Rinded, Iron-Oxide Concretions in Navajo Sandstone Along the Trail to Upper Calf Creek Falls, Garfield County

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Utah Geosites
2019

Utah Geological Association Publication 48

M. Milligan, R.F. Biek, P. Inkenbrandt, and P. Nielsen, editors

Cover Image: *View of a concretion along a trail in Upper Calf Creek Falls.*

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Utah Geosites showcases some of Utah's spectacular geology, both little-known localities and sites seen by visitors to Utah's many national and state parks and monuments. The geosites reflect the interests of the many volunteers who wrote to share some of their favorite geologic sites. The list is eclectic and far from complete, and we hope that additional geosites will be added in the coming years. The Utah Geological Survey also maintains a list of geosites https://geology.utah.gov/apps/geosights/index.htm.

We thank the many authors for their geosite contributions, Utah Geological Association members who make annual UGA publications possible, and the American Association of Petroleum Geologists—Rocky Mountain Section Foundation for a generous grant for desktop publishing of these geosite papers.

Design and desktop publishing by Jenny Erickson, Graphic Designer, dutchiedesign.com, Salt Lake City, Utah.

Suggested citation for this geosite:

Loope, D.B., and Kettler, R.M., 2019, Rinded iron-oxide concretions in Navajo Sandstone along the trail to Upper Calf Creek Falls, Garfield County, *in* Milligan, M., Biek, R.F., Inkenbrandt, P., and Nielsen, P., editors, Utah Geosites: Utah Geological Association Publication 48, 7 p., https://doi.org/10.31711/geosites.v1i1.59.

PRESIDENTS MESSAGE

I have had the pleasure of working with many different geologists from all around the world. As I have traveled around Utah for work and pleasure, many times I have observed vehicles parked alongside the road with many people climbing around an outcrop or walking up a trail in a canyon. Whether these people are from Utah or from another state or country, they all are quick to mention to me how wonderful our geology is here in Utah.

Utah is at the junction of several different geological provinces. We have the Basin and Range to the west and the Central Utah Hingeline and Thrust Belt down the middle. The Uinta Mountains have outcrops of some of the oldest sedimentary rock in Utah. Utah also has its share of young cinder cones and basaltic lava flows, and ancient laccoliths, stratovolcanoes, and plutonic rocks. The general public comes to Utah to experience our wonderful scenic geology throughout our state and national parks. Driving between our national and state parks is a breathtaking experience.

The "Utah Geosites" has been a great undertaking by many people. I wanted to involve as many people as we could in preparing this guidebook. We have had great response from authors that visit or work here in the state. Several authors have more than one site that they consider unique and want to share with the rest of us. I wanted to make the guidebook usable by geologists wanting to see outcrops and to the informed general public. The articles are well written and the editorial work on this guidebook has been top quality.

I would like to personally thank Mark Milligan, Bob Biek, and Paul Inkenbrandt for their editorial work on this guidebook. This guidebook could not have happened without their support. I would like to thank Jenny Erickson for doing the great desktop publishing and the many authors and reviewers that helped prepare the articles. Your work has been outstanding and will certainly showcase the many great places and geology of Utah. Last, but not least, Thank you to the American Association of Petroleum Geologists, Rocky Mountain Section Foundation for their financial support for this publication.

Guidebook 48 will hopefully be a dynamic document with the potential to add additional "geosites" in the future. I hope more authors will volunteer articles on their favorite sites. I would like to fill the map with locations so that a person or family looking at the map or articles will see a great location to read about and visit. Enjoy Guidebook 48 and enjoy the geology of Utah.

Peter J. Nielsen
2019 UGA President

INTRODUCTION

Concretions are hard rock masses, usually spheroidal, but commonly oblate or discoidal, that are formed by strongly localized precipitation of minerals in the pores of an otherwise weaker sedimentary rock (see Bates and Jackson, 1980, for a more extensive definition). The iron-oxide-rich concretions in the Jurassic Navajo Sandstone in southern Utah are unusual in two fundamental ways. First, they are cemented by iron oxide (Fe_2O_3, or $Fe(OH)_3$); most other concretions are cemented by silica (SiO_2), calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), or siderite ($FeCO_3$). Second, unlike other concretions, they are not strongly cemented throughout, but instead, the iron oxide is concentrated in a very strongly cemented, sharply defined, exterior rind or shell. In the smaller concretions, the entire interior lacks iron-oxide cement, and is similar to the rock outside the concretion; in the larger concretions, there is a central zone that is strongly cemented by iron oxide, but the sandstone between the central core and the rind has no iron-oxide cement.

