Petrology and Depositional Setting of Mississippian Rocks Associated with an Anoxic Event at Samak, Western Uinta Mountains, Utah

Petrology and Significance of a Mississippian (Osagean-Meramecian) Anoxic Event, Lakeside Mountains, Northwestern Utah

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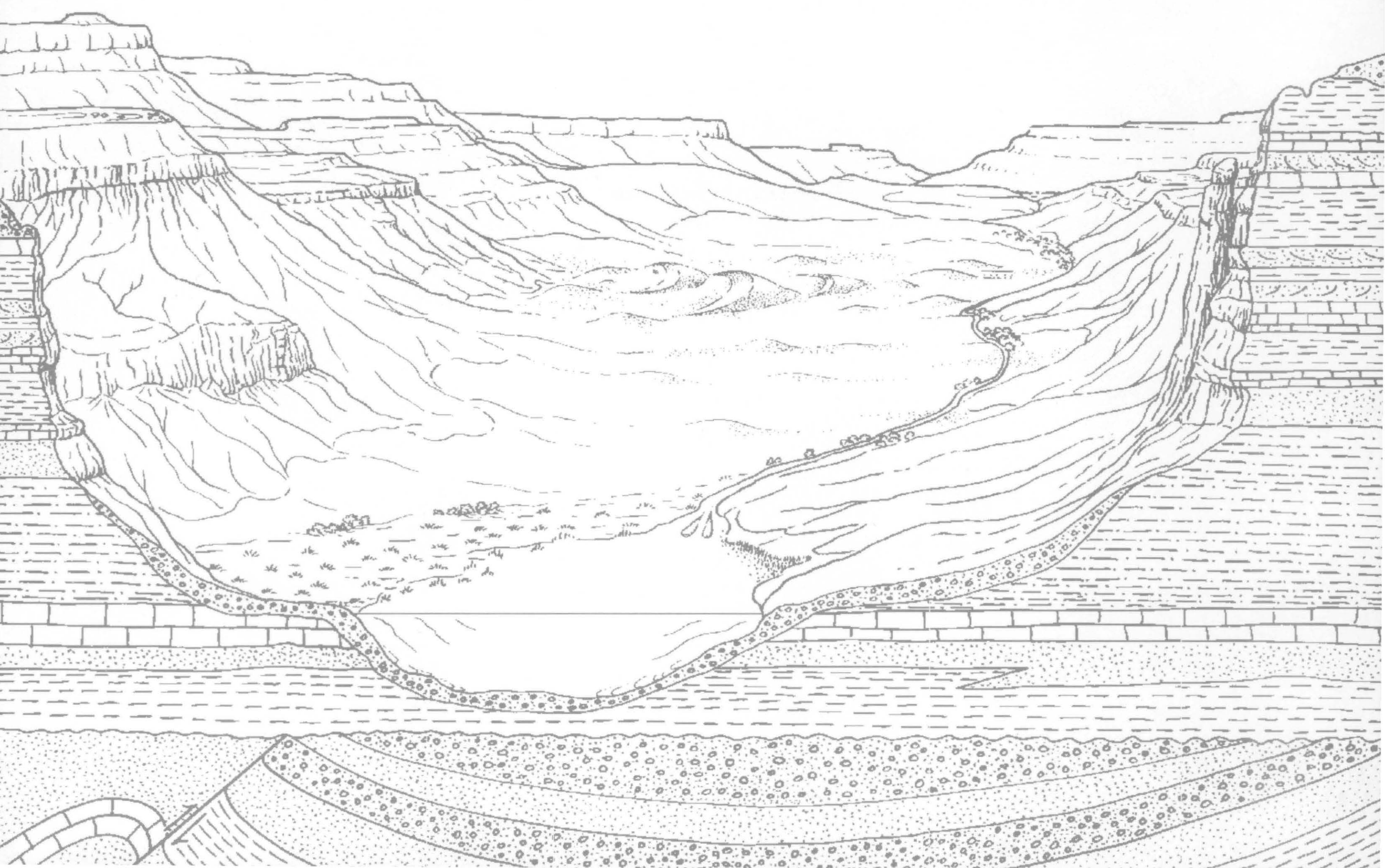

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Petrology and Depositional Setting of Mississippian Rocks Associated with an Anoxic Event at Samak, Western Uinta Mountains, Utah

By K.M. NICHOLS and N.J. SILBERLING

Petrology and Significance of a Mississippian (Osagean-Meramecian) Anoxic Event, Lakeside Mountains, Northwestern Utah

By K.M. NICHOLS and N.J. SILBERLING

Chapters S and T are published together in a single volume and
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U.S. GEOLOGICAL SURVEY BULLETIN 1787–S, T

EVOLUTION OF SEDIMENTARY BASINS—UINTA AND PICEANCE BASINS

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

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(T) Petrology and significance of a Mississippian (Osagean-Meramecian) anoxic event, Lakeside Mountains, northwestern Utah, by K.M. Nichols and N.J. Silberling.

Chapter S

Petrology and Depositional Setting of Mississippian Rocks Associated with an Anoxic Event at Samak, Western Uinta Mountains, Utah

By K.M. NICHOLS and N.J. SILBERLING

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1787

EVOLUTION OF SEDIMENTARY BASINS—UINTA AND PICEANCE BASINS

CONTENTS

Abstract S1
Introduction S1
Stratigraphic petrology S3
    Lithic unit 1—Oolitic grainstone S4
    Lithic unit 2—Laminated pelletal limestone S4
    Lithic unit 3—Lower crinoidal grainstone-packstone S5
    Lithic unit 4—Crinoidal wackestone-packstone S6
    Lithic unit 5—Ostracode lime mudstone S8
    Lithic unit 6—Spiculitic bryozoan-crinoidal packstone S8
    Lithic unit 7—Upper crinoidal wackestone-packstone S10
    Lithic unit 8—Dolostone S10
Discussion S11
References cited S12

FIGURES

1. Map showing location of Samak, western Uinta Mountains, Utah, and of studied stratigraphic section S2
2. Charts showing stratigraphy of Mississippian rocks at Samak S3
3–23. Photomicrographs of:
    3. Dolomitized oolitic grainstone, lithic unit 1 S4
    4. Fecal-pellet bioclastic grainstone, lithic unit 2 S4
    5. Fecal-pellet bioclastic packstone, lithic unit 2 S5
    6. Finely bioclastic fecal-pellet wackestone, lithic unit 2 S5
    7. Fecal-pellet bioclastic grainstone laminae, lithic unit 2 S5
    8. Solution-compacted mass of crinoid columnals and their rim cements, lithic unit 4 S6
    9. Extremely dissolved, solution-compacted bioclastic grainstone or wackestone grainstone, unit 4 S6
    10. Extremely dissolved, solution-compacted phosphatized mass of crinoid columnals, lithic unit 4 S7
    11. Extremely solution compacted, leached phosphatized mass of crinoid columnals, lithic unit 5 S7
    12. Ostracode lime mudstone, lithic unit 5 S8
    13. Ostracode lime mudstone, lithic unit 5 S8
    14. Bioclastic wackestone, lithic unit 5 S9
    15. Black chert, lithic unit 5 S9
    16. Partly silicified spiculitic bioclast packstone, lithic unit 6 S9
    17. Neomorphosed, solution-compacted packstone, lithic unit 6 S10
    18. Neomorphosed, partly silicified, solution-compacted, peloidal packstone, lithic unit 6 S10
    19. Solution-compacted, bioclastic, peloidal wackestone, lithic unit 6 S10
    20. Solution-compacted wackestone-packstone, lithic unit 7 S10
    21. Solution-compacted crinoidal and bryozoan wackestone-packstone, lithic unit 7 S11
    22. Solution-compacted crinoidal and bryozoan bioclasts in original packstone or grainstone, lithic unit 7 S11
    23. Coarsely crystalline secondary dolomite, lithic unit 8 S11

Petrology and Depositional Setting of Mississippian Rocks Associated with an Anoxic Event at Samak, Western Uinta Mountains, Utah

By K.M. Nichols *and* N.J. Silberling

Abstract

Shelf carbonate deposition in the Uinta and Piceance basins study area of the U.S. Geological Survey Evolution of Sedimentary Basins program was interrupted by an anoxic event during Mississippian time. Rocks influenced by this event, assigned by previous workers to the upper part of the Lodgepole Limestone and lower part of the overlying Brazer Dolomite, are especially well exposed and easily accessible near Samak, Utah, at the west end of the Uinta Mountains. In the Samak section, the upper few meters of normal marine-shelf limestone of the Lodgepole, originally rich in echinoderm ossicles and other open-marine, normal-salinity bioclasts, has undergone partial dissolution, solution corrosion, and concentration of insoluble components such as conodonts, and replacement by phosphate, culminating in a 2–3-cm-thick layer of pelletal phosphate at the top of the Lodgepole. Above this layer, comprising the lowermost part of the Brazer, deposits of the anoxic event are distinctive organic-rich ostracode lime mudstone that grades upward through about 20 m of spiculitic, bioclastic wackestone and packstone and then into normal shelf limestone and dolostone.

Mississippian rocks associated with the anoxic event at Samak reflect the incursion of upwelled, nutrient-rich marine water far onto the shelf. The stratigraphy and petrology of these rocks indicate the existence of a broad carbonate shelf having little topographic relief; they do not support the postulated "Deseret deep starved basin" model of previous workers.

INTRODUCTION

Mississippian phosphatic rocks in northwestern Utah are anomalous with respect to the thick, laterally variable sequence of subtidal to peritidal shelf carbonate rocks that stratigraphically underlies them as well as the thick sequence of peritidal carbonate and (or) craton-derived siliciclastic rocks that overlies them. These phosphatic rocks were included in the Delle Phosphatic Member by Sandberg and Gutschick (1984), who established this unit for exposures in the southern Lakeside Mountains (location LSM, fig. 1), Utah, where it was defined as the basal member of the Woodman Formation. These authors extended the Delle as the basal member of several different Mississippian formations in western Utah, northeastern Nevada, and southeastern and central Idaho and regarded the Delle Phosphatic Member as characteristic of their postulated "Deseret deep starved basin."

In the Samak area, at the west end of the Uinta Mountains, Mississippian strata were assigned, in ascending order, to the Lodgepole Limestone and Brazer Dolomite by Sandberg and Gutschick (1980). Because revision of this stratigraphic nomenclature was beyond the scope of a study in the U.S. Geological Survey Evolution of Sedimentary Basins—Uinta and Piceance Basins program, these names are retained herein, but their usage is not endorsed by us. The lowermost 17 m of the Brazer was termed the phosphatic member by Sandberg and Gutschick (1980) and presumably is the same as rocks included by these authors in the Delle Phosphatic Member when they extended usage of this name to the Samak area in 1984. We prefer not to use the member name here, however, because placement of its upper limit is essentially arbitrary, as explained below, and its thickness as a rock unit is trivial. Instead, we previously informally named this episode of anomalous anoxic deposition the "Delle phosphatic event" (Silberling and Nichols, 1990, 1991) because this event initiated anoxic, phosphatic deposition in the type section of the Delle Phosphatic Member. This concept is referred to herein simply as the anoxic event. Regionally, the Delle

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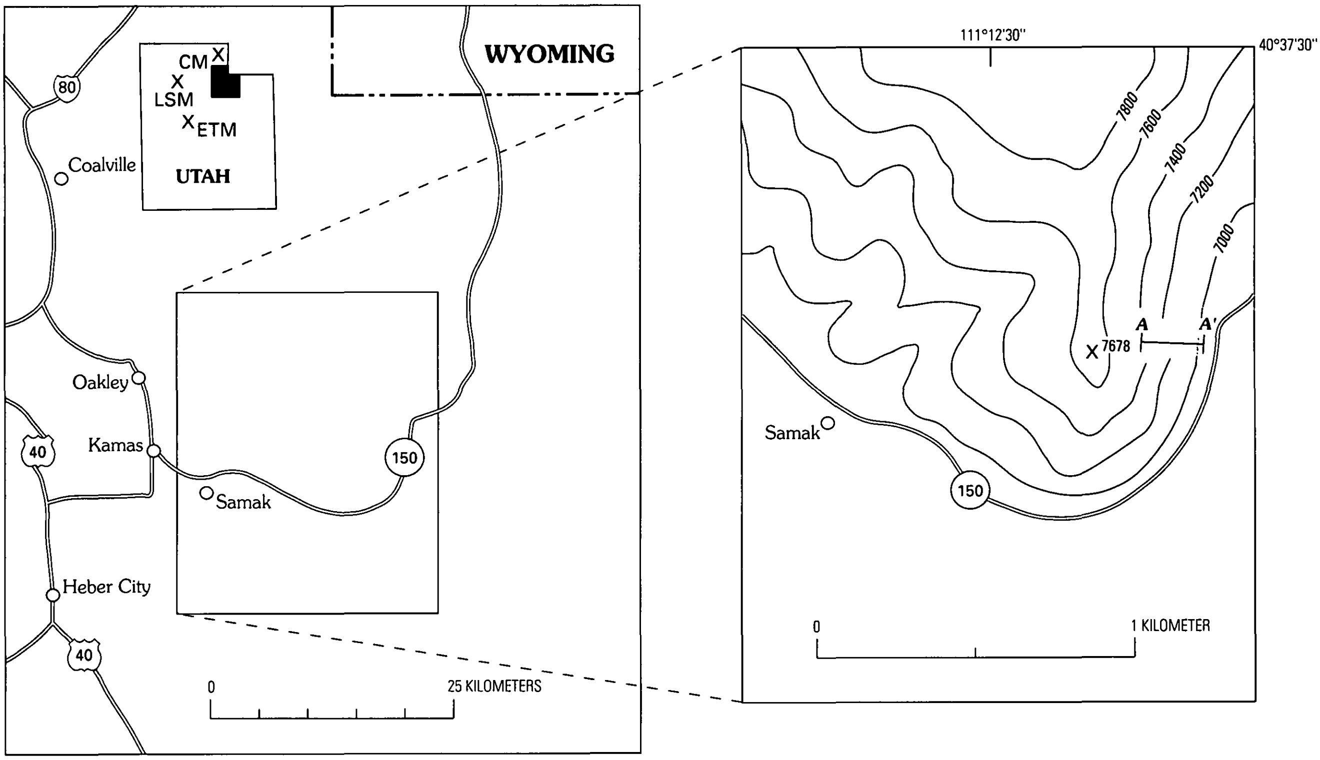


Figure 1. Location of Samak, western Uinta Mountains, Utah, and of studied stratigraphic section (*A–A'*) shown in figure 2. LSM, Lakeside Mountains; ETM, East Tintic Mountains; CM, Crawford Mountains. Topographic contours in feet, interval 200 ft.

Phosphatic Member is better regarded as the result of an anoxic geochemical event rather than as a formal rock unit because it cannot be recognized away from the vicinity of its type section using a consistent set of lithic criteria (see also Nichols and Silberling, this volume).

Although rocks of the anoxic event are relatively thin, they are of particular interest within the Evolution of Sedimentary Basins—Uinta and Piceance Basins study area (lat 38°30′–42° N., long 107°–112°30′ W.) (referred to herein as the study area) because they have an unusual depositional and diagenetic history and because they form the basis for inferences about economically important paleogeographic features such as the nature and location of the Mississippian shelf margin (Lane and others, 1980; Sandberg and Gutschick, 1980, 1984). Furthermore, assumptions about depositional environments during the Delle event and the postulated "Deseret deep starved basin" have significantly influenced interpretations of Mississippian facies patterns, eustatic sea-level history, diagenetic features, conodont and ostracode biofacies, and the Cordilleran paleotectonic history of Utah, Nevada, and Idaho (Rose, 1976; Sando, Dutro, and others, 1976; Poole and Sandberg, 1977; Sandberg and Gutschick, 1977, 1979, 1980, 1984; Gutschick and others, 1980; Lane and others, 1980; Sandberg, Poole, and Gutschick, 1980; Sando, Sandberg, and Gutschick, 1981; Sandberg, Gutschick, and others, 1982; DeCelles and Gutschick, 1983; Gutschick and Sandberg, 1983; Poole and Claypool, 1984; Gutschick, 1987; Sohn and Sando, 1987; Hintze, 1988.

Throughout the study area rocks influenced by the anoxic event are characterized by the abrupt disappearance of normal-marine shelf benthic fossils, the occurrence of pelletal or oolitic phosphorite, stratigraphically isolated massive beds or intervals of megascopically unfossiliferous lime mudstone, the rare occurrence of pelagic fossils such as radiolarians and goniatites, and the pervasive dissolution of limestone and replacement by silica. In the western part of the study area rocks affected by the anoxic event are as thick as 60 m. The rocks immediately older than those deposited during the anoxic event are thought by Sandberg and Gutschick (1984) to lie within the *Gnathodus typicus* Conodont Zone and are the same age everywhere that the effects of the event are recognized.

