Comparing orbiter and rover image-based mapping of an ancient sedimentary environment, Aeolis Palus, Gale crater, Mars

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Highlights

- Orbital facies were mapped at the Darwin, Cooperstown, and Kimberley waypoints in Gale crater.
- Orbital maps were compared with ground-based observations from the Curiosity rover.
- Integrated orbital and rover observations are necessary to construct high fidelity depositional models.

Abstract

This study provides the first systematic comparison of orbital facies maps with detailed ground-based geology observations from the Mars Science Laboratory (MSL) Curiosity rover to examine the validity of geologic interpretations derived from orbital image data. Orbital facies maps were constructed for the Darwin, Cooperstown, and Kimberley waypoints visited by the Curiosity rover using High Resolution Imaging Science Experiment (HiRISE) images. These maps, which represent the most detailed orbital analysis of these areas to date, were compared with rover image-based geologic maps and stratigraphic columns derived from Curiosity's Mast Camera (Mastcam) and Mars Hand Lens Imager (MAHLI). Results show that bedrock outcrops can generally be distinguished from unconsolidated surficial deposits in high-resolution orbital images and that orbital facies mapping can be used to recognize geologic contacts between well-exposed bedrock units. However, process-based interpretations derived from orbital image mapping are difficult to infer without known regional context or observable paleogeomorphic indicators, and layer-cake models of stratigraphy derived from orbital maps oversimplify

depositional relationships as revealed from a rover perspective. This study also shows that fine-scale orbital image-based mapping of current and future Mars landing sites is essential for optimizing the efficiency and science return of rover surface operations.

1. Introduction

Geologic maps provide a two-dimensional representation at the surface of the three-dimensional spatial and temporal relationships of lithologic or chronostratigraphic units that make up a planet's crust. For planets and other solar system bodies whose surfaces can only be studied remotely via telescopic, flyby, orbital, airborne, lander, or rover observations, photogeologic mapping is an important tool for providing insight into the geometric disposition of geologic units and the evolution of planetary surfaces. Despite the increased sophistication and spatial resolution of recent orbiter image-based geologic mapping efforts, considerable uncertainties remain in the manners in which investigators gather their observations and interpret orbiter image data [Wilhelms, 1990; Hansen, 2000; Tanaka *et al.*, 2009].

Independent ground truth of orbital geologic interpretations is currently impossible for most of the martian surface, but such comparisons can be made for the seven locations that have been visited by rovers or landers: Chryse Planitia (Viking 1), Utopia Planitia (Viking 2), Ares Vallis (Mars Pathfinder), Meridiani Planum and Gusev crater (Mars Exploration Rover (MER) mission Opportunity and Spirit rovers, respectively), Vastitas Borealis (Phoenix Mars lander), and Gale crater (Mars Science Laboratory (MSL) Curiosity rover). Orbiter and rover or lander image-based comparisons can provide important insights into the fidelity of paleoenvironmental interpretations made with these datasets by establishing a connection between “mega-scale” orbital observations and those made on-site at the rover “macro- to micro-scale.” Understanding

the value-added nature of geologic investigations using multiple spatial scales is particularly important for currently active rover missions like MSL and MER Opportunity which rely heavily on orbital geologic interpretations to assist in science activity and traverse planning [Grotzinger *et al.*, 2014; Arvidson *et al.*, 2014; Arvidson *et al.*, 2015; Crumpler *et al.*, 2011, 2015]. Future missions including InSight, the European Space Agency (ESA) ExoMars 2018 rover, and the Mars2020 rover will also use orbital image datasets and geologic interpretations of these datasets to guide landing site selection. Orbiter and rover image-based comparisons can also be used to extend geologic interpretations made from orbital data, particularly those regarding paleoenvironment and past conditions for habitability, to elsewhere on the planet where ground-truth observations are unlikely to be available.

Gale crater, landing site of the MSL Curiosity rover (Figure 1), provides an ideal place for such a comparison given the variety of scales at which this location has been mapped from images acquired from orbit [Malin and Edgett, 2000; Pelkey *et al.*, 2004; Anderson and Bell, 2010; Milliken *et al.*, 2010; Thomson *et al.*, 2011; LeDeit *et al.*, 2013; Calef *et al.*, 2013; Rice *et al.*, 2013b; Grotzinger *et al.*, 2014] and the sequence of sedimentary rocks present in Gale crater now known to represent conditions favorable for past habitability [Grotzinger *et al.*, 2014]. This study presents orbital facies maps constructed from High Resolution Imaging Science Experiment (HiRISE) images and interpreted cross-sections produced at a scale of 1:500 from HiRISE images and digital terrain models (DTMs) for three major Curiosity rover field investigation sites, waypoints informally named Darwin, Cooperstown and Kimberley (Figure 2). The rover team analyzed these waypoints during Curiosity's ~10 km traverse across Bradbury Rise from Yellowknife Bay to the base of Aeolis Mons [Vasavada *et al.*, 2014]. The orbital facies maps and cross-sections presented here, which represent the most detailed observations

and interpretations based on orbital images of these areas to-date, are then compared to geology observations derived from the Curiosity rover Mast Camera (Mastcam) and Mars Hand Lens Imager (MAHLI) at each waypoint. In addition to providing a systematic comparison of orbiter and rover image-based geologic observations and interpretations at each waypoint, this study presents a critical examination of the validity and significance of geologic mapping and stratigraphic interpretations made using remotely acquired orbiter image datasets. Conclusions are drawn about the past depositional settings and paleoenvironments present in Gale crater using correlations between rover and orbiter image data.

2. Background

Flyby and orbiter images of the martian surface acquired during the 1960s and 1970s by the Mariner and Viking spacecraft enabled the creation of increasingly detailed and comprehensive geologic maps such as those by *Scott and Carr* [1978], *Scott and Tanaka* [1986], *Greeley and Guest* [1987], and *Tanaka and Scott* [1987]. Geologic maps based on Mariner 9 and Viking data remained state-of-the-art until the early 2000s when a series of high-resolution orbital imaging systems onboard Mars Global Surveyor (MGS), Mars Odyssey, Mars Express, and the Mars Reconnaissance Orbiter (MRO) acquired thermal, visible, and near-infrared images of the martian surface that have enabled detailed local and regional geologic mapping efforts down to the sub-meter scale (e.g., *Rice et al.* [2013a], *Okubo* [2014], and *Sun and Milliken* [2014], among many others). Analysis of these recent datasets has also led to refinements and updates to a global geologic map of Mars [*Tanaka et al.*, 2014].

