Petrology, petrochemistry, and stromatolites of the Middle to Late Proterozoic Beck Spring Dolomite, eastern Mojave Desert, California

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The Beck Spring Dolomite is the medial unit of the Middle to Late Proterozoic Pahrump Group, the oldest sequence of sedimentary rocks in eastern California. Stratigraphic sections of the Beck Spring Dolomite examined in the eastern Mojave Desert and Death Valley regions consist of four members. These are, in ascending order, a lower cherty member, a lower laminated member, an oolitic–pisolitic member, and an upper cherty member. More than 80% of the Beck Spring Dolomite is algal-laminated dolomite with a possible Middle to Late Riphean stromatolite assemblage characterized by cf. *Conophyton*, eroded, irregular columnar forms similar to *Kussiella* or *Baicalia*, and several types of stratiform *Stratifera*. Petrographic, X-ray diffraction, and atomic absorption spectroscopic analyses indicate that the formation is composed of well-ordered replacement dolomite with less than 25% acid-insoluble residue. Concentrations of Fe and Mn are two to six times higher in the algal-laminated members than in the oolitic–pisolitic member, whereas the concentrations of Ca, Mg, Ba, Sr, Na, and K show no systematic variations. Stratigraphic relationships, primary and secondary sedimentary structures, petrology, and stromatolite assemblages suggest deposition during Middle to Late Proterozoic time on a platform that most likely included offshore shoals, restricted lagoons, and broad tidal flats with ponds, channels, and levees.

La Dolomite de Beck Spring est l'unité médiane du Groupe de Pahrump, d'âge protérozoïque moyen à tardif, elle représente la plus vieille séquence sédimentaire dans la Californie orientale. Les coupes stratigraphiques de la Dolomite de Beck Spring examinées dans les régions du désert Mojave oriental et de la vallée de la Mort comprennent quatre membres. Ce sont, de la base au sommet, un membre chertifère inférieur, un membre de lamines inférieur, un membre oolitique–pisolitique et un membre chertifère supérieur. La Dolomite de Beck Spring est formée de plus de 80% de dolomite laminée algaire, incluant un assemblage de stromatolites datant possiblement du Riphéen moyen à tardif, caractérisé par cf *Conophyton*, des formes columnaires érodées et irrégulières analogues à *Kussiella* ou *Baicalia* et plusieurs types de *Stratifera* stratiformes. Les analyses pétrographiques, de diffraction des rayons-X et d'absorption atomique révèlent que cette unité lithologique est formée d'une dolomite de remplacement, avec un bon ordre structural, et que la proportion de résidu acide insoluble est inférieure à 25%. Les concentrations de Fe et de Mn sont deux à six fois plus élevées dans les membres de lamines et algaires que dans le membre oolitique–pisolitique, tandis que les concentrations de Ca, Mg, Ba, Sr, Na et K ne montrent pas de variations systématiques. Les relations stratigraphiques, les structures sédimentaires primaires et secondaires, la pétrologie et les assemblages de stromatolites suggèrent comme période de dépôt le Protérozoïque moyen à tardif, sur une plate-forme qui incluait vraisemblablement des hauts-fonds extracôtiers, des lagunes fermées et de vastes platiers tidaux avec étangs, chenaux et levées.

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Introduction

The Pahrump Group, a continental-margin deposit of Middle to Late Proterozoic (Riphean) age is well exposed in the eastern Mojave Desert, Death Valley, and adjacent areas to the south (Figs. 1, 2).The region is bounded on the west by the Panamint Range and on the east by the Kingston Range. Strata extend northward to the Funeral Mountains and southward at least to the Silurian Hills and the Halloran Summit complex (Stewart 1976; Wright *et al.* 1976). The region is bounded on the northwest and west by branches of the Garlock and Death Valley fault systems and on the east by the Clark Mountain thrust complex.

The Pahrump Group is an assemblage of shallow marine and nonmarine siliciclastic and carbonate rocks. Together with the overlying late Precambrian and Cambrian strata, the Pahrump Group forms a deposit of essentially unmetamorphosed strata nearly 7 km thick. The Pahrump Group consists of three formations, which are, in ascending order, the Crystal Spring Formation, the Beck Spring Dolomite, and the Kingston Peak Formation (Fig. 2). The Crystal Spring Formation rests with profound unconformity on crystalline rocks, from which U–Pb ages of 1.4–1.8 Ga have been obtained (Silver *et al.* 1962; Labotka and Albee 1977; Labotka *et al.* 1980*a*, 1980*b*), and is intruded by 1.08 Ga diabase sills (Hammond 1986; Heaman and Grotzinger 1992). The initiation of Pahrump Group sedimentation appears to be bracketed beween 1.1 and 1.8 Ga (Wright *et al.* 1976).

To provide a more comprehensive framework for the sedimentologic history and geologic evolution of the Death Valley region, this paper describes the petrography, whole-rock petrochemistry, and stromatolite paleoecology and biostratigraphy at both formation and member levels. Five stratigraphic sections were selected for study: three dominated by carbonate facies (Beck Spring type area, Snow White mine, Acme mine); a mixed siliciclastic–carbonate facies (Saratoga Spring); and a metamorphosed mixed siliciclastic–carbonate facies (Silurian Hills).

Previous studies

Stratigraphic and some petrologic studies of rocks assigned to the Pahrump Group have been carried out by Diehl (1976), Wright *et al.* (1976, 1978), Roberts (1976, 1982), and Maude

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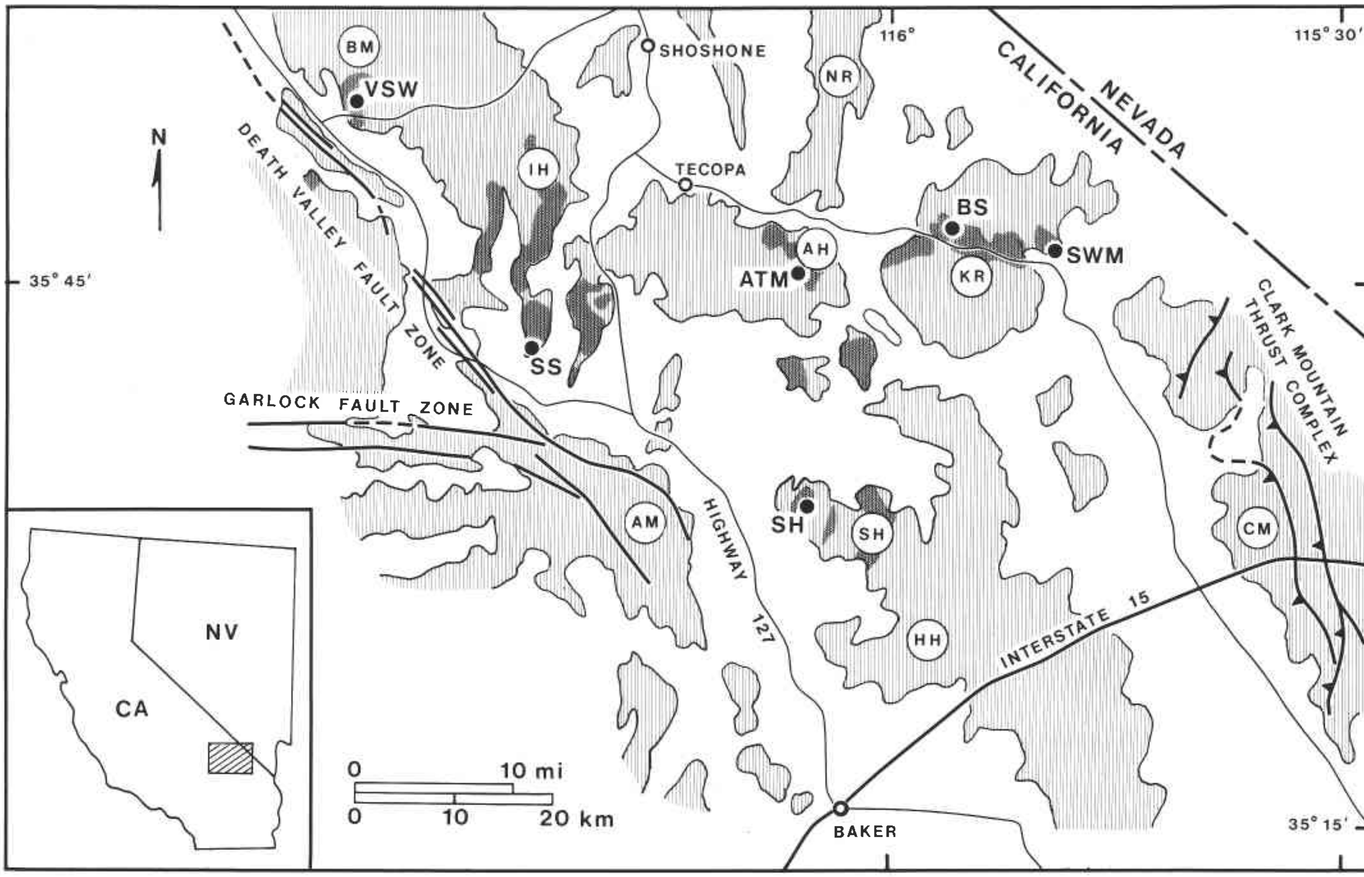

FIG. 1. Index map showing location of study localities: VSW, Virgin Spring Wash; SS, Saratoga Spring; ATM, Acme talc mine; BS, Beck Spring; SWM, Snow White mine; SH, Silurian Hills. Major mountain ranges: BM, Black Mountains; IH, Ibex Hills; NR, Nopah Range; AH, Alexander Hills; KR, Kingston Range; CM, Clark Mountains; HH, Halloran Hills; SH, Silurian Hills; AM, Avawatz Mountains. Dark stippled areas indicate outcrops of Pahrump Group rocks.

(1983). The general petrology, stratigraphy, and regional depositional patterns of the Beck Spring Dolomite have been described by Gutstadt (1968) and Shafer (1983). The diagenetic history of the oolitic–pisolitic member of this formation has been described and debated extensively by Tucker (1982, 1983) and Zempolich *et al.* (1988). The biogeology of the black cherts of the upper Beck Spring Dolomite, which contain some of the earliest fossil eukaryotic organisms, has been described by Cloud *et al.* (1969), Licari (1971, 1978), and Pierce and Cloud (1979). The original report of columnar and stratiform stromatolites was made by Licari (1971) from exposures of the Beck Spring Dolomite in the Alexander Hills and Kingston Range, but the stromatolites were not described in detail.

Stratigraphy and sedimentary structures

The locations of the five measured stratigraphic sections are shown in Fig. 1. Measurements were made using a Jacob's staff and Brunton compass or Abney level, and samples were collected from each distinctive lithologic interval. The Beck Spring Dolomite is dominated by medium to dark grey, laminated dolomite. Nearly all of the observed laminations appear to be biosedimentary laminations produced by algal-mat activity (cryptalgalaminites; Aitken 1967; Monty 1976). As reported by Gutstadt (1968), the type section at Beck Spring in the Kingston Range consists of three informal members. These are, in ascending order, the lower laminated, middle oolitic–pisolitic, and upper cherty members. Licari (1971) reported an additional basal "lower cherty" member in his description of the stratigraphic section at the Acme mine (Fig. 1). The present study shows that this lowermost member also is present, though less conspicuous, at the Snow White mine and at the type locality at Beck Spring (Fig. 1).

Carbonate facies

The dominantly carbonate facies occur at Beck Spring, Snow White mine, and Acme mine. All three sections show similar planar- to wavy-laminated structures of presumed algal origin with minor chert in the lower cherty and lower laminated members, similar allochemical types and distributions in the oolitic–pisolitic member, and a cherty and stromatolitic upper member (Fig. 3).

