Evidence for hydraulic fracturing at Gale crater, Mars: Implications for burial depth of the Yellowknife Bay formation

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A B S T R A C T

NASA's Curiosity rover identified a formerly habitable environment within strata informally known as the Yellowknife Bay formation. The stratigraphic relationship, and thus depositional age, of these rocks relative to other geologic units in Gale crater is not clear from orbital data alone. If part of lower Aeolis Mons (informally known as Mount Sharp), the Yellowknife Bay rocks have been deeply buried and exhumed prior to 3.2–3.3 Ga. If part of younger alluvial fan deposits, however, they likely have never experienced more than \( \sim 100 \) m of burial. Knowledge of burial history can thus constrain the stratigraphic placement of Yellowknife Bay and the habitable environment preserved therein. The mechanics of natural hydraulic fractures observed in mudstone at YKB allow us to evaluate its burial history and imply a minimum burial depth of 1.2 km. This is consistent with burial by the entirety of lower Mount Sharp and a depositional age of \( \sim 3.6–3.8 \) Ga, providing observation-based evidence that Mount Sharp was once much more laterally extensive than its present form. Rocks of the Yellowknife Bay formation thus represent the oldest strata that Curiosity will encounter during its journey in Gale crater, and any additional habitable environments discovered along Curiosity's future path represent conditions at younger times.

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1. Introduction

Strata of the Yellowknife Bay (YKB) formation, some of the first targets of detailed scientific investigation by the Mars rover Curiosity, revealed evidence of an ancient habitable environment on Mars within Gale crater (Grotzinger et al., 2014; Vaniman et al., 2014). The Yellowknife Bay region, in which the YKB formation is exposed, occurs at the distal end of a Late Hesperian/Amazonian (<3.2–3.3 Ga) alluvial fan known as Peace Vallis that resides within broader crater fill deposits comprising a region known as Aeolis Palus (Grant et al., 2014) (Fig. 1a). The rocks observed at YKB and elsewhere along Curiosity’s traverse are consistent with deposition in an alluvial-fluvial-lacustrine system (Grotzinger et al., 2015), and the mineralogy, chemistry, and organic compounds measured in mudstones at YKB have made them some of the most intriguing rocks examined thus far in the mission (Freissinet et al., 2015; McLennan et al., 2014; Vaniman et al., 2014). Because the YKB formation – and the Sheepbed mudstone member in particular – represents an ancient habitable environment on Mars, it is important to constrain the stratigraphic position and relative age of these rocks to place these findings into the context of the broader evolution of that planet. In addition, understanding the burial history of the YKB formation can aid in constraining the temperature, pressure, and fluid interactions that the rocks and organic compounds may have experienced prior to their surface exposure at \( \sim 78 \pm 30 \) Ma (Farley et al., 2014). However, analysis of orbital imagery does not unequivocally identify the contacts between the YKB formation, topographically higher units of the alluvial fan system, and strata of lower Aeolis Mons (informally known as Mount Sharp), leaving questions as to the stratigraphic placement, relative age, and burial history of the YKB formation and its record of habitable conditions.

Understanding the stratigraphic position of the YKB formation relative to other units in Aeolis Palus and Mount Sharp is thus necessary in order to reconstruct the temporal evolution of conditions in Gale crater through geologic time, particularly if changes in habitable conditions are observed elsewhere along Curiosity’s traverse. To address this issue and constrain the burial history of YKB (and, by extension, its relative age) we integrate geologic observations of vein networks in the YKB rocks with fracture mechanics to estimate the burial depth of the Sheepbed mudstone member of the YKB formation. When combined with crater counts, estimates of crater infill and degradation within Aeolis Palus, and large-scale stratigraphic relationships between Mount Sharp and surrounding
units, these burial depth estimates can be used to constrain the depositional age of the mudstone and, by extension, the age of habitable conditions recorded at YKB.

2. Background

2.1. Stratigraphy and geologic setting

The Yellowknife Bay region is situated in an alluvial fan system at the distal end of Peace Vallis, in a map unit referred to as “Lower Fan” (LF) in Palucis et al. (2014) and “bedded, fractured” (BF) in Grant et al. (2014) (Fig. 1a). This unit lies to the south of the topographically higher “Upper Fan” unit of Palucis et al. (2014) (“AF” unit of Grant et al., 2014). Both units are part of a broader deposit referred to as Aeolis Palus (Fig. 1). From a stratigraphic point of view, the rocks exposed within Aeolis Palus (including the YKB formation) examined by Curiosity are collectively termed the Bradbury group. To the south, the Bradbury group interfingers with sediments of the Mount Sharp group, where the lowest exposed section of the Mount Sharp group is dominated by laminated mudstones of the Murray formation (Grotzinger et al., 2015). The Mount Sharp group is in turn unconformably overlain by the Siccarr Point group (Fraeman et al., 2016), which includes eolian sandstones of the Stimson formation (Banham et al., 2016). The reader is referred to Grotzinger et al. (2014, 2015) for a more detailed description of the stratigraphic section and physical attributes of the different lithologies.