The Viking 1 and 2 landers afforded the first opportunity to ground-truth orbital geologic map interpretations of Mars [*Binder et al.*, 1977; *Mutch et al.*, 1977; *Sharp and Malin*, 1984;

Jakosky and Christensen, 1986; Crumpler et al., 2001; Thomson and Schultz, 2007]. Nearly twenty years later came confirmation of orbital interpretations at the Ares Vallis landing site for the Pathfinder mission [*Komatsu and Baker, 1997; Rice and Edgett, 1997, Smith et al., 1997*]. The landing site selection process for the MER Spirit and Opportunity was the first to take advantage of meter-scale high-resolution image data provided by MGS and Mars Odyssey [*Golombek et al., 2003*]. Subsequent to landing, *Golombek et al.* [2005] and [2006] addressed inconsistencies between orbital geologic interpretations and observations of in situ geochemistry and depositional environments observed with the MER Opportunity and Spirit rovers. Beginning in late 2006, Spirit and Opportunity surface science operations made use of images from the HiRISE camera onboard MRO as a tool for geologic interpretation and mission planning [*Arvidson et al., 2006; Golombek et al., 2006; Wray et al., 2009; Wiseman et al., 2010; Crumpler et al., 2011, 2015; Arvidson et al., 2015*]. The Phoenix Lander mission which launched in 2007 also made use of HiRISE images during the selection and hazard evaluation of its landing site in the northern plains of Mars [*Arvidson et al., 2008; Golombek et al., 2008; Seelos et al., 2008*]. The MSL mission is the first rover mission to use HiRISE orbital images during the landing site selection process [*Anderson and Bell, 2010; Golombek et al., 2012; Grotzinger et al., 2012; Rice et al., 2013a*], and HiRISE image-based mapping of the Gale crater ellipse has provided critical context for Curiosity rover observations since landing [*Calef et al., 2013; Rice et al., 2013b; Grotzinger et al., 2014; Arvidson et al., 2014*].

2.1. Previous Orbiter Image-Based Mapping of the MSL Curiosity Landing Ellipse

The main focus of previous mapping studies of Gale crater has been on the strata of Aeolis Mons, the ~5 km-thick mound in the center of the crater [*Malin and Edgett, 2000;*

116 *Milliken et al.*, 2010; *Thomson et al.*, 2011; *Zimbelman and Scheidt*, 2012]. Prior to Curiosity's
117 landing in Gale crater, only *Anderson and Bell* [2010] published a geologic map of the MSL
118 landing ellipse, a 20 km by 7 km ellipse positioned on Aeolis Palus, the plains surrounding
119 Aeolis Mons. Since landing, *Le Deit et al.* [2013], *Calef et al.* [2013], *Rice et al.* [2013b],
120 *Sumner et al.* [2013], and *Grotzinger et al.* [2014] have mapped some or all of the area covered
121 by the MSL landing ellipse at varying scales and levels of detail.

122 *Anderson and Bell* [2010] mapped the area covered by the MSL landing ellipse, including
123 the three areas explored in this study, using MRO Context Camera (CTX) images (6 m/pixel).
124 Although the map scale was not explicitly stated in the study, they mapped with a focus on
125 geologic features and stratigraphic relationships observable at a scale of hundreds of meters to
126 kilometers. Over the area of Aeolis Palus traversed by the Curiosity rover, *Anderson and Bell*
127 [2010] mapped two geomorphic units: a hummocky plains unit and a mound-skirting unit. The
128 three areas examined in this study were mapped as part of the hummocky plains unit. The
129 hummocky plains unit was described as “hummocky terrain of smoothly-varying thermal inertia”
130 with a fairly uniform albedo in CTX images and was interpreted by *Anderson and Bell* [2010] to
131 represent largely unconsolidated material transitioning to fractured bedrock. Sinuous ridges
132 locally found on this unit were interpreted as inverted fluvial channels, but no other indicators of
133 geologic process were described. The mound-skirting unit, which was interpreted to be younger
134 than the hummocky plains unit, was described as an erosion-resistant, mesa-forming geologic
135 unit, the surface of which shows many small pits and ridges interpreted to be largely fluvial and
136 eolian in origin.

137 *Le Deit et al.* [2013] produced a geologic map of the entire interior of Gale crater using
138 Mars Express High Resolution Stereo Camera (HRSC), CTX, and HiRISE images and HRSC

DTMs to construct cross-sections across large swaths of the crater interior. They distinguished several “crater floor” units, although all of Bradbury Rise traversed by the Curiosity rover was mapped as a single crater floor unit (Cf1). The Cf1 unit extends from the northern crater rim to the base of Aeolis Mons and was interpreted to represent fluvial, alluvial, and colluvial deposition in a bajada complex located downstream from valleys incised into the northern rim of Gale crater. The Cf1 unit was interpreted to be younger than the lowest strata of Aeolis Mons, but likely older than most of the upper mound strata.

A detailed mapping effort focused on the MSL landing ellipse was presented in *Grotzinger et al.* [2014] (Figure 3), summarizing the preliminary efforts of *Calef et al.* [2013], *Rice et al.* [2013b], and *Sumner et al.* [2013]. Prior to Curiosity’s landing, the MSL science team undertook mapping using HiRISE images and DTMs derived from HiRISE stereo via the methods of *Kirk et al.* [2008]. The main objectives were to guide initial traverse planning after the rover landed and to provide context and guidance for subsequent traverse and science investigation planning. Through this effort, the landing ellipse was subdivided into six geologic units: alluvial fan (AF), bedded fractured (BF), cratered surface (CS), hummocky plains (HP), rugged terrain (RT), and striated (SR). The Curiosity rover encountered bedrock mapped as the BF unit in Yellowknife Bay [*Grotzinger et al.*, 2014; *Arvidson et al.*, 2014], but the terrain across which the rover traversed to the base of Mount Sharp was mapped primarily as HP and RT, with intermittent exposures of CS and SR [*Calef et al.*, 2013; *Rice et al.*, 2013b; *Arvidson et al.*, 2014; *Grotzinger et al.*, 2014; *Vasavada et al.*, 2014]. The HP unit exhibits low surface roughness, uniform tone, and decimeter-scale topographic hummocks [*Grotzinger et al.*, 2014] and corresponds generally to *Anderson and Bell’s* [2010] hummocky plains unit. The RT unit was identified in HiRISE images as isolated exposures throughout the first third of the traverse to

Aeolis Mons, although larger (100s m²), more continuous exposures of RT were mapped in the southern part of the landing ellipse. The RT is characterized by its brightness relative to surroundings, topographic variability, meter to decameter-scale surface roughness, and contains erosion-resistant scarps [Grotzinger *et al.*, 2014]. The CS unit is characterized by sub-planar surfaces containing a relatively high density of sub-kilometer diameter impact craters that occur at different elevations throughout the landing ellipse [Grotzinger *et al.*, 2014; Jacob *et al.*, submitted]. The RT and CS units described in Grotzinger *et al.* [2014], though mapped in greater detail, correspond generally to the mound-skirting unit of Anderson and Bell [2010]. Exposures of the SR unit occur exclusively in the south central portion of the landing ellipse, and consist of isolated light-toned outcrops exhibiting distinct northeast-southwest trending lineations visible in high-resolution orbital images [Grotzinger *et al.*, 2015]. Relative age relationships between the HP, RT, CS, and SR unit are often ambiguous, and Rice *et al.* [2013b] acknowledged that these units, particularly the RT and CS units, may represent distinct textural or geomorphic surface expressions rather than stratigraphic units that can be projected into the subsurface.

