Fitted-Fabric Grainstones – Commonly Overlooked Evidence for Vadose Diagenesis and Subaerial Exposure

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ABSTRACT

Some carbonate grainstones have distinctive fitted fabrics that form due to dissolution in the vadose zone that are only rarely recognized or correctly interpreted. These grainstones have flattened and concavo-convex grain contacts where the grains fit together like puzzle pieces and are commonly lined with early marine or meteoric cement. Examples of these fitted fabric grainstones have been identified in carbonates from the Archean to the Holocene and likely occur in shallow marine, eolian and lacustrine carbonate grainstones throughout the geologic record.

Fitting occurs due to dissolution at grain contacts by meteoric or mixed marine-meteoric fluids that over time flattens the grain contacts. Although these grainstones may at first appear to be compacted, burial compaction can be ruled out because there is commonly no sign of pressure solution, the early cement that forms at the surface clearly postdates the fitting of the grains and is unaltered by the fitting process, and because these fabrics are found in Pleistocene and Holocene grainstones that have never been buried. Because this feature forms during periods of subaerial exposure, it can help to identify cryptic exposure surfaces and sequence boundaries.

INTRODUCTION

The term fitted-fabric grainstone is used here to describe the appearance of some carbonate grainstones that have flattened and concavo-convex grain contacts that fit together like puzzle pieces yet are lined with early cement that show little or no signs of burial compaction or pressure solution. These fitted fabrics form due to dissolution at grain contacts in the vadose zone (the interval below the surface but above the water table) and are therefore evidence of subaerial exposure. Fitted fabric grainstones are common in the rock record but have only rarely been identified, primarily due to lack of awareness of the feature and its origin.

Clark (1979), in a discussion of an ooid grainstone with fitted fabrics found in Cussey and Friedman (1977), wrote that the original idea that fitted fabrics came from dissolution in the vadose zone came from R. J. Dunham (1924-1996), who called it "vadose compaction." According to Clark, Dunham found ancient examples in the Mississippian Gasper Limestone and a modern example forming in beachrock at Cayo Arenas, Mexico and summarized these findings in an unpublished report for Shell Oil Company. Clark later interpreted fitted fabric grainstones in the Permian Zechstein Formation of the Netherlands (Clark, 1980, 1986) and the Jurassic Arab A Formation of Qatar (Clark et al., 2004) to have formed due to vadose compaction. Others who worked with Dunham or may have been aware of this report have also referred to vadose origin of the fitted fabric grainstones. Wilson (1975, p.430) described a fitted fabric grainstone from the Arab C Formation of Qatar as having formed due to "early solution." Sellwood et al (1985) interpreted "overpacking" of grains under cemented hardgrounds in the Jurassic Great Oolite of the UK to be due to vadose dissolution and Hird and Tucker (1988) interpreted a fitted fabric ooid grainstone from the Carboniferous Brofiscin Oolite in Wales to form due to meteoric waters causing "dissolution at grain contacts into concavo-convex and fitted fabrics." All credit for the initial observations and interpretations should go to Dunham and these earlier authors.

Despite these earlier references, most fitted fabric grainstones go unnoticed due to lack of awareness of this feature or are misinterpreted as having formed due to burial compaction. This is likely because there has never been a publicly available paper devoted solely to their description and interpretation. Once one is aware of the feature, it becomes clear that they are very common. The purposes of this paper are therefore to establish criteria to recognize fitted fabric grainstones, to demonstrate how commonly they occur and to discuss their origin, distribution and utility as an indicator of subaerial exposure.

DESCRIPTION AND OCCURRENCE OF FITTED FABRIC GRAINSTONES

Grainstone is a grain-supported carbonate rock with little or no mud between the grains (Dunham, 1962). Grainstones that develop fitted fabrics are generally deposited in high-energy environments such as shoals, barrier bars and beaches or eolian settings, but not all such grainstones develop fitted fabrics.

