DIAGENESIS, GEOCHEMISTRY, AND ORIGIN OF A PRECAMBRIAN DOLOMITE: THE BECK SPRING DOLOMITE OF EASTERN CALIFORNIA[1]

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ABSTRACT: The Beck Spring Dolomite is a middle to late Proterozoic formation exposed in the Death Valley region of eastern California. It is a platform carbonate sequence dominated by cryptalgal laminites with some stromatolites and grainstones and is inferred to have been deposited in shallow subtidal to intertidal environments. Original fabrics are well preserved in the Beck Spring Dolomite, in contrast to many Phanerozoic dolomites. The diagenetic pattern is similar to that of many shallow-water limestones: early fibrous cements (dolomite) are followed by later sparry cements (also dolomite), and several phases of internal sedimentation are evident. Cavity structures, where the cements occur, include birdseyes, laminoid fenestrae, stromatactis, sheet cracks, and neptunian dikes.

Four types of synsedimentary-early diagnetic fibrous dolomite are distinguished; they show features comparable to those of fibrous calcite, together with some new fabrics. Type A forms isopachous fringes consisting of length-slow acicular to columnar pseudopleochroic crystals with fine, substrate-parallel color banding. The dolomite is mostly nonluminescent with some bright blotches, and inclusion trains define acicular crystallites within the columnar crystals. Type B consists of length-slow columnar crystals with distinctive bladed relic structures, defined by inclusions and nonluminescence, surrounded by inclusion-free and brightly luminescent dolomite. Type C consists of bladed to wedge-shaped pseudopleochroic crystals with undulose extinction (mostly fascicular optic); inclusion trains define acicular crystallites within crystals. Type C commonly forms mammillated crusts and botryoids. Type D fibrous dolomite forms thin layers of acicular crystals, with a distinctive geometry of the cement layers thickening into the corners of cavities. Fibrous carbonates frequently are interpreted as replacements, and types B and C contain relic structures indicating such an origin, but types A and D have fabrics which could be primary.

The later diagenetic dolomite spar has all the features of a direct precipitate: increase in crystal size cavity-ward and delicate growth zonation and terminations (revealed by cathodoluminescence). However, truncation surfaces indicate phases of dissolution-reprecipitation, and silts within the spar mosaic represent internal sedimentation of crystal fragments.

The depositional components (pisolites and micrite) and some fibrous dolomites have oxygen isotopic values around $-2‰$ versus PDB, compatible with a marine origin. However, Na (around 220 ppm) and Sr (around 65 ppm) contents are very low, suggesting precipitation from dilute waters. Taking a uniformitarian approach that early dolomite is always a replacement, the geochemical data are best interpreted in terms of meteoric-marine mixing-zone dolomitization of $CaCO_3$ sediments and early cements. An alternative, however, is primary marine precipitation of poorly ordered calcian dolomite and early diagenetic stabilization to stoichiometric dolomite. The dolomite spar has very negative values of $\delta^{18}O$ ($-9.6‰$ versus PDB) and is more depleted in Na (34 ppm) and Sr (47 ppm), reflecting precipitation from meteoric waters of very low ionic strength during burial diagenesis.

A replacement origin for the dolomite of the depositional components and fibrous cements can be reconciled with the lack of obliterative replacement fabrics by invoking an original high-Mg calcite mineralogy.

This study, demonstrating that Precambrian dolomites can be treated in the same way as Phanerozoic limestones, shows that both possess similar petrographic, trace element, and stable isotope characteristics. However, in this Precambrian formation, the principal diagenetic mineral is dolomite, whereas in most Phanerozoic carbonate formations it is low-Mg calcite.

INTRODUCTION

Carbonate rocks are an important component of many Proterozoic sequences, but little attention has been given to their diagenesis and geochemistry. One particular problem of Proterozoic carbonates is that many are composed of dolomite. The conditions of formation of dolomite are still unresolved. Dolomite does not precipitate from modern seawater, which is supersaturated with respect to dolomite, be-

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cause of kinetic factors, and it has not been synthesized in the laboratory at surface conditions. Although many claims of primary dolomite have been made, the widely held view now is that most dolostones are of replacement origin.

This paper is principally concerned with the diagenesis and geochemistry of the Proterozoic Beck Spring Dolomite in eastern California. A brief account (Tucker, 1982) noted that this dolomite formation is comparable to Phanerozoic limestones in terms of structures, fabrics, and stable isotope geochemistry, and a case was made for Precambrian dolomites being different from Phanerozoic dolomites, where obliterative replacement fabrics are characteristic. Apart from the excellent preservation of the sedimentary structures and fabrics of the depositional components, a feature of the Beck Spring Dolomite emphasized in this paper is the development of fibrous dolomite as the first cement generation. Several types can be recognized, some with replacement fabrics and others with fabrics that could be primary. The cements have been studied by cathodoluminescence, and both stable isotopes and trace elements of the depositional components and cements have been determined.

Although from isotope and fabric data, Tucker (1982) suggested a marine, primary origin for the dolomite of the Beck Spring sediment and some early cements, trace element data (Sr and Na) are best interpreted in terms of an early diagenetic origin for this dolomite. However, the nature of the original precipitates is still a matter of discussion; either they were composed of $CaCO_3$ and then dolomitized, the most likely taking a uniformitarian approach, or they were composed of poorly ordered calcian dolomite that stabilized to stoichiometric dolomite during early diagenesis.

STRATIGRAPHY AND LOCATION

The Beck Spring Dolomite is a formation within the Pahrump Group of mid-late Proterozoic age of eastern California (Fig. 1) (Wright et al., 1976). It is underlain by the Crystal Springs Formation, a mixed siliciclastic-carbonate sequence that rests on a granite-gneiss basement. Above the Beck Spring Dolomite is the Kingston Peak Formation, and this contains beds of probable glacial origin in the upper part. Overlying the Pahrump Group with slight angular unconformity is the Noonday Dolomite, the lowest formation in a conformable Late Precambrian to Cambrian sequence. An age of 1200–1400 Ma has been assigned to the Beck Spring Dolomite (Licari, 1978).

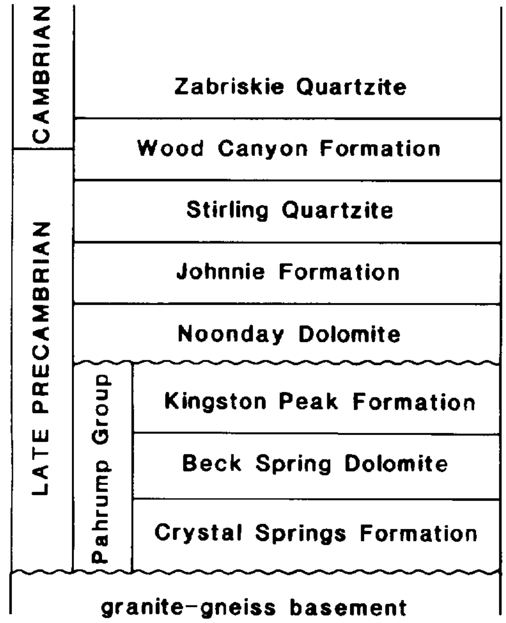


FIG. 1.—Late Precambrian-Cambrian stratigraphy of the Death Valley region, eastern California (after Wright et al., 1976).

The Beck Spring Dolomite is exposed in the Death Valley region of eastern California (Fig. 2). Particularly good exposures occur in the Alexander Hills at the southern end of the Nopah range (about 15 km east of Tecopa Hot Springs) and in the Kingston Range a little farther to the east. Sequences were studied in detail in the dry valleys to the east of the Western Talc Mine on the western side of the Alexander Hills and to the east and southeast of Horse Thief Springs in the Kingston Range. Other outcrops are located in the Saratoga Hills, Silurian Hills, and Black Mountains, and in the Panamint Mountains on the western side of Death Valley.

FACIES AND ENVIRONMENTS

The Beck Spring Dolomite of the Alexander Hills and Kingston Range is a typical Precambrian platform carbonate sequence about 300 m thick. The formation consists of thin to thick

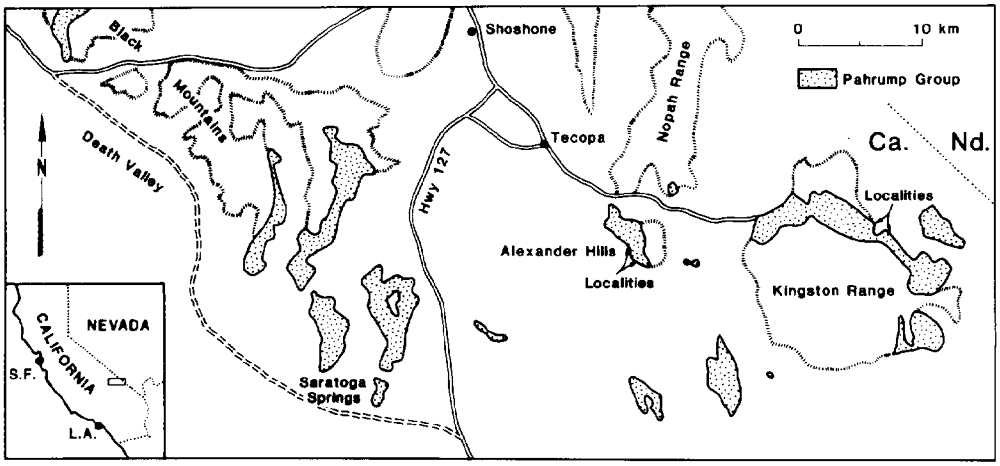


FIG. 2.—Map showing location of exposures of the Pahrump Group in eastern California and localities mentioned in text.

bedded dolostones of various facies with no major stromatolite buildups. Four informal members have been recognized by Gutstadt (1968) and Marian and Osborne (1980): lower cherty member, lower laminated member, oolitic-pisolitic member and upper cherty member. The principal lithofacies are cryptalgal laminites, intraformational breccias (flakestones), stromatolites, and grainstones.