The lower cherty member (20–60 m thick) is light to medium grey (N4–N5), well-laminated, and especially cherty in its lowermost part. It is in gradational contact with the red-brown to orange shale and dolomite of the underlying Crystal Spring Formation. Well-developed beds of intraformational conglomerate with intraclasts of millimetre and centimetre size are present. Some fine-grained intraclastic beds are similar to deposits of curled, desiccated algal-mat chips described from Andros Island, Bahamas (Shinn *et al.* 1969; Ginsburg and Hardie 1975; Hardie 1977). Laminae are generally 1–2 mm thick and subparallel to convolute. Chert-filled fenestrae are common in convolute laminated intervals.

The lower laminated member (160–180 m thick) is dominated by well-laminated, medium grey (N4 – N5), thin-bedded dolomite with laminae 1 – 5 mm thick. Pseudodomal and stratiform stromatolites (*Stratifera*), irregular spar-filled fenestrae, vugs and channels, breccia and chip breccia, and eroded and draped laminae also are abundant at all localities. Conical columnar stromatolites (cf. *Conophyton*) occur in this interval at the Acme mine, and Shafer (1983) reported eroded, columnar stromatolites (SH-C of Logan *et al.* 1974) from this interval in the Black Mountains.

The oolitic – pisolitic member (60 – 70 m thick) is light to medium grey (N5 – N6) and contains moderately sorted and rounded allochemical grains that are 1 – 2 mm to more than 1 cm in diameter. Many ooliths and pisoliths are selectively silicified. Allochems occur in beds and lenses up to 5 m thick which are interbedded with broadly undulose, coarsely laminated dolomite and irregular, contorted, and brecciated dolomite. The coarsely laminated dolomite grades to finely laminated, wavy to wrinkled dolomite in the upper part of the unit. Spar- and chert-filled fenestrae and red-brown-weathering chert nodules appear near the top of the oolitic – pisolitic member.

The upper cherty member (150 – 180 m thick) consists mostly of 0.5 – 1 m thick beds of medium grey (N4 – N5) to tan (5YR 6/4) dolomite with abundant red-brown-weathering chert nodules and interbeds as much as 0.3 m thick. The dolomite is sandy with contorted laminae prominent around chert nodule and lenses. Rare, red-brown-weathering, granule sandstone beds (0.4 – 0.6 m thick) and chocolate brown shale lenses (0.5 – 1 m thick) are the only siliciclastic units present. Well-developed 2 – 3 cm thick beds contain prominent sheet cracks (straight-sided in cross section). Immediately above the oolitic – pisolitic zone at the Acme mine and in a similar position at Beck Spring and in the Black Mountains (Shafer 1983) is a series of beds of columnar-layered and columnar stromatolites similar to members of the groups *Baicalia* Krylov or *Kussiela* Krylov. The eroded, irregular columns commonly are surrounded and overlain by abundant deposits of laminated intraclasts. Curled stromatolitic laminae, eroded and draped laminae, and wrinkled, wavy laminations also are present throughout the lower portion of the upper cherty member. Laminations are irregular, indistinct, or absent in the upper part of the upper cherty member. The contact with the red-brown siltstone assigned to the overlying Kingston Peak Formation is sharp.

Mixed carbonate – siliciclastic facies

The mixed carbonate – siliciclastic facies is best developed at Saratoga Spring. The Silurian Hills section also contains abundant siliciclastic intervals within a dominantly recrystallized limestone section. However, the Silurian Hills rocks have been metamorphosed to biotite grade (Shafer 1983), and the alteration limits useful descriptions to gross lithology only. The carbonate – siliciclastic facies section at Saratoga Spring differs from the dominantly carbonate facies sections in that it contains abundant sand and shale layers, widespread chert, and distinctive variations in weathering colors (Fig. 4). It consists of only three members: a lower cherty member (275 m thick), a laminated member (45 m thick), and an oolitic – pisolitic member (10 m). No upper cherty member was observed at Saratoga Spring or Silurian Hills. Coarse-grained siliciclastic units in the Saratoga Spring section consist of sand- to granule-size grains. They range in composition from quartzarenite to subarkose (McBride 1963), contain an average of 25% carbonate intraclasts, and occur as thin beds and

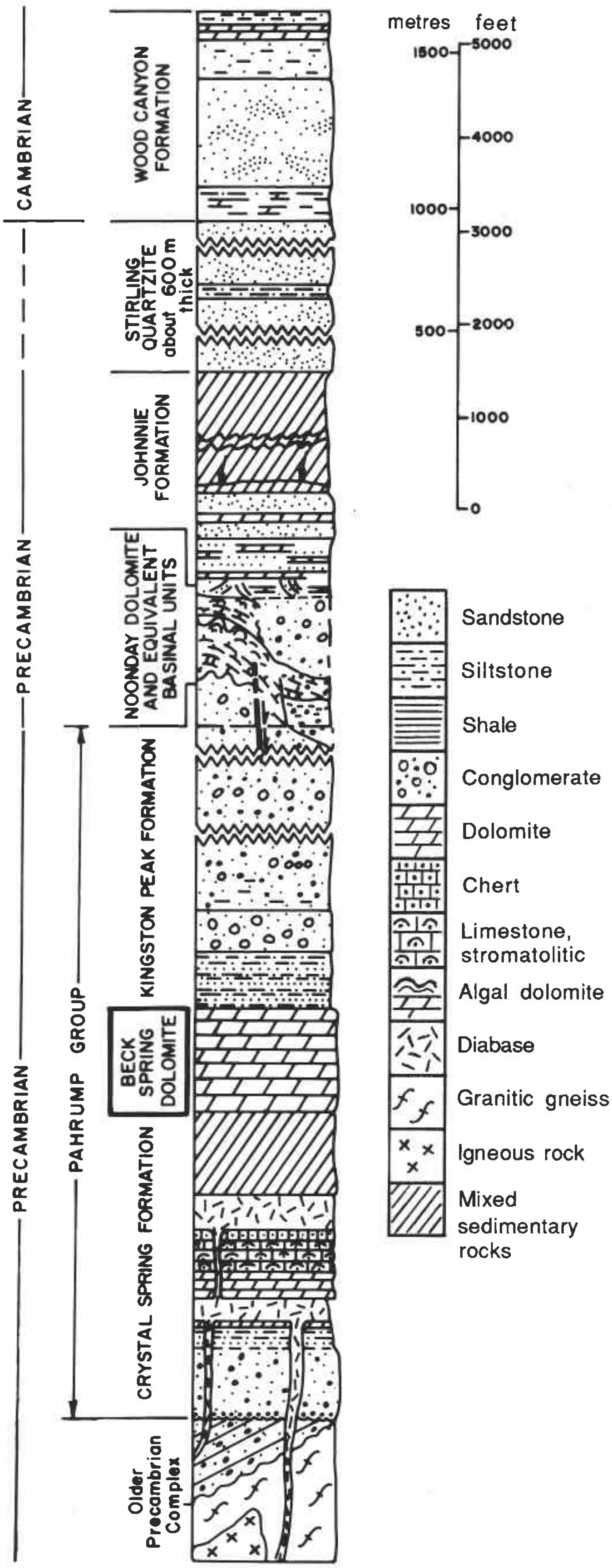

FIG. 2. Generalized columnar section of Precambrian to Lower Cambrian strata, Death Valley and eastern Mojave Desert region (modified from Wright *et al.* 1976, Fig. 1).

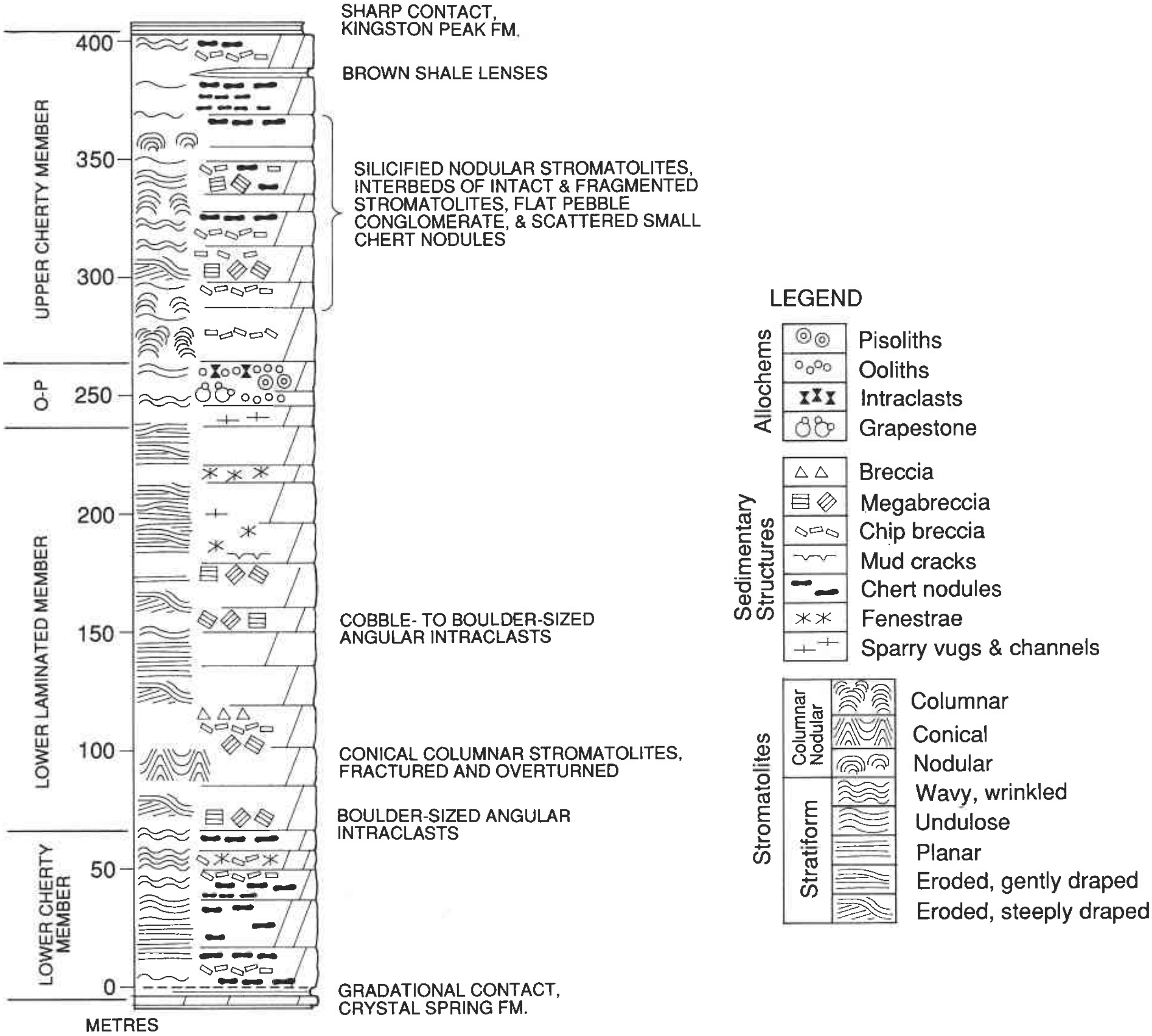

FIG. 3. Composite columnar section for carbonate facies of the Beck Spring Dolomite, based on stratigraphic sections at Beck Spring and the Snow White and Acme mines. O–P, oolitic–pisolitic member.

lenses within both carbonate and shale units. Shale occurs as flaggy, medium orange (10R 5/4 or 10R 3/4) to medium grey (N4–N5) beds generally less than 0.5 m thick. Weathered dolomite ranges in color from dark grey (N3) to medium orange-brown (5YR 5/6), with most beds medium grey (N4–N5) to light brown (5YR 6/4). Chert nodules, wavy and wrinkled laminae, and sandy dolomite occur throughout the lowest 75% of the measured section. Moderately sorted and rounded carbonate intraclasts commonly are mixed with grains of quartz and potassium feldspar in many of the dominantly carbonate units. Intraclasts are as much as several centimetres long, but most clasts are less than 1 cm. Sandy dolomite beds display planar to low-angle cross-stratification and some laminated, lenticular stratification. Partially silicified pisoliths up to 5 mm in diameter are the only allochems present in the oolitic–pisolitic member.