The processes involved in the formation of the Navajo concretions have been extensively studied by geologists ever since the Martian rover *Opportunity* imaged small, spheroidal, iron-rich concretions on the surface of Mars (Moore, 2004). The Navajo concretions were quickly recognized as possible terrestrial analogs to the Martian "blueberries" (Chan and others, 2004). At present there are three main explanations for how these concretions formed. The first interpretation of the Navajo concretions (Chan and others, 2004; Beitler and others, 2005) views the iron-oxide cement and the "rinded" aspect of today's concretions as primary features—just a thin, three-dimensional band of sandstone (circular when viewed in two dimensions) that had been cemented by iron oxide (Chan and others, 2004). A complication of this interpretation is that, because iron is not transported by water containing oxygen, mixing of an iron-bearing water (devoid of oxygen) with a second, oxygenated water mass is required (Chan and others, 2004). Mixing is typically not required for growth of silica, calcite, dolomite, or siderite concretions.

The second interpretation (Loope and others, 2010; Weber and others, 2012) is that solid, spheroidal concretions were originally well-cemented throughout by siderite ($FeCO_3$). The rinds formed secondarily, during much later alteration of the older, primary siderite. A weakness of this interpretation is that unaltered siderite has not been found in any Navajo concretions.

The third interpretation (Yoshida and others, 2018) holds that the original spheroidal concretions were solid spheres cemented by calcite ($CaCO_3$). The rinds formed later when acidic, iron-bearing waters invaded the Navajo. The calcite of the concretions buffered the acidic waters, forcing iron oxide to precipitate. A weakness of this interpretation is that it does not explain the localization of iron into a distinct, strongly cemented rind nor the presence of abundant iron in a spatially isolated core zone.

All the research cited above was stimulated by the discovery, on Mars, of small, iron-rich, spheroidal concretions (the aforementioned blueberries), but the concretions exposed at this GeoSite are neither small nor spheroidal. They are, however, iron-rich, calcite-free, rinded, and very interesting. We think that the spatial arrangement of their internal features aid interpretation of the small, rinded spheroids. In this article, we briefly present our interpretation (Loope and others, 2010; Loope and others, 2011; i.e., the second interpretation above) of the very large, non-spheroidal, rinded concretions that are common on the beautiful trail to Upper Calf Creek Falls.

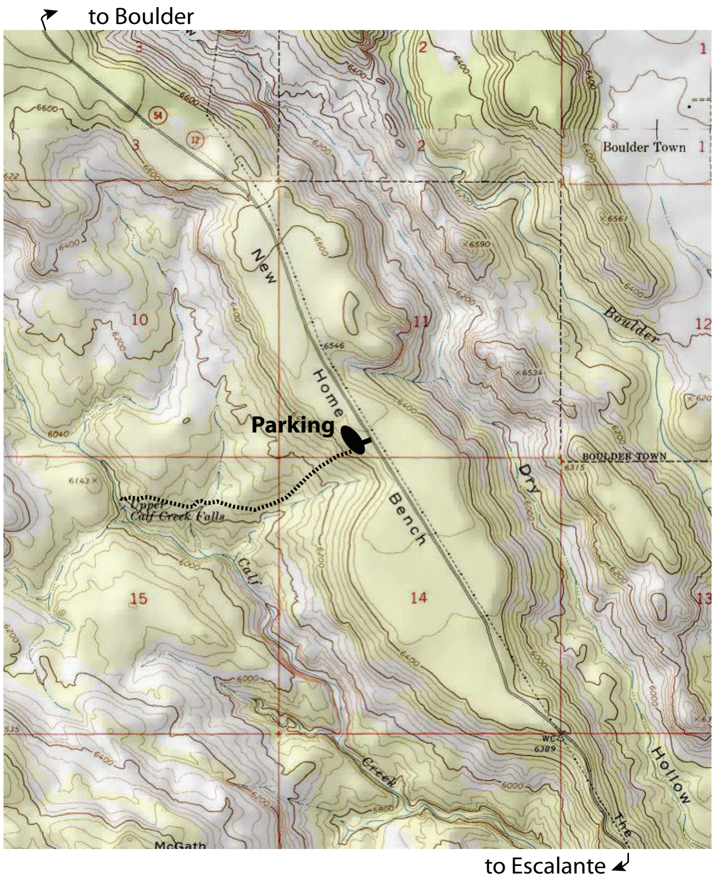

Figure 1. Topographic map showing location of parking area and trail head for Upper Calf Creek Falls.

