Late Smithian microbial deposits and their lateral marine fossiliferous limestones (Early Triassic, Hurricane Cliffs, Utah, USA)

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Abstract

Recurrent microbialite proliferations during the Early Triassic are usually explained by ecological relaxation and abnormal oceanic conditions. Most Early Triassic microbialites are described as single or multiple lithological units without detailed ecological information about lateral and coeval fossiliferous deposits. Exposed rocks along Workman Wash in the Hurricane Cliffs (south-western Utah, USA) provide an opportunity to reconstruct the spatial relationships of late Smithian microbialites with adjacent and contemporaneous fossiliferous sediments. Microbialites deposited in an intertidal to subtidal interior platform, are intercalated between inner tidal flat dolosiltstones and subtidal bioturbated fossiliferous limestones. Facies variations along these fossiliferous deposits and microbialites can be traced laterally over a few hundred of meters. Preserved organisms reflect a moderately diversified assemblage, contemporaneous to the microbialite formation. The presence of such a fauna, including some stenohaline organisms (echinoderms) indicates that the development of these late Smithian microbial deposits occurred in normal marine waters as a simple facies belt subject to relative sea-level changes. Based on this case study, the proliferation of

microbialites cannot be considered as direct evidence for presumed harsh environmental conditions.

Keywords Early Triassic · Late Smithian · Microbial deposits · Metazoan fauna · Lingulids · Biotic recovery · Depositional environments

1. Introduction

The biotic recovery after the Permian-Triassic mass extinction is usually considered to have lasted as long as the entire Early Triassic (Erwin 2001; Flügel 2002). The patterns and causes of this delayed recovery are strongly debated, and possibly involve environmental, ecological and preservational factors (Erwin 1996; Payne and Clapham 2012; Pietsch et al 2014; Tang et al. 2017; Bagherpour et al., 2017). Even if diagenetic processes can alter primary geochemical signals (Thomazo et al. 2016), Early Triassic sediments record some of the largest known Phanerozoic carbon isotope excursions (Atudorei 1999; Payne et al. 2004; Galfetti et al., 2007; Grasby et al., 2013). Such global and large carbon isotope fluctuations may reflect severe environmental disturbances – e.g. anoxia, euxinia, hypercapnia, high temperature, ocean acidification, nutrient-rich waters – that postponed or interfered with the biotic recovery (Wignall and Twitchett 1996; Payne et al. 2010; Sun et al. 2012; Grice et al. 2005; Knoll et al. 2007; Grasby et al. 2013). Moreover, the amount of skeletal organisms in the aftermath of the Permian-Triassic extinction was apparently unusually reduced (Baud et al. 1997; Payne et al. 2006). This managed to an increase in the calcium carbonate saturation state that could explain the flourishing of microbialites in the Early Triassic (Pruss and Bottjer 2004; Pruss et al. 2006; Bottjer et al. 2008; Ezaki et al. 2008, 2012; Woods 2014; Abdolmaleki and Tavakoli 2016). However, several authors have argued that some Early Triassic microbialites developed in normal marine settings rather than in harsh environmental conditions (Schubert and Bottjer 1992; Olivier et al. 2014, 2016; Collin et al. 2015; Vennin et al. 2015; Fang et al. 2017). The presence of Early Triassic microbial deposits should also be analysed by taking into account that a significant number of lineages survived in potential refugia, and that skeletal organisms can be observed either as intercalated with or included into microbialites, for instance just after the Permian-Triassic boundary (Brühwiler et al. 2008; Kaim et al. 2010; Hautmann et al. 2011; Forel et al. 2013; Bagherpour et al. 2017; Tang et al. 2017). Some authors now regard these Early Triassic microbial deposits as part of diverse, ecologically normal marine ecosystems, qualifying them as “microbialite metazoans”

(Yang et al. 2015). Consequently, the debate hinges on whether Early Triassic microbialites occurred when environmental conditions were hostile to metazoans – notably for CaCO₃-precipitating invertebrates (Pörtner et al. 2005), or because the surviving metazoans were too decimated to rapidly recolonize shallow-marine habitats (Algeo et al. 2011). Therefore, detailed sedimentological studies are of primary importance for documenting the palaeoenvironments in which Early Triassic microbial deposits and skeletal metazoans co-occurred (Kershaw 2017).

Along the western margin of Pangea, the Sonoma Foreland Basin of the western USA was the site of Early Triassic marine sedimentation (Collinson et al. 1976; Paull and Paull 1994; Dickinson 2013; Caravaca et al. 2017). In southwestern Utah, the Lower Triassic sediments exhibit transitional deposits between the marine Thaynes Group and the continental Moenkopi Group (*sensu* Lucas et al. 2007a). The Hurricane Cliffs expose various sedimentary deposits such as conglomerates, sandstones, and microbial and fossiliferous carbonates (Gregory 1950; Blakey 1979; Lucas et al. 2007a). Several areas give access to stratal architectures that suggest rapid lateral facies variations over several tens of metres (Nielson 1991; Olivier et al. 2014). About four kilometres south of the Hurricane airport, near the head of Workman Wash, exceptional Early Triassic outcrops document the nature and the spatial relationship between late Smithian microbialites and coeval fossiliferous deposits. The aim of this paper is (i) to describe the main sedimentary succession at Workman Wash and to interpret the evolution of the depositional settings, (ii) to demonstrate that microbial and fossiliferous limestones coexisted as lateral facies belts influenced by relative sea-level changes, and (iii) to discuss the environmental and ecological significance of such a microbial-metazoan association in the aftermath of the Permian-Triassic biotic crisis.

2. Geological framework

During the Early Triassic, the western USA was located at a near-equatorial position, on the western margin of Pangea (Fig. 1b). During the Sonoma Orogeny, the onset of the Golconda Allochthon led to the formation of a north-south foreland sedimentary basin, which covered a large area including eastern Nevada, Utah, Idaho and parts of Wyoming (Collinson et al. 1976; Dickinson, 2006, 2013; Caravaca et al. 2017). From the north towards the southwest, the Sonoma Foreland Basin recorded a major transgressive trend during the Smithian (Paull and Paull 1993; Goodspeed and Lucas 2007; Brayard et al. 2013). The

presence of heterogeneities of the basin basement generated differential flexural subsidence, which impacted the sedimentary record and thicknesses (Caravaca et al. 2017).

