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Miocene lacustrine algal reefs—southwestern Snake River Plain, Idaho

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Abstract

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The Hot Spring limestone is a shallow-water algal carbonate within a late Tertiary transgressive lacustrine sequence exposed in the southwestern Snake River Plain. This 5 m thick lensoid sequence crops out over an 80 km^2 area that closely approximates original areal extent of nearshore carbonate accumulation. Reefal bodies consist of closely packed algal cylinders, several decimeters in height, each of which includes a dense laminated carbonate wall surrounding porous digitate carbonate that radiates outward and upward from one or more hollow tubes. These coalesce upsection into separate vertical columns several meters in diameter. Moderately well-sorted terrigenous and molluscan debris deposited between columns during growth indicates these structures were resistant to wave erosion and, therefore, were true reefs. Thick rings of littoral carbonate surrounding the upper walls of each column record the final stages of reef development.

Structural attributes exhibited by these Miocene carbonate bodies are also common to a number of Tertiary and Quaternary algal buildups reported from other lacustrine settings. Although features within the Hot Spring limestone are complex in gross morphology and structural detail, both columnar reefs and algal cylinders display little variation in size, shape, or internal structure between areas of varying water depth and wave energy, thus reflecting the importance of biological processes as well as physical processes during reef development.

Introduction

Processes of deposition and diagenesis of lacustrine carbonate have become the object of increasing attention over the past two decades, and it is now widely recognized that limestone formation in lake settings may give rise to a wide range of carbonate mineralogies and facies recording the importance of a variety of physical, biological, and chemical factors during deposition and lithification of carbonate sediment (e.g. Cohen and Thouin, 1987). Among lacustrine environments in which carbonate sediment accumulates, those in which reefal communities predominate (e.g. Dean and Eggleston, 1975) are among the most interesting and least understood. One such reefal deposit is a spectacular nearshore algal carbonate within the Miocene Chalk Hills Formation of the southwestern Snake River Plain.

Regional setting

The Snake River Plain of southern Idaho is an arcuate rift basin containing a thick Cenozoic sequence of volcanic and sedimentary rocks that become progressively younger from west to east along the basin axis (Fig. 1). Rifting began in the western part of the basin during the Miocene and proceeded eastward with time such that the center of volcanism is presently located under Yellow-

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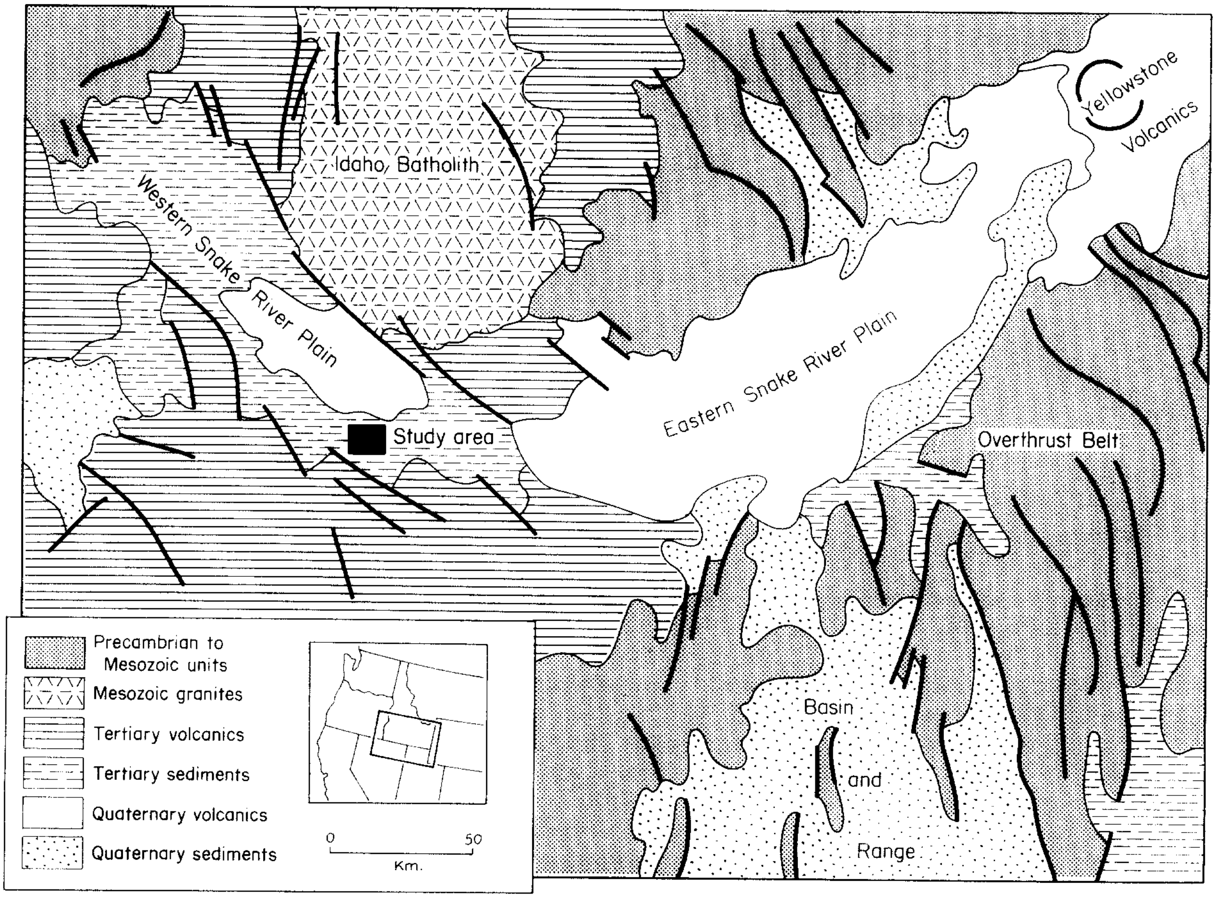


Fig. 1. Generalized geologic map of the Snake River Plain, southern Idaho, showing major tectonic provinces. The study area is located north of the Bruneau Canyon and south of the Snake River in the western Snake River Plain. Modified from King and Beikman (1974).

stone National Park in northwestern Wyoming (Armstrong et al., 1975).

Cenozoic fill of volcaniclastic sediment and volcanic rock is greatest in the western part of the Snake River Plain, attaining thicknesses of up to 2 km (Wood and Hawk, 1988). During Miocene to middle Pleistocene regional subsidence, the Snake River was dammed at about 1100 m in elevation along the western margin of the plain by faulting or lava flows, during which time the Idaho Group was deposited in a variety of lacustrine, deltaic, floodplain, and finally alluvial environments. Two transgressive lake sequences, one late Miocene and one Pliocene, are separated by basin-wide unconformities. Younger formations and bounding unconformities dip less steeply toward the center of the Snake River Plain. This dip records downwarping of the central rift as the area approached isostatic equilibrium (Smith et al., 1982). About two million years ago, following filling of the basin, an outlet to the Snake River developed along the western margin of the plain and subsequent entrenchment of the Snake River and its tributaries resulted in the dissection of Idaho Group sediments and deposition of the Upper Pleistocene to Recent Snake River Group of locally derived gravels, basalts, and lake silts (Malde and Powers, 1962; Malde, 1987).

The Hot Spring limestone

The Hot Spring limestone, first described by Littleton and Crosthwaite (1957), is a unit within the Miocene Chalk Hills Formation of the Idaho Group. This formation consists of interbedded sediments and volcanic flows and is unconformably overlain by the Pliocene Glenns Ferry Formation. Limestone crops out along the southeastern margin of the western Snake River Plain within an 80 km^2 elliptical area. The unit attains a maximum thickness of 8 m in the center of this area, but thins to less than 2 m at present lateral limits, suggesting that present areal extent closely approximates original areal distribution.