A key point for this study is that within the Gale crater alluvial–fluvial-lacustrine system, strata of the Murray formation in the Mount Sharp group represent more distal and generally finer-grained equivalents to the commonly coarser-grained fluvial facies of the Bradbury group (Grotzinger et al., 2015). This implies that the accumulation of sediment that forms both groups was contemporaneous in the early history of Gale crater, but locations of net accumulation and erosion likely changed over time as the basin evolved. Indeed, upper units of the alluvial fan system within the Bradbury group, sometimes referred to as the Peace Vallis fan deposits, are inferred to superpose and thus post-date the formation and large-scale erosion of Mount Sharp (Palucis et al., 2016, 2014) and the Mount Sharp group. Specifically, age estimates from crater counts by Grant et al. (2014) suggest a crater retention age of ~3.2–3.3 Ga (Late Hesperian) for the broader Aeolis Palus region, whereas the deposition of lower Mount Sharp is estimated to have occurred near the Noachian–Hesperian time-stratigraphic boundary at ~3.5–3.8 Ga (e.g., Thomson et al., 2011). The alluvial fan system emanating from Peace Vallis may have been long lived or episodic, and the YKB strata may represent an older period of deposition within the fan system that was contemporaneous with the build-up of lower Mt. Sharp. A key question is whether the YKB strata should be grouped with the younger “Peace Vallis fan”
deposits or if they instead represent deposition within the alluvial/fluvial system at an earlier time.

The strata of Mount Sharp itself can be divided into lower and upper formations that are separated by an erosional unconformity (Malin and Edgett, 2000; Milliken et al., 2010; Thomson et al., 2011). Orbital imagery shows rocks of the lower formation only within the central portion of Gale crater; but because they are relatively flat-lying (Milliken et al., 2010) we consider it likely they once had a greater lateral extent (or lateral equivalents), possibly extending to the walls of the crater. Significant erosion precludes knowledge of the original stratigraphic thickness of lower Mount Sharp or the Mount Sharp and Bradbury groups as a whole, but elevation measurements from the modern floor of Gale crater to the contact with the upper formation indicate the currently exposed portion of the lower formation is ∼1–2 km thick along the north face (e.g., Fig. 1b). It is thus possible that the current location of YKB was once overlain by approximately 1–2 km of sediment (or more) that was eroded away prior to the deposition of sediments that comprise Aeolis Palus and the Peace Vallis fan deposits.

The YKB formation of the Bradbury group is subdivided into three members. The uppermost members, Glenelg and Gillespie Lake, are predominantly sandstones, whereas the lowermost member, Sheepbed, is a ∼1.5 m thick, laterally extensive mudstone (Grotzinger et al., 2014). Curiosity observed a suite of diagenetic features within the Sheepbed mudstone that includes raised ridges, nodules and hollow nodules, a possible sedimentary dike, and a ubiquitous network of fractures filled with fine-grained Ca-sulfate (Grotzinger et al., 2014; Siebach et al., 2014; Stack et al., 2014). Where fractures intersect nodules, these too are filled with Ca-sulfate (Grotzinger et al., 2014; Nachon et al., 2014). Estimates of hydration state derived from data collected by the ChemCam laser-induced breakdown spectroscopy (LIBS) instrument and low sulfur content in the host mudstone as determined by the APXS instrument (Grotzinger et al., 2014) indicate that the hydrated sulfate is confined within the crosscutting mineralized fractures. These observations suggest that the mudstone was relatively well-lithified at the time the sulfate-precipitating fluids intruded, and thus the fracture network reflects stresses exerted on the YKB rocks after their lithification.

Orbital images reveal that at least some of the uppermost units on the crater floor adjacent to Mount Sharp superpose its lower strata, consistent with the presence of an extensive erosional unconformity between the Mount Sharp group and both the overlying Siccar Point group and the uppermost units of the Bradbury group. Whether the YKB formation lies stratigraphically above or below such an unconformity within the Bradbury group is not clear from orbital data alone, leaving its stratigraphic placement relative to rocks of the Mount Sharp group uncertain. Proper placement of YKB into Gale crater’s stratigraphy thus carries important implications for the age of the habitable environment recorded in the Sheepbed mudstone relative to other rocks encountered during Curiosity’s mission.