Figure 1 shows, for comparison, a cemented ooid grainstone without fitting (Fig. 1A), a grainstone that has been subjected to burial compaction (Fig. 1B) and a fitted fabric grainstone (Fig. 1C). The ooid grainstone without fitting (Fig. 1A) has round grains that show no signs of fitting with point contacts between grains where they are touching. The interparticle pore space is filled with fibrous isopachous rim cement followed by blocky calcite. The grainstone that has been compacted in a burial environment (Fig. 1B) has pressure solution sutures between the grains and no isopachous rim cement that separates them. Figure 1C shows a fitted fabric grainstone for comparison. Fitted-fabric grainstones may be subjected to later burial compaction but, in most cases, they do not show pressure solution features at grain contacts. The grains fit together with flattened, polygonal or concavo-convex contacts but are also coated with early isopachous rim cement around and between most of the grains.

Figure 2 shows a well-fitted ooid grainstone from the Jurassic of Morocco (from p. 357 of Scholle and Ulmer-Scholle, 2003). The grains fit together like puzzle pieces and unaltered isopachous rim cement fills gaps between the grains. Some lamina on the ooids have been dissolved. There are pillars of undissolved grain where grain contacts are maintained and there is no cement between the grains which are important to the interpretation of how fitted fabric grainstones form.

A literature review done mainly online turned up more than 40 examples of fitted fabric grainstones from the Archean to the Holocene that are presented in Online Table 1. In these examples, a few authors noticed the compaction but attributed it to burial or pressure solution, but the majority did not mention the fitted nature of the grainstones at all. In some cases, there is only minor fitting where there are only small patches of fitted grains with a few flattened contacts, in others moderate fitting with flattened contacts occurs across the thin section and in other cases the grains are highly fitted to each other like puzzle pieces such as in Figures 1C and 2 (online Table 1).

In Holocene and Pleistocene strata, fitted fabric grainstones are found in beachrock, barrier bar facies and carbonate eolianites, all of which have been subjected to vadose diagenesis. Figure 3A is an example from a Pleistocene grainstone with a caliche crust found on the west side of the island of Barbuda in the Leeward Islands of the Caribbean. Figure 3B is an example from Pleistocene of San Salvador Island, Bahamas with isopachous cement between well-fitted peloids and intraclasts in what is interpreted to be beach facies. Another good Pleistocene example is a well fitted ooid grainstone from

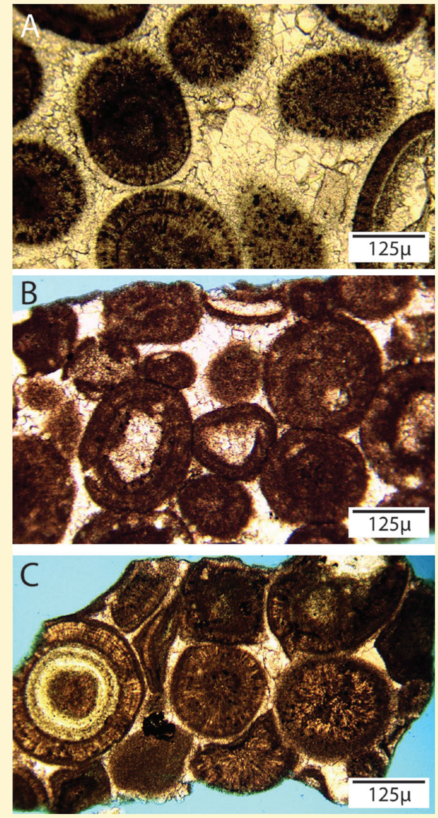

Figure 1: Grainstones from well cuttings in Cretaceous Quintuco Formation, BDC-1, Neuquén Basin, Argentina. A) Cemented ooid grainstone with no obvious burial compaction and no fitted fabric. B) Ooid grainstone subjected to burial compaction with pressure solution sutures between ooids (white arrows). C) Fitted fabric ooid grainstone with grains fitted to each other with layers of cement between the grains.

the Miami Oolite (Figs. 3C and 3E of what is interpreted to be barrier bar facies in Halley et al., 1977). These Pleistocene examples are both around 125,000 years old and have never been buried.

