Microbial Carbonates from Core and Outcrop, Tertiary (Eocene) Green River Formation, Uinta Basin, Utah

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Abstract

Recent discoveries in Early Cretaceous microbialites in the deepwater offshore of Brazil (pre-salt Santos Basin reservoirs) as well as other large oil deposits in microbialites reveal the global scale and economic importance of these distinctive carbonates. Evaluation of the various microbial fabrics and facies, associated petrophysical properties, diagenesis, and bounding surfaces are critical to understanding these reservoirs. Utah is unique in that representative outcrop analogs of microbial reservoirs are present and cores from these areas are available for detailed study. The Eocene Green River Formation from the Uinta Basin of eastern Utah contains excellent examples of microbial carbonates.

The Uinta Basin is a major depositional and structural basin which subsided during the early Cenozoic along the southern flank of the Uinta Mountains. Freshwater lakes developed between the eroding Sevier highlands to the west and the rising Laramide-age uplifts to the north, east, and south. The Green River Formation, consisting of up to 6000 ft of sedimentary rocks, accumulated in and around Lake Uinta. Three major depositional facies are associated with lake sedimentation: alluvial, marginal lacustrine, and open lacustrine. The open lacustrine environment is represented by nearshore and offshore shales and mud-supported carbonates, including microbialites.

Analysis of newly acquired Green River cores reveals a variety of microbial fabrics and related features. The overall section consists of medium gray siltstones and mudstones to light brown dolomitic mudstones with dark brown clay-rich and black organic-rich zones. Within the dolomitic mudstone are well-displayed, porous, microbial laminae and stromatolites with bulbous heads. Grainstones composed of ooids, coated grains, pisolites, and peloids often overlie the microbialites. Soft-sediment deformation, bioturbation, and rip-up clasts are also often associated with these microbialites. The grainstones and microbialites exhibit excellent storage capability consisting of microintercrystalline, interparticle, and moldic pore types.

Outcrops of the Green River Formation in the eastern part of the Uinta Basin also display many of the features observed in core, both vertically and horizontally. They offer a production-scale analog of the characteristics, geometry, distribution, and bounding surfaces of microbial and related lacustrine facies.

I

Overview of Microbial Carbonates

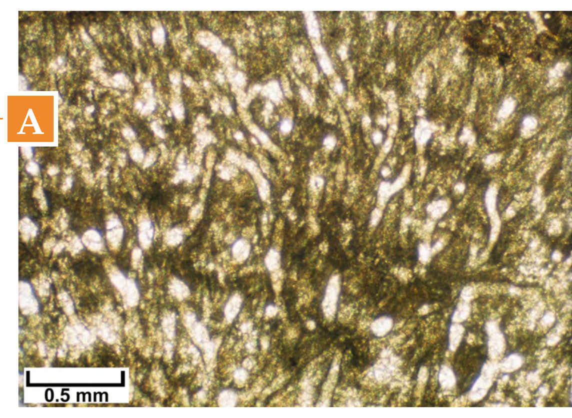
Definitions:

Microbialites

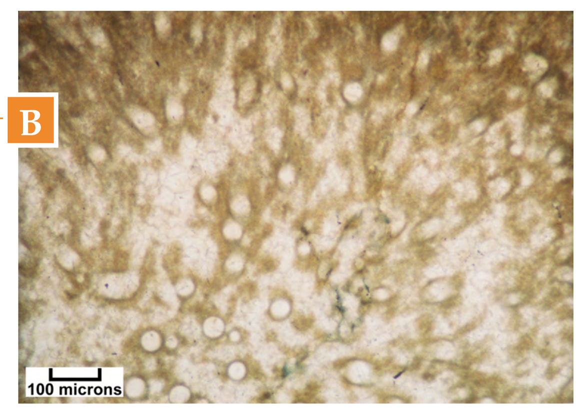
Organosedimentary deposits that have accreted as a result of a benthic microbial community trapping and binding of detrital sediment and/or forming the locus of mineral precipitation.

Burne and Moore, 1987

Green River Microbialite Fabrics in Thin Section



A - Filamentous cells that curve and branch within a laminated microbial structure. Federal No. 15-24B core (West Willow Creek field), 4787.5 ft. (Plane light)



B - Spherical (coccoid?) cell and filamentous structures that curve and branch within a dense microbial structure. Federal No. 15-24B core (West Willow Creek field), 4787.5 ft. (Plane light w/ white card)

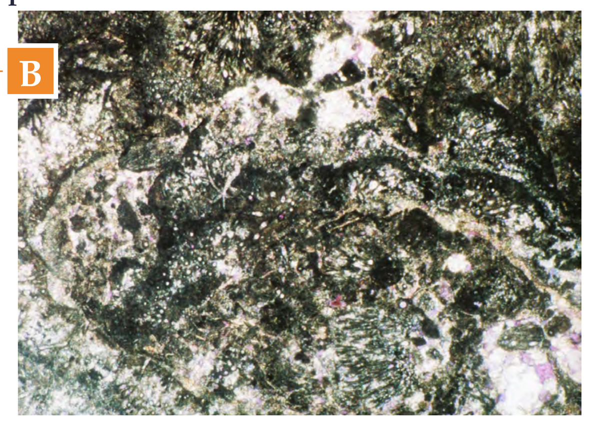
MISS (Microbially Induced Sedimentary Structures)

Primary sedimentary structures formed by the interaction of microbes with sediment and physical agents of erosion, deposition, transportation, or deformation traces of microbial activity. These structures commonly form by microbial mats (which may be comprised of bacteria, fungi, protozoans, archea, or algae), or evidence thereof, and are preserved in the sedimentary geological record.

Wikipedia posting of 11/26/2010

Green River MISS Example in Core and Thin Section

A - Conventional core segment showing vaguely laminated MISS (Microbially Induced Sedimentary Structures). Federal No. 15-24B core (West Willow Creek field), 4786.5 ft.



B - Low magnification thin section micrograph of MISS. Microbial cellular remains and dense micritic rinds define small "heads" within a vaguely laminated interval. Federal No. 15-24B core (West Willow Creek field), 4787.5 ft. (Crossed nicols w/ acc. plate)

Microbial Types Observed in the Green River Formation:

Stromatolites

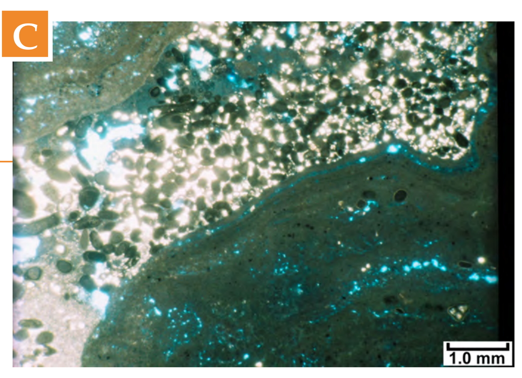
(def.) = laminated, biosedimentary structures, with calcification due to the growth of cyanophytes.

Riding, 2000

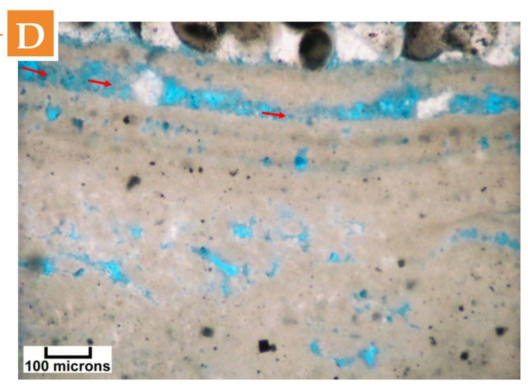
Green River Stromatolites

A - Large stromatolite domal head in which the synoptic relief diminishes upwards. Oolitic/peloidal sediments fill the space between stromatolites. The stromatolite grew on an oolitic/pisolitic/oncolitic substrate. Skyline 16 core, 964.5-966.0 ft.

B - Branching digitate stromatolites that grew on a substrate of peloidal dolomite displaying erosional relief. Gray layers of silt grains and ooids fill the space between the microbial "digits". Skyline 16 core, 972.8-973.3 ft.



C - Stromatolitic laminae within small digitate heads seen in the core photo in B. Note vague internal microbial laminations and the porosity (in blue) within the heads. Quartz silt (in white) and ooids fill the space between the heads. Skyline 16 core thin section, 973.0 ft. (Plane light)



D - Highly magnified view of the margin of a digitate stromatolite head shown in the core photo in B. Note the well-defined laminae as well as the preservation of filamentous cell remains in the porous areas between the laminae (see red arrows). Skyline 16 core thin section, 973.0 ft. (Plane light w/ white card)

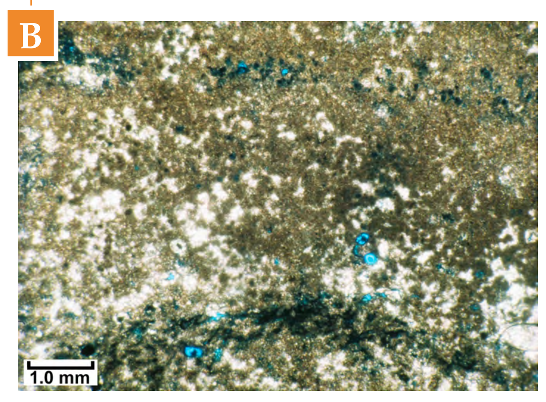
Thrombolites

(def.) = calcareous structures with a clotted microtexture and no internal laminae, built by cyanobacterial microbes. (from Greek word "thrombo" = a clot)

Aitken, 1967; Kennard and James, 1986

Green River Thrombolites

A - Low-relief thrombolitic head (in the lower half of the core segment) draped with stromatolitic laminae and thin beds of rip-up clasts. Skyline 16 core, 936.7-937.1 ft.



B - Clotted structure within the thrombolite head shown in core (above A). The white areas between the dense microbial clots consist of sparry calcite cement. Skyline 16 core thin section, 937.0 ft. (Plane light)

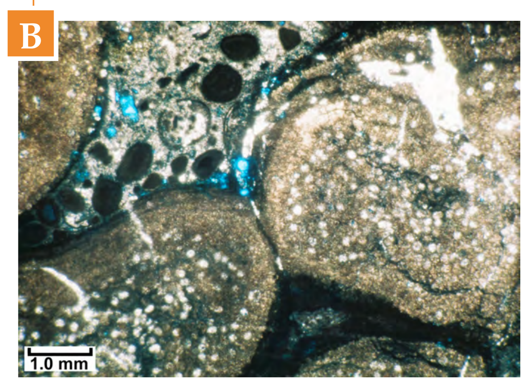
Oncolites

(def.) = sedimentary structures formed out of oncoids, which are layered spherical growth structures formed by cyanobacterial growth. Oncolites are very similar to stromatolites, but instead of forming columns they form approximately spherical structures. Often the oncoids form around a central nucleus, such as a shell particle, and the calcium carbonate structure is precipitated by encrusting microbes.

Wikipedia posting of Oncolites 4/19/2011

Green River Oncolites

A - Oncoid-rich carbonate layer overlain (with sharp contact) by laminated, dark gray shale. Red arrows point to some individual oncoids. Skyline 16, 929.7-930.0 ft.



B - Cross section through portions of several oncoids. Note the clotted texture (with spherical cell structures) within the oncoid interiors, overlain with dense laminated oncoid margins. Ooids and coated grains are present between the oncoids. Skyline 16 core thin section, 937.0 ft. (Plane light)

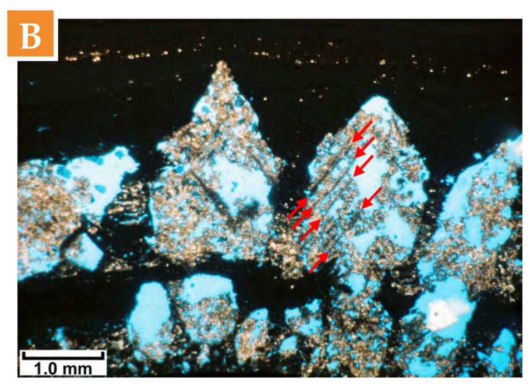
Tufa/Travertine

(def.) = a porous or compact form of CaCO3 deposited out of solution from a mineral spring or lake.

Riding, 2000

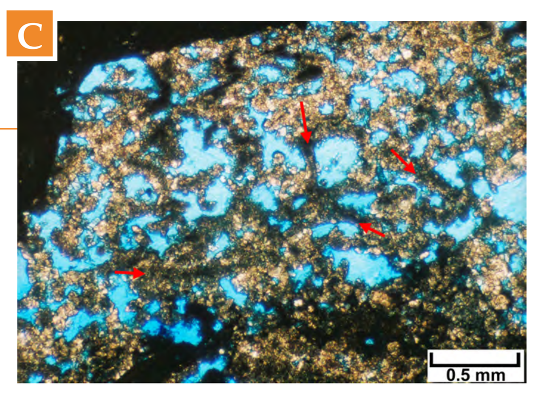
(def.) = limestone deposited by mineral springs, especially hot springs. Travertine often has a fibrous or concentric appearance and exists in white, tan, and cream-colored varieties.

Wikipedia posting on Travertine, 3/2/2012



B - Cluster of small evaporate crystal molds (from the core segment in A) that are preserved in growth position, surrounded by dense black shale. Their morphology is suggestive of gypsum crystals. The molds are partially filled with a porous, lacy tufa/travertine (in light brown). Note preserved clay drapes that form along evaporate crystal growth faces (see pairs of red arrows), Skyline 16 core thin section, 650.7 ft. (Plane light)

Green River Tufa/Travertine



C - Micrograph of interconnected lacy tufa/travertine in which filamentous cellular remains are preserved in dark brown (see red arrows). Skyline 16 core thin section, 650.7 ft. (Plane light)

A - Core segment dominated by a very porous, lacy tufa/travertine that has created a distinctively laminated deposit, as well as partially filling evaporate crystal molds. Skyline 16 core, 650.0-651.2 ft.

Regional Setting

Ancient Eocene Lake Basins

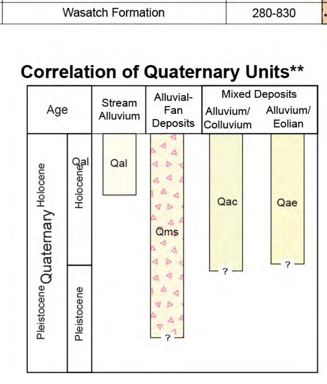
Location of the Skyline 16 core.

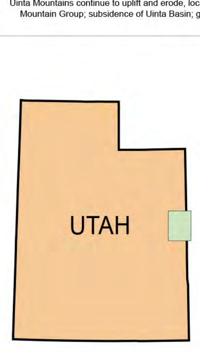
From Vanden Berg, 2011.

