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Structure and stratigraphy of Home Plate from the Spirit Mars Exploration Rover

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[1] Home Plate is a layered plateau observed by the Mars Exploration Rover Spirit in the Columbia Hills of Gusev Crater. The structure is roughly 80 m in diameter, and the raised margin exposes a stratigraphic section roughly 1.5 m in thickness. Previous work has proposed a pyroclastic surge, possibly followed by aeolian reworking of the ash, for the depositional origin for these beds. We have performed a quantitative analysis of the structure, stratigraphy, and sedimentology at this location. Our results are consistent with an explosive volcaniclastic origin for the layered sediments. Analysis of bedding orientations over half of the circumference of Home Plate reveals a radially inward dipping structure, consistent with deposition in the volcanic vent, or topographic draping of a preexisting depression. Detailed observations of the sedimentology show that grain sorting varies significantly between outcrops on the east and west sides. Observations on the western side show a well-sorted population of sand sized grains which comprise the bedrock, while the eastern margin shows a wider range of grain sizes, including some coarse granules. These observations are consistent with primary deposition by a pyroclastic surge. However, aeolian reworking of the upper stratigraphic unit is not ruled out. Identification of explosive volcanic products on Mars may implicate magma interaction with subsurface hydrologic reservoirs in the past.

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1. Introduction

[2] The Mars Exploration Rover Spirit saw limited exposures of bedrock, and very few layered rocks for the first several hundred sols of its mission [*Squyres et al.*, 2004a]. This underscored the significance of the first images at close range of a formation named "Home Plate," which revealed extensive outcrops of clearly stratified bedrock. Home Plate (located at 14.64°S, 175.53°E) was first identified from Mars Orbiter Camera (MOC) images as a target of interest based on its light-toned appearance compared to the surrounding soil and rocks of the Columbia Hills, where Spirit has spent the latter part of her mission. From orbital images, Home Plate stands out as the largest expanse of lighter toned material in the Inner Basin of the Columbia Hills. Among sites visited by Spirit, Home Plate is unique, although a few smaller bright features in the Columbia Hills seen from orbit may be analogous. From rover images, Home Plate is a subcircular plateau, up to a few meters high in places, composed of stratified sedimentary rocks [*Squyres et al.*, 2007]. The sedimentary sequence here exhibits several units, each characterized by distinct morphologies. Several possible interpretations were consistent with initial observations, including fluvial, aeolian, and volcaniclastic deposits. Detailed observations were conducted to help address these competing possibilities, all of which can exhibit similar morphologies and can be difficult to distinguish even on Earth. Each possibility, however, would have distinct implications for the local geologic history. The origin of this enigmatic deposit is addressed here using quantitative structural and morphological techniques, providing complementary information to the chemical and mineralogical analysis suite of the MER Athena payload. Stereo images from both the engineering and science cameras are used to assess the internal structure of the bedding exposed at Home Plate in a quantitative manner. In combination with sedimentological and stratigraphic observations, these data constrain the potential hypotheses regarding the origin of this unique landform, ultimately determined to be volcaniclastic in origin. Hydrovolcanic features and pyroclastic deposits have been identified elsewhere on Mars based on orbital data [*Hynek and Phillips*, 2003; *Wray et al.*, 2008; *Jaeger et al.*, 2007], and modeling has been carried out to understand the formation of such deposits [*Wilson*

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and Mouginis-Mark, 2003; *Wilson and Head*, 2004, 2007]. Home Plate offers the first ground truth example for refining and testing these predictions *in situ*. While the origin of Home Plate has implications for the geologic history of this location, particularly regarding the role of localized, explosive volcanism within Gusev crater, the observations and tools presented here may also aid in the interpretation of similar deposits elsewhere on the planet. Specifically, a technique for robust plane fitting from rover stereo images is described here, and may applicable to future remote geological investigations.

2. Regional Setting

[3] Spirit landed on 4 January 2004 in Gusev crater, a 150 km diameter impact crater in the southern highlands of Mars. This landing site was selected primarily because of its association with Ma'adim Vallis, the main trunk of a large valley network that breaches the southern rim of the crater. This association suggests the possibility of a standing body of water at some time in the Martian past [*Grin and Cabrol*, 1997]. In addition to fluvial landforms, a notable feature of the regional geology is Apollinaris Patera, a large volcano 250 km to the north, indicating volcanism also had a significant presence in this region of Mars [*Robinson et al.*, 1993; *Martınez-Alonso et al.*, 2005]. Indeed, upon Spirit's landing, the plains around the rover were found to be uniformly basaltic in composition [*McSween et al.*, 2004; *Arvidson et al.*, 2006; *Morris et al.*, 2006]. After thoroughly characterizing the basaltic rocks of the Gusev plains, Spirit undertook a traverse to the Columbia Hills, in search of what appeared from orbit to be older geologic units and new lithologies. This small area of higher terrain is isolated among the otherwise flat topography of the plains. In orbital images, the basaltic plains clearly embay the older hills [*Crumpler et al.*, 2005]. Although the process that uplifted or emplaced the hills remains unknown, they may be remnants of the intersection of multiple crater rims, or remnants of the Gusev crater central peak [*McCoy et al.*, 2008]. Within this new terrain, Spirit has found new classes of rocks, evidence of aqueous alteration, and the first sedimentary rocks of the mission [*Squyres et al.*, 2006].

[4] After climbing Husband Hill, Spirit descended roughly 70 m into the Inner Basin of the Columbia Hills (Figure 1). In this area, Home Plate is one of the more prominent geologic structures, and appears to contain the largest expanses of bedrock. Several topographic ridges surround Home Plate, and may be genetically related. These include Mitcheltree Ridge to the east, and Low Ridge to the south. These ridges contain smaller outcrops of layered rock, and are capped by large, and often vesicular basaltic rocks. The stratigraphic relationship of these ridges to Home Plate remains unclear.

3. Home Plate Observational Campaign

[5] Because of the approaching winter and declining power levels, Spirit conducted an initial survey of Home Plate over the course of roughly 26 sols. Spirit first approached Home Plate on sol 748, at the northwest corner of the structure, after descending from Husband Hill. The outcrop at this location is the thickest and most diverse stratigraphic section observed at Home Plate to date. At this location, Spirit analyzed the target "Barnhill" on the outcrop, and also a float rock, "Posey". After this initial survey, Spirit drove to the top of Home Plate to gain a better vantage point for imaging the entire structure. In addition, Spirit carried out two analyses using its Instrument Deployment Device (IDD), on the targets "Stars" and "Crawfords". Following the *in situ* campaign, Spirit undertook a clockwise traverse, imaging prominent outcrops between drives. This traverse continued through sol 774, when Spirit left Home Plate to find a favorable location for winter operations. Spirit's departure at the Eastern side of the structure completed a survey of roughly one third of the circumference of Home Plate.

[6] After a mobility hiatus during the Martian winter, Spirit returned to Home Plate, and conducted an extensive campaign along the southeastern margin of the structure. This included both close range remote sensing along the outcrop, as well as a set of nine *in situ* observations of the cross-bedded rocks on the eastern margin. Together, these two analysis campaigns cover roughly half of the Home Plate margin, providing an extensive data set for interpreting its origin and context within the Inner Basin.

4. Stratigraphy

[7] Bedrock outcrops along the margin of Home Plate reveal a diverse stratigraphic sequence. Several distinct morphologies have been observed, which can be delineated into distinct geologic units. Chemically and mineralogically, these units are very similar, and comprise the Barnhill rock class. Further, all of the units at Home Plate have similar major element compositions to nearby vesicular basaltic rocks of the Irvine rock class [*Schmidt et al.*, 2008]. The two basic units identified at Home Plate include a planar-bedded to massive lower unit, and a cross-bedded upper unit. An intermediate layer between these serves as a useful marker bed for correlating outcrops. No exposed contact has been observed at the base of this section, and the nature of the underlying material is unknown.

4.1. Lower Unit

[8] The northwest margin of Home Plate contains the most complete section observed to date, including the best exposures of the lower stratigraphic unit. The lowest unit in the observed depositional sequence is characterized by thick beds which are planar and parallel over several meters (Figure 2, bottom right). In Microscopic Imager (MI) images of this unit, 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 on the northwest corner, the bedding has been eroded back into nearly planar outcrops. There is some variation in physical strength between beds, as some tend to form ledges, while others are recessed. This pattern indicates variable depositional conditions throughout the lower unit. While this characteristic does not discriminate unambiguously between depositional processes, it is consistent with a pyroclastic deposit, which can show rapid fluctuations in grain size, sorting, and induration between beds [*Crowe and Fisher*, 1973].

