the Little Falls and adjacent stratigraphic units. In the overlying lower Tribes Hill, calcite is more abundant as a result of the limestones and calcareous dolostones present. Buyce and Friedman (1975, p. 813) implied that potassium feldspar is more common in the Tribes Hill than in the Little Falls. Based on several X-ray analyses of the lower Tribes Hill in the vicinity of Little Falls, there does appear to be significantly less potassium feldspar in the Little Falls. Although minor, pyrite is often present in the residues of the lower Tribes Hill, a situation similar to that in Unit D of the Little Falls. Of course, quartz is much more significant in the Potsdam, where most of the specimens are sandstones and to a lesser extent in the Galway. Whereas there is a low proportion of carbonate in most Potsdam samples, it is somewhat surprising to note that calcite is a relatively significant constituent, usually being more common than microcline. Calcite is the second most important constituent, in the Hoyt and Gailor. Chlorite is commonly present, although generally minor, in Hoyt residues.

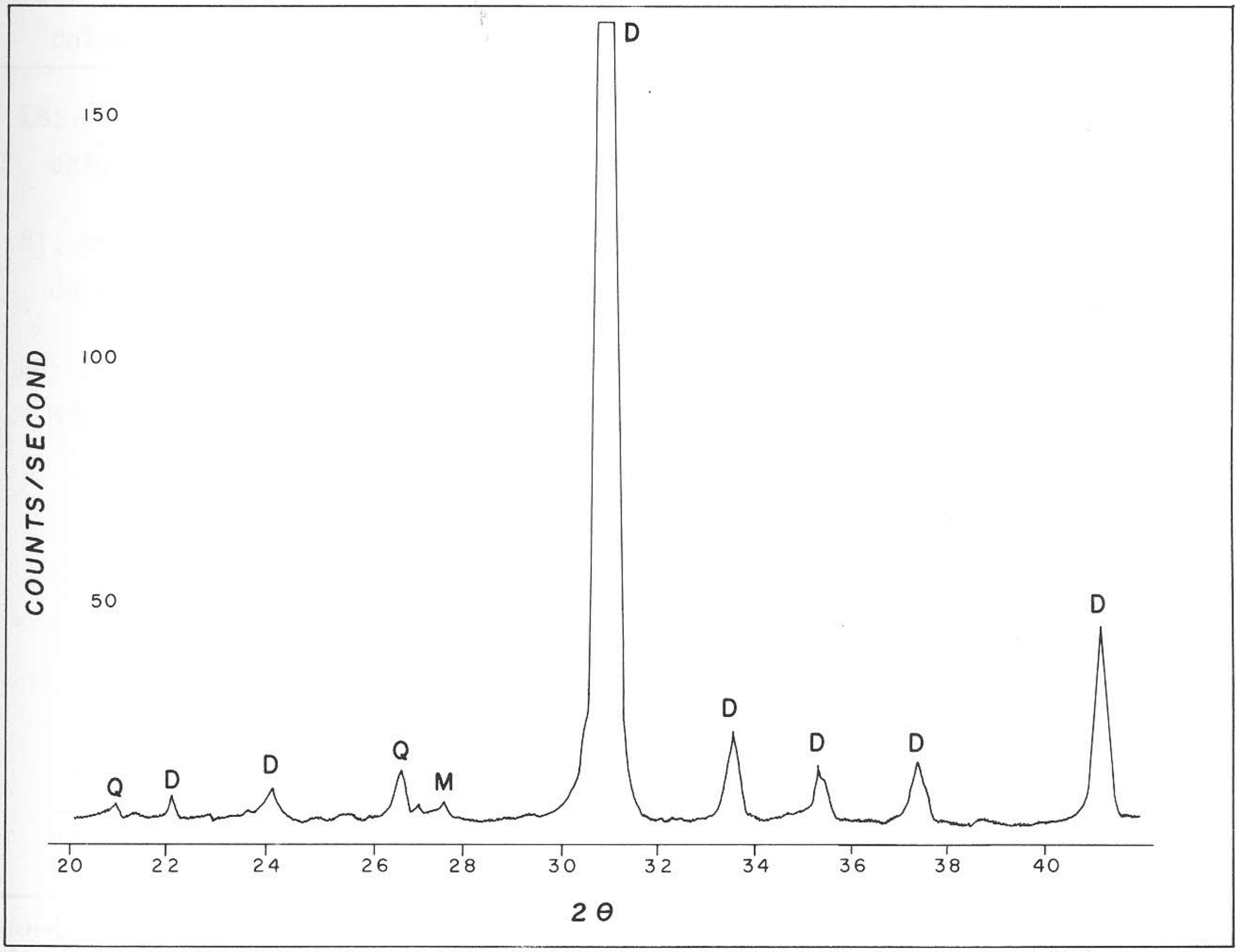

Figure 28. X-ray diffractogram of typical sample (G11) of Little Falls Dolostone, showing major components of dolomite (D), quartz (Q) and microcline (M). Cu radiation, Ni filter; scanning rate 1°/minute.

DENSITY DETERMINATIONS AND CALCITE-DOLOMITE RATIOS

Densities (see Table 1), as determined with an air comparison pycnometer (see "Methods of Study"), are reflective of the relative proportions of quartz, microcline, dolomite, and calcite with densities of approximately 2.65 g/cm^3, 2.60 g/cm^3, 2.86 g/cm^3, and 2.71 g/cm^3, respectively. Because calcite is very rare in the Little Falls, density values essentially reflect the relative proportions of insoluble residue (mainly quartz and microcline) and dolomite. Unit D possesses the highest average density, indicative of its general low terrigenous content (it is significantly different from Units A, B, and C—see Table 1). Except for the Galway, the mean densities of all the other stratigraphic units are significantly lower than those of the subdivisions of the Little Falls owing either to a greater terrigenous content (e.g., Potsdam) or to a greater amount of calcite (e.g., Gailor, Hoyt, and Tribes Hill).

Calcite/dolomite ratios were determined using a procedure previously reported (Zenger, 1968) that utilizes the fact that there is a considerable difference between the densities of dolomite and calcite. The air pycnometer measures volumes precisely enough that the calculated densities of the carbonate fraction quite accurately reflect the relative proportions of the two minerals, assuming that calcite and dolomite are the only carbonate minerals present. The very minor amount of ferroan dolomite in the Little Falls does not affect this determination in a significant way. Dolomite, as a percent of the total carbonate, is given in Table 1. As mentioned above, the calcareous content of the Little Falls is generally low. Unit D seems to have the least calcite of all the subdivisions of the Little Falls; its relative dolomite content is significantly more than Units A, B, and C and that of A is significantly more than the dolomite content of Units B and C (Table 1). Calcite is also minor in the Galway. Although dolomite is the dominant carbonate mineral in the Gailor (including the "Ritchie"), Hoyt, and Tribes Hill, calcite is much more common than in the Little Falls owing to the presence of more limestones and mixed carbonates in these other units.

An attempt was made to determine whether there is any correlation between calcite/dolomite ratios and insoluble residue contents in the units with limestones and mixed carbonates as well as dolostones (i.e., Gailor, Hoyt, and Tribes Hill). The correlation coefficients for dolomite (as the percent of total carbonate)

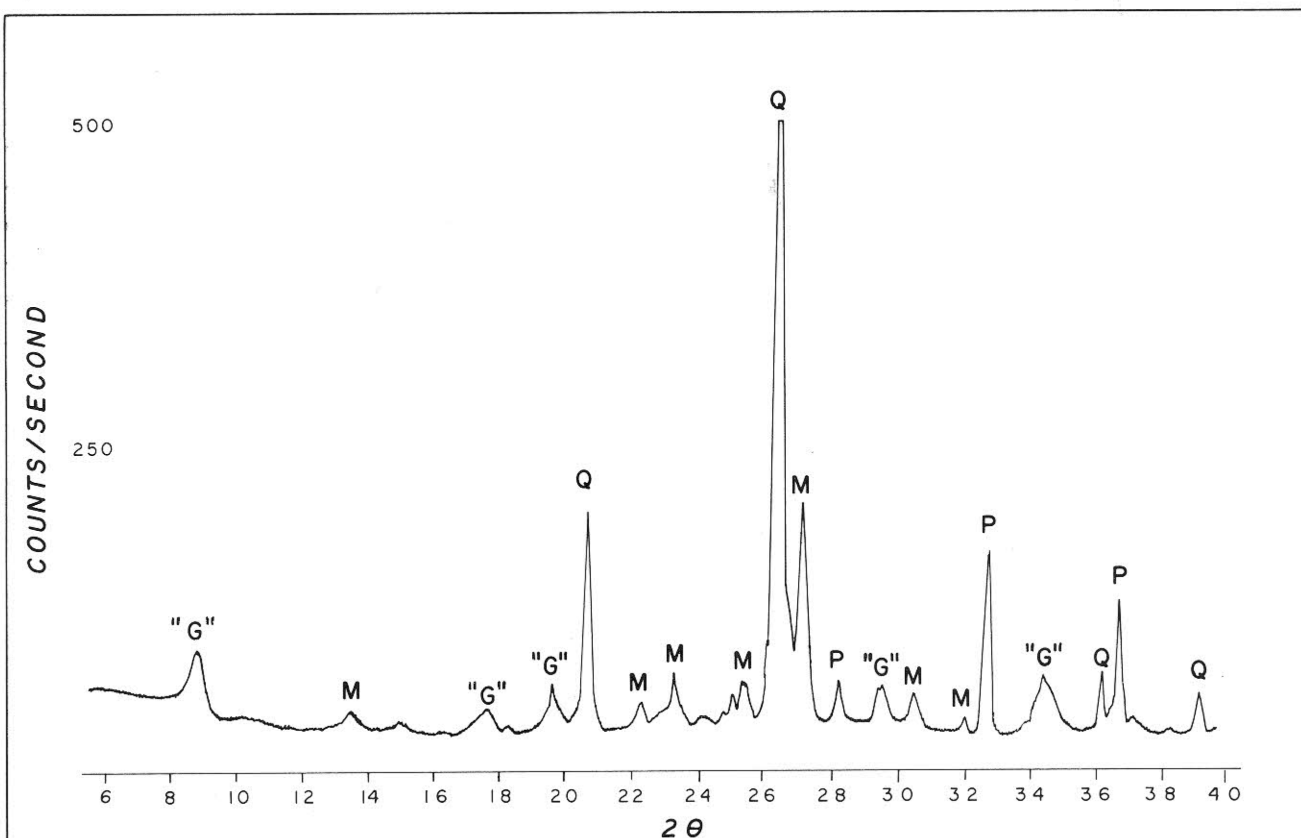

Figure 29. X-ray diffractogram of insoluble residue of sample G11 (see Fig. 28 for whole rock analysis). Q (quartz), M (microline), P (pyrite), "G" ("glauconite"). Cu radiation, Ni filter, scanning speed 1°/minute.

TABLE 2 - Carbon and Oxygen Isotope Data (Relative to PDB) of Selected Samples of Little Falls Dolostone

Sample	δO^{18} ($^o/oo$)	δC^{13} ($^o/oo$)
SH2; algal stromatolite, Unit B, Loc. 20	- 5.61	-1.79
H71; medium to coarse deci-micron-sized dolostone, Unit D, Loc. 17	- 4.45	-1.65
H56; fine centimicron-sized dolostone; Unit C, Loc. 17	- 6.06	-0.85
E8; coarse centimicron-sized dolostone; Unit A, Loc. 16	- 6.71	+0.45
N1, coarse centimicron-sized dolostone, Unit C, Loc. 40	- 7.49	-2.08
RH; secondary dolomite rhomb; Middleville(?) area	-11.34	-1.07

vs. insoluble content in these units are as follows:

Gailor	0.2945 (n = 16)
Hoyt	0.1131 (n = 19)
Tribes Hill	0.1367 (n = 54)

In all cases the values are well below the 95% confidence level so we accept at that level the null hypothesis that there is no correlation between these variables.

CARBON AND OXYGEN ISOTOPE ANALYSES

Five samples of dolostone and one of dolomite (dolomite crystal from a vug) were analyzed for carbon and oxygen isotopes by the Institute of Geophysics, University of California, Riverside. These data are presented in Table 2; their interpretation will be discussed later.

MICROSCOPIC PETROGRAPHY

Introduction

The bulk of the interesting petrographic aspects of the Little Falls is revealed by study of thin sections of this unit with the petrographic microscope, supplemented in numerous instances by the electron probe microanalyzer. A few selected samples were observed with the scanning electron microscope.

Mineralogy

Dolomite. Terms for crystal size and crystallization fabrics follow the classification of Friedman (1965a). Dolomite occurs both as the major mineral in the rock fabric proper and also as later rhombs in vugs and fractures; the emphasis will be on the characteristics of dolomite in the fabric. With the exception of an idiotopic fabric in porous zones or in voids, the dolomite is primarily subhypidiotopic (i.e., between xenotopic and hypidiotopic (see Fig. 30).[1] As is characteristic of textures of dolostones, in contrast with limestones, dolomite crystal boundaries are more planar or more gently curved than those of calcite leading to a polygonal appearance in the two-dimensional thin section. Strictly speaking, where dolomite crystals are in contact, it is usually not practical to distinguish between true crystal faces and compromise boundaries; the terms hypidiotopic, subhypidiotopic, etc. are thus used in a descriptive way only. Perhaps a term is needed to describe this general appearance of dolostone textures, as characterized by relatively planar intercrystalline boundaries whether they be crystal faces or compromise boundaries. G. M. Friedman (1969, written communication) has suggested "homalotopic,"

[1] Notations within parenthesis in captions of photomicrographs refer to specimen numbers; stratigraphic occurrence and more information on specimens are given in Appendix B.

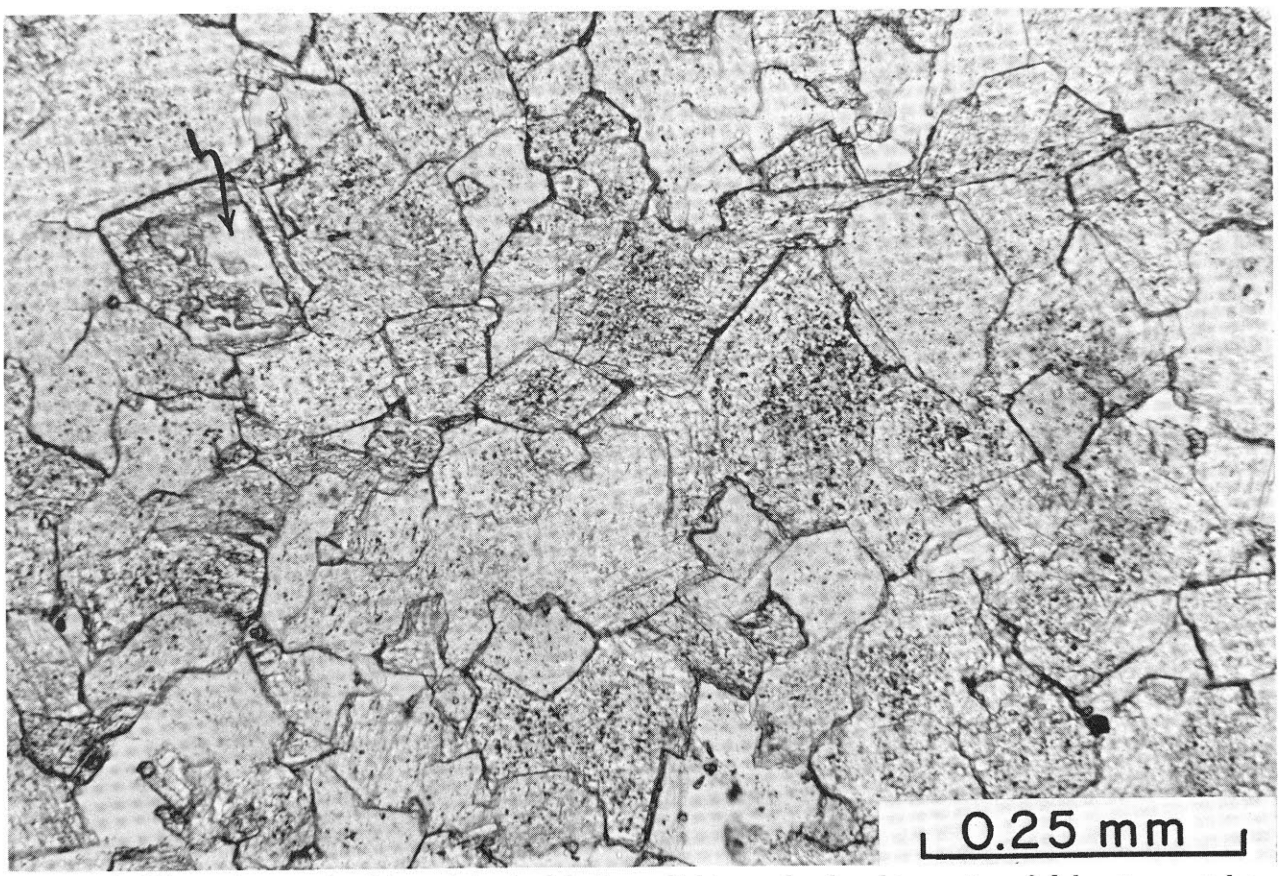

Figure 30. Photomicrograph of homalotopic dolostone; light, partly rhombic center of dolomite crystal in upper left (see arrow) is chert; plane polarized light (H56).

from the Greek "homalos," meaning plane, and "topos" referring to place, region, site, or position.

Microscopically, the more finely crystalline dolostone (i.e., decimicron-sized and micron-sized) appears to be more xenotopic but as viewed with the scanning electron microscope (Fig. 31), the crystal boundaries are not only quite planar but also rhombic. However, xenotopic fabrics do occur and dolomite crystal boundaries may rarely be consertal, especially in some instances where the crystals are very large. Where the irregularities involve dolomite against dolomite the explanations may be a porphyrotopic fabric (Fig. 32), with smaller crystals embaying the larger ones, or pressure solution. Of course, where dolomite is in contact with another mineral, the crystal boundary may be very irregular owing to an irregular surface against which the dolomite is growing, or to corrosion of the dolomite.

The crystal size of dolomite varies widely from micron-sized to millimeter-sized. Despite this considerable range, the great bulk of the dolomite crystals are coarse decimicron-sized to fine centimicron-sized[1], with crystal dimensions between 50 and 200 μm. Very few equigranular specimens consist of crystals outside of this size range. Generally, the more finely crystalline (i.e., micron-sized, fine and medium decimicron-sized) and more coarsely crystalline (i.e., medium and

[1] I have subdivided the decimicron-sized range into fine, medium, and coarse, in a manner parallel with Friedman's (1965) subdivisions of the centimicron-sized range.

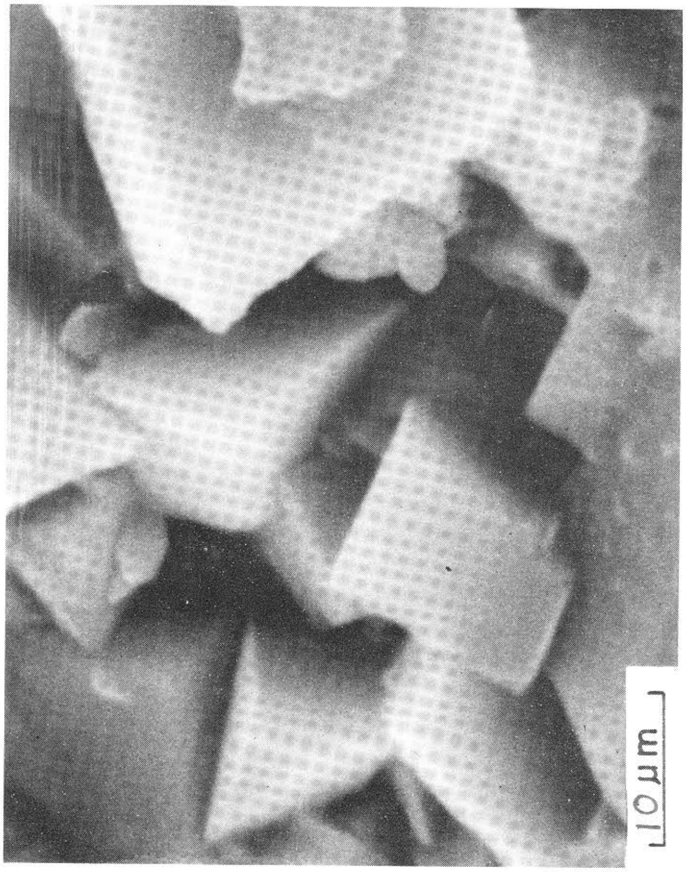

Figure 31. Scanning electron photomicrograph of very fine-crystalline dolostone (M21) showing rhombic shape of the small crystals.

Figure 32. Photomicrograph of porphyrotopic dolostone (E1) showing undulatory extinction of larger crystals (see arrows) and embayment of margins by smaller crystals; crossed polarized light.

coarse centimicron-sized, and millimeter-sized) dolomite occurs in association with particular fabrics and structures within the more common coarse decimicron-sized to fine centimicron-sized dolomite.

Micron-sized dolomite is relatively rare, usually associated with finer decimicron-sized dolomite. The most common occurrences of these finer grained varieties are in algal stromatolitic laminations commonly showing a fabric similar to the "structure grumeleuse" (Fig. 33) of Cayeux (1935), in dolomitic intraclasts (Fig. 34), in relict grains (to be discussed below), and as possible products of degradational neomorphism of larger dolomite crystals, particularly along crystal margins or in rhomb-shaped areas within crystals (Fig. 35). In such occurrences, much of the dolomite is actually fine decimicron-sized.

Coarser centimicron-sized up to millimeter-sized crystals occur:

(1) As secondary crystals in vugs.
(2) As pockets within the more finely crystalline dolomite (Fig. 36). These pockets range up to a few millimeters in size and generally possess boundaries that are relatively sharp. They may be roughly spherical to more elongate or irregular in shape and there appears to be no consistent orientation with regard to the bedding. Because crystal boundaries are not very planar and because the crystals do not become larger inward, it is suggested that these pockets do not represent void filling but rather neomorphism. It is

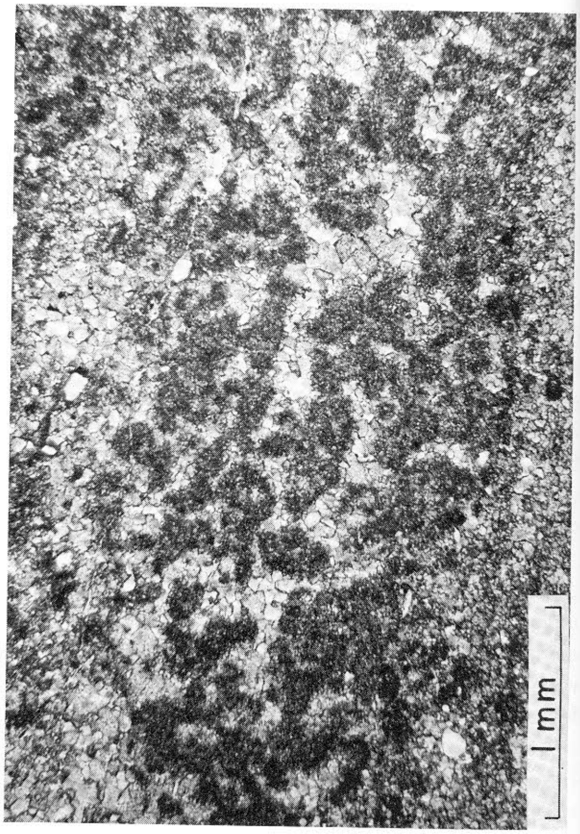

Figure 33. Photomicrograph of clotted fabric similar to "structure grumeleuse" in lamination of specimen (3L) of algal stromatolite; plane polarized light.

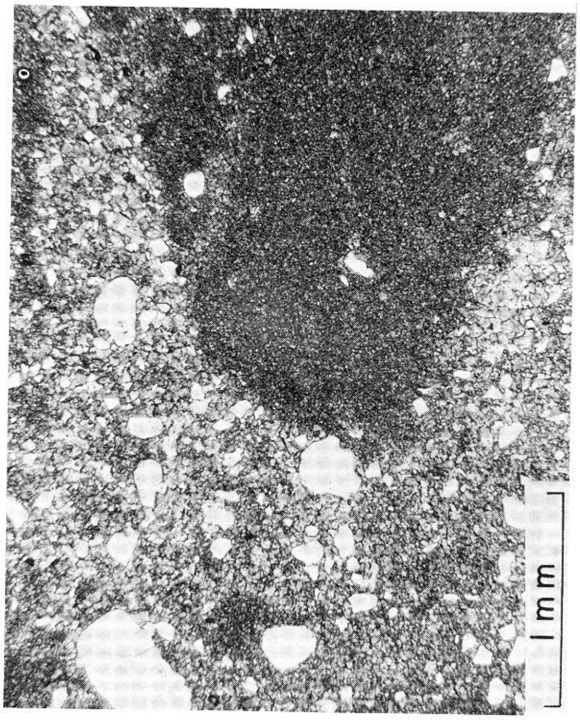

Figure 34. Photomicrograph of portion of finely crystalline dolomitic intraclast showing some neomorphic effects, particularly that of a diffuse boundary; plane polarized light (23M).

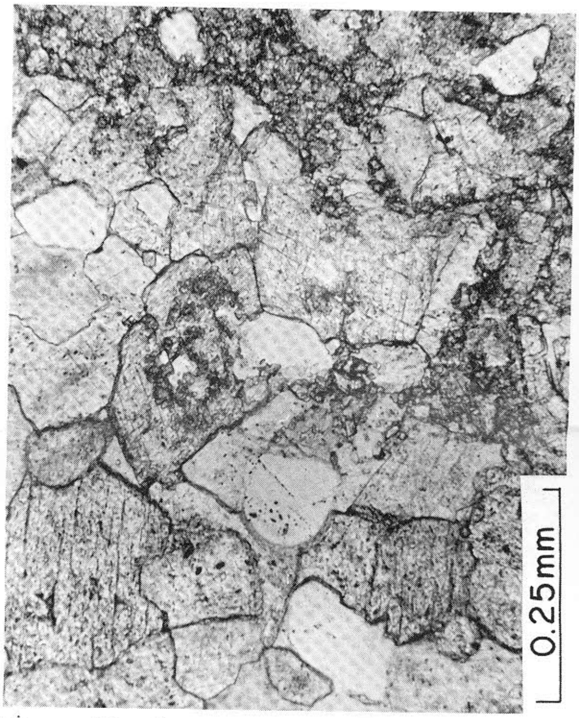

Figure 35. Photomicrograph of possible grain diminution by degradational neomorphism within and around dolomite crystals; solution effects would be less likely alternative explanation; white grains are detrital quartz; plane polarized light (D17).

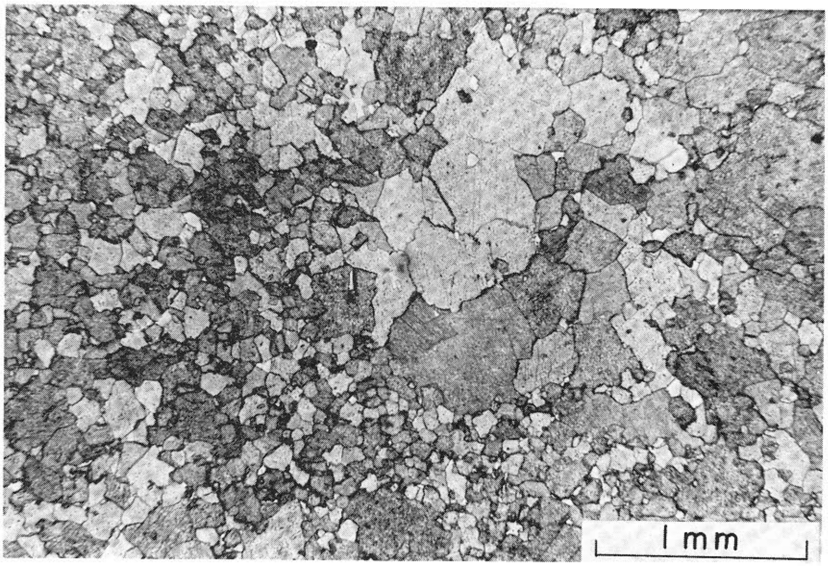

Figure 36. Photomicrograph of pocket of coarser dolomite crystals in more finely crystalline groundmass, resulting probably from neomorphism; plane polarized light (N1).

Figure 37. Photomicrograph of rhombic "shadowy" centers of dolomite crystals; note sug gestion of relict grain, as demarcated by these dusty zones, in center of photograph; plane polarized light (21M).

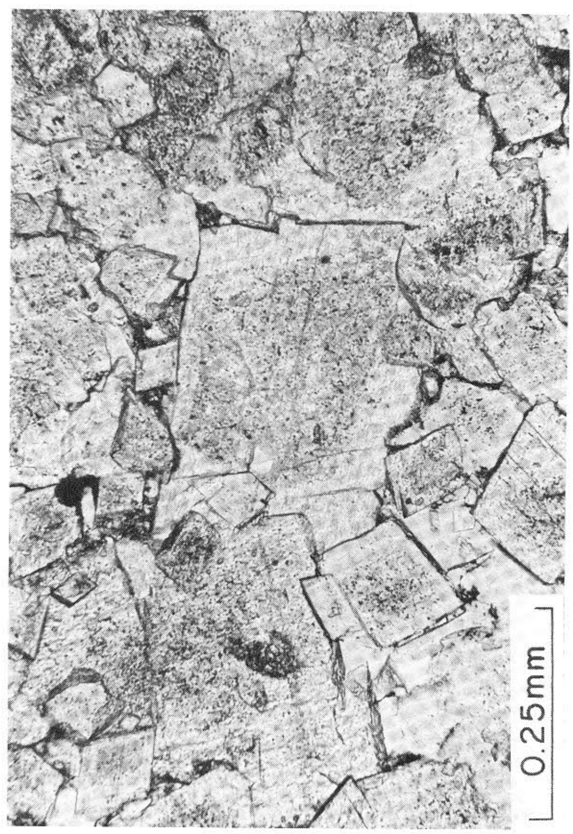

Figure 38. Photomicrograph of rhombic "shadowy" zones in coarse dolomite crystals; plane polarized light (H73).

also very possible that such pockets represent burrow mottling.

(3) As the coarser elements in a porphyrotopic fabric (Fig. 32). These crystals commonly show an undulatory extinction characteristic of late diagenetic dolostones (Choquette, 1971).

The foregoing should not be taken to imply that specimens of more common crystal size (i.e., coarse decimicron-sized to fine centimicron-sized) are completely equigranular. Some, for example, have alternate, mm-thick laminae, or cross-laminae, of the two crystal sizes.

Most dolomite crystals, excluding the void-filling spar, appear "dirty" because of inclusions which may be large and identifiable (e.g., hematite inclusions) but often present a cloudy or dusty appearance. Frequently the inclusions are clustered in rhomb-shaped areas (which may be little more than a stain) centered in and forming the bulk of the crystal; these are surrounded by clearer dolomite rims (Figs. 37, 38). Such "dusty" centers and clear rims have been noted by many workers, perhaps the best description being that provided by Murray (1964, p. 399–403). He attributed the cloudiness to remnants of replaced material and the clear rims to later precipitation of dolomite into a surrounding moat resulting from excess solution of carbonate immediately outside the original rhomb in order to provide the carbonate necessary to offset the 12 to 13 percent volume difference between calcite and dolomite. More recently, Sibley (in press), in considering cloudy-centered, clear-rimmed dolomite rhombs from the Pliocene of Bonaire, offered the following explanation for their origin: "The initial dolomitizing fluids were near saturation with respect to calcite and, therefore, many crystals of calcite were included in the centers of dolomite rhombs. Later, as the water became undersaturated with respect to calcite, inclusions within the rhombs dissolved and further growth was inclusion-free." In several instances, in the Little Falls, the shadowy rhombs of several adjacent crystals are practically in contact and outline a relict grain, such as a peloid (Fig. 37); such a relationship does indeed support Murray's contention that the dust represents inclusions. However, the clear rims are not uniformly around these dusty centers, which are essentially in contact in these instances. Schuon (1976) has described Ordovician (Wisconsin) and Plio-Pleistocene (Bonaire) dolomite rhombs with similar cloudy centers and clear rims. Using microchemistry and scanning electron microscopy, she described the cloudy centers as apparently being perforated by many small holes. In these Ordovician rhombs, the silicon content is higher in the clear rim; I noted no such distinction in the Little Falls. In fact, in a few thin sections of the Little Falls I noted dolomite crystals with clear centers and cloudy rims! Perhaps Sibley (in press) has the best explanation. It appears that more work, such as electron probe microanalysis, can profitably be done on these common but peculiar crystals.

Minor, slightly ferroan dolomite (distinguished by staining with an acidic solution of potassium ferricyanide) occurs as rims on euhedral faces of dolomite crystals, which probably have grown into a void. Occasional crystals in porous zones are completely ferroan and these too, are judged to be void-filling crystals. Much more rare and puzzling is the occurrence of ferroan centers of dolomite crystals. Semiquantitative analysis with the electron probe microanalyzer (Fig.

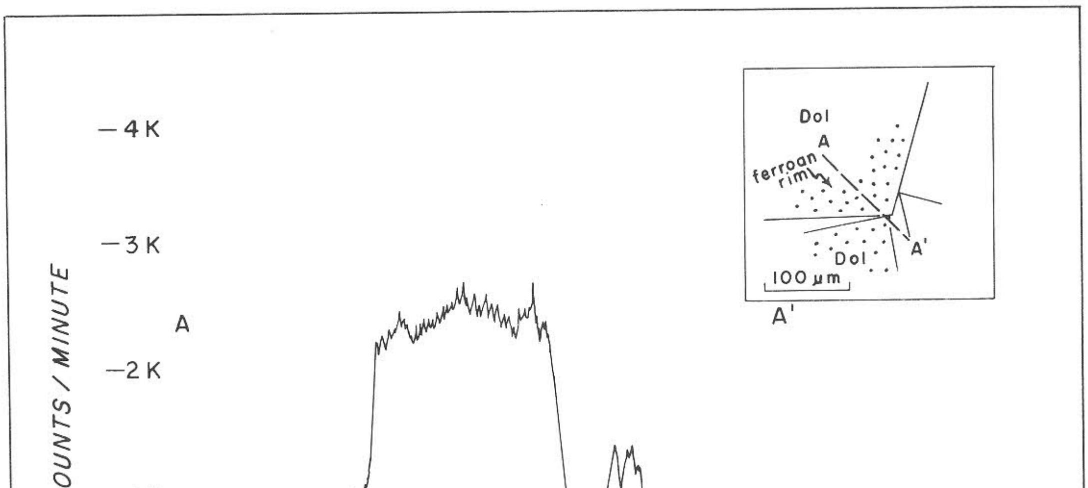

Figure 39. Electron probe stage traverse for FeKα in ferroan rims of dolomite crystals along line A-A^1 as indicated in inset (H61).

39) shows that there is definitely less than two, and probably less than one, weight percent iron in the ferroan areas.

Dolomite Grain Types. Although quartz grains are now probably the dominant recognizable clastic component in the Little Falls, carbonate grains, many of them relics, are very significant and it is appropriate to consider these following the discussion of dolomite. Because no original calcium carbonate remains, it is in the dolomitic grains, coupled with the relatively coarse crystal size, that we have evidence that at least a considerable part of the dolomite in the Little Falls is of the replacement type. As will be mentioned under "Paragenesis," it is likely that most of these dolomite grains, excluding possibly some intraclasts, were composed initially of calcite or aragonite.

Intraclasts generally consist of micron-sized to decimicron-sized dolomite and usually are not significantly quartzose (Fig. 34). Their shape varies from oval to elongate. In hand specimen these intraclasts may be several centimeters long. In thin section, their size ranges from centimeters down to medium sand size. Some intraclasts have internal structures, such as sheet cracks, and some laminated ones are obviously derived from stromatolites because they occur immediately above the algal structures. In fact, the elongate shape of many intraclasts suggests that they were derived from sediment between desiccation cracks.

Some intraclasts are very discrete, with apparently well-defined boundaries; even these boundaries, however, are commonly not sharp on a microscopic scale, probably owing to neomorphism, either in conjunction with the replacement of a calcareous clast by dolomite or, after the incorporation of a dolomitic clast. Many intraclasts are relics and are more subtly distinguished by a greater amount of inclusions (Fig. 40), by a darker stain, or by a slightly different size of component crystals. Dolomite crystals commonly transect the borders of these relict clasts. Others, even more vague, may be difficult to distinguish from mottles. Most intraclasts are generally elongate parallel with the bedding but zones of edgewise breccia are present, sometimes associated with hemispherical algal stromatolites or with flat algal laminae. Clasts in edgewise breccia in Unit D (see Figs. 15, 41) at Little Falls (loc. 13) and at St. Johnsville (loc. 31) contain appreciable quartz and calcite.

Recognizable relics of skeletal remains are extremely rare in the Little Falls. In fact, I observed them in only one of hundreds of thin sections examined. Although it is possible that dolomitization completely obliterated some skeletal material, the presence of those few in a specimen of very "average" dolomite suggests that they were not abundant. In this particular specimen (Fig. 42) from Unit B, the fossil relics are gently arcuate structures ranging from 2 to 5 mm in length

Figure 40. Photomicrograph of portion of relict intraclast defined primarily by pyrite; note dolomite crystal boundaries transecting clast; plane polarized light (H74).

and are about 100 μm in thickness. The relict shells are transected by dolomite crystals and no structure whatsoever remains. These are probably parts of brachiopod valves but possibly they are trilobite remains such as sections of thoracic segments, or less likely, spines.

The term "peloid" was introduced by McKee and Gutschick (1969, p. 555–556) and has been used by many subsequent workers to refer, in a non-genetic way (in contrast to the term "pellet"), to irregular to rounded grains of micron- to decimicron-sized calcite. Such bodies are abundant in the Little Falls although the fine-crystalline internal texture is invariably nearly totally obliterated. About one-quarter of the thin sections of the Little Falls have at least some of these relict grains that are mainly distinguished by more cloudy or "dusty" areas which may have a greater abundance of inclusions. Such peloids practically escape notice without careful observation and are best viewed using the upper element of the condenser or in reflected light (Zenger, 1979). This mode of preservation is commonly associated with the previously described shadowy rhombic centers of dolomite crystals. Peloids generally range in size from 100 μm to 1600 μm, most being medium sand size. Their presumed original fine-crystalline texture is completely absent owing to neomorphism and/or replacement, and they are judged to be peloids based on their roundness and shape; they range in cross section from being near circular to elongate, probably representing various sections through the bodies (Fig. 43). It is possible that some of the circular bodies are ooids but generally, in definite oolitic patches, a very high proportion of the bodies are circular. Relict peloids are closely packed in most occurrences and consequently form a grain-supported fabric.

Ooids are as common, if not more so, than peloids. Their preservation in dolomite is generally very poor (Figs. 44, 45), in contrast with that in chert, where concentric and radial structures are preserved (Figs. 46, 47). Very similar concentric and radial structures are illustrated by Pettijohn (1975, p. 84) from the Cambrian Warrior Limestone in Pennsylvania. In pockets of chert where ooids have been dolomitized as well as silicified, relict laminae may still be seen (Fig. 48). More often, however, the internal structure has been completely obliterated in the dolomitic ooids and they are commonly preserved, in a manner similar to peloids, as a faint, "dusty" circular area of brownish stain (Fig. 45), or, as areas of fine inclusions within which the crystals are essentially of the same size as in the groundmass beyond. In some instances, the crystal size within the completely dolomitized ooid is distinctly greater and the fabric more equigranular than that of the surrounding dolomite. Ooids may have micritic rims which demarcate their boundaries. In dolomitized ooids associated with chertified ooids from Unit D along East Canada Creek (loc. 30), the margins of the structure are defined by a thin stained (brownish) zone within which are large, centimicron-sized, clear crystals, in places restricted to the confines of the ooid but normally at the periphery, transecting the rim.

A low proportion of Little Falls ooids reveals the presence of a recognizable nucleus; rarely, quartz grains are visible in the centers of silicified ooids (see later discussion under "Chert"). If the nucleus originally consisted of fine crystalline carbonate, diagenesis has no doubt obliterated its identity. If the nuclei were small (many concentric rims extend well into the center of the ooid), the cut effect would provide a high proportion of sectioned ooids without the nucleus showing. Bathurst (1971, p. 77) maintained that an

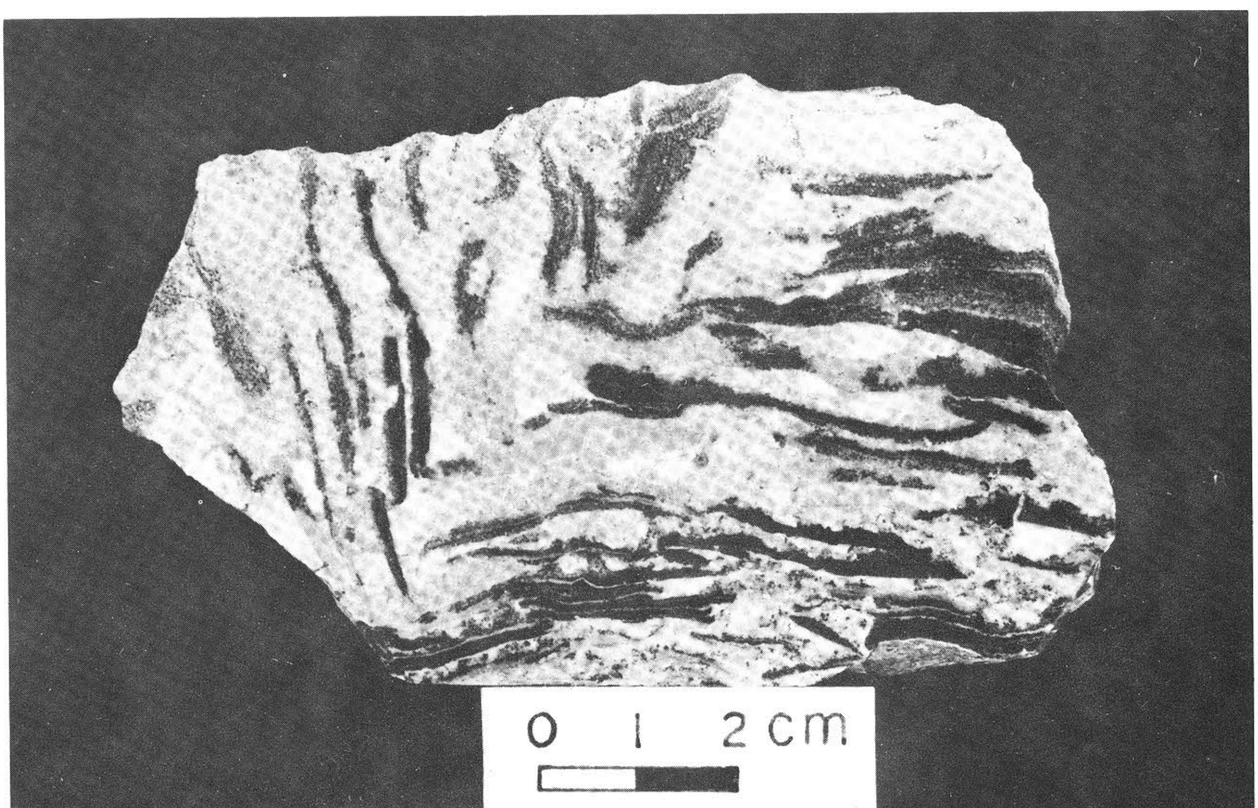

Figure 41. Photograph of polished slab of edgewise breccia in lighter dolostone; clasts are enriched in quartz and calcite (J13).

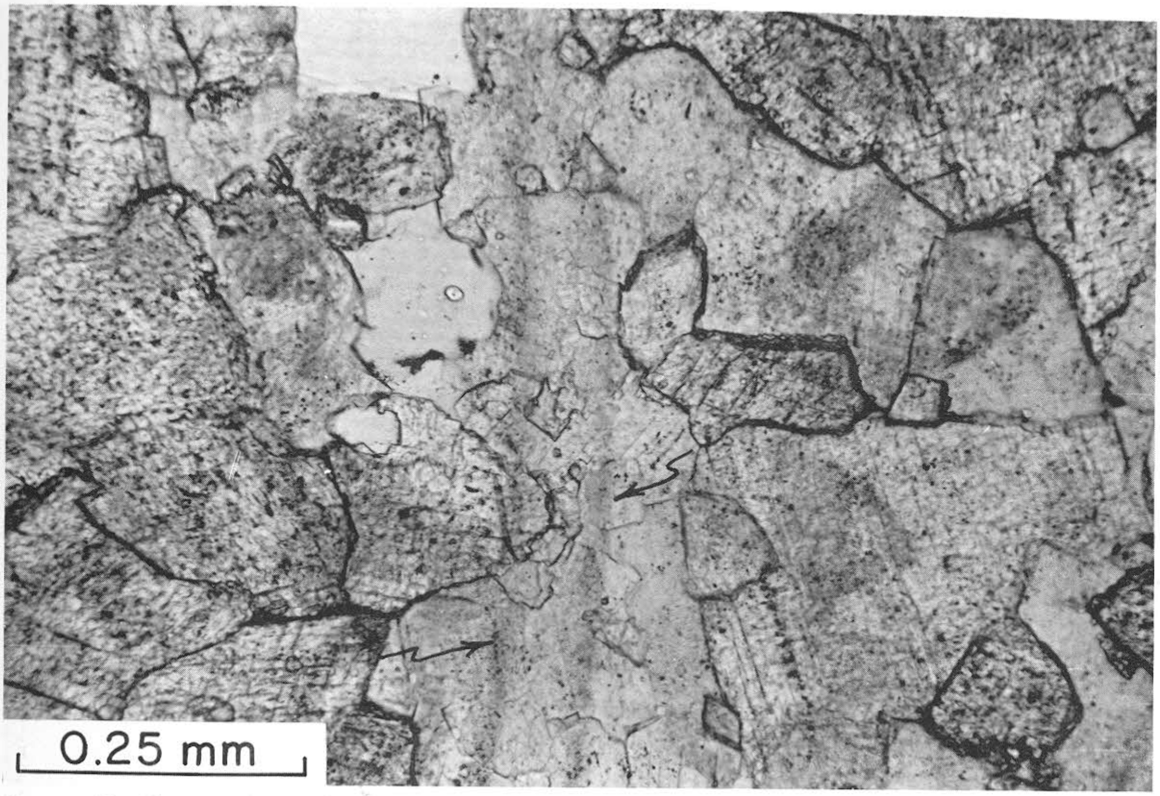

Figure 42. Photomicrograph of relict shell (brachiopod?) in centimicron-sized dolostone; arrows indicate vague margins of shell which is located in center, paralleling shorter margin of photo; plane polarized light (D17).

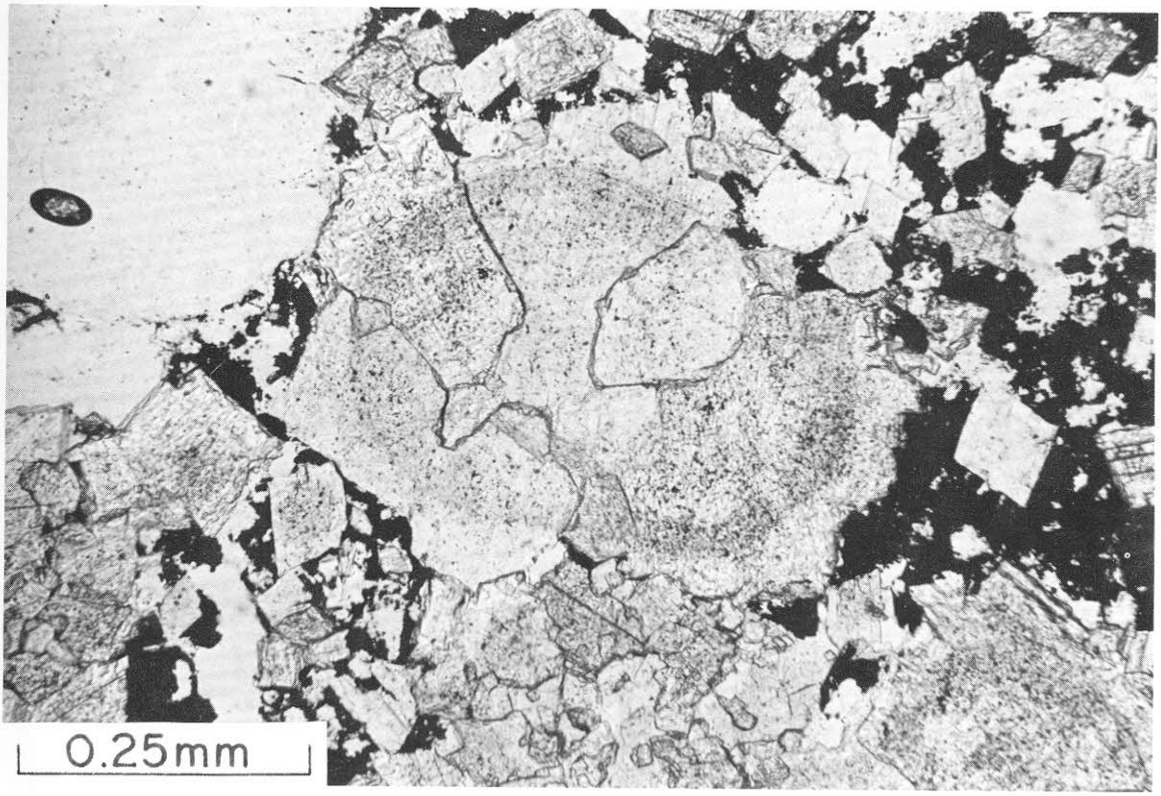

Figure 43. Photomicrograph of nearly obliterated, relict peloid or ooid (center of photograph) in porous dolostone; note dolomite crystals transecting grain; large white grain in upper left corner is quartz; black material is anthraxolite; plane polarized light (H67).

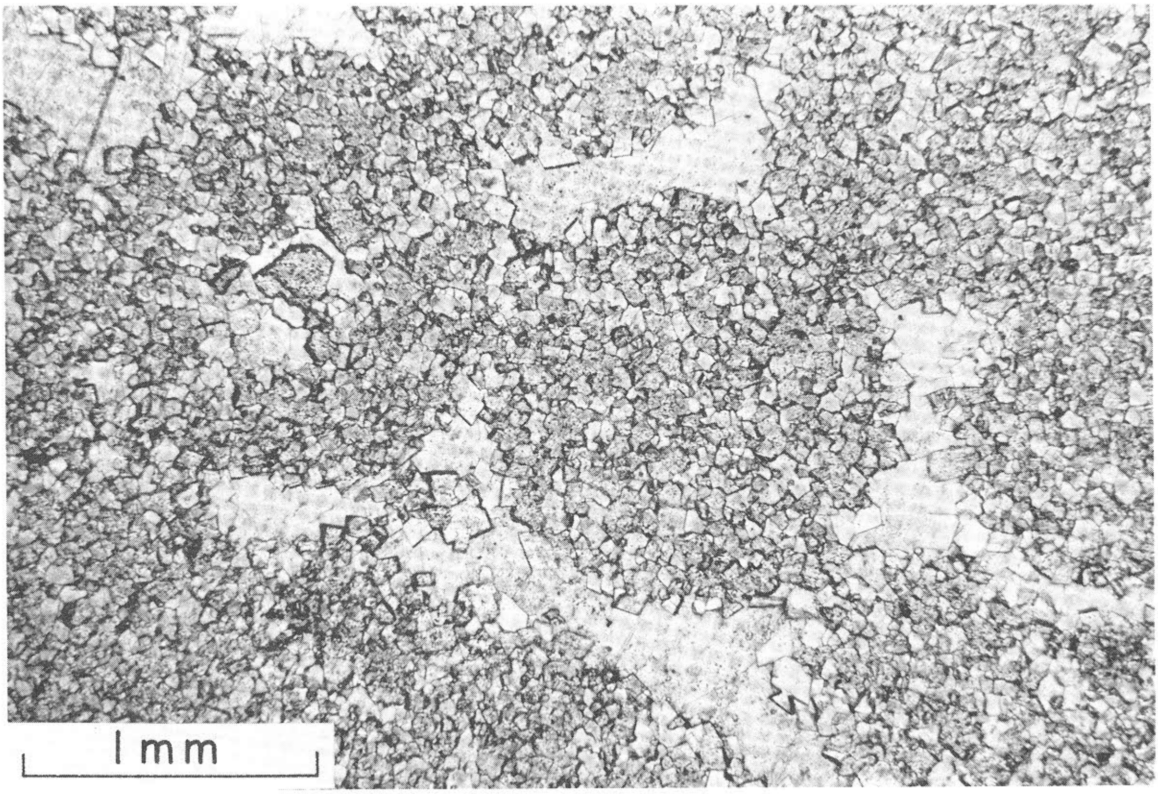

Figure 44. Photomicrograph of poorly preserved, dolomitized, grain-supported oolite; light-colored, void-filling calcite between ooids; plane polarized light (J6).