The limestone is separated from the underlying Chalk Hills Basalt dated at 8.4 Ma (Armstrong et al., 1975) by 30 m of drab, burrowed mudstone with isolated sand lenses. These fine-grained but poorly sorted, crayfish-burrowed massive sediments become distinctly pinkish-red in the top few decimeters, and are often intensely root mottled where in contact with overlying limestone. Massive bedding, oxidized color, the absence of fish fossils, and the predominance of bioturbation structures, all indicate that this unit represents deposition and pedogenic alteration of floodplain sediment. A single layer of rounded quartzite pebbles occurs at the contact between mudstone and limestone at several localities.

Deposits overlying the limestone consist predominantly of fine-grained, horizontally stratified ashy silts and sands containing locally abundant disarticulated fish bones, rare terrestrial vertebrate bones, and allochthonous rounded wood fragments. These are interpreted as being lacustrine in origin; they persist upsection for 30 m where they are truncated by gravel at the unconformable base of the Pliocene Glenns Ferry Formation. They are similar to lacustrine silts of approximately the same age that crop out sporadically along the entire southern margin of the Snake River valley to eastern Oregon (Swirydczuk et al., 1982).

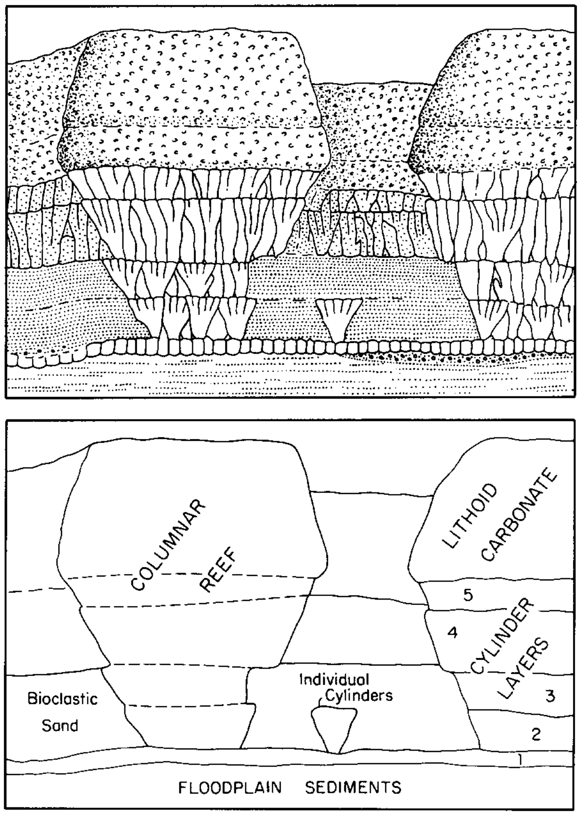


Fig. 2. Line drawing of a typical outcrop of the Hot Spring limestone. In this exposure, five layers of algal cylinders are visible. The first layer of cylinders overlies floodplain deposits. They are short and equant, and are associated with transgressive strandline gravels at the base of the unit throughout the study area. The two columnar reefs in the foreground began to form during growth of the second-layer cylinders. Coarse carbonate sand composed of gastropod debris and ooids is found in intercolumn spaces at the bottom of the section. A ring of dense lithoid carbonate surrounds the columns at the top of the section, hiding from view part of the fifth- and all of the sixth-layer cylinders. Columnar reefs are about 7 m in height.

General features

The Hot Spring limestone displays several levels of organizational complexity (Fig. 2). At the smallest scale, it is composed of horizontal layers of vertical, closely packed, generally cylindrical to conical carbonate units. These range in height from 10 to 150 cm in height, in diameter from 10 to 40 cm, and display somewhat variable shapes and internal structures. We refer to these structures as algal "cylinders". Adjacent cylinders in the basal limestone layer form a nearly continuous carbonate sheet across the outcrop area, but those in subsequent layers occur grouped into vertical masses or "columns" separated by coarse siliceous and carbonate sand (Fig. 2). These larger columns represent a second level of structural organization. In the following, we proceed in discussion from fine to coarse features, from the structure and morphology of carbonate cylinders, to columns, to intercolumnar sediment and its relation to the carbonate cylinders and columns.