Driving Instructions and Hiking Suggestions

The trailhead is 7.4 miles (11.8 km) southwest of Boulder, UT and 20.5 miles (32.8 km) northeast of Escalante along a portion of Utah Highway 12 that follows the narrow, flat surface of New Home Bench, above the canyons of Calf Creek (to the west) and Dry Hollow (to the east; figure 1). The turnoff for the trailhead is on the west side of the highway, between mile 80 and mile 81. The parking area is ≈ 500 feet (150 m) from the highway, but getting there can be rough for a low-clearance vehicle (you can instead park along the highway). At its start, the trail to Upper Calf Creek Falls drops about 500 feet (150 m) down a steep outcrop of Navajo

Sandstone, the most difficult part of the short 0.9 mile (1500 meter) one-way hike. Take care to step only on bare sandstone, avoiding the ball-bearing-like gravel. In summer, you can depend on Calf Creek as a great way to cool off; soak your shirt and hat (at least) before hiking out of the canyon. If you wander off the trail, avoid stepping on the dark soil crust that stabilizes the loose sand.

GPS Location of Trailhead: 37°51'34" N, 111°26'18" W (WGS84)

GEOLOGIC CONTEXT

Boulder-strewn New Home Bench is an example of inverted topography. About one million years ago, major flood events deposited large boulders (derived from the Aquarius Plateau to the west) in a stream valley cut into the Navajo Sandstone (Marchetti and others, 2012). The boulders effectively armored the streambed, preventing further erosion of the bedrock below the boulders. Soon thereafter, erosion of the bedrock commenced on both the east and west sides of the boulder accumulation; one million years of erosion produced the two deep canyons of Calf Creek and Dry Hollow, and stranded the (inverted) flat surface between them (figures 1 and 2).

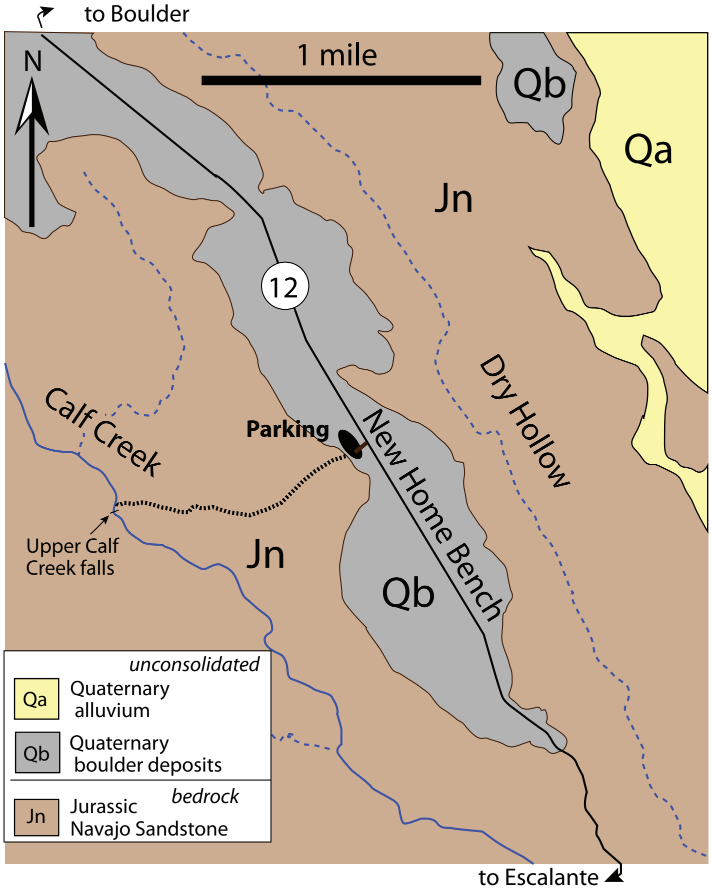

Figure 2. *Geologic map showing distribution of unconsolidated deposits and bedrock in the vicinity of Upper Calf Creek Falls.*

The Navajo Sandstone, well-exposed in the canyons below New Home Bench, was deposited in the Early Jurassic (200 million years ago) by very large, southward migrating sand dunes (Kocurek and Dott, 1983). Even though the Navajo has not been tilted, most of the bedding in the Navajo slopes southward at about 20-25°. These layers of sand were not deposited parallel to the floor of the giant dune field. Instead they were deposited on the dunes' downwind slopes at angles as steep as 32° (the angle of repose of dry sand); compaction of the sandstone formation during burial under thousands of feet of younger rock diminished the slopes we see today by about 20% (Hunter, 1981).