Stratigraphic Column for Geologic Map

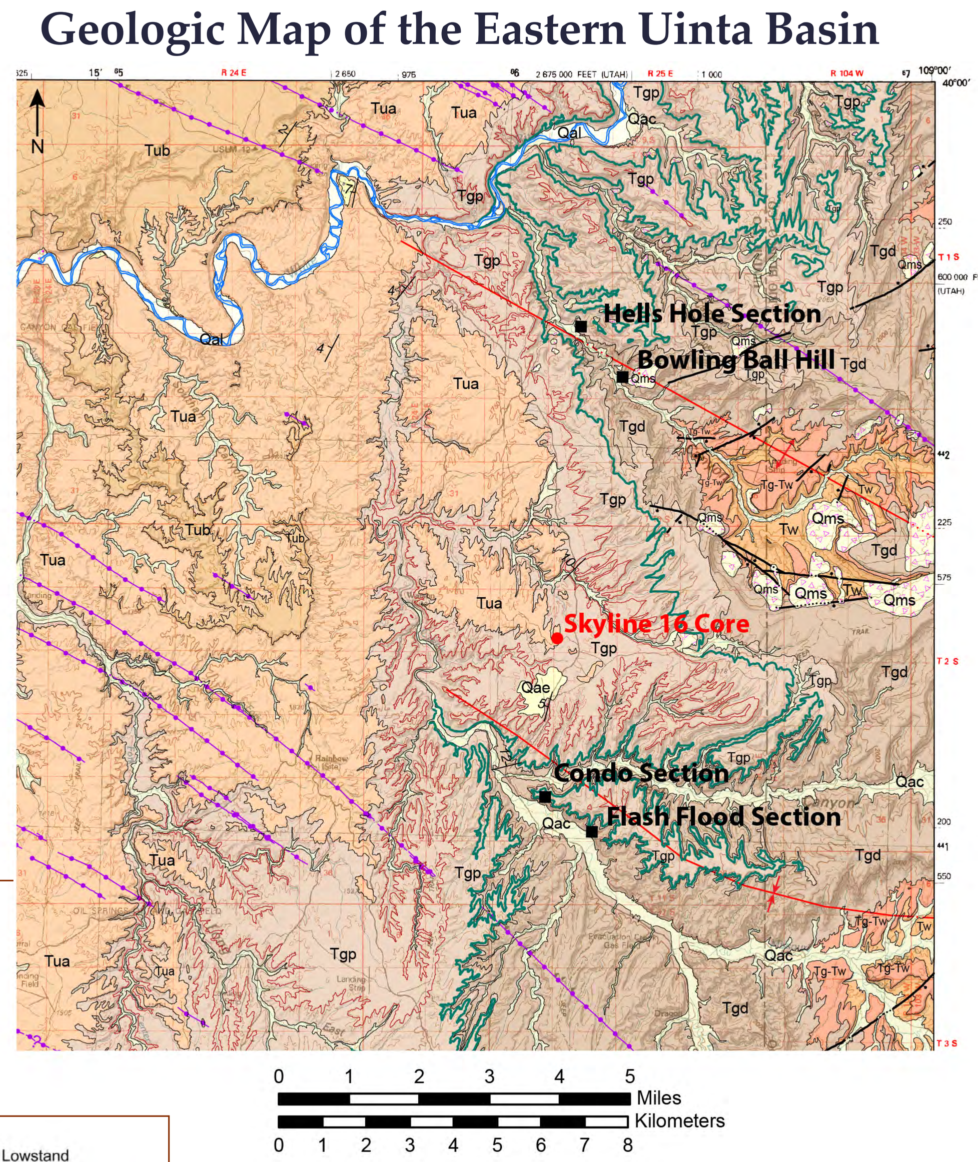
SYSTEM	SYMBOL	FORMATIONS	Thickness* (meters) (not to scale)	LITHOLOGY	NOTES
Quaternary	Q**	Unconsolidated deposits	less than 50		
Tertiary	Tub	Member B of Uinta Formation	30-225		Contains gilsonite deposits
	Tua	Member A of Uinta Formation	60-180		
	Tgp	Parachute Creek Member of Green River Formation	247-950		Tuffaceous bed B; Horse Bench Sandstone Bed; Mahogany oil shale zone
	Tgd	Douglas Creek Member of Green River Formation	45-520		Uinta Mountains continue to uplift and erode; creation of Lake Uinta as the Uinta Basin continues to subside; contains oil shale and oil reserves; Long Point Bed
	Tg-Tw	Green River-Wasatch Formations transition zone	60-220		Uinta Mountains continue to uplift and erode, locally exposing the Uinta Mountain Group; subsidence of Uinta Basin; gas reservoir in Uinta Basin
	Tw	Wasatch Formation	280-830		

Correlation of Quaternary Units**





Geologic Map of the Eastern Uinta Basin



Locations of the Skyline 16 core as well as the outcrop sections accessed for this study.

Geologic map modified from Sprinkel, 2009.

Map Symbols

CONTACT
Includes approximately located

HORSE BENCH SANDSTONE BED
Brownish- to yellowish-orange, tuffaceous sandstone and siltstone interbedded with marlstone in the Parachute Creek Member of the Green River Formation; about 1-15 m thick and about 100-135 m above the top of Mahogany oil-shale zone; a marker bed that generally forms a prominent topographic bench.

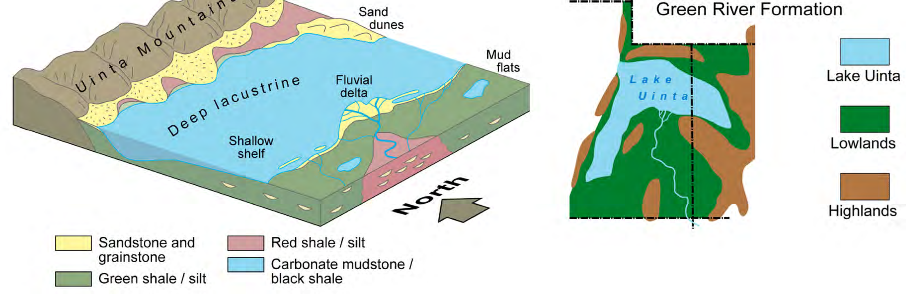
MAHOGANY OIL-SHALE ZONE
Zone of oil-shale beds about 150 m below top of the Parachute Creek Member of Green River Formation; the Mahogany oil-shale zone is about 20-30 m thick; the line on the map represents the approximate location of the richest bed called the Mahogany "ledge", which is about 1-9 m thick (thins southeastward) and about 10-12 m below the top of the zone.

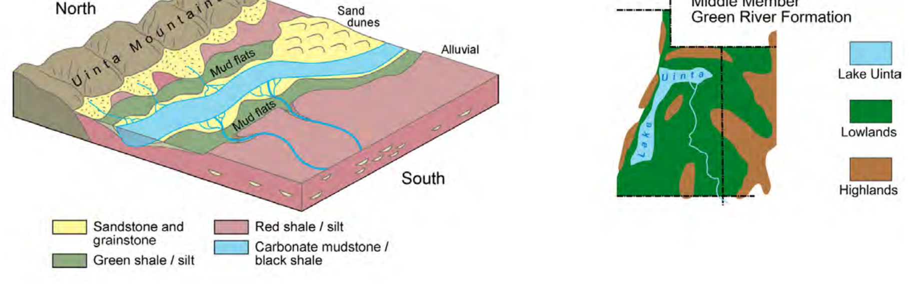
FAULT
Steeply dipping - Dashed where approximately located; dotted where concealed; bar and ball on downthrown side where offset is known.

GILSONITE VEIN
Solid where exposed, dashed where approximately located, and dotted where concealed.

FOLD AXIS
Anticline
Syncline

Generalized Depositional Setting for Lake Uinta



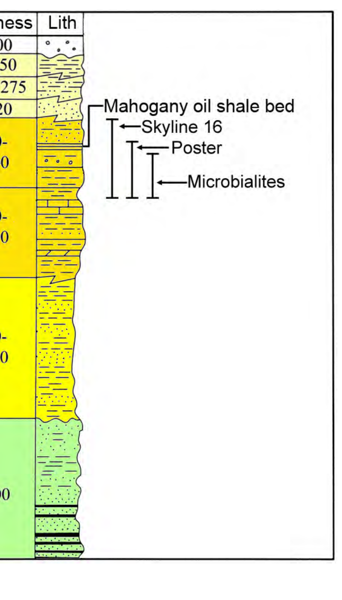


A – high-lake levels and B – low-lake levels. The Uinta Mountains were the source for the sediments in the northern portion of the lake while sediments in the southern portion of the lake were sourced from the much larger Four Corners area.

From Morgan and others, 2003

Regional Stratigraphic Column, Eastern Uinta Basin

Age	Map Unit		Thickness	Lith
Q	Alluvium - dunes		0-200	
EOCENE	Uinta Fm	Member C	60-250	
		Member B	about 275	
		Member A	0-220	
	Green River Fm	Parachute Creek Mbr	500-1200	
		Douglas Creek Member	400-1800	
PALEO	Wasatch Formation		600-3000	
CRET	Mesaverde Group		2400	



Note the stratigraphic position of the entire Skyline 16 cored interval (left bar), the portion of the core used in this study (middle bar), and the interval in which **microbialites** and associated carbonate facies occur (right bar). In addition, the location of the famous Mahogany oil shale bed is also shown.

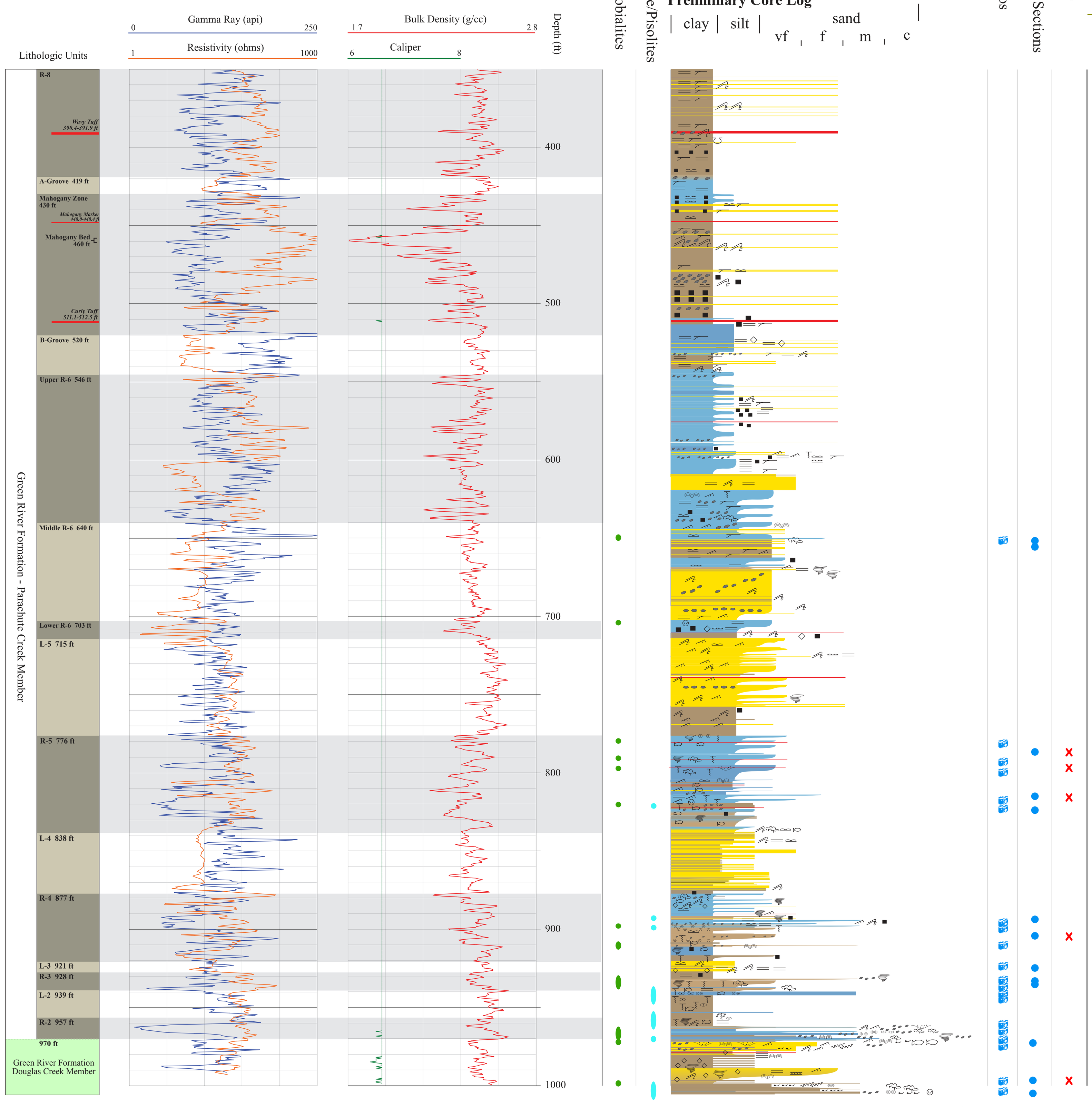
Modified from Hintze and Kowallis, 2009.

SKYLINE 16 CORE

II

Graphical Description for the Lower Portion of the Skyline 16 Core

Well name: **Skyline 16**
Operator: Utah Geological Survey - University of Utah
Location: T11S, R25E, Sec. 10, UTM E 661445, UTM N 4415109 (NAD83)
Ground elevation: 6014 ft
Year drilled: 2010
Cored interval: 20-1006 ft
Core housed at the Utah Core Research Center



* Core description by Vanden Berg and Birgenheier

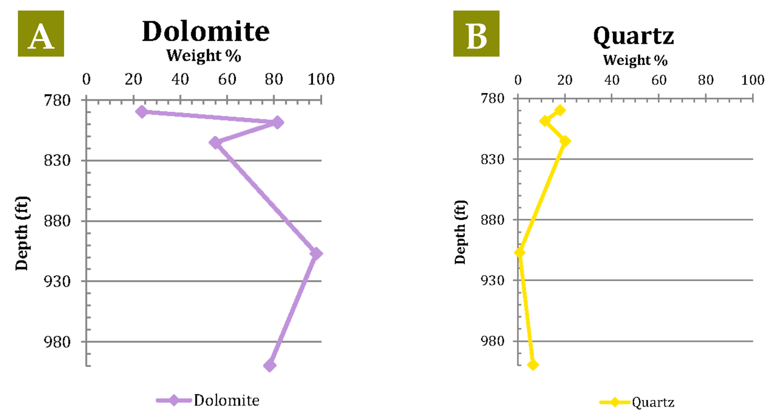
Microbialites and grainstones (oolitic, pisolitic, peloidal/skeletal) are plotted to the immediate left of the core lithology log. Note that microbialites and grainstones make up less than 10% of the interval where they occur, but they account for the vast amount of megascopic (visible) porosity in this lacustrine system.

Also shown are wireline logs for the cored interval as well as informal lithological units recognized in both core and outcrops within the basin. Note the distribution of thin sections, core close-up photos and XRD analyses used for this microbialite reservoir study.

Core Log Explanation

- Calcareous/dolomitic mudstone
- Siltstone / very fine sandstone - often bitumen stained
- Clay-rich mudrock - slightly calcareous/dolomitic
- Ash / tuff
- Pyrite/ Marcasite/ Pyrrhotite crystals
- Flat/planar lamination
- Low angle lamination
- Wavy lamination
- Ripples
- Soft sediment deformation/ convolute bedding
- Scour with massive fill
- Mudrock intraclast
- Organic-rich interval
- Gar fish scales
- Shell debris
- Microbialite
- Stylolites
- Concretion
- Synaeresis cracks
- Ripple cross lamination
- Deformed cross bedding
- Ostracods
- Dewatering structure

Mineralogy of Selected Microbialite and Grainstone Samples from the Skyline 16 Core



A - Variation (by wt. %) of Dolomite and B - Quartz (mostly in the form of chert) in selected carbonate intervals.

Core Photos of Skyline 16 Samples Analyzed by X-Ray Diffraction

789.5 ft.

798.5 ft.

815.0 ft.

907.0 ft.

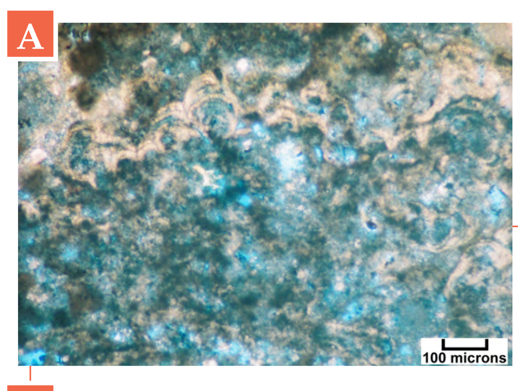
999.5 ft.

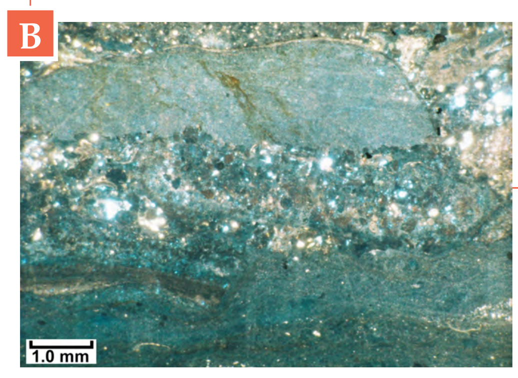
RESERVOIR ANALOGS
FROM SKYLINE 16 CORE

Thin section examination of dolomitic microbialites and associated carbonate facies in the Skyline 16 core display a nice variety of analogs for porosity types, hydrocarbon storage potential, and flow potential.