2.2. Curiosity's Traverse of Bradbury Rise

Upon landing on Aeolis Palus in August of 2012, the Curiosity rover traversed east from Bradbury Landing to an embayment of rock outcrop called Yellowknife Bay [Grotzinger *et al.*, 2014] (Figure 2). Before Curiosity's departure from Yellowknife Bay toward the base of Aeolis Mons in July of 2013, the MSL team selected several waypoints along the planned traverse path across Bradbury Rise, a topographic high that extends north several kilometers from the base of Aeolis Mons to the distal end of the present-day Peace Vallis fan [Vasavada *et al.*, 2014; Arvidson *et al.*, 2014] (Figures 1 and 2). These three waypoints: Darwin, Cooperstown, and

Kimberley, were selected at approximately equidistant spacing along the planned route using HiRISE images and the orbital geologic map of *Calef et al.* [2013] [*Vasavada et al.*, 2014] (Figure 2a, Table 1). The Darwin site was chosen because of the presence of a conspicuous ~200 m diameter sub-circular outcrop of bright bedrock amid the hummocky plains of Bradbury Rise (Figure 2b). Similar isolated occurrences of bright bedrock were observed in HiRISE images throughout Bradbury Rise and the Darwin waypoint was chosen as a representative of these outcrops [*Vasavada et al.*, 2014]. The Cooperstown area (Figure 2c) was selected for study based on the presence of a variety of bright outcrops observed in HiRISE images, some of which exhibited meter-scale polygonal forms bounded by fractures that appeared similar in the HiRISE images to fracture-delineated polygonal forms in the fine-grained sedimentary rocks observed at Yellowknife Bay. These waypoints served as intermediate stops between Yellowknife Bay and the third waypoint, Kimberley (Figure 2d). The Kimberley area attracted interest early in the mission due to the presence in HiRISE images of a layered stratigraphy expressed by differential erosion of the terrain. Some outcrop exposures in this area of the ellipse contained striations, regularly spaced linear features extending ~tens of meters in length, that were particularly distinct from other outcrops observed in the landing ellipse region [*Grotzinger et al.*, 2014; *Grotzinger et al.*, 2015]. It was anticipated that an imaging and geochemical analysis campaign would help determine the origin of the striated outcrops, as well as their relationship with the nearby hummocky terrain and overlying bedded rocks [*Vasavada et al.*, 2014; *Grotzinger et al.*, 2015].

The MSL team also acquired opportunistic remote sensing and contact science observations of float rocks, outcrops, eolian deposits, and regolith in between each of the three waypoints described above. However, the orbiter and rover image-based observations at Darwin,

Cooperstown, and Kimberley are broadly representative of the geology observed during the traverse across Bradbury Rise (Figures 4-15), and also provide the best opportunities for direct comparison due to the exposures of bedrock and surficial deposits that can be resolved and distinguished in HiRISE images.

3. Data and Methods

3.1 Orbital Facies Mapping

Maps based on planetary orbital image datasets most commonly use the terms “geologic unit” or “geomorphic unit” to refer to the two-dimensional surface areas bounded by drawn contacts. These terms are sometimes used interchangeably in planetary mapping, although conventional planetary mapping guidelines offer clear distinctions. According to Wilhelms [1990], a geologic unit is distinguished in planetary image data by its topographic expression and remotely observed surface properties, and refers to a “sheetlike, wedgelike, or tabular body of rock that underlies the surface...and not a surface, a geomorphic terrain, or a group of landforms.” As part of the most recent global geologic mapping effort for Mars, *Tanaka et al.* [2014] define geologic map units as “temporally unique geologic materials of substantial thickness and extent for portrayal at map scale,” and use primary formational morphology, brightness and/or albedo, and spatial, stratigraphic, and relative crater age relationships to delineate units. Materials interpreted to be surficial in nature or features interpreted to be the result of secondary modification processes are not mapped as units.

Others prefer the term “geomorphic unit” in a planetary mapping context (e.g., *Anderson and Bell* [2010], *Sun and Milliken* [2014]). Use of the term “geomorphic unit” generally avoids the three-dimensional geometrical interpretation, implicit assumption of “rock” as opposed to

unconsolidated surface materials, interpretation of primary formational versus secondary modification features, temporal implications, or other exclusions implied by the Wilhelms [1990] or Tanaka et al. [2014] definitions in favor of a more generic terminology. However, definitions for “geomorphic unit” vary widely across the terrestrial and planetary literature and in the context of terrestrial mapping, a geomorphic unit is most commonly used to refer to a landform or group of landforms whose shape, structure, dimensions, or characteristics are indicative of a common process (e.g., *Haskins et al.* [1998]).

In this study, the term “orbital facies” is used instead of “geologic unit” or “geomorphic unit” since designations and subdivisions made from orbital visible-range images here were based solely on variable brightness, local-scale color hue (spectral) variability, and surface texture at a local and small scale [*Grotzinger and Milliken*, 2012]. Orbital facies mapped using HiRISE images may indeed be geologic or geomorphic units according to the definitions employed by *Wilhelms* [1990], *Tanaka et al.* [2014], or others and can be interpreted as such with supporting observations particularly from topographic (i.e., interpretive geologic cross-sections) or ground-based rover datasets. However, the reason for using the term “orbital facies” here (*sensu Grotzinger and Milliken* [2012]) is to clarify that surface areas distinguished locally at the fine scale employed during this study’s mapping can, but need not have three-dimensional geometry, substantial thickness, a common formation process, a temporal association, nor must they represent lithified bedrock. Such an objective approach also prevented the need to distinguish primary depositional from secondary modification features during orbiter image-based mapping where such interpretations would have been uncertain and speculative.

Orbital facies maps at the 1:500 scale were produced for each waypoint using a 240 m by 360 m rectangular area around the Darwin, Cooperstown, and Kimberley waypoints,

respectively, using 25 cm/pixel HiRISE color and gray-scale images (Figures 2 and 3). The intention of mapping at this scale was to enable orbital facies distinctions of the finest level of detail possible with orbital images for comparison with rover observations. Orbital facies contacts were mapped as shapefiles on equidistant cylindrical-projected grayscale and color HiRISE mosaics in ArcGIS. To test whether orbital facies represented stratigraphic units that could be reasonably projected into the subsurface, interpretive cross-sections were constructed for each waypoint using topographic profiles across the mapping area of each waypoint extracted from DTMs created by the HiRISE team for the MSL project [Kirk *et al.*, 2008; Golombek *et al.*, 2012; Calef *et al.*, 2013] (Figures 4, 8, 12). Although a number of subsurface interpretations are likely possible for each cross-section, an attempt was made to present straightforward interpretations assuming approximately horizontal strata and superposition (younger strata overlie older strata) since structural features indicating otherwise were generally lacking in the study areas.