The study area is located in Washington County (southwestern Utah, USA), about 8 km south of Hurricane city, near the head of Workman Wash between the Three Brothers and White Face heights (37°5'56.62''N, 113°17'44.60''W; Fig. 1a). The studied Permian-Triassic succession is capped by the Three Brothers volcanic rocks, which are remnants of early Pleistocene lava (<http://geology.utah.gov/apps/intgeomap/index.html>; Hayden, 2004). The Permian-Triassic transition can be observed on the western side of the Hurricane Cliffs, whereas only Triassic rocks outcrop on its eastern side along Workman Wash (Fig. 2). Blakey (1979) was the first to illustrate this area that Brayard et al. (2015) and Jattiot et al. (2017) later referred to as “Black Rock Canyon”. Lucas et al. (2007a) recently revised the stratigraphic nomenclature of Early Triassic rocks in southwestern Utah with a lectostratotype section from Timpoweap Canyon, located a couple of kilometres northeast of Hurricane. For these authors, Early Triassic rocks of the Hurricane Cliffs begin with a chert breccia unit of the Rock Canyon Conglomerate Formation (Moenkopi Group), which is overlain by a second unit comprised of the various types of limestones and calcareous shales of the Sinbad Formation (Thaynes Group). Finally, limestones of the Sinbad Formation are capped by clastic deposits of the Lower Red Formation (a new digitation of continental deposits of the Moenkopi Group; see Figure 2 of Lucas et al. 2007a for subdivisions and lateral correlations between stratigraphic units of Thaynes and Moenkopi groups). These Triassic deposits rest unconformably on silicified and recrystallized mudstones of the Permian Kaibab Formation (Reeside and Bassler 1922; Gregory 1950; Blakey 1979; Stewart et al. 1972; Nielson and Johnson 1979; Nielson 1991; Olivier et al. 2014). The presence of the ammonoid genera *Owenites*, *Anasibirites* and *Wasatchites* in the Timpoweap Formation (= junior synonym of the Sinbad Formation) at Virgin Dam and near Cedar City indicates a middle to late Smithian age for this stratigraphic unit in this area (Lucas et al. 2007a; Brayard et al. 2013).

3. Studied sections and lithological units

Five sections have been logged between the Three Brothers and the White Face volcanic peaks (Fig. 1). Section #1 is located on the western side of Hurricane Cliffs (Fig. 2a). About 300 m away, four additional sections (#2-5) have been logged along the northern flank of Workman Wash (Fig. 2b). Among them, section #1 provides the most complete sedimentary succession of Early Triassic deposits that cap Permian limestones of the Kaibab

Formation (Figs. 3 and 4). These latter deposits correspond to a succession of dolostones, dolosiltstones and bioclastic limestones that are more or less dolomitized, silicified and bioturbated. This Permian succession is interrupted by a pluri-metre thick channelized breccia interval. Just below this conglomeratic interval, Permian limestones reveal an extensive karstification extending up to 2 metres thick in this area. A second karstified interval is observed approximately 3 metres below a surface that probably represents the top of the Kaibab Formation and the Permian-Triassic transition (Fig. 4). Above this surface, the Early Triassic sedimentary succession is approximately 70 metres thick. Unfortunately, scree slopes hide the outcrop 30 metres before the Early Pleistocene basalts that cap the section (Fig. 2b). This Early Triassic succession displays in ascending order deposits of the Rock Canyon Conglomerate, Sinbad, and Lower Red formations. Along section #1, deposits of the Rock Canyon Conglomerate Formation are about 17 metres thick (Fig. 4). They can be subdivided into 4 successive lithological units. The first one corresponds to a first yellow clastic unit that is at least 3.5 metres thick. It is overlain by a 3 metres thick red bed unit that is itself capped by a second yellow clastic unit. A 5 metre thick conglomeratic breccia unit marks the end of the Rock Canyon Conglomerate Formation. Above it, the Sinbad Formation consists of a single 18 metre thick fenestral-microbial limestone unit. A third level of yellow clastic deposits characterizes the uppermost part of the section, which is considered here to belong to the Lower Red Formation. Section #2 is only 5 metres thick and can be subdivided into two lithological units of the Sinbad Formation (Fig. 5). Most of this section corresponds to a first fenestral-microbial unit. The second lithological unit made of bioclastic limestones is only visible in the first decimetres of the section. Section #3 is around 19 metres thick and can be subdivided into 4 lithological units (Fig. 6). A basal bioclastic unit, capped by a 12 metre thick fenestral-microbial unit and a single bed of a pel-fenestral unit represent the deposits of the Sinbad Formation. The uppermost part of the section corresponds to the yellow limestone unit of the Lower Red Formation. Section #4 is 16 metres thick and consists of four lithological units (Fig. 7). A basal breccia unit outcrops over a thickness of one metre; it is capped by a 4 metre thick fenestral-microbial unit. Above this rests a third bioclastic lithological unit of more than 7 metres thick. These first three units belong to the Sinbad Formation. The uppermost part of the section corresponds to the yellow clastic unit of the Lower Red Formation. Section #5 corresponds to one single, 15 metre thick fenestral-microbial unit of the Sinbad Formation (Fig. 8).

4. Facies descriptions

A bed-by-bed macro- and microscopic sedimentological analysis of the five sections, which included the observation of more than 150 thin sections, allowed us to identify 13 main facies (Table 1). These facies can be grouped into several categories, including terrigenous (F1, F2), dolomitized (F3-F6), fenestral-microbial limestones (F7) and fossiliferous (F8-F13) deposits. The fenestral-microbial limestones (F7) appear as the most complex facies in composition and the most common at the scale of the outcrop.