MICROBIALITES:

STROMATOLITES



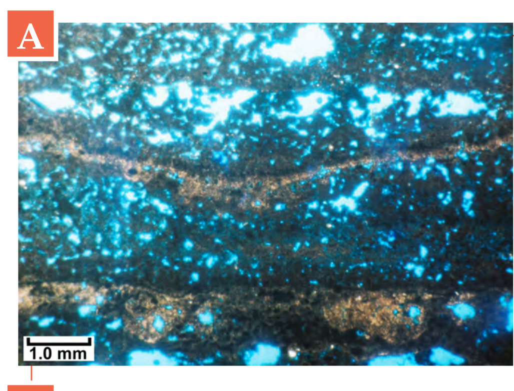


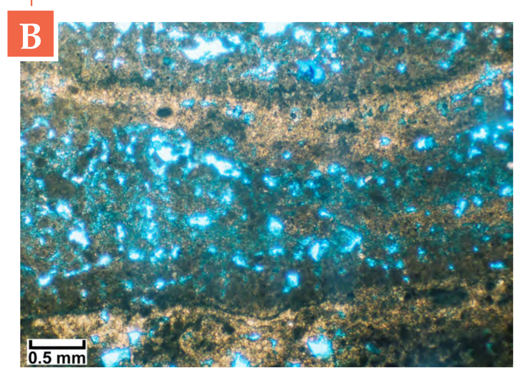
C - Low-relief stromatolites interbedded with ooids containing stromatolitic rip-up clasts. Excellent porosity within the microbialite fabrics consists of preserved primary megascopic pores and microporosity. Red arrow indicates the location of micrographs shown in A and B. 824.0-824.5 ft.

A - Preserved primary porosity within a stromatolitic interval. Megascopic pores are the result of constructional processes associated with tubular cells and pustular microfabrics. 824.4 ft. (Plane light)

B - Considerable microporosity within very fine grained carbonates associated with a stromatolitic interval. 824.4 ft. (Plane light)

THROMBOLITES



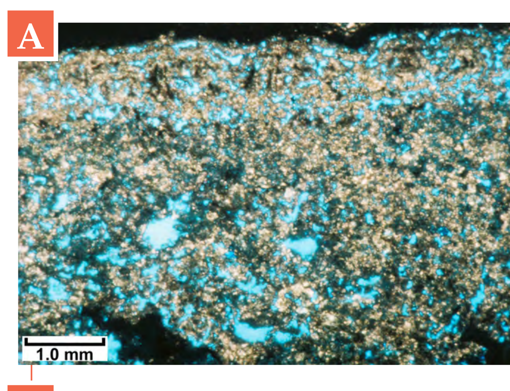


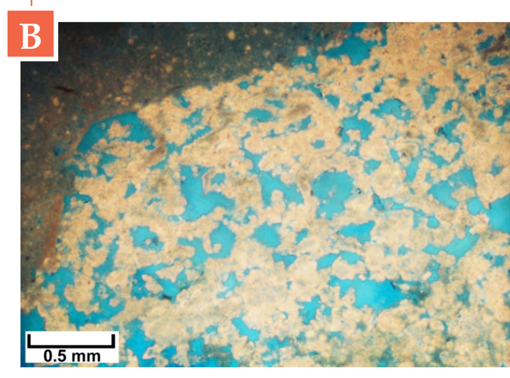
A - Excellent preserved primary porosity within a thrombolitic interval. Megascopic pores are intimately associated with clotted constructional fabrics. Note also the small primary vugs. 1002.2 ft. (Plane light)

B - Closer view of well-connected preserved pores associated with a clotted microbial fabric. 1002.2 ft. (Plane light)

C - Low-relief thombolites associated with ooids and microbialite rip-up clasts. Small primary vugs are also present. Thrombolites seem to preserve greater amounts of megascopic porosity than stromatolites. Red arrow indicates the location of micrographs shown in A and B. 1002.0-1002.5 ft.

TUFA/TRAVERTINE





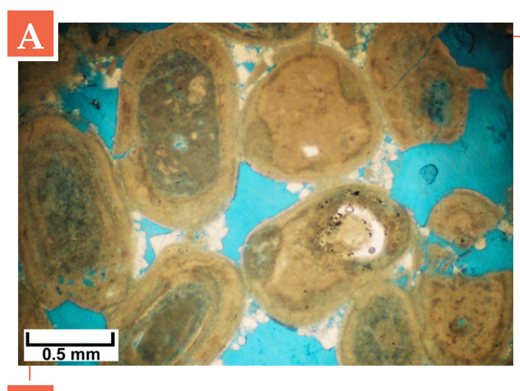
C - Irregular layers of porous tufa/travertine filling voids that are associated with large evaporite crystal molds. Red arrow indicates the location of micrographs shown in A and B. 650.5-651.2 ft.

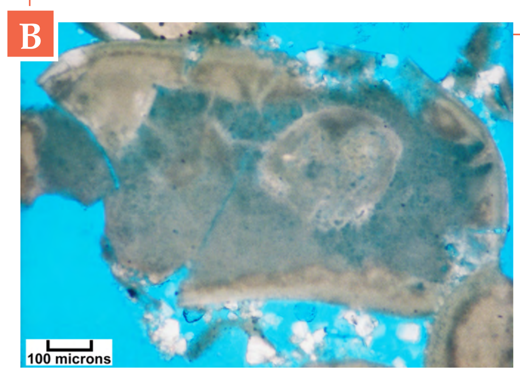
A - Delicate lacy tufa/ travertine fabrics composed of crystalline dolomite growing within open voids. Remnants of fine-grained clay-rich mudstones line the walls of the voids. 650.5 ft. (Plane light)

B - Closer view of delicate interlocking tubular microbial fabrics within void-filling tufa/ travertine. Note the well-preserved, well-connected megascopic pore space (in blue). 650.5 ft. (Plane light w/ white card)

GRAINSTONES:

OOLITES



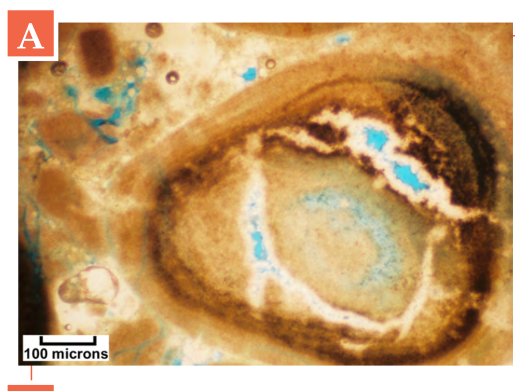


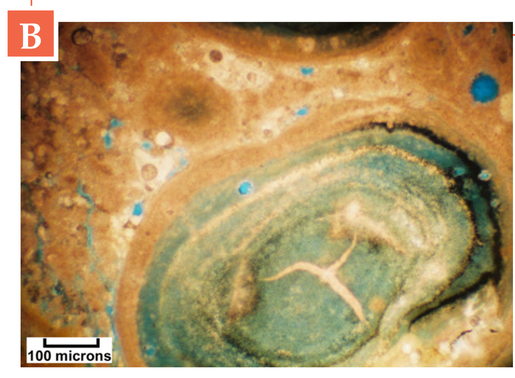
A - Excellent preserved interparticle porosity (blue) between very lightly cemented ooids. Note the small amounts of sparry calcite cement crystals (in white) lithifying this oolite. 1003.0 ft. (Plane light w/ white card)

B - Highly magnified view of impressive microporosity (dark blue) within an oolitically coated grain. This microporous composite grain is part of a very porous oolitic bed. 1003.0 ft. (Plane light w/ white card)

C - Porous oolites with bedding defined by grain size differences. Primary interparticle porosity is visible within the coarser beds. Red arrow indicates the location of micrographs in A and B. 1002.6-1003.0 ft.

PISOLITES



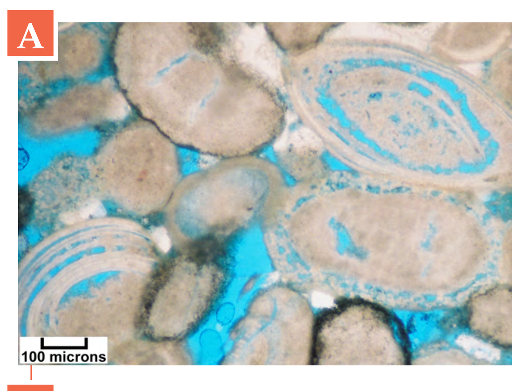


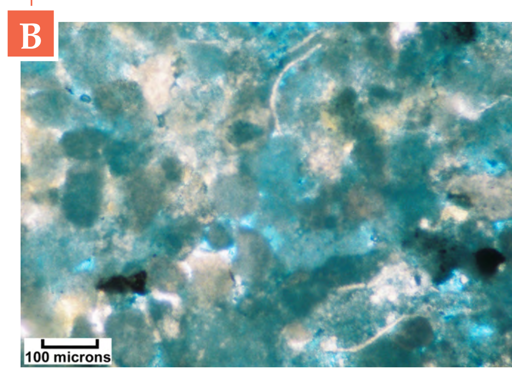
A - An individual pisoid within a cemented bed containing peloids and oolitically coated grains. Note the partially open microfractures ("septarian cracks") within the pisoid as well as some preserved pores between grains. 898.4 ft. (Plane light w/ white card)

B - View of a pisoid exhibiting significant internal microporosity (in light blue). 898.4 ft. (Plane light w/ white card)

C - Grainstone beds capped with a thin pisolitic bed. Above the pisolites, with a very sharp contact, is a laminated black shale. Red arrow indicates the location of micrographs shown in A and B. 898.2-898.7 ft.

PELOIDAL/SKELETAL



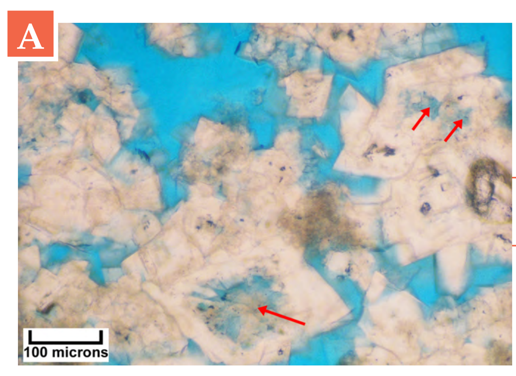


A - Abundant preserved interparticle and intraparticle pore space is displayed in this peloidal/ skeletal calcarenite. The skeletal grains are articulated and single valve ostracods. 939.5 ft. (Plane light w/ white card)

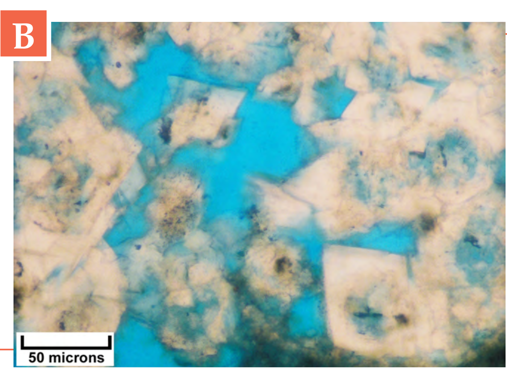
B - Very significant preserved interparticle porosity (light blue) and peloidal microporosity (dark blue) are displayed in this sample. Thin ostracod shells are also present. 824.4 ft. (Plane light)

C - The lower half of this core segment shows a very porous peloidal/skeletal grainstone (in light to medium gray) overlain by a sharp erosional contact. Red arrow indicates the location of micrograph shown in A. 939.0-939.6 ft.

DOLOMITES:



A - Excellent porosity can be seen between clusters of dolomite crystals associated with tufa/travertine. Note also the presence of hollow dolomite crystals (see red arrows). 650.7 ft. (Plane light w/ white card)

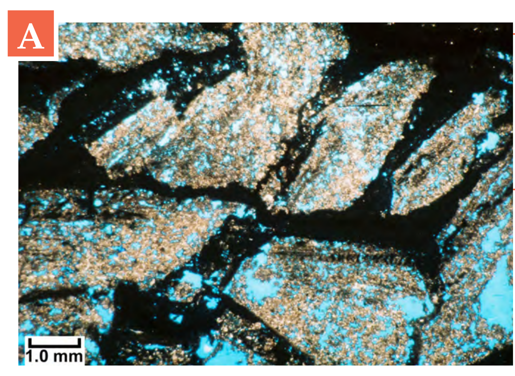


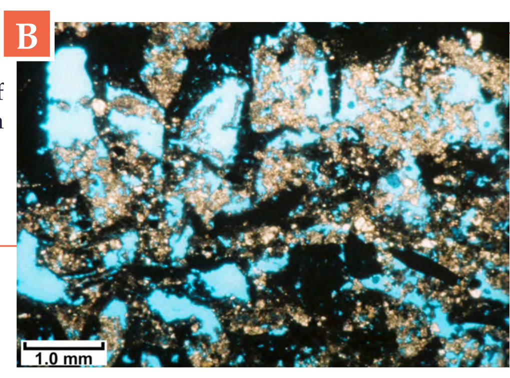
B - Well-connected pores are present between individual dolomite crystals and small crystal clusters associated with tufa/travertine. Hollow dolomite cores are common. 650.5 ft. (Plane light w/ white card)

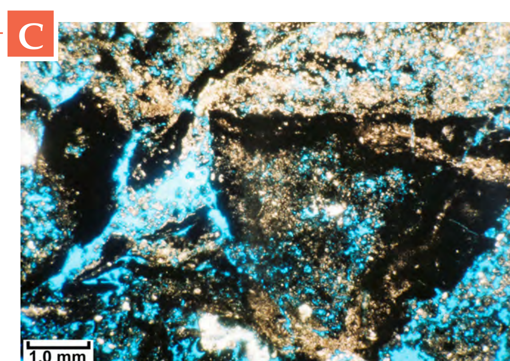
C - Porous dolomites occur as the orangish lacy patterns on this core surface. The most porous dolomites are associated with tufa/travertines. Red arrow indicates the location of micrograph shown in A. 650.5-650.9 ft.

EVAPORITE DISSOLUTION:

B - Numerous molds retaining the shape of evaporate crystals (most likely gypsum) can be seen between dense black sediments. Clusters of small dolomite crystals have precipitated within some of these molds. 650.7 ft. (Plane light)







A - Several lozenge-shaped molds (most likely from dissolved gypsum) occur between dense black sediments. Abundant dolomitic tufa/travertine has precipitated within these molds. 650.5 ft. (Plane light)

C - Good visible matrix porosity is associated with dissolution of evaporate minerals (probably gypsum) and associated collapse of the sediment matrix (black and white areas here). 789.5 ft. (Plane light)

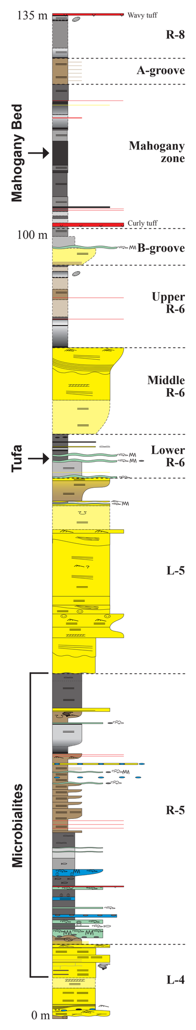
D - Disrupted sediments associated with evaporate crystal dissolution and sediment collapse are shown here in a representative core segment. Porosity associated with dolomitization is present in the orangish patches. Red arrow indicates the location of micrograph shown in C. 789.5-790.0 ft.