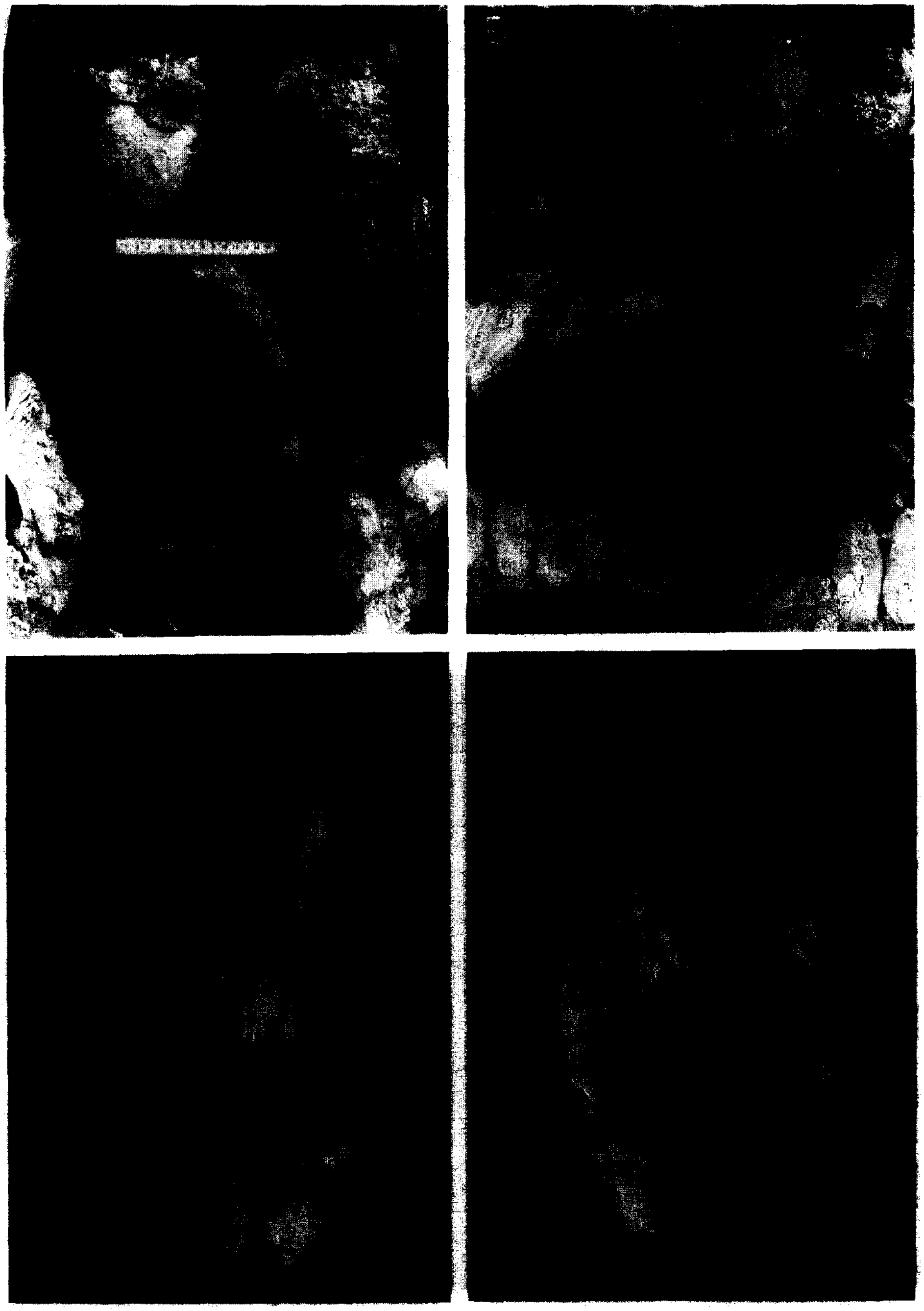


Fig. 3. Hot Spring limestone cylinders. A. Photograph of two typical cylinders. The cylinder on the right consists of a main axis with a single projection that has budded off the main colony, while the cylinder on the left is a simple vase-shaped colonial structure. Scale is 15 cm. B. Typical first and second-layer cylinders. As seen here, the first-layer forms are short and squat, and are separated from the second layer of cylinders by a unit of coarse terrigenous sand and brecciated carbonate debris. Small rounded cylinders in the second layer have been overgrown by the taller branching forms. In these branching colonies, the inner digitate zone is exposed at the top. Scale is 15 cm. C. Slabbed cylinder showing an inner digitate zone containing several hollow tubes, surrounded by a dense outer zone. Note that the contact between the digitate and the dense zone appears to be abrupt, but locally interdigitate space extends into the outer wall. Also notice the small projection off the main axis in the lower right. Scale is 8 cm. D. Slabbed cylinder in which the digitate zone extends beyond the dense zone at the top of the colony. This cylinder contains one central hollow tube. The outer zone is laminated, and successive laminae onlap the cylinder in an upward direction. This results in thinning and eventual termination of the outer wall 6 cm from the top. Scale is 8 cm.

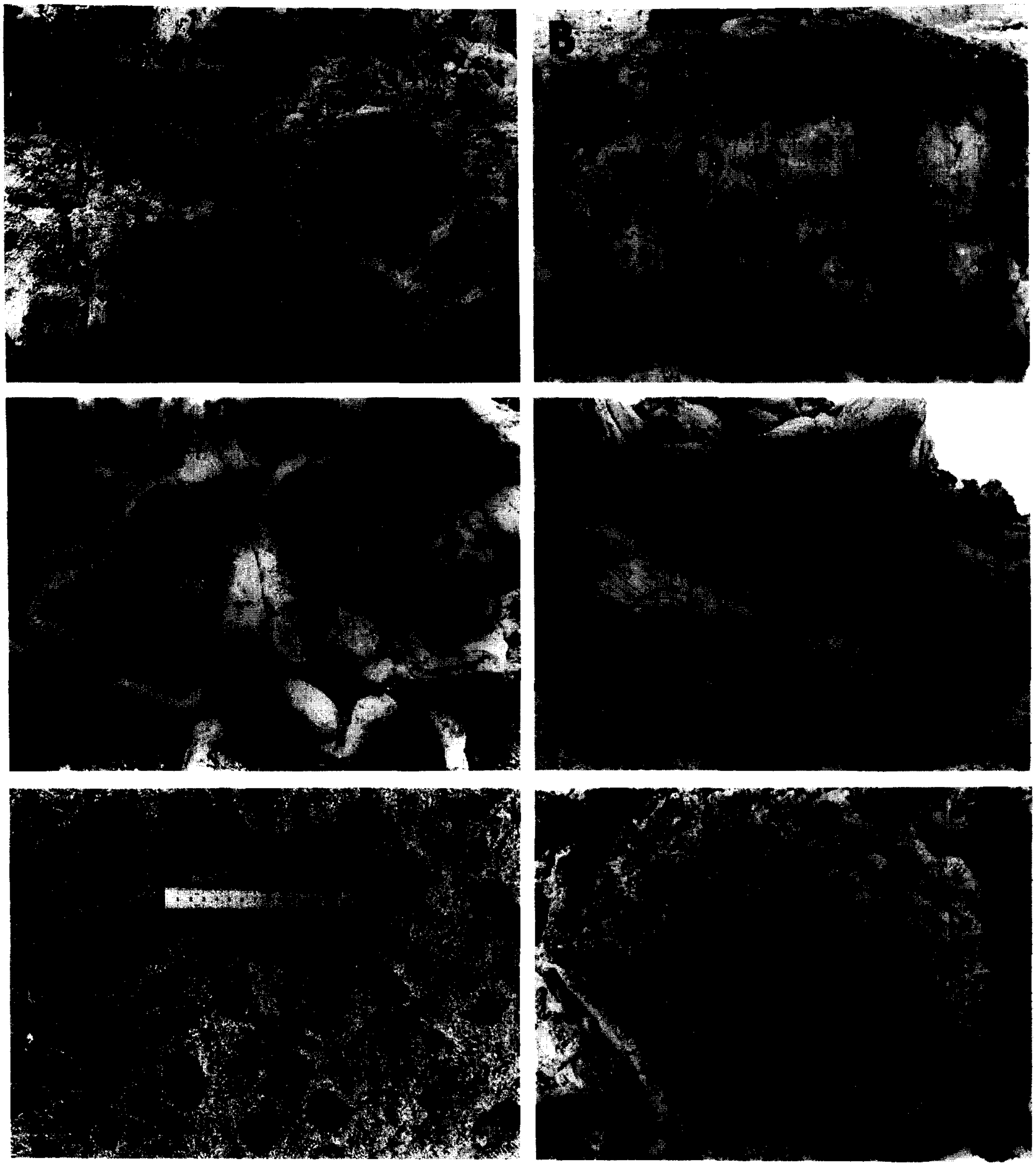


Fig. 4. Variation in cylinder morphology. A. First-layer cylinders. The lens cap is resting on a horizontal erosion surface cut onto short first-layer forms. Cylinders in the second layer are directly attached to the top of the first layer. B. Third-layer cylinders. In these specimens the inner digitate zone is well exposed at the top. The bottoms exhibit several "prop-root" extensions. C. In this view of the tops of two cylinders, notice three zones, consisting of an outer dense carbonate wall, an inner digitate carbonate zone, and several central hollow tubes. D. Photograph (looking up) of the bottom of a cylinder layer. In contrast to those shown in B, cylinders in this layer have rounded bottoms. E. The amural cylinders in this layer lack dense outer walls. Digitate carbonate surrounding hollow tubes is intergrown with digitate limestone in adjacent cylinders. Frequently, layers of this type develop into individual cylinders toward the top or bottom of the layer. Scale is 15 cm. F. Compound cylinder. Each curved plate consists of an outer dense zone and an inner digitate zone.

Carbonate cylinders

Cylinders represent the smallest and most distinct morphologic units of the Hot Spring limestone (Figs. 3, 4). Externally, they resemble vases, the bottoms of which are either smooth (Fig. 4B, D) or possess root-like extensions. Small projections frequently bud from cylinder bottoms near the main axis, or branch from cylinder tops, forming new cylinders of roughly equal size (Fig. 3A, B). Except for those in the lowermost layer which initiated growth on terrigenous pebbles, cylinders in successive layers are directly attached to those in the layer below. Cylinder height ranges from 10 to 150 cm, while diameter ranges from 10 to 20 cm.

Structurally, cylinders consist of three zones: dense outer walls of laminated carbonate, medial porous zones of digitate carbonate, and inner walls of laminated carbonate surrounding one or more central hollow tubes (Figs. 3C, D, 4C). The porous zone is volumetrically the most important, and is made up of laminated carbonate digits that branch and radiate outward and upward from cylinder axes forming irregular or tubular spaces (Fig. 4E). Based on thin-section examination, porosity of digitate carbonate is estimated at approximately 50%; contacts between porous digitate zones and dense outer walls are commonly abrupt (Fig. 3C).

Dense outer walls form sheaths around the sides and bottoms of cylinders and are distinctly laminated. Internally, successively younger laminae extend further up onto inner digitate portions of each cylinder, but do not cover upper cylinder surfaces. As a result, several centimeters of digitate carbonate representing the last living portion of each cylinder is not surrounded with a dense outer wall (Fig. 3D). This relation suggests that although growth of the two zones was contemporaneous, digitate portions grew somewhat faster, or initiated growth somewhat sooner than laminated walls.