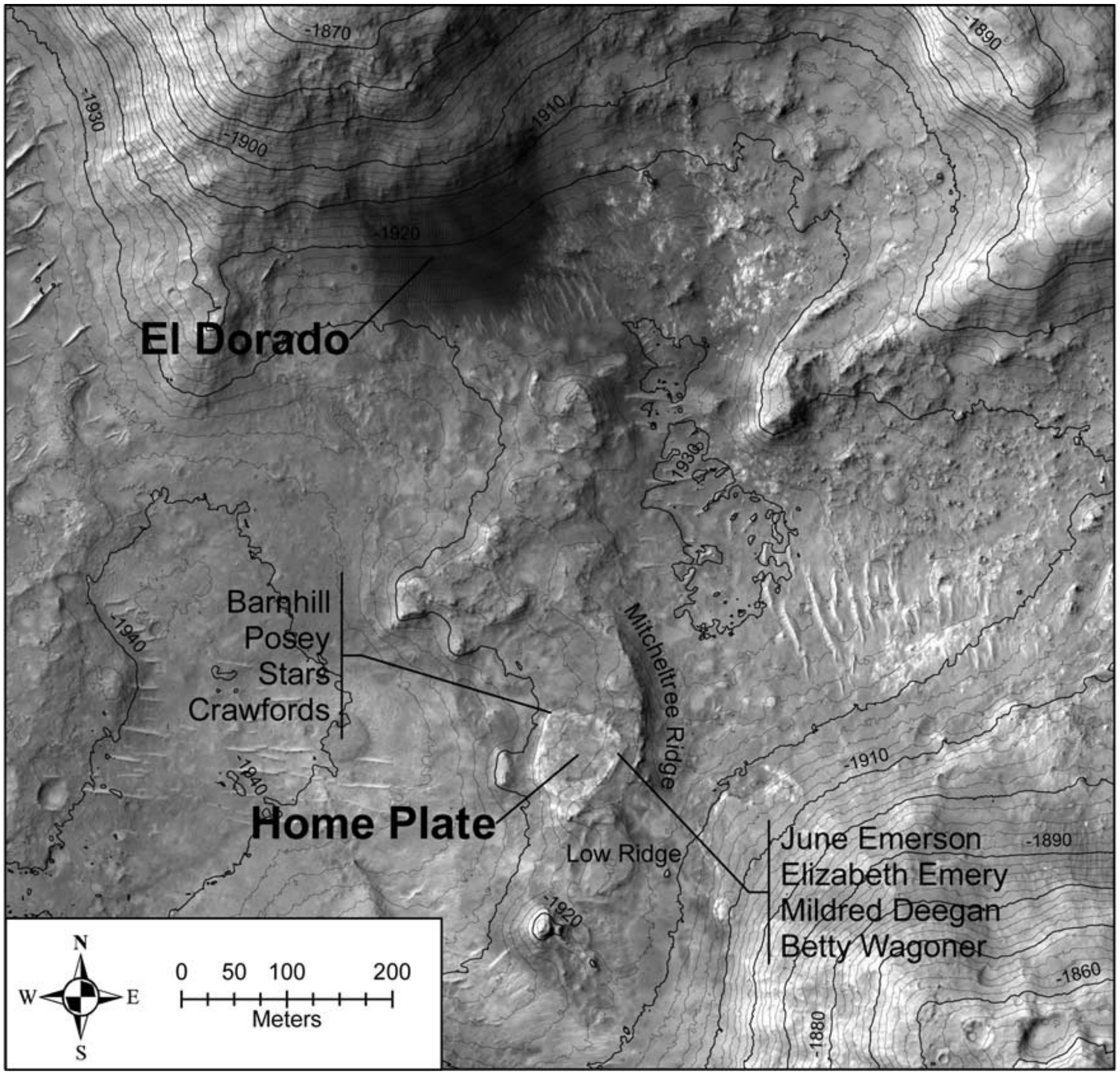

Figure 1. Map of the Inner Basin of the Columbia Hills, where Spirit has been conducting operations for the latter half of her mission. Home Plate stands out as a subcircular light-toned platform roughly 80 m in diameter. Topographic measurements indicate a dip of 3–4° to the northwest for the surface of Home Plate. Several small ridges are situated immediately around Home Plate, including Mitcheltree Ridge to the east and Low Ridge to the south. The dark feature near the top of the image is a modern aeolian dune field known as El Dorado. Contours at 2 m intervals are derived from stereogrammetry using HiRISE images PSP_001777_1650 and PSP_001513_1655 (image credit NASA/JPL/University of Arizona).

[9] Within the lower unit, an apparent bomb sag has been identified from Pancam images (see Figure 2, bottom right) [*Squyres et al.*, 2007]. 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 deformation of the underlying layers [*Fisher and Schmincke*, 1984]. In this area, the strata of the lower unit appear to curve beneath a clast several centimeters wide, which is embedded within the outcrop. Topographic measurements were made to evaluate whether the apparent curvature in the bed associated with this clast is truly a topographic depression, as opposed to an effect of the outcrop and viewing geometries. Stereo data acquired at close range to the bomb sag indicate that the layer does deflect roughly 2 cm downward from an otherwise linear exposure in the vicinity of the bomb. This observation supports the case for a bomb sag in the lower unit of Home Plate, and an explosive origin for the clasts which comprise it.

[10] At the top of the lower unit, a transition to a massive facies occurs, as shown in the stratigraphic section (Figure 2, middle right). The change from planar-stratified to massive facies is gradual, with the prominent bedding at the bottom of the unit becoming less distinct, and eventually disappearing. It was not possible to extract any structural information from this part of the unit, although it appears to be conformable with the planar-bedded section beneath it. MI images of this massive section show a texture similar to the planar beds, with nodular textures, but no clearly identifi-

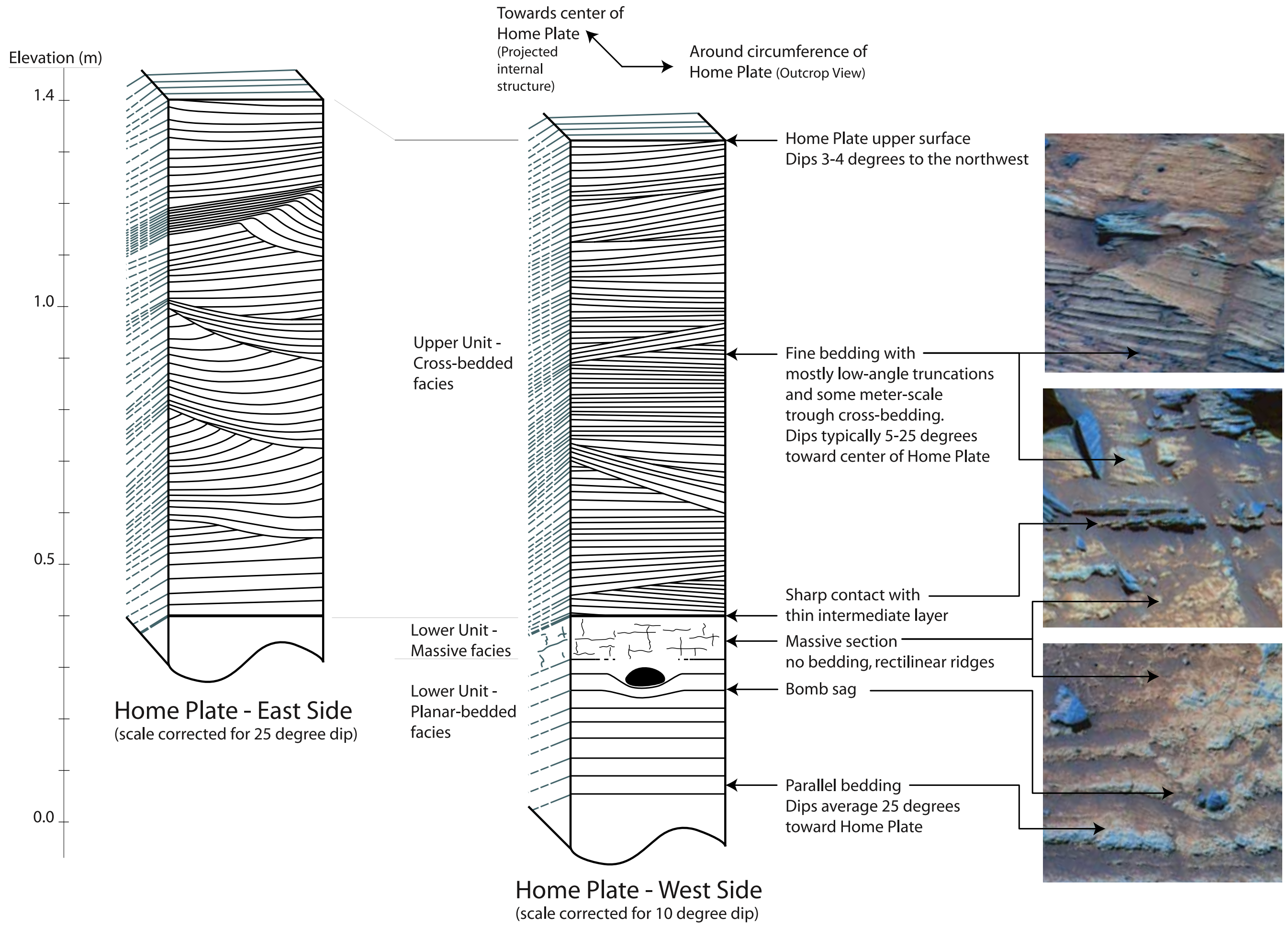

Figure 2. Stratigraphic column of Home Plate outcrops, with representative examples. The primary division is between the lower unit, where planar bedded and massive facies are observed, and the upper unit, dominated by cross stratification. The presence of a putative bomb sag in the lower unit points to an explosive volcanic origin for the Home Plate sediment. On the east side of Home Plate, the lower unit has not been identified, although a correlation is indicated between a prominent layer seen at the base of the upper unit at both locations. After correcting for the average structural dip on both the west and east sides of Home Plate, the stratigraphic thickness of the upper unit is calculated to be similar to within 10 cm between outcrops. The side panel of each column indicates the projected internal structure, which dips toward the center of Home Plate at each location visited by Spirit. Examples of each unit are indicated to the right. Each image on the right is a Pancam false color stretch using filters L2, L5, and L7 (753, 535, and 432 nm, respectively). Image numbers are (top) 2P228456914EFFAS6MP2440L2M1; (middle) 2P192944022EFFAO55P2275L2M1; and (bottom) 2P193032914EFFAO55P2276L2M1.