The easily accessible Mississippian section near Samak at the west end of the Uinta Mountains (fig. 1) was chosen for detailed sedimentologic and petrographic study because it includes the best expression of the anoxic event east of the Wasatch Mountains. This section, which is autochthonous with respect to Sevier-Laramide thrust faulting, provides an excellent tie-point between the Mississippian lithic units in the Uinta Mountains (Dockal, 1980) and those farther to the west in Utah. In the Samak section, rocks most affected by the anoxic event comprise a thickness of approximately 30 m within about 260 m of

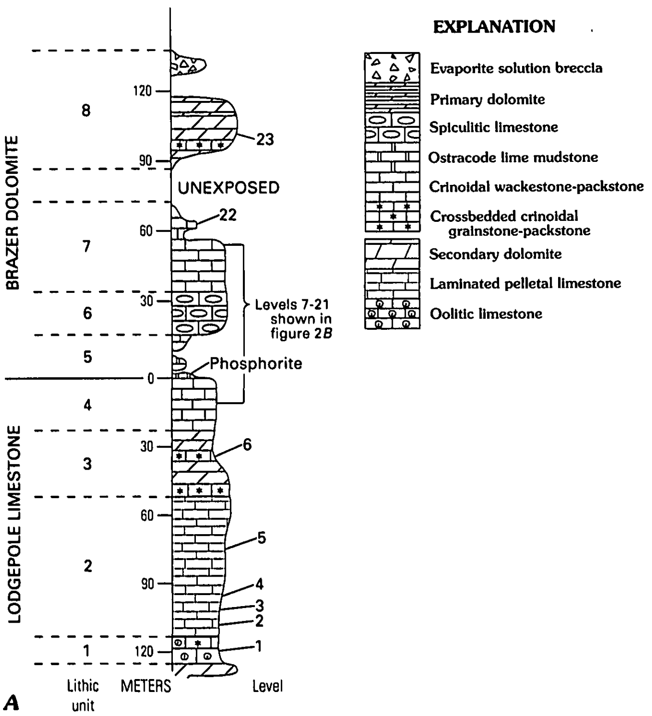
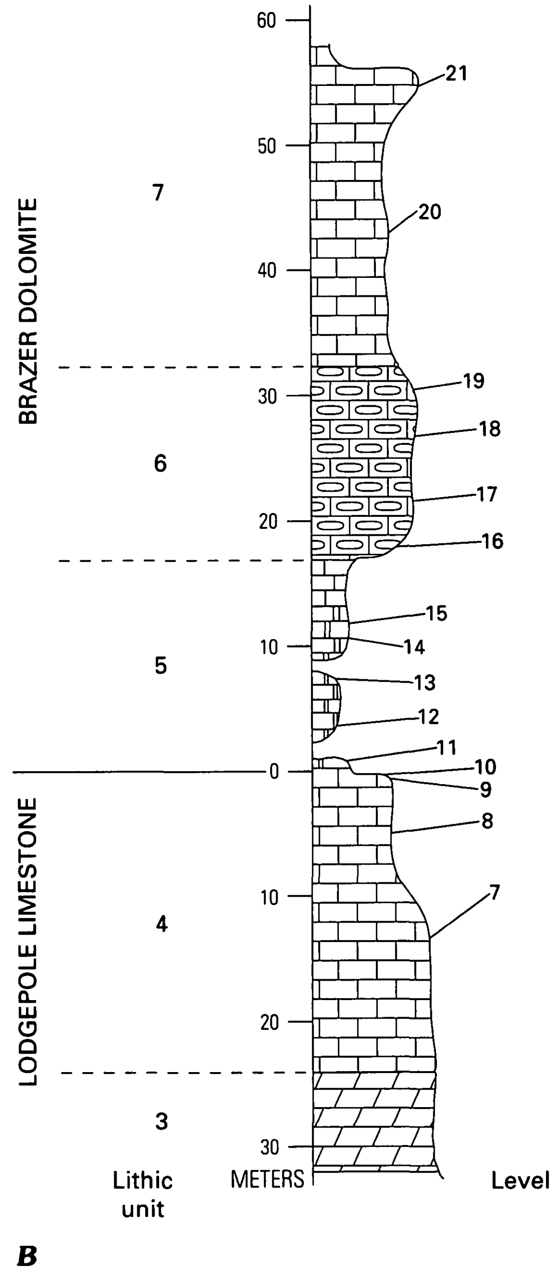


Figure 2. Stratigraphy of Mississippian rocks at Samak, western Uinta Mountains, Utah. *A*, Generalized stratigraphy of Mississippian rocks. Numbers indicate stratigraphic levels discussed in text. *B*, Stratigraphy of rocks associated with the anoxic event. Numbers indicate lithic units and stratigraphic levels discussed in text.



reasonably well exposed Mississippian marine carbonate rocks (fig. 2) assigned by Sandberg and Gutschick (1980) to the Lodgepole Limestone and Brazer Dolomite.

Our observations and interpretation of depositional environments at Samak agree closely with those in the comprehensive, unpublished doctoral thesis by Dockal (1980) and lead to a much different Mississippian (Osagean and Meramecian) paleogeography and depositional history for the eastern Great Basin and the western part of the study area than that proposed by Sandberg and Gutschick (1980, 1984) and Lane and others (1980).

STRATIGRAPHIC PETROLOGY

In the Samak section, the anoxic event altered the upper few meters of the Lodgepole Limestone and is represented by anomalous carbonate-rock deposits that represent the lower part of the Brazer Dolomite. Neither the base of the Lodgepole nor the uppermost part of the Brazer is exposed. The partial section at Samak is divided here into eight distinct lithic units (fig. 2*A*) that represent distinct depositional environments which have actual or potential regional significance. In ascending order, these units are (1) oolitic grainstone, (2) laminated pelletal limestone, (3) crinoidal grainstone-packstone, (4) lower crinoidal wackestone-packstone, (5) ostracode lime mudstone, (6) spiculitic bryozoan-crinoidal packstone, (7) upper crinoidal wackestone-packstone, and (8) dolostone. The Lodgepole-Brazer contact lies between units 4 and 5. Because strata in the Samak section are very gently dipping, stratigraphic thicknesses of units 1 through 3 were estimated using an altimeter and are precise only to several meters. Units 4 through 6, including the strata influenced by the anoxic event, were measured using a Jacob's staff.

Lithic Unit 1—Oolitic Grainstone

The stratigraphically lowest outcrops in the Samak section, beginning about 5 m uphill from the highway grade (fig. 1), are 2–3 m of massive, cliff-forming, sugary, secondary dolostone containing scattered ghosts of echinoderm ossicles. Although assigned to the Devonian Fitchville Formation by Spreng (1979), this dolostone is regarded here as part of the overlying, partly dolomitized, oolitic rocks and thus part of the Mississippian, following Dockal (1980). Above the massive secondary dolostone is about 5 m of thick-bedded, partly dolomitic, oolitic grainstone (level 1, fig. 2*A*), which in favorable exposure exhibits conspicuous large-scale, planar crossbedding. Ooids predominate as allochems in the stratigraphically lower part of the grainstones (fig. 3), whereas bioclasts and peloids (probably micritized ooids and rounded bioclasts) are more abundant in higher beds. Bioclasts in this unit are mainly crinoid ossicles. Large fragments of colonial algae are present along with ossicles in the lower oolitic grainstone beds.

By tracing this unit eastward in the Uinta Mountains, Dockal (1980) demonstrated that it is in the basal part of the Mississippian section. It may occupy the same stratigraphic position as the oolitic rocks that characterize the base of the type Gardison Limestone in the East Tintic Mountains (location ETM, fig. 1) (unpublished data).

Lithic Unit 2—Laminated Pelletal Limestone

Thick beds of cross-stratified oolitic grainstone unit are abruptly overlain by regularly thin and medium parted, fine-grained limestone of unit 2 (levels 2–5, fig. 2*A*), much of which exhibits pronounced planar lamination. Subordinate, distinct, medium-thick interbeds are coarse bioclast-intraclast packstone and grainstone.

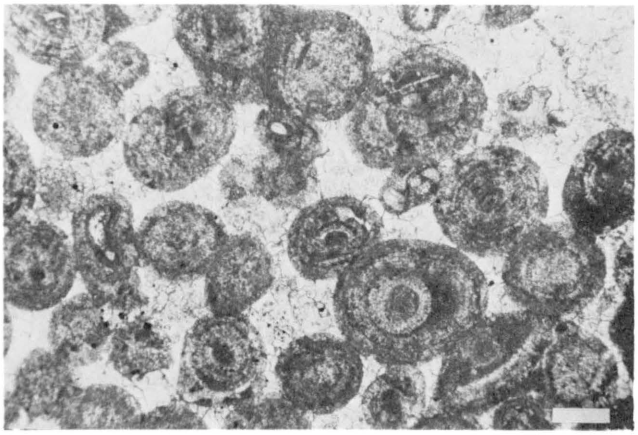


Figure 3. Photomicrograph of dolomitized oolitic grainstone. Level 1, lithic unit 1 (fig. 2). Cores of oolites are mainly fossil fragments; sparry cement mainly replaced by secondary dolomite, whereas ooids and bioclasts are still calcitic. Bar scale, 0.2 mm.

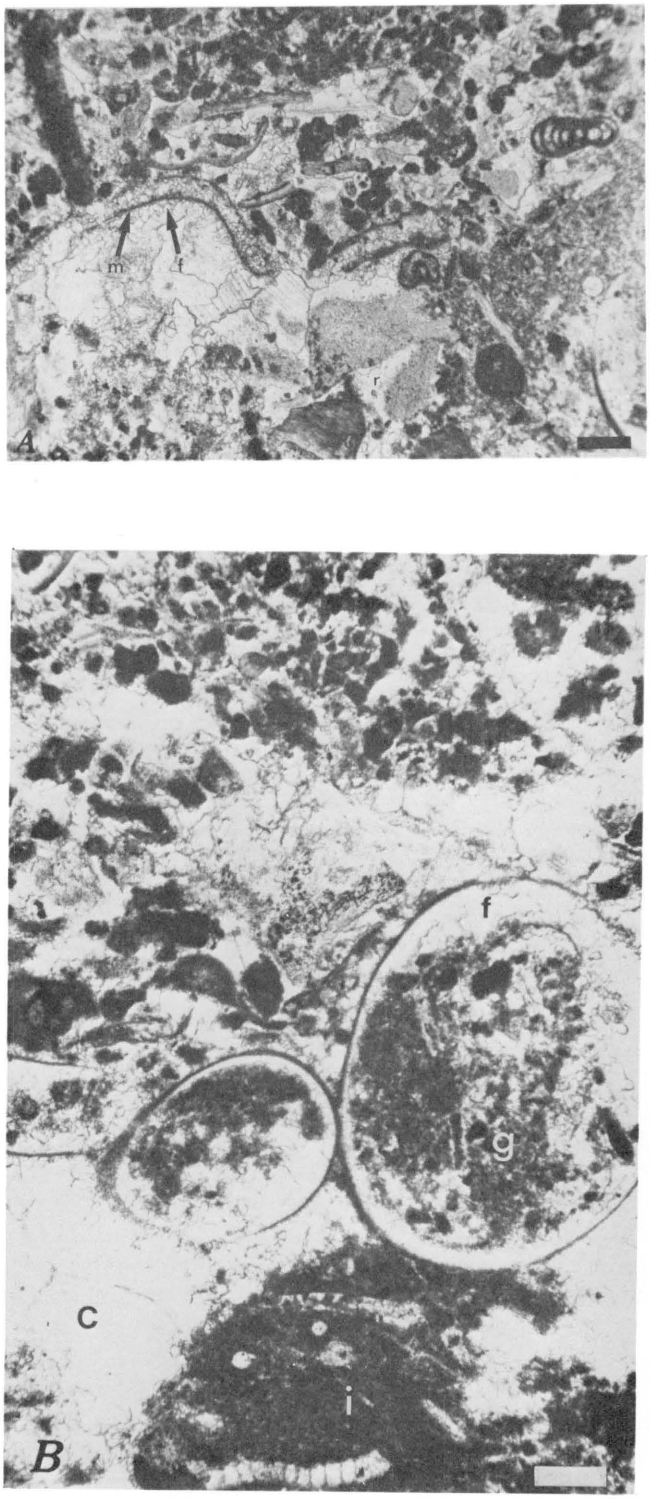


Figure 4. Photomicrographs of fecal-pellet bioclastic grainstone from a tempestite bed. Level 2, lithic unit 2 (fig. 2). Bar scales, 0.2 mm. *A*, Finer grained part of tempestite bed showing fringing cement (f), micritic envelope (m), rim cement around echinoid grain (r), and endothyrid in lower center of view. *B*, Coarser grained part of tempestite bed showing intraclast (i), coarse sparry void-filling calcite cement (c), fringing cement (f), and cross section of whorl of low-spired grazing gastropod (g).

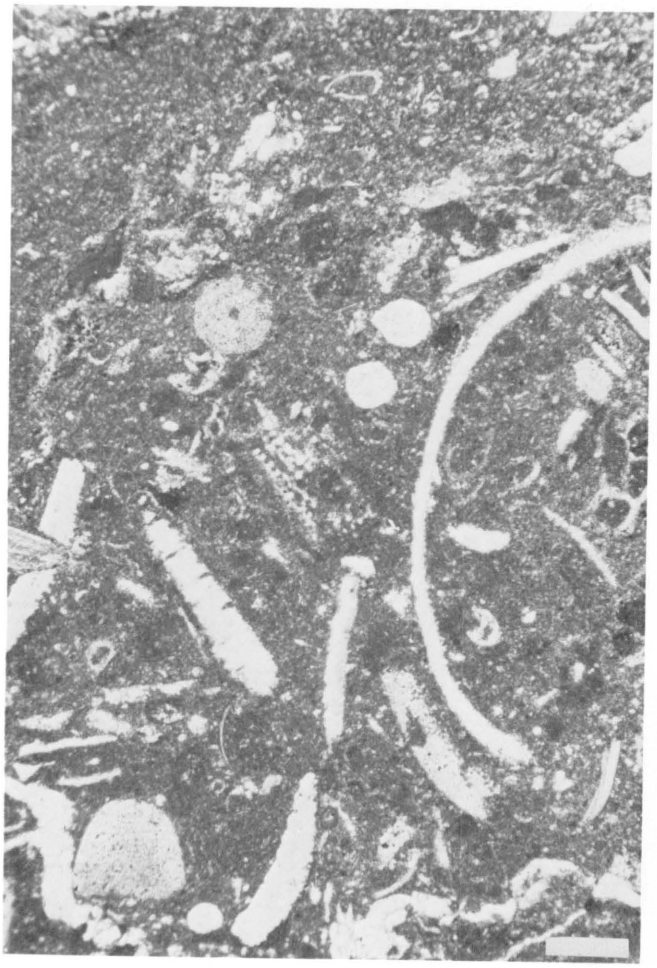


Figure 5. Photomicrograph of fecal-pellet bioclastic packstone grading up into wackestone lamina at top of view. Level 3, lithic unit 2 (fig. 2). Bar scale, 0.2 mm.

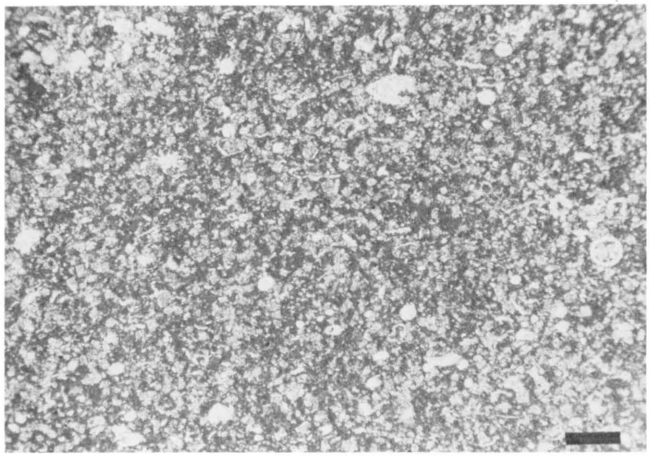


Figure 6. Photomicrograph of partly dolomitized, finely bioclastic fecal-pellet wackestone in which layering is produced by oriented thin shell fragments; cloudy dolomite subhedra replace much of original mud matrix. Level 4, lithic unit 2 (fig. 2). Bar scale, 0.2 mm.

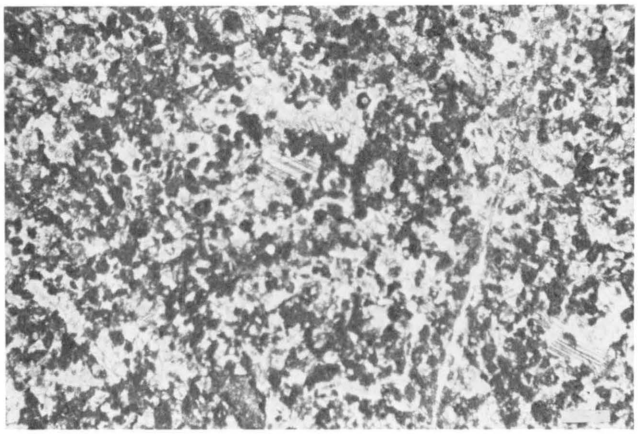


Figure 7. Photomicrograph of fecal-pellet bioclastic grainstone laminae in a grainstone-packstone laminated rock. Level 5, lithic unit 2 (fig. 2). Bar scale, 0.2 mm.