Iron-Oxide-Cemented Concretions

Shortly after you reach the base of the steep descent of the trail from the parking area, you will start to see black, iron-oxide-cemented slabs (some displaying bedding, and some with connected corners like boxes; figures 3 and 4). Also present along the trail are

Figure 3. *Slabs of rinds from broken concretions. Note that some slabs connect forming "boxworks" (see figure 9, part 3 for origin).*

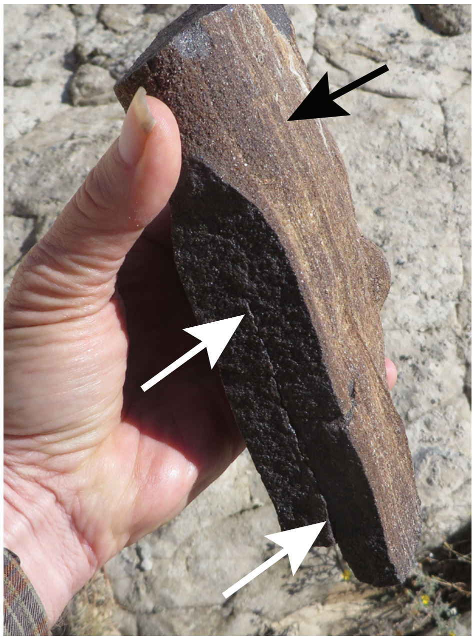

Figure 4. *Dense piece of concretion rind that shows bedding (black arrow) and a central fracture (white arrow; See figure 9, part 3).*

gray, discoidal masses of bedded sandstone also cemented by iron oxide (figure 5). These are texturally distinct from the dark gray (also iron-rich), non-bedded volcanic boulders that have rolled down from New Home Bench; you should be able to see layering and feel the evenly-sorted grains of relatively fine sand in the remains of the concretions (but not in the volcanic boulders). The slabs are fragments of the dense rinds and the discoids were the central core zones of concretions.

Along the trail, there are several examples of concretions that are in place and sufficiently eroded to show their interior structure (figures 6 and 7). Note that some iron-rich rinds follow fractures in the concretions. Recall that all three interpretations of the iron-rich Navajo concretions (see Introduction) have them forming in bedded (explaining the texture of the rinds and discoids) rock, not loose sediment (explaining why the iron accumulations followed fractures).

Figure 5. *Core stone representing the central portion of a broken concretion. White arrows show bedding planes. Inset shows scattered pseudomorphs (see text).*

Figure 6. *Horizontal view of an in-place concretion that is composed of a boxwork of dense rinds; core has been completely removed by weathering. Site is along the trail, 250 feet (75 m) from Upper Calf Creek Falls. 37°51'17" N, 111°27'04 W.*

Figure 7. *Downward view of weathered, in place concretion, showing boxwork of rinded sandstone slabs. Same site as Figure 6.*

Figure 8a shows a large, nearly intact concretion, and figure 8b shows a microscopic view of a core stone with siderite-shaped iron-oxide crystals (pseudomorphs) that provide strong evidence for the former presence of siderite. The iron that remains in the core of large concretions provides a major clue to the origin and evolution of all rinded concretions (figure 9). Figures 10 and 11 explain the role that iron-oxidizing microbes played in initiation and thickening of the densely cemented rinds.

Many of the minerals that form in the deep, oxygen-deprived subsurface are unstable near Earth's land surface and atmosphere. Before uplift of the Colorado Plateau, the Navajo Sandstone was buried by thousands of feet of younger sedimentary rocks. John Wesley Powell's research team first realized that many thousands of feet of sedimentary rocks had been stripped away during uplift of the Colorado Plateau (Dutton, 1880). We now know that canyon cutting and uplift in this area accelerated about six million years ago (Marchetti and others, 2012). If siderite crystals formed the concretions while the Navajo Sandstone was deeply