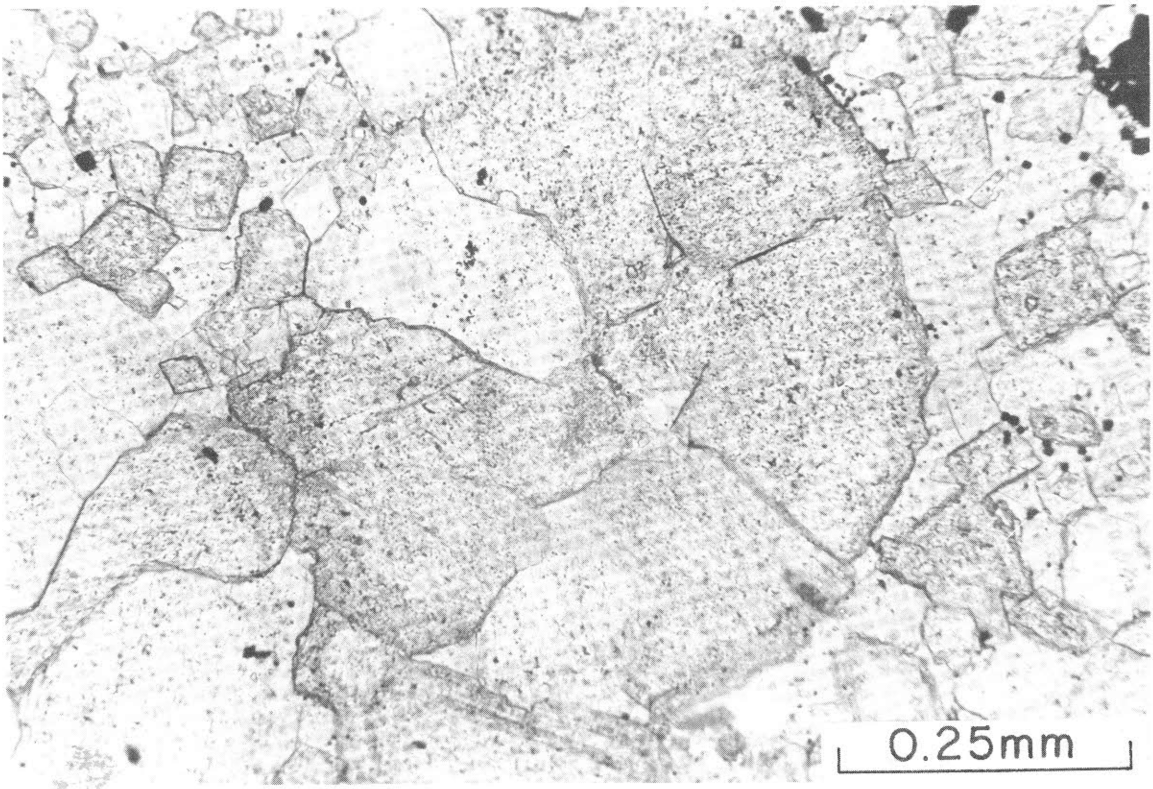

Figure 45. Photomicrograph of relict ooid preserved in dolomite (center of photo); in part defined by boundaries of large crystals but upper left and top of ooid defined by organic(?) stain; plane polarized light (I6).

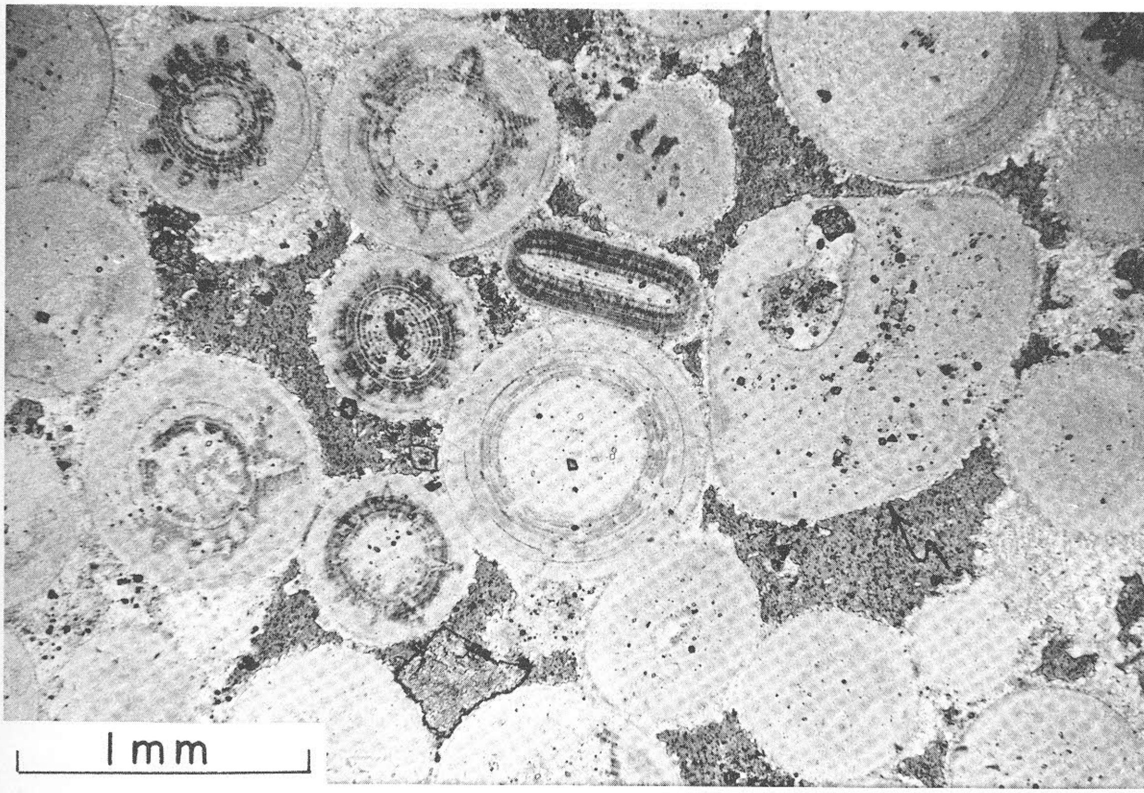

Figure 46. Photomicrograph of field of chertified ooids, with concentric and radial structure preserved; grapestone grain composed of compound ooids indicated by arrow; grain supported fabric; darker, interstitial material is void-filling calcite stained with Alizarin Red S; plane polarized light (5L).

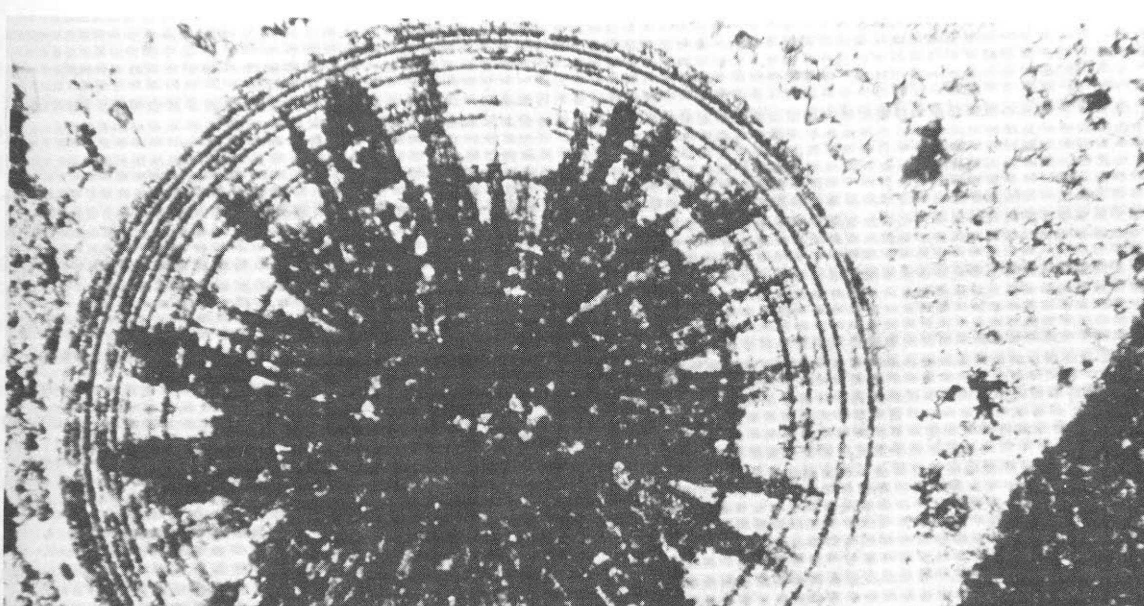

Figure 47. Chertified ooid exhibiting concentric laminae and radial structures which are dark, probably representing organic matter; plane polarized light (H69).

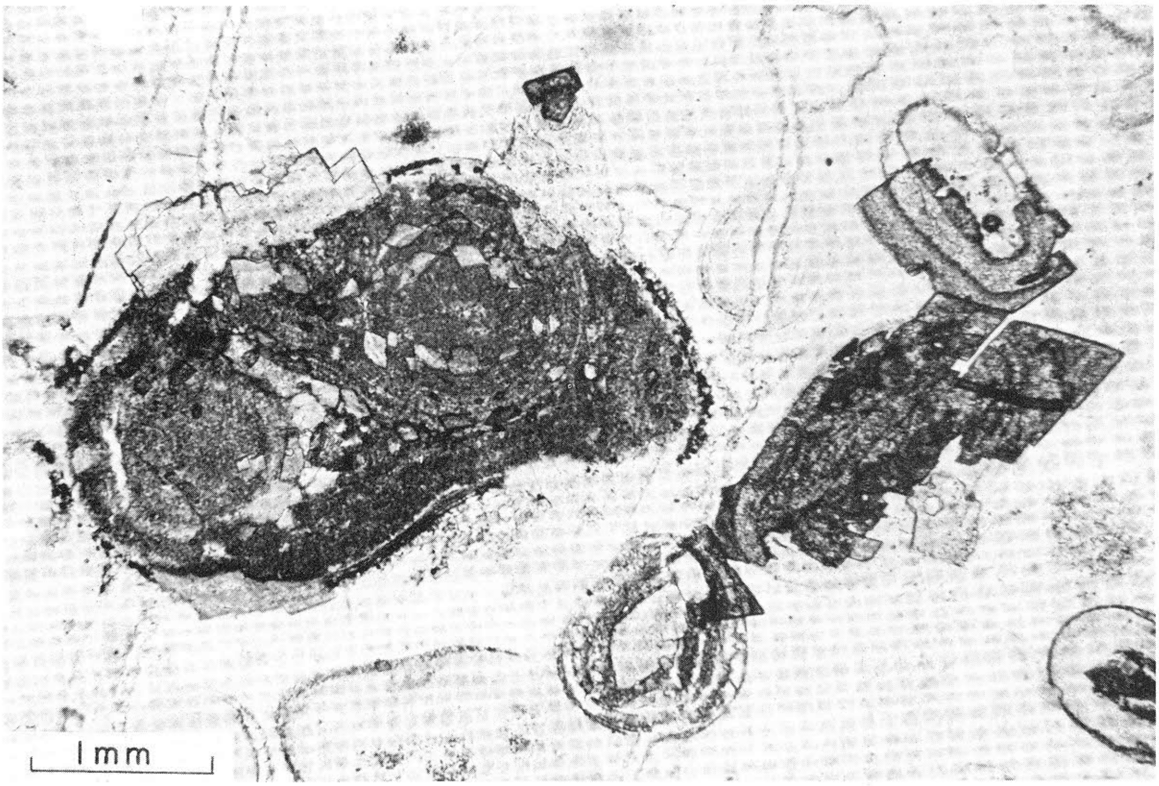

Figure 48. Photomicrograph of field of chert (light) containing silicified, dark (organic rich?) ooids and a compound ooid (left center) in turn replaced by light, dolomite rhombs in which the relict concentric laminae can be seen; note dolomite crystals along upper margin transecting megaquartz-filled fracture, upper left part of photograph; plane polarized light (J2).

ooid *may* have a recognizable detrital nucleus. Kahle (1974, p. 30) claimed that ooids may or may not have a detrital nucleus but elsewhere (p. 31) indicated that "ooids" with radial structure but devoid of a nucleus are technically considered "spherulites." Friedman and others (1973, p. 551) also described "spherulites" as carbonate particles in a hypersaline pool adjacent to the Red Sea but considered them essentially identical to ooids in origin. Most Little Falls ooids, whether with an observable nucleus or not, whether with radial structure or not, do possess well-defined concentric laminae where suitably preserved (i.e., in chert) and no doubt formed as true ooids (their sphericity and evenness of laminae indicate they are not oncolites) and they will be considered as such.

Ooids generally range in size from 300 μm to 1400 μm but the greatest number by far are in the coarse sand range. Compound ooids (Fig. 48), surrounded by later oolitic coats, have been observed in some of the oolitic zones, and such grains constitute a kind of grapestone. There is no discernible stratigraphic significance to the occurrence of oolitic beds but chertified ooids are most common in Unit D.

Rounded and irregular to oval to more circular areas of dolospar surrounded by micron- and fine decimicron-sized dolomite are enigmatic (Fig. 49). They range in size from less than 100 μm to more than 1 mm but most are in the fine and medium sand range. Generally they are separate and only occasionally in contact. In some instances the internal sparry areas appear to be void fillings but normally a drusy texture is not observed; the crystals are very similar in size and shape to those outside these "micrite-rimmed grains." In fact, where the rims are weakly developed, dolomite crystals can be seen transecting them. It is conceivable that the very finely crystalline rims are similar to "micrite envelopes" around original skeletal fragments, as described by Bathurst (1966) or to "lime-mud envelopes" illustrated by Sanders and Friedman (1967, p. 181). However, there is no direct evidence for the abundance of skeletal fragments. Also, the drusy carbonate filling the interiors of the micrite envelopes is lacking. Rarely, detrital quartz grains are within the interior, floating in the spar. The occurrence of irregular "micrite-rimmed grains" in association with algal stromatolites suggests the possibility that these bodies might represent organic, perhaps algal structures. They do bear some similarity to the catagraph-bearing stromatolitic microstructure described by Bertrand-Sarfati (1976, p. 256–258). I think the most likely explanation for these bodies, however, seems to be neomorphism prior to dolomitization. Aggradational neomorphism of the interiors of peloids, intraclasts, or ooids, for example, could produce these textures and they might have been retained during and after dolomitization although some have been

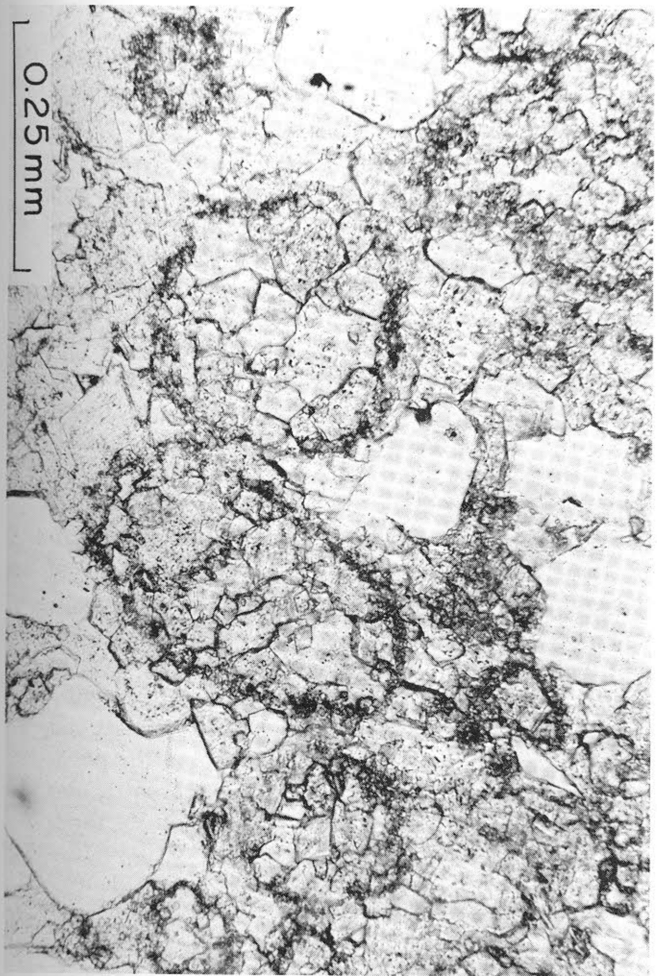

Figure 49. Photograph of "micrite-rimmed grains" in quartzose dolostone; note dolomite crystals transecting micrite rims on left side of grain immediately left of center; rounded, white grains are detrital quartz; plane-polarized light (H28).

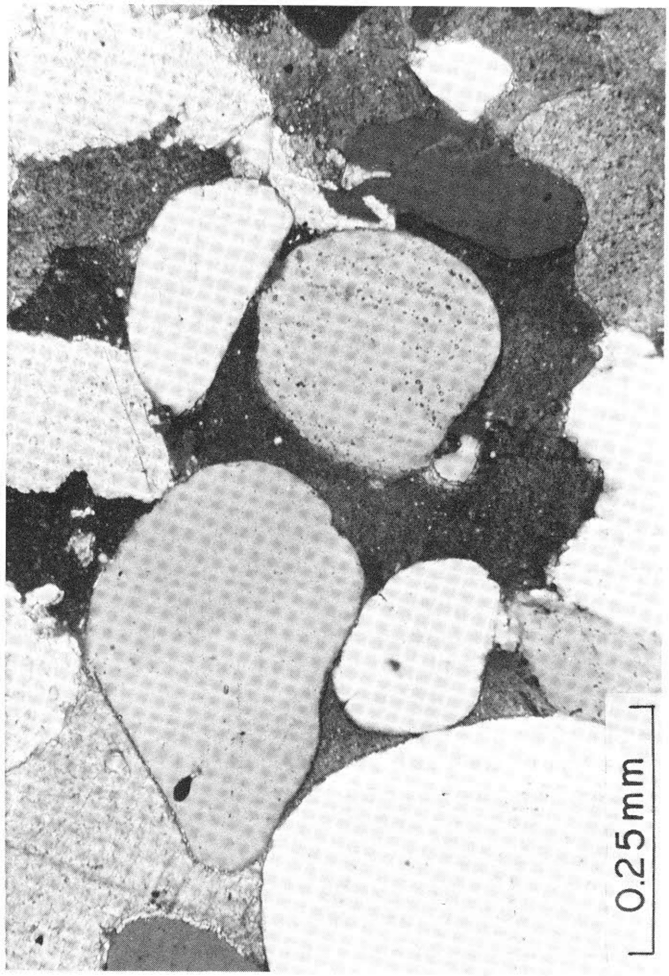

Figure 50. Rounded, sand-size quartz grains (white or light gray) in dolomite groundmass; crossed polarized light (17L).

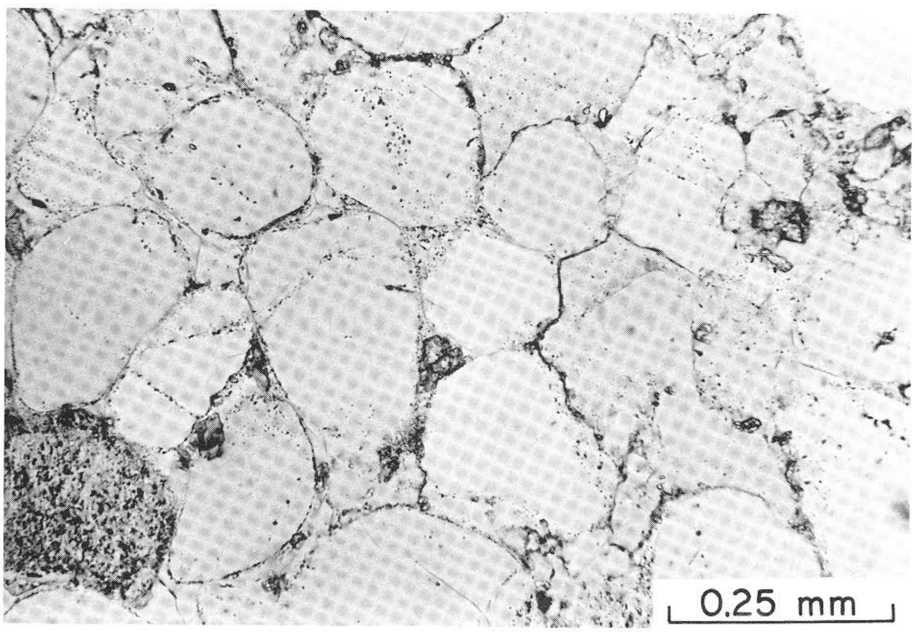

Figure 51. Photomicrograph of orthoquartzite showing grain support; many rounded grains have narrow secondary quartz overgrowths; dark grain, lower left is perthite; plane polarized light (A50).

more altered in cases where the rim is transected by dolomite crystals.

Illing (1954, p. 30) applied the name "grapestone" to irregularly shaped compound grains composed, in turn, of carbonate sand grains, there being no restriction on the type of particle. The constituent grains, as he observed them in the Bahamas, are cemented by aragonite. Grapestone relics, now completely dolomitized in the Little Falls, are relatively uncommon and the internal structure is generally lost. In chertified oolitic pockets are compound ooids, which, as just mentioned, qualify as grapestone (Fig. 48); most are covered by later developed oolitic coats.

Quartz and Chert. The major occurrence of quartz, which is the second most abundant mineral in the Little Falls, is as detrital grains (Fig. 50) ranging from clay-size, as observed under the scanning electron microscope, up to boulder size in some of the conglomerates near the base. As shown by the X-ray and insoluble residue data, there is a range from low-insoluble dolostone through quartzose dolostone and dolomitic sandstone to orthoquartzite (Fig. 51). The main mode of quartz grain size in sandstones and orthoquartzites is in the medium sand range but invariably there is significant representation of fine and coarse sand; many sandstones are classed as fine grained and fewer as coarse grained. The great bulk of quartz grains is clustered over a range of a few hundred μm centered on the fine to medium sand interval and sorting is generally good to excellent. Dolomitic sandstone occurs as laminations in less quartzose dolostone. Granules, pebbles, cobbles, and boulders are found only in samples near the Precambrian contact. The silt-sized to very fine-grained quartz is most common in low-insoluble dolostone samples, including algal stromatolites; however, no samples were observed that could be called siltstone.

In some decimicron-sized dolostone there appears to be a rough correlation between the sizes of quartz grains and dolomite crystals. But, in some fine to medium decimicron-sized dolostones near Newport (loc. 4; Fig. 31) and at Little Falls (loc. 21), the associated quartz is medium-grained. Also, there are numerous examples of centimicron-sized dolostone that have their included quartz in the silt- to very fine sand-sized range. In sandstones and orthoquartzites, quartz most commonly is medium grained whereas the associated dolomite is generally fine centimicron-sized.

As expected, roundness of sand- and silt-sized quartz grains seems to correspond to their size. The fine, medium, and coarse sand grains are mostly well to very well rounded (Figs. 50, 51), Very fine sand- and silt-sized quartz, whether present in abundance or as grains floating in dolomite, is generally subangular, not atypical of smaller grains which undergo less attrition during transport and which probably are derived from the sand-sized grains.

Quartz grains in sandstones and quartzites are generally in contact (Fig. 50), whereas in slightly quartzose dolostones they are floating (Figs. 30, 35), except where relict peloids are sufficiently common to make an overall grain-supported texture.

According to Blatt, Middleton, and Murray (1972), the great bulk of quartz grains in sandstones have width to length ratios of 0.61 to 0.71. Quartz grains in the Little Falls would generally fit in here but with an average value more toward the upper end owing to a substantial representation of more equidimensional grains. There is a detectable tendency for the more elongate quartz grains to lie with their long axes parallel with the stratification.

Folk (1968b) presented a descriptive classification of quartz grains based on the nature of extinction in both single and polycrystalline grains. His subdivision of single grain types into subdivisions based on the number of degrees of rotation of the flat stage for the sweep of the extinction shadow is somewhat open to question in view of the classic paper on the significance of undulatory extinction in quartz by Blatt and Christie (1963); these workers demonstrated the possible discrepancy between the extinction angles measured on a flat stage vs. a universal stage. Considering this, I have divided quartz grains in the Little Falls into four types:

(1) Single quartz grains with straight extinction (grain extinguishes uniformly).
(2) Single grains with undulatory extinction (some grains being much more strained than others).
(3) Composite grains composed of two or more individuals with vague to distinct noncrenulate contacts; the roughly equidimensional individuals show different, although relatively close, optical orientation and the extinction is normally undulose.
(4) Polycrystalline grains consisting of two or more individuals with markedly different optical orientation and usually undulose extinction; the contacts between the individuals are very crenulate (Fig. 52).

In the sand-sized range, the greater proportion of quartz grains are single grains showing undulatory extinction. As is characteristic of mature sands (Blatt and Christie, 1963, p. 560), there is a relatively large (more than 35 percent) proportion of single grains with straight extinction; in some specimens these are more common than single grains with undulatory extinction and overall average at least 35 percent of the total number of grains. Composite grains are present in every thin section but are minor. Even in orthoquartzites only a few polycrystalline grains were noted; Blatt and Christie (1963, p. 570–571) concluded that polycrystalline quartz grains, being thermodynamically unstable, wear out more rapidly during transport which results in their low proportion in mature sandstones and orthoquartzites. However, they are the major constituent in thin sections of conglomeratic beds near the base of the Little Falls where they were observed up to 25 mm in greatest dimension; where present in finer grained sandstones, they usually are among the largest grains present.

Detrital quartz includes some relatively large inclusions, such as zircon, rutile (see Fig. 53), and tourmaline (?). Ten percent or less of the quartz grains contain very small, acicular crystals of rutile; these needlelike crystals are about 1 μm in width and generally 10–20 μm in length. They may be randomly oriented but in numerous cases display a striking orientation, there being consistent angles between the two or three sets of parallel crystals observed.

Vacuoles are very common in most quartz grains and some of these contain a liquid filling which in turn may contain a gas bubble. The vacuoles may occur in bands or may be distributed randomly. Very small inclusions, or microinclusions, are not nearly as common as vacuoles and they are unidentifiable using the conventional light microscope.

Authigenic quartz, in its various forms, is a locally significant component. The most common occurrence is as secondary overgrowths on detrital quartz grains (Figs. 53, 54). Usually, the boundary between the detrital core and the overgrowth is marked by a thin zone of vacuoles and/or microinclusions; however, a boundary may not be discernible and the overgrowth may be identified by its euhedralness or its interlocking with adjacent overgrowths. Quartz overgrowths are well developed in most dolomitic sandstones and orthoquartzites, and also in quartzose dolostones where they occur sporadically on floating quartz grains. Generally the overgrowths are relatively small but occasionally contribute a significant amount to the total quartz in a detrital core and overgrowth pair. Although strain shadows are continuous from the detrital core out into the overgrowths, the latter are generally clearer than the enclosed detrital grain owing to considerably fewer microinclusions and vacuoles. Normally, adjacent overgrowths join along smooth and commonly planar intercrystalline boundaries; in some orthoquartzites, however, the contacts are crenulated

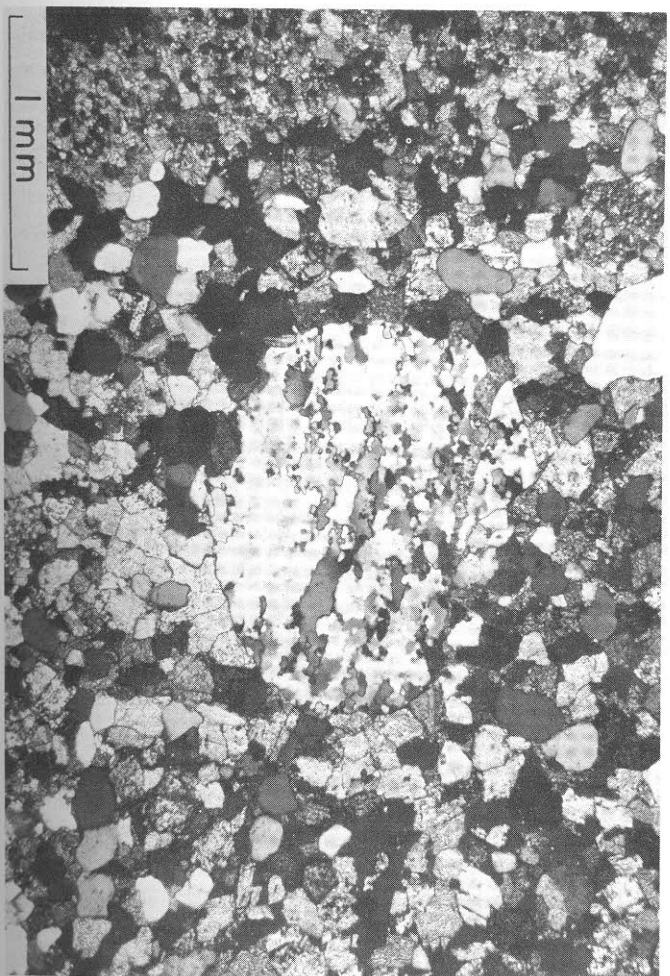

Figure 52. Photomicrograph of polycrystalline quartz grain (center) containing several elements with crenulate contacts (see text), in quartzose dolostone; crossed polarized light (A44).

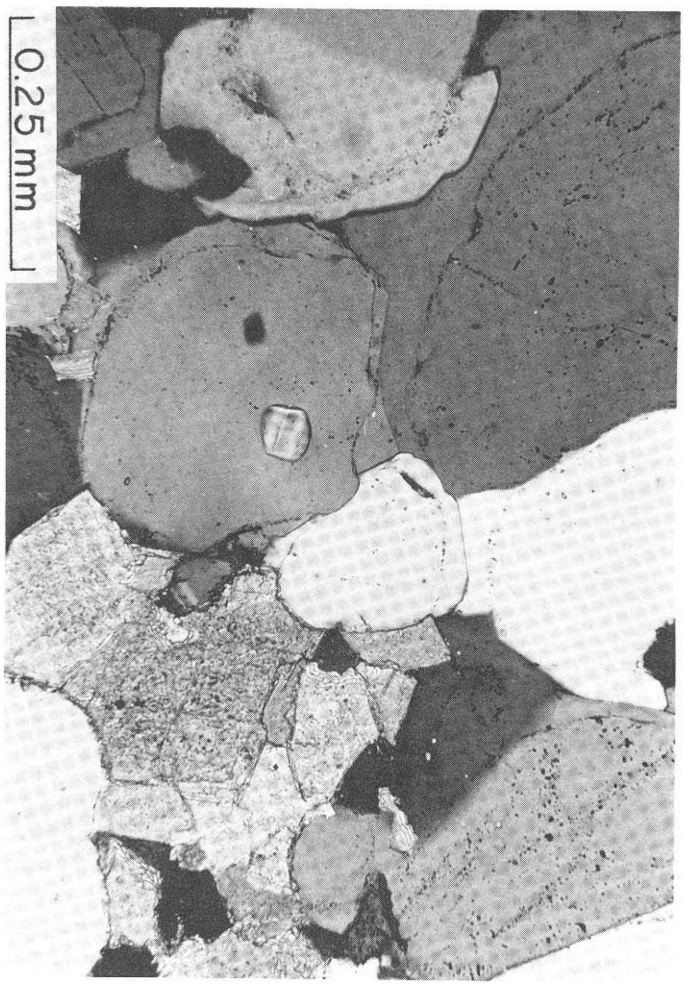

Figure 53. Photomicrograph of dolomitic sandstone showing well-developed quartz overgrowths, particularly in upper portion of figure; cluster of dolomite crystals in lower right quarter, very light quartz grain in top center has some rutile.

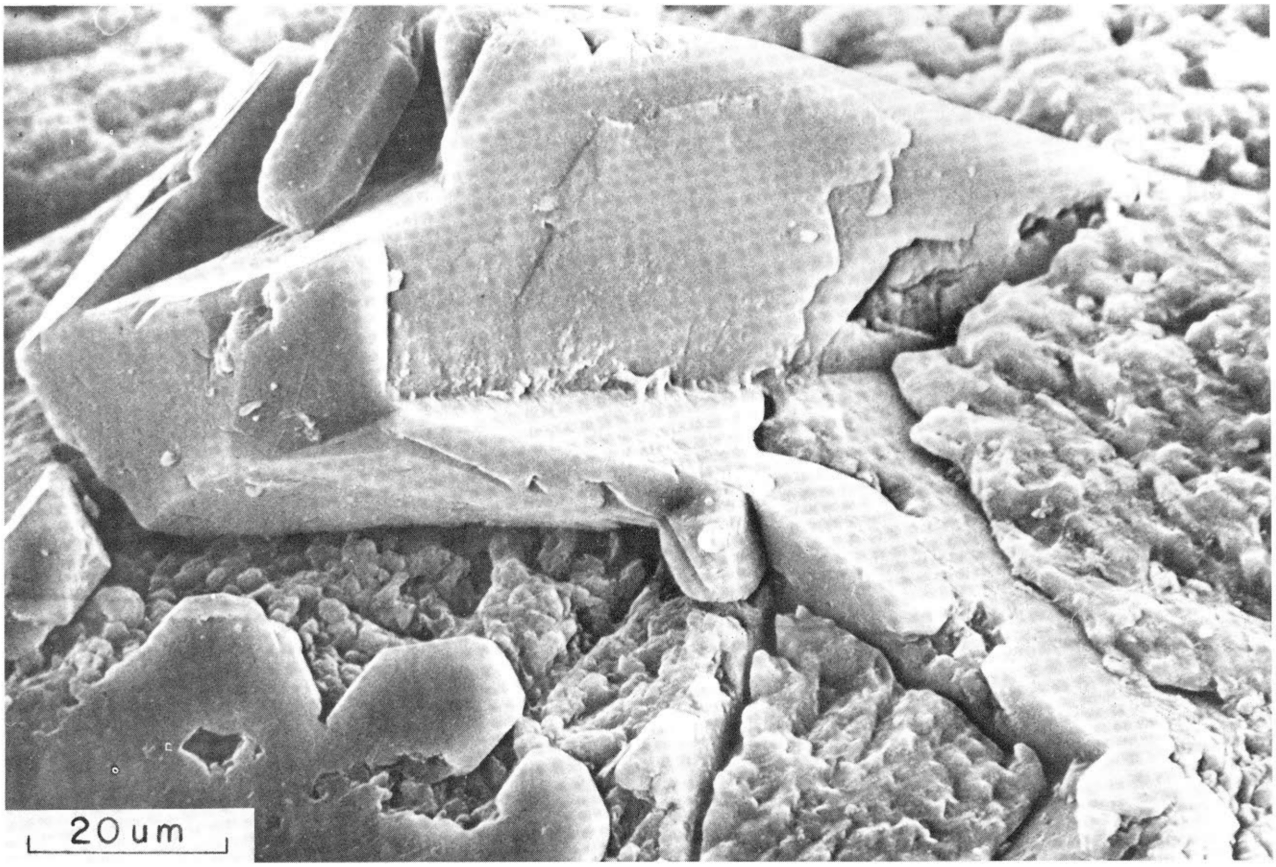

Figure 54. Scanning electron photomicrograph of detrital quartz grain with development of euhedral overgrowths; roughened surface of detrital grain is diagenetic and "fractures" seen in lower right mark outlines of positions of dolomite crystals (14L).

and probably reflect pressure solution. Overgrowths may have very irregular margins against chert, undoubtedly resulting from corrosion by the latter.

No evidence was observed for detrital grains and their previously formed overgrowths having been transported into the Little Falls basin of deposition—probably all overgrowths, even if bounded by irregular edges, developed in place. The boundary between the core and overgrowth is undoubtedly a zone of thermodynamic instability and the rigors of transportation tend to remove the overgrowth, although according to W. B. Rogers (1980, written communication), reworked overgrowths are fairly common in the geologic record.

As described in the section on "Stratigraphy," chert occurs in massive beds and, on a smaller scale, as partially silicified algal stromatolites, as thin and usually irregular seams and laminae, as elongate, sharply bounded pods (measured in centimeters) commonly containing silicified (chertified) ooids (Fig. 46), even more locally as interstitial material, and as extremely uncommon detrital grains. (Interestingly, a very well-rounded sand-sized chert grain was observed in specimen 8S (loc. 26) a short distance above the Precambrian contact.) In thin section, chert is typically microcrystalline, consisting of an aggregate of tiny equidimensional quartz crystals a few μm in greatest dimension, giving the mass a pinpoint birefringence (Folk, 1968b, p. 80).

The most common chert occurrence in thin section is as the groundmass of laminations containing corroded quartz grains in varying abundance, and occasionally dolomite. The most interesting chertification, however, is that of ooids. Such occurrences are relatively common in Unit D, to a lesser extent in Unit C, and very infrequently below in Unit B. These chertified ooids are of the same size as the dolomitic ooids but the internal structure is much better preserved in the chert (Figs. 44–47). Concentric laminae can be best observed under plane polarized light, where they consist of alternations of clear and vacuole-rich quartz ranging from 2 or 3 μm to tens of μm in thickness. A high percentage of ooids display radial, petaloid to parallel-sided to irregular dark areas usually tens of μm wide (Figs. 46, 47). These extend from the center of the ooid toward, but not usually reaching, the perimeter and generally have a much greater concentration of vacuoles than the alternate zones; the situation may be reversed, however, and the radial areas may consist of vacuole-free, clear quartz. Under crossed polarizers, the microquartz in some ooids is seen to be slightly elongate radially. It is possible that this radial elongation may represent radial orientation of calcite or aragonite in the original carbonate ooid. The radial orientation of calcite crystals in some Holocene and ancient marine ooids has been described by Bathurst (1971, p. 77) and Eardley (1938), although Halley (1974, p. 187) described secondary, radially oriented *aragonite* crystals in Salt Lake ooids. Kahle (1974), also studying Salt Lake ooids with radially oriented, acicular aragonite crystals, concluded that the radial arrangement was depositional and not diagenetic. Supported by the report by Friedman and others (1973, p. 550–551) of ooids with "primary" radial rims associated with algal stromatolites in hypersaline pools adjacent to the Red Sea, Kahle generalized in proposing that the radial grain orientation in the rim of many ooids in limestones and dolostones of the geologic record is of depositional origin. The radial rays in the silicified ooids in the Little Falls (Figs. 46, 47) resemble somewhat those illustrated by Kahle (1974, p. 34) and could represent radial structure in the original carbonate ooid; certainly they formed early as they can be seen in the collapsed oolitic material in the half-moon ooids (see discussion below of "deformed ooids"). On the other hand, the irregular length of the rays and their apparent superposition on a basic concentrically laminated structure suggests they probably are secondary in this case.

Generally, detrital nuclei are not recognizable in the silicified ooids but occasionally a quartz grain can be seen in the center of a body. Small euhedra of dolomite occur in many of the silicified ooids. Large calcite crystals occupy the voids in the upper parts of deformed and collapsed ooids in an interesting specimen from Unit D at loc. 17 in Little Falls (Fig. 55). Generally Little Falls ooids, whether dolomitized or chertified, show no evidence of deformation and are commonly circular (or near circular) in section, do not interpenetrate, lack microstylolitic contacts, and do not have spalled off outer laminae. However, at one horizon at the type locality (loc. 17, subunit 63, specimen H69) the great proportion of the chertified ooids show either one or both of two kinds of deformation. 1) Darker relict laminae, now deformed and silicified, located in the lower part of a circularly or elliptically outlined body with lighter, secondary coarser quartz or ferroan calcite occupying the upper part, the combination producing a geopetal structure (Fig. 55). The contact between the two components is normally convex-up and there is considerable similarity to the "half-moon oolites" of Carozzi (1963). 2) Apophyses, usually associated with ooids no longer possessing a circular outline, extending outward to adjacent ooids, in places forming chains of up to four connected bodies, as observed in the plane of the thin section (Fig. 55); these are apparently similar to some of the deformed ooids described and illustrated by Sarkar (1973) and Radwanski and Birkenmajer (1977), and to ooids and pisolites reported by Kettenbrink and Manger (1971) and Conley (1977).

A considerable body of literature on the subject of deformed ooids has developed in addition to those works cited above, including Carozzi (1961), Chandra and others (1977), Choquette (1955), Coogan (1970), Mazzullo (1977), and Wherry (1915). Owing to their rare occurrence in the Little Falls I will state my conclusions as to their origin here but the details and reasoning as well as a discussion of past work will be presented elsewhere. I believe that the geopetal structures in the "half-moon oolites" resulted from collapse of the laminae following solution of part of the

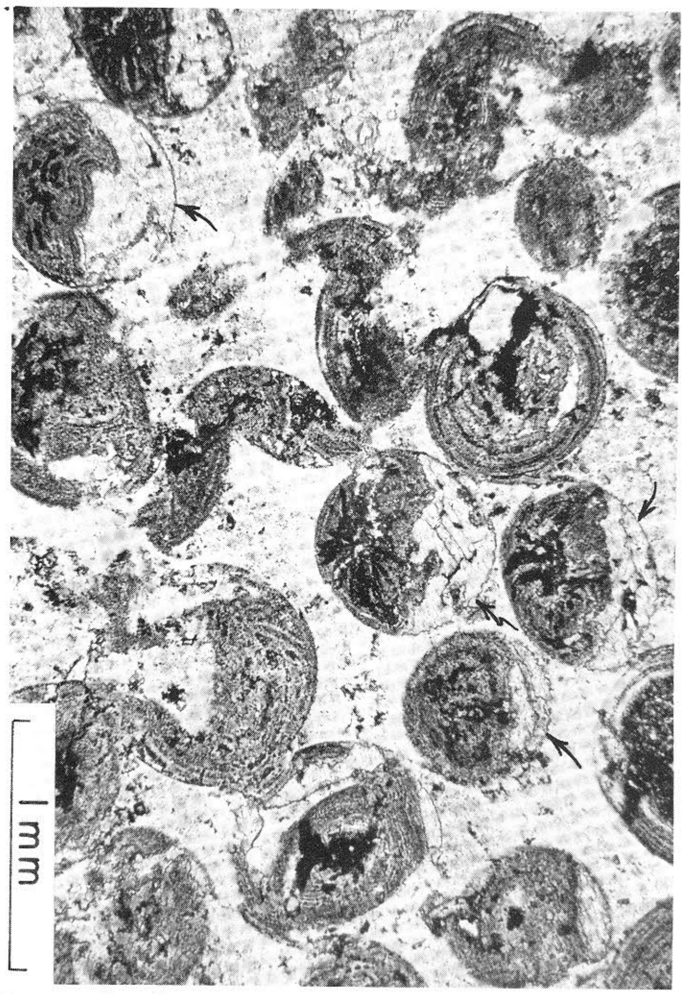

Figure 55. Photomicrograph of silicified ooids, darker owing to organic(?) content, in groundmass of light chert; "half-moon ooids," indicated by arrows, have calcite filling upper void; note apophyses in center and left of photo; plane polarized light (H69).

carbonate precursor at a very early stage prior to or during chertification. The origin of the apophyses and linked ooids is more difficult to determine; I favor a plastic deformation resulting from compaction although the possibility of fragmentation and collapse of rigid ooids (Conley, 1977) or of pressure solution effects (R. B. Halley, 1977, written communication) cannot be discounted.

In several thin sections, rhomb-shaped areas of chert occur in the center of dolomite crystals (Figs. 30, 56), especially near larger areas of chert. These apparently have resulted from a replacement of dolomite by chert. Figure 57 is an electron probe photomicrograph showing the elemental distribution in such a fabric.

Another type of microquartz, chalcedony, was observed rarely, in less than 5 percent of the thin sections studied, and not commonly in these. It occurs typically in mm-sized pockets and consists of cauliflowerlike masses radiating bundles of fibrous quartz. These masses have faint, brownish, concentric "growth bands" which are narrow zones with a higher than normal amount of vacuoles and staining. They may occur in association with silicified ooids but usually are separate. As viewed under a gypsum plate, they are seen to consist of either length-slow chalcedony (which is

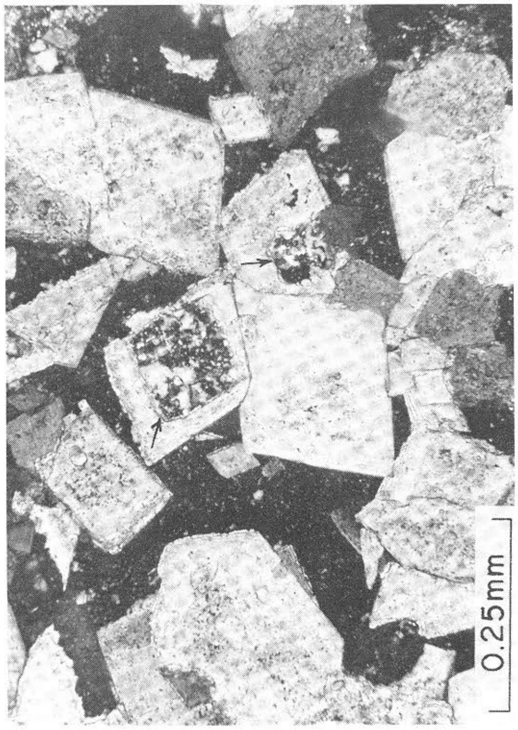

Figure 56. Photomicrograph of rhombic chert centers (mottled, see arrows) in dolomite crystals; crossed polarized light (A23).

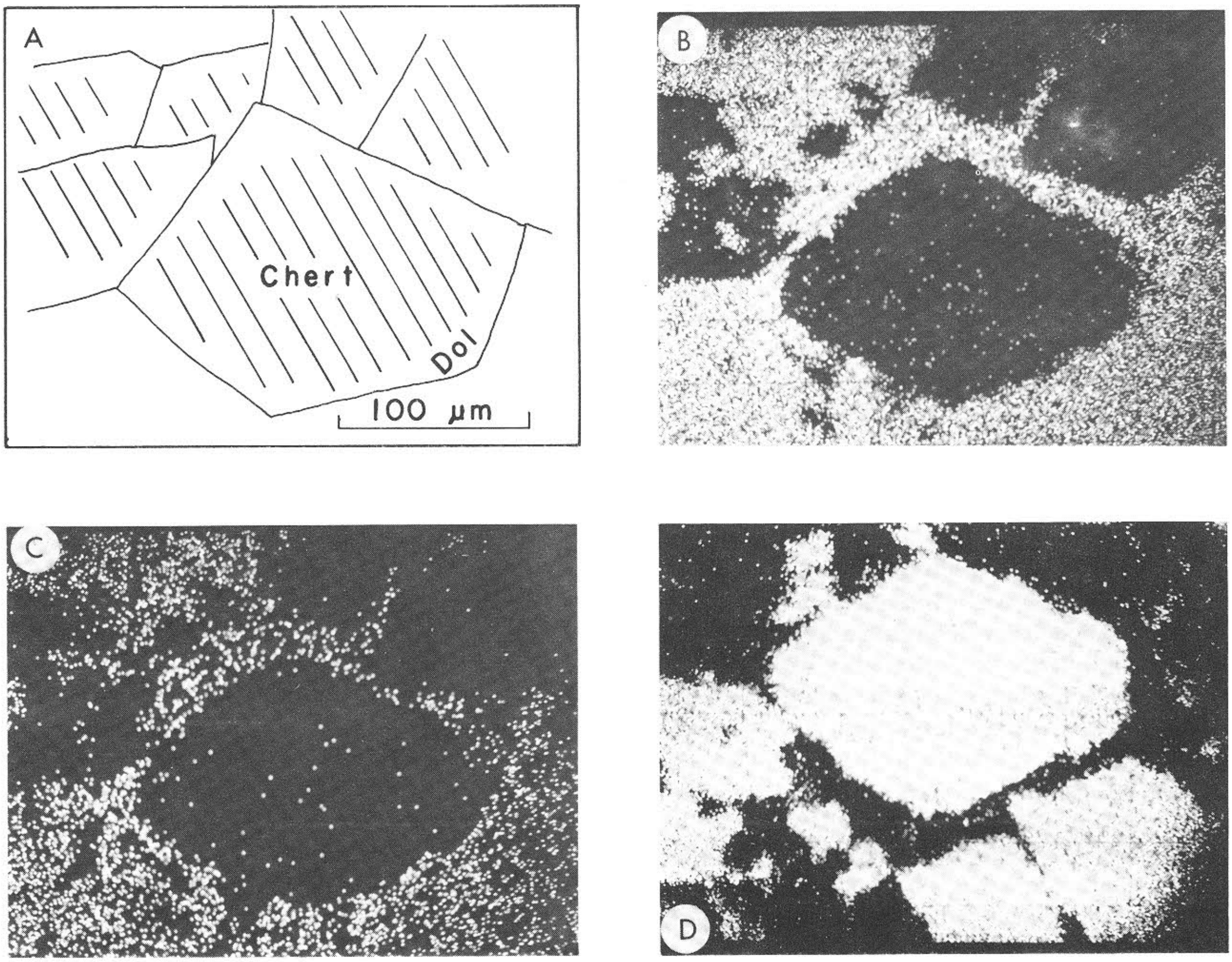

Figure 57. Electron probe photomicrographs of rhombic chert centers of dolomite crystals; A, sketch of area of analysis; B, C, and D, X-ray beam scan images for CaKα, MgKα, and SiKα, respectively.

most common) or as the length-fast variety (see more discussion under "Dolomitization").

Microcline and Perthite. X-ray diffraction analyses suggest that the only feldspar present is microcline, based on the strong and characteristic reflection from {220} at about $2\theta = 27.4°$ (Figs. 28, 29). Thin section petrography shows that "feldspar" constitutes the second most common detrital mineral in the formation, after quartz. It contributes generally less than 5 to 10 percent of the terrigenous fraction but approaches 50 percent in *a few* low-insoluble dolostones. Of this total, only a small proportion consists of discrete grains of microcline, as distinguished by its cross-hatched twinning (Fig. 58). Most of the feldspar grains, on the other hand, consist of the normal very light gray birefringence which includes irregular to discontinuous thin darker bands (from 2 μm up to 15 μm in width) or aligned blebs which occasionally contain some crystalline material (Fig. 59). Electron probe microanalysis shows that the bands as well as the main parts of the crystals consist of aluminum and potassium silicate. The bands resemble those in "string perthite" and "rod perthite" (Moorhouse, 1959, p. 49). There is no indication of albite in the X-ray diffraction analyses of insoluble residues nor has sodium been detected using the electron microprobe. I suggest that the majority of these banded feldspars are altered (weathered?) microperthite.

The microcline and microperthite grains occur in the same size range as quartz in the dolomitic sandstones and orthoquartzites, averaging a few tens of micrometers more. These grains are not as well rounded as quartz primarily because of the cleavage faces and overgrowths bounding many of the grains. These overgrowths are relatively common and are distinguished by a lack of perthitic bands, by clearer or "dirtier" feldspar, or by a combination of these. On the bases of chemical analyses, Buyce and Friedman (1975) claimed that Cambrian and Lower Ordovician rocks of New York State contain considerably more authigenic potassium feldspar than younger Paleozoic carbonates in the State. They (p. 813) sampled the Little Falls at only

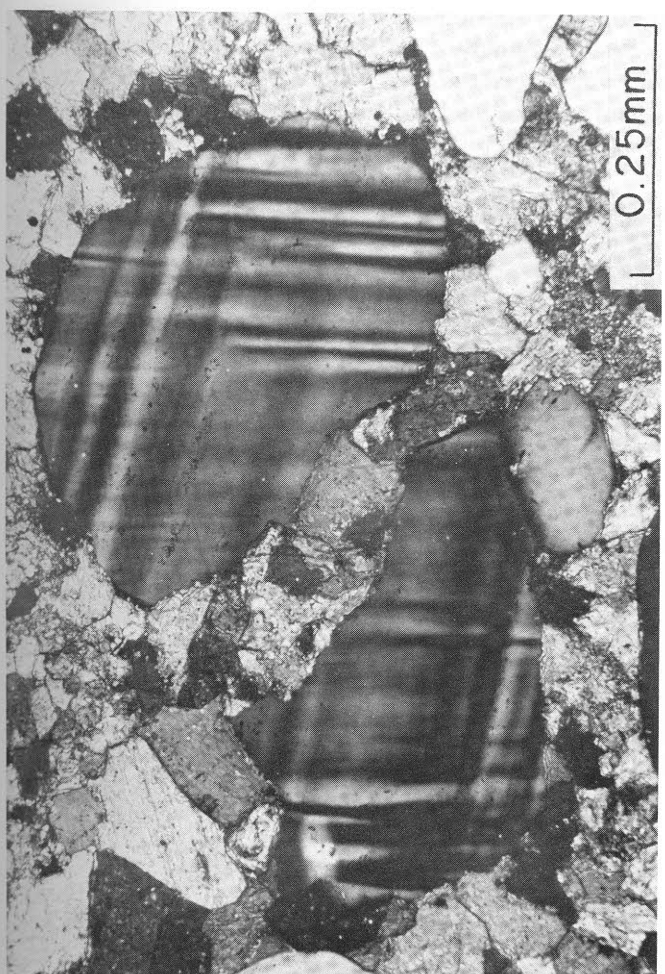

Figure 58. Photomicrograph of fractured microcline grain (plaid pattern) in groundmass of slightly quartzose (white or light-gray grains) dolostone; possibility(?) of "cement spreading" of portions of grain by crystal growth; crossed polarized light (A44).