TABLE 1. Mineral composition of the Beck Spring Dolomite (N = 56)

Mineral	Range (%)	Mean ± SD (%)
Dolomite	0–100.0	85.9±25.9
Calcite	0–98.1	3.4±17.2
Quartz	0–71.5	5.4±14.4
Chert	0–41.5	3.6±8.9
Potassium feldspar	0–11.5	0.5±1.8
Plagioclase	0–0.9	Trace
Magnetite	0–3.0	0.2±0.5
Hematite	0–5.3	0.3±0.9
Limonite	0–8.8	0.2±1.2
Pyrite	0–0.5	Trace
Acid plutonic rock fragments	0–2.1	0.2±1.2
Biotite	0–2.0	0.1±0.3

Petrography

Procedures

Mineralogic and textural data were obtained by examining 71 thin sections and 141 slabbed hand samples. All samples containing siliciclastic grains were stained with sodium cobaltinitrate for feldspar identification (Friedman 1971). Volume percentages of minerals and allochemical constituents were determined using the Gagolev–Chayes method of modal analysis (Galehouse 1971). Fabric and porosity types were

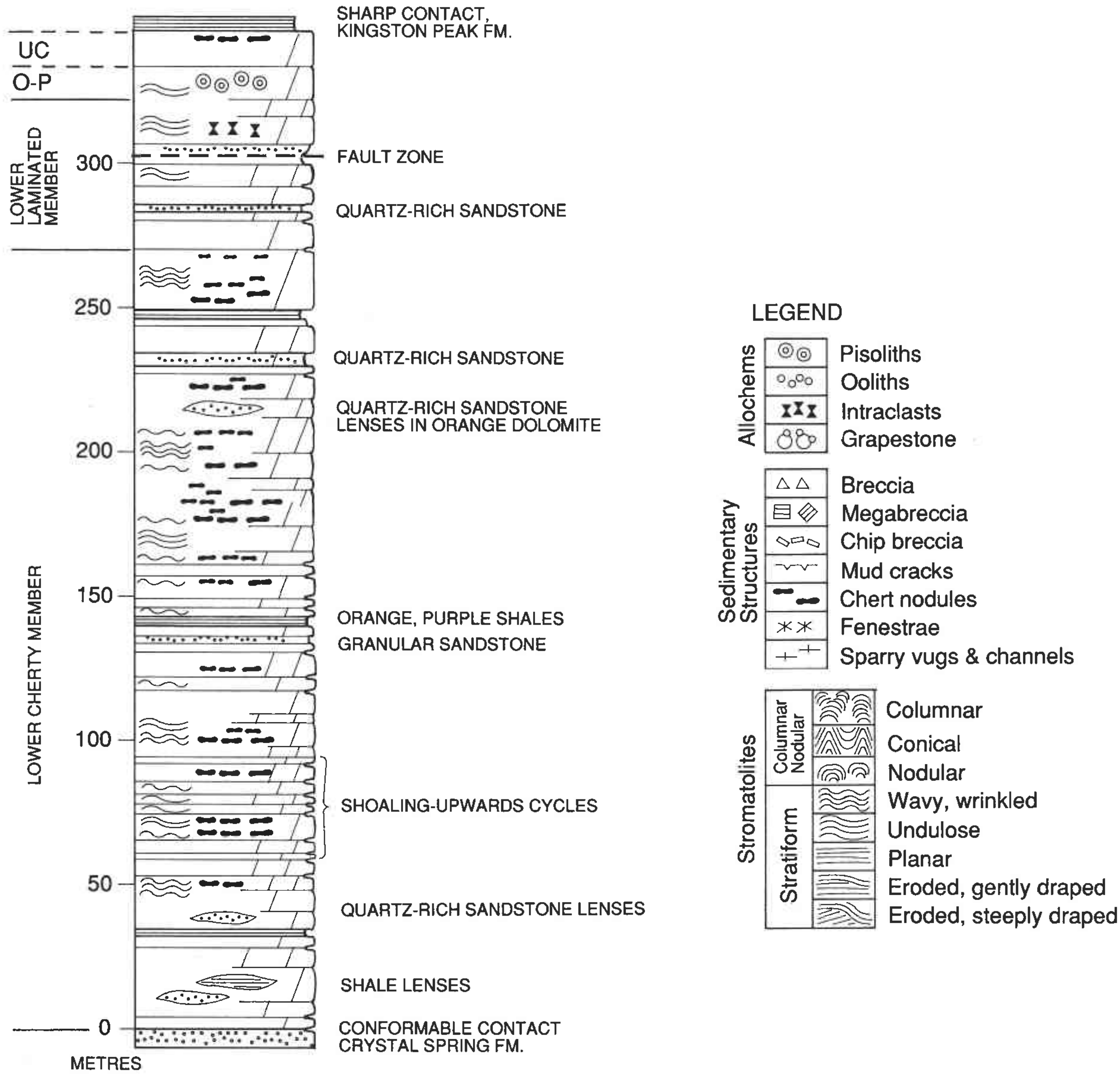

FIG. 4. Composite columnar section for mixed carbonate–siliciclastic facies of the Beck Spring Dolomite, based on the stratigraphic sections at Saratoga Spring and Silurian Hills. O–P, oolitic–pisolitic member; UC, upper cherty member.

defined according to Choquette and Pray (1970). Siliciclastic rocks were classified using the system of McBride (1963). Carbonate rocks were classified according to Folk (1962) and Dunham (1962), and carbonate grain size was described using the nomenclature of Folk (1965). "Chip breccia" is used to describe rocks containing component allochems less than 5 mm in maximum dimension, and "breccia" is used for rocks with allochems from 5 mm to about 10 cm in maximum dimension.

Results

Mineral composition

The carbonate is uniformly dolomite of probable replacement origin (Tables 1–3). Micrite and microspar are predominant in the lower laminated, lower cherty, and upper cherty members, whereas microspar and spar dominate in the oolitic–pisolitic interval.

Early diagenetic chert commonly fills fabric-selective fenestral pores. Colloform chalcedonic-opaline crusts line interlaminar spaces in samples from the lower members at the Snow White and Acme mines. Slightly undulose, monocrystalline quartz also fills dolomolds, late-stage veins, and allochem cores. Detrital quartz was observed only in subarkoses at Saratoga Spring and in intraclastic rocks. The mono- and polycrystalline quartz grains in the thin siliciclastic–intraclastic beds at Saratoga Spring are well sorted, well rounded, and display undulose extinction. Plagioclase, microcline, and potassium feldspar form as much as 11.5% of the mineral content of the siliciclastic rocks at Saratoga Spring. Several of the arkosic beds at this locality show a marked bimodality in grain size. The large grains (0.5–2.3 mm) are mostly well-rounded, mono- and polycrystalline quartz, microcline, and potassium feldspar, whereas the small grains (0.02–0.30 mm) are dominantly subangular monocrystalline quartz. The iron oxides and sulfides form less than 3% of the total volume of the rock but are distributed throughout the formation and are especially concentrated in the siliciclastic-rich carbonate strata at Saratoga Spring. Magnetite occurs as very finely disseminated, euhedral grains and clusters 0.01–0.015 mm in diameter. Hematite and associated alteration products rim and (or)

TABLE 2. Mineralogy and textural attributes of the carbonate facies of the Beck Spring Dolomite

	Lower cherty and lower laminated members (mean ± SD; N = 22)	Oolitic–pisolitic member (mean ± SD; N = 13)	Upper cherty member (mean ± SD; N = 12)
Allochem			
Ooliths (%)	0.1±0.1	2.1±1.9	0
Pisoliths (%)	0	10.6±5.8	0.4±0.2
Peloids (%)	3.2±3.3	10.5±7.4	0.6±0.7
Intraclasts (%)	7.0±1.4	7.9±6.3	5.5±7.6
Grapestone (%)	0	trace	0
Total (%)	10.3±4.6	33.8±10.2	6.1±8.6
Size (mm)	0.01–5.5	0.04–10.0	0.06–10.0
Mineralogy			
Micrite (%)	23.9±5.5	10.2±2.9	25.7±21.4
Microspar (%)	36.8±3.7	22.6±11.2	30.9±9.5
Spar (%)	22.7±7.7	33.7±10.6	24.9±27.6
Quartz chert (%)	2.5±2.1	1.8±1.2	10.9±9.9
Fe oxides (%)	0.2±0.1	0.2±0.2	0.4±0.5
Support	Matrix:crystalline: grain = 68:18:14	Matrix:crystalline: grain = 31:15:54	Matrix:crystalline: grain = 78:22:0

TABLE 3. Mineralogy and textural attributes of the mixed carbonate–siliciclastic facies of the Beck Spring Dolomite

	Lower cherty and lower laminated members (mean ± SD; N = 7)	Oolitic–pisolitic member (mean ± SD; N = 3)
Allochem		
Ooliths (%)	0	0.1±0.1
Pisoliths (%)	0	13.8±19.4
Peloids (%)	4.0±6.8	20.8±29.3
Intraclasts (%)	2.8±7.3	6.2±8.7
Total (%)	6.8±11.8	40.8±18.8
Size (mm)	0.04–10.0	0.18–6.0
Mineralogy		
Micrite (%)	34.3±34.9	41.0±7.7
Microspar (%)	28.2±21.6	15.6±13.3
Spar (%)	9.4±13.4	0
Quartz chert (%)	19.4±18.7	0.7±0.5
Fe oxides (%)	0.9±1.0	0.1±0.1
Support	Matrix:crystalline: grain = 43:29:29	Matrix:crystalline: grain = 0:0:100

replace magnetite euhedra and also line many of the late-stage fractures. Isolated euhedral pseudomorphs, possibly of halite, gypsum, and anhydrite, occur in cherty and micritic laminae in samples from the lower laminated and upper cherty members at Saratoga Spring, Beck Spring, and the Acme and Snow White mines (Marian 1979; Shafer 1983).

Allochemical grains

Intraclasts and peloids constitute as much as 50% of some samples, especially in the lower laminated member (Tables 2, 3). Both appear to have been initially micritic in composition. Intraclasts show peloidal or laminated internal structure and range in size from 0.15 to 5.5 mm. Peloids range in diameter from 0.01 to 0.45 mm, with a modal size of approximately 0.15–0.20 mm. Peloidal deposits are moderately sorted, whereas mixed intraclast–peloid deposits are poorly sorted. Most intraclasts are derived from associated algal-laminated beds. The origin of the peloids is less clear. Peloids with obscure borders may be clotted, micritic remnants produced by aggrading neomorphism (Beales 1965; Bathurst 1975). The distinct, compact forms, however, probably were deposited as peloids. The peloids originally may have been produced by interstitial-dwelling infauna that have left no fossilized trace or by comminution and degradation of algal-mat particles (Wolf 1965).

Well-preserved ooliths and pisoliths occur in all of the study areas. They may have had initially micritic or microspar compositions. Details of radial fibrous and concentric microstructure are preserved in many samples. Core replacement by chert, quartz, and spar is common, and ooids and peloids in samples from Beck Spring are completely silicified. Ooliths average 1.5 mm in diameter, whereas pisoliths are as much as 6 mm in diameter. Aggregate grains of grapestone (Illing 1954) with two to seven component particles are preserved at Beck Spring and the Black Mountains (Shafer 1983). Possible relict grains of leached grapestone also occur in samples of chip breccia from the lower laminated member at the Snow White mine.

