DR. PANKAJ KHANNA (Orcid ID : 0000-0001-7165-3082)

Article type : Original Manuscript

**Late Cambrian microbial build-ups, Llano Area, Central Texas:
A three-phase morphological evolution**

PANKAJ KHANNA^{*,†}, HEATH H. HOPSON^{*}, ANDRÉ W. DROXLER^{*}, DYLAN A. DROXLER[‡], DANIEL LEHRMANN[‡], BRIAN KUBIK^{*}, JACOB PROCTOR^{*}, PULKIT SINGH^{*} and PAUL M. (MITCH) HARRIS^{*}

^{} Department of Earth, Environmental, and Planetary Sciences, Rice University, 6100 Main Street, MS-126, Houston, TX- 77005, USA (E-mail: pankaj89@gmail.com)*

[†] ANPERC, King Abdullah University of Science and Technology, Thuwal - 23955, Saudi Arabia

[‡] Geoscience Department, Trinity University, San Antonio, Texas 78212, USA.

Associate Editor – Ola Kwiecien

Short Title – Late Cambrian microbial build-ups, Texas

ABSTRACT

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as [doi: 10.1111/SED.12679](#)

This article is protected by copyright. All rights reserved

Although Late Cambrian microbial build-ups were recognized in the Point Peak Member of the Wilberns Formation in Central Texas (USA) nearly 70 years ago, only a few studies focused specifically on the build-ups themselves. This study focuses on the interpretation of the regional (15 measured sections described in literature representing an area of 8000 km²) and local (field and drone photogrammetry studies in 25 km² area from within south Mason County) microbial build-up occurrence, describes their growth phases and details their interactions with the surrounding inter-build-up sediments. The study establishes the occurrence of microbial build-ups in the lower and upper Point Peak members (Point Peak Member is informally broken up into the lower Point Peak and the upper Point Peak members separated by *Plectotrophia* zone). The lower Point Peak Member consists of three <1 m thick microbial bioherms and biostrome units, in addition to heterolithic and skeletal/ooid grainstone and packstone beds. One, up to 14 m thick, microbial unit associated with inter-build-up skeletal and ooid grainstone and packstone beds, intercalated with mixed siliciclastic-carbonate silt beds, characterizes the upper Point Peak member. The microbial unit in the upper Point Peak member displays a three-phase growth evolution, from an initial colonization phase on flat based, rip-up clast lenses, to a second aggradation and lateral expansion phase, into a third well-defined capping phase. The ultimate demise of the microbial build-ups is interpreted to have been triggered by an increase of water turbidity caused by a sudden influx of fine siliciclastics. The lower Point Peak member represents inner ramp shallow subtidal and intertidal facies and the upper Point Peak member corresponds to mid-outer ramp subtidal facies. Understanding the morphological architecture and depositional context of these features is of importance for identifying signatures of early life on Earth.

Keywords Central Texas, depositional model, Late Cambrian, microbial build-ups, morphology, photogrammetry

INTRODUCTION

Microbialites are: “organo-sedimentary deposits which accrete as a result of a benthic microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation” (Burne & Moore, 1987). Microbes have created build-ups in shallow-marine environments since the Archean, *ca* 3.45 Ga (Riding, 2006; Woo & Chough, 2010; Riding 2011). They diversified and reached their peak in the late Proterozoic. Since the beginning of the Phanerozoic, metazoans became the prominent reef builders (Riding, 2006), although microbialites flourished, as a response to mass extinction events when metazoans dramatically declined (Schubert & Bottjer, 1992; Riding, 2006). The metazoan Middle Cambrian mass extinction (Boucot, 1990; Kiessling, 2009) triggered an extensive development of microbial build-ups in the Late Cambrian on Laurentia, Baltica, Siberia and Gondwana (Lochman-Balk, 1970; Lee et al., 2015).

Shallow seas at tropical latitudes on Laurentia provided optimum conditions during the Late Cambrian for the development of microbial build-ups (Lochman-Balk, 1970; Van Der Voo, 1988; Golonka et al., 1995; Lee et al., 2015). Based on a series of measured sections, well-dated by biostratigraphy and regionally correlated across Laurentia, Lochman-Balk (1970) established four main regressions and three transgressions during the Late Cambrian. The youngest of the three transgressions initiated the growth of well-developed microbial build-ups in the Point Peak Member of the Wilberns Formation (Fig. 1), observed in several locations within an 8000 km² area, and associated with the Llano Uplift of central Texas (Fig. 1A and B; Bridge et al., 1947; Ahr, 1971; this study). Complete or partial exposures the Wilberns Formation have been identified at 22 locations within the study area (Fig. 1B), out of which 15 locations have Point Peak Member exposures (sections 2 to 8, 10, 13 to 18 and 22; Fig. 1B to D). From 11 of the Point Peak Member exposure locations, microbial facies (sections 2 to 8, 10, 17, 18 and 22; Fig. 1B to D) have been reported (Bridge et al., 1947; Ahr, 1971; this study). Location 3 (Fig. 1B) is the focus of this study, which includes 12 outcrops (Figs 2 and 3). These build-ups, spectacularly exposed in cross-section (cliffs) and plan view (pavements) outcrops, provide a unique opportunity to understand, in three-dimensions, their initial establishment and the subsequent processes involved in the morphological evolution of microbialites within a regional depositional context.

The morphology of modern microbial build-ups provides a wealth of information regarding the biological and physical factors influencing their initiation, overall development and ultimate

demise, in addition to the palaeo-environmental conditions in which they grew (Andreas & Reid, 2006; Suosaari et al., 2016, 2018). Their morphology can be interrogated at different scales, including macroscopic such as build-ups or mats, mesoscopic such as stromatolitic columns or thrombolitic growth, and microscopic such as *Girvanella*, *Epiphyton*, *Renalcis* and other individual components (Lee et al., 2015).

Exquisitely exposed in 2D and 3D, microbial build-ups, observed in a series of world-class outcrops in two newly accessible private ranches (Fig. 2), are the basis of this study. The main focus of this paper is the description and interpretation of the overall growth evolution of the microbial build-ups in the lower and upper Point Peak members at macroscopic and mesoscopic scales and the interpretation of factors contributing to their evolution, such as accommodation, hydrodynamics and sedimentation patterns. Ultimately, the goal of this study is to place the morphological evolution of these microbial build-ups in a regional and local context in order to develop an overall depositional model for their formation.

GEOLOGICAL BACKGROUND AND STRATIGRAPHIC CONTEXT

Late Cambrian regional context

The Late Cambrian Laurentian craton is commonly referred to as the Great American Carbonate Bank (GACB; cf. Ginsburg, 1982; Trettin & Balkwill 1979; Morgan, 2012). The GACB was covered by marine waters (Ford & Golonka 2003, Golonka et al., 2003; Schulz et al., 2008) in which a mix of limestone, dolomites and lesser amounts of fine-grained and coarse-grained siliciclastics were widely deposited. Sloss et al. (1949) named the latest Precambrian to Early Ordovician strata of Laurentia the ‘Sauk sequence’. Palmer (1981) further subdivided the Sauk sequence, based on trilobite faunal discontinuities, into Sauk I, II and III, deposited, respectively, from latest Precambrian to early Middle Cambrian, early Middle Cambrian to early Late Cambrian, and early Late Cambrian through to Early Ordovician (Morgan, 2012; Read & Repetski, 2012). Each Sauk sub-sequence has been further divided into smaller sequences on the basis of detailed biostratigraphic and lithostratigraphic analysis (Morgan, 2012, and references therein).

Late Cambrian local context, central Texas

The Llano Uplift in central Texas is a structural dome of Precambrian igneous (1030 ± 30 Myr) and metamorphic (1120 ± 25 Myr) rocks exposed over an area extending approximately 100 km east/west and 70 km north/south (Garrison et al., 1979; Blackburn et al., 2017). The oldest Palaeozoic strata in the Llano region, termed the Moore Hollow Group (Bridge et al., 1947; Miller et al., 2012; Morgan 2012), consist of the Riley and Wilberns formations. In turn, the Riley Formation consists of the Hickory Sandstone, Cap Mountain Limestone and Lion Mountain Sandstone Member. The overlying Wilberns Formation has four members (Fig. 1A); the Welge Sandstone, Morgan Creek Limestone, Point Peak Member and San Saba Member (Paige, 1911; Bridge et al., 1947). The Ordovician Ellenburger Formation (Cloud & Barnes, 1948) overlies the Moore Hollow Group. The unconformable contact between the Lion Sandstone and Welge Sandstone Member is defined as the boundary between the Sauk II and Sauk III supersequences (Miller et al., 2012).