Planar cryptalgal laminites make up nearly 70% of the Beck Spring Dolomite. For the most part, the lamination is continuous and regular, forming units several meters thick. Locally, however, the lamination is disrupted and fragmented, or linked domes are developed. The lamination is typically an alternation of dense and less dense clotted micrite (dolomite) with laminoid fenestrae (next section). Calcified algal filaments are present within these laminae. Layers of intraformational breccia composed of clasts of cryptalgal laminite are typically several to several tens of centimeters thick, show imbrication of clasts, and have sharp, erosive bases. Columnar, bulbous, and digitate stromatolites occur in several distinct units but especially in the upper cherty member where columnar forms show branching, are overturned and eroded, and show regrowth and coalescence. Grainstones occur in the higher parts of the Beck Spring Dolomite and consist of catagraphs (calcified algal grains), ooids, and pisolites. Interpretations of the lithofacies (Gutstadt, 1968; Marian and Osborne, 1980) suggest that the Beck Spring Dolomite was deposited mainly in shallow subtidal to intertidal environments on a stable platform. The planar cryptalgal laminites probably accumulated on broad tidal flats and in adjacent subtidal areas as a result of sediment trapping, binding, and precipitating activities of blue green algae. The intraformational breccias formed through desiccation or penecontemporaneous erosion of algal mats and were deposited by tidal-channel and storm processes. Grainstones were very likely formed and deposited in more agitated shoal areas, and some of the columnar and domal stromatolites probably grew in these higher energy, shallow, subtidal–low-intertidal environments. Periods of subaerial exposure are indicated by abundant clasts of cryptalgal laminite (which could reflect desiccation in high-intertidal–supratidal zones), some cements of a vadose-marine origin (see later section), and cavities of a possible karstic origin. Evaporite pseudomorphs are rare (Marian and Osborne, 1980).

CAVITY STRUCTURES

Cavity structures are common throughout the Beck Spring Dolomite of the Alexander Hills and Kingston Range. Most are of synsedimentary or early diagenetic origin, and many different types can be distinguished. It is within these cavities that fibrous dolomite is particularly well developed.

Irregular to equant fenestrae are common in the grainstones composed of catagraphs and are directly comparable to the birdseyes of Phanerozoic tidal-flat limestones. These fenestrae, up to several millimeters across and squarish, circular, or irregular in cross section, are filled with fibrous and sparry dolomite and in some cases with internal sediment. These fenestrae probably formed in the same way as birdseye structures, through gas entrapment and desiccation of sediments on an intermittently exposed tidal flat. Laminoid fenestrae are common in the cryptalgal laminites. Typically several centimeters long and several millimeters high, they are generally filled with cement only. Slight desiccation of algal-laminated sediments is the likely cause of these cavities. At some horizons, laminoid fenestrae connect with vertical fractures to give a brick-wall pattern to the rocks. Disruption and brecciation of some cryptalgal beds has given rise to tepee structures, and the associated laminoid cavities commonly are filled with much internal sediment, which was deposited after growth of an initial layer of isopachous fibrous dolomite.

The grainstones and micritic dolomites contain civities of the stromatactis type. These have an irregular, ragged roof, a smooth floor of internal sediment, and a cement filling of fibrous followed by sparry dolomite (Fig. 3). These cavities are several centimeters long and 1 centimeter high on average, and they generally occur in clusters. These cavities probably formed as a result of local cementation of the sediment to form thin crusts, followed by the winnowing of uncemented sediment from below the crusts to leave cavities, a mechanism similar to that proposed by Bathurst (1982) for the 'classic' stromatactis of Paleozoic limestones.

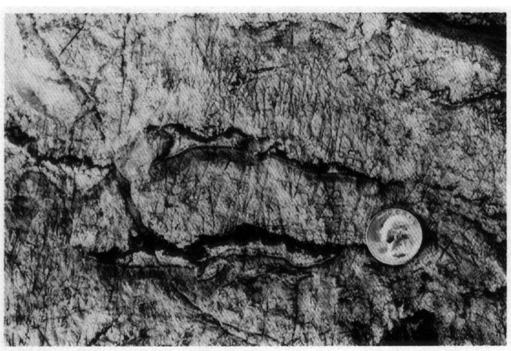


FIG. 3.—Stromatactis cavities with dark internal sediment, first-generation fibrous dolomite (black) and second generation dolomite spar (white). Beck Spring Dolomite, Kingston Range, California.

Irregular vertical to subvertical cavities several centimeters wide and up to several tens of centimeters long occur at various levels in the Beck Spring Dolomite. These cavities have sharp walls, but most are irregular, with embayments and side branches. A few are straight-sided, dikelike in character, and clearly truncate sedimentary lamination. Some cavities are lined by a dark fibrous dolomite layer, but perhaps the most distinctive feature, apart from the neptunian dikelike character, is the calcisiltite fill. The origin of these cavities is unclear, but they probably formed in several ways. In some cases the cavities appear to be products of solution and are reminiscent of karstic phenomena. In others, however, initial isopachous fibrous cements suggest marine-phreatic precipitation as the first event after cavity formation. Dikelike cavities filled with calcisiltite appear to have formed relatively late, as a result of fracturing of the sediment.

DIAGENESIS

As will emerge, the style of diagenesis in the Beck Spring Dolomite is very similar to that of Phanerozoic limestones, but the mineralogy is different. Fibrous dolomite is the first-generation cement, coating pisolites and catagraphs in grainstone beds and algal-laminite clasts in intraformational conglomerates, and lining synsedimentary and early diagenetic cavities. Remaining voids between grains and within cavities are filled with dolomite spar. Internal sediments are also common.

Terminology in this paper follows that of Kendall and Broughton (1978): *fibrous* refers to a carbonate mosaic of acicular or columnar crystals. The latter are both markedly elongate with acicular crystals being needlelike and less than 10-μm wide, and columnar crystals more than 10-μm wide and a length-width ratio in excess of 6:1.

Four varieties of fibrous dolomite are distinguished: types A, B, C, and D (Table 1 and Fig. 4). These possess many carbonate fabrics not previously described.

Type A Fibrous Dolomite

This fibrous dolomite forms isopachous layers up to 1 mm thick, and where succeeded by

TABLE 1.—*Principal types of fibrous dolomite in the Beck Spring Formation, along with their characteristic features and origin of fabrics (also see Fig. 4)*

Fibrous dolomite	Occurrence	Crystal form	Extinction	Inclusion patterns	Cathodo-luminescence	Origin of fabrics
Type A	isopachous fringes up to 1 mm thick	acicular to columnar; planar growth surface	uniform	substrate-parallel growth banding, substrate-normal inclusion-defined crystallites	mostly non-luminescent	primary or crystallite coalescence
Type B	isopachous fringes up to 2 mm thick	columnar, with rhombohedral terminations	uniform	inclusion-defined crystallites, random, and elongate, bladed, triangular shapes	non-luminescent relic structures surrounded by red luminescence	complex replacement involving crystallite precursors
Type B_2	isopachous, syntaxial on type A	as B	uniform	as type B	non-luminescent triangular areas	primary
Type C	isopachous fringes to discrete botryoids	acicular, columnar & wedge-shaped crystals, smooth growth surface	undulose, mainly fascicular optic	as type A	dull or nonluminescent	crystallite coalescence
Type D	isopachous fringes thickening into cavity corners	acicular	uniform	as type A	dull or non-luminescent	primary or crystallite coalescence

internal sediment, the junction is a planar surface (Fig. 5). Elsewhere, type A fibrous dolomite is succeeded (syntaxially) by fibrous dolomite of type B_2, discussed later. Crystals of the type A fibrous dolomite are mostly acicular to columnar (widths 5–50 μm) and generally are oriented normal to the cavity wall, including the finer crystals within the well-developed marginal zone. Type A fibrous crystals are length-slow; that is, the C-axes or optic axes of each crystal are confined to a plane

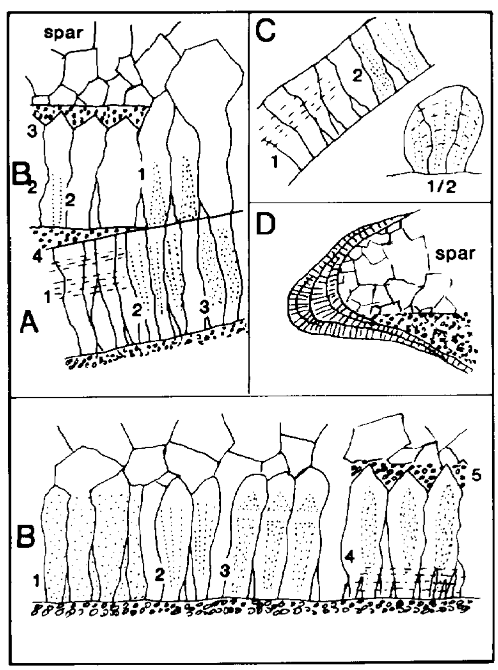


FIG. 4.—Sketches showing the principal features of the various types of fibrous dolomite. Type A has 1) a substrate-parallel growth banding, 2) inclusion trains, or 3) evenly distributed inclusions, and 4) a planar surface where overlain by internal sediment. Type B shows various inclusion patterns: 1) even distribution, 2) inclusions arranged in trains, inclusion-defined wedges and blades, inclusion-free zones adjacent to crystal boundaries, 3) clear, substrate-parallel zone and then inclusion-defined terminations, or 4) a marginal zone of fine, substrate-parallel color banding giving way to inclusion-defined blades, and 5) terminations on columnar crystals where overlain by internal sediment. Type B_2 occurs syntaxially on type A and shows 1) inclusion-defined scalenohedral terminations, or rarely, 2) inclusion trains, and 3) terminations on columnar crystals where overlain by internal sediment. Type C forms isopachous fringes and botryoids with 1) substrate-parallel growth banding, and 2) inclusion trains. Type D, of acicular crystals, has an uneven geometry of layers thickening into cavity corners.

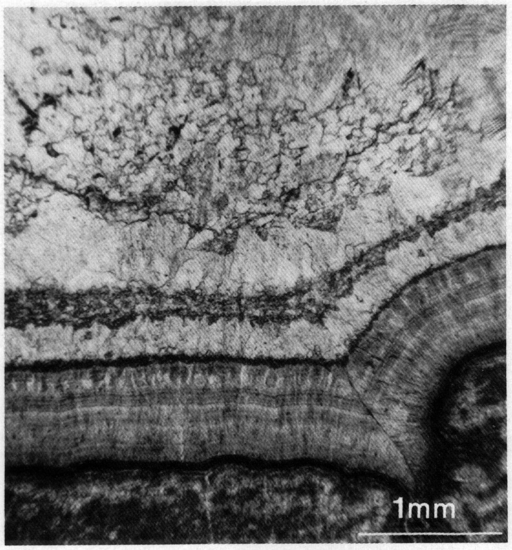


FIG. 5.—Type A fibrous dolomite coating lithoclasts, overlain by a thin layer of internal sediment, then type B_2 fibrous dolomite and a thicker layer of internal sediment before dolomite spar. Note the sharply defined line within the type A fibrous layer, where growing cement crystals came into mutual contact in the corner of the cavity. Cathodoluminescence shows that the patch of smaller crystals within the dolomite spar is a lens of crystal fragments; these represent an internal sediment washed in during a pause in sparry dolomite precipitation.

parallel to the substrate. The prominence of intercrystalline boundaries as a result of relief differences between adjacent crystals shows that the C-axes have no preferred orientation within a plane parallel to the substrate (checked with the universal stage). The crystals mostly show unit extinction. One distinctive feature of type A fibrous dolomite is a sharply defined line (a smooth surface in three dimensions) where two fibrous layers came into contact during growth. This feature is particularly well seen in the corners of cavities where the fibrous dolomite from adjacent cavity walls has met along a straight line bisecting the corner (Fig. 5).