Radial fans of calcite crystals, approximately 50 μm in length, occur in both porous digitate and dense laminated carbonate (Fig. 5 C), but are less common in digitate zones which consist primarily of structureless micrite and pseudospar. In some portions of digitate carbonate, linear micritic tubes and rounded clots, similar to cryptalgal fabrics described by Monty (1976), are apparent (Fig. 5B). Both dense and digitate zones contain allochthonous ostracods, sponge spicules, pennate diatoms, and minor amounts of terrigenous material scattered throughout.

One or more hollow tubes lined with dense carbonate occur in the central portions of most cylinders (Fig. 4C). The origin of these tubes is two-fold. Most extend from cylinder bases and represent a primary void in the digitate zone at the time of growth initiation. Others, however, result from the progressive infolding of the outer dense wall during later ontogenetic stages of cylinder growth. Most tubes extend to the tops of cylinders, but some exit through cylinder sides while others completely terminate within digitate carbonate. A few cylinders contain no central tubes. The origin of these tubes is not precisely known, but two lines of evidence suggest they originate as primary voids in cylinder structures rather than being developed around some now-absent object. Nowhere were tubes found to contain material (other than lacustrine sediment) that was surrounded during carbonate deposition, a relation suggesting that they were water-filled voids during cylinder growth. That tube walls are typically lined with dense carbonate similar to that developed along cylinder exteriors also suggests that tubes existed as primary voids during cylinder development.

Algal cylinders that make up the basal limestone layer are typically short, squat, and commonly display oxidized rims and pitted irregular grooves which may have been produced during subaerial exposure and dissolution soon after growth (Fig. 4A). A thin layer of coarse terrigenous sand containing highly pitted cylinder fragments commonly separates the first and second cylinder layers (Fig. 6B) suggesting that initial carbonate deposition rate was somewhat episodic. Cylinders throughout upper portions of the limestone are significantly taller than first-layer forms (Figs. 4B, 6A, B), commonly branch, and expand in diameter upsection (Fig. 3B).

Density of packing within different layers also produced variation in cylinder morphology. Close packing commonly resulted in the overgrowing of

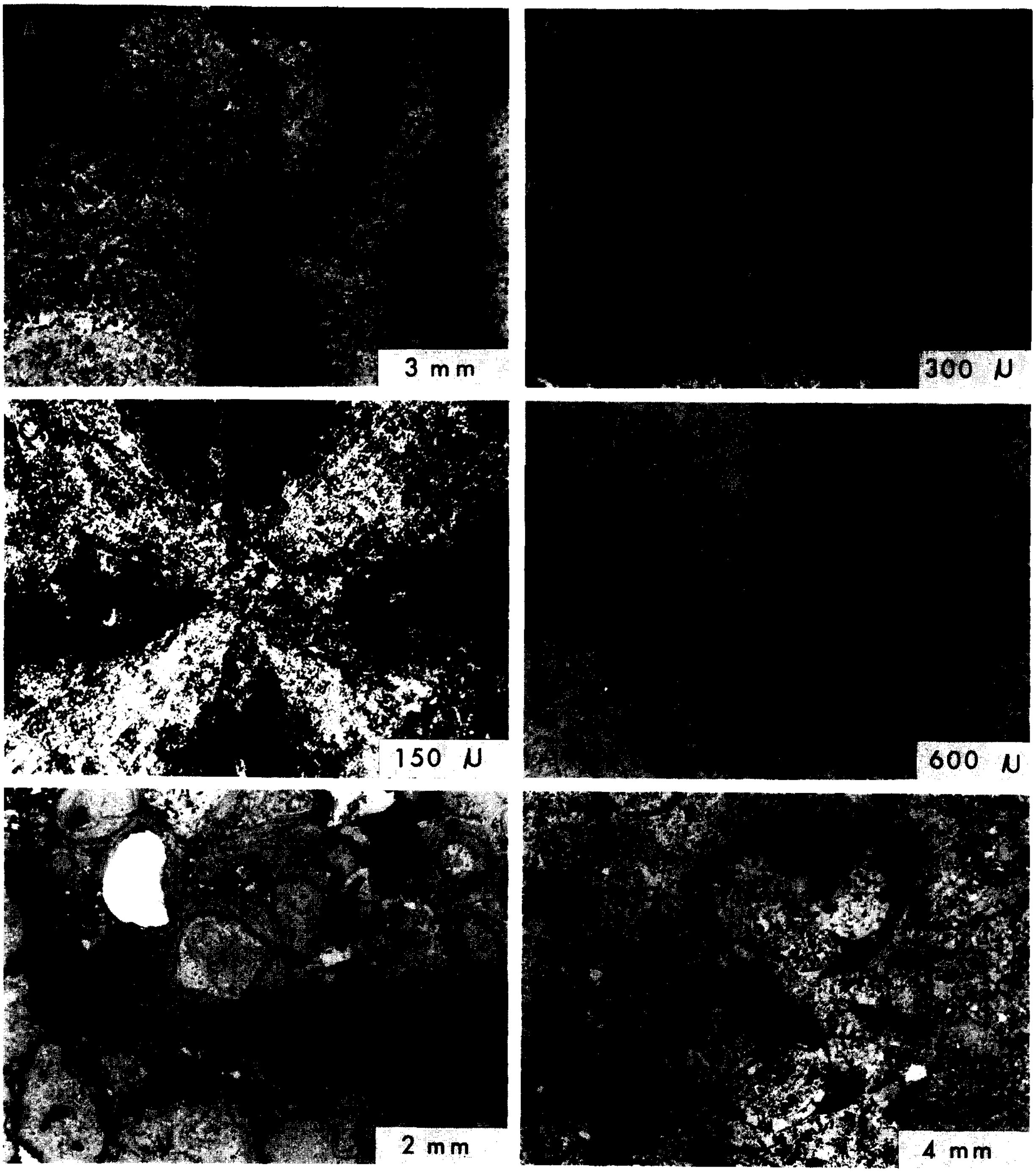
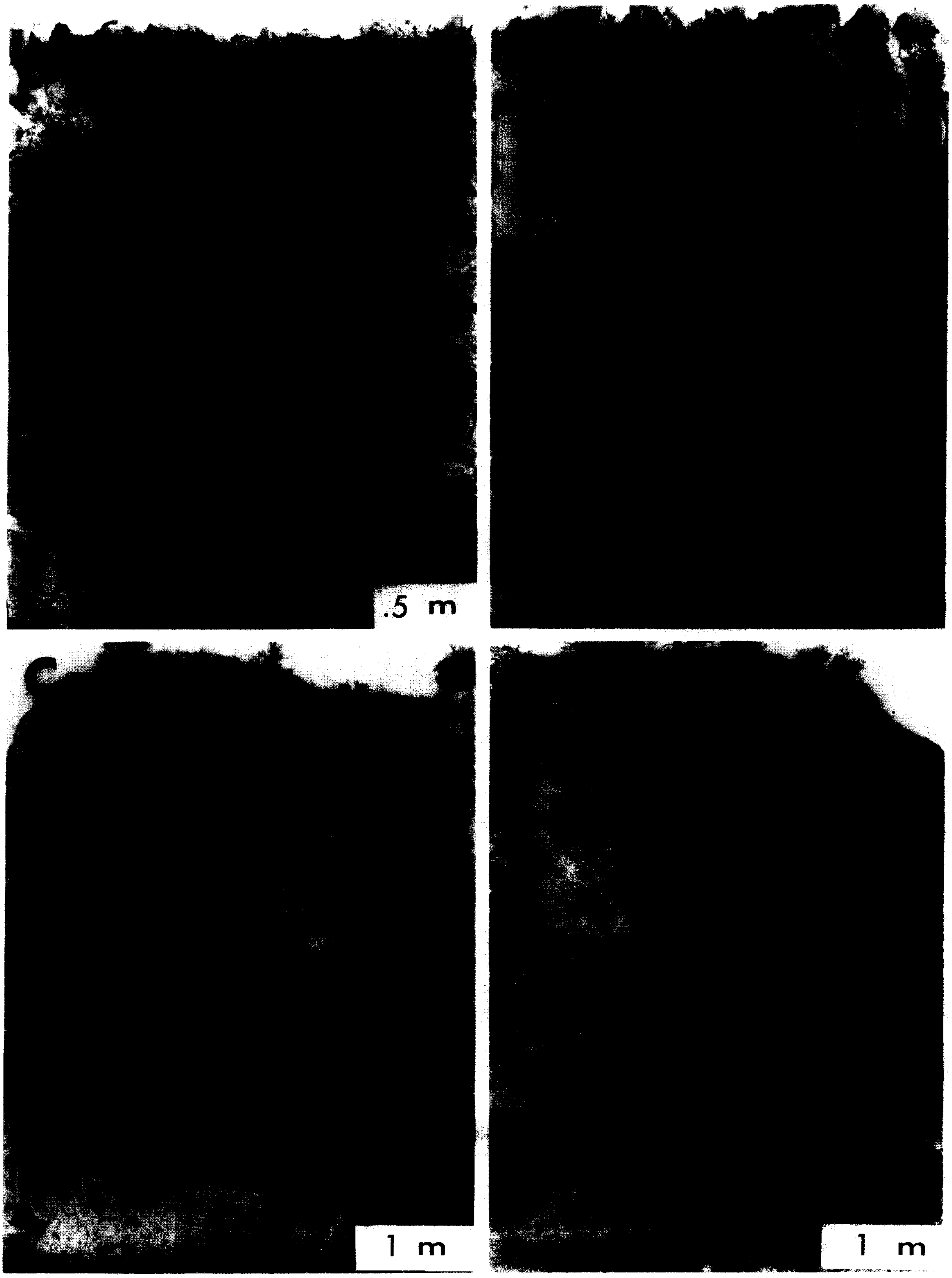