The microbial build-ups examined in this study lie within the Point Peak Member of the Wilberns Formation exposed in the southern part of Mason County (Sliger, 1957; Ahr, 1967, 1971; Spincer, 1997; Section 3, purple rectangle in Fig. 1B). Outcrops in this study are observed along the Llano and James rivers and Mill Creek. Based on Bridge et al. (1947) and Ahr (1971), two trends are observed that are key to the current study: (i) the presence of lower and upper microbial units separated based on a key bed of brachiopods – the *Plectotrophia* zone; and (ii) the absence of microbial build-ups in the north-eastern portion of the study area (Fig. 1C and D). The brachiopod species *Plectotrophia bridgei* and *Billingsella*; both epifaunal suspension feeders, define the *Plectotrophia* zone. Parke (1953) and Sliger (1957) were the first to make geological maps of this area. Later, Ahr (1967, 1971) published a detailed petrological and sedimentological study of the Point Peak and San Saba Members. Spincer (1997) studied the palaeoecology of the Upper Cambrian build-ups with a focus on the Llano region, and Johns et al. (2007) conducted studies on sponges found associated with the build-ups. Morgan (2012) defined the sequence stratigraphy for the GACB and Miller et al. (2012) further examined the biostratigraphy of Cambrian and Lower Ordovician strata in the region and defined the Point Peak Member based on trilobite zonation into the upper *Idahoia* and *Ellipsocephaloides* zone.

Recently (Proctor et al., 2019) examined 126 cores, 7.5 cm in diameter and up to 50 cm in length, through the upper Point Peak microbial build-ups utilizing dual-energy tomography and thin section analysis to identify and upscale mineralogy and porosity-type fractions to create diagenesis and porosity type logs.

METHODS

Field survey

The main outcrops of the Point Peak Member occur either along cliffs or on bedding plane exposures, or pavements, along the Llano and James rivers and Mill Creek (Fig. 2). During field seasons from 2013 to 2015, the microbial build-ups within the lower and upper Point Peak members, within the 25 km² of the field area, were mapped along the Llano and James rivers and Mill Creek, as well as their respective gullies. Microbial build-ups outcropping along these transects were systematically photographed with a Nikon COOLPIX camera (Nikon, Tokyo, Japan) and located with the integrated GPS unit. These photographs were subsequently imported to ArcGIS (Esri, Redlands, CA, USA) to mark the location of the encountered microbial build-ups within an error of 5 to 10 m. The Sliger (1957) geological map of the field area was complemented by additional detailed observations on the microbial reef occurrences made during this study (Fig. 3).

Aerial imagery – data acquisition

Outcrops along the Llano River include three cliffs (Fig. 2); the Shepard (600 m in length; Location 1), the Zesch (400 m in length; Location 3) and the Goat's Graveyard cliff (300 m in length; Location 5), exposing the upper Point Peak microbial facies. Moreover, there are two pavements along the Llano River (Fig. 2); the Shepard pavement (500 x 100 m; Location 2) which exposes the lower Point Peak microbial facies and the Zesch pavement (300 x 200 m; Location 4) which exposes part of the upper Point Peak microbial facies. The James River localities include two outcrops (Fig. 2); a composite of pavement and a cliff referred to as the James River pavement (600 x 200 m; Location 11) and a cliff outcrop named the Faulted Build-ups (Location 12). A complete Point Peak section crops out along lower Mill Creek cliff (Lauren's Cliff; Location 10; Fig. 2). Farther up Mill Creek, three other outcrops (Fig. 2), including Upper Mill Creek (Location 6), Fallen Blocks (Location 7)

and DroxRock (Location 8) expose the upper Point Peak member. A fifth outcrop, a lower Point Peak microbial pavement, is juxtaposed against the upper Point Peak DroxRock outcrop, along the Schmidt Fault (Location 9; Fig. 2).

Camera Wings Aerial Photography (Austin, TX, USA), was hired to conduct an aerial photography survey with a drone (quadcopter) equipped with a Sony NEX-7, 24.3 MP camera (Sony, Tokyo, Japan), the highest resolution camera available at the time of the data acquisition. The drone included a gimble (to maintain the camera in a horizontal position during acquisition) and a GPS to record the geographical and elevation position at which the photographs were taken.

The aerial survey was conducted in February 2014 to collect digital photographs. A total of 12 outcrops (Fig. 2) were selected for the drone survey; five outcrops along the Llano River (three cliffs and two pavements), four outcrops along Mill Creek (four cliffs) and two outcrops along the James River (one pavement and an adjacent cliff, and one cliff outcrop across the Simons Fault Zone). Markers were placed in the field on the pavement outcrops before the drone survey, and the precise locations for several markers were collected using DGPS (differential GPS) with data post-processing yielding an accuracy of 10 cm. A Trimble Total Station unit (Trimble, Sunnyvale, CA, USA) was used to determine the location coordinates of all the markers in a local coordinate system with a millimetre accuracy.

For pavement outcrops, the drone was assigned to fly 40 m above the ground and the flight path was automated. For cliff outcrops, the drone was flown manually at a distance ranging from 20 to 40 m in front of the outcrop face. During the data collection for both pavements and cliffs, a 90% photograph overlap was kept. The total number of photographs for each outcrop varied according to the size of the outcrop. The largest image dataset was collected for the James River pavement where a total of 540 photographs were collected.

Data processing

The digital photographs and camera positions, saved in EXIF file format (Exchangeable Image File Format), were imported to Agisoft 1.0 (Agisoft LLC, St. Petersburg, Russia) for building virtual outcrop models. The Align Photograph tool (found in Agisoft 1.0) was used to refine the camera position for each photo and to build an initial sparse 3D point-cloud model in a random 3D coordinate

system. A build-mesh tool was selected to create a polygonal mesh that uses the 3D point cloud to make edges, vertices, and faces. To geo-reference the location of the model, ground control points were integrated with the polygonal mesh. The geo-referenced model was used to build a dense point cloud to further build a dense high-resolution mesh. The final step, to create a virtual outcrop model, included building a texture of the 3D mesh model. The virtual outcrop model was exported in 3 different file formats, TIFF file format (exports an orthophotograph of the outcrop), DEM (Digital Elevation Model in xyz format) and KMZ (Google Earth® readable file format).

OBSERVATIONS AND RESULTS

Lower and upper Point Peak microbial units

Three microbial units (types 1, 2 and 3; each <1 m in height) consisting of biostromes and bioherms (Fig. 4) have been identified in the lower Point Peak member. Glauconitic siltstones, thinly bedded mixed siliciclastic–carbonate wackestone–packstone facies, detrital sands (skeletal/non-skeletal) and interclastic conglomerates have been reported (Mabry et al., 2015; Kelleher et al., 2017) as additional lower Point Peak member facies. The skeletal grainstones are composed of mostly trilobite, brachiopods and eocrinoid fragments. The microbial units within the lower Point Peak member are identified as: (i) type 1 – biostrome referred to as ‘Dan Strom’ (Fig. 4A and B); (ii) type 2 – flat to round top, oval-shaped microbial bioherms referred to as ‘Bread Loaf’ (Fig. 4C and D); and (iii) type 3 – conical microbialites (Fig. 4E and F). Dan Strom changes from a biostrome to bioherm growth form at the Lauren’s Cliff outcrop (Location 10; Fig. 2), Bread Loaf are individual bioherms (Location 2; Fig. 2), and conical microbialites occur as a biostrome (Location 9; Fig. 2). Further, siliciclastic sediment is found trapped within microbialites, with a reduction in the siliciclastic proportion from type 1 to type 2 to type 3.

The upper Point Peak member outcrops in the study area consist of a microbial unit, up to 14 m thick (based on photogrammetry), with a build-up/bioherm macro morphology (Figs 5 to 7). A name was given to each individual build-up along cliffs and on pavements to simplify their overall description and analyses. The build-ups display an organized morphological growth structure and are surrounded by up to a few metres thick skeletal and oolitic grainstone and packstone beds, intercalated with thin, mixed carbonate-siliciclastic silty layers (Fig. 8). A series of four small sections

are measured at Twin herm to demonstrate the interaction of microbial growth and inter-buildup sediments (Fig. 8). Systematic and comparative analyses of the multiple microbial build-ups and their inter-build-up sediments, exposed along the different cliffs and pavements, resulted in the identification of similarities and differences in their morphology and heterogeneities, as well as in their vertical and lateral facies distribution. A systematic three-phase growth evolution of the upper Point Peak microbial build-ups was first recognized during the field survey and was confirmed to occur throughout the field area by drone imagery combined with qualitative and quantitative analysis using photogrammetry and detailed field mapping (Fig. 9). One of the microbial build-ups, referred to as ‘Mitch Herm’, exposed along the eastern side of Zesch Cliff on the Llano River, illustrates the typical evolution of the build-ups, from their establishment, distinct three-phase growth pattern and ultimate demise (Fig. 9). The mesoscale structures of the microbial build-ups have either stromatolites and/or thrombolites within each microbial growth phase (Fig. 10). Thin section analysis of the microbial build-ups was conducted in each one of the three-phases and calcimicrobes including *Girvanella*, *Epiphyton*, *Renalcis* and the sponge *Wilbernicyathus donegani* were identified (Fig. 11). Detailed descriptions of mesoscopic and microscopic fabrics of the three-phases are described below.

