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## **Evidence for plunging river plume deposits in the Pahrump Hills member of the Murray formation, Gale crater, Mars**

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## **ABSTRACT**

Recent robotic missions to Mars have offered new insights into the extent, diversity and habitability of the Martian sedimentary rock record. Since the *Curiosity* rover landed in Gale crater in August 2012, the Mars Science Laboratory Science Team has explored the origins and habitability of ancient fluvial, deltaic, lacustrine and aeolian deposits preserved within the crater. This study describes the sedimentology of a *ca* 13 m thick succession named the Pahrump Hills member of the Murray formation, the first thick fine-grained deposit discovered *in situ* on Mars. This work evaluates the depositional processes responsible for its formation and reconstructs its palaeoenvironmental setting.

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The Pahrump Hills succession can be sub-divided into four distinct sedimentary facies: (i) thinly laminated mudstone; (ii) low-angle cross-stratified mudstone; (iii) cross-stratified sandstone; and (iv) thickly laminated mudstone–sandstone. The very fine grain size of the mudstone facies and abundant millimetre-scale and sub-millimetre-scale laminations exhibiting quasi-uniform thickness throughout the Pahrump Hills succession are most consistent with lacustrine deposition. Low-angle geometric discordances in the mudstone facies are interpreted as ‘scour and drape’ structures and suggest the action of currents, such as those associated with hyperpycnal river-generated plumes plunging into a lake. Observation of an overall upward coarsening in grain size and thickening of laminae throughout the Pahrump Hills succession is consistent with deposition from basinward progradation of a fluvial-deltaic system derived from the northern crater rim into the Gale crater lake. Palaeohydraulic modelling constrains the salinity of the ancient lake in Gale crater: assuming river sediment concentrations typical of floods on Earth, plunging river plumes and sedimentary structures like those observed at Pahrump Hills would have required lake densities near freshwater to form. The depositional model for the Pahrump Hills member presented here implies the presence of an ancient sustained, habitable freshwater lake in Gale crater for at least *ca*  $10^3$  to  $10^7$  Earth years.

## INTRODUCTION

Ancient lake deposits are among the most attractive astrobiology targets for *in situ* rover and lander missions to Mars. Environments containing long-lived surface water could have once hosted life and may be conducive for the concentration and preservation of organic matter (Farmer & DesMarais, 1999; Summons *et al.*, 2011; Hays *et al.*, 2017). Observations from ground-based and orbital missions to Mars demonstrate the presence of a widespread sedimentary rock record exposed on the Martian surface (Sharp, 1973; Malin & Edgett, 2000; Grotzinger & Milliken, 2012, Stack *et al.*, 2015, Rogers *et al.*, 2018), including evidence that water may have persisted on the Martian surface for geologically significant timescales. The presence of ancient deltas (Fassett & Head, 2005; Lewis & Aharonson, 2006, Ehlmann *et al.*, 2008; Di Achille & Hynek, 2010; Ansan *et al.*, 2011;

Schon *et al.*, 2012; Rice *et al.*, 2013; DiBiase *et al.*, 2013; Morgan *et al.*, 2018; Goudge *et al.*, 2018), sublacustrine fans (Dromart *et al.*, 2007; Metz *et al.*, 2009), putative shorelines (Parker *et al.*, 1989; Parker *et al.*, 1993; Clifford & Parker, 2001; Perron *et al.*, 2007) and hundreds of candidate crater lake basins (Goldspiel & Squyres, 1991; Cabrol & Grin, 1999, 2001; Fassett & Head, 2008; Warner *et al.*, 2010; Goudge *et al.*, 2012) observed in orbital datasets help to support this interpretation. However, clear evidence for *in situ* lacustrine deposits requires ground-based surface observations.

A subset of possible Martian crater lake basins has been interpreted to contain ancient lacustrine deposits exposed at the surface (Cabrol & Grin, 1999; Malin & Edgett, 2000; Fassett & Head, 2008; Goudge *et al.*, 2012), although only at two sites have such deposits been investigated *in situ* by rover missions. An ejecta block near Santa Maria crater in Meridiani Planum studied by the *Opportunity* rover team was interpreted as possibly lacustrine in origin, although its lack of context made it difficult to eliminate alternative aeolian depositional hypotheses (Edgar *et al.*, 2014). The Mars Science Laboratory (MSL) Science Team has explored several lacustrine deposits in Gale crater with the *Curiosity* rover. At Yellowknife Bay, a lacustrine origin was favoured for the 1.5 m thick interval of clay-bearing mudstones of the Sheepbed member (Grotzinger *et al.*, 2014). Lacustrine deposits have also been interpreted in the Murray formation, the stratigraphically oldest rocks exposed in the eroded foothills of Aeolis Mons (informally Mount Sharp), the 5 km high central mound within Gale crater (Grotzinger *et al.*, 2015; Fedo *et al.*, 2017, 2018; Rivera-Hernández *et al.*, 2018).

The MSL Science Team carried out a detailed examination of the Murray formation at an outcrop named Pahrump Hills (see Supplementary Information S.1), a *ca* 13 m thick section whose strata have been informally designated as the Pahrump Hills member (Grotzinger *et al.*, 2015). Since the Pahrump Hills member represents the first and oldest continuous exposure of the Murray formation encountered by the rover, the Science Team devoted a six and a half month long campaign to this location with the intention of compiling a reference section for the basal Murray formation. The Science Team used the rover's integrated payload to obtain a dense record of sedimentary structures and textures, together with compositional measurements. This study builds on earlier work by Grotzinger *et al.* (2015), and uses the characterization of grain size, sedimentary structures and

stratal geometries to reconstruct sedimentary processes and palaeoenvironments of the lower Murray formation depositional system preserved at Pahrump Hills. This analysis and complementary palaeohydraulic modelling are used to provide stronger constraints on the lacustrine depositional model for the Murray formation exposed at Pahrump Hills than the initial analysis of Grotzinger *et al.* (2015), with new implications for the salinity, longevity and habitability of the ancient Gale crater lake.

## **GEOLOGICAL SETTING**

Gale crater (centred at 5.37°S, 137.81°E), selected as the field site for the *Curiosity* rover (Grotzinger *et al.*, 2012; Golombek *et al.*, 2012), is a *ca* 154 km diameter crater located on Mars' crustal dichotomy boundary (Fig. 1A), a global topographic distinction that separates the ancient, heavily cratered southern highlands from the smooth northern plains of Mars. Gale crater is one of a class of crater basins on Mars that contain thick sedimentary sequences in central mounds (Malin & Edgett, 2000; Grotzinger & Milliken, 2012; Bennett & Bell, 2016; Day *et al.*, 2016). The formation of Gale crater is dated to *ca* 3.6 to 3.8 Ga (Thomson *et al.*, 2011; Le Deit *et al.*, 2013), occurring near the transition between the Late Noachian and Early Hesperian periods. Deposition of crater-filling materials within Gale has been estimated to have begun shortly after the crater's formation, continuing through the Hesperian epoch (Thomson *et al.*, 2011; Le Deit *et al.*, 2013; Grant *et al.*, 2014; Palucis *et al.*, 2014) and possibly into the early Amazonian (Palucis *et al.*, 2014), with deposition interrupted by at least several major periods of erosion resulting in recognizable unconformities within the rock record at Gale crater (Malin & Edgett, 2000; Rossi *et al.*, 2008; Anderson & Bell, 2010; Milliken *et al.*, 2010; Thomson *et al.*, 2011; Le Deit *et al.*, 2013; Fraeman *et al.*, 2016; Kite *et al.*, 2016; Watkins *et al.*, 2016; Banham *et al.*, 2018). Aeolian erosion of crater-filling deposits and spatially isolated but active aeolian sedimentation have continued to the present-day (Day & Kocurek, 2016; Ewing *et al.*, 2017, Bridges & Ehlmann, 2017).

Gale crater contains within it a nearly 5 km high mound of layered strata, Aeolis Mons (Fig. 1A), the stratigraphy of which is interpreted to preserve a record of the evolution of ancient sedimentary processes and environmental changes with implications for the habitability of early Mars (Anderson & Bell, 2010; Milliken *et al.*, 2010; Thomson *et al.*, 2011; Fraeman *et al.*, 2012; LeDeit *et al.*, 2013; Grotzinger *et al.*, 2014). Earlier orbiter data-based interpretations of the Gale rock record included deposition by volcanic (Scott *et al.*, 1978; Scott & Chapman, 1995; Greeley & Guest, 1987; Malin & Edgett, 2000; Bridges *et al.*, 2010; Thomson *et al.*, 2008), aeolian (Anderson & Bell, 2010; Kite *et al.*, 2013; Milliken *et al.*, 2014; Kite *et al.*, 2016), fluvial (Anderson & Bell, 2010) and lacustrine (Cabrol *et al.*, 1999; Malin & Edgett, 2000) processes, as well as deposition from springs (Rossi *et al.*, 2008; Andrews-Hanna *et al.*, 2012). Ground-based observations acquired by *Curiosity* during the first five years of its mission confirm that deposition of strata exposed on the floor of Gale crater and in the foothills of Aeolis Mons was dominated by sedimentary processes in fluvial, deltaic, lacustrine and aeolian depositional environments (Williams *et al.*, 2013; Vasavada *et al.*, 2014; Grotzinger *et al.*, 2014, 2015; Stack *et al.*, 2016; Rice *et al.*, 2017; Edgar *et al.*, 2017; Banham *et al.*, 2018). Volcanic, spring or surface hydrothermal deposits have not been discovered to date.

Aeolis Palus, the plains that make up the present-day floor of Gale crater, is composed primarily of fluvial and fluvio-deltaic sandstones and conglomerates which have been designated informally as the Bradbury group (Williams *et al.*, 2013; Vasavada *et al.*, 2014; Grotzinger *et al.*, 2015; Stack *et al.*, 2016; Rice *et al.*, 2017) (Figs 1B and 2). The occurrence of systematic facies variations, along with the discovery of southward-prograding clinof orm deposits over an elevation range of *ca* 80 m led Grotzinger *et al.* (2015) to interpret the Bradbury group as a network of braided rivers flowing south from Gale crater's northern rim. This sediment routing system was capable of transporting cobbles up to *ca* 10 cm in diameter (Williams *et al.*, 2013; Grotzinger *et al.*, 2015; Szabó *et al.*, 2015; Mangold *et al.*, 2016) in water depths estimated to be between 0.03 to 0.9 m based on the grain-size distribution of conglomerate clasts (Williams *et al.*, 2013). These rivers were interpreted by Grotzinger *et al.* (2015) to have fed a series of metre to decametre-scale stacked delta mouth bars composed of dipping clinof orms that prograded towards the south. A natural prediction of this

depositional model was that *Curiosity* should encounter distal basinal lacustrine facies, the lateral facies equivalents of these proximal fluvio-deltaic deposits, as it continued to traverse basinward to the south (Grotzinger *et al.*, 2015).

Aeolis Palus is bounded to the south by a distinct topographic break in slope *ca* 10 m high. The Murray formation, the basal exposed unit within the stratigraphic succession of Aeolis Mons, is exposed south of this topographic break and is mappable in orbiter-derived visible images for *ca* 30 km along the base of Aeolis Mons (Figs 1B and 3A). The Murray formation is distinguished in visible orbital images by its bright to intermediate tone, massive to subtly layered appearance, the presence of metre-scale polygonal fractures throughout, and its relative inability to retain craters compared to surrounding units (Edgett & Malin, 2000; Malin & Edgett, 2000; Anderson & Bell, 2010; Milliken *et al.*, 2010; Thomson *et al.*, 2011; Grotzinger *et al.*, 2015; Fraeman *et al.*, 2016). Analysis of orbiter-derived visible to near-infrared spectroscopic data indicates the presence of hematite, hydrated silica, phyllosilicates and sulphates throughout the Murray formation (Milliken *et al.*, 2010; Fraeman *et al.*, 2016).

Pahrump Hills is a *ca* 225 m-long outcrop located along the boundary between Aeolis Palus and the northern contact of the Murray formation, at the southern end of Amargosa valley (Fig. 3). The Pahrump Hills member exposed here represents the northernmost, lowest elevation, and likely stratigraphically oldest exposure of the Murray formation encountered by the rover (Figs 1B and 3A). As viewed in images from the High Resolution Imaging Science Experiment (HiRISE) onboard the Mars Reconnaissance Orbiter, Pahrump Hills strata are partially isolated from the main exposure of the Murray formation by strata interpreted to be overlying Stimson formation (Calef *et al.*, 2013; Grotzinger *et al.*, 2015; Watkins *et al.*, 2016; Stack *et al.*, 2017; Kronyak *et al.*, 2017; Banham *et al.*, 2018), a younger aeolian sandstone unit interpreted to unconformably overlie the Murray formation (Watkins *et al.*, 2016; Banham *et al.*, 2018) (Figs 2 and 3B).

## DATA AND METHODS

### The Pahrump Hills Campaign

The MSL Science Team devoted six and a half months (Sols 753 to 923, where ‘Sol’ denotes the designated Martian day of the MSL mission) to a detailed investigation of the Pahrump Hills outcrop with the aim of characterizing a reference section for the basal Murray formation. The first drill sample of the Murray formation (Confidence Hills) was acquired on Sol 759 shortly after arriving at the base of Pahrump Hills (Fig. 3C and 3D). Drilling was followed by reconnaissance characterization of the Pahrump Hills outcrop (Sols 780 to 794, Loop 1) during which the rover was commanded to make observations using only its remote sensing instruments [Mast Camera (Mastcam), Chemistry Camera (ChemCam), Mars Descent Imager (MARDI) and Navigation cameras (Navcam)] at predetermined locations (Fig. 3C). Observations from this reconnaissance traverse were used to select locations for a second traverse of the outcrop (Sols 805 to 862, Loop 2) (Fig. 3C and D), during which the team employed the *Curiosity* dust removal tool (DRT) and contact science instruments [Mars Hand Lens Imager (MAHLI) and the Alpha Particle X-ray Spectrometer (APXS)] to acquire fine-scale textural and bulk geochemistry observations. Observations from the first and second loops of the Pahrump Hills ‘walkabout’ were synthesized to inform selection of two additional drill locations, Mojave and Telegraph Peak, on Sols 882 and 908, respectively (Fig. 3C and D). *Curiosity* drove away from the Telegraph Peak drill location on Sol 923 marking the end of the Pahrump Hills campaign.