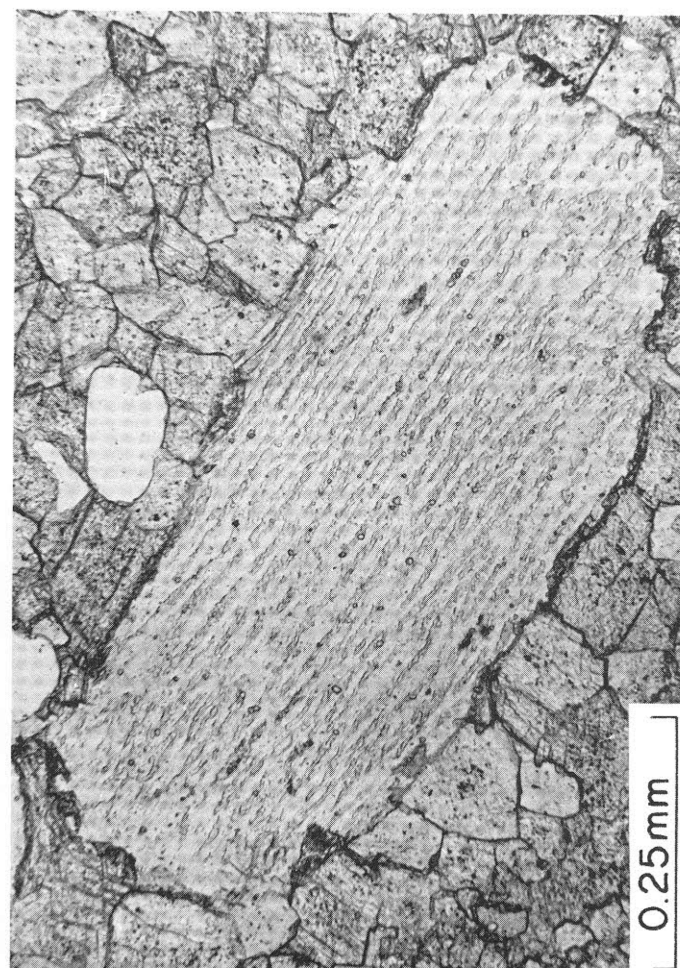

Figure 59. Photomicrograph of large perthite grain in groundmass of dolomite; note "nibbling" by dolomite crystals along margins of grain; plane polarized light (A44).

one locality and felt that it did not seem to fit the pattern as it contained little normative feldspar. I suggest that there may be more potassium feldspar in the Little Falls than their one sample would indicate; certainly there is more than in younger carbonate rocks I have worked on, such as the Middle Silurian Lockport (Zenger, 1965) and Herkimer (Zenger, 1971b) Formations. However, there probably is significantly less than in the overlying Lower Ordovician Tribes Hill Formation (see section on "X-ray Diffraction Analysis").

Present in many thin sections is a dark brown to opaque, "crusty" material observed associated in places with the perthite grains. Its patchy distribution and its chemical composition (potassium aluminum silicate as determined by electron probe microanalysis), suggests that it is some form of alteration product of the feldspars. In other places, this dark material is associated with pockets of what appears to be finely crystalline, pore-filling feldspar locally resembling chert. Such feldspar is similar to the authigenic, chert-like K-feldspar recently described for apparently the first time by Sibley (1978).

Calcite. Minor amounts of calcite are found in some 40 percent of the Little Falls thin sections examined. As discussed below under "Paragenesis," there is no pre-dolomite calcite and no calcitic grains were observed. Normally the calcite content consists of a few void-filling crystals. With the exception of certain sandstones and quartzites in which the total carbonate is very low, calcite never rivals dolomite as the dominant carbonate mineral. Very few samples of dolostones have more than 10 percent calcite. Obvious secondary calcite occurs in vugs and fractures, some of the latter being microfractures seen only in thin section.

The most common occurrence is as huge millimeter- to even centimeter-sized void-filling crystals (Fig. 60), which produces the luster mottling seen in some hand specimens. This coarse calcite is commonly poikilotopic with "inclusions" of dolomite rhombs. The calcite may appear patchy, owing to the irregularity of the void, and its continuity and size can be determined by the large dark area when a crystal is at extinction. In the form of these large crystals, calcite may also serve as a cement in what were once porous sandstones and ooids (see Fig. 46). In some specimens, the calcite distribution is controlled by stratification.

Less commonly, the calcite appears as small, non-poikilotopic crystals (Fig. 44). In such occurrences, the calcite *may* be slightly ferroan, the iron content being low (less than 2 weight percent) as in the ferroan do-

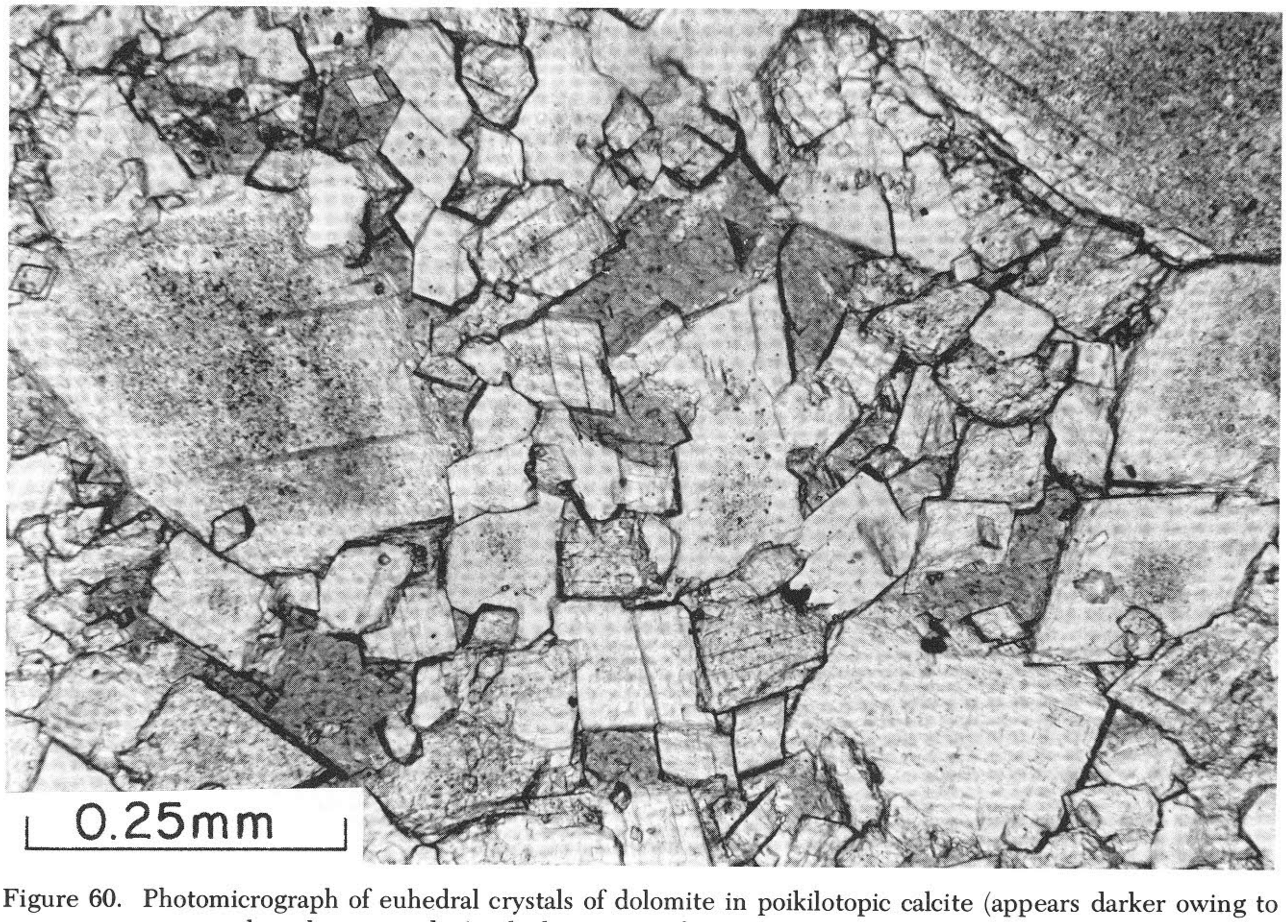

Figure 60. Photomicrograph of euhedral crystals of dolomite in poikilotopic calcite (appears darker owing to staining by Alizarin Red S) which is part of one large mm-sized crystal; note porphyrotopic nature of dolomite crystals, plane polarized light (H61).

lomite. Whole crystals are ferroan and no ferroan rims, similar to those on dolomite crystals, were seen.

Epitaxial borders and rhomb-shaped centers of dolomite crystals are two very interesting, although minor, occurrences of calcite; these fabrics are discussed under "Dedolomitization."

"Glauconite." Field workers (e.g., Dunn and Fisher, 1954, p. 490) have made reference to glauconite in the Little Falls Dolostone. As viewed with a hand lens, this "glauconite" has the appearance of a dense, turquoise-green interstitial material; it is not the darker green of more typical glauconite. Although this material is present in about one-quarter of the thin sections of the Little Falls, it rarely composes over a few percent of a specimen. I believe that this "glauconite" is authigenic. Folk (1968b, p. 101) mentioned glauconite forming rarely as a pore-filling cement; the mineral occurs more commonly as grains, within tests of organisms, as coatings on detrital minerals, and as diagenetic products (Millot, 1970, p. 204). The consensus seems to be that a considerable variety is included under the name glauconite but Bentor and Kastner (1965) suggested that the observed range is partly attributable to insufficient purity of the mineral. As it occurs in the Little Falls the "glauconite" is *very* faint yellow to *very* light green to mainly olive in plane polarized light. Under crossed polarizers (Fig. 61), it is usually microcrystalline with a low, "mottled" birefringence of dark green to light gray to yellow. The mineral is biaxial negative with a probable 2V of less than 30°. Commonly, pale green or yellow "glauconite" in the center of an interstitial pocket grades outward to the olive, apparently more impure "glauconite" which consists of a more "felted" microcrystalline texture, as viewed under crossed polarizers, and which contains corroded quartz, as well as other inclusions. These two varieties have much in common; it may be that the olive, felted type represents a more impure, possibly altered form of the other.

Microscopically, then, there are differences between this mineral and typical glauconite, which is characterized by its brighter greenness. As discussed in the section on X-ray diffraction, diffractograms of the "glauconite" show a similarity to illite and muscovite; in the Little Falls material there is good representation of the {002} reflection at 2θ just below 18° (Fig. 62) which seems more typical of illite. In a run of "true" glauconite from the Pomona College collection, this reflection was absent.

Electron microprobe 2θ scans were run on several samples of Little Falls "glauconite" (Fig. 63). Elements

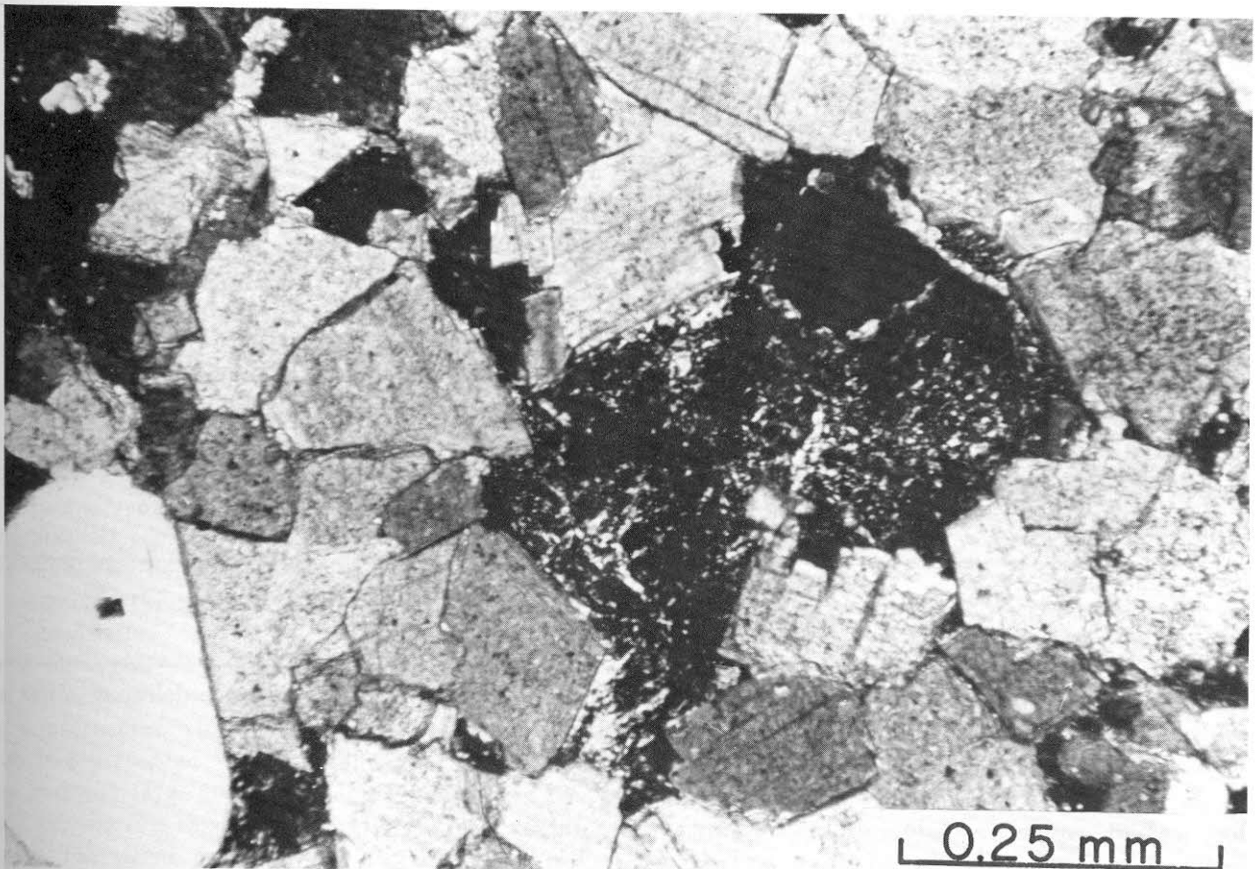

Figure 61. Photomicrograph of small pocket of "glauconite" (dark, mottled) in center and right center, in groundmass of anhedral dolomite crystals; white grain, lower left is detrital quartz; solid black at top of pocket is pyrite; crossed polarized light (H60).

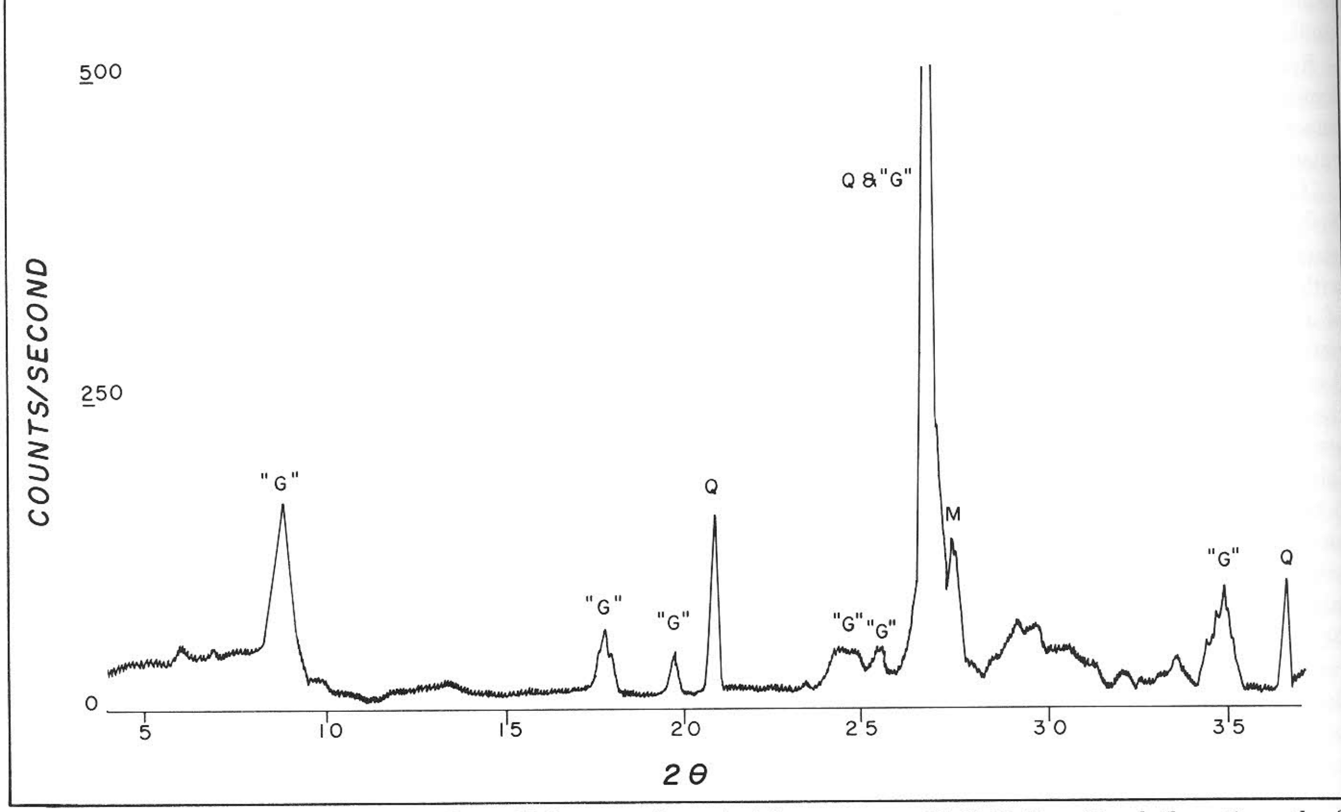

Figure 62. X-ray diffractogram of residue of "glauconite"—rich dolostone near Wolf Hollow Creek (loc. 5) north of Middleville; Q (quartz), "G" ("glauconite"), M (microcline); Cu radiation, graphite monochromator; scanning rate 1°/minute.

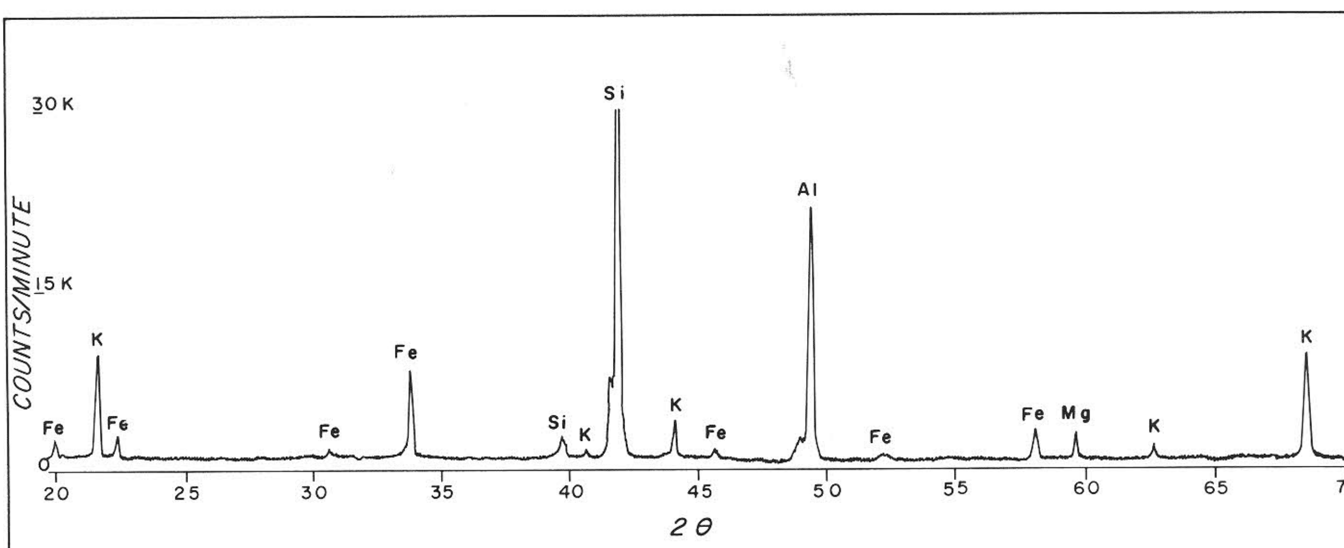

Figure 63. Electron probe microanalyzer 2θ scan of small pocket of "glauconite" in quartzose dolostone (H60; see Fig. 61); standard elemental symbols; scanning rate 1°/minute.

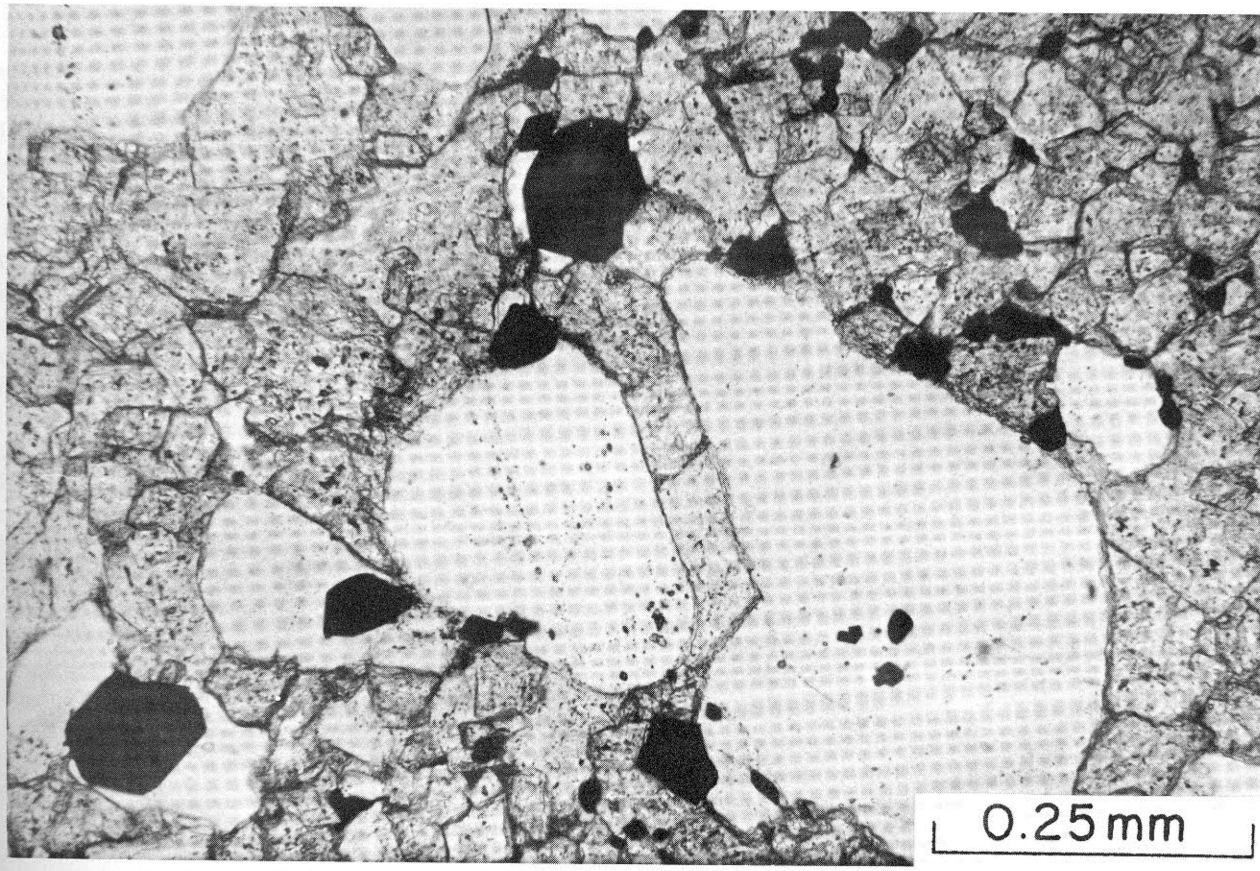

Figure 64. Photomicrograph of pyrite crystals (partly replaced by hematite) replacing dolomite and quartz (light) in quartzose dolostone; plane polarized light (13L).

present, in general order of decreasing abundance, are silicon, aluminum, potassium, iron, and magnesium. Iron content is generally low, compared to other cations, except in one specimen where it is nearly equal in abundance to potassium. Analyses of glauconites as reported in the literature (Grim, 1953, p. 372; Bentor and Kastner, 1965, p. 159) show a substantial amount of iron, seldom less than 10 weight percent. However, W. D. Huff (1976, written communication) pointed out that the composition of glauconite can vary widely—there are high- and low-iron varieties. This variation is due in turn to variation in the percentage of expandable layers in glauconite from practically a pure illite to more than 60 percent smectite. I suggest that more work should be done on this Little Falls material; in the meantime, the green clay mineral will be referred to as "glauconite."

Iron Minerals. Iron mineralization is present in the great majority of thin sections although usually to a very minor extent. The commonest mineral is pyrite, which is represented in X-ray diffraction analyses of many residues (Fig. 29). Generally it constitutes less than 1 percent of a thin section but rarely may reach 5 percent. The pyrite occurrence is variable; most frequently it is present as interstitial crystals or grains ranging in size between 5 and 20 μm. There are pockets up to nearly a millimeter across where there is appreciable concentration of such interstitial pyrite. Irregular splotches of pyrite probably represent replaced carbonaceous material. Some pyrite grains are round, in which case they almost certainly are detrital. Most common, however, is euhedral pyrite (Fig. 64); although the crystals are usually less than 20 μm in size, they may attain dimensions of 50 to 100 μm. A very common association consists of pyrite euhedra within "glauconite" pockets (Fig. 61). Although the larger crystals are commonly centered on interstitial areas, they frequently show replacement relations with adjacent quartz grains and dolomite crystals (see also following discussion of "Paragenesis").

Dolomite crystals occasionally contain pyrite "inclusions" generally in the micron-sized range; these can contribute to a central, rhombic "dusty" area in the crystal. In one instance, they outline a relict clast (Fig. 40). Large pyrite crystals, commonly more than 100 μm across, occur in fracture fillings; although it is possible that these represent void filling, a replacement origin seems more probable. Fracture fillings, mottles, or pockets of interstitial "glauconite" may control the distribution of individual crystals or clusters of crystals of pyrite but often there appears to be no controlling factor.

Hematite, too, has several modes of occurrence. More commonly it occurs as discrete interstitial grains or crystals but it is rarely observed as a "local" thin matrix or padding between quartz grains and dolomite crystals. The euhedral crystals would appear to be pyrite (Fig. 64) but for the reddish coloration under reflected light. The centers of the larger crystals often show a brassy reflection, confirming the complete pyrite nature of the original crystal. These characteristics, coupled with the detection of sulfur in the centers (electron probe microanalysis; see Fig. 65) provide a solid case for hematite pseudomorphic after pyrite.

The most unusual and interesting occurrence of hematite is as micron-sized inclusions in dolomite crystals. Although these may be randomly located, more commonly they are arranged in a 3 to 30 μm-thick zone, commonly rhombic in outline, and followed both outwardly and inwardly by at least as great a thickness of hematite-free dolomite (Fig. 66). Such hematite-zoned crystals are practically restricted to the upper part of Unit D. The red coloration contributed by the hematite can be seen in hand specimen as a reddish groundmass or mottles characteristic of that stratigraphic horizon. Given the small size of the inclusions, it was impossible to apply the electron microprobe to determine whether any pyrite is present in their centers; however, it is probable that this hematite is also pseudomorphic after pyrite.

Limonite occurs more rarely than pyrite and hematite. A few thin sections show dolomite crystals containing limonitic splotches, undoubtedly a secondary effect. Limonite also forms zones, as does the hematite, and occasionally "limonitic" material surrounds hollow (dissolved?) centers of dolomite crystals.

Heavy Minerals. Although rutile occurs as rutilated quartz and although some tourmaline and possibly sphene are present, zircon is the commonest detrital heavy mineral. Usually contributing less than 1 weight percent of a sample, the zircon grains may locally occur sufficiently close together so as to represent a lamination parallel to the general stratification. The zircons are mostly subangular to subrounded and are predominantly of medium silt-size (20–30 μm). They are identified by their high relief, high birefringence, and by the presence of zirconium and silicon as determined by electron probe microanalysis.

Anthraxolite. Anthraxolite, a bituminous substance derived from an unknown petroleum residue (Hunt, 1978), has long been noted (Vanuxem, 1842, p. 33–34) in vugs and as inclusions in the famous "Herkimer Diamonds," or secondary quartz crystals, in the Little Falls. Dunn and Fisher (1954) presented a comprehensive report on the occurrence and properties of anthraxolite in both the Little Falls and overlying Lower

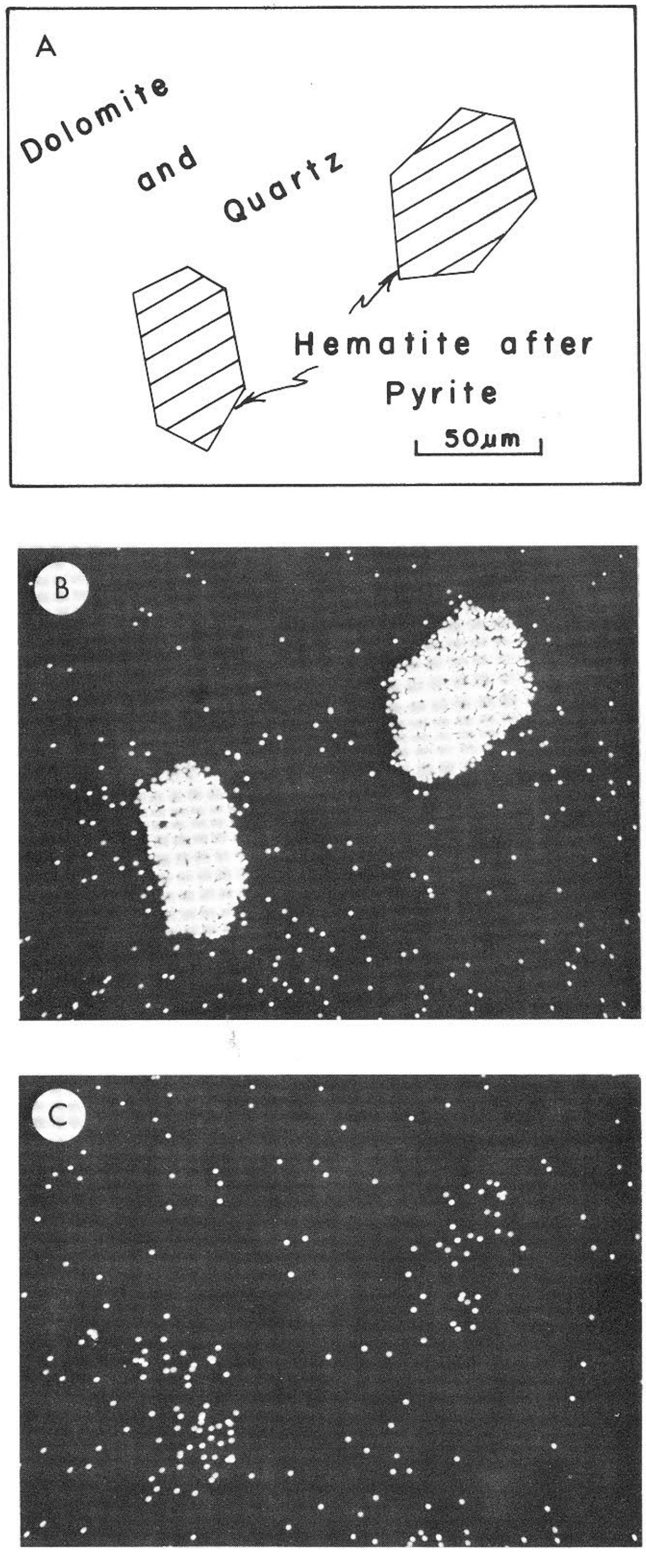

Figure 65. Electron probe photomicrographs of hematite pseudomorphic after pyrite, with pyritic centers of crystals remaining; groundmass is quartzose dolostone; A, sketch of area of analysis; B and C, X-ray beam scan images for FeKα and SKα, respectively (13L).

Ordovician carbonates in the Mohawk Valley. Overall anthraxolite is minor in amount, although locally it can be significant. Analyses of two specimens from the Little Falls contain 90.42 and 90.5 percent carbon and the hydrogen-oxygen ratio is much lower than that of asphaltic bitumen (Dunn and Fisher, 1954, p. 496). Anthraxolite is considered by most authorities (see Hunt, 1963, p. 255) to be a pyrobitumen which is defined as an insoluble (in carbon disulfide) bitumen that decomposes prior to melting. This particular material in the Little Falls is insoluble in dichloroethane which acts as a solvent, as carbon disulfide, but which is less noxious (S. R. Larter, 1979, oral communication).

Hand specimen characteristics are its black color, conchoidal fracture, and vitreous to dull luster. Dunn and Fisher (1954, p. 498) concluded that the primitive carbonaceous material must have been a liquid; they frequently observed anthraxolite in the lower portion of vugs despite its lower specific gravity (1.32–1.41) than the minerals found in the upper part (e.g., calcite, dolomite, and quartz).

Viewed microscopically, anthraxolite is black and opaque; it is locally abundant, on the microscopic scale, as interstitial material commonly in porous zones (Fig. 43). It may be an obvious void filling in large pores as evidenced by its location beyond euhedral dolomite, often with ferroan rims, which grew into the particular void. It is also found interstitial to dolomite and quartz crystals in what were probably small voids remaining after dolomitization. Frequently, in specimens where there is megascopic anthraxolite in vugs, there is the microscopic occurrence as well. In hand specimens without vugs containing the hydrocarbon, blackish seams and mottles may be a clue to the presence of the microscopic form.

DIAGENESIS

PARAGENESIS

Paragenesis, or the order of formation of associated minerals, was determined through a study of textural relations in thin section, aided in specific instances, by the use of the electron probe microanalyzer. In describing the petrography of ores, Moorhouse (1959, p. 487–493) presented a good summary of the various geometric criteria for determining the sequence of mineral formation; many of these criteria are useful in determining the paragenesis of carbonates and other sedimentary rocks. Moorhouse pointed out that there are different ways of looking at paragenesis; one can consider the relative times of the *beginning* of the formation of the minerals, the *end* of formation, or the complete *periods* of formation. In the latter case it is

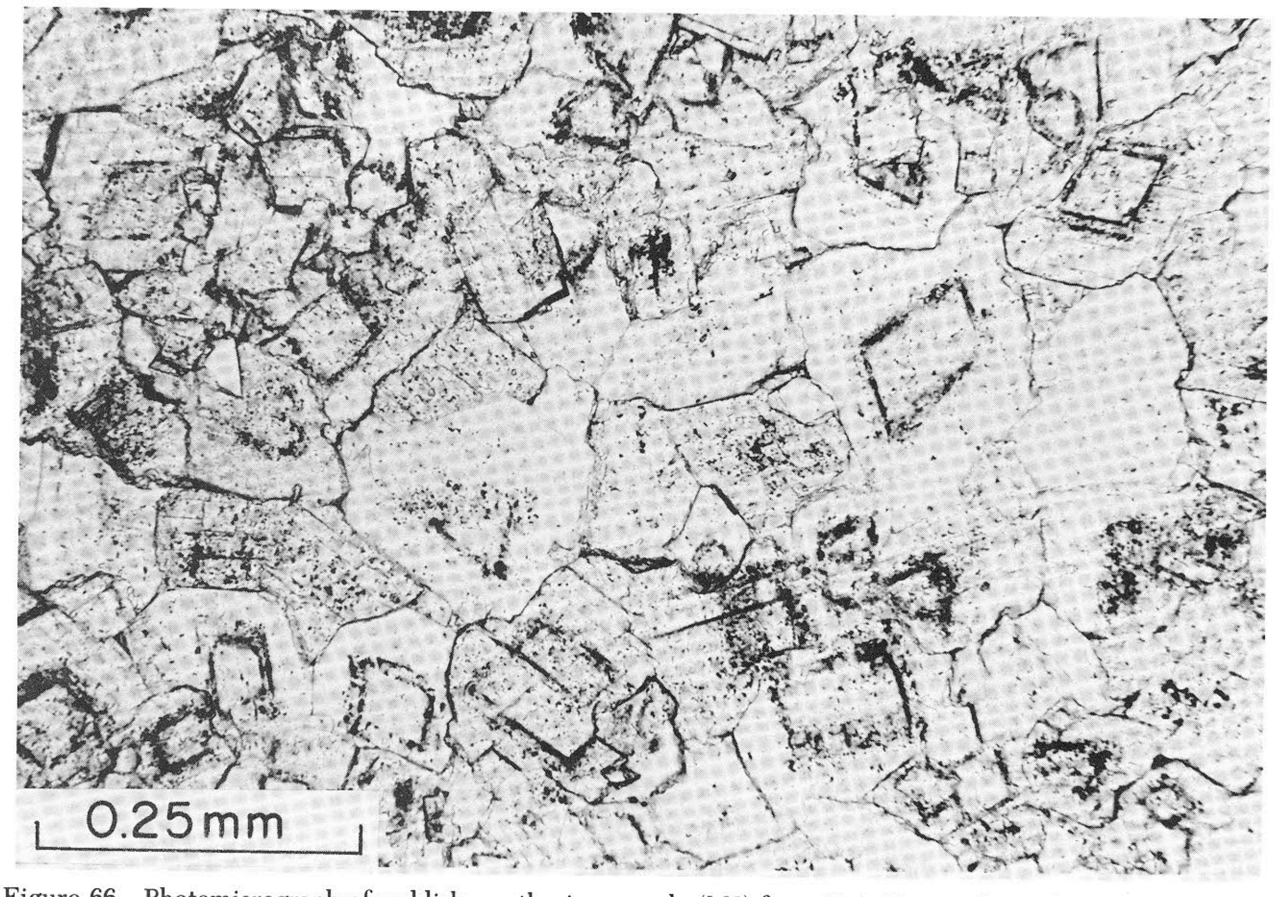

Figure 66. Photomicrograph of reddish-weathering sample (M1) from Unit D near Canajoharie; coloration owing to rhombic zones of hematite within dolomite crystals; plane polarized light.

difficult to distinguish between continuous formation (i.e., growth of a crystal) and episodic appearances of a particular mineral phase. Also, although evidence for the replacement of one mineral by another aids in determining paragenesis, minerals occurring at different times in the paragenetic sequence do not necessarily show replacement relations. Moorhouse also does well to describe some of the many uncertainties involved in interpreting textures and fabrics in order to determine paragenesis; certainly there are many such equivocal relations in the Little Falls.

Original Little Falls sediments consisted of a mixture of terrigenous grains, mainly quartz and feldspar (microcline and perthite), and carbonate minerals. Modern, shallow, warm-water carbonate sediments consist primarily of aragonite and high-magnesian calcite, with lesser amounts of low-magnesian calcite (Taft, 1967, p. 151); dolomite is extremely minor. Stehli and Hower (1961) and Friedman (1965b) showed that in deep-water carbonates, low-magnesian calcite dominates high-magnesian calcite, the latter being more stable in that environment than aragonite. Gomberg and Bonatti (1970) contended that the high-magnesian calcite fraction of shallow-water carbonate was converted to low-magnesian calcite after transportation into the deep-water environments.

Ancient carbonate rocks consist primarily of low-magnesian calcite and dolomite. "One of the problems facing chemists and geologists alike is the abundance of metastable carbonate minerals in modern sediments and their absence in carbonate rocks" (Taft, 1967, p. 151–152). It is well known that magnesium is rapidly lost from high-magnesian calcite; Stehli and Hower (1961, p. 362) showed that the calcite of Pleistocene carbonate rocks from Florida was predominantly of the low-magnesian variety. Stabilization of carbonate minerals, especially where reacting with meteoric water, has also occurred in the Late Pleistocene in Jamaica (Land and Epstein, 1970) and Bermuda (Land, 1970). Chave (1954) and Weber (1969) among others, demonstrated the presence of relatively high amounts of $MgCO_3$ in the skeletal calcite of modern echinoderms and both workers pointed out that essentially all pre-Pleistocene echinoderm fossils examined had lost most of their supposed original magnesium, having recrystallized to low-magnesian calcite containing less than 4 mole percent $MgCO_3$. The content of skeletal aragonite in rocks shows a general decrease with age (Bathurst, 1971, p. 274–275), especially where the rocks possess any degree of permeability. On the other hand, impervious shales or the primary organic matrix of the skeleton (Kennedy and Hall, 1967) may protect the aragonite from dissolution. Skeletal aragonite has been reported in rocks as old as Upper Devonian (Grandjean, and others, 1964; original reference not seen, see Bathurst, 1971, p. 275) and Lower Carboniferous (Hallam and O'Hara, 1962).

It is very likely that the original carbonate sediments in the Little Falls consisted of aragonite and/or high magnesian calcite but there is, of course, no definite evidence. There is, in fact, scarcely any skeletal material recognized. The "oldest" carbonate mineral now present with the quartz and feldspar grains is dolomite; presumably, much of the early diagenetic carbonate history is lost. No pre-dolomitization calcite, if ever present, remains. Despite the near absence of recognizable skeletal material, other evidence suggests that dolomite developed by replacement rather than by primary precipitation; many sections, however, simply do not shed any light on the problem and it is conceivable that some of the initial dolomite could have been primary or penecontemporaneous (this matter will be discussed later under "Dolomitization"). Relict ooids and peloids consist of dolomite, as do the few shells observed (Figs. 42–45). Very likely, any original metastable carbonate components were either directly replaced by dolomite or were altered to low-magnesian calcite prior to dolomitization. Sibley (in press) has suggested that if early calcitization (i.e., stabilization) of metastable carbonates occurs, dolomitization could be inhibited. If such were the case, one could assume that, in general, dolomitization would be relatively early, prior to stabilization. As will be discussed later, I do not believe that most dolomitization of the Little Falls occurred during early diagenesis.

Before describing paragenetic relations of dolomite to other minerals, a few words are in order regarding dolomite growth about which more will be said in the section on "Dolomitization." The coarser crystals in the porphyrotopic fabric (Figs. 32, 60) almost certainly represent a longer period of crystal growth than the associated smaller crystals. Cloudy centers and clear rims (Figs. 37, 38) of many dolomite crystals suggest at least two stages of growth. The absence of inclusions in the clear rims suggests that they formed by passive precipitation into space around a dolomite crystal developed by replacement. Epitaxial, slightly ferroan dolomite rims (Fig. 39) seen in many sections probably represent yet a later stage; this late stage of growth is further suggested by coarser, void-filling crystals which are completely stained blue by the potassium ferricyanide. Choquette (1971) described a late ferroan dolomite cement in Mississippian carbonates in the Illinois Basin; these void-filling crystals show undulatory extinction. It was intimated in Choquette's paper that later diagenetic, or epigenetic, dolomite might generally show these characteristics. It is not always an easy matter to distinguish between the development of coarser dolomite textures by replacement of an original coarser calcareous fabric vs. that resulting from passive precipitation in "early" late diagenesis; in the latter case, the identity of an original void may be largely lost. However, the ferroan dolomite rims are generally present in what were once porous pockets where there was lacking a competition among growing dolomite crystals. For instance, the rims are not present where dolomite crystals are closely packed in the rock fabric proper (i.e., not including free faces of crystals growing into voids), in which practically all of the crystal margins are compromise boundaries. Such a geometry is evidence against another hypothesis—that when the larger, "early" late diagenetic dolomite crystals were forming, ferrous iron migrated into the lattice of the margins of already-present dolomite crystals. I believe that the ferroan rims and the "early" late diagenetic ferroan spar formed at the same time. The idea of later migration of ferrous iron into dolomite crystals could more easily explain the rare occurrence of rhomb-shaped centers of ferroan dolomite within dolomite crystals; if one assumes the incorporation of iron in crystals as they grow, however, then an early stage of growth of ferroan dolomite is necessitated. As discussed under "Dolomitization," preliminary work using cathodoluminescence reveals stages of dolomite crystal growth as indicated by manganese-"enriched" zones.

Katz (1971) and Wood and Armstrong (1975) have described zoned dolomite crystals from the Jurassic of Israel and the Mississippian of Alaska, respectively. Katz attributed hematite zones to oxidation of ferroan dolomite as the crystals grew. Although subscribing to the development of zones during crystal growth, Wood and Armstrong (1975, p. 24–25) felt that as dedolomitization of unstable ferroan dolomite occurred, the excess iron in the calcite lattice was expelled outward to the rim of the growing rhomb.

I did not observe zones of ferroan dolomite *within* the dolomite crystals and there is no evidence that hematite zones, as are common in specimens from Unit D (Fig. 66), resulted from the oxidation of ferroan dolomite as the crystals grew. These hematite zones in the Little Falls follow light brownish stained zones and although possessing distinct rhomb-shaped outlines, are somewhat irregular along the outer edges, in contrast to those of Katz which possess smooth outer margins but irregular inner ones (which evidence Katz took to signify oxidation during crystal growth). The crystals with hematite zones do not show more inward zones of dedolomitization and the expulsion mechanism of Wood and Armstrong cannot be invoked. I propose that the hematite zones in the Little Falls resulted from oxidation and possible replacement of pyrite by hematite after the crystals had grown.

I also interpret all possible dedolomitization as occurring *after* crystal growth. Calcite is everywhere younger than the dolomite. It occurs most commonly

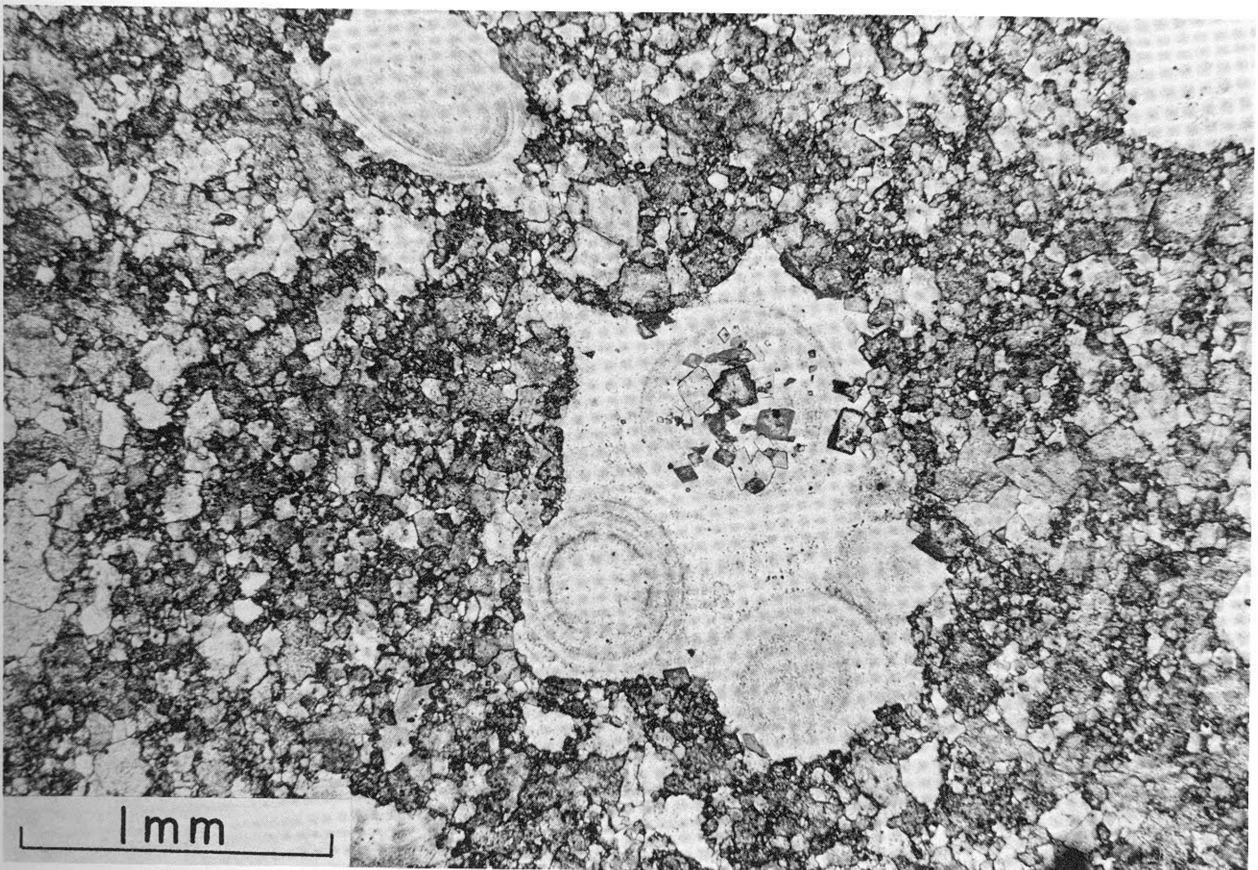

Figure 67. Photomicrograph of dolomitic groundmass "impinging" on pockets of chertified ooids (light); note discrete rhombs in large silicified ooid, right center; plane polarized light (5L).

as the huge, mm-sized poikilotopic calcite crystals (Fig. 60) filling the more internal parts of irregular voids, and followed outward by earlier-formed minerals. Inclusions of dolomite euhedra occur in the poikilotopic calcite but there are no floating terrigenous components, further supporting the argument for a late void-filling origin. (Freeman (1969) would generalize that it is typical to have calcite as the ultimate cement in both primary and secondary voids.) There are numerous examples of calcite-filled fractures that transect dolomite crystals; the calcite is usually in local optical continuity with the dolomite crystals through which it passes. In section after section calcite can be seen resting on quartz overgrowths with enfacial junctions. The calcite in the epitaxial rims and rhombic centers of dolomite crystals is also believed to belong to this late stage generation (see discussion under "Dedolomitization").

As mentioned earlier, very few sections contain ferroan calcite cement. Association of ferroan and nonferroan calcite is lacking and there is no unequivocal way, such as the use of enfacial junctions (Bathurst, 1964, p. 362–365), to determine their relative times of formation. Possibly the ferroan calcite represents deeper and earlier formation than the nonferroan variety (see discussion on "Dedolomitization").

There is textural evidence suggesting two stages of chert formation and this consists of geometric relations with dolomite. Dolomite crystals of the groundmass can be seen rimming fields of chertified ooids (Fig. 67). Beyond the dolomite "fronts" and within the chert field are isolated rhombs. There is some dilemma here in determining with certainty the time relations between the dolomite and the chert. Very small, isolated rhombs of dolomite in chert just referred to could represent minor dolomitization caught "in the act" by chertification as described by Dietrich and others (1963) and as considered to be the case in the upper part of the Lost Burro Formation (M.-U Devonian), east-central California (Zenger and Pearson, 1969). Very poorly preserved relict ooids can be distinguished in the dolomitic groundmass. In the chert, however, ooids are much better preserved, displaying the concentric and radial structure described previously. It is thus clear from these observations that the chert did not replace previously dolomitized ooids. One could, however, imagine that dolomitization of an oosparite, for example, could have proceeded so far, in various directions, followed by subsequent chertification of the other undolomitized carbonate up to the faces of the dolomite rhombs. The major evidence supporting the contention that some dolomite followed

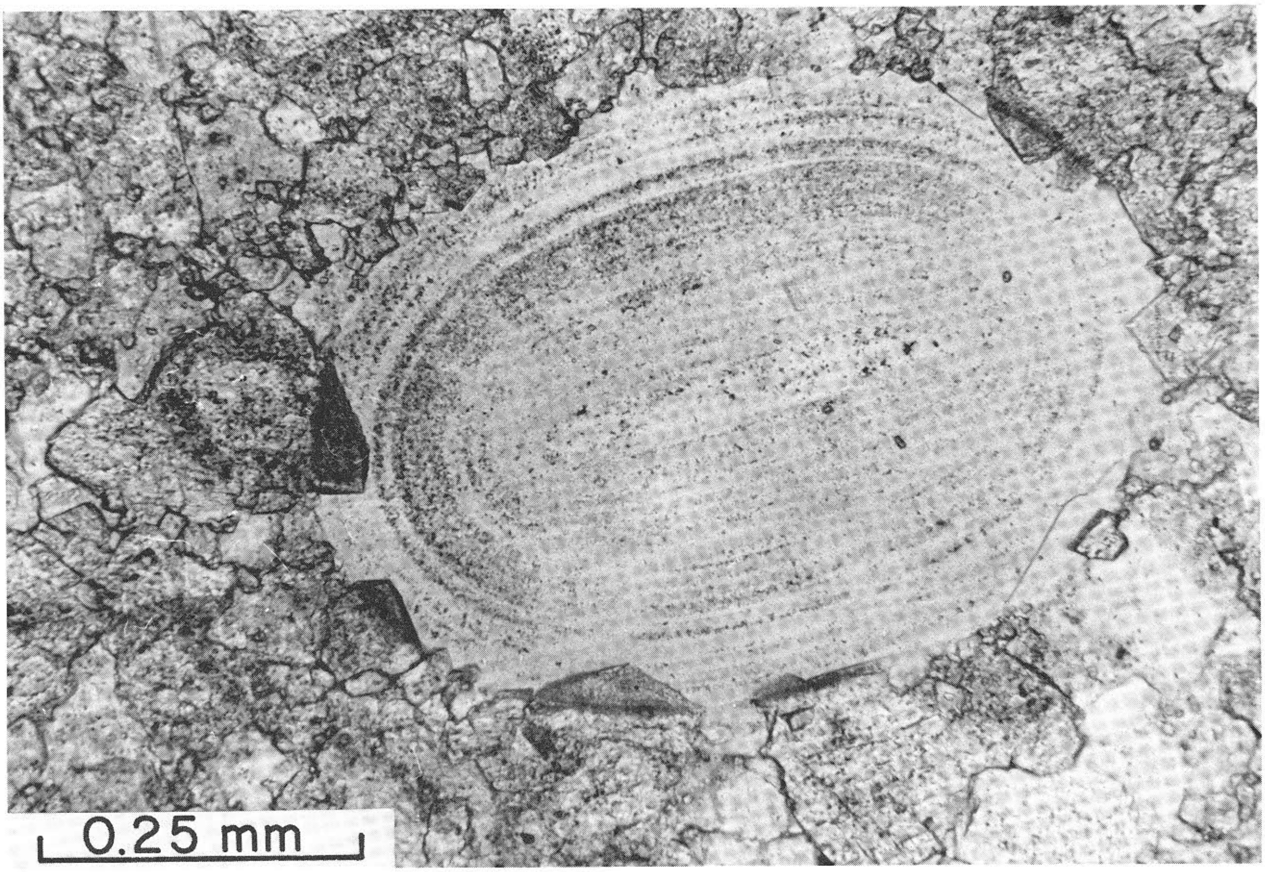

Figure 68. Photomicrograph of close-up of isolated, elongate, chertified ooid shown along upper left margin of Fig. 67; note dolomite crystals, dusty with chert inclusions, "nibbling" at margins of ooid; plane polarized light (5L).