Upper Point Peak microbial build-ups: initiation and three-phase growth

The microbial build-up substratum

In general, a distinctly flat base, as observed along the Llano River from the Shepard and Zesch cliff outcrops (Figs 5 and 6), characterizes the microbial build-ups. The ‘Fallen Blocks’, an easily accessible outcrop along Mill Creek (Location 7; Fig. 2), consists of a fully developed 8 m thick build-up that was dislodged from the cliff. Today this build-up lies on its flank, tilted 90° and, therefore, offers an accessible 3D exposure of its flat base (Fig. 12). The Fallen Blocks and its inter-build-up bed sharply contrast with the underlying mixed carbonate–siliciclastic silty and sandy, thin, mostly recessive beds, intercalated with resistant skeletal/non-skeletal grainstone and packstone beds. The sharp contact, referred to as the ‘Switch’ (Fig. 9), corresponds to the typical flat base observed in other build-ups as well. The centre of the build-up base consists of a 10 cm thick flat bottom lens of rip-up clasts (Fig. 12B and C). A core drilled through the initial growth of the microbial build-up displays a few scattered small rip-up clasts and large trilobite fragments associated with the growth of

an initial stromatolitic column (Droxler et al., 2016). The Switch in the inter-build-up area (adjacent to the Fallen Blocks outcrop) is represented by a sharp lithological change from underlying dominantly siliciclastic, easily erodible facies to a carbonate, metre thick, prominent and resistant bed, made of skeletal-oolitic packstone to grainstone facies. Its base, forming a well-developed overhang, is contemporaneous to the initiation of the microbial growth in adjacent build-ups. In summary, the microbial growth initiated on flat-based low-relief lenses of rip-up clasts/flat-pebbles (at Fallen Blocks), contemporaneously with the initial accumulation of an inter-build-up bioclastic grainstone bed. Similar substrates for growth are common in other Late Cambrian microbial reefs (Cowan & James, 1993; Chen, 2014; Lee et al., 2015). Moreover, flat-pebble deposits or large shell accumulation, have been observed in modern subtidal microbialites, growing in high energy tidal channels between the Exuma Cays, Bahamas (Dill et al., 1986; Feldman et al., 1998; Reid et al., 1999; Ginsburg & Planavsky, 2008).

Phase 1: colonizing phase

The colonizing growth phase consists of individual microbial build-ups, which form distinct 3 to 5 m high, oblong-shaped edifices covering areas ranging from 10 to 300 m² (Fig. 13). The interiors of Phase 1 build-ups are composed of stromatolite columns (Fig. 10H and I). Thrombolitic micritic rinds that are resistant to erosion wrap around the stromatolitic columns (Figs 9 and 10H to J). Spaces between the columns are filled with relatively coarse skeletal and fine-grained non-skeletal carbonate sediments (Fig. 10K). The side and top of the Phase 1 coalesced columns are eventually fully encapsulated by a 50 cm to 1 m thick thrombolitic micritic rind (Figs 9 and 10L to O). The rind is mostly micritic (Fig. 11B to D), however, at DroXRock a calcimicrobe *Renalcis* (Fig. 10L and M) is observed within the rind. Thin section analysis of Phase 1 rind shows calcimicrobes *Girvanella* (Fig. 11B) and *Tarthinia* (Fig. 11C) within the micritic matrix. An orchocladine lithistid sponge, *Wilberniacyathus donegani*, is also identified from a rind thin section at DroXRock (Fig. 11A). The interior of Phase 1 at DroXRock displays burrow tubes, containing very fine fragmental skeletal debris (Fig. 11F).

The James River pavement (Fig. 7) and adjacent cliff present a spectacular view of microbial outcrops that cover a portion of the exposed river bed, 600 m long and 200 m wide. The James River

bed exposes Phase 1 of build-up growth and is arguably the best location to investigate the build-ups and inter-build-up sediments of the first growth phase in detail (Fig. 7). Four different scales of the microbial column and mound clustering are identified. The smallest scale (few decimetres) is represented by circular to oblong features characterized by a stromatolitic interior and distinct grey micritic rind on their outskirts (Fig. 13D; small). The smallest scale clusters into medium-scale mounds, a few metres in length, with their own characteristic rinds (Fig. 13D; medium). The medium-scale mounds cluster into a larger scale, ovoid-shaped mounds, a few tens of metres in their longest axis (Fig. 13D; large). The large-scale mounds cluster into complexes, a few hundreds of metres long, which are also surrounded by their own rind (Fig. 13E). James River outcrops (Fig. 7A) demonstrate that there are two complexes within the James River bed, as well as cases where clustering is minimal and individual large-scale or medium-scale build-ups (Fig. 7C and D) exist without clustering with others. The preferential orientation of the complex, large-scale and medium-scale Phase 1 build-ups is towards the north-east/south-west, whereas the smallest-scale column orientation axes do not display a clear preferred orientation (Khanna, 2017).

Inter-build-up sediments (beds 1 and 2; Fig. 8) contemporaneously accumulating with the first growth phase, consist of highly resistant 1 to 2 m thick skeletal and oolitic lime grainstone to packstone beds that dip towards the build-ups well-defined rinds. The beds thin immediately adjacent to the build-ups and completely pinch out beneath them (Figs 9 and 13A to C). The dip angles of the inter-build-up beds are enhanced by the differential compaction of the sediments underlying the microbial build-up. A silty siliciclastic enriched bed accumulated over the first grainstone bed and clearly onlaps the sharp margin of Phase 1 build-up rind, and, therefore, marks the end of phase one microbial growth (Fig. 9).

Phase 2: aggrading and laterally expanding phase

The microbial build-ups resumed growth during Phase 2, aggrading and inter-fingering with inter-build-up skeletal/non-skeletal grainstones, without the development of a sharp outer rind as in Phase 1 (Fig. 9). Growth was characterized by juxtaposed columnar stromatolites with inter-build-up fill consisting of bioclastic and oolitic grainstone and packstone. Phase 2 microbial build-up growth preferentially nucleates over the elevated and hard substratum of the Phase 1 rind (Figs 9, 10A and

10B). Stromatolitic columns that grow upwards and prograde outwards expanding the diameter of the build-up beyond that of the underlying Phase 1 define Phase 2 growth (Figs 9 and 10E to G). A distinct geomorphic feature, referred to as a honeycomb structure, is observed in several build-ups within Phase 2 (Figs 9, 10A and 10B), where the growth patterns consist of radially oriented, stacked microbial columns, each separated by sub-horizontal micritic thin beds. Detailed observation of the growth of stromatolitic columns in Phase 2 at Shepard Cliff revealed two separate growth phases within Phase 2 of the Granddaughters build-ups (Fig. 14), where an individual stromatolitic column of Phase 2B established on top of Phase 2A.

Inter-build-up strata (beds 3 to 7; Fig. 8) consist of three to four, 1 to 2 m thick grainstone and packstone beds separated by mixed carbonate–siliciclastic packstone–grainstone intercalation referred to as a heterolithic unit (Fig. 8). The inter-build-up grainstone bed thickness and carbonate to siliciclastic proportions vary from Shepard Cliff (thinner grainstone beds) to Zesch Cliff (thicker grainstone beds). The grainstone beds thickness also varies relative to the margins of the build-ups, i.e. on the eastern margin of the Wayne build-up, the inter-build-up grainstone beds are much thinner than on its western margin (Fig. 5). Three sections (2 to 5 m thick) were measured along the James River to document the lithology of inter-build-up beds (Fig. 8). The grainstone beds contain trilobite (Fig. 11H) and brachiopod shell fragments, peloids and ooids (Fig. 11I). The grainstone beds are separated by semi-continuous to continuous, thin siliciclastic-dominated heterolithic facies with thin fine-grained starved skeletal grainstone ripples (Bed 4; Fig. 8B). Additionally, asymmetric ripples and sand dunes/waves are associated with the grainstone beds.

Phase 3: capping phase.

Phase 3 of build-up growth, referred to as the capping phase and the final form of microbial growth, initiated on Phase 2 microbial reefs and, at a few locations extended beyond the underlying Phase 2 build-up and above the inter-build-up sediments (Fig. 9). Phase 3, which is well displayed on the Shepard and Zesch cliffs along the Llano River, is only accessible along the James River in addition to DroxxRock and the Fallen Blocks along Mill Creek. Phase 3 growth is similar to Phase 1 rind in terms of overall morphology and composition and is the capping phase of the microbial build-ups.

The calcimicrobes *Renalcis* and *Epiphyton* are identified within the Phase 3 micritic thrombolitic growth (Fig. 10D). At the end of Phase 3, the demise of the microbial reef complex is marked by a siliciclastic-rich siltstone bed (Bed 8: Fig. 8), onlapping Phase 3 and laying directly on the Phase 2 inter-build-up strata.

INTERPRETATION

Lower Point Peak microbial build-ups

The three lower Point Peak microbial units (types 1, 2 and 3; Fig. 4) along the Llano River and Mill Creek (Section 3; Fig. 1B) consist of biostrome and bioherms, up to a metre thick, intercalated with grainstones and/or heterolithic facies, that stack to form a 12 to 15 m thick microbial composite unit. In addition to the microbial facies, Mabry et al. (2015) described a complete set of facies which include siltstones, heterolithic siltstone and lime packstone, skeletal and oolitic grainstones, bioturbated packstones, flat-pebble conglomerates and associated sedimentary structures in the lower Point Peak at Section 3 (Fig. 1B). The siltstone and heterolithic facies are interpreted to represent low-energy intertidal environments, skeletal and oolitic grainstones are interpreted to represent an open-marine high-energy environment, flat-pebble conglomerates are interpreted to represent storm beds, and the lower Point Peak microbialites are interpreted to represent shallow subtidal to intertidal environments (Mabry et al., 2015). Based on the siliciclastic content trapped within the lower Point Peak microbialites, Type 1 is interpreted as the most proximal microbial growth, followed by Type 2 and Type 3.