4.1. Fenestral-microbial limestones (Facies F7)

Limestones with microbial laminations and fenestrae occur in the five studied sections (Fig. 9A). Macroscopically, the fenestral-microbial beds sometimes appear truncated, and more commonly display lateral thickness variations, forming dm-scale lens-like to flat morphologies (Fig. 10). These fenestral-microbial beds can also locally interfinger with breccia (F1) or bioclastic (F10) deposits (e.g. section #5 in Fig. 8). Another feature of this fenestral-microbial facies is to record common lenses of macroscopic skeletal organisms such as gastropods and ammonoids (Figs. 9C-D and 10). Brayard et al. (2015) identified three main taxa of gastropods in these levels, corresponding to “*Coelostylina* sp. A”, *Angularia* sp., and *Worthenia windowblindensis*. All these taxa are large-sized gastropods, with shell sizes reaching ~ 10 cm in length for the largest sampled specimens of “*Coelostylina* sp. A”. Sampled ammonoids correspond to a rich and well-preserved prionitid fauna, typical of the late Smithian *Anasibirites multiformis* beds in the western USA Basin (Brayard et al. 2013; Jattiot et al. 2016, 2017), including *Anasibirites kingianus*, *A. multiformis*, *Wasatchites perrini*, *Hemiprionites walcotti*, *H. typus* and *Arctoprionites resseri*.

Microscopically, F7 is relatively diverse in composition and texture, making it possible to distinguish 5 subfacies (F7a-e; Table 1). In some cases, fenestral-microbial deposits are made of abundant pisoids (subfacies F7a; Fig. 11A) or intraclasts (subfacies F7e; Fig. 11B). Subfacies F7b is characterized by large cm- to dm-scale fenestrae (Fig. 9B). Diversified endostromatolites, commonly made of irregular to domal micritic laminae or sparitic laminae (Fig. 11C-E), developed in the fenestrae. Acicular to botryoidal cements are also observed associated with these endostromatolites (Fig. 11F). Subfacies F7c is characterized by lamellar siliceous sponges co-occurring with micritic stromatolites and common ostracods (Fig. 11G and H). Locally, this subfacies records some root-like structures and circum-granular cracks (Fig. 12A). Subfacies F7d corresponds to microbial-fenestral deposits that display a conglomeratic nature, with abundant polygenic and subangular to

subrounded lithoclasts (Fig. 12B). A common feature shared by all these subfacies includes the presence of frequent biofilms that are a few tens of microns thick and that have a micritic nature. These biofilms are observed coating different types of substrates, such as pel-oncoid-fenestral deposits, pel-oidal grainstones, or gastropods and ammonoids (Fig. 12C-E). In other cases, the biofilms developed micritic stromatolites with microscopic planar, irregular to domal morphologies (Fig. 12F and G). Locally, some cement crusts show enigmatic structures (Fig. 12H).

4.2. Fossiliferous limestones (Facies F8-F13)

Six facies (F8-F13) with a moderately diversified fauna (including echinoderms, gastropods, siliceous sponges, ostracods, bivalves, lingulid brachiopods, and phosphatic remains) and a more or less intense degree of bioturbation are identified (Table 1). These facies are distinguished according to their textures, sedimentary structures, as well as their grain abundances. Facies F8 is a mud-supported limestone with frequent echinoderms. Facies F9 is an intensively bioturbated packstone (locally wackestone) with abundant echinoderms and frequent siliceous sponge spicules (Fig. 13A). Facies F10 is a bioturbated grain-supported bioclastic (mainly gastropods and bivalves) limestone that also includes abundant ooids (Fig. 13B).

Facies F11 corresponds to an intensively bioturbated and bioclastic packstone composed of abundant bioclasts of gastropods, echinoderms, bivalves and vertebrate phosphate remains. Beds attributed to this facies displays a spectacular abundance of well-preserved lingulid brachiopods frequently preserved in their burrows (Figs. 9E and 14). Such a remarkable macroscopic assemblage deserves a short description here as it has important implications in terms of depositional setting and palaeoecology. A majority of lingulid specimens are complete articulated shells preserved perpendicular to the bedding, with the ventral side upward, showing that they are preserved *in situ* and in life position. The shells are elongated, twice as long as wide. Most measurable specimens are between 15 and 20 mm in length; a few complete specimens reach 21 mm. The dorso-ventral thickness is about 5 mm. The posterior part of the shell is rounded, the anterior part is spade-shaped and the lateral borders are parallel. Although no internal structure could be observed, these shells are tentatively attributed to *Lingularia* sp., the most frequent Mesozoic lingulid genus (Biernat and Emig 1993; Zonneveld et al. 2007; Posenato et al. 2014; Holmer et al. 2016). Interestingly, the shell length of the specimens found at Workman Wash tends to exceed the values reported for other Early Triassic lingulids (e.g. Zonneveld et al. 2007, Posenato et al.

2014, Peng et al. 2007). Several shells described here are concordantly emplaced in their dwelling burrows that tend to be deep (about 150 mm), densely distributed locally (about 500 burrows/m²) and filled by a yellow-to-orange dolomitized micrite (Fig. 9E). Burrows are cylindrical, vertical though not totally straight, and rounded to slightly elliptical in cross section. Many of them correspond to pedicle traces whose diameters are particularly homogeneous (5 mm in average). Several burrows are spreitenate and they preserve concave-up laminae whose width is comprised between 8 and 12 mm (Fig. 14B). Some of these laminae are found immediately below the posterior part of *Lingularia* shells preserved *in situ* and that have the same width. All these features warrant the identification of these trace fossils as *Lingulichnus verticalis* that are typical lingulid equilibration traces (Hakes 1976; Szmuc et al. 1977; Zonneveld and Pemberton 2003; Zonneveld et al. 2007). They are associated with some U-shaped and J-shaped burrows that we identify as *Lingulichnus hamatus*, an ichnofossils interpreted as a lingulid reburrowing structure (Zonneveld and Pemberton 2003; Zonneveld et al. 2007). Some horizontal, more or less sinuous traces also occur on the top of the beds representing facies F11. The dominance of vertical, cylindrical and U-shaped burrows of suspension feeders, the frequent occurrence of equilibrichnia-related laminae, the relative rarity of horizontal structures and the low ichnological diversity suggest an attribution of these beds to the *Skolithos* ichnofacies (Seilacher 1963; Frey and Seilacher 1980; Frey and Pemberton 1984, 1985; MacEachern et al. 2007; Buatois and Mángano 2011). Finally, it should be noted that the beds attributed to Facies F11 also yields large shells of indeterminate bivalves.

