STRATIGRAPHY AND SEDIMENTOLOGY OF HOME PLATE AND ASSOCIATED INNER BASIN OUTCROPS.
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Introduction

The Mars Exploration Rover Spirit saw few occurrences of bedrock, and no clear evidence of sedimentary rocks, for the first several hundred sols of its mission [1]. The first Pancam images showing layered bedrock at Gusev crater were acquired on sol 744, at a formation called "Home Plate", shown in Figure 3. Home Plate (located at 14.64°S, 175.53°E) was first identified from Mars Orbiter Camera (MOC) imagery as a target of interest, based on its light-toned appearance compared with the surrounding dust and rocks of the Columbia Hills. From rover imagery, Home Plate is a sub-circular plateau, up to 2 meters high in places, comprised of layered, sedimentary rocks. The sedimentary sequence exhibits several distinct units, each with characteristic morphologies. Further, Home Plate is surrounded by ridge structures which for the first time at Gusev, these rocks present questions which may be solved by structural investigative techniques, in addition to the standard chemical and mineralogical analysis suite of the MER Athena payload. Stereo imagery taken by Spirit presents a quantitative way to assess the internal structure of Home Plate, and the layers which comprise it. Structural measurements of Home Plate and associated ridges support a volcaniclastic origin for the deposits which drape underlying topography.

Home Plate Stratigraphy

Lower Unit: Pancam images from Sols 747-750 show some of the best examples of the diversity of layering exhibited in the Home Plate depositional sequence. At this site several distinct units are exposed, which can be delineated into morphologic units. The lower unit in this sequence is characterized by thick beds which are planar and parallel in the outcrops observed by Spirit. In MI images of of this unit on Sol 747, a knobby texture is apparent, though it is difficult to tell whether these are original clasts, or diagenetic textures. In the only clear exposure of the lower unit at this site, the layers have been eroded back into nearly planar outcrops. There is some variation in physical strength between the layers, as some tend to form ledges, while others are recessed. This pattern indicates variable depositional conditions throughout the lower unit.

Within the lower unit, a potential bomb sag has been identified from Pancam imagery at site 124 Position 55. On Earth, bomb sags are typically associated with volcaniclastic deposits, where outsized clasts thrown out of an explosive vent are emplaced ballistically into an otherwise fine-grained ash deposit. The high-energy impact causes disruption and soft-sediment deformation in the underlying layers. In this area, one of the layers of the lower unit seems to curve beneath a clast several centimeters wide, which appears to be embedded within the outcrop. An important test is whether the apparent curvature in the layer associated with this clast is actually a topographic depression, as opposed to an effect of the outcrop and viewing geometries. Stereo imagery was acquired at close range to the putative bomb sag. This data shows that the layer does deflect roughly 2 cm from an otherwise linear exposure in the vicinity of the suspected bomb. The observation supports the case for a bomb sag in the lower unit of Home Plate, and thus an explosive origin for the sediments which comprise it.

At the top of this lower unit is an approximately 10 cm thick massive section. The transition to from planar-stratified to massive facies is gradual, with the prominent layers at the bottom of the unit becoming less distinct, and eventually disappearing. As there are no clear layers in this part of the section, it is impossible to extract any structural information, although the gradual transition implies a conformable contact with the planar bedded section beneath it. MI images of this massive section show a texture similar to the lower unit layers, with nodular textures, but no clearly identifiable grains. This unit is roughly 10 cm thick, as shown in the stratigraphic column in Figure 1.

Upper Unit: The upper unit of Home Plate accounts for the majority of the exposed section, roughly 90 cm out of 1.3 m. This unit is thin bedded, with characteristic low angle cross-bedding occurring throughout the section and at least one occurrence of high-angle cross bedding. The upper unit exhibits fine laminations typically a few mm in thickness. Two competing hypotheses have been proposed for the upper unit of Home Plate [2]. In the first interpretation, the upper unit is conformable with the lower unit, deposited in a later stage of the same pyroclastic surge. Cross stratification, often referred to as a "sandwave" facies in volcaniclastic settings, is common in pyroclastic surge deposits [3]. Alternatively, the upper unit represents material which has been reworked by aeolian processing from the same material which comprises the lower unit, being lithified at a later time. In this case, the action of some amount of water would likely be required to indurate the sediment. Thus, a central question for understanding the origin of Home Plate is discerning the depositional environment of the upper unit.