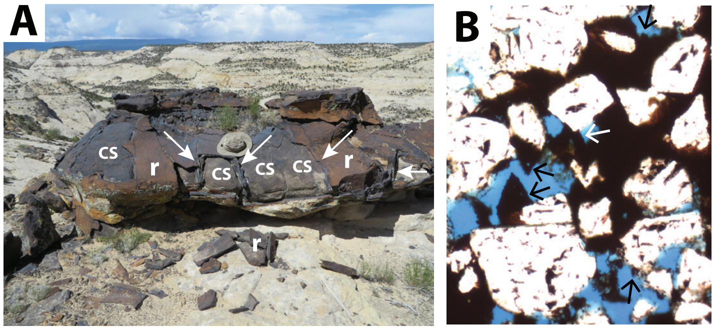

Figure 8. A) Large, nearly intact, rinded concretion on the rim of Dry Gulch (N37°50'44.9"; W111°25'29.4). Rinds (r) plate the concretion's perimeter, but some have fallen away, exposing cores (CS). Note that rinds are also developed along joints (arrows). Hat is 14.5 inches (37 cm) wide. B) Photo taken of a thin section through a microscope showing the fine-scale composition of the core of a large Calf Creek concretion. White is quartz, black is iron oxide, blue is open pore space. Arrows point to rhombic (diamond-shaped), iron-oxide in the shape of (pseudomorphs after) siderite crystal. Width of field of view is 0.015 inches (0.37 mm; see Loope and Kettler, 2015, figure 2) and Loope et al. (2011, figure 5).

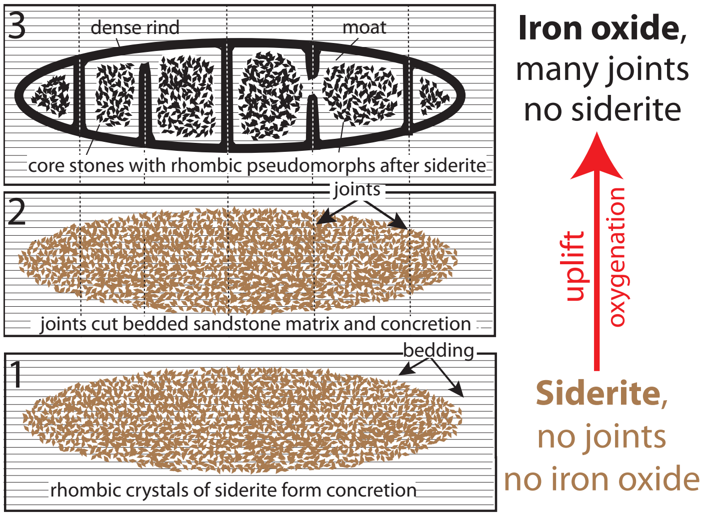

Figure 9. Interpretation of the evolution of a large, rinded concretion: 1) in deep, oxygen-free pore water, siderite crystals grow, forming a concretion in bedded, unfractured Navajo Sandstone (size of crystals greatly exaggerated). 2) with uplift and erosion of the Colorado Plateau, joints break the surrounding sandstone and the concretion; 3) in shallow, oxygenated water near the land surface, siderite starts to dissolve into the only remaining oxygen-free water (inside the concretion). Dissolved iron diffuses outward to the perimeter and to the joints. At these locations where oxygen-free water meets oxygenated water, rinds form and thicken. Moats represent space occupied by pseudomorphs that were dissolved, providing iron for rind growth. If the concretion remains water saturated, rinds continue to thicken, the moats to widen, and the cores to shrink. When the water table dropped below large concretions, iron could no longer migrate, so siderite crystals were oxidized in place, forming pseudomorphs. In smaller concretions, all the siderite dissolved before the water table dropped below the concretion, so no pseudomorphs remain in them (they are just rind and moat; see figure 11D). Modified from Loope et al. (2016, figure 23), see also Loope and Kettler (2011, figure 3).