2.2. Burial histories; relation to age

Although Aeolis Palus exhibits a surface crater retention age that is younger than the inferred formation age of Mount Sharp, YKB itself is too small to carry out statistically meaningful crater counts to estimate its depositional age. YKB occurs in a region of low elevation relative to the rest of Aeolis Palus, and thus it is possible that the YKB region represents an erosional window into older rocks beneath an unconformity between older strata of the Bradbury group (contemporaneous with those of the Mount Sharp group) and younger strata of the Bradbury group currently exposed elsewhere within Aeolis Palus. If this is the case, the YKB formation, including the organic-bearing Sheepbed mudstone member, was once deeply buried and is older in age than the topographically higher rocks that Curiosity has been exploring since crossing into the Mount Sharp group on Sol 753. If instead the YKB formation post-dates the formation and large-scale erosion of Mount Sharp, it would be closer in age to units of the Peace Vallis fan deposits and other deposits that define the surface of Aeolis Palus. In this case, deposition of the YKB sediments occurred after Mount Sharp had reached its current form, and the rocks of the YKB formation were never deeply buried. Both of these possibilities, and the inability to distinguish between them using orbital data and rover imagery alone, are discussed in Grotzinger et al. (2014). A more recent interpretation of the stratigraphy, outlined by Grotzinger et al. (2015), infers the YKB formation to have been deposited early in the history of Gale and subsequently deeply buried by the formation of lower Mount Sharp. In contrast, Palucis et al. (2014) infer the YKB formation to be a component of the younger Peace Vallis fan that formed after the large-scale erosion of Mount Sharp.

In this study we test these two hypotheses by assessing the likely burial depth of the Sheepbed mudstone member of the YKB formation. In the event that YKB represents an erosional window into older strata of the Bradbury group that were deposited during the early evolution of Mount Sharp in the Late Noachian/Early Hesperian (∼3.5–3.8 Ga) (Grotzinger et al., 2015), the Sheepbed mudstone was once buried by at least 1–2 km of sediment. That material was eroded away prior to the formation of the currently exposed Peace Vallis fan deposits, and lateral equivalents of YKB in the Mount Sharp group remain in the subsurface today. As noted above, the burial depth in this scenario may be even greater than 1–2 km because the original thickness of the lower formation is poorly constrained, as is the original lateral extent and thickness of the upper formation. Indeed, orbital images of Mars indicate numerous impact craters have been fully buried and subsequently exhumed to various degrees over geologic time, and Gale crater may represent a point along this continuum (e.g., Malin and Edgett, 2000). This ‘deep’ burial scenario implies the presence of a significant unconformity between the YKB formation and overlying units in the Bradbury group, including those of the Peace Vallis fan.

The second hypothesis is that YKB is part of the younger Peace Vallis alluvial fan system (e.g., Palucis et al., 2016, 2014) and was therefore deposited at 3.2–3.3 Ga based on crater counts of Aeolis Palus (Grant et al., 2014). Unlike lower Mount Sharp, there is no clear evidence that the Peace Vallis fan was ever deeply buried; crater depths and diameters, crater degradation state, and height of inverted fluvial channels indicate that erosion has not exceeded ∼20–40 m within the Peace Vallis fan deposits (Grant et al., 2014). Thus, if YKB is part of this younger fan system then it has likely only ever been buried to a depth of this order. Multiplying this estimate by a very conservative value of 2.5 implies a maximum burial depth of ∼100 m if YKB is part of the younger Peace Vallis fan system.

The two hypotheses outlined above thus predict distinct and large differences in burial depth experienced by the sediments at Yellowknife Bay since their deposition. Because burial depth plays a first-order role in the magnitude of stresses exerted on material within a compacting sedimentary basin such as Gale crater, this entails large differences in the vertical stress exerted on the rocks. To differentiate between the two scenarios, we therefore investigate a stress-dependent morphologic feature: the network of sulfate-filled fractures observed by Curiosity in the Sheepbed mudstone. By estimating the stresses under which these fractures formed, the burial depth of YKB at the time of fracturing can be estimated. Estimates of burial depth can then used to constrain whether rocks of the YKB formation in the Bradbury group formed contemporaneous with the early evolution of Mount Sharp or if
they instead formed several hundred million years later, after the large-scale erosion of Mount Sharp, as part of the evolution of the younger Peace Vallis fan system.

3. Fracture formation

The fractures’ formation mechanism is crucial to describing the state of which they formed, and must therefore be identified first. Two formation mechanisms have been proposed for the sulfate-filled fractures: that they are a) desiccation cracks that later filled with Ca-sulfate, or b) natural hydraulic fractures driven by elevated fluid pressure in buried sediments (Grotzinger et al., 2014; Schieber et al., 2017). These two mechanisms generate fractures under distinctly different states of stress (one planar and tensile, the other compressive and lithostatic). Because stress state influences fracture morphology (Cosgrove, 2001; van der Pluijm and Marshak, 2003), the observed morphology of the fracture network records the stress state at the time of formation and can be used to distinguish between desiccation and hydraulic processes.

Desiccation cracks form under horizontal tensile stresses generated by the dehydration and subsequent contraction of a layer of sediment (Weinberger, 1999). This horizontal tensile stress leads to purely extensional opening of vertical cracks that propagate perpendicular to the direction of maximum tensile stress. Fracture opening relieves stress in the immediate vicinity of the newly-formed crack, causing a “stress shadow” that influences the propagation direction of younger cracks, which curve into it. As a result, though the overall network appears macroscopically polygonal, close inspection of the vicinity of each intersection reveals that individual intersections are orthogonal (Goehring, 2013).

