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TRATIGRAPHY AND DIAGENETIC ISTORY OF THE LOWER PART F THE TRIASSIC CHITISTONE IMESTONE, ALASKA

Stratigraphy and Diagenetic History of the Lower Part of the Triassic Chitistone Limestone, Alaska

By AUGUSTUS K. ARMSTRONG *and* E. M. MACKEVETT, JR.

GEOLOGIC RELATIONS OF KENNECOTT-TYPE COPPER DEPOSITS, WRANGELL MOUNTAINS, ALASKA

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An examination of the sabkha facies and other sedimentary features of the host rock for the Kennecott copper deposits

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STRATIGRAPHY AND DIAGENETIC HISTORY OF THE LOWER PART OF THE TRIASSIC CHITISTONE LIMESTONE

By AUGUSTUS K. ARMSTRONG and E. M. MACKEVETT, Jr.

ABSTRACT

This paper focuses on detailed petrographic and stratigraphic studies of the lower part of the Chitistone Limestone (Triassic), the carbonate rocks that host massive copper sulfide lodes at the Kennecott mines. Some implications of the studied rocks relevant to ore formation are mentioned.

The Chitistone Limestone and superimposed Upper Triassic and Jurassic sedimentary rocks formed in a marine basin on and surrounded by the Nikolai Greenstone, a thick, extensive, largely subaerial succession of tholeiitic basalt with an intrinsically high copper content. The lowermost 130 meters of the Chitistone contains three incomplete upward-shoaling lime-mud cyclic sequences, each consisting of shallow subtidal limestone that grades upward into intertidal stromatolitic fine-grained dolomite. The youngest cycle contains well-developed sabkha features and dolomitic pisolitic and laminate caliches and underlies shallow-marine limestone. These sedimentary structures represent a regional sabkha facies that developed between 90 and 130 meters above the Nikolai Greenstone. This facies originally contained abundant gypsum and anhydrite, but exposure to vadose weathering leached most of the gypsum and anhydrite and developed a vuggy zone interbedded with porous dolomitic caliche. Subsequent marine deposition capped the porous zone with an impermeable seal. The resulting rock, and possibly others, probably served as permeable conduits for the ore-forming solutions.

INTRODUCTION

PURPOSE AND SCOPE

This paper provides detailed stratigraphic and petrographic information on the carbonate rocks that constitute the lower part of the Chitistone Limestone (Triassic). Investigations leading to this report are part of broader studies of Kennecott-type copper sulfide deposits, which are localized in the lower parts of the Chitistone. These studies are still in progress and as yet inconclusive. Consequently, this report concentrates on detailed outcrop and underground descriptions and interpretations of the rocks and minimizes their relevance to the ore deposits. The stratigraphy and microfacies analysis of three lime-mud upward-shoaling cycles are described and illustrated, and the focus of the study is on the last cycle, which contains sabkha sedimentary stuctures and a dolomitic caliche bed at its top. Undoubtedly, carbonate rocks in lower parts of the Chitistone were important in localizing the massive copper-sulfide rich lodes that typify Kennecott-type deposits. In particular, permeable parts of the sabkhas probably were conduits for the ore-forming solutions, and the sabkhas may have been a source of sulfur for the ore.

The present report elaborates on an earlier report (Armstrong and others, 1969) and refines the previous work by concentrating on detailed studies of lower parts of the Chitistone and by discussing additional localities (fig. 1).

STUDY AREA

The study area is along the southern flank of the Wrangell Mountains where the Chitistone Limestone hosts the major Kennecott-type copper deposits and is well exposed (fig. 2). This paper is largely based on detailed studies of rocks from five stratigraphic sections of lower parts of the Chitistone that were measured in 1974. The location of the five sections are shown on figure 1 and their stratigraphic relations on figure 3. The present report is supplemented by data from previously studied stratigraphic sections (Armstrong and others, 1969; Armstrong and MacKevett, 1976; fig. 1) and, to some extent, by broad-scope geologic studies of the McCarthy quadrangle that are summarized in MacKevett (1976).

WORK METHODS

Field studies conducted in 1974 and 1977 focused on detailed stratigraphic studies of the lower 140 m of the Chitistone Limestone with particular attention given to sedimentary structures and sampling. Oriented thin sections of 350 specimens representative of the outcrop sections and underground exposures were studied under the microscope. Friedman's (1959) methods were used for staining thin sections, alizarin red for calcite and potassium ferricyanide for ferrous iron in dolomite. Polished rock specimens were etched for 60 seconds in 1 molar HCl for study with a scanning electron microscope (SEM).

The carbonate rock classification is Dunham's (1962).

ACKNOWLEDGMENTS

The underground studies in the Bonanza, Jumbo, and Mother Lode mines were conducted in 1974 in conjunction with M. L. Silberman of the U.S. Geological Survey, P. R. Holdsworth, former manager, Alaskan Exploration Inexco Mining Company, and Prof. Clay Smith and George Linn, New Mexico Institute of Mining and Technology. Dr. R. M. Lloyd, of Shell Development Company, helped Armstrong in examining the critical Donoho Peak section. Outcrop and underground studies at the Kennecott mines in 1977 were done with the generous support of W. D. McCullough and C. B. Douthitt of Coastal Mining Company. We appreciate the generous help, critical review, and suggestions given by Philip W. Choquette, Robert N. Ginsburg,

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GEOLOGIC SETTING

The distribution and structural relations of the Chitistone Limestone are discussed in several reports relevant to the McCarthy quadrangle, notable MacKevett's (1965, 1970, 1974, 1976). The Chitistone occupies a northwest-trending belt along the southern flank of the Wrangell Mountains, almost entirely in the McCarthy 1° by 3° quadrangle. Outcrops are known at a few Alaskan localities north of the Wrangell Mountains, and in the Yukon Territory (MacKevett, 1976). The Chitistone disconformably overlies a thick platform of Nikolai Greenstone (upper Middle and(or) lower Upper Triassic) consisting of tholeiitic basalt that for the most part was extruded under subaerial conditions. Recent paleomagnetic investigations indicate that the Nikolai Greenstone formed in largely subaerial environments at low paleolatitudes in the proto-Pacific region (Hillhouse, 1977). Inasmuch as the Nikolai and Chitistone are components of the same tectonic terrane, it is implicit that the Chitistone formed in a similar paleoenvironment. The lowermost approximately 130 m of the Chitistone contains carbonate rocks formed in supratidal and intertidal depositional environments. This sequence is superseded by limestone of shallow marine origin, which constitutes most of the upper part of the Chitistone.

Age-diagnostic fossils are rare in the Chitistone Limestone. The Chitistone's age, Karnian Stage of the Late Triassic, is best documented by ammonites of the genus *Tropites*, which are widely but sparsely distributed in the stratigraphically medial and upper parts of the formation. Silberling (*in* Armstrong and others, 1969) stated, "A fauna comprising *Tropites* cf. *T. welleri* Smith, *Arcestes*, and *Halobia* cf. *H. superba* Mojsisovics, was collected about 152 m above the base of the Chitistone at Green Butte (USGS Mesozoic loc. M1707) and is indicative of a late Karnian age."

The Chitistone grades upward into more open marine carbonates of the Nizina Limestone, of Late Triassic

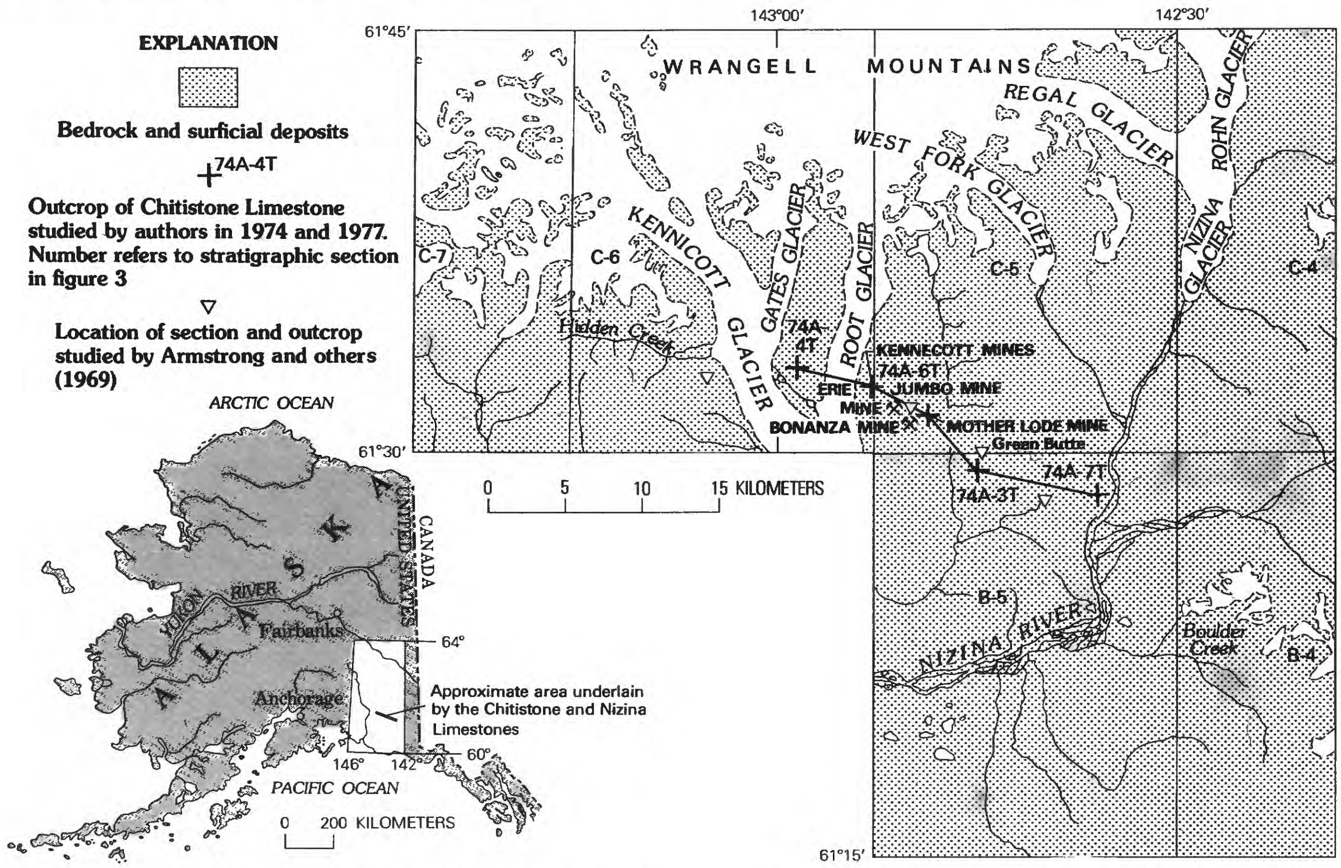


FIGURE 1.—Part of the McCarthy 1° by 3° quadrangle, Alaska, showing locations of stratigraphic sections and mines discussed in this report, and index map of Alaska showing approximate area underlain by Chitistone Limestone. Modified from Armstrong and others (1969).

age, which in turn grade upward into the McCarthy Formation, of Late Triassic and Early Jurassic age. This gradation reflects a general progressive deepening of the marine depositional environments. Deformation and local metamorphism of the Chitistone are mainly consequences of a regional orogeny during parts of the Late Jurassic and Early Cretaceous.

DESCRIPTIONS OF MEASURED STRATIGRAPHIC SECTIONS[1]

The outcrops of Chitistone Limestone at Donoho Peak (74A-4T), Green Butte (74A-3T), and Nizina River (74A-7T) are in stratigraphic order and unaffected by faulting or metamorphism throughout their lowermost 140 m (fig. 3). The Erie mine section (74A-6T) was measured to a horizon some 105 m above its base where dolomitization and tectonic fracturing have obscured stratigraphic relations. Section 74A-2T was measured on Bonanza Ridge east of Bonanza Mine.

[1] In this report all stratigraphic positions are given in meters above the Nikolai Greenstone-Chitistone Limestone contact; 85 m means 85 m above the base.

DONOHO PEAK SECTION (74A-4T)

A smooth flat surface marks the top of the Nikolai Greenstone, but evidence of extensive subaerial weathering of the Nikolai is lacking. The marine transgression that marks the base of the Chitistone probably removed any existing regolith on the Nikolai Greenstone.

The basal Chitistone consists of gray-yellow calcareous shale and nodular argillaceous lime mudstone, 0.3-2 m thick, in sharp contact with the underlying Nikolai Greenstone. The Chitistone Limestone from 2 to 10 m is massive, gray lime mudstone that contains fragments of mollusk shells preserved as micritic en-

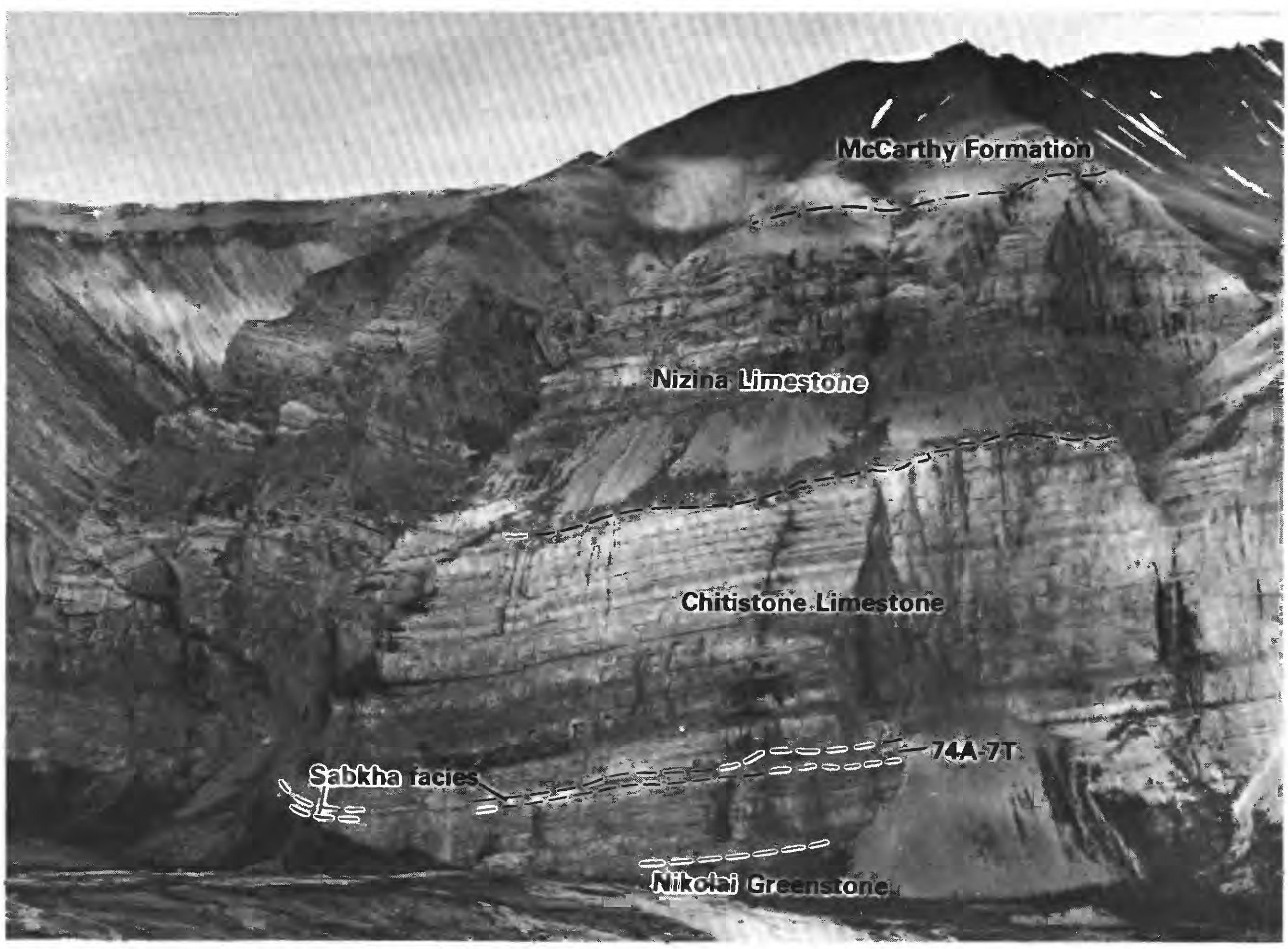


FIGURE 2.—Cliffs on west side of Nizina Valley (sec. 36, T. 4 S., R. 15 E.); relief is approximately 1 km. Folded Triassic rocks are unconformably overlain by Albian and younger Cretaceous rocks. Location of Nizina River section (74A-7T) is marked. Photograph by David L. Jones.