Fig. 5. Photomicrographs of zones comprising the Hot Spring cylinders. Polars crossed in all except B. A. Digitate zone. Laminations within this zone are defined by alternating layers of pseudospar and micrite. B. Crude laminations within a digit. Darker micritic areas have a clotted texture suggestive of the fabric produced by coccoid blue-green algae. C. Radial calcite fan surrounding a central void. Radial fans are common in both dense and digitate zones, as well as in the lithoid carbonate rings surrounding the columns. D. Microfabric of a dense zone. Laminations in this zone are defined by the linear arrangement of elongate void spaces as seen here, or by linear micritic areas. Laminations in this photograph are oriented vertically. E. Microfabric of a coarse carbonate sand unit found between columns at the base of the limestone. This sample is composed predominantly of ooids. F. Coarse carbonate sand of relatively well-sorted snail shells and minor amounts of volcaniclastic sand cemented by calcite.


.5 m
1 m
1 m

individual cylinders by adjacent colonies (Fig. 3B). Where cylinder density was extremely high, dense outer walls either did not develop around the cylinders or were very thin. Layers of this type of colony consist of intergrown, outwardly radiating bundles of digits (Fig. 4E). Conversely, large (about 1 m^2) cylinders consist of curved digitate plates around a central axis (Fig. 4F) evidently formed where cylinder distribution was patchy and lateral growth unrestricted.

Carbonate columns

The lowest layer of cylinders in the Hot Spring limestone is thin and relatively continuous (Figs. 6, 7). In contrast, second-layer cylinders besides being taller, form patches ranging from a few meters to several tens of meters in diameter (Fig. 7A). This arrangement into distinct clusters marked the beginning of the development of columns. Cylinders in successive layers for the most part coincided in distribution with second-layer forms, maintaining spaces between columns, but expanding laterally with growth through branching. Successive column layers therefore have more cylinders than underlying layers and columns expand upsection, progressively reducing intercolumn spaces. In some cases, this space was completely overgrown toward the top of the limestone unit and here uppermost cylinders again form a nearly continuous layer (Fig. 7A).

Whereas cylinders along column margins in the lower few layers are in contact with allochthonous intercolumn sediment, upper portions of columns are separated from this sediment by a layer of porous structureless carbonate, somewhat analogous in occurrence to denser laminated carbonate rinds around individual cylinders (Figs. 6C, 7C). Porous lithoid carbonate rinds around reefal columns thicken upward, frequently attaining widths of up to 100 cm, but do not extend over column tops. Rind thicknesses average 25 cm, but increase abruptly upward as a series of inverted steps which define one or more planes oriented subnormal to the sides of columns (Fig. 6D). These planes are either horizontal or dip at a low angles (Fig. 6C, D), and do not correspond either to contacts between cylinder layers or to bedding within intercolumnar sediment. Where columns are closely spaced, lithoid carbonate rinds may surround several columns to form large irregularly shaped reefal masses. In thin section, this carbonate consists primarily of micrite and radial calcite fans, fabrics similar to those observed in algal cylinders.

Intercolumnar sediment and fossils

Intercolumnar sand coarsens and changes in composition upward from coarse shelly oolitic grainstone between column bases to fine sandy ash between (and overlying) column tops (Fig. 2). The most abundant allochem in coarse carbonate sand between lower portions of columns is the gastropod, *Lithoglyphus columbianus*, that today lives in high-energy freshwater environments (Fig. 5F). Locally derived algal carbonate debris is the second most abundant allochem, followed by volcaniclastic sand, ooids, ostracods, sponge spicules, and a diverse flora of pennate diatoms (Fig. 5E). Fish are absent. In general, these shelly units are porous, well sorted, and are horizontally stratified with major bedding contacts corresponding to bedding between cylinder layers (Fig. 7D). Like some lower cylinder layers, upper surfaces of shelly units are frequently oxidized. Intercolumnar sediment lateral to upper layers but separated from cylinders by lithoid carbonate rinds, consists of fine ashy sand and silt. More rapid erosion of

Fig. 6. Outcrop photographs of the Hot Spring limestone. A. Four successive cylinder layers. Notice an increase in cylinder height above the first layer. B. Four cylinder layers. The thin light-colored first layer has been partially removed by erosion and is separated from the second layer by a unit of terrigenous sand containing brecciated carbonate fragments. Hammer is 50 cm long. C. Columnar reef surrounded by a ring of lithoid carbonate. Note that the lower terminus of this ring plunges at a low angle to the horizontal. Subhorizontal lines on the ring parallel to the lower terminus delineate steps along which the lithoid carbonate ring becomes progressively thinner. D. Note two ledges at the bottom of the lithoid ring in this photograph, marking the top of the intercolumn sediment during two stages of lithoid carbonate growth. The ledges are horizontal in this outcrop.