The laminated fine-grained limestone is predominantly composed of fecal pellets mixed with varying proportions of finely comminuted bioclasts and lime mud. The pellets are generally uniform in size, and the planar lamination reflects an inverse variation in bioclast size and lime mud content. These fine-grained, evenly bedded rocks are wackestone to grainstone in texture (figs. 5–7). The coarse, intraclastic, shelly interbeds are discontinuous and as thick as 10 cm. They occur at 0.2–2 m intervals in the laminated pelletal limestone, generally have sharp contacts with the enclosing fine-grained limestone, and tend to be either normally or inversely graded. Intraclasts in these beds are composed of the enclosing fine-grained limestone, and bioclasts are commonly whole fossils of brachiopods, corals, endothyrids, and gastropods (fig. 4). Large, low-spired gastropods dominate some beds.

Rocks of this distinctive unit, which is about 50 m thick, are interpreted as deposits formed on a current-swept subtidal flat, the coarse, shelly interbeds being storm deposits or tempestites.

This same lithic unit forms the major part of the type Gardison Limestone in the East Tintic Mountains and the rock unit commonly referred to the Lodgepole Limestone at locations in northwestern Utah such the Lakeside Mountains (Nichols and Silberling, 1990) and Crawford Mountains (unpublished data). This widespread lithologic unit has been recognized by Dockal (1980, fig. 2) in sections in the Uinta Mountains as much as 100 km east of the Samak section.

Lithic Unit 3—Lower Crinoidal Grainstone-Packstone

Rocks of this unit, which is about 25 m thick, are massive and cliff forming, partly owing to secondary dolomitization. Peloidal, ossicle-rich, coarse bioclastic grainstone and packstone (for example, level 6, fig. 2*A*) are gradationally intercalated with massive, sugary, secondary dolostone. Remnant bedding characteristics within the massive units include irregular current layering and large-scale, high-angle crossbedding.

Dockal (1980, fig. 8) traced this part of the section into microbial-mat primary dolostone and related rocks farther to the east in the Uinta Mountains. Thus, secondary dolomitization within this unit most likely was an eogenetic, perhaps permeability controlled, effect of evaporitic environments farther inland on the shelf.

High-energy, shoal-water, crossbedded, crinoidal limestone, resembling that of unit 3 in the Samak section, occupies a similar stratigraphic setting in rocks assigned by previous workers to the Lodgepole Limestone in the Crawford Mountains where it forms a conspicuous 3-m-thick unit near the top of a thick interval corresponding lithologically to unit 2 of the Samak section (unpublished data).

Lithic Unit 4—Crinoidal Wackestone-Packstone

The uppermost unit of the Lodgepole Limestone is about 25–30 m thick and is massive, pelleted crinoidal lime wackestone that grades upward into bioturbated, diffusely and irregularly interstratified, fecal-pelleted lime wackestone, packstone, and, more rarely, grainstone. Pelmatozoan columnals and other bioclasts, including a few solitary corals and brachiopod shells, are abundant in the packstone and grainstone. The base of unit 4 is not necessarily a primary lithic boundary because the protolith of the underlying secondary dolostone is unknown.

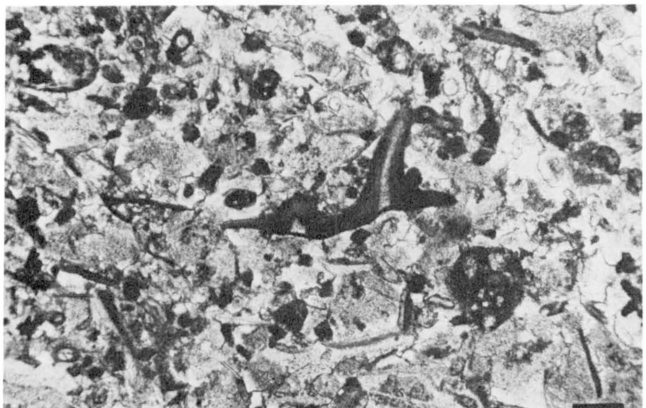


Figure 8. Photomicrograph of solution-compacted mass of crinoid columnals (cloudy large grains) and their rim cements, which are probably remnants of an original grainstone fabric; minor components are fecal pellets, spiney brachiopod shell fragments, and endothyrids. Level 7, lithic unit 4, (fig. 2). Bar scale, 0.2 mm.

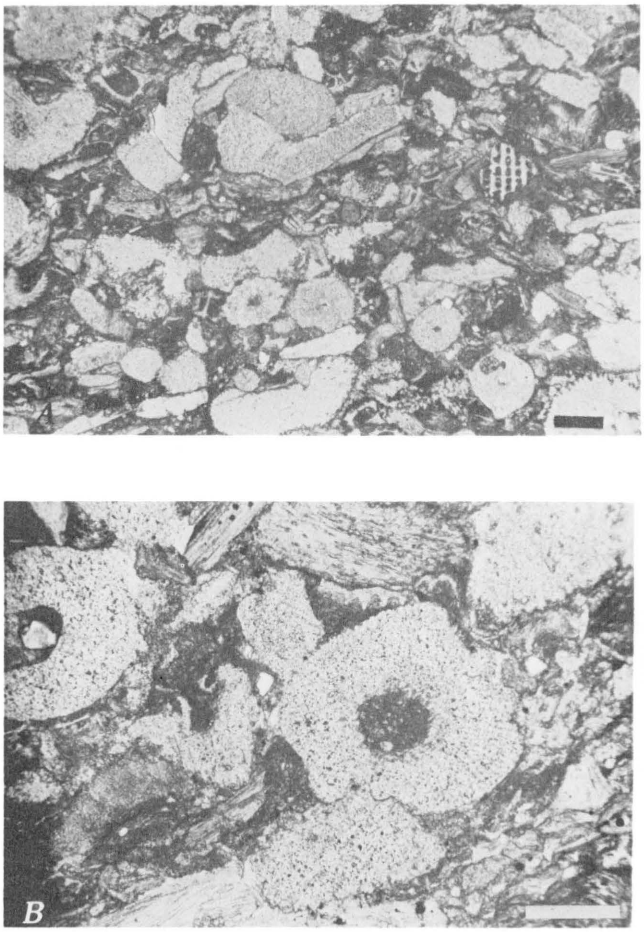


Figure 9. Photomicrographs of extremely dissolved, solution-compacted bioclastic grainstone or wackestone grainstone. Level 8, lithic unit 4. Bar scales, 0.2 mm. *A*, Grain boundaries are dissolution surfaces. *B*, Magnification of different view than *A* showing solution suturing of grains and thin-walled bioclasts crushed between crinoid columnals; white areas are voids.

Rocks having the character of unit 4 in the Samak section are present at the top of the type Gardison Limestone in the East Tintic Mountains and virtually throughout northwestern Utah where they form the highest part of rock units referred to the Gardison, Lodgepole, or Joana Limestones. Nowhere in Utah is this regionally extensive unit of subtidal platform deposits more than a few tens of meters thick.

In the Samak section the uppermost 10–15 m of unit 4, as seen in thin section, is increasingly solution compacted, so that original textures and bedding characteristics are increasingly obscured upward (figs. 8, 9). The more resistant allochems, such as coarse shell fragments and crinoid ossicles, are compacted, as indicated by highly sutured grain boundaries and collapsed remnants of more delicate bioclasts such as bryozoan fragments (fig. 9). Phosphate occurs in the uppermost 1 m of the Lodgepole Limestone as scattered peloids and pore fillings within

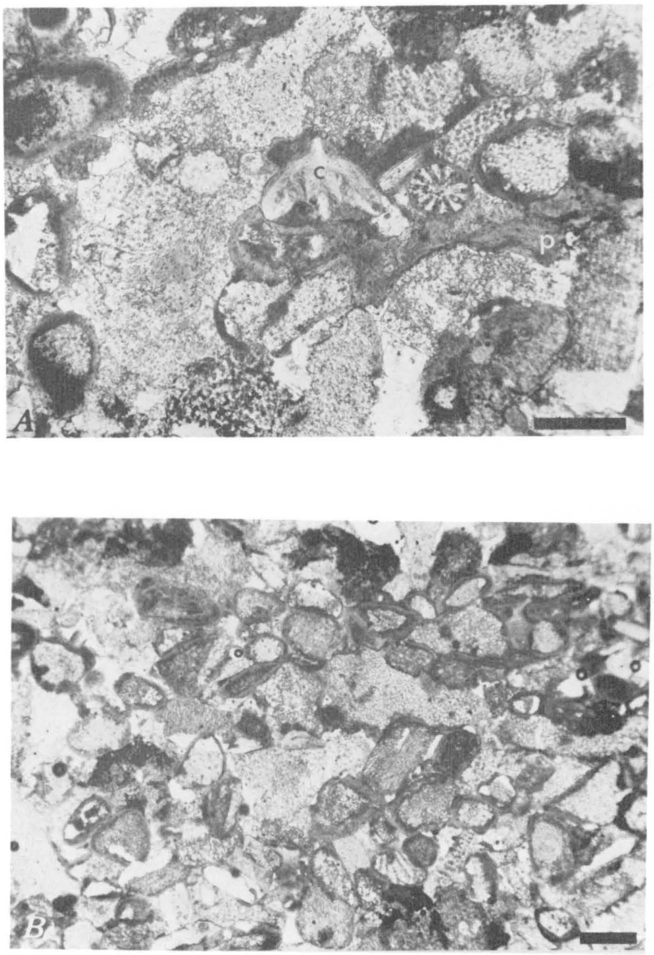


Figure 10. Photomicrographs of extremely dissolved, solution-compacted phosphatized mass of crinoid columnals; grain boundaries are dissolution surfaces. Level 9, lithic unit 4 (fig. 2). Bar scales, 0.2 mm. *A*, Phosphate fills pores in crinoid grains and is replacive following solution sutures of grains (p); conodont (c). *B*, Lower magnification of different view of *A* showing extreme degree of volume compaction and total loss of matrix and cement; three of the grains in this view are fragments of conodonts and illustrate the abundance of conodonts in these highly dissolved limestones; white spaces are voids.

crinoid ossicles (fig. 10). This interval mainly consists of ossicle remnants, the original outlines of which have been totally destroyed and whose boundaries are entirely solution seams separating one from another. In the highest few centimeters of the interval, phosphate replaces the ossicles and other remaining allochems following these solution seams, so that the grains first are rimmed with phosphate and then ultimately are transformed into phosphate peloids (fig. 11). The phosphatizing solutions probably followed the same pathways as the carbonate-dissolving solutions and thus may be related to them. In outcrop the top of the crinoidal wackestone-packstone unit is an irregular layer of phosphate pellets 2–3 cm thick that grades sharply down into the underlying partly phosphatic limestone.

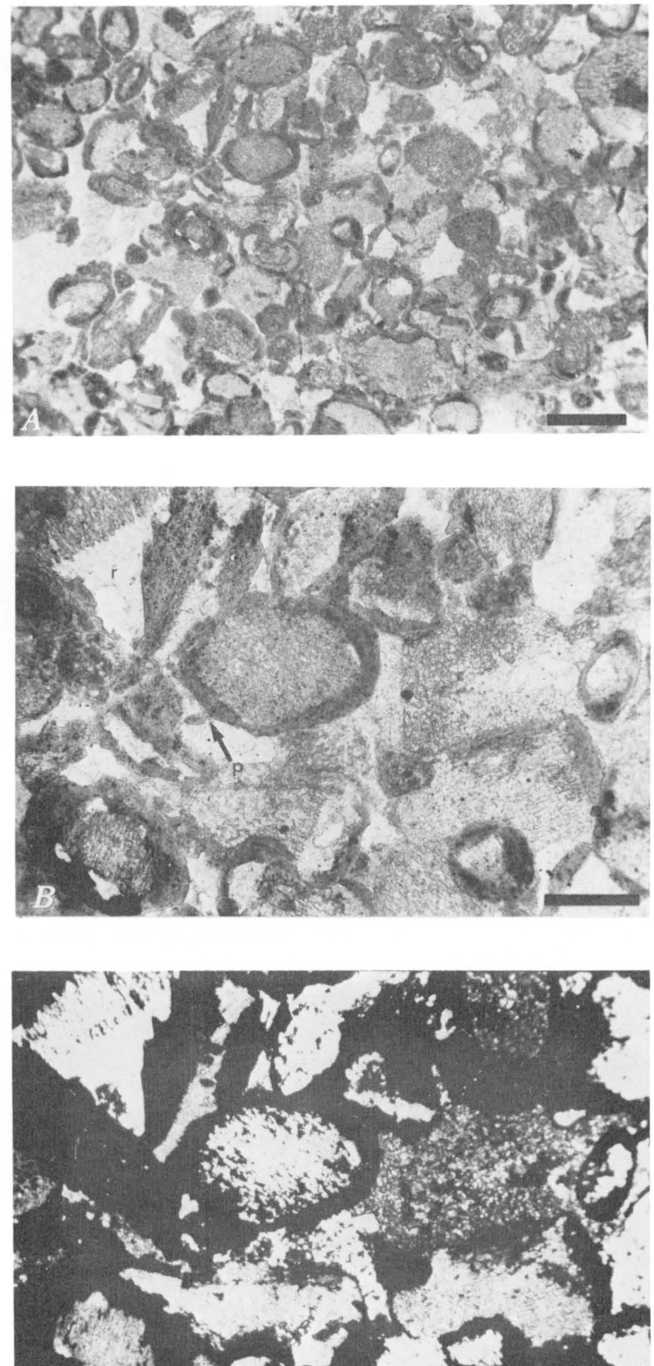


Figure 11. Photomicrographs of extremely solution compacted, leached phosphatized mass of crinoid columnals. Level 10, lithic unit 5 (fig. 2), and KAM–1 of Lane and others (1980, p. 125). Bar scales, 0.2 mm. *A*, White spaces are mostly voids; conodonts are very abundant (estimated 1 percent of grains) in this rock and at this level (Lane and others, 1980, p. 125, table 4), although none are in this view. *B*, Magnification of left center of *A*, plane light; phosphatic pore fillings in cloudy single crystals of calcite (c), phosphatic replacement rim (p), calcite rim cement (r). *C*, Magnification of left center of *A*, crossed nicols; black areas are phosphate and voids, which can be differentiated in *B*.

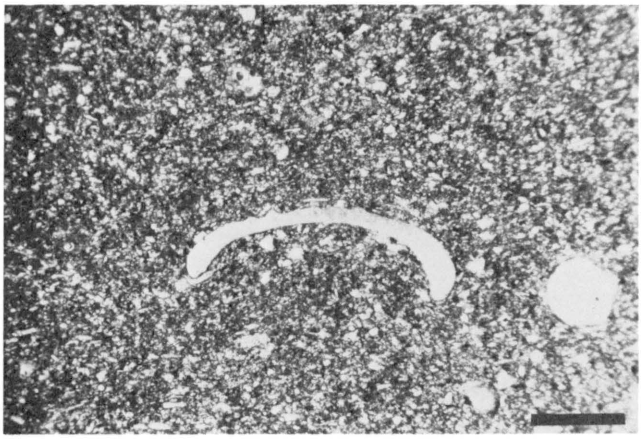


Figure 12. Photomicrograph of ostracode lime mudstone showing the finely fragmental "micropackstone" texture of the matrix formed mainly of 10–20-micron bioclasts; ostracode shell in center of view, thin brachiopod shells are present in other areas out of view; large white spots are voids. Level 11, lithic unit 5, (fig. 2). Bar scale, 0.2 mm.

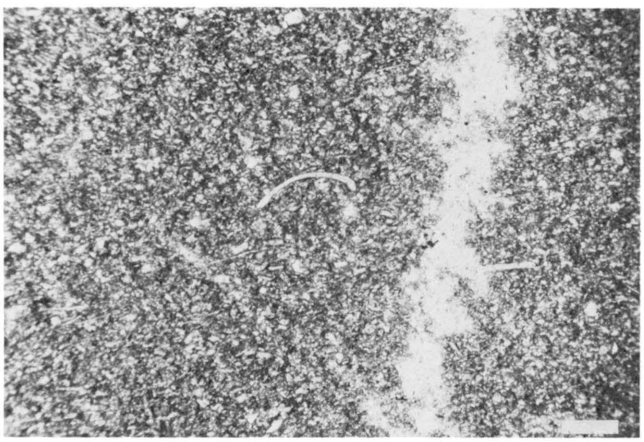


Figure 13. Photomicrograph of ostracode lime mudstone showing the finely fragmental "micropackstone" texture of the matrix; the only identifiable larger bioclasts are ostracode shells. Level 12, lithic unit 5 (fig. 2), and KAM–1A of Lane and others (1980, p. 125). Bar scale, 0.2 mm.

Lithic Unit 5—Ostracode Lime Mudstone

The ostracode lime mudstone unit, lithic unit 5, is recessive and poorly exposed, especially in the lower two-thirds of its total thickness of 17 m. In shallow excavations, dense, black, laminated, platy lime mudstone of this unit lies with sharp contact on the underlying phosphate-pellet layer of lithic unit 4. X-ray diffraction analysis of the impure-looking lime mudstone from level 11, as well as from level 14, reveals no detectable mineral phases other than calcite, and thus the pigment and impurity in these limestones are probably entirely organic matter. Sparse outcrops of the ostracode lime mudstone unit at level 12 and higher levels also are laminated, platy weathering, and dark on fresh surfaces but weather brownish or pinkish gray.