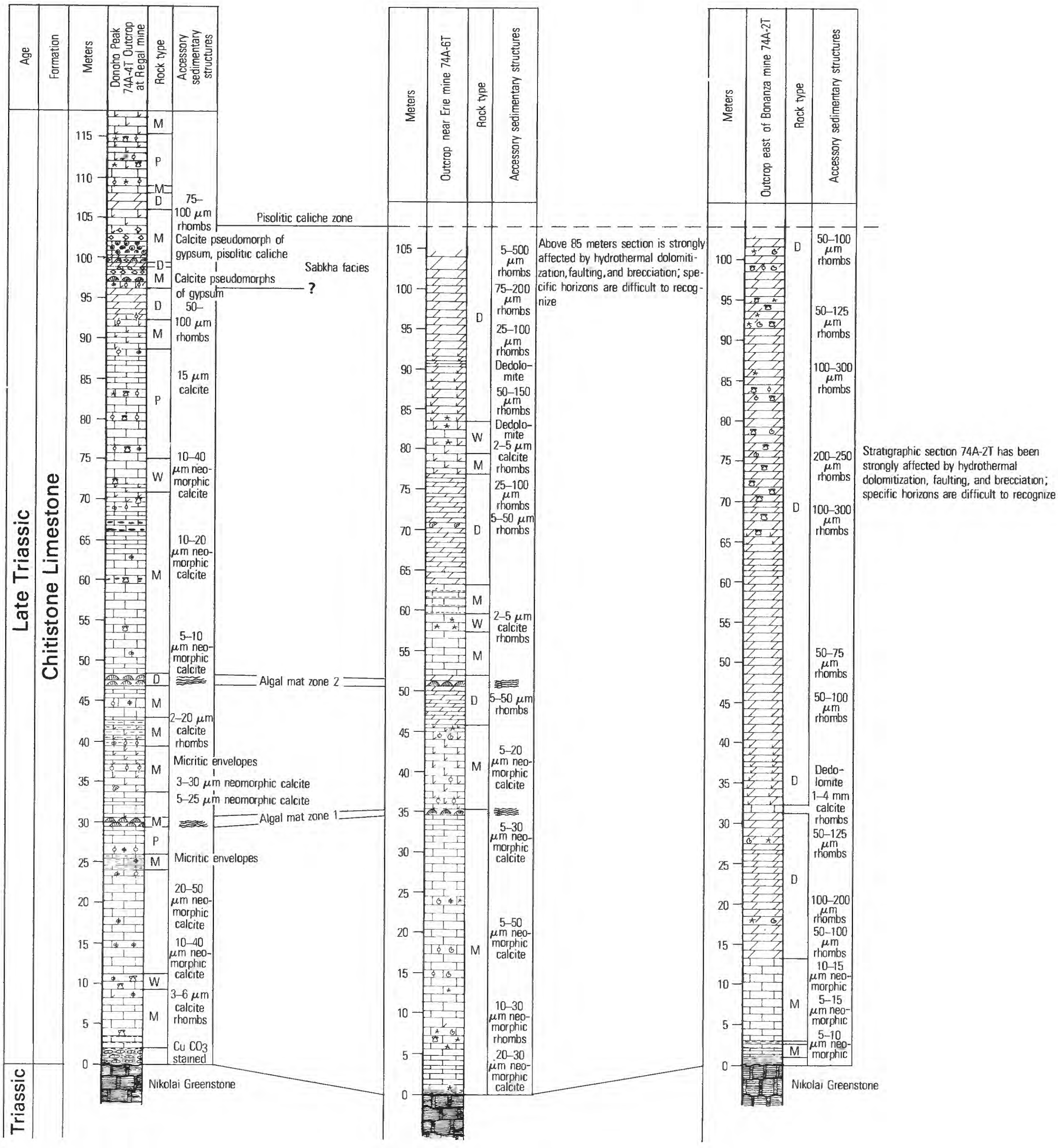


FIGURE 3.—Stratigraphic correlation of lower part of Chitistone Limestone, showing lithology and sedimentary structures. See figure 1 for locations of sections.

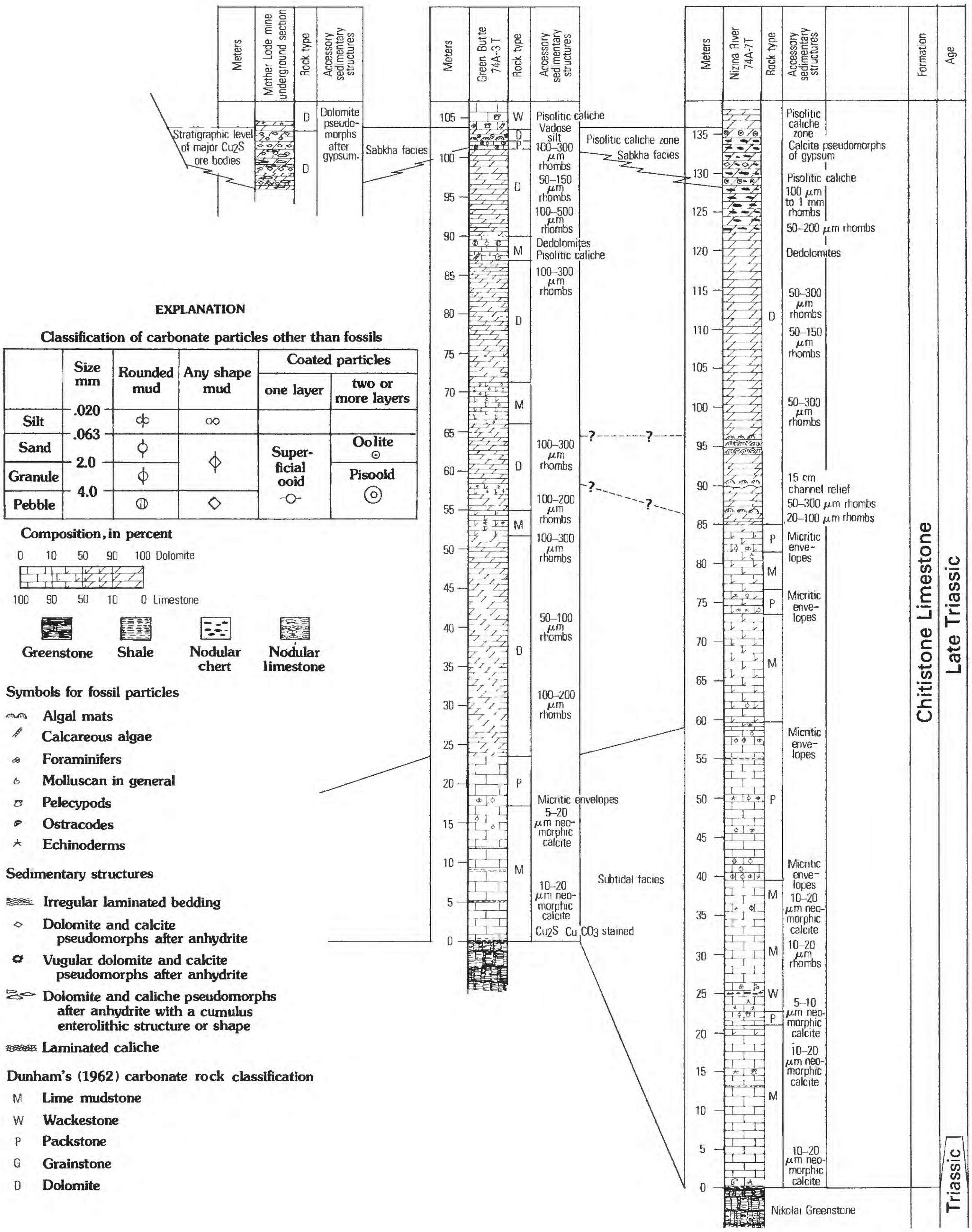


FIGURE 3.—Continued

velopes with sparry calcite fillings. The lime mudstone beds are typically composed of calcite crystals between 2 to 6 μm in size and argillaceous material; above 10 m they consist of calcite crystals in the 10 to 20 μm size range (fig. 4*A*). The environment of deposition for the lime mudstone is interpreted to be shallow, restricted marine.

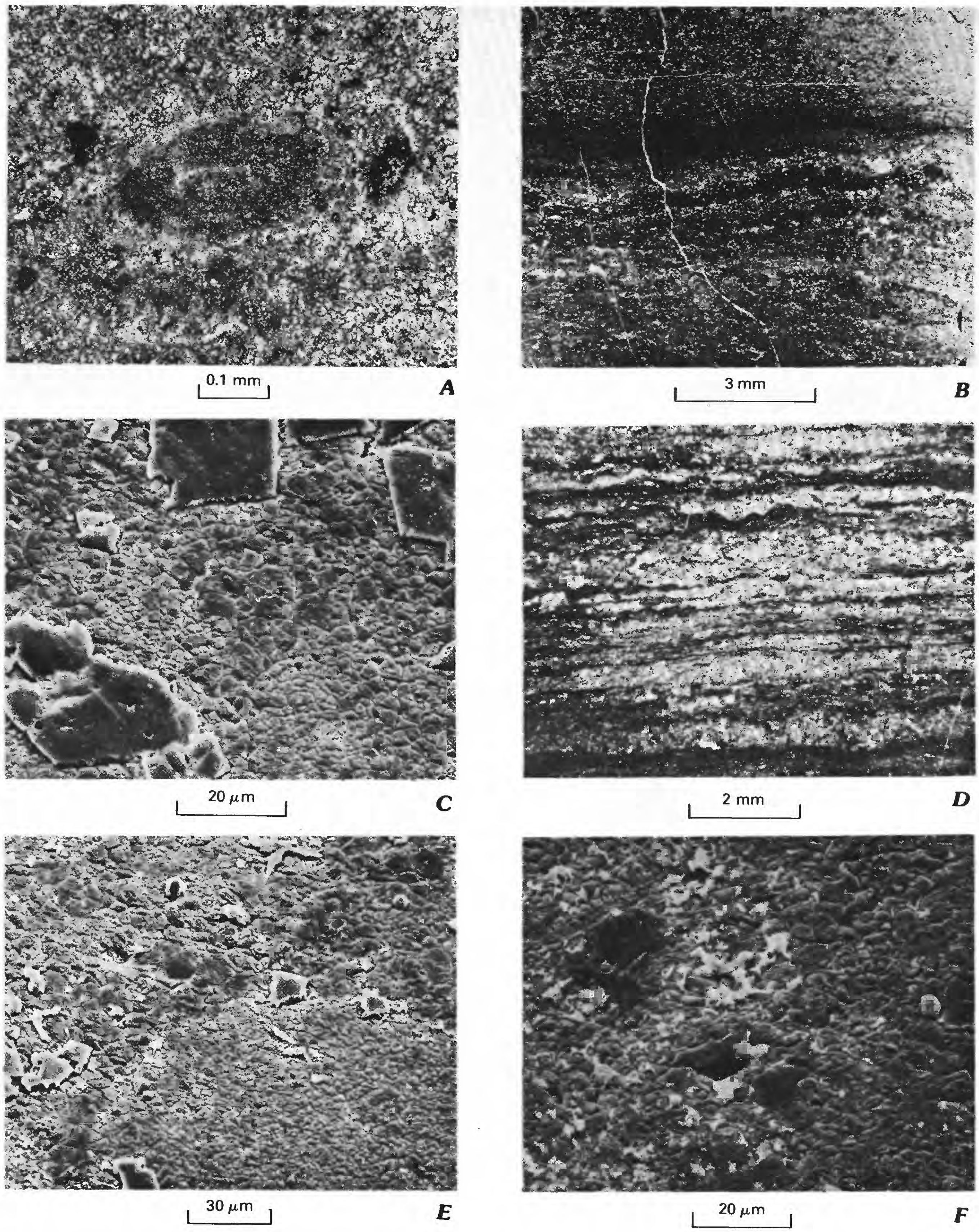
At the Donoho Peak section, a thin-bedded platy argillaceous, dark-gray pelletoid lime mudstone to packstone occurs between 24 to 26 m. It is overlain by a 1-m-thick pellet to mud-lump lime mudstone and packstone. A 1-m-thick bed of slightly argillaceous, dark-gray dolomitic lime mudstone at 30-31 m contains laminae that are interpreted as weakly developed algal mat structures (fig. 4*B*). Park (1976, fig. 1a) and Kingsman and Park (1976) stated that lamination is an intrinsic characteristic of stromatolites, and Park's figure 1a shows sedimentary features similar to those from 30-31 and 47-48 m levels. This laminated mudstone (fig. 4*B*) is in part a reflection of alternating bands of different dolomite content. The limestones from the 31- to 47-m interval are similar to the underlying beds except for a well-developed layer (38 to 43 m) of dark-gray argillaceous, platy pelletoid dolomitic lime mudstone and packstone. A pelletoidal packstone from 37 m (fig. 4*C*) is typical of the nonargillaceous carbonate rocks of this interval. Similar pelletoidal packstones are found up to 55 m in the Nizina River section. The pellets commonly contain subhedral dolomite rhombs and local micritic envelopes, and they are coated with fibrous calcite. Spaces between the pellets are filled by microspar or sparry calcite cement.