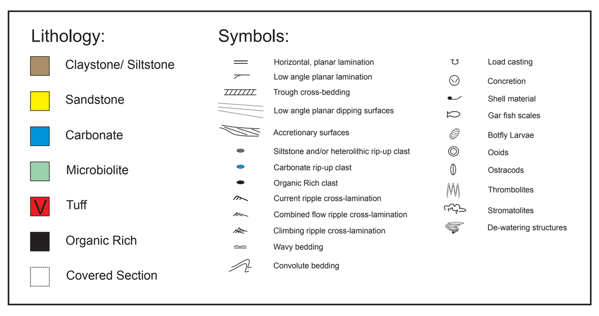
OUTCROP EXAMPLES

III

Four spectacular outcrops were studied in the eastern Uinta Basin (south of Vernal, Utah) for the distribution and lateral continuity of microbialites and related carbonate facies.

CONDO SECTION





From Rosenberg, 2013

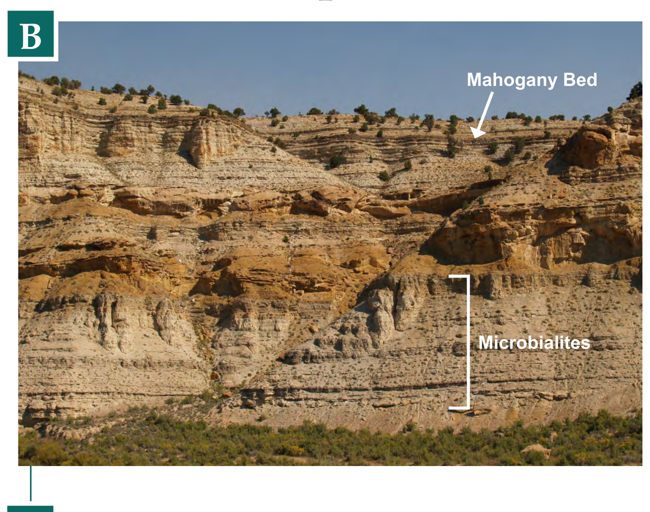
A

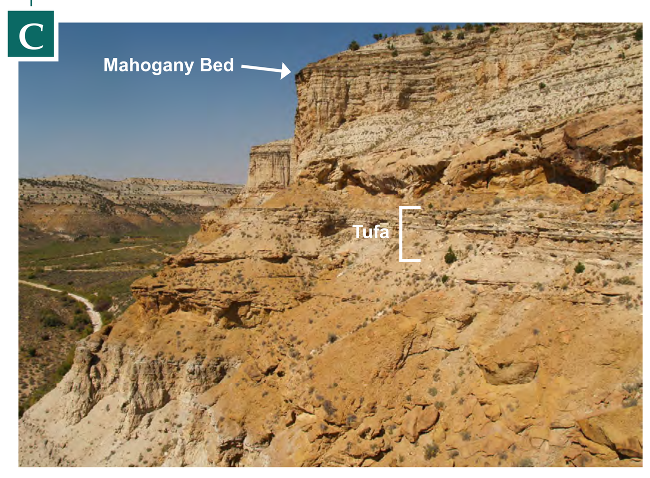
A - Measured Condo section (see location on panel I). Microbialite intervals are concentrated mostly in the lower half of this 443 ft (135 m) section.

B - View of the entire Condo section taken from the base of the outcrop. Note the general vertical distribution of the microbialite-rich interval as well as the famous Mahogany bed (oil shale).

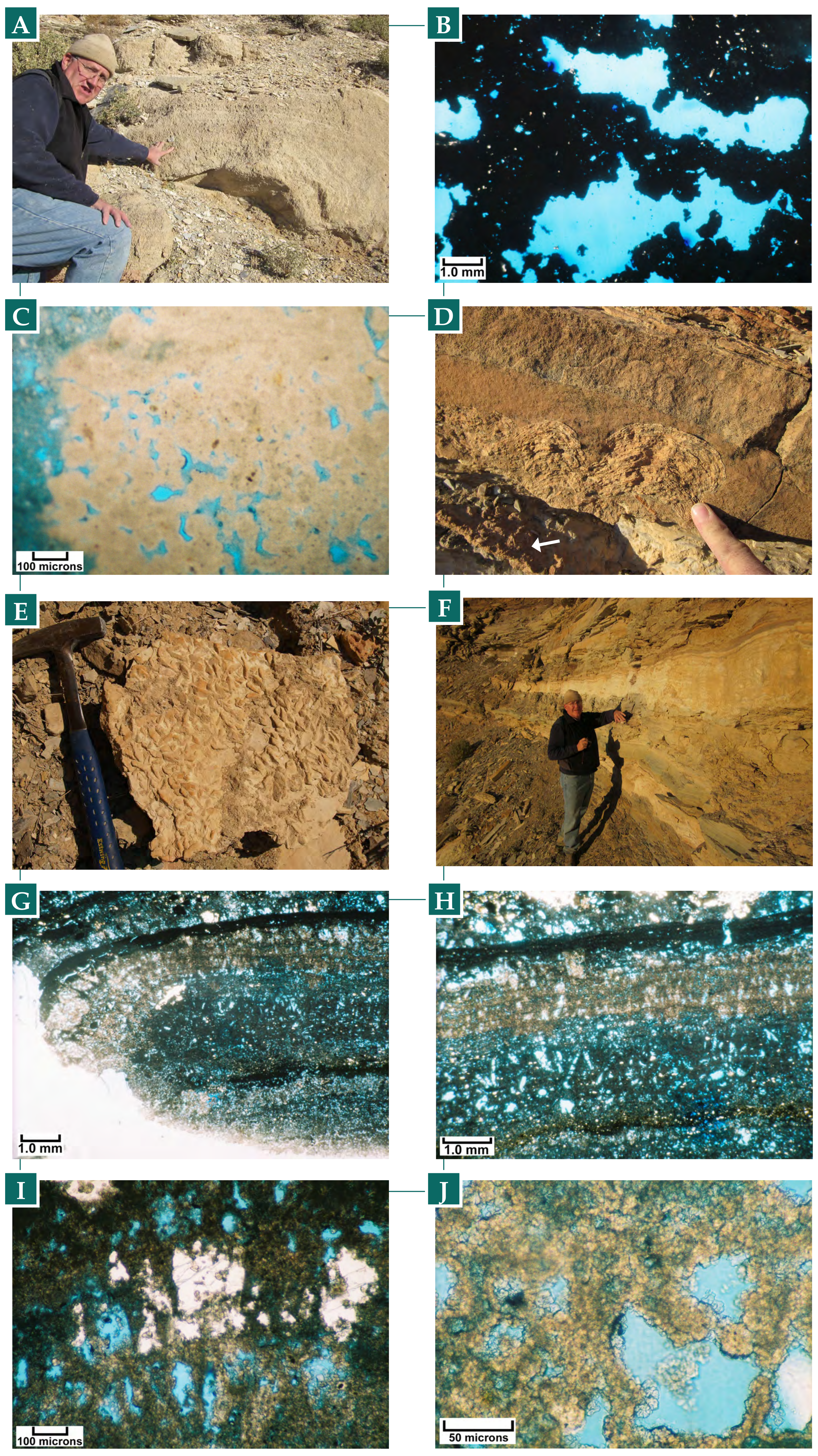
C - View of the upper portion of Condo section, taken from near the top of the microbialite-rich interval. Note the location of a tufa/travertine-rich interval as well as the Mahogany bed.

Outcrop Views





Microbialite and Evaporite Examples in Condo Section



A - A meter-scale thrombolite head (right side of photo). Note the steep margin of this domal structure. (R-5 oil shale zone)

B - Low magnification image of the clotted microfabric (in black) of a thrombolitic head like the one shown in A. Note the large open pores (vugs; in blue) that are the preserved as part of the microbial construction of this thrombolite. (Plane light)

C - Highly magnified image of the clotted microfabric (in light brown) of a thrombolitic head like the one shown in A. Note the open pores (in blue) that are an important result of thrombolitic growth. (Plane light w/ white card)

D - Small domal stromtolite heads (adjacent to the finger) that grade upwards into even smaller branching stromatolites. This stromatolitic bed has grown over densely packed evaporate (gypsum?) crystal casts (white arrow). (Lower R-6 oil shale zone)

E - Close-up of evaporate crystal casts shown in D. (Lower R-6 oil shale zone)

F - Continuous beds of tufa (in very light colored bands) and stromatolites. (Lower R-6 oil shale zone)

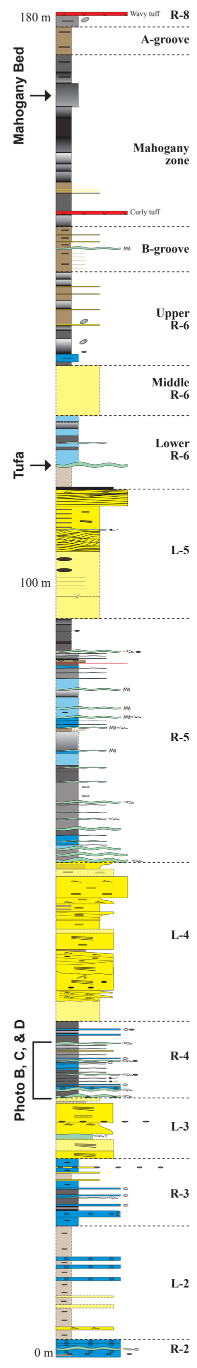
G - Margin of a stromatolite head (in thin section) from the Condo section. Note the well-developed laminations as well as the abundant preserved primary pores (in blue) between microbial filaments. (Plane light)

H - Closer view of stromatolitic laminae with well-developed porosity (in blue) between constructional microbial filaments. (Plane light)

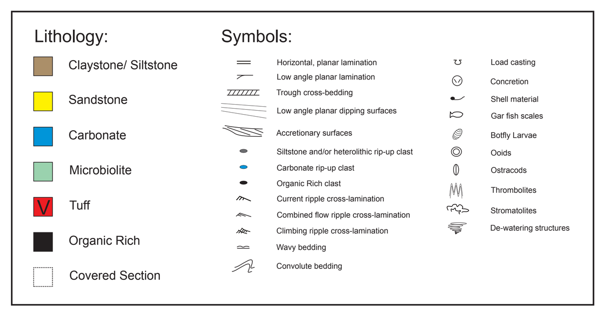
I - Highly magnified microbial filaments within stromatolitic laminae protect primary pores (in blue). Calcified evaporate crystals (probably after gypsum) are present in the white patches. (Plane light)

J - Interlocking microbial filaments are preserved by the precipitation of small dolomite crystals. Note the open pores (in blue) encased by the dolomitized filaments. (Plane light)

FLASH FLOOD SECTION



A



From Rosenberg, 2013

Outcrop Views

A - Measured Flash Flood section (see location on panel I). Microbialite intervals are concentrated mostly in the lower half of this 591 ft (180 m) section. Microbialites and associated carbonate facies are shown in blue/green.

B - View of a portion of the Flash Flood section in which microbialites and associated carbonate facies are present.

C - Outcrop view of representative thin, continuous stromatolite beds in the light colors (below hand).

D - Single stromatolite head in the Flash Flood section. Note the porous laminated microbialite head that has changed orientation and relative relief from bottom to top.

BOWLING BALL HILL

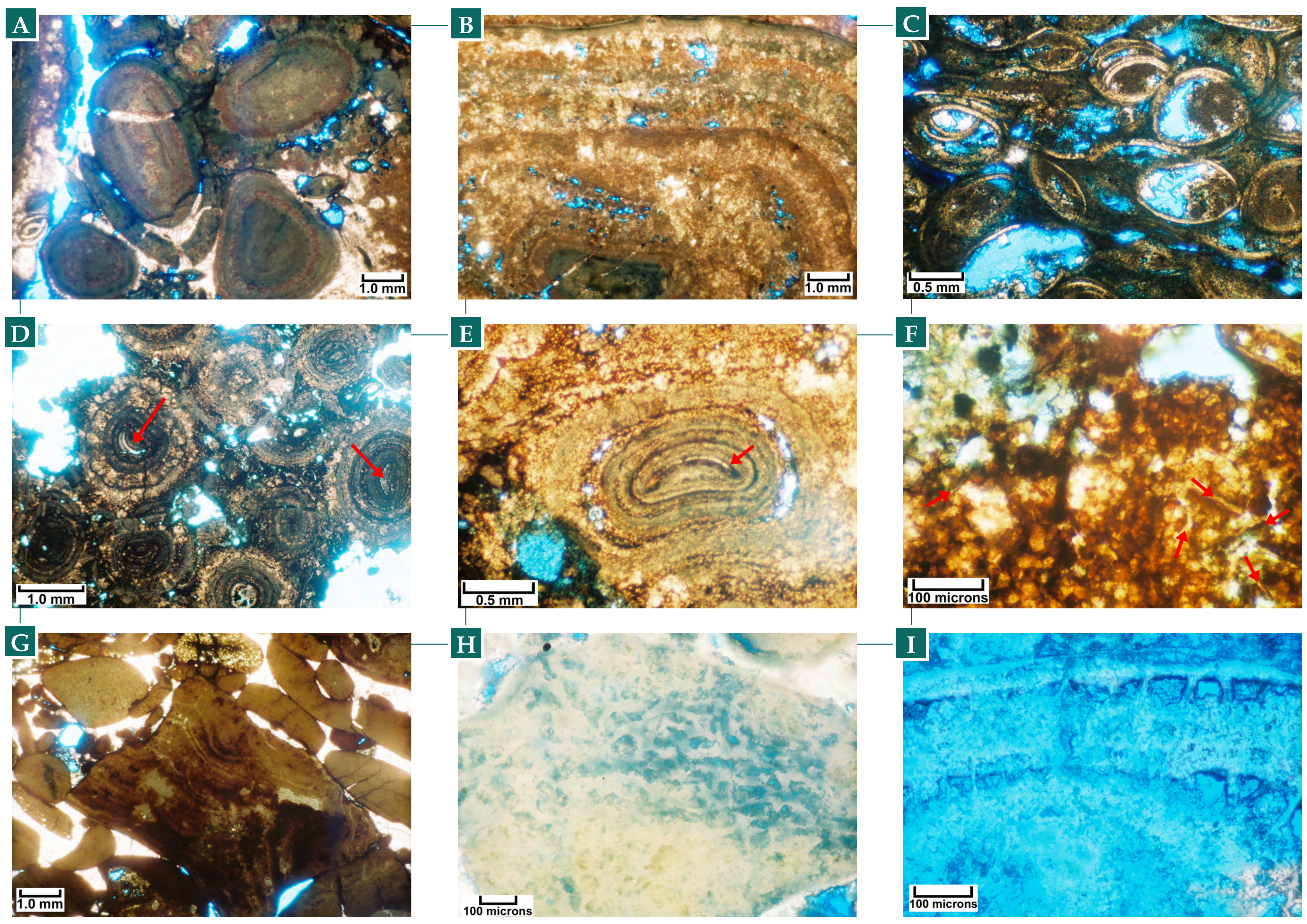
Outcrop Views

A - View of Bowling Ball hill. Note the location of the dolomitized "Bowling Ball" stromatolite zone in the lower foreground as well as the Mahogany bed in the middle right.

B - View of the large rubble blocks from the "Bowling Ball" zone composed of multiple meter-scale coalesced stromatolite heads.

C - Inclined bedding plane surfaces of partially silicified oolite/pisolite beds that are associated with microbialite facies on Bowling Ball hill.