The ostracode lime mudstone unit generally can be described as sparsely bioclastic, more or less laminated, organic lime mudstone to wackestone; however, rather than being micritic, the matrix consists of discrete, subequidimensional, 10–30-micron grains that appear to be bioclasts. Scattered among these grains in most samples are thin, flat shell fragments as long as 100 microns and oriented parallel with stratification, giving a layering to the rock (figs. 12, 13). The fabric of this matrix could be termed micropackstone rather than lime mudstone. Larger bioclasts in this matrix are mainly ostracodes that are commonly thick shelled (figs. 12, 14*B*, *C*). Some laminae several meters above the base of the unit and higher are wackestones that, in addition to the ubiquitous ostracodes, contain abundant fragments of thin-shelled brachiopod shells (fig. 14*A*) and rare solitary corals (fig. 14*B*). Near the top of the unit, bioclasts include bryozoan fragments and some highly corroded echinoderm debris. Thus, within the upper part of unit 5 ostracode lime mudstone grades upward into wackestone that has a more normal-marine assemblage of bioclasts.

Chert replacement in some beds of the ostracode lime mudstone and bioclastic wackestone high in the unit has preserved the original matrix and bioclasts (fig. 15). No radiolarians were observed by us in unit 5, but they are reported by Dockal (1980) from this unit in the Samak section.

Petrographically, the ostracode lime mudstone at Samak is similar to that of units 13 and 16 of the type Delle Phosphatic Member in the Lakeside Mountains (Nichols and Silberling, 1990, fig. 2; this volume), which are interpreted as restricted, possibly hypersaline deposits. Ostracode lime mudstone is a distinctive part of the rocks influenced by the anoxic event at most of their occurrences in western Utah (unpublished data).

Unit 5 corresponds to the "phosphatic member" of the Brazer Dolomite of Sandberg and Gutschick (1980), which in 1984 was incorporated into their Delle Phosphatic Member. As explained above, we do not recognize this formal member here because placement of its upper boundary within the lithologically transitional sequence of unit 5 is arbitrary, using the lithic criteria that define the top of the type Delle section in the Lakeside Mountains.

Lithic Unit 6—Spiculitic Bryozoan-Crinoidal Packstone

The contrast between the massive, 15-m-thick, cliff-forming rocks of lithic unit 6 and the underlying, recessive strata of unit 5 reflects in part an upward transition from matrix-supported to allochem-supported limestone (fig. 16). More importantly, this contrast is also the result of partial silicification and solution compaction related to the development of stylolitic bedding. The boundary between units 5 and 6 is conspicuous in outcrop mainly because of these secondary effects. In unit 6, secondary chert is present as pervasive webbing and as irregular thin layers at about medium-bedded intervals. Much of the matrix in the rocks comprising unit 6 resembles that of the underlying ostracode lime mudstone and bioclastic wackestone of unit 5 in that it has a finely fragmental micropackstone fabric (figs. 17–19). Allochems are mainly fine grained and include abundant calcareous spicules and peloids. Bryozoan and

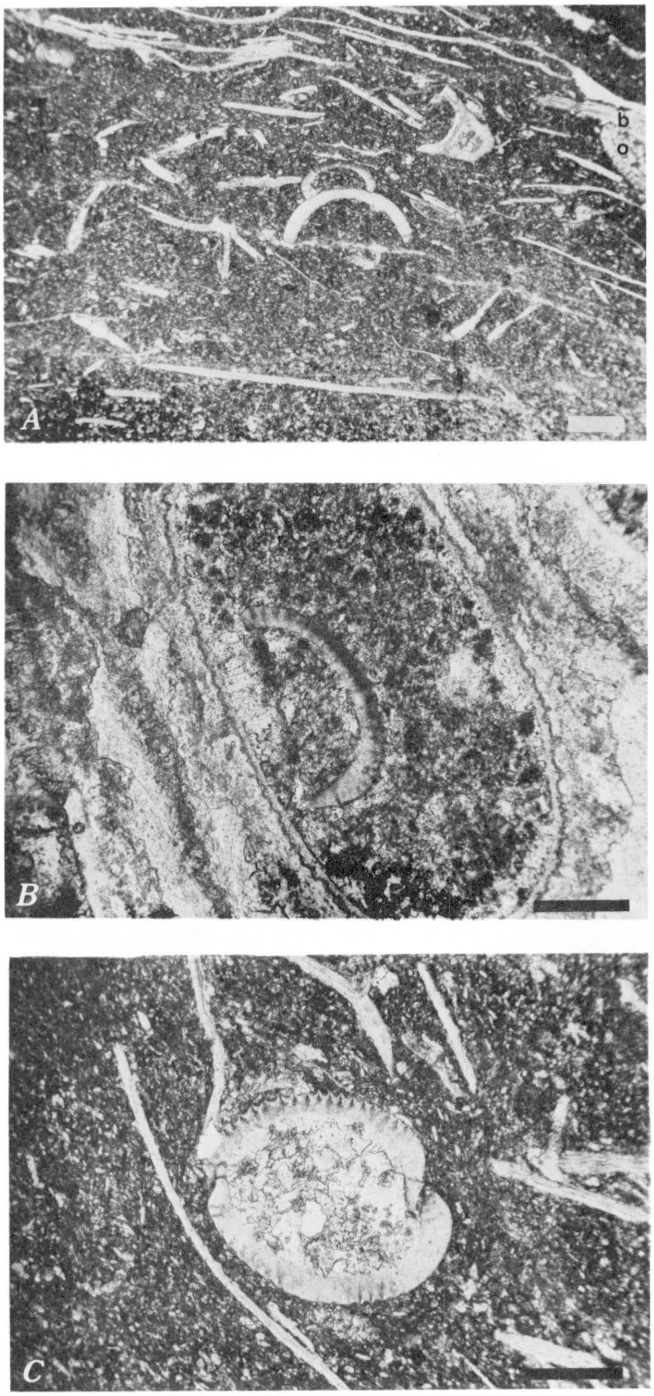


Figure 14. Photomicrographs of bioclastic wackestone in the ostracode lime mudstone unit. Level 13, lithic unit 5 (fig. 2), and KAM–2 of Lane and others (1980, p. 125). Bar scales, 0.2 mm. *A*, Exceptionally shelly laminae containing thick-shelled ostracode grains (o), very thin shelled brachiopod grains (b), and indeterminate thin, flat shell fragments. *B*, Transverse view of rare solitary coral showing two partly silicified septa; interseptal space is filled with ostracode shell in pelleted fine-grained packstone matrix. Fine-grained packstone matrix outside of coral calyx is not pelletal as in *A*. *C*, Thick-shelled ostracode and unidentifiable thin (brachiopod?) shell fragments in bioclastic wackestone.

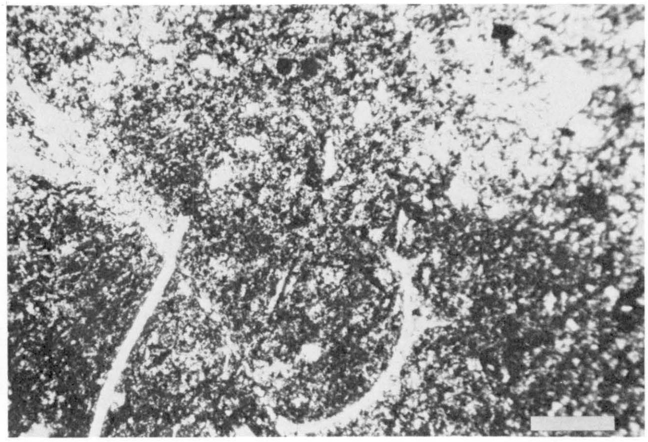


Figure 15. Photomicrograph of black chert that is silicified and dolomitized lime wackestone having "micropackstone" texture of the matrix and containing larger shells of ostracodes and brachiopods; scattered white spaces are dolomite euhedra; patches of dark pigment are most likely organic material. Level 14, lithic unit 5 (fig. 2) ,and KAM–3 of Lane and others (1980, p. 125). Bar scale, 0.2 mm.

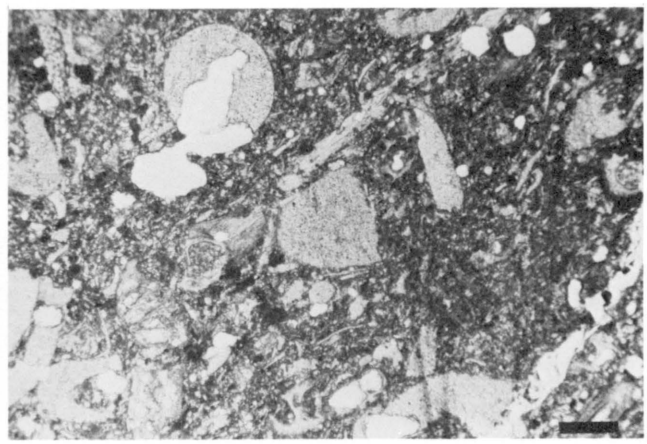


Figure 16. Photomicrograph of partly silicified spiculitic bioclast packstone; large bioclasts are solution-corroded crinoids and bryozoans; white spaces are voids. Level 16, lithic unit 6 (fig. 2), and KAM–5 of Lane and others (1980, p. 125). Bar scale, 0.2 mm.

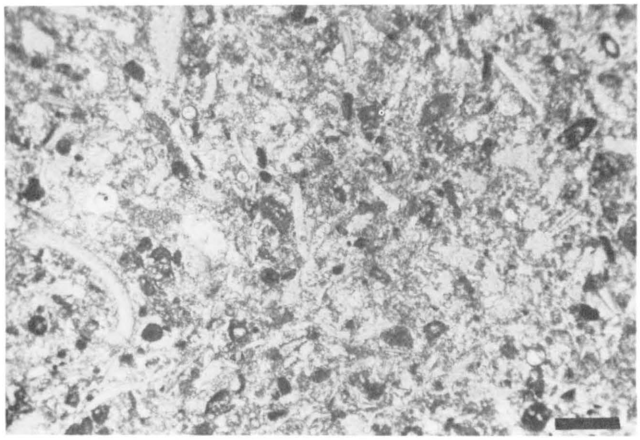


Figure 17. Photomicrograph of neomorphosed, solution-compacted packstone of poorly sorted crinoids, ostracodes, bryozoans, peloids, and sponge spicules. Level 17, lithic unit 6 (fig. 2). Bar scale, 0.2 mm.

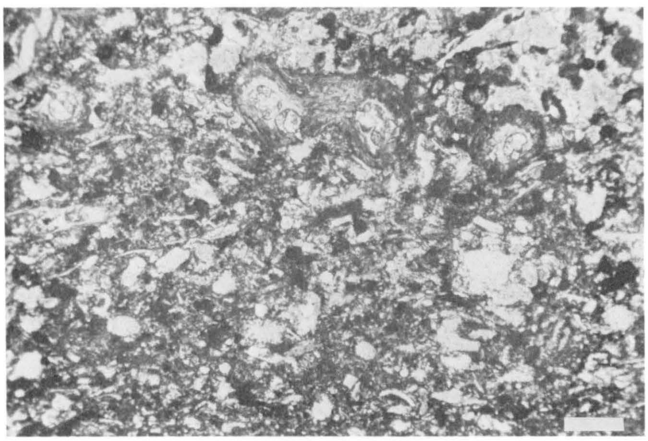


Figure 18. Photomicrograph of neomorphosed, partly silicified, solution-compacted, peloidal packstone containing poorly sorted crinoid, bryozoan, and brachiopod debris. Level 18, lithic unit 6 (fig. 2). Bar scale, 0.2 mm.

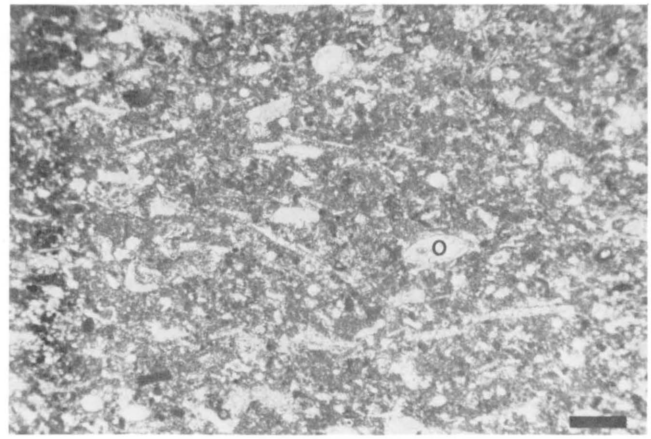


Figure 19. Photomicrograph of solution-compacted, bioclastic, peloidal wackestone containing debris of echinoderms, ostracodes (o), and unknown thin shell fragments. Level 19, lithic unit 6 (fig. 2), and KAM–6 of Lane and others (1980, p. 125). Bar scale, 0.2 mm.

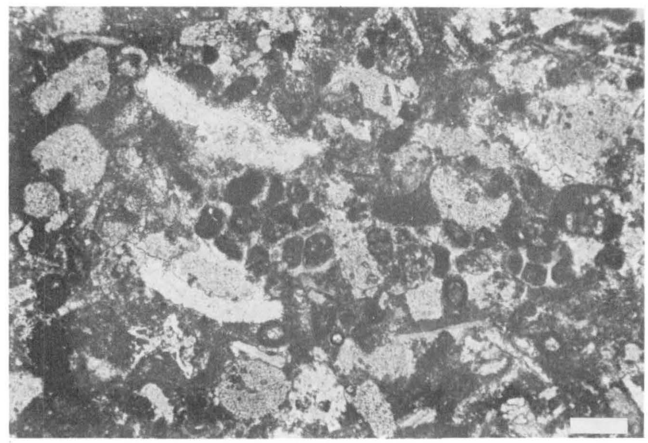


Figure 20. Photomicrograph of solution-compacted wackestone-packstone containing corroded echinoid and bryozoan debris and peloids that may originally have been micritic pore fillings in bryozoans. Level 20, lithic unit 7 (fig. 2), and KAM–7 of Lane and others (1980, p. 125). Bar scale, 0.2 mm.

crinoidal bioclasts predominate, but, as noted by Dockal (1980), ossicles generally are more abundant upward within the unit. Thus, the spiculitic packstone unit represents a transition from the underlying anomalous lime mudstone and wackestone of unit 5 to the more normal marine shelf limestone of the overlying unit 7.

Lithic Unit 7—Upper Crinoidal Wackestone-Packstone

Rocks of lithic unit 7 are diffusely interstratified, conspicuously crinoidal, bioclast-peloid lime mudstone, wackestone, and packstone in irregular, medium-thick beds comprising a monotonous interval of 25–30 m, the top of the unit being unexposed. Solution compaction blurs the distinction between wackestone and packstone fabrics (figs. 20–22). Secondary chert nodules are present sparsely throughout the unit, and some have poorly developed wood-grained texture. Planar lamination is present in fine-grained packstone that is interstratified with lime mudstone low in the unit.

Lithic Unit 8—Dolostone

An unexposed interval of about 25 m separates units 7 and 8. Near the base of lithic unit 8 is a conspicuous thick bed of solution-compacted, partly dolomitized crinoidal-packstone that is overlain by 25 m of exposure formed of dolostone. The dolostone interval consists of alternating

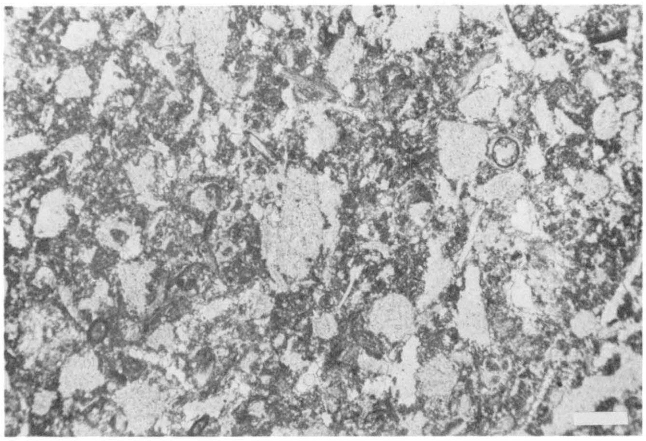


Figure 21. Photomicrograph of solution-compacted crinoidal and bryozoan wackestone-packstone; dark peloids may have originally been micritic pore fillings in bryozoa, two micrite-filled skeletal fragments of which are in middle part of view. Level 21, lithic unit 7 (fig. 2), and KAM–8 of Lane and others (1980, p. 125). Bar scale, 0.2 mm.