Texture and fabrics

The lower laminated and cherty members are dominated by matrix-supported mudstone and wackestone facies, which may represent deposits of moderate-energy shoals and (or) associated lower energy subtidal environments (Tables 2, 3). The minor grain-supported carbonate strata within the lower laminated and cherty members are intraclastic and peloidal rocks. Porosity in these members is mostly fabric-selective laminoid fenestrae (Choquette and Pray 1970; Grover and Read 1978). Fracture-channel porosity is also common. Solution enlargement of the fenestrae has produced dramatic "vuggy" or "bird's eye" rocks. The fenestrae are commonly filled with coarsely crystalline spar and quartz.

Strata of the oolitic–pisolitic member are both grain and matrix supported, but originally may have been mainly grain supported. Much of the matrix may have formed by extensive degradation and replacement of small allochems among the larger grains, giving the illusion of a matrix-supported rock. Principal porosity types include fracture, interparticle, and intraparticle porosity; most pores are of mesopore size and are filled with chert, spar, quartz, and iron oxides.

The upper cherty member is dominantly matrix supported, with poor sorting of scattered peloids and intraclasts. The porosity is primarily laminoid fenestrae with minor moldic and fracture porosity. The fenestrae, molds, and fractures are filled with chert, some spar, and late-stage quartz.

The fenestral fabrics, ooliths, pisoliths, peloids, grapestone, sheet cracks, chip breccias, and laminated dolomicrites are indicative of shallow, moderately agitated marine conditions with occasional emergence. The sparse chert pseudomorphs of probable evaporitic minerals indicate possible transient hypersaline conditions.

Diagenetic history

Tucker (1982, 1983) and Zempolich *et al.* (1988) described and discussed the diagenetic history of the oolitic–pisolitic member of the Beck Spring Dolomite in detail; the diagenetic histories of the fine-grained laminated and cherty members, however, were not addressed. The preservation of fine fabric detail, especially within the oolitic–pisolitic member, is remarkable and requires an unusual explanation. The diagenetic model proposed by Zempolich *et al.* (1988) suggests original deposition as magnesium calcite and aragonite followed by direct transformation to dolomite without an intermediate calcite stage. The absence of an intermediate calcite stage is presumed to have minimized the fabric destruction that usually accompanies dolomitization. Cement stratigraphy indicates deposition of early radial fibrous dolomite, followed by sparry cements, ferroan dolomite, and late-stage silica and chert. Stable-isotope and trace element analyses of the carbonate cements and allochems by Tucker (1982, 1983) and Zempolich *et al.* (1988) showed low Sr and Na contents of the late-stage cements, depletion of ^{18}O in spar, and possible depletion of ^{13}C in spar. Zempolich *et al.* (1988) attributed these characteristics to meteoric water influx and (or) cement precipitation during burial with a concomitant increase in temperature.

Petrochemistry

Atomic absorption spectroscopic (AAS) elemental analyses were performed in an attempt to construct a geochemical profile for the Beck Spring Dolomite which might be used in regional correlations and to provide supporting data to better understand the diagenetic history of the formation. X-ray diffraction (XRD) analyses were performed to identify dolomite and calcite and to determine the crystallographic structure of the dolomite and the mineralogy of the insoluble residues.

Analytical methods

Whole-rock samples, free of obvious weathering effects, were crushed in a jaw crusher and then pulverized in a Spec Ball Mill. Sample powders were dried at 120°C for a minimum of 24 h. Sample powders were dissolved in a solution of three volumes concentrated HCl, one volume concentrated HNO_3, and five volumes deionized, distilled water. All AAS samples and synthetic standards were diluted to appropriate levels with ionization-suppressant solutions (approximately 1500 ppm Na from NaCl in 3% HCl). Synthetic standards were matched to rock sample matrices in terms of background Ca–Mg levels and acid contents. All elements except Fe were measured by the standard curve method. Fe, at concentrations of 2000 ppm or less, was determined by the method of standard additions (Dean and Rains 1971). Sample absorbances were measured using a Perkin–Elmer (P–E) Model 370 Double Beam Atomic Absorption Spectrometer equipped with appropriate hollow cathode element lamps and a P–E Model 165 chart recorder. Ca, Mg, Sr, and Ba were analyzed using N_2O as the oxidant and acetylene as the fuel. Fe, Mn, K, and Na were analyzed in an air–acetylene flame. Reported values (in ppm) represent the mean of 15 separate determinations and were calculated using linear regressions along drift-corrected standard curve segments. The relative standard deviation for measurements of Ca, Mn, Na, and K was less than 1.0%, and Mg, Fe, and Sr analyses had standard deviations of less than 2.5%. Ba measurement precision varied widely from 3.6 to 71.0%, with a mean relative standard deviation of 23.4%.

Whole-rock sample powders prepared for AAS analyses were also used for XRD studies. Insoluble residues from samples yielding more than 10 wt.% insoluble residue were collected by dissolution of large volumes of whole-rock sample powders. A 15–20% sample volume equivalent of fluorite was added as an internal standard to all whole-rock and insoluble-residue samples. Analyses were performed using a Philips (Norelco) XRD unit equipped with a Norelco goniometer, a Norelco scintillation detector with a focusing crystal monochromator, a Hewlett–Packard data control and processing unit, and a Honeywell chart recorder. The radiation was copper (Cu) $K\alpha$.

Results and discussion

AAS analyses

Ca and Mg levels and ratios are essentially the same for all Beck Spring Dolomite samples, except for a few from Silurian Hills and Saratoga Spring which have been calcitized (Table 4). No trends are apparent in Ba, Na, and K values. Na, K, and Sr values are low in all the members (70–120 ppm) and do not differ significantly among them. Na, K, and Sr contents from the whole-rock samples for the oolitic–pisolitic member are consistent with those reported for the component allochems and cements by Tucker (1983) and Zempolich *et al.* (1988). Reequilibration with fresh meteoric groundwater may explain the low Na, K, and Sr values and also is consistent with the proposed mechanism of dolomitization. The Silurian Hills sample has Sr concentrations nearly an order of magnitude higher (1074 ppm) than those from the other study areas. Cements precipitated from Sr-rich groundwater may be responsible for these elevated Sr values. Samples from the Silurian Hills show evidence of extensive replacement and calcitization in thin section.

Fe/Mn levels are two to six times higher in the laminated and cherty members than in the oolitic–pisolitic member. This may be due to original deposition of the laminated and cherty members in more Fe–Mn-rich nearshore, brackish, or siliciclastic-rich environments, as opposed to an open marine environment for the oolitic–pisolitic member; greater diagenetic alteration and loss of Fe and Mn from the oolitic–

TABLE 4. Trace element composition of the Beck Spring Dolomite members

Element	Lower cherty and lower laminated members (mean ± SD; N = 7)	Oolitic–pisolitic member (mean ± SD; N = 7)	Upper cherty member (mean ± SD; N = 3)
Ca (ppm)	219 000±19 300	193 000±69 000	209 000±31 000
Mg	120 000±13 500	113 000±42 000	116 000±22 900
Fe	3 130±4 210	502±236	1 050±672
Mn	243±194	66.2±42.6	102±48.0
Ba	33.2±37.3	72.9±19.8	83.0±10.6
Sr	121±70.6	71.2±17.8	80.2±12.7
Na	163±100	191±112	121±33.3
K	124±200	29.9±28.4	92.0±68.8
Insoluble residue (wt.%)	5.0±7.1	13.6±30.2	8.6±12.4

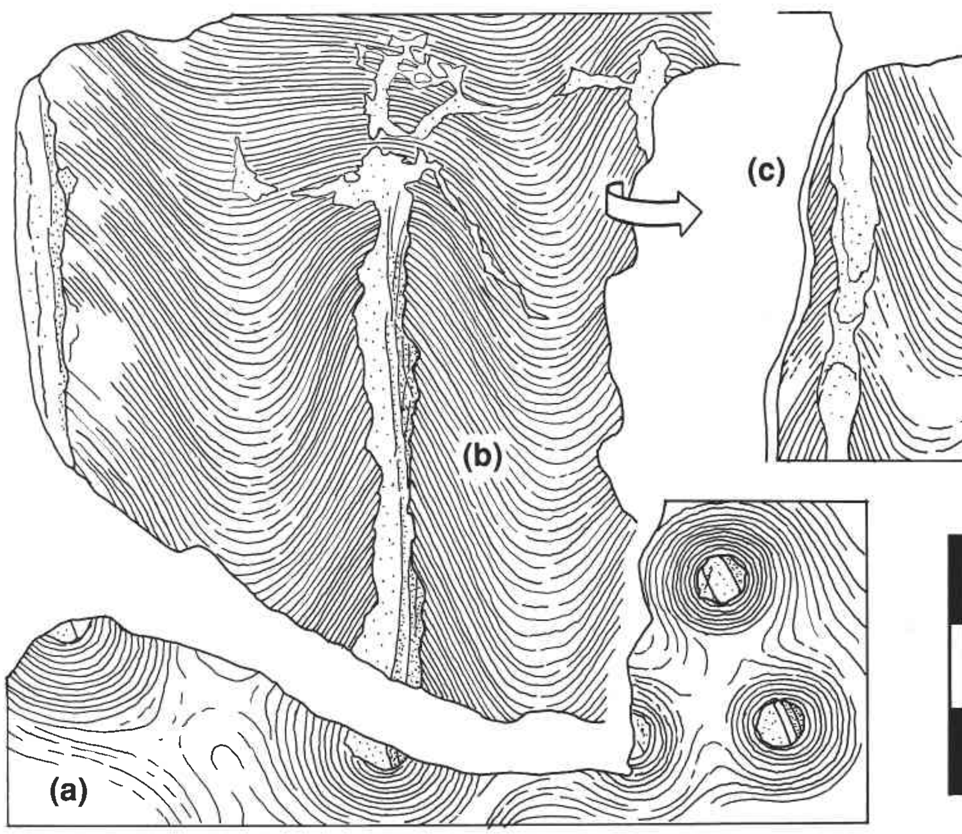

FIG. 5. Illustration of a portion of the conical stromatolite outcrop. (*a*) Exposure of column bases; viewpoint is up the column axes. (*b*) Exposure along column axes showing infilled axial cores. (*c*) View of column face perpendicular to view *b*. Scale bar = 30 cm.

pisolitic member as a result of its greater primary fabric porosity; or selective concentration of Mn and Fe by algae in the laminated and cherty members. Holocene blue-green algae are known to highly concentrate Fe and Mn (Jones *et al.* 1978) in laboratory culture. It is not known whether the measured Fe and Mn occur in carbonate minerals or accessory minerals or are adsorbed to clays. Some of the Fe and Mn may have been leached from accessory minerals, notably magnetite, during sample preparation. However, Fe/Mn ratios in the samples (2.75–29.0) indicate Mn concentrations well in excess of the usual levels found in magnetite and hematite (98–750; Deer *et al.* 1966). In addition, Fe concentrations (up to 11 400 ppm) are much higher than could result from the dissolution of the highest observed magnetite concentrations (0.8%), and oxides usually do not dissolve substantially in HCl. The Fe and Mn may have come from clays in the samples, since the principal form of migration of Mn, Fe, and Ba, at least in fresh water, is thought to be in suspension adsorbed to clay particles (Leutwein and Weise 1962). However, analyses of Fe and Mn concentrations versus weight percent insoluble residue show no apparent correlation between high Fe and Mn and high insoluble residue levels.