Microbialite Examples from Bowling Ball Hill



A - Grouping of several small oncoids in a thin section from a microbial near Bowling Ball hill. Note the rounded margins but irregular shape of individual oncoids. Ostracods and clotted microbial fabrics surround these oncoids, especially along the right margins of this micrograph. (Plane light)

B - Cross section through a representative oncoid from a microbial bed near Bowling Ball hill. Note the patches of good porosity (in blue) preserved within some of the cortex bands in this oncoid. Remnants of some of the filamentous microfabrics can also be seen. (Plane light)

C - Articulated ostracods and carbonate mud shown in this micrograph provide the sediment fill between many of the microbialite heads and oncoids from Bowling Ball hill. Note the geopetal fills containing peloids within some of the cavities formed by paired ostracod shells. (Plane light)

D - Small pisoids in thin section from carbonate facies associated with microbialite beds near Bowling Ball hill. Many of the nuclei (see red arrows) of these pisoids are broken ooids (which are also present in Great Salt Lake shoreline sediments). (Plane light)

E - Cross section of a typical pisoid associated with microbialite beds. Note that this particular large grain contains a single ostracod valve (see red arrow) as the nucleus. (Plane light)

F - Highly magnified image from within a representative pisoid from grainstone/rudstone facies associated with microbialite beds. Note the "ghosts" of filamentous or tubular (microbial) structures (see red arrows) within these dolomitized grains. Preserved pores are light blue. (Plane light)

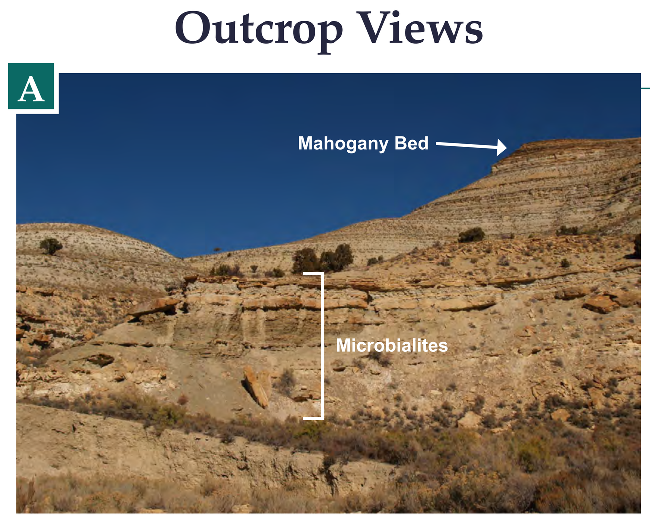
G - Silicified rip-up clasts in this low magnification image are composed of massive to laminated microbialite fabrics. It is likely that these clasts were derived from eroded and/or exposed thrombolitic and stromatolitic heads. (Plane light)

H - Porous (in blue) microfabric preserved within a dolomitized thrombolitic head from Bowling Ball hill. (Plane light w/ white card)

I - Highly magnified view of the microbial "building blocks" or microstructure of a representative oncoid from a microbial interval near Bowling Ball hill. Note the tubular and filamentous elements of this microfabric. (Plane light w/ white card)

HELLS HOLE SECTION

Outcrop Views

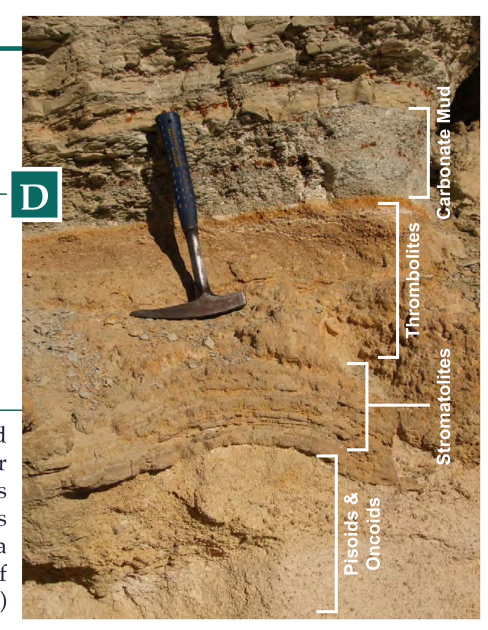


A - View of the entire Hells Hole section, taken from the base of the outcrop. Microbialite-rich intervals are common within the carbonate facies in the lower part of this section. The famous Mahogany bed is present near the top of the section.

B - View of two dolomitic thrombolite beds (in orange), one at the base of this view and the other (5 ft [1.5 m] thick) at the level of the person.

C - Fresh rock surface of a dominantly thrombolitic bed. Note the well-preserved megascopic pore system that was controlled by the growth habit of the original microbial fabric.

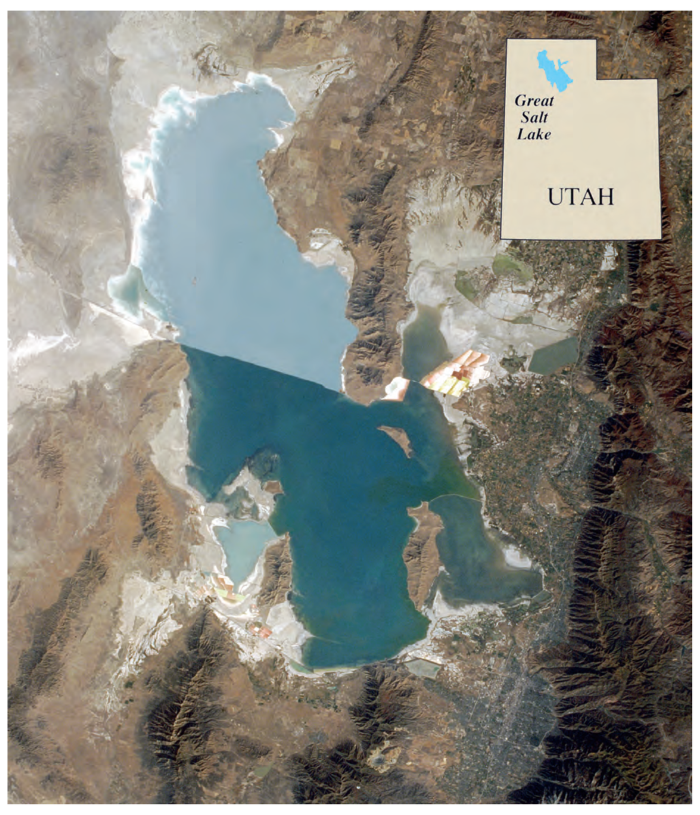
D - A typical microbialite interval and associated facies. The light tan interval near the base is composed of pisoids and oncoids (as a grainstone/rudstone). The tan beds beneath the hammer are stomatolitic, while a thrombolite dominates the area to the right of the hammer. (similar to Skyline 16 core)



GREAT SALT LAKE, UTAH: A MODERN ANALOG

IV

Satellite Image of Great Salt Lake



NASA #STS047-097-021; date: September 1992

General Characteristics

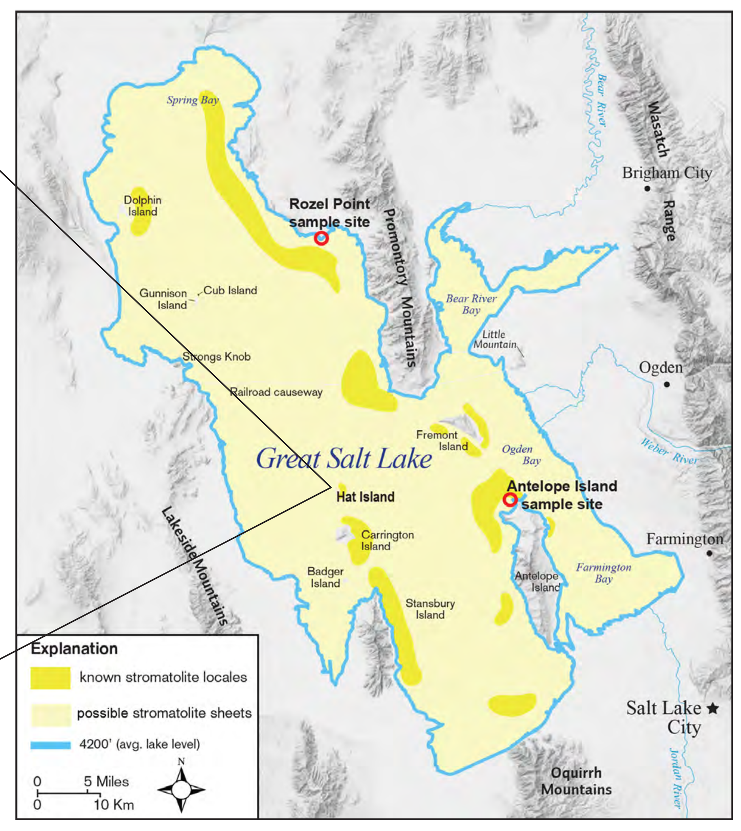
- Remnant of Pleistocene Lake Bonneville
- 33rd largest lake in the world (largest fresh or saltwater lake in the United States after the Great Lakes)
- Averages 75 miles (121 km) long by 35 miles (56 km) wide
- Surface Elevation: about 4200 ft (1280 m) covering 1,034,000 acres (418,500 ha)
- Lake Level Fluctuations: 1 to 2 ft (0.3-0.6 m) annually on average
- Maximum Depth: about 33 ft (10 m)
- Volume: 15,390,000 acre-ft (18,980 hm^2)
- Salinity: south arm = 12 to 14%, north arm = 24 to 26% (near its salt-saturation point)
- Chemical Composition: chloride = 54.5%, sodium = 32.8%, sulfate = 7.2%, magnesium = 3.3%, potassium = 2%, calcium = 0.2%

Gywnn, 1996

Stromatolites near Hat Island, Great Salt Lake

In September 2007, the lake level was nearly 5 ft (1.5 m) below the average of 4200 ft (1280 m).
Photo by Jim Van Leeuwen; courtesy of the Utah Division of Wildlife Resources, Great Salt Lake Ecosystem Program.

Stromatolite Areas in Great Salt Lake



Modified from Eardley, 1938; Gwynn and Murphy, 1980; Davis, 2012.

RESERVOIR ANALOGS

MICROBIALITES

Views of Great Salt Lake Microbial Deposits

A - Remains of stromatolite heads, Rozel Point.

B - Partially submerged stromatolite, Rozel Point.

C - Closer view of exposed remains of stromatolite heads, Rozel Point.

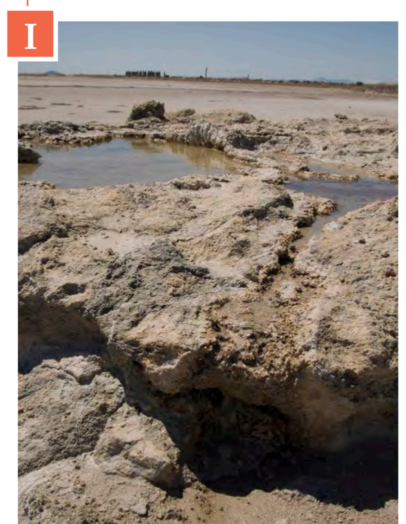
D - Close up of stromatolite displaying laminations and porous microstructures, Rozel Point.

E - Close up of cemented stromatolitic beachrock, Antelope Island.

F - Northwest beach of Antelope Island composed of complex microbial and associated oolitic deposits.

G - Close up of pustular microbial deposits, Antelope Island.

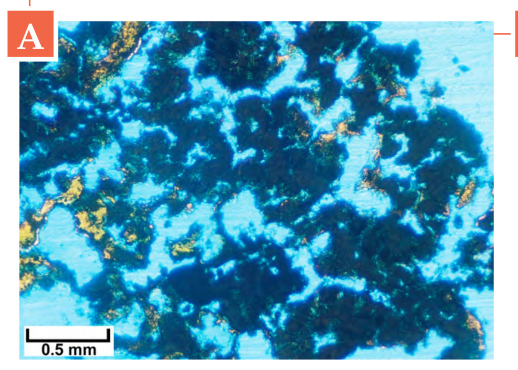
H - Small microbial tufa deposit and active associated spring, Rozel Point.



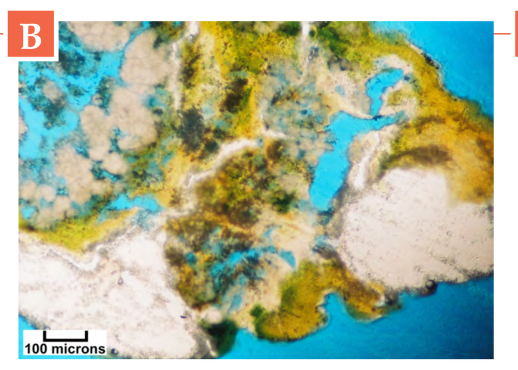
I - Closer view of spring and thrombolitic microbial tufa deposits, Rozel Point.

Microbialite Examples: Antelope Island

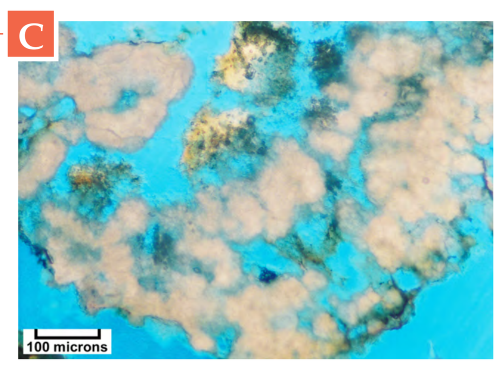
Pustular microbialites - large number of discrete pustular microbial structures composed of very lightly lithified, clotted thrombolitic fabrics with moderate amounts of filamentous cells. The margins of some pustules display a honey-brown, highly organic crust. Detridal silicate and carbonate grains are incorporated into some pustules.



A - Close-up view of a microbial pustule structure with honey-brown organic crust and filamentous cells bridging pores as well as incipient acicular cements. (Plane light)

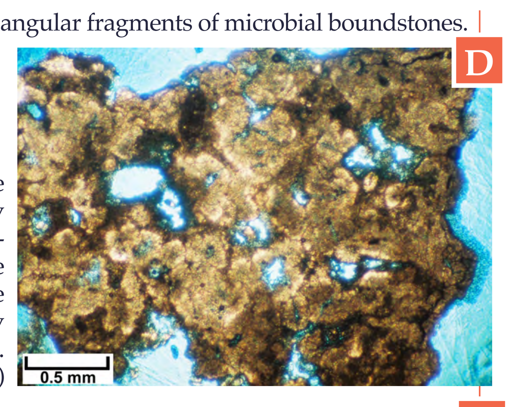


B - Small microbial pustule incorporating two silicate silt grains into honey-brown organic crust. (Plane light w/ white card)

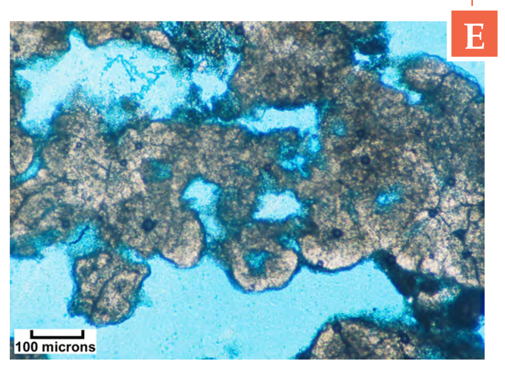


C - Heavily calcified "lumpy/bumpy" structures within a small microbial pustule. (Plane light w/ white card)

Coarse lag containing large angular fragments of microbial boundstones.



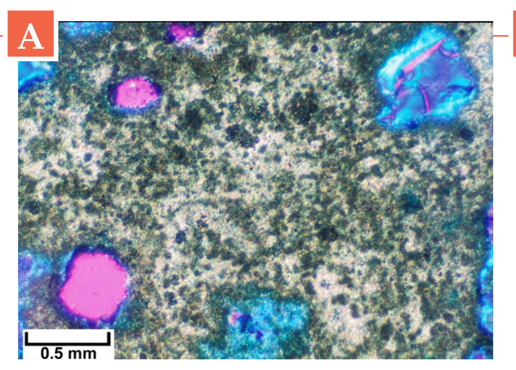
D - View of the internal lumpy texture of a well-lithified microbialite fragment. Note the internal primary constructional pores. (Plane light)



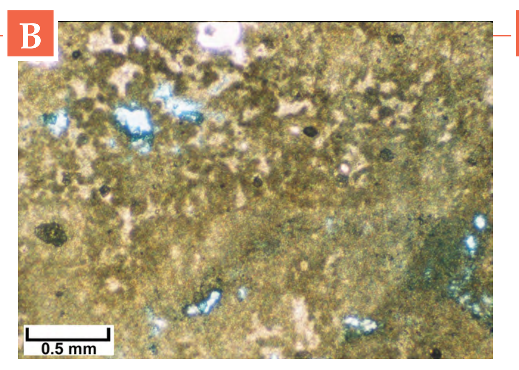
E - Overview of well-defined spherulitic structures within a microbial fabric. (Plane light)

Microbialite Examples: Rozel Point

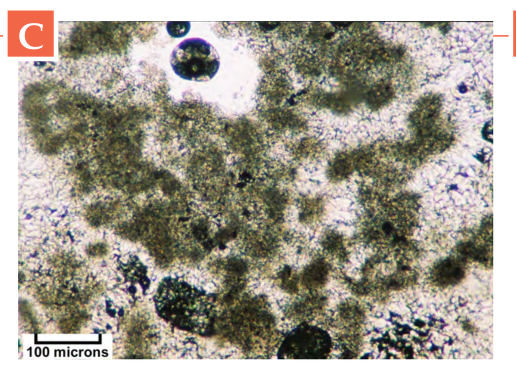
"Tufa" deposits - pustular microbialite thrombolitic heads consisting of laminated structures around the margin and clotted fabric in the interiors; primary constructional pores associated with the microbial heads are partially filled with quartz silt, ooids, and lime mud.