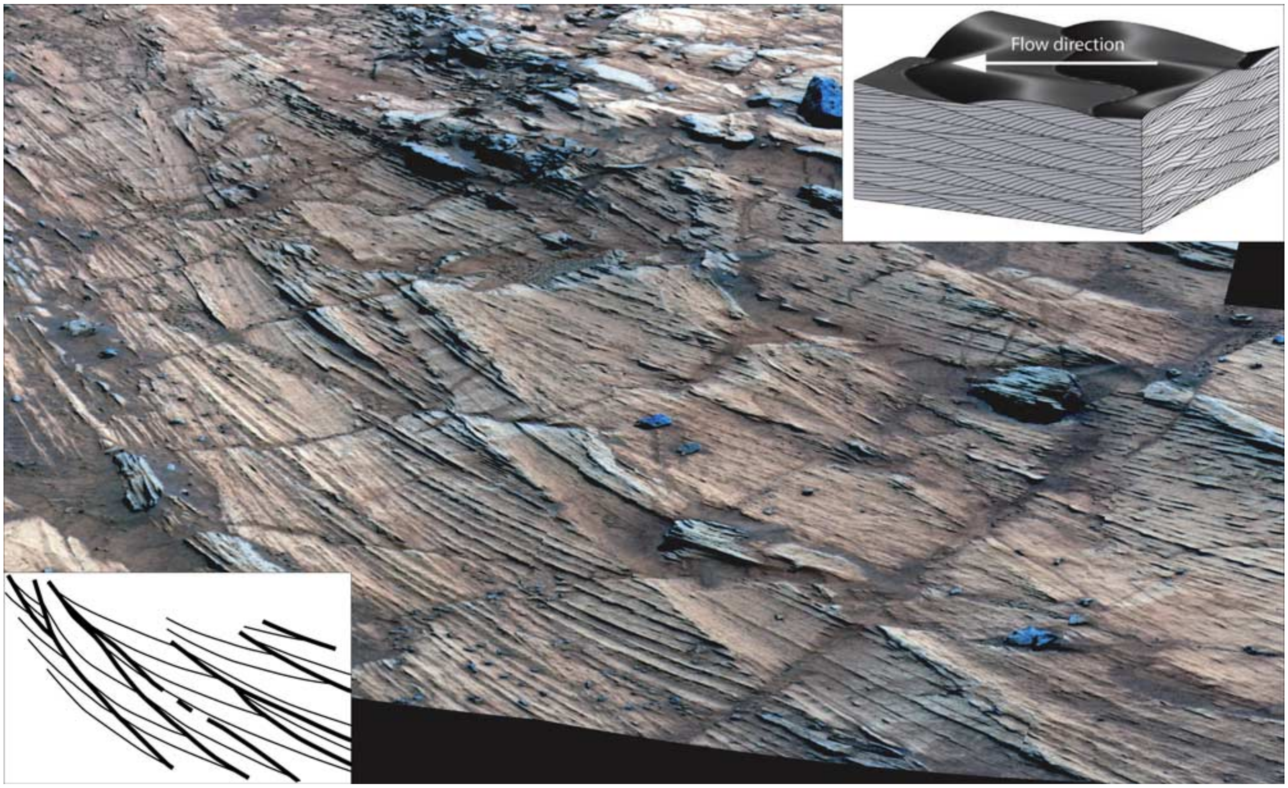

Figure 3. One example of high-angle cross bedding observed at Home Plate, from sol 1150. An interpreted sketch is shown the lower inset, with erosional boundaries between cross-bed sets marked as thick lines with representative cross strata shown as thin lines. At this location, cross strata show a consistent orientation with respect to bounding surfaces, and bounding surfaces occasionally intersect at low angles. This suggests a uniform migration direction, which was oblique to the outcrop. The top inset shows one possible bed form reconstruction for this outcrop. The horizontal distance across the lower part of the image is approximately 2 m. The mosaic is a false color stretch, as in Figure 2 (mosaic credit NASA/JPL/Cornell University).

able grains. This part of the lower unit is roughly 10 cm thick, as shown in the stratigraphic column in Figure 2. As indicated in Figure 2, the lower unit has not been clearly identified on the eastern side of Home Plate. It is likely obscured by modern aeolian cover, but may simply not have been preserved (or ever deposited) in the section here. A correlation may exist with other rocks exposed on the east side between Home Plate and Mitcheltree Ridge, although poor exposures have prevented a conclusive determination.

4.2. Upper Unit

[11] The upper unit of Home Plate accounts for the majority of the vertical section, roughly 90 cm out of 1.3 m on the northwestern corner. This unit is thin bedded, with characteristic low-angle cross bedding occurring throughout the section and at least one location with high-angle cross bedding on the eastern edge (Figure 2, top right). The upper unit exhibits fine stratification, with individual strata typically a few millimeters in thickness. Two competing hypotheses have been proposed for the upper unit of Home Plate [*Squyres et al.*, 2007]. 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 "sand wave" facies in the case of volcaniclastic deposits, is a common feature of terrestrial surge beds [*Wohletz*, 1998]. Alternatively, the upper unit may represent material which has been reworked by aeolian processing from the same material which comprises the lower unit, being lithified at a later time. Thus, a central question for understanding the origin of Home Plate is discerning the depositional environment of the upper unit.

[12] Two facies are prevalent within the upper unit of Home Plate. From the northwestern to the southern corners of Home Plate, images have been acquired of nearly the entire margin, and in some places repeatedly. Thus, the image data sets are highly representative of the actual outcrops at Home Plate. At most locations on the northern and southern perimeter, beds 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 [*Fisher and Schmincke*, 1984] or an aeolian sand sheet facies similar to that described at Meridiani Planum by *Grotzinger et al.* [2005].

[13] On the eastern margin of Home Plate, large-scale trough cross bedding dominates the section (Figure 3). Concave upward erosion surfaces are common and extend over meter-scale wavelengths. Bed sets within this facies contain strata that parallel or asymptotically approach ero-

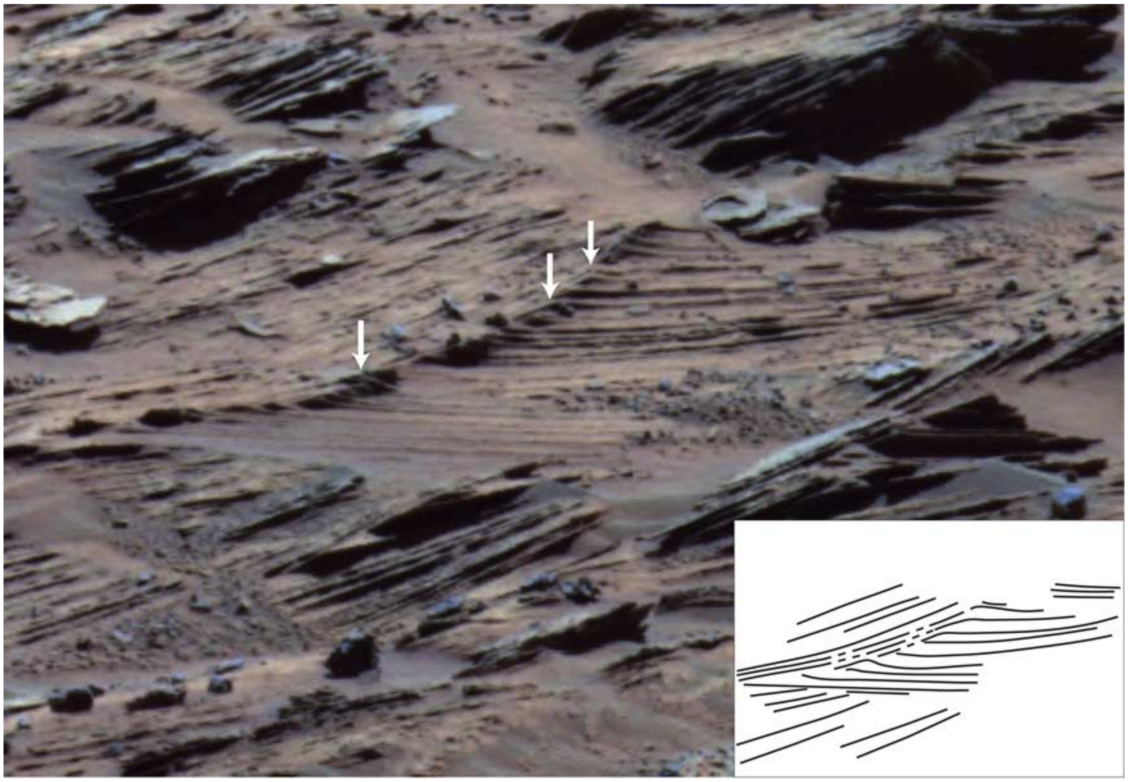

Figure 4. High-angle cross bedding exposed on the eastern side of Home Plate. This example shows evidence for the preservation of stoss-side laminae along with the crest of the bed form. Locations where preservation of the crest is apparent are shown with white arrows. The inset shows a sketch of the interpreted strata. Preservation of the crest of such a bed form implies rapid deposition relative to lateral migration. The outcrop here is north-south trending, on the eastern margin of Home Plate. The image is approximately 1 m across, and is a false color stretch as in Figure 2, of sol 774 image 2P195076279EFFAPDSP2381L7M1.