### Instruments and data

Sedimentary facies observed at Pahrump Hills were characterized in this study using images from the *Curiosity* Navcam (Maki *et al.*, 2012), Mastcam (Bell *et al.*, 2017, Malin *et al.*, 2017), ChemCam remote micro-imager (RMI) (Maurice *et al.*, 2012; Le Mouélic *et al.*, 2015) and MAHLI (Edgett *et al.*, 2012; Edgett *et al.*, 2015; McBride *et al.*, 2015) cameras. The Navcam, Mastcam and ChemCam instrument suites are located on the *Curiosity* rover Remote Sensing Mast, mounted *ca* 2 m



above the surface, and MAHLI is mounted on the rover's deployable arm. The Navcam stereo mosaics orthorectified to a HiRISE basemap and digital elevation model were used in this study to localize outcrops examined at Pahrump Hills, and to determine the stratigraphic position of outcrops based on absolute differences in elevation. Colour mosaics from the 34 mm (M-34) and 100 mm (M-100) fixed-focal-length Mastcams were used to characterize laminations, sedimentary structures, grain size and the nature of geological contacts. At a 2 m distance, the M-34 and M-100 cameras can achieve resolutions of 440  $\mu\text{m}/\text{pixel}$  and *ca* 150  $\mu\text{m}/\text{pixel}$  (medium to coarse sand), respectively (Malin *et al.*, 2017). The ChemCam RMI provides focused grey-scale images with a sub-millimetre pixel resolution that can provide resolution higher than Mastcam, but with a narrower field of view (20 mrad across; 1024 x 1024 pixels) (Maurice *et al.*, 2012; Le Mouélic *et al.*, 2015). This study used ChemCam RMI images of surface targets acquired at distances between 2.1 m and 6.5 m (*ca* 40 to 130  $\mu\text{m}/\text{pixel}$ , coarse silt to fine sand) from the ChemCam mast unit. Colour images from the MAHLI camera acquired at working distances between 2.6 cm (*ca* 16  $\mu\text{m}/\text{pixel}$  resolution) and *ca* 27 cm (*ca* 100  $\mu\text{m}/\text{pixel}$  resolution) were used to measure laminae thicknesses, and MAHLI images acquired between 2.6 cm (*ca* 16  $\mu\text{m}/\text{pixel}$  resolution, medium silt) and *ca* 9.5 cm (*ca* 40  $\mu\text{m}/\text{pixel}$  resolution, coarse silt) working distances were used to characterize grain size, shape and sorting. The Mastcam and MAHLI images employed in this study are non-colour corrected images with a minimal stretch applied to enhance contrast in some cases. The Mastcam images have been perspective or spherically projected.

### **Lamination thickness and grain-size measurements**

The method used in this study to measure lamination thickness is similar to that employed by Hurowitz *et al.* (2017). The thicknesses of individual laminae visible within the MAHLI field of view were measured using the orthogonal distance in pixel units between successive boundaries that define a discernible lamina, then pixel length was converted to a measured distance using the pixel resolution of the corresponding image (Supplementary Information S.3, Table S3-1). In this study, only those

MAHLI images offering a viewing perspective approximately parallel to bedding were used to minimize the possibility of measuring apparent rather than true lamina thickness since no correction for lamination dip was applied (Fig. S3-1). It is also unlikely that lamination dip would significantly affect the measured results: even if the laminae dipped 10°, a 2 mm lamina would appear 2.032 mm thick, which is less than 2% error on the measurement. Of the set of MAHLI images used in this study for thickness measurements, only one image location (Telegraph Peak) was also measured by Hurowitz *et al.* (2017). The M-34 images were used previously by Grotzinger *et al.* (2015) to measure lamination thicknesses at Pahrump Hills, but this study uses MAHLI or M-100 (only for the Salsberry Peak location) images because measured lamination thicknesses are below the pixel resolution of the M-34 camera.

For MAHLI images in which individual grains were resolvable, grain shape, rounding and sorting were classified using the schemes of Blatt *et al.* (1972), Powers (1953) and Harrell (1984), respectively. Grain size was measured via the circular intercept method (Hilliard, 1964) or via grain tracing or diameter measurement when grains were few (Supplementary Information S.2), and grain size was classified according to the schemes of Wentworth (1922) and Lazar *et al.* (2015). Lazar *et al.* (2015) recommended that very fine-grained rocks composed of at least 50% silt-sized or finer (<62.5 µm) grains be referred to generically as ‘mudstones’. In this study, as in Grotzinger *et al.* (2015), the term ‘mudstone’ has been adopted to describe any rock containing 50% or more of its surface area composed of detrital grains unresolvable by the MAHLI camera. Edgett *et al.* (2015) showed that high contrast grains as small as *ca* 30 to 40 µm in diameter, *ca* 2 to 3 pixels across in MAHLI images acquired at the smallest working distances, could be resolved in MAHLI images with the appropriate outcrop context. However, the resolvability of grains nearing the pixel resolution limits of the MAHLI camera is highly dependent on surface texture, phase angle, dust or sand cover, the contrast of the individual grains relative to the surrounding rock matrix, and one’s confidence in distinguishing clastic grains from secondary diagenetic textures (Yingst *et al.*, 2016). In this study, grain size assessments were made using MAHLI images taken at working distances between 2.6 cm and 9.5 cm, corresponding to pixel scales between *ca* 16 µm and 40 µm/pixel. Under ideal lighting, viewing and

surface conditions, grains ranging in diameter between 30  $\mu\text{m}$  and 80  $\mu\text{m}$  (two times pixel scale) should be resolvable in the images used in this study. To account for variability in these conditions, use of the term ‘mudstone’ in this study implies that the rocks probably are composed predominantly of grains finer than fine sand (<125  $\mu\text{m}$ ), but quantitative visual assessment of the relative proportion of clay, silt or very fine sand-sized particles within most of the very fine-grained rocks observed at Pahrump Hills is not possible. The ChemCam RMI images were used qualitatively to confirm grain-size observations and measurements made in MAHLI images. An alternative method of determining grain size in the rocks at Pahrump Hills by Rivera-Hernández *et al.* (2018) used ChemCam LIBS data supplemented by MAHLI and ChemCam RMI observations to attempt finer grain-size categorization than that presented here.

## **SEDIMENTARY FACIES**

Facies and subfacies at Pahrump Hills are distinguished on the basis of grain size, sedimentary structures including bedforms, bedding style and thickness, and relative erosional resistance to weathering. Facies are presented in order of increasing grain size. Four distinct sedimentary facies are identified at Pahrump Hills: thinly laminated mudstone, low-angle cross-stratified mudstone, thickly laminated mudstone–sandstone and cross-stratified sandstone (Table 1). Three of these facies were first described by Grotzinger *et al.* (2015) (Table 1): an additional facies, the low-angle cross-stratified mudstone facies, originally included in their thinly laminated mudstone facies is distinguished here. The conglomerate facies observed just prior to *Curiosity*’s arrival at Pahrump Hills is not included in this study due to uncertainties in the age and stratigraphic context of the conglomerate relative to the Pahrump Hills member.

### *Thinly laminated mudstone*

The thinly laminated mudstone facies is light grey (for example, Fig. 4A) to reddish-tan (for example, Fig. 4B) in colour on dust-free or brushed surfaces and is uniformly very fine-grained (Fig. 4A to D). Grain size is generally below the resolution of ChemCam RMI images (*ca* 40 to 130  $\mu\text{m}/\text{pixel}$ ) and the highest resolution Mastcam images (*ca* 150  $\mu\text{m}/\text{pixel}$ ) examined in this study, although in nearly all of the closest stand-off MAHLI images, clusters of dark pixels typically 2 to 10 pixels across, i.e. coarse silt to fine sand, are discernible (for example, Fig. 4D). Since these dark features, if they are detrital grains, make up less than 50% of the total observable surface area of the rock targets imaged, this facies is most likely to be composed predominantly of silt-sized or finer grains. No obvious grading was observed within this facies in Mastcam, RMI or MAHLI images.

This facies is characterized by the ubiquitous presence of sub-millimetre to millimetre-thick parallel laminations defined by resistant, sometimes knobby and irregularly-shaped ledges (Fig. 4C). The thinly laminated mudstone facies is divisible into two sub-facies based on laminae continuity, thickness and erosional expression (Fig. 5). The uneven, discontinuously laminated subfacies exhibits laminations of variable thickness that are faintly discernible, but are traceable only over maximum length scales of a few centimetres (Fig. 5A). The rhythmic sub-facies is characterized by laminations exhibiting extremely regular and even thickness that are traceable at least across the field of view of context Mastcam mosaics and often over length scales greater than 1 m (Fig. 5B). Twenty-seven laminae measured within the rhythmic subfacies at the base of Pahrump Hills range in thickness from 0.2 to 0.8 mm, with a mean thickness of 0.5 mm (Shoemaker Pelona target, Figs 6 and S3-1, Table S3-1). Ninety-two laminae measured within the rhythmic subfacies midway through the section range in thickness from 0.4 to 2.2 mm with a mean thickness of 1.4 mm (Telegraph Peak target, Figs 6 and S3-1, Table S3-1).

Sedimentary bedforms and cross-stratification are largely absent from the thinly laminated mudstone facies, with one instance of possible centimetre-scale ripple cross-lamination observed in this facies (Fig. 7). At least two stacked sets of north/north-west dipping foreset laminae were

observed at the Book Cliffs area, each approximately 2 cm in height. Foresets appear slightly curved and concave up, indicating asymptotic downlap onto the underlying bounding surfaces. More common in this facies, however, is the occurrence of geometric discordances expressed as the abrupt angular truncation of low-angle inclined subhorizontal laminations (Fig. 8). Lamination dip is difficult to constrain visually given the general planview exposures of this facies. The observable lateral extent of each truncation surface is limited by the field of view of the Mastcam image (for example, Fig. 8C) or the size of the block in which it was observed (for example, Fig. 8A). The number of laminae truncated by any one surface ranges from about ten to a hundred or more indicating that truncated lamina sets range in thickness from *ca* 1 cm to more than 1 m. Laminae above the truncation surface are always concordant with, and thus drape, the truncation surface.

#### ***Low-angle cross-stratified mudstone***

The low-angle cross-stratified mudstone facies contains discernible dark grains embedded within a light grey matrix, but these grains make up no more than a few percent of the visible surface area (Fig. 9). Grains range in size from *ca* 40  $\mu\text{m}$  to *ca* 115  $\mu\text{m}$  (silt to very fine sand, Table S2-3), with most grains falling within the coarse silt size range (*ca* 30 to 60  $\mu\text{m}$ , Fig. 9C). Two-hundred and thirty-two individual laminae within this facies range in thickness from *ca* 0.3 to 3.0 mm, with an average thickness of 0.6 mm and a mode of 0.5 mm (Chinle area, Figs 6 and S3-1, Table S3-1). Laminae are traceable up to *ca* 2 m laterally, although most laminations can be traced confidently only over several tens of centimetres due to discontinuity of outcrop exposure.

The low-angle cross-stratified mudstone facies is characterized by inclined laminae exhibiting apparent dips  $<10^\circ$  that sometimes show very even, regular thickness (Fig. 10). Laminations form sets ranging from *ca* 5 to 12 cm in thickness in which laminae downlap onto underlying truncation surfaces that appear to dip  $<5^\circ$  (Fig. 11A and B). Apparent dip directions of lamina sets are variable, with dip directions appearing to reverse relative to the immediately underlying set (Fig. 11A and B). Variably dipping laminations sometimes form cross-stratified sets measuring up to *ca* 1.0 to 1.5 m in

width and *ca* 20 to 30 cm in height (Fig. 11B and C), suggesting dune-scale three-dimensional bedforms. In one case, laminations form a structure measuring *ca* 10 cm in width with laminations that appear to transition laterally from concave up to concave down (Fig. 11D), providing additional evidence for the presence of three-dimensional bedforms within this facies. Laminae thicknesses remain constant throughout the curvature of the cross-strata.

### ***Thickly laminated mudstone-sandstone***

The thickly laminated mudstone–sandstone facies is dark grey in color on dust-free surfaces and exhibits specular reflection giving some facets a bright and shiny appearance (Fig. 12B and D). Weathered surfaces exhibit abundant pits filled with reddish-brown dust (Fig. 12C). Most pits are well-rounded and circular or sub-circular in shape, although rare pits appear polygonal and nearly square-shaped (Fig. 12C). Visible *in situ* grains, whose relief is flush with the outcrop surface, are distinguished by well-defined boundaries and a lighter grey colour compared to the dark grey matrix, although they are not observed to be uniformly present throughout the rock (Fig. 12D). Measurement of 83 grains reveals that the majority are circular, well-sorted and extremely well-rounded, with long axes, taken to represent grain diameter, ranging from 200  $\mu\text{m}$  to 1 mm (fine to coarse sand) (Fig. S2-1 and Table S2-1). Grains are clast-supported. Individual grains are not resolvable within the dark grey matrix suggesting a grain size of very fine sand or finer.

Planar laminae are most prominently expressed on weathered surfaces and are discernible due to alternations in relative resistance to weathering (Fig. 13). The expression of laminae may be due to changes in the relative proportion of sand-sized or mud-sized grains present within or between laminae, but distinct sand–mud couplets have not been positively identified in this facies. Individual laminae are on the order of several millimetres thick. Thicknesses measured for 60 laminae discernible in a Mastcam right-eye image mosaic with *ca* 1 mm/pixel image resolution range from 3.3 to 9.2 mm and exhibit an average thickness of 5.5 mm (Salsberry Peak target, Figs 6 and , Table S3-1). Because M-100 images were the only image data available to measure laminations of this facies,

laminations on the order of the thinnest laminations measured elsewhere at Pahrump Hills were not resolvable. Laminae can be traced laterally over length scales of tens of centimetres, although tracing laminations to greater distances is made challenging by the irregular, blocky nature of the outcrop and the presence of cross-cutting veins and fractures.

### ***Cross-stratified sandstone***

The cross-stratified sandstone facies contains white, tan and grey-coloured coarse silt to coarse sand-sized grains that make up at least *ca* 30% of the exposed rock surface area (Fig. 14). One hundred and twenty-nine individual grains measured in a MAHLI image of a dust-free, un-brushed surface within Whale Rock range in diameter from *ca* 50 to 900  $\mu\text{m}$  (coarse silt to coarse sand) with an average grain size of 240  $\mu\text{m}$  (fine sand) (Fig. S2-2, Table S2-2). The remainder of the exposed surface area is dark grey matrix in which individual grains generally cannot be resolved, suggesting a predominant grain size of very fine sand or finer. Discernible grains within this facies are matrix-supported, sub-rounded to rounded, well-sorted, and exhibit moderately low to high sphericity (Fig. 14). Grains appear randomly oriented and no obvious grading is observed within individual laminae. Laminae thickness is sub-millimetre to millimetre-scale. Measurement of 34 laminae reveals a thickness range of 0.3 to 4.5 mm with an average individual lamina thickness of 1.8 mm (Figs. 6 and S3-1, Table S3-1). Sedimentary structures observed within this facies include stacked sets of ripple-scale and dune-scale cross-stratification (Figs 15 and 16), including subcritically climbing ripples and dunes bounded by low angle bounding surfaces (Figs 15C, 15D and 16B). Cross-stratified beds range in thickness from *ca* 2 to 10 cm (Fig. 15). Individual foresets dip predominantly to the south-east, are tangential to basal truncation surfaces, and sometimes form wedges that thin down-dip (Fig. 16A). Foreset laminations are sometimes observed to exhibit very even, regular thicknesses (Fig. 16B). Climbing ripples whose crest heights are <1 cm and whose angle of climb is *ca* 40° also occur (Fig. 16B).