At the Donoho Peak section a stratigraphic level between 47 to 48 m is laminated dark-gray argillaceous dolomitic lime mudstone (fig. 4*D*) lithologically similar to the bed at 31 m. The higher bed contains thinner, better developed laminae. Alizarin red staining of thin sections reveals alternating bands of dolomite-rich and dolomite-poor carbonate minerals. The section from 49 to 93 m at Donoho Peak and 59 to 85 m at the Nizina River section contains some dolomite rhombs (fig. 4*E*, *F*) but is primarily pelletoid-molluscan-echinoderm lime mudstone and wackestone. The scanning electron micrograph of a specimen from Donoho Peak at 69 m (fig.4*E*) shows that the pellets are composed of 2- to 6-μm calcite crystals and micrite between pellets of calcite crystals 8 to 20 μm across and some subhedral dolomite in the 10- to 15-μm size range. The limestone from 72 m at Donoho Peak is typical pelecypod-gastropod-echinoderm-pelletoid dolomitic wackestone to packstone. Above 86 m bioclasts of mollusks and other invertebratés are rare or absent. SEM pictures (fig. 4*F*) and photomicrographs (fig. 5*A*) of peloid packstone at 88 m and 115 m show that the pellets again are composed of calcite crystals 5 μm long but contain more clay between the crystals than the adjacent micrite matrix, which has calcite crystals 5 to 20 μm in size. (A similar sequence in the Nizina River section from 59 to 85 m (fig. 5*B*, *C*, *D*) is composed of lime mudstone and peloid packstone with 10 to 35 percent dolomite that forms euhedral to subhedral rhombs 10-60 μm in size.) At 94 to 98 m (and at 86 to 122 m in the Nizina River sections) the rocks are brownish-gray dolomite with calcite void fillings. Some beds contain well-preserved pelletoid texture and relict fragments of echinoderms. Dolomite (fig. 5*E*, *F*) containing vugs lined with large dolomite rhombs and filled with calcite is found at 95 m.

The texture from 97 to 105 m at Donoho Peak is complex (fig. 6), but the rocks are predominantly dolomitic. The stratigraphic interval between 97 to 99.5 m is composed of brownish-gray dolomite with abundant 2- to 15-cm vugs filled with dolomite and calcite. At about 97-100 m is a 25- to 40-cm-thick bed of dolomitic limestone (fig. 6*A*, *B*, *E*; fig. 7) consisting of dolomitic mudstone, peloids, and laminated crust. The vugs or cavities in these beds are lined with large (0.5-1 mm) rhombs of limpid dolomite with superposed sparry calcite. A 5- to 10-cm-thick bed of yellowish-orange, pyritic, argillaceous dolomite is interbedded within this unit.

At Donoho Peak at about 101 to 104 m is calcitic dolomite which has the relict texture of a molluscan-ostracode wackestone-packstone. The fossil fragments were molds that are now filled by dolomite in 50- to 100-μm rhombs.

FIGURE 4.—Specimens from the Donoho Peak section. *A*, *B*, *D*, photomicrographs, plane-polarized light; *C*, *E*, *F*, scanning electron micrographs. Stratigraphic positions given in meters above the Nikolai Greenstone-Chitistone Limestone contact. *A*, Lime mudstone. Aggrading neomorphism has produced calcite rhombs 10 to 20 μm in size. Faint outlines of peloids with smaller calcite rhombs are darker. 15 m. *B*, Laminated, dolomitic peloid lime mudstone. Laminations are interpreted to be intertidal algal mats. 31 m. *C*, Peloid dolomitic packstone to grainstone. Dolomite rhombs are larger than calcite rhombs. 37 m. *D*, Laminated dolomitic peloid lime mudstone. Laminations are interpreted to be intertidal algal mats. 48 m. *E*, Dolomitic lime mudstone; in thin section the rock shows peloids. Peloid (lower right) is composed of smaller calcite rhombs than calcite crystals in matrix. 69 m. *F*, Peloid packstone. Peloids are lighter colored rounded areas to left. Peloid contains greater amounts of clay minerals (white material) between calcite rhombs, and matrix between peloids is formed by larger 5- to 12-μm calcite rhombs. 88 m.


0.1 mm
A
3 mm
B
20 μm
C
2 mm
D
30 μm
E
20 μm
F

The section from 104 to 122 m shows evidence of a marine transgression followed by an open platform environment of deposition, by a decrease in dolomite and an increase of limestone with abundant remains of mollusks, echinoderms, and brachiopods (fig. 5*A*).

ERIE MINE SECTION (74A-6T)

The Erie Mine section, 74A-6T, was measured west of the Erie mine. The section was measured to a horizon some 105 m above the Nikolai Greenstone where dolomitization and tectonic fracturing has obscured the stratigraphic relations. The basal bed of the Chitistone is 0.7 m of calcareous, brownish-red shale and is overlain by 34 m of gray lime mudstone and echinoderm-molluscan-peloid wackestone. The calcite rhombs in the micrite are 10 to 30 μm in size and are the result of aggrading neomorphism. Laminations, which are suggestive of algal mats, are found at 35 and 51 m above the Nikolai Greenstone. Dolomitic peloid lime mudstone are found from 35 to 46 m. Dolomitic lime mudstone is present from 46 to 63 m. Light-gray dolomite in beds 5 to 15 cm thick is present between 63 to 70 m. These beds contain vugs with sparry calcite filling and also have poorly developed algal laminations. These dolomites appear to have replaced a peloid lime mudstone with dolomite rhombs that are about 4 μm in size. Dolomitic lime mudstone and echinoderm wackestone are present from 77 to 83.5 m. Massive, chert-free dolomite is found from 83.5 to 105 m above the base.

BONANZA MINE OUTCROP SECTION(74A-2T)

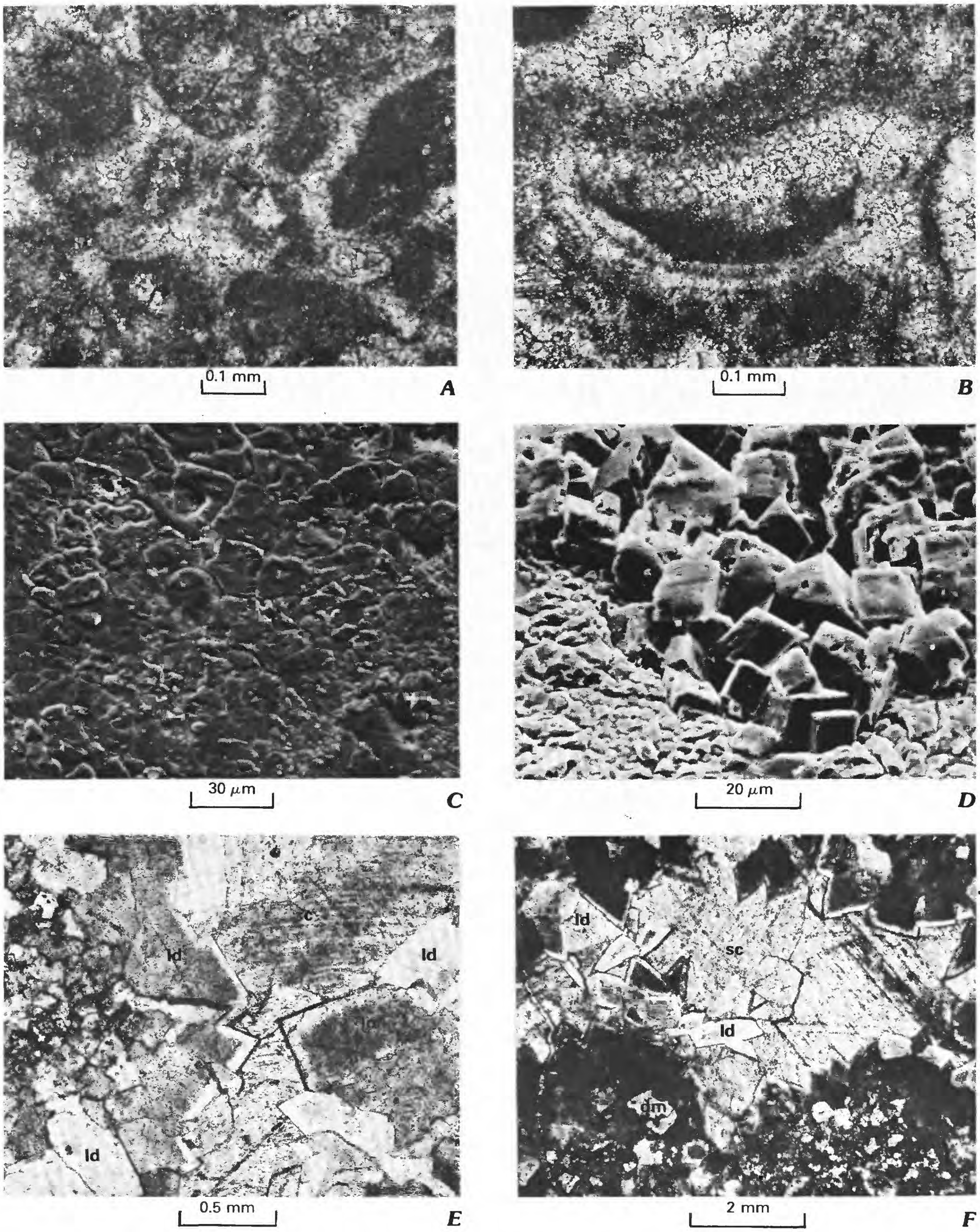
The Chitistone Limestone section 74A-2T on Bonanza Ridge was measured about 600 m south of the Bonanza mine (fig. 8). The Chitistone near the main Kennecott mines from west of the Jumbo mine to McCarthy Creek has been extensively dolomitized, tectonically brecciated, and faulted. Outcrops on Bonanza Ridge are difficult to correlate with nearby outcrop sections at Donoho Peak to the west (74A-4T), or at Green Butte mine to the southeast (74A-3T) (fig. 3). However, limestone in the stratigraphic interval 4 to 18 m above the Nikolai provides reasonably valid stratigraphic correlations. These basal beds are 1 to 2 m of calcareous shale and thin-bedded argillaceous lime mudstone and 10 to 12 m of bioturbated, argillaceous, gray, thin-bedded lime mudstone. The characteristic structure of these beds is crinkly bedding surfaces formed by anastomosing tracks, trails, and burrows. These beds were deposited on a restricted platform. The lime mudstone is composed of 5- to 15-μm crystals of calcite. The Chitistone Limestone at about 20 m above the Nikolai has been brecciated and altered to medium- and coarse-grained dolomite.

The dolomite from 21 m above the Nikolai Greenstone has the relict fabric of a crinoid-peloid packstone. The crinoid bioclasts are now large dolomite crystals, and the outlines of the peloids are marked by dark, probably organic, inclusions within clusters of dolomite rhombs. The matrix is composed of 75- to 125-μm subhedral dolomite rhombs. Some intercrystalline pores or vugs are present as well as 20- to 300-μm-wide fractures. Both are filled by sparry calcite.

A fractured dolomite at 44 and 48 m above the Nikolai Greenstone contact is composed of 80- to 150-μm subhedral dolomite rhombs. The fracture filling shows that some voids were partly lined with 1- to 2- mm dolomite rhombs, and the remaining voids are filled with sparry calcite. Dedolomitization has affected both the large dolomite rhombs and the smaller dolomite rhombs of the matrix.

A dolomite at 81 m above the base has relict crossbedding and was derived from a peloid-echinoderm wackstone-packstone. Thin section studies

FIGURE 5.—Specimens from the Donoho Peak and Nizina River sections. *A*, *B*, *E*, *F*, photomicrographs, plane-polarized light; *C*, *D*, scanning electron micrographs. Stratigraphic position given in meters above the Nikolai Greenstone-Chitistone Limestone contact. *A*, Dolomitic molluscan-echinoderm peloid packstone, Donoho Peak section. Most molluscan fragments are now micritic envelopes, peloids contain dolomite rhombs; calcite has undergone aggrading neomorphism. Peloids have radial fibrous calcite cement on their surface, space between peloids is sparry calcite. Arrow points to dolomite rhombs that formed within the micrite of some peloids. 115 m. Specimens *B*-*F* are from the Nizina River section. *B*, Brachiopod(?) shell fragment with possible geopetal filling in a matrix of micrite and pseudospar calcite. 41 m. *C*, Limestone composed of 5- to 25-μm calcite crystals, no apparent dolomite or clay minerals. This specimen in thin section (fig. 5*B*) is a peloid molluscan packstone that shows evidence of aggrading neomorphism. 41 m. *D*, Dolomitic limestone; dolomite is in clusters formed by 10- to 30-μm subhedral rhombs, calcite matrix is 2 to 15 μm in size. In thin section rock is a peloid packstone with selective dolomitization of some peloids. 74 m. *E* and *F*, Dolomite and calcite, 95 m. Specimens have same fabric as underground zebra beds associated with Mother Lode and Bonanza mine ore bodies. dm, fine-grained dolomite matrix; ld, shows large and composite dolomite zoning. Crystals labeled ld consist of limpid dolomite only in their outermost margins. Some crystals are not entirely limpid dolomite. sc, final void-filling sparry calcite. Thin fracture filled with calcite can be seen on left of 5*F*. Fracture shows sequence of events; sparry calcite is youngest; it cuts across dolomite matrix, large dolomite rhombs, and vug-filling sparry calcite.


0.1 mm
A
0.1 mm
B
30 μm
C
20 μm
D
c
ld
ld
ld
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E
ld
sc
ld
dm
2 mm
F

show the rock is composed of dolomite crystal replacement of echinoderm bioclasts and a matrix of 100- to 200-μm subhedral dolomite rhombs. The rock at 86 m is also characterized by vugs 1 to 6 mm in size. These are lined with 0.5- to 1-mm limpid dolomite rhombs, and filled with sparry calcite. The large rhombs show evidence of dedolomitization.

GREEN BUTTE SECTION (74A-3T)

The Green Butte section was measured adjacent to and north of the Green Butte mine. The Triassic carbonate rock section above the Nikolai Greenstone at Green Butte is some 1,067 m thick, of which 701 m is the Chitistone Limestone and 366 m is the Nizina Limestone (Armstrong and others, 1969). The section measured in 1974 is the lower 110 m of the Chitistone Limestone.

