Introduction: The Yellowknife Bay formation preserves evidence of a habitable fluvial-lacustrine environment and exhibits evidence of two periods of aqueous activity [1], but Yellowknife Bay’s placement in the geologic history of Gale Crater is uncertain. Are these rocks exhumed strata formed contemporaneously with lower Mt. Sharp, or are they younger deposits formed by the Peace Vallis alluvial fan? The presence of natural hydraulic fractures in the Sheepbed mudstone [2,3] may help constrain the burial depth, and thus age, of these strata, enhancing our knowledge of the timing and availability of water in Gale Crater.

Each of the three members of the Yellowknife formation exhibits crosscutting fractures filled with Ca-sulfate, though these are most prominent in the Sheepbed Mudstone [1,4]. Their presence can be used to infer the state of stress under which they formed and, hence, an approximate burial depth required to produce them [2]. Thus, the morphology of these fractures and the mechanics of their formation can tell us how deeply the Yellowknife Bay formation was buried at the time fracturing occurred.

The sulfate-filled fractures are thought to be either a) desiccation cracks which later filled with Ca-sulfate, or b) natural hydraulic fractures (i.e., veins) driven by abnormally high fluid pressure in buried sediments [1,4]. These two scenarios require distinct states of stress during brittle failure. The morphology of the fractures, which reflects state of stress, can be used to discern which of these mechanisms is responsible.

Desiccation cracks form under a relatively uniform, tensile state of stress generated by the dehydration and volume change of a layer of sediment [5]. The far-field tensile stress results in vertical cracks that form polygonal networks. Each crack relieves stress in its vicinity as it forms, influencing the orientation of nearby cracks, and subsequent cracks propagate orthogonally to first-formed cracks. Though the overall crack network is polygonal, individual crack intersections are orthogonal [6]. If the sulfate-filled fractures at Yellowknife represent desiccation cracks they would be expected to exhibit orthogonal intersections, a feature that would be readily observable in images acquired by Curiosity.

Propagation of a natural hydraulic fracture is driven by pressure within the crack rather than by uniform far-field stress, and the direction of propagation is less constrained [7]. In addition to varied angles of intersection, hydraulic fracturing tends to produce irregular wall morphology and often encapsulates blocks of host rock between closely spaced veins [8]. Irregular fracture morphology is thus consistent with natural hydraulic fracturing.

Results: Fracture Morphology. MastCam and MAHLI images from Sols 1-500 were examined for the presence of sulfate-filled fractures, focusing on images that represent plan view geometry to minimize distortion due to oblique viewing angles. The image analysis software ImageJ was used to measure visible angles of intersection between sulfate-filled fractures in 86 images. The frequency distribution of intersection angles is given in Figure 1. For 133 unique intersections observed, the mean intersection angle is 71.5°.

![Figure 1: Frequency distribution of intersection angles observed in MastCam and MAHLI images of sulfate-filled fractures.](image)

A schematic of a fracture network observed by Curiosity is shown in Fig. 2. The network displays nonplanar walls (A in Fig. 2), blocks of host rock surrounded by sulfate-filled fractures (e.g., B), and several oblique angles of intersection.

Discussion: Fracture Mechanics. Oblique intersection angles, irregular morphology and entrained blocks of host rock indicate that the sulfate-filled fractures at Yellowknife Bay are a product of natural hydraulic fracturing – i.e., a vein network, consistent with the analysis of [2,3]. Based on this result, the mechanics of hydraulic fracturing can be applied to investigate the conditions under which these fractures would have formed.

We model the stress state of rocks within Gale Crater as that of a confined sedimentary basin, where the sources of stress are compaction of the sediments,
pore fluid pressure, and thermal expansion [7]. Differential stress as a function of burial depth is therefore calculated using estimates for the Hesperian geothermal gradient [9,11] and representative values for the physical properties of terrestrial mudstone, which have been shown, by comparison of drilling data, so be similar to the John Klein and Cumberland drill sites [1,10].

The efficacy of pore fluid pressure in initiating fracture is a function of the parameter \( \lambda \), which is the ratio of pore fluid pressure to lithostatic pressure. In terrestrial sedimentary basins, \( \lambda \) is approximately 0.4 at depths \( \leq 3 \) km and rapidly increases to 0.5-0.9 at greater depth once pore close-off occurs, generally due to compaction or diagenesis, e.g. the precipitation of pore-filling clays (though \( \lambda \) increase can also occur at shallower depths due to freezing of pore fluid). [7]

Fracture occurs when the differential stress at depth is sufficient to exceed either the tensile strength or the Mohr-Coulomb failure envelope of the rock. The failure envelope in this analysis is predicted using mechanical properties of terrestrial mudstones [10, 12]. Though the tensile strength of terrestrial mudstones is quite variable (0.63 – 18.6 MPa, we use 10 MPa [8, 12]), drill data for the Sheepbed mudstone are similar to analog tests on arkosic sandstone, indicating that the mudstone is not particularly weak.

Fig. 3 plots Mohr Circle representations of stress state for kilometer depth increments versus the failure envelope. Fracture occurs where the stress state intersects the failure envelope (red line). For relatively little pore close-off in the sediments (\( \lambda = 0.4 \)), hydraulic fracture initiates at a depth of 4-5 km for strata in Yellowknife Bay.

**Summary:** We have shown that the Yellowknife Bay mudstone will fracture if buried beneath 4-5 km of sediment. This solution, however, is not unique. A layer of well lithified mudstone (i.e., with a higher value of \( \lambda \)) would fracture at shallower depths. With the same tensile strength, for example, a more lithified rock (\( \lambda = 0.6 \)) will fracture under only 3.5 km load. For either such scenario the implication is that these strata may be equivalent in age to lower Mt. Sharp.

The largest source of error in this analysis is the poor constraint on the mechanical properties of the mudstone itself. While we have shown that little pore closure is required to cause the observed fracturing, an increased value of tensile strength requires correspondingly higher stress; either deeper burial or an increase in \( \lambda \). Such a scenario does not preclude fracturing, as increases in \( \lambda \) can arise simply from freezing of pore fluid, but does affect how deeply the sediments were buried at the onset of fracture. These issues will be the focus of our ongoing work.

**References:**
4. Vaniman, D.T. et al. (2014), Science, 343.6169, 1243480
11. Hahn, B.C. et al. (2011) LPSC 42, #2340