The gray-scale visual and topographic basemaps providing coverage over the study areas were made from twelve HiRISE 25 cm/pixel stereo pairs that were processed, georeferenced, and projected via the methods of Calef *et al.* [2013] to create a visible mosaic and a DTM with 1 m grid spacing and absolute elevations tied to Mars Orbiter Laser Altimeter (MOLA) data. The processing of the HiRISE color mosaic used throughout this work (Figure 3) to aid in orbital facies mapping interpretations was performed using a combination of the Integrated Software for Imaging Spectrometers (ISIS) (e.g., Anderson *et al.* [2004]; Edmundson *et al.* [2012]) and the DaVinci software packages (<http://davinci.asu.edu>). Color images were tied and projected to existing basemaps via a series of manually and automatically chosen ground control points used to update the spacecraft and camera pointing [Edmundson *et al.*, 2012]. Prior to map projection,

the images were normalized for CCD-to-CCD variations within a single image. After map projection, the data were normalized for image-to-image variations to account for spatial and temporal variations such as illumination and observing geometry as well as atmospheric opacity. An across-track filter was used to remove any additional across-track image slope, and the normalized radiance data were stretched using a running (or moving-window) histogram stretch following the techniques described by *Edwards et al.* [2011]. This specialized stretch is designed to emphasize local-scale morphology and color variations by maximizing the dynamic range on a ~5000x5000 pixel segment of the image and also serves to remove any residual regional influence [*Edwards et al.*, 2011]. The resulting color HiRISE mosaic highlights the local-scale color (spectral) variability, where blue-purple hues commonly indicate mafic materials (e.g., sand dunes, blocks) and neutral colors (e.g., gray) indicate dustier terrains.

3.2 Rover Image-Based Geologic Mapping

Prior to Curiosity's arrival at each waypoint stop, the focusable Mastcam M-100 (100 mm fixed focal length) camera was used to acquire context mosaics. In this study, one mosaic was chosen for each waypoint that provided a "rover's eye view" of as much of the orbital mapping area as possible (Figures 6, 10, and 13). Each of the waypoint mosaics was white-balanced and perspective projected. Mosaics were used to map visible distinctions that fall into three general categories: bedrock lithology, unconsolidated surficial deposits, and undifferentiated bedrock and surficial deposits (Figures 5, 6c, 10c, 13c). Bedrock boundaries define areas in which a particular lithology dominates and include conglomerates and sandstones of varying bedding characteristics (Figure 5). Although pixel scale varies within each mosaic and between mosaics, the mosaic pixel scale is generally on the order of ~1 cm/pixel or better for the

majority of outcrop visible within each scene, permitting distinctions between outcrops of conglomerate and those containing sand-sized or finer grains as well as the identification of macroscopic textural elements such as vugs and platy versus apparently massive beds. Unconsolidated surficial deposits include sand (e.g., Figure 5c), accumulations of float (e.g., Figure 5f), defined here as loose pebble- to boulder-sized rocks not clearly connected to an outcrop, and undifferentiated sand and float (e.g., Figure 5i). Where subdivisions are difficult to define due to image resolution or viewing geometry, the bedrock or unconsolidated deposit is designated as “undifferentiated.” “Undifferentiated” examples include bedrock outcrops where multiple lithologies are finely inter-bedded (e.g., Figure 5a), where bedrock is intermittently exposed amongst other materials like sand or float, or where sand and float are intermixed (e.g., Figure 5i). As was the case for the orbital facies mapped from the HiRISE images, the outcrop lithologies and surficial deposits mapped in the rover mosaics can, but do not necessarily, represent distinct stratigraphic or geomorphic units.

To enable the comparison between orbiter and rover image-based observations, the distribution of orbital facies for each waypoint was mapped on the corresponding rover mosaics by identifying key landmark features in both the Mastcam mosaics and HiRISE images (Figures 6b, 10b, 13b). This mapping was done manually in ArcGIS by performing feature matching between the HiRISE image of each waypoint projected in ArcGIS viewed side-by-side with the corresponding Mastcam mosaic, which was displayed but not projected in a separate ArcGIS project. Landmarks such as boulders, scarps, and sand dunes visible in both the Mastcam mosaics and HiRISE images were used as aids in the placement of orbital facies boundaries on the Mastcam mosaics. Foreshortening and the different viewing geometry between orbital and ground-based images complicates the translation of orbital facies mapped in plan-view onto the

rover mosaics, so the distribution of orbital facies mapped on rover mosaics should be considered approximate, though generally faithful to the corresponding locations mapped on HiRISE images. A quantitative, automated comparison of the orbital and rover surface maps would have been possible if this study had used Mastcam orthophotos for which the geographic location of each pixel within the mosaics was known. Unfortunately, the workflow required to create Mastcam orthophotos is not supported by existing MSL mission tools and it was considered out of the scope of the present study to develop new software to facilitate such a quantitative analysis.

The stratigraphy for each waypoint was determined using observations of lithology, texture, and fabric gleaned from Mastcam M-100 and M-34 mosaics and MAHLI images (Figures 5, 7, 11, and 14). To construct the stratigraphic columns in Figure 15, contact science locations were localized in HiRISE images relative to the rover traverse and distinctive features visible in both rover mosaics and orbital images. Elevation values for the top and bottom of each outcrop were then extracted from the HiRISE DTM and matched with georeferenced rover stereo mosaics from the Curiosity navigation cameras (Navcam) [Maki *et al.*, 2012] to calculate outcrop thickness. Changes in bedding, grain-size, and erosional profile observed in the Mastcam and MAHLI images were then plotted in a stratigraphic column for each contact science location (Figure 15). The corresponding orbital facies projected as stratigraphic units were plotted alongside each rover image-based stratigraphic column (Figure 15).

Vasavada et al. [2014] provided an overview of the outcrop characteristics observed at both the Darwin and Cooperstown waypoints. This study expands on those results, presenting the first annotated rover image-based mosaics and stratigraphic columns for the express purpose of making direct comparisons between rover and orbiter geologic interpretations.

4. Orbiter and Rover Image-Based Mapping

4.1. Darwin

4.1.1 Orbital Facies

Five orbital facies were mapped at the Darwin waypoint: smooth dark, smooth hummocky, boulder hummocky, resistant cratered outcrop, and bright outcrop orbital facies (Figure 4). The resistant cratered outcrop orbital facies and the bright outcrop orbital facies are interpreted to represent lithified bedrock characterized by the presence of small scarps, visible stratification, and in a few locations the retention of craters. The bright outcrop orbital facies is characterized by its distinct brightness visible in the gray-scale HiRISE image compared to the surrounding terrain (Figures 2b and 3). This orbital facies exhibits meter-scale variations in surface texture indicated by apparent changes in brightness and/or shadows, meter-scale polygonal fracture forms visible on planar surfaces, and bright and dark alternations suggestive of bedding, although these textures are not ubiquitous throughout the entire exposure of this orbital facies. The bright outcrop orbital facies appears white and tan in the HiRISE color mosaic and exhibits color variation likely caused by the presence of float blocks or accumulations of windblown mafic sand on the outcrop. The bright outcrop orbital facies occurs primarily in the sub-circular plan-form feature at the center of the mapping area, although several occurrences of bright outcrop are mapped within the surrounding smooth hummocky orbital facies. The resistant cratered outcrop orbital facies is distinguished by the presence of impact craters that have diameters at decimeter-scale, a variable surface texture suggested by the meter-scale changes in relative brightness and color hue, and accumulations of dark boulders on the scarps that

demarcate the boundaries of this unit. This orbital facies forms a scarp-forming capping material expressed at the tops of local topographic highs.