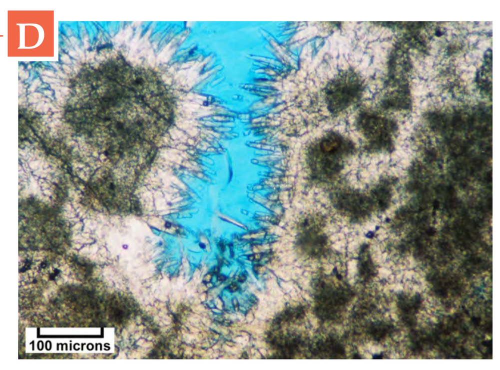
A - Close-up view of clotted microbialite head interior including primary constructional pores. (Crossed-nichols w/ accessory)



B - A different view of clotted microbialite head interior and open constructional pores. (Plane light)



C - Tightly cemented microbialite pores filled with acicular crystals. (Plane light)



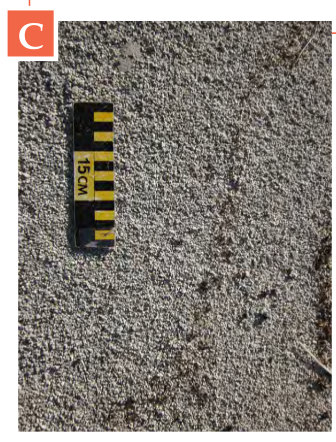
D - Close-up view of constructional pores within a microbialite head; pores are lined with acicular radial cements. (Plane light)

CARBONATE GRAINS ASSOCIATED WITH MICROBIALITES

Views of Great Salt Lake Carbonate Grains Associated with Microbialites

A - Beach deposits composed primarily of hypersaline ooids, Rozel Point.

B - Close up of hypersaline ooids along the beach at Rozel Point.

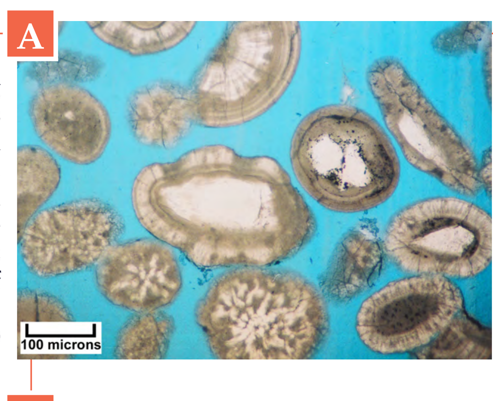


C - Close up of beach deposits consisting of ooids and coated grains, Antelope Island.

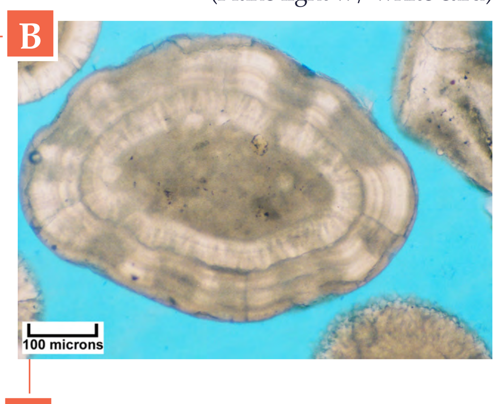
Examples of Grains and Cements: Antelope Island

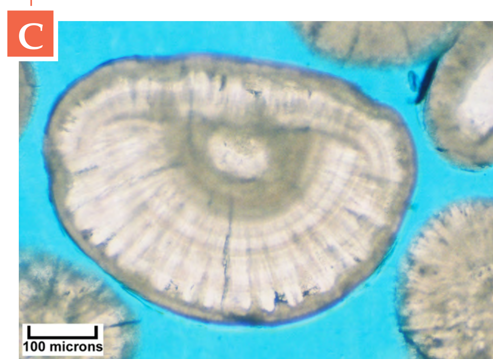
Hypersaline ooids display extensive radial recrystallization and cerebroid margins. Many ooids are broken across their cortex layers, and then are re-coated (regenerated ooids). Nuclei include quartz grains, well-rounded peloids (some with micro-pyrite), broken ooid fragments, chert grains, igneous (volcanic?) rock fragments, and microbialite fragments.

A - Ooids displaying various characteristics such as radial recrystallization, cerebroid margins, and regeneration. Note cerebroid ooid with quartz nucleus near the center of the image. (Plane light w/ white card)

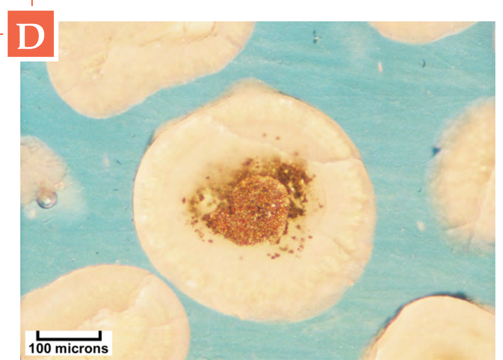


B - Single, large cerebroid ooid. (Plane light w/ white card)



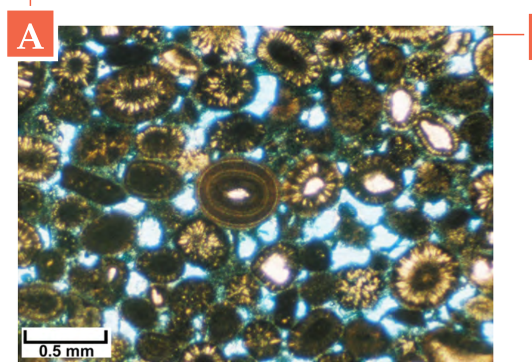


C - Single, regenerated ooid with broken ooid nucleus. (Plane light)

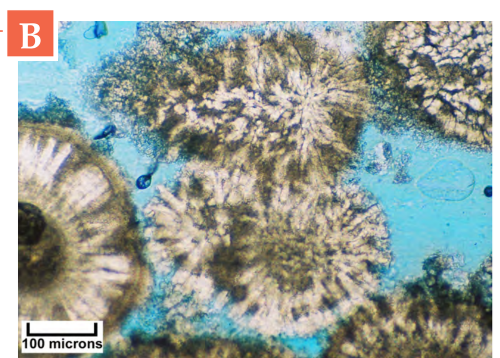


D - Single, ooid with a brassy pyritic nucleus. (Plane light and Reflected light)

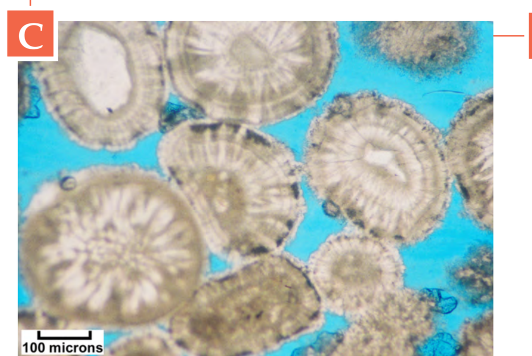
Moderately well-cemented oolitic clasts occur within a beachrock crust. Ooid nuclei include angular siliciclastic grains, rounded pellets, and occasional microbial fragments. Cements include micritic (precipitated from Great Salt Lake water either microbially or inorganically), isopachous microfibrous cement (from phreatic Salt Lake brines [inorganic]), acicular patchy cements of unknown origin, radially bladed cements that inherits that crystal orientation and morphology of the radial recrystallized bundles within certain ooids.



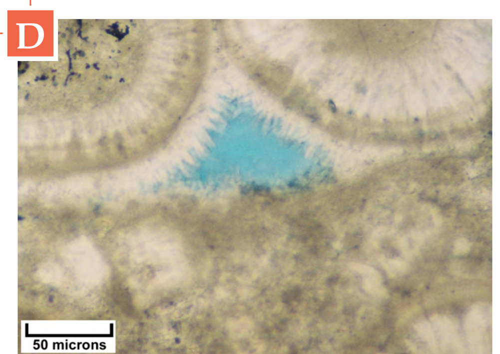
A - Overview of medium to well-sorted oolitic sands showing abundance of interparticle micrite cement. (Plane light)



B - View of radially recrystallized ooids with rough grain margins and micritic cements. (Plane light)



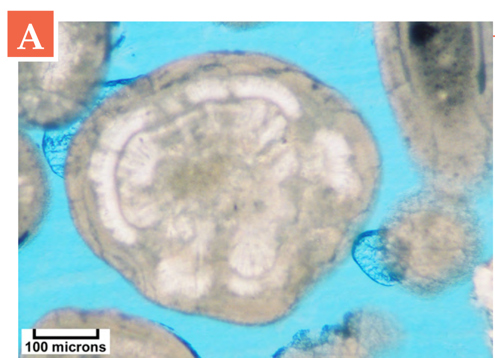
C - Regenerated ooids and meniscus cements at grain contacts. (Plane light w/ white card)



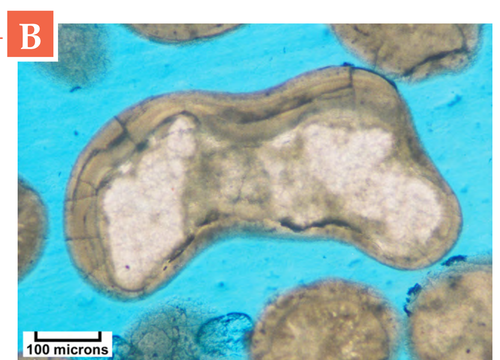
D - Ooid contacts with extensive acicular radial axial cements as well as micritic cements. (Plane light w/ white card)

Examples of Grains and Cements: Rozel Point

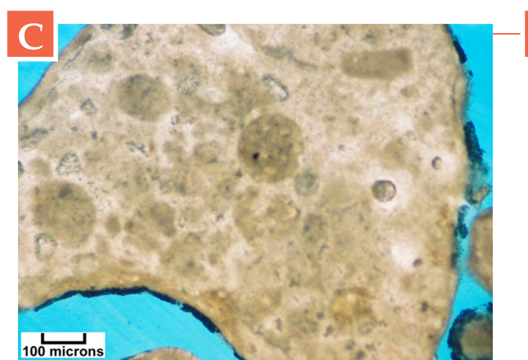
Beach lag deposits - ooids, coated grains, intraclasts composed of ooids, pellets, oolitically coated microbial and oolitically coated volcanic fragments.



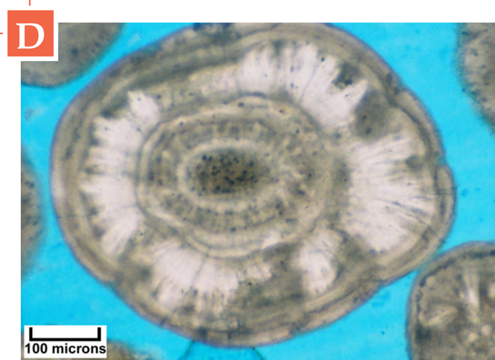
A - Typical cerebroid ooid with an irregular and "bumpy" cortex margin due to syndepositional radial recrystallization within the ooid. The nucleus of this ooid appears to be a small microbialite fragment. (Plane light)



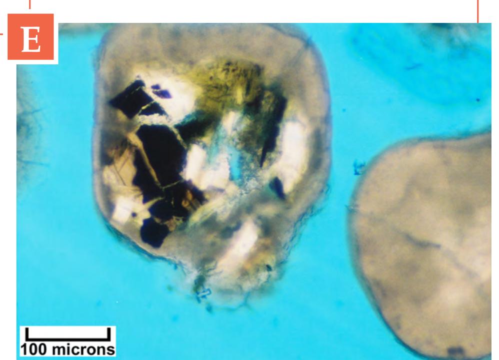
B - Asymmetrical ooid with a compound nucleus consisting of two angular microbialite fragments (in white). (Plane light)



C - Well-lithified beachrock clast composed of peloids surrounded by dense microfibrous cements. (Plane light)



D - Cerebroid ooid displaying radial recrystallized cortex bands (in white) coated by tangential oolitic coatings. Note the irregular or 'bumpy" grain outline and the peloid nucleus. (Plane light w/ white card)



E - Ooid with asymmetric cortex coatings around a nucleus composed of an igneous rock fragment. (Plane light w/ white card)

EVAPORITES

A - Typical gypsum (selenite) crystals growing in the microbial muds along the shore of Great Salt Lake.

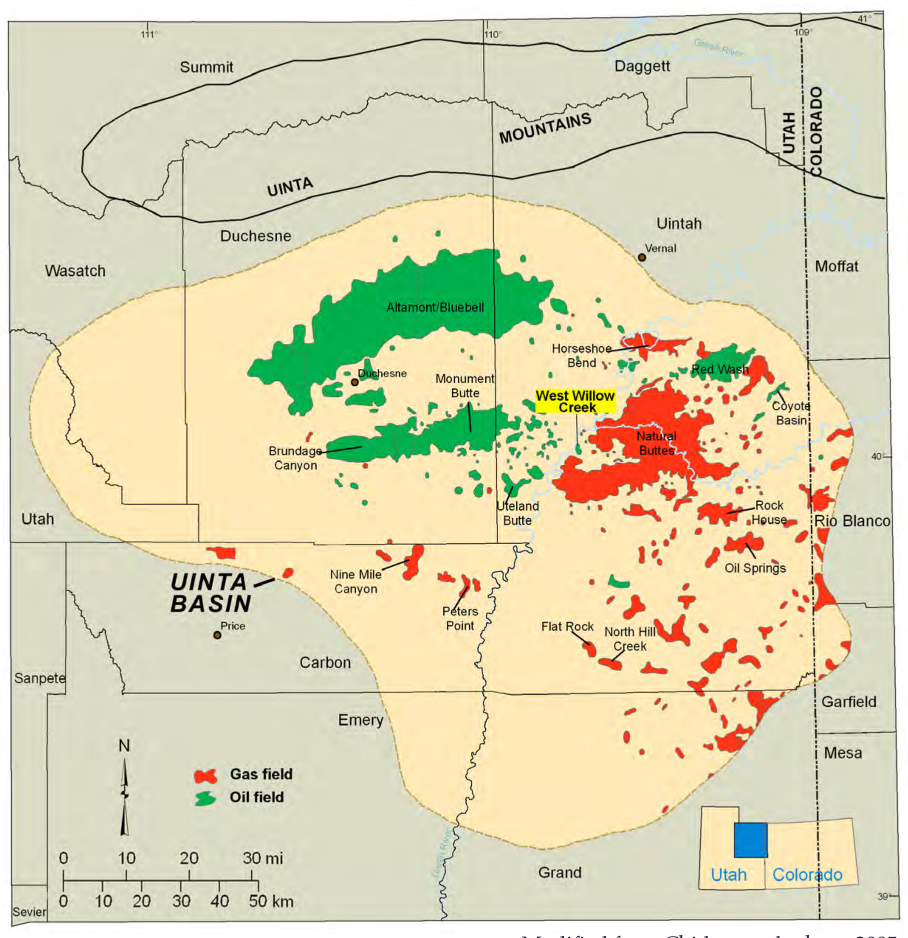
B - Close-up view of a large gypsum crystal recovered from Great Salt Lake sediments.