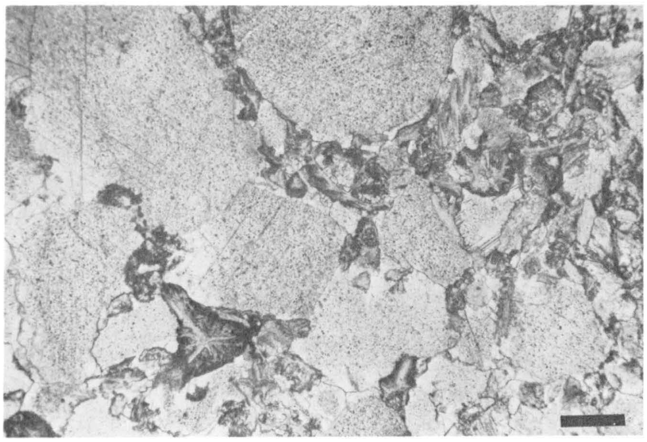


Figure 22. Photomicrograph of solution-compacted crinoidal and bryozoan bioclasts in an original packstone or grainstone. Level 22, lithic unit 7 (fig. 2), and KAM–14 of Lane and others (1980, p. 125). Bar scale, 0.2 mm.

1–2-m-thick packages of brownish-gray, vaguely bioclastic, massive, sugary secondary dolostone (fig. 23) and finely crystalline, partly laminated, light-colored dolostone. Some light-colored dolostone contains birds-eyes, and in places fragments of light-colored dolomite are reworked as rip-ups into overlying, coarsely crystalline, secondary dolostone beds. This interstratified primary and shelly secondary dolostone indicates episodic exposure and evaporitic conditions during deposition, and it resembles much of the type Brazer Dolomite in the Crawford Mountains (location CM, fig. 1).

The highest outcrop shown on figure 2*A*, about 10 m above the more or less continuous exposures of dolostone, is a massive, coarse dolostone breccia that most likely

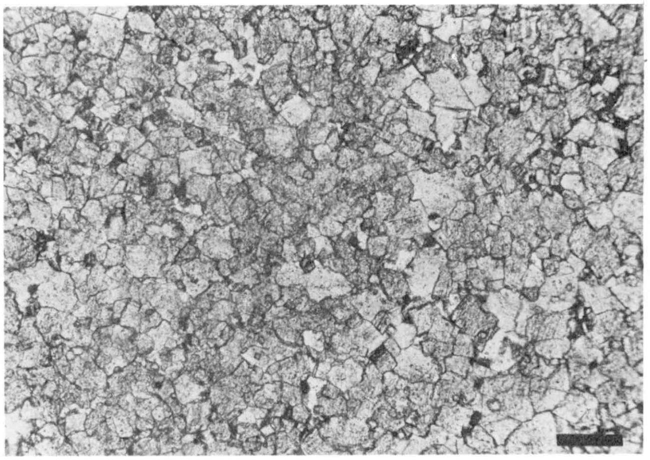


Figure 23. Photomicrograph of coarsely crystalline secondary dolomite. Level 23, lithic unit 8 (fig. 2). Bar scale, 0.2 mm.

resulted from evaporite solution. From here to the top of the ridge (fig. 1) are only scattered outcrops of brownish-gray sugary dolostone.

DISCUSSION

The section at Samak, in which the rocks affected by the anoxic event occur, is part of the North American Mississippian carbonate shelf and comprises lagoonal, tidal-flat, shoal, and evaporitic deposits (Dockal, 1980). Some of the lithic units representing shelf depositional environments are widespread, extending from the Uinta Mountains across western Utah. The anoxic event thus affected a broad shelf area of little topographic relief.

An alternative interpretation of the Mississippian depositional system in the area of the Uinta and Piceance basins is based on the concept of the "Deseret deep starved basin," a concept that requires assigning some of the Mississippian carbonate rocks at Samak to a variety of deep-water, basinal, slope, and platform-margin facies (Lane and others, 1980; Sandberg and Gutschick, 1980). Unit 5, for example, the ostracode lime mudstone, was assigned to the "basinal and lower slope facies" on the east side of the "Deseret deep starved basin" by Lane and others (1980, table 4) and Sandberg and Gutschick (1980, fig. 3). In our interpretation, the ostracode lime mudstone, the rock type that is the hallmark for deposits of the anoxic event throughout northwestern Utah, has none of the important characteristics required of a slope deposit. The anoxic event may represent an abrupt increase in water depth on the shelf, but it does not involve the development of a discrete deep basin delimited by distinct slope and platform-margin environments.

In the Samak section the anoxic event resulted in carbonate dissolution and limestone replacement by phosphate in the uppermost part of unit 4 and in deposition of the peculiar organic-rich limestone of unit 5. The bioclast-producing, normal-marine biota was abruptly exterminated and recovered only gradually during deposition of the higher parts of unit 5 and on though unit 6 (Dockal, 1980).

The abrupt biotic event at the base of unit 5 and the extensive solution compaction in the subjacent limestone raises the possibility of exposure and the influx of meteoric water at this time. Nonetheless, occurrence data for conodonts in this part of the Samak section provided by Lane and others (1980, table 4) indicate that no hiatus took place between units 4 and 5 within the resolution of their zonation. Eleven conodont species and variants are reported by Lane and others from their sample KAM–1, which, judging from the location of the sample number painted on the outcrop, represents the uppermost few centimeters of limestone in unit 4. The stratigraphic ranges of all of these kinds of conodonts, as given by Lane and others (1980, table 2), overlap those of conodonts reported from various levels through unit 5. Both the uppermost part of unit 4 and all of unit 5 were thus deposited within the time span of the Upper Typicus Zone (Lane and others, 1980), without biostratigraphically perceptible interruption.

Unusually large recoveries of conodont elements are reported by Lane and others (1980, table 4) from sample KAM–1, which yielded an amazing extrapolation of 1,194 elements per kilogram. Dockal (1980, p. 80) also reported a high yield of conodonts from limestone immediately below unit 5, about 30 km east of the Samak section. This high yield corroborates the relative overabundance of conodonts in thin sections of the limestones in the upper few meters of unit 4 (fig. 10). According to Lane and others (1980, p. 125), high abundances of conodonts, such as those reported in the Samak section, represent foreslope sedimentary environments. In this case, however, an alternative explanation is simply that the conodonts are concentrated as insolubles in this extremely solution compacted limestone. In general, the interpretation of absolute water depth on conodont abundances (Sandberg and Gutschick, 1979; Lane and others, 1980) is imprudent in the absence of other kinds of data and without consideration of other variables.

Rocks influenced by the anoxic event at Samak, as well as those elsewhere in western Utah, show evidence of the effects of upwelling marine water, such as relatively high concentrations of phosphate and silica, high organic productivity, and the subsequent development of anoxia in bottom waters and in the shallow subsurface. The model proposed by Heckel (1977), applied by Dockal (1980) to Mississippian rocks in the Uinta Mountains area, provides insight as to how upwelled, deep-marine water could be introduced far onto the shelf and how anoxia in the lower water column on the shelf could be maintained. In this model, generation of a mixing barrier, such as a thermocline related to an increase in water depth across the shelf, acting in concert with oceanward wind-driven surface currents, would establish the circulation pattern in shelf waters of a quasi-estuarine cell that would bring cool, oxygen-deficient, nutrient-rich upwelling water landward across the shelf beneath oxygenated surface waters. The waters of the quasi-estuarine cell that would replace the normal, fully oxygenated waters of the normal anti-estuarine circulation cell on the shelf. Broad topographic features on the shelf, such as a silled margin, could affect the maintenance and nature of quasi-estuarine circulation, but the generally broad, flat configuration of the shelf surface would be preserved. Therefore, the anomalous shelfal rocks representing the anoxic event in the study area need not be related to an ephemeral deep basin such as the postulated "Deseret deep starved basin." Platform-margin carbonate buildups that might rim such a deep basin and form important hydrocarbon reservoirs in this part of Utah, as predicted by Rose (1976), have neither been recognized nor are they expected in the rock record.

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Chapter T

Petrology and Significance of a Mississippian (Osagean-Meramecian) Anoxic Event, Lakeside Mountains, Northwestern Utah

By K.M. NICHOLS and N.J. SILBERLING

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1787

EVOLUTION OF SEDIMENTARY BASINS—UINTA AND PICEANCE BASINS

CONTENTS

Abstract **T1**
Introduction **T1**
Petrologic observations **T2**
  Lodgepole Limestone **T2**
  Delle Phosphatic Member of the Woodman Formation **T4**
  Younger rocks **T9**
Discussion **T10**
Regional geologic implications **T11**
References cited **T11**

FIGURES

1. Map showing geology of study area in southern Lakeside Mountains, Utah **T3**
2. Chart showing generalized stratigraphy of type Delle Phosphatic Member of the Woodman Formation and adjoining strata, Lakeside Mountains **T4**
3. Photographs showing deposits in the Lodgepole Limestone **T4**

4–5. Photomicrographs of deposits in the Lodgepole Limestone showing:
  4. Fecal-pellet crinoidal packstone 8 m below top **T5**
  5. Fecal-pellet crinoidal wackestone immediately underlying type section of Delle Phosphatic Member **T5**

6. Photograph and sketch of burrows in silicified limestone filled with pelletal phosphorite **T6**
7. Photograph of slabbed cross-sectional surface showing contact between rocks of anoxic event and underlying limestone, central Wasatch Mountains **T6**

8–14. Photomicrographs of Delle Phosphatic Member showing:
  8. Flattened phosphate pellets in solution-compacted secondary chert, level 14 **T7**
  9. Dolomitized calcareous mudstone, level 9 **T7**
  10. Pelletal phosphate crust, level 11 **T7**
  11. Oolitic and pisolitic phosphorite, level 11 **T8**
  12. Detrital oolitic and pelletal phosphorite, level 8 **T8**
  13. Bored phosphate grain, level 8 **T9**
  14. Endolithic algal borings in oolitic phosphate grains, level 11 **T9**

15. Photograph showing limestone pinch-and-swell structure, Delle Phosphatic Member, level 15 **T9**
16. Photomicrograph of neomorphosed limestone composing a pinch-and-swell dissolution structure, Delle Phosphatic Member, level 15 **T10**
17. Photograph of megascopically featureless, ostracode lime mudstone that defines top of type Delle Phosphatic Member, level 16 **T10**
18. Photomicrograph of ostracode lime mudstone at top of Delle Phosphatic Member, level 16 **T11**

Petrology and Significance of a Mississippian (Osagean-Meramecian) Anoxic Event, Lakeside Mountains, Northwestern Utah

By K.M. Nichols *and* N.J. Silberling

Abstract

Phosphatic rocks are a distinctive part of the Lower and middle parts of the Mississippian rock record in the western part of the study area of the U.S. Geological Survey Evolution of Sedimentary Basins—Uinta and Piceance Basins program and are particularly significant because of their influence on interpretations about the paleogeography and depositional framework of this part of the Paleozoic section. These rocks have been included in the Delle Phosphatic Member, which at its type section in the Lakeside Mountains, northwestern Utah, is a member of the Woodman Formation. Deposition of the Delle Phosphatic Member was initiated by an abrupt anoxic event. Throughout western Utah, rocks influenced by this event are characterized by the absence of normal marine-shelf benthic fossils, evidence for limestone dissolution, pelletal, pisolitic and oolitic phosphorite, secondary chert, and megascopically unfossiliferous, massive lime mudstone sandwiched within thick sequences of normal-marine subtidal and peritidal Mississippian shelf-carbonate and craton-derived siliciclastic rocks. Features of the Delle phosphatic rocks such as shelf sedimentary structures and evidence of endolithic algal boring of phosphate layers, coupled with the stratigraphic context of the anoxic event, indicate a generally shallow depositional environment for rocks influenced by this event and are not compatible with the concept of a deep, sediment-starved depositional basin, the "Deseret deep starved basin" of previous authors. The peculiar nature of this event most likely resulted from anoxic bottom water and strongly reducing in-sediment conditions alternating with oxygenated, possibly subaerial, conditions. These conditions probably were produced by incursion far onto the Early Mississippian shelf of nutrient-rich, organically productive water that was possibly produced by upwelling in the Antler foreland trough in central Nevada. This interpretation places the Early Mississippian carbonate shelf-margin to the west of the Lakeside Mountains rather than in central Utah as required by the "Deseret deep starved basin" model.

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INTRODUCTION

Phosphatic rocks have long been known within the Lower Mississippian at various locations in northwestern Utah (Cheney, 1957; Schell and Moore, 1970; Gutschick, 1976). These and associated rocks that reflect anoxic deposition are anomalous with respect to the thick, laterally variable sequence of normal subtidal to peritidal shelf carbonate rocks that stratigraphically underlies them as well as to the thick sequence of peritidal carbonate and (or) craton-derived siliciclastic rocks that overlies them. The Delle Phosphatic Member was proposed by Sandberg and Gutschick (1984) to include these phosphatic rocks, and the type section of this member in the Lakeside Mountains, Utah, was treated as the basal member of the Woodman Formation. Sandberg and Gutschick (1984) regarded the Delle Phosphatic Member as characteristic of their "Deseret deep starved basin," and the unit has been extended by these authors throughout a wide area of western Utah, northeastern Nevada, and southeastern and central Idaho as the basal member of several different Mississippian formations. Away from the vicinity of its type section, however, we cannot recognize the top of the Delle Phosphatic Member using a consistent set of lithologic criteria. Consequently, for the purpose of regional discussion we find it more useful to treat the rocks in question as those affected by an abrupt, widespread anoxic depositional event that initiated deposition of the Delle Phosphatic Member at its type section. The anoxic event caused diagenetic alteration of pre-existing carbonate rocks, and its effect on deposition diminishes upsection in varying ways at different places. The term "Delle phosphatic event (DPE)" has been applied informally by Silberling and Nichols (1990, 1991) to this particular phenomenon, and it is used herein in the same sense and referred to as "the anoxic event."

Although relatively thin, rocks influenced by the anoxic event are of particular interest within the Uinta-Piceance study area (lat 38°30′–42° N., long 107°–112°30′ W.), not only because of their peculiar depositional and diagenetic history, but also because they form the basis for inferences about economically important paleogeographic features such as the nature and location of the Mississippian shelf margin. Furthermore, assumptions about the depositional environment during the anoxic event and about the postulated "Deseret deep starved basin" have significantly influenced interpretations of regional Mississippian facies patterns in the Cordillera, eustatic sea-level history, diagenetic features, conodont and ostracode biofacies, and the paleotectonic history of Utah, Nevada, and Idaho (Rose, 1976; Sando and others, 1976; Poole and Sandberg, 1977; Sandberg and Gutschick, 1977, 1979, 1980, 1984; Gutschick and others, 1980; Lane and others, 1980; Sandberg and others, 1980; Sando and others, 1981; Sandberg and others, 1982; Gutschick and Sandberg, 1983; DeCelles and Gutschick, 1983; Poole and Claypool, 1984; Gutschick, 1987; Sohn and Sando, 1987; Hintze, 1988).

Throughout the study area rocks deposited during the anoxic event are characterized by the absence of normal marine shelf benthic fossils, the occurrence of pelletal or oolitic phosphorite and stratigraphically isolated massive beds or units of megascopically unfossiliferous lime mudstone, the rare occurrence of pelagic goniatites and radiolarians, and pervasive limestone dissolution and replacement by silica. In the western part of the study area rocks most strongly affected by the anoxic event are a few meters to several tens of meters thick. According to Sandberg and Gutschick (1984), the rocks immediately older than the anoxic event lie within the *Gnathodus typicus* Conodont Zone and are permissibly the same age everywhere the rock record of the event is recognized. Thicker manifestations of the event, such as the section in the southern Lakeside Mountains in which the Delle Phosphatic Member was typified, may represent a condensed sequence of most of the Osagean and the lowest Meramecian Provincial Series (Sandberg and Gutschick, 1984). Our studies suggest, however, that abbreviation of the section resulted from carbonate dissolution and resulting compaction of stratigraphic section as well as from slow accumulation of sediment.

Outcrops in the Lakeside Mountains that include the type section of the Delle Phosphatic Member were chosen for detailed sedimentologic and petrographic study, the results of which serve to constrain depositional and paleotectonic interpretations of the anomalous Delle interval. In the type section, which is easily accessible, pelletal, pisolitic, and oolitic phosphorite and associated rock types are present at more stratigraphic levels and through a greater thickness and variety of rocks than in related sections elsewhere in the study area and yet are characteristic in kind and stratigraphic setting of other expressions of the anoxic event in the region. In the Lakeside Mountains (fig. 1), rocks beneath the type section of the Delle Phosphatic Member were assigned by Sandberg and Gutschick (1984) to the Lodgepole Limestone, and the Delle was established as the lower member of the Woodman Formation (fig. 2). Strata immediately overlying the Delle Phosphatic Member in the Lakeside Mountains were treated by them as the Needle Siltstone Member of the Woodman Formation. This usage of Lodgepole Limestone and Needle Siltstone Member is not endorsed by us, but, because revision of stratigraphic nomenclature is beyond the scope of this paper, this part of the nomenclature used by Sandberg and Gutschick (1984) in the Lakeside Mountains is retained herein. Our interpretation of the nature, depositional environments, and paleotectonic setting of these rocks in this expanded and more fully documented version of Nichols and Silberling (1990) differs from that proposed by Sandberg and Gutschick (1984) and indicates a much different Mississippian (Osagean-Meramecian) paleogeography than that proposed by them for the western part of the study area.