In contrast to the outcrop-scale tensile stress generated by contractional processes such as desiccation, the stress state leading to natural hydraulic fracture within a compacting sedimentary basin is dominated by the vertical, or overburden, stress and the fluid pressure (Cosgrove, 1995). In order to fracture the rock, fluid pressure must equal the lithostatic overburden or the strength of the rock (whichever is greater). In this setting the horizontal stresses are effectively uniform and there is no regional stress state to influence fracture propagation direction in the horizontal plane. In addition, the effective normal stress on a fracture wall is miniscule due to the contribution of near-lithostatic fluid pressure, which precludes the development of strong stress shadows. Propagation direction is instead influenced at small scales (i.e., centimeters) by local variations in rock strength (Cosgrove, 2001; Engelder, 2014). In the absence of strong stress shadows, orthogonal intersections do not dominate. This stress state also tends to produce “wandering” fractures that encapsulate irregular blocks of host rock between closely spaced veins (van der Pluijm and Marshak, 2003). A network of natural hydraulic fractures can thus be identified by varied intersection angles and propagation directions.

Because desiccation cracking and hydraulic fracturing lead to measurable differences in intersection angle between fractures, we analyze intersection angles to identify the likely formation mechanisms of the sulfate-filled fractures at YKB.

4. Methods

4.1. Fracture formation mechanism

We examine color Mastcam images of the YKB formation to evaluate fracture morphology and intersection angles. Only those images acquired within 2–3 m of the rover are selected and all images are vertically-projected in order to minimize distortion due to oblique viewing angles. The vertical projection assumes a planar surface and uses the known position and viewing geometry of the camera to produce an image equivalent to an “overhead” view of the surface. Distortion is minimal for relatively flat regions near the rover, which is why our study focuses on images that met these criteria.

Several different fracture morphologies and compositions of infilling materials have been observed during Curiosity’s mission and are described in detail elsewhere (Grotzinger et al., 2014; Koryak et al., 2015; Nachon et al., 2014; Schieber et al., 2017; Siebach et al., 2014). These include polygonal fractures up to several centimeters in width that are filled by unconsolidated sediment, linear fractures with orthogonal intersections that are filled with Ca-sulfate, sometimes standing in positive relief, raised ridges which contain multiple generations of erosion-resistant mineral infill, and vertically oriented, mineralized fractures that crosscut different lithologies and can be several centimeters in width and tens of meters in length (Fig. 2). Raised ridges observed at YKB, as their name implies, are more resistant to erosion than the surrounding mudstone and are composed of minerals other than Ca-sulfate (Siebach et al., 2014). Some mineralized fractures imaged by Curiosity exhibit clear orthogonal intersections, even if they exhibit significant curvature over longer length scales (e.g., the “J” type intersections in Fig. 2d). These fracture patterns may be consistent with failure due to desiccation or thermal cycling, and multiple types of mineralized fractures suggests that the sulfate-bearing fluids, when they intruded, may have infiltrated multiple generations of fractures.

In this study we focus on a specific type of fracture network observed at YKB that consists of thin, sulfate-filled fractures that crosscut both the Sheepbed mudstone member and overlying Glenelg sandstone member (Fig. 3a, b). These fractures range in width from sub-mm up to 8 mm and can be differentiated from raised ridges at YKB in two regards: they crosscut the raised ridges and are therefore younger, and their fracture fill weathers flush, or even slightly depressed, relative to the host rock (Grotzinger et al., 2014).

In addition to qualitative morphologic analysis, we conduct systematic measurements of intersection angles between sulfate-filled fractures where clearly visible within the Sheepbed mudstone. The NIH image analysis software ImageJ is used to measure visible angles of intersection between sulfate-filled fractures in 81 images containing 427 unique intersections (Table S1). Statistical analysis of intersection angles determined whether orthogonal intersections were dominant.

4.2. Estimates of burial depth

We estimate the burial depth of the Yellowknife Bay formation by determining the stresses required to generate the observed fractures. Because overburden is the dominant source of stress, these stresses are a function of burial depth. The stress state of rocks within Gale Crater can be modeled as that of a confined sedimentary basin, where the sources of stress are overburden, pore fluid pressure, compaction of the sediments and thermal expansion (Engelder, 2014). In this case the greatest principal stress is the effective vertical stress, which arises from the competing effects of overburden and fluid pressure. Effective vertical stress is defined simply as $\sigma_v = \rho g d - P_f$, where $\rho$ is the density of overlying sediment, $g$ is gravity (3.711 m/s$^2$ for Mars), $d$ is burial depth and $P_f$ is pore fluid pressure. For simplicity, we take the density of overlying sediment to be a constant representative of terrestrial sand- and mudstone: 2.5 g/cm$^3$. This value results in conservative estimates of burial depth, as a lower density (e.g., that of unconsolidated sediments) results in greater burial depth.