WEST WILLOW CREEK FIELD:
A PRODUCING MICROBIAL RESERVOIR IN THE UINTA BASIN

V

FIELD OVERVIEW

Oil and Gas Fields in the Uinta Basin of Utah and Colorado

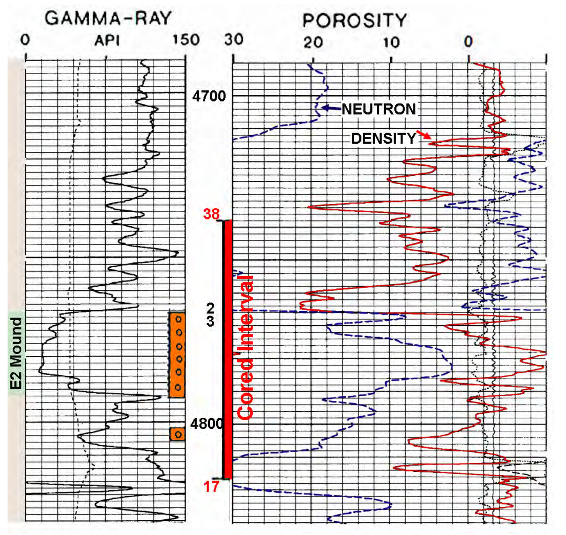


Modified from Chidsey and others, 2005.

Compensated Neutron-Formation Density and Gamma-Ray Log, Federal No. 15-24B Well, West Willow Creek Field

Cumulative Production: 15,639 BO, 5025 MCFG, and 8674 BW (abandoned in 2007).

The red bar on the right displays the cored interval; the perforated interval is indicated by circles on the outside left of the center column.



General Field Data

- Producing Reservoir – Eocene Green River Formation (E2 bed)
- Depositional Environment – nearshore, shallow water, lacustrine stromatolitic carbonate buildup
- Type of Trap – combination stratigraphic (microbial mound) with updip structural pinchout
- Oldest Stratigraphic Horizon Penetrated – Cretaceous Mesaverde Group
- Surface Formation – Tertiary (Eocene) Uinta Formation
- Spacing – federal unit
- Current Operator – XTO Energy Inc.

Discovery Well

- Mapco Inc, No. 7-25B well
- Location: SW1/4NE1/4 section 25, T. 9 S., R. 19 E., Uintah Co., Utah
- T.D. – 9232 ft (2814 m)
- Completed – November 7, 1981
- IPF – 21 BOPD and 5 BWPD

Production & Reserves

- Producing Wells – 5
- Abandoned Producers – 3
- Dry Holes – 2
- Monthly Production (May 1, 2015) – 546 BO, 7628 MCFG, and 117 BW
- Cumulative Production (as of May 1, 2015) – 1,135,498 BO, 12.1 BCFG, and 65,955 BW
- Estimated Original Oil in Place – 8 MMBO
- Estimated Original Gas in Place – 2.95 BCFG
- Secondary Enhanced Oil Recovery Program – pressure maintenance (reinjection of casing head gas into the gas cap); gas injection ceased in 1997 because of premature gas cap breakthrough in structurally lower producing oil wells.

Osmond, 2000; Utah Division of Oil, Gas, and Mining, 1994, 2015.

Reservoir Data

- Productive Area – 560 acres (230 ha)
- Gross Pay – 25 to 100 ft (8-20 m)
- Net Pay – 10 to 40 ft (3-12 m)
- Net to Gross – 0.4
- Geometry of Reservoir Rock – mound, 1240 acres (500 ha)
- Hydrocarbon Column – 200 ft (60 m)
- Average Porosity – 8 to 18%
- Permeability – 0 to 4.1 mD
- Water Salinity – TDS (mg/l) = 73,741; chemical components (ppm): chloride = 42,000, sulfate = 2844, bicarbonate = 464, calcium = 2844, magnesium = 194, iron = 2, sodium = 27,119
- BHT – 147°F (64°C)
- Type of Drive – gas cap expansion
- Initial Reservoir Pressure – 1330 psi

Petrography

- Lithology – limestone to dolomite, stromatolitic and thrombolitic, ostracodal to oncolitic grainstone, rudstone, boundstone, packstone, and wackestone
- Pore Types – interparticle, intraparticle, shelter, intercrystalline, vuggy, and abundant microporosity
- Diagenesis – cementation and early dolomitization

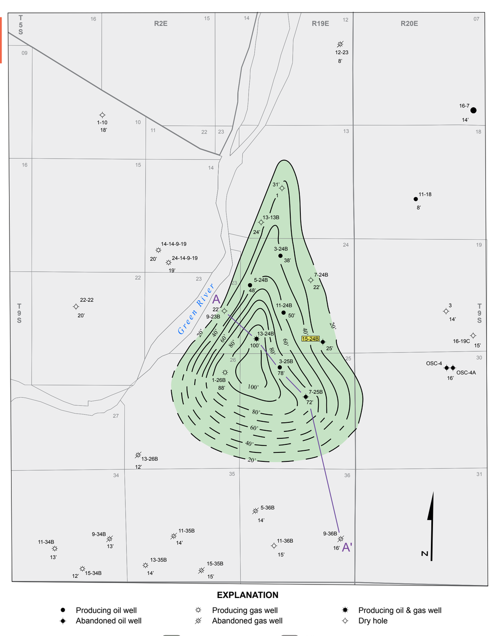
Oil & Gas Characteristics

- Oil – API Oil Gravity – 32°, sweet, paraffin base, pour point = 100° F
- Associated Gas (from No. 1-26B Federal well) – Composition (Mol %): methane = 87.2, ethane = 5.3, propane = 3.7, iso-butane = 0.6, n-butane = 1.2, iso-pentane = 0.3, n-pentane = 1.2, higher hydrocarbon components = 0.5, carbon dioxide = 0.4, nitrogen = 0.4; specific gravity = 0.673; heating value = 1060 Btu/ft^3
- GOR – 387 to 1005 ft^3/bbl

E2 CARBONATE BED, GREEN RIVER FORMATION

Isopach Map of the E_2 Carbonate Bed

A



Cross section A-A' is shown in figure E.

Modified from Osmond, 2000

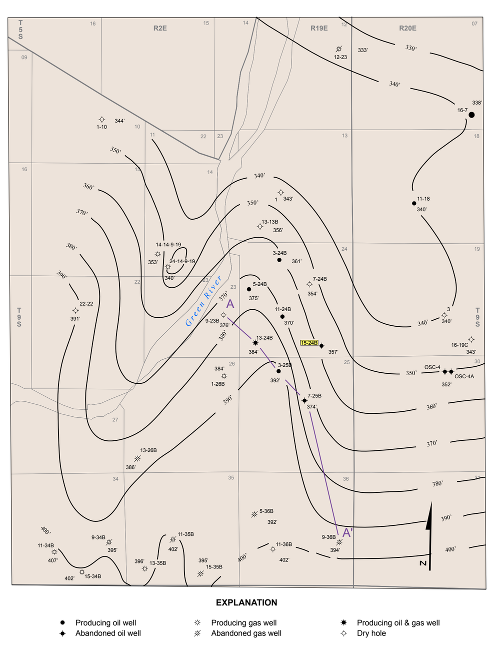
Isopach Map of the Interval Between the E2 Carbonate Bed and Top of the Uteland Butte Limestone

B

Modified from Osmond, 2000

Isopach Map of the Interval Between the Base of the E2 Carbonate Bed and DP Marker

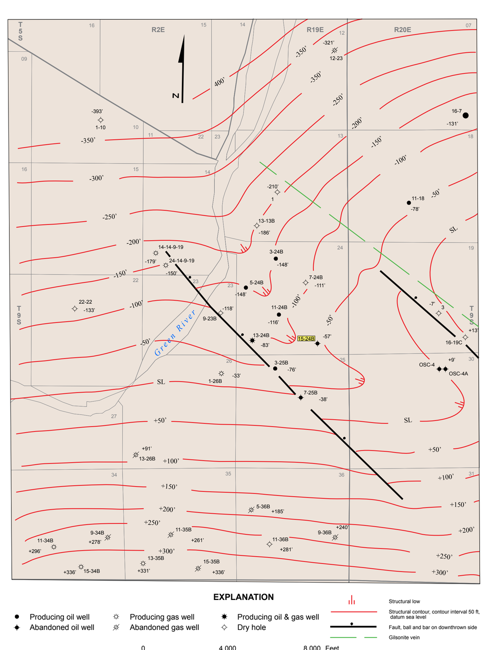
C



Modified from Osmond, 2000

Structure Contour Map, Base of the E2 Carbonate Bed

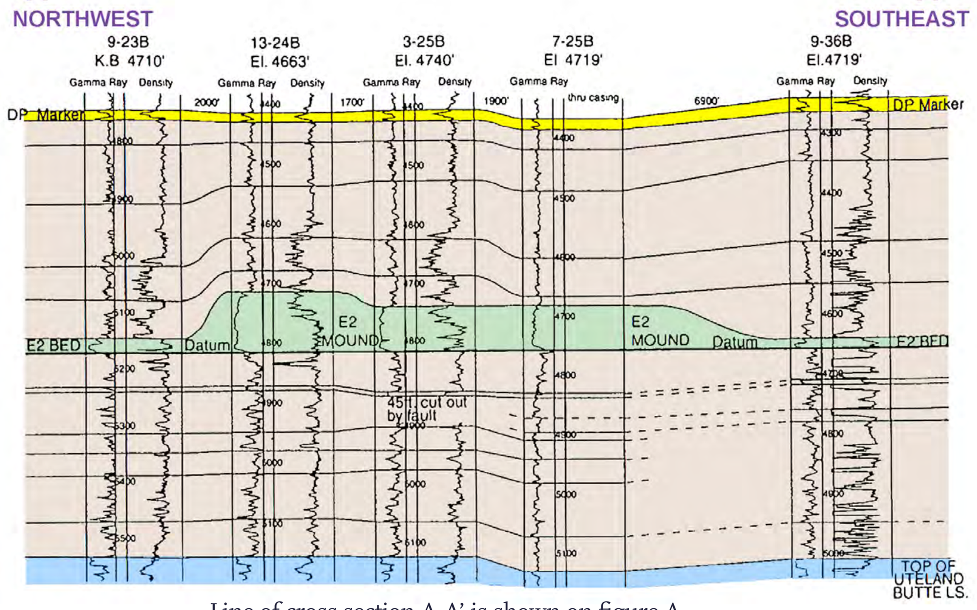
D



Modified from Osmond, 2000

Stratigraphic Cross Section

E

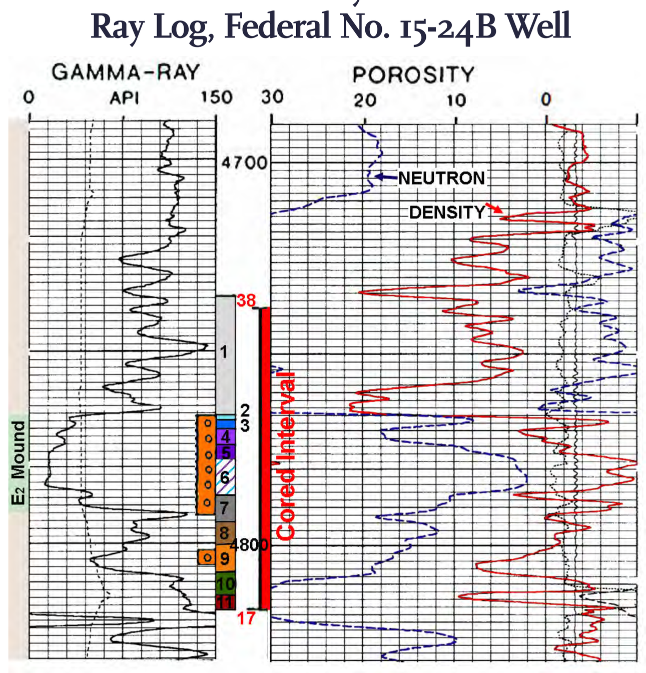


Line of cross section A-A' is shown on figure A.

Modified from Osmond, 2000

CORE DESCRIPTION: E2 CARBONATE BED, FEDERAL NO. 15-24B WELL

Compensated Neutron-Formation Density and Gamma-Ray Log, Federal No. 15-24B Well



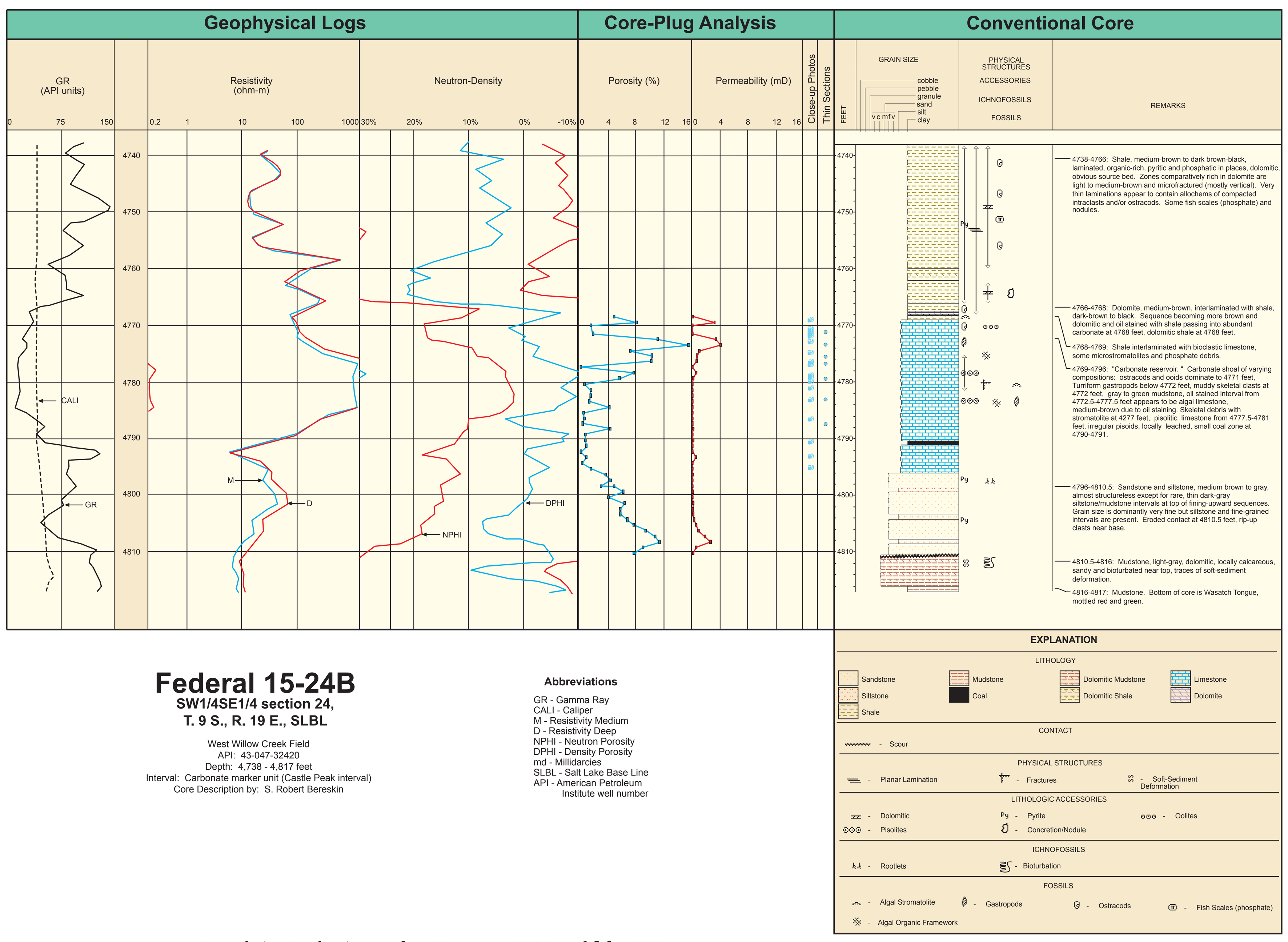
The numbered/color-coded stratigraphic units are described in the table below; the perforated interval is shown indicated by circles on the outside left of the center column.