The substrate-parallel laminae, 2 to 20 μm thick, are accentuated by color changes from light to dark shades of brown, and by zones of differing inclusion density. The color banding gives rise to a pseudopleochroism of the scheme: ω = brown, Σ = colorless. The color banding probably results from slight variations in organic matter, as has been suggested elsewhere for the brown color of fibrous calcite (Kendall and Tucker, 1973; Lindholm, 1974; Marshall, 1981) and neomorphosed bivalve shells (Hudson, 1962).

Also within type A fibrous dolomite are numerous dark micron-sized inclusions, ranging from 1 to 5 μm. There is no suggestion that these are inclusions of mineral matter, like the microdolomites that occasionally occur in fibrous calcite (Lohmann and Meyers, 1977). Vapor bubbles have not been observed; so, the inclusions could be single-phase fluid inclusions. Examination of fracture surfaces with the SEM shows numerous holes, often of a negative crystal character with a rhombic shape (Fig. 6A). The faces of most rhombs are parallel to equivalent faces of the other rhombs nearby. A few holes are more irregular: some are elongate, other negative rhombs connect with narrow, blind "corridors." Relics of mineral matter were not seen in any of the negative rhombs.

The dark inclusions commonly define the substrate-parallel laminae, but elsewhere, inclusions are randomly distributed, or concentrated within individual fibrous crystals with inclusion-free areas adjacent to and along intercrystalline boundaries. Towards the outer part of this fibrous fringe, inclusion-free patches are more equant. Of particular interest are linear trains of inclusions, which are arranged normal or subnormal to the substrate (Fig. 6B). The inclusions define parallel-sided clear zones around 5 μm wide and 100–200 μm long. These inclusion-defined "needles" occur in groups or bundles, either all parallel, or with a slight fanning. Each bundle occurs within a single fibrous crystal. This inclusion pattern could indicate an acicular crystallite precursor to the fibrous dolomite (discussed further later).

When type A fibrous dolomite is viewed under cathodoluminescence, it is mostly nonluminescent (Fig. 7). However, red luminescent streaks occur along some crystal boundaries and substrate-parallel growth zones, and equant to irregular patches of bright red luminescence also occur.

Type B Fibrous Dolomite

This variety of fibrous dolomite forms isopachous layers up to 2 mm thick within cavities and around grains. Where developed on a flat substrate, type B fibrous crystals are mostly columnar, with widths up to 150 μm. Type B

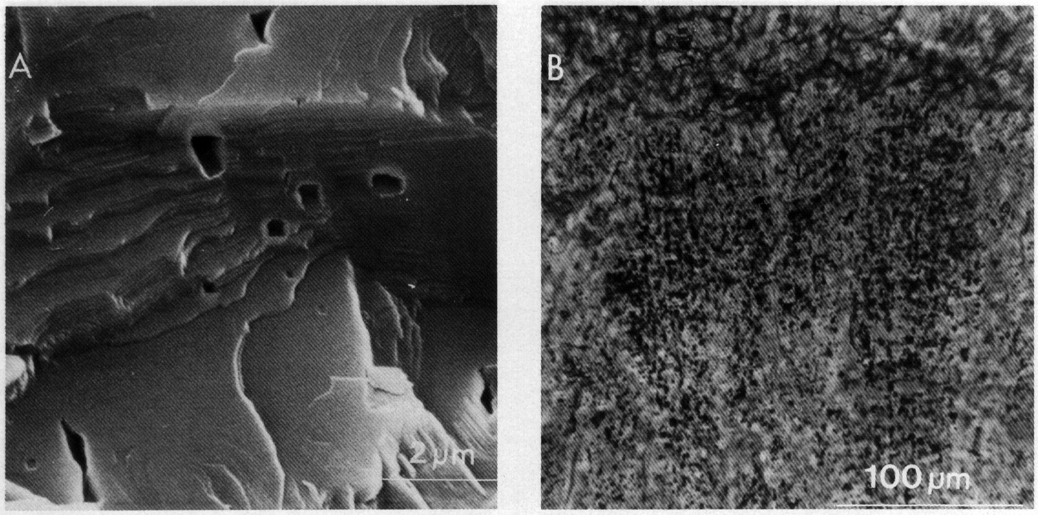


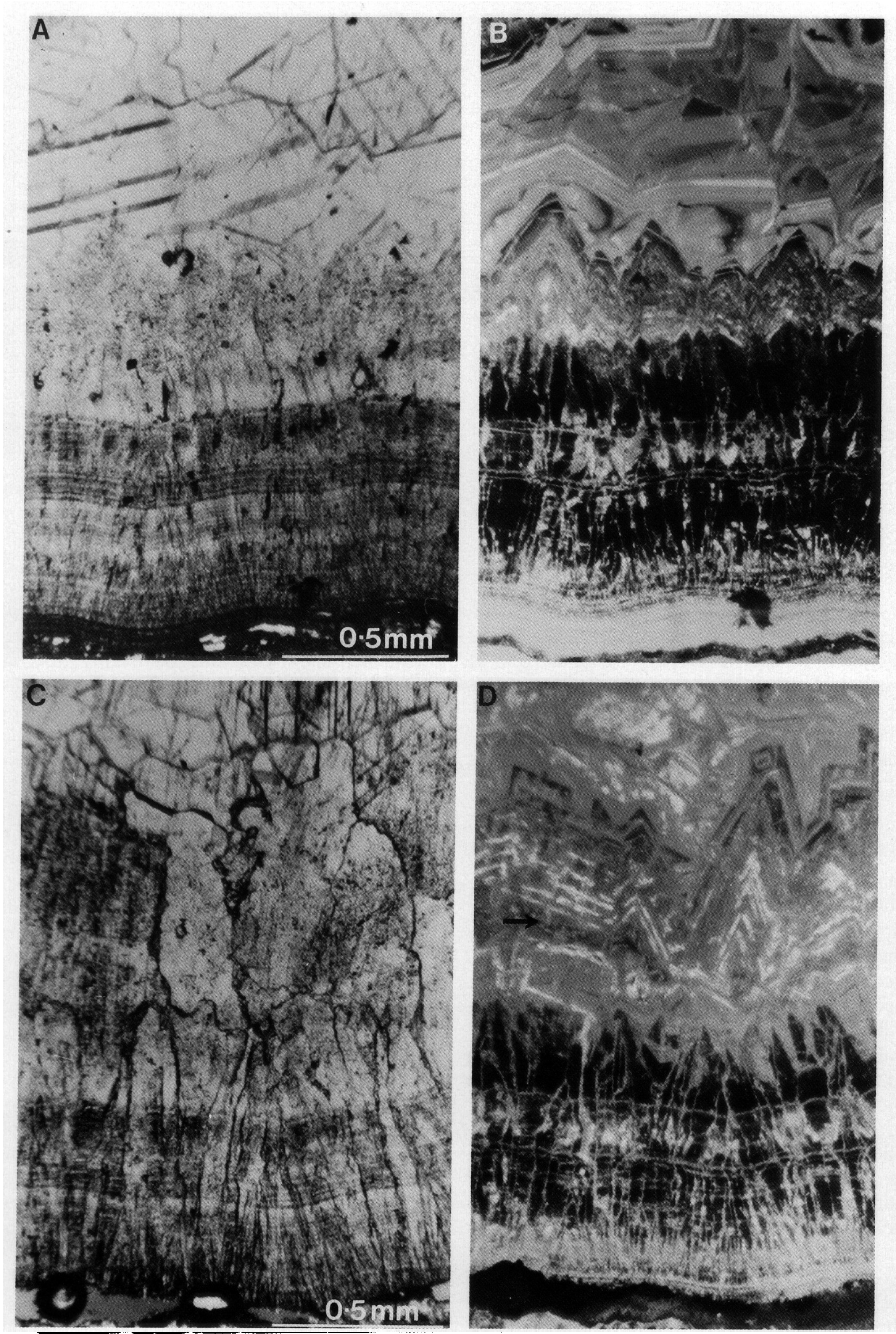
FIG. 6.—Inclusions in type A fibrous dolomite. A is a fracture surface under SEM showing holes, mostly of a negative crystal character, though some are less regular. B shows dark inclusions (the holes in SEM) arranged in trains normal to substrate. Such patterns could indicate an acicular precursor to the columnar crystals.

crystals are length-slow and all c-axes are in a plane parallel to the substrate. Close to the substrate, a well-developed marginal zone of smaller elongate crystals may exhibit a range of orientations. Where the substrate is non-planar, fans of columnar crystals with wedge shapes are commonly developed on convex parts of the substrate. Cleavage and twin planes are not common in this fibrous dolomite and extinction is mostly uniform.

Rhombohedral faces terminate the outer margin of type B fibrous dolomite. They are best seen where internal sediment overlies the fibrous layer. Where fibrous layers meet, as in the corners of cavities, the boundary tends to be slightly irregular with a zig-zag appearance because of the juxtaposition of crystal terminations upon columnar crystals.

Dark micron-sized inclusions are common in type B fibrous dolomite and are identical to those of type A fibrous dolomite. In some fibrous dolomite type B layers, a substrate-parallel growth layering in the innermost part is defined by both dark inclusions and color banding (Figs. 4, 8). The inclusions locally define a substrate-normal linear pattern, which could represent the former position of needle-like crystallites (as in type A fibrous dolomite). Within the columnar crystals that follow the marginal laminated zone or comprise the whole fibrous layer if a marginal zone is not developed, dark micron-sized inclusions are abundant. The latter may be evenly distributed, but more commonly they define substrate-normal/subnormal elongate zones separating inclusion-free areas (Figs. 4, 8). The inclusion-rich zones range in shape from elongate triangles, flaring up from the substrate, to narrow blades tapering towards the cavity center. The inclusion-defined zones occur within single columnar crystals, with clear areas forming the marginal parts of these crystals. Rarely within some of the triangular-shaped, inclusion-rich areas, trains of inclusions define relic needle-like crystallites oriented normal-subnormal to the substrate. In the outer-most part of the fibrous layer, the inclusions define a zone of crystal terminations.

Under cathodoluminescence, the laminated innermost zone, if present, is nonluminescent, like type A fibrous dolomite. The main part of the type B fibrous dolomite layer also may be nonluminescent, but more commonly it has discrete nonluminescent areas with dull red to bright red luminescing dolomite between (Figs. 9A, B, C). The dark areas have distinct elongate, triangular, and bladed shapes, vertically or subvertically arranged relative to the substrate, which coincide with the inclusion-defined areas noted above. Boundaries of the


A
B
0·5mm
C
D
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nonluminescent areas tend to be sharp, but some junctions with the adjacent luminescent dolomite are ragged and embayed. In some cases, a faint nonluminescent chevron pattern directed towards the cavity center occurs on both sides of the nonluminescent blades. Dolomite in the outer part of the fibrous layer, where terminations are developed, typically is nonluminescent. Where the fibrous dolomite is seen in transverse or oblique section, the nonluminescent areas are triangular or diamond-shaped (Fig. 9D).