Two common facies are observed at Home Plate. At most locations on the northern and southern perimeter, layers are planar or low angle stratified. Truncation surfaces are typically inclined only a few degrees from bedding planes, and occur throughout the section. This bedding style is not uniquely diagnostic of a particular depositional mode, and is consistent with either surge deposition or an aeolian sand sheet facies [4].

On the eastern margin of Home Plate large-scale trough cross bedding dominates the section (Figure 2). Concave upward erosion surfaces are common and extend over meter-scale wavelengths. Bed sets within this facies exhibit laminations which parallel or asymptotically approach erosional lower surfaces. Cross bed sets range in scale from tens of centimeters to a few meters in width, and tens of centimeters in thickness. Trough cross bedding is typically formed by migration of sinu-

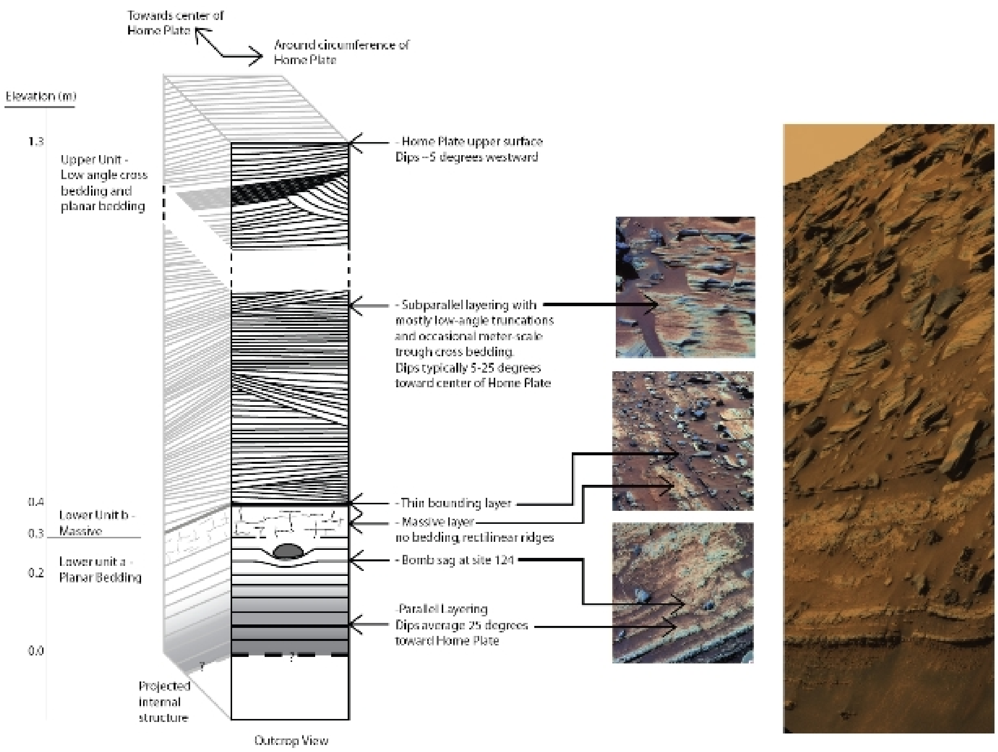

Figure 1: Stratigraphic column of Home Plate deposits, with representative examples. The primary division is between the lower unit, where planar bedded and massive facies are observed, and the upper unit, dominated by low angle cross stratification. The presence of a bomb sag in the lower unit points to an explosive volcanic origin for Home Plate sediment. The side panel of the column indicates the projected internal structure, which dips into the outcrop at each location visited by Spirit. Representative examples of each unit are indicated