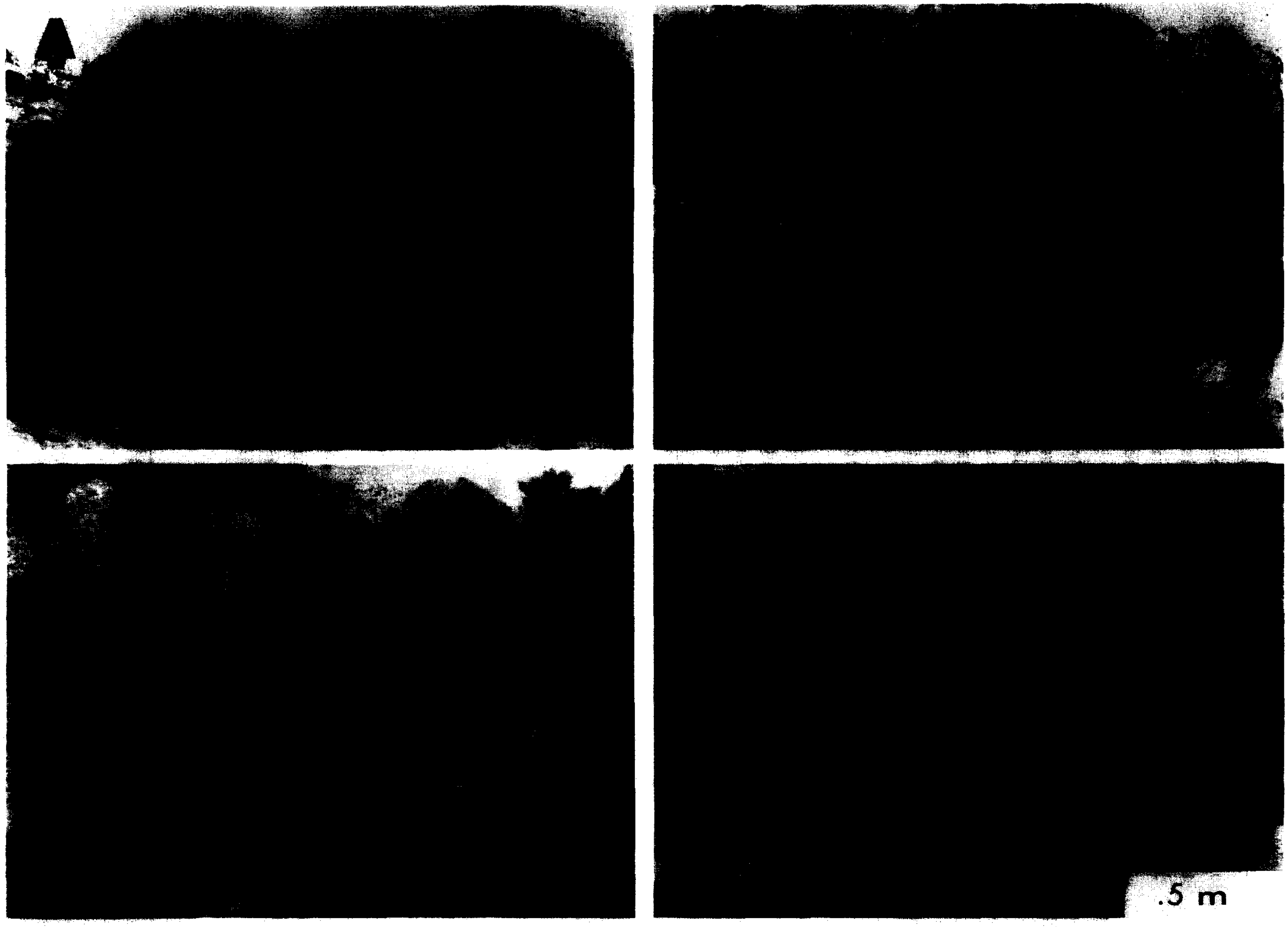


Fig. 7. Outcrop photographs of Hot Spring columnar reefs. A. Two reefal columns. Note the fanning outward of the cylinders in the column-forming layers, and the resulting reduction of the intercolumn space. Hammer is 50 cm. B. Five cylinder layers in a large column. The bottom layer was truncated removed by erosion prior to deposition of the second layer. Note the horizontal nature of the cylinder layers. Hammer is 50 cm. C. Broken column exposing a section through a ring of lithoid carbonate surrounding a small reef. Cylinders are not overlain by lithoid carbonate at the top of the column. D. Contact between reefal carbonate (left) and inter-reef carbonate sand. Growth of the second and third cylinder layers was coeval with two periods of bioclastic deposition on the right.

this material relative to carbonate and coarse carbonate sand, commonly results in the nearly complete excavation of reefal masses, which now occur in the Snake River Plain in much the same form as they did on the Chalk Hills lake floor during Miocene time.

Interpretation

Excellent exposures of the Hot Spring limestone throughout this area record the importance of a variety of physical, biological, and chemical processes during carbonate deposition along this Miocene lake margin. In a stratigraphic context, the occurrence of limestone between drab, burrowed, fluvial-floodplain mudstone and horizontally laminated, fine grained ashy lacustrine siltstone suggests that carbonate deposition took place during lacustrine transgression. Underlying mudstone is lithologically identical to fluvial-floodplain deposits reported from many modern and ancient settings and contains terrestrial vertebrates. Ashy siltstone with fish fossils clearly records deposition in deeper lake settings. The oxidized crayfish-burrowed and root-mottled top of the fluvial mudstone sequence records episodic subaerial exposure of floodplain units prior to lake transgression and flooding. The exact origin of the cobble monolayer overlying the oxidized mudstone surface and immediately underlying the limestone is, owing to its thinness, more problematic. It is, however, strikingly similar to other cobble monolayers that occur at unconformable surfaces within the Miocene–Pliocene fill near the mouth of the Bruneau River, and probably represents a basal fluvial-derived beach-shoreface lag gravel that was sorted and deposited during initial stages of the Chalk Hills transgression.

Many features within the Hot Spring limestone also record deposition in a deepening nearshore setting. First, layers of cylinders exhibit great lateral extent across the study area and within individual layers cylinder height is nearly constant. Lateral continuity and uniformity suggest that the greater height of cylinders above the basal layer probably relates to greater water depths associated with the lacustrine transgression. Cylinder height appears to have been limited by water depth and growth of cylinders within single layers evidently ceased when cylinders reached the lake surface or when the water surface was lowered during minor fluctuations in lake level.

Similarly, the overall lithology of intercolumn sediment records deepening water and lower wave energy during limestone deposition. Coarse-grained shelly oolitic units only occur in the lower half of the limestone whereas upper portions of columns are surrounded by ashy siltstone; this fining-upward trend suggests that as transgression proceeded, water depth increased somewhat, and progressively finer sediment was deposited in intercolumn spaces. Absence of fish remains, however, suggests persistence of relatively shallow-water conditions.

Diatoms from intercolumn sediment also indicate accumulation in relatively shallow environments. Centric diatoms are rare, but include two very large species of *Melosira* and an unknown *Cyclostephanos* species. Common pennate genera include *Achnanthes*, *Amphora*, *Caloneis*, *Cocconeis*, *Cymbella*, *Diatoma*, *Diploneis*, *Epithemia*, *Eunotia*, *Gomphoneis*, *Gomphonema*, *Navicula*, *Neidium*, *Rhopalodia*, and *Surirella*. This flora is quite diverse and is unusual in the predominance of pennate, non-planktonic taxa. Most species are attached shallow-water benthic types; few planktonic taxa are present. Similar forms occur, but are somewhat less common, in the carbonate mass that comprises individual cylinders.

Coarse oolitic gastropodal debris filling intercolumn spaces at the bottom of the section are distinctly bedded and major bedding planes always correspond to the tops of adjacent cylinder layers indicating that intercolumn spaces were being filled with this coarse material during growth of the lower cylinder layers (Fig. 2). The well-sorted nature of these units, together with the presence of ooids that locally may be the dominant allochem, indicates that this intercolumnar material was continuously sorted by waves during deposition. Since growth of cylinders that make up the lower portions of columns and deposition of coarse intercolumn material was contemporaneous, the columns themselves must have been wave resistant structures, and are therefore properly called reefs.

The distribution and thickness of lithoid carbonate rinds surrounding the upper portions of columns further constrains estimates of water depth and reef height during deposition. As noted earlier, the thickness of rinds increases abruptly upward as a series of inverted steps that define subhorizontal planes among neighboring columns and there is no lateral correspondence between changes in rind thickness and bedding between cylinder layers. Furthermore, cylinder growth and lithoid carbonate deposition were not precisely synchronous, because the lithoid carbonate extends to column tops without overgrowing cylinders of upper layers that were added slightly in advance of lithoid carbonate deposition. Rind growth also postdated deposition of coarse shelly intercolumn sediment as abrupt thickening only occurs where reefs are surrounded by ashy siltstone.