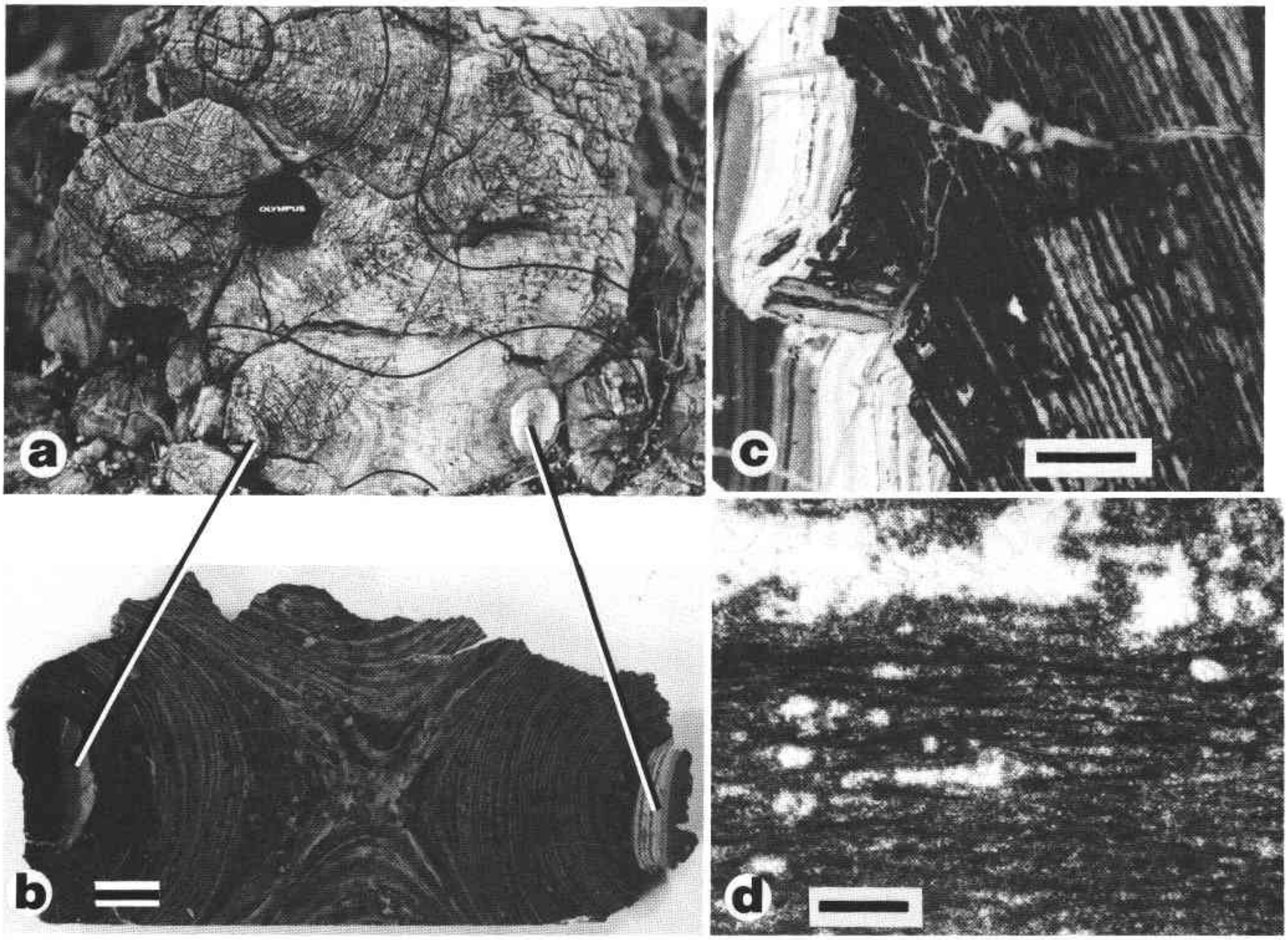

FIG. 6. (*a*) Photograph of horizontal cross sections of conical stromatolite columns showing close lateral column associations and linkages to adjacent columns. Note prominent infilled cores. Lines are added to emphasize column outlines. Lens cap is 52 mm in diameter. (*b*) Horizontal section of sample from above photograph showing cross section through replaced cores and "figure eight" pattern formed by interconnecting laminae. Scale bar = 2 cm. (*c*) Detail of column laminae and replaced axial core showing a fragment of column laminae in core matrix. Scale bar = 1 cm. (*d*) Striated ribbon microstructure. Note lenticular dolospar area between striae. Scale bar = 200 μm.

XRD analyses

The principal carbonate is dolomite, with good ordering based on the presence and sharpness of the primary dolomite superstructure peaks (Goldsmith and Graf 1958). Two samples from Saratoga Spring contain calcite and also show loss or reduction in reflection intensity from the ordering peaks, which indicates a possible breakdown in the stoichiometric ordering due to secondary calcitization. Mole percent Ca–Mg values, computed from AAS data, range from $Ca_{54}Mg_{46}$ to $Ca_{60}Mg_{40}$.

Quartz and traces of magnetite dominate the insoluble residues of the Beck Spring Dolomite. The insoluble residues are medium dark grey to black and are texturally similar to powdered charcoal when dry. Petrographically, most residues show numerous rounded quartz grains in a felty black matrix. The black felty material may be the clinochlore leutenbergite, which was detected in one sample, but the presence of graphite cannot be discounted because its main characteristic XRD peaks overlap those of quartz. Talc and clinochlore were identified in residues from Virgin Spring Wash (Fig. 1), an area with numerous faults. These minerals probably formed as a result of low-grade metamorphism associated with faulting and (or) subsequent igneous intrusion along the faults.

Stromatolites

Classification and biostratigraphy

The Beck Spring stromatolites were classified based on observable characteristics (i.e., mode of occurrence, column shape, lamina shape, microstructure). The macromorphological nomenclature of Hofmann (1969) and Walter (1976) was used; the microstructural descriptions follow Komar (1966). The fourfold Russian biostratigraphic subdivision of the Middle to Late Proterozoic is used. The four intervals are the Early, Middle, and Late Riphean periods and the Sinian period, with boundaries at approximately 1650, 1350, 1050, and 800 Ma (Bertrand-Sarfati 1981; Harland *et al.* 1982; Christie-Blick and Levy 1989).

Descriptions

Four types of stromatolite morphologies are recognized in the Beck Spring Dolomite: conical, columnar forms similar to members of the group *Conophyton*; eroded, irregular columnar forms similar to members of the groups *Baicalia* Krylov or *Kussiella* Krylov; a variety of nodular forms; and stratiform types (*Stratifera* Korolyuk). The morphologies and distributions of the modular forms are highly variable and have not been extensively evaluated as part of this study.

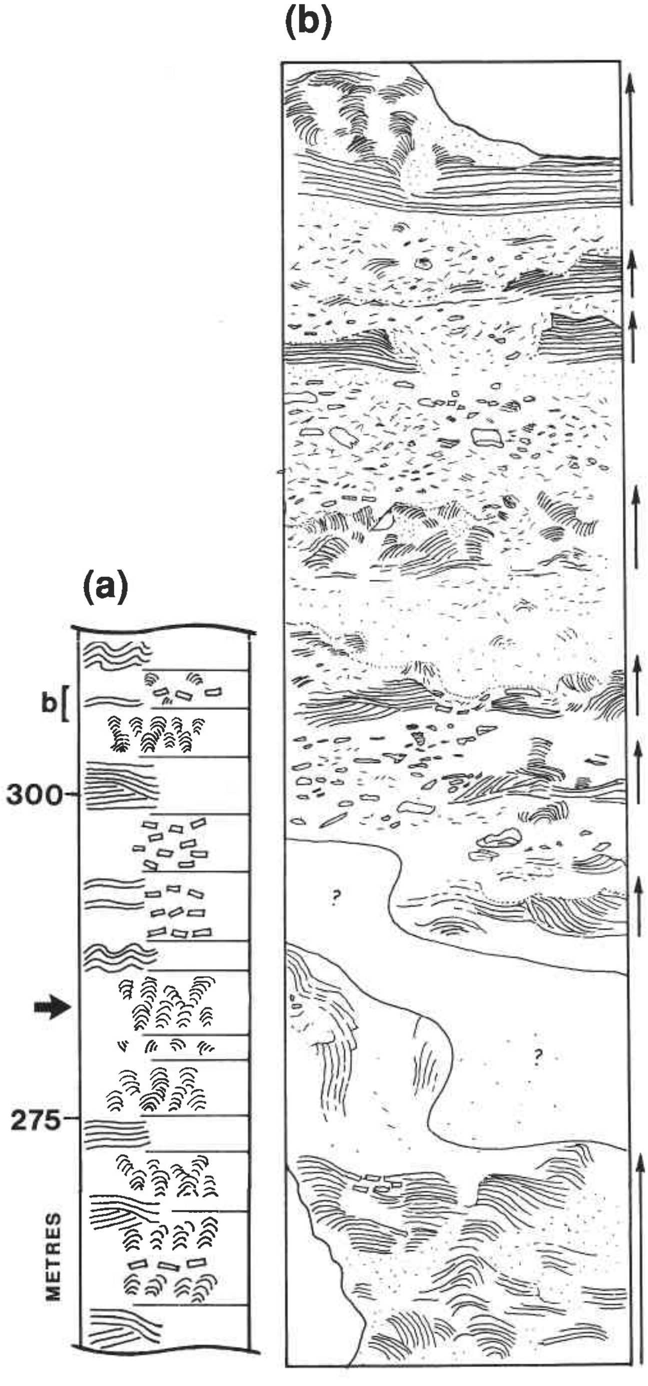

FIG. 7. (*a*) Detailed section of eroded, irregular columnar stromatolite interval at Acme mine. Arrow indicates location of the photograph in Fig. 8*a*. Symbols as in Fig. 3. (*b*) Details of interval from 308 to 310 m, illustrating typical cycles of stratiform to columnar growth and subsequent disruption (arrows). Top of illustrated outcrop is shown in Fig. 8*d*.

Conical columnar forms

The conical columnar forms, which were found only at the Acme mine, occur as laterally linked, locally overturned columns in an 8–10 m thick interval bounded above and below by coarse breccia beds and broadly planar-laminated dolomicrite and dolomicrosparite (Fig. 5). The breccia bed immediately below the conical stromatolites is composed primarily of conical column fragments and debris. The conical columns are circular to subcircular in cross section and as much as 0.4 m in diameter. Axes of the columns appear to have been erect, straight, subparallel, and spaced 15–45 cm apart. Maximum observed synoptic relief is 25 cm. Column margins are without walls (naked), and column laminae interconnect laterally (Fig. 6*a*) with adjacent columns to form a nearly continuous growth surface. Laminae are extremely uniform in thickness (0.8–1.0 mm) and curve steeply (50–60°) upwards to form the sides of the cones. Rare linear ridges connect adjacent column crests. Horizontal cross sections through adjacent columns show distinctive "figure eight" patterns (Fig. 6*b*). The axial zones in nearly all the observed columns have been eroded to form subcylindrical tubes filled with layered dolomite and dolospar (Fig. 6*c*). The layering in the axial zone infills is nearly perpendicular to the column axes, suggesting that the columns were horizontal when the axial zones were infilled. Large-scale fractures in the columns are filled with the same layered carbonate. The microstructure (Fig. 6*d*) is a fragmented ribbon-striated to linearly striated form. The moderately conical laminae, circular cross sections, and striated microstructure with lenticular inclusions suggest that these forms belong to the group *Conophyton*. The Beck Spring forms show similarities to published descriptions of *Conophyton garganicum* Korlyuk (Maslov 1938; Komar *et al.* 1965; Komar 1966; Krylov 1967).