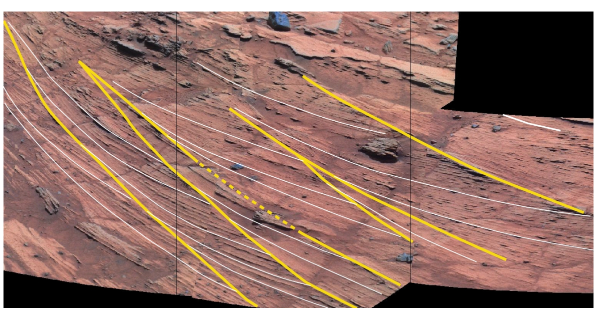

Figure 2: One example of large-scale trough cross bedding observed at Home Plate. The lines mark erosional boundaries between bed sets, seen on sol 1150. At this location, cross laminae show a preferred orientation with respect to bounding surfaces. Horizontal distance across image is $\sim$2 meters.

ous crested bedforms [5]. However, the link from stratigraphy to specific flow conditions is less certain. The cross bed sets on the eastern margin of Home Plate show a consistent orientation between bounding surfaces and internal stratification throughout the section, as shown in Figure 2. For a cross section nearly perpendicular to the flow direction, trough cross laminae would show a variety of orientations with respect to erosion surfaces. Hence, the flow direction is interpreted to be oblique to the outcrop orientation at this location.

Home Plate & Inner Basin Structural Relationships

We have used topographic information derived from stereo imagery to make precise structural measurements of the layered materials at Home Plate and associated ridges. From Pancam image pairs, range and topographic data can be derived out to 100 meters or more from the rover [6–8]. Layers are first traced from the images, and the corresponding topographic data is then extracted. A best-fit plane is calculated for each layer using linear regression to minimize the residuals in the direction orthogonal to the plane. From the best-fit plane, the strike and dip are calculated, along with their corresponding errors.

Statistical criteria are used to select only those layers which provide a well-constrained planar fit. Principal component eigenvalues describe the variance in three orthogonal directions, both within the plane (first and second components), and out of the plane (third component). The criteria exclude layers for which the topography is too linear to adequately constrain the third dimension and those for which the noise in the data is larger than the component of the signal which describes the planar fit. The range to the outcrop was less than 5 m at each of the imaging positions, and noise was typically under 1 cm in amplitude.

Lower Unit: The lower unit of Home Plate was best imaged at the northeastern corner of Home Plate. The unit primarily erodes back into nearly planar outcrops hindering determination of structural attitudes. However, the exposed face of the rock Barnhill had suitable surface topography to allow derivation of the dips within the lower unit. From this area, 4 layer traces were extracted which were well fit by planes. The dip azimuth of these layers is uniformly southeast, falling within a narrow range between S40°E and S65°E, with a mean of S58°E. The mean dip angle for the whole dataset was fairly steep at 25°. The lower unit bedding attitudes are nearly identical in strike, but have slightly higher dips compared to the upper unit layers directly above them.

Upper Unit: The upper unit of Home Plate is particularly well-suited to the structural topographic analysis described here, due to its characteristic erosional patterns. In many places, this unit forms ~10 cm scale spurs which project out of the outcrop face.

Overall, the dip magnitudes within this part of the stratigraphic section range from roughly 0-35 degrees, with a 1-σ range of 5-25°. Dip azimuths vary between outcrops, although at each location studied, they exhibit a consistent trend. Azimuths overwhelmingly trend southeast at the first site visited by Spirit, on the northwestern corner of Home Plate, as shown in Figure 3. This orientation projects roughly into the outcrop at this location, radial to the Home Plate structure. At this location, a large number of layers could be extracted, due to the thorough imaging, and small distance to the outcrop, which minimizes noise in the topographic data. At the second and third outcrops along the northern edge, Site 125, positions 38 and 100, similarly consistent trends were found, despite the fewer number of measurements. At both of these locations, dip directions were uniformly southwest, which again corresponds to the direction towards the center of Home Plate. At the fourth and fifth sites on the eastern margin layers dip westward and northwestward, respectively, again in the radial direction.