Figure 3C is an example from the Cretaceous of Argentina that shows fitted fabric in a thin section made from well cuttings in a mixed carbonate-siliciclastic grainstone with the fitting being associated with the carbonate grains. Figure 3D is from the subsurface in a well drilled in south Florida, USA which shows excellent fitting between miliolid forams and ooids. Figure 3E is an only partially cemented fitted-fabric grainstone found in

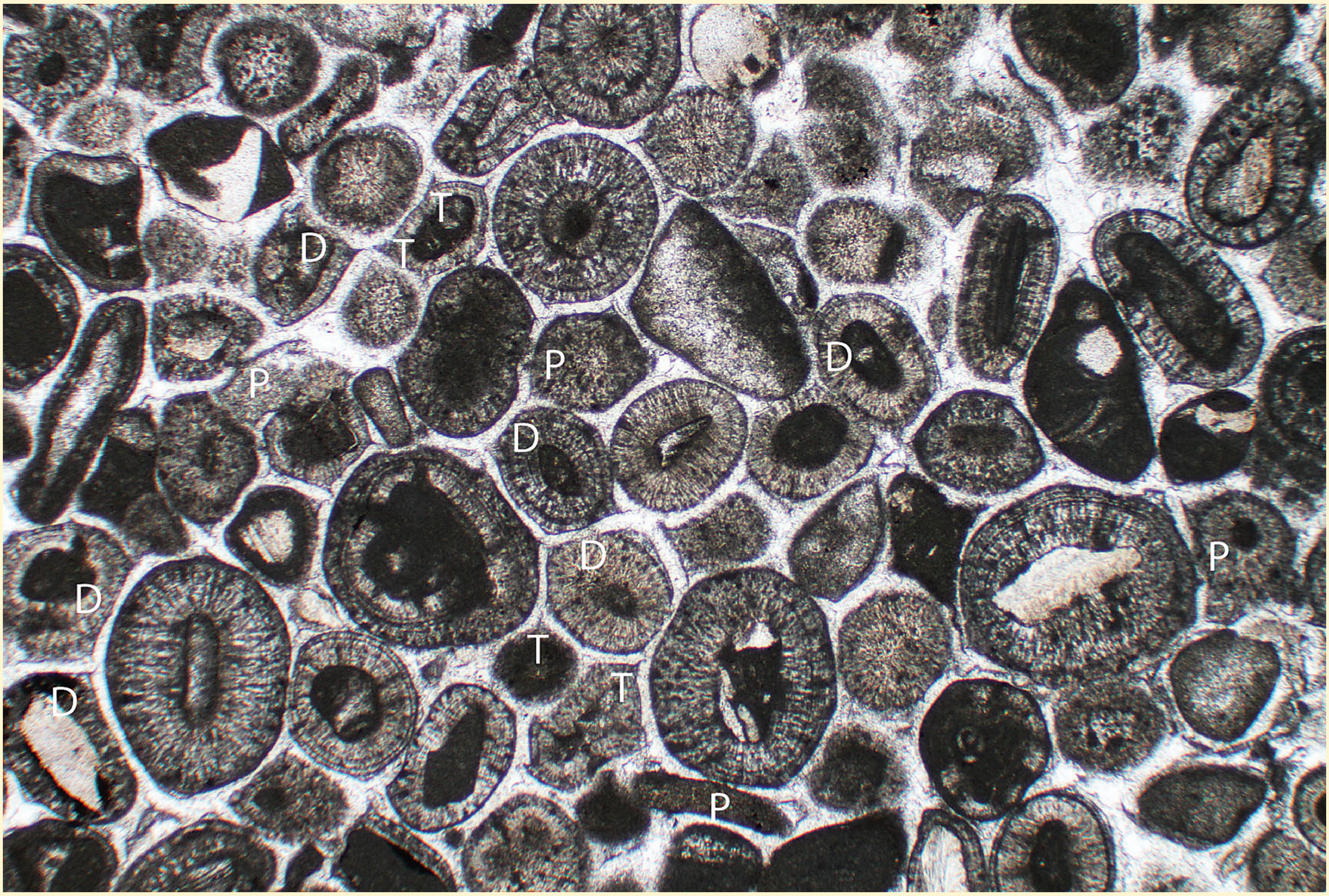

Figure 2: Fitted fabric grainstone from Jurassic of Morocco (courtesy of Peter Scholle and Dana Ulmer-Scholle). Some layers of ooids missing where dissolution (D) has occurred. Note the presence of pillars (P) of undissolved grain between some grains. Some ooids have little tails (T) on them suggesting they were once larger than they currently appear.

well cuttings from the Cretaceous of offshore Angola. Figures 3F is a well-fitted example from the Jurassic Arab D of Saudi Arabia which occurs in a grainstone unit that is just below a sequence boundary and a regional evaporite unit. Figure 3G is a well-fitted grainstone from the Mississippian of Wyoming, USA (from Westphal et al., 2004). Figure 3H is from the Ordovician of Pennsylvania, USA that shows moderate fitting of ooids and some echinoderm fragments.

These examples show that fitted fabrics occur in grainstones composed of ooids, peloids, intraclasts and skeletal grains. More soluble grains such as ooids and peloids are commonly fitted to less soluble grains such as quartz grains or some skeletal grains. Fitted fabrics most commonly are preserved in grainstones with grains composed of calcite, but they can also occur in grainstones with what were aragonitic grains and the presence of dissolved aragonite might supply some $CaCO_3$ for later cementation. Fitted fabrics are common in grainstones deposited in both calcite and aragonite seas (*sensu* Sandberg, 1983).