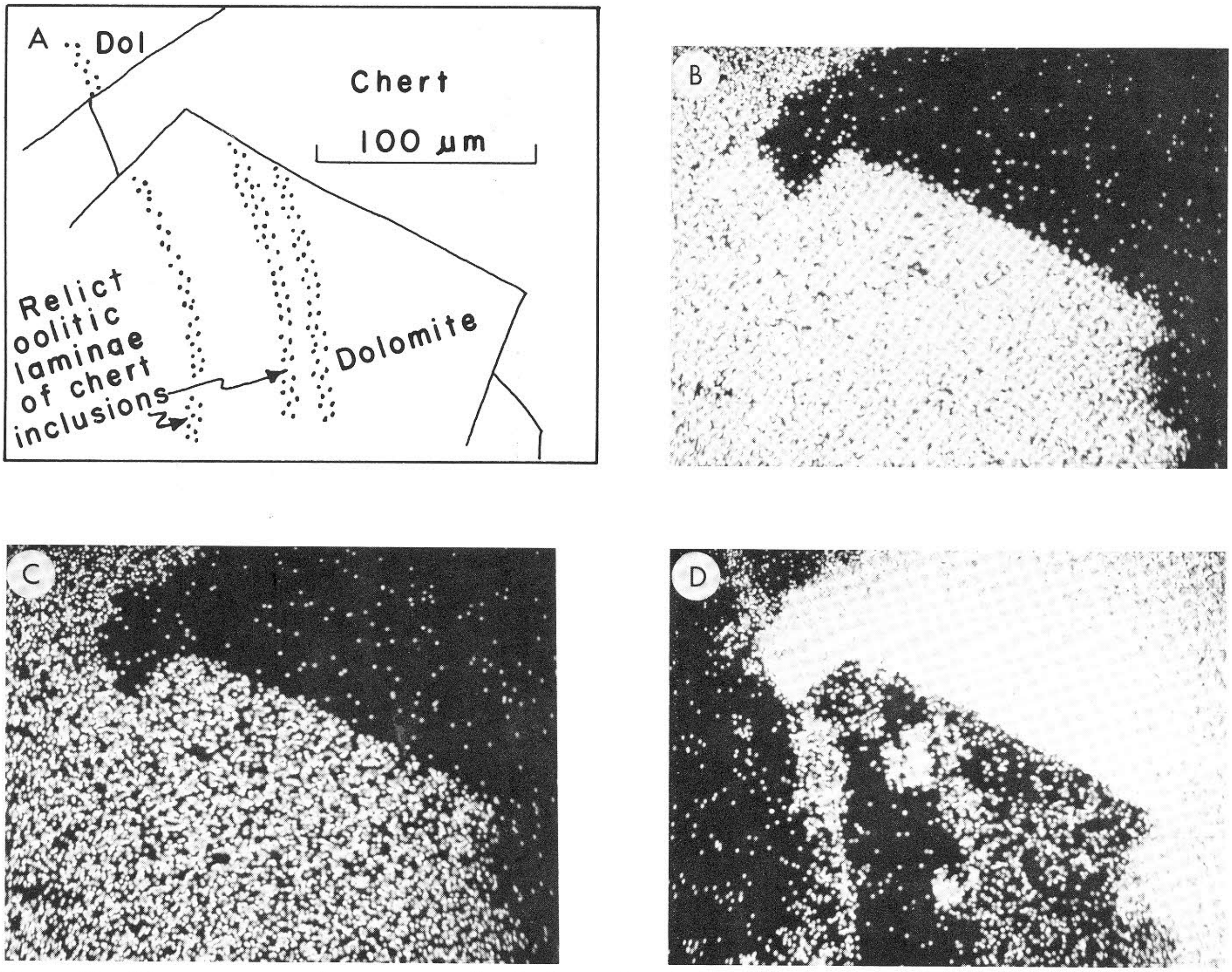

Figure 69. Electron probe photomicrograph of relict oolitic laminae preserved as chert inclusions in dolomite crystal transecting ooid; A, sketch of area of analysis: B, C, and D, X-ray beam scan images for CaKα, MgKα, and SiKα, respectively. (I6).

chertification is that the margins of dolomite crystals against chert have a very "dusty" appearance (Fig. 68). In the chert field, where dolomite crystals can be seen to transect relict ooids, this dust within dolomite crystals may be arranged in laminations which are aligned with those of the truncated, chertified ooid outside the crystal. With the use of the electron probe microanalyzer it was demonstrated that these bands are indeed silica rich and represent inclusions of chert (Fig. 69).

It may be then, that we have here very early chertification prior to the main dolomitization. There is other evidence that some chert formed later than the main dolomitization. For example, some dolomite crystals in chert have severely corroded margins (Fig. 70). And, there are the rhomb-sized chert centers of dolomite crystals mentioned previously (see Figs. 56, 57). The rhomb-shaped outline of the chert indicates a post-dolomite origin. I believe that the chert replaced "unstable" centers of dolomite crystals rather than having been passively precipitated. Dunham and Olson (in press) reported megaquartz in dolomite centers in the Hanson Creek Formation (Ord.-Sil.) of Nevada; however, there are small carbonate inclusions in some of the Little Falls chert. Some workers (Dietrich and others, 1963; Dunham and Olson, in press) have suggested that such intricate textural relations between chert and dolomite reflect a close, even concurrent, association of silicification and dolomitization. I believe that the textural relations in the Little Falls represent considerable diagenetic time, however. For example, I interpret the development of coarse dolomite crystals (up to 1.5 mm in greatest dimension) followed by their corrosion by chert to be late diagenetic (see later discussion of dolomitization).

Quartz grains as well as their overgrowths are commonly corroded by chert. Calcite fills in voids in some samples of chert; for example, large calcite crystals fill the upper parts of collapsed chertified ooids (Fig. 55) and occur in fracture fillings which transect the ooids.

The great bulk of dolomitization occurred prior to

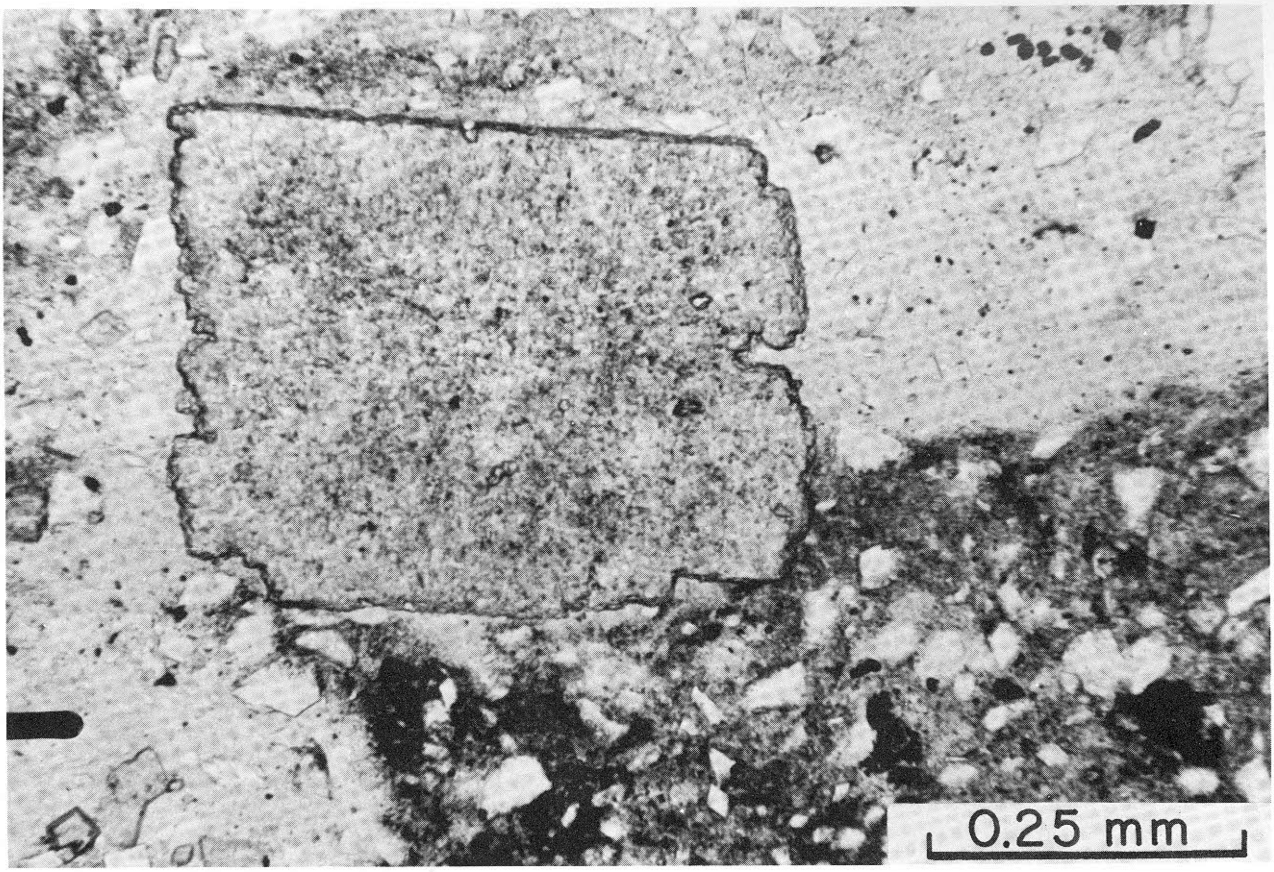

Figure 70. Photomicrograph of large, corroded dolomite crystal in silty chert; plane polarized light (H64).

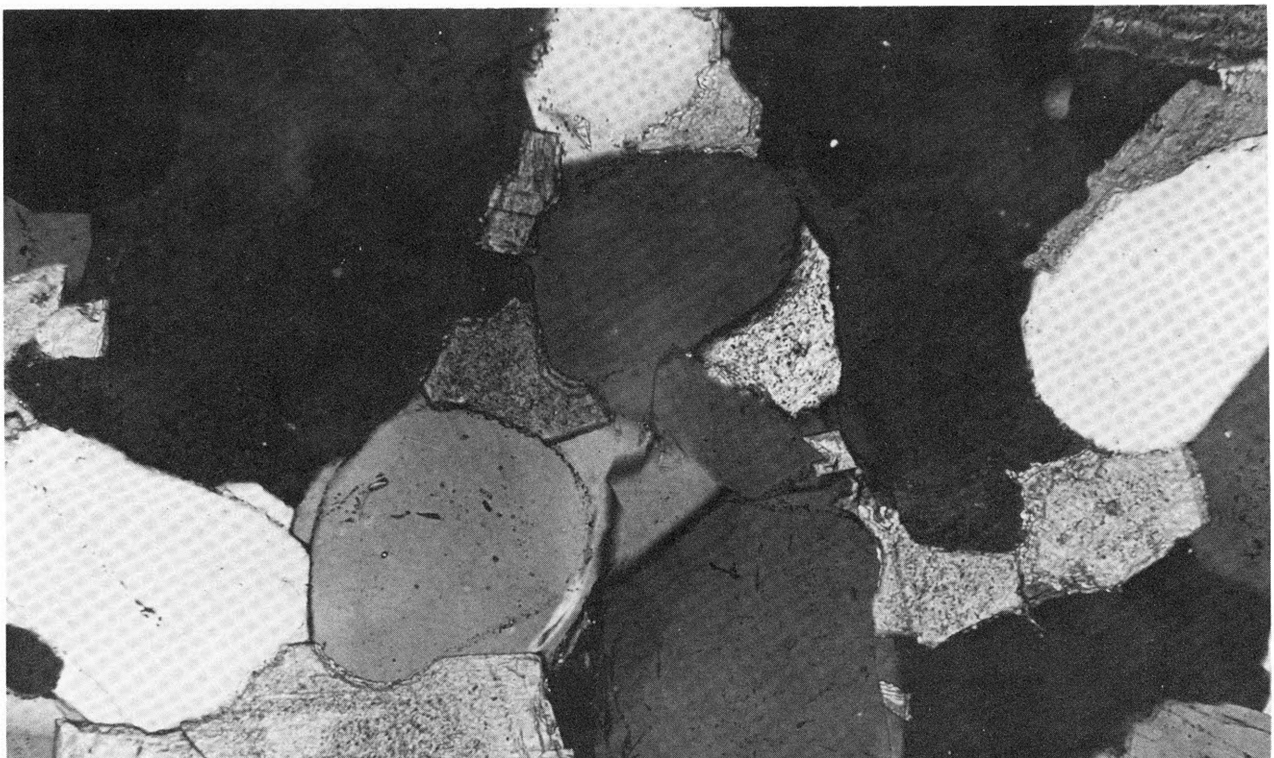

Figure 71. Photomicrograph of dolomite vs. secondary quartz overgrowth relations; evidence consists of dolomite crystals ("stippled" pattern) conforming to rounded detrital nucleus (white to gray) but euhedral against overgrowth: note rutile needles in quartz grain in lower center of photo; crossed polarized light (H61).

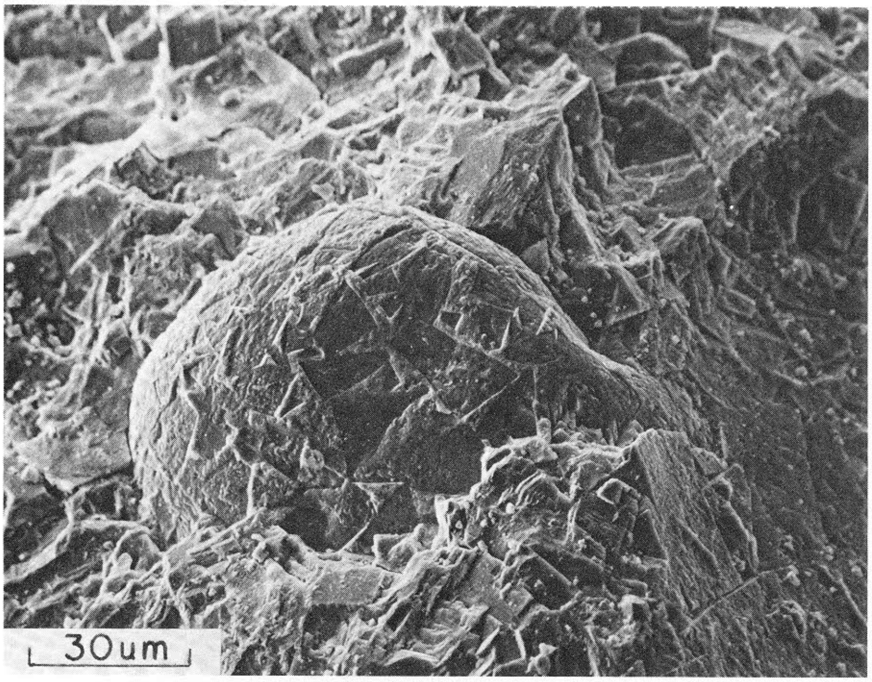

Figure 72. Scanning electron photomicrograph of rounded quartz grain in quartzose dolomite; note impressions of dolomite crystals against more subdued surface of detrital nucleus (dark) vs. secondary quartz (light) built up adjacent to (and subsequent to) dolomite crystals (which were removed from grain in preparation of specimen, 18M).

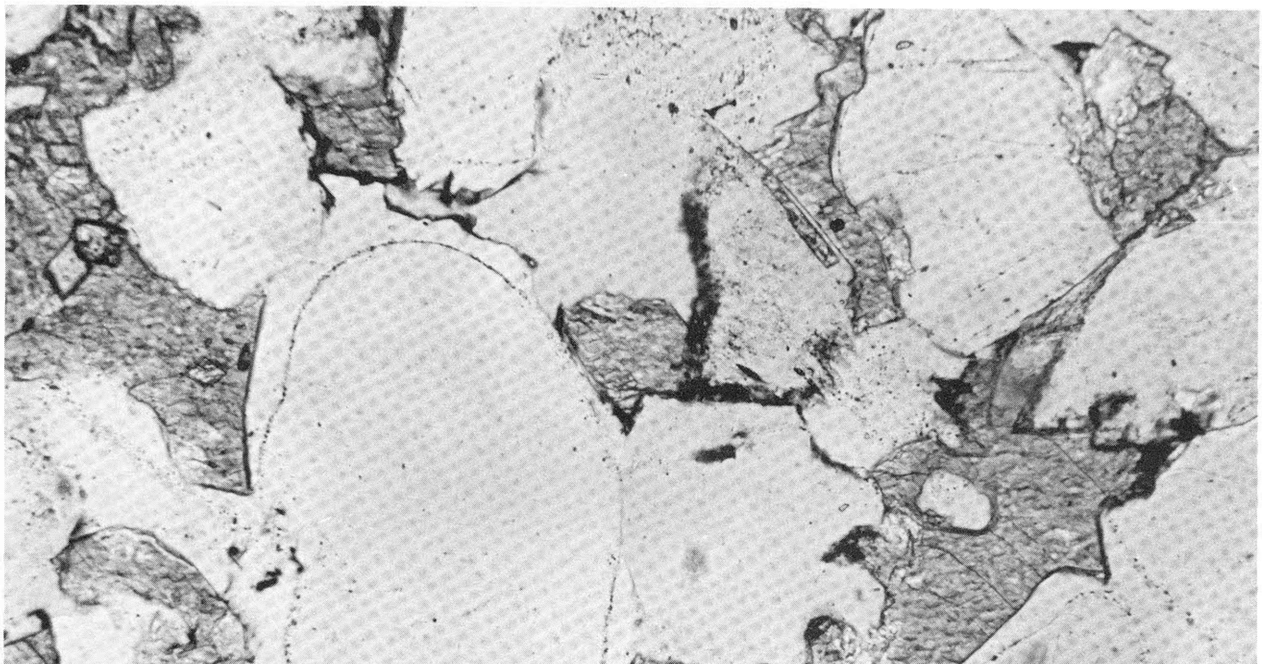

Figure 73. Photomicrograph showing location of late-stage calcite (stained, dark) outward from secondary quartz overgrowths; plane polarized light (26L).

the development of quartz overgrowths. Dolomite crystals invariably "hug" the rounded detrital core of quartz but become euhedral against the overgrowth (Fig. 71). Because the dolomite does not transect the detrital core, it seems logical to assume that it would not replace the quartz in the overgrowths either. Consequently the enfacial junctions of the secondary quartz in the overgrowths against the dolomite probably represent a later growth of the quartz. On the other hand, Walker (1957, p. 267) described selective carbonate replacement of overgrowths of quartz grains in the Ordovician Oneota Formation of Wisconsin that halted at the more "resistant" grain boundary. However, scanning electron microscopy also suggests that quartz overgrowths followed dolomitization (Figs. 54, 72). Apparently, perthite overgrowths preceded quartz overgrowths. In one section, the overgrowth of a perthite grain directly borders a portion of the detrital nucleus of a neighboring quartz grain, the remaining margin of which is followed outward by a quartz overgrowth.

Calcite is distinctly younger than the quartz overgrowths as shown by its position void-ward of the overgrowths and by enfacial junctions of calcite against the authigenic quartz.

Both the calcite and dolomite replace perthitic feldspar. Calcite is focused along lamellae, along cleavage, or occurs apparently randomly. Dolomite generally replaces perthite peripherally, although in one instance it is localized along the cleavage. Occasional detrital perthite grains possess authigenic overgrowths and there are small occurrences of the feldspar that could be entirely authigenic.

"Glauconite" is authigenic and in its purer form appears as small pockets of void-filling "cement" postdating dolomite formation, including ferroan dolomite. The "glauconite" occurs between dolomite or secondary quartz overgrowths and the late calcite beyond. There is recognized the possibility that dolomite could be replacing the "glauconite" but I think it more probable that the interstitial "glauconite" developed in a porous framework of dolomite crystals and quartz. As partial support for this contention, some dolomite rhombs are corroded by the "glauconite." In addition, there are no inclusions of "glauconite" in the dolomite. Considering the significant amount of potassium feldspar, some of it being altered to a brownish material mentioned under "Mineralogy" there would seem to be an adequate supply of Al^{3+} and K^{+} ions available for the formation of low-iron "glauconite." Depending on how late in diagenesis this formed, there could have been a potential supply of such ions from the overlying Tribes Hill with its abundant potassium feldspar (Buyce and Friedman, 1975).

Whereas some interstitial pyrite may be detrital, the great bulk consists of subhedral to euhedral crystals commonly showing replacement relations with calcite, quartz, and dolomite (Fig. 64). A common association consists of pyrite euhedra in "glauconite." Except possibly where occurring as zones in dolomite crystals, hematite developed late in paragenesis. As mentioned above in the section on "Mineralogy," in many instances one can see the reddish reflection of hematite from a crystal form of pyrite; electron probe microanalysis demonstrates that sulfur, and hence pyrite, often remains in the core of the crystals (Fig. 65). A good deal of the hematite, then, is pseudomorphic after pyrite.

Anthraxolite corrodes and, locally, penetrates dolomite crystals, including the later-stage ferroan dolomite rims and whole crystals (Fig. 43). Thus, the solidification of this organic material certainly postdates the main develpment of dolomite, including the coarser, probably late diagenetic dolospar. Anthraxolite is also associated with secondary minerals in vugs. Based on position inward from the walls of the vugs, the order of formation of the other minerals seem to be invariably dolomite-quartz-calcite. According to Dunn and Fisher (1954, p. 498), the anthraxolite infiltrated the Little Falls as a liquid. They believed that the secondary dolomite preceded solidification of the "proto-anthraxolite." Although this idea fits better with the microscopic evidence, I did find one vug at East Canada Creek (loc. 30, unit 6) which showed anthraxolite between the vug wall and dolomite, suggesting an earlier age for the former. The formation of the secondary dolomite and quartz crystals in vugs and the entry of the proto-anthraxolite overlapped considerably. Generally, in the Little Falls, the solidification of the anthraxolite preceded or accompanied the growth of the "Herkimer diamonds"; inclusions of anthraxolite in the tiny liquid-filled voids in some quartz crystals suggest this sequence. On the other hand, some vugs have anthraxolite deposited snuggly against dolomite and quartz crystal faces, suggesting a later occurrence in these cases. Dunn and Fisher (1954, p. 498) noted that calcite followed anthraxolite based on the position of calcite above the anthraxolite in vugs and the fact that calcite cross cuts anthraxolite.

An interesting question involves the time relationships between the secondary dolomite, quartz, and calcite seen in smaller voids in thin section and those latest secondary occurrences observed macroscopically in vugs; the order of formation seems to be the same in both instances. One might naturally assume that the vugs and vug-filling minerals were considerably later but this need not be the case. For example, dolomite overgrowths in the Kingsport Formation (L. Ord.) of the east Tennessee zinc district are considered to be of the same age as the white dolomite gangue, which fills fractures, and the dolomite cement of breccias (U.S. Geol. Surv., 1974, p. 3–4). However, I do favor a later diagenetic development of the mineral occurrence in vugs in the Little Falls based primarily on textural relations with anthraxolite. Late diagenetic dolospar and the quartz overgrowths (which lack anthraxolite inclusions as observed microscopically) preceded the time of anthraxolite formation; the dolomite and quartz overgrowths are corroded by anthraxolite in the small void fillings within the "groundmass." In the vugs, dolomite lines the walls followed by the "Herkimer diamonds," many of which trapped inclusions of anthraxolite, and consequently must predate the quartz crystals. Finally, calcite crystals formed in the vugs and the Ca^{2+}-bearing solutions penetrated the somewhat porous rock, forming the large poikilotopic crystals discussed earlier, and the calcite filled microfractures.

An ingenious attempt to relate the time of secondary quartz and anthraxolite formation to the lower Paleozoic section in New York was discussed by Dunn and Fisher (1954, p. 498):

"Using a bubble-filling technique, Dr. F. G. Smith of the University of Toronto obtained a termperature of formation of 51° ± 2°C. for one quartz crystal. Using an average temperature gradient of 1°F. for 60 feet together with the temperature of formation of 51° ± 2°C. (120°F. to 127°F.) and assuming an average surface temperature of 70°F., we arrive at the interesting disclosure that the dolomites had 3000 to 3500 feet of sedimentary cover when the quartz crystals were forming. Computing the average thickness of sedimentary strata which presumably covered the Mohawk Valley would indicate that the quartz crystallization and anthraxolite solidification took place not earlier than post-Queenston time and possibly as late as Onondaga time. The upper limit is less predictable since it is doubtful just how much, if any, of the Middle Silurian (Clintonian) sediments extended as far as the Mohawk Valley region. The time of formation of anthraxolite can be further restricted. Field criteria illustrate that block faulting postdated the formation of the anthraxolite. [The surface of the once liquid anthraxolite in vugs is not horizontal but rather is parallel to the bedding which dips gently as a result of the faulting.] The normal faulting may be as late as Lockport time. This would confine the period of anthraxolite formation to post-Queenston and pre-Lockport time. Either Medinan or Clintonian time appears as close an approximation for the anthraxolite formation as is now possible."

Following is my suggestion for the paragenetic sequence, beginning with the earliest event. Although diagrams showing paragenetic relations by bars of differing length representing the duration of the various processes may seem impressive, they commonly are very tenuous; in addition to the difficulty in determining the beginning and termination of specific diagenetic processes, there is the further complication of deciding whether certain processes "reoccur" or are actually more or less continuous. The list presented below simply implies that a particular event has occurred prior to or following the subsequent or preceding process(es), respectively:

Original carbonates and terrigenous grains
Penecontemporaneous or very early dolomite(?)
Chert
Early to mostly late diagenetic (decimicron and fine-centimicron-sized dolomite)
Late diagenetic dolomite (coarse centimicron-sized to mm-sized crystals; ferroan dolomite rims and crystals)
Quartz overgrowths
"Glauconite"
Chert
Anthraxolite
Secondary dolomite crystals (in vugs)
Anthraxolite
Secondary quartz crystals (in vugs)
Anthraxolite
Calcite (poikilotopic calcite and calcite crystals; "dedolomite"—see section on "Dedolomitization")
Hematite (after pyrite)

Swett (1965, p. 937) described a well-documented paragenetic sequence from Cambro-Ordovician carbonates (Durness Limestone) in northwest Scotland as follows (from older to younger): recrystallization-dolomitization-silification-calcitization [= dedolomitization]-dolomitization. He envisioned that this sequence is not restricted to these carbonates alone but that it can be found in numerous lower Paleozoic sections elsewhere. (His suggestion is especially intriguing given the very likely closer geographic proximity of the Durness and Little Falls across the Proto-Atlantic during the Late Cambrian.) However, the Little Falls seems to show two stages of chertification, one preceding dolomitization, and the dedolomitization appears to be younger than all dolomitization.

DOLOMITIZATION

In the immediately preceding discussion of paragenesis, it was pointed out that no original calcium carbonate remains; relatively common relict peloids and ooids, as well as very rare shell debris, indicate that replacement has occurred although there is no direct evidence in most thin sections. With the exception of the finely crystalline (micron-sized to primarily medium decimicron-sized) dolostone associated with algal stromatolites, and in Unit D, dolomite crystals are generally coarse (primarily coarse decimicron-sized to fine centimicron-sized and ranging up to coarse centimicron-sized, and even including millimeter-sized crystals that occur in vugs). The coarse crystallinity itself strongly suggests that the dolomite is not primary (i.e., precipitated from solution at or above the sediment-water interface). Most ancient dolostones assumed to be primary are very finely crystalline; it seems unlikely that neomorphism during diagenesis of a very finely crystalline primary dolomite would produce the coarse textures, including the porphyrotopic type, present in the Little Falls, but this is a possibility.

Before discoveries made in the 1950's and 1960's, modern dolomite was considered to be practically nonexistent, occurring mainly as isolated rhombs in Holocene sediments (Zenger, 1972b). Over the past 20 years, researchers, primarily from oil companies, have reported numerous occurrences of Holocene dolomite around the world, for example: the Persian Gulf (Illing and others, 1965); the Bahamas (Shinn and Ginsburg, 1964; Shinn and others, 1965); the Florida Keys (Shinn, 1968b), and the Netherlands Antilles (Deffeyes and others, 1965). In these places the "dolomite" occurs as very fine crystals forming penecontemporaneously in or beneath the supratidal zone. The material is actually a protodolomite (Graf and Goldsmith, 1956), which is both calcium-rich and disordered. Following these discoveries of Holocene occurrences there was a flood of published reports on supratidal dolostones from the geologic record—ancient analogs of the Holocene examples, such as: Laporte (1967), Manlius Formation, Lower Devonian, New York; Matter (1967), Middle Ordovician, western Maryland; Roehl (1967), Stony Mountain (Ordovician) and Interlake (Silurian), Williston Basin; Schenk (1967), Macumber Formation, Mississippian, Canadian Maritime Provinces; Thompson (1970), Juniata Formation, Ordovician, central Appalachians. There is much evidence to support these particular cases but overgeneralization resulted (see Zenger, 1972a) to the point that the presence of dolomite alone was practically considered indicative of the supratidal environment! Textoris (1969) listed evidence to be used in establishing a penecontemporaneous, supratidal origin for an ancient dolostone: dolostone occurring closer to terrigenous sources and limestone farther away; intercalated limestones with characteristics of intertidal and shallow subtidal deposition; desiccation cracks; birdseye structures; intraclasts; evaporite crystal molds; vertical burrows; low, laterally-linked hemispherical stromatolites; dolomite rhombs in micrite. Although many of these pieces of evidence are in themselves equivocal, their collective nature seems to be convincing (Zenger, 1972a). I would add also a fine-crystalline texture and "flat" algal laminae which may be more common in the carbonate supratidal zone than are laterally-linked domal stromatolites. I prefer the use of the term, "peritidal," (Folk, 1970) to embrace both the intertidal and supratidal zones because of the frequent difficulty in distinguishing these paleoenvironments in their geologic record.

Judging from the evidence, a considerable portion of the initial carbonate and terrigenous sediments of the Little Falls probably accumulated in the peritidal zone. However, the presence of *Lingulepis*, ooids, and grapestone suggest the possibility of subtidal deposition for many intervals, and for some sequences or beds there is no remaining evidence indicating the environment of deposition; this subject is discussed in the final section of this monograph.

Hemispherical stromatolites are relatively common, particularly in Unit B. There are fewer occurrences of beds with wavy laminations which probably represent cryptalgalaminae. Also present are desiccation cracks and intraclasts, some being in the form of edgewise breccias (Figs. 15, 41). Assuming that these evidences do indicate at least some peritidal deposition, two characteristics of the dolomite are strikingly different from Holocene occurrences. The bulk of dolomite crystals in the Little Falls is in the 50 to 200 μm size range, in contrast to both the 1–5 μm crystal size of modern material and to the <50 μm size of the purported ancient analogs. Also, the dolomite in the Little Falls appears to be stoichiometric (or nearly so) and well-ordered, in contrast to the disordered and calcium-rich protodolomite of the Holocene (Fig. 74). It is possible that the diagenetic environment could have caused a coarsening of the texture by further replacement and/or neomorphism and an ordering of an original finely crystalline, penecontemporaneous peritidal protodolomite; Graf and Goldsmith (1956, p. 184–185) suggested that metastable protodolomite is a precursor of stable, stoichiometric, ordered dolomite. Evidence for or against this conceivable part of the history of the dolomite is lacking and permits only speculation. There are numerous examples of ancient "supratidal" dolostone in which the very fine-crystalline nature has been preserved (D. J. Shearman, 1969, oral communication). It has been demonstrated that protodolomite can persist over long periods of geologic time, having been reported from Paleozoic rocks (P. W. Choquette, 1971, written communication; Goldsmith and Graf, 1958; Lippmann, 1973, p. 188). In addition, there remains some doubt whether protodolomite is necessarily a precursor of ideal dolomite (Lippmann, 1973, p. 188).

Dolomitization of peritidal carbonate sediments need not occur penecontemporaneously in that setting.

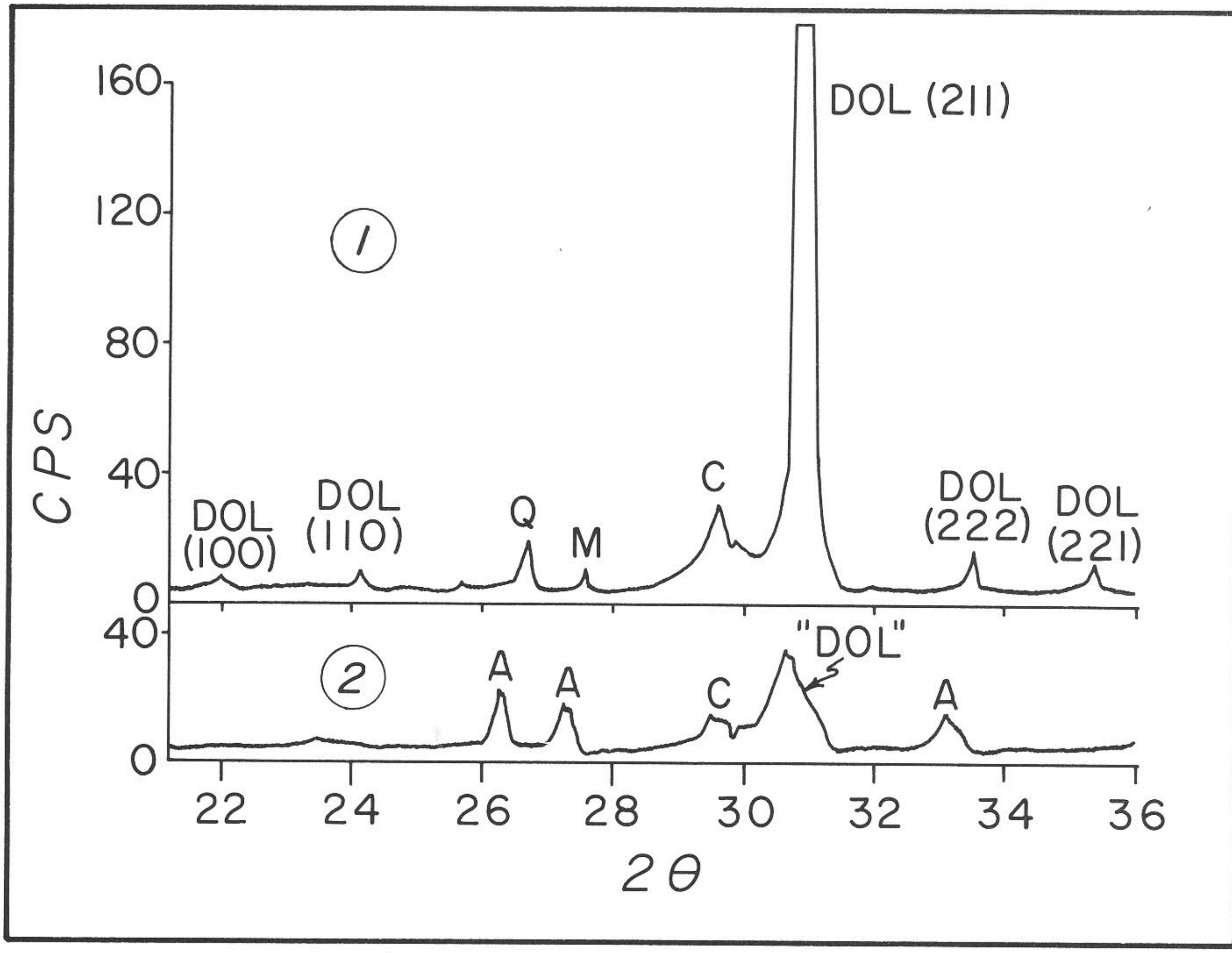

Figure 74. Comparison of X-ray diffractograms of sample of algal stromatolitic dolostone, Unit B (1), and one from Holocene dolomitized aragonite crust from supratidal zone, Bloxam's Key, Bahamas (2). Note line broadening and displacement of main dolomite (DOL) reflection {211} in the protodolomite (2). Also note apparent absence or insignificance of ordering reflections {100} and {221}. Although not shown here, a longer scan showed the absence of {111} in Holocene sample. A (aragonite), C (calcite), Q (quartz), M (microcline); modified from Zenger, 1972a.

In interbedded or mixed carbonates (e.g., dolomitic limestones) where there is a high correlation between beds or structures interpreted as peritidal and dolomitization, a very strong case may be made for penecontemporaneous dolomitization. On the other hand, Freeman (1966; 1972) observed various dolomitic units with peritidal characteristics in which dolomitization seems to have occurred much later in diagenesis. The Joachim and Plattin Formations (Ordovician) of Arkansas contain evidence of peritidal deposition, such as algal stromatolites, desiccation cracks, burrows and evaporite crystal molds (Freeman, 1966). However, he hypothesized a post-lithification origin for the dolomite based on the occurrence of dolomite rhombs along stylolites (not as insoluble residues) and floating in sparry calcite cement. In later work on the Triassic Muschelkalk Limestone of Spain, Freeman (1972) found that despite the ubiquity of peritidal characteristics in the unit, the dolomite was mainly joint-controlled and hence postorogenic. However, when dealing with pervasively dolomitized units, one is not able to correlate between dolomite and peritidal characteristics since all precursor carbonate has been replaced; such is the case in the Little Falls.

Over the years there had developed what I consider to be another overgeneralization (Zenger, 1972a)—that all significant dolomitization is dependent on hypersaline brines with high Mg^{2+}/Ca^{2+} ratios. The common association of dolostone and evaporites in the geologic record no doubt prompted this belief; it was further supported by laboratory experimentation and theory which showed that the high Mg^{2+}/Ca^{2+} ratios of brines could reverse the inhibiting effect of the hydration of Mg^{2+} ions and permit them to more readily enter a carbonate lattice, thus enhancing dolomitization (see, for example, Land, 1967). It seemed, then, that dolomitization at or near earth surface conditions would be kinetically impossible without having high Mg^{2+}/Ca^{2+} ratios. Studies of interstitial pore waters in Holocene dolomitic crusts in the Persian Gulf sabkha (Kinsman, 1973) and in the Florida Keys (Shinn, 1968b) further indicated a relationship between high chlorinity and high Mg^{2+}/Ca^{2+} ratios and dolomitization. Friedman and Sanders (1967) went so far as to claim that dolomite is an evaporite mineral.

Although I accept that many ancient dolostones owe their origin to hypersaline brines characterized by high Mg^{2+}/Ca^{2+} ratios, such conditions are not *necessary* for dolomitization. Atwood and Bubb (1970) claimed that their analyses of interstitial water from the same dolomitic crust studied by Shinn (1968b) on Sugarloaf Key showed nearly normal concentrations and Mg^{2+}/Ca^{2+} ratios. Interstitial waters of dolomite crusts on northern Andros Island, Bahamas, also showed essentially normal chlorinities and Mg^{2+}/Ca^{2+} ratios (O. P. Bricker, 1970, written communication). However, there is a good possibility that there has been a change in the chemistry of the interstitial water in the crusts since the time of dolomitization. In the Holocene carbonate sediments of Shark Bay, Australia, although evaporitic conditions prevail, dolomite is minor and the major carbonate mineral is aragonite (Davies, 1970, p. 179). There are numerous examples from the geologic record of evaporites associated with limestones rather than with dolomite (Sonnenfeld, 1964, p. 126).

There is no direct stratigraphic or petrographic evidence in the Little Falls to indicate that the dolomite in that unit results from evaporitic conditions in the depositional environment, or that it developed through any of the main early diagenetic processes that have been proposed to account for dolomitization by hypersaline solutions in many modern and ancient dolostones, such as: seepage refluxion (Adams and Rhodes, 1960); capillary concentration (Friedman and Sanders, 1967); and, evaporative pumping (Hsü and Siegenthaler, 1969). There are no evaporites in the outcrop or, so far as I am aware, in the subsurface. On the other hand, evaporites could have been removed by solution in the depositional environment (for example, see Muir and others, in press) or later during diagenesis.

In a paper affecting much subsequent research, Folk and Pittman (1971) proposed that length-slow chalcedony, namely lutecite and quartzine, is nearly always formed in a sulfate-rich environment associated with evaporites. Consequently they concluded that the presence alone of length-slow chalcedony could be taken as sufficient evidence for "vanished" evaporites in situations where they were no longer present. They presented a model explaining how the length-slow variety would be favored under high concentrations of sulfate ions. Although West (1973) had used the presence of lutecite to indicate the former presence of gypsum, he urged some degree of caution by stressing that other confirmatory evidence should be sought; he proposed that the presence of strontium minerals, particularly celestite, is also a positive indication of earlier calcium sulfate. He advised petrologists to use at least two of the various criteria in order to reliably ascertain the former existence of evaporites. There is not a great amount of chalcedony in the Little Falls but the length-slow variety is more abundant than the length-fast type. A common occurrence is in pockets associated with silicified ooids. Some specimens of such ooids contain just length-slow chalcedony, whereas at least one included only the length-fast type; often both varieties can be observed in the same thin section. Fibrous chalcedonic overlays of the siliceous ooids are very commonly length-fast. Although the length-slow, spherulitic chalcedony commonly occurs in rounded, mm-sized pockets resembling, on a small scale, the nodules of anhydrite in modern sabkhas and in some ancient analogs and more closely, small globular masses of gypsum in intertidal, algal-laminated sediments in a core from Abu Dhabi (personal observation, courtesy Marathon Oil Company), they generally are discrete and separated. This fact, coupled with the occurrence of length-fast chalcedony in similar pockets, weakens any contention that these represent pseudomorphs after nodular anhydrite or gypsum.

Furthermore, I have not recognized any definite pseudomorphs after crystals of sulfate minerals such as celestite. A sample (M3) of chertified cryptalgalaminate from Unit D in the abandoned quarry just east of Canajoharie (loc. 39, subunit 4) contains numerous subhedral to euhedral rhomb-shaped alkali-feldspar crystals averaging about 40 μm in length and exhibiting near-parallel extinction. Although such outlines could possibly represent former celestite crystals pseudomorphed by feldspar (D. J. Shearman, 1978, oral communication), I consider them to be original authigenic crystals; in fact, some appear to possess detrital cores. Such small alkali-feldspar crystals are not common elsewhere in the Little Falls but in fact are present in some other cherts. These rhomb-shaped feldspar crystals seem to be similar to the authigenic K-feldspar crystals with adularia habit in the Cambrian Jacobsville Sandstone of Michigan (Sibley, 1978).

One other possible example of pseudomorphs after sulfates is a unique mosaic of calcite crystals in a calcareous, quartzitic breccia with very minor length-slow chalcedony (sample D27) at Little Falls (loc. 18). The brecciated fragments are essentially all calcite but contain very minor dolomite. The possible "net-structure" consists of winding to straight seams of microcrystalline calcite outlining irregular or rhombic areas 200 to 500 μm in greatest dimension which are composed of one or more crystals of calcite (Fig. 75). There is a resemblance between these structures and the "net structure" in the Lower Purbeck Beds of Dorset, England (West, 1964, p. 321) which resulted from compression of gypsum lenses, the reduction of the interstitial material to thin walls, and the replacement of gypsum by calcite. Brown (1931, p. 517 and his Fig. 22) described "net-like" development of small calcite crystals as they begin to replace anhydrite in the cap rock of salt domes. Further replacement resulted in a completely fine-grained groundmass of calcite unlike the situation in the Little Falls sample in which there exist the two textures in the calcite. The irregular areas could represent former anhedral gypsum as described by West (1964), but the rhombic areas are more of a problem. Given this rhomb-shaped calcite and the small crystals of dolomite, it is very likely that the mosaic represents a rather unique kind of dedolomitization; the calcite again appears to be a very late event. I. M. West has examined a thin section of this sample (1978, written communication) and states that the fabric ". . . could be net texture." Neither did West note any crystals pseudomorphic after evaporites. Both West and D. J. Shearman (1978, oral communication), who also examined the slide, concurred that the relations suggest dedolomitization; there simply is no confirmatory evidence that the precursor dolomite(?) replaced former sulfates.

It appears, then, that the lack of definite evidence of the presence of strontium minerals detracts from the reliability of the presence of length-slow chalcedony alone as being indicative of the former presence of evaporites.

Interestingly, Mazzullo (1977, p. 393) and Mazzullo and Friedman (1977, p. 408) found no evidence, including length-slow chalcedony, for the presence, or former presence, of evaporites in either the Galway Formation or the Gailor Dolostone of the Saratoga Springs area, or in the Cambro-Ordovician rocks of the Mohawk Valley. However, partly coeval strata from the southern Champlain Valley of New York and Vermont showed definite evidence of periodic deposition under evaporitic conditions. More recently, Friedman (in press) has suggested that Cambro-Lower Ordovician dolostones of the northeastern United States generally show indirect evidence of the former presence of evaporites.

There is very little fossil material in the Little Falls, other than the relatively common algal stromatolites. I found less than a handful of occurrences of the inarticulate *Lingulepis*? and have seen a silicified, high-spired gastropod reportedly collected somewhere in the middle of the formation (D. M. Hurley, 1969, oral

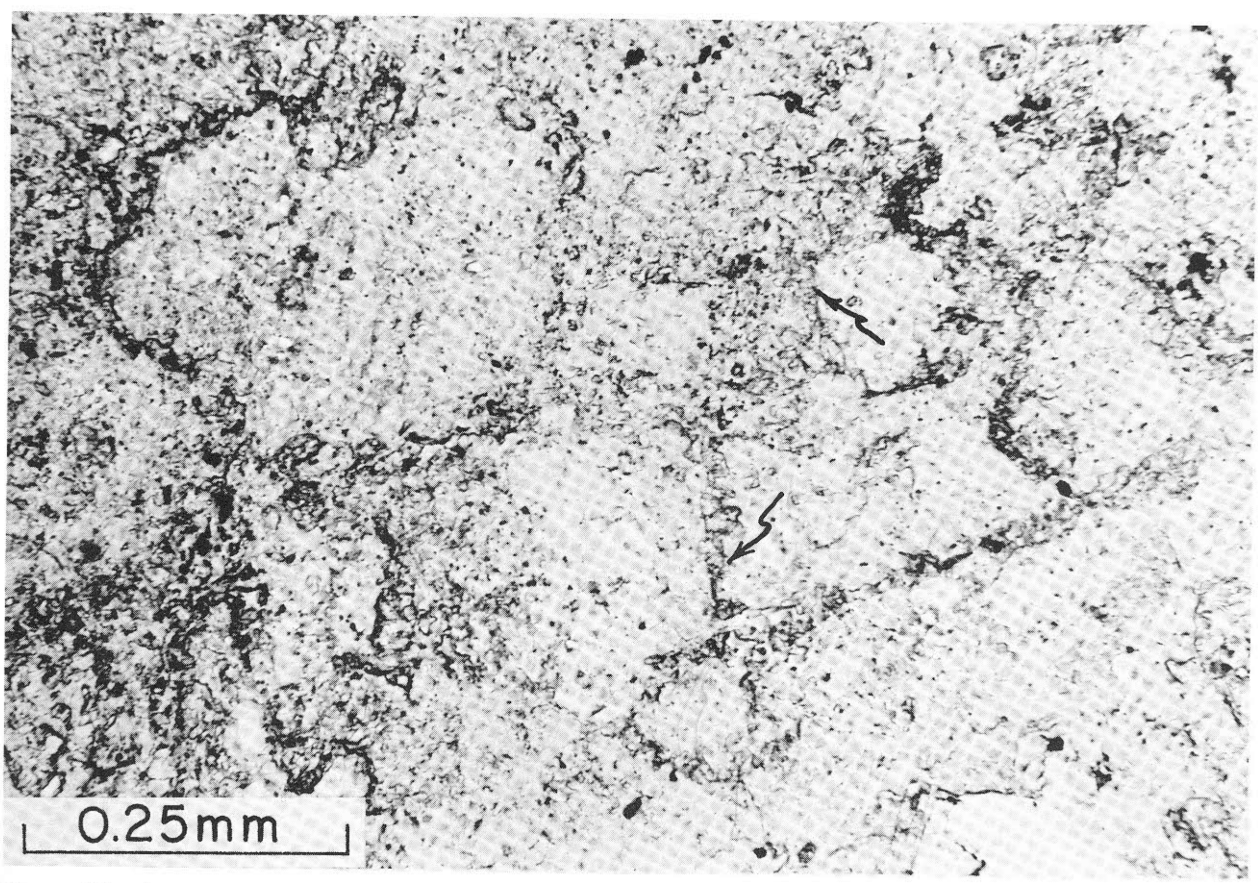

Figure 75. Photomicrograph of possible "net-structure" in calcite; "nets" consist of more finely crystalline calcite; note rhombic outlines (see arrows), suggesting dedolomitization; plane polarized light (D27).

communication) at the type locality. D. W. Fisher (1969, oral communication) found a loose specimen of the trilobite *Elvinia* that must have come from the Little Falls, at the foot of the Noses. Only one thin section contained relict, but recognizable, arcuate skeletal fragments of brachiopod valves or, less likely, trilobite segments (i.e., largest fragment is 6 mm long and 0.1 mm thick; Fig. 42). Possibly, fossils were more common in the carbonate sediments than now appears, but were later obliterated by dolomitization. However, trilobites in the laterally equivalent dolomitic Galway and in the limestones and dolostones of the Hoyt indicate that there was a respectable fauna at that time elsewhere in New York and that dolomitization did not obliterate all of them.

Halley and Eby (1973) concluded that the abundance of high-relief stromatolites in the Cambro-Ordovician stromatolitic sequences resulted from hypersalinity (not necessarily sufficiently hypersaline to induce the formation of evaporites) that excluded burrowers and grazers which would have preyed on the algal mats, preventing their buildup. There is considerable relief (up to 25 cm) between the stacked heads in the Little Falls, although the relief between the adjacent laterally linked "heads," of which the stacked heads are usually composed, is normally well less than 2 cm. Mazzullo and Friedman (1975, p. 2136) attributed the very presence of cryptalgal sediments in the Ordovician of eastern New York and western Vermont to excessive salinities which excluded predators from devouring the mats. (Given the presence of benthonic forms such as trilobites and brachiopods elsewhere in equivalent Upper Cambrian rocks in New York, and of an amazing variety of cavity-dwelling organisms in Lower Cambrian reefs of Labrador (Kobluk and James, 1978), it is unlikely that grazers had not evolved; however, the possibility is worth considering as it would indicate that algal stromatolites were not necessarily limited to salinities that would be restrictive to the mat eaters.)