Closely related to type B fibrous dolomite is the fibrous dolomite which is syntaxial upon type A fibrous dolomite, here designated type B_2. It consists of colorless columnar crystals and contains few inclusions (Fig. 7). Some of the latter form elongate zones within crystals, with inclusion-free dolomite adjacent. Where type B fibrous dolomite overlies internal sediment (Fig. 5), it consists of columnar crystals mostly normal to substrate. Many crystals extend all the way across the fibrous layer, and where overlain by internal sediment, obtuse rhombohedral terminations are present.

Under cathodoluminescence, nonluminescent shapes occur in the type B_2 columnar crystals (Fig. 7). Where such crystals directly overlie type A fibrous dolomite, the nonluminescent shapes can be traced back into the earlier type A crystals. Many nonluminescent areas have shapes which define acute (scalenohedral) terminations. Obtuse rhombohedral terminations on the outer part of this fibrous dolomite layer and within some of the earlier growth stages show various shades of red luminescence.

FIG. 8.—Type B fibrous dolomite showing well developed color banding close to substrate, then columnar crystals within which inclusion-defined blades occur. Dolomite spar succeeds the columnar crystals.

Type C Fibrous Dolomite

This fibrous dolomite forms thin isopachous crusts, up to 200 μm thick, but fans and botryoids are especially well developed on substrate convexities (Fig. 10A). In some cases, isolated spherulitic structures occur, reaching 1 mm in diameter (Fig. 10B). The dolomite is brown and pseudopleochroic but generally contains substrate-parallel clear zones. Dark micron-sized inclusions commonly define a substrate-parallel growth layering and, in places,

FIG. 7.—Transmitted (p.p.l.) and cathodoluminescence photomicrographs of type A fibrous dolomite, succeeded by type B_2 fibrous dolomite and then sparry dolomite. In A, the marginal spar crystals show inclusion-defined terminations. B, the CL equivalent of 6A, shows the predominantly nonluminescent character of the type A fibrous dolomite, but with irregular patches of bright luminescence. The type B_2 fibrous dolomite is largely nonluminescent in bladed shapes that can be traced back into crystals of the type A layer. The sparry dolomite shows well defined growth zones, but in detail the marginal part displays a blotchiness which may represent some later dissolution-reprecipitation. C shows features similar to A but in its CL equivalent; D, brightly luminescent (yellow) growth zones in the marginal spar are seen to be discontinuous, and a fracture cutting the type A layer is filled with a similar luminescing dolomite. Of note is the elongate patch (arrowed) within the marginal spar (its outline is a type B truncation surface) of dull and dark luminescing dolomite. This is interpreted as a solution cavity which was occluded during a later phase of spar precipitation (spar of similar luminescence forms a later growth zone, towards the top of the photomicrograph).

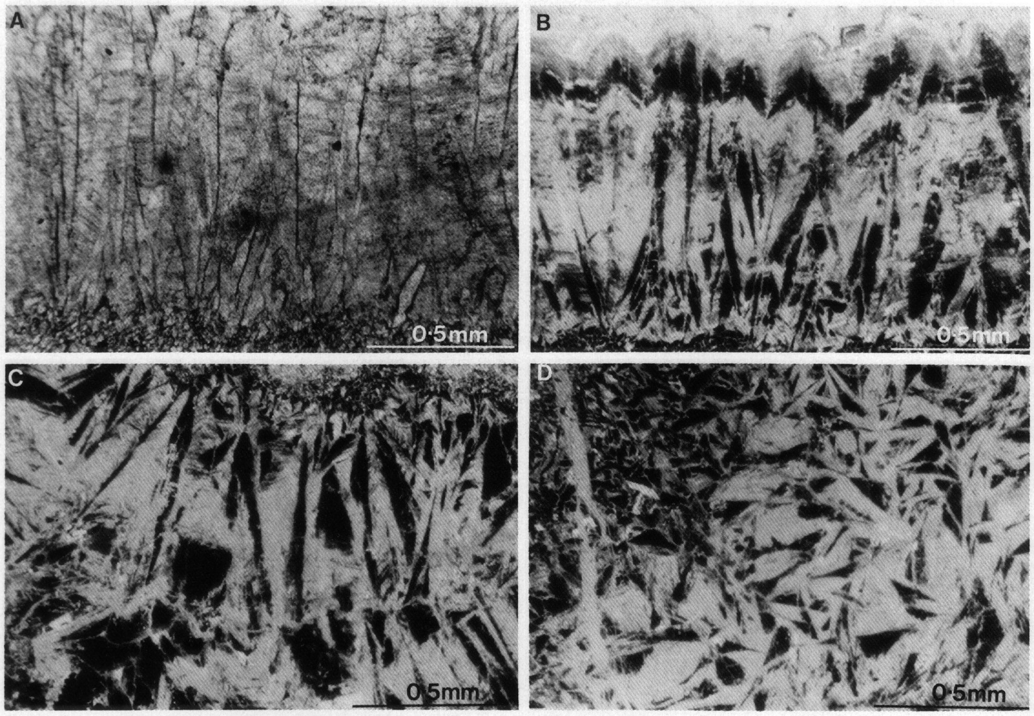

FIG. 9.—Type B fibrous dolomite. In A, the nature of the crystals is well seen, in addition to some twin planes. B occupies the same area under CL, showing the nonluminescent blades within columnar crystals, the brightly luminescent adjacent areas, and the nonluminescent terminations towards the margin of the fibrous fringe. C shows the nonluminescent relic structures within a type B mosaic. The field is dominated by crystals growing down from a cavity roof; the lower part is occupied by the distal ends of crystals which grew up from the cavity floor. D is an oblique to transverse section across type B fibrous dolomite showing the nonluminescent triangular shapes which occur within columnar crystals surrounded by bright luminescent (red) dolomite.

a linear, normal-to-substrate pattern, suggesting the former existence of needlelike crystallites.

Most type C crystals are broad and wedge-shaped, with single crystals occupying the entire width of the fibrous layer. Undulose extinction is a distinctive feature, with the most common type being a fascicular-optic arrangement (divergent optic axes). Radiaxial crystals (convergent optic axes) and crystals with oblique unit extinction are less common. Most crystals are length-slow, but in some cases they are length-fast. Cathodoluminescence does not reveal any additional fabric information; these fibrous crystals show a uniform dull red luminescence or are nonluminescent.

Type D Fibrous Dolomite

This fibrous dolomite is pale brownish yellow, but not conspicuously pseudopleochroic. It forms thin crusts, 50–200 μm thick, of acicular crystals (Fig. 11A). An incremental growth layering is developed in some of these fibrous fringes. A distinctive feature of this fibrous dolomite is the geometry of its layers: apart from isopachous crusts, the layers characteristically thicken into the nooks and crannies of larger cavities (Fig. 11B). In some cases, certain layers are only developed in such embayments or concavities of the substrate. In one instance, where this type D fibrous dolomite is well developed, a small cavity has been filled by isopachous layers which can be correlated with impersistent layers of the same dolomite in a nearby subcavity extending from a larger void.

INTERPRETATION OF FIBROUS DOLOMITES

The fibrous dolomites of the Beck Spring Dolomite have much in common with the fi-

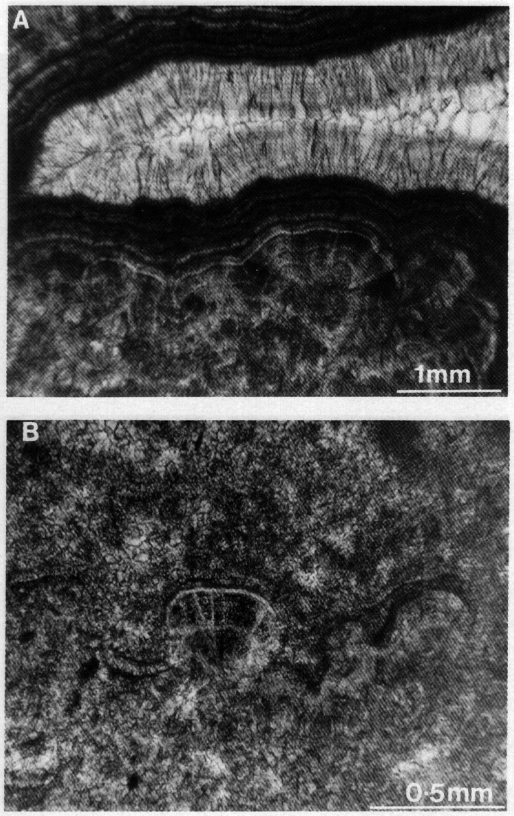

FIG. 10.—Type C fibrous dolomite. In A, the type C fibrous dolomite (darker) is overlain by type A fibrous dolomite (lighter with fine substrate-parallel growth layering). Type C here consists of crystal fans with undulose extinction. B shows an isolated fibrous botryoid of fascicular-optic dolomite overlain by micritic internal sediment. Dark inclusions define a concentric and radial pattern within the wedge-shaped crystals.

brous calcites of Phanerozoic limestones. The latter are characterized by columnar crystals, undulose extinction, cloudiness due to minute inclusions, noncompetitive growth fabrics, and close association with internal sediments (Kendall and Tucker, 1973; Bathurst, 1975; Lohmann and Meyers, 1977; Mazzullo, 1980; and others). Fibrous calcites are now considered to be replacements of synsedimentary or early diagenetic acicular cements, precipitated in marine environments. Two mechanisms have been put forward for the replacement of acicular carbonate by fibrous calcite. In discussing radiaxial fibrous calcite, Kendall and Tucker (1973) proposed a solution-precipitation process involving the migration of a fluid film from the substrate through the acicular precursor cement. This replacement front dissolved the original cement on one side and precipitated the fibrous calcite behind. They suggested that the original cement consisted of interfering bundles of acicular crystals and that preferential replacement between bundles resulted in the generation of the convergent optic axes and the curved twin planes that are characteristic of radiaxial fibrous calcite. An alternative mechanism for the formation of some fibrous calcites involves diagenetic coalescence of crystallites (Kendall, 1977). Kendall introduced the term *fascicular-optic calcite* for fibrous calcite with divergent optic axes, produced by the coalescence of fanning acicular cement bundles or splays. The former existence of acicular crystals is shown by micron-sized inclusions defining needlelike shapes within the fibrous calcite crystals. Fluid films would also have been involved in this process of crystallite coalescence. Fabrics somewhat similar to those of fibrous calcite in marine limestones occur in speleothems (Kendall and Broughton, 1978, Braithwaite, 1979), but these are the product of more complex growth processes. The speleothem growth surface consists of numerous crystallites precipitated as syntaxial overgrowths which coalesce immediately behind the surface to generate large columnar calcite crystals with fabrics of a neomorphic character.