ORIGIN OF FITTED–FABRIC GRAINSTONES

The grains in these fitted-fabric grainstones (Figures 1C, 2 and 3) would not have tumbled randomly into such fitted relationships due to depositional processes. Instead, the grains are interpreted to have been dissolved and fitted to each other in the vadose zone - after deposition but prior to early cementation and burial (Clark, 1979).

Figure 4 is a diagenetic model for the formation of fitted-fabric grainstones (in part based on ideas from Dunham presented in Clark, 1979). When grainstones within the vadose zone are exposed to meteoric diagenesis, most fresh water from rainfall percolates down between the grains until it reaches the water table, but some of that water forms a meniscus around grain contacts (Figure 4A). If the fluids are undersaturated with respect to calcite, dissolution occurs which leads to flattening of the grain contacts over time (Fig. 4B) and eventually to fitting of the grains. Continued downward flow eventually flushes hundreds or thousands of volumes of fluid through the pore system, removing dissolved carbonate and delivering more undersaturated water. The degree of fitting is primarily controlled by the amount of dissolution that occurs prior to cementation. Round grains subjected to this sort of dissolution might produce more polygonal fitting while those with more irregular shapes might produce a fabric that has more concavo-convex fitting. Note that pillars of undissolved material remain that maintain a gap between the grains (Fig. 4B) as were seen in Figure 2. The pillars may be only a few microns in diameter and will not always be captured in a given thin section slice but are necessary to maintain the gap between the grains (Dunham via D.N. Clark, pers. comm, 2010).