Facies F12 is a bioclastic packstone-grainstone rich in peloids (Fig. 13C). Facies F13 is a grainstone (locally packstone) notably characterized by frequent intraclasts (Fig. 13D). Apart from Facies F8 and F9, these bioclastic limestones display dm- to m-scale trough cross bedding with low angle fore sets or small asymmetrical ripples, and common mud drapes for F10.

4.3. Terrigenous (F1-F2) and other carbonate facies (F3-F6)

In addition to the fenestral-microbial (F7) and bioclastic limestones (F8-F13), 6 other facies can be identified (Table 1). Facies F1 corresponds to a channelized conglomerate breccia with angular to subrounded polygenic clasts (Fig. 9F). Facies F2 is a thin-bedded dolosiltstone with common bioturbation, trough cross stratifications and asymmetrical ripples that locally display some mud drapes. The remaining facies are carbonate-dominated, but terrigenous components can be sometimes observed. F3 corresponds to a dolomudstone

characterized by some bioturbation and no preserved fauna. F4 is a dolostone devoid of fauna and sedimentary structures. F5 is a silty peloidal packstone with some bivalves, rare gastropods and some micritized ooids. This facies is characterized by some mud clasts, mud drapes and trough cross bedding with low angle foresets. F6 is a wackestone/packstone limestone with keystone vugs. It is characterized by frequent reworked clasts of microbial crusts and rare bioturbation.

5. Multi-scale lateral facies variations

Figure 15 shows the correlation of the 5 studied sections, along which no evidence of faults was found. Such a correlative scheme is possible because some beds can be laterally traced across the sections. First, a 20-30 cm thick bed, particularly rich in lingulid brachiopods in section 4, can be traced laterally through sections #3 and #2. This “lingulid” marker bed was not found in section #1 and could not be followed laterally into section #5 because of ground vegetation (Fig. 2B). Second, the correlation of section #1 is attempted through its conglomerate unit that has a lateral equivalent observed at the base of section #4. Last, the position of section #5 was estimated with a tolerance of few centimetres, in laterally following as far as possible successive beds of sections #4 and #5.

At a first order, the stratigraphic succession of the Black Rock Conglomerate, Sinbad and Lower Red formations can be easily observed laterally although some lithological units display important thickness variations. For example, the yellow clastic unit 3 of section #4 stratigraphically starts much lower compared to other sections (Fig. 15). This could be explained in two ways. First, the yellow clastic unit 3 could lay unconformably over the fenestral microbial unit, thus explaining changes in thickness between the different sections. Second, there could be a lateral facies variation between the fenestral microbial unit and this yellow clastic unit. No evidence of a significant erosional surface has been identified in the field. Thus, the studied locality likely records lateral facies variations at the scale of few hundreds of metres. Such lateral facies variations are well expressed in the stratigraphic distribution of the bioclastic unit. Between sections #3 and #4, the bioclastic facies F12 is observed laterally to different subfacies of the fenestral-microbial limestone (F7) over a few tens of metres. Located more than 100 m away, section #5 also records a thin bed of bioclastic limestone (F10), highlighting again the lateral proximity between fossiliferous and microbial deposits. In section #5, the intercalation of a dm-scale thick bed of breccia also emphasizes that such terrigenous sediments are recurrent, even above the Rock Canyon Conglomerate

Formation. These observations demonstrate important lateral facies changes over a few tens of metres in the Hurricane Cliffs area, whereas previous studies only presumed their existence after larger-scale lithostratigraphic correlations (Blakey 1979; Nielson and Johnson 1979).

Some facies changes can also be laterally traced at the scale of a single bed. For example, across sections #2, #3 and #4, the “lingulid” marker bed exhibits at least two facies. Over a few tens of metres (Fig. 15), this marker bed is made of a packstone rich in siliceous sponge spicules (F9), which evolves into an intensively bioturbated limestone with some lingulids, echinoderms, bivalves and gastropods (F11). As indicated by the number of identified subfacies, the fenestral-microbial limestone (F7) is probably the facies displaying the most important changes in terms of composition. Even within a subfacies, the distribution of some structures such as biofilms or stromatolites has a restricted lateral extension. Likewise, the presence and abundance of some coated grains such as ooids, oncoids, or pisoids can shift markedly at the scale of a thin section, not to mention some macroscopic organisms (ammonoids, gastropods, or ostracods) whose distribution is highly heterogeneous in this fenestral-microbial limestone. Indeed, some accumulations of gastropods are observed only in some local dm-scale lenses (Fig. 9C). Similarly, ammonoids also accumulated in some (pluri)dm-scale lenses (Fig. 9D). Additionally, ammonoids are preferentially concentrated in some specific beds and over a few tens of decimetres (Fig. 10). On a smaller scale, some microscopic skeletal organisms such as ostracods also display a similar heterogeneous distribution. In these fenestral-microbial limestones, ostracods are usually observed associated with siliceous sponges and stromatolites within sediments displaying a micritic fabric (Fig. 11G).

6. Depositional environments and relative sea-level fluctuations

Observed sedimentary features point towards a mixed siliciclastic-carbonate marine depositional system (Fig. 16), whose minimum depth is probably localized within an area corresponding to a supratidal-subtidal interior platform showing the deposition of fenestral-microbial limestones (F7). This facies locally records multiple phases of emersions, as emphasized by frequent pisoids, mud cracks, root structures and truncation surfaces (Figs. 10, 11A, 12A). This fenestral-microbial facies belt thus likely separated an inner tidal flat from a subtidal interior platform. In the inner tidal flat, terrigenous deposits (F2) dominated the sedimentation, whereas carbonates only occurred as isolated muddy pools (F3). Additionally, the correlation scheme suggests that the fenestral-microbial facies belt was not laterally

continuous (Fig. 15), but was intersected by broad channels into which fossiliferous limestones were deposited (F13). Facies F13 includes sedimentary grains (intraclasts) derived from the fenestral-microbial limestones and bioclasts (echinoderms) characteristic of more open marine settings. These latter settings correspond to the subtidal interior platform where various fossiliferous limestones (F8-F12) were deposited. Both in the inner tidal flat and in the subtidal interior platform, the presence of megaripples with mud drapes and mud clasts emphasizes a tide-influenced regime. Some fossiliferous limestones (F8 and F9) appear devoid of tide- or wave-generated sedimentary structures, suggesting the presence of some protected areas. The presence of breccia (F1), notably intercalated within the fenestral-microbial limestones, indicates the proximity of the paleoshoreline, echoing previous observations by Olivier et al. (2014) in the vicinity of Workman Wash. This facies (F1) displays poorly sorted and angular clasts of cherts and limestones that suggest debris flows derived from the Permian Kaibab Formation. Such facies models also fit well with previous paleoenvironmental reconstructions, which highlighted a sedimentary system characterized by a clear polarity with an open sea that stood east of the Hurricane Cliffs (Blakey, 1979). The relatively small size of the Workman Wash depositional system, also characterized by a flat slope and a tidal autocyclic character, generated the rapid facies displacements and the important lateral facies variations observed at the scale of a few tens to hundreds of metres (Fig. 15).