sional lower surfaces. Exposed cross-bed sets are typically a few meters in horizontal extent, and tens of centimeters in thickness. It is well established that trough cross bedding is formed by migration of sinuous crested bed forms [*Rubin*, 1987]. However, the link from stratigraphy to specific flow dynamics 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 3. For a cross section nearly perpendicular to the flow direction, trough cross bedding should show a variety of orientations with respect to erosion surfaces. For this reason, the flow direction is interpreted to be oblique to the outcrop orientation at this location. Further, the consistent orientation of the cross beds implies a uniform migration direction of the bed forms. This observation is consistent either with a pyroclastic surge, or aeolian dunes that generally migrated in one direction. One possible bed form reconstruction is shown in Figure 3 (top inset), created using software developed by *Rubin and Carter* [2006]. In this inset, a sinuous-crested bed form is shown migrating uniformly in a direction oblique to the exposed section. This is a simple formation hypothesis for the outcrops seen at Home Plate; more complex geometries, particularly ones involving multiple superimposed bed forms, may also be consistent with observed cross-bedding geometries.

[14] In one location on the east side of Home Plate a unique high-angle bed form is preserved, as shown in Figure 4. The outcrop here is interpreted to expose a cross section nearly parallel to the flow direction, which was likely left to right in this image. Interpreted lee side strata are inclined at a steep angle to the prevailing bedding orientation. In this example, the crest of the bed form and some of the windward side appears to have been preserved. Stoss preservation indicates that the bed form was climbing at a supercritical angle, or slightly steeper than the stoss-side laminae. Climb angles near or above this critical angle occur when the deposition rate is high relative to the lateral migration of the bed form. For terrestrial aeolian deposits, evidence of supercritical climb is rare in the geologic record [*Kocurek*, 1991; *Rubin and Hunter*, 1982]. Further, the continuity of the laminae between the stoss and lee sides of the bed form in Figure 4 is unusual for a simple aeolian bed form, which tend to be dominated by traction on the windward side and both fallout from suspension and avalanching on the lee side. In cases where aeolian dune crests are preserved, the processes would produce different stratification patterns and discontinuous laminations between the stoss and lee sides [*Ahlbrandt and Fryberger*, 1982]. In contrast, stoss depositional forms are commonly documented in pyroclastic surge deposits [*Crowe and Fisher*, 1973; *Cole*, 1991]. In this case, laminae are often continuous over the crest of the dune [e.g., *Fisher and Waters* 1970,

Plate 3]. Both the presence of cohesive sediment and rapid fallout from suspension over the whole bed form can allow preservation of the crest in a surge deposit [*Crowe and Fisher*, 1973]. The observation of a supercritically climbing bed form favors the pyroclastic interpretation for the upper unit, although it is the only example seen thus far at Home Plate.

[15] Ideally, details of the cross bedding observed in the upper unit of Home Plate could provide clues as to the depositional process that formed it. Cross-bedded sediments are most commonly deposited by aeolian or fluvial processes on Earth. However, volcanic surge deposits can also show complex cross stratification, and the discrimination between primary surge deposits and those reworked by aeolian processing is difficult even in terrestrial settings [*Smith and Katzman*, 1991]. Very little chemical or morphological evidence has been found for fluvial action in the Columbia Hills [*Squyres et al.*, 2007]. Further, as discussed in section 5, a large fraction of the sediment comprising the upper unit is unresolvable by the MI, implying grain sizes less than 100 μm. As shown in Figure 17 of *Grotzinger et al.* [2005], dunes are not predicted to form in subaqueous flows on Mars for grain sizes less than $\sim$200 μm. However, the aeolian and surge interpretations are both consistent with many of the observed characteristics. In particular, large-scale trough cross bedding is well documented on Earth in both aeolian deposits [*Rubin*, 1987; *Ahlbrandt and Fryberger*, 1982] and volcaniclastic surges [*Wohletz*, 1998]. All of the cross bedding seen at Home Plate is at the $\sim$10 cm to 1 m scale or larger. In most cases, bed forms are truncated, indicating larger original heights. No bed forms have been observed at centimeter-scale wavelengths.

4.3. Intermediate Layer

[16] At the northwestern corner of Home Plate, a thin, erosion resistant bed was observed between the upper and lower units (Figure 2, center of middle inset). This bed typically appears as a doublet of two prominent strata, roughly 2 cm thick in total. The physical strength of this layer, in combination with its position between two morphologically distinct units makes it a useful marker bed for correlating outcrops.

[17] The intermediate layer cannot be traced continuously around Home Plate, disappearing particularly on the northeastern margin. However, a similar unit is observed on the southeastern edge of Home Plate. At several locations, an erosion resistant "fin" appears close to the bottom of upper, cross-bedded unit. Further, the bed often appears as a doublet, of similar thickness to that observed on the other side of Home Plate. The location of this layer at the bottom of the exposed section is also consistent with the disappearance of the lower unit on the southeast margin. Thus, the combined similarity in thickness, stratigraphic position, and morphology suggest that these strata are correlative over 180° of the circumference of Home Plate. The observation of this intermediate layer on both the northwest and southeast sides of Home Plate also requires deposition by a process which was uniform over at least tens of meters.

4.4. Home Plate Upper Surface

[18] Observations of the top of Home Plate, which Spirit drove onto at the northeastern and western margins, show a heavily fractured, dust covered surface. Several subcircular dust filled depressions are likely remnants of small impact craters, indicating an ancient surface. Where upper unit rocks are exposed, they have been rotated and displaced, making their stratigraphic interpretation difficult. While Spirit has not driven into the center of Home Plate, some exposures of bedrock are continuous and appear to be largely intact from rover and orbital images. This indicates that the modern surface is primarily a product of bedrock erosion, rather than infill by aeolian material. In addition, there appear to be localized areas where dark, vesicular basaltic rocks are scattered around the surface. The stratigraphic position of these rocks relative to the Home Plate sequence is unknown, although geochemical results indicate a genetic relationship [*Schmidt et al.*, 2008].

[19] Aeolian erosion has left a smooth upper surface to the Home Plate structure, although a small raised rim exists in some locations, particularly on the southern margin. The topography of the upper surface of Home Plate can be quantified using orbital stereo images. We have used High Resolution Imaging Science Experiment (HiRISE) images (image numbers PSP_001777_1650 and PSP_001513_1655) to derive a digital elevation model (DEM) for the Columbia Hills via the method of *Kirk et al.* [2008]. From this data set, Home Plate can be adequately approximated by a plane, which dips 3–4° to the northwest (Figure 1). While the upper surface of Home Plate has clearly undergone some degree of erosion, the magnitude and azimuth are similar to the surrounding gradient of the Inner Basin, as measured from the same data set. This long-wavelength tilt of the upper surface of Home Plate may reflect draping of the preexisting topographic slope.

5. Sedimentology

[20] Spirit made observations of several targets at two locations around the perimeter of Home Plate with the Microscopic Imager. Three of these targets (Posey, Crawfords, and Stars) were rocks from the upper cross-bedded unit, on the western side. Stars and Crawfords were both on top of Home Plate, indicating an origin in the uppermost part of the section, although the rocks in this area appear to have been rotated and shifted from their original positions. Posey, on the other hand, was clearly out of place, located to the side of Home Plate. Although its exact position in the stratigraphic column cannot be determined, its fine-scale stratification clearly correlates with the character of the upper unit of Home Plate. All of these images were taken roughly parallel to bedding planes. A fourth target on the west side, Barnhill, was imaged within the lower unit, on sols 747 and 750 (Figure 5). This target was of in-place bedrock at the northwest corner of Home Plate, so its stratigraphic position is well established. Finally, a set of seven observations were made on the east side of Home Plate, with five in the upper unit, and two on the intermediate fin layer. All of the east side targets were in place in the outcrop, and most were perpendicular to bedding planes, exposing a sequence of strata.

[21] Figure 5 shows an MI image of the lower unit target Barnhill. While the lower unit of Home Plate is stratified at centimeter scales, it is massive at smaller scales. Further, there is little evidence of individual clasts within this rock.