Figure 4C shows the next stage in development of fitted-fabric grainstones which is the precipitation of cement that lines the grains and fills the gaps between them. Most of the cases examined for this paper have isopachous rim cement, but some other type of early cement may be precipitated in the gaps as well. Isopachous rim cement can form in both meteoric and marine settings (Harris et al., 1985). If the cement is meteoric in origin this indicates a change in conditions from undersaturated fluid to a supersaturated fluid capable of precipitating calcite. If it is a marine cement, it would indicate a sea level rise and a shift from vadose to marine diagenesis. In either case, the cements form at or very near the surface and postdate the fitting of the grains which means that the fitting also must occur at or very near the surface. The cement is a key to the interpretation, because if the fitting was due to burial compaction or pressure solution the cements would also be affected. In one example after another the grains are fitted

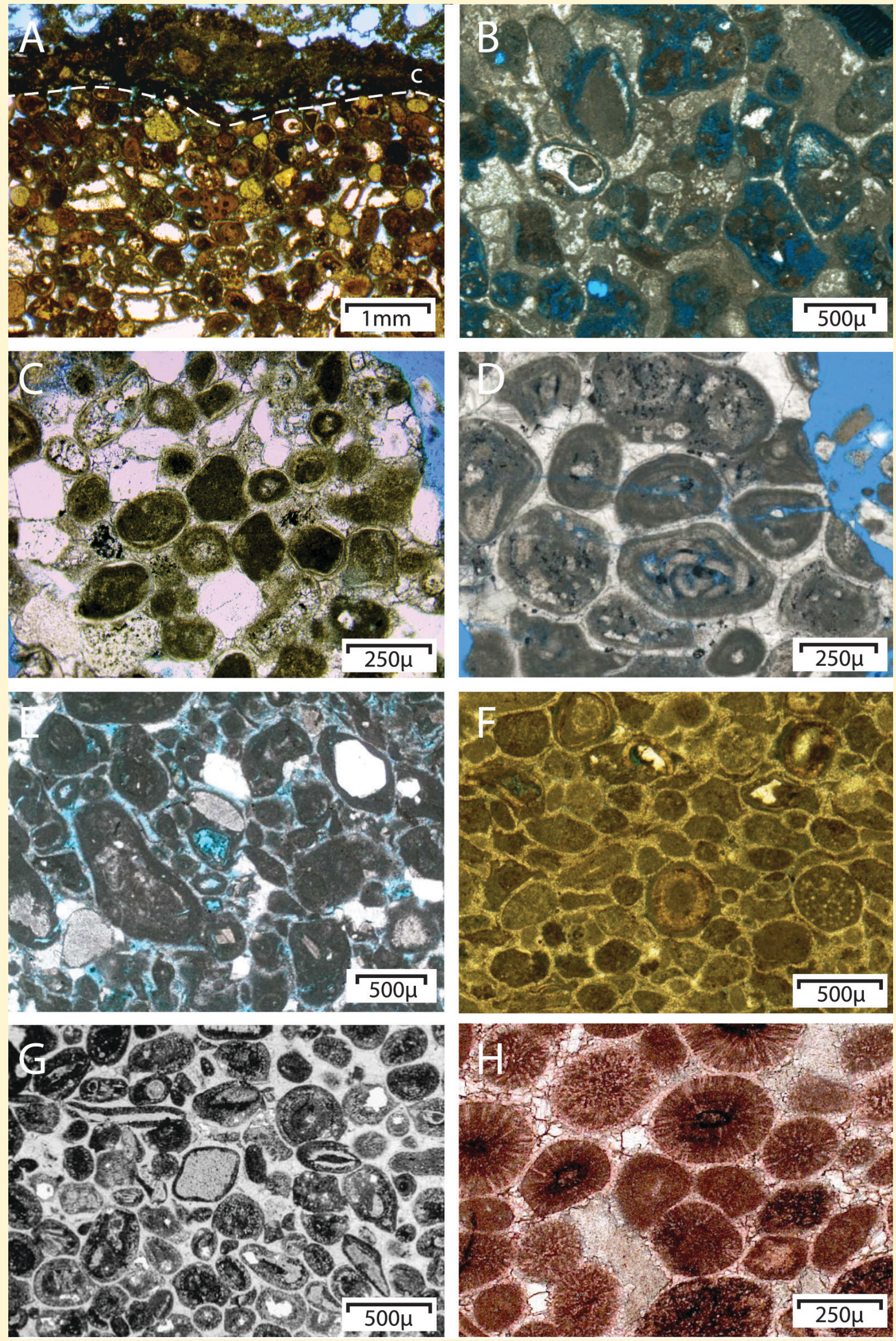

Figure 3: Examples of fitted fabric grainstones. A) Pleistocene ooid grainstone with fitted fabric from the west side of Barbuda, Leeward Islands, Caribbean, with caliche crust (c). B) Pleistocene intraclast-peloid grainstone, San Salvador Island, Bahamas (Courtesy Shawn M. Fullmer). C) Sandy ooid grainstone, Cretaceous Quintuco Formation, Neuquén Basin, Argentina. D) Miliolid-ooid grainstone with fitted fabric, Cretaceous Gordon Pass Formation, USGS core 3978, Virginia Key, FL, USA. E) Fitted fabric in intraclast-peloid grainstone, Cretaceous Pinda Formation, Bagre Field, Offshore Angola. F) Fitted fabric in intraclast peloid grainstone from Jurassic Arab D Formation, Saudi Arabia (from M. Al-Nazgah) G) Fitted fabric skeletal-ooid grainstone from Mississippian Madison Group, Wind River Basin, Wyoming, USA (from Westphal et al., 2004) H) Fitted ooid grainstone from Black River Formation, Union Furnace, Pennsylvania, USA (stained with alizarin red s) (courtesy C. Laughery and J. Kostelnik).