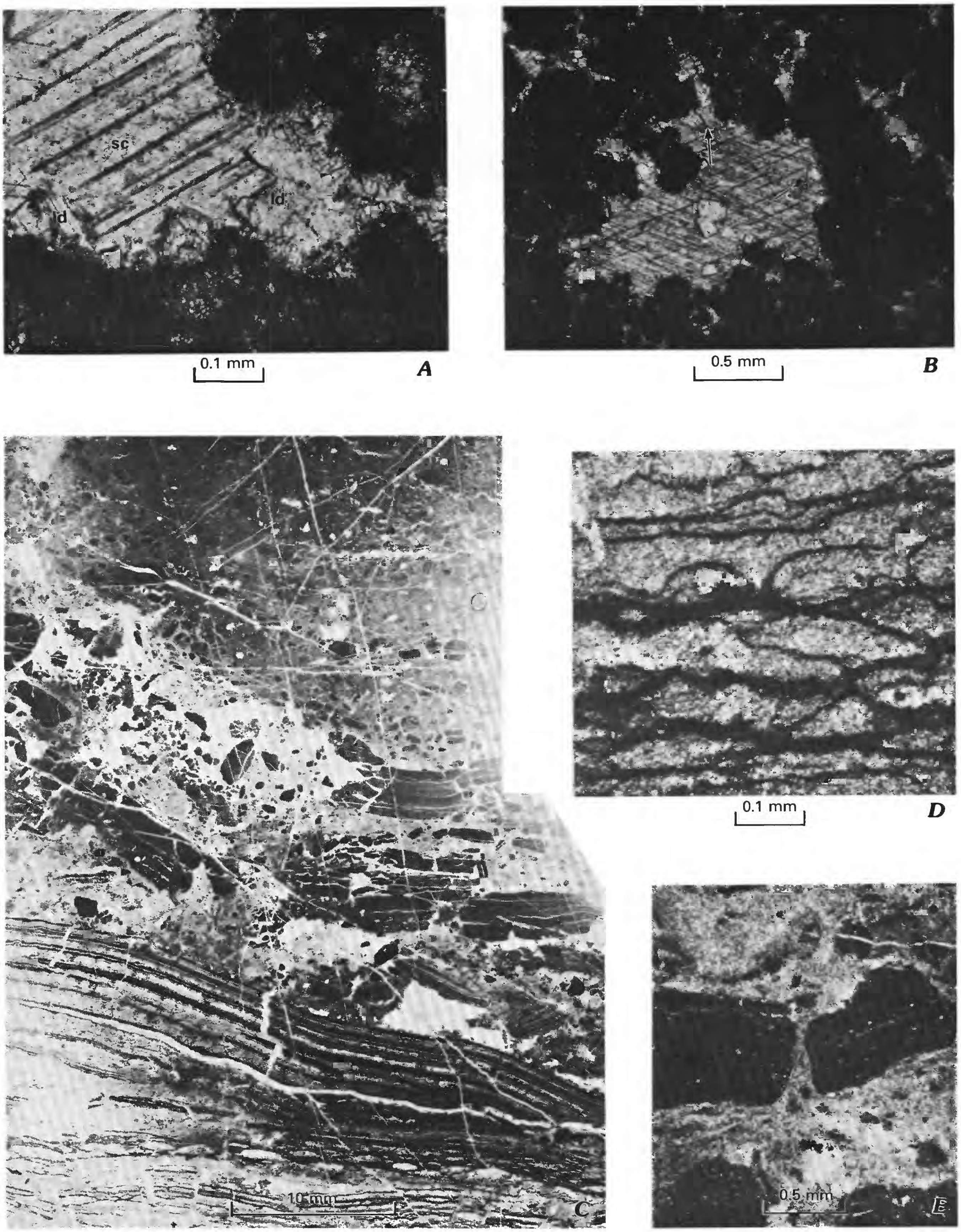
The top of the Nikolai Greenstone is a smooth surface not strongly altered by weathering. The basal Chitistone beds are 0.7 m of calcareous dark-gray to black shales, followed by 1.3 m of pale-yellow-weathering, thin-bedded, argillaceous lime mudstone. The section from 2 to 23.5 m is predominantly lime mudstone in which the calcite crystals have been subjected to aggrading neomorphism. The calcite crystals are now 10-20 μm in size. The section from 24.5 to 87 m above the Nikolai Greenstone is predominantly dolomite that is pale yellowish orange to yellowish gray in weathered outcrop, medium bedded, and chert free. Thin sections show that it is composed of subhedral rhombs, 100 to 300 μm in size. The intercrystalline pores are filled by sparry calcite. Lime mudstone to peloid-algae-molluscan packstone is present between 87 and 90 m. Between 90 and 103.5 m is yellowish-brown-gray dolomite. At 102 to 103 m are dolomitic pisooids and laminated crust. At 103.5 m are massive, gray, algae-molluscan-echinoderm wackstone and packstone. These latter beds are interpreted as representing a regional marine transgression.

NIZINA RIVER SECTION (74A-7T)

The Chitistone Limestone is exposed on the west side of the Nizina River in a series of spectacular cliffs (fig. 2). The upper contact of the Nikolai Greenstone, beneath the Triassic sediments, is smooth and shows little evidence of pre-sedimentation weathering. The basal Chitistone beds consist of 0.2-0.3 m of gray shale that contains nodules of limestone. They are overlain by gray, argillaceous lime mudstones 1.5 to 2 m thick that contain abundant worm burrows and trails. Above these beds to 40 m above the base are gray, massive, chert-free, lime mudstones and peloid packstones with no obvious sedimentary structures. The lime mudstones, to a stratigraphic level of 55 m, are formed by calcite crystals that have been affected by aggrading neomorphism. The calcite rhombs are now 10 to 30 μm in size. These lime mudstones and peloid packstones are characterized by massive beds, a general lack of well-preserved fossil remains, and abundant peloids. The limestones from 35 to 59 m are massive, light gray, and chert free. They are composed of peloid-rounded mud-lump molluscan-echinoderm packstone. The calcite crystals in these rocks have also been subjected to aggrading neomorphism. The fossil bioclasts are generally preserved as micritic envelopes. A thin section of a sample at 40 m shows it to be a peloid-molluscan packstone. This specimen when examined by the scanning electron microscope and EDAX analyzer is composed of calcite crystals in the 5- to 30-μm size range. Examination of the areas between the calcite rhombs showed 1- to 3-μm-wide to 1- to 10-μm-long crystals of anhydrite. The origin of this anhydrite in these peloid sediments is not known but possibly is related to late diagenetic fluids in the limestone which were rich with SO_4 ions. The fluids must have been low in Mg ions for the SEM studies reveal no dolomite in either limestone sample at 40 or 42 m. The dolomitic limestones from 59 to 85 m above the Nikolai contact are composed of lime mudstone and peloid packstone with 10 to 35 percent dolomite. The dolomite is composed of euhedral rhombs 10-60 μm in size.

Sedimentary structures and vug fillings are found in the Nizina River section at 86, 90, and 94-96 m (fig. 5*E*, *F*). Algal mats at 94 m are associated with laminated crust and pisooids. The sedimentary structures at 95 m have vugs lined with large (1-2 mm) subhedral to euhedral limpid dolomite rhombs and partly filled

FIGURE 6.—Photomicrographs, plane-polarized light of specimens from Donoho Peak section. Stratigraphic position given in meters above the Nikolai Greenstone-Chitistone Limestone contact. *A*, Dolomitic-lime mudstone; dark areas are dolomitic lime mudstone composed of very small crystals of dolomite and calcite. ld, large limpid dolomite rhombs that line void walls; sc, sparry calcite that fills cavities. 99.7 m. *B*, Peloid lime mudstone. Peloids are composed of a mixture of very small dolomite and calcite rhombs. Arrows point to subhedral and anhedral limpid dolomite rhombs that line voids. Remainder of void is filled by sparry calcite. Thin section is from caliche beds at 100.3 m. *C*, Laminated crust, showing in lower part of view vesicles formed by overlapping upward lenses and parallel laminations. Above parallel lamination is breccia formed of broken crusts. 100 m. *D*, Enlarged view of laminae of crust (fig. 6*C*) with convex vesicles filled with small subhedral rhombs of clear dolomite and calcite. 100 m. *E*, Enlarged view of broken crust (fig. 6*C*) showing calcite filling. 100 m.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with sparry calcite. The beds exposed at the 95-m level have the characteristic gray dolomitic matrix and white dolomite and calcite vug fillings that are lithologically similar to the zebra beds associated with the ore bodies in the Mother Lode, Bonanza, and Jumbo mines. Massive dolomite that is chert free and contains no obvious sedimentary structures occurs between 97 and 122 m. Some beds may be composed of dolomite rhombs as large as 1 mm. The brown dolomite from 122 to 135 m contains black nodular chert. Dolomite and calcite void fillings are found at 131 m above the base. An unusual sedimentary breccia occurs at 130 m (fig. 9*A*, *D*). Voids between the dolomite clasts of the breccia apparently were initially filled by radiaxial fibrous dolomite and subsequently by radiaxial calcite.

DISCUSSION OF SPECIFIC SEDIMENTARY FEATURES

MICRITIC MATRIX AND LIME MUDSTONE

Bathurst (1971, p. 511) stated that the upper size limits of crystals of lithified micrites is 3-4 μm. Scanning electron micrographs of micrite crystals from the Chitistone Limestone from the Donoho Peak section show that the size of the micrite calcite crystals at 4 m above the base range from 5 to 15 μm; at 37 m they are between 3 and 7 μ m; and at 88 m they are from 4 to 15 μm. The Nizina River section shows similar large crystals in the lime mudstone. There the lime mudstone at 10 m has micrite crystals from 5 to 20 μm in size and at 42 m from 5 to 30 μm in size. Dolomitic limestones at 74 m show micrite crystals composed of calcite from 5 to 10 μm in size.

Studies of the Chitistone lime mudstone and micritic matrix shows the typical micrite crystals are generally in excess of 2 μm in size and have been affected by aggrading neomorphism. In a strict sense many of the Chitistone lime mudstone would be classified as microspars.

PELOIDS

McKee and Gutschick (1969) applied the term peloid to cryptocrystalline or microcrystalline material irrespective of size or origin. This would include structureless lime-mud (micrite) particles from 0.020 to 4 mm in size. Pellets or peloids can be formed as fecal pellets from any number of organisms, or by the process of micritization. Bathurst (1971, p. 389) stated that micritization of skeletal debris forms a considerable part of the modern lime sand in Bimini Lagoon, Bahamas. Algae bore into the grains forming small tubes, which are subsequently filled with micrite. If this process proceeds the entire skeletoid grain will be replaced by micrite and will form a peloid indistinguishable from a fecal pellet.

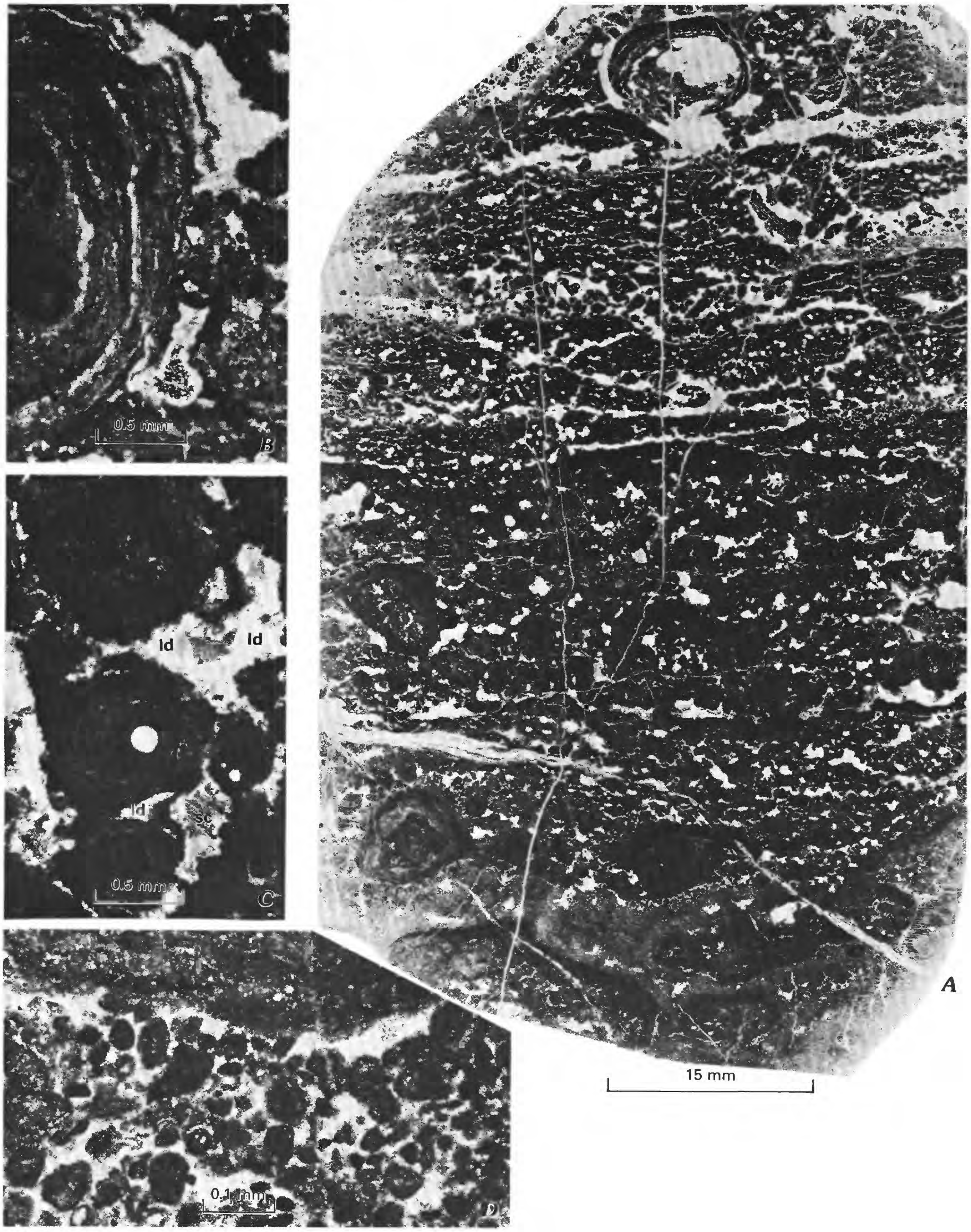
The lower part of the Chitistone Limestone contains abundant peloids. They may have well-defined shapes or blurred outlines. Peloids with well-defined outlines when examined under the petrographic microscope show a diagenetic sequence of events. These events are the deposition of the peloids, a first-stage $CaCO_3$ cement, filling of voids between peloids by sparry calcite cement, and development within many of the peloids of euhedral rhombs of dolomite (fig. 10).

SEM examination of the peloids reveals in detail their crystal structure, inclusions of clay, and outlines. A specimen at 69 m from the Donoho Peak section shows (fig. 4*E*) the peloid to be composed of calcite crystals in the 3-4μm size range, whereas the interpeloid cement is in the 7- to 20-μm size range, and peloid packstone from 88 m (fig. 4*F*) shows the peloids to be 100-300 μm in diameter, formed by 2- to 3-μm calcite rhombs, with abundant clay minerals between the calcite rhombs. The matrix between the peloids is very low in clay minerals and is formed by 5- to 20-μm calcite rhombs.