Crystals of the fibrous dolomites in the Beck Spring Dolomite, at least types A, B, and C, possess features, summarized in Table 1 and Fig. 4, which suggest a neomorphic origin. However, a primary origin must also be considered for the fabrics of types A, B_2, and D. Discussion of the original mineralogy of the fibrous dolomites is deferred until a later section of this paper, but all fabrics should not be assumed neomorphic simply because the mineralogy is dolomite, which normally is replacive. Regardless of origin, the mode of occurrence of the fibrous dolomite, lining cavities and coating grains, clearly demonstrates that it (or its precursor) was a synsedimentary or early diagenetic cement.

Type A Fibrous Dolomite.—On a number of fabric criteria, type A fibrous dolomite would be interpreted as a replacement of an acicular precursor, but before pursuing this, the possibility of a primary origin must be considered. Several fabrics of type A fibrous dolomite, the

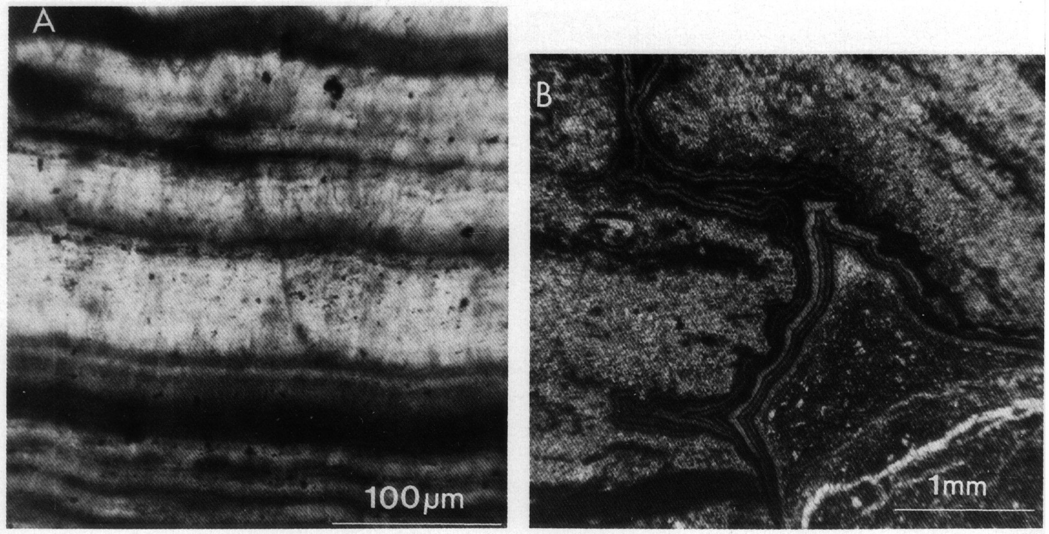

FIG. 11.—Type D fibrous dolomite. A shows the numerous thin layers of barely discernible acicular crystals. B shows the distinctive geometry of this dolomite type with layers thickening into the corners of a cavity (the latter occurring between intraclasts), whereas in the small subcavities, layers are isopachous. The cavity is mainly occluded by internal sediment, lower right, and a small area of dolomite spar (white).

columnar nature of the crystals and the fine substrate-parallel layering, are rather similar to fabrics of a primary origin in speleothems (Kendall and Broughton, 1978) and radial-fibrous ooids (Sandberg, 1975; Tucker, in prep.). Although Kendall and Broughton (1978) have noted the fabric similarity of primary fibrous calcite in speleothems with supposed replacement fibrous calcite in limestones, they considered the precipitational environment (freshwater vadose with thin-water films) to be significantly different, and so continued to support a replacement origin for fibrous calcites in limestones. However, radial-fibrous ooids commonly consist of columnar ("ray") crystals in a palisade structure, and these have a delicate growth layering (Sandberg, 1975, Figs. 8, 9, 10). These crystals are not formed by the coalescence of acicular crystallites, and the growth layering is accretionary, demonstrating that the crystals grew with a flat surface. The inference is that fibrous calcite in a marine limestone, and in this case the type A fibrous dolomite could be primary, especially if it possesses delicate growth zones and there is no unequivocal evidence for replacement such as the fabrics recorded by cathodoluminescence in type B fibrous dolomite (Fig. 9).

In a replacement origin for type A fibrous dolomite, the linear, substrate-normal arrangements of inclusions (Fig. 5B), would record the nature of the original cement crystals. These would be acicular crystallites arranged in fanning bundles and splays, and parallel palisades. Similar relic crystallites defined by inclusions have been described from fibrous calcites in limestones (Kendall, 1977; Marshall, 1981), but they also occur in speleothems (Kendall and Broughton, 1978; Braithwaite, 1979). The preservation of inclusion-defined needles suggests that replacement involved some form of crystallite coalescence. This appears to be a less destructive replacement process than a migrating fluid film. In this scenario, the columnar crystals would have formed by coalescence of a bundle of acicular crystals, so that the increase in columnar crystal size across the fringe reflects the increasingly preferred orientation of crystallites away from the substrate. The consistent substrate-parallel c-axis orientation of the fibrous crystals likely is a feature inherited from the original cement.

The original cement fabric would have been similar to that occurring in modern reefs, where splays of bladed high-Mg calcite constitute isopachous cement fringes (see, for example, James and Ginsburg, 1980). The substrate-parallel growth layering, the relationship to overlying internal sediments (a planar surface), and the smooth surface developed where two fibrous dolomite layers meet indicate that the cement grew as a substrate-parallel layer with a planar surface. In addition to speleothems and radial-fibrous ooids, such growth is shown by several types of modern submarine cement: the spherulitic aragonite cement of Schroeder (1972), for example, has delicate, smooth growth zones but is composed of numerous acicular crystals; and the radiating acicular calcite cementing Recent sands of the Fraser River Delta (Garrison et al., 1969) shows a similar fine-growth layering.

The zones within the type A fibrous dolomite mosaics free of inclusions and with bright luminescence are interpreted as areas of dissolution of the columnar crystals and infilling with later dolomite cement. The latter was precipitated syntaxially upon the walls of the solution cavities so that the fibrous mosaic was maintained.

Thus, interpretations of the fabrics of type A fibrous dolomite are equivocal; the fabrics can be exlained in terms of a primary origin (by comparison with speleothems and radial-fibrous ooids) or in terms of a replacement origin (by comparison with fibrous calcite of ancient marine limestones and modern submarine acicular cements).

Type B Fibrous Dolomite.—Type B fibrous dolomite is more complex in origin than the other types, but for most of the mosaic a neomorphic origin is likely. The locally developed, nonluminescent marginal zone with fine color banding is similar to type A fibrous dolomite, and can be interpreted similarly as of either replacement or primary origin. The coarser crystal mosaic, which succeeds a laminated marginal zone or totally composes type B mosaics, is more complex in origin.

The nonluminescent elongate, triangular, and bladed shapes coinciding with areas rich in inclusions, generally randomly dispersed but occasionally defining needles, could be areas once occupied by crystallites. The substrate-parallel surface at the distal end of some inclusion-rich areas could represent a growth surface of the former cement. The mostly triangular cross sections of the nonluminescent areas (Fig. 9D) have the appearance of being sections through trigonal crystals. This would suggest that replacement of an original acicular cement took the form of columnar crystals growing through the fringe: the replacement crystals probably grew as a result of both crystallite coalescence and cavity-ward migration of a fluid film. The development of terminations on the replacement front is also suggested by the zig-zag surface where two type B fibrous layers meet.

Several possible origins are apparent for the brightly luminescent dolomite which surrounds the nonluminescent shapes. Replacement of the original acicular cement layer by the blades could have been localized, in which case, the crystallites that were not replaced were either dissolved to leave voids later filled by the luminescing dolomite, or the luminescing dolomite replaced the remaining crystallites as a result of a fluid film mechanism, in which inclusions were not preserved. An additional possibility is that an original acicular cement was completely replaced by nonluminescing, bladed dolomite, and that either this was partially dissolved and the voids filled by luminescing dolomite, or the luminescing dolomite partially replaced the nonluminescing dolomite via a fluid film. The slightly irregular boundaries to some nonluminescent blades and the nonluminescent chevron pattern of some blades could indicate local replacement by the luminescent dolomites. Whatever the mechanism for the formation of type B fibrous dolomite, it certainly was early, because nonluminescent terminations have been eroded and fragments of this crust occur in the internal sediments.

Type B_2 Fibrous Dolomite.—The type B_2 fibrous dolomite can be considered a replacement of an acicular precursor, but more likely is a direct precipitate. The evidence for replacement is somewhat equivocal, based only on the occurrence of a few inclusion trains and the columnar nature of the crystals. The latter is not simply an effect of overgrowth on preexisting columnar crystals (type A), because type B_2 crystals are still columnar where they occur upon internal sediment. The columnar-crystal form alone does not require a replacement origin, as discussed previously, and the nonluminescent blades within B_2 crystals may simply record a stage during crystal growth, when scalenohedral terminations were developed. The inclusion trains could indicate replacement of an acicular precursor, but more likely they simply reflect crystallite development at the growth surface, with columnar crystals formed behind. The brightly luminescent dolomite follows the nonluminescent blades as a later growth stage, but where cavity-wards crystal growth continued, the obtuse rhombohedral growth of luminescing dolomite took over as equant dolomite spar was precipitated. The change in crystal-growth form probably represents a change in pore-water chemistry. Where type B_2 fibrous dolomite has developed upon internal sediment, the more irregular although still predominantly fibrous mosaic results from nucleation upon randomly oriented crystal fragments in the internal sediment.

Type C Fibrous Dolomite.—A replacement origin for type C fibrous dolomite is suggested by coarse, wedge-shaped crystals with linear patterns of inclusions, and the undulose extinction is typical of many neomorphic fibrous calcites. In this case, an origin by crystallite coalescence can adequately explain the fabrics now seen. The original cement would have consisted of acicular crystals, most of them extending the full width of the cement fringe, arranged in botryoids and splays of crystals diverging away from the substrate. Crystallographic coalescence of splays produced the large, wedge-shaped fascicular-optic dolomite, and coalescence of more uniformly oriented crystallites and converging crystallites gave rise to the less common unit-extinguishing and radiaxial-fibrous types.