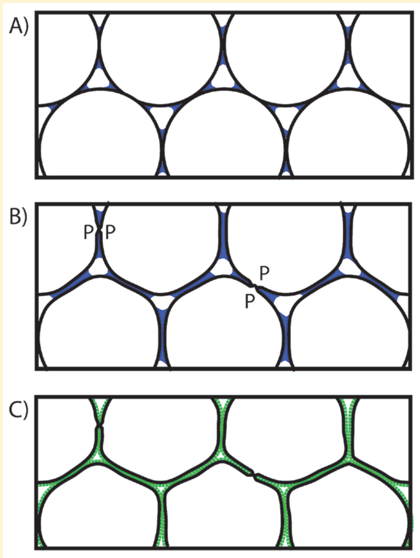

Figure 4: Schematic diagenetic model for development of fitted fabric grainstones. A) Round grains deposited and exposed to vadose diagenesis. Most fresh water percolates down to water table but some collects at grain contacts as a meniscus. B) Fresh water dissolves grains where meniscus forms leading to flattening of contacts. Gaps between grains maintained by pillars of undissolved grain (P). C) Isopachous rim cement (green color on figure) of either meteoric or marine origin fills gaps between grains.

to each other, but both the grains and the cements are unaltered by the fitting process, later burial compaction or pressure solution.

DISCUSSION

The fitting of carbonate grains due to dissolution in the vadose zone is a fundamental diagenetic process that has never been fully documented. Because there is little general awareness of this process, fitted fabric grainstones have long been overlooked or misinterpreted even though they are quite common. The author of this paper went back through projects done earlier in his career and found fitted fabrics in the Ste. Genevieve Limestone of the Illinois Basin, the Cretaceous Pinda Formation of offshore Angola (Fig. 3E), the Madison Group in Wyoming (see Westphal et al, 2004, Figure 3G), and the Black River Formation in the northern Appalachian Basin (Fig. 3H) that went unrecognized at the time. Once one is aware of the feature it becomes clear that they are very common. They occur in shallow marine, lacustrine and eolian carbonates from the Archean to Holocene and in every time period in the Phanerozoic (see online Table 1). Theoretically, any previously uncemented marine, eolian or lacustrine grainstone (or sandstone with appropriately soluble grains) might develop fitted fabrics in the in vadose zone given the right conditions.