The distal facies of the lower Point Peak member occur *ca* 80 km east of Section 3 (Fig. 1B), and consists of a single microbial unit, up to 30 m thick at Section 17 (Bridge et al., 1947; Ahr, 1967; Fig. 1C), and thins southward, to only a few metres at Section 22. Microbial unit thickness within the lower Point Peak member (Fig. 1C), hence, increases relatively from west to east (sections 2 to 8, 17, 18 and 22) along the transect shown in Fig. 1C (with the exception of Section 22). Barnes & Bell (1977) isopach map for Point Peak Member suggests that the basement was towards west, indicating that nearshore facies should occur to the west, and distal facies towards the east, which is observed in Fig. 1C. Section 22 could potentially represent a distalmost setting, where water was too deep for maximum microbial growth and was probably distal from a siliciclastic or carbonate source.

Additionally, there are no microbial units in the lower Point Peak member in the Fig. 1D transect (sections 10, 13 to 16), however, these sections are as thick as those along the Fig. 1C transect. This is most likely due to presence of a siliciclastic source towards the north-east (current orientation), potentially due to a local shoreline, as reported in McBride et al. (2002).

Upper Point Peak microbial build-ups

The upper Point Peak microbial unit is exposed only along sections 2, 3 and 10, located in the western part of the region in Fig. 1B, suggesting that, following lower Point Peak deposition, the locus of microbial deposition shifted westwards during upper Point Peak. A regional cross-section in Fig. 1C demonstrates that relatively, the upper Point Peak member thins from west to east (Fig. 1C), however, the regional transect in Fig. 1D demonstrates that the thickness of the upper Point Peak member is highly variable. Based on Barnes & Bell (1977) it should be noted that Fig. 1C and D are not dip sections, which is most likely the reason for high thickness variability along the Fig. 1D transect.

The upper Point Peak microbial unit (Section 3; Fig. 1B) lies above a flat surface, referred to as Switch, separating mixed carbonate-siliciclastic bedded strata below from pure carbonate microbial growth above. Thin lenses of rip-up clasts/flat-pebble conglomerates (Fig. 12B and C), interpreted as a transgressive lag developed during transgression, formed from erosion and reworking of the partially cemented, fine-grained heterolithic beds underlying the Switch. During the Switch, significant accommodation was created allowing for the development of thick microbial mounds, which established on well-cemented flat-pebble conglomerate lenses. The transgression also significantly shut down the rate of siliciclastic influx, as indicated by a dramatically reduced proportion of siliciclastic facies overlying the Switch.

Three-phase growth model

The three-phase growth model (Fig. 15) is further developed to include the role of accommodation, build-up and inter-build-up sediment accumulation, microbial growth forms, turbidity, and siliciclastic fluxes in the establishment, growth and ultimate demise of the microbial build-ups. An initial transgressive lag (Fig. 15) formed a series of lens-like accumulations of flat-pebble intraclasts with a mixed grainy bioclastic matrix based on a series of core transects drilled through the Switch

(Hopson, 2018). The intraclasts are interpreted to have formed during a transgression by the reworking and winnowing of partially cemented fine-grained, mixed carbonate-siliciclastics. Following the deepening event the locality transitioned from a mixed carbonate-siliciclastic, shallow subtidal/intertidal depositional environment into a high-energy, purely carbonate subtidal environment, these lenses of flat-pebble intraclasts acted as a stable substrate with relatively high bathymetric relief on which microbial growth initiated.

Microbial build-up Phase 1 growth occurred contemporaneously to the deposition of inter-build-up 1 to 2 m thick oolitic-bioclastic grainstone deposits. Phase 1 microbial build-ups grew on the transgressive lag (Fig. 15) in the form of numerous juxtaposed, decimetre-wide, convex upward, stromatolitic columns. Over time, the different columns coalesced to form larger metre-scale build-ups. These columns exhibit a small-scale thrombolitic rind, usually grey in colour, no more than a centimetre in thickness. With sufficient accommodation, microbial growth outpaced the inter-build-up grainstone deposition and developed an appreciable 2 to 3 m high synoptic relief. The size of Phase 1 growth was initially controlled by the extent of the underlying growth substrate; small lenses of transgressive flat-pebble lag inhibited the formation of large fully developed build-ups, but lenses that are more extensive allowed build-ups to grow very large and include all three of the growth phases. Continued cementation and lithification within an open marine environment developed the Phase 1 margin into a well-defined, micritic-thrombolitic microbial rind (Swartz et al., 2015), eventually completely encompassing it on the top. The rind thickens towards the build-up sides, reaching thicknesses up to 1 m whereas the top rind of Phase 1 is more typically 20 to 40 cm in thickness.

A shallowing event, reducing accommodation and increasing the siliciclastic sediment input, is marked by siltstones onlapping the sides of Phase 1 rind and ends Phase 1 microbial growth. The shallowing event increased the siliciclastic influx as the shoreline advanced shelfward, subsequently leading to a decrease in carbonate content due to the negative effects of turbidity on the carbonate factory. Evidence of increased levels of siliciclastic influx, occurring at the end of the Phase 1 is reported from James River (two samples of the silty unit onlapping Phase 1 reported 36% and 60% CaCO_3 ; Singh et al., 2016; Hopson, 2018). Typically, these silts onlap the sides of Phase 1 build-ups without interfingering, and never cover the full Phase 1 microbial reefs.

As bioclastic grainstone deposition replaced siliciclastic accumulation, Phase 2 growth initiated using the top of the Phase 1 rind as a substrate (Fig. 15). The growth structures are characterized by numerous juxtaposed columnar stromatolites similar to the ones observed in the Phase 1 reef interior. Incremental pauses in relative sea-level rise periodically constrained vertical growth of the columns and induced lateral expansion beyond the margins of the underlying Phase 1 growth. These lateral expansions, coupled with low synoptic relief of the build-ups, allowed interaction of the reef margin with inter-build-up sediment creating interfingering between boundstone and surrounding bioclastic grainstones and inhibiting the formation of a well-defined build-up rind. More localized variations in the influx of fine mixed carbonate-siliciclastic sediment during Phase 2 might explain the occurrence of Phases 2A and 2B (Fig. 14C). The end of Phase 2 is characterized by an ooid-rich grainstone. Unlike Phase 1, a large-scale thrombolitic rind around the build-up body is not developed within Phase 2.

Phase 3 microbial growth acts as a capping phase for the full Phase 2 build-up, but also forms individual mounds overlying some of the Phase 2 build-up flanks and the inter-build-up sediment (Fig. 15). With the end of grainstone deposition, Phase 3 growth became thrombolitic in nature. Increased accommodation allowed the build-ups and mounds to develop significant synoptic relief of 2 to 3 m in height. Phase 3 grows beyond the boundaries of the underlying Phase 2 build-ups and downlaps onto the Phase 2 inter-build-up grainstones. The ultimate demise of the upper Point Peak microbial reef complex is marked by a large influx of fine-grained siliciclastics. The initial fine-grained deposits onlapping the sides of the Phase 3 rinds contain as much as 84% siliciclastics (Singh et al., 2016; Hopson, 2018), explained by closer proximity to the shoreline and a reduction in accommodation. This increase in turbidity in the water column would have limited light penetration and ended microbial growth.

DISCUSSION

The main findings of this study are the recognition and documentation of a three-phase evolution of the microbial unit in the upper Point Peak member, in addition to microbial build-ups and biostromes in the lower Point Peak member, and their regional depositional context. Two major factors, significantly influencing the growth of the build-ups, are sea-level fluctuations and siliciclastic input.

In mixed carbonate–siliciclastic settings, siliciclastics commonly move seaward on the shelf due to sea-level falls, thereby shutting down the carbonate factory. In contrast, during sea-level rise siliciclastics retreat landward, allowing the carbonate factory to re-establish on top of the previous lowstand siliciclastic rich deposits (Droxler & Jorjy, 2013). The influx of siliciclastics can also increase due to climate change and increased precipitation on exposed land. In particular during the Cambrian land plants had not yet appeared on Earth, potentially resulting in increased runoff and, therefore, an influx of siliciclastics onto the shelf. Inferring the water depth based solely on synoptic relief is problematic because synoptic relief is a function of growth rate, inter-build-up accumulation rate and possibly water turbidity. The inter-build-up sediments display sand dunes/waves, which can be used to infer an approximate water depth for their formation. Dunes have been reported to have amplitudes of one-third of the water depth in which they form (Stein, 1965), and their preservation potential is reported to be approximately one-third of the size of the dune (Leclair & Bridge, 2001). Therefore, dunes preserved in the rock record may be used to suggest an approximate water depth in which they formed that is at most nine times their amplitude. The subtidal carbonate sand dunes in the James River are 1.2 m and 1.8 m in height, hence, the interpreted water depth is estimated to be at most 10 to 15 m and likely somewhat less.