## SEDIMENTARY SUCCESSION AT PAHRUMP HILLS

The sedimentary succession at Pahrump Hills is illustrated in Fig. 17. The base of Pahrump Hills is composed of thinly laminated mudstone, with both the Confidence Hills and Shoemaker areas exhibiting geometrically discordant laminae of the rhythmic subfacies (Fig. 8). Thinly laminated mudstone in the vicinity of Pink Cliffs (-4459.5 m) is the best example of the uneven, discontinuously laminated subfacies exposed at Pahrump Hills (Fig. 5A). About 3 m above the base of the section (-4458 m), the Book Cliffs area exhibits parallel laminations of the thinly laminated mudstone facies, but with abundant distinguishable silt to very fine sand grains (i.e. Fig. 4D). Book Cliffs is also the only area composed of thinly laminated mudstone that exhibits possible ripple cross-lamination (Fig. 7). An interval of thinly laminated mudstone approximately 1 m thick (-4457.5 to -4456.5 m) separates the Book Cliffs area from the erosion-resistant ridges exposed in the Alexander Hills area (-4456 m). The thinly laminated mudstone between Book Cliffs and Alexander Hills consists of geometrically discordant laminae of highly even and regular thickness and is a prime example of the rhythmic subfacies (Fig. 5B). The ridges at Alexander Hills are composed of the rhythmic subfacies of the thinly laminated mudstone. Differential cementation due to secondary diagenesis rather than a change in primary grain size or lamination style probably best explains the variation in outcrop expression throughout this interval since no noticeable change in grain size was observed in the erosion-resistant ridges versus recessively-weathering bedrock.

A *ca* 1 m thick interval of the rhythmic subfacies of the thinly laminated mudstone [fig. 7b of Grotzinger *et al.* (2015)] occurs above Alexander Hills (-4456 m to -4455 m). At -4455 m, a sharp, irregular contact varying a few tens of centimeters in elevation occurs between thinly laminated mudstone and a broad, shallow lens consisting predominantly of low-angle cross-stratified mudstone (Fig. 18A and B). This lens, whose eastern and western ends are referred to as Gilbert Peak and Chinle, respectively, extends *ca* 20 m from east to west and is *ca* 70 cm thick at its centre (30:1 aspect ratio). The upper contact of the lens is gradational into overlying thinly laminated mudstone. At the



Chinle area, sets of low-angle cross-stratified mudstone pass upward into climbing ripple lamination of the cross-stratified sandstone facies (Fig. 18C and D). The interval of thinly laminated mudstone (-4454.5 to -4452 m) that overlies Chinle and Gilbert Peak is composed of rhythmic thinly laminated mudstone.

Cross-stratified sandstone also occurs in two discrete lenses named Newspaper Rock and Whale Rock which are located in the upper half of the Pahrump Hills section (-4454 m and -4452 m, respectively) (Fig. 18). The Whale Rock lens is *ca* 8 m in length, reaches a maximum thickness of *ca* 1.5 m (*ca* 5:1 aspect ratio), and tapers to the north-west and south-east. The Newspaper Rock lens measures *ca* 30 to 40 cm at its thickest and is *ca* 6 m in length (15:1 aspect ratio, Fig. 18D). The two lenses are separated laterally by *ca* 10 m, with the Whale Rock lens occurring *ca* 2 m higher in the section than the Newspaper Rock lens (Fig. 18A). The basal contact of the Newspaper Rock lens (Fig. 18D) is largely obscured by sand, but at Whale Rock the basal contact is sharp and overlies thinly laminated mudstone (Fig. 18E). The upper contacts of Whale Rock and Newspaper Rock are both gradational with overlying thinly laminated mudstone.

Approximately 3.5 m of thinly laminated mudstone is inferred to be present above Whale Rock (-4451 to -4448 m), although this interval was not examined in detail because the steepness of the outcrop and abundance of angular pebbles and cobbles precluded safe traverse of the rover. Mastcam images show this recessive interval to grade up-section from predominantly mudstone to the thickly laminated mudstone–sandstone exposed at Salsberry Peak, an outcrop whose base is located at -4448.5 m. Salsberry Peak forms a 1.5 to 2.0 m thick caprock at the top of the Pahrump Hills section (Fig. 13).

## **DEPOSITIONAL PROCESSES AND ENVIRONMENTS RECORDED WITHIN THE PAHRUMP HILLS MEMBER**

### *Depositional interpretation for the thinly laminated mudstone*

A depositional model for the Pahrump Hills member must account for the occurrence of a nearly 13 m thick section of continuously exposed, uniform, sub-millimetre to millimetre-scale parallel laminated mudstone. Processes considered for the deposition of the thinly laminated mudstone facies include: aeolian traction deposition, suspension settling of dust or ash from the atmosphere, suspension settling through a water column and deposition by currents in a subaqueous setting.

Thin planar laminations of uniform thickness are characteristic of some types of aeolian strata, with the uniformity of laminae resulting from the consistency of wind velocity and deposition rate in a given area over time (Hunter, 1977). The aeolian stratification types that might best fit the lamination style observed at Pahrump Hills include plane bed lamination or subcritically climbing translational strata (Hunter, 1977; Hunter, 1981). Plane bed lamination, formed when winds are strong enough to suppress ripple formation, is relatively rare in modern and ancient aeolian deposits on Earth (Hunter, 1977, 1981). The conditions needed to suppress aeolian ripple formation might be even less likely to occur on Mars if the atmospheric pressure at the time of Pahrump Hills member deposition was as low as that of present-day Gale crater (7 to 11 millibars) (Martínez *et al.*, 2017). Furthermore, sets of aeolian plane bed laminations are typically thin and often indistinctly defined when observed on Earth, rarely exceeding *ca* 0.5 to 1.0 m in thickness before transitioning into other types of aeolian stratification (Hunter, 1977; Hunter, 1981). Given the thickness and lateral extent of the thinly laminated mudstone facies at Pahrump Hills, as well as the distinctness of laminae observed there, an origin as aeolian plane bed deposits seems unlikely.

Subcritically climbing wind ripple lamination is a more plausible aeolian interpretation for the thinly laminated facies. Wind ripple stratification is very commonly observed in modern and ancient aeolian systems on Earth, and several known outcrops on Earth up to 7 m thick are composed almost

entirely of low-angle to flat climbing wind ripple strata, for example Hunter (1981) and Clemmenson & Hegner (1991). A wind ripple stratification interpretation for the thinly laminated mudstone facies at Pahrump Hills would be particularly compelling if ripple-foreset cross-lamination, inverse grain-size grading, preserved ripple forms, or a transition into aeolian cross-beds had been observed throughout the outcrop. Yet evidence for such features are largely absent at Pahrump Hills, with only one instance of possible ripple-foreset cross-lamination observed at Book Cliffs. As also noted by Grotzinger *et al.* (2015), there is no evidence that the thinly laminated mudstone at Pahrump Hills is interbedded with or grades into aeolian cross-bedded strata. A subcritical climbing wind ripple interpretation cannot be entirely precluded based on the absence of evidence for features typically observed in aeolian settings and given resolution limits that preclude observation of characteristics like inverse grading, but this interpretation is less convincing as a result.

Another possible explanation for the thin, uniform laminations at Pahrump Hills is suspension settling of wind-blown dust, silt or distal volcanic tephra from the atmosphere. Grotzinger *et al.* (2015) rejected this interpretation based on the observations that on Earth volcanic tephra and aeolian loess deposits are generally massively bedded unless fragments or particles have fallen through a water column in which increased fluid drag and variable settling velocities enable effective grain-size sorting and lamina formation. Siebach *et al.* (2017) showed that the composition of the Pahrump Hills member does not match that of Mars dust, suggesting that an origin as a duststone is unlikely. This study finds no additional evidence to support an interpretation that the thinly laminated mudstone was deposited by suspension settling from the atmosphere.

A third process considered to explain the uniformity and thinness of laminations observed throughout the Pahrump Hills mudstone succession is suspension settling through a water column in a low-energy setting. Metres-thick fine-grained laminated rhythmites have been observed in overbank levée and splay deposits on Earth (e.g. Farrell, 1987) but an overbank interpretation for Pahrump Hills seems unlikely given that thick, very fine-grained overbank suspension deposits are exceedingly rare in pre-vegetated fluvial systems preserved in the rock record on Earth (Davies & Gibling, 2010; Long, 2011, Gibling *et al.*, 2014; McMahon & Davies, 2018). Furthermore, there is no evidence for

subaerial exposure within the section at Pahrump Hills (for example, reworking by wind, pebble lags and desiccation cracks), nor for point bar deposits or stacked channel deposits that would probably be associated with overbank deposits of the thickness of the Pahrump Hills mudstone. Rather, observations presented here for the very fine grain size, lamination thickness and general lack of bedforms indicative of traction transport within the thinly laminated mudstone facies are most consistent with deposition in a subaqueous lacustrine setting.

Continuous, thin laminations of uniform thickness are commonly found as varves in proglacial and periglacial lakes on Earth that experience repeated seasonal changes that affect the grain size, composition and sorting of sediments entering the lake (Smiley, 1955; Anderson & Dean, 1988). Cyclic forcing or modulation within the fluvio-lacustrine system on a number of different timescales, including daily or annual changes in temperature and river flow, could have been responsible for the formation of uniform, thin laminations at Pahrump Hills. Although varves have been interpreted by some to result predominantly from suspension settling from hypopycnal plumes (overflows) entering lakes (e.g. Antevs, 1951), bottom-hugging turbidity currents are also thought to be an important depositional mechanism in varve formation (e.g. Sturm & Matter, 1978; Anderson & Dean, 1988). The occurrence of low-angle truncation surfaces observed throughout the thinly laminated mudstone facies (Figs 8 and 17) suggests a depositional process in addition to passive settling from suspension. Truncation surfaces are distinct in that they are invariably overlain by laminae that are conformable with the underlying truncation surface itself with no observed lateral changes in laminae thickness (Fig. 8A). They most closely resemble subaqueous ‘scour and drape’ structures (Dott & Bourgeois, 1982; Duke *et al.*, 1992; Cheel & Leckie, 1993; de Luca & Basilici, 2013) which form when scouring of deposited sediment by wave or current action is followed by deposition of sediment settling through the water column to form beds or laminae that drape the original scour without the influence of currents or waves. The absence of evidence for wave action, for example symmetrical bedforms or hummocky cross-stratification, throughout the thinly laminated mudstone facies favours deposition of the scour and drape structures by current action.

In the context of a subaqueous lacustrine setting, the occurrence of scour and drape structures in the Pahrump Hills member further constrains the depositional origin of the thinly laminated mudstone facies. Grotzinger *et al.* (2015) proposed deposition from either hyperpycnal or hypopycnal plumes as possible interpretations for the thinly laminated mudstone facies. The presence of abundant scour and drape structures probably rules out deposition solely by hypopycnal plumes, which would only be expected to passively rain out sediment. By contrast, bottom-hugging turbidity currents can originate from plunging river plumes, i.e. hyperpycnal flows (Mulder & Syvitski, 1995; Mulder *et al.*, 2003) or wave-generated resuspension. As noted by Grotzinger *et al.* (2015), the section at Pahrump Hills does not show evidence for coarser graded beds and is largely lacking in bedforms characteristic of flow deceleration sequences that would be expected from failure of a sandy clinof orm fed by a coarse-grained braided river.

In modern and ancient deposits associated with plunging river plumes on Earth, thick deposits of parallel laminated fine-grained sediments are common and characteristic (Mutti *et al.*, 1996; Myrow *et al.*, 2008; Lamb *et al.*, 2008; Bhattacharya & MacEachern, 2009; Olariu *et al.*, 2010; Zavala *et al.*, 2011). Internal scour surfaces (Zavala *et al.*, 2006; Bhattacharya & MacEachern, 2009) and low-angle laminations (Zavala *et al.*, 2006; Lamb *et al.*, 2008; Zavala *et al.*, 2011) occur in facies associated with the collapse and lofting of a plume's suspended load and are particularly common in shallow water systems (Zavala *et al.*, 2011). Although the presence of traction transport bedforms is often an important indicator of the waxing and waning of flows characteristic of plunging plume deposition (Mulder *et al.*, 2003), planar laminated mudstones and siltstones lacking evidence for traction transport are commonly observed in the distal reaches of hyperpycnal systems where deposition of the finest-grained material occurs either by lofting by the hyperpycnal plume and subsequent settling from the water column (Zavala *et al.*, 2011, and sources within) or via passive settling between flow events.

Similarities between the thinly laminated mudstone facies and distal plunging plume deposits recognized on Earth, coupled with the common occurrence of scour and drape structures throughout the Pahrump Hills section, favour an origin for the bottom currents as muddy hyperpycnal river plumes. In this depositional context, the mudstone laminations, which range from 0.2 mm to *ca* 10 mm in thickness and averages *ca* 2 mm overall (Fig. 6), are interpreted to represent deposition primarily by plunging plumes (Mulder *et al.*, 2003; Lamb *et al.*, 2008). Although it is unlikely that every single lamination within the thinly laminated mudstone facies represents an individual event bed, a significant proportion of the laminae at Pahrump Hills may represent event beds. Given the total thickness of this facies (*ca* 11 m) and an average laminae thickness of *ca* 2 mm, there could be as many as thousands of event beds recorded in the Pahrump Hills succession.

***Depositional interpretation for the low-angle cross-stratified mudstone and cross-stratified sandstone facies***

Grotzinger *et al.* (2015) proposed two possible interpretations for the depositional origin of the coarse-grained cross-stratified lenses observed at Pahrump Hills: (i) subaqueous channelized delta foreslope deposits deposited under decelerating flow conditions after an initial phase of scour; or (ii) fluvial deposits that were incised into lacustrine deposits during lake level drawdown. Observations presented in the current study support the former interpretation. Given the absence of mudcracks and the paucity of coarser grained sandstones and gravels throughout the section, it seems unlikely that the Pahrump Hills member records evidence of substantial lake drying that would be expected if the Whale Rock–Newspaper Rock–Chinle lenses are regarded as subaerial fluvial deposits. Furthermore, the sandstones and conglomerates of the Bradbury group (Williams *et al.*, 2013; Vasavada *et al.*, 2014; Grotzinger *et al.*, 2015; Stack *et al.*, 2016; Rice *et al.*, 2017), the most plausible analogue for the river systems that fed the Gale crater lake (Grotzinger *et al.*, 2015), probably were deposited as wide sheets of coarse alluvium exhibiting width to thickness ratios greater than 1000:1, typical of a

braided fluvial fan (Gibling, 2006). In contrast, sandy lenses cut into the Pahrump Hills mudstone have widths that are too narrow compared to their thickness (aspect ratios range from 5:1 to *ca* 30:1) to represent alluvial braid plain channels.

The sandstone facies exposed at Chinle/Gilbert Peak, Whale Rock and Newspaper Rock are most consistent with an interpretation in which each lens represents the incision of a sublacustrine channel followed by deposition during a short-lived, energetic plunging plume event. The occurrence of these three sandstone lenses at different stratigraphic heights within the Pahrump Hills succession suggests that each lens represents a distinct plume event. The upward transition from low-angle cross-stratified mudstone to dune and ripple cross-laminated sandstone in the upper part of the Chinle outcrop is consistent with variations in the flow velocity (Mulder & Alexander, 2001; Sumner *et al.*, 2008; Zavala *et al.*, 2011). The presence of variably dipping, convex laminations within Chinle and Gilbert Peak could represent cross-sections through bar deposits within a shallow, broad channel or Froude-supercritical bedforms such as antidunes or cyclic steps (Kostic & Parker, 2006; Kostic, 2011; Cartigny *et al.*, 2011; Postma *et al.*, 2014). Cross-laminated sets observed at Whale Rock and Newspaper Rock could also be consistent with bedforms such as migrating scour and fill structures formed during Froude super-critical flows (e.g. Cartigny *et al.*, 2014). Froude-supercritical bedforms would be consistent with plunging plumes, which have Froude numbers near one (Lee & Yu, 1997; Lamb *et al.*, 2010). Palaeocurrent directions inferred from the southward dip of climbing ripple foresets within Whale Rock suggest a predominantly southward sediment transport direction, consistent with sediment transport and progradation of a river system from the northern rim of Gale crater towards the centre of the crater basin.