The upper unit of Home Plate exhibits ubiquitous cross-stratification, which could complicate structural measurements. However, all of the measurements were made in areas of low-angle cross-bedding to minimize this effect. At the first outcrop, where the most measurements were made, layers showed a mean slope perpendicular to the overall trend of less than 3°, up to a maximum of only 8°. The fact that the cross-bedding angles are very shallow is also shown simply by the tightness of the calculated distributions around a mean dip direction.

Associated Ridges: To the southwest of Home Plate several layered outcrops were imaged and their structural attributes were calculated. Three locations, on Low Ridge, Mitcheltree Ridge, and the intervening Troll outcrop, show consistent westward dips, allowing these outcrops to be structurally correlated despite the fact that they are physically discontinuous. In contrast, the well expressed Prat layer on Low Ridge shows a well-defined but conflicting westward dip over a roughly 10 meter long exposure. The mean dip of the eastern Low ridge layers is roughly 12 degrees to the west, while the upper unit layer on the north face dips more shallowly to the north-

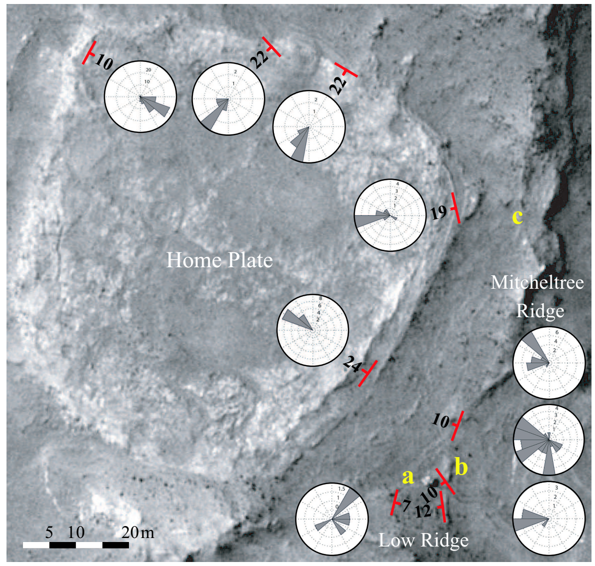

Figure 3: Map of Structural measurements from layered outcrops in the Inner Basin. Strike dip marks indicate the mean direction and magnitude while the associated rose plots show the measured dip orientations of the entire data set. These plots show that bedding attitudes at each location are generally tightly clustered in azimuth.

east (Figure 3). This variability indicates the presence of a small synform within Low Ridge, and shows that these outcrops do not all follow radial trend observed at Home Plate, but instead are oriented in at least two oblique directions, consistent with draping of underlying topography by volcaniclastic material.

Sedimentology

The sedimentological observations at Home Plate suggest a high degree of physical processing for the sediment population which comprises the upper unit of Home Plate. All of the samples which have been imaged with the MI have shown a narrow size distribution of particles, with a similar size range to that observed at the El Dorado sand sheet. No clasts have been observed in the upper unit which could not have been transported by aeolian activity. Further, the roundness of the clasts is difficult to explain with a primary volcaniclastic interpretation. It is possible that a large fragment of the upper unit is comprised of accidental material, which was already rounded and sorted before being swept into the pyroclastic surge. Hydrovolcanic deposits are known to have a high fraction of accidental clasts. However, the chemical similarity to both the lower unit nearby vesicular basalts suggests that the upper unit material is derived from a common source [2].

In contrast to Home Plate, Figure 4 shows targets imaged at three nearby ridges with a distinct microscopic texture (locations are indicated in Figure 3). These rocks also exhibit a framework of densely packed, well rounded and sorted clasts. The grain-size distributions for these three samples are indistinguishable, providing strong evidence for a single stratigraphic unit which can be correlated between outcrops. However, their distribution is clearly separable from the clastic rocks observed at Home Plate, suggesting these rocks occupy