PETROLOGIC OBSERVATIONS

Lodgepole Limestone

The type section of the Delle Phosphatic Member (line *A–A′*, fig. 1) overlies about 100 m of carbonate rocks assigned to the Lodgepole Limestone by Sandberg and Gutschick (1984). About 30 m below the base of the Delle the Lodgepole is cut by low-angle bedding-plane faults on which some strata may have been omitted. Massive, secondary dolomite obliterates 10–12 m of the limestone above this fault zone. Below the fault zone is a thick sequence of regularly thin to medium parted, fecal-pelleted lime packstone, much of which exhibits pronounced planar lamination (fig. 3*A*). Only the uppermost 10 m of this interval is shown on the columnar section. Partly graded, discontinuous interbeds as thick as 10 cm and composed of crinoidal, coralline, and shelly debris are present at 0.2–2-m intervals in the laminated lime packstone and are interpreted as storm deposits or tempestites (fig. 3*B*). Both the pelleted fabric and pervasive current lamination of this lime packstone unit are features characteristic of mid-shelf environments (for example, Enos, 1983). The uppermost unit of the Lodgepole, beginning above the secondary dolomite of the fault zone and about 18 m below the

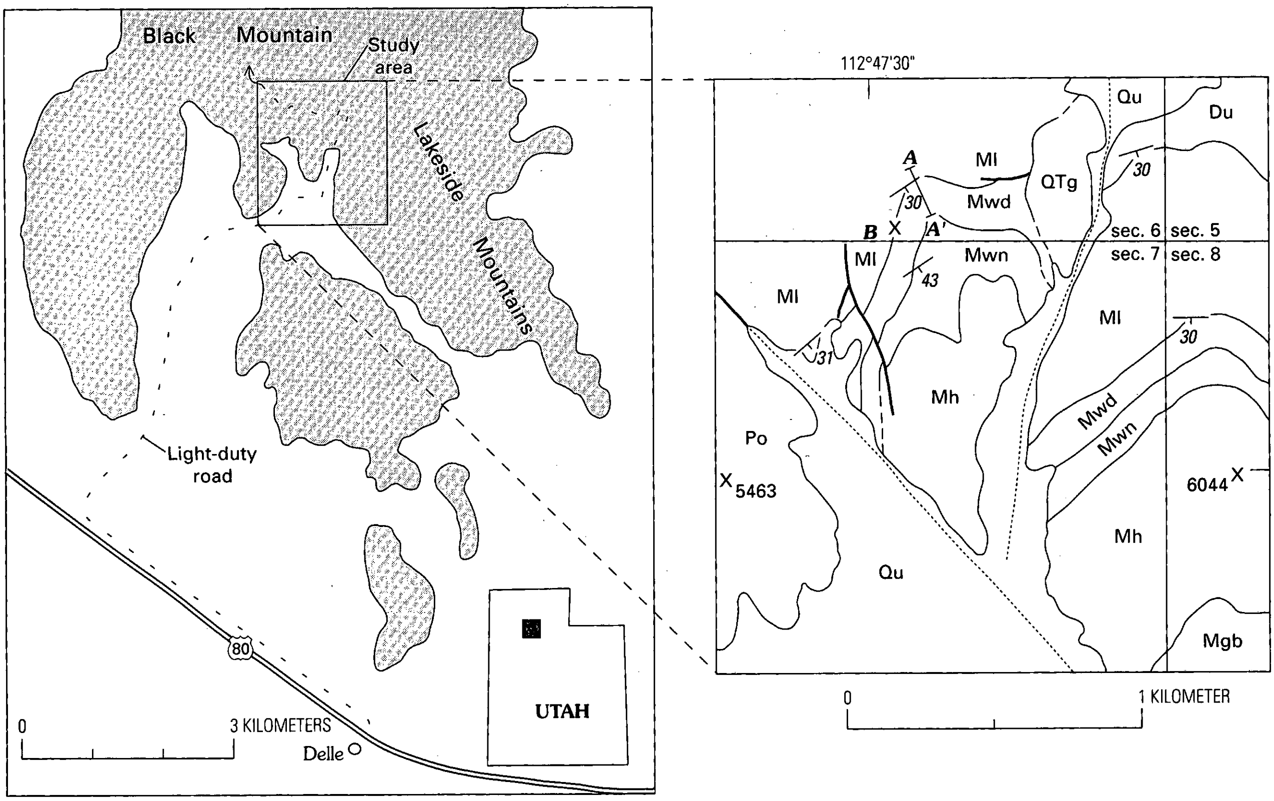

Figure 1. Geology of study area (T. 1 N., R. 8 W.) in southern Lakeside Mountains, Utah. Qu, Quaternary deposits, undifferentiated; QTg, Quaternary or Tertiary gravel; Po, Permian and Pennsylvanian Oquirrh Formation; Mississippian—Mgb, Great Blue Limestone; Mh, Humbug Formation; Mwn, Needle Siltstone Member of Woodman Formation (as used by Sandberg and Gutschick, 1984); Mwd, Delle Phosphatic Member of Woodman Formation; Ml, Lodgepole Limestone (as used by Sandberg and Gutschick, 1984); Du, Devonian, undifferentiated; heavy line, fault; dotted line, concealed fault; dashed line, concealed contact. Elevations in feet. Line *A–A'*, Type section of Delle Phosphatic Member. *B*, Location of trenched section.

projected top of the Lodgepole, is massive, chert-nodule-rich, pelleted, crinoidal lime wackestone grading upward into bioturbated, diffusely interstratified, fecal-pelleted lime wackestone and packstone (fig. 4) containing abundant crinoid columnals and other bioclasts including a few solitary corals and brachiopod shells. At the type section, which is along a ridge crest, the upper 7–8 m of this wackestone-packstone unit is not exposed, but it can be observed in the gully leading downhill to the south, as at location *B* (fig. 1).

The highest beds of limestone assigned to the Lodgepole are well exposed in the gully leading south from the base of the Delle type section, but trenching is required, as at location *B*, to expose higher beds and the base of the Delle. Here, the uppermost 10–20 cm of the Lodgepole Limestone (level 1, fig. 2) is blotched, red-stained, solution-compacted, fecal-pelleted, bioclastic wackestone (fig. 5). Phosphate is present in this rock both as replacement bodies within the remaining limestone matrix and as void fillings within the pores of crinoid columnals, bryozoans, and other bioclasts. This partly dissolved, compacted limestone is the "deep-water winnowed encrinite" of Sandberg and Gutschick (1984, p. 140, 142). Immediately above the highest Lodgepole Limestone (level 1) and exposed by trenching at location *B* is 0.5 m (level 2) of punky, red, dissolution-compacted, microcrystalline quartz and illitic clay and scattered partially dissolved calcitic bioclasts similar in kind to those of the immediately underlying limestone. Above this residuum is a 40-cm-thick resistant level (level 3) composed of silicified limestone nodules that probably are dissolution remnants in a matrix of laminated siliceous mudstone and pelleted phosphorite. Features interpreted as burrow cavities as wide as several millimeters in the secondarily silicified nodules are infilled by phosphorite pellets (fig. 6). The stratigraphically lowest occurrence of phosphorite pellets (level 3, fig. 2) and the base of the Delle Phosphatic Member are thus associated with carbonate dissolution and apparent burrowing. The pelletal phosphorite that marks the beginning of the anoxic event elsewhere in central and western Utah either commonly fills complexly pinnacled solution cavities in the underlying limestone (fig. 7)(Sandberg and Gutschick, 1984, plate 1B) or is associated with a layer of insoluble material as thick as a meter that was produced by dissolution of the underlying

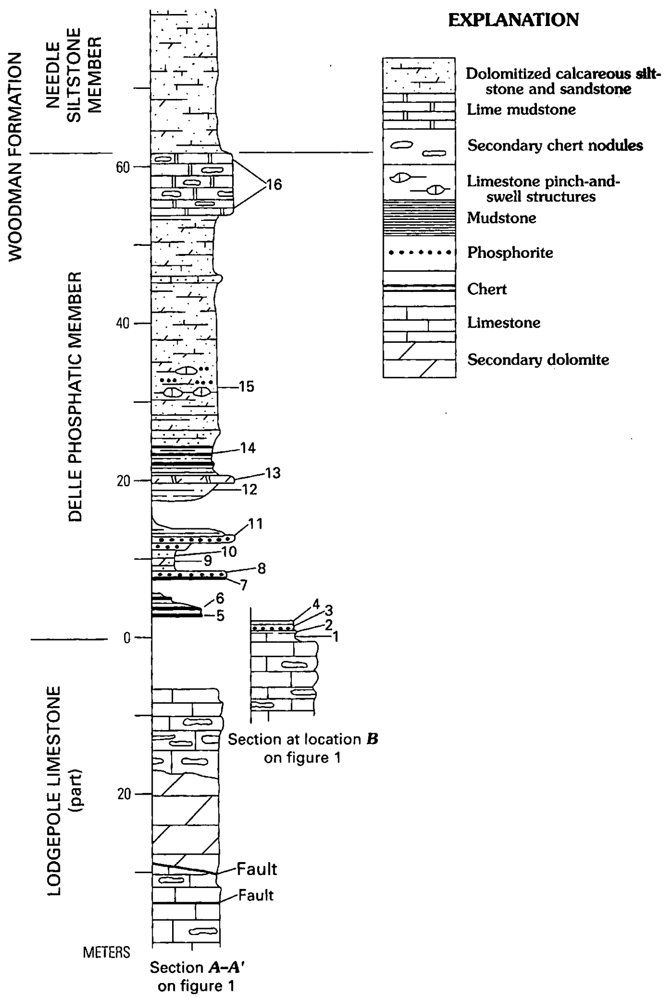

Figure 2. Generalized stratigraphy of type Delle Phosphatic Member of the Woodman Formation and adjoining strata, Lakeside Mountains. Numbers label stratigraphic levels discussed in text; stratigraphic names are those applied by Sandberg and Gutschick (1984).

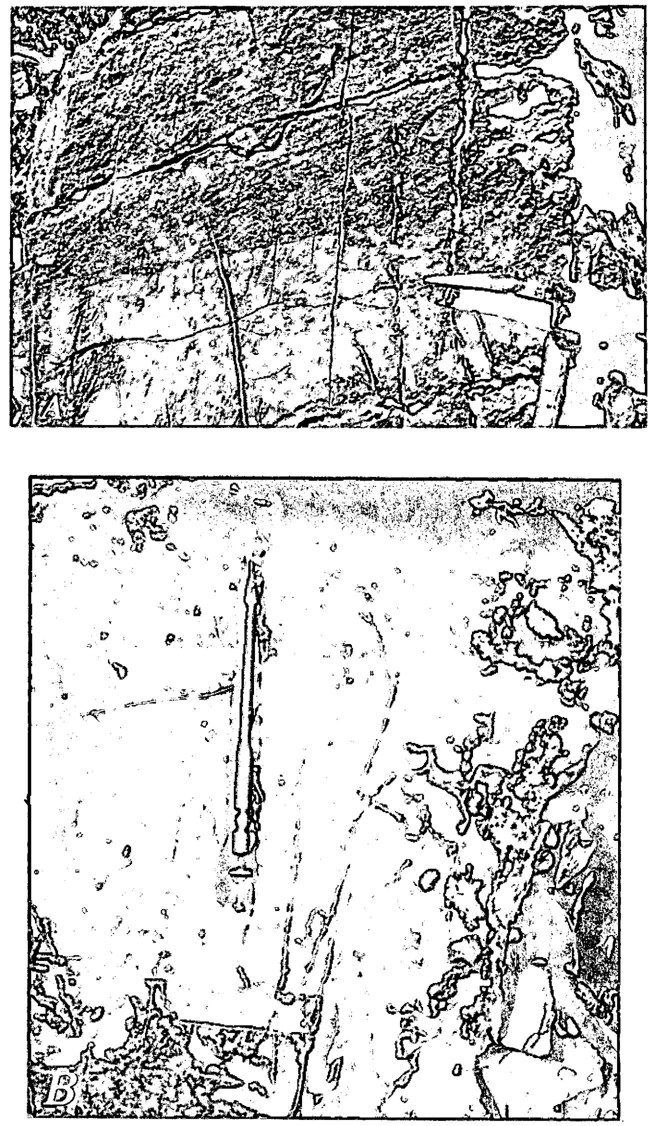

Figure 3. Lodgepole Limestone, east side of Lakeside Mountains. *A*, Laminated fecal-pellet packstone from same part of section as *B*. *B*, Tidal-flat storm deposit or tempestite within lime mudstone in the upper part of the Lodgepole Limestone (of Sandberg and Gutschick, 1984) underlying type section of the Delle Phosphatic Member.

limestone. Along with other insoluble materials, conodonts have been concentrated by carbonate dissolution in the limestone immediately underlying rocks of the anoxic event. The high yield of conodonts from this level, as reported from outcrops farther east in the study area and elsewhere in Utah, has been interpreted as indicating absolute water depth (Lane and others, 1980, p. 125; Sandberg and Gutschick, 1979); however, it is probably the result of concentration by limestone dissolution and compaction.

Delle Phosphatic Member of the Woodman Formation

The lower 20 m (below level 13, fig. 2) of the type Delle Phosphatic Member in the Lakeside Mountains is poorly exposed but consists of a heterogeneous succession of diagenetically reconstituted rocks characterized by phosphorite and by replacement silica and dolomite.

Above level 3, in the highest 1.0 m of trenched section at location *B* (fig. 1), four thin, indurated layers of pale-yellowish-brown phosphatic, siliceous mudstone or impure chert are in the otherwise punky, deeply weathered material that characterizes the basal part of the Delle. In a particularly cherty layer (level 4) bands of scattered, round, or elliptical voids as much as 200 microns in diameter may represent the former presence of calcified radiolaria. Phosphorite in these layers is present as flattened shreds that are interpreted to have been originally pellets, as explained below.

Figure 4. Photomicrograph of fecal-pellet crinoidal packstone 8 m below the top of the Lodgepole Limestone (of Sandberg and Gutschick, 1984) underlying type section of the Delle Phosphatic Member, Lakeside Mountains. Scale bar, 0.2 mm.

Figure 5. Photomicrograph of strongly solution compacted, partly phosphatic, fecal-pellet crinoidal wackestone from the top of the Lodgepole Limestone (of Sandberg and Gutschick, 1984) immediately underlying type section of the Delle Phosphatic Member at locality *B* (fig. 1), Lakeside Mountains. Scale bar, 0.2 mm.

The stratigraphically lowest beds exposed in the cut banks of the road leading to the radio towers on top of Black Mountain in the type section of the Delle (fig. 1) are about 0.5 m higher than level 4. In the road cut at level 5, pale- and moderate-yellowish-brown siliceous mudstone and impure chert similar to that of level 4 at location *B* grades into 5–10-cm-thick interbeds of black phosphatic chert (level 6) bearing scattered radiolarians visible on weathered surfaces. The black phosphatic cherts at this level and higher in the section at levels 7 and 14 have a distinctive solution-compacted fabric of laterally discontinuous, lenticular and sinuously flattened grains of internally featureless phosphate, along with sparse grains of quartz silt enveloped in microcrystalline silica (fig. 8). These rocks are interpreted to have been relatively pure limestone beds that contained scattered replacement pellets of phosphate and underwent solution compaction prior to or during silicification. Laminae of uncompacted, phosphate pellets in grain-to-grain contact are present in some of these cherts (fig. 8) and support the interpretation that the flattened fabric was produced by dissolution of a limestone matrix in parts of the rocks where scattered pellets were originally matrix supported. Thus, rather than being primary biogenic siliceous rocks, or "lydites" as they are characterized by Sandberg and Gutschick (1984, p. 143), we interpret these black phosphatic cherts to be secondary replacements of beds that were originally limestone.