Type D Fibrous Dolomite.—Fabrics of type D fibrous dolomite show little evidence for a replacement origin. The acicular crystal form and substrate-parallel growth layering are typical of primary precipitates. The interesting feature of type D dolomite is the geometry of the layers (Fig. 11B). The preferential development within the embayments of larger cavities suggests the operation of meniscus effects and water lenses in partially air-filled cavities. It would appear that water collected in subcavities, and that cements were precipitated preferentially there. Small cavities, however, remained water-filled (microphreatic lenses) and cement fringes precipitated there were isopachous. A vadose zone is indicated for type D fibrous dolomite, although its acicular character suggests marine waters. These cements thus are thought to have precipitated in a high-intertidal environment. Analogous cements occur in modern beach rocks (see, for example, Taylor and Illing, 1969).

DOLOMITE SPAR

The later stage of cementation in the Beck Spring Dolomite produced sparry dolomite. This succeeds the fibrous dolomite and fills all remaining cavities. The spar consists of equant crystals with unit extinction. Crystal boundaries range from straight to ragged and embayed (Fig. 7A, C). Twin planes are prominent. In large cavities crystal size conspicuously increases towards the cavity center. Spar crystals are colorless and mostly free of the dark inclusions which characterize the earlier fibrous cements. However, in marginal zones of the sparry dolomite, the former position of crystal terminations commonly is delimited by chevron patterns of dark inclusions (Fig. 7A). Under the SEM, these have an appearance similar to the empty holes of the fibrous cements. Most marginal spar crystals are syntaxial on the earlier fibrous crystals.

Cathodoluminescence shows that much of the sparry dolomite possesses delicate obtuse rhombohedral growth zones, revealed in various shades of red luminescence (Fig. 7). However, fabrics revealed by CL demonstrate that cement precipitation was not a simple process of passive cavity filling. Disconformities or truncation surfaces (Fairchild, 1980a), prominent in some cavities, are of two types: those that can be traced around a cavity (type A of Fairchild) and those that occur within crystals (type B of Fairchild). The first type has relatively smooth to irregular surfaces and is revealed by the luminescence of dolomite cutting across growth zones of earlier dolomite (Fig. 12). The truncation surface does not coincide with crystal boundaries, but cuts across them. The second type typically consists of irregular patches of blood red luminescence, which may extend across several crystals within areas of pale red and orange colors (Fig. 7D). Blood red luminescing dolomite occurs farther out within these cavities as a later growth zone of the spar. Where the type B truncation surfaces enclose a relatively large area (up to 500 μm across), inward-directed (centripetal) growth zones may be seen. In some cases, spar crystals with delicate growth zones have central parts of different luminescence, cutting across the zones. Spar crystals in the marginal areas of the cavities commonly display a blotchy luminescence, and discontinuous growth zones are partly occupied by dolomite of a conspicuous yellow luminescence (Fig. 7D).

The effects of compaction or tectonic fracturing are seen where fibrous dolomite crusts have fractured and broken away from the cavity wall. These secondary cavities and cracks

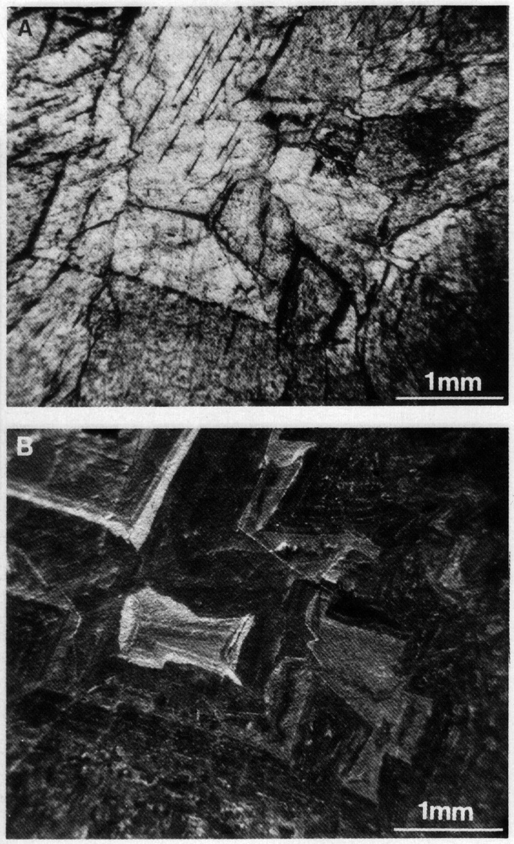

FIG. 12.—Central part of spar-filled cavity showing irregular boundary (a type A truncation surface) between earlier dull luminescing and later bright luminescing dolomite. A transmitted light; B is same area but with cathodoluminescence.

have been filled with spar; luminescence permits the "dating" of this fracturing relative to spar formation. The spar precipitated on the fracture surfaces is of the blood red luminescent variety.

The fabrics and CL characteristics clearly show that the sparry dolomite is a cavity-filling cement. Many of the features are identical to those shown by drusy, sparry calcite (para-axial mosaics) of Phanerozoic limestones, where competitive growth processes account for many of the fabrics (Bathurst, 1975). However, the CL observations indicate that cement precipitation was not a continuous inward-directed pore-filling. The truncation surfaces, fully discussed by Fairchild (1980a, 1982) and Kendall (1982), reveal phases of dissolution either affecting the latest precipitate, and so traceable around the cavity, or occurring within cement crystals. Blotchy luminescence of marginal spar also is thought to reflect partial dissolution of crystals. CL also reveals phases of internal sedimentation of crystal fragments interrupting spar precipitation (see next section).

INTERNAL SEDIMENTS

Internal sediments are prominent within many cavities of the Beck Spring Dolomite. They were deposited at various times relative to the cement generations, but especially immediately before and immediately after the fibrous cements. Most early internal sediments are micritic to calcisiltic (that is, grains up to 50 μm in diameter), whereas later internal sediments are generally coarser, consisting of clear grains and darker micritic grains up to medium sand grade (0.5 mm). The clear grains actually are fragments of crystals, and these are envisaged as originating by internal erosion of fibrous cements or tectonic fracturing. In some cavities, large subrounded fragments of fibrous crust (up to 2 mm long) occur within the internal sediments.

Cathodoluminescence of internal sediments confirms that the larger silt-sized particles are angular crystal fragments. Some of these are enveloped by an overgrowth of luminescent color differing from the detrital core, which can be matched with growth zones of sparry cement, which was growing from the roof of the cavity. It appears that the crystal fragments were behaving like ooids or cave pearls; they were being moved around as syntaxial dolomite was precipitated upon them, and during this time, equivalent dolomite was being precipitated from the cavity roof. When the detrital grains became cemented in the cavity floor, then the remaining void space was occluded, with spar growing from both the bottom and top of the cavity.

Some coarse, sparry dolomite mosaics contain areas of smaller equigranular crystals, which at first sight are reminiscent of a neomorphic hypidiotopic mosaic (Fig. 5). However, luminescence shows that these are layers of crystal debris, washed in during sparry dolomite precipitation. Overgrowths upon these crystal fragments also are revealed by CL.

GEOCHEMISTRY

Depositional components, fibrous dolomite, and sparry dolomite of the Beck Spring Do-

TABLE 2.—*Isotope data from the Beck Spring Dolomite*

Depositional Components	$\delta^{13}C$	$\delta^{18}O$
P-1	+3.89	-2.19
P-3	+3.77	-1.59
P-8	+4.27	-1.98
P-2	+4.23	-2.33
P-19	+4.05	-2.57
M-10	+4.04	-3.54
M-2	+4.52	-3.36
M-6	+3.95	-1.22
M-12	+4.37	-2.00
M-18	+4.02	-0.77
A-16	+4.74	-0.47
A-15	+4.38	-0.57
A-14	+4.52	-1.29
$\bar{x}$	+4.21	-1.84
Fibrous Dolomite	$\delta^{13}C$	$\delta^{18}O$
B5	+4.21	-1.79
2.84	+3.74	-3.16
11	+3.78	-3.32
A1-5	+2.76	-4.34
B9	+2.78	-4.41
B18	+2.72	-4.70
A8-15	+3.01	-5.30
19	+3.55	-5.79
$\bar{x}$	+3.32	-4.10
Dolomite Spar	$\delta^{13}C$	$\delta^{18}O$
S-12	+2.90	-6.08
S-21	+2.26	-8.11
S-7	+1.73	-8.21
S-13	+0.61	-8.32
S-20	+0.45	-8.86
S-1	+0.72	-9.57
S-3	+2.11	-9.95
S-19	+1.97	-10.38
S-14	+2.49	-11.04
S-11	+2.06	-11.67
S-10	+2.48	-13.15
$\bar{x}$	+1.80	-9.58
Internal Sediment	$\delta^{13}C$	$\delta^{18}O$
A1	+2.5	-6.81
A32	+0.96	-6.22
K3	+2.99	-9.96

TABLE 3.—*Geochemical analyses of the Beck Spring Dolomite, obtained by atomic absorption of the acid soluble fraction*

Depositional Components	Na	Sr	K	Fe	Mn
A11	236	56	12	398	134
A6	143	68	39	444	197
A10	297	60	24	507	167
A70	100	61	5	243	168
A71	104	59	10	297	153
284	244	75	7	523	167
AL1	281	61	10	367	98
K11	169	102	17	967	149
K12	212	87	5	460	102
K31	265	83	43	445	76
K10	284	92	62	543	126
A1.2	183	46	34	650	130
A72	-	80	82	410	150
A17	196	58	68	300	100
A20	-	55	37	690	160
A21	291	63	14	590	150
A22	309	62	37	480	170
K32	259	79	165	440	70
$\bar{x}$	223	69	37	486	137
For Ca $\bar{x}$ = 21.3 % (n = 18) For Mg $\bar{x}$ = 12.9 % (n = 18)	Ca : Mg = 50.3 : 49.7				
Fibrous Dolomite	Na	Sr	K	Fe	Mn
K11	209	66	28	468	87
K12	185	71	48	469	77
K13	207	65	30	419	79
K14	180	66	28	350	65
K31	209	62	25	345	69
K10	161	56	17	471	102
K15	177	62	39	517	106
A1	245	56	39	420	120
K32	209	65	31	350	71
$\bar{x}$	198	63	32	423	86
For Ca $\bar{x}$ = 21.9 % (n = 9) For Mg $\bar{x}$ = 12.9 % (n = 9)	Ca : Mg = 50.8 : 49.2				
Dolomite Spar	Na	Sr	K	Fe	Mn
A1	20	37	20	245	382
A6	85	45	5	363	375
A10	40	31	5	593	490
A11	25	39	9	310	385
284	57	46	20	1430	615
K11	59	68	47	1260	338
K10	52	84	77	1760	538
A2	11	82	6	410	380
A17	14	36	2	200	500
A18	12	46	4	310	660
A20	29	37	14	540	400
A21	14	32	13	370	380
A22	23	34	15	410	390
$\bar{x}$	34	47	18	631	449
For Ca $\bar{x}$ = 21.6% (n = 13) For Mg $\bar{x}$ = 13.1 % (n = 13)	Ca : Mg = 49.9 : 50.1				

lomite were separated and sampled using a scalpel and dental drill. Samples were analyzed for stable isotopes by means of conventional techniques and for the elements Ca, Mg, Na, Sr, Fe, Mn, and K by means of atomic absorption spectroscopy (fraction soluble in hot 10% HCl). The results are presented in Tables 2 and 3 and in Figures 13, 14, and 15.