Eroded, irregular columnar forms

The eroded, irregular columnar stromatolites occur at the Acme mine in 3–5 m thick beds in a dolomite deposit associated with abundant breccia beds and disrupted, laminated dolomicrites and dolomicrosparites (Fig. 7). Similar forms in the Black Mountains and at Beck Spring were described by Shafer (1983). Columns are broad, tuberous to bumpy, subcylindrical, irregular to club shaped, and have round to ovoid cross sections (Fig. 8). They are generally 2–8 cm in diameter and 10–20 cm high. Many columns are broken, restacked, and locally coalesced, with brecciated debris filling the interspaces (Fig. 8*b*). The column margins are naked to ragged with abundant peaks, cornices, and bridges. Laminae are gently to steeply convex and are uniformly 1 mm thick. Microstructure (Fig. 8*c*) is a slightly diffuse ribbon type, similar to the "film microstructure" described by Bertrand-Sarfati (1976). The irregular disposition of the column sections gives the appearance of branching, but this may be due to erosion and subsequent regrowth at a slightly divergent angle. The two samples sectioned for reconstruction show only this inferred erosion-induced reorientation (Figs. 9*a*, 9*b*). Field observations suggest that there are branched forms in many exposures (Figs. 8*a*, 9*c*), but further sampling and sectioning are required to confirm this. The eroded, irregular columnar forms were originally assigned by Licari (1971) to the groups *Kussiella* Krylov or *Colonella* Komar. Many samples, however, lack *Colonella*'s straight columns, smooth margins, and regular subcylindrical columnar cross sections. The more regular, straight, club-shaped columns with possible parallel branching (Fig. 8*d*) resemble members of the group *Kussiella* (Komar 1966). The irregular, tuberous, and bumpy columns with naked to ragged column margins, banded microstructure, and divergent branches (Figs. 8*b*, 9*c*) are more characteristic of the group *Baicalia* (Krylov 1967; Preiss 1972, 1976). These forms are similar to eroded samples of *Baicalia burra* Preiss (Preiss 1976).

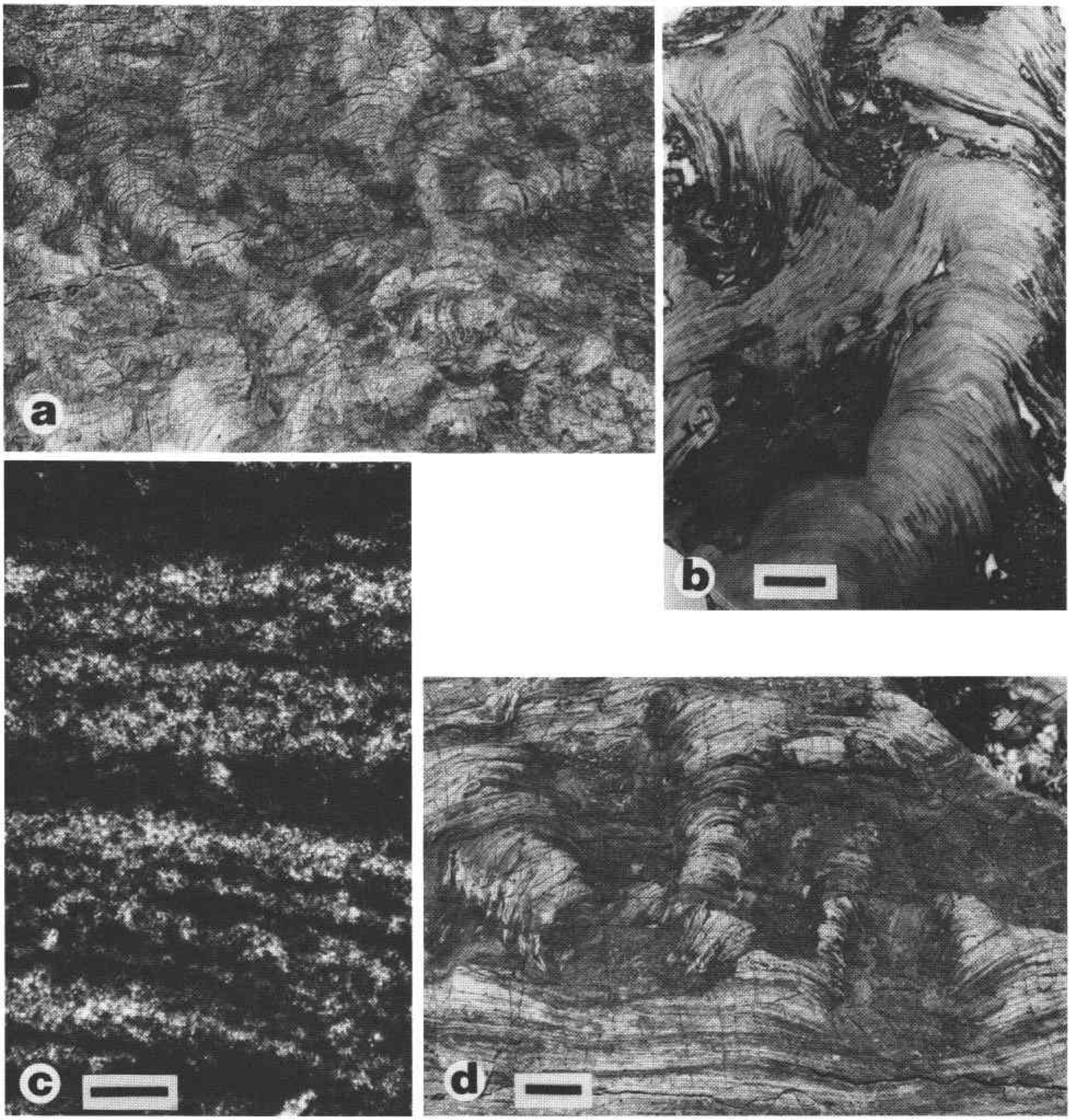

FIG. 8. Photographs of irregular, eroded, and locally broken columnar forms. (*a*) Outcrop surface showing erosion-induced pseudobranching and possible true branching. Lens cap is 52 mm in diameter. (*b*) Column detail showing interconnected laminae, ragged and eroded margins, and abundant fine breccia in column interspaces. Irregular white vugs are filled with coarsely crystalline dolospar. Scale bar = 2 cm. (*c*) Ribbon microstructure composed of alternating dark micritic laminae and clotted dolomicrospar. Scale bar = 200 μm. (*d*) Club-shaped forms showing several broken segments of columns. Typical flat *Stratifera* growth is apparent at the base of the photograph. Scale bar = 3 cm.

Stratiform forms

The stratiform stromatolites occur as regular, continuous units extending laterally for tens of metres. Continuous beds range in thickness from less than 0.8 m to nearly 30 m. Beds are commonly disrupted by tongues of tabular breccia, flat pebble conglomerate, sandstone, and shale. The stratiform stromatolites are widely distributed throughout the Beck Spring Dolomite in the study area. Planar to broadly undulose forms are dominant in the lower members at Beck Spring, and the Snow White and Acme mines. Highly crenulated morphologies (Figs. 10*a*, 10*b*, 10*d*) occur at Saratoga Spring and in the upper cherty member at Beck Spring and the Snow White and Acme mines.

Planar to broadly undulose types form arches and domes as much as 0.5 m high and 1–2 m long. Laminae in the broadly undulose to domal forms are 1–5 mm thick and smooth with high to moderate inheritance. These laminae are continuous for metres, with only diastemic surfaces and sheet cracks present. The laminae show distinct banded or ribbon microstructure (Fig. 10*c*) and may be composed of peloids.

The laminae of the wrinkled, wavy forms average 1 mm in thickness, show moderate inheritance, and commonly are

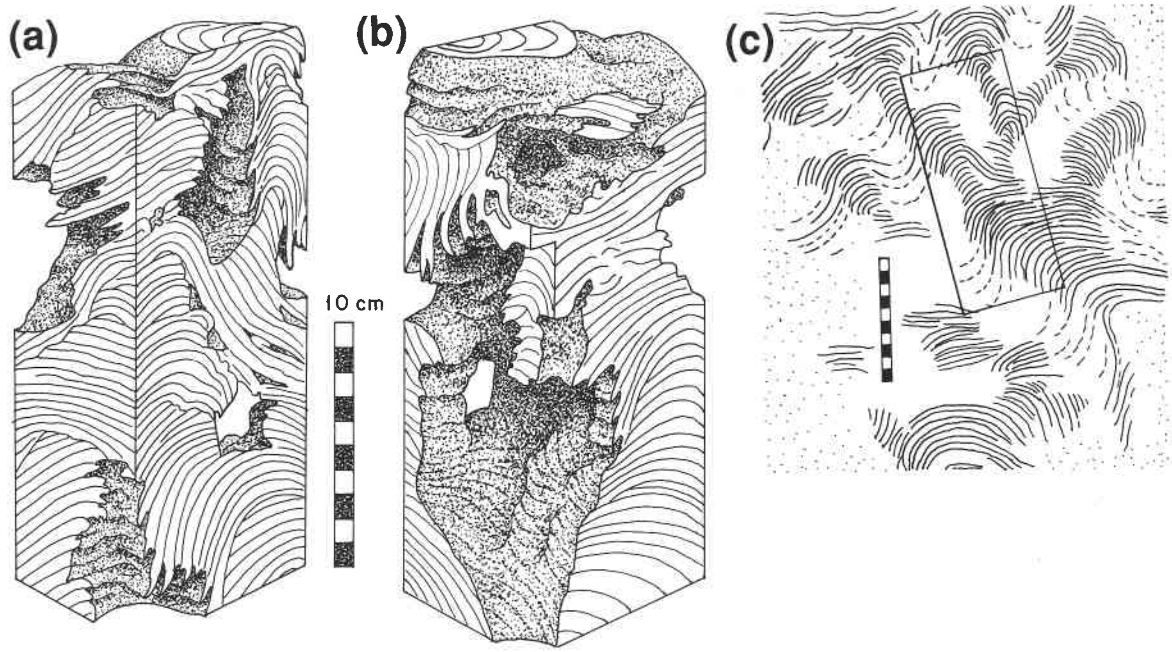

FIG. 9. Reconstructions of irregular, broken columnar forms. (*a*) Growth form reconstructed by serial slab method from sample shown in Fig. 8. Note large, presumably erosional cavities and apparent column coalescence in the lower left corner. (*b*) Reverse side of reconstruction in *a*. (*c*) Generalized sketch of the outcrop surface from which the sample in *a* and *b* was obtained. Scale bar = 10 cm.

silicified and weather differentially. Microstructure of the laminae appears uniformly peloidal.

The distinctive stratiform morphology, smooth laminations, and high to moderate inheritance indicate that these forms most likely belong to the group *Stratifera* Korolyuk (Komar 1966). Of the forms for which detailed descriptions are available, *Stratifera undata* Komar is the most similar.

Stromatolite paleoenvironments and age ranges

Environmental interpretation of the assemblages is difficult because few Holocene analogues of the columnar stromatolites have been thoroughly studied (Logan *et al.* 1974; Donaldson 1976; Playford *et al.* 1976; Dill 1991). Based on both Holocene examples and facies in ancient deposits (Rezak 1957; Awramik 1971; Donaldson 1976; Hoffman 1976; Horodyski 1977, 1989; Kerans and Donaldson 1989), *Conophyton* has been interpreted as primarily a subtidal form. The conical columns at the Acme mine are smooth, show no curls or erosion of growth surfaces, have limited fenestral porosity, and have extremely regular, uniform laminae; this is suggestive of a low-energy, nonexposed growth environment. The maximum 25 cm column height and limited column stacking suggest fairly shallow subtidal conditions (Kerans and Donaldson 1989). However, the eroded axial zones, fractured columns, and associated planar macrolaminated strata containing evaporitic mineral pseudomorphs suggest emergence and (or) exposure. The conical forms probably grew in a low-energy lagoonal setting and subsequently were exposed and eroded as the lagoon filled with stromatolites and associated sediments. The eroded conical columns were then submerged, possibly as a result of local slumping or drowning by rising water levels, and the axial zones were infilled with layered dolomite.