Previous regional studies of the Upper Cambrian microbial build-ups in central Texas (Lochman-Balk, 1970; Golonka, 2007; Morgan, 2012) show the study area to be a part of a low-latitude mixed shelfal carbonate–siliciclastic system, characterized by the lateral juxtaposition and stacking of neritic carbonates and siliciclastics. The depositional setting has been previously interpreted as a rimmed-margin platform (Barnes & Bell, 1977). Reconstruction of the depositional setting of the Upper Cambrian microbial build-ups requires an understanding of the local palaeogeography and stratigraphy, in addition to using modern microbial systems as possible analogues (Lochman-Balk, 1970; Purdy & Gischler, 2003; Reid et al., 2003; Andres & Reid, 2006; Tcherepanov et al., 2008; Droxler & Jorjy, 2013; Lee et al., 2015).

Palaeogeographic setting

Trade winds

Winds and wind-driven currents most likely played a role in influencing the dominant north-east/south-west orientation of the microbial build-ups along the James River outcrops (Khanna, 2017). During the Late Cambrian, the trade winds can be expected to have blown in the same direction as present-day trade winds (Fig. 16A), and in the Southern Hemisphere south-easterly to easterly winds would have prevailed (Dalrymple et al., 1985). The North American continent during the Late Cambrian was located just south of the equator and rotated 90° to the east. Figure 16B and 16C show that the current major axes of the build-ups display a consistent north-east/south-west orientation, parallel to the direction of south-easterly trade winds (Fig. 16A) when the build-up preferential orientation is corrected for the 90° west North America rotation since the Late Cambrian.

Tide

At the James River pavement outcrop (Location 11; Fig. 2) inter-build-up skeletal to ooid grainstones have been identified, developing low relief bedforms (Fig. 16D). Additionally, on the north-east and south-west margins of the Phase 1 build-ups in James River (Fig. 16E), microbial hash (defined as fine-grained microbial debris) has been identified, indicating bi-directional tidal flow. There is less volume of hash along the north-east margins than along the south-west margins of the build-ups exposed along the James River, indicating that the major flow direction was from the north-east to south-west (present-day orientation) or from the south-east towards the north-west once Laurentia is rotated to its Late Cambrian position. Additionally, palaeo-channel features are identified within the James River pavement outcrop (Fig. 16F), through which the tides and currents could have deposited and further redistributed the sediments.

Storms and waves

Storms and wave activity have been reported from both the lower and upper Point Peak members. Within the lower Point Peak, flat-pebble conglomerates commonly occur as preserved signatures of storms (Sepkoski, 1982; Myrow et al., 2004). Within the upper Point Peak, specifically adjacent to microbial build-ups ooid-skeletal grainstone sand bodies exist (Fig. 16F). Ooids are interpreted to form in shallower waters; however, at this location they are adjacent to microbial build-ups which are

relatively deeper. Hence, storms are interpreted to eventually transport these ooids to relatively deeper waters, between the build-ups.

Conceptual depositional model

The outcrops examined in this study (Section 3; Fig. 1B) expose the complete thickness of the Point Peak Member of the Wilberns Formation, which includes the lower and upper Point Peak. Both of these units together represent a composite section of stacked inner and mid-outer platform facies. This is supported by regional transgressive–regressive cycle maps (Lochman-Balk, 1970), which indicate transgression during deposition of the Point Peak Member. The lower Point Peak at Section 3 (Fig. 1B) represents inner ramp facies, and following transgression the mid-outer ramp facies moved towards the shoreline depositing the distal facies on top of the inner ramp facies in the study area.

The Point Peak Member is interpreted to have been deposited on an extensive ramp more than 100 km in dip width, consistent with the regional setting documented for the Late Cambrian of this area (Lochman-Balk, 1970; Golonka, 2007; Morgan, 2012). In general, two carbonate factories associated with microbial build-up growth and carbonate sand shoals are identified, one each in the inner and mid-outer ramp (Fig. 17).

Inner ramp facies are siliciclastic influenced as evidenced in regional depositional maps (Lochman-Balk 1970; Golonka, 2007) and by studies within the immediate study area (Mabry et al. 2015; Kelleher et al., 2017). Downdip from the coastal zone, the first carbonate factory recognized consists of carbonate shoals formed by ooid and skeletal grainstones. Three types of smaller microbial build-ups are found in close proximity and/or directly associated with the ooid/skeletal grainstone shoal facies belt (Figs 4 and 17; types 1, 2 and 3). In general, the Type 1 smaller microbial heads are associated with greater siliciclastic sediments (for example, the Dan Strom and Bread Loaf build-ups), the siliciclastic flux is minimal in the Type 2 build-ups and siliciclastic component is absent in present in Type 3 build-ups. The interpreted positions of types 1, 2 and 3 smaller build-ups within the regional depositional model is based on siliciclastic content. Seaward of the shoals and small build-ups was an extensive shelf where low sedimentation rates resulted in the deposition of glauconites. The upper Point Peak microbial unit (Fig. 1B, section 3) was deposited on the broad ramp, behind the offshore oolitic grainstone shoal. The north-east/south-west orientation (current) of the upper

microbial build-ups is interpreted to be perpendicular to the local shoreline towards the north-east (McBride et al., 2002), which is most likely due to the influence of open currents generated by trade winds in addition to tide currents. This microbial unit is found associated with inter-mound oolitic sand bodies including the thick inter-build-up grainstones at Zesch Cliff (with thinner heterolithic units; Fig. 6) versus thinner inter-build-up grainstones at Shepard Cliff (with thicker heterolithic units; Fig. 5).

CONCLUSIONS

1. Microbial build-ups, associated with inter-reef bioclastic and ooid grainstones and packstones, occurred in a wide range of size, shape and architecture during deposition of the Point Peak Member of the Wilberns Formation in a Late Cambrian shallow sea in central Texas.
2. Two distinct microbial units are identified in the Point Peak Member, separated by a significant time marker horizon, the *Plectotrophia* zone.
3. The lower Point Peak member consists of <1 m thick bioherms and biostromes, associated with heterolithic and skeletal/ooid grainstone and packstone beds, and interpreted to have accumulated as inboard platform intertidal and shallow subtidal facies across an area 80 km wide. In contrast, the upper Point Peak is characterized by up to 14 m thick individual build-ups, associated with inter-build-up skeletal and ooid grainstone and packstone beds, intercalated with a few, mixed siliciclastic–carbonate silt beds. The upper Point Peak is interpreted to have accumulated as outboard platform subtidal facies.
4. Based on field mapping, sampling and three-dimensional outcrop models built using high-resolution drone imagery, a three-phase growth evolution characterizes the upper microbial unit. The initiation of the microbial build-up occurred on top of lenses of flat-pebble rip-up clasts, interpreted as transgressive lags. The build-up grew in three distinct phases:

- Phase 1 microbial build-ups are oblong, 3 to 5 m high and 10 to 300 m² in surface area. Their interior consist of groups of stromatolitic columns wrapped by thrombolitic rinds.
 - Phase 2 is characterized by vertically aggrading and laterally expanding microbial columnar build-ups that nucleated over Phase 1. Phase 2 stromatolitic columns grew in close association with bioclastic and oolitic grainstone and packstone, infilling the inter-reef.
 - Phase 3 is a micritic thrombolitic rind that wraps around the Phase 2 growth. It lacks contemporaneous inter-build-up sedimentation. Fine-grained siliciclastic rich beds onlap the base of Phase 3 build-ups. An influx of siliciclastics, recorded in the rind, induced high turbidity in the water column, which most likely triggered the ultimate demise of the upper microbial unit.
5. Drone imagery was crucial in identification and mapping different scales of microbial heads or complexes within Phase 1. Four scales have been identified: (i) small-scale microbial heads (few decimetres) enclosed within; (ii) medium-scale microbial heads (few metres); (iii) large-scale microbial heads (few tens of metres); and (iv) microbial complexes (few hundreds of metres).
6. The major axes of the upper Point Peak build-ups display a consistent present-day north-east/south-west orientation, parallel to the direction of south-easterly trade winds when the build-up preferential orientation is corrected for the 90° rotation towards the west since the Late Cambrian.

ACKNOWLEDGEMENTS

This research was a part of the Rice/Trinity Industry Microbial Consortium (funded by Shell, Statoil, Chevron and ConocoPhillips). Part of this research was possible because of newly accessible outcrops on private lands. We are grateful to the owners Mr and Mrs Don and Rosie Shepard and caretakers Mr and Mrs Mark and Priscilla Krauss of Eagle Ridge Ranch, and Mr and Mrs Gene and Patsy Zesch, Mr Scott Zesch for allowing us to conduct research on their ranches. We would also like to thank the reviewers, whose critical comments has helped us drastically improve this manuscript as well as Dr

Accepted Article

Jeff Dravis for his comments and suggestions throughout the research project. The authors declare no conflicts of interest from their affiliations or funding.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

- Ahr W.M. (1967) Origin and palaeoenvironment of some Late Cambrian algal reefs, Mason County area, Texas. Unpublished Ph.D. thesis, Rice University, Houston, TX, 130 pp.
- Ahr, W.M. (1971) Paleoenvironment, Algal structures, and fossil algae in the Late Cambrian of Central Texas. *Journal of Sedimentary Petrology*, **41**, 205-216.
- Andres, M.S. and Reid, R.P. (2006) Growth morphologies of modern marine stromatolites: A case study from Highborne Cay, Bahamas. *Sedimentary Geology*, **185**, 319-328.
- Barnes, V.E. and Bell, W.C. (1977) The Moore Hollow Group of Central Texas. The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations **88**, 169 pp.
- Blackburn, T., McLean, N. and Bowring, S.A. (2017) U-Pb Geochronological and Thermochronological Time-Temperature Constraints of $^{40}\text{Ar}/^{39}\text{Ar}$ Hornblende Reference material HB3gr. *Geostandards and Geoanalytical Research*, **41**, 325-334.
- Boucot, A. (1990) Phanerozoic extinctions: how similar are they to each other? In: *Extinction Events in Earth History* (Eds E.G. Kauffman and O.H. Walliser), pp. 5–30. Springer, Berlin.
- Bridge, J., Barnes, V.E. and Cloud, P.E. (1947) Stratigraphy of the Late Cambrian, Llano uplift, Texas. *Geol. Soc. Am. Bull.*, **58**, 109-124.
- Burne, R.V. and Moore, L.S. (1987) Microbialites: Organosedimentary Deposits of Benthic Microbial Communities. *Palaaios*, **2**, 241-254.
- Chen, J. (2014) Surface and subsurface reworking by storms on a Cambrian carbonate platform: Evidence from limestone breccias and conglomerates. *Geologos*, **20**, 13–23.
- Cloud, P.E. & Barnes, V.E. (1948) The Ellenburger group of central Texas. University of Texas-Austin, Bureau of Economic Geology Publication **4621**, 473 pp.