## **DEPOSITIONAL MODEL FOR PAHRUMP HILLS**

Observations of sedimentary structures, textures and grain size presented here support a depositional model for the Pahrump Hills member in which southward-flowing river-fed plunging plumes deposited event beds in a lacustrine setting (Fig. 19). As braided rivers flowed south into a

lake within Gale crater, sediment-laden plumes plunged near the toes of delta mouth bar clinoforms (Grotzinger *et al.*, 2015), scouring previously deposited sediments. Such a process would have deposited the coarser sandstone lenses observed in the upper half of the Pahrump Hills section. Suspension settling through the water column following plume lofting or via passive fallout between plume events deposited the draping laminations of the scour and drape structures observed throughout the thinly laminated mudstones at Pahrump Hills. Deposition recorded within the thinly laminated mudstone in the lower half of the Pahrump Hills section must have occurred at a position distal enough from the lake margin such that deposition was dominated by suspension settling and/or lofting of fines towards the end of each plunging plume event, but shallow enough to record evidence for scouring earlier in the event to form the observed scour and drape structures. Such conditions could be achieved at the distal ends of subaqueous plume lobes or at plume margins (Zavala *et al.*, 2011). As the river system prograded basinward either via delta progradation or lakeward shift of the river mouth, successive channelized flows including the proximal mudstone and sandstone lenses at Chinle, Newspaper Rock and Whale Rock were deposited near the plunge point. A slight backstep of the system, or channel switching could explain the return to thinly laminated mudstone above Whale Rock, but continuing progradation resulted in a transition from the thinly laminated mudstone to thickly laminated mudstone and sandstone higher up in the succession observed at Salsberry Peak.

The overall thickening-upward trend observed in the lamination measurements from the Pahrump Hills succession (Fig. 6) supports a progradational model for the river system into the basin. The trend reported here is consistent with the thickening trend reported by Grotzinger *et al.* (2015) and seen in the Hurowitz *et al.* (2017) thickness measurements between the Alexander Hills, Chinle and Telegraph Peak areas of Pahrump Hills. The thickening-upward trend observed at Pahrump Hills is likely to be the result of a transition up-section to a more proximal, shallower water environment created as the river system prograded out into the basin. Proximal to the basin margin, plunging plumes would be expected to have increased sediment load and would have deposited coarser, thicker laminae. As the plumes extended further into the basin, they would thin, become more dispersed, and lose flow competency resulting in the deposition of increasingly thinner laminae with distance from



the lake margin. The occurrence of coarser-grained lenses exhibiting sedimentary structures characteristic of traction transport in the upper half of the Pahrump Hills section, coupled with the transition into coarser-grained thickly laminated mudstone-sandstone suggests that the Pahrump Hills member records a progradational succession in which the distal lacustrine setting preserved at the base of the section transitions up-section to a more proximal basin margin environment (Fig. 19).

## PLUNGING PLUME ANALYSIS

The observations here suggest that plunging river plumes may have been the dominant depositional mechanism in the ancient lake recorded at Pahrump Hills. Given the specific conditions under which plunging of a river plume is triggered, this interpretation places important constraints on the salinity of the ancient lake in Gale crater.

Seas and lakes that lack a riverine outlet or significant exchange with groundwater often accumulate solutes, which are delivered by river runoff and left behind and concentrated by evaporation. A global compilation of rivers on Earth (Mulder & Syvitski, 1995) shows that plunging river plumes are relatively uncommon in saline water bodies because saline water is denser than the incoming riverine freshwater, although high suspended sediment concentrations during large floods can sufficiently increase the effective river water density to allow plunging, for example Wright *et al.* (1986). In addition to the necessary condition of a negative buoyancy anomaly for river water, the plume velocity and discharge must also satisfy an instability criteria to trigger plunging (Akiyama & Stefan, 1984; Parker & Toniolo, 2007). Here, two physical constraints on the occurrence of plunging are used to show the range of sediment concentrations and associated fluid densities within a Gale crater lake.

River plunging occurs at a critical densimetric Froude number,  $Fr_d \approx 0.5$  and plumes collapse just beyond the plunge point to  $Fr_d \approx 1$  (Lee & Yu, 1997; Lamb *et al.*, 2010). The densimetric Froude number at which plumes collapse should be the same for both Earth and

Mars since the transition from potential energy of the plume just prior to collapse to purely kinetic energy upon collapse requires a condition of  $Fr_d \approx 1$ . The densimetric Froude number, by definition, can be written as:

$$Fr_d^2 = \frac{\rho_L U^3}{(\rho_P - \rho_L) g q} \quad (1)$$

where  $U$  is the layer-averaged plume velocity,  $g = 3.71 \text{ m}^2/\text{s}$  is the acceleration due to gravity on Mars,  $q$  is the volumetric river discharge per unit width,  $\rho_P$  is the plume density and  $\rho_L$  is the lake density (Fig. 19). To estimate the lake density from Eq. 1, the river discharge, flow velocity near the plunge point and the density of the river plume need to be constrained.

Conglomerates of the Bradbury group are exposed intermittently along the 10 km traverse between Bradbury Landing and the base of Pahrump Hills (Williams *et al.*, 2013; Mangold *et al.*, 2016) and may inter-finger with the Murray formation at Pahrump Hills (Grotzinger *et al.*, 2015). Here, it is assumed that these gravels were deposited by rivers that fed the ancient lake, and the reconstruction estimate of Williams *et al.* (2013) based on gravel transport thresholds is used, which yields a maximum flow depth of 0.9 m and a maximum average flow velocity of 0.75 m/s, i.e.  $q = 0.68 \text{ m}^2/\text{s}$ .

To constrain the flow velocity at the plunge point, it is assumed that the sand lenses in the Pahrump Hills member (Chinle/Gilbert Peak, Whale Rock and Newspaper Rock) were deposited near the plunge point. Scour to produce the channel forms and deposition of sands within the lenses both suggest an energetic environment proximal to the plunge point where mouth bar clinofolds create steep topographic slopes and where plunging plumes accelerate due to flow collapse (Fig. 19). The sand lenses within Pahrump Hills contain climbing cross-strata with sets that range in thickness from 2 to 10 cm and critically climbing ripples with crest

heights <1 cm, suggesting that the bedforms were near the stability threshold between ripples and dunes. Through an exhaustive compilation of current ripple data on Earth, Lapotre *et al.* (2017) showed that the stability boundary between ripples and dunes is well-represented by a constant Yalin Number of  $\chi = 4$ , where the Yalin Number is defined as:

$$\chi \equiv \frac{u_*^2 D^{1/2}}{\nu(Rg)^{1/2}} \quad (2)$$

in which  $u_*$  is the bed shear velocity,  $D$  is the particle diameter,  $\nu$  is the kinematic viscosity of water and  $R$  is the submerged specific density of sediment. Particle diameter,  $D$  is set to 0.24 mm, as observed for Whale Rock,  $R = 2.0$  and  $\nu = 10^{-6} \text{ m}^2/\text{s}$  for basaltic sand in freshwater. The bed shear velocity can be related to the layer-averaged flow velocity,  $U$ , using:

$$U = C_f^{-0.5} u_* \quad (3)$$

where  $C_f$  is a bed friction coefficient which is estimated to  $C_f \approx 5 \times 10^{-3}$  from (Sequeiros *et al.*, 2010). Using these values with Eq. 2 and  $Fr_d \approx 1$  yields an estimate of the flow velocity near the plunge point of  $U = 0.38 \text{ m/s}$ . Given these values, depths at the plunge point are predicted to be  $q/U = 1.8 \text{ m}$  and plumes tend to collapse to about 70% that depth after plunging (Lee & Yu, 1997; Lamb *et al.*, 2010), yielding a plume flow thickness of 1.3 m. This hyperpycnal flow thickness is consistent with the sizes of the sand lenses (*ca* 1 m).

Finally, the river plume density can be found from mass balance to be:

$$\rho_p = c\rho_s + (1-c)\rho_w \quad (4)$$

where  $c$  is the depth-averaged, volumetric sediment concentration (dimensionless),  $\rho_s = 3000$  kg/m<sup>3</sup> is the density of basaltic sediment and  $\rho_w = 1000$  kg/m<sup>3</sup> is the density of the river water, assuming freshwater. Suspended sediment loads in coastal rivers tend to be dominated by the mud fraction, which is transported as washload and is notoriously difficult to predict. Instead, riverine sediment concentration,  $c$ , is set to be an independent variable and Eqs 1 to 4 are used to predict the lake density required for plunging. Combining Eqs 1 to 4 shows that lake density required for plume plunging is reflective of characteristics of the bedforms deposited near the plunge point represented here by the Yalin number and grain size, which were held constant based on observations from the sand lenses at Pahrump Hills.

Figure 20 shows the generic river plume density,  $\rho_p$ , calculated by mass balance via Eq. 4 as a function of the input suspended sediment concentration of the river,  $c$ . Also shown in Fig. 20 is predicted lake density,  $\rho_L$ , calculated by combining Eqs 1 to 4 and solving for  $\rho_L$  as a function of input suspended sediment concentration of the river,  $c$ , needed for the plume to plunge. The difference in suspended sediment concentration,  $c$ , between these two curves shows the added river sediment concentration needed for a plume both to plunge and to reach the velocities needed to produce the bedforms at the stability threshold between ripples and dunes (Yalin number = 4, grain size of  $D = 0.24$  mm) that were observed within the sand lenses at Pahrump Hills. The difference in fluid density,  $\rho$ , between these two curves for a given value of  $c$  represents the density differential between the river plume and the lake needed for the plume to plunge while also reaching the velocities required to produce the bedforms observed within the Pahrump Hills sand lenses.

The analysis shows that the feeder rivers must have had sediment concentrations that exceeded 1% in order to plunge while also satisfying conditions required to produce the bedforms observed in the sand lenses at Pahrump Hills. Even in a freshwater lake, plumes with  $0 < c < 1\%$ , despite being denser than the lake water, would not plunge and also produce velocities that explain the observed bedforms in the sand lenses at Pahrump Hills. As the suspended sediment concentration and plume density are increased, the predicted lake density must also increase for the plunging plume velocities to be consistent with the observed bedforms. For example, sediment concentrations of approximately 2.5% produce a plume with density of  $\rho_p = 1050 \text{ kg/m}^3$  and require a saline lake with a density of  $\rho_L = 1028 \text{ kg/m}^3$  similar to Earth's oceans to explain the observed bedforms. Salinity levels that exceed ocean water would require river plume sediment concentrations that exceed several percent.

Minimum values measured for suspended sediment concentrations in alluvial rivers on Earth rarely exceed 1.5% (Mulder & Syvitski, 1995). Freshwater river plumes have density equivalence with Earth's oceans with sediment concentration of *ca* 1.4% (Fig. 20), which explains why plunging river plumes are exceedingly rare in the ocean but are common in freshwater lakes and reservoirs (Fan & Morris, 1992; Kostic & Parker, 2003). Mulder & Syvitski (1995) showed that only nine out of 150 rivers analyzed that drain to the ocean are capable of producing plunging plumes annually; and that these nine 'dirty' rivers all have average annual minimum sediment concentrations of  $< 1.5\%$ . Sediment concentrations during extreme flood events (for example, 100 year flood) can be higher (Mulder & Syvitski, 1995); however, concentrations beyond 10% are unlikely to produce the observed ripple and dune stratification due to buoyancy stratification that suppresses turbulence (Baas *et al.*, 2016).

Due to the ubiquity of possible event beds in the Pahrump Hills member, plunging plumes could have been relatively common and, given minimum sediment concentrations of  $< 1.5\%$  during typical floods on Earth, this suggests that the lake water had a density near freshwater (Fig. 20). Lake densities greater than Earth's oceans would require sediment

concentrations that exceed *ca* 2.5%, which could be possible for more extreme and infrequent flood events. Based on the calculations presented here, lake densities greater than 1176 kg/m<sup>3</sup> (corresponding to *c* = 10%) are unlikely within the Gale crater lake.

## **IMPLICATIONS OF A HYPERPYCNAL ORIGIN FOR THE HABITABILITY OF GALE CRATER AND OTHER MARTIAN CRATER LAKE DEPOSITS**

Several different interpretations have been proposed regarding the salinity of the ancient Gale crater lake recorded in the Pahrump Hills section. The potential for short episodes of evaporation and increased salinity (Kah *et al.*, 2018) recorded in the Pahrump Hills section, or, alternatively, the presence of a deep, saline lake (Schieber *et al.*, 2015) was based on an interpretation of millimetre-scale laths in the basal strata of Pahrump Hills as pseudomorphs after a primary evaporitic phase. Additionally, the presence of hematite and jarosite in the basal Pahrump Hills member, coupled with observed enrichments in Zn, Ni and Mn, have been proposed to possibly represent deposition in an acid saline lake (Rampe *et al.*, 2017). However, Hurowitz *et al.* (2017) proposed that hematite, jarosite and trace mineral enrichments result from oxidative processes in a shallow lacustrine setting, and that chemical and sedimentological features associated with saline fluids resulted from interaction with late diagenetic brines, rather than saline lakewater. Grotzinger *et al.* (2015) also used the lack of primary bedded evaporite deposits and the lack of evidence for sedimentary structures suggestive of subaerial exposure and evaporation to suggest that the ancient lake in Gale crater probably was relatively fresh. The analysis in this study supports a dominantly freshwater interpretation for the ancient Gale crater lake, and suggests that evidence for enhanced salinities would represent, at most, ephemeral episodes – constrained to the lowermost exposed strata – recorded within the Pahrump Hills member.

The presence of a 13 m thick progradational succession at Pahrump Hills recording thousands of laminae, many of which may be individual events beds, suggests that the freshwater lake in Gale crater was relatively stable and long-lived. Whilst accurately determining the time duration represented by this section is impossible without absolute age dates, application of reasonable recurrence intervals for plunging plumes can provide a general constraint. The calculations presented in the previous section support a freshwater interpretation for the Gale crater lake, suggesting that conditions necessary for plunging could have been relatively common. If such conditions were achieved seasonally, the section at Pahrump Hills could represent deposition on the order of  $10^3$  Earth years. If the salinity of the Gale crater lake was closer to that of Earth's oceans, plunging events might have occurred less frequently. Mulder & Syvitski (1995) found that it is common for rivers entering the Earth's oceans to generate hyperpycnal flows at intervals ranging from <100 to 1000 Earth years, with a maximum interval of one flow every 1000 to 10,000 Earth years. If plunging was relatively rare in the Gale crater lake, deposition of the Pahrump Hills section could have spanned up to  $10^5$  to  $10^7$  Earth years.

The record of an ancient stable freshwater lake preserved within the Pahrump Hills member has important implications for the sustained habitability of the Gale crater sedimentary succession. Salinity is an important constraint on habitability since high solute concentrations decrease the availability of water molecules for hydration reactions and may limit cellular function (Grant, 2004; Knoll & Grotzinger, 2004; Tosca *et al.*, 2008; Grotzinger *et al.*, 2014). In this study, the fluid density of the ancient Gale crater lake is constrained to be likely similar to that of freshwater on Earth (*ca*  $1000 \text{ kg/m}^3$ ) and most likely no higher than Earth's oceans ( $1027 \text{ kg/m}^3$ ). This result suggests that the water activity of the ancient Gale crater lake would likely have been conducive to sustained habitable conditions at the surface of Mars during Pahrump Hills member deposition. The first habitable freshwater lacustrine environment explored by the MSL Science Team in the Sheepbed mudstone of Yellowknife Bay (Grotzinger *et al.*, 2014) is *ca* 80 m lower in the stratigraphy than the Pahrump Hills member. Therefore, the presence of these two freshwater lake deposits suggests either

a continued record of habitable conditions within Gale crater, or multiple episodes in which habitable conditions were sustained at the surface.