Stable Isotope Data

As has been noted elsewhere (Tucker, 1982), stable isotope data from the Beck Spring Dolomite give information that is consistent with the petrographic interpretations. Values of $\delta^{18}O$ and $\delta^{13}C$ from a) depositional components, b) fibrous dolomite, and c) sparry dolomite (Table 2) are internally consistent for each group and together they show a clear trend of increasingly negative $\delta^{18}O$ and less positive $\delta^{13}C$ from the depositional components through the fibrous dolomite to the sparry dolomite (Fig. 13).

On a broad scale, the isotope data rule out any major reequilibration with meteoric water following sedimentation and diagenesis, in spite of the rocks being at least 1 billion years old. In addition, the consistent differences between the three groups of samples suggest that a major episode of Phanerozoic-type late diagenetic dolomitization was not responsible for the formation of the dolomite in the Beck Spring sequence.

The fibrous dolomite values range from similar to those of the depositional components to values with significant depletion in ^{18}O and, to a lesser extent, in ^{13}C. This range in isotope values is consistent with the petrographic data presented earlier, suggesting that some fibrous dolomites show little alteration other than the possible effects of crystallographic coalescence and are composed of nonluminescent dolomite, whereas others show a degree of later replacement, and consist of a fair proportion of bright, luminescent dolomite. The similarity of a few fibrous dolomite $\delta^{18}O$ and $\delta^{13}C$ values to those of the depositional components suggests a common origin. The isotopic results from the Beck Spring fibrous dolomites are comparable to those obtained from fibrous calcites of Phanerozoic limestones (compare Davies and Krouse, 1975; Walls et al., 1979).

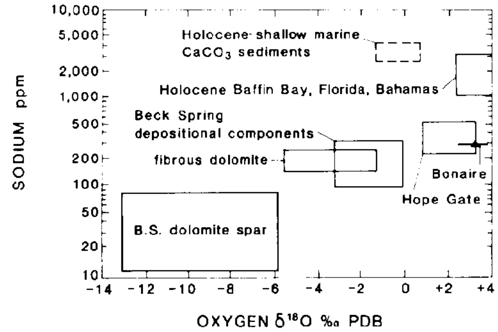

FIG. 14.—Sodium data from the Beck Spring Dolomite plotted against $\delta^{18}O$. Also shown are data for dolomites from the Holocene (Baffin Bay, Florida, and the Bahamas) and the Plio-Pleistocene (Hope Gate Formation, Jamaica and Bonaire), as well as modern $CaCO_3$ sediments (references given in text).

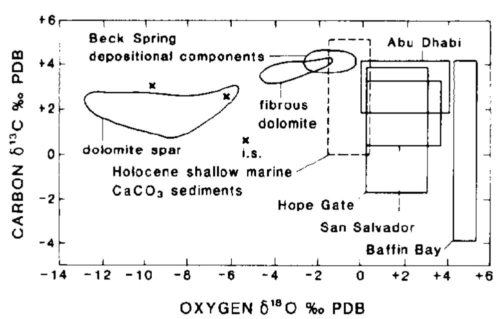

FIG. 13.—Isotope results from the Beck Spring Dolomite (depositional components, fibrous dolomite, sparry dolomite and internal sediments, i.s.) plotted on a $\delta^{13}C$–$\delta^{18}O$ diagram. Data from Recent dolomites (Abu Dhabi sabkha and Baffin Bay) and Plio-Pleistocene dolomites (Hope Gate Formation, Jamaica, and San Salvador Island, Bahamas), as well as modern $CaCO_3$ sediments, are shown (references given in text).

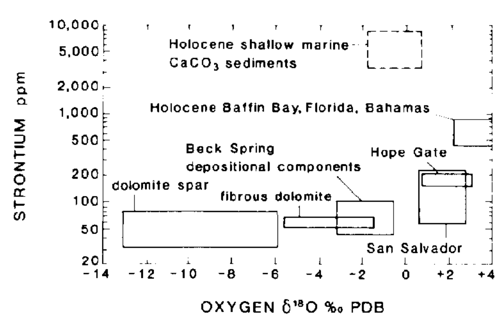

FIG. 15.—Strontium data from the Beck Spring Dolomite, plotted against $\delta^{18}O$. Also shown are data for dolomites from the Holocene (Baffin Bay, Florida and the Bahamas) and the Plio-Pleistocene (Hope Gate Formaton, Jamaica and San Salvador Island, Bahamas), as well as modern $CaCO_3$ sediments (references given in text).

The sparry dolomite has a wide range of isotope values (Table 2, Fig. 13). The more negative $\delta^{18}O$ signature of the spar relative to the fibrous dolomite and depositional components can be interpreted in terms of the diagenetic influx of meteoric waters (which are characteristically depleted in ^{18}O) or precipitation during burial (where increasing temperatures would result in fractionation of the oxygen isotopes and more negative $\delta^{18}O$).

Several internal sediments were analyzed, and these show values intermediate between the values for fibrous dolomite and equant dolomite (Table 2). The three internal sediments sampled were deposited upon fibrous dolomite and consist largely of crystal silt, so that the intermediate values can be explained as reflecting an internal sediment that consisted of fragments of early crystals cemented by later sparry dolomite.

In terms of the origin of the dolomite of the depositional components and some fibrous dolomite, the isotope data are equivocal. But, their actual values, their values relative to the sparry dolomite, and the similarity of the overall isotope story to that of the limestones could indicate a marine origin for the carbonate. This is not to say that the dolomite is primary; it could be seafloor or subseafloor replacement of a metastable precursor (high-Mg calcite or poorly ordered calcian dolomite). On the other hand, the isotope values of the depositional components and fibrous dolomite would also be consistent with an early diagenetic replacement origin. Such dolomite, as forms in meteoric-marine mixing zones and in hypersaline-sabkha environments (Fig. 13), can retain the original (marine) $\delta^{13}C$ values of the precursor $CaCO_3$ (see, for example, Land, 1973a; Supko, 1977; McKenzie, 1981) and have $\delta^{18}O$ values close to the precursor $CaCO_3$ or up to 3 or 4‰ heavier (see, for example, Land, 1973a, 1973b; Supko, 1977; Sibley, 1980; McKenzie, 1981). Because we do not know the $\delta^{18}O$ of billion-year-old seawater, a reference point with which to evaluate the $\delta^{18}O$ data is lacking.

Trace Elements

Atomic absorption analyses of Ca and Mg confirm X-ray diffraction data that the dolomite of the Beck Spring is close to stoichiometric, with Ca:Mg deviating little from 50:50. From Table 3, it can be seen that for the trace elements, as for the isotope data, there are consistent differences between the three sample groups. The important elements in terms of the precipitational environment of the dolomite are strontium and sodium, and the occurrence of these in dolomite has been discussed recently by Land (1980). In fact, the behavior of Na and Sr in dolomite precipitation is unclear; much discussion has taken place over the values of their distribution coefficients, and kinetic factors also determine the concentration of these elements in dolomite.

With regard to Na, both modern marine high-Mg calcite and aragonite generally contain 2000 to 4000 ppm. In modern dolomites (see Fig. 14), high values (1000–3000 ppm) typify those of hypersaline (Baffin Bay) and evaporative (sabkha) environments (Land and Hoops, 1973), whereas low Na values (200–500 ppm) are characteristic of mixing-zone dolomites such as those in the Pleistocene Hope Gate Formation of Jamaica (Land, 1973a), and Pliocene Seroe Domi Formation of Bonaire (Sibley, 1980). There is no modern normal marine dolomite, of course, so the Na content of such a precipitate is unknown. The Na values from the depositional components (average 225 ppm) and fibrous dolomite (198 ppm) of the Beck Spring are low, just like the Plio-Pleistocene mixing-zone dolomites. The low Na could suggest precipitation from dilute waters rather than seawater and thus imply dolomitization of $CaCO_3$. However, an alternative is that the dolomite was originally precipitated as a poorly ordered calcian dolomite, with a marine sodium value, and during stabilization to stoichiometric dolomite, the sodium was lost. The slightly lower values for the fibrous dolomite are thought to reflect the patches of brightly luminescent dolomite. The low value of Na (34 ppm) in the later diagenetic dolomite spar is taken to indicate precipitation from low ionic strength waters.

With regard to strontium, values reach 10,000 ppm in modern marine aragonitic ooids and cements, but in high-Mg calcite the Sr value is 1000 to 2000 ppm. In hypersaline and evaporative dolomites (see Fig. 15), Sr ranges from 600 to 900 ppm (Behrens and Land, 1972), but in mixing-zone dolomites (references same as above) 100 to 250 ppm is typical, although such dolomite in the Falmouth Formation of Bermuda (Land, 1973b) has 3000 ppm (because of closed system replacement of Sr-rich aragonite). Like Na, the Sr content of marine dolomite is unknown, but a figure of 500 to 800 ppm has been suggested. The Sr values of the Beck Spring are very low indeed (Table 3, Fig. 15). The fibrous dolomite (63 ppm) is again slightly lower than the depositional components (69 ppm) and an explanation similar to that given for the Na differences applies. Also, as with the Na values, the low Sr of the depositional components and fibrous dolomite would appear to preclude precipitation from marine fluids and warrant comparison with mixing-zone replacement dolomites. However, again, one must bear in mind the possibility that a poorly ordered calcian dolomite was the initial marine precipitate, and that its Sr was strongly depleted on stabilization to stoichiometric dolomite. Since the distribution coefficient $D^{Sr}_{dolomite}$ is very low, wet recrystallization taking place even in seawater would reduce the Sr content considerably (Land, 1980). Although more variable, Sr of the dolomite spar is lower (47 ppm) and, like the Na, this reflects the low Sr of later diagenetic pore waters.

With regard to the other trace elements, K follows Na and Sr, reflecting the similar chemical behavior of these elements and their similar relative concentrations in seawater and meteoric water. The Fe^{2+} concentration is relatively low compared to many other Precambrian dolomites (see Fairchild, 1980b) and as expected, Mn follows Fe. The slightly higher values for the depositional components (Fe: 486 ppm Mn: 137 ppm) probably are reflections of detrital and organic effects relative to the inorganic-chemical precipitate origin of the fibrous dolomite, with averages for Fe of 423 ppm and for Mn of 86 ppm. The somewhat higher Fe value (631 ppm) and much higher Mn (450 ppm) of the dolomite spar reflect the higher concentrations of these elements in later diagenetic waters.