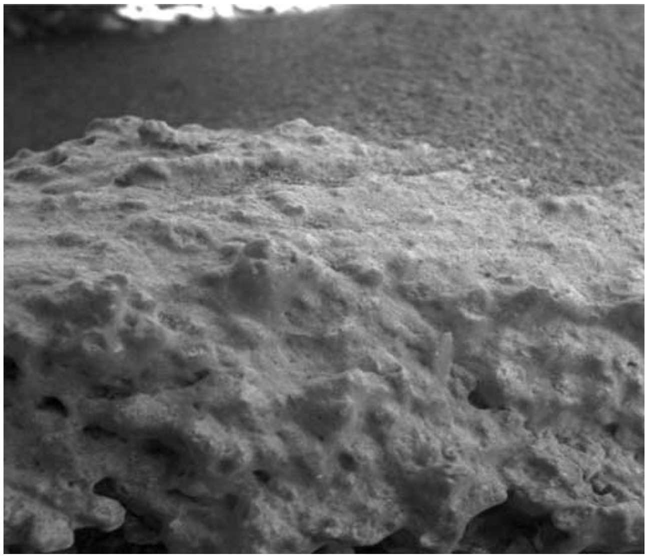

Figure 5. Unbrushed surface of Barnhill, a target within the lower unit of Home Plate, taken on sol 750. The view is 3 cm across. Image 2M192958525FFLAO55P2977M2M1.

The lack of a clastic texture suggests either that the sediment size is largely below the resolution of the MI (less than 100 μm), or that diagenetic or weathering processes have obscured the original clastic texture. The latter interpretation is supported by the knobby texture seen in some lower unit rocks, as shown in Figure 5. When they can be measured, these roughly equant knobs are of a coarse to very coarse sand size (roughly 1 mm in diameter, or between 1 and -1 on the ϕ scale).

[22] In contrast to the lower unit, MI images of upper unit rocks show abundant dark clasts typically hundreds of microns in diameter, and up to nearly 3 mm for the largest example (Figure 6d). In some cases, the rocks appear to be clast supported, as in the case of Crawfords, on the northwestern side of Home Plate (Figure 6a). However, particularly on the eastern side of Home Plate, a significant volumetric fraction of the rocks appears to be composed of material finer than the resolution of the MI ($\sim$100 μm [*Herkenhoff et al.*, 2004]), as seen in Figures 6c and 6d. In the case of a mature aeolian deposit, material below this threshold is often removed by suspension, leaving a well-sorted framework of coarser particles which move by saltation. This attribute is observed for modern aeolian deposits imaged by Spirit, one example of which is shown in Figure 6b. This image was taken at the 170 m wide sand sheet known as "El Dorado", to the north of Home Plate (Figure 1). At this location, the apparent lack of finer grained material was also indicated by a lack of sediment cohesion within a trench dug by the rover [*Sullivan et al.*, 2006]. In contrast, the poorly sorted character of many surge deposits on Earth is consistent with a large fine-grained fraction [*Smith and Katzman*, 1991].

[23] The upper unit exhibits several differences in sedimentology between the east and west side of Home Plate. On the west side, grains are highly rounded, appearing to be nearly spherical for the largest, best resolved grains. In contrast, on the east side of Home Plate, grains are more angular, and occasionally elongated. Grain roundness is an important characteristic for distinguishing between depositional processes. Very round grains typically indicate extensive transport and abrasion prior to deposition. An excellent example is the El Dorado sand sheet, shown in Figure 6b. In contrast, juvenile pyroclasts are typically angular, experiencing only minor physical abrasion during transport [*Wohletz*, 1983]. While the rock targets on the west side of Home Plate are strikingly similar to modern aeolian deposits in terms of roundness, the east side targets are more consistent with a limited degree of transport and abrasion. Ultimately, these contrasting observations alternately provide support for either a pyroclastic or an aeolian depositional mechanism for the upper unit.

[24] The second important characteristic of the upper unit clasts is their degree of sorting, which again varies between the two sides of Home Plate. To quantify the sorting characteristics, we have measured the diameters of several hundred grains in selected patches of the MI images for each of the upper unit targets. In addition, we performed the analysis on El Dorado, the modern aeolian deposit observed by Spirit earlier in the mission. This was done for comparison in recognition of the fact that aeolian deposits are typically among the most mature sediments found in terrestrial environments [*Prothero and Schwab*, 2004].

[25] Figure 7 shows a plot of the sediment size distribution for each of the targets on the west side, along with El Dorado. All of the distributions fall within a very narrow size range from 100 to 500 μm. The mean grain diameters for the three Home Plate rocks range from 216 μm for Posey to 313 μm for Crawfords, while the aeolian El Dorado is intermediate at 288 μm. Further, the width of these distributions, which gives a measure of the sorting, is similar. Standard deviations range from 48 μm to 65 μm for Home Plate, while El Dorado falls within these bounds, at 56 μm. On the basis of grain size and sorting alone, the clast population found on the west side of Home Plate is indistinguishable from a modern, texturally mature sand sheet. However, pyroclastic deposits are also capable of transporting sand sized sediment, and physically sorting the sediment to varying degrees [*Wohletz*, 1983]. From the observations of the west side alone, the aeolian reworked hypothesis is favored, but a primary volcaniclastic origin cannot be ruled out.

[26] On the east side of Home Plate, very different sorting characteristics are seen. While the distributions from the west side have a fairly narrow peak around the mean diameter, the east side shows a significant tail of much coarser material, and a peak at somewhat finer grain sizes (Figure 8a). The mean grain diameters for these rocks are similar to the west side, while the standard deviations are uniformly higher (Figure 8b), consistent with the coarse tail of the distributions. The largest clast found within the cross bedding on the east side was approximately 1.5 by 2.8 mm in size. This diameter is far larger than any observed at El Dorado, the largest of which are under 0.5 mm. It is, however, consistent with the size range of granules that have been transported by saltation-induced creep in modern eolian deposits on Mars [*Jerolmack et al.*, 2006]. These granules can form small low-relief bed forms known as granule ripples, and have been observed at both rover locations [*Greeley et al.*, 2004]. Of course, large clasts are

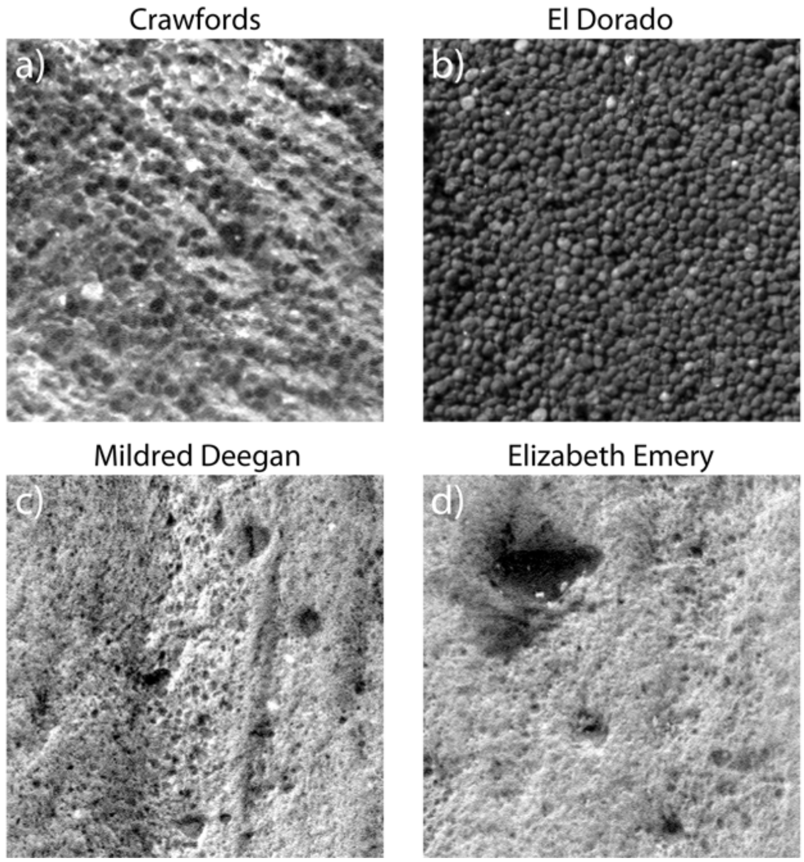

Figure 6. MI views of Home Plate upper unit rock targets (Crawfords, Mildred Deegan, and Elizabeth Emery), compared with the modern El Dorado dune field also observed by Spirit. In the rock Crawfords, a consistent population of well-rounded and -sorted clasts are observed. This population is nearly identical to that observed at El Dorado, both in terms of shape and sorting. However, on the east side of Home Plate, images of the lower two rock targets show a more poorly sorted texture, with several outsized clasts. The largest clast, from Elizabeth Emery, is nearly 3 mm in diameter. Aeolian activity cannot transport grains of this size by saltation on Mars (although saltation-induced creep may be possible), giving weight to the primary pyroclastic surge interpretation for the upper unit. Each image is a subframe 1 cm across. Image numbers are 2M194100679EFFAODQP2936M2M1, 2M189317855EFFAL00P2956M2M1, 2M234495019EFFATF3P2936M2M1, 2M234405984EFFATF3P2936M2M1.

common in pyroclastic surge deposits, and can be emplaced as part of the surge cloud, or ballistically for the largest clasts.