Exploration beyond Pahrump Hills has revealed that the Murray formation extends at least 300 m in thickness (Grotzinger *et al.*, 2015; Fedo *et al.*, 2017, 2018; Rivera-Hernández *et al.*, 2018). Initial analysis of the overlying Murray formation indicates the recurrence of similar facies as those seen at Pahrump Hills throughout this interval (Fedo *et al.* 2017, 2018) and the analysis presented here can serve as a guide during further refinement of the Murray formation depositional interpretation. The facies association described for Pahrump Hills may also serve as a reference for the recognition of river-fed crater basin lake deposits by future *in situ* missions to Mars at new landing sites. The Mars 2020 rover mission currently in development is NASA's next flagship Mars rover mission and the first in a series of missions whose goal is to return Mars samples to Earth. The Mars 2020 project is currently considering Jezero crater, an open-basin crater lake site containing a preserved inverted delta and a thick sequence of basin-filling deposits (Fassett *et al.*, 2005; Goudge *et al.*, 2015, 2017, 2018), as one of three final candidate landing sites. Should Jezero crater be chosen as the landing site for the Mars 2020 rover, the facies associations and depositional model presented here for the Pahrump Hills member – primarily the occurrence of thinly laminated mudstone containing low-angle scour and drape structures interbedded with channelized sand-lenses – could be used as a comparison enabling the recognition of river-fed lake deposits at the Mars 2020 field area.

## CONCLUSIONS

This study presents a depositional model for the Pahrump Hills member of the Murray formation in which thinly laminated mudstones are interpreted to represent deposition of event beds via suspension settling and lofting at the distal margins of river-generated hyperpycnal flows entering an ancient lake in Gale crater. The occurrence of 'scour and drape' structures throughout the thinly laminated mudstone facies favours a subaqueous lacustrine interpretation for the Pahrump Hills member over subaerial alternatives such as airfall of volcanic or aeolian material or aeolian tractional



or grainfall deposition. Coarser-grained lenses within Pahrump Hills succession that exhibit dune and ripple cross-lamination are interpreted to represent predominantly southward transport in shallow subaqueous channelized flows. The occurrence of these channelized deposits in the upper half of the Pahrump Hills section, combined with the overall thickening and coarsening-upward trend observed as the thinly laminated mudstone transitions conformably into planar thick laminated sandstone capping Pahrump Hills, is interpreted as an overall progradational succession. Palaeohydraulic modelling places additional constraints on the salinity of the ancient Gale crater lake. In order for hyperpycnal flows to plunge and form ripple and dune cross-stratification like that observed in the sandy lenses of Pahrump Hills, the density of the lake body was likely to be similar to that of freshwater on Earth and no denser than Earth's seawater. The presence of thousands of laminae within the Pahrump Hills section supports an overall lake duration likely on the order of  $ca\ 10^3$  Earth years, with a maximum possible duration up to  $ca\ 10^7$  Earth years, consistent with the stability implied by the progradational sequence. These results are consistent with the long-term persistence of an ancient sustained freshwater lake, the key component of the habitable environment described at this site.

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## FIGURE CAPTIONS

**Figure 1:** (A) Gale crater viewed in a Mars Odyssey Thermal Emission Imaging Systems (THEMIS) daytime infrared basemap draped with topography from the Mars Global Surveyor Mars Orbiter Laser Altimeter (MOLA) topography. (B) *Curiosity*'s field site in Gale crater. The white line marks the rover's traverse from Bradbury Landing to the Sol 2053 position. The extent of the Murray formation recognized in orbital images (shown in yellow) was mapped on a Context Camera (CTX) basemap at a scale of 1:15k.

**Figure 2:** Schematic stratigraphic column of the sequence of rocks explored by the *Curiosity* rover team in Gale crater [after Grotzinger *et al.* (2015) and Fedo *et al.* (2017)].

**Figure 3:** The location of the Pahrump Hills outcrop. (A) In relation to the *Curiosity* landing site, the rover's traverse through the Bradbury group of Aeolis Palus and the northern extent of the Murray formation (mapped in yellow) shown on a grey-scale High Resolution Imaging Science Experiment (HiRISE) mosaic. (B) Pahrump Hills (outlined in yellow) shown on a colour HiRISE mosaic. Image IDs: ESP\_021610\_1755 and ESP\_033649\_1750. White line indicates *Curiosity*'s traverse through the area. (C) The *Curiosity* rover's walkabout strategy at Pahrump Hills annotated with main areas explored by the rover. Yellow dot indicates the rover position when the mosaic in (D) was acquired; dashed yellow lines indicate the ground coverage of the mosaic in (D) in plan view. (D) Main areas explored at Pahrump Hills annotated on a Mastcam M-34 mosaic acquired on Sol 751. Drill location abbreviations: CH = Confidence Hills; MJ = Mojave; TP = Telegraph Peak.

**Figure 4:** Mars Hand Lens Imager (MAHLI) images of brushed thinly laminated mudstone facies observed at: (A) Telegraph Peak (MAHLI image 0905MH0001900010302821C00) showing the grey colour of brushed bedrock and the thin laminations, (B) Maturango target at Confidence Hills

(MAHLI z-stack 0755MH0001930000204562R00) showing the red colour of brushed bedrock, indentations made by the brush bristles, surface roughness and lack of clearly defined clasts, (C) Ricardo target at Shoemaker (MAHLI z-stack 0806MH0004420000300695R00) showing the grey colour of brushed bedrock, brush indentations and laminations, and unbrushed outcrop observed at (D) Anaverde target at Book Cliffs (MAHLI z-stack 0814MH0001810000301371R00). White arrows point to possible dark silt to very fine sand-sized grains.

**Figure 5:** Sub-facies of the thinly laminated mudstone facies. (A) Discontinuous, unevenly laminated sub-facies exposed at Pink Cliffs acquired with the Mastcam M-100 camera on Sol 810. (B) Rhythmically laminated sub-facies exposed at the Calico Mountain area near Telegraph Peak acquired with the Mastcam M-100 camera on Sol 837.

**Figure 6:** Elevation versus lamination thickness for five areas measured within Pahrump Hills. Solid points represent mean values; error bars in x represent one standard deviation.

**Figure 7:** Possible ripple cross-lamination observed in Book Cliffs in: (A) Mastcam M-100 mosaic acquired on Sol 813, (B) ChemCam RMI image mosaic of the Goblin Valley target, unannotated, (C) ChemCam RMI image mosaic of the Goblin Valley target, annotated to show possible ripple cross-lamination sets separated by planar laminations.

**Figure 8:** Geometric discordances within the thinly laminated mudstone facies: (A) Mastcam M-34 mosaic acquired on Sol 797 midway through the rover's traverse from Whale Rock to the base of the section at an elevation approximately equivalent to Alexander Hills; with (B) annotated laminae and truncation surfaces. (C) Confidence Hills imaged by Mastcam M-34 on Sol 803; and (D) annotated

laminae and truncation surfaces. (E) and (F) Show example truncations surfaces within the mosaic in (C), whose tone, contrast and colour has been enhanced to highlight laminations.

**Figure 9:** Mars Hand Lens Imager (MAHLI) images of the low-angle cross-stratified mudstone at the Goldstone target at Chinle taken at successively decreasing working distances: (A) MAHLI image (0830MH0001900010301787C00) acquired at a working distance of 26.5 cm showing the brushed bedrock spot and through-going laminations, (B) MAHLI z-stack (0831MH0001700000301834R00) acquired a working distance of 6.9 cm showing a close-up view of the brushed spot, (C) MAHLI z-stack (0831MH0001700000301832R00) acquired at a working distance of 3.8 cm. Arrows indicate the location of discernible silt to very fine sand-sized grains.

**Figure 10:** Variable lamination characteristics observed within the low-angle cross-stratified mudstone at Chinle. (A) Laminated intervals exhibiting extremely regular and even thickness underlain by an interval of laminations exhibiting uneven thickness observed in an oblique MAHLI image (0828MH0004540000301740R00). (B) Laminations of very even, uniform expression and uneven thickness observed in a Mastcam M-100 mosaic acquired on Sol 792.

**Figure 11:** Variably dipping laminations observed at the Chinle area in a Mastcam M-100 mosaic acquired on Sol 821: (A) unannotated Mastcam; and (B) lamination traces. (C) and (D) Show variable dipping convex to concave laminae geometries. Arrows indicate apparent dip direction; circle with the cross indicates an apparent dip direction into the page.

**Figure 12:** (A) Navcam mosaic showing the location of the Kanosh cobble relative to the Salsberry Peak outcrop and nearby field of boulders and cobbles. (B) Mastcam M-100 mosaic of the Kanosh

cobble shed from the Salsberry Peak outcrop acquired on Sol 940. (C) Circular (yellow arrow) and dust-filled rectangular pits (white arrows) observed in a MAHLI image 0942MH0001630000303660R00 of the Little Devil target. (D) Rounded grains observed in the Devils Punchbowl MAHLI target (0942MH0001630000303664R00).

**Figure 13:** (A) Laminations within Salsberry Peak observed in Mastcam M-100 mosaic acquired on Sol 855.

**Figure 14:** (A) Light-toned white and tan grains present in the Sierra Nevada target at Whale Rock (MAHLI image 0860MH0004580000302120R00). (B) Inset showing close-up view of light grains in a dark grey very fine-grained matrix.

**Figure 15:** Dune and ripple-scale cross-stratification observed in a Mastcam M-100 mosaic acquired on Sol 821 at; (A) and (B) Whale Rock, and (C) and (D) subcritically climbing dune and ripple-scale cross-stratification in the upper portion of Chinle. Bounding surfaces between sets are annotated in red.

**Figure 16:** (A) Dune foresets at Whale Rock observed in a Mastcam M-100 mosaic acquired on Sol 862; tangential foresets thin towards the base. (B) Critically climbing ripples at Newspaper Rock in a Mastcam M-100 mosaic from Sol 921.

**Figure 17:** Stratigraphic column for the Pahrump Hills succession.

**Figure 18:** (A) Cross-stratified mudstone and sandstone lenses at Pahrump Hills annotated in a Mastcam M-100 mosaic from Sol 751: (B) and (C) Gilbert Peak/Chinle (Mastcam M-100 mosaic acquired on Sol 821). (D) Newspaper Rock (Mastcam-100 mosaic acquired on Sol 903). (E) Whale Rock (Mastcam M-100 mosaic acquired on Sol 837).

**Figure 19:** Schematic illustrating the conceptual model for the deposition of the Pahrump Hills member mudstone and sandstone lenses via river-fed plunging plumes in an ancient Gale crater lake. Proximal sand lenses form from the incision of subaqueous channels (dashed lines within the plume) when the plume plunges.

**Figure 20:** Fluid density of a modelled river plume as a function of suspended sediment concentration of the river calculated by mass balance via Eq. 4. Also plotted is the lake density in Gale crater as a function of river sediment concentration required for the river plume to plunge and to reach the velocities needed to produce the bedforms observed in sand lenses within the Pahrump Hills section. The blue vertical dashed line represents the minimum suspended river sediment concentration needed for the plume plunge in the Gale crater lake, and also highlights the minimum river plume and lake densities needed for plunging to occur. The red vertical dashed line indicates a suspended river sediment concentration of 1.5%.

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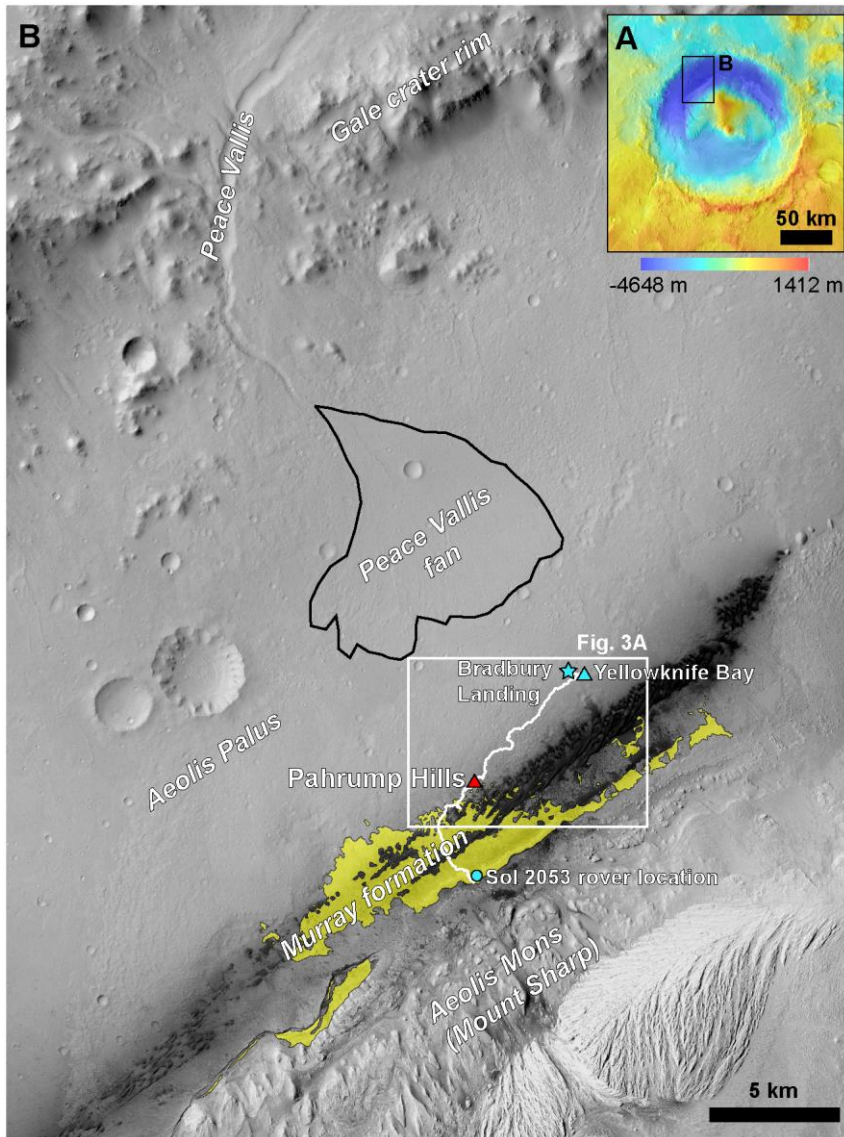
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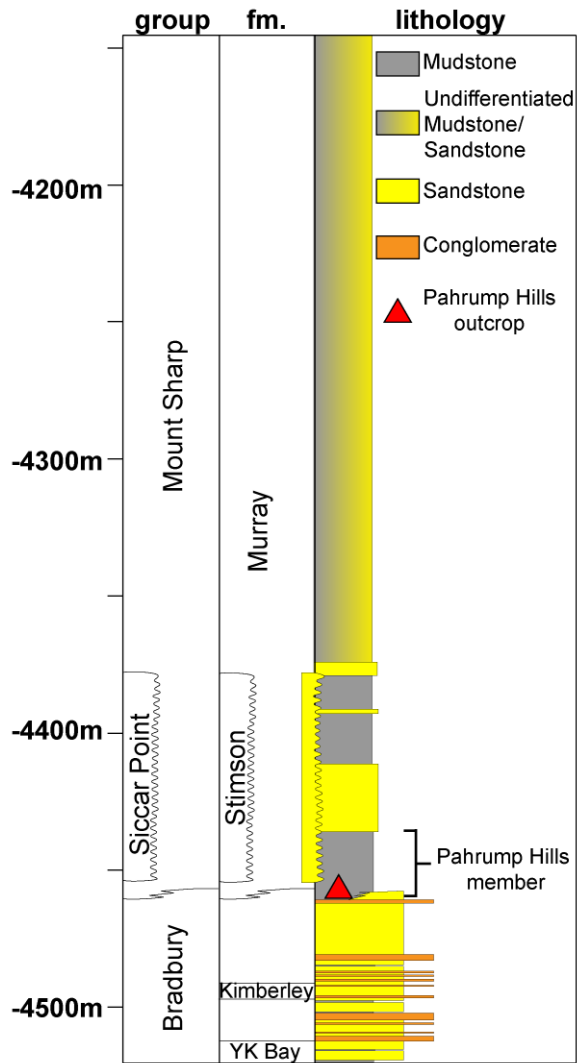
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## TABLES