Cowan, C.A. and James, N.P. (1993) The interactions of sea-level change, terrigenous-sediment influx, and carbonate productivity as controls on Late Cambrian Grand Cycles of western Newfoundland, Canada. *Geological Society of America Bulletin*, **109**, 16-42.

Dalrymple, R. W., Narbonne, G. M. and Smith, L. (1985) Eolian action and the distribution of Cambrian shales in North America. *Geology*, **13**, 607–610.

Dill, R.F., Shinn, E.A., Jones, A.T., Kelly, K. and Steinen, R.P. (1986) Giant subtidal stromatolites forming in normal salinity waters. *Nature*, **324**, 55–58.

Droxler, A.W. and Jorjy, S.J. (2013) Deglacial origin of barrier reefs along low-latitude mixed siliciclastic and carbonate continental shelf edges. *Annu. Rev. Mar. Sci.*, **5**, 65-90.

Droxler, A. W., Hopson, H. H., Khanna, P. Proctor, J., M., Lehrmann, D. J. and Harris, P.M. (2016) Transgressive Lag of Flat Rip-up Clasts – Substratum for Initial Growth of Late Cambrian Large Microbial Bioherms. AAPG Annual Convention and Exhibition, 19-22 June, Calgary, Canada, Program with Abstracts.

Feldman, M. and McKenzie, J.A. (1998) Stromatolite–thrombolite associations in a modern environment, Lee Stocking Island, Bahamas. *Palaaios*, **13**, 201–212.

Ford, D. & Golonka, J. (2003) Phanerozoic paleogeography, paleoenvironment and lithofacies maps of the circum-Atlantic margins. In: *Thematic set on Paleogeographic Reconstruction and Hydrocarbon Basins: Atlantic, Caribbean, South America, Middle East, Russian Far East, Arctic* (Ed. J. Golonka), *Marine and Petroleum Geology*, **20**, 249–285.

Garrison, J. R., Jr., Long, L.E. and Richmann, D. L. (1979) Rb-Sr and K-Ar geochronologic and isotopic studies, Llano uplift, central Texas. *Contributions to Mineralogy and Petrology*, **69**, 361-374.

Ginsburg, R.N. (1982) Actualistic depositional models for the Great American Bank (Cambro-Ordovician). *International Congress of Sedimentology*, **11**, 114.

Ginsburg, R.N. and Planavsky, N.J. (2008) Diversity of Bahamian stromatolite substrates. In: *Links Between Geological Processes, Microbial Activities & Evolution of Life*, (Eds Y. Dilek, H. Furnes and K. Muehlenbachs), pp. 177-195. Springer Academic Press, Amsterdam.

Golonka, J. (2007) Phanerozoic Paleoenvironment and Paleolithofacies maps. Early Paleozoic. *Geologia*, **35**, 589-654.

Golonka, J., Ross, M.I. and Scotese, C.R. (1995) Phanerozoic paleographic and paleoclimate modelling maps. In: *Pangea: Global Environment and Resources*, (Eds A.F. Embry, B. Beauchamp & D.J. Glass), CSPG Memoir **17**, 1-48.

Golonka, J., Bocharova, N.Y., Ford, D., Edrich, M.E., Bednarczyk, J. & Wildharber, J. (2003) Paleogeographic reconstructions and basins development of the Arctic. In: *Thematic set on paleogeographic reconstruction and hydrocarbon basins: Atlantic, Caribbean, South America, Middle East, Russian Far East, Arctic*, (Ed. J. Golonka), Marine and Petroleum Geology, **20**, 211–248.

Hopson, H.H. (2018) Detailed characterization of Upper Cambrian microbial buildup deposition history. Unpublished M.S. thesis, Rice University, Houston, TX, 97 pp.

Johns, R.A., Dattilo, B.F. and Spincer, B. (2007) Neotype and redescription of the Late Cambrian anthaspidellid sponge, *Wilberncyathus donegani* Wilson, 1950. *J. Paleontol.*, **81**, 435–444.

Kelleher, C., Lhemann, A., Swartz, H., Yazbek, L. D., Mercado, L., Lehrmann, D., Hopson, H., Khanna, P. and Droxler, A. (2017) Sedimentology and depositional environments of cyclic microbial bearing strata of the Cambrian Point Peak Member of the Wilberns Fm., Exposed along Mill Creek the Llano River, and James River, Mason County, TX. Geological Society of America, South-Central Section, 50th Annual Meeting, 21-22 March, Baton Rouge, LA. Abstracts with Programs, **48**. doi: 10.1130/abs/2016SC- 271661.

Kiessling, W. (2009) Geologic and biologic controls on the evolution of reefs. *Annu. Rev. Ecol. Evol. Syst.*, **40**, 173–192.

- Khanna, P. (2017) Transgressive reef morphology evolution: A qualitative and quantitative comparison of Uppermost Pleistocene and Upper Cambrian reefs in offshore and Central Texas (USA). Unpublished Ph.D. thesis, Rice University, Houston, TX, 204 pp.
- Kyle, J.R. and McBride, E.F. (2014) Geology of the Voca frac sand district, western Llano uplift, Texas. In: Proceedings of the 48th Annual Forum on the Geology of Industrial Minerals (Ed. F.M. Conway) *Arizona Geological Survey Special Paper* **9**, 1–13.
- Leclair, S.F. and Bridge, J.S. (2001) Quantitative interpretation of sedimentary structures formed by river dunes. *Journal of Sedimentary Research*, **71**, 713-716.
- Lee, J., Chen, J. and Chough, S.K. (2015) The middle-late Cambrian reef transition and related geological events: A review and new view. *Earth-Science Reviews* **145**, 66-84.
- Lochman-Balk, C. (1970) Late Cambrian faunal patterns on the craton. *Geol. Soc. Am. Bull.*, **81**, 3197-3224.
- Mabry G., Yazbek L., Ford, C., Lehrmann D., Khanna P., Hopson H., Fessahaie M. and Droxler A. (2015) Sedimentology and Depositional Environments of Cyclic Microbial Bearing Strata of the Cambrian Point Peak Member of the Wilberns Formation, Exposed Along the Llano River and Mill Creek, Mason County, TX. AAPG Annual Convention and Exhibition, 31 May to 3 June, Denver, CO, Program with Abstracts.
- McBride, E.F., Abdel-Wahab, A.A. and Milliken, K.L. (2002) Petrography and diagenesis of a half-billion-year-old cratonic sandstone (Hickory), Llano region, Texas. University of Texas, Austin, Bureau of Economic Geology, Report of Investigation No. 264, 77 pp.
- Miller, J.F., Loch, J.D. and Taylor, J.F. (2012) Biostratigraphy of Cambrian and Lower Ordovician Strata. In: *The Great American Carbonate Bank: The Geology and Economic Resources of the Cambrian—Ordovician Sauk Megasequence of Laurentia*, (Eds J. R. Derby, R. D. Fritz, S. A. Longacre, W. A. Morgan, and C.A. Sternbach), AAPG Memoir **98**, 87 – 202.

Morgan, W. A. (2012) Sequence stratigraphy of the great American carbonate bank. In: *The Great American Carbonate Bank: The Geology and Economic Resources of the Cambrian—Ordovician Sauk Megasequence of Laurentia*, (Eds J. R. Derby, R. D. Fritz, S. A. Longacre, W. A. Morgan, and C.A. Sternbach), AAPG Memoir **98**, 37–79.

Myrow, P.M., Tice, L., Archuleta, B., Clark, B., Taylor, J.F. and Ripperdan, R.L. (2004) Flat-pebble conglomerate: its multiple origins and relationship to metre-scale depositional cycles. *Sedimentology*, **51**, 973–996.

Paige, S. (1911) Mineral resources of the Llano-Burnet region, Texas with an account of the Pre-Cambrian Geology, United States Geological Survey Bulletin **450**, 103 pp.