These relations demonstrate that lateral accretion of lithoid carbonate took place on the margins of columnar reefs between the surface of fine intercolumn sediment and reef tops. Continued carbonate rind accretion and continued but episodic accretion of intercolumnar ashy silt gave rise to abrupt subhorizontal increases in rind thickness. Because planes of thickening record positions of the intercolumn sediment–water interface, and because rinds extended from this interface to column tops during lateral accretion, distances between planes of thickening and column tops are an exact measure of reef height during the latter stages of limestone deposition. Evidently, as lacustrine transgression proceeded, water depth increased, inter-reefal shelly grainstone deposition gave way to silty ash deposition, and rates of inter-reef sediment accumulation decreased relative to rates of reef growth. Reef heights, as recorded by heights of lithoid carbonate rinds, were at least 6 m.

Observation of endolithic algae in modern tufa indicates that carbonate surface fabric is partly controlled by molluscan grazing. As the Chalk Hills lake deepened, algal growth, photosynthesis, and carbonate production evidently decreased. While we have no direct evidence for a change in the density or pattern of grazing by gastropods in the Miocene lake, spacing of cylinders is extremely close, and dense outer walls around individual cylinders are less well developed toward the basin center. Such lateral differences may record variable interplay between biological and chemical processes at algal carbonate surfaces.

In summary, patterns of nearshore carbonate deposition that gave rise to the Hot Spring limestone appear to have been strongly influenced by the transgressive nature of the Chalk Hills lake in which the unit originated. The first layer of cylinders grew as a continuous sheet in a shallow, high-energy nearshore setting during initial colonization on a layer of beach cobbles deposited on underlying fluvial-floodplain mudstone. With transgression, subsequent layers of cylinders became grouped into columnar masses that grew rapidly into discrete algal reefs as the lake deepened. Early columns experienced fairly intense wave energy as coarse shelly oolitic debris accumulated between these early reefal masses.

With continued transgression, although reef growth was able to keep up with relative rates of lake level rise, both the size and accumulation rate of inter-reef sediment decreased giving rise to reefs that attained heights of several meters above the Chalk Hills lake floor. As wave energy at the sediment–water interface decreased with increasing depth, coarse inter-reef deposition gave way to the accumulation of ashy silts at the same time that reefs, now at their maximum heights, became progressively encrusted with porous lithoid carbonate. This lateral rind accretion continued with lake deepening and silt deposition until the entire area was blanketed with fine-grained deep lake sediment.

Analogy with other algal carbonates

Because algal reefs of the Hot Spring limestone are a somewhat unusual limestone sequence, comparison with other occurrences of nearshore algal carbonate aids in accessing facies relationships and growth forms. Algal limestone accumulation may occur in both lakes and oceans (e.g. Bradley, 1929; Playford and Cockbain, 1976; Walter, 1976), and low-relief stromatolitic structures are now reported from a wide variety of lacustrine (Surdam and Wolfbauer, 1975; Surdam and Wray; 1976;

Osborn et al., 1982) and marine (e.g. Awramik, 1981) settings. In spite of this apparent ubiquity, subtidal marine bioherms are largely restricted to Shark Bay, Australia (Hoffman, 1959, 1976; Logan, 1961; Logan et al., 1974) and margins of the Great Bahama Bank (Dravis, 1983; Dill et al., 1986). Modern lacustrine buildups exhibit similar scarcity, occurring in nearshore settings along the Great Salt Lake, Utah (e.g. Eardley, 1938), Lake Tanganyika in Africa (Cohen and Thouin, 1987), and Green Lake, New York (Dean and Eggleston, 1975; Eggleston and Dean, 1976). Older lacustrine reefs are reported from the Miocene Ries Crater in Germany (Riding, 1979) and from along Quaternary shores of Basin and Range lakes in the southwestern United States (e.g. Scholl, 1960). Among reefal accumulations exhibiting meter-scale relief, buildups from Lake Tanganyika, the Ries Crater, and the Basin and Range province are perhaps the best understood. Similarities and differences between these occurrences and the Hot Spring limestone serve to shed light on the spectrum of algal buildups known from Cenozoic lacustrine settings.

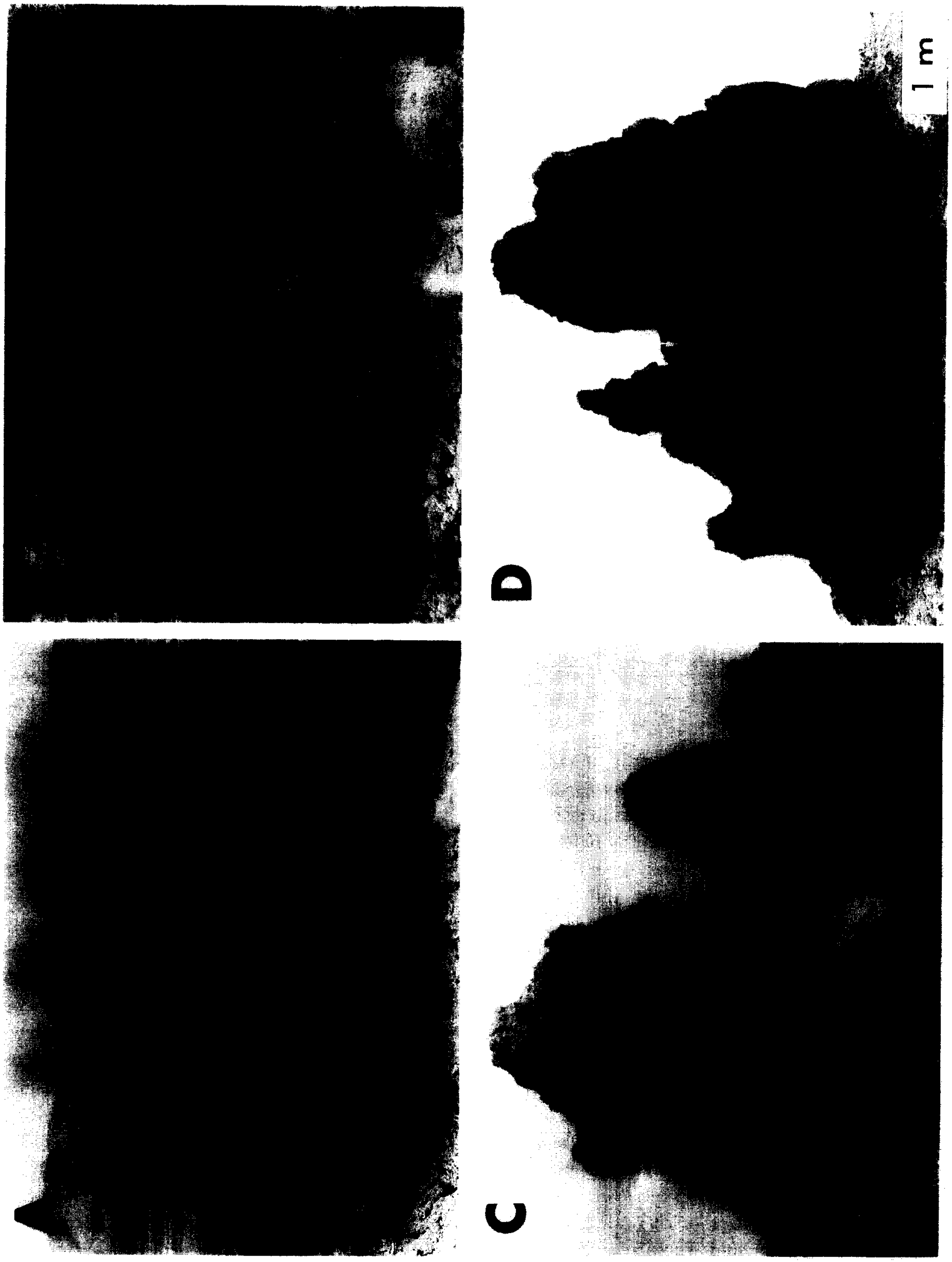
Lake Tanganyika, Africa

Cohen and Thouin (1987) recently described a number of thrombolitic reefs or bioherms that are widespread in Burundian and Tanzanian nearshore waters of Lake Tanganyika at depths between 15 and 50 m. These extend over several square kilometers and increase in height and diameter with increasing depth. In deeper zones they may coalesce to form laterally continuous buildups (Cohen and Thouin, 1987). These shore-to-basin trends match upsection trends in the Hot Spring Limestone. In addition, the internal structure of Lake Tanganyika bioherms is highly porous and nonlaminar, and appears to be generally similar to "digitate carbonate" from the Hot Spring Limestone. An important observation from a biologic perspective is that the Lake Tanganyika buildups are extensively grazed by two species of gastropod that may attain densities of 50 individuals per square meter (Cohen and Thouin, 1987). Given the great abundance of gastropodal shell hash between reefs in the Hot Spring Limestone, a similar habitat for the Idaho molluscs seems reasonable.