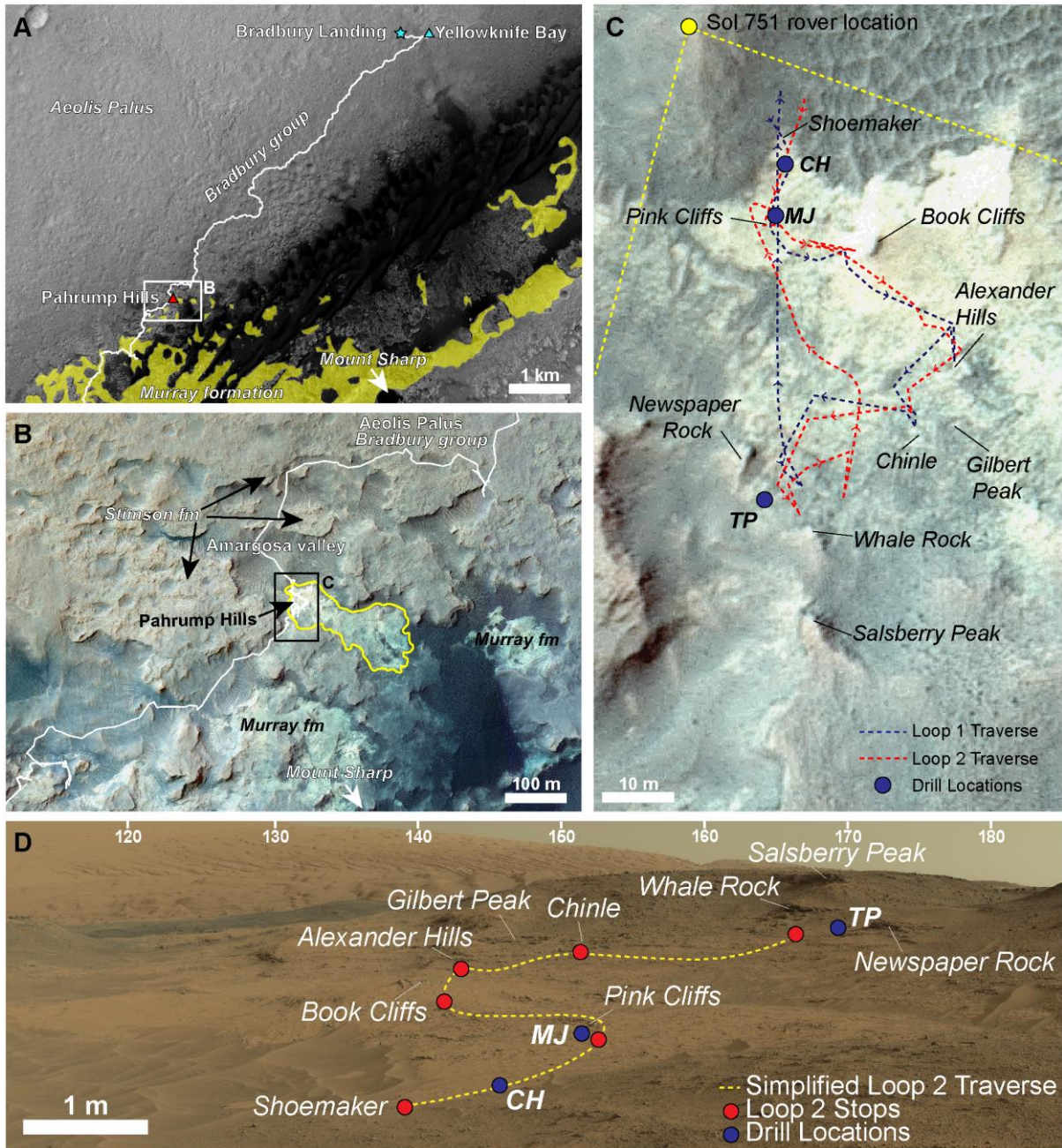
**Table 1.** Pahrump Hills sedimentary facies

<i>Grotzinger et al. (2015)</i>	This study	Facies description	Interpretation	Outcrop areas	Relevant target names (Sol #)
Thinly/finely laminated mudstone	Thinly laminated mudstone	Parallel thinly laminated grey to reddish mudstone; consists of rhythmically laminated and uneven, discontinuously laminated subfacies; low-angle geometric discordances observed throughout	Event beds (including scour and drape structures) deposited by plunging plumes in a distal lacustrine setting	Shoemaker Confidence Hills Pink Cliffs Book Cliffs Alexander Hills Telegraph Peak	Pelona; Ricardo (805-806) Maturango (755, 756) - Anaverde (814); Goblin Valley (787, 815) - Calico Mountain (837)
	Low-angle cross-stratified mudstone	Thinly laminated grey mudstone exhibiting variably dipping low-angle cross-stratification	Froude-supercritical bars or bedforms deposited in a sublacustrine channel in a basin margin lacustrine setting	Chinle Gilbert Peak	Goldstone (830-832)
Thickly laminated mudstone-siltstone	Thickly laminated mudstone-sandstone	Thick laminations composed of dark grey sandstone and mudstone	Event beds deposited by plunging plumes in a proximal lacustrine setting	Salsberry Peak Kanosh	- Little Devil; Devil's Punchbowl (942-943)
Cross-laminated sandstone	Cross-stratified sandstone	Dune and ripple cross-stratified sandstone composed of coarse silt to coarse sand-sized white/tan grains within a dark grey, fine-grained matrix	Climbing dune-scale and ripple-scale bedforms deposited in a sublacustrine channel in a proximal basin margin setting	Upper Chinle	-
				Whale Rock Newspaper Rock	Sierra Nevada (854, 860) -
Conglomerate	-	-	-	-	-

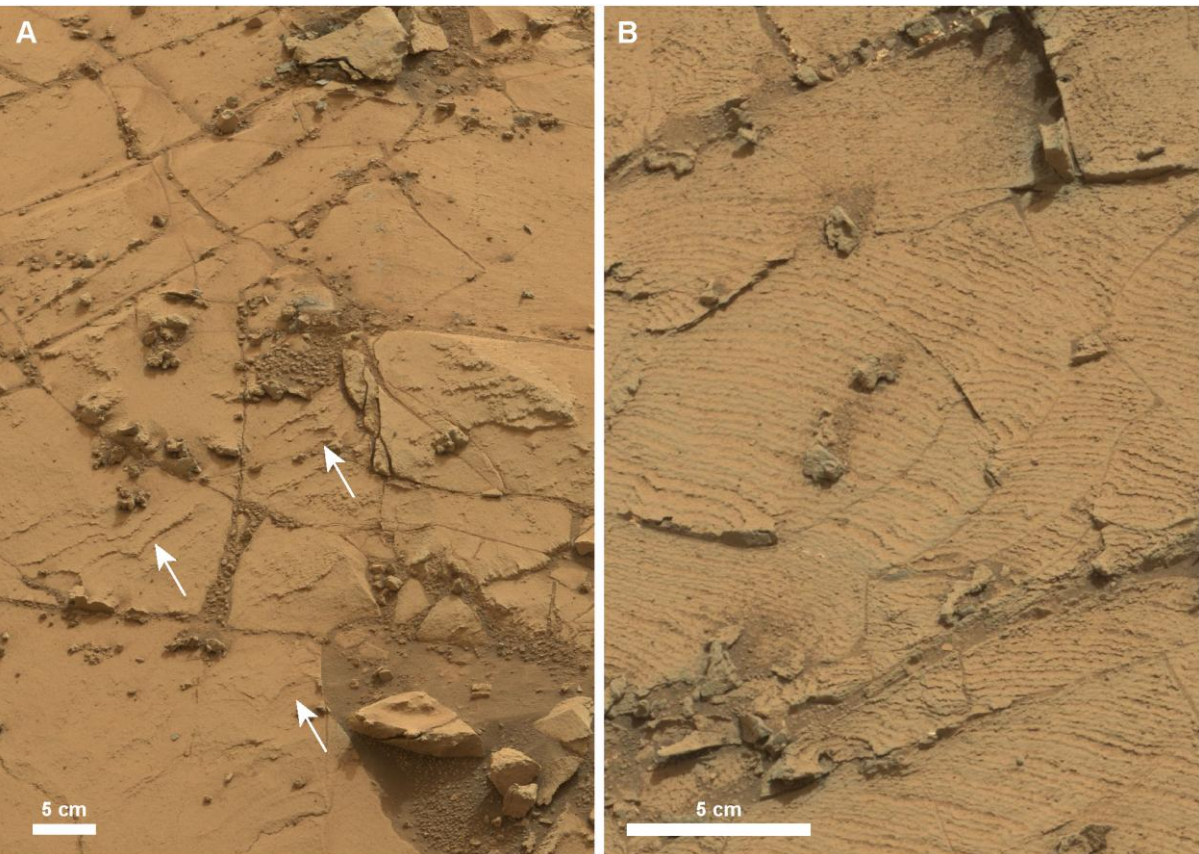
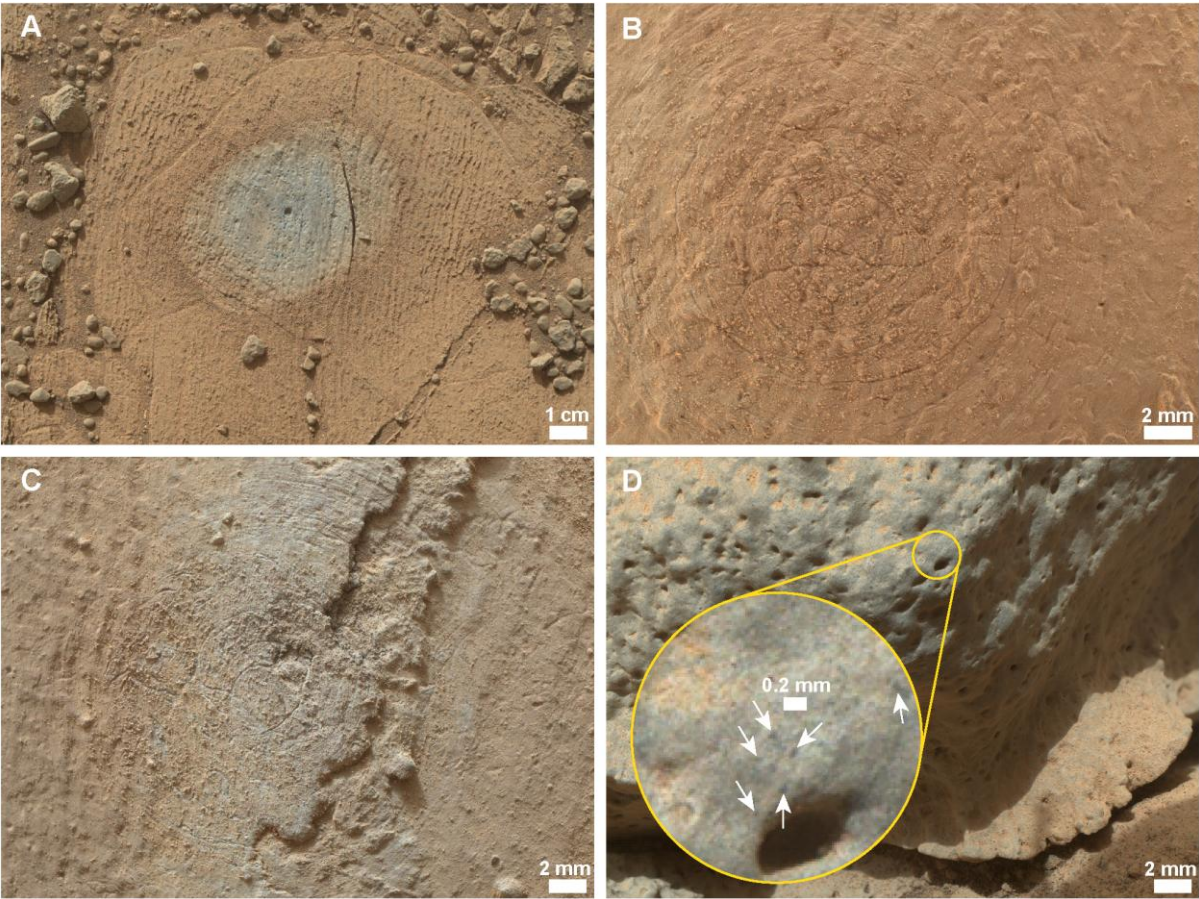


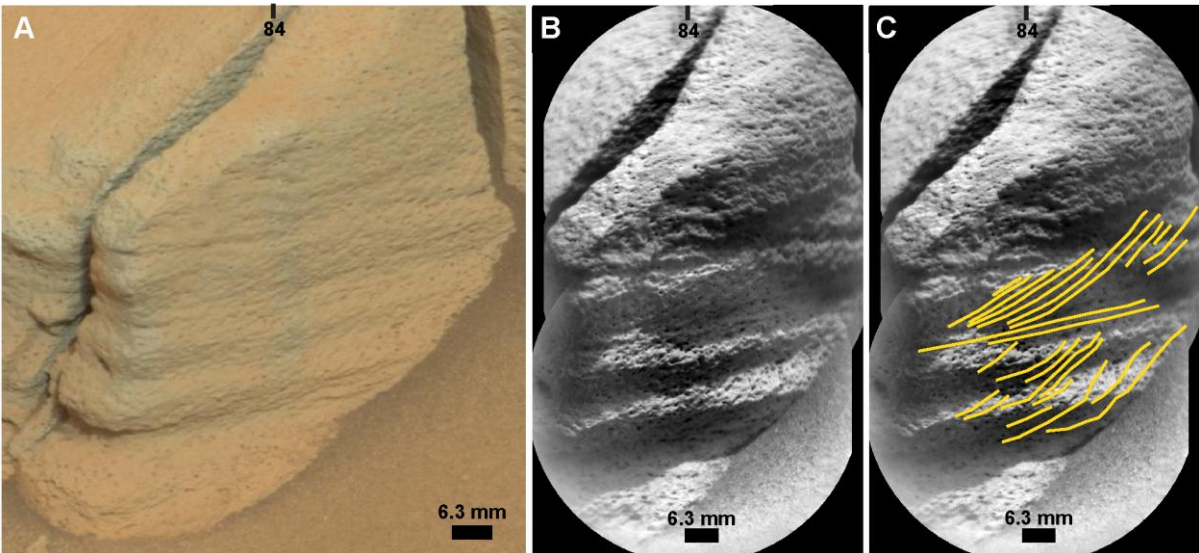
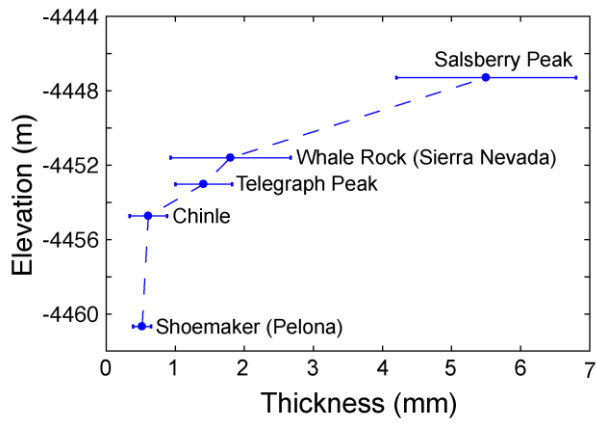