Horizontal stresses are generated by the geothermal gradient and lateral confinement of the sediments as they are compacted.
Fig. 2. Examples of fractures encountered during Curiosity’s traverse of Yellowknife Bay and lower Mt. Sharp. Unlike hydraulic fractures, these larger-scale examples exhibit ~90° angles of intersection and are commonly vertically oriented. The types of fractures shown here were not the focus of this study, but their morphologic characteristics can be compared to the candidate hydraulic fractures shown in Fig. 3. a) Open fractures near the John Klein drill hole in Yellowknife Bay that have been filled with unconsolidated sediment. These types of fractures are ubiquitous in the rocks encountered in Gale crater. Mastcam image 0267ML116500100001. b) ~0.5–1 cm scale fractures with orthogonal intersections and raised profiles; fractures are commonly filled with Ca-sulfate. Mastcam image 0727MR003108000402930R01. c) Large light-toned fractures (white arrows), commonly vertically oriented, that can be traced for several meters or more. Mastcam image 0855MR0037760060501040E01. d) Portion of rover Navcam mosaic acquired on Sol 940 showing “J” intersections in Murray fm. mudstones in lower Mt. Sharp. These fractures exhibit curvature but intersect at approximately orthogonal angles.

These are represented by

$$\sigma_H = \left( \frac{v}{1-v} \right) \sigma_{v,\text{eff}} - \left( \frac{E}{1-v} \right) \alpha \Delta T - P_f$$

(1)

Here $v$, $E$, and $\alpha$ are Poisson’s ratio, Young’s modulus, and the coefficient of thermal expansion of the rock (0.33, 20 GPa, and $11.6 \times 10^{-6}$ K$^{-1}$, respectively), and $\Delta T$ is the geothermal gradient (Engelder, 2014). The first term in this expression represents elastic stresses induced by the inability of the sediments to expand laterally as they are compressed from above. The second term arises from stresses induced by variable thermal expansion between the top and bottom of a column of sediment due to the geothermal gradient, which we take to be 15 K/km according to estimates for the average Late Noachian/Early Hesperian heat flux (Hahn et al., 2011; Squyres and Kasting, 1994). Because the geothermal gradient is multiplied by the coefficient of thermal expansion (of order $10^{-6}$), however, the model is effectively insensitive to its precise value.

The magnitude of the pore fluid pressure, $P_f$, is calculated as a ratio of lithostatic pressure: $P_f = \tau \rho gd$. A value of $\tau = 1$ represents pore fluid pressure equal to lithostatic pressure, indicating impermeable rock, whereas $\tau \approx 0.4$ indicates permeable rock and hydrostatic fluid pressure. In terrestrial basins, hydrostatic pressure persists to the depth of pore closure (approximately 3 km), which is a function of both compaction and diagenesis (Engelder, 2014). Although the permeability of the rocks at Yellowknife Bay cannot be directly measured, low permeability can be inferred from the fact that vein-filling Ca-sulfate is restricted to the mineralized fractures and sulfur contents are very low in the host rock (Grotzinger et al., 2014). While this suggests $\tau > 0.4$ at the time of fracture formation, we do not assume a value of $\tau$ and instead investigate the effect of its variation on estimates of burial depth.

Given the state of stress described above, one must next discern whether the applied stress is sufficient to fracture the rock. We evaluate this criterion by comparing Mohr circle representations of the state of stress to the Coulomb envelope (the red line in Fig. 4), which is determined by the tensile strength, cohesion,
Fig. 3. Examples of hydraulic fractures in the Yellowknife Bay (YKB) formation (Bradbury group) and the Murray formation (Mount Sharp group). a) Ca-sulfate filled veins in the Sheepbed mudstone of YKB. Fractures commonly ‘wander’ (black arrows) and encapsulate fragments of host rock (white arrow). Mastcam image 0270MR1186024000E1. b) Image of Sheepbed mudstone and overlying Gillespie Lake sandstone showing a range of fracture intersection angles and vertical to sub-horizontal orientations in cross-section and plan view, consistent with hydraulic fracturing. Mastcam image 0153MR0377000000E1. c) Mudstone in the Murray fm. of the Mount Sharp group. Thin, light-toned mineralized fractures that encapsulate fragments of host rock and exhibit wandering (black arrows) are also observed in this unit, which is part of lower Mt. Sharp and thus subjected to significant burial. Mastcam image 1361MR0066730000701548DL. d) Fracture morphologies in Murray fm. mudstone in lower Mt. Sharp showing cm-scale raised Ca-sulfate filled fractures (black arrow) and thinner raised ridges with darker minerals (white arrows). Thin, Ca-sulfate filled fractures that exhibit wandering are also present and appear to be crosscut by the thicker fractures, indicating multiple episodes of fracturing and mineralization. Mosaic of Mastcam images acquired on Sol 1274, sequence 5966.