BIOCLAST DEBRIS

Bioclastic debris is relatively rare within the lower part of the Chitistone Limestone and consists primarily of ostracodes and fragments of pelecypods, gastropods, and echinoderms. Most of the pelecypods and gastropods were aragonite and are now preserved as micritic envelopes. These fragments do not show the details of the original shells, but only the original outlines are preserved as a dark thin outer zone that encloses an infilling of sparry calcite cement. Bathurst (1971, p. 333) considered these dark outer rims to be the results of the infilling of algal borings by carbonate mud, resulting in a micritic envelope. This process preserves the original shell outline after the solution of the aragonite and before the complete infilling by sparry calcite.

FIGURE 7.—Photomicrographs, plane polarized light of specimens from Donoho Peak section. Stratigraphic position given in meters above Nikolai Greenstone-Chitistone Limestone contact. *A-D*, Dolomitic-pisooid caliche. *A*, View of textures illustrating packing and size range of pisooids; large clear areas are filled with rhombs of clear dolomite and sparry calcite. Note reverse grading of pisooid at bottom of figure. *B*, Enlarged view of a pisooid showing banding and light and dark areas. *C*, Pisooids and light-colored limpid dolomite (ld) void filling and final sparry calcite (sc) void filling. *D*, Small pellets or pisooids beneath larger pisooid. Surface of pisooid is covered with small dolomite rhombs; centers of voids are filled with calcite. 97.2 m.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PELLET, PISOOID, AND LAMINATED CALICHE

Two lithologically distinctive and stratigraphically useful caliche marker beds are in the Donoho Peak section at 97 to 97.8 m (fig. 7*A-D*) and at 99.7 to 101 m. Similar caliche beds are at 102 m in the Green Butte section, and at 135 m in the Nizina River section. The beds are from 0.3 to 1.3 m thick, weather a light gray to light-yellowish gray, and are easily recognized in the field by their color, the bands of laminated crust, and large peloids and pisolites up to 10 mm in diameter.

Thin sections and SEM studies show that the caliche (fig. 6*C-E*; fig. 7*A-D*) is composed of dolomitic-micritic micropellets and large laminated pisolites in a micritic matrix with numerous voids filled by clear dolomite and sparry calcite (fig. 6*C-E*; fig 7*A-D*). Nontectonic fractures are abundant. The interparticulate voids and nontectonic fractures are filled first by limpid dolomite and then sparry calcite. The laminated crusts (fig. 6*B*; fig. 5*F*) are formed by wavy bands 10 to 100 μm thick of dark micrite separated by thin 10- to 500-μm bands of light to clear calcite and dolomite. The Chitistone Limestone laminated crust resembles

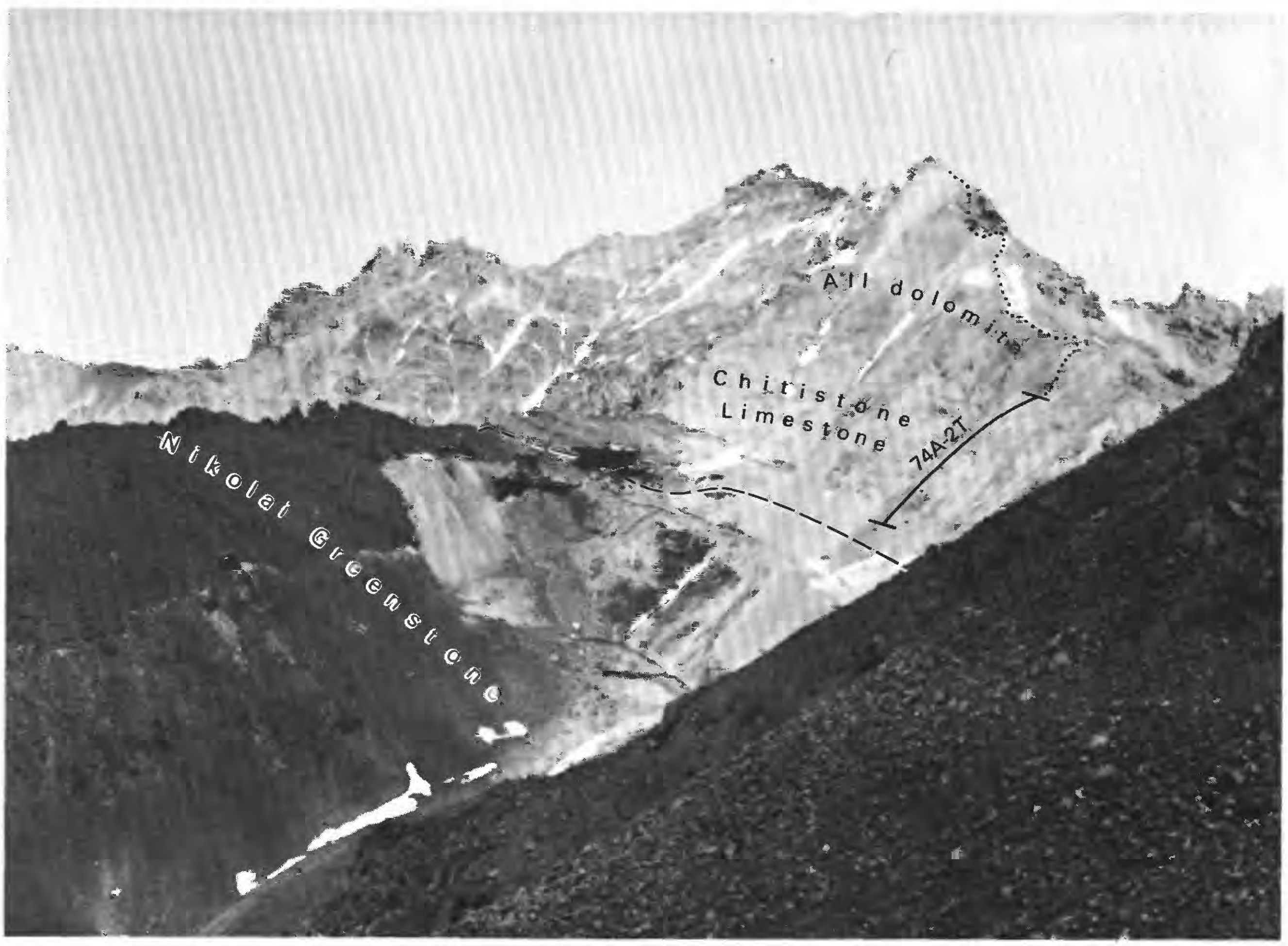
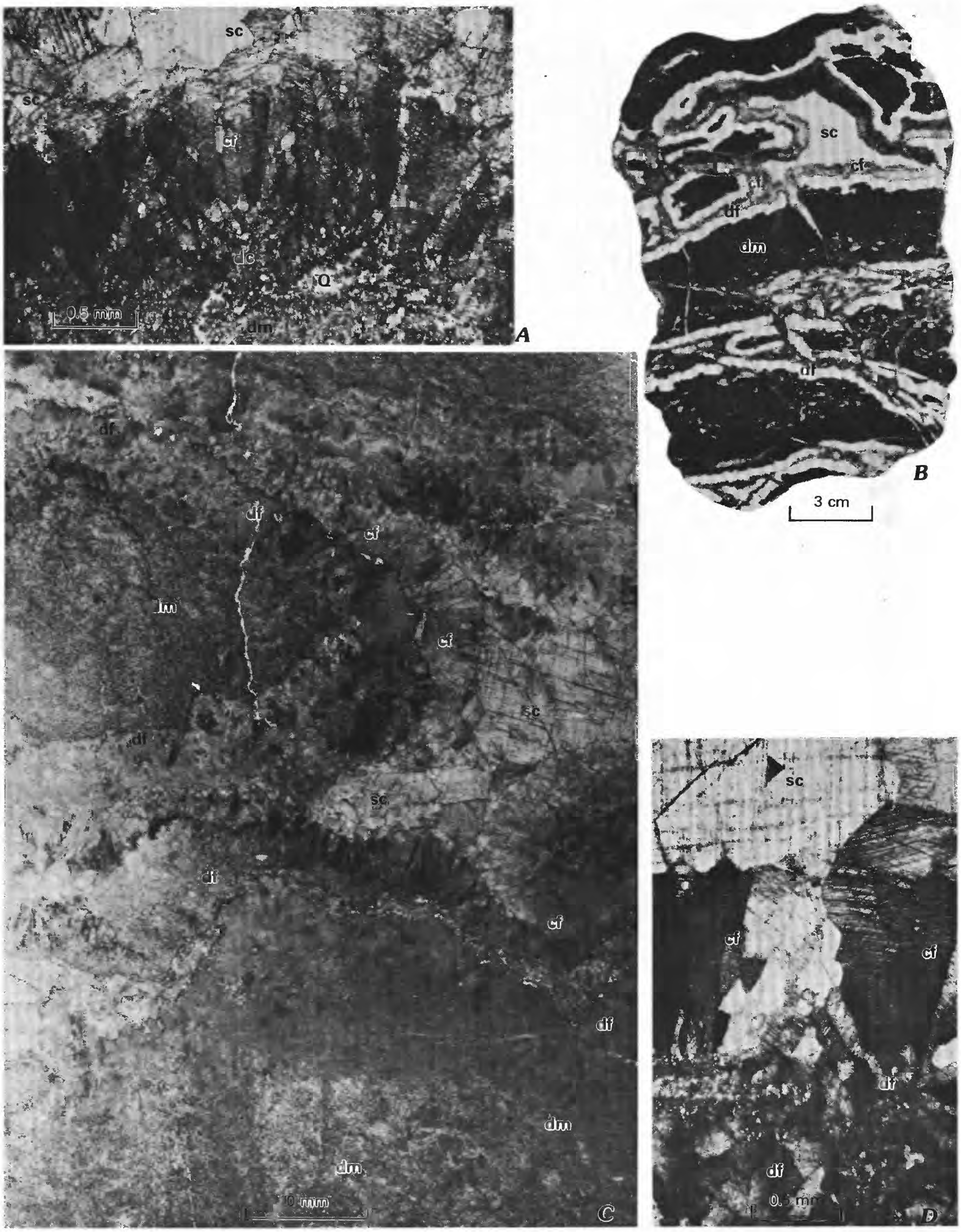


FIGURE 8.—View of Bonanza Ridge looking west toward ruins of Bonanza mine bunkhouse and power plant (center). The Glory Hole is on ridge above power plant. Chitistone Limestone on Bonanza Ridge is dolomitized and makes the irregular outcrop. Outcrop is vertically jointed. Location of section east of Bonanza mine (74A-2T) is marked. Line of traverse above measured section shown by dotted line. Photograph by David L. Jones.

FIGURE 9.—Photomicrographs and photograph of sedimentary breccia from Nizina River section, from the Chitistone Limestone 130 m above its base. *A*, Thin section in plane light. dm, dolomite matrix; df, thin band of fibrous dolomite; Q, quartz; cf, radiaxial fibrous calcite; sc, sparry calcite. *B*, Polished slab of the breccia; dm, dark dolomite matrix. Birdseye-like structures and nontectonic brecciation are clearly visible. df, light-colored fibrous dolomite; cf, overlying darker radiaxial fibrous calcite; sc, white sparry calcite that fills center of voids. *C*, Thin section, crossed nicols. dm, fine-grained dolomite matrix; df, fibrous dolomite; cf, radial fibrous calcite; sc, sparry calcite. *D*, Thin section, crossed nicols, same symbols as above.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closely the Quaternary laminated crust described by Read (1974, p. 260, figs. 8a, b) from Shark Bay, Australia. Some dark bands are separated by fibrous calcite up to 20 μm in length (fig. 6*C*); these may represent filled desiccation cracks.

The Chitistone caliches contain pisolites (fig. 7*A-C*) and large micritic peloids (fig. 5*B*, *C*, *F*). The pisolites and peloids may be compound; those over 1 mm in size are usually irregular in shape. Reverse grading of pisolites is common (fig. 7*A*, *D*). Fossil bioclasts are rare, and are generally small broken echinoderm fragments.

Scanning electron micrographs of the pisolite caliche at 135 m in the Nizina River section clearly show the pisolites to be composed of a mixture of 5- to 10-μm calcite crystals and 0.5- to 10-μm rhombs of dolomite. Large (30 to 150μm) crystals of calcite and dolomite occupy spaces between the pisolites and are readily distinguished from carbonate crystals that form the pisolites. The bands of the pisolites are characterized by differing proportions of dolomite and calcite crystals.

The caliche zone at 100 m in the Donoho Peak section is characterized by well-developed laminated crusts (fig. 6*C*, *D*).

The caliche zone at 102-103 m in the Green Butte section contains well-developed peloids and laminated crusts. The pisolites are dolomitic and similar to those at the 135-m level in the Nizina River section.

The peloids, pisolites, and laminated caliche beds are all associated with carbonate sediments that indicate deposition in subtidal to supratidal environments. Esteban's (1976) classification would place these as vadose marine or vadose hypersaline caliche. Sedimentary structures in these beds are algal mats, dolomite or calcite pseudomorphs after gypsum-anhydrite, and mud chips.

Examination under the SEM of the pellets and pisolites shows that they are dolomitic, generally with dolomite rhombs in the 0.5- to 10- μm size range. Scholle and Kinsman (1974) and Purser and Loreau (1973) have shown that caliche crust on Pleistocene limestone in Abu Dhabi, Trucial Coast, Persian Gulf, and Bonaire, Netherland Antilles, form in supratidal vadose areas that are characterized not by fresh water but by hypersaline brine. The resultant textures of these crusts are largely vadose, but the mineralogy—aragonite and dolomite— and chemistry are of marine character. This environment could account for the abundance of microdolomite in the pisolites in the Chitistone Limestone. The Chitistone pisolites may have formed in part from dunes of skeletal grainstone, subjected to marine vadose weathering in hot semiarid conditions under the influence of fluctuating saline brines and rain water (schizohaline environment of Folk and Land, 1975). This environment would be the surface of a stable supratidal sabkha.