Vugs are common in various stratigraphic intervals and the possibility that these represent the sites of former evaporites needs to be considered. The size of vugs ranges from a few millimeters (microvugs), through mostly centimeter-sized, to more rarely meter-sized caverns. Although there may be a general bedding control on vug distribution, they do not represent bedded evaporites; nor does their arrangement and shape (relatively widely spaced and irregular, though basically tabular) resemble the nodular anhydrite occurrences in the sabkha of the Persian Gulf (Shearman, 1966). Recently, Milliken (1978) described widely spaced silicified evaporite nodules ranging from 2 to 60 cm in size in carboniferous limestones of southern Kentucky and northern Tennessee. Such size and discreteness, atypical of sabkha evaporites, seems not unlike the distribution of vugs in the Little Falls. However, whereas Milliken attributed her occurrence to displacive growth of evaporites within invertebrate skeletons, there is no supporting evidence for a fossil control of evaporite formation, followed by solution, in the Little Falls. Stromatolitic intervals commonly are vuggy but vugs are by no means limited to such structures. One, generally small, type of vug is slitlike, and is parallel with stromatolitic laminae; these are probably sheet cracks resulting from desiccation but they constitute a small proportion of the total vugs. The larger vugs occur in a variety of dolostones as distinguished by grain size and color. Given the size range of the vugs, their shape, and the barrenness of the Little Falls, it is unlikely that they are voids left by the dissolution of fossils. An originally mottled dolomitic limestone could have the calcitic portions (with their greater rate of solubility) dissolved (see also Murray, 1960, p. 80). However, it would be difficult to account for the larger, meter-sized caverns, though rare, in this manner. I have presumed that most of the vugs are secondary and hence were relatively late in formation; possibly they formed prior to lithification. Heckel (1972) proposed an inorganic origin for "stromatactis" in calcilutite mounds in the Tully Limestone (Devonian, New York) that involved nonuniform compaction and internal gravity collapse of local areas of more loosely packed mud particles (rendered less coherent by decay of organic matter) during earliest unmixing of water that originally helped support the mass. However, the Little Falls vugs do not have the flat floored appearance, they do not occur in mud buildups, and no fossils are associated. Parks (1977) described tabular vugs in late Paleozoic phylloid-algae mudbanks in New Mexico. Two of his proposed mechanisms are dewatering contraction and gas bubbles. It seems that, other than the sheet cracks just mentioned, desiccation could hardly account for the larger vugs in the Little Falls. He referred to tabular gas bubbles in modern organic-rich sediments and he concluded that such bubbles could be the precursors of his tabular voids. Many vugs in the Little Falls are basically tabular and irregularities on this basic plan, coupled with enlargement, could have been caused by later solution. Obviously, this theory is incapable of being tested. The large size of the vugs might seem to be evidence against this possibility. On the other hand, I suspect that the greater part of the volume of large secondary vugs in the Little Falls, and other ancient carbonates for that matter, represent enlargement resulting from solution enhancement of the much smaller space which was initially dissolved. Thus, the exact cause of the vugs remains unsolved; I do think it unlikely that they represent evaporites.

Non-intraformational dolostone breccias are present at a few localities, notably at the railroad cut west of

Randall (loc. 56; Figs. 20, 21) and just northeast of Mayfield (loc. 68). The two most likely explanations are faulting and solution-collapse. Mazzullo and Friedman (1975, p. 2134–2135) described what they felt were evaporite solution-collapse breccias in the Lower Ordovician Great Meadows Formation in easternmost New York. They found a lack of size sorting and bedding, a gradational upward contact from disrupted to evenly bedded rocks, and a sharp lower contact as a surface affected by solution. The thicknesses of their breccias range from 2 to 7 feet (0.6–2.1 m). The impressive breccia exposed near Randall (loc. 56) has been described in the section on stratigraphy. There, the massive breccia (Figs. 20, 21) rests on Precambrian crystallines at the southwest end of the outcrop. To the northeast the breccia "interfingers" with well-bedded Little Falls dolostone; the thickness of the breccia (more than 20 m) would require the solution of a considerable thickness of evaporites resting directly on the Precambrian surface, were this to be the explanation. Such a thick, cross-cutting breccia would more likely result from cavern collapse following solution of carbonates rather than of evaporites (Beales and Oldershaw, 1969). There remains no evidence of solution, however, as the breccia rests directly on the Precambrian. I suggest that a fault exists between the Little Falls and the crystallines; the intact stratigraphy is that of the upper part of the Little Falls (upper part of units B, C, and D). The breccia could be the result of faulting but this possibility offers some problems—there are no clasts from the Precambrian gneiss in the breccia. The coarse polymict breccia near Mayfield (loc. 68), probably Little Falls in assignment, contains clasts up to 4 feet (1.2 m) in greatest dimension. It forms the center of the outcrop and grades laterally to the bedded sequence in which there are some brecciated fragments. Some of the clasts are cracked, the fractures being filled by the dark brown dolomitic sandstone matrix. Neither lower nor upper contacts of the breccia are exposed and there is no conclusive evidence to confirm or refute carbonate or evaporite solution collapse. A NE-SW trending fault (Fisher and others, 1970) cuts through the area, possibly very near this exposure. Whereas it is very possible that solution collapse has resulted in these breccias, their cross-cutting relations and the lack of definite evidence of evaporites suggests, rather, collapse over dissolved carbonates. Although also difficult to explain tectonically, the proximity of breccias to known or inferred faults suggests the possibility that these could be fault breccias. (It may be significant in this regard that a coarse breccia containing clasts up to 2.5 feet (0.8 m) in greatest dimension occurs in Canadian strata along Route 67 (loc. 78) northeast of Amsterdam; this exposure lies along an escarpment of a major fault (Fisher and others, 1970).)

Several chert laminae and thin beds are "brecciated"; they commonly appear as a "tranquil" breccia and seem to owe their origin to intra-unit fracturing that was for some reason focused in the chert. I interpret these fractures as having occurred shortly after chert formation and related to that process; the resulting "breccias" are not related to solution collapse.

Thus, while there is no one compelling evidence for the presence, or former presence, of evaporites in the Little Falls, there are several features which, if taken collectively at least suggest the possibility that hypersaline conditions, with or without evaporites, may have existed at times during deposition of the original carbonate sediments. Low temperature hypersaline waters are enriched in the heavy oxygen isotope, 0^{18}, and their corresponding $\delta 0^{18}$ values are positive; the same should be true for carbonates formed in such a medium (Milliman, 1974, p. 33). However, the limited stable isotope data (Table 2), in particular the strongly negative values of $\delta 0^{18}$, suggest that hypersaline solutions at earth-surface temperatures had essentially little, if any, effect on dolomitization of Little Falls carbonates. But, as is discussed later, all we can say is that the *bulk* of the crystals, as they exist presently, were not likely affected by hypersaline surface waters.

Recent paleogeographic reconstructions (Scotese and others, 1979) position central New York at about 19° south latitude during the Late Cambrian (Franconian). If this situation was analogous to present climatic belts, conditions might generally be expected to be more humid than arid. However, there are low latitude deserts today (e.g., in Africa and Australia) but they lie leeward of continental expanses. To the east of Late Cambrian New York lay eastern Canada, Greenland, and Scotland (Scotese and others, 1979) and much of this area may have been emergent lowland (Dott and Batten, 1976, p. 199) possibly effecting a relatively dry climate conducive to evaporate formation.

In the last few years there have been a number of both field- and theory-oriented reports suggesting an alternative to the contention that brines are necessary for dolomitization during early diagenesis. Perhaps the "pioneer" paper in this regard is that of Hanshaw and others (1971) on the dolomitization of the Middle Tertiary aquifer (Ocala Limestone) beneath Florida. There, brackish ground waters with Mg^{2+}/Ca^{2+} ratios just above 1 (resulting from mixing of potable water and ocean-derived brines) are affecting the replacement. They recognized that the three-phase system calcite-dolomite-water occurs at a Mg^{2+}/Ca^{2+} ratio of unity in ground water systems, appreciated earlier by Hsü (1963). Subsequently, independent work by Badiozamani (1973) and by Folk and Land (1975) has developed the concept of dolomitization by mixing of sea water and meteoric water which produces solutions of relatively low concentrations and Mg^{2+}/Ca^{2+} ratios (these models are termed "dorag" and "schizohaline," respectively). Theoretical calculations by Badiozamani (1973) indicate that mixing ground waters with up to 30 percent sea water results in undersaturation with respect to calcite but dolomite saturation increases. Dealing with the kinetics and thermodynamics of dolomite formation, Folk and Land (1975) contended that in hypersaline solutions, precipitation is rapid and true dolomite does not form owing to the insufficient time and energy available to permit the necessary ordering. Only where high Mg^{2+}/Ca^{2+} ratios exist can the metastable protodolomite form and this material is aphanitic and poorly ordered. But, at reduced salinities, dolomite can nucleate at lower Mg^{2+}/Ca^{2+} ratios, approaching 1:1 in ground water. They concluded that the absence of foreign ions and the slow rate of crystallization typical of the phreatic environment is conducive to the growth of limpid (clear) dolomite crystals; an ideal environment would be one of mixing of fresh and saline waters in which the salinity would be reduced but a relatively high Mg^{2+}/Ca^{2+} ratio maintained. In addition to the Wisconsin (Badiozamani, 1973) and subsurface Florida occurrences (Hanshaw and others, 1971), several other examples of such dolomitization have been given from the geologic record such as the Pleistocene of Jamaica (Land, 1973), the late Paleozoic of Bear Island, Svalbard (Folk and Siedlecka, 1974), the Ordovician strata of Egypt and Devon Island (Land, Salem, and Morrow, 1975), and the Lower and Middle Paleozoic rocks of Nevada (Dunham and Olson, 1978). Characteristics of such schizohaline dolostones are: 1) generally much coarser and clearer crystals than those in penecontemporaneous peritidal dolomite 2) sharp X-ray diffraction reflections attesting to a more ordered dolomite 3) typically negative ("light") δO^{18} values and, 4) low contents of Na^+ and Sr^{2+}. In their paper describing the "type locality" of the schizohaline environment on Bear Island, Folk and Siedlecka (1974, p. 1–2), defined this setting as "... one having extreme and rapid changes of salinity from hypersaline to dilute, even fresh. The environment is split ("schizo") between alternating epochs of hyper- and hyposalinity and seldom has normal sea water salinity. Strictly speaking, the term should be restricted to changes essentially occurring within the time of 'early' diagenesis, before deep burial of the rocks." They itemized evaporites, length-slow chalcedony, and very fine crystalline dolomite as evidence of hypersalinity and limpid dolomite crystals, coarse sparry calcite, and microspar calcite as evidence of hyposalinity. Land and others (1975, p. 1622) generalized that most marine carbonates are deposited initially from marine-influenced solutions but that subsequently they became flushed by cleaner continental waters. Microprobe analyses of crystals from the El Naqb Formation (Ordovician, Egypt) showed them to be depleted in Na^+ and Sr^{2+} in their outer zones relative to their cores, suggesting that the outer parts formed from a more dilute solution. These workers, as well as Folk and Siedlecka (1974), interpreted hollow, boxlike dolomite crystals to be the result of solution of an earlier impure, less stable dolomite formed by hypersaline solutions, there remaining an outer, clean part formed by more dilute waters. Although the mixing models have been rather well-received, several questions remain, not the least of which regards their potential to account for the widespread sheet dolostones of the geologic record. This may not be so formidable a problem. Dunham and Olson (1978) believed that subtidally deposited lime carbonates in east-central Nevada became dolomitized diagenetically in the subsurface as a result of dilution of marine pore water by fresh ground water derived from recharge areas to the east. They maintained that not only do fresh water lenses float on denser saline pore water beneath subaerially exposed carbonate terrain in humid climates, but these lenses also are capable of extending for some distance laterally into submarine sediments; intrusion of meteoric water does not require subaerial conditions. The lenses and surrounding brackish zones would shift with transgression and regression and consequently, the contacts between limestone and dolomite as well. They envisioned migrations of the contacts on the order of magnitude of several kilometers. Manheim (1967, p. 89) noted that JOIDES (1965) drilling off Florida revealed fresh and brackish waters in sediments 120 kilometers seaward of the coast. Although this situation may appear to be a hydrologic enigma, the possibility of such extensive fresh water lenses in the past, coupled with transgressions and regressions, does indeed suggest that such a model might account for widespread dolomitization.

Little Falls dolostones differ in several respects from purported schizohaline cases. As discussed, there is no definite indication of the former presence of evaporites. Crystals are seldom less than 10 μm, which is the size typical of the hypersaline phase of the schizohaline environment. Although no hollow, boxlike crystals of dolomite were observed in the Little Falls, there is some evidence that the centers of crystals are different than the margins. These effects include a possible corrosional, or pitted, appearance (Fig. 35), luminescent, Mn-rich zones (see also end of this section on "Dolomitization"), ferroan rims (Fig. 39), and the occurrence of calcite or chert (Figs. 56, 57) in many centers. Conceivably a less stable (protodolomite?) could be represented by the corroded, replaced, or filled-in centers.

The oxygen isotope data (Table 2) of six selected samples show significantly negative values of δO^{18}. The samples range in crystal size from relatively fine crystalline dolostone (decimicron-sized in an algal stromatolite (SH2; Unit B) and in a typical sample from Unit D (H71)) through a fine centimicron-sized sample from Unit C (H56) and two coarse centimicron-sized samples (E8 and N1; Units A and C, respectively) to the extreme of a large secondary dolomite rhomb from a vug. The values of $\delta 0^{18}$ range from highs of −4.45 and −5.61 ‰ in the finer crystalline samples through values below −6 ‰ for the coarser samples to −11.74 ‰ for the rhomb. The δC^{13} values, which show no trend with crystal size and which are all negative but one sample, range from +0.45 to −2.08 ‰, averaging −1.17 ‰. There is a general parallel with the isotope data of 19 samples from the Ordovician El Naqb Formation reported by Land and others (1975, p. 1607). Those workers also found that the larger the dolomite crystal the more negative the $\delta 0^{18}$ values, which they took as reflecting equilibration with lighter ground waters; the values ranged from +0.4 to −1.9 ‰, much higher than those from the Little Falls, even though the El Naqb values were sufficiently low to indicate to those workers that hypersaline waters were not involved in dolomitization. Their δC^{13} values, ranging from +1.1 to 1.8 ‰, are higher than those from the Little Falls. A comparison of the stable isotope data of the Little Falls with that of the Hansen Creek Formation (Ord.-Sil.) of central Nevada (J. B. Dunham, 1978, oral communication) reveals the same results; most values of $\delta 0^{18}$ from the Hanson Creek are higher than −4 ‰ and those for δC^{13} are slightly positive. The implication of the oxygen isotope data is that Little Falls dolomite, or the great bulk of it, formed under the influence of considerably lighter or warmer waters than would typical schizohaline dolomite. It is of interest to note that although δC^{13} values of the Little Falls samples are slightly depleted relative to those in the schizohaline units referred to above, all are in the range of marine carbonates. Degens and Epstein (1964) noticed that in their "late diagenetic-epigenetic dolomites of marine facies," δC^{13} was not affected by dolomitization. Land and others (1975, p. 1607) suggested that the carbonate C^{13} is more resistent to depletion than the carbonate 0^{18} because of the larger reservoir of carbon in the marine sediments relative to that in the HCO_3 of the diagenetic solutions.

Later development of much of the dolomite in the Little Falls is further suggested by the dolomite crystal size. Not only is there a dearth of very fine crystals (< 10 μm) that could represent the hypersaline phase of the mixing environment but the great bulk of crystals seems to be significantly coarser than the "limpid" dolomite of the dilute phase. Crystals from the El Naqb Formation range from 4 to 250 μm, with the modes occurring below 60 μm and with very little representation above 100 μm (Land and others, 1975, p. 1603–1604). Folk and Siedlecka (1974, p. 3) recorded a range from 50 to 100 μm for their limpid dolomite on Bear Island. Most of the crystals I observed in the "schizohaline" Hansen Creek Formation (courtesy J. B. Dunham, 1978, oral communication) are in the decimicron-sized range. The upper range of dolomite crystals (excluding those in vugs) in the Little Falls, however, is coarse centimicron-sized; these giants commonly exhibit undulatory extinction. An approximate average size of all Little Falls crystals is 100 to 120 μm, significantly greater than that for the schizohaline dolostones considered (Fig. 76). Specimens do not exhibit the modes in the finer crystalline sizes (<

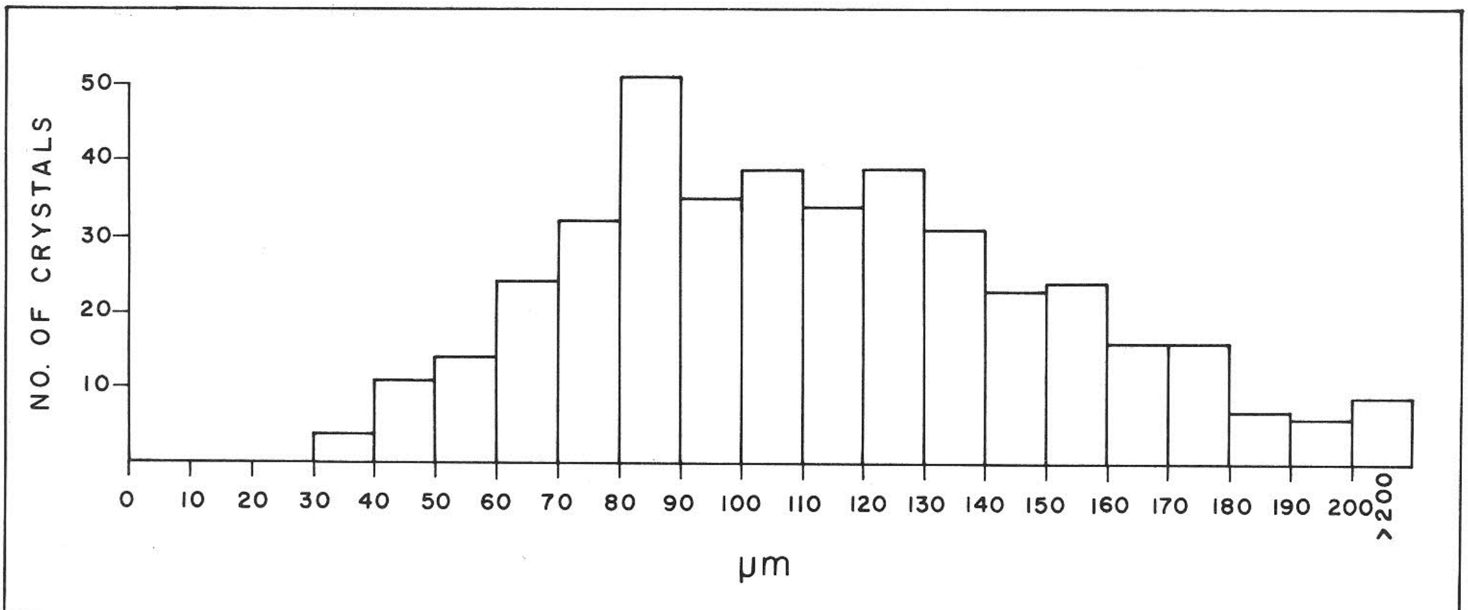

Figure 76. Size distribution of dolomite crystals in typical sample of Little Falls Dolostone (H56); see text for discussion.

60 μm) shown by Land and others (1975).

The combination of complete dolomitization, generally coarse to very coarse crystal size, and very depleted δO^{18} values strongly suggest that much of the dolomitization (i.e., the continued neomorphic growth of the dolomite crystals and the diagenetic development of overgrowths) occurred at burial depths well below the sea water-meteoric water mixing zone (i.e., 100 meters). The larger dolomite crystals, including void-filling dolomite, possess many of the characteristics of the late diagenetic dolomite in the Ste. Genevieve Formation (Mississippian, Illinois Basin) described by Choquette (1971): low oxygen isotope values, ferroan dolomite as rims or throughout entire crystals, and undulatory extinction. I, too, would judge this kind of dolomite to be late diagenetic.

There is ample opportunity for dolomitization by phreatic ground waters below the zone of influence of surface generated solutions alone. These deeper ground waters may consist of juvenile waters, meteoric waters, and connate (formation) waters. The latter is derived ultimately from sea water (Degens and Chilingar, 1967, p. 480), although dissolution of carbonates and evaporites and salt filtration have made notable contributions (Blatt, Middleton, and Murray, 1972, p. 338) and such processes have caused considerable changes from sea water, such as an increase in Ca^{2+} and Sr^{2+}. Runnells (1969) described possible diagenetic effects that could result from the mixing of subsurface solutions if they are undersaturated with respect to one or more minerals. He showed that mixing of waters that have an ion in common with the associated rock-forming minerals ("common-ion effect") could result in supersaturation and precipitation at low concentrations. For example, waters with low concentrations of calcium chloride (relatively common) in contact with carbonate rocks might cause the precipitation of dolomite (Runnells, 1969, p. 1196–1197; Degens and Chilingar, 1967, p. 480).

The impressively negative values of δO^{18} in Little Falls samples represent the major phase of dolomitization. These values seem too low to represent dolomitization by meteoric water-sea water mixing at temperatures commensurate with those in the shallow burial zone or eogenetic zone (Choquette and Pray, 1970). It is unlikely that unheated meteoric water alone in a vadose zone would provide the amount of light oxygen required (see Choquette, 1971); there is no evidence of vadose silt-filled cavities, as described by Dunham (1969), in the Little Falls although such evidence could be hard to come by in the pervasively dolomitized unit. I suggest that the major part of diagenetic dolomite growth, including the outer zones of smaller crystals, the ferroan dolomite rims, and the main bulk of the large dolomite crystals with undulatory extinction, as well as the development of the negative δO^{18} values were effected by warm to hot ground waters, either connate waters, hydrothermal waters, or possibly mixtures of these.

The strongly negative oxygen isotope values from the Little Falls are not greatly different than those reported from incipient hydrothermally affected rocks in the Leadville Limestone (Engel and others, 1958), nor from those reported by Friedman and Hall (1963) in lower temperature environments associated with lead-zinc ore bodies in the Upper Mississippi Valley. The latter workers noted little fractionation between dolomite-calcite pairs, a situation I have also noted in a sample from the Silurian Lockport Formation (western New York). Such relationships suggest the possibility of a reaction between calcite and deeper solutions during late diagenetic neomorphism prior to dolomitization.[1] However, there are no co-existing calcite-dolomite pairs in the Little Falls. The final phase of dolomitization no doubt involved neomorphism and grain growth of the groundmass dolomite as well as passive precipitation of the mineral in voids.

δO^{18} values for late diagenetic dolostone in the Ste. Genevieve Formation range from -5.0 to -7.3 ‰ according to Choquette (1971) and are thus very similar to those in the Little Falls. Accordingly, I at first assumed that the temperature of formation of the late diagenetic dolomite of the Little Falls probably was in the range of 50°C to 130°C as Choquette (1971, p. 334) concluded for the Ste. Genevieve. The presence of anthraxolite certainly suggests relatively high burial temperatures. Tissot and others (1974) pointed out that the H/C and O/C atomic ratios of bituminous substances decrease with increasing burial depth and higher temperatures. Based on the hydrogen, carbon, and oxygen concentrations of two samples of Little Falls anthraxolite (Dunn and Fisher, 1954), the H/C atomic ratios are about 0.26 and the O/C ratios about 0.03 suggesting very high temperatures possibly even below the oil "window" ($>150°$). Recently, through the courtesy and efforts of E. R. Olson and J. Freckman, University of California, Riverside, an attempt was made to conduct fluid inclusion studies on a few selected specimens of the Little Falls. Four specimens (H71, H56, E8, and N1) with isotope analyses (see Table 2) were examined optically and were all found wanting in having a satisfactory number of sufficiently large inclusions. Specimen N1 was observed to contain

[1] Discussions with D. F. Sibley (1979, oral communication) have emphasized the two possibilities for the development of coarse, obliterative (="neomorphic"; see Beales and Hardy, 1977) dolomite. This fabric could result from neomorphism of earlier-formed dolomite or by late-stage replacement of calcite. As the following discussion will show, there are other suggestions of neomorphism of earlier dolomite. This possibility might better explain the range of dolomite crystal sizes and the fact that there is no predolomite calcite remaining.

some inclusions of about 12 μm diameter. Four "workable" inclusions were analyzed and the following temperatures (°C) of homogenization (assumed to represent the approximate temperature of formation) were recorded: 94°, 128°, 131°, and 132° (E. R. Olson, 1978 oral communication). These values are not pressure-corrected (depth of burial not known); such correction would result in even higher temperatures! I recognize that these few data points for one sample hardly provide a basis for a firm conclusion regarding the whole formation. However, the figures at least seem to support the contention, based on other evidence, such as isotope data, presence of anthraxolite, and textural relations, that the bulk of the dolomite formed in contact with hydrothermal (most likely) and/or hot connate (formation) waters. Such waters, by exchange with the pre-existing dolomite during neomorphism or by precipitation of dolomite overgrowths, probably accounted for the low values of $\delta 0^{18}$ observed. I assume that fractures and vuggy porosity permitted access to the rocks for the hot solutions.

I would like to acknowledge the possibility that although the final product consists of coarse to very coarsely crystalline dolostone characterized by negative values of $\delta 0^{18}$, dolomitization could have commenced in very early or early diagenesis while the carbonate sediments were in communication with surface-derived solutions, either sea water with its vast reservoir of Mg^{2+}, or a mixture of sea water and meteoric water. Such early dolomitization might be represented by the finest crystals and by the centers of the larger ones. The presence of very fine-crystalline dolostone, of very fine crystals in more coarse crystalline dolostone, and dolomite crystals with dissolved and filled-in or replaced centers, similar to those hollow, boxlike crystals reported in schizohaline dolostone, are, admittedly, flimsy pieces of evidence to support such a suggestion of early origin. This suggestion remains sheer speculation in view of the lack of oxygen isotope data for larger, zoned, individual crystals which could shed light on the matter.

If we assume that all or most dolomitization oc-

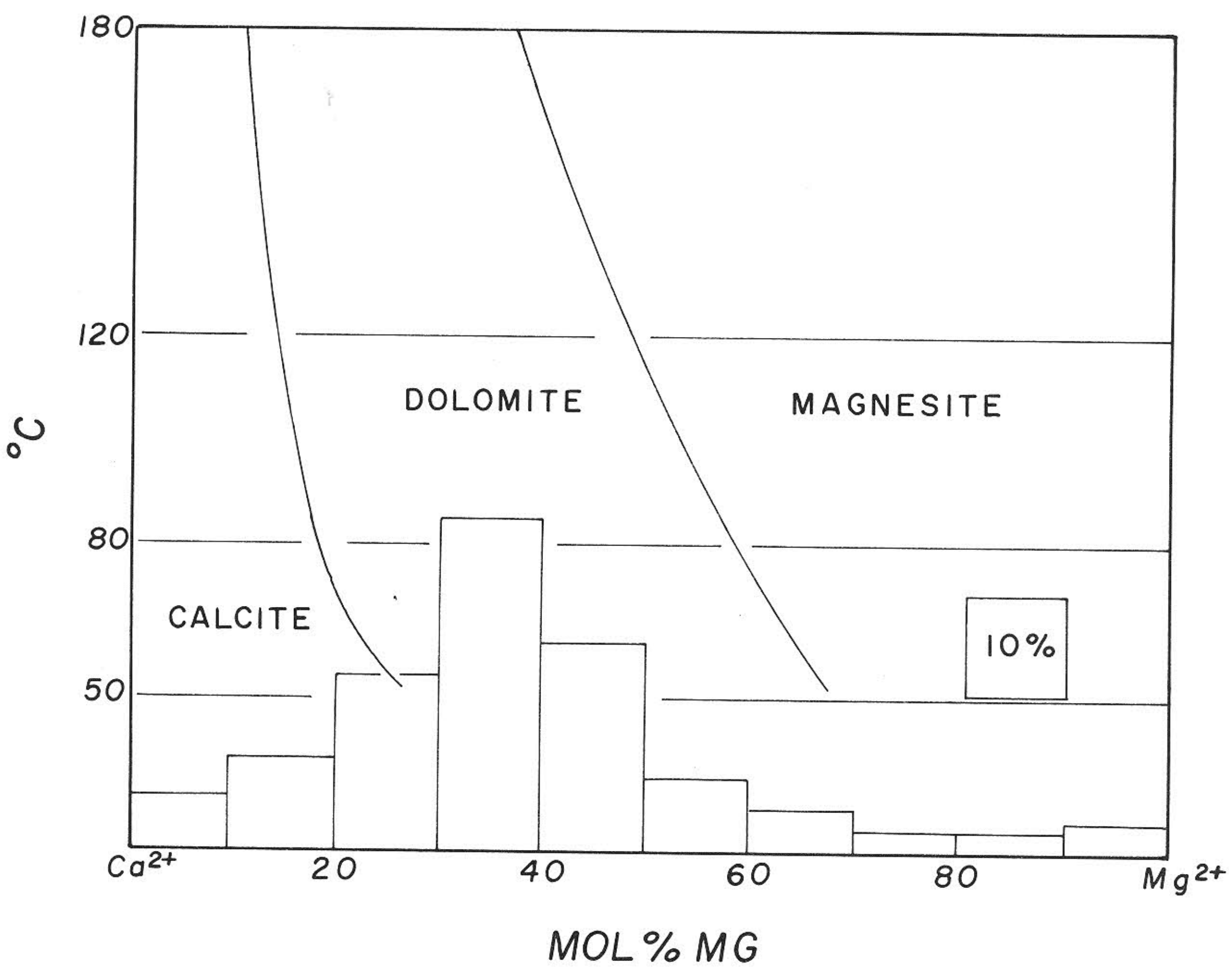

Figure 77. The equilibrium positions for calcite-dolomite and dolomite-magnesite and the frequency of Ca^{2+} and Mg^{2+} in pore solutions (modified from Usdowski, 1968, p. 30); see text.

curred subsequent to the time when the carbonate sediments were affected by sea water itself, there remains the question of a source of magnesium. There is no evidence of high-magnesian calcite-precipitating organisms to provide even a partial supply of magnesium. Magnesium-rich organic laminae of algal stromatolites could have released magnesium even at a late stage (Gebelein and Hoffman, 1973), but these structures are much too limited to account for the dolomitization of the main, nonstromatolitic mass of the Little Falls.

Normally, connate brines are impoverished in magnesium compared with sea water. Blatt and others (1972, p. 338) and Folk (1974, p. 46) point out that the lower content of magnesium could be due to its extraction for dolomitization and authigenesis of chlorite. A concentration of dissolved salts, including magnesium could develop on one side of a semipermeable rock body by salt filtration (Berner, 1971, p. 111); such brines might have sufficiently high concentrations of magnesium to dolomitize limestone. There is, however, in this case no evidence of shale or compacted clay horizons which would be required for the extensive dolomitization.

Neither are there laterally adjacent shale sequences, the compaction of which could provide magnesium-rich solutions for dolomitization of the original carbonates. Some magnesium could have been supplied by solution of dolostones of the overlying Tribes Hill Formation but there is a question of quantity to begin with, as well as a lack of evidence of solution in that unit which would have been required to provide a significant amount of magnesium.

The Precambrian crystallines acted as a literal basement for the Little Falls throughout most of its extent in the western Mohawk Valley. Ground water from the Precambrian metamorphics of the Adirondacks could have contained significant amounts of magnesium to promote dolomitization (see Sonnenfeld, 1964) despite the fact that the Mg^{2+}/Ca^{2+} ratios of the waters probably were relatively low owing to the abundance of a Ca-bearing plagioclase compared to the less common magnesium contributors, hornblende and biotite (Garrels, 1967, p. 406). Given that there was little dolomitization, and hence loss of magnesium prior to dolomitization of the Little Falls, the basal carbonate unit on the Precambrian in the subsurface, connate brines may have been relatively enriched in that element, in contrast with their normal content ranging from about 1/6 to 1/12 that of sea water (Folk, 1974, p. 47).

Although there would probably have been relatively low Mg^{2+}/Ca^{2+} ratios in either connate brines or hydrothermal waters the more critical issue for subsurface dolomitization was the total amount of available magnesium. The higher temperatures of the mesogenetic zone (Choquette and Pray, 1970), particularly in hydrothermal waters, permit dolomitization by solutions having lower Mg^{2+}/Ca^{2+} ratios than those nearer the surface. The number of non- or partially-hydrated Mg^{2+} ions becomes greater at higher temperatures, thus reducing this inhibiting effect on dolomitization (Murata and others, 1972, p. 4). Neither is kinetics so critical, the conditions necessary to obtain equilibrium being stable over longer periods of time than under earth surface conditions. According to Usdowski (1968, p. 28–31) time and temperature will permit dolomitization of limestone precursors providing that the reacting solutions have a higher content of magnesium than those at equilibrium with calcite and dolomite; he claimed that most pore waters contain more magnesium than correspond to this equilibrium (see Fig. 77).

Very limited published data are available on the chemistry of ground water in the Precambrian crystallines north of the Mohawk Valley (R. M. Waller, 1978, written communication) and essentially none for Herkimer County wherein lies the type Little Falls. Only four analyses have been reported (Waller and Ayer, 1975) of relatively "fresh" waters (i.e., low concentration of dissolved solids) from Precambrian rocks in the Black River Basin several tens of miles north-northwest of Little Falls. Three of these list figures for calcium and magnesium content, the average Mg^{2+}/Ca^{2+} ratio by weight being 0.19; corrected to a molar ratio, this would be 0.32. Referring to Usdowski's data (1968, p. 30; see Fig. 77), waters of 24 mol % Mg^{2+} should dolomitize calcite at slightly less than 60°C, which would not seem to be unreasonable in this case. Similarly, Murata and others (1972, p. 4) stated that "At temperatures around 60°C, solutions with a magnesium/calcium ratio of about 0.33 to 2.0 are at equilibrium with dolomite; those with lower and higher ratios are at equilibrium with calcite and magnesite, respectively." They do, however, point out that concentration of ground waters can be significant and that low salinity pore water may not promote dolomitization even though the Mg^{2+}/Ca^{2+} ratios fall into the appropriate range. Lovering's data (1969) for dilute solutions seem to indicate that for a Ca^{2+}/Mg^{2+} molar ratio of 3.15, a minimum temperature of more than 160°C would be required for dolomitization! Owing to their "freshness" (generally less than 100 mg/L, or 100 ppm), the reported values of calcium and magnesium content are undoubtedly, to some unknown extent, unrepresentative of ground waters that have been in contact with the crystallines for a longer time. And, there is also the good possibility of differences between these few analyses and the chemistry of the Precambrian crystalline ground waters back in the early Paleozoic. On the other hand, the range in Ca^{2+}/Mg^{2+} ratios in formation waters is great (Blatt and others, 1972, p. 338) and it may have been more likely that lower Ca^{2+}/Mg^{2+} molar ratios could be provided by such waters. Of course, if earlier dolomitization was followed by aggrading neomorphism with reequilibration with ground water, the Mg^{2+} for the earlier stage could have been sea water or mixed sea water-meteoric water.

In summary, although original Little Falls carbonate sediments and their terrigenous associates no doubt accumulated in peritidal and adjacent shallow subtidal environments, little dolomitization occurred there, and concentrated sea water probably played an insignificant role in the process; it is impossible to prove whether the more finely crystalline dolomite formed penecontemporaneously in the peritidal zone. Possibly, some dolomitization was accomplished in a shallow-burial schizohaline environment but it is very unlikely that light meteoric waters produced the final observed negative values of δO^{18}. The coarse crystallinity, presence of anthraxolite, oxygen isotope values, and scant fluid inclusion data, suggest that most dolomitization, including neomorphism of pre-existing dolomite, was effected by deeper subsurface waters, probably hydrothermal waters or hot formation waters (or mixture of these waters). Given the higher temperatures and time available in the mesogenetic zone, either of these waters or mixtures of them, could have provided sufficient magnesium. Although the final product is classed as late diagenetic, the total dolomitization picture may represent replacement at various diagenetic times with neomorphism of the dolomite marking the final phases. If such were the case, it is suggested that the more finely crystalline dolostone in parts of Unit B and in much of Unit D, experienced an earlier cessation in replacement and/or neomorphism than the coarser dolostones of these units, as well as that in typically coarser Units A and C.

The idea of dolomite grain growth and/or overgrowth cementation might be tested with trace element and cathodoluminescence study of individual crystals. Preliminary work with the luminoscope reveals some zoning parallel to growth faces but inside the ferroan dolomite rims, in cases where the two types of zones occur in the same specimen. Of the five Little Falls samples examined, three showed luminescent zones. One from Middleville (loc. 11) displayed two well-defined zones, an outer thin one (a couple of μm in width) and a neighboring, slightly more internal, wider one (about 10 μm in width). Zones similar to the wider one were observed in specimen H67 from Little Falls (loc. 17) and in specimen M3 from Canajoharie (loc. 39). All zones are found toward the periphery of the crystals but inside an outermost, dark external zone immediately parallel to the crystal face. This dark zone shows less luminescence than the normal background luminescence of dolomite; these dark zones are the ferroan dolomite rims described earlier.

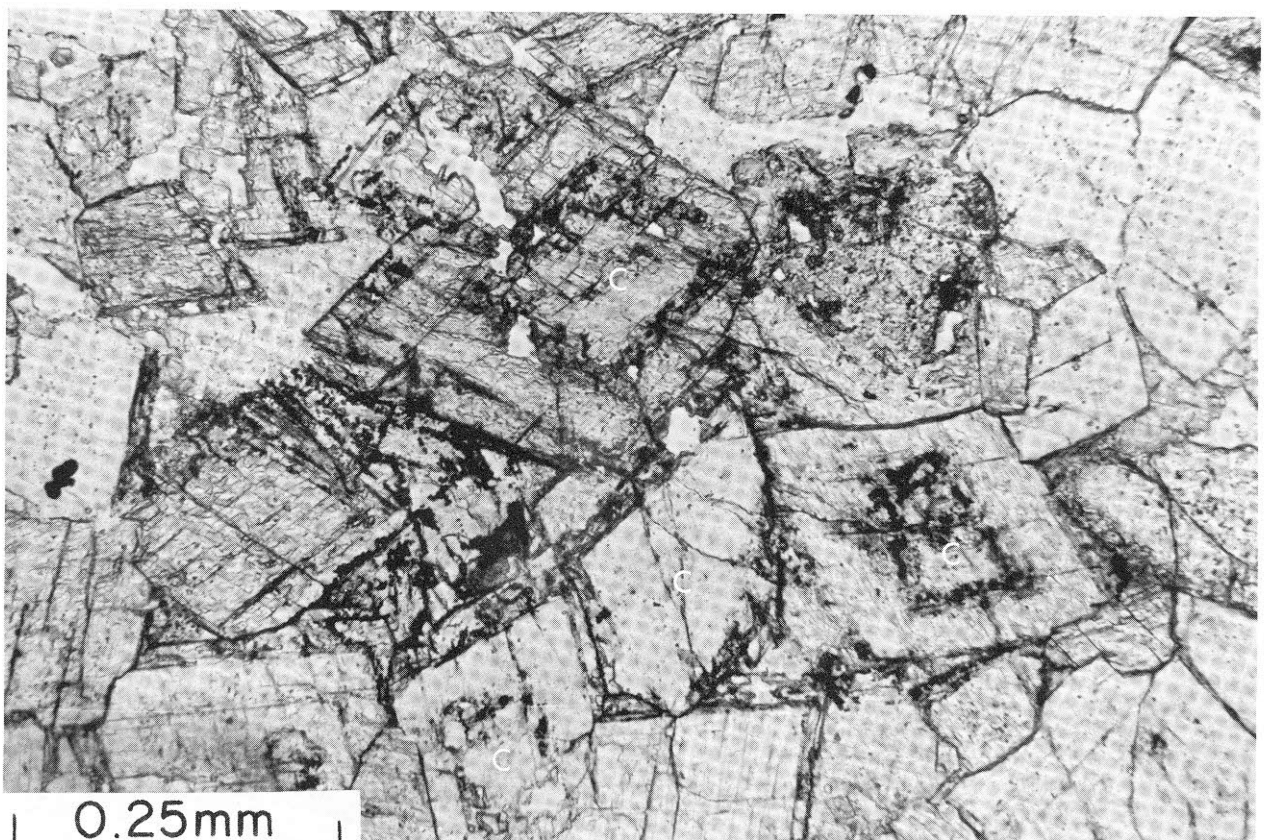

Figure 78. Photomicrograph of calcite centers (C) surrounded by rhomb-shaped limonitic bands within dolomite crystals; plane polarized light (A44).

According to Pierson (1977), luminescent zones mark small concentrations of Mn^{2+}, as low as 100 ppm; Fe^{2+}, on the other hand, occurring with Mn^{2+}, tends to inhibit luminescence in dolomite if it reaches 10^4 ppm (= 1 wt% Fe^{2+}), which is about the amount determined semi-quantitatively by electron probe microanalysis (Fig. 39). A sample (N1) from Flat Creek (loc. 40) composed in part of coarse centimicron-sized crystals, has no internal zoning, which would have added support to the working hypothesis that the centers of the larger crystals represent much earlier development. However, one sample is insufficient to draw conclusions from; more work is warranted in this promising area of study, not only for the Little Falls but for dolostones in general. Much as we still need control at the field and thin section scales, the characteristics of individual dolomite crystals assume greater and greater significance in our endeavor to understand dolomitization.

DEDOLOMITIZATION

The term dedolomitization is used, owing to its familiarity, in spite of the persuasive argument for "calcitization" by Smit and Swett (1969). If, as I believe, dedolomitization occurred in the Little Falls, it did so to a relatively limited degree. In particular, there are two fabrics, mentioned earlier under "Mineralogy," which I suggest may represent dedolomitization.

One such fabric consists of rhomb-shaped calcite centers of dolomite crystals (Figs. 78, 79). More commonly observed in specimens from the overlying Tribes Hill, these are rare in the Little Falls. The calcite centers, unlike the polycrystalline dedolomite described by Shearman and others (1961), consist of larger, single crystals in optical continuity with the surrounding dolomite. It is more likely, however, that they represent passive precipitation in a void resulting

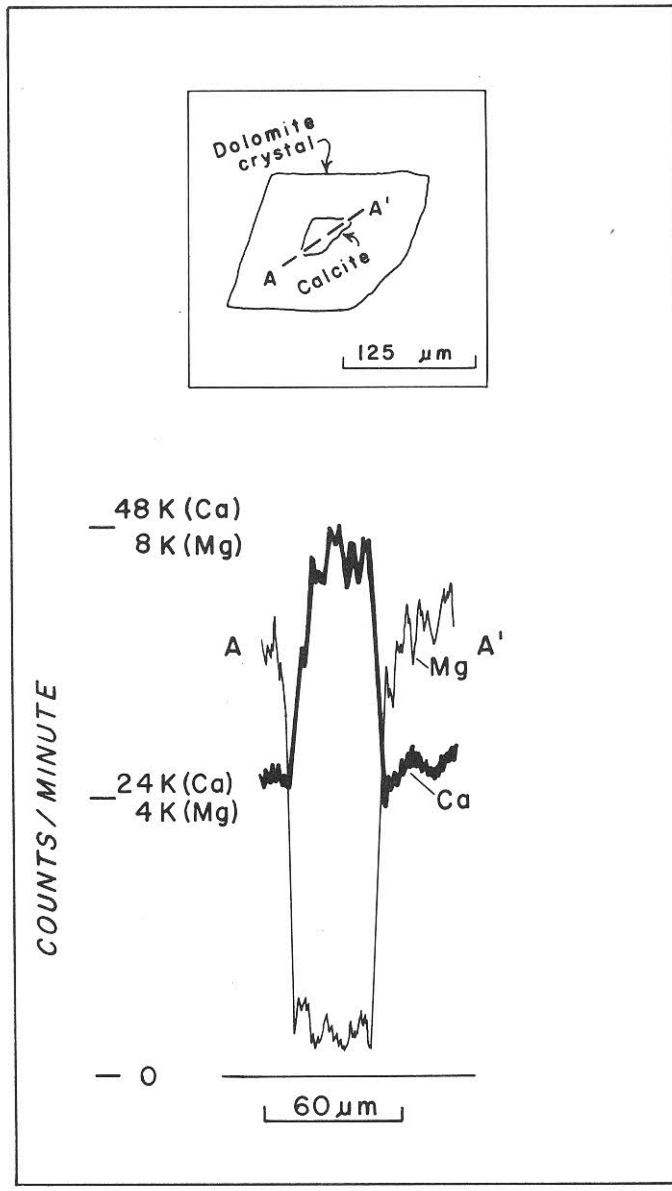

Figure 79. Electron probe stage traverse for CaKα and MgKα across calcitic center (along line A-A¹ —see inset at top) of dolomite crystal (12SJ).

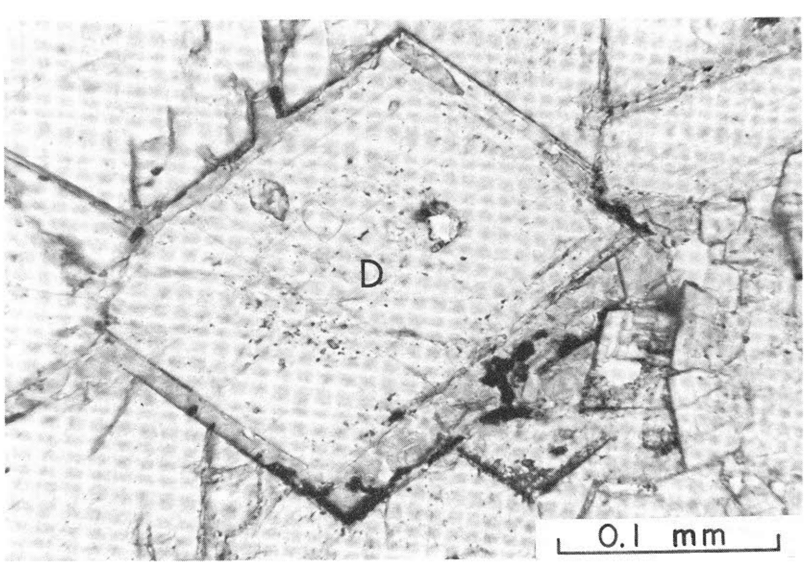

Figure 80. Photomicrograph of calcite rim (darker owing to staining with Alizarin Red S) on dolomite crystal (D); plane polarized light (A40).

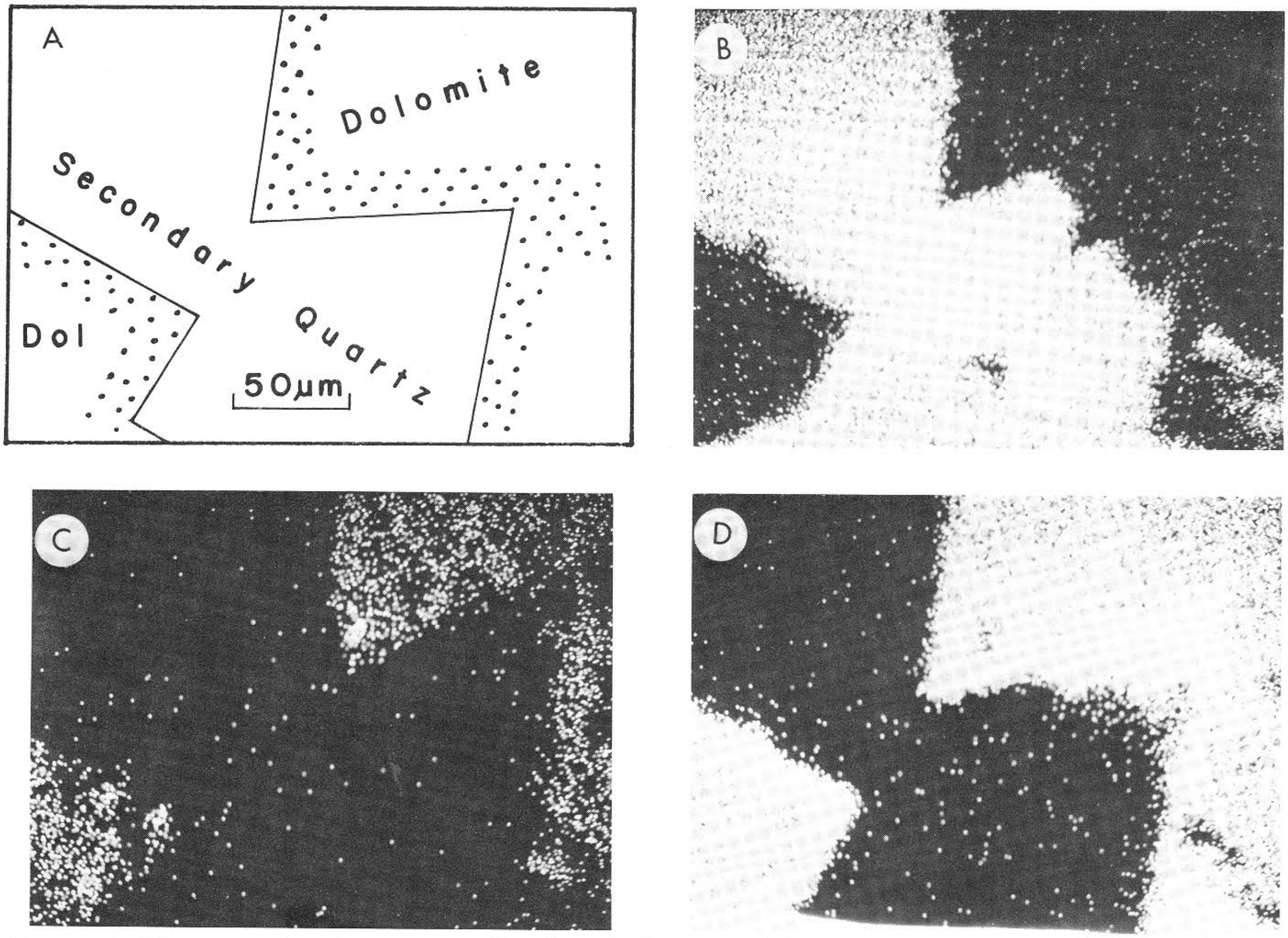

Figure 81. Electron probe photomicrographs of epitaxial rims on dolomite crystals. A, sketch of area of analysis, stippled pattern representing calcite rims; B, C, and D, beam scan images for SiKα, MgKα, and CaKα, respectively (A40; after Zenger, 1973, p. 120).

from solution of the central part of dolomite crystals. Longman and Mench (1978, p. 248–249, 270, 272) attributed a similar fabric in the Cretaceous Edwards Limestone (Texas) to leaching of the centers of dolomite crystals followed by a refilling with calcite; their reference to this calcite as "dedolomite" is somewhat perplexing.

The other, more interesting fabric, is that of epitaxial calcite borders (as distinguished by staining with an acidic solution of Alizarin Red S and by electron probe microanalysis) on dolomite crystals. I have described this fabric and its possible generation by dedolomitization elsewhere (Zenger, 1973) and the reader is referred there for details. One type of border, the calcite rim (Figs. 80, 81), is even and uniform in thickness, ranging between 5 and 25 μm. A second type of border, also composed of calcite optically continuous with the host dolomite, consists of coarser crystals and forms an irregular margin (Fig. 82); these bear some resemblance to the "calcite envelopes" of Goldman (1952) and that term is also used here. I believe that these "calcite envelopes" formed by passive precipitation on the dolomite crystals. Although this may have been the mechanism for the development of the calcite rims, I favor the process of dedolomitization in that case.

These epitaxial rims commonly are followed outward by the late void-filling calcite; it is assumed that the calcite of both the rim and void-fill are essentially of the same age as they are in close spatial and optical relationship. It has been shown that void-filling calcite forms enfacial junctions against authigenic quartz, indicating a later development of the calcite. Where dolomite crystals with rims are enclosed within authigenic quartz crystals (Fig. 83). it seems more feasible to account for the relations by dedolomitization rather than by passive precipitation of calcite into a "moat" formed by very even dissolution of the dolomite. Discontinuities in the rims exist and would be less likely explained by passive precipitation. Although the inner margins of most rims are even, the occurrence of some with very ragged inner edges (Zenger, 1973, p. 122) suggests a truncation of the dolomite crystal by replacement and would be difficult to account for by

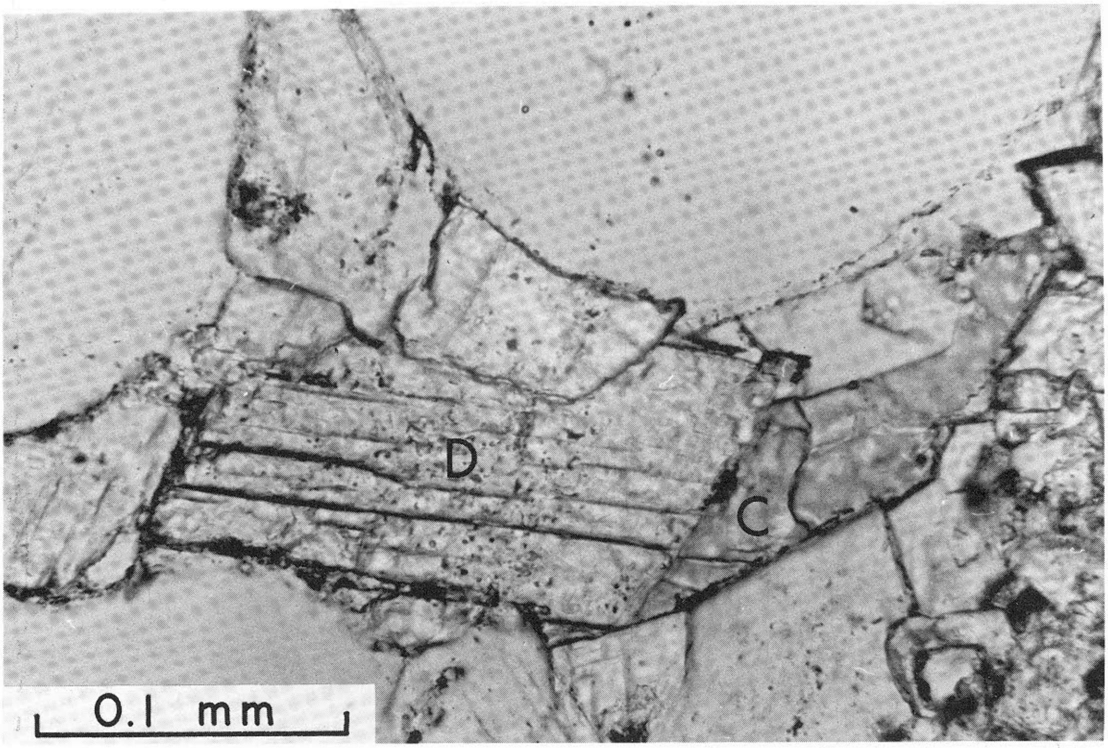

Figure 82. Photomicrograph of irregular calcite envelope (C) (stained with Alizarin Red S) on dolomite crystal; large light grains are detrital quartz; plane polarized light (A40).