[27] Together, the textural evidence on the east side of Home Plate paints a picture that is the inverse of the situation on the west side: on the east side, a pyroclastic surge origin is favored, but aeolian reworking cannot be ruled out. While observations have illuminated a spatial heterogeneity to the upper unit of Home Plate, it is clear that the cross-bedded outcrops are all part of a single unit, which is expected to have formed via a single process. There is no compelling evidence to suggest multiple processes are required to produce different parts of the upper unit, or that only part of the section may have undergone aeolian reworking.

6. Structure

6.1. Method

[28] We have used topographic data derived from stereo images to make precise structural measurements of the stratified materials at Home Plate. The Panoramic Camera (Pancam) is the primary science imaging tool onboard the MER rovers. This pair of cameras is capable of taking stereo images with a 30 cm baseline in both red and blue wavelengths [*Bell et al.*, 2003]. From Pancam image pairs, range and topographic data can be derived out to 100 m or more from the rover [*Squyres et al.*, 2003]. To a lesser extent, we have also made use of stereo images from both the Navigation Camera (Navcam), and the Hazard Avoidance Cameras (Hazcams). Image pairs are taken specifically for stereogrammetry, and topographic data is derived via the automated software pipeline maintained by NASA's Multimission Image Processing Lab (MIPL) [*Maki et al.*, 2003; *Alexander et al.*, 2006].

[29] Strata were first traced manually from the original images, and the corresponding topographic data was subsequently extracted. Layers which could be followed over a significant fraction of the image (typically greater than 75 pixels), and which had a natural three-dimensional topog-

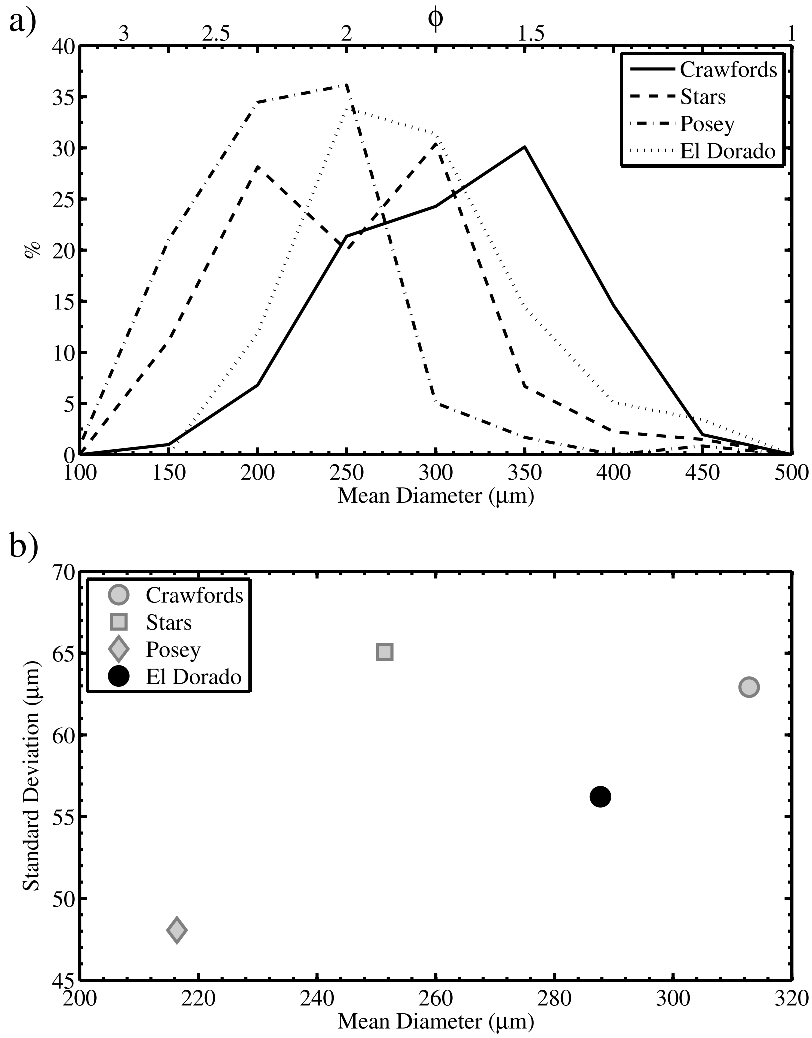

Figure 7. (a) Percent grain size distribution for three upper unit rocks from the west side of Home Plate, compared to a modern sand sheet (El Dorado), also observed by Spirit. The four distributions are very similar, demonstrating the high degree of sorting of the sediment which comprises the upper unit. Bin size is 50 μm. (b) Mean grain diameter plotted against the standard deviation of the grain size population. Again, Home Plate clasts exhibit textural maturity comparable to modern aeolian sediment.

raphy in the outcrop worked best for this analysis, so efforts were made to select layers which exhibited these qualities.

[30] A best fit plane is calculated for each layer using linear regression to minimize the residuals in the orthogonal direction. From the best fit plane, the strike and dip are calculated, along with their corresponding errors. Spirit conducted an extensive though rapid imaging campaign as it circumnavigated the northern and eastern sides of Home Plate. The data used in this analysis are from site 124 position 55, site 125 positions 38, 100, and 218, and site 129 positions 25 and 262 (Figure 9). These sites were chosen on the basis of their well-exposed outcrops of intact bedrock, and the suitability of the images for this analysis. Measurements were made for both the planar-bedded lower unit and the cross-bedded upper unit of Home Plate. However, measurements of the upper unit were only taken in areas of low-angle cross bedding, in order to elicit larger-scale structural information, rather than bed form signatures. Retrieved bedding orientations mostly show dip angles higher than that exhibited by the cross bedding, affirming that this was the case.

[31] Mathematical 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 first criterion limits the percentage of the variance in the first principal component to less than 99.5%. This prevents layers for which the topography is too linear to adequately constrain the second dimension from being included in further analyses. The second criterion requires the ratio of the variance described by the second principal component to that of the third to be greater than 15, ensuring that the signal which describes the planar fit is significantly larger than the out-of-plane error in the data. These empirical values were found to reliably exclude poorly constrained measurements. The range to the outcrop was less than 5 m

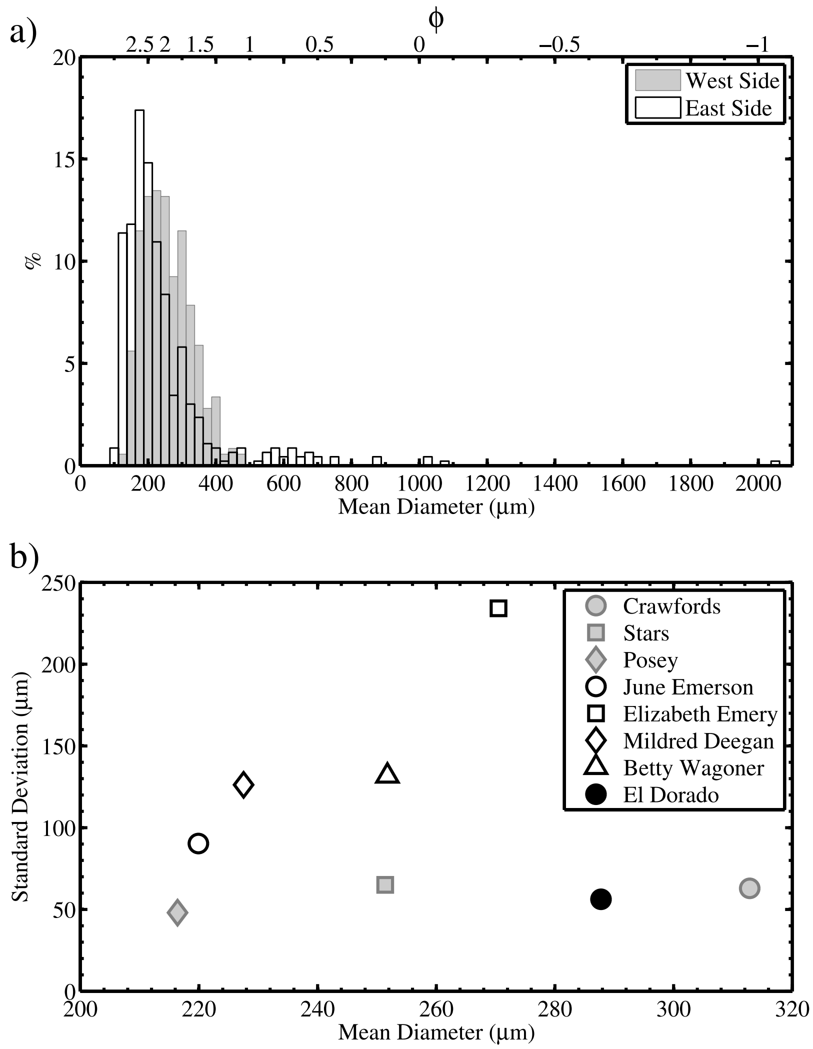

Figure 8. (a) Percent grain size distribution for all measured upper unit rocks on the east and west sides of Home Plate. The east side rocks show a long tail of coarser grains out to over 2 mm, and a peak at smaller grain sizes. Bin size is 25 μm. (b) Mean grain diameter plotted against the standard deviation of the grain size populations. This plot demonstrates the relatively poorer sorting of the east side rocks (unfilled markers) compared to the west side (gray markers). The modern aeolian deposit El Dorado is also included for comparison.

at each of the imaging positions, and noise was typically under 1 cm in amplitude.