SEDIMENTARY BRECCIAS

The Nizina River section contains a sedimentary breccia at the 130-m level (fig. 9*A-D*). The sedimentary breccia occurs above a pisolitic caliche at 129 m and below beds with pseudomorphs of gypsum at 130-131 m, and pisolitic caliche at 135 m. The sedimentary breccias are associated with rocks of intertidal to supratidal to saline vadose-weathering origin. These breccia fragments are unlike any of the other breccias in the Chitistone Limestone. They may be up to 10 cm long and 3 cm thick and contain birdseye structure. Interclast cavities are elongated subparallel to bedding. The matrix of the clasts is composed of 100- to 150-μm subhedral dolomite rhombs commonly separated by black, partly oxidized pyrite cubes, 4 to 12 μm in size. Surfaces of the fragments are covered with white elongate crystals wich extend 2 to 5 mm into interclast cavities. The coarse-grained dolomite is in turn overlain by gray radiaxial calcite which extends 2 to 6 mm

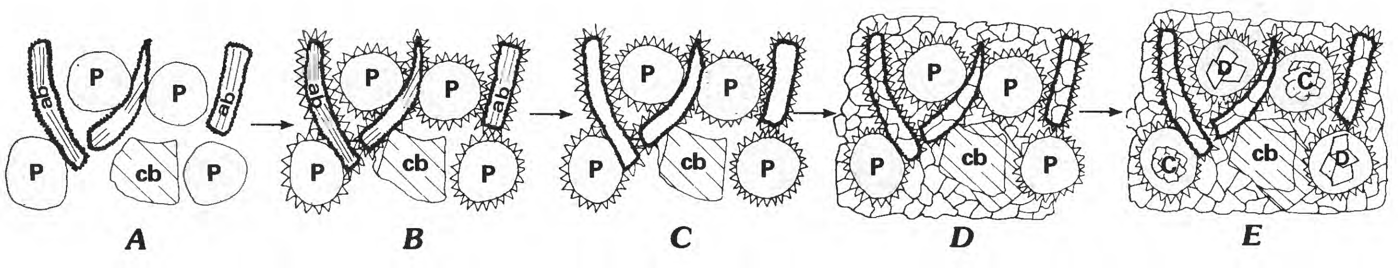


FIGURE 10.—Probable sequence of alteration of peloid-bioclastic grainstone as exemplified by a thin section from the Chitistone Limestone. *A*, Original sediments consisting of bioclasts of mollusks (ab) with a micritic envelope, echinoderm calcite bioclasts (cb), and peloids (P). *B*, First-stage $CaCO_3$ cement. *C*, Dissolution of aragonite clasts. Micritic envelope and first-stage $CaCO_3$ provide strength to molluscan bioclast molds. *D*, Complete cementation by second-phase $CaCO_3$ cement, syntaxial overgrowth on crinoid calcite bioclasts. *E*, Many peloids within the Chitistone Limestone contain dolomite (D) rhombs and microspar (C) from the micrite. Peloid-molluscan-echinoderm packstone would show similar sequence of events: micritic matrix may go to microspar, resulting in a rock very similar in appearance to the above grainstone.

into the cavaties. The remaining voids are partly filled by sparry calcite. Between the elongate dolomite rhombs and the radiaxial calcite is a diffuse band consisting of disjunct 100- to 300-μm quartz grains with calcite inclusions and some scattered 20- to 30-μm pyrite crystals.

The sequence of events for the formation of these breccias appears to be: (1) Carbonate muds were deposited in a subtidal-intertidal to possible supratidal environment. (2) The carbonate muds were partially cemented. (3) The partly lithified sediments were fractured. (4) The matrix of the sediments may have originally been dolomite or was progressively altered from calcium carbonate to dolomite during the above stages. Coarse dolomite rhombs were deposited on cavity walls of the fractured and porous sediments. (5) Radiaxial fibrous calcite was deposited over the dolomite that may represent recrystallized fibrous aragonite cement (Kendall and Tucker, 1973). (6) Voids were filled by coarse sparry calcite, probably in a fresh-water diagenetic environment. Eugene Shinn (written commun., 1976) interpreted the cements to be submarine (subtidal) in origin.

Evamy's (1973) study of the intertidal-supratidal sediments of the Trucial Coast of the Persian Gulf showed sedimentary structures similar to those in the Chitistone breccias.

The sequence of carbonate minerals that fill the voids and cavities of the breccia at 135 m in the Nizina River section provides clues to the history and genesis of the breccia. Kendall and Tucker (1973) suggested that radiaxial fibrous calcite, similar to that found in our breccias, is a replacement after acicular aragonite or fibrous magnesium calcite. Folk (1974) indicated that acicular carbonates are the results of slow sideward crystal growth in marine or tidal environments rich in magnesium. If these two assumptions are correct, then the radiaxial calcite was probably formed originally in marine waters.

ZEBRA BEDS AND VUG FILLINGS

In the Bonanza and Mother Lode mines, some massive copper sulfide ore bodies occur at stratigraphic levels. Many ore bodies are associated with what the miners term zebra beds, a unit that has specific carbonate rock fabrics, sedimentary structures, and environments of deposition. A photograph (fig. 11) and samples of these beds at the 503-m (1,650-foot) level, adjacent to a large massive ore body in the Mother Lode mine, show that zebra beds comprise a matrix of subhedral 50- to 200-μm light-brown-gray dolomite with abundant flat-bottomed, cumulus, enterolithic vugs lined with light-gray to white zoned coarse dolomite. Centers of the vugs are partly filled with sparry calcite (fig. 12). Abundant 5- to 100-μm-wide fractures cut the dolomite matrix and both the dolomite and calcite vug fillings. These fractures are filled with sparry calcite and copper minerals. The intercrystalline pores between dolomite rhombs of the matrix contain sparry calcite. The outcrop specimen from the Nizina River section from 95 m above the Nikolai Greenstone (fig. 5*E*; fig. 12*C*) shows the same mineralogy and sequence of mineralization except that the fine fractures in the Nizina River section are filled with calcite and are devoid of copper minerals.

Our underground studies at the Kennecott mines show that some ore bodies bottom in the zebra beds and that they probably are wider and best developed in the zebra beds, but their upper parts transect stratigraphically higher beds.

Fine-grained uniform dolomite that contains burrow and small-scale cut-and-fill structures underlies the zebra beds. The overlying beds are 1- to 3-m-thick beds of dolomitic-pisolitic-laminated caliche overlain in turn by coarse-grained dolomite with dolomite pseudomorphs after crinoid bioclasts.

The zebra beds of the Mother Lode (figs. 11 and 12) and Bonanza mines and the Nizina River section have sedimentary structures similar to *Stromatactis*. *Stromatactis* was first used taxonomically by Dupont (1881) for distinctive crystalline carbonate features that he considered stromatoporoids in Devonian limestones of Belgium. Lecompte (1937, 1954) thought these features were precipitated calcite resulting from the decomposition of algae. Bathurst (1959) concluded that *Stromatactis* refers only to an enigmatic flat-bottom crystalline feature. *Stromatactis* sedimentary structures are associated with lime mud banks in England, Ireland, and Nevada. The lime mud banks may have hundreds of meters of relief above the adjacent deeper water sediments (Lees, 1961, p. 103, fig. 2; Lees, 1964; Schwarzacher, 1961, p. 1483, figs. 2-4; Ross and others, 1975). Most of the *Stromatactis* decribed are on inclined prograding beds. Lee (1961, fig.5) described a cross section of a Waulsortian bank with growth layers of lime mudstone, inclined beds of *Stromatactis* and bioclastic debris parallel with the inclination. The zebra beds of the Chitistone Limestone do not show these relations.

Zebra beds in the Chitistone Limestone are parallel with the underlying and overlying beds. This relation is well displayed in the inclined shafts of the Mother Lode and Bonanza mines. The inclined shafts parallel the beds just below the zebra beds. At various levels from the inclined shaft there are drifts into or across the zebra beds. This parallelism also is well displayed in the outcrops west of the Bonanza mine on Bonanza Ridge and on the Nizina River (fig. 2). There is no indication in these or other outcrops examined of mounds or banks developed within the lower 150 m of the Chitistone Limestone.

Kendall and Skipwith's (1969,p. 859) photographs of the trenches they dug in Holocene sabkha deposits of Abu Dhabi show nodular and contorted anhydrite that is parallel to the surface and the underlying bedding and has nearly identical shapes as the stratiform vugs within the zebra beds shown on the tunnel wall in figures 11 and 12 from the Mother Lode mine, and from the Nizina River outcrop section at 95 m above the Nikolai Greenstone.

Evidence for a sabkha deposition environment for the zebra beds includes: (1) their position in the top suite

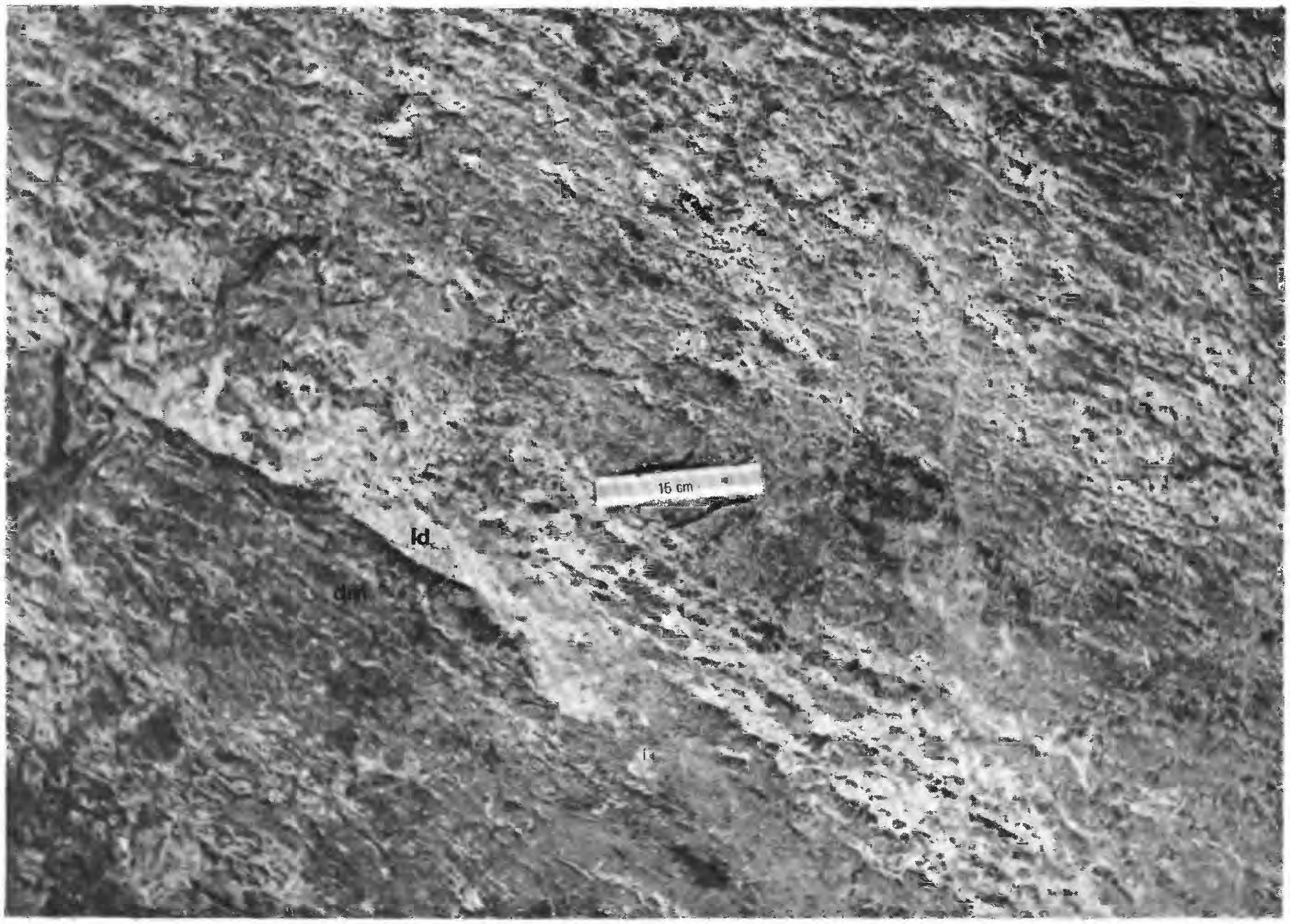
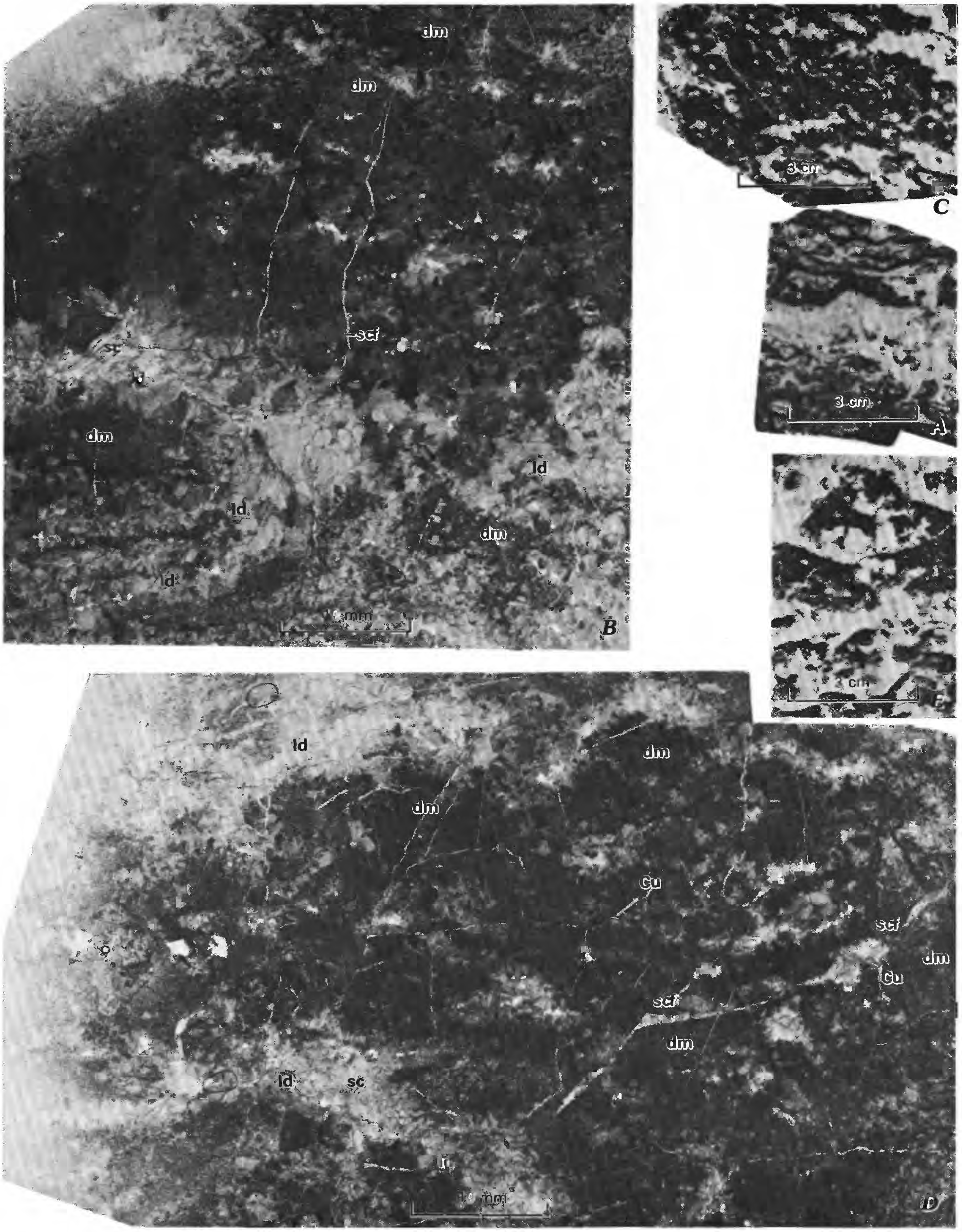


FIGURE 11.—Wallrock, adjacent to ore bodies, from 503-m (1,650-foot) level of Mother Lode mine. Beds dip about 30°. Dark area is dolomite matrix rock (dm), light areas are cavities lined with limpid dolomite (ld) and final void filling by sparry calcite. Beds beneath the unit are uniform gray dolomite with burrows and small-scale cut-and-fill structures. Overlying these beds is coarse-grained dolomite with dolomite pseudomorphs of echinoderms that resemble *Stromatactis* of the literature. White areas are dolomite and calcite cavity fillings of what we interpret as pseudomorphs after interbedded anhydrite and gypsum.