Above the road-cut exposures in the lower part of the type Delle, the next 17 m of the Delle is poorly exposed up to level 13 (fig. 2). Outcrops of relatively resistant rock types within this poorly exposed lower Delle interval represent less than 20 percent of the section and are (1) black, phosphatic-chert replacement of limestone (levels 5–7), (2) black pelletal, pisolitic, and oölitic phosphorite in conspicuous beds as thick as 10 cm (levels 8 and 11), (3) yellowish-brown, illitic siliceous mudstone and impure secondary chert (for example, at levels 4 and 10), and (4)

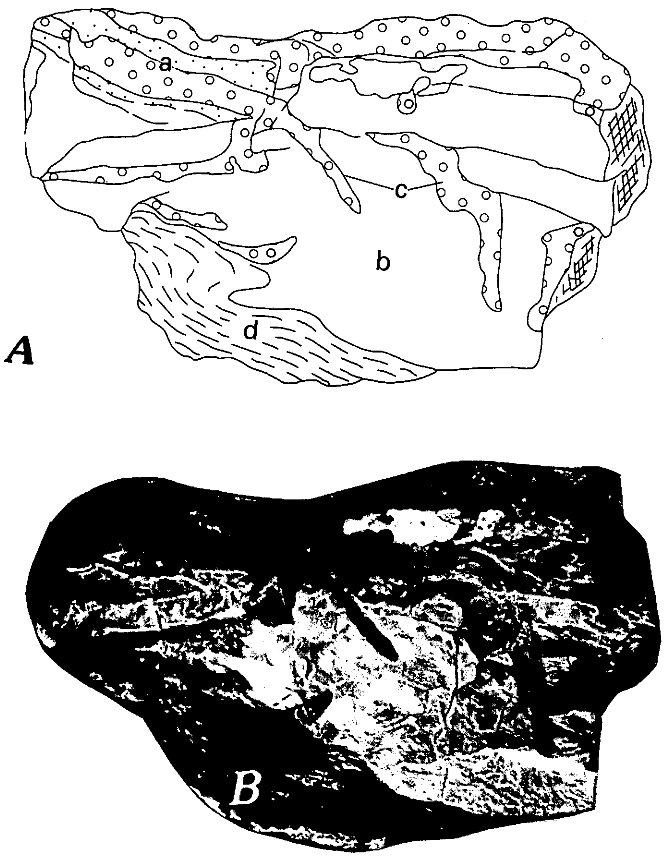

Figure 6. Sketch (*A*) showing laminated, pelletal phosphorite and siliceous mudstone (a), dense, silicified limestone (b), burrows in silicified limestone filled with pelletal phosphorite (c); and red quartz-illite limestone-solution residuum (d). *B*, Photograph of cross sectional surface of remnant silicified limestone nodule from level 3 (fig. 2), a sketch of which is shown in *A*. Natural size.

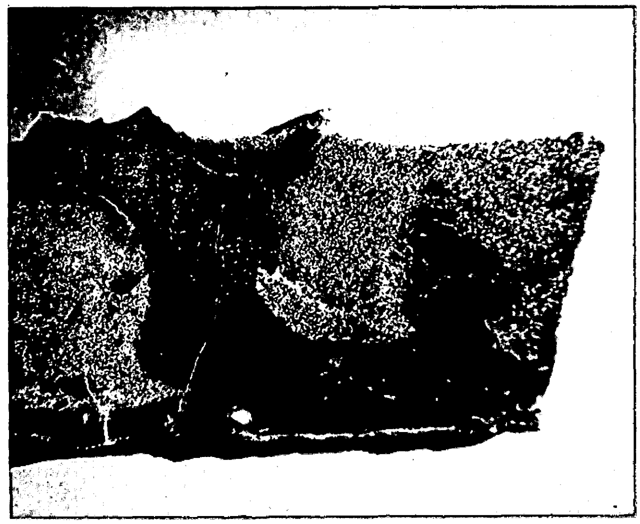

Figure 7. Slabbed cross-sectional surface showing contact between rocks formed during the anoxic event and underlying limestone assigned to Gardison Limestone by Bromfield and others (1970), central Wasatch Mountains, Utah, about 120 km east-southeast of the study area in the Lakeside Mountains. Detrital phosphate ooids, peloids, and bioclast (mainly ossicle) replacements fill solution cavities having a complex pinnacle geometry in the underlying partly phosphatic, crinoidal packstone. Natural size.

dolomitized calcareous mudstone and silty limestone (levels 9 and 12). More than a decimeter of vivid, red-weathering mudstone or shale overlies the phosphorite bed of level 11. Authigenic ammonium feldspar, or buddingtonite (fig. 9) (X-ray diffraction identification by R.M. Pollastro, U.S. Geological Survey, oral commun., 1988), is in phosphatic, cherty, and dolomitized beds at several levels (levels 3–5, 9)(fig. 9) and is associated with pseudomorphs after framboidal iron sulfide in level 9. Both buddingtonite and framboidal iron sulfide indicate strongly reducing in-sediment conditions. In contrast to these diagenetically anomalous rocks, a conspicuous and laterally persistent 0.6-m-thick unit of evenly bedded, partly dolomitic, megascopically unfossiliferous lime mudstone is at level 13. Mudstone immediately underlying this limestone also weathers vivid red.

Conspicuous, well-indurated, laterally discontinuous beds of pelletal and oolitic phosphorite are present at levels 8 and 11 (fig. 2) in the lower part of the Delle. Phosphate grains are closely packed in these rocks, which have little or no matrix; the pore space between the phosphate grains is filled with large, commonly cloudy, poikilitic calcite crystals that are in optical continuity from void to void. Laterally within single beds and from bed to bed the character of the phosphate grains and the manner in which they are aggregated changes among three different types: (1) pelletal phosphatic crust composed of closely packed aggregates of internally featureless phosphate pellets cemented by an isopachous, delicately lamellar, phosphate cement (fig. 10); (2) pisolitic phosphorite composed of poorly size sorted aggregates of concentrically coated phosphate grains (fig. 11); and (3) detrital aggregates of ooidal and other kinds of phosphate grains most likely formed by erosion and reworking of the pisolitic phosphorite (fig. 12). Any one of these three types can constitute an entire bed as thick as 10 cm.

Within the pisolitic phosphorite of level 11 the grain size of pisoids tends to decrease both stratigraphically upward and downward, and the pisolitic phosphorite is bordered by irregular layers a few millimeters thick of dense, black phosphorite. These layers are reworked into oolitic detrital beds as large solid lumps. The pisolitic and pelletal-crust phosphorite in the lower Delle resembles that described by Southgate (1986) from the Cambrian of Australia and interpreted by him as phoscrete formed in the surficial sediment on semiemergent flats associated with an epeiric marine basin. In further support of a phoscrete origin for some of the phosphorites in the Delle—particularly that at level 11—are well-developed endolithic algal borings (figs. 13, 14) in both the pisolitic and detrital oolitic

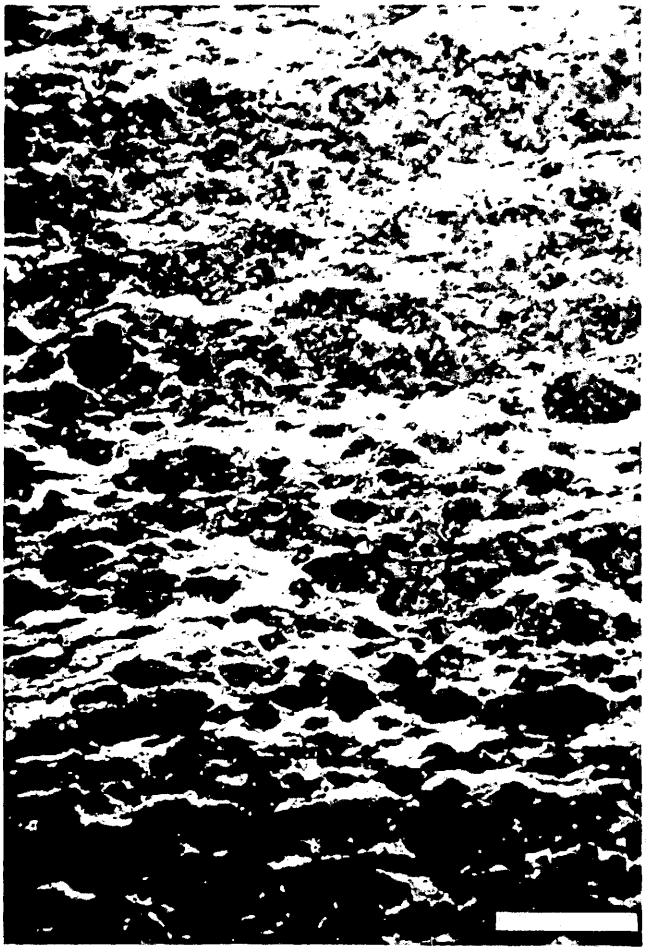

Figure 8. Photomicrograph showing flattened phosphate pellets in solution-compacted secondary chert (light areas), Delle Phosphatic Member, level 14 (fig. 2). Note less compacted fabric of phosphate pellets in more grain supported layer in lower part of view. Scale bar, 0.2 mm.

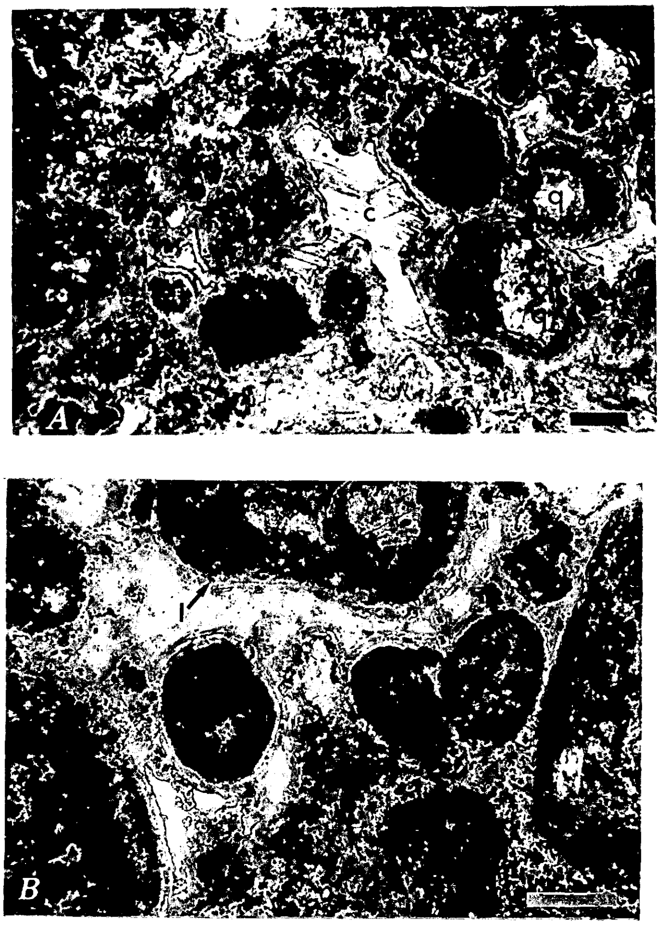

Figure 10. Photomicrographs of pelletal phosphate crust, Delle Phosphatic Member, level 11 (fig. 2). Scale bars, 0.2 mm. *A*, Poikilitic, single-crystal late calcite cement (c); authigenic quartz euhedra (q). *B*, Closer view of *A*; laminated, isopachous, phosphate cement (l).

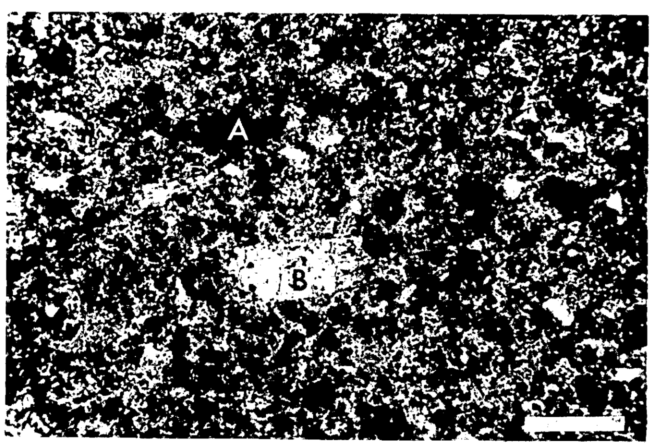

Figure 9. Photomicrograph of dolomitized calcareous mudstone, Delle Phosphatic Member, level 9 (fig. 2). Framboidal ferric oxides after pyrite (A); authigenic ammonium feldspar or buddingtonite (B). Scale bar, 0.2 mm.

phosphorite. These borings are 10–20 microns in diameter and as long as a few hundred microns. In size and configuration they are virtually identical to borings in carbonate substrates by modern blue-green algae such as *Hyella* (Golubic, 1969; Budd and Perkins, 1980). They are both too large and of the wrong shape to be fungal borings, and they lack the verrucrose surface texture indicative of sponge borings. In modern marine environments, living blue-green algae, such as *Hyella*, are restricted to the upper photic zone (intertidal to about 20 m water depth) (Budd and Perkins, 1980). Furthermore, algal borings—especially of an encrusted surface—in older sedimentary rocks are generally strong evidence for deposition at shallow depths. Algal boring in the phosphorite of the Delle took place after authigenic quartz euhedra had grown in some grain interiors (figs. 13, 14), and diagenesis of the phosphorite and possibly the dissolution of its probable original lime-mud matrix most likely preceded exposure at the sediment surface and algal infestation. The complexly interwoven

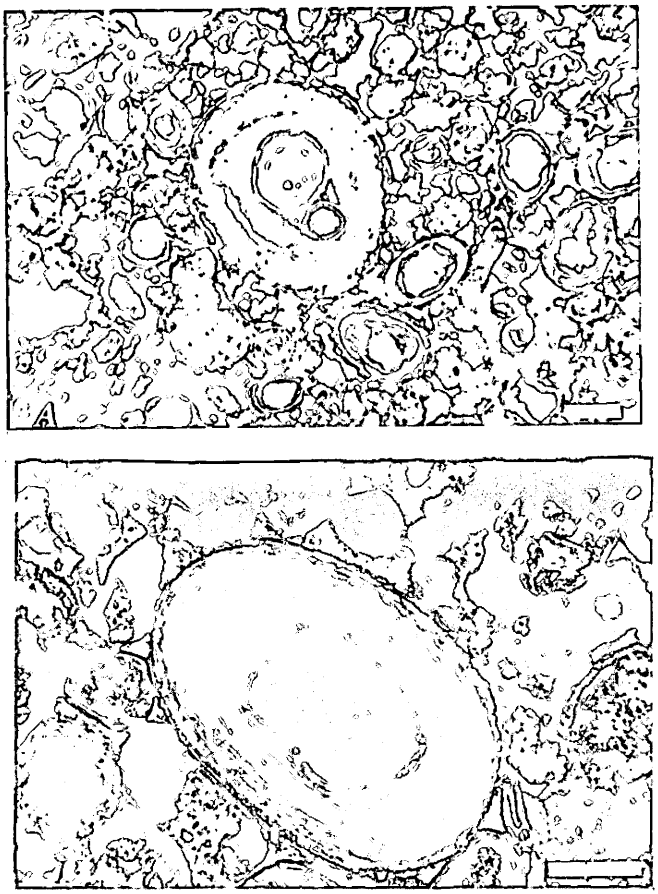

Figure 11. Photomicrographs of oolitic and pisolitic phosphorite, Delle Phosphatic Member, level 11 (fig. 2). Scale bars, 0.2 mm.

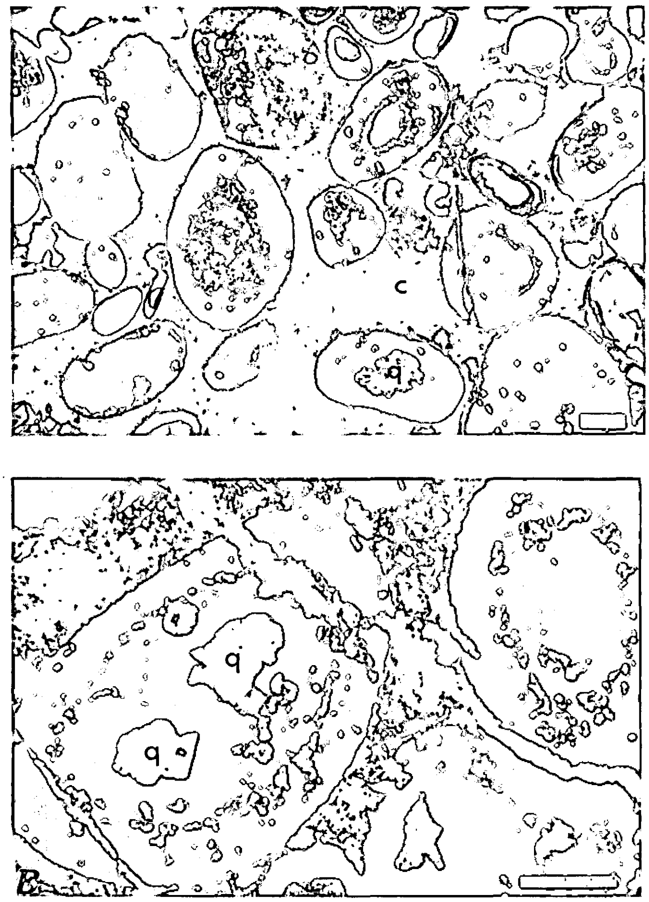

Figure 12. Photomicrographs of detrital oolitic and pelletal phosphorite; Delle Phosphatic Member, level 8 (fig. 2). Scale bars, 0.2 mm. Poikilitic late calcite cement (c); grain-interior aggregates of authigenic euhedral quartz (q).

pattern of algal borings in the Delle phosphorite are filled with the same single-crystal poikilitic calcite cement that fills the intergranular areas.

The upper two-thirds of the Delle type section, between levels 13 and 16, is mainly yellowish-brown-weathering, very sparsely fossiliferous, partly laminated, secondarily dolomitized calcareous siltstone, mudstone, fine-grained sandstone, and silty secondary dolomite. Marine benthic fossils, such as bryozoans, are sparsely present at a few levels. In addition to quartz, detrital mica, potassium feldspar, and plagioclase indicate derivation of these clastic rocks from the craton, not from the Roberts Mountains allochthon, as argued by previous authors (Sandberg and Gutschick, 1984, p. 143). Other rock types in the lower 25 m of this interval are black, phosphatic, replacement chert (at and near level 14) and laminae of phosphate pellets associated with limestone pinch-and-swell structures (as at level 15).