Modified from Osmond, 2000

Major Characteristics of the E2 Carbonate Bed, Federal No. 15-24B Core

UNIT	DEPTH (ft)	THICKNESS	DESCRIPTION
1	4738-69	31 ft	SHALE; black, fissile to blocky, very fine laminations with fish scales and pyritized ostracods and very thin pyritized laminations; very thin, (algal?) coal laminations and lacey coal patterns on lamination surfaces; chert nodules up to 2 inches long and up to 1-1/4 inches thick on bedding; irregular chert nodule piercing overlying laminations; few thin, oil-saturated tuff laminations up to 2 inches thick.
2	4769-69.9	0.9 ft	LIMESTONE, ostracodal in laminations that thicken upward, base is oil-stained tuff with ostracods.
3	4769.0-72.5	2.6 ft	LIMESTONE, light gray, upper part contains gastropods up to 3/4 inch diameter with calcite crystal-lined vugs in chambers; lower part, oncolites up to 3/4 inch diameter; tubes of light gray limestone on bedding; 50° dip on bedding; vertical fracture partially filled with white calcite; horizontal stylolite at base.
4	4772.5-77.25	4.75 ft	LIMESTONE, brown, fine crystalline, oncolites and irregular vertical tubes, oil stained, stromatolites in lower part.
5	4777.25-78.4	1.15 ft	LIMESTONE, gray, very fine crystalline, oncolites up to 2 inches diameter, vertical and horizontal fractures, 1/32 inch, white calcite filling, horizontal stylolites.
6	4778.4-90.7	12.3 ft	LIMESTONE with some DOLOMITE, brown, fine crystalline; oncolites with dolomite crystal-lined vugs In centers, grades down into dolomite, gray, with abundant gastropods with white calcite filling upper parts of chambers, middle part, vertical fracture, 1/4 inch, white calcite filled, with slickensides; lower middle part, oncolites 1 inch in diameter; lower 3.6 feet, turritellid gastropods with white calcite filling chambers; flatened thin-shelled pelecypod, oncolites; vertical fracture, 1/32 inch, with white calcite filling; color changes from brown, oil stained, at top to gray, non-oil stained, at base.
7	4790.7-90.9	0.5 in 0.5 in	COAL, black, vitreous, hard, possibly alginite. SILTSTONE, light gray, no roots.
8	4790.9-96.5	5.6 ft	SHALE, black, interbedded with black limestone; abundant rotund and turretellid gastropods to 2-1 /2 inches, pelecypods, white calcite filling gastropod chambers, flat shale pebbles at base.
9	4796.5-03	6.5 ft	SILTSTONE, gray, unlaminated, calcareous, bioturbated(?); black oblique, organic marks, 4 inches by 1/4 inch, smooth on one edge, serated on the other edge; ghosts of oncolites.
10	4803-16.5	13.5 ft	SHALE, gray-green, dip of bedding is horizontal at top, 10° in middle and 20° at the base. Possible effect of fault(?).
11	4816.5-1 7	0.5 ft	SHALE, mottled maroon and gray, wavey laminations.

Modified from Osmond, 2000



Cumulative Production: 15,639 BO, 5025 MCFG, and 8674 BW (abandoned in 2007). Utah Division of Oil, Gas, and Mining well records.

After Bereskin and others, 2004

WEST WILLOW CREEK FIELD:
A PRODUCING MICROBIAL RESERVOIR IN THE UINTA BASIN

MICROBIALITES AND ASSOCIATED CARBONATE GRAINS: E_2 CARBONATE BED, FEDERAL NO. 15-24B WELL

VI

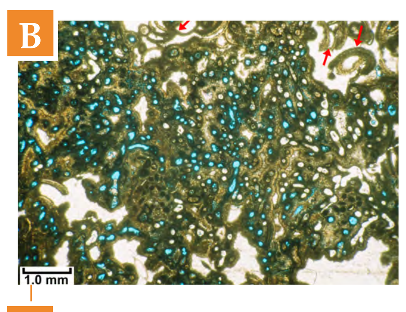
STROMATOLITIC MICROBIALITES

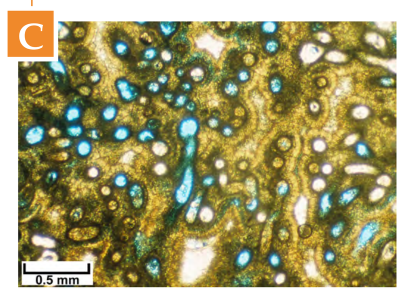
A


A - Microbialite consisting of digitate stromatolitic heads displaying synaptic relief and sharp margins. Internally, these heads/fingers exhibit distinct cellular structures with open pores associated with these features. Fibrous, isopachous cements line some interior and exterior pores. Microscopic pyrite lines some of the internal pores. Significant preserved interparticle and intraparticle pore space exists, although very coarse calcite spar occludes some of the porosity. There are abundant articulated ostracods between the microbial heads/fingers. Red arrow indicates the location of micrographs in B and C. 4773.3 ft., porosity = 15.6%, permeability = 4.1 mD

B - Overview of microdigitate microbialite head with internal cellular structure. Calcite spar occurs between and partially replaces microbialite structures. Ostracods occur in space between heads (see arrows). Porosity in blue. 4773.3 ft. (Plane light)

C - Microbialite boundstone with early isopachous fibrous cements lining pores. Note preserved interparticle and intraparticle pores. 4773.3 ft. (Plane light)

B


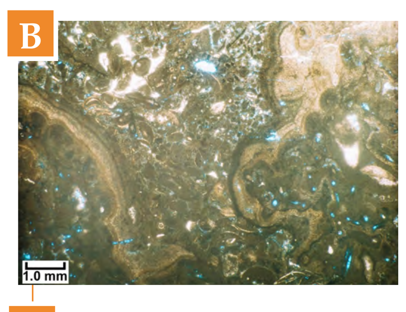
C


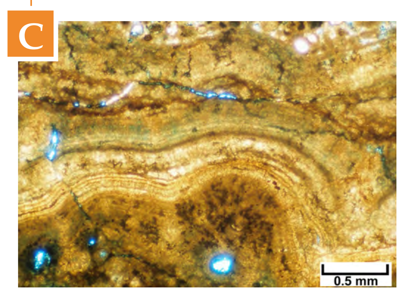
A


A - Laminated (stromatolitic) microbialite fabric with small hemispherical "heads" that have grown on top of or "trapped" grainstones composed of "hard" peloids, ooids, and ostracods. Good to excellent primary interparticle porosity within trapped and interbedded grainstones. Minor late cement plugging by coarse calcite cement. Red arrow indicates the location of micrographs in B and C. 4774.5 ft., porosity = 7.4%, permeability = 1.0 mD

B - Portions of two hemispherical stromatolitic domes covering peloidal/ ostracodal grainstones. 4774.5 ft. (Plane light)

C - Close-up view of well-laminated, dense (stromatolitic) microbialite head. 4774.5 ft. (Plane light)

B


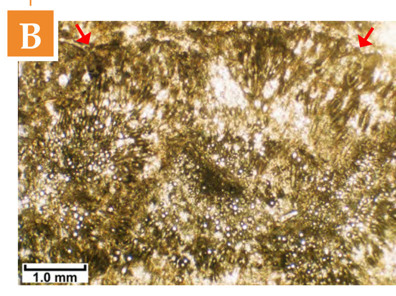
C


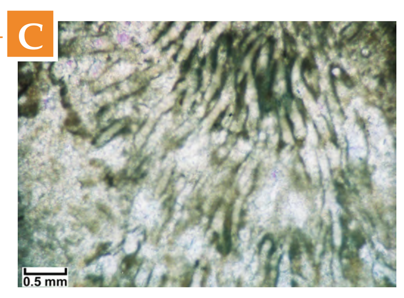
A


A - Complex microbialite head with mostly stromatolitic and some thrombolitic internal characteristics. Radial, micritic, and filamentous micro-textures abound along with excellent preservation of hollow filamentous and branching cells. Patches of microporosity are present around some of the filamentous areas. Red arrow indicates the location of micrographs in B and C. 4787.5 ft., porosity = 0.4%, permeability = 0.02 mD

B - Cross section of a radiating pustular microbialite "head." Note the tubular and cellular microstructures. Arrows show the top surface of the "head." 4787.5 ft. (Cross nichols w/ accessory)

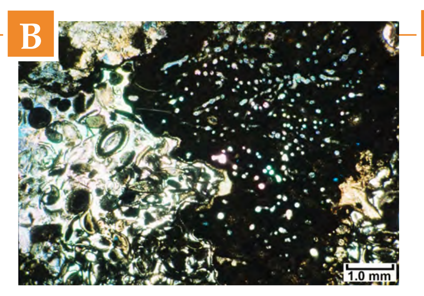
C - Radiating tubular or filamentous microstructure surrounded by microsparry cement. 4787.5 ft. (Plane light)

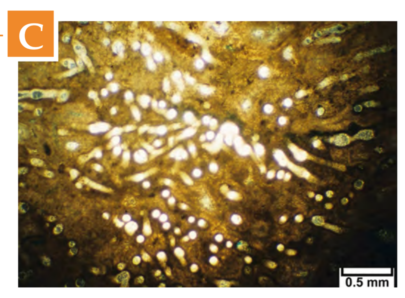
B


C


THROMBOLITIC MICROBIALITES

A


B


C


A - Dense, dark-colored thrombolitic microbialite heads with significant vertical synoptic relief. Sharp, laminated margins with interiors of the heads composed of clotted and cellular structures. Between the heads are ostracods and calcite spar cement. Red arrow indicates the location of micrographs in B and C. 4771.5 ft., porosity = 1.9%, permeability = 0.03 mD

B - Steep-sided margin of a massive thrombolitic head with ostracods filling cavity between the margins of the head. 4771.5 ft. (Plane light)

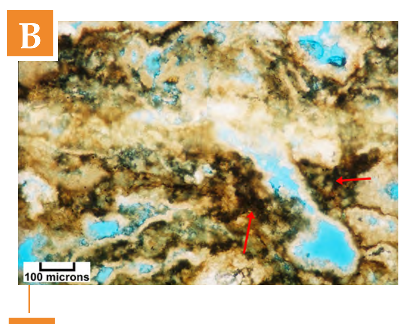
C - Tubular or filamentous textures within the same thrombolitic head. 4771.5 ft. (Plane light)

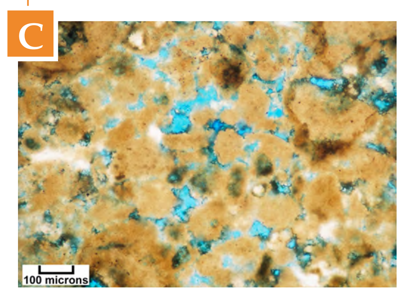
A - Clotted (thrombolitic) fabric with laminated (stromatolitic) crusts that together form small heads and "fingers." Occasional small oncolites occur in layers between heads. Other fill between heads includes "hard" peloids, ooids (some regenerated), and ostracods. Good matrix porosity (and oil staining) within heads and in the grainstone fill between heads. Red arrow indicates the location of micrographs in B and C. 4776.4 ft., porosity = 10.2%, permeability = 0.62 mD.

A


B - Close-up view of clotted (thrombolitic) texture (see red arrows) with layers of good matrix porosity lined with isopachous cements. 4776.4 ft. (Plane light w/ light white card)

C - Excellent interparticle porosity between "hard" peloids and ooids which occur between thrombolitic "heads." 4776.4 ft. (Plane light w/ white card)

B


C


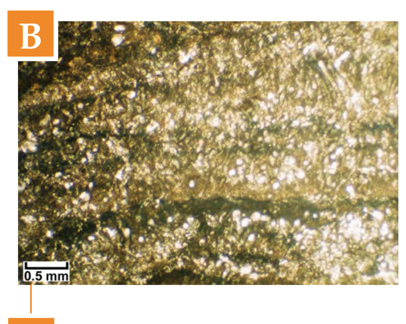
ONCOLITES

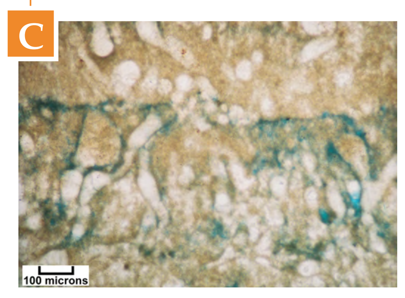
A - Oncolitic rudstone composed of large compound oncoids displaying good internal laminated microbial coatings. Laminae are defined by alternating dark micritic/organic layers alternating with thicker light-colored layers containing detrital carbonate sediment. Oncoids also display internal tubules and filamentous cells. Patches of microporosity are developed within the oncolites. Red arrow indicates the location of micrographs in B and C. 4779.5 ft., porosity = 5.6%, permeability = 0.12 mD.

A


B - Multiple dark/light layer couplets within an oncoid. Note the abundance of tubules/ filaments within the thicker light layers. Microporosity occurs in the dark layers. 4779.5 ft. (Plane light)

C - Microporosity developed along and around microtubules within an oncoid cortex. 4779.5 ft. (Plane light w/ white card)

B


C


SUMMARY & CONCLUSIONS

- The lacustrine Eocene Green River Formation of the Uinta Basin, Utah, contains excellent examples of microbial carbonates – stromatolites, thrombolites, oncolites, and tufa/travertine – which can serve as analogs for highly productive non-marine microbial reservoirs worldwide.

- The newly acquired Skyline 16 Green River core displays (1) low-relief stromatolites and thrombolites, (2) excellent primary megascopic pores and micro-porosity within microbial fabrics, (3) porous dolomite associated with lacy tufa/travertine, (4) grainstones composed of ooids, pisoids, peloids, and skeletal material with abundant interparticle and intraparticle porosity, (5) sharp contacts between grainstones and microbialites, and (6) evaporite crystal molds within dense, black organic-rich sediments.

- Outcrops of the Green River Formation in the eastern part of the Uinta Basin display many of the microbial features observed in core. Thrombolitic heads contain large, open, constructional pores. Well-developed laminations in stromatolitic heads have abundant primary porosity between microbial filaments. Pisoids, ooids, oncoids, ostracods, and peloids are frequently associated with the microbial facies. Densely packed gypsum(?) crystal casts are also common.

- Great Salt Lake, Utah, is a hypersaline lake and serves as a modern analog for the Green River Formation. Microbial stromatolites, pustular thrombolites, and tufa deposits are found within the lake and along its shores. Open constructional pores are common and often lined with acicular radial cements. Beaches and nearby dunes consist of abundant associated hypersaline ooids and coated grains.

- West Willow Creek field produces oil from small microbial mounds (E_2 carbonate bed) within the Green River Formation—the only such known field in the Uinta Basin. Microbialite heads often consist of stromatolitic crusts with thrombolitic internal characteristics. Associated grainstones between laminated microbial fabrics are composed of peloids, ooids, and ostracods providing good to excellent interparticle porosity. Oncolites are another significant component to the microbial system.

- The entire Skyline 16, Federal No. 15-24B (West Willow Creek field), and other cores containing microbial carbonates are available for examination at the Utah Geological Survey's Utah Core Research Center in Salt Lake City, Utah.

ACKNOWLEDGMENTS

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The poster design was by Jeremy Gleason, and Nikki Simon of the UGS. Cheryl Gustin, Stevie Emerson, and Jay Hill of the UGS prepared figures; Thomas Dempster and Brad Wolverton of the UGS Core Research Center prepared samples and photographed cores. X-ray diffraction analysis was conducted by Peter Nielsen and Steve Herbst of the UGS. Gary Aho, Sage Geotech, was a consultant to the Skyline 16 drilling project; the coring company was Himes Drilling. Morgan Rosenberg, University of Utah Department of Geology and Geophysics MSc. student, under the direction of Dr. Lauren Birgenheier, measured and described the Green River Formation sections. We also appreciate the encouragement and significant discussions with Prof. Scott Ritter, Brigham Young University Department of Geological Sciences and V. Paul Wright, BG Group.

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UTAH DNR GEOLOGICAL SURVEY