6.2. Results

6.2.1. Lower Unit

[32] The lower unit of the stratigraphy was best imaged at the northwestern corner of Home Plate, and this was the only location suitable for structural analysis. Overall, the lower unit appears to have low resistance to physical erosion, and primarily erodes back into nearly planar outcrops. Such small topographic variation renders much of the unit unsuitable for this study, due to the inability to uniquely determine the three-dimensional attitude from a linear exposure. Only one area, on the rock Barnhill, had suitable surface topography to allow derivation of the dips within the lower unit. The images of Barnhill best suited to this analysis were from Spirit's Front Hazcam on sol 751. From this area, six bedding traces were extracted which were well fit by planes. The dip azimuth of these beds is uniformly southeast. The mean dip angle for the whole data set was fairly steep at 26°, with the steepest being over 36°. The lower unit bedding attitudes are nearly identical in strike, but have slightly higher dips compared to the upper unit strata directly above them.

6.2.2. Intermediate Layer

[33] On the east side of Home Plate, the erosion resistant layer immediately below the upper unit is exposed parallel to bedding in several places. Where images are available at close range, it is possible to tightly constrain the structure. Here, we made 7 measurements of the bedding which showed excellent agreement in attitude. For this layer, the mean azimuth was N74°W, roughly radial to Home Plate, with a standard deviation of only 3°. The dips within this unit are the steepest measured at Home Plate, ranging from 33 to 42°, with a mean of 36°. This result is significant in that it lies at or above the angle of repose, where dry sediment becomes unstable to avalanching.

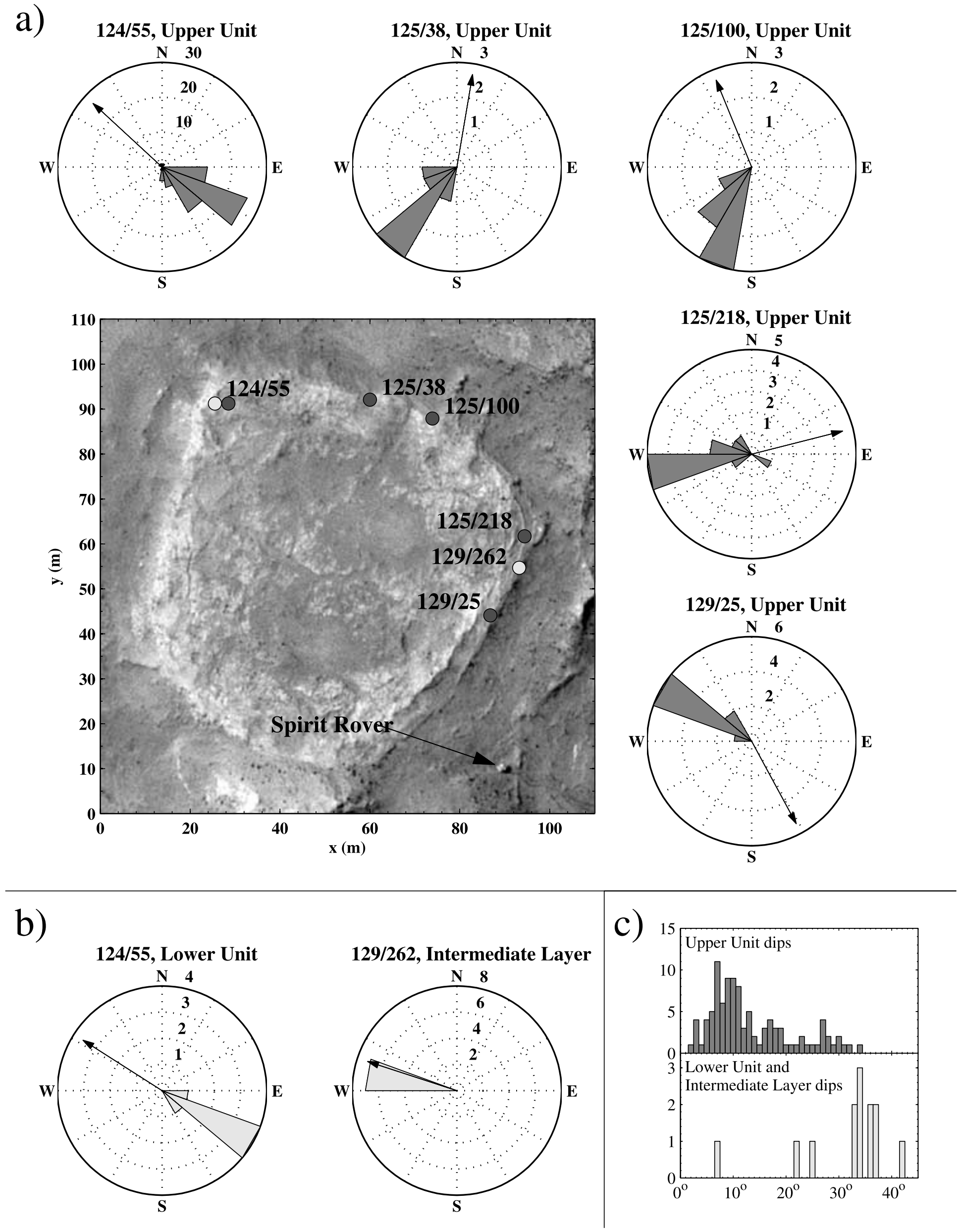

Figure 9. Structural data for Home Plate, at each of the sites visited by Spirit. For each of the locations indicated on the map, the corresponding rose plot shows dip azimuths of the measured beds. The black arrow on each plot shows the average orientation of the associated outcrop face to demonstrate that they are not correlated with the fitted bedding planes. (a) Measurements within the upper unit, for five locations around the circumference. Together, these plots depict the radial inward dipping structure found at Home Plate over nearly half of its circumference. The base map is an orthogonal projection of HiRISE image PSP_001513_1655; north is up. (b) Results for the lower unit, taken on the northwest corner, and the intermediate "fin" layer, taken on the eastern margin. These dip azimuths show excellent agreement with the overlying strata of the upper unit. (c) Histograms of the overall dip magnitudes for the upper unit, and the lower unit together with the intermediate layer which shows similar dip magnitudes. The generally smaller dips of the upper unit relative to underlying strata implies a shallowing trend with increasing height in the stratigraphic section.

6.2.3. Upper Unit

[34] The upper unit of Home Plate is particularly well suited to the structural topographic analysis described here, due to characteristic erosional patterns. In many places, this unit has eroded to form undulating surfaces and ~10 cm scale spurs which project out of the outcrop face. This surface relief allows well-constrained measurements of the three-dimensional bedding structure.

[35] Imaging at each of the four locations mentioned above provided adequate topography for structural measurements of the upper unit. A total of 93 measurements were used in this analysis from all of the sites.

[36] Overall, the dip magnitudes within this part of the stratigraphic section range from roughly 0–35°, with a 1-σ range of 5–25°. Dip azimuths vary widely between outcrops, although they exhibit a consistent trend at each individual location. Azimuths overwhelmingly trend southeast at the first site visited by Spirit, on the northwestern corner of Home Plate, as shown in Figure 9. This orientation projects roughly into the outcrop at this location, radial to the Home Plate structure. Here, a large number of beds could be analyzed because of thorough imaging at close range 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 usable layers. At both of these locations, dip directions were uniformly southwest, which again corresponds to the direction toward the center of Home Plate. At the fourth and fifth sites on the eastern margin, strata dip westward and northwestward respectively, again both in the radial direction.

[37] The upper unit of Home Plate exhibits ubiquitous cross stratification, which complicates 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 variability induced by cross stratification is small is also shown simply by the tightness of the calculated distributions around a mean dip direction, as illustrated by Figure 9.

7. Discussion

[38] The most consistent hypothesis for the origin of Home Plate includes rapid deposition of material by a pyroclastic surge, followed by possible aeolian reworking. Evidence of ballistic ejecta in the form of a bomb sag, and steeply inclined strata with variable bedding and grain sorting characteristics are consistent with such a high-energy process. While an impact event could also produce a surge with similar deposits, chemical evidence, most notably the lack of Ni enrichment, makes this a less favorable scenario, as discussed by *Squyres et al.* [2007]. The presence of abundant vesicular basaltic rocks in the area further strengthens the case for a volcanic origin.