Palmer, A.R. (1981) Subdivision of the Sauk sequence. In: Short Papers for the 2nd International Symposium on the Cambrian System (Ed. M.E. Taylor), *U.S. Geological Survey Open File Report* 81-743, 160–162.

Parke, R.P. (1953) Geology of the Southwest Mason-Llano River Area, Texas. Unpublished M.S. thesis, Texas A&M University, College Station, TX, 106 pp.

Proctor J.M., Droxler A.W., Derzhi N., Hopson H.H., Harris P. M., Khanna P. and Lehrmann D.J. (2019) Upscaling lithology and porosity type fractions from the micro- to the core-scale with thin section petrography, dual energy computed tomography, and rock typing: Creation of diagenesis and porosity type logs. *Interpretation*, **7**, B9-B32. doi.org/10.1190/int-2017-0187.1.

Purdy, E.G. and Gischler, E. (2003) The Belize margin revisited: 1. Holocene marine facies. *International Journal of Earth Sciences*, **92**, 532–551.

Read, J.F. and Repetski, J.E. (2012) Cambrian – Lower Middle Ordovician passive carbonate margin, southern Appalachians. In: *The Great American Carbonate Bank: The Geology and Economic Resources of the Cambrian – Ordovician Sauk Megasequence of Laurentia* (Eds J. R. Derby, R. D. Fritz, S. A. Longacre, W. A. Morgan and C. A. Sternbach), AAPG Memoir, **98**, 357–382.

Reid, R.P., Macintyre, I.G. and Steneck, R.S. (1999) A microbialite/algal ridge fringing reef complex, Highborne Cay, Bahamas. *Atoll Res Bulletin*, **466**, 1–18.

Reid, R.P., James, N.P., Macintyre, I.G., Dupraz, C.P. and Burne, R.V. (2003) Shark Bay stromatolites: Microfabrics and reinterpretation of origins. *Facies*, **49**, 299.

Riding, R. (2006) Microbial carbonate abundance compared with fluctuations in metazoan diversity over geological time. *Sediment. Geol.*, **185**, 229–238.

Riding, R. (2011) Microbialites, stromatolites, and thrombolites. In: *Encyclopedia of Geobiology*. (Eds. J. Reitner and V. Thiel), pp. 635–654. Springer, Heidelberg.

Schubert, J.K. and Bottjer, D.J. (1992) Early Triassic stromatolites as post-mass extinction disaster forms. *Geology*, **20**, 883.

Schulz K.J., Stewart D.B., Tucker R.D., Pollock J.C. & Ayuso R.A. (2008) The Ellsworth terrane, coastal Maine: Geochronology, geochemistry, and Nd-Pb isotopic composition – Implications for the rifting of Ganderia. *Geological Society of America Bulletin*, **120**, 1134–1158.

Sepkoski, Jr., J.J. (1982) Flat-pebble conglomerates, storm deposits, and the Cambrian bottom fauna. In: *Cyclic Event and Stratification* (Eds G. Einsele and A. Seilacher), pp. 371–388. Springer-Verlag, Berlin.

Singh, P., Droxler, A.W., Hopson, H.H., Khanna, P., Lehrmann, D., Droxler, D.A., Rodelli, D., Jovane, L., Harris, P.M. and Dravis, J. (2016) Ultimate demise of large Upper Cambrian microbial reefs (Mason County, Central Texas). Geological Society of America Annual Meeting. 25-28 September, Denver, CO, Abstracts with Programs, 48. doi: 10.1130/abs/2016AM-283255,

Sliger, K.L. (1957) Geology of the Lower James River Area. Unpublished M.S. thesis, Agricultural and Mechanical College of Texas (Texas A&M), College Station, TX, 94 pp.

Sloss, L.L., Krumbein, W.C. and Dapples, E.C. (1949) Integrated facies analysis. In: *Sedimentary Facies in Geologic History* (Ed. C. R. Longwell), Geological Society of America Memoir, **39**, 91–124.

Spincer, B.R. (1997) The palaeoecology of some Late Cambrian reefs from central Texas, the Great Basin and Colorado, USA. Unpublished Ph.D. dissertation, University of Cambridge, Cambridge, England, 234 pp.

Stein, R.A. (1965) Laboratory Studies of Total Load and Apparent Bed Load. *Journal of Geophysical Research*, **70**, 1831-1842.

Suosaari, E.P., Reid, R.P., Playford, P.E., Foster J.S., Stolz, J.F., Casaburi, G., Hagan P.D., Chirayath, V., Macintyre, I.G., Planavsky, N.J. and Eberli, G.P. (2016) New multi-scale perspectives on the stromatolites of Shark Bay, Western Australia. *Scientific Reports*, **6**, 20557. DOI:10.1038/srep20557.

Suosaari, E.P., Awramik, S.T., Reid, R.P., Stolz, J.F. and Grey, K. (2018) Living Dendrolitic Microbial Mats in Hamelin Pool, Shark Bay, Western Australia. *Geosciences*, **8**, 212. doi:10.3390/geosciences8060212.

Swartz, H., Kelleher, C., Lhemann, A., Lehrmann, D., Suarez, M., Hopson, H., Khanna, P. and Droxler, A. (2016) Stable isotope and elemental geochemistry from 1-D profiles are a useful tool for revealing 3-D phasing architecture of Upper Cambrian microbial reef complexes, Wilberns Formation, Mason County, TX. Geological Society of America, South-Central Section, 50th Annual Meeting, 21-22 March, Baton Rouge, LA. Abstracts with Programs, **48**. doi:0.1130/abs/2016SC-271661.

Tcherepanov, E.N., Droxler, A.W., Lapointe, P., Dickens, G.R., Bentley, S.J., Beaufort, L., Peterson, L.C., Daniell, J. and Opdyke, B.N. (2008) Neogene evolution of the mixed carbonate-siliciclastic system in the Gulf of Papua, Papua New Guinea. *Journal of Geophysical Research*, **113**, F01S21.

Trettin, H.P. and Balkwill, H.R. (1979) Contributions to the tectonic history of the Innuitian Province, Arctic Canada. *Canadian Journal of Earth Sciences*, **16**, 748–769.

Accepted Article

Van Der Voo, R. (1988) Paleozoic paleogeography of North America, Gondwana, and intervening displaced terranes: comparisons of paleomagnetism with paleoclimatology and biogeographic patterns. *Geol. Soc. Am. Bull.*, **100**, 311-324.

Woo, J. and Chough, S.K. (2010) Growth patterns of the Cambrian microbialite: phototropism and speciation of Epiphyton. *Sediment. Geol.*, **229**, 1–8.

FIGURE CAPTIONS

Fig. 1. Stratigraphic column and measured sections. (A) Stratigraphic column for Cambrian strata of the Llano Uplift (modified from Barnes & Bell, 1977; Kyle & McBride, 2014). Legend: blue = limestone; purple = dolomite; yellow= siliciclastic sandstone; green = shale; red = granite. (B) Location of 22 sections measured through the Upper Cambrian strata across the Llano Uplift (modified from Miller et al., 2012). The Point Peak Member of the Wilberns Formation, which contains the microbial intervals and is the focus of this study, has been measured and reported from 15 of these sections. Dashed red lines depict location of west to east profiles. This study is focused on the upper microbial unit in the Point Peak Member located near section 3 – purple rectangle on (B). (C) and (D) West to east profiles of the Point Peak Member (modified from Bridge et al., 1947; Ahr, 1967). The base of Point Peak Member is marked with a black line and the top with green. The orange dashed line highlights the *Plectotrophia* zone that is used as a regional marker and divides the lower (red outline) and upper Point Peak microbial unit (blue outline) into two microbial units.

Fig. 2. Study area displaying the location of 12 outcrops (pavements and cliffs), Mason County, central Texas. Yellow lines represent cliff outcrops and red rectangles represent bedding plane outcrops or pavements. All the outcrops are located along the Llano and James rivers and Mill Creek.

Fig. 3. Point Peak Member mapped in the study area, integrated with the Sliger (1957) geological map (north of Llano River and west of Honey Creek fault represents no data regions).

Fig. 4. Three types of microbial buildups in the lower Point Peak member. (A) Type 1 (Location 10; Fig. 2); a vertical cross-section of Lauren's Cliff displaying mixed carbonate–siliciclastic sediments. The red rectangle represents type 1, referred to as Dan Strom. (B) A close-up of the Dan Strom from (A), showing individual microbial heads. (C) Type 2 (Location 2; Fig. 2); digitally-developed bird's

eye view of the outcrop at Location 2 created using 408 photographs. The red rectangle shows the location of (D). This bed consists of Bread Loaf bioherms. (D) Close-up of one perfectly preserved microbial build-up among the Bread Loaf bioherms. (E) Type 3 (Location 9; Fig. 2); vertical cross-section displaying the conical growth of several microbial heads within one of several biostrome beds. (F) Close-up of Type 3, showing typical conical morphology, outlined by the dashed yellow line.

Fig. 5. Shepard Cliff's eastern side exposed along the Llano River (Location 1; Fig. 2). The upper panel is uninterpreted and the lower panel is an interpreted version. An orange line indicates the base and a blue line indicates the top of the microbial unit. The individual circular to semi-circular and oval shapes are microbial buildups. The inter-reef grainstone beds are coloured translucent orange to emphasize their relative continuity. James Lee and Wayne represent upper Point Peak microbial build-ups.