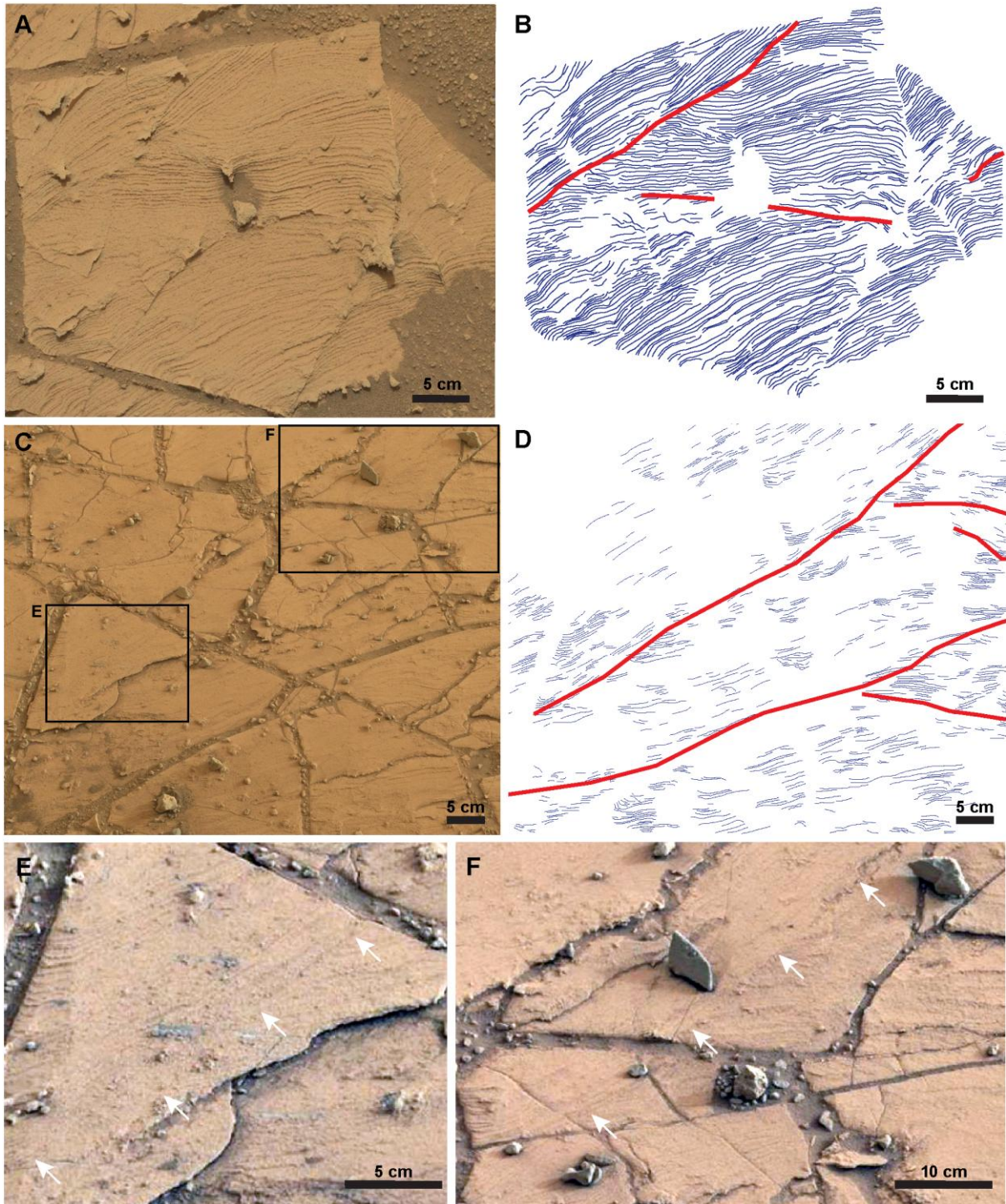


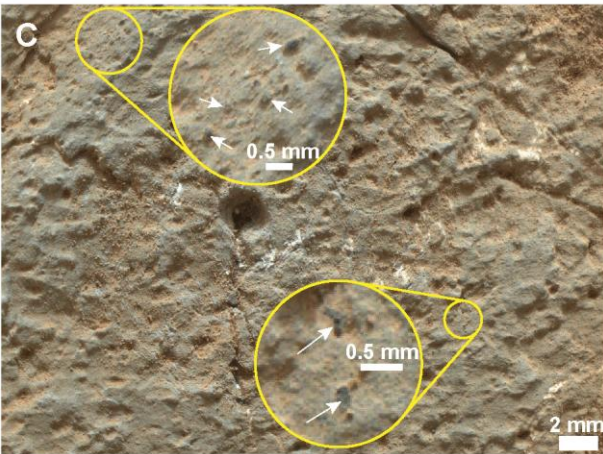
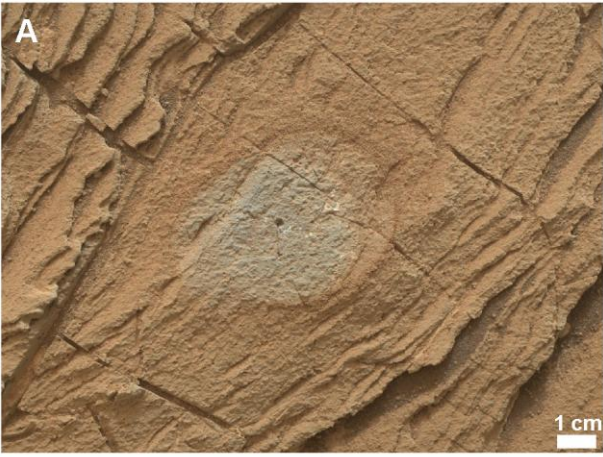




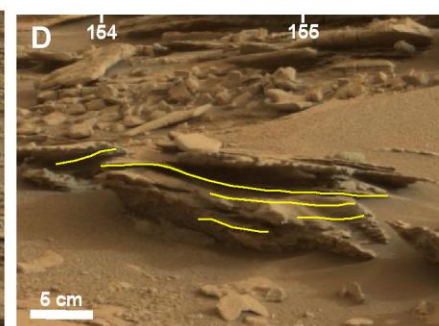
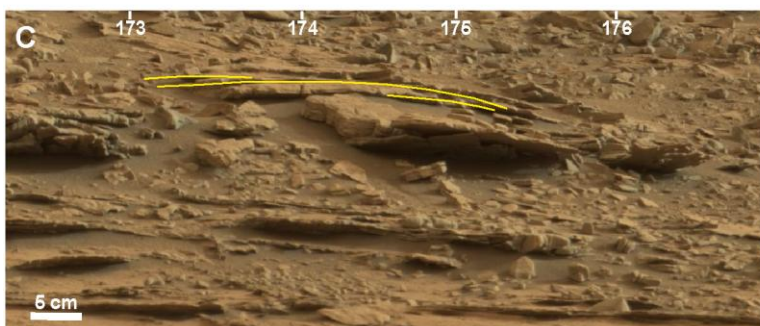
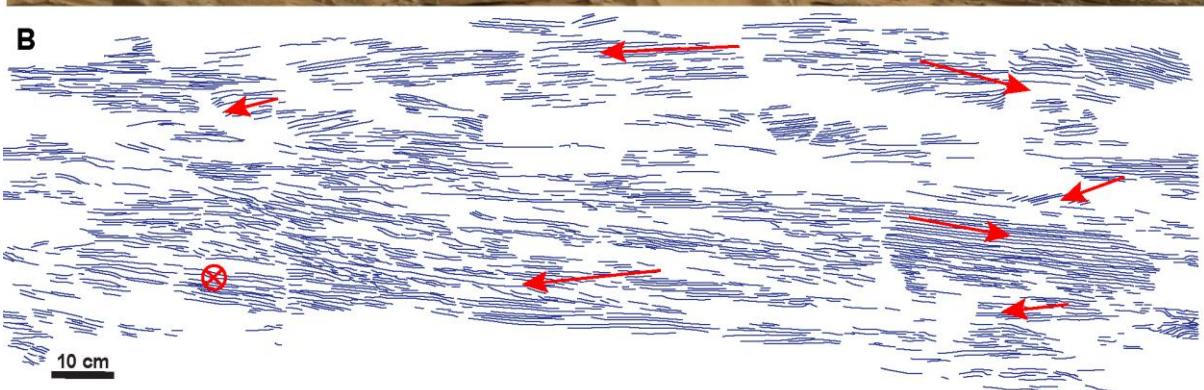
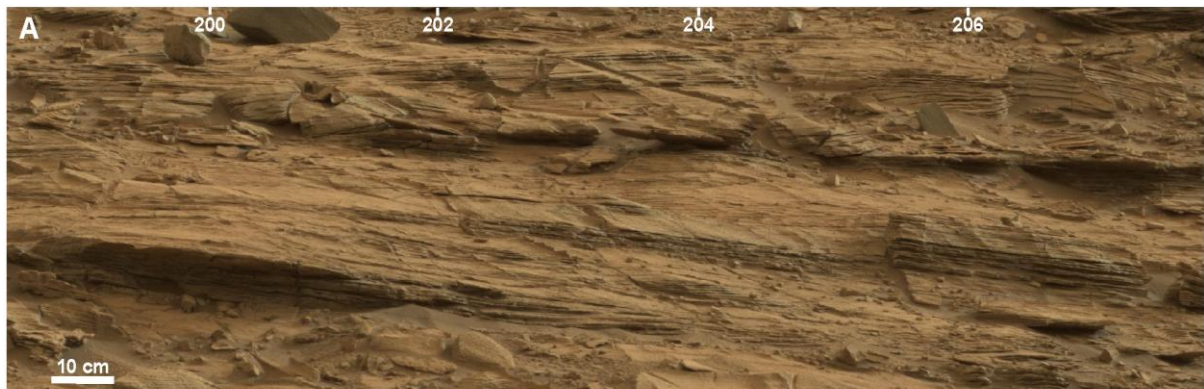
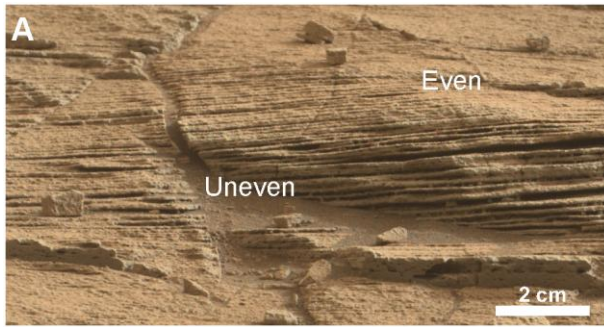