FIGURE 12.—Specimens from zebra beds in the Mother Lode mine at 503-m (1,650-foot) level adjacent to ore bodies. Stratigraphic position of specimen given in centimeters above mine floor. *A*, Polished surface of zebra rock. Dark areas are dolomite matrix, light areas are limpid dolomite and calcite pseudomorphs after anhydrite. 200 cm. *B*, Photomicrograph of thin section; dm, fine-grained dolomite matrix. Anhydrite pseudomorphs are lined first by large limpid dolomite rhombs, then by sparry calcite (sc). Tectonic fracture, now filled by sparry calcite (scf), crosscuts all textures. These fractures also contain copper mineralization. 250 cm. *C*, Polished surface. Dark areas are dolomite matrix, light areas are limpid dolomite and calcite pseudomorphs after anhydrite. 200 cm. *D*, Photomicrograph of thin section; fine-grained dolomite matrix. Anhydrite pseudomorphs are lined first by large limpid dolomite rhombs(ld), then by sparry calcite (SC). Tectonic fracturing crosscuts all textures and the fractures are filled by sparry calcite (SCF) and copper minerals (Cu). 200 cm. *E*, Polished surface. Dark areas are dolomite matrix, light areas are limpid dolomite and calcite pseudomorphs after anhydrite and gypsum. 170 cm.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of beds of a sequence which goes from molluscan-peloid wackestone (subtidal) to beds dominantly composed of dolomite and devoid of fossil fragments; (2) the sedimentary structures of the zebra beds, and the shapes of the vugs which, with their flat bottoms and lenticular, enterolithic form suggest that they are pseudomorphs after anhydrite and gypsum; and (3) the finer grained subhedral dolomite matrix between the dolomite and calcite-filled vugs.

An alternative idea (P. W. Choquette, written commun., 1979) for the origin of the zebra beds is collapse brecciation due to solution of evaporites beneath the zebra beds.

The sequence of events for the formation of the zebra beds, as indicated from the study of the polished slabs, SEM and energy-dispersive X-ray analyzer examination, and thin sections, is probably the following (fig. 13).

1. A coastal sabkha carbonate developed in the Chitistone Limestone at a stratigraphic level of some 90-120 m above the Nikolai Greenstone.

2. Sabkha diagenesis of these carbonate sediments probably included dolomitization and concurrent emplacement of diagenetic gypsum crystals and anhydrite nodules within the sabkha sediments (Kinsman, 1966, 1969).

3. The gypsum crystals and anhydrite nodules dissolved from the zebra beds with associated dedolomitization of some of the dolomite matrix. Field and petrographic studies do not clearly define the time in which this event occurred. The outcrop sections at Donoho Peak, Green Butte, and Nizina River and the underground exposures in the Mother Lode mine have sequences that are interpreted as sabkha deposits containing beds with dolomitic caliche. The dolomitic caliche may represent formation of hypersaline brine in the vadose weathering zone (Scholle and Kinsman, 1974). During periods of vadose weathering, meteoric ground water may have penetrated and dissolved the gypsum crystals or anhydrite nodules within the underlying sabkha sediments and formed the vugs.

4. Coarse-grained white zoned dolomite was deposited on the walls of the vug. Petrographic evidence does not define the time of this event. The Nizina River outcrop beds and the samples from the zebra beds in the mines contain voids that are filled by limpid dolomite rhombs and sparry calcite. The void fillings and mineralogy of outcrop samples and mine samples are identical. The outcrop example suggests an early diagenetic origin for the large clear dolomite crystals (fig. 5*E*, *F*). The extensive voids created by the removal of the gypsum- anhydrite (figs. 11 and 12) indicates that a thick section of sediments above this zone would crush the dolomite matrix framework and brecciate the zebra zones. Thus it can be argued that the partial infilling of the vugs by coarse dolomite occurred at shallow depths and possibly in the sabkha environment. Folk and Land (1975, p. 63) gave theoretical arguments that dolomite probably forms most readily by a reduction in salinity, particularly in a schizohaline environment (alternating between hypersaline and near-fresh conditions) as in a floodable sabkha or a phreatic mixing zone. Flushing marine saline waters with fresh water lowers salinity but maintains a high Mg/Ca ratio; crystallization is slower and the interfering effect of foreign ions is reduced. Folk and Land

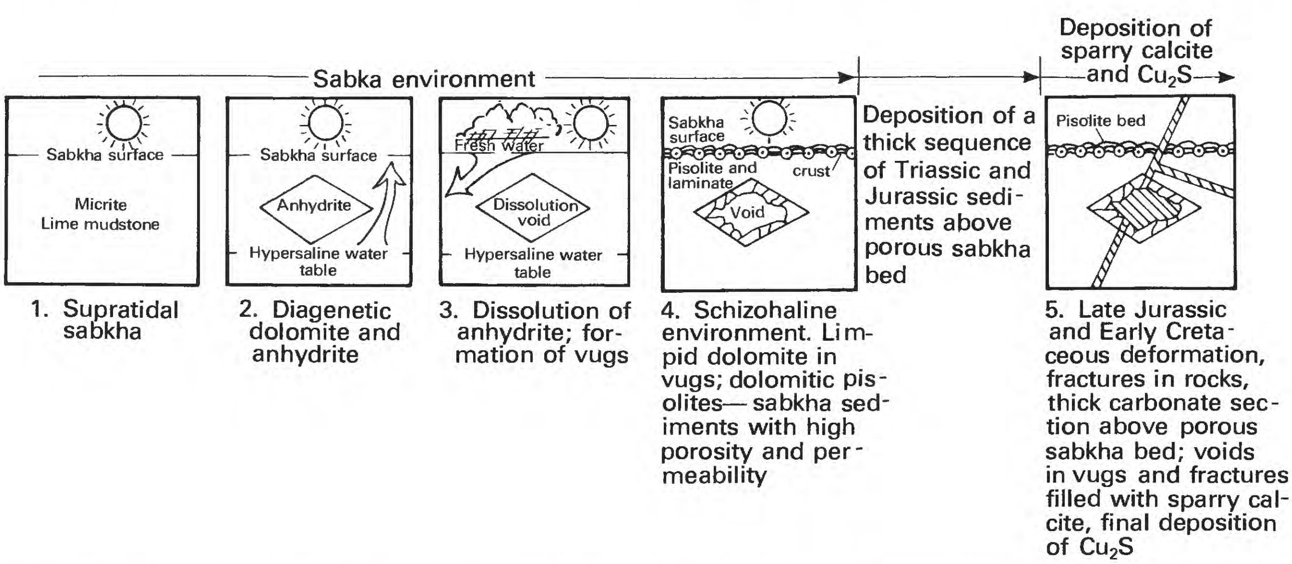


FIGURE 13.—Probable sequence of events in devopment of vugs and cavity filling of zebra beds. Concepts are from samples from Mother Lode mine and Nizina River section.

stated (p. 67) that dolomite formed from dilute solutions is characteristically limpid.

5. The event that formed the fractures that are 10 μm to 0.5 μm wide clearly followed limpid dolomite formation. The fracturing may have occurred during or after the deposition of the coarse-grained sparry calcite that fills the remaining pore space in the vugs. Sparry calcite fills the fractures within the matrix and the intercrystalline pores of the dolomite matrix. Deposition of this calcite was the last major event. If one accepts Folk and Land's (1975, p. 60) concept that blocky calcite can be formed only in low Mg/Ca water that is derived from meteoric water or where Mg has been removed from marine water by formation of dolomite or absorption clays, it is possible that the calcite is the product of phreatic fresh water. The purity of the calcite and its large crystals support this hypothesis. Fracturing and calcite void filling may have extended through several episodes as indicated by some calcite which fills voids and is then cut by fractures and filled by another cycle of calcite vein filling.

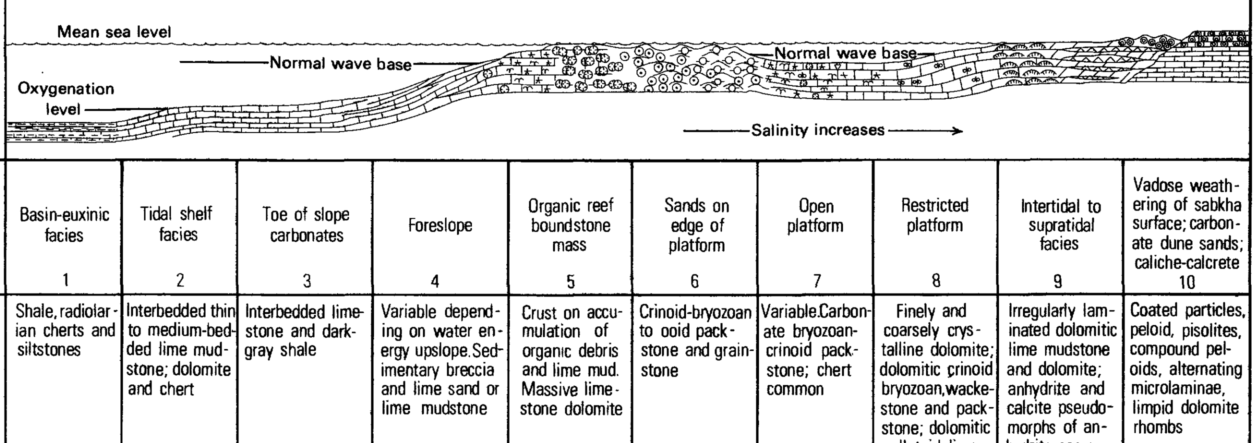
In the mines many of the fine fractures associated with the zebra beds contain not only sparry calcite but copper minerals; therefore copper mineralization occurred late in the long diagenetic history of these carbonate rocks.

INTRAFORMATIONAL STRATIGRAPHIC CORRELATION AND ENVIRONMENTS OF DEPOSITION

The correlations shown in figure 3 for the lower part of the Chitistone Limestone are based on sedimentary features and microfacies. The interpretation of carbonate microfacies, sedimentary structure, and depositional models (fig. 14) follow the stratigraphic concepts published by Wilson (1970, 1975).

The lower 100 to 120 m of the Chitistone Limestone exposed from Donoho Peak to the Nizina River outcrops fits Wilson's (1975, p. 297) concept of upward-shoaling carbonate sediment cycles that are composed predominantly of lime mudstone (micritic) sediments whose faunas and sedimentary structures show a pro-

Diagrammatic cross section for Mesozoic carbonate facies



Facies and facies numbers	Basin-euxinic facies 1	Tidal shelf facies 2	Toe of slope carbonates 3	Foreslope 4	Organic reef boundstone mass 5	Sands on edge of platform 6	Open platform 7	Restricted platform 8	Intertidal to supratidal facies 9	Vadose weathering of sabkha surface; carbonate dune sands; caliche-calcrete 10
Lithology	Shale, radiolarian cherts and siltstones	Interbedded thin to medium-bedded lime mudstone; dolomite and chert	Interbedded limestone and dark-gray shale	Variable depending on water energy upslope. Sedimentary breccia and lime sand or lime mudstone	Crust on accumulation of organic debris and lime mud. Massive limestone dolomite	Crinoid-bryozoan to ooid packstone and grainstone	Variable. Carbonate bryozoan-crinoid packstone; chert common	Finely and coarsely crystalline dolomite; dolomitic crinoid bryozoan, wackestone and packstone; dolomitic pelletoid lime mudstone	Irregularly laminated dolomitic lime mudstone and dolomite; anhydrite and calcite pseudomorphs of anhydrite common; algal mats	Coated particles, peloid, pisolites, compound peloids, alternating microlaminae, limpid dolomite rhombs
Color	Dark brown to black	Gray to brown	Gray to dark brown	Gray to light gray	Light gray	Light gray	Light gray	Light gray to gray	Gray-yellow, brownish red	Gray-light gray, yellowish brown
	Very even millimeter laminations, rythmic bedding, ripple cross laminations, burrows, and worm trails on bedding surfaces	Thoroughly burrowed. Thin to medium wavy to nodular beds; bedding surfaces show diastems	Laminations may be minor, massive beds common, lenses of graded sediments; lithoclasts and exotic blocks	Slumps in soft sediments, foreset bedding, exotic blocks	Massive to thick beds, some cross bedding, to massive organic structures or open framework with roofed cavities	Medium to large-scale crossbedding; festoons common	Abundant burrows	Birdseye structures, algal mats on or near intertidal zone, stromatolites in very shallow water, graded cross bedding	Anhydrite-gypsum rhombs, bedded anhydrite, cracks, chips, algal mats	

EXPLANATION

Solitary corals — **Bryozoans** — **Ooid** — **Pisooid** — **Algal mats**

Colonial corals — **Echinoderms** — **Superficial ooid** — **Pelletoids** — △△△ **Anhydrite gypsum**

FIGURE 14.—Depositional model for Upper Triassic carbonate facies of the Wrangell Mountains. Concepts for model are from Wilson (1970, 1975).

gressive change through restricted shallow marine carbonates with megafossils to dolomite and caliche (facies numbers 8-10, fig. 14). In these cycles a sharp upper contact occurs with open marine beds at the base of the next cycle.

Work on modern sabkhas has shown that the saline supratidal flats are aggradational features which gradually extend over subtidal, intertidal, and lagoonal sediments (Evans and others, 1964; Purser and Evans, 1973). Wood and Wolfe (1969) describe in detail nine similar sabkha cycles from the Upper Jurassic and Lower Cretaceous Arab/Darb Formation of Saudi Arabia. Similar cycles were described by Wilson (1967) from the Duperow Formation (Devonian) of the Williston basin, western North Dakota and adjacent areas. The Duperow contains 12 such cycles. Wilson estimated the time of each cycle at about 500,000 to a million years. Evans and others (1969) described sabkha cycles deposited on the Trucial Coast on the Persian Gulf; each cycle lasts on the order of 1,000 years.