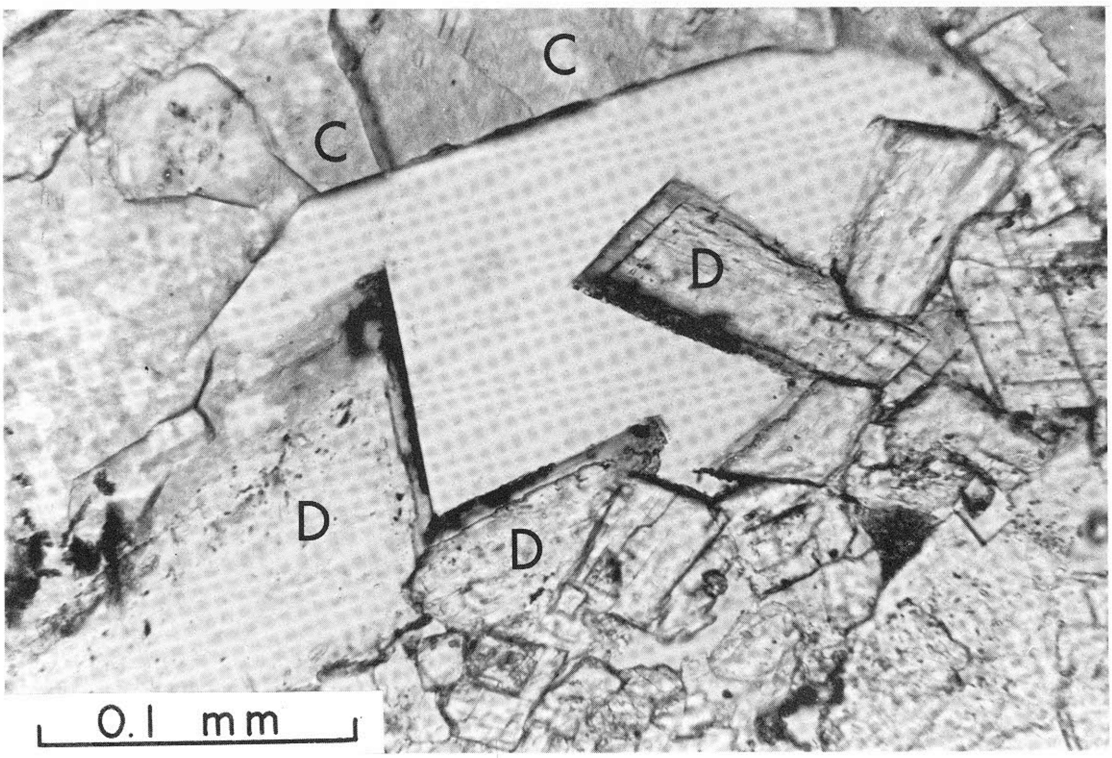

Figure 83. Photomicrograph illustrating relations between calcite rims (stained and darker), void filling calcite (C) and secondary quartz (light, center). Along upper portion of photo are enfacial junctions of void-filling calcite (C) against the authigenic quartz. Extending into quartz from lower side are several dolomite crystals (designated "D") with their darker calcite rims; plane polarized light (A40).

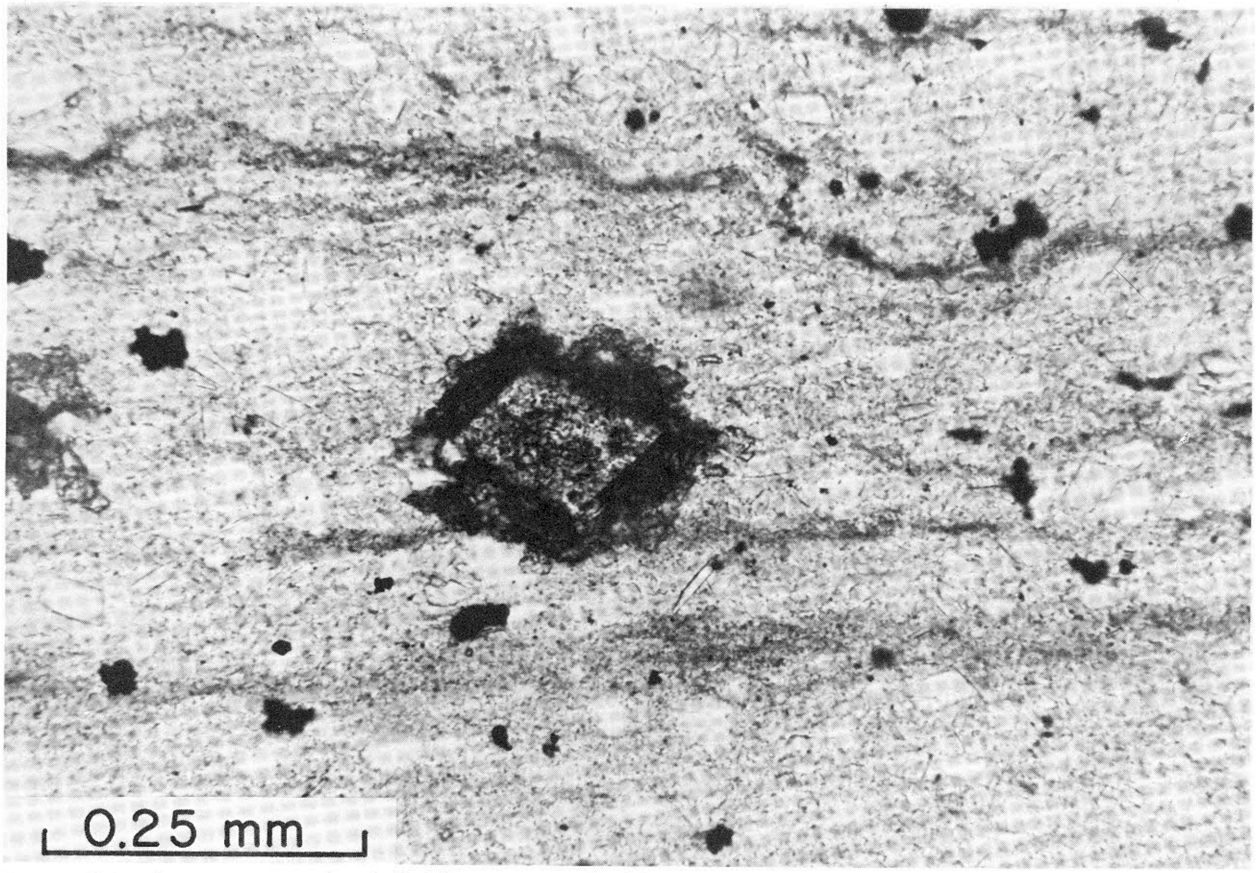

Figure 84. Photomicrograph of dedolomitization(?) fabric in laminated, microstylolitic chert; note conspicuous patch of dark (partly owing to stain), microcrystalline calcite, displaying crude rhombic outline, epitaxial on inner dolomite rhomb; small, white crystals are authigenic feldspar (M3): plane polarized light (see text for further description).

precipitation. The iron content, as determined by electron probe microanalysis, is variable; I think this situation suggests dedolomitization of the margins of dolomite crystals, only some of which were previously composed of ferroan dolomite. The variable iron content, coupled with the fact that by far the great majority of ferroan rims are not calcitic, suggests that ferroan dolomite alone did not control the sites of dedolomitization.

Calcite zones resembling these rims, but *within* dolomite crystals have been noted by others; Katz (1971) and Wood and Armstrong (1975) attributed these to dedolomitization *during* crystal growth.

In addition to these described fabrics which probably represent dedolomitization, there are two other unusual possible examples. In one case already briefly discussed under "Dolomitization" as a possible case of relict net-texture in calcite (loc. 18, subunit 23, specimen D27; see Fig. 75), the microcrystalline "net," although generally irregular in its pattern, commonly displays partial rhombic outlines. The calcite crystals do not always extinguish as units within the microcrystalline seams. The presence of the rhombic outlines suggests dedolomitization. According to D. J. Shearman (1978, oral communication), dedolomitization fabrics very similar to these are common in the French Mesozoic and I. M. West (1978, written communication) has observed similar fabrics in the Jurassic Portland and Purbeck limestones of England; West interprets these as resulting from dedolomitization. The calcite crystals, ranging from 200 to 500 μm in size, are assumed to be larger than the dolomite precursor so that generally an irregular crystal mosaic is formed, as predicted (see Clark and Epting, 1978), but the rhombic outlines may represent direct pseudomorphs of the dolomite.

Another very likely candidate for a dedolomitization fabric is that shown in a chertified cryptalgalaminate from near Canajoharie (loc. 39, subunit 4, specimen M3). This fabric consists basically of widely separated pockets of calcite, ranging from about 150 to 210 μm in greatest dimension and showing little variation in size throughout the thin section; within most of these pockets is a well-defined dolomite rhomb that may occupy the great bulk of the volume of the pocket (depending on the cut effect; Fig. 84). The enveloping microcrystalline calcite is optically continuous (i.e., epitaxial) with the dolomite. This optical nature of the calcite and the presence in it of floating quartz and feldspar grains indicates that the calcite was not passively precipitated in a void. Although the margins of the pockets are generally very irregular against the surrounding chert, they commonly define a subtly defined rhombic outline (Fig. 84). When viewed under crossed polarizers, the pattern seems to be that of a zoned dolomite crystal corroded by the surrounding chert. I conclude that the margins of a corroded dolomite rhomb have been dedolomitized. Such borders are not unlike, in shape, the calcite envelopes previously described. However, whereas the former are polycrystalline, the latter consist of coarser calcite spar which has been passively precipitated. The microstylolite-like partings (probably original algal laminae) can be observed as "relics" within the calcite, usually at or near the contact of the dolomite rhomb and the calcitic margin. Although the dedolomitization appears to be the latest event, it cannot be determined whether the pressure solution preceded or followed the development of the outer portions of the supposed precursor dolomite crystals.

De Groot (1967) demonstrated experimentally that dedolomitization is a near surface process. I have no field evidence that the dedolomitization signifies an ancient emergence and accompanying replacement during Little Falls time. Although minor, the related and ubiquitous late-stage calcite occurs throughout the Little Falls and I have not detected a disconformity within the unit. I suspect that the dedolomitization postdates Little Falls sedimentation.

It has become common practice to attribute dedolomitization to the calcium sulfate of evaporites which could provide the necessary Ca^{2+} ions to ground waters to effect dedolomitization (Goldman, 1952; De Groot, 1967). There is the presence (in addition to other possible evidence discussed under "Dolomitization") of minor length-slow chalcedony and "half-moon" ooids to suggest the earlier presence of evaporites. I am not aware of any evidence of gypsiferous deposits in the overlying Ordovician. This scheme must be considered as a working hypothesis at this stage.

Ubiquitous, although minor, is the occurrence of hematite after pyrite in the Little Falls. Evamy (1963) and Folkman (1969) subscribed to the idea that oxidation of pyrite [for example, to hematite] could have liberated sulfate ions which, when coupled with available Ca^{2+} ions from ground waters in a carbonate environment, could have provided the calcium sulfate to accomplish the dedolomitization. However, in view of the oxidation of pyrite throughout the Little Falls, it is difficult to imagine why there is not more evidence of dedolomitization, were this process the responsible one.

Because the suspected dedolomitization is limited in amount, it seem very possible that ground waters percolating through the overlying Ordovician limestones could evolve into solutions with sufficiently high Ca^{2+}/Mg^{2+} ratios to cause a replacement of the dolomite.

As mentioned, I have assumed that the "dedolomite" is of the same age as the other poikilotopic and void-filling calcite. It seems to be the consensus that: 1) dedolomitization is effected by Ca-rich solutions of surface or near-surface origin, and 2) most late-stage void-filling calcite, in general, is the result of freshwater phreatic conditions (Freeman, 1973). E. A. Shinn (1978, written communication), however, considers the possibility of a deep and warm origin for late-stage calcite. Analyses of some of his samples from deep wells give δO^{18} values of -2 to -4 ‰ for the late calcite. Although these values in themselves could signify freshwater as well as warm formation waters, the carbon isotope values were more positive than those for freshwater Pleistocene limestone, thus suggesting a deep origin. Shinn also realizes that the values of δO^{18} are compatible with the shallow "mixing zone" as well.

I have no isotope data for the late calcite in the Little Falls. I assume that, with the possible exeption of the relatively minor ferroan calcite, the calcite had a shallow burial origin. Sometime after the termination of the dolomitization process, the formation was brought into the telogenetic zone (Choquette and Pray, 1970) by uplift and erosion. If subsequent work reveals that the calcites are of deeper origin, it could suggest a rethinking of the supposedly well-documented shallow burial environment of the dedolomitization process.

ENVIRONMENT OF DEPOSITION

GENERAL

Little Falls sediments accumulated along the southern margin of the present Adirondack area which is thought to have been one of generally low relief in Late Cambrian time. The area of deposition was near the northeastern margin of an extensive epeiric sea that covered much of North America excluding the Canadian Shield. The roughly east-west outcrop belt at its easternmost point lies well to the west of the edge of the theorized Cambrian continental slope which extended into the deeper Proto-Atlantic Ocean in the position of present-day Vermont. Fisher (1977) considered the Little Falls Dolostone to occupy a "continental margin setting" following initiation of the rifting of the Proto-Atlantic. Specifically, he assigned the Little Falls to the proximal shelf facies and indicated (see his Fig. 4) that the formation represents the subtidal and lower intertidal environments.

COMPARATIVE SEDIMENTOLOGY

In attempting to assess the environment of deposition of the Little Falls, I will use primarily a "comparative sedimentological" approach (Ginsburg, 1974), referring to Holocene marine carbonate and terrigenous environments as a general guide. As urged by Reinhardt and Hardie (1976, p. 18), we should interpret our environments by piecing together information from various modern examples rather than forcing one particular model. I also maintain that much can be gained by comparison with studies of other ancient carbonate units which may have had more in common with the Little Falls than modern "analogs." The present, as a key to the past, has to be used with some caution.

There are, in addition, some problems in invoking such a comparative approach to help with the interpretation of the Little Falls in particular. For example, so far as I am aware, there have been very few reports of Holocene mixed sand-carbonate environments that are at all analogous to the Little Falls situation. The carbonate-siliciclastic setting at Mont Saint-Michel Bay, France (Larsonneur, 1975) does not possess the purity of sands represented by the Little Falls orthoquartzites, which are devoid of argillaceous matter; much silt and mud is present at Mont Saint-Michel. Perhaps the closest analogy is the Persian Gulf, where eolian quartz sand occurs intimately associated with carbonate either as individual grains in sabkha deposits or as dunes (Schneider, 1975, p. 213; Shinn, 1973). Even in the literature there are few reports of such mixed assemblages where the dolomitization has been so pervasive so as to significantly hinder the interpretation. Many of the beds in the Little Falls consist of nondescript dolostone revealing little other than the equigranular to inequigranular, homalotopic texture referred to previously. Where there is a complete lack of even relict grains and structures, reliable interpretation becomes impossible. Employing the various permutations of characteristics of the sandstone and dolostone as observed in the field and in hand specimen, I was able to distinguish well over 100 lithologies, and the complexities increase at the microscopic scale! It is impossible to justifiably resolve genetic or environmental distinctions among most of these. Another deterrent is the poor lateral continuity on all scales. Most of the larger sections are along streams in gulleys where there is very little extent of exposure; consequently, it becomes very difficult indeed to gain much insight into the geometry of the deposit. On a larger scale the outcrop density is low, the only complete sections of the formation being the composite ones at Little Falls and the Noses.

With these complications it would be impractical to attempt to establish a coherent relationship of a mosaic of subfacies even were they all interpretable. Following is a discussion of various elements ranging from

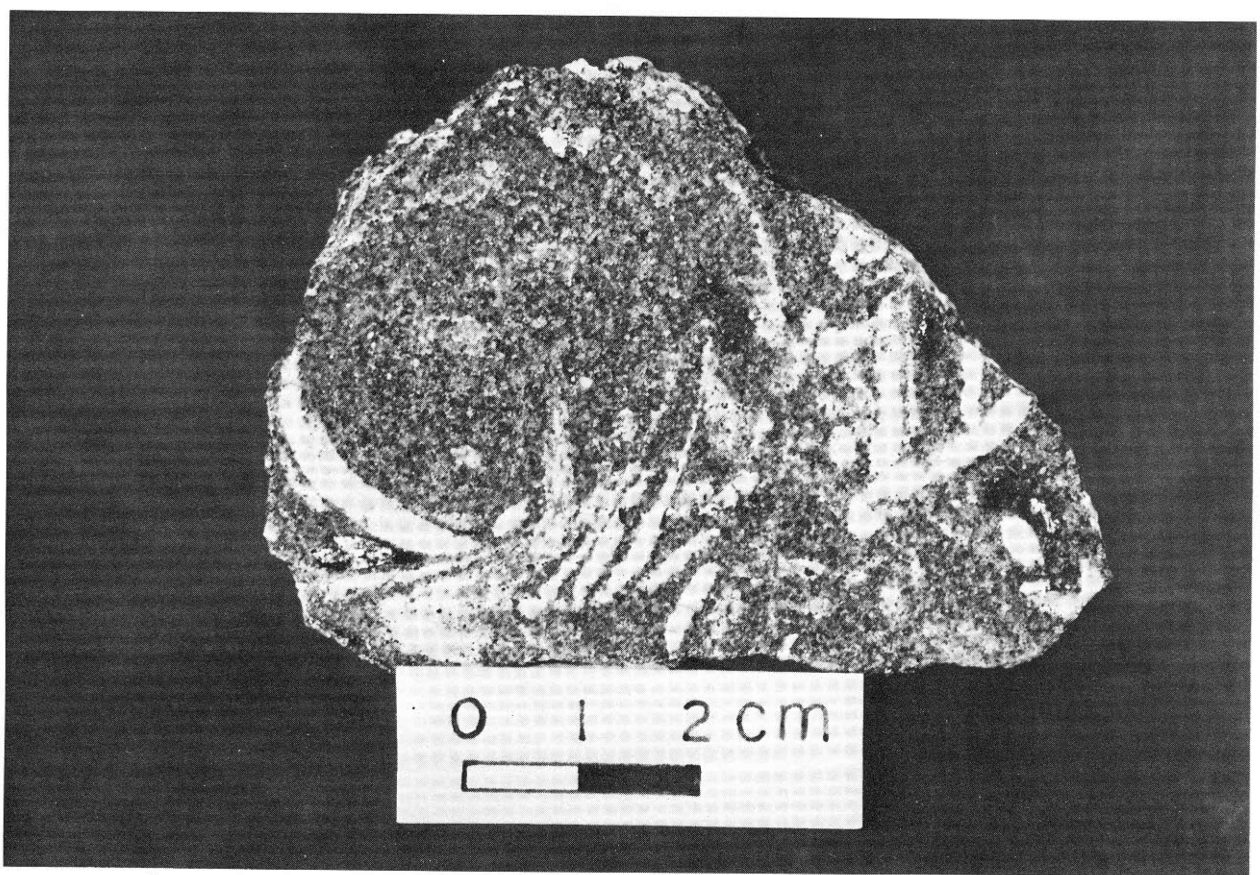

Figure 85. Photograph of polished slab of fucoidal (*Planolites*?) dolomitic sandstone (24M) from Middleville; trace fossils consist of quartz-free, finely crystalline dolomite; bedding plane view.

textures to structures to sediment associations that can shed light on the general environment of deposition prior to the camouflage by diagenesis, particularly dolomitization.

CRITERIA

Invertebrate Fauna

The extreme rarity of shelled forms has been mentioned. The few scraps of unidentifiable shells or trilobite fragments seen in one thin section (Fig. 42) and the one silicified gastropod (D. M. Hurley, 1969, personal communication), the stratigraphic position of which is unknown, shed no light on the environment of deposition. The specimen of the trilobite *Elvinia* found in float by Fisher (Dunn and Fisher, 1954) could represent very shallow water but it could as well have been washed up into the peritidal zone. Of the four occurrences of lingulids preserved on bedding surfaces, one is in the Tribes Hill Formation (subunit 10, loc. 33), one is in the Galway Formation (subunit 1, loc. 102), and two are from the Little Falls proper (Unit B, subunit 5, loc. 6 and Unit D, subunit 12, loc. 13). Invariably the lingulids occur in fine- to very finely-crystalline, dark, laminated dolostone.

Tertiary species of *Lingula* of New Zealand lived in water depths of 0 to 60 feet (18.3 m) and lingulids are plentiful on some exposed Japanese mud flats (Tasch, 1973, p. 251, 294). Although *Lingula* is an infaunal brachiopod, fossil lingulids are seldom found preserved in their burrows. Commonly, as is the case here, where they do occur, they are abundant on bedding surfaces. Possibly some ancient lingulids were not infaunal but rather epifaunal (Rudwick, 1965, p. 203). It has also been suggested that the lingulids found littering the bedding surfaces of black shales may have been epiplanktonic. Today, *Lingula* can tolerate brief periods in brackish water. Because Little Falls lingulids have no faunal associates, it is very possible that they represent the intertidal zone. On the other hand, Paine (1969, p. 27) has found that all Holocene intertidal lingulid species inhabit sediments predominantly composed of sand-sized particles, much coarser than the average grain size in the fine-crystalline dolostones in which they are found here. Thus, the Little Falls lingulids could have been either shallow subtidal or intertidal.

Bioturation

Discrete burrows are very rare in the Little Falls. I have observed a few vertical structures filled with ma-

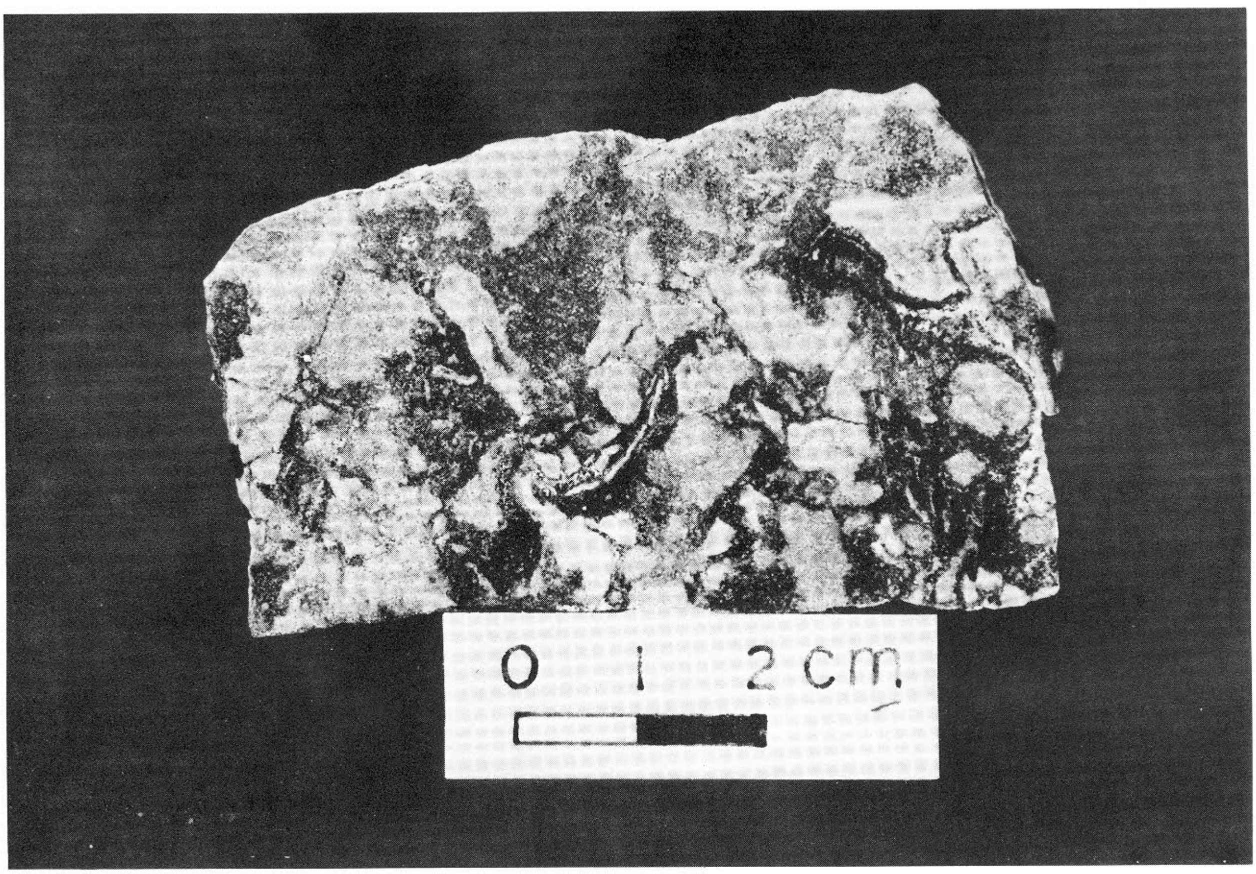

Figure 86. Photograph of polished slab showing mottling owing to disruption of bedding by bioturbation(?), Unit D (G20), immediately beneath Tribes Hill at Little Falls (loc. 13); dark areas are more quartzose, more feldspathic, more pyritic, and less dolomitic than light mottles.

terial from the overlying beds transecting algal stromatolites and other laminations. Their blunt bottoms and greater width seem to distinguish them from desiccation cracks.

"Fucoids," trace fossils characteristic of the lower beds of the overlying Tribes Hill Formation, are also very sparse in the Little Falls; they are most common in Unit D. They appear to be tubular structures generally oriented horizontally and are probably most appropriately assigned to the ichnogenus *Planolites* (Fig. 85). In the dolomitic limestone of the Tribes Hill, the "fucoids" are generally dolomitic, in contrast to the finer and darker biomicrite. In the Little Falls, however, no precursor calcium carbonate remains and the "fucoids" are much more subtle because of the complete dolomitization. A specimen (24M; Fig. 85) from Middleville shows the "fucoids" to consist of fine decimicron-sized dolomite crystals in a groundmass of dolomitic sandstone. In another example (I8) from Beardslee (loc. 30), the elongate, horizontally oriented "fucoids" are composed of nonporous, fine centimicron-sized, quartz-free dolostone in contrast to the more finely crystalline, porous, and silty dolostone of the matrix. In these cases, the lighter mottles represent the burrows and the darker dolostone the matrix.[1]

"Mottled dolomitic micrite and biomicrite" is one of the lithofacies established by Braun and Friedman (1969, p. 123–125) in describing the petrology of Tribes Hill Formation in the Mohawk Valley and was described as follows: "This lithofacies is made up of a compact well-bedded mottled limestone in which the mottles are composed of irregular patches of dolomite." The mottling in the mixed carbonates of the Tribes Hill is very conspicuous in the field and hand specimens owing to the high contrast between the lighter dolostone and the darker micrite. Even in completely dolomitized beds of the Tribes Hill, the mottling is generally more evident than in the Little Falls. Braun and Friedman (1969) attributed the predominantly horizontally oriented mottles to burrowing by worms or other soft-bodied organisms, followed by burrow filling and subsequent dolomitization. Because this lithofacies is cut by tidal channels they interpreted its environment of deposition as the tidal flat but they realized its rich fauna suggests proximity to the subtidal zone.

[1] There is some confusion in the use of the term "mottle." General usage refers to the discrete, discontinuous spots (in 2D) as the mottles and to the more continuous phase as the "matrix." Braun and Friedman (1969, P. 123–125), however, referred to the irregular, anastomosing patches as the mottles. Neither can one equate mottle with burrow unequivocably; where mottles are rounded and well-defined, they most likely represent the burrow. On the other hand, in extremely bioturbated sediments, the most continuous "matrix" (or mottle according to Braun and Friedman (*ibid.*)) probably represents the burrow.

In the basal beds of the Tribes Hill at Little Falls, irregular areas of euhedral dolomite crystals, quartz, and a dark alteration product of perthite or "glauconite" represent at one time more porous mottles resting in a more finely crystalline matrix of xenotopic dolostone. The mottles are very dark and in the field stand out conspicuously against the lighter matrix. Although present throughout the Little Falls, the mottling is less common and much more subtle (Fig. 86). In Unit D, some of the mottling is made obvious by the red and gray contrast. Probable burrows could have been considerably modified by compaction prior to dolomitization in a manner somewhat analogous to that demonstrated by Shinn and others (1977).

The scale of the mottling in the Little Falls is from millimeters to centimeters. Some mottles are parts of disrupted laminations, but commonly the geometric relations are much more complicated. There seems to be no consistency in the differences in lithology of the mottle and the groundmass.

In Unit D the discrete or discontinous element (mottle) usually consists of lighter colored, xenotopic to hypidiotopic, low-quartz dolostone, having little porosity, as contrasted to the darker continuous areas (matrix) containing disseminated euhedral dolomite crystals and silt-size quartz (and some authigenic quartz) in a matrix of "glauconitic" chert partly obscured by a brownish alteration product. Both types of rock are present as distinct laminations at some other horizons. If this mottling is analogous to that in the dolomitic limestones of the Tribes Hill, the dark micrite of that unit is represented by the light, hypidiotopic dolospar, and the silty and cherty dolostone represents the dolomitic "mottles" as used by Braun and Friedman (1969). Whether such a stage of mottled dolomitic limestone or calcareous dolostone ever existed is, of course, conjectural. The silty, cherty dolomitic areas commonly are very pyritic; the pyrite probably represents original organic matter. This fact could support a theorized bioturbated origin for the fabric. The general geometric relations suggest complete disruption most likely due to burrow mottling. On the other hand, I did not observe relict grains resembling fecal pellets which might be expected.

Although there are no specific earmarks, soft sediment deformation of the unlithified sediments could possibly explain the fabric. Osmond's (1956) roiled type of mottling theoretically results from soft sediment deformation of two contrasting laminae, producing a mottled effect similar to burrow mottling (see his Fig. 7). Although disrupted laminae commonly can be seen in the mottled beds, there is a lack of continuity of deformed laminae which might be expected in penecontemporaneous deformation.

Most intertidal burrowing organisms excavate deeper, usually vertical burrows, in contrast with horizontal burrows in the shallow subtidal zone (Rhoads, 1967).

As indicated earlier, few if any definite vertical burrows were observed. The "fucoids" present represent horizontal burrowing. Assuming that bioturbation was the cause of the mottling, the control seems to be largely parallel with the bedding. I suggest that the bioturbation represents primarily the shallow subtidal environment with possibly some representation of the lower intertidal zone. Bioturation similar in appearance to some of that in the Little Falls has been observed by D. H. Craig in the West Texas Permian (1978, oral communication); he interprets the features as high subtidal to lower intertidal.

Ooids

Modern ooids with concentric rims form in regions of agitated waters. Blatt and others (1972, p. 420) considered as a prerequisite strong bottom currents which could exist in tidal bars or tidal deltas. Most of our information on modern marine ooids comes from the Bahama Banks. Bathurst (1971, p. 134–135) described oolite shoals along the Bank margins, generally 1–6 km landward of the 100 fathom line, one such example being Browns Cay. Strong tidal currents cross the shoal with flood velocities up to about 150 cm/sec. The grains are in constant movement and the surface of the oolite is marked by ripple marks. He stated that the growth of the ooids is clearly related to the turbulence and to the passage of a thin layer of hypersaline water to and fro over the shallow margin of the bank. Since the highest content of ooids in the oolite is found at a depth of about 6 feet (1.8 m) below low water. Bathurst suggested that this could be the optimum depth condition for ooid growth. He (1971, p. 132) also believed that ooids in the *oolitic* lithofacies (as contrasted with the *oolite* facies), such as famous Joulters Cay, did not form there despite their abundance; the water is not so agitated as on the oolite shoals and the ooids are not polished. He envisioned that flood tides have carried the ooids toward the Bank to areas where the ebb tides could not return them. Elsewhere, Bathurst (1968, p. 7) pointed out that in Bimini Lagoon (Bahamas), oolitic coats 3 μm thick have grown in sufficiently quiet conditions that the ooids are not polished. Because the growth rate of ooids is so slow (30 μm to 180 μm in 2000 years), perhaps minimal agitation is required to prevent their being cemented. On the other hand, enough turbulence is necessary to keep the grain suspended so that a high level of supersaturation surrounds the ooid surface.

With their well-developed concentric laminae (as seen where preserved in chert—see Figs. 46, 47, 67, 68), the Little Falls ooids probably formed in a shallow, subtidal zone of moderate turbulence which generally was sufficiently continuous to prevent much cementation. Turbulence was probably less than in the oolite shoals of the Bahamas which display ripples and cross-stratification. I did not recognize cross-stratification in the relatively thin oolite beds in the formation. The dolomitized and silicified ooids are generally in grain contact and were initially oolite grainstones or packstones; there is no evident carbonate mud remaining, suggesting a turbulent water environment of deposition (as well as formation). Braun and Friedman (1969) assigned their oolitic lithofacies in the overlying Tribes Hill Formation to the subtidal environment, based on the varied fauna. In addition, ooids in the Little Falls are also associated with quartz as fillings between the heads of SH- and LLC-type algal stromatolites, often constituting a relatively low percentage of the grains. Even if ooids formed in the very shallow subtidal environment, they could have been washed into the intertidal environment where the high relief algal stromatolites proably formed.

Stromatolite-associated ooids are rarely silicified, so that it cannot be determined whether they have radial rims. Friedman and others (1973, p. 551) reported an association of ooids with radial rims and algal stromatolites in hypersaline pools along the Red Sea. In the Little Falls, most of the occurrences of the silicified ooids possessing radial rims are not associated with algal stromatolites and there appears to be no mutual, genetic relationship between them.

Intraclasts

Intraclasts are a relatively common grain type in the Little Falls and their nature has been discussed briefly in the section on "Petrography." Some intraclasts are discrete whereas others may be nearly obliterated. In one direction, clasts may grade into peloids. Under the microscope, the borders of even the distinct intraclasts are vague owing to neomorphism and/or replacement (Fig. 34). The commonest intraclasts are elongate, very finely crystalline, low in quartz content, and nonporous. Some, also very finely crystalline, consist of a clotted or grumous texture similar to the "structure grumeleuse" (Cayeux, 1935, p. 271) seen in the organic laminae of many algal stromatolites in the Little Falls (Fig. 33). Both of these types are, in fact, commonly associated with stromatolites at certain localities; for example, at the Middleville quarry of Eastern Rock Products, Inc. (loc. 6), laminae can be observed in the process of having been removed from the stromatolites and incorporated as clasts in the quartzose dolostone or dolomitic sandstone fillings between and above the heads. Another occurrence of the light-weathering, very fine-crystalline clasts is in the alternating dolomite and sandstone beds where they are included within the latter. These commonly are parallel with the bedding and may be sufficiently abundant to constitute flat pebble conglomerates.

Intraclasts derived from the stromatolitic heads were probably broken free along sheet cracks in the intertidal zone whereas the flat pebbles and some rounded, more equidimensional clasts associated with nonstromatolitic dolostone could have been produced either by desiccation or by ripping up compacted, or at least slightly cemented, layers in the peritidal or shallow subtidal zone. Penetration of some intraclasts by quartz grains indicate that the former were relatively soft at the time of deposition.

A unique edgewise breccia occurs in Unit D at about the same stratigraphic horizon, as nearly as can be determined, at several localities including Little Falls (subunit 10, loc. 13), East Canada Creek (subunit 9, loc. 30: see Fig. 15), and St. Johnsville (subunit 42, loc. 31; see Fig. 41). The clasts are blackish and tabular as observed in the field. Viewed under the microscope they consist of centimicron-sized dolomite euhedra, angular, silt-size quartz (some of which may be authigenic), and large, mm-sized poikilotopic calcite crystals representing an original porosity(?). They are commonly laminated. Most of these clasts lie at high angles to the bedding. In a couple of instances the clasts are connected by thin stringers or apophyses. Clearly not derived from algal stromatolites of any sort, the clasts probably represent laminae which were partly indurated (cemented?) but which could still react plastically. I suggest these were deformed and broken by vigorous surf. Because these three localities with similar clasts may be at the same stratigraphic horizon, I suggest the possibility of storm activity over a fairly wide area. Such activity could have occurred in the shallow subtidal environment or in the lower part of the intertidal zone.

A third kind of intraclast is grapestone (sand-size grains bound together by micrite) which consists of two to several ooids (Figs. 46, 48). These have been connected, probably by cementation, and on some, oolitic coats later developed (in some cases, e.g., M21, the coats may be oncolitic). The details of any early cementation are completely obscured by dolomitization, silicification, and neomorphism. These compound ooids, after cementation of their components, existed in a sufficiently turbulent environment to develop the overall oolitic coat which commonly consists of many concentric laminae. The ooids composing the grains generally are not truncated proving that they are intraclasts rather than lithoclasts. All the compound ooids I have observed in the Little Falls are associated with abundant, normal ooids.

On the Bahama Bank, grapestone is associated with ooids in the "stable sand" habitat where less turbulence permits the grapestone elements to be cemented together. Bathurst (1971, p. 132) proposed that the

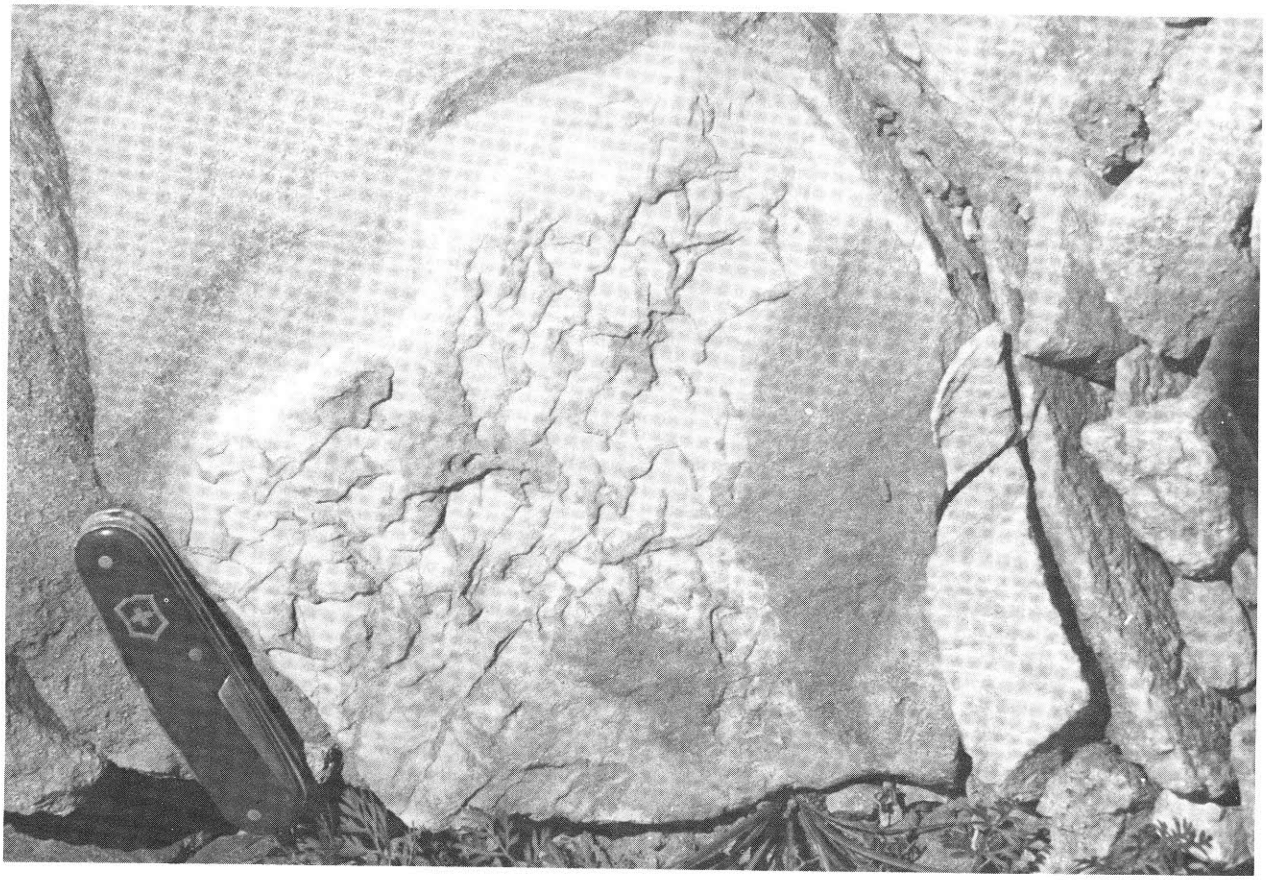

Figure 87. Fillings of incomplete mud cracks in loose block of Little Falls Dolostone, Unit B; block is from sequence of alternating algal stromatolites and sandstones (field subunit 20), Eastern Rock Products quarry just north of Middleville (loc. 6).

ooids are not actually forming there but rather farther offshore in the oolite shoals after which they are carried bankward by flood tides, ebb tides being of insufficient strength to carry them back. Winland and Mathews (1974) believed that the elements in the grapestone grains in the Bahamas consist of recrystallized ooids. They concluded that the ooids formed as the sea transgressed onto the Bahama Platform after the last glacial low stand. With continued deepening water over the oolite sites, the depositional environment has changed from an oolitic mode to a grapetone mode. They stipulated that grapestone formation, which they took to be a form of submarine cementation, is favored by uneven turbulence, low sedimentation rates, and high water circulation rates.

The fact that, in the Little Falls the grapestone, or compound ooids with *impressive oolitic coats,* are associated with normal ooids implies that both had a common origin and that they formed about where they were deposited. The compound ooids required periods of low turbulence in order for cementation to occur prior to their being oolitically coated in more turbulent waters.

I suggest a shallow subtidal site for the development of the compound ooids, where generally agitation was sufficient to prevent cementation of the ooids except occasionally in the formation of the much rarer compound ooids. Certain specimens (e.g., J2, loc. 31; see Fig. 48) with a high ratio of grapestone to ooids may have experienced longer periods with but slight agitation. Although I envision a subtidal environment for the development and deposition of both normal and compound ooids, some could have been later transported into the intertidal zone. Either depositional site could account for the excellent sorting observed.

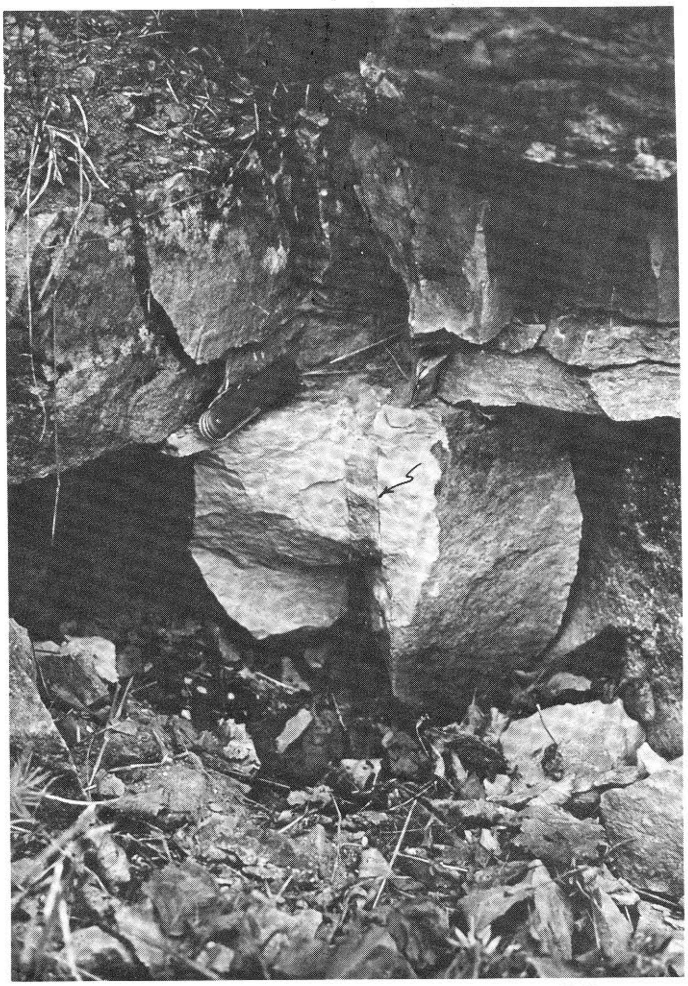

Figure 88. Sandstone dike (note arrow) cutting dolostone bed, Unit A; lowest part of section as exposed at base of Little Nose (loc. 52); knife handle is 8 cm long.

Peloids

This grain type in the Little Falls is generally preserved only as ghosts, represented by a brownish staining in relatively coarse (i.e., centimicron-sized) dolospar (e.g., H74, G10) and microscopically can be recognized most efficiently by using reflected light or by inserting the upper lens of the condenser (Zenger, 1979). Some specimens (e.g., B21, loc. 5) contain better preserved peloids which maintain their finer crystalline character. Despite their near obliteration by dolomitization and/or neomorphism, it can be recognized that they generally are part of an original grain-supported fabric. Most commonly of fine, medium and coarse sand size, they seem to grade upward into more irregular, mm-sized intraclasts. In their poorly preserved state they are occasionally difficult to distinguish from relict ooids; normally a field of peloids exhibits more "elongateness" and a greater range in size.

On the Bahama Banks, aragonite mud and peloids are best developed in the interior regions west of Andros Island, farthest from waves and tidal activity (Bathurst, 1971, p. 137). Most of the peloids are assumed to be fecal pellets, probably of a polychete (Bathurst, *loc. cit.*, p. 138). Shape and sorting are relatively meaningless when dealing with fecal pellets, which naturally are rounded, and whose size distribution is undoubtedly determined more by variation in size of the contributor's gut than any external sorting mechanism. I should add that, in addition to their subtidal occurrence on the Bank, pellets also occur in the intertidal zone and supratidal zone (Roehl, 1967, p. 1989; Shinn and others, 1969); probably most of these deposited in the supratidal zone have been transported there.

Given the fact that it is commonly difficult, even in Holocene occurrences, or in well-preserved ancient carbonates, to ascertain the origin of peloids (e.g., pellets vs. intraclasts vs. micritized grains), it is unrealistic to hope for more in the poorly preserved specimens in the Little Falls; little environmental significance can be attached to the peloids in their own right, although an abundance is suggestive of shallow subtidal conditions. Possibly the brownish stain represents remnant organic content which in turn would suggest fecal pellets.

Disregarding their exact origin, however, I believe their association with relict intraclasts and quartz sand grains suggests relatively more agitated conditions than would usually be considered for peloids; I suggest a shallow subtidal or possibly intertidal environment. Mazzullo and Friedman (1975, p. 2129–2143) assigned peloids in Lower Ordovician carbonates of eastern New York and southwestern Vermont to three lithofacies based largely on grain associations of the peloids, such as bioclasts which are essentially absent in the Little Falls. Braun and Friedman (1969, p. 122) interpreted their pellet mud facies in the Tribes Hill to represent primarily the intertidal zone; the associated skeletal fragments were thought to have been washed in from the subtidal zone.

Desiccation Features

Desiccation polygons on bedding surfaces were rarely observed, probably owing to limited lateral exposures. A loose block from the alternating sandstone-stromatolite sequence at the Middleville quarry (loc. 6) shows sandstone fillings of incomplete mud cracks (Fig. 87) and similar desiccation cracks are present in the dolostone of subunit 33 at Timmerman Creek at St. Johnsville (loc. 31). However, vertical sections show filled cracks to be be fairly common. Generally these occur in the finer crystalline dolostone and are filled with sandstone or dolomitic sandstone which is continuous downward from an overlying bed or lamination. Such filled cracks are evident in some of the dolomitic beds intercalated with sandstones in subunit 22 at the Middleville quarry (associated with the incomplete mud cracks just referred to), in the lower part of Unit A at Little Nose (loc. 52), and in the very fine-crystalline dolostone of Unit D (subunit 2) in the abandoned quarry just east of Canajoharie (loc. 39). Where the fillings consist of coarse decimicron- to fine centimicron-sized dolostone in the predominantly medium decimicron-sized dolostone of host rock, these cracks can be seen to pinch out downward from the overlying bed donating the filling. Occasionally such cracks cross stromatolitic laminae. They are usually at least a couple of millimeters in width and usually several millimeters to over a centimeter in length. I assume these all represent desiccation cracks and indicate exposure of the sediments. Syneresis cracks develop subaqueously by compaction of lime mud or by an increase in salinity which Burst (1965) found could

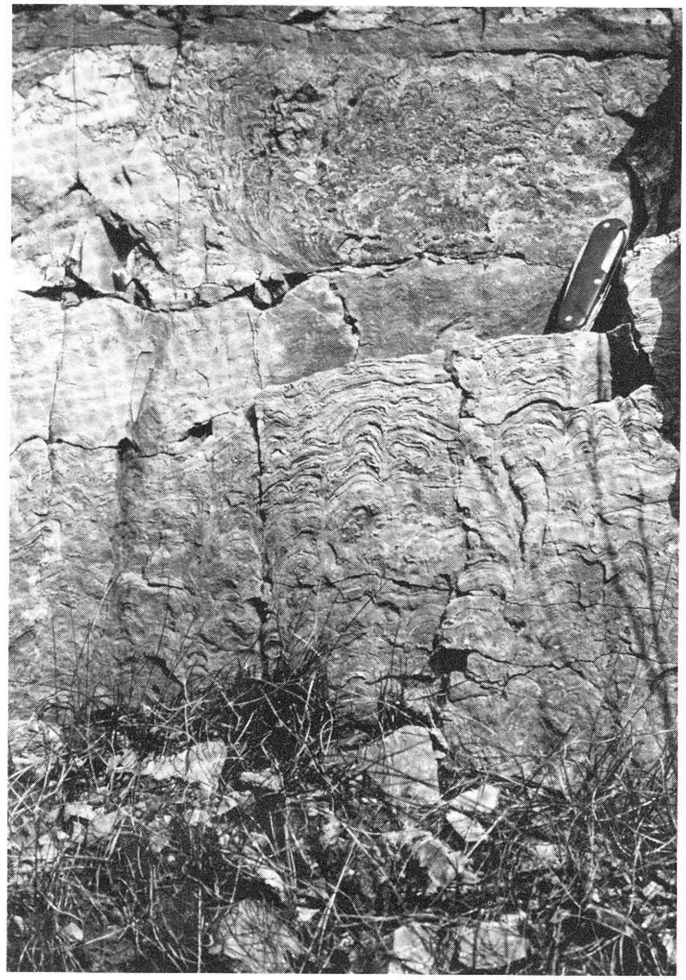

Figure 89. Algal stromatolites type LLH-C at and below knife (8 cm in length) with large type SH-C/LLH above; truncated by thin dolomitic sandstone near top; east side of arterial southwest of Little Falls (Unit B; loc. 20).

generate shrinkage cracks in clastics bearing montmorillonite. However, syneresis cracks are not so well developed, the cracks are narrow, and they do not possess well-developed V-shapes in cross section (Reineck and Singh, 1975, p. 51). Furthermore, clays form too insignificant a part of these dolostones to permit the contraction even were the salinity appropriately high.

It is possible that some "desiccation" cracks, especially where more closely spaced, could represent surface cracks of unknown origin into which the overlying unconsolidated sand or sand and carbonate were washed. Some other small (up to 1 cm in width) tabular bodies of sand transect dolostone beds and may be very long relative to their width, unlike the desiccation cracks; I suggest these structures are sandstone dikes (Fig. 88).