Fig. 4. Schematic representation of the Coulomb failure envelope employed in this work. The stress state of the rock, determined by lithostatic pressure, fluid pressure and Eq. (1), is illustrated through Mohr Circle representation (black and green circles). The failure envelope is determined by the tensile strength (\(T_s\)) and cohesion (C) of the rock. Failure occurs where a Mohr Circle meets the failure envelope (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and coefficient of friction of the rock in question (Engelder, 2014; van der Pluijm and Marshak, 2003). These mechanical properties have not been measured for the rocks at YKB (the data gathered by Curiosity is insufficient to uniquely ‘measure’ the strength of the rock), but can be inferred from drilling data obtained by Curiosity. Curiosity possesses a rotary percussion drill that extracts powder from boreholes on Mars through a sequence of successive percussion (hammering to break the rock apart) and rotation (to draw the resulting powder out of the borehole) (Okon, 2010). During operations, drill performance data such as drill power, percussion level, and rate of penetration into the rock are collected. This in-flight data has been compared to Earth analog tests conducted on terrestrial rocks using a duplicate of the drill aboard Curiosity. Such data are too limited to be able to quantitatively estimate mechanical properties of the target rock, but do provide information on its relative strength.

As noted in Grotzinger et al. (2014), the rate of penetration and level of percussion during drilling into the Sheepbed mud-
stone are in family with the parameters recorded during testbed drilling of terrestrial rocks, including mudstone, prior to launch. Specifically, it is noted in Grotzinger et al. (2014) that rate of penetration into the Sheepbed mudstone was similar to that measured for siltstone/mudstone from the Ridge Basin (California) that was once buried several kilometers (their Fig. S4). In addition, “hardness” tests conducted by Curiosity, which measured penetration into the rock as a function of percussion level, indicated that the toughness of the Sheepbed mudstone is between that of the terrestrial sand- and mudstone measured (Grotzinger et al., 2014; their Fig. S3). As a result, though the tensile strength of the martian mudstone is not known quantitatively, it is inferred to be within the range of similar terrestrial rocks. There are no indicators that the rock is exceptionally weak. We therefore examine a range of Coulomb envelopes based upon the range of measured properties for terrestrial sandstones, siltstones, and mudstones.

The tensile portion of the Coulomb envelope, which describes the stresses at which a rock will fail when subjected to combined tensile and shear loading, is an arcuate envelope between the tensile stress ($T_s$, the failure limit under pure tensile loading) and the cohesion ($C$). Because laboratory data are not available to constrain the precise shape of this envelope for the rocks at YKB, it is represented by an ellipse, centered on the origin, of major axis $C$ and minor axis $T_s$. For terrestrial sand- and mudstone, $T_s$ ranges from 0.5–20 MPa and $C$ between 2–10 MPa (both depending on degree of lithification and the direction of loading relative to bedding planes) (Corkum and Martin, 2007; Lin, 1983). Finally, frictional failure (combined normal and shear loading) is described by the linear Coulomb envelope, where $\tau = C + \mu T_s$ (Fig. 4). Here, $\tau$ and $T_s$ are the shear and normal stresses, respectively, at failure, and $\mu$ is the coefficient of friction, which we take to be the standard value of 0.6.

The Mohr Circle representations provide a graphical comparison of the state of stress to the failure criteria (Engelder, 2014; van der Pluijm and Marshak, 2003), and fracturing occurs when the stress state (circles in Fig. 4) intersects the failure envelope. Opening (or “Mode 1”) fractures occur where stresses intersect the tensile portion of the envelope, while shear (“Mode 2”) fractures occur when the frictional envelope is exceeded. Due to the simplified geometry of our modeled failure envelope (Fig. 4; necessary in the absence of experimental data for the rock in question), in some cases the state of stress intersects the failure envelope at the confluence of these failure regimes; in these cases, we refer to the result as “mixed mode” fracturing.

5. Results

Sulfate-filled fractures within YKB exhibit “wandering,” encapsulate blocks of host rock (e.g., Fig. 3a, b) and, in oblique exposures, the observed plane of fracturing varies in orientation from vertical to subhorizontal (Fig. 3b). In some cases (e.g., Fig. 5a, b) these fractures do exhibit linear sections with minimal wandering, suggesting that local stress fields may have developed in the basin as it compacted. Even when linear fractures are present, however, other fractures in the network often intersect them at oblique angles. Indeed, the overall network morphology exhibits no clear preference for orthogonal intersections, indicating that strong stress shadows were not present when fractures intersected. These qualitative features are consistent with a vein array and natural hydraulic fracturing (Grotzinger et al., 2014; Nachon et al., 2014; Schieber et al., 2017; van der Pluijm and Marshak, 2003).

The frequency distribution of observed intersection angles, shown in Fig. 5c, demonstrates that orthogonal intersections do not dominate within this network fractures. For 427 unique intersections, the mean intersection angle is 57.9° with a standard deviation of 20.8°. The average value indicates that stress shadows – the relief of far-field stresses in the vicinity of an open crack – did not strongly influence the morphology of intersecting cracks. The large standard deviation confirms that cracks formed in a wide variety of orientations, consistent with crack-local stresses dominating at the time of formation. This quantitative aspect of the fracture morphology at YKB reinforces our conclusion that the small-scale, sulfate-filled fractures at Yellowknife Bay – such as
those illustrated in Figs. 2, 3 and 5 – are a product of natural hydraulic fracturing and validates our use of the mechanics of hydraulic fracturing (Section 4) to investigate the conditions under which they formed.