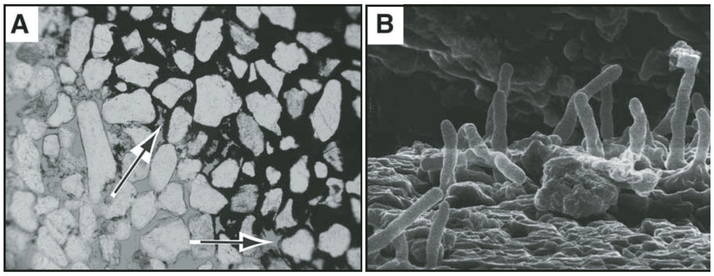

Figure 10. Microbes in the iron-oxide-cemented rind of a concretion. A) Arrows point to fuzz in pore space between sand grains at the inner edge of a rind. White is quartz, black is iron-oxide cement. Field of view ~500 microns. B) Scanning Electron Microscopy (SEM) image of microbes (about 4 microns in diameter) on the surface of a sand grain; the surface of a second sand grain (in the background) is also covered by microbes.

buried, those crystals would have been oxidized about one million years ago, when they encountered oxygen-bearing groundwater (beneath the stream that carried the boulders that now cap New Home Bench; Marchetti and others, 2012). The iron oxide in the concretions along Calf Creek do not bear sufficient uranium for U-Th/He radiometric dating, but those along the canyon of Russell Gulch in western Zion National Park do have enough uranium (P.W. Reiners, personal communication, 2015). Analysis of samples from both the rinds and cores of Zion concretions showed that the iron oxide crystallized about half a million years ago (Loope and others, 2016). That timing fits well with canyon-cutting rates that are based on one-million-year-old lavas on the rim of Russell Gulch, and puts siderite alteration, rind growth and, core oxidation at shallow depth.

The presence of rhombic, iron-oxide pseudomorphs in concretion cores (figure 8b) is a strong indication that iron oxide was not a primary cement: rhombic crystals of siderite that formed in the relatively deep subsurface were the initial cement of these concretions. Siderite crystals were unstable in shallow groundwater and many (but not all) were dissolved to form the rind; those that didn't contribute to the rind were oxidized in place, above the water table. Further, the overall distribution of iron in the large concretions is inconsistent with alteration of an iron-free (calcite) precursor (see third interpretation in the Introduction). Entry of iron from outside a pre-existing concretion cannot explain the rind-moat-core structure of the concretions. In many of the largest concretions most of the iron lies in their cores (figure 8a), and each iron-rich core is surrounded by an iron-free moat, which, in turn, is surrounded by very-strongly cemented rind (figure 9).

Admittedly, siderite crystals have not been found in the concretions. We attribute this to their (former) location within a relatively porous and permeable matrix—this guaranteed full exposure of the crystals to oxidizing water. Like all science, our interpretation (and all three hypotheses for the Navajo concretions) could be wrong.

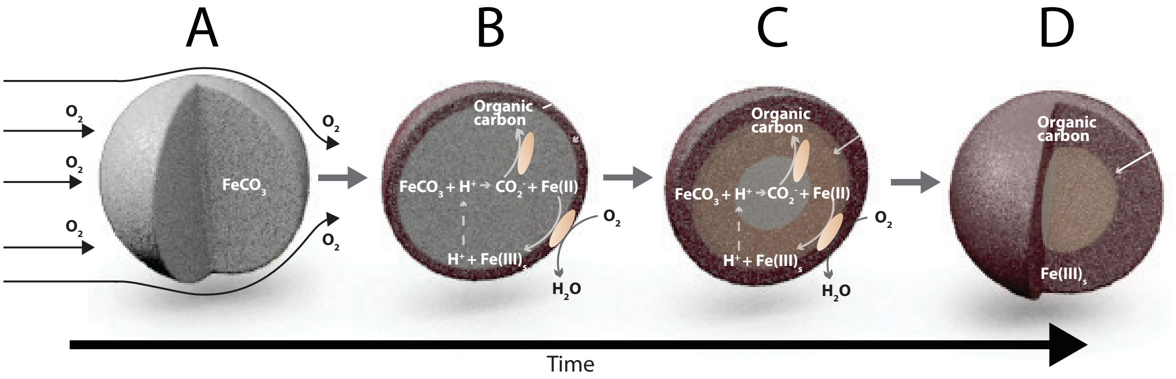

***Figure 11.** (A) spheroidal siderite ($FeCO_3$) concretion that grew in oxygen-free water (and therefore contains no iron oxide) is exposed to oxygenated groundwater; B) microbial colony starts to metabolize the siderite (gaining energy and carbon); iron-oxide rind (the waste of the microbial colony) is starting to form as the siderite recedes; C) rind further thickens as siderite recedes; D) siderite entirely dissolved, rind growth is complete, and colony dies in fully oxygenated water. In this case, no core stone (or iron-oxide pseudomorphs after siderite) remains (compare to figure 9).*

ACKNOWLEDGMENTS

We thank Peter Mozley and Edward Simpson for providing helpful reviews of this paper.

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