Tabular, slitlike vugs, one to several millimeters in width and up to more than a centimeter in length, follow the contour of some stromatolitic laminae. These voids may be completely open, save for a thin, drusy lining, or they may be completely filled with secondary minerals of which dolomite is the most important. Under the petrographic microscope, void-filling sparry mosaics are seen as discontinuous laminae in many thin sections of algal stromatolites and these are taken to be the same as those observable in hand specimen. Although perhaps enlarged by subsequent solution, these slitlike voids were initially sheet cracks resulting from desiccation. Some smaller ones appear to grade into the planar type of birdseye structures of Shinn (1968a).

Birdseye Structures

Shinn (1968a) synthetically produced two kinds of birdseye structures evident in many ancient analogs of modern tidal flat carbonates: 1) planar isolated voids 1–3 mm high and several millimeters in width, and 2) isolated, bubblelike voids. According to Shinn (*ibid.*), both types occur in Bahamian supratidal sediments, to a lesser extent in intertidal sediments, and not at all in subtidal sediments. He concluded that the planar type resulted from alternate wetting and drying whereas the more spherical types were once gas bubbles. However, P. F. Hoffman, (1978, oral communication) pointed out that birdseyes can occur in modern sediments beneath pustulose algal mats, and thus be of subtidal origin.

In the immediately preceding discussion of desiccation features, it was mentioned that sheet cracks are present in algal stromatolites where they occur along laminations. In a few instances they appear to grade into the planar type of birdseye structure. However, they are never common in any specimen and consequently do not present the impressive fenestrate pattern so typical of birdseyes. Only in one specimen (H66) are there small, circular (in two dimensions) pockets, mostly 200 to 400 microns across, (and filled with decimicron-sized dolospar) which could represent former gas bubbles but they are not abundant and are not aligned parallel to the bedding. Basically, birdseye structures are very uncommon in the Little Falls, if present at all. There is not only the problem of forming birdseye structures but also of maintaining them (P. W. Choquette, 1978, oral communication). Even were the structures to remain dry, it is likely that compaction would destroy them unless protected by cementation, early dolomitization, or possibly a grain-supported fabric (i.e., an uncemented carbonate mud would be more susceptible to compaction). The very rare occurrence of anything resembling birdseyes, with the exception of the planar desiccation sheets in some algal stromatolites, could suggest either the lack of penecontemporaneous dolomite or cementation. On the other hand, the absence of birdseye structures in grain-supported rocks tends to indicate that generally they never existed in the Little Falls sediments.

Algal Boundstones

Combining the definition of Dunham (1962) and the usage of Aitken (1967) and Halley (1971b) I will class all algal structures in the Little Falls as algal boundstones, which supposedly resulted from a trapping and binding of detrital particles by blue-green and possibly non-calcareous, green algae; the use of the term "algal" is not intended to imply the presence of algal structures themselves. This general category includes algal stromatolites, thrombolites, and cryptalgalaminate carbonates (Halley, 1971b).

By far the dominant type of algal boundstone in the formation is the domal algal stromatolite, consisting of hemispherical, laminated structures ranging from a few centimeters to (rarely) a meter in thickness (Figs. 6–8). Type SH is the commonest form but type LLH (Logan and others, 1964) is also abundant as a main structure as well as usually providing the internal structure of the SH type. The two forms may be related vertically within a zone (Fig. 89; see also Fig. 8). Algal stromatolites are by far commonest in Unit B. They occur in Unit A (subunit 2) and are replaced by chert in Unit C (subunit 95) along the escarpment at Little Nose (loc. 52) and possibly in the chert in Unit C (subunit 6) northeast of Little Falls (loc. 23).

With little variation, the megascopic internal laminated structure consists of convex-up alternations of very fine-crystalline, dusky brown (5YR 2/2) and fine-crystalline, pale yellowish-brown (10YR 6/2) laminae. As observed microscopically, the stromatolitic laminae range from 0.1 to 5 mm in thickness, most commonly being between 0.3 and 1.5 mm. The basic association of laminae consist of couplets of micron- to fine decimicron-sized (3 μm to 10 μm), darker dolomite alternating with dolospar, which in some specimens is medium decimicron-sized, but in others may be coarse decimicron-sized to rarely fine centimicron-sized. The darker, micron-sized laminae may include some organic content but probably the small crystal size causes most, if not all, of the darkness as seen microscopically. Detrital quartz grains ranging from angular silt to well-rounded medium sand usually compose less than 5 percent of the stromatolitic structure overall but are more abundant in the coarser laminae.

In many stromatolites, the darker, finely crystalline laminae have a microscopic clotted or grumous expression similar to the "structure grumeleuse" of Cayeux (1935, p. 271; see Fig. 33).[1] Similar structures occur in

[1] Fairchild (in press) described a fabric similar to "structure grumeleuse" in Dalradian (Precambrian, Scotland) algal stromatolites.

Figure 90. Algal stromatolite of type LLH-C and base of overlying sandstone, Unit B, exposed on east side of arterial southwest of Little Falls (loc. 20); note low relief between "heads"; knife handle 8 cm long.

a non-dolomitized algal stromatolite from the partly equivalent Hoyt Limestone at Lester Park west of Saratoga Springs and in some modern fresh water stromatolites. Only rare "clots" resemble discrete peloids which are often incorporated in modern marine stromatolites. One exception at the base of a stromatolite along the arterial at Little Falls (loc. 20) has distinct peloids, probably pellets, within the coarser member of a couplet. The coarser areas within the grumous fabric are very irregular and almost certainly do not represent the molds of filaments. However, in clasts derived from a stromatolite horizon at the Middleville quarry (loc. 6, specimen A43), the clearer areas are rod-shaped and may possibly represent former filaments. It is possible that diagenesis has disrupted a "vermiform" microstructure (Bertrand-Sarfati, 1976, p. 255) which is common in Precambrian and Cambrian stromatolites where the sinuous areas of clear spar may be the sites of former filaments; an example is *Girvanella*.

Laminae may consist of more vague, second-order laminae and consequently would be classed as "composite alternating laminations" (Monty, 1976, p. 195). As mentioned in the discussion of "Desiccation Features," certain laminae, consisting of void-filling dolomite or calcite, are interpreted to represent sheet cracks.

The darker, aphanitic laminae may represent the organic rich member of the couplet, and the coarser one may contain the trapped inorganic matter. The simple periodicity represented by the alternate laminae is obvious but whether this is tidal, lunar monthly, or seasonal cannot be determined. Studies of modern algal mats in this regard have produced conflicting results (P. F. Hoffman, 1978, oral communication). Possibly the laminae reflect storms and/or excessive tides and accompanying higher velocities and energy. Gebelein (1969) reported that in Bermuda more sediments are transported by flood tides than at ebb tides. In intertidal algal mats at Cape Sable, Florida, high-tide flooding deposits a sediment-rich lamination proportional in thickness to the period of flooding, whereas the organic-rich laminae form during low tides (Gebe-

He attributed the rounded, irregular masses of fine-grained dolomite to early calcification promoted by bacterial decay and the associated alkaline environment. Fairchild interpreted the more coarsely crystalline dolomite of the fabric to desiccation, to removal of organic matter, or to lateral growth expansion.

lein and Hoffman, 1969).

Type SH-C, the commonest domal stromatolite, generally has an internal structure consisting of laterally linked heads (LLH-C). Although the maximum local relief between domes of type LLH is usually less than a centimeter or two (Fig. 90), that of type SH ranges up to a maximum of 25 cm and most of these would qualify as "high-relief" stromatolites. They are particularly well developed in the Little Falls and Middleville areas where they contribute to that sequence, in Unit B, of alternating stromatolites and sandstones averaging about 14 feet (4.3 m) in thickness. Although a particular unit may have either the type SH or type LLH occupying its entire interval, an upward sequence of SH-C/LLH-C→LLH-C (Fig. 8) is a common situation; more rarely, one may observe LLH-C→SH-C/LLH-C (Fig. 89). There are "local" complexities; at intervals along the vertical extent of an SH head there may be thin linkages to adjacent stromatolites (Fig. 91).

Invariably the overlying bed which fills the space between heads is very quartzose, occasionally being practically an orthoquartzite which may be cross-stratified. Associated with quartz in more dolomitic capping are relict ooids, intraclasts, peloids, and "catagraphs" (i.e., "micrite-rimmed grains"). The foundation of the domal stromatolites is variable and may consist of the following: very quartzose dolostone to dolomitic sandstone; relatively low-quartz, centimicron-sized dolostone; oolitic chert or dolostone; and, interlaminated dark, micron-sized, slightly quartzose dolostone and very fine-grained to fine-grained dolomitic sandstone (Fig. 91). The latter association with its wispy, dark laminae, probably represents cryptalgalaminae which previously may have been prevented from building up to a domal stromatolite because of the influx of abundant quartz.

Based largely on the work of Logan (1961) on the classic algal stromatolites in hypersaline Shark Bay, Australia, domal and columnar forms have been taken by most workers to indicate the lower, or higher-energy, part of the intertidal zone. The continuous flat, algal-laminated sediments can develop in the more protected upper part of the tidal flat extending into the supratidal zone. The discrete, club-shaped structures extend from the more vigorous surf at the seaward edge of the tidal flat landward to the general vicinity of the normal high tide mark. Just below this level, the discrete structures tend to become confluent at their tops, grading shoreward into sinuous domes and finally to algal laminated sediments in the supratidal zone. Logan (1961, p. 528) proposed that the vertical relief of an individual domal structure is determined by the tidal range at its location. For example, his club-shaped structures on the seaward edge of the reefs stand at 2–2.5 feet (0.6–0.8 m) and diminish in

Figure 91. Photograph of polished slab of portion of algal stromatolite, mainly type SH; minor lateral linkages as well as laminations of dolostone and dolomitic sandstone between heads; note laminated base of stromatolitic layer; from Eastern Rock Products, Inc., quarry (loc. 6) near Middleville.

height landward. Goldring (1938, p. 12–17) described the zonation of *Cryptozoon proliferum* in the Hoyt Limestone from larger, more closely packed forms at the Petrified Sea Garden (loc. 125) northward to smaller and less crowded forms at Lester Park (opposite loc. 124) to yet more subdued structures at the road junction north of the Park; she assumed the open ocean to be in the southerly direction. Halley (1971b, p. 69, 76) could trace a change over a short lateral distance at one horizon in the Hoyt from high-relief, unlinked stromatolites to low-relief, laterally linked stromatolites to cryptalgalaminate carbonates. Paleocurrent determinations corroborated his concept of a shoreward succession of stromatolitic morphologies. Assuming that the maximum stromatolite height is equivalent to the tidal range, Davis (1975, p. 305–306) suggested a range of 1 meter for tides affecting stromatolite growth

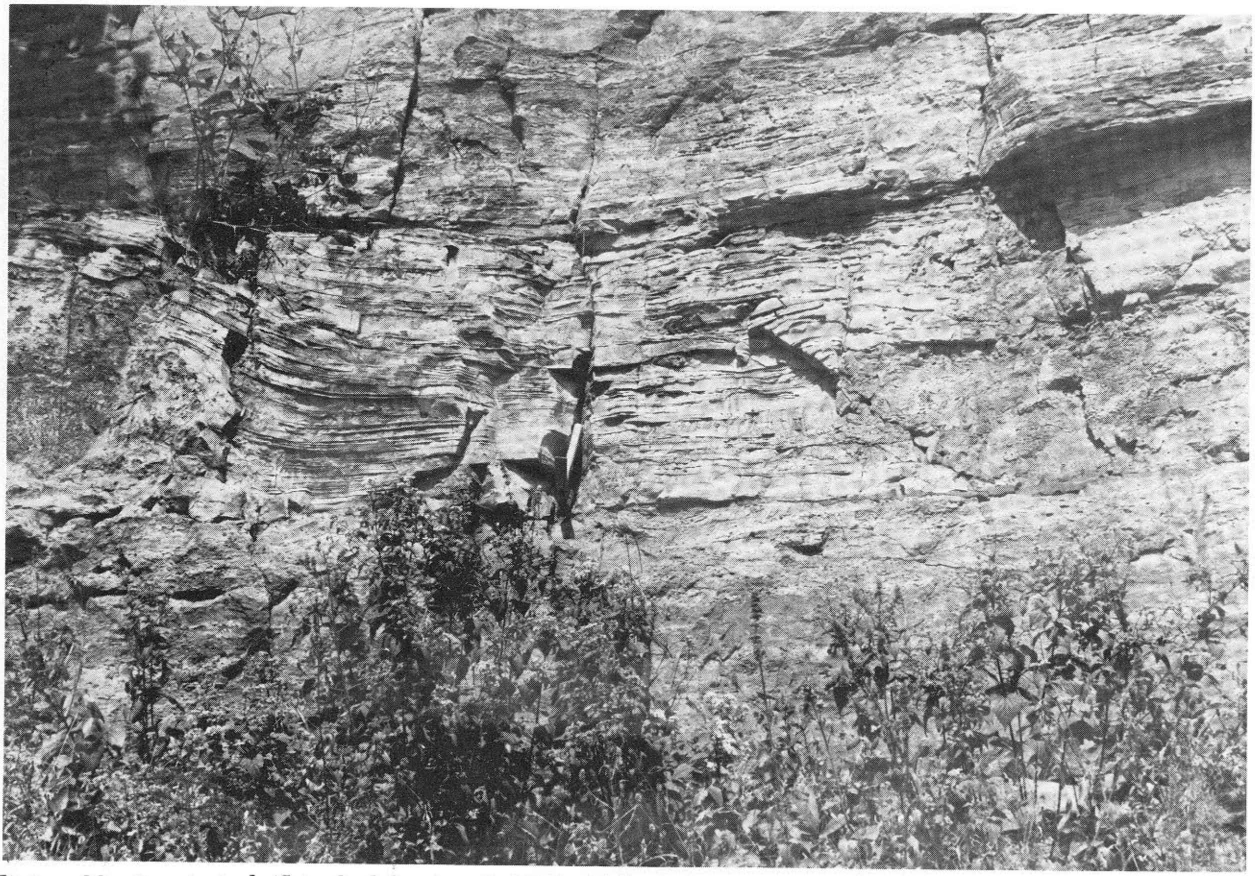

Figure 92. Laminated (flat algal laminae?) Little Falls Dolostone immediately north of Route 5 east of Palatine Bridge (loc. 41).

Figure 93. Large oncolite-like structure, but probably type SH-C, in Unit B (note arrows) exposed on east side of arterial southwest of Little Falls (loc. 20).

in the Prairie du Chien group (Lower Ordovician) of the Upper Mississippi Valley. He took the capping algal mat crust to represent the supratidal zone. Indeed, it has become relatively common practice to assign an intertidal environment to hemispherical stromatolites and a supratidal site to flat-algal-laminated, or cryptalgalaminate, sequences in the geologic record (e.g., Braun and Friedman, 1969; Mazzullo and Friedman, 1975; Mazzullo and Friedman, 1977).

In the Bahamas, algal mats and the associated algal laminated sediments are generally restricted to the supratidal zone, because of the intertidal and subtidal predators that prevent any mat development in those areas (Garrett, 1970). Roehl (1967, p. 2002) described very extensive mats from the supratidal zone on Andros Island. On the other hand, modern algal stromatolites have been described from subtidal environments, such as Bermuda, where they are laminated and may be domal, ranging up to 10 cm in height (Gebelein, 1976, p. 382). Playford and Cockbain (1976) have described impressive stromatolites growing in depths below mean sea level down to 3.5 m in Hamelin Pool, Shark Bay, about the only site in the world where diverse and abundant marine forms are forming; conditions there are very hypersaline with, consequently, a restricted metazoan fauna. As Garrett (1970) has indicated, invertebrate grazers had not developed by Proterozoic and earliest Paleozoic times, and subtidal stromatolites, being safe from predation, could have been more abundant.

Invoking comparative sedimentology, I suggest that domal stromatolites in the Little Falls strongly suggest intertidal conditions, type SH lying in the lower, higher energy part of the zone and type LLH representing the lower energy, more landward part of the zone. The type SH stromatolites have a maximum relief of about 25 cm, therefore the tidal range (or sea level change) was at least that much. Exposures are insufficient to demonstrate any lateral change from one type to another at any horizon, although I would predict a decrease in relief in the landward direction toward the north. The arenite deposits (quartz sands, ooids, "catagraphs," and intraclasts) surrounding the stromatolitic heads, indicate some vigorous currents. Possibly these stromatolites were subtidal; a condition such as hypersalinity may have inhibited a mat-eating fauna during Little Falls deposition. It is possible, though less likely, that these invertebrates simply had not developed by this time in the Late Cambrian.

Horizontal laminations abound in the Little Falls. Between one-quarter and one-third of nonstromatolitic samples of the Little Falls are laminated. In a small percentage of these the laminae are wavy to undulatory and probably are cryptalgalaminate (Aitken, 1967, p. 1170). Cryptalgalaminate dolostone is found at the base of some domal stromatolites, such as in Unit B along the arterial south of Little Falls (loc. 20). Other

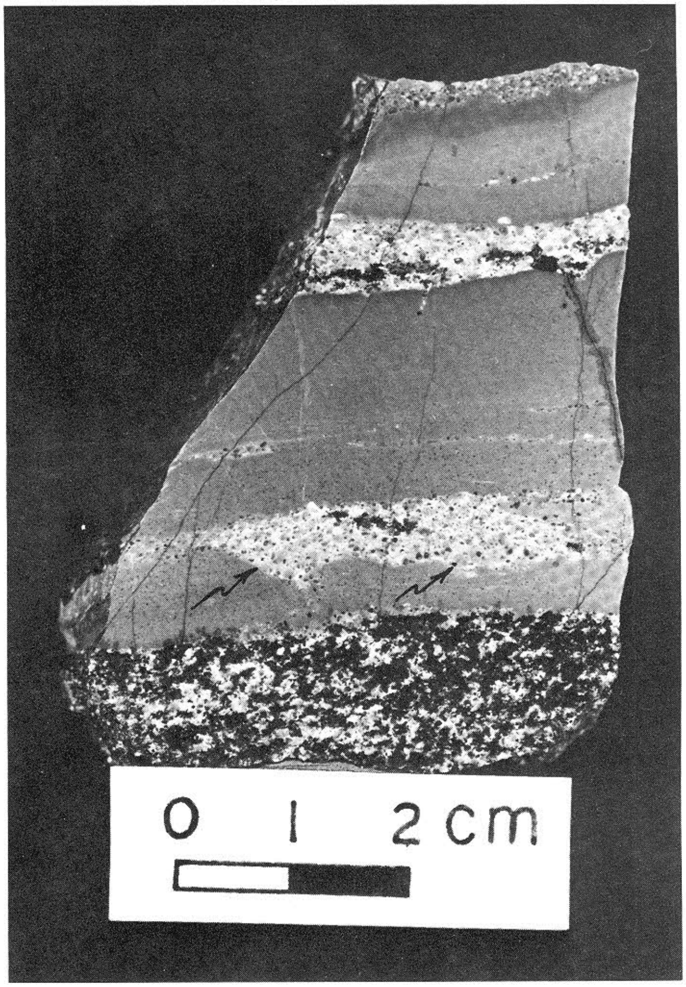

Figure 94. Photograph of polished slab of specimen showing alternating laminae of orthoquartzite and very fine-crystalline dolostone; note possible scour effects on bottom of quartzitic lamination (see arrows); Talarico quarry just west of St. Johnsville (loc. 30A).

suspected zones of cryptalgalaminate dolostone occur in subunits 9 and 13 along East Canada Creek (loc. 30), about 20 feet (6 m) above the base of the exposure along Route 5 east of Canajoharie (loc. 41; Fig. 92), and as thin and wavy dolomitic and cherty laminae, appearing as wavy partings, in the old quarry east of Canajoharie (loc. 39, subunits 4 and 5). Some thin sections from locations 17 and 18 at Little Falls have thin, undulating laminae that show an encrusting relationship to the underlying layer. One specimen (H29) has flattish laminae that, except for their lack of domal geometry, are similar to those in algal stromatolites, i.e., a very fine-crystalline, dolostone with grumous structure alternating with coarser dolospar. Certain laminae are very quartzose, some being actually sandstones (e.g., D35, H32); in these the quartz is very fine sand to fine sand size.

Thrombolites, or stromatolite-like structures that are characterized by a macroscopic clotted texture and lack of laminations, are essentially absent in the Little

Falls, although they are quite common in the partially equivalent Hoyt Limestone. Along the arterial at Little Falls (loc. 20) a change from type SH to type LLH to thrombolites(?) occurs in one unit below a capping sandstone. Aitken (1967, p. 1173) pointed out that thrombolites may require hypersaline conditions; their near absence here may constitute an argument against a hypersaline environment for the Little Falls sediments. Under "Dolomitization" I have discussed the possibility that the algal stromatolites suggest hypersaline conditions, either by virtue of their high relief, as suggested by Halley and Eby (1973), or more simply by their very presence which could signify harsh conditions not conducive to predators (Mazzullo and Friedman, 1977).

Type SS structures (oncolites), which presumably indicate a subtidal environment, have not been recognized with certainty in the Little Falls, but some relict grains could be oncolites. A unique, large, elongate body, some 40 cm long and 25 cm high, occurs in Unit B within the stromatolitic-sandstone sequence at location 20 (Fig. 93) and displays very even laminations that show no smaller scale doming or undulations. Although this structure could be an inverted, stacked hemispheroid type of oncolite (Logan and others, 1964), it is more likely a type SH stromatolite with an impressive constant radius and a lack of internal type LLH structure.

Laminations

Of the approximately one-quarter of Little Falls samples which possess planar laminations, most are *not* cryptalgalaminate. Unit D contains the highest percentage of laminated beds, followed by Units B, A, and C, in that order. There is seemingly an infinite number of associations of laminae. Some examples of couplets are as follows: dolostone laminae with differing amounts of quartz; low quartz, decimicron-sized dolostone alternating with centimicron-sized dolostone; very fine-crystalline dolostone and orthoquartzitic laminae (Fig. 94); dolomitic, quartzose chert alternating with quartzose, slightly cherty dolostone; alternating fine and coarser orthoquartzite; mosaic dolostone alternating with relict peloid-, intraclast-, or "catagraph"- bearing dolostone; cherty, calcitic, idiotopic dolostone alternating with hypidiotopic dolostone containing little interstitial material. Some laminae are distinguished by differences in only one constituent or property, such as microvugs, pyrite, packing of grains, secondary calcite, amount of secondary quartz overgrowths, proportion of dolomite crystals with shadowy centers, and intracrystalline hematite zoning.

Within a thin section, laminae range from 0.2 mm to 8^+ mm, most being between 0.5 to 4 mm. I did not observe any noticeable grading in either quartzite or carbonate packstone laminae. Generally the contacts between them are not sharp. Employing the criteria of Aitken (1967, p. 1170), I conclude that essentially all of these laminae are *not* cryptalgal. Commonly the laminae are planar (Fig. 94) and do not bear an encrusting relationship to the underlying bed. They may pinch and swell to compensate for the underlying relief, such as scours. These laminae are not usually associated with recognizable domal algal stromatolites. Breccias of chips of dolostone identical to the associated dolostone are infrequent. Relict grains are commonly in contact and are not supported by a matrix of dolospar; there are many exceptions, however. Quartzose laminae containing rounded quartz in the fine- to coarse sand size would be better explained by inorganic deposition from currents rather than by trapping and binding by an algal mat. There is a slight tendency for elongate quartz grains to be aligned parallel to the bedding.

Some laminations are the result of diagenetic effects such as pyrite content and quartz overgrowths, but these could result from an original lamination control, for example, organic material and porosity, respectively. In the Bahamas, graded laminated carbonates containing birdseyes are characteristic of the supratidal zone (Roehl, 1967, p. 1998; Shinn and others, 1969, p. 1209–1210). Wanless (1975, p. 276–277), using the Bahamas as a modern analog, interpreted laminites in the Cambrian Muav Limestone of the Grand Canyon as representing overbank deposits of tidal creeks (resulting from storm flood waters) on supratidal levees. Mud and pellet-sand laminae were deposited during these brief periods of flooding; these are basically stick-on deposits and the filament length limited the thickness to less than a millimeter.

Laminations seem too thick to be explained by daily or twice-daily tides. More likely, storms or especially high astronomical tides were responsible. Yet, grading, which would be expected from settling of suspended sediment, is rare to lacking in the various laminae with distinguishable grains, whether they be carbonate or quartz. Frequently the laminae are only a few quartz grains thick and grading might be difficult to ascertain. On the other hand, the very slight tendency for the elongate quartz grains to be parallel to the bedding suggests a traction effect. With the wide range in types of laminae, it is obvious that they did not all have the same origin.

Rhythmic Sedimentation

Cyclic carbonate sedimentation has been described from numerous ancient carbonate units that have been interpreted as representing tidal deposits (e.g., Hoffman, 1975; Fischer, 1975; Reinhardt and Hardie, 1976). Commonly involved are shoaling upward sequences (e.g., Hoffman, 1975, and Reinhardt and Hardie, 1976) signifying progradation of the shoreline although Fischer's Lofer cycles (1975) involves an upward succession from terrestrial to subtidal. However, repetitive patterns of sedimentation can be found in shallow subtidal sediments as a result of shifting facies typical of migrating shorelines.

I was not able to recognize any apparent vertically repeated cycles or rhythmic sedimentation throughout the Little Falls, but repetitive patterns do occur within the formation. On the smallest scale is the alternation of algal stromatolitic laminae, many of which are less than a millimeter in thickness; the same is true of cryptalgalaminate structures. Other laminae, in contrast, are commonly several millimeters in thickness; although there are reoccurrences of the same couplets (Fig. 94), their great range in types complicates the detection of any pattern that could be present.

The laminae in the algal stromatolites and the cryptalgalaminate dolostone could possibly represent diurnal or semi-diurnal tidal effects, as discussed earlier, but this is impossible to determine. The other, thicker types of laminations may represent more widely separated events such as excessive high tides. high winds, storms, or combinations of these events.

Other kinds of rhythmic sedimentation involve intercalations of thicker beds, as contrasted with laminations, and they may reflect similar controls. The most striking type, referred to several times previously, consists of alternations of sandy dolostone and algal stromatolitic dolostone. These "cycles" form sequences about 14 feet (4.3 m) in thickness and are restricted to Unit B; they are well exposed at several localities in the Little Falls and Middleville areas (locs. 6, 11, 17, 20), and undoubtedly represent the same sequence. The algal stromatolitic member of the couplets, whether type LLH-C or SH-C, or vertical intergradations of the two types, ranges in thickness from 0.3 feet (0.1 m) to 2 feet (0.6 m). The other member, consisting of sandy dolostone, dolomitic sandstone or even orthoquartzite, ranges in thickness from 0.1 feet (3 cm) to 1.5 feet (0.4 m); these also contain intraclasts of the fine-crystalline stromatolites, ooids, "catagraphs" and large (2^+ mm) relict grains that could be rounded intraclasts, pisolites, or oncolites. Both members of these couplets may vary in thickness laterally because the type SH heads are separated by the same clastic material that overlies them. Occasionally a thin (3–4 cm) zone of laminated sandstone or dolostone truncates the stromatolitic heads of the previous cycle (Fig. 89). Type SH heads arise rather sharply from the top of such thin laminated units (probably cryptalgalaminates; see Fig. 91). Also rarely intervening in the normal arrangement of these couplets are thin units of nonstromatolitic dolostone; these occur within the sandy member and are commonly mud-cracked, the cracks being filled with the sandy sediment. These cyclic patterns seem too thick to represent normal tidal control. Rather, the stromatolitic intervals probably represent a longer period during which episodic events developed the laminae. The generally nonlaminated quartzose, intraclastic, and oolitic cappings and inter-head fillings were deposited under higher energy conditions that may have existed very locally, i.e., between the heads which were cemented to at least some degree. Probably the sandy members of the couplets represent rapid deposition. On the other hand, these inter-head deposits may sporadically be laminated and very occasionally are interrupted by lateral linkage between heads of type SH stromatolites (Fig. 91). Some of the filling between heads may have been formed during growth of the stromatolites but the major part of the head probably represents relief above the surrounding sediment; the more or less constant radii of the stromatolitic laminae could not have developed on the sides of the domes if deposition had been sufficiently rapid to enclose the heads.

The sands may have eventually buried the heads, resulting in the temporary cessation of stromatolitic growth; possibly the tidal range was the limiting factor until burial occurred. The algal stromatolites, commonly possessing sheet cracks, and the more minor, nonstromatolitic dolostones with desiccation cracks probably represent the lower intertidal zone and higher intertidal zone, respectively. The sandy material represents more energetic surf between the heads and generally deposition after stromatolitic growth. During this time there was considerable delivery of quartz sand, probably by winds. The sharp contact and truncation of the upper parts of some sandstone and stromatolite members (Fig. 89) alike resulted from erosion in the upper(?) intertidal zone, followed by the development of the thin interval of laminated dolostone or sandstone which served as the base for the upward growth of the next unit of type SH or LLH stromatolites.

Another type of rhythmic association consists of dolomitic sandstone and decimicron-sized, in places laminated, low quartzose dolostone; the sandstones commonly contain dolostone intraclasts. Immediately beneath the algal stromatolite-sandstone cycles just described, two 8-foot (2.4 m) thick sequences of such repetitions occur at the same stratigraphic horizon in Unit B in the Middleville quarry (loc. 6, subunit 19) and along the arterial southwest of Little Falls (loc. 20). Possibly, they represent an earlier development of rhythmic sedimentation leading to this stromatolite-sandstone alternation which reflect the ability of algal mats to colonize the tidal flat between major incursions of sand.

Another, somewhat similar, cyclic development was observed in subunit 9 at Little Nose (loc. 52), where mud-cracked dolostones and quartzose dolostones alternate with beds of cross-stratified orthoquartzite. In this case, there is no stromatolitic sequence above.

Grain vs. Mud Support

It has become common practice among carbonate petrologists to interpret a fabric consisting of grains which are floating in carbonate spar (i.e., not in contact) as having resulted from initial deposition of grains in carbonate mud, which supported the grains and later underwent neomorphism to a coarser crystal size. Such a fabric, then, is assumed to constitute evidence of a neomorphosed, as contrasted with a precipitated, origin for the spar.

Swineford (1947, p. 84–85) described loose packing of grains in carbonate- and silica-cemented sandstones of the Dakota and Kiowa Formations in Kansas. He presented evidence from thin sections that could account for this fabric without the necessity of appealing to deposition of a carbonate mud. One such possibility he recognized is the replacement of the periphery of grains by calcite. The other, and more intriguing, mechanism is the tendency of calcite to force particles apart during the course of crystallization. The evidence consisted of grains having been forced apart along incipient fractures, with the fragments scattered and rotated so that they are no longer in optical continuity with each other. Fig. 58 shows a grain of microcline in the Little Falls that may have been spread slightly by the growth of dolomite or the carbonate precursor. Krinsley and Donahue (1968, p. 860–861), using transmission electron microscopy, felt that the presence of striations on quartz grains in limestone could be caused by the growth of cement forcing individual grains apart. Spry (1969, p. 149–152) gave a good discussion of the significance of the force of crystallization, particularly in metamorphic rocks. It seems to be the consensus that in metamorphic rocks (e.g., growth of porphyroblasts), or even in sedimentary rocks with "any appreciable overburden," the expansion effect of crystal growth is negligible. There are examples in modern sediment of cement spreading, for example the displacive growth of gypsum crystals. In situations where cementation has been early and at shallow burial depths, it seems very possible to generate a loose fabric consisting of a lack of grain support and with carbonate cement but no matrix.

In most of the Little Falls dolomitic sandstones and quartzose dolostones containing relict ooids and peloids, the fabric was one of grain support and the original sediments were either packstones or grainstones (Dunham, 1962). In some other cases, where there is a

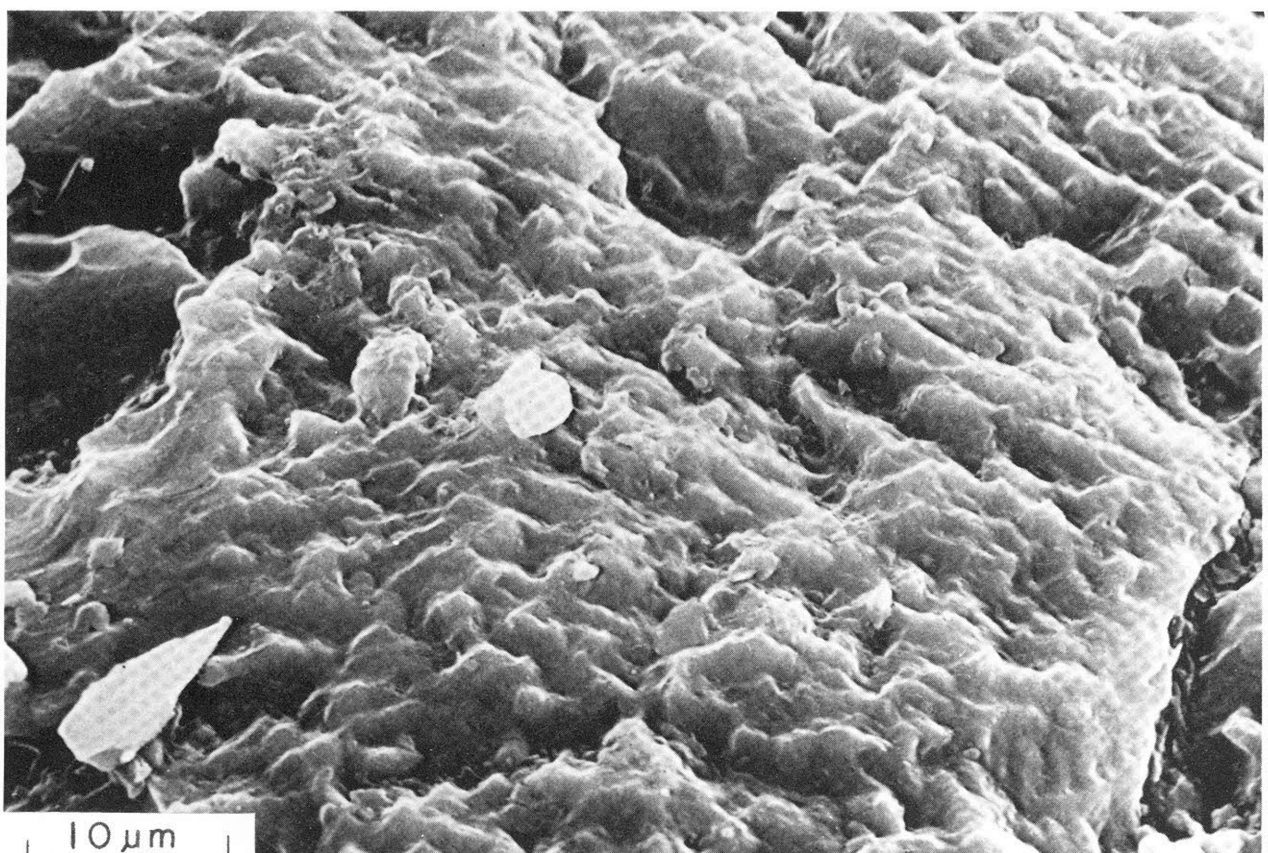

Figure 95. Scanning electron photomicrograph of "frosted" surface of quartz grain caused by incipient silica overgrowths; in this case the "lineation" could possibly represent original upturned plates modified by the overgrowth (14L).

slightly looser packing, it is possible that some cement spreading occurred and recourse to a carbonate mud matrix would not be necessary. Most Little Falls samples have less than 25 percent detrital quartz and feldspar; many of these lack carbonate grains, or at least a sufficient number when coupled with the quartz to provide a grain-supported fabric. Quartz grains are commonly floating in the low-insoluble dolostones.

It is not difficult to envision a supporting mud matrix in the more finely crystalline dolostones, such as in Unit D, which would be in keeping with the common association of a sparsity of grains and micrite that represents a poorly washed environment (Folk, 1959). On the other hand, many of the coarser, centimicron-sized dolostones from Units A and C have very low quartz content, the grains being surrounded by dolospar. Unless relict grains have gone unrecognized, it appears for the reasons just discussed, that such low-quartz dolostones must have experienced considerable neomorphic grain growth; assuming the original dolomite was mud, they too would signify *relatively* quiet water conditions. The very fact that once-micritic material, such as peloids, now consists of coarse dolomite crystals attests to the impressiveness of the aggrading neomorphism. It would indeed be dangerous in such dolostones to assume that a high sparite/micrite ratio is necessarily indicative of agitated subtidal conditions of deposition (see Laporte, 1971, p. 728–729).

Such a situation, however, leaves us with the problem of accounting for the lack of such extreme grain growth in the more finely crystalline dolostones. Perhaps these were less porous and were consequently more protected from the solutions promoting neomorphism.

Quartz Sand Grains

Terrigenous quartz particles in the Little Falls range from medium silt- to boulder-size clasts, the overwhelming number being sand-size grains. Silt, typically subangular to angular, and commonly corroded by encompassing chert and dolomite, occurs as disseminated grains, as thin stringers, or as laminations in dolostone, as a minor constituent in the matrix of orthoquartzites, and dispersed in chert. Most probably the silt represents fragments broken from the sand-size grains. Quartz clasts coarser than 2 mm range in size from granules through boulders in the basal Little Falls. Only the sand-size fraction will be considered further here.

As mentioned in the section on "Stratigraphy," detrital sand-size quartz grains in the Little Falls commonly are frosted (i.e., they possess a dull opaque surface). It had been generally assumed that such frosting on sand grains resulted from a sand-blasting effect in an eolian environment until Walker (1957) pointed out that frosted surfaces also can result from other processes, including differential solution of quartz surfaces by percolating ground water, incipient quartz overgrowths, pressure solution along contacts between adjacent grains, and carbonate replacement of quartz along grain boundaries.

Pressure solution along contacts between adjacent quartz grains in the Little Falls is an insufficient general explanation because frosted surfaces were observed on grains completely separated from their neighbors by dolomite. Walker (1957) stressed that carbonate replacement of quartz is more common than realized. Although fine dolomite crystals can be observed to corrode quartz in Little Falls in sections, the more common situation is the occurrence of frosted quartz grains in a coarser dolomitic matrix that does not apparently corrode the quartz. Also, frosted quartz occurs in orthoquartzites with little to no dolomite content.

The frosting appears as a roughened surface (Fig. 54) vaguely resembling the surface of modern and ancient eolian sand grains illustrated by Krinsley and others (1976, p. 132). Saltating sand grains experience high velocity collisions which result in "upturned plates," which are roughly parallel ridges (thought by Krinsley and others (1976) to be cleavage scarps) ranging in length from 0.5 to 10 μm. Such upturned plates are not distinctly recognizable on the Little Falls grains, but in a few instances (e.g., Fig. 95) it may be that we are observing the modification of such structures by later precipitation of silica (D. H. Krinsley, 1978, oral communication). A frosted appearance can result from the reflection of light from an irregular surface on which the positive features are separated by a few microns; such topography need not depend on a sand-blasting effect.

The quartz grain surfaces are not the original ones despite the extremely high degree of roundness; they have been modified by quartz precipitation and by dissolution or etching. Marzolf (1976) illustrated and described sand grain surfaces from the Navajo Sandstone which also have a frosted appearance. He contended that the present frosted surfaces are not indicative of any particular depositional process, but to diagenetic alteration consisting of a complex alternation of quartz solution and deposition.

On the meager evidence of modification of possible upturned plates alone it would be dangerous to presume an eolian history for the frosted Little Falls grains. However, these grains from fine sand to coarse sand size are well to normally extremely well rounded. It seems to be the consensus that eolian action rounds grains far more effectively than fluvial or even beach processes (Pettijohn, 1975, p. 60–61). Although it has been suggested that beach processes could rework sand and develop well-rounded grains, studies of mod-

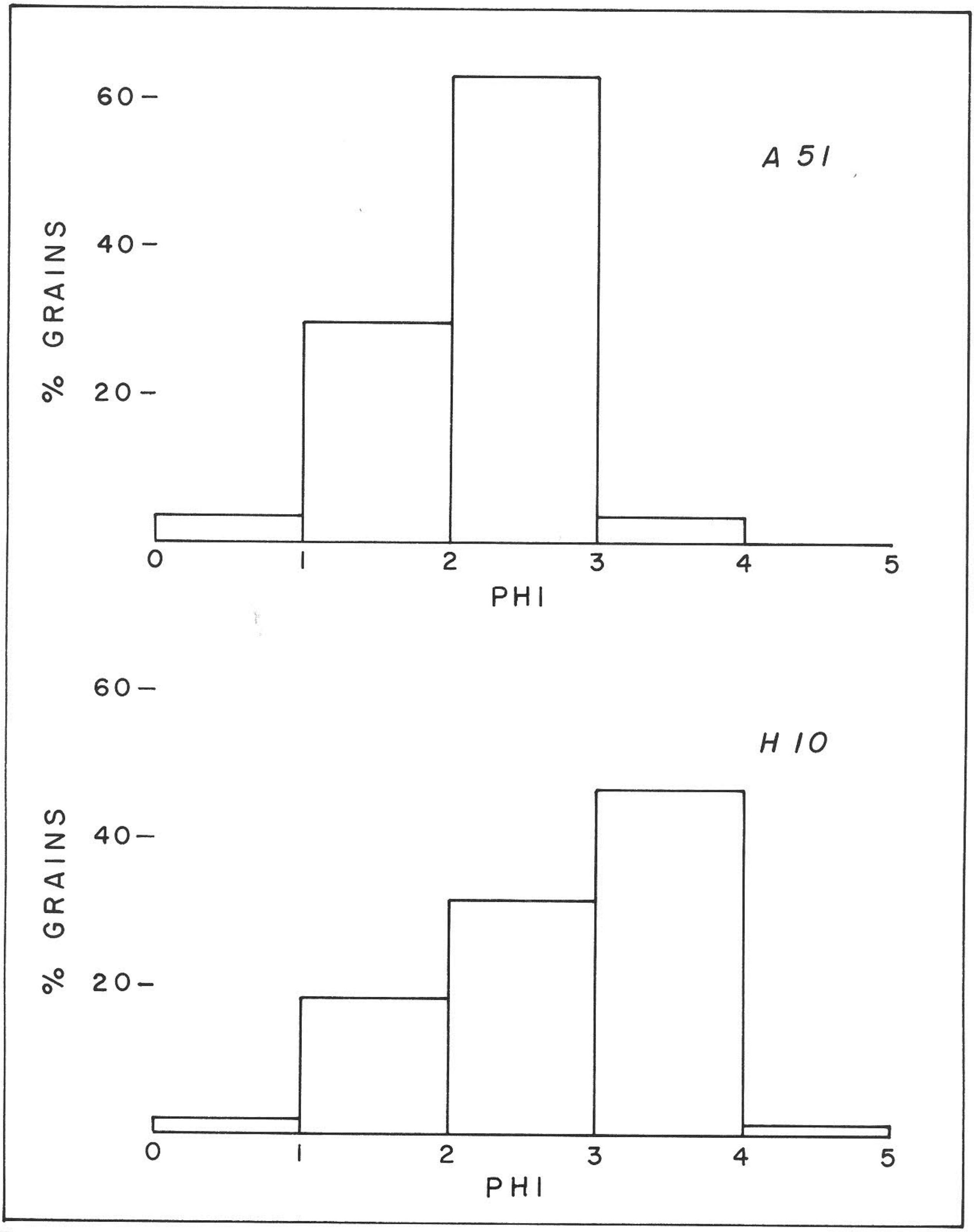

Figure 96. Distribution of quartz sand grain sizes in two orthoquartzites, from Middleville (A51) and Little Falls (H10); note the lack of bimodality as described by Folk (1968a) and strong representation in the size range 0.1 to 0.3 mm; see text for discussion.

ern beaches do not show a significant increase in roundness as compared to their presumed sources (Pettijohn and others, 1972, p. 83). There is remarkably little argillaceous content in the Little Falls and essentially no shales, a situation not unlike that of many other orthoquartzites (Pettijohn and others, 1972, p. 227). Although these workers concluded that most ancient orthoquartzites accumulated on shallow marine shelves where, based on the present, most of the clay in suspension was carried over the shelf edge, they acknowledged that eolian action could also explain the absence of clays. In addition, the good sorting points further to the textural maturity of the sandstones. Chemical maturity is evidenced by the practical absence of plagioclase feldspars, the presence of a generally low amount of the more resistent K-feldspar, and the limited heavy mineral content (particularly zircon with minor rutile and tourmaline).

Such mature sandstones are commonly associated with transgressive situations in the geologic record. Sands of this nature are very rare today, existing only as small accumulations derived from the erosion of older quartz arenites (Pettijohn and others, 1972, p. 221). "The quartz arenites exhibit the best sorting, the best rounding, the highest concentration of quartz and the most restricted heavy mineral suite of any of the sands. On the basis of these characters, most investigators have concluded that such sands could not have been derived directly from a weathered granite, that instead, they were derived from pre-existing sandstones. In short they are multicycle" (*ibid.*).

However, I have little recourse to former sandstones which could have contributed quartz grains to the Little Falls depositional environment. The formation rests directly on Precambrian gneisses. One of the unanswered questions is why there is not transgressive Potsdam Sandstone beneath the Little Falls in its outcrop belt in the Mohawk Valley, despite its presence to the east and its existence in the subsurface to the south and west. There is no evidence (except possibly the supermature quartz grains in the Little Falls) that Potsdam exposures existed to the north during Little Falls deposition. The basal meter of Unit A is feldspathic quartzite with granules to boulders of Precambrian-derived metaquartzite and vein quartz which suggests that Little Falls sediments were the first to be deposited on the Precambrian surface in this area. This matter is again considered under "Summary and Conclusions."

Impressive weathering apparently occurred on the Precambrian crystallines, and the resulting material was subjected to intensive eolian processes acting on a

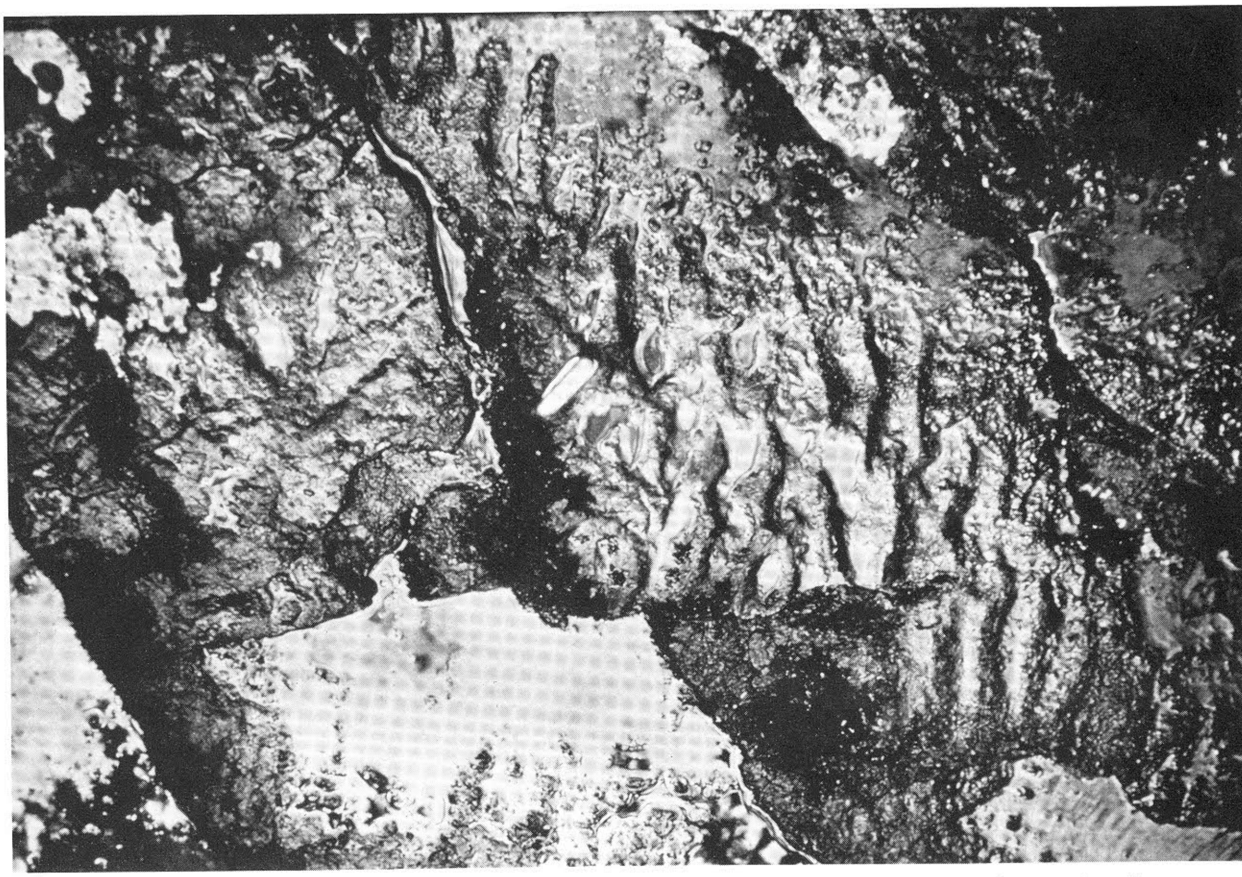

Figure 97. Current ripple marks (lee side to southeast = left) in bed of Lasher Creek in isolated outcrop of Little Falls Dolostone well below measured section of loc. 49; southeast of loc. 52 in SW 1/9 Randall 71/2′ quadrangle.

nonvegetated landscape. The wind was the essential agent in the sorting and rounding of the quartz and probably served as well to winnow out any clay-size fraction.

Folk (1968a) observed that many of the "supermature" orthoquartzites of the early Paleozoic were bimodal, but with good sorting in the modes which are generally coarse sand (0.5–1.0 mm) and very fine to fine sand (0.09–0.18 mm). Folk attributed this distribution to a selection process operating today in some deserts such as the Simpson Desert, Australia. The fraction between 0.1 and 0.3 mm is concentrated in sand dunes via saltation; the "lag" deposits between dunes consist of larger grains, ranging from 0.5 to 3 mm, that can only be rolled, and the finer suspended fraction that eventually settles out with the coarser fraction, either as "matrix" or as separate laminations. Folk's illustrations of some supermature orthoquartzites examples show a striking lack of intermediate sizes. He reported that the diameter ratio between the two modes ordinarily ranges from 4:1 to 8:1. Such bimodality could be retained in stream deposits or marine transgressive sediments derived from such lag deposits.

Although I subscribe to an eolian history for Little Falls sand grains, I cannot detect any significant bimodality of the type Folk describes. Grain measurements (approximately 250 grains per section) on selected sandstones indicate there is no mode in the coarse sand range. Also, there is no real lack of the intermediate size grains (Fig. 96); there is good representation of the 0.18–0.25 mm category, which should be that selectively transported into sand dunes. Little Falls sandstones are commonly unimodal in the fine-sand (occasionally very fine-sand) range. Certainly the "cut effect" affects grain size measurements, as determined in thin section, and give apparent grain sizes less than the actual ones (see Textoris, 1971); however, the amount would be insufficient to conceal any significant bimodality, such as that described by Folk (1968a), not to speak of providing conspicuous, but unreal, unimodal peaks. The high concentration below 0.18 mm, however, suggests that the sands may not have been derived exclusively from dunes, but also from suspension. Perhaps the shoreline transgressed a Precambrian terrain having no large-scale segregation of dunes and deflationary areas so that a range of sand sizes could be incorporated in the Little Falls carbonates.