Although it has not yet been demonstrated that the African buildups actually grew at depths where they presently occur, Hot Spring limestone layers evidently formed at somewhat shallower depths than bioherms in Lake Tanganyika. Similarly, Lake Tanganyika reefs seemingly show a lower degree of organization than the Idaho forms, but Lake Tanganyika interiors are rarely exposed, and differences in structural complexity may be more apparent than real. Nonetheless, initial Hot Spring limestone accumulation on beach cobbles is inferred to have been in depths of only a few centimeters, while Lake Tanganyika facies at depths less than 15 m presently include Chara meadows, ooid shoals, and gastropodal coquinas. These lithologies are only weakly developed in Chalk Hills sections containing algal reefs. Similarly, Lake Tanganyika buildups apparently consist largely of rather unstructured algal colonies while Chalk Hills reefs exhibit greater organizational complexity at a scale of both cylindrical algal colonies and composite columnar reefs. The reasons for differences between these two occurrences are largely unknown, but similarities are conspicuous, and suggest a commonalty of form and accretionary process between algal carbonate in these two settings.

Ries Crater, Germany

Upper Miocene algal bioherms grew in shallow nearshore waters within the Ries Crater of southern Germany. These bear a more striking resemblance to the Hot Spring limestone. The smallest structural unit within Ries carbonate bodies consists of erect branching tufts a few centimeters across, identified as *Cladophorites* by Ries (1926). Although Wolff and Fuchtbauer (1976) interpreted these as having been formed by the activity of both green and blue-green algae, Riding (1979) believes that green algae were the only significant biotic component. We were unable to isolate diagnostic algal structures in the Hot Spring limestone, either from dendritic or laminated portions of cylinders, or from lithoid carbonate rings surrounding reefal columns; however the similarity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between structures in these units and those in the Ries Crater leaves little doubt that in both cases carbonate precipitation was induced by photosynthetic algal processes.

Basic structural units of Ries bioherms, termed "cones" by Riding (1979), are externally identical in form and size to cylinders which comprise the Hot Spring limestone. Internally, however, Ries cylinders are structurally much less organized, and consist of irregular masses of (1) *Cladophorites* tufa, (2) dissolution voids filled with biodetritus and peloids, and (3) later calcite and dolomite cements.

Riding (1979) described the following features similar to subfacies in the Hot Spring limestone: (1) cylinders are organized into much larger columns ("compound cones"), (2) columns are encased in a lithoid carbonate ("laminated sinter"), and (3) individual columns are separated by lensoid channels of bioclastic material ("ostracod and gastropod sand"). In these respects, the Ries Crater bioherms are nearly identical to the Idaho reefs and as such, suggest similar physical conditions and biological interactions during their growth.

Basin and Range tufa deposits

Pleistocene and Recent algal carbonate tufas are abundant along the margins of many Basin and Range lakes of the southwestern United States. We examined four rather spectacular tufa-precipitating lakes as well as several other dry lake beds in Nevada and California in a attempt to identify and evaluate characteristic nearshore algal deposits (Fig. 8). Sites include algal carbonate buildups along the southwestern end of Searles Lake in southeastern California (Scholl, 1960), Pyramid Lake and Winnemucca Lake in western Nevada (e.g. Russell, 1883, 1887; Jones, 1925), and Mono Lake in eastern California. All are remnants of Pleistocene Lakes (e.g. Russell, 1887; Dunn, 1953; Scholl and Taft, 1964). Algal carbonate in the Hot Spring limestone displays many features in common with these settings but differ in some respects.

At a meter-scale, small tufa pinnacles with morphologies resembling Hot Spring cylinders occur along former shorelines of Winnemucca Lake in Nevada, and along the margins of several other southwestern lake systems (Fig. 8A). Following upsection trends in the Chalk Hills sequence, pinnacle height increases lakeward to a maximum of 50 cm, while cobbles coated with algal carbonate occur along the former shore. Unlike Hot Spring cylinders, these pinnacles are generally unzoned and consist of porous lithoid tufa lacking structural organization. Other pinnacles with knobby external surfaces consist of dense laminated dendritic tufa surrounding a hollow central axes (Fig. 8B). These average 1 m in height and 20 cm in diameter. They are larger than more porous pinnacles which occur only a few hundred meters along shore in close association with large volcanic boulders that have thick coatings of layered dendritic tufa. This tufa is similar in appearance to the internal fabric of the dense pinnacles. Similar dendritic carbonate dominates the texture of other tufa bodies in this region. Their external form, however, is commonly dome-shaped. Many tufas exhibit a distinct zonation of porous to dense carbonate from the centers to margins of individual buildups.

Large tufa towers are common to the four Great Basin lakes studied. These resemble reefal columns in the Hot Spring limestone (Fig. 8C, D). Towers in Mono and Searles Lake exhibit a pronounced linear distribution in space, an arrange-

Fig. 8. Tufa deposits from the southwestern United States. A. Small porous pinnacles of lithoid tufa from Winnemucca Lake, Nevada. These occur in a broad belt along the lake margin, and grade shoreward into carbonate-coated cobbles. This facies tract is a good analogue for the first cylinder layer and the underlying beach cobbles in the Snake River Plain deposit. B. Dense pinnacles of dendritic tufa from Winnemucca Lake. These pinnacles also occur along a former lake margin, but form only a small isolated patch. The internal structure of these pinnacles is much different from those shown in A. C. Tufa tower from Mono Lake, California. Spring water from underlying faults flows up through central canals and runs out along the horizontal ledges that may coincide with former lake level. This tower consists mainly of lithoid tufa. D. Tufa tower from Searles Lake, California. This tower is composed of porous lithoid tufa.

ment reflecting the fact that most large tufa towers form over springs issuing from underlying faults (e.g. Scholl, 1960). They attain maximum heights of 15 m and range in shape from spires to low mounds. Internal fabrics vary (e.g. Scholl, 1960) but, in contrast to Hot Spring columns, are generally porous and uniform throughout individual towers.

Each of the characteristic features of the Hot Spring Limestone may be found in one or more modern tufas. These include: dense laminated carbonate exteriors, porous digitate interiors, central hollow tubes, small meter-scale structures that increase in height basinward, and larger towers analogous in size to columnar Hot Spring reefs. In spite of these similarities, playa lake carbonate bodies exhibit a vastly greater amount of spatial variation in height and textural organization than is typical of algal bioherms in Idaho, in Lake Tanganyika, or in the Ries Crater. The external and internal fabrics of the Great Basin tufas have been studied in some detail, but no link has been defined between specific growth forms and environmental conditions. Morphologically, the Idaho limestone is far more organized and less diverse in both external and internal structure. Tufa deposits are spatially variable almost to the point that each individual deposit has a unique combination of internal and external features. In comparison, structures within the Hot Springs limestone are remarkably uniform over the entire areal extent of the sequence, and vertical changes in development can be directly related to inferred changes in the lake depth during the Chalk Hills transgression.

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