The studied Early Triassic stratigraphic column, which involves three successive formations (Rock Canyon Conglomerate, Sinbad, Lower Red), displays a clear evolution of the type of sediments and thus of depositional settings (Figs. 15 and 16). The transition from proximal and shallow deposits (F2-F4) of the siliciclastic units (Rock Canyon Conglomerate Formation) to the carbonates (F7) of the fenestral-microbial unit (Sinbad Formation) is consistent with an increase in accommodation coupled with the general retrogradation of these facies belts. The high accumulation of fenestral-microbial limestones (F7) explains the frequent traces of emersion recorded by this facies, despite a more distal and deeper position in the interior platform. The installation of bioclastic and bioturbated facies in the *Anasibirites multiformis* beds (Brayard et al. 2013; Jattiot et al. 2017) likely reflects a maximum of accommodation recorded in the Workman Wash area. The return of inner tidal flat siliciclastic deposits (F5) in the yellow clastic unit 3 (Lower Red Formation) probably marked an accommodation decrease and a rapid facies progradation. Such facies evolution fits well with the Smithian third order transgressive-regressive sequence recorded in the western USA

Lower Triassic succession (Paull and Paull 1993, 1997), which is characterized by an early-middle Smithian transgression (Goodspeed and Lucas 2007; Brayard et al. 2013).

7. Ecological and environmental implications

It is usually assumed that a return to pre-extinction levels of taxonomic and functional diversity after the end-Permian extinction crisis did not occur until the end of the Early Triassic, or at least late in the Spathian (Schubert and Bottjer, 1995; Flügel 2002; Payne et al. 2006; Lehrmann et al. 2006; Chen and Benton 2012; Pietsch and Bottjer 2014; but see e.g. Brayard et al. 2009, 2017; Foster et al. 2015). In the presumed absence of developed benthic faunas, Early Triassic microbialites have been initially considered as disaster forms (i.e. opportunistic generalist taxa *sensu* Schubert and Bottjer 1992). These disaster microbialites were first considered to have formed in normal marine settings (Schubert and Bottjer 1992, 1995), like several subsequent studies (Kershaw et al. 1999; Lehrmann 1999; Lehrmann et al. 2001; Ezaki et al. 2008; Yang et al. 2011). Nevertheless, as noted by Tang et al. (2017), Early Triassic microbialites were progressively reinterpreted to have flourished as a consequence of harsh environmental conditions, such as hot temperatures, high carbonate saturation, or elevated CO₂ (Pruss and Bottjer 2004; Pruss et al. 2006; Mary and Woods 2008; Mata and Bottjer 2011; Pietsch et al. 2014; Song et al. 2014; Abdolmaleki and Tarakoli 2016). Lehrmann et al. (2015) suggested that ecological relaxation and abnormal ocean chemistry were not mutually exclusive to explain the proliferation of Early Triassic microbial deposits. However, diversified assemblages have been documented from various Early Triassic intervals and latitudes (Krystyn et al. 2003; Twitchett et al. 2004; Beatty et al. 2008; Kaim et al. 2010; Hautmann et al. 2011, 2013; Hofmann et al. 2011, 2013a, b, 2014; Baud et al. 2015; Fu et al. 2016; Foster et al. 2017; Brosse et al. in press). Moreover, the onset of complex ecosystems is now documented to have occurred rapidly after the end-Permian mass extinction (Haig et al. 2015; Brayard et al. 2017). Hence, the scenario of an ecological vacation that led to a global post-extinction delayed recovery has become increasingly unlikely. Moreover, new evidences that Early Triassic microbialites could have formed in normal marine environments are growing (Olivier et al. 2014, 2016; Vennin et al. 2015; Tang et al. 2017; Bagherpour et al. 2017). Therefore, the causes of the Early Triassic microbialite proliferation and their relationships with a delayed biotic recovery scenario remain highly controversial. This notably results from the poor knowledge of the physico-chemical parameters of Early Triassic seas into which microbialite developed. Indeed, such

palaeoenvironments are reconstructed from analyses of the microbialites themselves without information from lateral coeval sediments. Sedimentological and palaeontological data from other types of coeval sediments can indeed indirectly provide insights on the chemical composition of waters in which microbial deposits developed (Bagherpour et al. 2017).

Among the four episodes of microbialite expansion initially identified for the Early Triassic (Pruss et al. 2006; Baud et al. 2007), only the Permian-Triassic boundary microbialites (PTBMs) have a geographical extent large enough to have a global significance (Kershaw et al. 2012). Deep-water forms of PTBMs with metazoans are known and recently described by Baud et al. (2017) and by Friesenbichler et al. (2018). Within interior platform PTBMs, skeletal remains of some brachiopods, bivalves, microconchids, gastropods, echinoderms and sparse ammonoids are mainly observed as interstratified beds or lenses (Lehrmann et al. 2001; Baud 2007; Hautmann et al. 2015; Tang et al. 2017; Bagherpour et al. 2017). Thus, reliable ecological and environmental information from contemporaneous deposits of PTBMs remains to be documented in more detail.