Fig. 6. Zesch Cliff exposed along the Llano River (Location 3; Fig. 2). The upper panel is uninterpreted and the lower panel is interpreted. An orange line indicates the base and a blue line indicates the top of the microbial unit. The individual circular to semi-circular and oval shapes are microbial buildups. The inter-reef grainstone beds are coloured translucent orange to emphasize their relative continuity. Inter-build-up grainstone beds are thicker on Zesch Cliff than Shepard Cliff (Fig. 5). Mitch, Patsy and Gene represent upper Point Peak microbial build-ups.

Fig. 7. (A) James River pavement (600 x 200 m; Location 11; Fig. 2) orthophotograph mosaic built using 560 aerial images utilizing photogrammetry workflow in Agisoft 1.0 and showing location of build-ups exposed on the pavement (yellow boxes). (B) to (D) Close-ups of the bird's eye view of areas outlined by yellow boxes in (A). These close-ups showcase the different sizes and shapes of microbial build-ups; (B) H3 build-ups; (C) Pi build-up; and (D) AleAndré build-up.

Fig. 8. Measured Twin Herm sections along the James River cliff. (A) Aerial view of the Twin Herm sections. Green = Phase 1; red = Phase 2; black outline = Phase 3 (refer to Fig. 9 for a detailed description of the three phases). White lines indicate the location of measured sections. STHS = South Twin Herm section – shown in (D); THS1 = Twin Herm section 1 – shown in (E); THS2 = Twin Herm section 2 – shown in (F) and NTHS = North Twin Herm section – shown in (G). TH1 (Twin Herm 1) and TH2 (Twin Herm 2) are the two microbial buildups at this location. (B) A side view looking at inter-build-up facies between TH1 and TH2. Besides TH1 the beds are identified to be dipping towards the build-up, similar to a moat in (C). (C) The modern large microbial build-ups surrounded by moving sand dunes in the Adderly tidal channel between Exuma Cays on the Great Bahama Bank margin. The interaction of microbial build-ups and inter build-up sediments is an analogue to Twin Herm. (D) to (G) Measured sections and spectral gamma-ray logs at 20 m spacing. Nine beds have been identified adjacent to the microbial build-up growth. The main lithofacies identified include: skeletal limestone; oolitic limestone; microbial boundstone; heterolithic siltstone and lime packstone; and silty limestone.

Fig. 9. The three-phase growth model. (A) Oblique drone image of Mitch Herm within the Zesch Cliff above the Llano River (Location 3; Fig. 2). (B) Growth phase interpretation of Mitch Herm and coeval sediments showing strata immediately below the Switch, the main microbial interval with its three distinct phases, and the overlying strata. The blue line represents the flat substrate on which microbial build-ups nucleated. Phase 1; colonizing phase is the first microbial growth with a stromatolitic interior (light green) and a thrombotic rind (green). Phase 1 growth is coeval with an inter-reef grainstone bed (coloured orange). Phase 1 is overlapped by a mixed carbonate siliciclastic silty layer. Phase 2, shown in red, nucleates on top of Phase 1 and grows upwards and outwards and interacts with the adjacent coeval grainstones. Phase 2 develops distinct 'box structures' after weathering, by selective erosion of trapped grains within the growth framework. Phase 3 represents the last phase and is similar to the Phase 1 thrombotic rinds, nucleating over the Phase 2 and extending outwards on top of the inter-reef grainstone beds (outlined in black).

Fig. 10. Mesofabric identified at DroxRock for upper Point Peak microbial build-up Phases 1, 2 and 3. (A) and (B) Uninterpreted and interpreted version of DroxRock phases 1, 2 and 3. Phase 1 rind (L) has a thrombolitic micritic texture with calcimicrobes including *Renalcis* (M): M–O is a transition from the rind towards the Phase 1 interior. Phase 1 interior (H) is stromatolitic (I), wrapped by a thrombolitic rind (J). Finer micritic sediments and skeletal grains fill the space between stromatolitic columns (K) within Phase 1 interior. Phase 2 (E) to (G) are stromatolitic columns. The red rectangle in (E) is a zoom in of (F). The thrombolitic rind is the texture of the Phase 3 (C), which commonly includes the calcimicrobe *Renalcis* (D). The yellow circles and red dots with yellow circles both represent the location of cored samples, which are used to display meso-scale features in this figure and micro-scale features in Fig. 11.

Fig. 11. Thin sections microphotographs of the Phase 1 rind include; (A) *Wilberniacyathus donegani* sponge within a micritic matrix from the rind (cross-polarized light); (B) calcimicrobe *Girvanella* within a micritic matrix (plane-polarized light); (C) calcimicrobe *Tarthinia* within a micritic matrix (plane-polarized light); and (D) clotted microbial fabric and internal cavities (cross-polarized light). (E) Microphotograph of calcimicrobe *Epiphyton* with micritic matrix within a Phase 3 rind (cross-polarized light). (F) Thin section microphotography of burrow tubes, containing very fine fragmental skeletal debris within the Phase 1 interior (cross-polarized light). Inter-build-up facies include; (G) cross-laminated detrital quartz grains within the heterolithic unit (plane-polarized light); (H) bioclastic grainstone with trilobite fragments, indicated by white arrows; and (I) ooid and peloidal grainstone (cross-polarized light).

Fig. 12. Fallen Block (Location 7; Fig. 2), displaying the base of the microbial buildups. (A) Fallen microbial blocks lying on its side and displaying the flat base of the build-up. Growth phases 1, 2 and 3 are shown as green, red and black transparencies, and are described in the caption for Fig. 9. (B)

View of the base of the build-up. A flat lens of rip-up clasts is outlined, and is shown in closer detail in (C). (C) Close-up of rip-up clasts from (B).

Fig. 13. Phase 1 morphology and adjacent inter-reef facies. (A) and (B) Build-ups from the James River. (C) Wayne build-up from Shepard Cliff. Phase 1 growth (green) and adjacent inter-reef grainstone bed (orange) is highlighted. (D) Phase 1 growth scaling relationships from James River (Location 10; Fig. 2); small = few decimetres in diameter, medium = few metres in diameter and large = few tens of metres in diameter. These images are from an area north of what is shown in Fig. 1. (E) Large-scale features cluster to form a complex scale; which is the largest scale and a few hundreds of metres across.

Fig. 14. Phases 1, 2 and 3 growth of microbial build-ups. (A) Part of Shepard Cliff displaying Mark build-up and the Granddaughters build-ups (Location 1; Fig. 2). Phase 1 of microbial growth is overlapped by a silty unit, on which microbial growth of Phase 2 continues, as observed at the Granddaughters build-ups. (B) Granddaughters build-ups displaying backstepping morphology indicating sub-phases in Phase 2.

Fig. 15. Three-phase depositional model for Upper Cambrian microbialites from initial colonizing Phase 1, to aggrading and expanding Phase 2 and finally capping Phase 3. The schematic model emphasizes the differences in growth forms between the phases as well as the interplay between buildup and adjacent strata.

Fig. 16. Palaeogeographic controls on depositional environments. (A) Palaeogeographic map of the Late Cambrian time period (Furongian; 497 to 485.4 Ma) modified from Blakey (2013), displaying the direction of trade winds (arrows) over Laurentia and the location of the field area in central Texas

(black star). (B) James River pavement displaying Phase 1, large-scale (see Fig. 13D) microbial build-ups. The microbial build-ups were mapped manually and then colour-coded based on their major direction of orientation in ArcMap 10.1 (Esri). (C) Rose diagram displaying the major direction of orientation of these microbial build-ups. (D) A close-up of the Twin Herm – yellow rectangle in (B). Inter-build-up grainstones are exposed in detail at Twin Herms (see Fig. 8B). A moat at the edge of the microbial build-up is coloured in yellow. The grainstone units have preserved asymmetric arcuate ripples (dotted black lines), and larger features display dune geometry: TH1 = Twin Herm 1 and TH2 = Twin Herm 2. (E) Close-up of the James River pavement orthophotograph looking at the Pi build-up – black rectangle in (B), coloured in green. Microbial debris (yellow) derived from Pi build-up is observed on the north-east and south-west margins of the build-up is also observed on margins of other buildups. (F) James River orthophotograph as shown in (B), but the focus here is the inter-build-up palaeo-channel pattern. The microbial build-ups are coloured with a blue diamond pattern and the palaeo-channel is shown in orange.

Fig. 17. Composite depositional model for the Upper Cambrian microbial build-ups of central Texas. The lower Point Peak represents the inner ramp facies and the upper Point Peak mid–outer ramp facies. The inner ramp consists of microbial build-ups and mixed carbonate–siliciclastic sediments. The outer ramp facies consists mostly of microbial build-ups, grainstones, with local mixed carbonate-siliciclastic beds: FWWB = fair-weather wave base.

Final Phase 3 silt

Capping Phase 3

Vertically aggrading and laterally expanding Phase 2B

Vertically aggrading and laterally expanding Phase 2A

Final Phase 1 silt

Colonizing Phase 1

Transgressive flat-pebble lag

LEGEND:

Flat-pebbles

Ooid & skeletal grainstone

Mixed siltstone

Stromatolite

Thrombolite