The smooth dark, boulder hummocky, and smooth hummocky orbital facies contain visible boulders and lack well-defined scarps, bedding, or craters. For these reasons, these three orbital facies are interpreted to represent unconsolidated surficial deposits. The smooth hummocky orbital facies is mapped predominantly in the area surrounding the sub-circular bright outcrop in the center of the study area, and is characterized by a generally uniform brightness and decimeter-scale hummocky topography (Figure 2b). In the HiRISE color mosaic (Figure 3), this orbital facies appears tan to brown in color indicating that it may include a layer of surface dust. The boulder hummocky orbital facies appears similar in morphology to the smooth hummocky orbital facies, but contains accumulations of dark boulders resolvable in HiRISE images and occurs in decimeter-scale areas within the bright outcrop orbital facies. The smooth dark orbital facies is mapped and distinguished primarily with the aid of the HiRISE color mosaic as it is characterized by a distinctly blue hue consistent with the presence of mafic materials (e.g., basaltic sands). This facies occurs in topographic lows and is interpreted as unconsolidated basaltic sand.

Two possible cross-sectional interpretations of the Darwin orbital facies projected into the sub-surface as stratigraphic units are presented in Figure 4b and 4c. In Figure 4b, the bright outcrop orbital facies is interpreted as the infill of a bowl-shaped basin whose substrate material is composed primarily of the smooth hummocky facies. The bright outcrop orbital facies, which occurs both in the basin and outside it, might represent erosional remnants of a more continuous layer. In this scenario, the smooth hummocky orbital facies is the oldest of the five facies. The resistant cratered outcrop, boulder hummocky, and smooth dark orbital facies were deposited

after the bright outcrop orbital facies. This stratigraphic model is particularly compelling because it is consistent with the interpretation that the Darwin basin is a filled impact crater, which matches the sub-circular shape of the bright outcrop orbital facies.

In the second interpretation (Figure 4c), the bright outcrop orbital facies is interpreted as a through-going horizontal layer in the subsurface rather than as a basin fill. In this model, the resistant cratered outcrop orbital facies directly overlies the bright outcrop orbital facies. This model is consistent with the interpretation of the smooth hummocky, smooth dark, and boulder hummocky orbital facies as relatively thin, discontinuous accumulations of surficial deposits overlying both the bright outcrop and resistant cratered outcrop orbital facies. Distinguishing between these two interpretations is difficult from orbital-based mapping alone, but rover image-derived observations, particularly of the areas mapped as smooth hummocky facies and bright outcrop facies, may be helpful in resolving the Darwin stratigraphy.

4.1.2 Rover Image-Based Geologic Mapping

The M-100 Mastcam mosaic of the Darwin waypoint shows a landscape dominated by exposures of conglomerate and sandstone bedrock overlain by localized sand drifts and fields of float (Figures 5a-c, 6, and 7). Several conspicuous accumulations of dark float of a fine-grained lithology are observed in the mosaic, predominantly occurring on local topographic highs. Extending across the center of the mosaic is a topographic depression containing bedded and resistant thin-bedded sandstone outcrops and the occasional coarser-grained conglomerate bed exposed amongst undifferentiated accumulations of sand and float (Figure 6c). Sandstone beds observed along the edges of the depression appear to dip toward the center of the basin such that the dip varies systematically around the depression, while outcrops near the middle of the basin show nearly horizontal dips. The bright exposure of undifferentiated sandstone and conglomerate

and float present on the northwestern edge of the basin (Figure 6c, blue box) is the location of contact science activities performed by Curiosity. Mastcam and MAHLI images of this outcrop allow additional detail to be resolved (Figure 7), and lithology and grain size changes within the outcrop are documented in detail in the stratigraphic column in Figure 15a. A basal pebble conglomerate (Figure 7b) is overlain by a ~50 cm-thick layer of very coarse sandstone (Figure 7c) containing pebble-rich lenses (Figure 7a). A discontinuous wedge of a cobble-bearing conglomerate overlies the sandstone interval and thin lenses of platy sandstone occur within this coarser-grained interval (Figure 7a). These platy lenses occur in both horizontal and vertical orientations. A ~1.5 m-thick interval of massive granule conglomerate fines upward to coarse sandstone and overlies the cobble conglomerate. The section is capped by an accumulation of dark float of an apparent fine-grained lithology (Figure 7a).

4.1.3 Comparison between Orbiter and Rover Image-Based Mapping

As expected, a comparison of the mapped distributions of orbital facies and rover image-based geology (Figure 6b and 6c) shows the increased level of detail and distinction possible with rover images. In addition, the rover image-based observations permit the identification of specific bedrock lithologies (e.g., sandstone and conglomerate), rock type (i.e., sedimentary), and a confirmation of whether surface exposures represent lithified bedrock or unconsolidated surficial deposits. The smooth hummocky orbital facies, interpreted from orbital images as a likely unconsolidated deposit, is observed on the ground to be composed of in-place sandstone and conglomerate outcrop intermixed with float blocks. Although the presence of in-place outcrop was not resolvable in the HiRISE image of the smooth hummocky orbital facies, there is a fairly good correlation between this orbital facies and areas mapped as either float or undifferentiated sandstone and conglomerate.

The resistant cratered outcrop facies also exhibits a fairly consistent correlation with accumulations of dark float exposed at the top of local topographic highs. However, the rover mosaic shows that the resistant cratered outcrop orbital facies does not appear to correspond to bedrock, but rather surficial concentrations of float blocks. There is a generally good correlation between the mapped distribution of the smooth dark orbital facies and areas containing higher proportions of sand or undifferentiated sand and float. This correlation is particularly apparent within the central depression at Darwin and is consistent with the orbital interpretation of the smooth dark orbital facies as a surficial deposit containing windblown sand. The bright outcrop orbital facies also corresponds fairly well with sandstone outcrops observed in Curiosity rover images, although the annotated rover mosaic shows the sandstone to be less extensive than the orbital mapping would indicate due to the presence of surficial sand and float (Figure 6c). Areas of bright outcrop orbital facies at the contact science location correspond to an exposure of undifferentiated sandstone and conglomerate containing little surficial sand or float cover and which appears to be coarser-grained than the sandstones cropping out in the central depression. The weakest correlation between an orbital facies and rover geologic mapping is seen with the boulder hummocky orbital facies, which fails to correspond directly to any unique lithology or surficial deposit observed in the rover mosaic. In the HiRISE image, the boulder hummocky orbital facies is distinguished primarily by the presence of resolvable boulders, but when these areas are observed on the ground in the Mastcam mosaic, the presence of in-place sandstone and conglomerate outcrop becomes the primary characteristics by which these areas are distinguished.