Baicalia forms have been reported from low- to moderate-energy environments and emergent to subtidal conditions (Preiss 1972; Donaldson 1976; Hofmann 1976; Horodyski 1989). The eroded, irregular columns of the stromatolites in the Beck Spring Dolomite suggest exposure to moderate- to high-energy currents. Refolded, curled laminae edges and associated breccia may indicate occasional emergent conditions.

The *Stratifera* forms have been reported from a wide range of environments. The wrinkled and wavy to broadly undulose stromatolitic forms are similar in gross morphology to algal mats of Holocene tidal-flat environments (Davies 1970; Kinsman and Park 1976; Hardie 1977).

Based on the published biostratigraphic age ranges of the observed groups (Krylov and Semikhatov 1976; Bertrand-Sarfati 1981), the Beck Spring Dolomite stromatolites should be of Early or Middle Riphean age (1650–1050 Ma). The *Baicalia–Conophyton* assemblage is a very typical Middle Riphean assemblage (Semikhatov 1976; Horodyski 1989). A *Baicalia* or *Jacutophyton*-like form, also of presumed Middle Riphean age, has been reported from the underlying Crystal Spring Formation (Howell 1971). Roberts (1976) reported *Baicalia* and *Conophyton* forms in his study of the lower member of the Crystal Spring Formation. However, as neither Howell (1971) nor Roberts (1976) provided detailed descriptions of stromatolite morphology and microstructure, their identifications must be considered tentative. If their identifications are correct, the Beck Spring stromatolites cannot be older than the *Baicalia–Jacutophyton–Conophyton* assemblages and would be Middle Riphean (1350–1050 Ma) in age or younger. A Middle Riphean or younger age is consistent with current age estimates of the Pahrump Group (Christie-Blick and Levy 1989).

Discussion and conclusions

The Beck Spring Dolomite is a tabular body of predominantly algal-laminated dolomite of uniform thickness and lithology dominated by shallow-marine platform facies. Sedimentary structures of the Beck Spring Dolomite show the

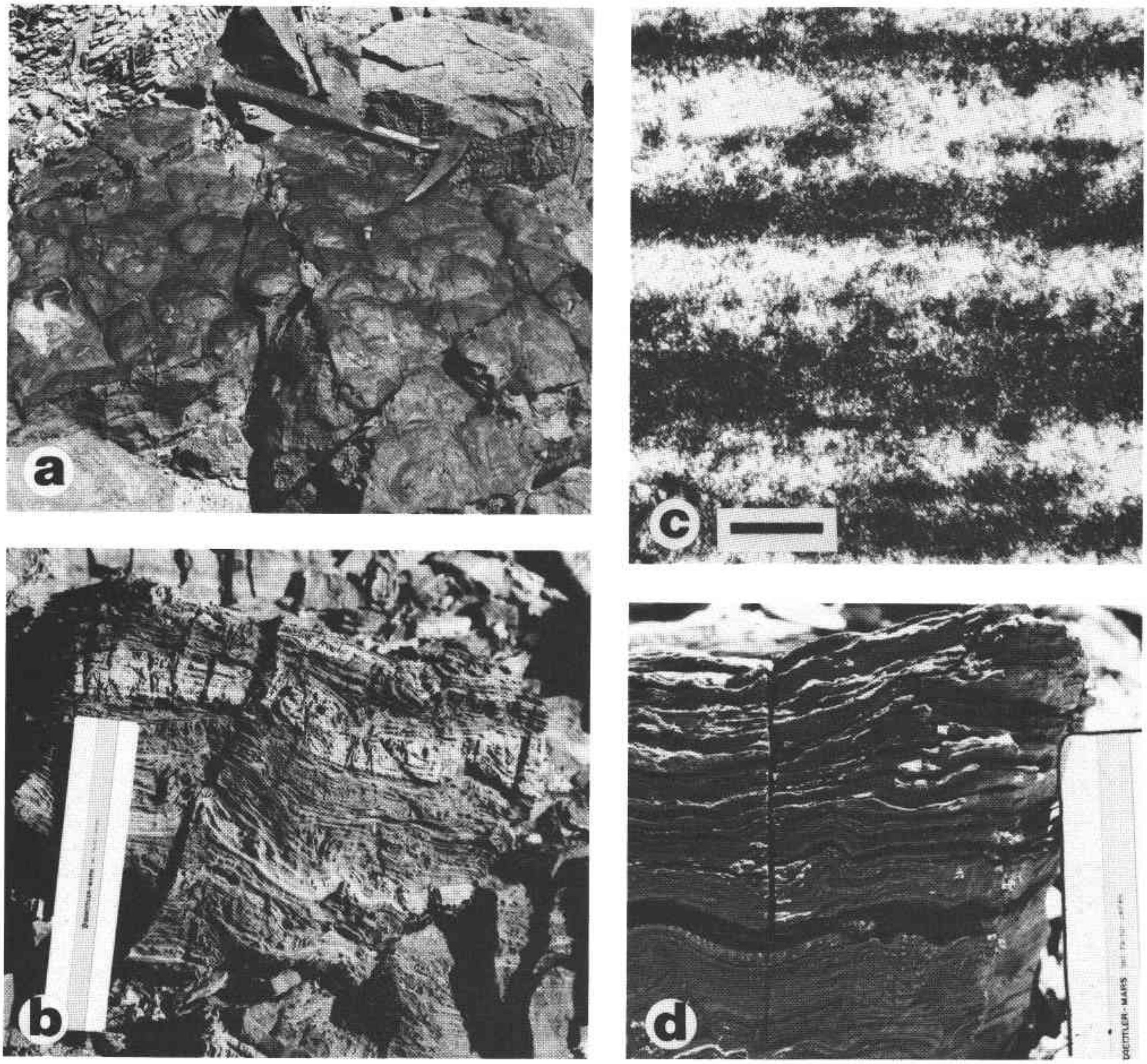

FIG. 10. Photographs of macro- and micro-structure of the stratiform stromatolites. (*a*) Cherty bedding surface of wavy or low-amplitude domal forms. Hammer is 33 cm long. (*b*) High wrinkled and wavy laminae and thin bedding. Scale is 15 cm long. (*c*) Distinct, banded microstructure from a planar-laminated form. Scale bar = 200 μm. (*d*) High wavy, laminated form. Scale is 15 cm long.

effects of algal domination of the environment. Omnipresent algal mats trapped and bound or agglutinated otherwise free-moving carbonate and siliciclastic grains, and erect columnar stromatolites acted as sediment baffles and most likely precipitated carbonate directly or indirectly. Primary sedimentary structures, similar to those present in shallow-marine siliciclastic deposits (e.g., low-angle planar cross-strata and lenticular bedding), are observed only in siliciclastic-rich dolomite where algal control of lamina morphology was reduced or eliminated.

Holocene analogs for the Beck Spring Dolomite commonly occur as laterally associated facies. The observed facies changes may record minor changes in sea level and associated migration of adjacent lithotypes, but they more likely resulted from development of offshore bars or shoals, perhaps related to regional subsidence (Marian 1979; Shafer 1983). The lack of abrupt lithologic changes and the persistence of presumed equivalent lithotypes through hundreds of metres of strata suggest slow, gradual subsidence. The depositional environments represented by the Beck Spring Dolomite, especially in the Saratoga Spring area, are quite similar to the mixed fluvial–tidal facies proposed for the underlying Crystal Spring Formation (Roberts 1976). The gradational nature of the Crystal Spring – Beck Spring contact at many localities also argues for similar depositional environments, at least between upper Crystal Spring and lower Beck Spring strata.

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Aitken, J. D. 1967. Classification and environmental significance of cryptalgal limestone and dolomites with illustrations from the Cambrian and Ordovician of southwestern Alberta. Journal of Sedimentary Petrology, **37**: 1163–1178.

Awramik, S. M. 1971. Precambrian columnar stromatolite diversity: reflection of metazoan appearance. Science (Washington, D.C.), **174**: 825–827.

Bathurst, R. C. G. 1975. Carbonate sediments and their diagenesis. Elsevier, Amsterdam.

Beales, F. W. 1965. Diagenesis in pelleted limestones. *In* Dolomitization and limestone diagenesis. *Edited by* L. C. Pray and R. C. Murray. Society of Economic Paleontologists and Mineralogists, Special Publication 13, pp. 49–70.

Bertrand-Sarfati, J. 1976. An attempt to classify Late Precambrian stromatolite microstructures. *In* Stromatolites. *Edited by* M. R. Walter. Elsevier, Amsterdam, pp. 251–260.

Bertrand-Sarfati, J. 1981. Stromatolite biostratigraphy. Precambrian Research, **15**: 353–371.

Choquette, P. W., and Pray, L. C. 1970. Geologic nomenclature and classification of porosity in sedimentary carbonates. American Association of Petroleum Geologists Bulletin, **54**: 207–250.

Christie-Blick, N., and Levy, M. 1989. Stratigraphic and tectonic framework of upper Proterozoic and Cambrian rocks in the western United States. *In* Late Proterozoic and Cambrian tectonics, sedimentation, and record of metazoan radiation in the western United States. *Edited by* N. Christie-Blick and M. Levy. American Geophysical Union, Washington, D.C., pp. 7–21.

Cloud, P. E., Licari, G. R., Wright, L. A., and Troxel, B. W. 1969. Proterozoic eukaryotes from eastern California. Proceedings of the National Academy of Sciences of the United States of America, **62**: 623–631.

Davies, G. R. 1970. Algal-laminated sediments, Gladstone embayment, Shark Bay, Western Australia. *In* Carbonate sedimentation and environments, Shark Bay, Western Australia. *Edited by* B. W. Logan. American Association of Petroleum Geologists, Memoir 13, pp. 169–205.

Dean, J. A., and Rains, T. C. 1971. Flame emission and atomic absorption spectrometry. Vol. 2. Marcel Dekker, New York.

Deer, W. A., Howie, R. A., and Zussman, J. 1966. An introduction to the rock forming minerals. Longman Group, London.

Diehl, P. E. 1976. Stratigraphy and sedimentology of the Wood Canyon Formation, Death Valley area, California. *In* Geologic features of Death Valley. *Edited by* B. W. Troxel and L. A. Wright. California Division of Mines and Geology, Special Report 106, pp. 51–62.

Dill, R. F. 1991. Subtidal stromatolites, ooids and crusted-lime muds at the Great Bahama Bank margin. *In* From shoreline to abyss: contributions in marine geology in honor of Francis P. Shepard. *Edited by* R. H. Osborne. Society of Economic Paleontologists and Mineralogists, Special Publication 46, pp. 147–171.

Donaldson, J. A. 1976. Paleoecology of *Conophyton* and associated stromatolites in the Precambrian Dismal Lakes and Rae Groups, Canada. *In* Stromatolites. *Edited by* M. R. Walter. Elsevier, Amsterdam, pp. 523–534.

Dunham, R. J. 1962. Classification of carbonate rocks according to depositional texture. *In* Classification of carbonate rocks. *Edited by* W. E. Ham. American Association of Petroleum Geologists, Memoir 1, pp. 108–121.

Folk, R. L. 1962. Spectral subdivision of limestone types. *In* Classification of carbonate rocks. *Edited by* W. E. Ham. American Association of Petroleum Geologists, Memoir 1, pp. 62–84.

Folk, R. L. 1965. Some aspects of recrystallization in ancient limestones. *In* Dolomite and limestones diagenesis. *Edited by* L. C. Pray and R. C. Murray. Society of Economic Paleontologists and Mineralogists, Special Publication 13, pp. 14–48.

Friedman, G. M. 1971. Staining. *In* Procedures in sedimentary petrology. *Edited by* R. E. Carver. Wiley-Interscience, New York. pp. 511–530.