Post-PTBMs microbial episodes in the Early Triassic have much more restricted geographic distributions (Mata and Bottjer 2012). Those observed in the southwestern USA basin are crucial since local and regional studies suggest the existence of lateral correlations between Smithian microbialites and different types of sediments containing an abundant and diversified fauna (i.e. brachiopods, bivalves, gastropods, ostracods, echinoderms, sponges and ammonoids; Stewart et al. 1972; Blakey 1974, 1977; Nielson and Johnson 1979; Dean 1981; Nielson 1991; Goodspeed and Lucas 2007; Ritter et al. 2013; Olivier et al. 2016). However, a major challenge on the field lies in the capacity to observe and to demonstrate the lateral transition and the contact between microbial deposits and these open marine skeletal limestones. Such lateral facies variation has been observed along an outcrop a few tens of meters long in Timpoweap Canyon, north of the Hurricane Cliffs (Olivier et al. 2014). At this site, a fenestral-microbial limestone deposited in contact with a dolomudstone characterized by sparse bioturbations and rare bioclasts (serpulids, bivalves and echinoderms). A few meters away, this mudstone evolves into a bioturbated limestone with a wackestone (locally packstone) texture and some gastropods, serpulids, bivalves and echinoderm plates. However, the limited extent of this outcrop does not provide a good spatial comprehension of its depositional setting.

At Workman Wash, the lateral continuity of deposits over a few hundred meters highlights the lateral transition between fenestral-microbial deposits and limestones

characterized by a relatively abundant metazoan fauna (Figs. 15 and 16). With some ostracods and gastropods, the fauna observed in the fenestral-microbial facies is neither diversified nor abundant, reflecting a microbe-dominated ecosystem. As microbialites flourished on this shallow sea floor of the internal platform, they were potentially a profuse resource for grazing gastropods (Batten and Stokes 1986; Schubert and Bottjer 1995; Pietsch et al. 2014), although this hypothesis remains to be corroborated (see discussion in Brayard et al. 2015). Furthermore, sponges are also observed associated with microbialites (Fig. 11G, H). This confirms the common occurrence of these metazoan reef-builders in Early Triassic reefs (Brayard et al. 2011; Marengo et al. 2012; Baud 2013; Vennin et al. 2015; Olivier et al. 2016; Baud et al. 2017; Friesenbichler et al. 2018). It implies that the local trophic network not only consisted of primary but also meso-consumers such as sponges. The common lenses of ammonoids preserved in the Workman Wash microbialites indicate the presence of higher-level consumers. The abundant lingulid brachiopods observed in a 30 cm thick interval could also be interpreted as opportunist meso-consumers (Rodland and Bottjer 2001). Thus, considered separately, both the microbial or lingulid-rich facies actually do not illustrate an ecosystem with a trophic level higher than microbe-dominated and possibly opportunist-dominated ones (Chen and Benton 2012). However, even if lingulid brachiopods are effectively common in some beds, the facies F11 in which they occur also includes frequent to abundant fragments of crinoids, gastropods and bivalves (Fig. 16). These observations better fit recent studies that point toward lingulids as ecological opportunists that dominated locally in some Early Triassic shallow marine environments rather than a disaster taxon (Zonneveld et al. 2007; McGowan et al. 2009). Other adjacent deposits of microbialites such as the facies F9 also comprises abundant elements of crinoids and frequent sponge spicules, coupled with an abundant infaunal activity. Overall, the depositional system reconstructed at Workman Wash shows that microbial and lingulid-dominant deposits are coeval with a moderately diversified benthic metazoan ecosystem. Such a biocoenosis including siliceous sponges (either present in reefs or in lateral deposits), crinoids, lingulid brachiopods, large-size gastropods and higher-level consumers, such as ammonoids and vertebrates, indicates that some Early Triassic marine ecosystems were not ecologically depauperate (Krystyn et al. 2003; Foster and Twitchett 2014; Baud et al. 2015; Brosse et al. in press). Additionally, the actual diversity of the Workman Wash palaeocommunity is probably underestimated, as suggested by ammonoids that are only preserved in the microbial-fenestral facies. Indeed, microbial deposits are known to favour rapid sediment stabilization and early lithification (Gall 1990; Tomescu et al. 2016). This may explain a differential preservation of some

organisms such as ammonoids. All these mechanisms highlight how differential taphonomic pathways can bias the fossil record in some Early Triassic marine settings.

From an environmental point of view, the presence of stenohaline organisms such as echinoderms in deposits lateral to the microbial-fenestral facies indicates normal marine conditions. The abundant lingulids observed in facies F11 also reflect an intense infaunal activity, implying the presence of nutrient-rich waters. The proximity of emerged lands may have provided an adequate nutrient supply to the depositional system, which in turn could have promoted the development of microbialites (Algeo et al. 2011; Olivier et al. 2016). In subtidal settings of the inner tidal flat (Fig. 16), the presence of an important terrigenous flux and intense sediment mobility (caused by tidal currents) could have inhibited microbialite development (Olivier et al., 2016). In such siliciclastic peritidal environments, microbial deposits are nevertheless known in other Early Triassic successions of the Sonoma Foreland Basin as microbially induced sedimentary structures (MISS; Grosjean et al., 2018). In the more open subtidal settings of the interior platform, the abundance of lingulid equilibration structures (in response to burial) and reburrowing structures (in response to exhumation) are consistent with a tidal regime. This relatively intense infaunal activity, coupled with the migration of tidal bars, may have prevented the development of microbialites in the more distal parts of the Workman Wash depositional setting.

8. Conclusions

For the first time, the late Smithian rocks of Workman Wash in the Northern Hurricane Cliffs (southwestern Utah, USA) provide a direct and continuous observation of the lateral facies transition between microbialites and contemporaneous fossiliferous limestones in the Early Triassic. Facies analysis reveals a shallow and proximal tide-dominated and mixed siliciclastic-carbonate sedimentary system. It was located along the southwestern margin of an epicontinental sea tongue corresponding to the Sonoma Foreland Basin. Above Permian limestones, the studied interval includes breccia and dolosiltstones of the Rock Canyon Conglomerate Formation, fenestral-microbial and bioclastic limestones of the Sinbad Formation, and yellow dolosiltstones of the Lower Red Formation. This lithological succession is in accordance with the Smithian third-order transgressive-regressive sequence recorded in the western USA.