The rover image-based observation that the smooth hummocky facies is at least partially composed of in-place bedrock rather than being composed completely of unconsolidated float

and sand is consistent with the cross-sectional model presented in Figure 4b in which the smooth hummocky facies is interpreted as the bedrock substrate that forms the Darwin basin. The model in Figure 4b is also supported by the rover-based observation that the sandstone beds around the interior edge of the depression appear to dip toward the center of the basin, indicating that the deposition of these beds was influenced by the geometry of a pre-existing depression.

4.2. Cooperstown

4.2.1 Orbital Facies

The smooth dark, boulder hummocky, smooth hummocky, resistant cratered outcrop, and bright outcrop orbital facies mapped at the Darwin area are also observed in HiRISE images of the Cooperstown waypoint (Figure 8). The bright outcrop orbital facies mapped at Cooperstown appears to be bluer in the HiRISE color image than that mapped at Darwin, perhaps indicating a greater proportion of mafic sand cover on the outcrop (Figure 3). Two orbital facies not present at Darwin were observed in the Cooperstown area: the bright striated outcrop and the bright fractured outcrop orbital facies. The bright striated outcrop orbital facies occurs as a small isolated outcrop in the lower right part of the mapping area and is characterized by its relative brightness in the gray-scale HiRISE mosaic and a white to tan color in the HiRISE color mosaic (Figure 9a). Most distinctive however, are the northeast-southwest trending lineations that occur across the bright striated outcrop orbital facies exposure at approximately even meter-scale spacing (Figure 9b). At Cooperstown, the bright fractured outcrop orbital facies is distinguished from surrounding bright outcrop orbital facies by the presence of distinct meter-scale polygonal fractures and a bright white-yellow color in the HiRISE color mosaic (Figure 2c and Figure 3).

The bright outcrop orbital facies mapped in the northeastern portion of the Cooperstown area forms a sub-circular outcrop shape in planform, possibly indicating a crater fill. However, other occurrences of the bright outcrop orbital facies are interpreted to extend in the subsurface throughout the mapping area as horizontal layers with the resistant cratered outcrop conformably overlying the bright outcrop facies strata (Figure 8b). The smooth hummocky, smooth dark, and boulder hummocky orbital facies are interpreted as unconsolidated surficial deposits overlying the resistant cratered and bright outcrop facies for the same reasons discussed for these orbital facies at the Darwin waypoint.

4.2.2 Rover Image-Based Geologic Mapping

The Cooperstown M-100 mosaic shows an area dominated by sandstone outcrops of variable texture, grain size, and bedding characteristics (Figures 5d-5e, 10a, 10c, and 11). The foreground of the Cooperstown mosaic (Figure 10a, bottom left) includes an exposure of dark, fine-grained sandstone containing centimeter-scale vugs (Figure 5e). The dark, vuggy sandstone transitions into exposures of inter-bedded platy, cross-stratified sandstone and more thickly-bedded sandstone (cm-scale beds) that occur on both the left and right sides of the mosaic (Figure 5d, 10c). This interval is overlain by sandstone with apparently massive texture (Figure 11). The massive sandstone is overlain by a distinct, erosion-resistant bed of pebbly sandstone (Figure 11a and 11b). Several float accumulations occur in the Cooperstown area (i.e., Figure 5f), including a mound near the center of the mosaic separating the two inter-bedded platy and bedded sandstone outcrops (Figure 10c). Float and intermittent sandstone outcrops dominate the rest of the area visible in the mosaic.

The stratigraphic section observed near the Cooperstown contact science location shows a basal interval of cross-stratified fine-grained sandstone overlain by nearly a meter of massive

coarse-grained sandstone that exhibits a sharp inclined basal contact (Figures 11a and 15b). Granule-sized clasts are present within the coarse sandstone, as are thin, platy lenses similar to those observed at the Darwin outcrop. The massive coarse-grained sandstone is overlain by a pebbly sandstone containing fine-grained, highly angular, and irregularly shaped clasts (Figure 11b).

4.2.3 Comparison between Orbital and Rover Image-Based Mapping

The comparison of orbital facies and ground-based geology observations is illustrated in Figure 10. The smooth dark orbital facies corresponds to some, but not all, of the areas mapped as float in the rover mosaic. Other occurrences of float in the area were mapped in the orbital images as resistant cratered outcrop, smooth hummocky, and bright outcrop orbital facies (Figures 10b and 10c). The boulder hummocky orbital facies corresponds well with an accumulation of dark float of a fine-grained lithology observed in the rover mosaic as expected since the largest of the boulders are visible in HiRISE (Figures 2c and 3). The resistant cratered outcrop orbital facies appears to correspond most directly with outcrops exposed on local topographic highs but does not correspond uniquely to a lithology or surficial deposit. For example, the outcrop of vuggy sandstone visible in the foreground of the Cooperstown rover mosaic corresponds to an area mapped as resistant cratered outcrop orbital facies, as does the resistant pebble sandstone bed and a mound of float located in the center of the mosaic field of view (Figures 10b and 10c). Although the resistant cratered outcrop orbital facies corresponds to a variety of bedrock lithologies observed from the rover perspective, the mapped boundaries of this orbital facies do correspond consistently with contacts between sandstone lithologies that show variable resistance to erosion. As at Darwin, the bright outcrop orbital facies at

Cooperstown is well correlated with outcrops of apparently massive, bedded, and platy sandstone viewed by the rover.

4.3. Kimberley

4.3.1 Orbital Facies

Three orbital facies, the smooth hummocky outcrop, smooth boulder outcrop, and bright bedded outcrop orbital facies, were mapped at the Kimberley waypoint in addition to orbital facies discussed previously (Figure 12a). As at Darwin and Cooperstown, the smooth hummocky orbital facies observed at Kimberley rarely forms scarps, appears smooth on a meter-scale, and exhibits no sign of internal stratification. Therefore, it is interpreted as an unconsolidated surficial deposit. However, there are small patches exposed within the smooth hummocky orbital facies that exhibit variable surface texture, appear to shed small boulders, and in some occurrences retain craters. These areas are more similar in brightness and color hue to the smooth hummocky orbital facies rather than the bright outcrop orbital facies and do not exhibit scarps as is common around exposures of the resistant cratered outcrop orbital facies. Therefore, these areas are mapped as a new orbital facies, the smooth hummocky outcrop. The smooth boulder outcrop orbital facies is distinguished by the presence of rounded hills that are uniform in tone and color and appear generally smooth except for the accumulations of boulders found on the sides of the hills (Figure 2d and 3). The bright bedded outcrop orbital facies appears gray and tan in the HiRISE color mosaic and is characterized by horizontal bedding planes visible in the orbital images (Figure 3). This orbital facies lacks the textural diversity apparent in the bright striated and bright fracture outcrop orbital facies. Although a small exposure of the bright striated orbital facies was observed in the Cooperstown area, this orbital facies is more extensively present in the Kimberley area (Figure 9c and 9d). From examining the HiRISE

images alone, it is difficult to ascertain the origin of the striations that distinguish this orbital facies. But at Kimberley, the striations are observed to be so linear within individual outcrop exposures that several possibilities exist to explain the geometry of these features: (1) the striations are defined by surface lineations rather than planes that extend into the subsurface, (2) the striations are defined by planes (e.g., beds) having an inclination that is steep relative to changes in outcrop topography, or (3) the striations are defined by three-dimensional curved planes, but outcrop topography consistently counteracts the curvature of these planes. The first two options are likely the most plausible, albeit indistinguishable from HiRISE images alone, while the third option requires a more contrived set of circumstances and is therefore less likely.