Others have noticed the compacted appearance of the fitted fabric grainstones but misinterpreted them as having formed due to burial compaction and/or pressure solution. Bathurst (1975) interpreted a Carboniferous ooid grainstone from Ireland with fitted fabric to have formed due to pressure solution (p.465, Figure. 322). Cussey and Friedman (1977) interpreted an ooid grainstone from the Jurassic of France with fitted fabric texture to have formed due to pressure solution and “load compaction” (Figure 4 of that paper).

Grainstones that have been subjected to burial compaction and pressure solution (Fig. 1B) are easily differentiated from fitted-fabric grainstones (Figs. 1C, 2 and 3). Grainstones subjected to burial compaction and pressure solution will have visible pressure solution sutures or stylolites between the grains (Fig. 1B) that in some cases may cut across cements as well. The fitted fabric grainstones have grains with flattened, polygonal or concavo-convex contacts with unaltered early cement around and between them. Although there might be minor later burial compaction, most fitted fabric grainstones show little evidence of pressure solution.

The fitted-fabric grainstones under discussion in this paper are not formed by the same process as the vadose pisolites of the Capitan Reef discussed by Dunham (1969) and Esteban and Pray (1977). Those pisolites grew into fitted relationships due to precipitation in the vadose zone while the fitted fabrics under discussion in this paper formed at first due to dissolution of grains due to dissolution in the vadose zone.

The degree of fitting may be related to time in the vadose zone, climate, fluid chemistry, the grain types or the timing of the cementation which would bring the fitting to an end. Fitting could extend as far below the surface as the fluids doing the dissolution remain undersaturated which could be a few cm to perhaps a meter or more. Al-Nazgah (2011) found more than 20 continuous meters of fitted fabric grainstone in some locations, but this was likely due to multiple episodes of deposition, exposure and fitting rather than a single event.

While porosity can in some cases be enhanced or created by subaerial exposure (Budd et al., 1995), the development of fitted fabrics would in most cases lead to a reduction in porosity. Both the fitting of grains and the early cementation decrease overall porosity and create hardgrounds (Sellwood et al., 1985).

Value as an Indicator of subaerial exposure. – Because they form in the vadose zone, fitted fabrics are an indication of subaerial exposure. Fitted fabrics may be more common than karst, caliche or any other indicator of subaerial exposure in carbonates and are easily recognized in thin sections from well cuttings, core and outcrops. They are therefore a useful tool when trying to identify exposure surfaces and picking sequence and cycle boundaries. In the Jurassic Arab D of Saudi Arabia, Al-Nazghah (2011) was able to correlate the fitted fabrics at the top of a thick grainstone package below an interpreted sequence boundary for 75 kilometers from one oil field to another and the surface likely extended even farther.

In most cases, the feature is found where one might pick a sequence boundary or subaerial exposure surface based on other criteria such as at the top of an ooid grainstone unit or where associated with marginal marine facies, karst or caliche. In other cases, they may help to identify cryptic exposure surfaces that are otherwise undetectable. If the grainstone has a fitted fabric as described here, it was altered in the vadose zone and is therefore evidence of subaerial exposure.

CONCLUSIONS

- Some grainstones have fitted fabrics which means that the grains fit together with flattened, polygonal or concavo-convex contacts that would not form due to normal depositional processes
- This fitting occurs due to dissolution in the vadose zone and fitted fabrics are therefore evidence of subaerial exposure
- They are common in carbonate grainstones and have been found in shallow marine carbonates from every time period in the Phanerozoic and as far back as the Archean

DEDICATION AND ACKNOWLEDGMENTS

This paper is dedicated to Robert J. Dunham who conceived of the main idea presented here. Thanks to Franz Meyer and David N. Clark for early discussions on the model and to Fred Read, Charlie Kerans, Antun Husinec and an anonymous reviewer for their helpful reviews. Thanks to all those who shared thin sections including Peter Scholle and Dana Ulmer-Scholle, Angola LNG, YPF, Mahmoud Al-Nazghah, and Chris Laughery and Jaime Kostelnik and Shawn M. Fullmer.

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Accepted August 2019