Located in an interior platform and over only a few hundreds of meters, intertidal to subtidal microbialites pass laterally to bioturbated and fossiliferous limestones containing a moderately abundant and diversified fauna including echinoderms, lingulid brachiopods, gastropods, bivalves, ostracods, siliceous sponges and vertebrate remains. Such a faunal assemblage coeval with microbialites reveals a moderately diversified biocoenosis, which is in stark contrast to traditional views of depauperate ecosystems in the Early Triassic. The fossiliferous limestones comprising stenohaline organisms also suggest normal marine conditions contrary to the harsh environmental conditions classically invoked to explain the presence of microbialites. At Workman Wash, microbialites rather reflect a shallow and proximal facies belt controlled by terrigenous flux, nutrient inputs and relative sea-level fluctuations.

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Figure captions

Fig. 1 a Present-day location of the study area in southwestern Utah, along the Hurricane Cliffs, about 8 km south of Hurricane city. **b** Early Triassic paleogeographic map showing the location of southwestern USA along the Pangea margin (after Brayard et al. 2013)

Fig. 2 a Field view of section #1 on the western side of the Hurricane Cliffs (see geographic location on Fig. 1a) showing the Permian-Triassic transition. The studied outcrop is about 70 m thick. **b** Field view of the eastern side of the Hurricane Cliffs, just south of the Three Brothers Tertiary volcanic peaks. Sections #2-5 were logged along the head end of Workman Wash. Geologists near section #5 for scale

Fig. 3 Legend for Figures 4-8 and 15

Fig. 4 Log of the studied interval on the western side of the Hurricane Cliffs. See location on Figures 1a and 2, Table 1 for facies descriptions, and Figure 3 for legend

Fig. 5 Log of section #2. See location on Figures 1a and 2b, Table 1 for facies descriptions, and Figure 3 for legend

Fig. 6 Log of section #3. See location on Figures 1a and 2b, Table 1 for facies descriptions, and Figure 3 for legend

Fig. 7 Log of section #4. See location on Figures 1a and 2b, Table 1 for facies descriptions, and Figure 3 for legend

Fig. 8 Log of section #5. See location on Figures 1a and 2b, Table 1 for facies descriptions, and Figure 3 for legend

Fig. 9 Field illustrations of some facies and macroorganisms. **a** Fenestral-microbial facies (F7). The lower part of the picture shows a macroscopic laminated microbial structure whereas the upper part displays a fenestral fabric (subfacies F7b; section #1, about 52 m). **b** Fenestral-microbial limestones (F7) with large fenestrae and endostromatolites (subfacies F7b; section #2, about 4 m). **c** Accumulation of large-sized gastropods (subfacies F7b; section #4, about 3 m). **d** Accumulation of ammonoids (subfacies F7c; section #5, about 6 m). **e** Intensively bioturbated interval corresponding to the marker bed with lingulid brachiopods (Facies F11; section #4, about 4.5 m). **f** Conglomerate breccia (Facies F1; base of section #4). **g** Yellow clastic unit (Facies F5; section #4, about 15 m)

Fig. 10 a Field view and **b** cartoon of the fenestral-microbial facies (F7) locally showing reefal morphology and truncation surfaces above the lingulid marker bed

Fig. 11 Natural-light thin-section photographs of the fenestral-microbial facies (F7). **a** Oo-pisoid subfacies F7a with pisoids (sometimes truncated), ooids and peloids in a sparitic cement. **b** Intraclastic subfacies F7e with abundant intraclasts in a sparitic cement. **c-f** Fenestral-limestone subfacies F7b with various types of endostromatolites. **c** Thin crusts of dense micrite with downward or upward growth directions at the roof and the floor of a fenestrae. **d** Coalescent stromatolitic columns with a marked lamination, which locally displays some putative residual calcified sheaths of filamentous bacteria (arrows). **e** Complex crust made of an alternation of sparitic and micritic laminae. **f** Acicular to botryoidal cements associated with a lamination of an endostromatolites in a large fenestrae. **g** Subfacies F7c with

an interval made of domal to columnar stromatolites, topped by a lamellar siliceous sponge. **h**
Lamellar siliceous sponge (subfacies F7c)

Fig. 12 Natural-light thin-section photographs of the fenestral-microbial facies (F7). **a** Root structures and circum-granular cracks, subfacies F7c. **b** Subfacies F7d with small fenestrae and abundant extraclasts. **c** Biofilm (white arrow) coating a pel-fenestral structure, subfacies F7c. **d** Biofilms coating a peloidal grainstone above an oncoidal-fenestral structure, subfacies F7c. **e** Biofilms coating a peloidal grainstone above a micritic stromatolite, subfacies F7c. **f** A stromatolitic crust displaying a columnar microfabric, subfacies F7c. **g** Planar to wavy structure of a stromatolite, subfacies F7c. **h** Enigmatic cemented crust, subfacies F7c

Fig. 13 Natural-light thin-section photographs of the bioclastic facies. **a** Spicule-echinoderm limestone (F9). Note the common echinoderm fragments (white arrows) and the darker (more micritic) areas reflecting a probable infaunal activity. **b** Oo-pel-bioclastic limestone (F10). **c** Pel-bioclastic limestone (F12). **d** Intra-bioclastic limestone (F13)

Fig. 14 Lingulid brachiopods in Facies F11, section #4, about 8 m (see Figure 2b and 7). **a** In-situ large complete shell of *Lingularia* in life position characterizing the marker bed attributed to facies F11 at Workman Wash. **b** Typical example of *Lingulichnus verticalis* associated to lingulid shells in facies F11. Note the pedicle trace and the set of downward-deflected laminae produced by upward adjustment of the lingulid in response to sediment aggradation (equilibration structure). Scale bar (valid for both photographs) is 5 mm

Fig. 15 Correlation of sections. See figures 1 and 2 for their location

Fig. 16 Schematic 3D reconstruction of the depositional setting for the late Smithian sedimentary rocks observed at Workman Wash

Table 1 Facies description and depositional environments

Figure01

Figure02

Figure03

<i>Lithologies</i>	<i>Sedimentary grains</i>	<i>Sedimentary structures</i>	<i>Biota</i>
Limestones	Peloids	Bioturbation	Ammonoids
Coarse dolomitic limestones	Ooids	Fenestrae	Bivalves (undifferentiated)
a Clays	Cortoids	Keystone vugs	Lingulid brachiopods
s Silts	Oncoids	Mud cracks	Echinoderms
Cg Conglomerates	Pisoids	Cross-bedding	Gastropods
	Aggregates	Asymmetric ripples	Ostracods
<i>Textures</i>	Intraclasts	Gypsum crytals	Phosphate remains
B Boundstone	Extraclasts	Acicular crytals	Serpulids
R Rudstone	Mud clasts	Karstification	Siliceous sponges
F Floatstone	<i>Microbial structures</i>	Cherty nodules	Sponge spicules
G Grainstone	Large fenestrae with endostromatolites	Erosional surface	
P Packstone	Microbial laminae (biofilms)		
W Wackestone			
M Mudstone			