The well-exposed and clearly defined outcrops visible in HiRISE at the Kimberley waypoint enable an interpretation of the bright striated outcrop, bright bedded outcrop, and smooth hummocky orbital facies as stratigraphic units that can be projected into the subsurface with greater confidence than at the previous waypoints. The cross-section presented in Figure 12b illustrates the interpreted relative age relationship between these orbital facies; the stratigraphically lowest and hence oldest facies exposed in this area is the bright striated outcrop orbital facies, which is overlain by the bright bedded outcrop and smooth hummocky orbital facies. The topographic profile extracted across the bright striated outcrop orbital facies shows that this facies exhibits up to 2 meters of relief over the area it is exposed at the surface, suggesting an erosional contact between the bright striated outcrop and the overlying bright bedded outcrop orbital facies. Buttes of the smooth boulder outcrop and the resistant cratered orbital facies are interpreted to overlie the bright bedded outcrop facies, although the relative age relationship between the smooth boulder and the resistant cratered orbital facies is unknown. The smooth hummocky, boulder hummocky, and smooth dark orbital facies are best interpreted as

unconsolidated surficial deposits that overlie eroded outcrops of the bright bedded, striated, and fractured outcrop orbital facies, as well as the resistant cratered and smooth boulder outcrop orbital facies. The stratigraphic relationship between the smooth hummocky outcrop orbital facies and the other facies mapped in the area is difficult to determine from orbital mapping alone. However, the mottled texture and brighter tone of the smooth hummocky outcrop facies compared to the surrounding smooth hummocky facies suggest that it may represent bedrock unlike the other “hummocky” facies which are interpreted as unconsolidated mantle deposits.

4.3.2 Rover Image-Based Geologic Mapping

The Kimberley M-100 mosaic covers an outcrop of south-dipping coarse-grained sandstone beds with variable resistance to erosion (Figures 5g, 13, 14c). Coarse sandstone beds containing granule-sized clasts underlie the south-dipping beds (Figure 14d). Fine-grained sandstones showing no preferential southward dip overlie the south-dipping sandstone beds (Figure 5h, 14a, and 14b). The three hills visible at the Kimberley outcrop are primarily covered in float (Figure 5I, 13c), although each hillside exhibits apparently massive interstratified sandstone. The terrain surrounding the Kimberley outcrop is largely covered in unconsolidated accumulations of float (Figure 13c).

The stratigraphic column shown in Figure 15 was constructed from observations made at and nearby the location of the Windjana drill site at the southeastern edge of the Kimberley outcrop (Figure 14). Here, coarse granule sandstone (Figure 14d) underlies the sandstone beds that transition from primarily horizontal to south-dipping orientations (Figure 14c). The south-dipping strata are overlain by cross-stratified very fine-grained sandstone beds bounded at the base by a sharp, undulatory contact (Figure 14a and 14b). The cross-stratified sandstone is overlain by sandstones of a grain size that is not resolvable in the Mastcam images and was not

observed with MAHLI, but appears to be relatively fine-grained (Figure 14a). Coarse-grained, possibly south-dipping beds are observed within this interval, but the presence of float and cover make it difficult to identify sedimentary structures or bedding within this interval. An accumulation of dark float occurs at the top of the hill informally named Mount Remarkable..

4.3.3. Comparison between Orbiter and Rover Image-Based Mapping

The comparison of orbiter versus rover image-based observations shown in Figure 13 reveals a relatively good correlation between orbital facies contacts and geology contacts observed in the Kimberley Mastcam mosaic. Due to the well-exposed outcrop at the Kimberley waypoint, there is a nearly perfect correlation between the mapped distribution of bright striated outcrop orbital facies and the south-dipping resistant and recessive sandstones mapped in the rover mosaic (Figures 13b and 13c). Using rover image-based observations of the bright striated outcrop orbital facies, the three possible origins of the striations described in the previous section can be re-evaluated. The presence of south-dipping sandstone beds of variable resistance in areas mapped as bright striated outcrop orbital facies indicate that the striations cannot be completely explained as surface lineations (option 1), but are due in large part to the intersection of inclined bedding planes with the modern day erosional outcrop topography (option 2). There is no evidence from ground-based rover observations that the bedding planes are curved, so option 3 can be eliminated.

Areas mapped as float in the rover mosaic correspond to the smooth hummocky orbital facies, and areas containing a higher proportion of sand to float are generally mapped in the HIRISE images as smooth dark orbital facies. The bright bedded outcrop orbital facies corresponds well with flat-lying platy sandstone beds mapped in the Mastcam mosaic, and the contact between these platy sandstones and underlying south-dipping sandstone beds is identified

with high fidelity in both the orbital map and rover mosaic (Figure 12a and 12c). The three hills present at the Kimberley waypoint were mapped in HiRISE images as smooth boulder outcrop orbital facies, which corresponds to accumulations of fine-grained float and intermittent exposures of sandstone on the slopes of the hills. The smooth appearance of these hills in orbital images is likely due to accumulations of sand and float on the hilltops.

5. Discussion

The comparison between orbital facies mapping and rover image-based geologic mapping at the Darwin, Cooperstown, and Kimberley waypoints illustrates several important points about the utility and validity of orbiter image-based geologic interpretations. Orbital facies mapping is useful for distinguishing in-place bedrock from unconsolidated deposits, and can be used to identify geologically significant contacts if outcrop exposure is good and adjacent facies exhibit differences in brightness, surface texture, or weathering characteristics such as resistance to erosion. This is particularly important since datasets such as THEMIS-derived thermal inertia (100 m/pixel) and CRISM (~18 m/pixel), which can also provide information about physical and compositional differences on the surface, have resolutions too coarse to allow meaningful distinction between orbital facies mapped at the scale employed in this study. At all three waypoints, the bright outcrop orbital facies, including the bright striated, bright bedded, and bright fractured outcrop orbital facies, were correctly identified during HiRISE mapping as in-place, lithified outcrop. The resistant cratered outcrop facies was also correctly identified as bedrock at Cooperstown and Kimberley. The smooth dark, boulder hummocky, and smooth hummocky orbital facies were correctly identified from orbital images as largely unconsolidated surficial deposits. The exception is the smooth hummocky orbital facies mapped at Darwin,

where intermittent exposures of sandstone and conglomerate bedrock could not be resolved from orbital images. The ability to distinguish between lithified rock outcrop and unconsolidated surficial deposits is important and particularly useful for planning rover science investigations and performing traverse and mobility assessment. In-place rock outcrops rather than unconsolidated deposits are often the desired science target for investigations of depositional processes, paleoenvironment, and geochemistry of ancient sedimentary rocks. Conversely, terrain consisting of unconsolidated surficial deposits may be favored over in-place outcrop when planning traverses that minimize wheel damage and hazard to the roving vehicle [Yingst *et al.*, 2014].