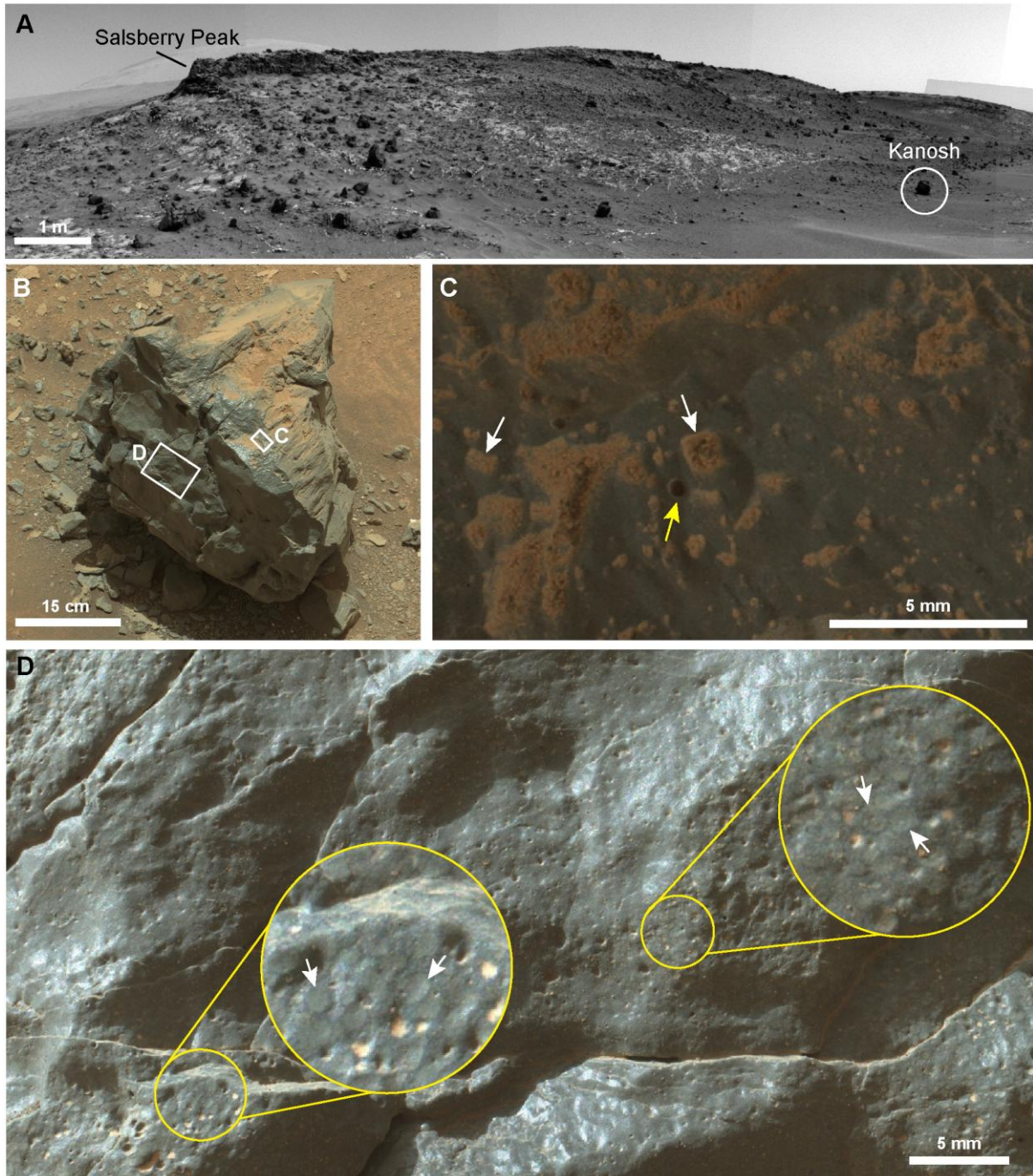


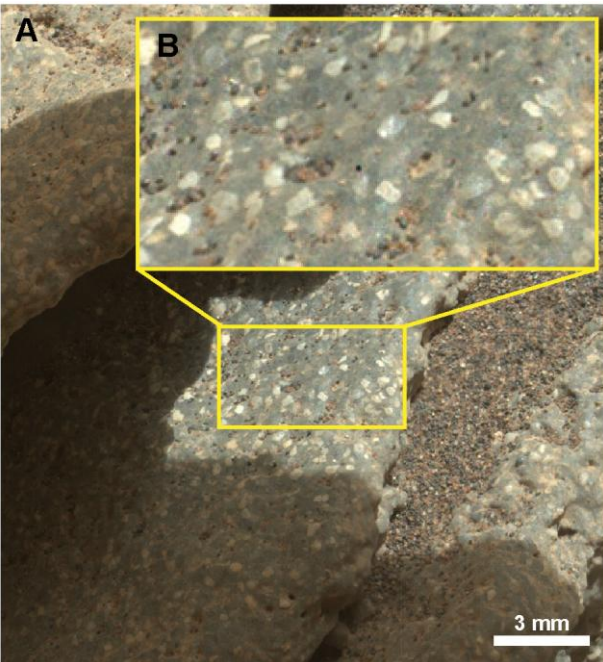
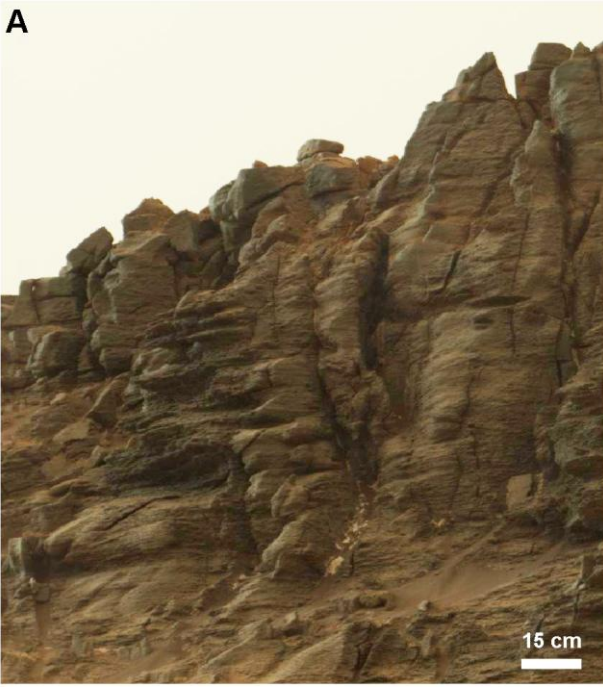




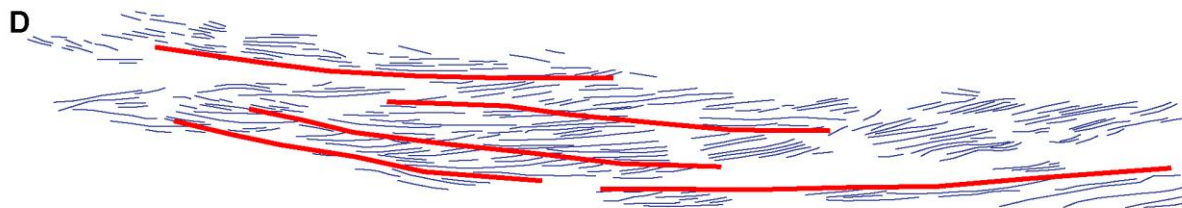
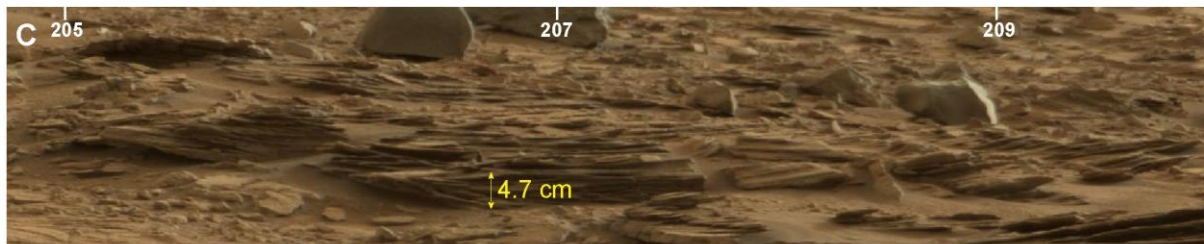
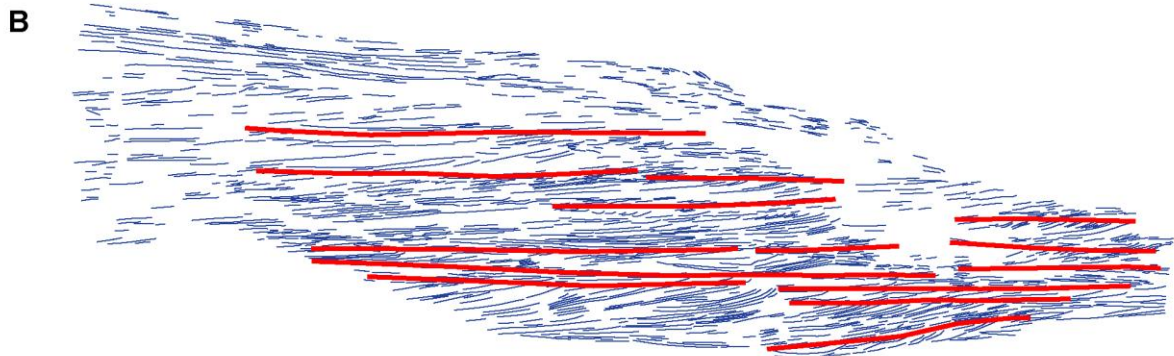
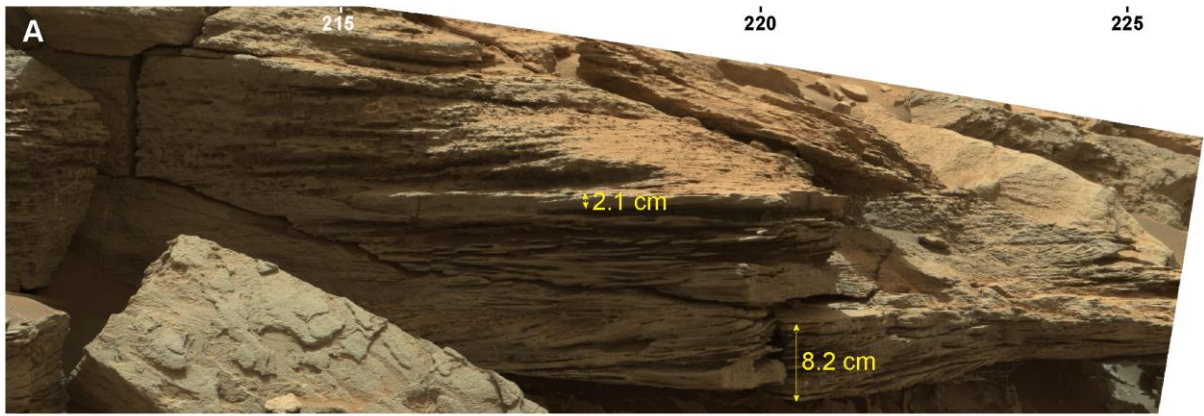




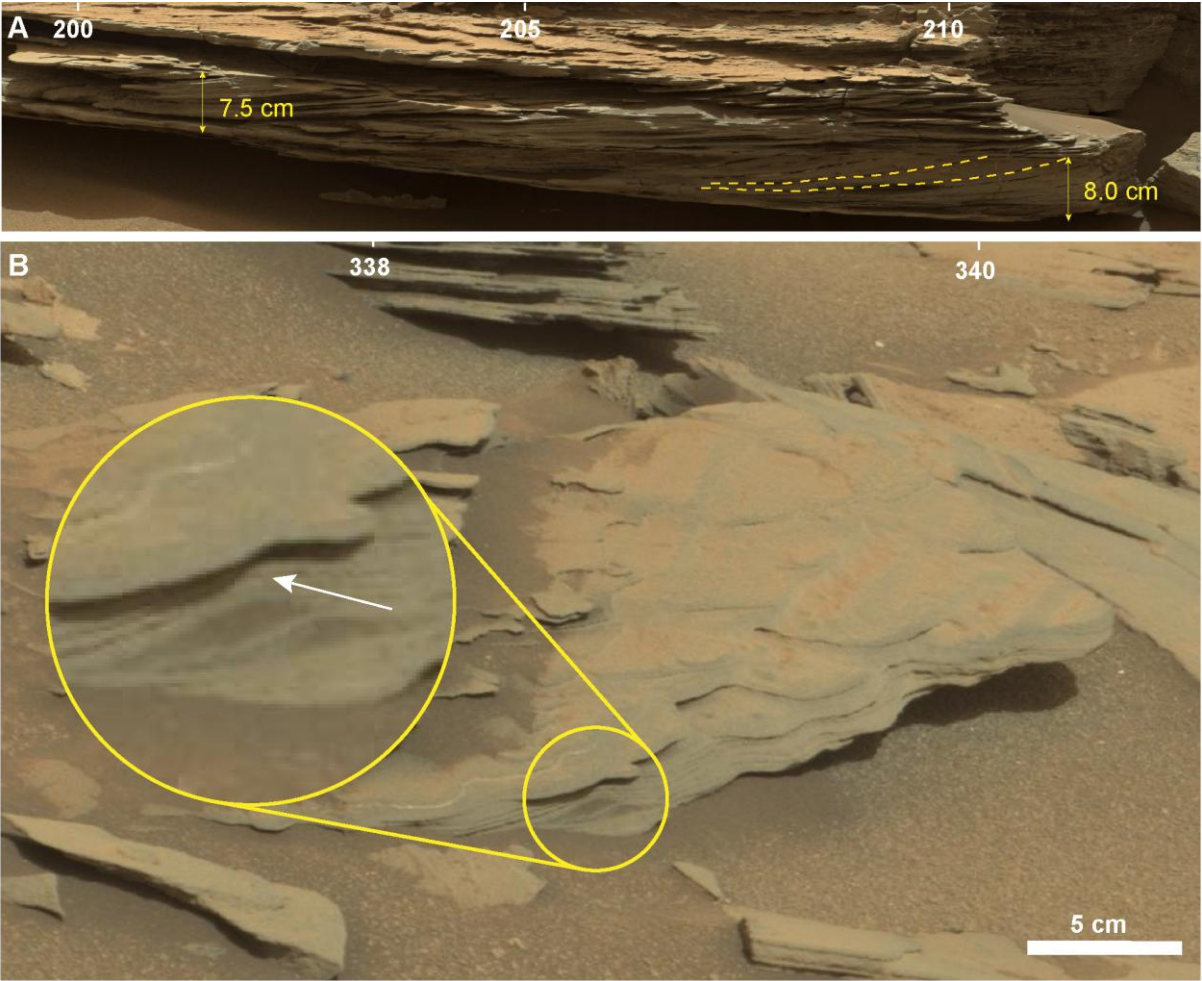


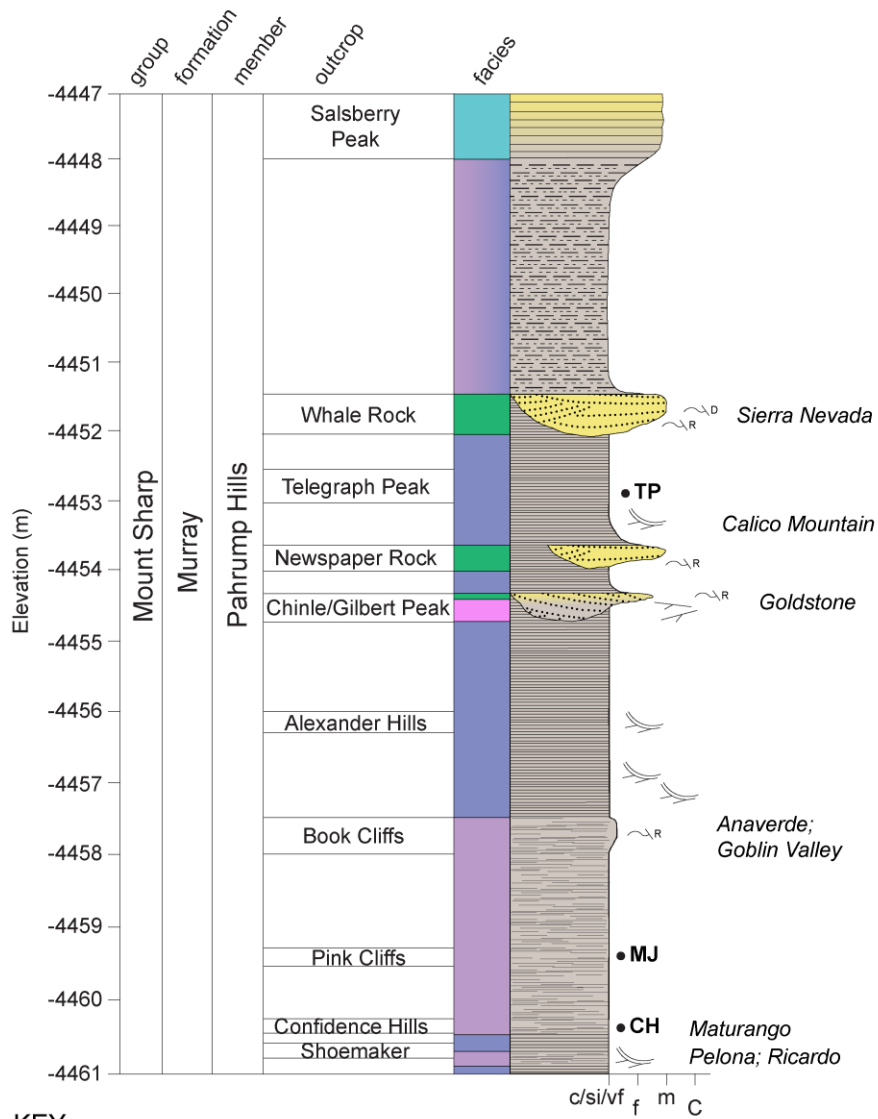












### KEY

#### Lithology

- Mudstone
- Sandstone
- Mudstone-Sandstone

#### Sedimentary Structures

- Low-angle cross-stratification
- Ripple cross-lamination
- Dune cross-stratification
- Low-angle truncations

#### Stratification

- Thick parallel laminations
- Rhythmic thin laminations
- Discontinuous, uneven parallel thin laminations
- Inferred thin laminations
- Cross-stratification

#### Drill Holes

- CH = Confidence Hills;
- MJ = Mojave; TP = Telegraph Peak

#### Facies

- Thinly laminated mudstone (uneven)
- Thinly laminated mudstone (rhythmic)
- Low-angle cross-stratified mudstone
- Thickly laminated mudstone-sandstone
- Cross-stratified sandstone