To conclude, the geochemical data show that a marine origin is untenable for the dolomite that now composes the depositional components and fibrous dolomite and they also rule out precipitation from hypersaline brines. The results fully support an early diagenetic origin for this dolomite, but they do not make any inference in the original mineralogy. The data compare well with those from meteoric-marine mixing-zone dolomites, with the low Sr and Na indicating dilute waters and the isotopes, heavy relative to the spar, indicating an original marine precipitate. The inference of this comparison would be for dolomitization of $CaCO_3$ sediments and early cements and not for primary dolomite precipitation. However, a valid alternate interpretation is that the original marine precipitate was a poorly ordered calcian dolomite which during early diagenesis converted to stoichiometric dolomite, with much depeletion of trace elements. The geochemical attributes of the dolomite spar are consistent with later diagenetic precipitation from low ionic strength pore waters.

DISCUSSION

It was noted in the Introduction and pointed out in Tucker (1982) that obliterative dolomite replacement fabrics, which are characteristic of many Phanerozoic dolomites, are rare in the Proterozoic Beck Spring Dolomite (and the Porsanger Dolomite of Norway). Depositional components, especially ooids in the Porsanger Dolomite, show original fabrics, and so a primary origin was suggested. Some fibrous dolomite cements described in this paper have fabrics which also could be primary, whereas others show clear evidence of replacement. The results of the geochemistry are best interpreted in terms of an early diagenetic origin for the dolomite of the depositonal components and fibrous dolomite but they give no indication of the nature of the original precipitate. This could have been a primary dolomite or calcite-aragonite.

If the original precipitate was a dolomite, it would presumably have been a calcian dolomite with poorly developed ordering peaks. Most early dolomite precipitates, however, are rhombic rather than acicular, and it has been suggested (Ricketts, 1982) that crystallographic constraints prohibit dolomite precipitation in a needle-crystal form. Nevertheless, early diagenetic stabilization of the calcian dolomite of the depositional components and fibrous dolomite to stoichiometric dolomite could account for the trace element and isotope geochemistry and for the petrographic evidence of some replacement. The postulation of a form of dolomite as the initial precipitate would require changes in the chemistry of seawater, because, as is well known (see, for example, Folk and Land, 1975; Chilingar et al., 1979). kinetic factors prevent dolomite precipitation in modern marine water. Appropriate changes in p CO_2, Mg/Ca ratio or SO_4^{2-} could induce dolomite precipitation from seawater. Changes in pCO_2-Mg/Ca ratio, ultimately controlled by geotectonics, are now accepted for Phanerozoic seawater to account for the pattern of carbonate cement, ooid, and skeletal mineralogy (Sandberg, 1975; Wilkinson, 1979); McKenzie and Piggott, 1981; Riding, 1982).

The uniformitarian approach that, as in most Phanerozoic dolostones, the early dolomite of the Beck Spring is a replacement of $CaCO_3$, intuitively is more acceptable in view of the kinetic problems in directly precipitating dolomite. In a dolomitization model, the points of interest are the anomaly of geochemical evidence for replacement and the common preservation of original fabrics and the original mineralogy of the Beck Spring fibrous cements (and depositional components).

At the present time, marine acicular cements are composed of either aragonite or high-Mg calcite. Both of these can form isopachous fringes with delicate growth zones. Aragonite and high-Mg calcite are metastable minerals, and they normally are converted to low-Mg calcite during diagenesis. With ancient cements, a concensus is emerging that replacements of bladed high-Mg calcite can be distinguished from replacements of acicular aragonite. Calcite-replaced aragonite cements generally consist of neomorphic spar or pseudospar, with little control exerted on the fabrics of the replacement calcite by the original aragonite (see, for example, Mazzullo, 1980). Calcite-replaced high-Mg calcite cements, on the other hand, generally consist of fibrous calcite of radiaxial to fascicular optic character, and the original cement fabric may exert considerable influence on the replacement.

The view is generally held that much of the dolomite in the geologic record has formed by replacement of $CaCO_3$. Most dolomite forming at the present time within hypersaline-evaporative environments is micritic (that is, < 10 μm in size), and replacement of aragonite mud, via high-Mg calcite, has been postulated (McKenzie, 1981). Where dolomite has replaced skeletal grains and sediment in Phanerozoic limestones, the process generally is fabric-destructive, especially if dolomitization is relatively late. However, where dolomitization is early, preservation of original fabrics can be very good, but in most documented cases the grains originally were composed of high-Mg calcite. In particular, dolomite can replace a high-Mg calcite grain and faithfully retain the grain's fabric and crystallographic orientation (see, for example, Land and Epstein, 1970; Sibley, 1980). In addition, in Plio-Pleistocene dolomitized limestones, the high-Mg calcite grains go to dolomite first. Grains originally of low-Mg calcite are initially resistant to dolomitization, but then appear to be replaced destructively. Where originally aragonitic grains have been dolomitized, then fabric destruction is the norm, (for a possible exception, see Murray, 1964, Fig. 4) and the product is either an irregular mosaic of dolomite or a dolomite cement filling voids left by aragonite dissolution, if this occurred before dolomite precipitation. Descriptions of early dolomitization of marine cement are scarce, but of note is a poorly developed fibrous-looking dolomite that apparently has replaced bladed high-Mg calcite (Müller et al., 1973). Early dolomite replacement appears to be similar to calcite replacement of metastable grains: fabric-retentive and conservative where high-Mg calcite is the original mineral, and fabric-destructive where aragonite is replaced.

From this discussion, and using the uniformitarian approach that most early dolomite is replacive, it would appear that the most likely precursor to the fibrous dolomite (and depositional components) of the Beck Spring Dolomite was high-Mg calcite. A high-Mg calcite precursor would provide a suitable template for dolomitization with much fabric retention, and it would supply up to 40% of the required Mg^{2+} ions. It is unlikely that acicular aragonite was the original precipitate, because as noted above, replacement of aragonite is generally fabric-destructive. Low-Mg calcite also is an unlikely precursor because it does not normally form acicular precipitates, and dolomite replacement generally is fabric-destructive.

In a dolomitization scenario, bladed high-Mg calcite would have been precipitated from marine pore waters and then replaced by dolomite during early diagenesis. From the geochemical data, the dolomitization is most likely to have taken place in the meteoric-marine mixing zone, rather than by reaction with hypersaline brines. The meteoric-marine mixing zone is now considered to be one of the most important locations of dolomitization (Land, 1973a, 1973b; Badiozamini, 1973; Folk and Land, 1975). Seawater is supersaturated with respect to dolomite, but dolomite does not precipitate there because of kinetic effects. In the meteoric-marine mixing zone, however, dolomite supersaturation is maintained and in the low ionic-strength solutions of this zone, kinetic factors are overcome. Dolomitization in the mixing zone has been demonstrated for several Plio-Pleistocene carbonate formations (see, for example, Land 1973a, 1973b, Sibley, 1980) and has been invoked for some Phanerozoic dolomite sequences (see, for example, Dunham and Olson, 1980; Choquette and Steinen, 1980).

From the data presented in this paper, it is clear that the Beck Spring Dolomite has many petrographic and geochemical features in common with Phanerozoic shallow-water limestones. But in the Beck Spring it is dolomite and not low-Mg calcite that is the dominant diagenetic mineral. Proterozoic dolomites in general show good fabric preservation of depositional components, commonly contain fibrous dolomite, and are cemented by dolomite spar. It is tempting to suggest that there is some wider significance in this "Proterozoic versus Phanerozoic style of diagenesis," which could, for example, explain the apparent abundance and dominance of dolomites over limestones in the Precambrian.

It could be argued that the original marine sediments and cements were generally of a composition such that dolomitization was the preferred early diagenetic process, rather than calcification. And, as has been noted earlier, high-Mg calcite grains and cements are more prone to dolomitization with fabric retention than those of aragonite. However, it is likely that original mineralogy is only a contributory factor, with greater importance residing in the nature of the early diagenetic shallow-burial environment. Of significance will be the chemistries of the meteoric and marine waters (p CO_2, Mg/Ca ratio, SO_4^{2-} and organic geochemistry) and the geotectonic setting, controlling sea-level fluctuations and the movement of pore waters through the sediment. Studies of Plio-Pleistocene dolomites in the Caribbean (Sibley, 1980) show that early dolomitization preferentially occurs where original metastable mineralogy is preserved, and conversion to low-Mg calcite has not taken place. Most early calcification takes place in shallow meteoric zones, and this is promoted by p CO_2 rich waters produced by soil processes. An overriding climatic control is involved since humid climates tend to favor plant growth and soil formation, whereas arid climates inhibit plant and soil development. Thus early calcification should be more efficient in humid climates and early dolomitization in arid climates (Sibley, 1980). With regard to the Proterozoic, soil processes were likely of little importance, compared to the Phanerozoic, because of the absence of vascular plants, although bacteria and blue green algae may have been involved in pedogenesis. Generally then, one could expect little early calcification of marine sediments, allowing the persistence of metastable mineralogies into meteoric-marine mixing zones for total dolomitization. Further discussion must await petrographic-geochemical studies of other Precambrian dolomites, and the not-so-uncommon Precambrian limestones should not be overlooked.

CONCLUSIONS

The mid-Proterozoic Beck Spring Dolomite has many petrographic and geochemical features in common with Phanerozoic limestones. In contrast to many Phanerozoic dolomites, original fabrics are well preserved so that the diagenetic history that can be deduced is similar to that of a shallow-water limestone, that is, early fibrous cements and later drusy spar. Synsedimentary and early diagenetic fibrous dolomite was precipitated in various cavity structures and around grains. Four principal types of fibrous dolomite are distinguished, and whereas some of these have fabrics which indicate a replacement origin, others could be primary. The later diagenetic sparry dolomite displays features of a direct precipitate such as delicate growth zones and crystal terminations, although phases of dissolution and internal sedimentation of crystal silt are recorded.

The geochemical data indicate an early diagenetic origin for the dolomite of the depositional components and fibrous dolomite, but they make no inference on the mineralogy of the original precipitates. The most likely interpretation, taking a uniformitarian approach, is dolomitization of $CaCO_3$ sediments and early cements in a meteoric-marine mixing zone model. An alternative, however, until relic $CaCO_3$ is found, is primary precipitation of poorly ordered calcian dolomite and early diagenetic stabilization to stoichiometric dolomite.

In a dolomitization interpretation, the good fabric preservation of the depositional components and fibrous dolomite of the Beck Spring Dolomite can be explained by an original marine sediment and fibrous cements composed of high-Mg calcite. In Phanerozoic (especially Plio-Pleistocene) dolomites, early dolomitization of high-Mg calcite is generally fabric-retentive and contrasts with the behaviour of aragonite (fabric-destructive) and low-Mg calcite (resistant) in a dolomitizing environment.

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