Estimated burial depths (based on the analysis described in Section 3) range from ~1 km to >10 km (Fig. 6) for reasonable variations in tensile strength, cohesion, and permeability of the Sheepbed mudstone. As expected, minimum burial depths occur when the mudstone is impermeable (τ = 1), though the exact depth is a strong function of the assumed mechanical properties of the rock.

As described in Section 4, we have investigated the dependence of burial depth on rock properties by varying our failure envelope based upon the range of properties of terrestrial sand- and mudstone: “weak” (T5 = 2 MPa, C = 10 MPa or 40 MPa), “average” (T5 = 10.4 MPa, C = 10 MPa), and “strong” (C = 40 MPa, T5 = 10.4 MPa). For a weak mudstone, the low tensile strength limits the build-up of stress, causing Mode 1 failure to dominate; failure occurs with as little as 1.2 km overburden. For a strong mudstone the minimum burial depth increases to 4.5 km. A mudstone similar to average terrestrial mudstone requires burial beneath at least 2.1 km to undergo hydraulic fracturing.

6. Discussion

Our results suggest that even if the strength of the Sheepbed mudstone were equivalent to the weakest terrestrial mudstone, it would require burial by >1 km of sediment for hydraulic fracturing to occur. This is a conservative lower bound, as it assumes completely impermeable rock with a very low strength (a somewhat unlikely scenario given that permeability and rock strength are inversely correlated) (Chang et al., 2006). While comparison to engineering drill data does not directly provide tensile strength or cohesion, those data do indicate that the Sheepbed mudstone is most similar to a moderately lithified terrestrial sand- or mudstone (Grotzinger et al., 2014), for which tensile strength and cohesion are on the order of ~10 MPa. We therefore consider our median values (solid blue symbols in Fig. 6) to be most representative of the rocks at Yellowknife Bay, and that the actual burial depth at the time of fracture was on the order of ~3 km.

Regardless of the dependence on the unknown mechanical properties of the Sheepbed mudstone, a considerable amount of burial (i.e., kilometers) is required to generate the hydraulic fractures observed by Curiosity. The presence of the observed vein network is inconsistent with burial depths on the order of 100 m or less. As such, deposition within the Peace Vallis fan system after the large-scale erosion of lower Mount Sharp (i.e., a shallow burial hypothesis) is not supported. In contrast, the estimated burial depth of 1–3 km is in good agreement with the current exposed thickness of the lower formation of Mount Sharp (e.g., Fig. 1b). We interpret these results to suggest that the lower formation of Mount Sharp previously extended across the current location of YKB and likely to the walls of Gale crater. As such, the current morphology of Mount Sharp represents an erosional remnant of a feature that was once more laterally extensive, in agreement with experimental and transport-based models of eolian erosion of crater-filling material (Day et al., 2016; Kite et al., 2013).

These constraints on burial depth provide a means to further constrain the age and stratigraphic position of the YKB formation. Specifically, we interpret the YKB formation to have been deposited and subsequently buried by sediments equivalent in thickness to what is now considered lower Mount Sharp during the evolution of that feature in the Late Noachian/Early Hesperian (~3.6–3.8 Ga) (Fig. 7). Although the estimates presented here provide a minimum burial depth, they do not provide a maximum value, and it remains unclear whether the upper formation of Mount Sharp also extended over the location of YKB or if the entire volume of Gale crater was once buried (Malin and Edgett, 2000). In this burial scenario, the facies represented by YKB sediments of the Bradbury group interfinger with more distal equivalents to the south (currently in the subsurface) in the Mount Sharp group, consistent with the stratigraphic interpretation of Grotzinger et al. (2015). Indeed, mudstones within the Murray fm. of the Mount Sharp group are demonstrably part of lower Mount Sharp and have thus experienced deep burial, and recent observations by Curiosity suggest they, too, exhibit similar Ca-sulfate filled fracture networks consistent with hydraulic fracturing (Fig. 3c, d).

The burial depth estimates presented here confirm that the topographic depression known as Yellowknife Bay represents an erosional window into rocks that are significantly older than those present in outcrops in other parts of Aeolis Palus, including the uppermost units of the Peace Vallis fan (Grotzinger et al., 2015). Given crater retention ages for the surface of Aeolis Palus and the lower fan unit are ~3.3 Ga (Grant et al., 2014), while a formation age of ~3.8–3.6 Ga is inferred for lower strata of the Bradbury and Mount Sharp groups, the YKB formation must have been deposited, buried by a kilometer or more of material (based on results presented here), and subsequently exhumed over a period of about 300–500 Myr, prior to formation of the uppermost units of the Peace Vallis fan in the Late Hesperian. This interpretation does not affect the inferred alluvial–fluvial-lacustrine depositional environ-
geometry of the YKB formation (Grotzinger et al., 2014). It does, however, suggest the presence of a large erosional unconformity within the Peace Vallis fan system that spans a significant amount of time, separating the Late Noachian/Hesperian Yellowknife Bay formation from the Late Hesperian/Amazonian fan units (see Fig. 7). These observations indicate that the Gale crater basin was a net sink for sediment during its early evolution but then transitioned to a net source of sediment, a source from which erosion rates were higher prior to 3.2–3.3 Ga. Erosion rates since that time been significantly lower, as evidenced by the minimal erosion of the Peace Vallis fan over the past \( \sim 3.2 \) Ga (Grant et al., 2014).