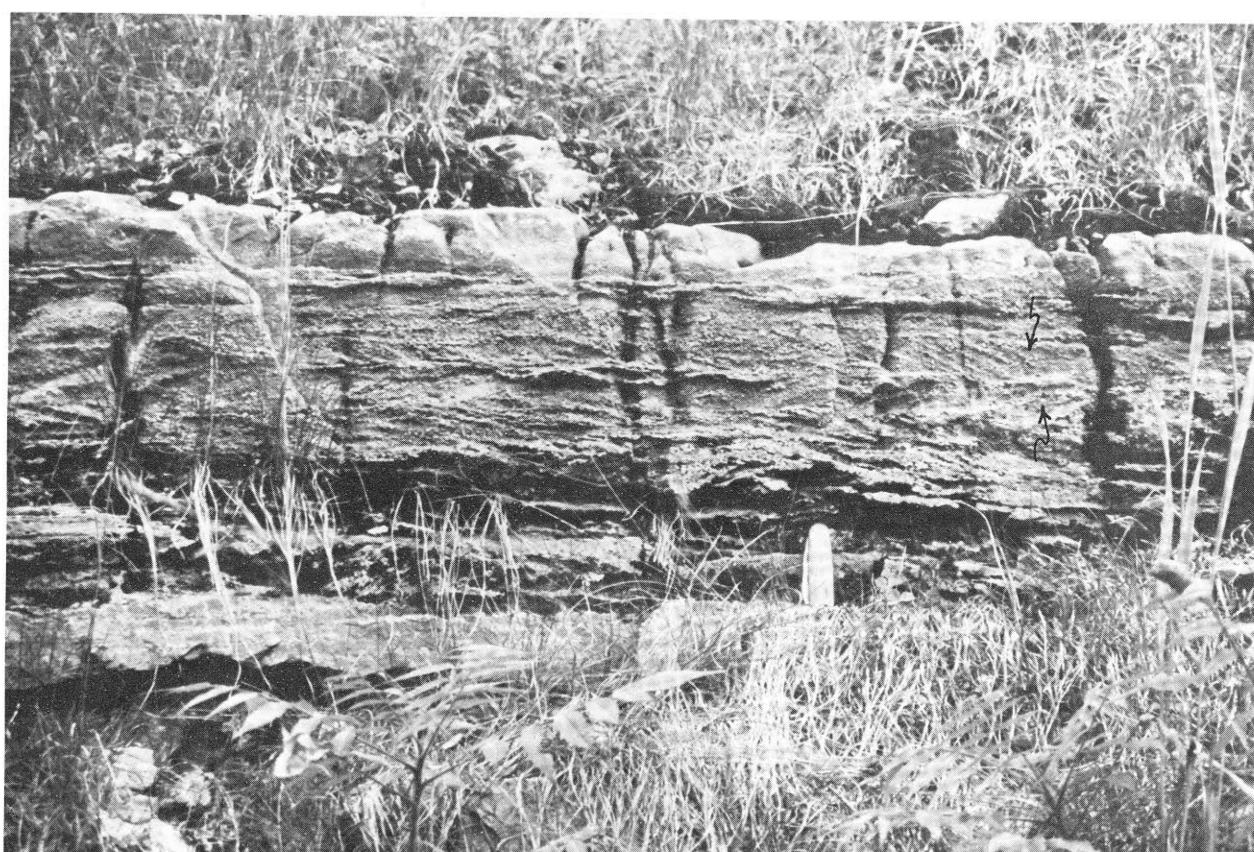

Figure 98. Cross-stratified (herringbone type?—see arrows) sandstone capping sequence of alternating stromatolitic dolostone and sandstone, Unit B, east side of arterial southwest of Little Falls (loc. 20); knife handle 8 cm in length.

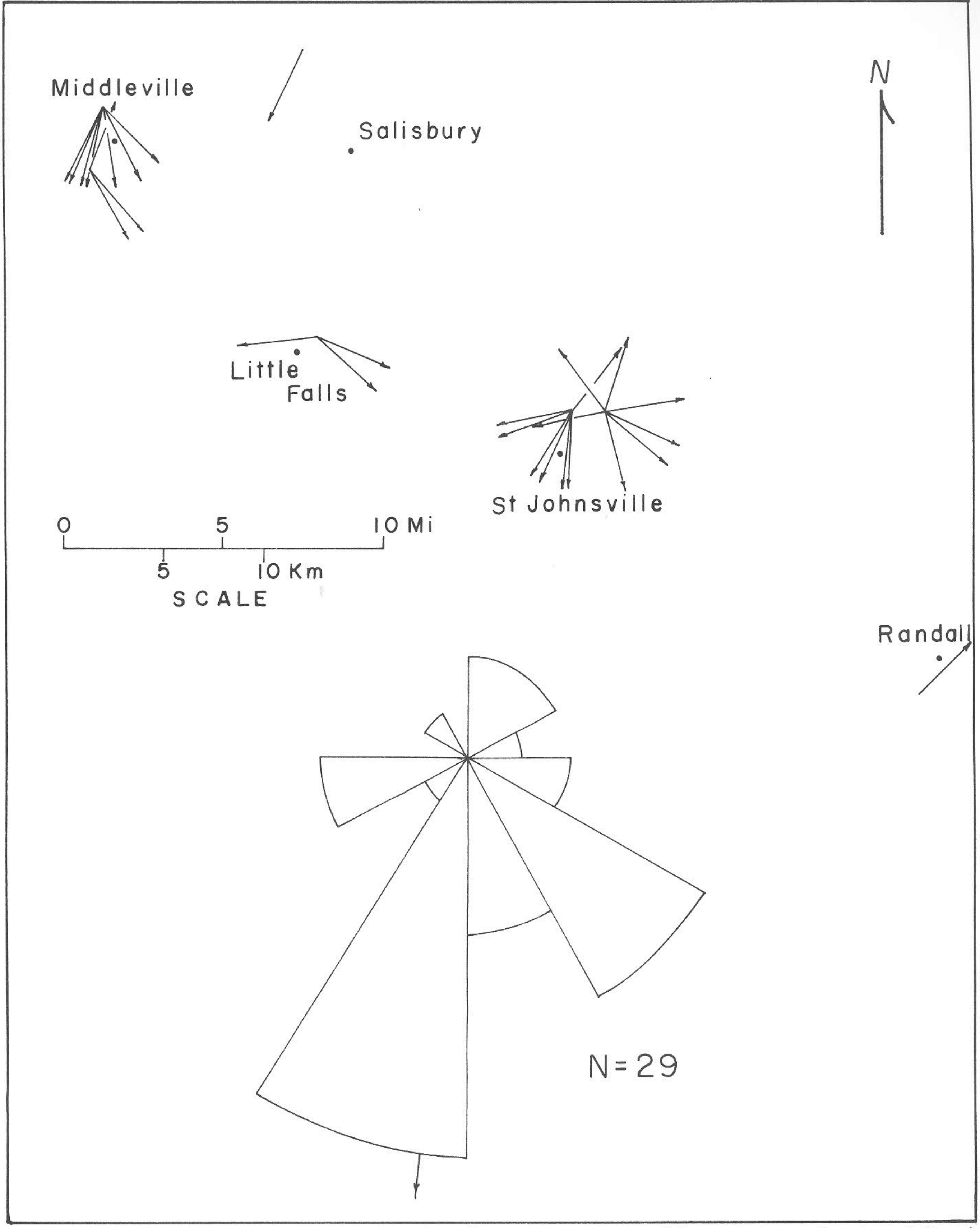

Figure 99. Paleocurrent directions in Little Falls Dolostone. Upper part of diagram shows direction of dip of foresets of cross-stratification at various localities. Lower part summarizes data in form of a current-rose diagram.

Cross-Stratification, Ripple Marks, and Paleocurrents

Orthoquartzite and dolomitic sandstone commonly exhibit cross-stratification (Fig. 10), which ranges from small-scale (units less than 5 cm in thickness) to predominantly large-scale (units usually more than 5 cm in thickness) (Reineck and Singh, 1975, p. 85) and rarely thicker than 0.3 meter. Most commonly, the cross-stratified sets have planar bounding surfaces with both tabular and wedge-shaped units within. Trough cross-stratification is rare and is primarily small-scale; I saw no large-scale scour and fill structures. Most cases of cross-stratification resulted from migration of small ripples and megaripples, which can be developed in sandy intertidal flats and shoals (Reineck and Singh, 1975, p. 87). Small current ripple marks (Fig. 97) were noted at only a handful of localities probably because of the rarity of bedding plane exposures. The larger scale cross-stratification probably represents megaripple bedding, although no megaripple surfaces were observed. Because megaripple bedding can form in beaches, shoals, and tidal channels, its presence is not very revealing.

Even though the quartz grains may have been worked extensively by eolian processes, the nature of the cross-stratification strongly suggests subaqueous deposition. The average dip of cross-stratified sandy beds and laminae is 25°, with a range of 10° to 43°. Although this magnitude would be within the reported range of dips of foresets in sand dunes (attaining angles up to 30° or 34° — Reineck and Singh, 1975, p. 94), eolian cross-stratification is larger scale and more generally tabular than that in the Little Falls. Beach cross-stratification, characterized by low dip angles and long lateral extent of beds, is unlike the cross-strata in the Little Falls. The thicker cross-stratified sand units probably represent deposition in topographically lower subtidal areas, possibly broad tidal channels.

Herringbone cross-stratification refers to a stacked set of adjacent layers with opposing directions of dip (Reineck and Singh, 1975, p. 86; Blatt, Middleton, and Murray, 1972, p. 154), and represents bimodal current flow of flood and ebb tides. Cross-stratified sets are eroded by the opposed current, providing rounded bed form surfaces termed reactivation surfaces (see Klein, 1970, p. 1118); I observed no such surfaces relative to Little Falls cross-stratification. One possible example of herringbone cross-stratification occurs at the top of the alternating sandstone-algal stromatolite sequence along the east side of the arterial at Little Falls (loc. 20, Fig. 98), although the two opposed cross-stratified units are separated by one to two centimeters of sandstone; separations by mudstone have been noted by Reineck and Singh (1975, p. 86). The consensus is that herringbone cross-stratification is indicative of tidally influenced environments and, although commonly taken to represent the tidal flat, it can form as well in a tidally influenced subtidal environment. Although practically each cross-stratified unit in the Little Falls shows one orientation, this situation would not exclude a tidal origin; for the most part, either the flood tide or ebb tide is dominant in modern environments.

Rarely were cross-laminations recognized in the dolostone, particularly in the field. Several thin sections showed vague inclined laminations of either more finely crystalline dolostone, or quartzose dolostone. These represent small-scale ripple bedding and ranged from planar to probably trough-shaped in one very poorly preserved specimen.

I noted only a few occurrences of ripple marks in plan view (see Fig. 97), all but one symmetrical form and one flat-topped form being small current ripples, (see Reineck and Singh, 1975, p. 29–34, 45) based on asymmetry, wave lengths less than 60 cm and ripple heights much less than 6 cm. In plan view the ripples have undulatory crests and represent a transition form between low-energy, straight-crested small ripples and higher energy small linguoid ripples. Reineck and Singh (1975, p. 75) indicate that small-current ripples are most common in tidal channels and on the intertidal flat although they are found elsewhere, including the shallow, subtidal sandy shelf. The one occurrence of flat-topped ripples near Spruce Lake (loc. 28, subunit 1) resembles that from the tidal flats of the North Sea illustrated by Reineck and Singh (1975, p. 369). These workers attribute this flattening, or "capping off" to capillary waves caused by strong winds on the surface of the thin film of water during general subaerial emergence.

Figure 99 summarizes the data on paleocurrents based on the dip direction of the foresets of cross-stratified beds. The upper part of the figure consists of arrows indicating the current direction at several localities as determined by measurement of true dip or its calculation from a pair of apparent dip sections. The data, admittedly too few for any sweeping conclusions, are in turn summarized in the current rose diagram in the lower part of the illustration.

Some general conclusions can be drawn, however. There is a significant orientation in the southerly and southeasterly sections, the vector mean being 187°. With such few data, the polymodal aspect is probably meaningless. There is a suggestion of a bipolar effect. In the three current ripple mark occurrences observed (not included in Fig. 99) that were preserved in plan view such that their strikes and direction of slope of the lee face could be determined, the currents flowed to the southeast.

These data are not opposed to a situation of tidal influence, whether on subtidal or intertidal sediments, along a roughly east-west coastline, with a paleoslope generally to the south. This situation fits with the general paleogeographic setting and if valid, the ebb flow appears to have been dominant, possibly by virtue of its effect being last in a tidal cycle.

Channeling

Channeling was observed only rarely in the Little Falls perhaps because of poor or inaccessible exposures.

The only "large-scale" channel (3 to 4 feet, or 1 meter, across) observed is a trough-shaped, truncating surface exposed along the precipitous walls of a steep ravine along Little Nose (loc. 52, subunit 57). Although the exact spot is high and inaccessible, it is evident that cross-laminated sands have filled a channel cut into fine-crystalline dolostone. Because this particular channel is so obvious, it would seem that even with the relatively limited exposures, were channels of this size common in the unit, they would have been observed more frequently.

Shinn and others (1969) described the large tidal channels on the west coast of Andros Island, Bahamas, which are largely subtidal. Impressive and conspicuous channels in the overlying Tribes Hill Formation contain blocks up to a meter across (Braun and Friedman, 1969, p. 125). Cross-stratified intrasparite fills channels in the lower Ordovician formations in eastern New York (Mazzullo and Friedman, 1975, p. 2132). In both studies, channels were interpreted as intertidal.

Thin (less than 0.6 foot, or 0.2 m), continuous (as observed in quarry walls) sandstone beds and laminae with no evidence of scouring at their base certainly do not represent channel fillings. However, some rare and relatively thicker (several feet) sandstone sequences, such as subunit 22 (loc. 6) at Middleville can be traced for several hundred feet and are cross-stratified. The contact with the underlying dolostone is not well exposed but does not appear to be scoured. This, coupled with the lack of a fining-upward sequence, seems to argue against these sands having been deposited in a very large (e.g., several hundred meters wide) tidal channel.

Small-scale scours (generally width and depth measured in millimeters, occasionally centimeters) in the Little Falls were observed in a few places in the field or in thin sections but they are not common. At location 17 (subunit 34), a scoured surface truncates laminae of a coarse decimicron- to centimicron-sized dolostone. As observed in thin section, the scouring involves truncation of laminae. Quartzose, intraclast-bearing dolosparite (A16; B4) or quartzose dolospar (A17) fill most scours, but in some sections, low-quartz dolospar rests laterally against truncated laminae of very quartzose dolostone. Peloids were not observed in the fillings of these "microchannels," reflecting the likely possibility that if, in fact, the peloids were pellets, there would be little likelihood that they would be preserved in such energetic environments.

Wanless (1975) described small scour depressions in the dololaminite facies of the Muav Limestone (Cambrian) which he felt is analogous to tidal flat deposits, particularly supratidal levee deposits, in the Bahamas.

I am skeptical as to the significance of the small scours in defining the environment of deposition; whereas they probably represent the tidal flat, they may have formed in the shallow subtidal zone. In the Little Falls the scours are normally associated with laminated dolostone showing a minimum of burrowing activity. In the Bahamas the well-laminated sediments occur in the supratidal zone (Shinn and others, 1969), but the laminae are generally thinner, more organic rich (i.e., cryptalgalaminate), and much more pelletiferous than those in the Little Falls.

SUMMARY AND CONCLUSIONS

Available evidence indicates that the source of the terrigenous sediments in the Little Falls was the region of the present-day southern Adirondacks. Polycrystalline quartz grains are ubiquitous, though rare, in the sandstones and sandy dolostones. Such quartz, while not diagnostic of igneous vs. metamorphic rocks, does indicate a crystalline source. Perthite followed by microcline are the most common feldspars in the Little Falls. Such feldspars are extremely abundant in the Precambrian charnockitic rocks of the southern Adirondacks; these rocks are exposed in the gorge at Little Falls directly beneath the Little Falls Dolostone (J. McLelland, 1978, oral communication). Rutilated quartz grains, locally composing up to 10 percent of the detrital quartz, indicate granulite facies metamorphism (N. Rast, 1968, oral communication); charnockites are typically found in association with the high rank metamorphism of the granulite facies. The mean insoluble residue content of Unit B (the only unit well exposed at Middleville) at Middleville localities is about 33 percent whereas at Little Falls it is 21 percent. Finally, the paleocurrent directions, based on the orientation of cross-stratification, have a vector mean of 187° (Fig. 99), further suggesting a northerly source of terrigenous sediment.

Except for the fact that the terrigenous component, mainly quartz, is extremely mature, there is no direct evidence either that other sandstones rested on the Precambrian surface prior to deposition of the Little Falls or that "outliers" of sandstone lay to the north, shedding second-cycle debris into the depositional area. Despite the extreme maturity of the sands (very well rounded, well sorted, low feldspar content, of which most is K-feldspar, and stable heavy mineral content of primarily zircon), I conclude that they are first-cycle in origin.

TABLE 3 - Comparison of Features of Holocene and Ancient Environments with Characteristics of Units of Little Falls Dolostone

	Abundance of features in Holocene tidally affected carbonate environments A = Absent R = Rare S = Significant C = Common			Abundance of features in Little Falls A = Unobserved R = Rare S = Significant C = Common (Figures represent percentages of samples or Units)			
Features	Subtidal	Intertidal	Supratidal	Unit A	Unit B	Unit C	Unit D
Invertebrate fossils	C	R	R	A	R	A	A
Domal algal stromatolites	R	C	R	R(4)	S(10)	R(5)	R(1)
Cryptalgalaminates	R	C	C	R(2)	R(3)	R(5)	S(17)
Distinct burrowing - vertical	R	C	R	R(2)	A	A	R(4)
Distinct burrowing - horizontal	S	R	R	A	A	A	A
Mottling (bioturbation)	C	S	R	C(20)	S(11)	S(8)	C(26)
Noncryptalgalaminations	S	S	C	C(27)	C(33)	S(10)	C(41)
Intraclasts	S	S-C	C	S(18)	S(18)	S(10)	S(26)
Peloids	C	S	R	R(2)	S(14)	S(15)	S(10)
Ooids	C	S	R	R(4)	S(12)	R(5)	S(12)
Desiccation cracks	A	C	C	S(11)	R(3)	S(8)	R(6)
Birdseyes	A-R	S	C	A[1]	A[1]	A[1]	A[1]
Channels and microscours	R-S	C	R	R	R	R	R
Cross-stratification	C	S-C	R	R(2)[2]	R(5)[2]	R(3)[2]	R(1)[2]
Ripple marks	C	C	R	A	R	A	A
Very fine crystalline dolomite	R	C	C	R	R-S	R	R-S
Grain support	C	R-S	R-S	S(20)[2]	C(35)[2]	S(17)[2]	S(23)[2]
Rhythmic sedimentation	S	C	C	R	S	R	S

[1] Excludes small sheet cracks in algal stromatolitic laminations

[2] Includes sandstones

Basal conglomeratic beds contain evidence suggesting direct derivation from the underlying Precambrian crystallines. The very basal bed above the nonconformity at Little Falls (loc. 15) contains boulders of foliated, slightly micaceous and feldspathic, quartz-rich metamorphic rocks. Orthoquartzites occur in the 3 to 4 feet (about 1 m) immediately above this conglomerate at this locality. Conglomeratic beds in the lowest 7 feet (2.1 m) at Salisbury Creek (loc. 26) are more immature, containing angular clasts of polycrystalline quartz and perthitic feldspar of granule, pebble, and cobble size (observed up to 150 mm in greatest dimension) with appreciable muscovite and chlorite in the matrix; the basal bed is very pyritic. Thus, the nature of the basal bed strongly suggests a direct influence by exposed basement and seems to argue against the existence of an earlier sandstone lying on the Precambrian, the erosion of which would have provided second-cycle, mature sands. I suggest that long-term weathering and eolian activity (unimpeded by vegetation) on the surface of relatively little relief, over great lengths of time, could have resulted in the maturity we observe without requiring the existence of a previous sandstone.

Relatively small amounts of plagioclase and mafic material would have been provided by the quartzitic and charnockitic crystallines to begin with; whatever was made available was essentially all removed by weathering, followed by suspension transport of the weathered products by wind and ultimately water from the inner shelf to the outer shelf and the Proto-Atlantic slope beyond.

The general relation of the thin basal sandstones and overlying carbonates, with some intercalated sandstones, indicates an initial transgressive situation. The absence of the Potsdam Sandstone beneath the Little Falls in the Mohawk Valley seems anomalous, given its presence north and northeast of Randall and its occurrence beneath the Little Falls in the subsurface south and west of the type area. One possible explanation for the lack of an impressive basal sandstone is a situation analogous to the "overstep" model of Dunbar and Rodgers (1957, p. 142). There are numerous examples of such overstep, such as the Precambrian-Ordovician limestone relations in the northern Canadian Shield (*ibid.*), and the Lower Ordovician Manitou Limestone overlapping Cambrian strata onto Precambrian rocks in Colorado (Gerhard, 1972, p. 9; 1978, written communication); in both cases the basal terrigenous sediments are less impressive than their counterpart in the Little Falls.

If the Precambrian surface of generally low relief in the area of the present outcrop belt of the Little Falls were somewhat higher than that in adjacent areas, sand could have been transported across this area into lower depositional sites. There is little evidence to support this theory. According to B. Selleck (1978, oral communication), who has been studying the younger, but facies-equivalent Potsdam-Theresa-Ogdensburg sequence along the northwesternmost edge of the Adirondacks, the thicknesses of the lower, sandier parts vary depending on the relief of the Precambrian surface; apparently these sandier units filled in the depressions and the onset of carbonate production coincided with the burial of the hills. North of the Randall area, where Potsdam sandstones are first observed east of Little Falls, there is evidence strongly suggesting some relief on the Precambrian surface. About 1.5 miles (2.4 km) west of Sammonsville (loc. 61) is a buried Precambrian hill from which the Potsdam apparently thickens to the southeast. Furthermore, there is no evidence contrary to the notion that the Precambrian surface in the Mohawk Valley was basically a peneplain. The occurrence of the Precambrian-Cambrian contact within slightly tilted fault blocks complicates the picture, but I suggest the existence of a slightly deeper basin, with greater relief, to the east of the Little Falls outcrop belt during initial Late Cambrian sedimentation in east-central New York.

As has been discussed throughout the section on "Depositional Environments," it has become fashionable to attempt to consider ancient shoreline carbonate sedimentation with respect to subtidal, intertidal, and supratidal environments of deposition. Accordingly, I have prepared a table (Table 3) which compares selected features such as fossils, structures, and textures in Holocene and purported ancient subtidal, intertidal, and supratidal environments with the occurrence of similar features, where they can be recognized, in the Little Falls. In the left side of the table is shown the relative abundance of particular features as they are represented in Holocene deposits and the ancient analogs. Their abundance is represented by four designations: A = absent; R = rare; S = significant; C = common. The divisions between these categories are vague, thus this tabulation is considered as a general picture at best. (I realize that other workers would disagree with some of the designations for abundance in modern deposits, although I have discussed this table with several carbonate sedimentologists and/or petrologists in an attempt to arrive at a general representation.) Subleties are involved is some categories; for example, in a few instances the letters represent a very relative significance. Very fine crystalline dolomite is certainly not common, in an absolute sense, in most Holocene peritidal environments but where dolomite is present, the great bulk of it is commonly of that texture. On the other hand, such dolomite is very rare in the subtidal zone and where occurring there, is usually detrital. In a similar vein, although vertical burrows may not be always common in the intertidal zone, the burrows that do occur there are commonly vertical ones.

It should be stressed that the designations for the abundance or significance of certain features (e.g., ooids, fossils, intraclasts, peloids) in a particular environment are based on the site of final deposition and not necessarily the site of production. Even with this understanding, I recognize there are still complications and ambiguities in such a scheme. For example, although peloids are shown as being common in the subtidal environment, this abundance presumably depends on the nature of the carbonate shelf or bank. Judging from the situation west of Andros Island in the Bahamas (Mathews, 1974, p. 245), peloids would be expected to be common if the shelf is protected by oolite shoals, reefs, or simply by its own extent, so as to provide a greater restriction which would result in increased salinity and greater residence time at the sediment-water interface. Another point involves the usually accepted distribution of birdseye structures. Most workers, following Shinn (1968a), would consider birdseyes to be absent in the subtidal setting, yet P. Hoffman (1978, oral communication) maintains that such features can develop subtidally beneath pustulose algal mats.

In the right half of the table (Table 3) are the abundance designations for corresponding features in the four units of the Little Falls. Numbers in parentheses represent percentages of the total number of units or samples in which a particular feature was observed. Here, "A" represents, more appropriately, "unobserved." Sandstones contribute toward the significance of structures such as cross-stratification and textures such as grain support. Compounding the difficulties already mentioned in the consideration of modern environments and ancient analogs are those of recognition and identification in the pervasively dolomitized Little Falls. It has been my contention that in ancient carbonate sequences, it is not always a straightforward matter of distinguishing between supratidal and intertidal (Zenger, 1972a, b), hence the value of the term "peritidal."

Before summarizing the data in Table 3, it is appropriate to at least consider the propriety of using such a classification as subtidal-intertidal-supratidal. That is, was there a tidal effect at the inner reaches of this wide, late Cambrian shelf which separated the landmass represented by the present Adirondacks from the slope into the Proto-Atlantic? In well-known stratigraphic works, Shaw (1964) and Irwin (1965) contended that in ancient epeiric seas with *very* low bottom slopes, friction would dissipate tidal effects (and wave action) so that the interior of the shelf seas would be tideless. Recently, Mazzullo (1978) has advocated a careful distinction between "shoaling" and "tidally influenced" deposition in ancient epicontinental seas. He pointed out that features such as oolite shoals, mud flats, channels, and fining-upward sequences need not imply tidal disposition inasmuch as similar lithofacies could develop by shoaling deposition in nontidal environments. Although he concluded that his Lower Ordovician rocks, representing sediments deposited on the outer shelf marginal to the more Proto-Atlantic slope, were tidally affected, he suggested that the interior regions of these seas may have been tideless owing to the dissipation of tidal energy by friction. Even more recently, however, Klein and Ryer (1978) maintained that a variety of sedimentological evidence, including herringbone cross-stratification, cross-strata with sharp set boundaries, interference ripple marks, flasers, clay drapes on ripples, etc., indicate that many sequences deposited in extensive, shallow epeiric seas of the past contain tidalites. They extended their finding of a positive correlation among shelf width, tidal range, and tidal current velocity of modern continental shelves (see also Cram, 1979, for supporting data) to ancient epeiric seas, concluding that the latter were, in fact, dominated by astronomical tides and by tidal circulation patterns. Of course, one may question this extrapolation from modern continental shelves to the vast, very shallow epeiric seas of the past, with their extremely gently sloping bottom profiles.

By applying the terms subtidal, intertidal, and supratidal to Little Falls sedimentation, there is obviously the implication that these sediments were tidally effected. Certainly there is little unequivocal evidence in the formation to really prove the former presence of tides and tidal currents, as contrasted with a shoal water carbonate environment adjacent to a low-relief land surface affected periodically by winds and storms and, on a longer term basis, by transgressions and regressions. However, despite the absence in the Little Falls of flasers, clay drapes (both of which can be explained by the lack of clays in general), reactivation surfaces, and the near-absence of herringbone cross-stratification and channels, I believe that the collective evidence of cross-stratification with sharp set boundaries, bipolar paleocurrent (i.e., cross-stratification) azimuths, small scale ripple marks, domal algal stromatolites, desiccation cracks, and intraformational and edgewise conglomerates strongly suggest an alternation of emergence and submergence that is easily, though not necessarily, explained by tidal cycles and processes.

The general picture presented by the data in Table 3 is that Units A–D overlap in character and environmental setting; all contain evidence for at least partial emergence (peritidal) and submergent (subtidal) conditions. For example, Unit A possesses many supratidal aspects including an absence of fossils, relatively abundant intraclasts, rare peloids and ooids, significant desiccation cracks, rare domal stromatolites, common laminations, an absence of ripple marks, and rare burrowing. Yet, the same unit is characterized by coarsely crystalline dolostone, rare cryptalgalaminate dolostone, an absence of birdseyes, common bioturbation, and a paucity of recognizable rhythmic sedimentation, which can be taken as suggestive of subtidal deposition. Unit B contains somewhat fewer characteristics usually indicative of supratidal deposition (e.g., rare invertebrate fossils, more finely crystalline dolostone, significant interclasts, common laminations, rare cross-stratification and ripple marks, absence of burrows, and more rhythmic sedimentation), but also more evidence of intertidal (domal algal stromatolites, rarer desiccation cracks, rare lingulids, more ripple marks) and subtidal conditions (significant ooids and peloids, absence of birdseyes, slightly more common cross-stratification, and more common grain support). Unit C is closer in character to Unit A than Unit B; it differs from the former in having fewer occurrences of intraclasts and laminations but more peloids, which suggests a greater influence of the subtidal environment although it is much less bioturbated. As indicated throughout the text, Unit D is the most distinct of the four units, although it too is characterized by "inconsistencies." It leads the other units in several features suggesting supratidal deposition, including an abundance of intraclasts, cryptalgal and noncryptalgal laminations, considerable fine crystalline dolostone, relatively few samples with grain support, a rarity of cross-stratification, and an absence of ripple marks. But, ooids (mostly chertified) are relatively abundant and bioturbation is most common in this unit. Actually, much of the difference between D and the older units results from the nature of the terrigenous and organic constituents, and dolomitization. Quartz sand is less common, finer grained, and less mature. Apparently the source of sediment in the area of the present southern Adirondacks had been reduced and/or the coarser terrigenous material had been trapped in a more landward direction (i.e., to the north, although Unit D is not present in that direction now, as a result of pre-Lowville erosion) because of transgression. Pyrite, probably reflecting original organic content, is more common than in other units. The dolomitization has created a much more finely crystalline product than in the underlying units. The unit seems to represent an environmental gradation between the main mass of Little Falls and the Tribes Hill, which with its relatively rich fauna and less pervasively dolomitized nature permits more confident subdivisions into subtidal, intertidal, and supratidal environments.

Assuming that the features have been correctly identified and interpreted, and that it is appropriate to consider the environments as tidally affected, no apparent simple picture emerges that relates stratigraphy and environment of deposition. The intimately related lithologies vertically must represent a close lateral association and relatively rapidly shifting environments.

It is a fact that progradation is occurring in most Holocene nearshore carbonate environments (Mathews, 1974, p. 254). Of paramount importance here is the point that, for the most part, carbonate sediment production is *in situ*. Although we can easily visualize progradation of carbonate shelves with regression, progradation can also proceed with submergence (i.e., transgression); rising sea water creates better circulation and more space, providing more ideal conditions for carbonate production. Mathews (1974, p. 340) has supported Irwin's (1965) use of lithologic responses to transgression as correlative events, by pointing out that short pulses of submergence is the style of Pleistocene sea-level fluctuation, followed by progressive restriction of the environment as sediment accumulates vertically and/or sea level gradually falls.

It is difficult to interpret the sandstones (i.e., particularly those above the basal conglomerates and sandstones) intercalated with the dolostones. They range from extremely thin laminations a quartz grain thick, to sequences several feet thick. I believe the sands have an eolian origin. The thin laminations and beds less than 0.5 feet (15 cm) in thickness, commonly without cross-stratification, probably represent sand saltated across the peritidal flats and deposited there, or subtidally. The relatively rare, thicker (generally thicker than a foot (0.3 m) and at one locality (6), up to 10 feet (3.1 m)) cross-stratified sandstones were probably deposited subtidally, as suggested by the bipolar orientation of the foreset beds; this distribution suggests the action of tides, ebb flow being dominant. Furthermore, it is unlikely that these sandstones represent beach dunes because of the low angle of dip of foresets reported for the latter. Evidence against their representing deposits in tidal channels is the rarity of channels as seen in the field and the lack of fining upward sequences. More likely, these thicker sandstones represent submerged bars deposited in the shoals between peritidal flat areas. Possibly they are somewhat analogous to the quartz sand dunes which prograde the southeast coast of Qatar Peninsula near Umm Said, Persian Gulf, and spill into the subtidal environment (Shinn, 1973). These accretion slopes in the Persian Gulf possess cross-stratification with dips over 20°, as in the Little Falls sandstones, but they are all planar and are dipping uniformly seaward. Although most cross-stratification in the Little Falls is planar, some is of the trough type, and there is apparently a bit more variation in the azimuths of the dips of these latter small-scale cross strata. It is conceivable that traced laterally, the thin sandstones would grade into the thicker, cross-stratified, subtidal(?) sandstones, but lack of continuity of exposures precludes testing this. Certainly these sandstones represent at least temporary progradation.

I agree completely with Mazzullo and others (1978,

p. 113), working in the Upper Cambrian-Lower Ordovician section near Saratoga Springs, who felt that the lithofacies were of local extent and undoubtedly represent a shoreline mosaic of peritidal flat areas separated by subtidal shoals. They (*ibid.*) concluded that ". . . reconstruction of cycles of deposition and paleoenvironmental-stratigraphy in this area are concerned not with regionally synchronous episodes of shoreline progradation and regression, but rather with a stacked shoreline facies mosaic that resulted from the independent and non-contemporaneous lateral migration of individual peritidal shoals and peripheral marine shelves."

In the Little Falls, then, I envision an initial, relatively rapid transgressive situation which resulted in the thin basal conglomeratic sandstones. Above this, the carbonate package represents an aggradational sequence; there is no simple picture of progradation, on a large scale, but rather there existed a close association of shifting peritidal and adjacent shallow subtidal deposits coupled with the influx of eolian quartz sand. The situation may be similar to that in part of the Dalradian (Precambrian, Scotland) described recently by Fairchild (in press) using transition probabilities: "Thus the generation of cycles by the . . . superposition of laterally equivalent facies predicted by "Walther's Law" does not apply . . . the facies would have formed a complex mosaic where there was no simple arrangement of facies in parallel belts."

Although Mazzullo and others (1978, p. 114) considered shelf-edge oolite banks in the Champlain Valley to represent Irwin's (1965) offshore turbulent zone Y, they believed that their nearshore low-energy zone is more complex than his zone Z in that " . . . sedimentation and resulting depositional environments reacted to a complicated hydrodynamic system of varying levels of turbulence with no suggestion, at this scale, of decreasing energy input for 80 kilometers to the west of the shelf edge. The broad expanse of shelf characterized by irregularly defined areas of contrasting energy conditions (zones Y and Z) and related lithofacies, to the lee of a major barrier (zone Y), appears to be more typical of epicontinental-sea sedimentation in New York than does a pattern of concentrically zoned depositional environments . . ."

Although Mazzullo and others (*ibid.*) could not account for the widespread energy conditions over such impressive distances, they suggested that the shelf in the present area of Saratoga Springs was transitional between the more turbulent part of the sea floor (zone Y—oolite banks) and "typical" zone Z (i.e., low-energy conditions) which might have existed to the west. The Little Falls outcrop belt does represent an area to the west and yet conditions were remarkably similar to those reflected by the section at Saratoga Springs. It appears that Irwin's zone Z is too simplified to explain nearshore carbonate depositional sites in general and these Late Cambrian environments in particular.

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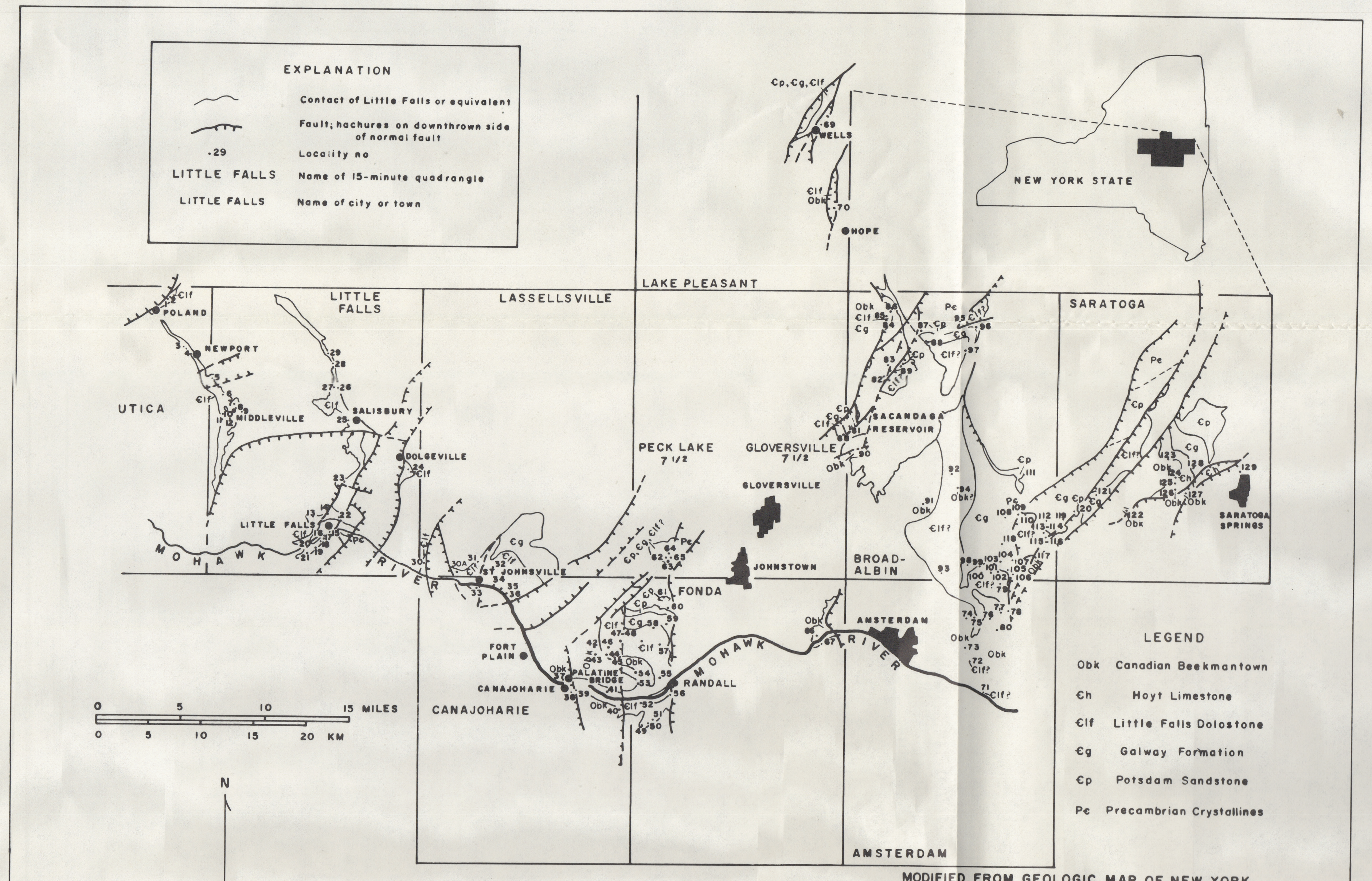
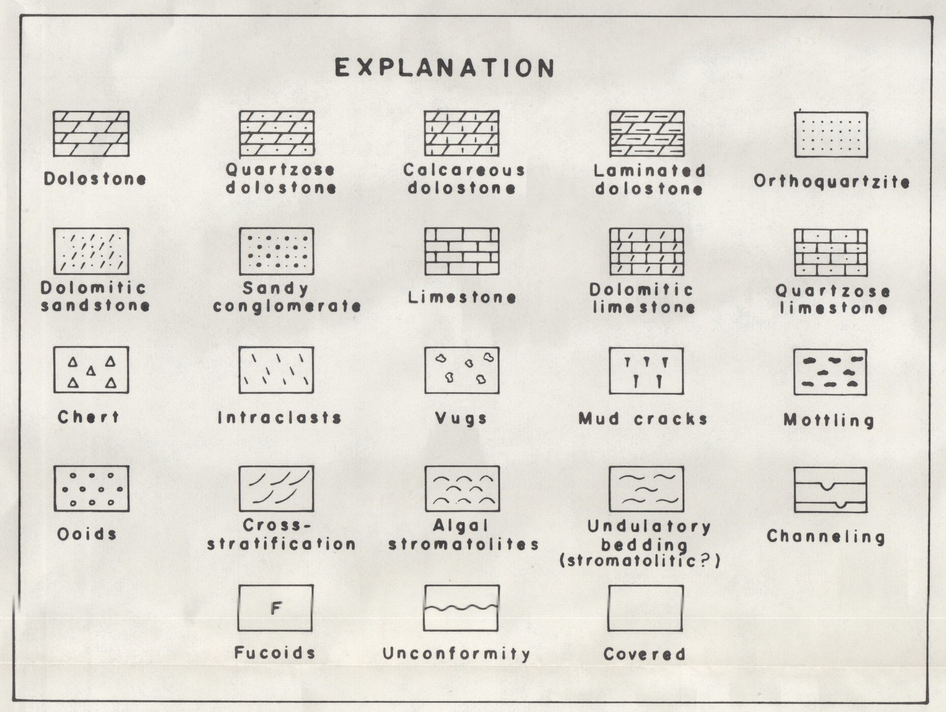
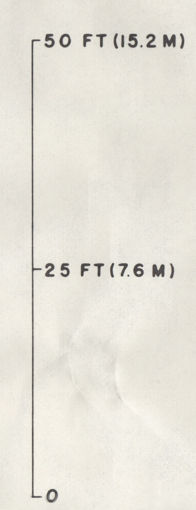


PLATE 1A INDEX AND LOCALITY MAP,
LITTLE FALLS DOLOSTONE AND EQUIVALENTS





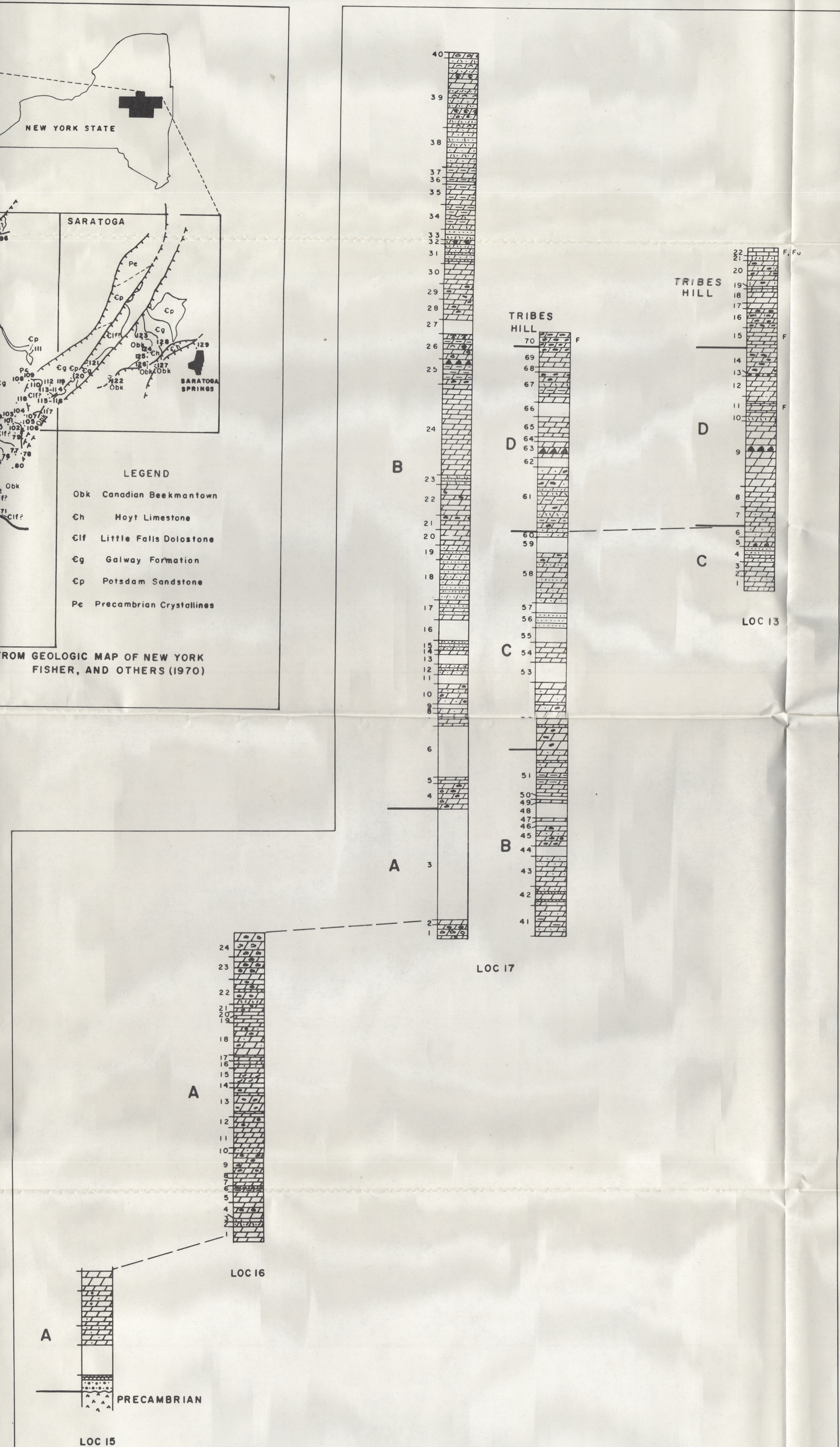


PLATE 1B
COLUMNAR SECTIONS
LITTLE FALLS AREA

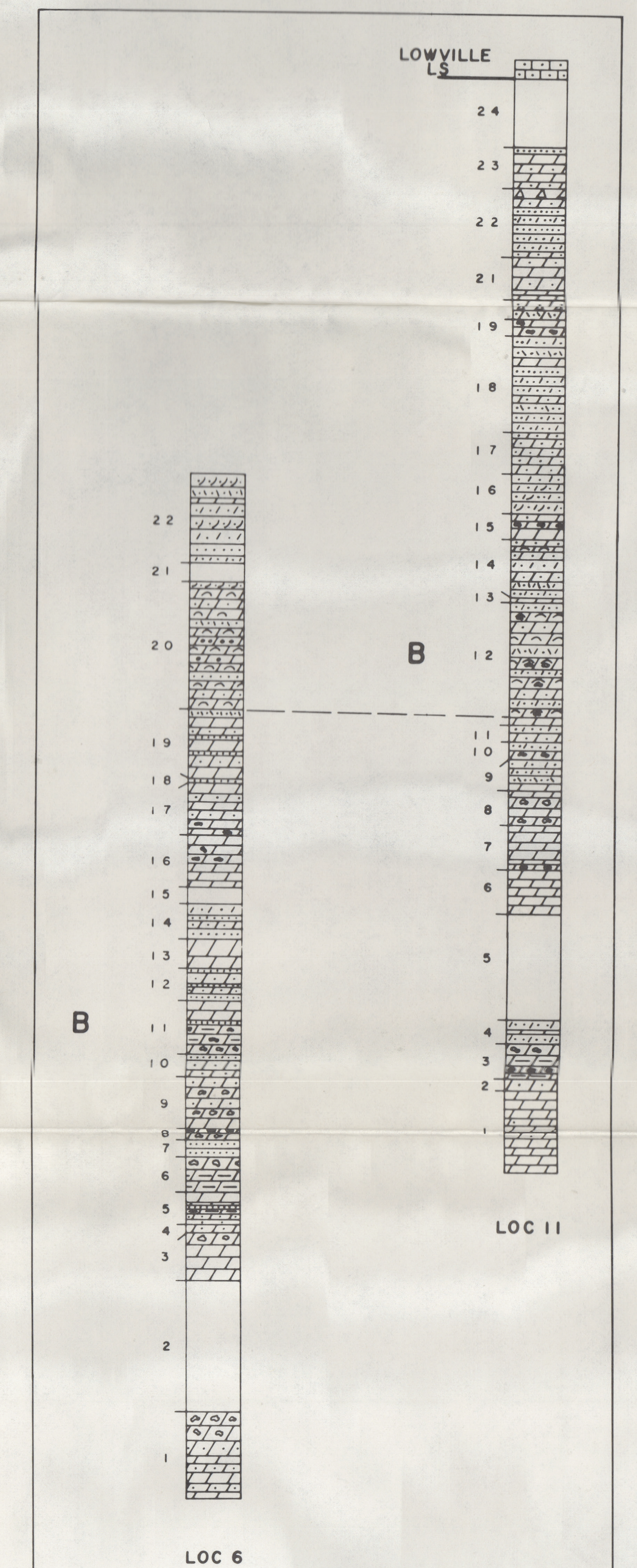


PLATE 1C
COLUMNAR SECTIONS
MIDDLEVILLE AREA

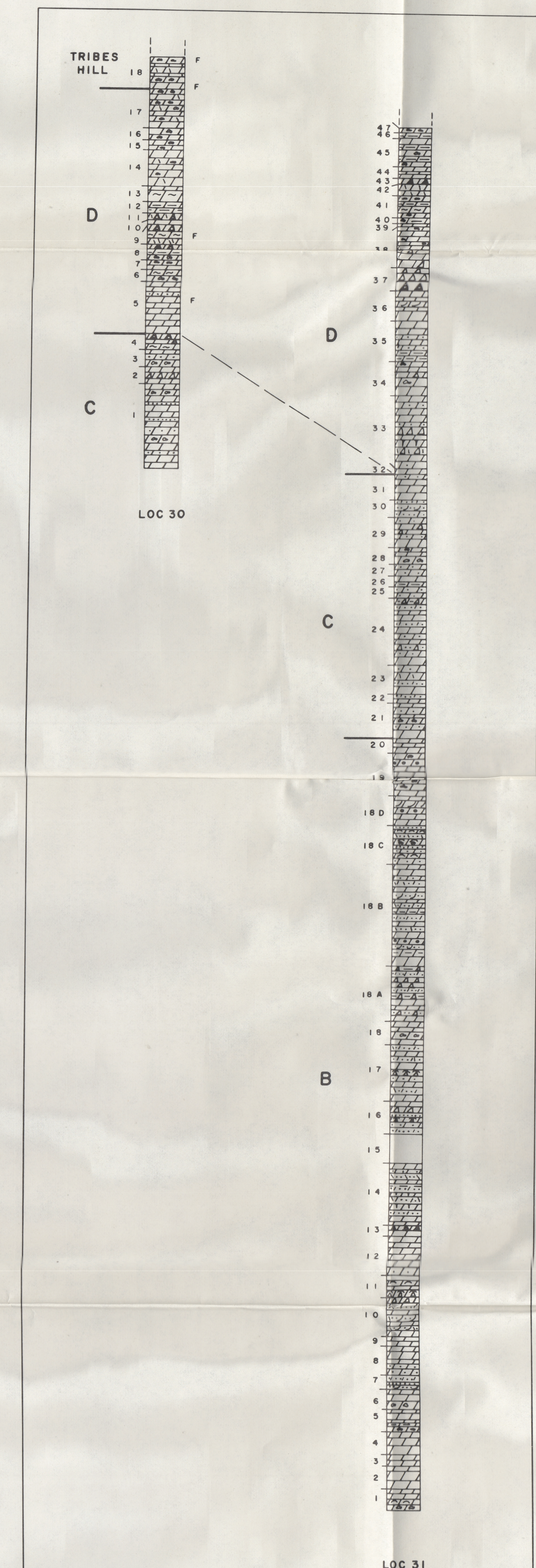


PLATE 1D
COLUMNAR SECTIONS
EAST CANADA CREEK-
ST. JOHNSVILLE AREAS

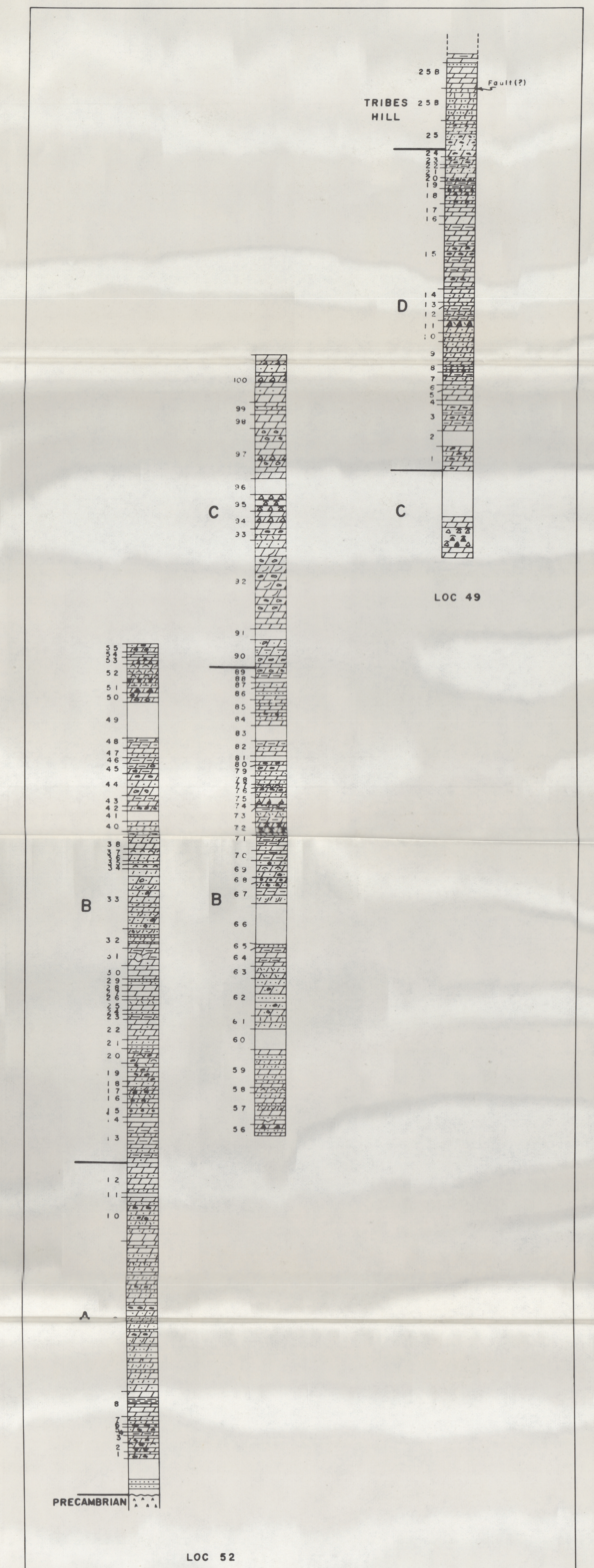


PLATE 1E
COLUMNAR SECTIONS
RANDALL AREA

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New York State Geological Survey
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PLATE 1. INDEX MAP AND COLUMNAR SECTIONS OF LITTLE FALLS DOLOSTONE