7.1. Structure and Origin of Home Plate

[39] One of the most striking characteristics of Home Plate is its bowl-shaped internal structure. Any depositional model must take account of this unusual attribute. One possible interpretation is that Home Plate is itself the volcanic vent which supplied the material for the observed deposits. Terrestrial analogs include tuff rings and maar volcanoes, both low-relief hydrovolcanic edifices which often exhibit surge deposits. In this case, the localized nature of the Home Plate materials can be accounted for, as proximal deposits are thicker and more volatile-enhanced than distal beds, and therefore more likely to be preserved. Both the bomb sag in the lower unit and the cross bedding of the upper unit further implicate a source proximal location [*Wohletz*, 1998]. Although it is difficult to put a quantitative constraint on the vent distance from a single bomb, ballistic modeling by *Wilson and Head* [2007] for a clast of this size strongly suggests a local source within Gusev crater, perhaps within a few kilometers. On the other hand, the lack of additional large ejecta blocks along with the well-sorted nature of the clastic rocks seen at some locations imply a degree of physical sorting which is not likely to be found at proximal locations, suggesting Home Plate itself is not the volcanic source. In addition, the size of Home Plate is at the very lower limit for tuff rings or maars on Earth, which are more typically hundreds of meters to kilometers in scale [*Cas and Wright*, 1987]. Home Plate is only 80 m in diameter, and potentially analogous deposits in the Columbia Hills are even smaller. Finally, the observation of bed forms interpreted to be oblique or nearly parallel to flow direction, as in Figures 3 and 4, is unexpected given the radial outward flow direction implied if the center of Home Plate is the volcanic source and the cross bedding is primary. If the upper unit has been reworked by the wind, the flow direction does not provide information about the vent location.

[40] While it remains possible that the center of Home Plate is the vent which produced the stratified material, our favored interpretation for the radial structure is deposition by a volcanic surge into a preexisting depression, most likely an impact crater. Surge deposits are well known to drape underlying topography and thicken in topographic lows [*Reading*, 1996]. Further, they are capable of overriding rough topography, and even traveling up topographic slopes [*Crowe and Fisher*, 1973; *Waters and Fisher*, 1971]. In this case, the thin surge beds 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 seen elsewhere at Gusev crater [*Grant et al.*, 2005]. Infilling by pyroclastic material is consistent with both the steepness and upward shallowing of dips observed from the lower unit and intermediate layer to the upper unit. Evidence of topographic draping has also been found on the ridges surrounding Home Plate and on Husband Hill, directly to the north [*Lewis et al.*, 2007; *Crumpler et al.*, 2006]. Deposition in a fresh, primary crater of this diameter would imply a maximum thickness up to ~16 m for the Home Plate material [*Melosh*, 1989], although depth measurements of similarly sized degraded craters on the Gusev plains suggests a few meters maximum thickness to be more likely.

7.2. Origin of Upper Unit Cross Bedding

[41] While the lower unit of Home Plate is likely to be a primary surge deposit, the cross-stratified upper unit of Home Plate may have undergone aeolian reworking and later lithification. The structural attributes of the upper unit are most consistent with a primary volcaniclastic origin. The inward dipping, bowl shape of the unit can be explained by draping of a topographic depression, as inferred for the lower unit. No evidence for a depositional hiatus in the form of an angular unconformity has been found at the base of the upper unit on either side of Home Plate, from structural or morphologic observations. Dip measurements of the underlying units average 25° for the west side and 35° for the east side. Particularly on the east side where strata are

steepest, formation of aeolian dunes on a substrate approaching the angle of repose is unlikely. Pyroclastic surges in contrast are capable of overriding topographic obstacles and depositing material on steep uphill slopes, particularly when the ash cloud has a higher fraction of entrained water to increase cohesion [*Cas and Wright*, 1987; *Cole et al.*, 2001]. Postdepositional compaction of the sediment alone cannot explain the observed magnitude of the radial dips, requiring a volume loss of tens of percent. In the case that Home Plate is itself the volcanic vent, evacuation of the magma chamber, and to a lesser extent thermal contraction, could provide additional inward collapse and rotation of the overlying sediments.

[42] Sedimentological observations suggest varying degrees of physical processing for the sediment population which comprises the upper unit of Home Plate. Images from the east side show several millimeter-size particles, and one clast nearly 3 mm in length. The coarse tail of the grain size distribution seen at this location (Figure 8) is more consistent with a pyroclastic origin, although the grains are not large enough to rule out aeolian transport by saltation-induced creep. In contrast, observations on the west side show a narrow size distribution of particles, with a similar size range to that observed at the El Dorado sand sheet (Figure 7). The well-rounded shape of many clasts on the west side suggests extensive transport and abrasion, as would be expected in an aeolian environment. We cannot rule out the possibility that a fraction of the upper unit is composed of accidental material that was already rounded and sorted before being swept into a pyroclastic surge. Hydrovolcanic deposits often include a large portion of material which is derived from preexisting country rock [*Ollier*, 1967; *Lorenz*, 1973]. However, the chemical similarity to both the lower unit and nearby vesicular basalts suggests that the upper unit material is derived from a common source [*Squyres et al.*, 2007; *Schmidt et al.*, 2008]. In summary, structural and sedimentological observations from the east side are supportive of a primary pyroclastic origin for Home Plate. On the west side, however, the observed sedimentology suggests aeolian reworking of pyroclastic materials. Future observations may help resolve this issue. In particular, observations of outsized clasts in the upper unit could constrain its genesis.

[43] Finally, it is notable that no examples of centimeter-scale cross bedding have been found within the upper unit of Home Plate. The discovery of these small-scale bed forms within the bedrock at the Opportunity rover landing site has been critical in establishing the dune-interdune depositional model for the bedrock at that location [*Squyres et al.*, 2004b; *Grotzinger et al.*, 2005]. The occurrence of these bed forms at Meridiani Planum has been put forward as a unique indicator of subaqueous, rather than subaerial flow. In contrast, the lack of similar features at Home Plate is consistent with the interpretation of purely subaerial transport, either within a pyroclastic surge, or by aeolian processes.

7.3. Implications of a Pyroclastic Surge Deposit at Gusev Crater

[44] The discovery of a preserved volcaniclastic deposit within Gusev crater sheds new light on the geologic history of this location. A common source of explosive volcanism arises from interaction of hot magma with a water reservoir. Particularly for small, basaltic sources such as that inferred for Home Plate, explosions typically result from rapid vaporization of surface or subsurface hydrologic sources [*Wohletz*, 1998; *Cas and Wright*, 1987]. While there is little evidence to suggest large amounts of water at the surface in the vicinity of Home Plate, the existence of a groundwater reservoir at the time of formation could have provided the necessary trigger for a phreatomagmatic explosion. In this scenario, the very existence of Home Plate may implicate subsurface water in the ancient past, a reservoir which is otherwise difficult to assess.

[45] In addition, the preservation of the Home Plate deposits through lithification provides information about aqueous interaction at this location. The rocks at Home Plate have been eroded to a large degree, and the paucity of loose rocks from the Home Plate sequence suggests poor resistance to physical abrasion. In the event that Home Plate is a primary volcaniclastic deposit, induration could have occurred nearly contemporaneously with deposition. If the cross bedding of the upper unit represents aeolian reworking of the pyroclastic material, lithification would have to have occurred some time after the volcanic explosion. In either case, water is the most likely mechanism for cementing loose ash particles into coherent rock. Indeed, chemical and mineralogical evidence suggests significant hydrothermal action at Home Plate and within the Inner Basin of the Columbia Hills [*Schmidt et al.*, 2008]. The formation of many terrestrial sedimentary rocks is aided by burial and compaction. Similarly, the thick section of sulfate bedrock of Meridiani Planum shows evidence for extensive deflation including crater degradation and a widespread lag of hematite grains [*Grotzinger et al.*, 2005]. Lacking similar morphologic evidence for burial and exhumation at Home Plate, lithification likely proceeded at the surface. More generally, if Home Plate were indeed lithified subsequent to the original volcanism, it demonstrates the potential for preservation of small sedimentary deposits on Mars, which would provide a valuable record of process and conditions through time.

8. Summary

[46] Quantitative analysis of the sedimentology and structure of Home Plate have provided new constraints regarding its origin. Structural analysis has provided an explanation for the singular observation of the Home Plate stratigraphy here, as the inward dip of the bedding suggests a unique depositional setting. Sedimentological observations have shown a varying clast population between the two sides of Home Plate. Observations on the east side favor a primary pyroclastic origin for the exposed stratigraphy of Home Plate, while observations on the west side are consistent with aeolian reworking of the upper unit. In either case, however, it is clear that Home Plate originates from explosive volcanic activity. The inward dips of the structure may arise as a result of deposition into a preexisting depression, likely an impact crater. Alternatively, the volcanic source may have been situated at the center of Home Plate, where vent collapse could also produce a radial structure. The nature of the lithification of Home Plate remains unknown, although hydrothermal processes are

suggested by geochemical evidence. Particularly in the case of aeolian reworking, this lithification must have occurred well after the initial depositional event. The recognition of Home Plate as a pyroclastic deposit provides direct evidence for explosive volcanism on ancient Mars, and may implicate subsurface hydrologic reservoirs as a trigger for the inferred surge. The rich stratigraphy characterized here and at Meridiani Planum by the Opportunity rover provide a framework for outcrop-scale interpretation of layered deposits on Mars.

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