The interpretation of deep burial further indicates that the mudstone of the Murray formation – which is exposed at higher elevation than YKB – is stratigraphically higher and therefore
younger than the Sheepbed mudstone. Comparison of textural, chemical, and mineralogical properties of the YKB mudstone with those currently being observed for mudstone of the Mount Sharp group can thus provide insight into the temporal evolution and diagenesis of ancient lake systems and their sediments within Gale crater during the Late Noachian/Early Hesperian. Although the geothermal gradient on ancient Mars is not well constrained, any attempts to understand the evolution of minerals and/or organic compounds in the Sheepbed mudstone through geologic time must consider burial by several kilometers and, thus, elevated temperature and pressure. Because the ancient martian geothermal gradient is most certainly lower than that of Earth, thermal degradation of organic compounds may require much greater burial depths on Mars. However, knowledge that the Sheepbed mudstone may have been buried by ~3 km of material provides an important constraint on how burial diagenesis may have affected clay minerals within that rock (Borinka et al., 2015). The burial depth and age estimates can be used in models of time-temperature integrals to assess potential chloritization or illitization of smectitic clays (Tosca and Knoll, 2009), and model results can then be compared directly to X-ray diffraction results for clays observed within the Sheepbed mudstone (Bristow et al., 2015). Orbital data indicate the presence of a clay-bearing zone higher up in the lower formation of Mount Sharp (Milliken et al., 2010). If rover observations indicate that these rocks are also mudstone, then their properties could be compared directly with those of the Sheepbed mudstone of YKB to understand the relationships between fine-grained sediment, temperature, pressure, and fluids as a function of space and time during the evolution of the Gale basin.

Burial depth also informs models of the role of diagenetic fluids and basin brines, which are just as likely to affect the chemistry, mineralogy and organic compounds within deeply buried martian rocks as their terrestrial counterparts. Although the Sheepbed mudstone does not exhibit evidence for mobilization of major elements (McLennan et al., 2014) and contains little evidence of chemical overprinting by sulfate-rich fluids, likely due to its inferred low permeability, this may not be true of stratigraphically higher mudstones in the Mount Sharp group currently being examined by Curiosity. As Curiosity treks up Mount Sharp it will encounter rocks that have experienced progressively less burial, a factor that might influence their degree of lithification, permeability, and porosity. This may in turn affect the degree to which diagenetic fluids have altered the original sediment composition and any organics trapped within those sediments. It is also possible that increased interaction with diagenetic fluids could lead to increased precipitation of minerals and occlusion of porosity, which would result in an increased degree of lithification for rocks above the YKB formation. In either case it is conceivable that a different burial history for mudstone in the Mount Sharp group may lead to greater variability in chemistry, or greater evidence for chemical alteration by diagenetic fluids, compared with rocks of the YKB formation.

Based on the results presented here, the recognition that the Sheepbed mudstone is older and was more deeply buried than mudstone in the Murray formation and elsewhere in lower Mount Sharp may help explain any differences or variability in chemistry, mineralogy, or organic content observed in such rocks by Curiosity during the remainder of its mission. Mudstones of the YKB formation can thus be used as the datum for constructing a time-series analysis of relationships between clay-sized sediment (including clay minerals), pore/diagenetic fluids, and organics in an ancient sedimentary basin on Mars.

7. Conclusions

Analysis of stress-dependent fractures in rocks of the Yellowknife Bay formation in Gale crater suggests that burial by at least 1–3 km is required to induce the hydraulic fracturing observed by Curiosity. This indicates that the rocks were rapidly and deeply buried, then rapidly exhumed during the Late Noachian/Early Hesperian, implying sedimentation (and later erosion) rates were significantly higher in Gale crater prior to ~3.3 Ga. This also implies that the lower formation of Mount Sharp was once more laterally extensive than its current morphologic expression, though whether or not the entire volume of Gale crater was once buried remains unconstrained. The YKB region explored by Curiosity represents an erosional window into the most ancient strata within Gale crater, and any southerly, distal facies that are temporally equivalent to the YKB formation are still confined to the subsurface. If correct, deep burial of the Sheepbed mudstone and overlying sandstones of the YKB formation also implies these are the oldest strata that will be encountered during Curiosity’s mission, and the habitable conditions recorded by these rocks occurred in Late Noachian/Early Hesperian. Curiosity’s current traverse through what is widely recognized as lower Mount Sharp (Grotzinger et al., 2015) is a trek through younger strata. Any habitable environments identified in these rocks represent later conditions that can be directly compared with those inferred for Yellowknife Bay to reconstruct the environmental and geologic timeline of Gale crater.

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Appendix A. Supplementary material

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References