Galehouse, J. S. 1971. Point counting. *In* Procedures in sedimentary petrology. *Edited by* R. E. Carver. Wiley-Interscience, New York, pp. 385–408.

Ginsburg, R. N., and Hardie, L. A. 1975. Tidal and storm deposits, northwestern Andros Island, Bahamas. *In* Tidal deposits. *Edited by* R. N. Ginsburg. Springer-Verlag, New York, pp. 201–208.

Goldsmith, J. R., and Graf, D. L. 1958. Structural and compositional variations in some natural dolomites. Journal of Geology, **66**: 678–693.

Grover, G., and Read, J. F. 1978. Fenestral and associated vadose diagenetic fabrics of tidal flat carbonates, Middle Ordovician New Market Limestone, southwestern Virginia. Journal of Sedimentary Petrology, **48**: 453–473.

Gutstadt, A. M. 1968. Petrology and depositional environments of the Beck Spring Dolomite (Precambrian), Kingston Range, California. Journal of Sedimentary Petrology, **38**: 1280–1289.

Hammond, J. G. 1986. Geochemistry and petrogenesis of Proterozoic diabase in the southern Death Valley region of California. Contributions to Mineralogy and Petrology, **93**: 312–321.

Hardie, L. A. 1977. Algal structures in cemented crusts and their environmental significance. *In* Sedimentation of the modern carbonate tidal flats of northwest Andros Island, Bahamas. *Edited by* L. A. Hardie. Johns Hopkins University Press, Baltimore, Md., pp. 159–177.

Harland, W. B., Cox, A. V., Llewellyn, P. G., *et al*. 1982. A geologic time scale. Press Syndicate of the University of Cambridge, Cambridge.

Heaman, L. M., and Grotzinger, J. P. 1992. 1.08 Ga diabase sills in the Pahrump Group, California: implications for development of the Cordilleran miogeocline. Geology, **20**: 637–640.

Hoffman, P. 1976. Environmental diversity of Middle Precambrian stromatolites. *In* Stromatolites. *Edited by* M. R. Walter. Elsevier, Amsterdam, pp. 599–612.

Hofmann, H. J. 1969. Attributes of stromatolites. Geological Survey of Canada, Paper 69-39.

Horodyski, R. J. 1977. Environmental influences of columnar stromatolite branching pattern: examples from the Middle Proterozoic Belt Supergroup, Glacier National Park, Montana. Journal of Paleontology, **51**: 661–671.

Horodyski, R. J. 1989. Stromatolites of the Belt Supergroup, Glacier National Park, Montana. *In* Middle Proterozoic Belt Supergroup, western Montana. *Edited by* D. Winston, R. J. Horodyski, and J. W. Whipple. American Geophysical Union, Washington, D.C., Field Trip Guidebook T334, pp. 27–42.

Howell, D. G. 1971. A stromatolite from the Proterozoic Pahrump Group, eastern California. Journal of Paleontology, **45**: 48–51.

Illing, L. V. 1954. Bahaman calcareous sands. American Association of Petroleum Geologists Bulletin, **38**: 1–95.

Jones, G. E., Murray, L., and Carr, N. G. 1978. Trace element composition of 5 cyanobacteria. *In* Third international symposium on environmental biogeochemistry and geomicrobiology. *Edited by* W. E. Krumbein. Science Publishers, Ann Arbor, Mich., pp. 967–974.

Kerans, C., and Donaldson, J. A. 1989. Deepwater conical stromatolite reef, Sulky Formation (Dismal Lakes Group), Middle Proterozoic, N.W.T. *In* Reefs, Canada and adjacent area. *Edited by* H. H. J. Geldsetzer, N. P. James, and G. E. Tebbutt. Canadian Society of Petroleum Geologists, Memoir 13, pp. 81–88.

Kinsman, D. J. J., and Park, R. K. 1976. Algal belt and coastal sabkha evolution, Trucial Coast, Persial Gulf. *In* Stromatolites. *Edited by* M. R. Walter. Elsevier, Amsterdam, pp. 421–434.

Komar, V. A. 1966. Upper Precambrian stromatolites in the north of the Siberian Platform, and their stratigraphic significance. [Translated from Russian by the Bureau for Translations, Foreign Language Division, Department of Secretary of State, Ottawa, 1967]. Trudy Geologicheskogo Instituta Akademiya Nauk SSSR, no. 154.

Komar, V. A., Raaben, M. E., and Semikhatov, M. A. 1965. *Conophytons* in the Riphean of the U.S.S.R. and their stratigraphic importance. [Translated from Russian by the Bureau for Translations, Foreign Language Division, Department of Secretary of State, Ottawa, 1968.] Trudy Geologicheskogo Instituta Akademiya Nauk SSSR, no. 131.

Krylov, I. N. 1967. Riphean and Lower Cambrian stromatolites of Tien-Shan and Karatau. [Translated from Russian by the Bureau for Translations, Foreign Language Division, Department of Secretary of State, Ottawa, 1969.] Trudy Geologicheskogo Instituta Akademiya Nauk SSSR, no. 171.

Krylov, I. N., and Semikhatov, M. A. 1976. Table of time ranges of the principal groups of Precambrian stromatolites. *In* Stromatolites. *Edited by* M. R. Walter. Elsevier, Amsterdam, pp. 693–694.

Labotka, T. C., and Albee, A. L. 1977. Late Precambrian depositional environment of the Pahrump Group, Panamint Mountains, California. California Division of Mines and Geology, Special Report 129, pp. 93–100.

Labotka, T. C., Albee, A. L., Lanphere, M. A., and McDowell, S. D. 1980*a*. Stratigraphy, structure, and metamorphism in the central Panamint Mountains (Telescope Peak quadrangle), Death Valley area, California. Part I. Geological Society of America Bulletin, **91**: 125–129.

Labotka, T. C., Albee, A. L., Lanphere, M. A., and McDowell, S. D. 1980*b*. Stratigraphy, structure, and metamorphism in the central Panamint Mountains (Telescope Peak quadrangle), Death Valley area, California. Part II. Geological Society of America Bulletin, **91**: 843–933.

Leutwein, F., and Weise, L. 1962. Hydrogeochemische Untersuchungen an erzgebirgischen Gruben- und Oberflachenwassern. Geochimica et Cosmochimica Acta, **26**: 1333–1348.

Licari, G. R. 1971. Paleontology and paleoecology of the Proterozoic Beck Spring Dolomite of eastern California. Ph.D. dissertation, University of California, Los Angeles.

Licari, G. R. 1978. Biogeology of the late pre-Phanerozoic Beck Spring Dolomite of eastern California. Journal of Paleontology, **52**: 767–792.

Logan, B. W., Hoffman, P., and Gebelein, C. D. 1974. Algal mats, cryptalgal fabrics and structures, Hamelin Pool, Western Australia. *In* Evolution and diagenesis of Quaternary carbonate sequences, Shark Bay, Western Australia. *Edited by* B. W. Logan. American Association of Petroleum Geologists, Memoir 22, pp. 140–194.

Marian, M. L. 1979. Sedimentology of the Beck Spring Dolomite, eastern Mojave Desert, California. M.S. thesis, University of Southern California, Los Angeles.

Maslov. V. P. 1938. On the nature of the stromatolite *Conophyton*. Problems of Paleontology, **4**: 323–332.

Maude, R. L. 1983. Stratigraphy, petrography and depositional environments of the carbonate-terrigenous member of the Crystal Spring Formation, Death Valley, California. Ph.D. thesis, Pennsylvania State University, University Park, Penn.

McBride, E. G. 1963. A classification of common sandstones. Journal of Sedimentary Petrology, **33**: 664–669.

Monty, C. L. V. 1976. The origin and development of cryptalgal fabrics. *In* Stromatolites. *Edited by* M. R. Walter. Elsevier, Amsterdam, pp. 447–478.

Pierce, D., and Cloud, P. E. 1979. New microbiota fossils from 1.3 billion year old rocks of eastern California. Geomicrobiology Journal, **1**: 295–309.

Playford, P. E., Cockbain, A. C., Druce, E. C., and Wray, J. L. 1976. Devonian stromatolites from the Canning Basin, Western Australia. *In* Stromatolites. *Edited by* M. R. Walter. Elsevier, Amsterdam, pp. 543–564.

Preiss, W. V. 1972. The systematics of South Australian Precambrian and Cambrian stromatolites, Part 1. Transactions of the Royal Society of South Australia, **96**: 67–100.

Preiss, W. V. 1976. Proterozoic stromatolites from the Nabberu and Officer Basins, Western Australia, and their biostratigraphic significance. Geological Survey of South Australia, Report of Investigations 47.

Rezak, R. 1957. Stromatolites of the Belt Series in Glacier National Park and vicinity, Montana. United States Geological Survey, Professional Paper 294-D, pp. 127–154.

Roberts, M. T. 1976. Stratigraphy and depositional environments of the Crystal Spring Formation, southern Death Valley region. *In* Geologic features of Death Valley, California. *Edited by* B. W. Troxel and L. A. Wright. California Division of Mines and Geology, Special Report 106, pp. 35–44.

Roberts, M. T. 1982. Depositional Environments and tectonic setting of the Crystal Spring Formation, Death Valley region, California. *In* Geology of selected areas in the San Bernardino Mountains, western Mojave Desert and southern Great Basin, California. *Edited by* J. D. Cooper, B. W. Troxel, and L. A. Wright. Geological Society of America, Cordilleran Section, Anaheim, Calif., pp. 143–154.

Semikhatov, M. A. 1976. Experience in stromatolite studies in the U.S.S.R. *In* Stromatolites. *Edited by* M. R. Walter. Elsevier, Amsterdam, pp. 613–633.

Shafer, D. C. 1983. Petrology and depositional environments of the Beck Spring Dolomite, southern Death Valley region, California. M.S. thesis, University of California, Davis, Calif.

Shinn, E. A., Lloyd, R. M., and Ginsburg, R. N. 1969. Anatomy of a modern carbonate tidal flat, Andros Island, Bahamas. Journal of Sedimentary Petrology, **39**: 1202–1228.

Silver, L. T., McKinney, C. R., and Wright, L. A. 1962. Some Precambrian ages in the Panamint Range, Death Valley, California. Geological Society of America, Special Paper 68.

Stewart, J. H. 1976. Late Precambrian evolution of North America: plate tectonic implications. Geology, **4**: 11–15.

Tucker, M. E. 1982. Precambrian dolomites: petrographic and isotopic evidence that they differ from Phanerozoic dolomites. Geology, **10**: 7–12.

Tucker, M. E. 1983. Diagenesis, geochemistry, and origin of a Precambrian dolomite: the Beck Spring Dolomite of eastern California. Journal of Sedimentary Petrology, **53**: 1097–1119.

Walter, M. R. 1976. Glossary of selected terms. *In* Stromatolites. *Edited by* M. R. Walter. Elsevier, Amsterdam, pp. 687–692.

Wolf, K. H. 1965. Petrogenesis and paleoenvironments of Devonian algal limestones of New South Wales. Sedimentology, **4**: 113–178.

Wright, L. A., Roberts, M. T., and Diehl, P. E. 1976. Precambrian sedimentary environments of the Death Valley region, eastern California. *In* Geologic features of Death Valley, California. *Edited by* B. W. Troxel and L. A. Wright. California Division of Mines and Geology, Special Report 106, pp. 7–15.

Wright, L. A., Williams, E. G., and Cloud, P. E. 1978. Algal and cryptalgal structures and platform environments of the late pre-Phanerozoic Noonday Dolomite, eastern California. Geological Society of America Bulletin, **89**: 321–333.

Zempolich, W. G., Wilkinson, B. H., and Lohmann, K. C. 1988. Diagenesis of Late Proterozoic carbonates: the Beck Spring Dolomite of eastern California. Journal of Sedimentary Petrology, **58**: 656–672.