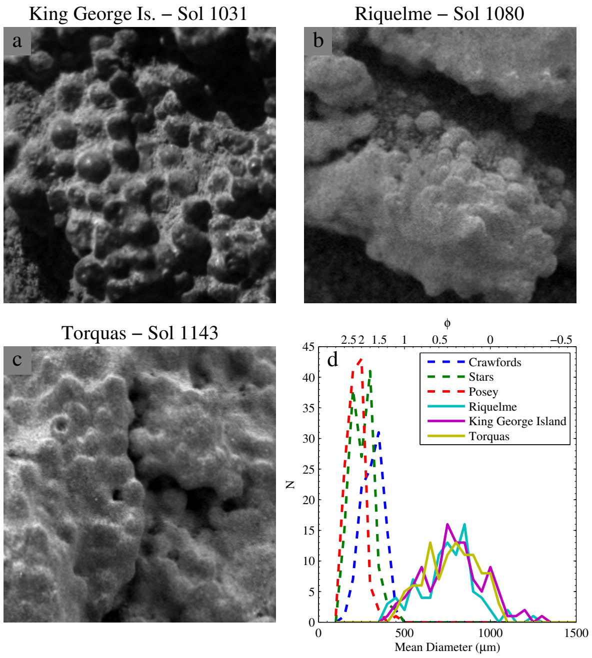

Figure 4: Comparison of three bedrock targets in the Inner Basin imaged at microscopic scales by Spirit. Each view is approximately 1 cm across. a) Post-brush view of King George Island, located on Low Ridge. b) Unbrushed surface of Riquelme, from a small outcrop north of Low Ridge. c) Unbrushed surface of Torquas, located on Mitcheltree Ridge, roughly 50 meters north of the other two targets. d) Grain size-frequency distributions for the three targets shown, together with three targets imaged at Home Plate.

a different stratigraphic position.

Summary

Quantitative analysis of the sedimentology and structure of Home Plate has provided new constraints regarding its origin. The radially inward dips of Home Plate layers argues for a unique depositional setting, most consistent with a volcanic surge draping the topography. The large-scale geometry of inward-dipping bowl-shaped beds may be derived from the original vent situated at the center of Home Plate, or may be inherited from a pre-existing depression, likely a crater. Further, the upper unit appears to be conformable with the lower unit, for the one outcrop where structural measurements of both units were possible. However, given that dip measurement are below the angle of repose for dry sediment, an aeolian interpretation can not be ruled out.

Sedimentological observations have shown a remarkably well sorted but distinct clast population in the upper unit of Home Plate and nearby ridges. The interpretation for the origin of Home Plate most consistent with these observations is initial deposition by a pyroclastic surge deposit. After deposition, some of the pyroclastic material may have been reworked, increasing the textural maturity of upper unit grains. The nature of the lithification of Home Plate remains unknown. Particularly in the case of aeolian reworking, a later event is required to lithify the sediment, which would likely have involved aqueous interaction. The recognition of explosive pyroclastic deposits provides new information on the styles of volcanism present on ancient Mars, and argues for the presence of subsurface hydrologic reservoirs.

Surge deposits are well known to drape underlying topography, and in particular, thicken in topographic lows [9]. Further, surge deposits are capable of overriding rough topography, and even traveling up topographic slopes [10, 11]. In this case, surge deposits could have been stripped away from most flat-lying areas, but remain protected within a natural depression. The rim of the preexisting impact crater could have been eroded before or after deposition by the pyroclastic surge, consistent with observed crater degradation elsewhere at Gusev crater [12].

The lack of an obvious relationship between Home Plate and the nearby ridges, as well as the of structural discordances among the ridge layers could imply one or more of the following geologic scenarios: 1) Separate formation events for each of the layered units at Home Plate and Low ridge, interspersed with periods of erosion. 2) Deposition of the layered materials on an uneven substrate, which led to the layers inheriting orientations based on the underlying topography. 3) Disruption of layers by impact processes or tectonic activity. However, no clear evidence of faulting has been observed thus far and impact craters have not disrupted structural organization on the scale of Home Plate.

Further rover observations will aim to determine the importance of each of these mechanisms in the formation and modification of Home Plate and the associated ridges.in the surrounding area. In particular, chemical and mineralogical studies will help to further elucidate the relationships between the ridges and Home Plate.

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