Figure04

Figure04suite

Figure05

Figure06

Figure07

Cg

BRFGPWMSa

F1

F2

F3

F4

F5

F6

F7

F7

F7

F7

F7

F8

F9

F10

F11

F12

F13

a

b

c

d

e

Figure 10 revised

Figure 11

Figure 12

Figure14

Figure15

Figure16

Table01

Facies		Textures	Biotic/non biotic grains	Matrix/ cements	Sedimentary structures	Zones	Environments	
F1	Conglomerate breccia	—	Polygenic clasts (cherts, bioclastic limestones, red beds), with diameter up to 15 cm (commonly elongated). Poorly sorted and angular to subrounded clasts.	Silty matrix	Stacked and amalgamated channel complexes (with individual channel up to 2 m large and 1,3 m thick). Locally, some m-scale isolated channels.	Peritidal (subtidal)	Chennalized inner tidal flat	
F2	Dolosiltstone	—	Common peloids. Abundant well sorted and subangular to subrounded quartz grains.	Dolomitized micritic matrix	Trough cross bedding and asymmetrical ripples. Mud drapes. Common bioturbation.		Inner tidal flat	
F3	Dolomudstone	M	—	Dolomitized micritic matrix	Trough cross bedding with low angle foresets. Asymmetrical ripples. Common bioturbation.			
F4	Dolostone	—	—	Dolomitic cement	—			
F5	Silty peloidal limestone	P	Frequent to rare bivalves. Rare gastropods. Abundant peloids. Frequent to common micritized ooids. Common cortoids and intraclasts. Rare oncoids. Rounded to subrounded mudclasts.	Dolomitized micritic matrix	Trough cross bedding with low angle fore sets. Mud drapes and mud clasts. Rare extraclasts. Surimposed asymmetrical ripples. Common to rare bioturbation.			
F6	Keystone vug limestone	P/W	Frequent peloids, common micritic and microbial (reworked?) clasts.	Dolomitized micritic matrix	Frequent keystone vugs. Rare bioturbation.	Swash	Interior platform	
F7	Fenestral-microbial limestone	F7a	Oo-pisoid limestone	R(G/P)/B	Abundant ooids. Abundant to common pisoids and intraclasts. Frequent to common peloids. Rare (fragmented) gastropods and ostracods.	Micritic matrix/sparitic cement		Abundant small fenestra. Some large fenestrae with endostromatolites. Locally, some vadose silt. Sparse microbial laminae.
		F7b	Fenestral-limestone	P(G,W)/F/B(M)	Frequent to rare ostracods. Locally, frequent ammonoids. Abundant to rare gastropods. Frequent to rare bivalves. Rare echinoderms. Abundant to frequent peloids. Abundant to rare ooids. Common oncoids and intraclasts. Common to rare cortoids and pisoids.	Sparitic cement/micritic matrix/acicular crystals		Abundant small fenestrae. Locally large fenestrae (with upward and downward growth stromatolitic crusts). Mud cracks and vadose silt. Common microbial laminae. Rare bioturbation (?).
		F7c	Sponge-microbial limestone	B	Common ostracods and sponges. Rare bivalves.	Micritic laminae. Acicular crystals		Stromatolites (micritic lamination). Locally, some root structures and circum-granular cracks.
		F7d	Conglomerate limestone	B/P-M	Frequent to rare gastropods and ostracods. Rare bivalves. Frequent to rare peloids and ooids. Rare intraclasts and oncoids. Abundant extraclasts (polygenic, poorly sorted, elongated up to 7 cm long).	Micritic matrix		Abundant thin, elongated and aligned fenestrae or large fenestrae with endostromatolites. Sparse microbial laminae.
		F7e	Intraclastic limestone	G/B	Abundant intraclasts (fragmented pisoidal, ooidal, and peloidal clasts). Rare bivalves, ostracods, and gastropods.	Sparitic cement		Frequent fenestrae. Rare microbial laminae (and bioturbation?).
F8	Echinoderm dolomicrite	W	Frequent echinoderms. Common to rare bivalves. Rare gastropods.	Dolomitized micritic matrix	Sparse bioturbation.	Subtidal (tide dominated)		
F9	Spicule-echinoderm limestone	P(W)	Abundant echinoderms. Frequent sponge spicules, bivalves, and gastropods. Common ostracods. Rare phosphate remains. Common peloids.	Micritic matrix	Abundant bioturbation.			
F10	Oo-pel-bioclastic limestone	P	Abundant gastropods. Frequent bivalves. Common echinoderms. Abundant ooids. Common peloids. Rare intraclasts	Micritic matrix	Trough cross bedding with low angle foresets. Some mud drapes and mud clasts. Frequent bioturbation.			
F11	Bioturbated and bioclastic limestone	P	Abundant to rare echinoderms. Abundant to frequent gastropods and bivalves. Common to rare ostracods. Frequent to rare phosphate remains. Some lingulid brachiopods. Frequent to rare peloids. Rare ooids.	Micritic matrix	Abundant bioturbation (<i>Arenicolites</i> , <i>Thalassinoides</i> , and <i>Paleoptycus</i>). Some small asymmetrical ripples.			
F12	Pel-bioclastic limestone	G/P	Frequent bivalves. Frequent to common gastropods. Frequent to rare echinoderms. Rare ostracods and phosphatic remains. Abundant peloids. Common to rare ooids. Rare intraclasts.	Micritic matrix/sparitic cement	Trough cross bedding with low angle foresets. Small erosive channel with lateral accretion. Frequent to common bioturbation.			
F13	Intra-bioclastic limestone	G(P)	Frequent gastropods and bivalves. Rare echinoderms, ostracods, and phosphatic remains. Abundant peloids. Frequent intraclasts. Common ooids.	Sparitic cement	Trough cross bedding with low angle foresets.			