The well-exposed Donoho Peak section, 74A-4T, is the best outcrop for interpreting environments of deposition for the lower 135 m of the Chitistone Limestone (figs. 3, 15).

The Chitistone Limestone as shown on figure 3 contains two well-developed physical correlation lines. One is the contact with the Nikolai Greenstone. The second, which is exposed in three of the measured outcrop sections, is the dolomitic-peloid-pisolitic laminated caliche beds that range from 30 cm to greater than 1 m in thickness. The caliche beds are developed at the Nizina River section at 135 m, the Green Butte section at 101-102 m and at the Donoho Peak 74A-4T at 97 to 98 and 99.8 to 100 m (fig. 16). Our underground studies in 1977 found a 60-cm-thick bed of dolomitic-pisolitic caliche above the zebra beds in the 503-m (1650-ft) level of the Mother Lode mine.

The lower half of the Chitistone Limestone can be correlated between the Donoho Peak section and the Erie mine section by two weakly developed incomplete upward-shoaling lime-mud (micrite) cycles that are developed at the 30- to 35-m and 48- to 52-m levels (facies 8 and 9, fig. 14). These lower incomplete carbonate deposition cycles were not recognized in the Bonanza mine outcrop section (probably due to faulting) or at the Green Butte section.

The incomplete carbonate deposition cycles that occur at 48 to 52 m at the Donoho Peak and Erie mine sections are probably a time-stratigraphic equivalent to the laminate-pisooid caliche bed found between 86 to 96 m in the Nizina River section.

The underground Mother Lode mine section shown on figure 3 is about 5 m thick. The sabkha facies contains algal mats, zebra beds, laminated beds, dolomite pseudomorphs after gypsum and anhydrite, penecon-

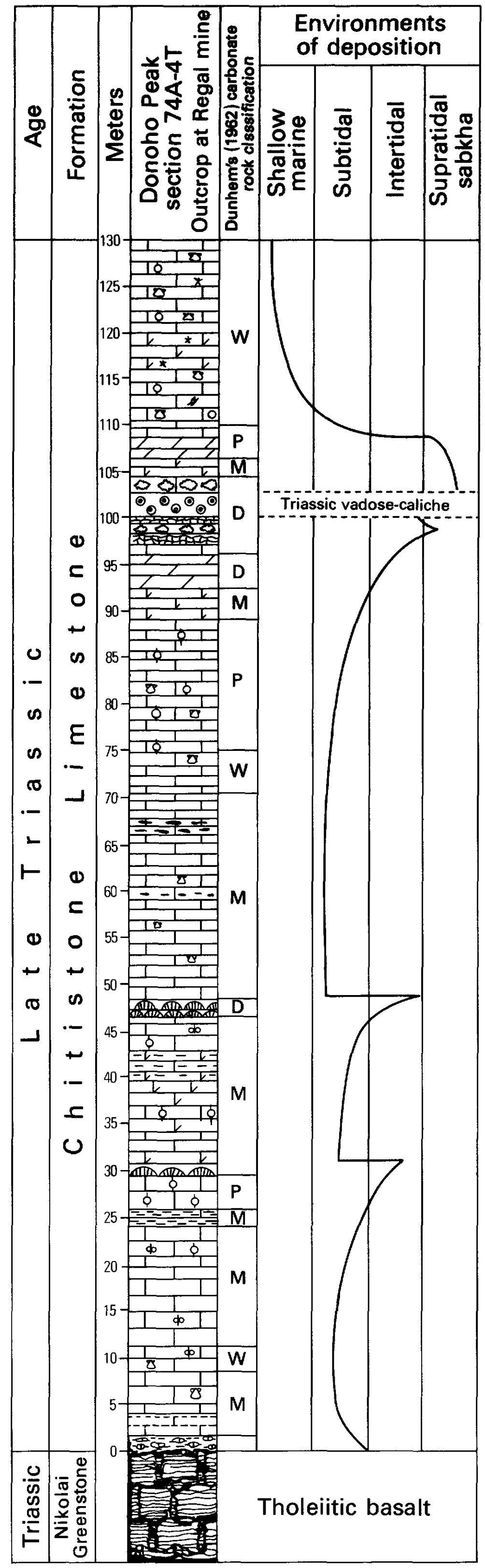


FIGURE 15.—Idealized and interpreted carbonate depositional cycles for lower 130 m of Chitistone Limestone. Model is based on the Donoho Peak outcrop section. Lithologic symbols shown in figure 3.

temporaneous sedimentary dolomite breccia, and possible solution collapse structures. The sabkha facies in the outcrops and underground is overlain by dolomite caliche 0.3 to 1.3 m thick. The caliche is formed by bands of laminated crust, peloids, and pisolites. Similar rocks are found in the Jumbo and Bonanza mines near bases of the ore bodies. This rock type, referred to as the zebra beds, is associated with intertidal to supratidal sedimentary structures and from drill hole data is known to be about 103 m above the Nikolai Greenstone (P. R. Holdsworth, oral commun., 1974). The zebra beds are composed of a matrix of subhedral 50- to 200-μm light-brown-gray dolomite with abundant flat-bottomed, cumulus enterorithic vugs lined with light-gray to white zoned coarse dolomite. Centers of the vugs are partly filled with sparry calcite. The ore bodies at the Mother Lode mine are stratigraphically higher than the other known Kennecott ore bodies. They are associated with sedimentary features similar to those found at 96 to 104 m at the Donoho Peak section, 101 to 104 m at the Green Butte section, and 95 m and also 129 to 135 m at the Nizina River section. The dolomite and sedimentary structures in the Nizina River section are correlated, as shown in figure 3, with the other sections, because they are the final supratidal cycle in this outcrop, contain the best sabkha features and the best developed caliche zone, and are overlain by pelecypod-echinoderm packstone that represents the second major regional marine transgression above the Nikolai Greenstone.

DIAGENETIC HISTORY OF THE CHITISTONE LIMESTONE OF BONANZA RIDGE

The Chitistone Limestone on Bonanza Ridge from west of the Jumbo mine east to McCarthy Creek and in section 74A-2T is extensively dolomitized except for the lower 20-30 m of the section (figs. 3, 8). Outcrop and petrographic studies of the carbonate rocks from Donoho Peak east to the Nizina River suggest the following sequence of events.

1. Deposition of the Chitistone Limestone on the Nikolai Greenstone. Development of a few thin beds of early diagenetic dolomite is associated with the algal mats. The original stratigraphic sequence probably was simlar to the relatively unaltered sections (fig. 10) at Donoho Peak, 74A-4T, and Nizina River, 74A-7T.

2. A late diagenetic stage, possibly low-temperature hydrothermal dolomitization of the entire Chitistone Limestone on Bonanza Ridge, except for the lower 20-30 m. These lower beds may have remained undolomitized owing to the higher clay content of these

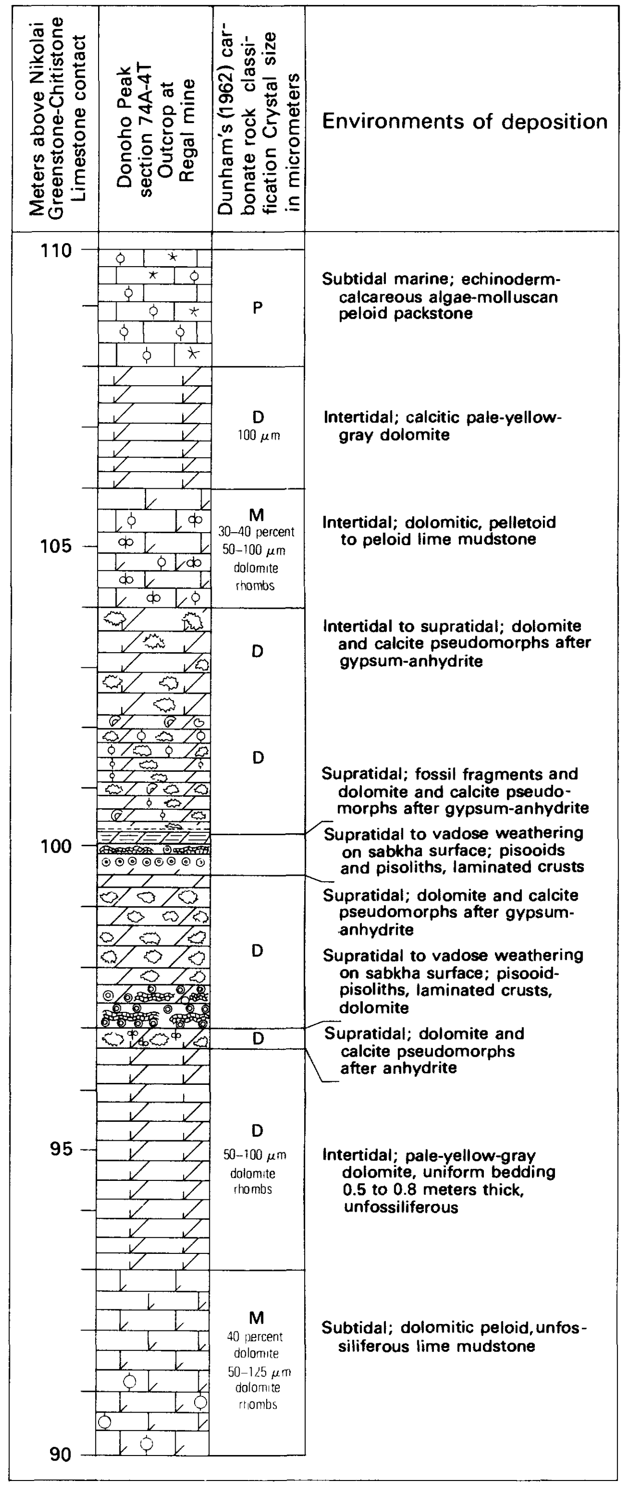


FIGURE 13.—Detailed section and interpretation of environment of deposition of complex carbonate rocks from 90 to 110 m in Donoho Peak section. Facies from 90 to 95 m is restricted platform to intertidal facies number 8 and 9 (see fig. 14). Above 108 m the facies number is 8 to 7, restricted to open platform. Note pisolite caliches at 97 to 97.8 m and 99.7 to 100 m interbedded with supratidal carbonates, facies number 9-10. Lithologic symbols shown in figure 3.

beds relative to the overlying carbonate rocks and their possible lower porosity and permeability to the magnesium-bearing fluids.

3. Tectonic fracturing, possibly in Jurassic and Early Cretaceous time, that resulted in the formation of numerous 10-μm- to 0.5-mm-wide fractures and, in some beds, the formation of angular dolomite breccias.

4. The circulation through the rocks of magnesium-rich fluids, which deposited or lined the larger cavities with 0.4- to 4-mm-zoned dolomite rhombs.

5. The introduction of calcium-carbonate-rich fluids that deposited sparry calcite in the fractures and remaining voids of the breccias and intercrystal spaces in the dolomite. This phase may be responsible for much of the dedolomitization (calcitification) of some of the dolomite.

The Bonanza Ridge outcrops are so altered to dolomite (formed as 0.5- to 2-mm-size rhombs) and so tectonically brecciated that many of the regional marker beds of the Chitistone Limestone are obliterated. These include the first and second laminated beds, which are well developed at Donoho Peak section 74A-4T and Erie mine section 74A-6T. Zebra beds crop out in the upper part of the Glory Hole diggings above the old power plant at the Bonanza mine. The Bonanza mine outcrop ore body was below the zebra beds. The zebra beds are a stratigraphic correlation for Bonanza Ridge outcrop.

The extensive, coarse-grained dolomite associated with the massive copper sulfide ore bodies is believed to reflect a late, probably low-temperature hydrothermal episode. The reasons for this interpretation are:

1. Dolomatization cuts across the stratigraphic section, irrespective of the original fabric or environment of deposition.

2.The dolomite is fairly coarse; rhombs are generally 100 μm or larger.

3. Stratigraphic sections at Donoho Peak and at the Nizina River contain dolomite zones restricted to layers with subtidal to supratidal sedimentary structures. This dolomite probably resulted from early diagenetic processes.

Dedolomitization or calcitification occurs in the rhombs of the fine-grained dolomite matrix and the limpid dolomite of the vugs adjacent to the sparry calcite and sparry calcite vein fillings of the zebra beds (fig. 5*F*). Von Morlot (1848), Evamy (1963, 1967), and Shearman, Khouri, and Tara (1961) showed that magnesium sulfate solution can be involved in the formation of dolomite, according to the equation $2CaCO_3 + Mg^{2+} + SO_4^{2-} \rightleftarrows CaMg(CO_3)_2 + CaSO_4$, and observed that this is a reversible reaction and suggested that gypsiferous solutions could bring about dedolomitization. This dedolomitization can also be caused by meteoric water with high Ca^{2+}/Mg^{2+} ratios. Some thin sections show extensive calcitification of dolomite rhombs adjacent to calcite-filled fractures.

CONCLUSIONS

Three lime-mud upward-shoaling carbonate cycles are present in the lower 135 meters of the Chitistone Limestone. The last cycle is characterized by a dolomitic caliche zone at its top. All of the known copper occurrences in the Chitistone are found within this 135-m interval. The overlying Chitistone Limestone above 135 m was deposited on an open shallow marine platform (Armstrong and others, 1969).

Not all of the factors which formed the large copper sulfide ore bodies are known, and studies are in progress. There appears to be some relation between the sabkha facies, in particular the zebra beds, and caliche and the formation of the massive copper sulfide ore bodies of the Bonanza Ridge. We believe that the regional sabkha facies that developed between 90 and 135 meters above the Nikolai Greenstone originally contained abundant gypsum and anhydrite, but exposure to vadose weathering leached most of the gypsum and anhydrite and developed a vuggy zone interbedded with porous dolomitic caliche. Subsequent marine deposition capped porous zones with an impermeable seal. This porosity served as permeable conduits for the ore-forming solutions.

LOCATION OF MEASURED SECTIONS SHOWN IN FIGURE 3

Donoho Peak, 74A-4T; outcrop at Regal mine; base of section is 50 m east of Regal mine, SE 1/4NW 1/4 sec. 1, T. 4 S., R. 13 E.

Erie mine, 74A-6T; outcrop 2 km west of Erie mine, SW 1/4 sec. 4, T.4 S., R. 14 E.

Jumbo mine, center sec. 15, T. 4 S., R. 14 E.

Bonanza mine outcrop, 74A-2T; 2 km east of Bonanza mine, SE 1/4 sec. 15, T. 4 S., R. 14 E.

Green Butte, 74A-3T; 25 m north of Green Butte mine, NE 1/4SW 1/4 sec. 30, T. 4 S., R. 15 E.

Nizina River, 74A-7T; SW 1/4 NE 1/4 sec. 36, T. 4 S., R. 15 E.

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