The limestone pinch-and-swell structures were interpreted as concretions by Sandberg and Gutschick (1984) but probably instead resulted from partial dissolution of once continuous limestone beds (fig. 15). Phosphate pellets are scattered within these pinch-and-swell structures, are in thin discontinuous selvages or crusts on their top surfaces, and are present as partings within the surrounding siltstone and mudstone. Even though radiolaria tend to be well preserved in these limestone bodies, mostly as ferric-oxide replacements, the original limestone fabric is coarsely neomorphosed (fig. 16). The presence in these pinch-and-swell structures of radiolarians and of large numbers of conodonts, which are concentrated as naturally occurring insoluble residues, was described at length by Sandberg and Gutschick (1984).

The conspicuous unit of dense, medium-bedded lime mudstone (fig. 17) that defines the top of the type Delle (level 16) is megascopically featureless except for many nodules of wood-grained secondary chert (DeCelles and Gutschick, 1983). Cross sections of ostracodes are conspicuous in thin section (fig. 18); fossils of marine-shelf benthic organisms generally are absent. This ostracode-rich limestone and the similar, but dolomitized limestone lower in the section at level 13 are believed to represent deposition

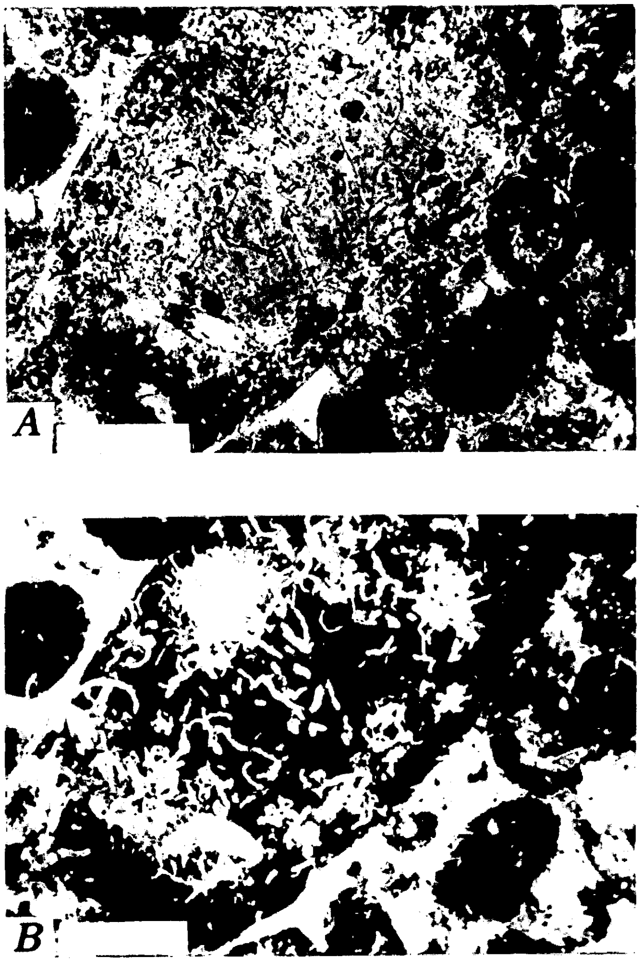

Figure 13. Photomicrographs of a bored phosphate grain, Delle Phosphatic Member, level 8 (fig. 2). Scale bars, 0.2 mm. Calcite fillings of borings are in optical continuity with intergranular cement and do not penetrate cement. *A*, Plane light. *B*, Crossed nicols.

in a restricted, possibly hypersaline, low-energy environment, and they are a distinctive, although minor, component of the rock record influenced by the anoxic event throughout central and western Utah. Both these rocks and those of the same character that formed during the anoxic event elsewhere in Utah were interpreted as regionally significant gravity and slope deposits by Sandberg and Gutschick (1984, p. 138), but nowhere do they bear evidence of gravity-flow deposition, slump folding, or any other features characteristic of such deposits.

Younger Rocks

Immediately overlying the Delle Phosphatic Member in its type section are dolomitized calcareous siltstone and fine-grained sandstone similar in composition and bedding characteristics to those that form much of the upper part of the type Delle. These are about 75 m thick and are referred on figures 1 and 2 to the Needle Siltstone Member of the Woodman Formation, following the terminology applied by

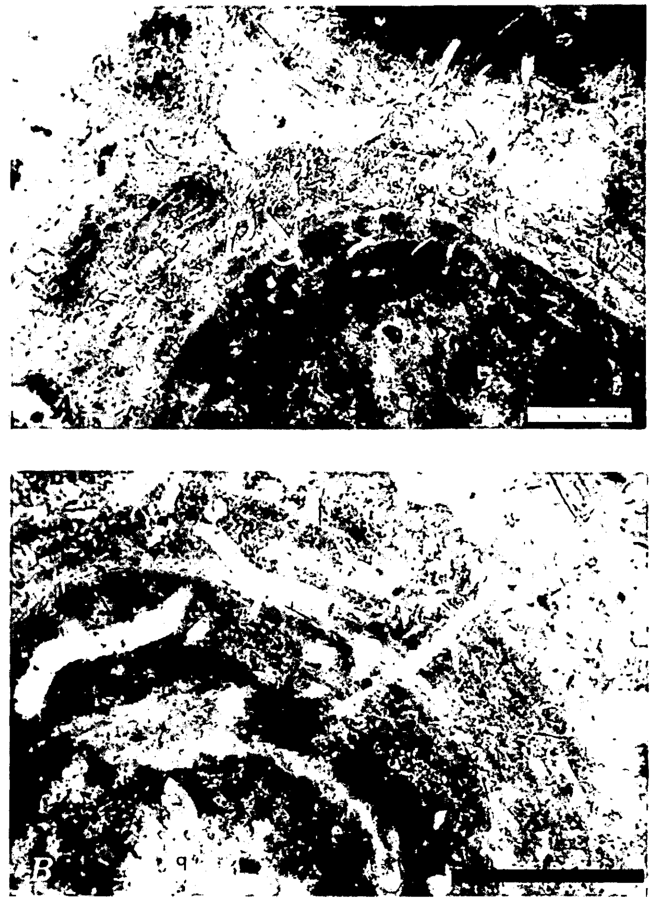

Figure 14. Photomicrographs of endolithic algal borings in oolitic phosphate grains, Delle Phosphatic Member, level 11 (fig. 2). Scale bars, 0.2 mm. Aggregate of authigenic euhedral quartz in *B* (q).

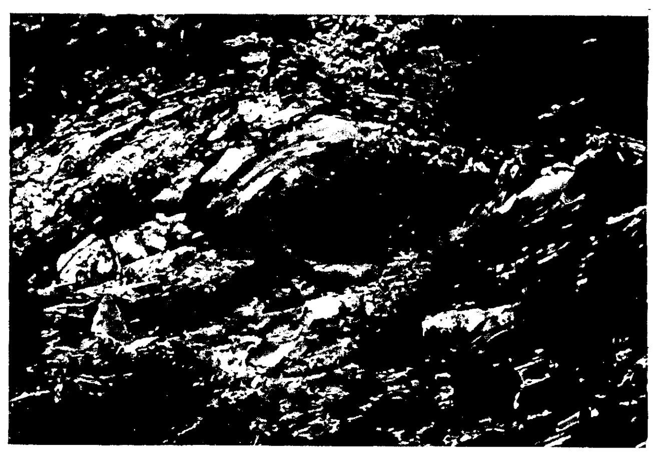

Figure 15. Limestone pinch-and-swell structure enveloped by stratification in enclosing dolomitic mudstone, Delle Phosphatic Member, level 15 (fig. 2). Maximum thickness of structure 25 cm.

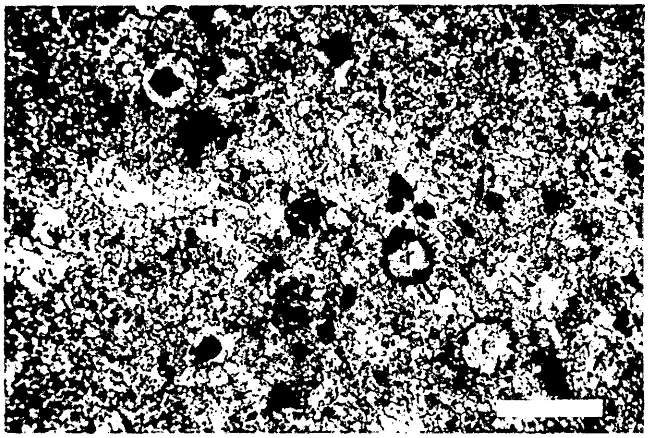

Figure 16. Photomicrograph of neomorphosed limestone composing a pinch-and-swell dissolution structure, Delle Phosphatic Member, level 15 (fig. 2). radiolaria (r). Scale bar, 0.2 mm.

Sandberg and Gutschick (1984, p. 141) to the strata immediately above the type Delle. The next higher map unit (Mh, fig. 1) is coarser and more conspicuously crossbedded quartzose sandstone to which the name Humbug Formation is applied. This unit is lithologically unlike either the Needle Siltstone Member of the Chainman Formation or the Woodman Formation, and in assigning it to the Humbug Formation we are following Hintze (1988), who applied the name Deseret Limestone to much or all of the underlying interval termed Needle Siltstone Member of the Woodman Formation by Sandberg and Gutschick (1984). The siltstones and sandstones assigned here to the upper part of the Delle and to the Woodman and Humbug show only tractional bedding characteristics indicative of peritidal depositional environments.

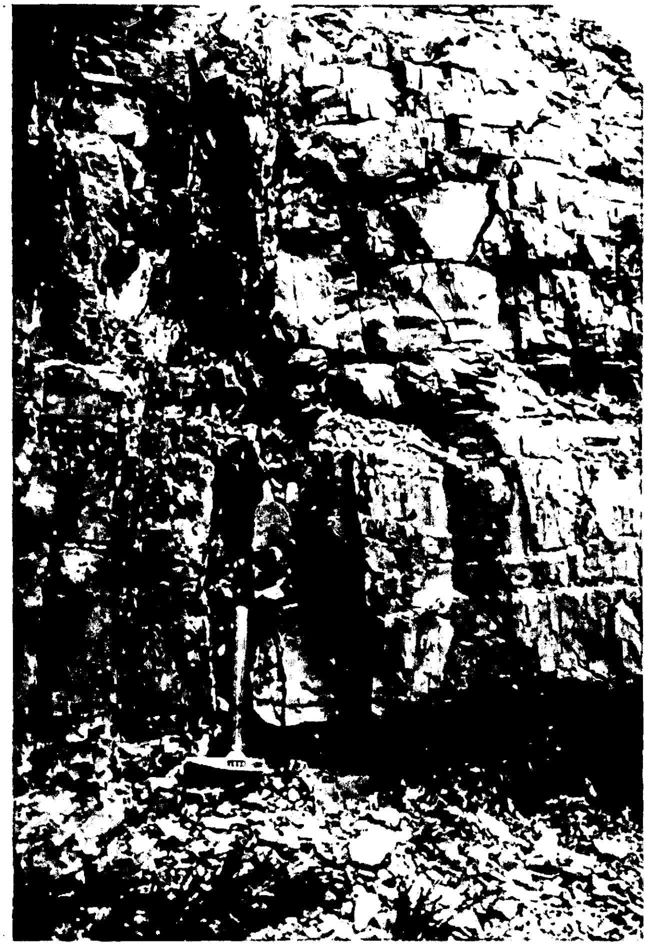

Figure 17. Megascopically featureless, regularly thin to medium parted ostracode lime mudstone containing secondary chert nodules. This rock type defines the top of the type Delle Phosphatic Member, Lakeside Mountains (level 16) (fig. 2). Hammer shown for scale.

DISCUSSION

The heterogeneous rocks in the lower part of the type Delle Phosphatic Member record fluctuating depositional and diagenetic environments, the effects of which have been complexly superimposed on one another. The abrupt disappearance of normal marine shelf benthic bioclasts and shelly fossils during deposition of these rocks can be explained by anoxia in bottom water related to the accumulation of organic matter. Reducing, organic-rich conditions within the sediment are indicated by the presence of phosphorite and ammonium feldspar, the development of iron sulfide minerals, and possibly the presence of some of the secondary dolomite, the formation of which may have been enhanced by sulfate reduction. Episodes of oxidation, on the other hand, are indicated by the low (mostly less than 0.5 percent) organic carbon content (Sandberg and Gutschick, 1984, p. 177), the general lack of black organic pigments in much of the section and infestations of algal endoliths. Episodic penecontemporaneous oxidation of iron sulfide minerals most likely produced the layers of vivid red mudstone associated with some phosphorite beds.

Although similar in some respects to basinal deposits, a deep-water origin for the anomalous rocks produced by the anoxic event is precluded by the sedimentary features and biotic content of the rocks and is especially implausible by stratigraphic context. The approximately 30-m-thick, partly phosphatic section in the Lakeside Mountains is sandwiched between normal marine mid- to inner-platform shelf deposits. Elsewhere in the study area the depositionally and diagenetically peculiar phosphatic rocks of the anoxic event are substantially thinner. Evidence is also lacking for regionally significant slope environments in the form of features such as turbidites, significant gravity-flow deposits, or soft-sediment slump folds. Within strata influenced by the anoxic event, the restriction of clastic

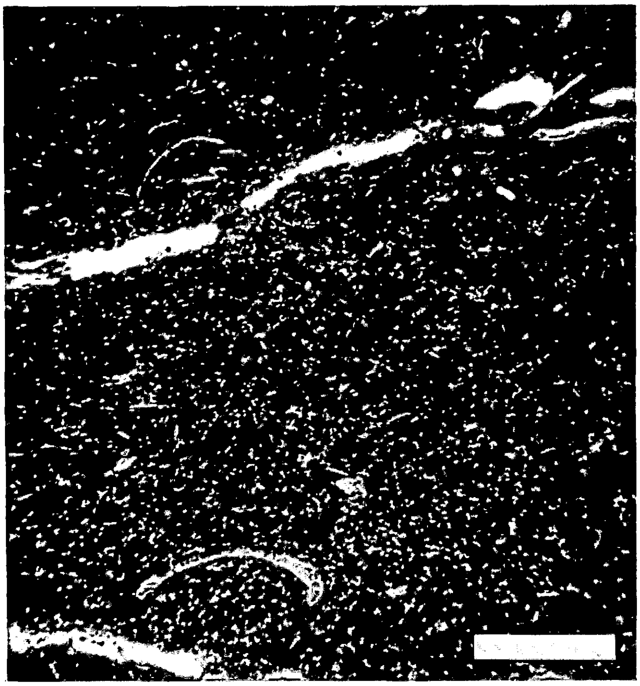

Figure 18. Photomicrograph of ostracode lime mudstone at top of Delle Phosphatic Member, level 16 (fig. 2). Scale bar, 0.2 mm.

sedimentary structures to only those that would have been produced above storm-wave base is evidence for shelf deposition, as are the endolithic algal borings in some phosphatic layers.

The nature and stratigraphic setting of rocks of the anoxic event can be explained by an incursion onto the shelf of nutrient-rich, organically productive, open-marine water. Such water would have favored the presence of pelagic organisms, such as radiolarians and goniatites, and the extermination of the normal marine shallow, shelly benthos. The apparent compaction of rocks affected by the anoxic event relative to that of shelf carbonate rocks of supposed equivalent age (Sandberg and Gutschick, 1980) can be explained by the absence as rock-forming constituents of the usual calcareous bioclasts, such as crinoid columnals, by the penecontemporaneous dissolution of calcareous material, for which there is abundant evidence as described above, and perhaps by one or more appreciable erosional disconformities.

REGIONAL GEOLOGIC IMPLICATIONS

The regionally extensive phosphatic system reflected by the anoxic event could not have been controlled by the geochemistry of local depressions such as lagoons and estuaries that surely existed on the Early Mississippian shelf. It is not coincidental that the anoxic event began at or just after final deformation in central Nevada of the Antler allochthon (Jansma and Speed, 1985). According to modelling by Speed and Sleep (1982), tectonic emplacement of the Antler allochthon onto the continental margin would have produced an elongate, asymmetrically deep foreland basin. Upwelling within this ephemeral foreland basin, as previously hypothesized by Roberts (1979), may have produced the nutrient-rich waters that so dramatically affected depositional and diagenetic environments on the broad Mississippian shelf on the continental side of the foreland basin (Nichols and others, 1988).

Interpretation of the Delle Phosphatic Member, and rocks influenced by the anoxic event in general, as part of the shelf succession has significant paleogeographic implications. The Early Mississippian shelf margin, instead of being east of the Lakeside Mountains, as required by the "Deseret deep starved basin model" (Rose,1976; Poole and Sandberg, 1977; Gutschick and others, 1980; Sandberg and others, 1982; Gutschick and Sandberg, 1983), must have been much farther to the west, well to the west of the study area.

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