Orbital facies maps can also be useful for recognizing distinct contacts between bedrock units, particularly when accompanied by a clear topographic scarp or mappable differences in brightness, color, or surface texture. The ability to recognize significant geologic contacts from orbiter image datasets is particularly important for making strategic decisions during mission surface operations that determine where a rover is sent to address hypotheses about the geologic nature of the site. Orbital geologic interpretations initially guided the MSL team in its decision to drive the Curiosity rover to Yellowknife Bay [Grotzinger *et al.*, 2014; Palucis *et al.*, 2014], and several examples from this study illustrate the utility of orbital facies mapping for identifying geologically significant contacts. At the Cooperstown waypoint, the mapped contact between the resistant cratered outcrop and the bright outcrop orbital facies in the vicinity of the contact science location represents a sharp transition between the massive and platy-bedded fine sandstone beds and the resistant pebbly sandstone. At Kimberley, where outcrop is well-exposed and orbital facies are easily distinguished in HiRISE images, the orbital map interpretations provided sufficient information to identify the contact between south-dipping coarse sandstone

beds and the overlying flat-lying platy sandstones (Figure 12a and Figure 12c), a stratigraphic relationship that was critical for determining the origin of the enigmatic striations observed in HiRISE images (Figure 9c and 9d).

There are also ways in which orbital map interpretations are limited, particularly when used alone without corresponding datasets acquired on the ground. Differences in relative brightness, color, or textural characteristics observed in orbital image datasets may indeed be suggestive of inherent differences in the material properties of bedrock units, but these orbital characteristics can be non-unique and heavily biased by unconsolidated materials exposed immediately at the surface. For example, the presence and distribution of thin, discontinuous surficial deposits of float, sand, and dust may result in the distinction of multiple orbital facies within the same geological unit due to changes in color and brightness caused only by these mantling materials. The two alternate cross-section interpretations presented for the Darwin waypoint illustrate this point. In the first cross-section (Figure 4b), the smooth hummocky orbital facies observed at the surface is interpreted as a distinct and important stratigraphic unit of at least several meters thickness that forms the substrate of the basin in which younger facies were deposited. In contrast, in the second cross-section interpretation (Figure 4c) the smooth hummocky orbital facies is interpreted as a relatively thin mantle deposit that is obscuring more extensive underlying exposures of bright outcrop and resistant cratered outcrop orbital facies. The two interpretations have very different implications for the timing and relative age relationship of the outcrops and deposits observed from orbital datasets and on the ground as well as the timing of basin formation, yet it is challenging to distinguish between the two hypotheses using the orbital image data. Rover image-based observations reveal that the smooth hummocky facies is in-part composed of in-place bedrock and that deposition of sandstone beds

688 within the Darwin depression appears to have been influenced by the geometry of pre-existing
689 depression; both observations are consistent with and best explained by the stratigraphic model
690 presented in Figure 4b. This example supports the rationale for sending rovers to the surface of
691 planetary bodies as it is difficult to ascertain the degree of heterogeneity at outcrop scale from
692 orbit, and to interpret the significance of that heterogeneity.

693 As another example of the non-uniqueness of orbital facies interpretations, consider two
694 areas, Darwin and Cooperstown, that exhibit similar remote sensing properties. At the Darwin
695 waypoint, the resistant cratered outcrop orbital facies corresponds to accumulations of
696 unconsolidated float blocks. In contrast, the resistant cratered outcrop orbital facies at
697 Cooperstown corresponds to a variety of in-place, lithified sandstone outcrops. Some of the
698 outcrops mapped as resistant cratered orbital facies at Cooperstown were fine-grained and
699 vuggy, whereas others were coarse-grained and contained pebble-size clasts, likely representing
700 very different depositional conditions and/or processes. Based solely on orbital mapping, these
701 resistant cratered outcrop facies occurrences could be interpreted and correlated as co-eval
702 deposits of a similar origin, but rover-based observations show that such a correlation would not
703 be valid. In addition, the bright outcrop orbital facies mapped at all three Curiosity waypoints
704 may suggest that a time-rock correlation of these orbital facies could be appropriate. However, a
705 closer examination of the bedrock outcrop with rover images at each waypoint (Figure 15), calls
706 into question the validity of such a correlation. At Darwin, the bright outcrop orbital facies
707 corresponds to an outcrop of coarse sandstones and pebble conglomerates, whereas the bright
708 outcrop mapped at Cooperstown corresponds to fine-grained platy-bedded and massive
709 sandstones. While a general regional correlation between these two locations may still be
710 possible, the rover data reveal no clear rationale for a geologic correlation of the contact between

the bright outcrop and overlying resistant cratered outcrop orbital facies mapped at Darwin with that same orbital facies contact mapped at Cooperstown.

The orbital and ground-based comparisons presented in this study also illustrate the difficulty in making process-based interpretations from orbital mapping alone, particularly in areas like Bradbury Rise in Gale crater where present-day topography and geomorphology provide few indications of past depositional process or paleoenvironment. For comparison, there are some locations on the surface of Mars where depositional interpretations are possible based almost solely on orbital observations, as is the case for inverted relief features such as channels or preserved fans or deltas, volcanic constructs such as lava flow lobes, or impact ejecta deposits. The Peace Vallis fan in Gale crater is an example of such a deposit. The present-day topography of this feature enables its identification as an alluvial fan, for which calculations of total volume and runoff can be made [Palucis *et al.*, 2014]. The distribution of inverted channel features and measurements of present-day fan slope also allows an evaluation of the relative importance of various depositional processes contributing to fan formation, particularly the role of distributary channel formation versus sheet flow, debris flow, and mud flow deposition throughout the fan [Palucis *et al.*, 2014]. Furthermore, the location of Yellowknife Bay at the distal end of the Peace Vallis fan led the MSL team to hypothesize that fine-grained sediments representing deposition in a lacustrine setting might be found there, a hypothesis that was “field checked” and proven correct by observations from the Curiosity rover [Grotzinger *et al.*, 2014; Palucis *et al.*, 2014]. In contrast, Bradbury Rise lacks diagnostic paleogeomorphic features such as those characterizing the Peace Vallis fan and unlike Yellowknife Bay, Bradbury Rise shows no clear temporal or spatial relationship with the Peace Vallis fan. Therefore, distinguishing a process-based sedimentary origin for the three waypoints examined in this study from orbital image data alone

is admittedly challenging. In these cases, rover image-based observations of lithology, grain size, and texture are essential for interpreting depositional hypotheses.

As a consequence of the various limitations described above, it is common practice for orbital stratigraphic interpretations to show simple “layer cake” stratigraphic models in which orbital facies are interpreted as stratal units of relatively constant thickness, horizontal deposition, and lateral continuity at least at the scale of the drafted cross-section. This is usually the simplest model to interpret the data. The cross-sections presented for each waypoints in Figures 4, 8, and 12 are modeled by this “layer cake” geometry, as is the regional schematic cross-section of Bradbury Rise incorporating all three waypoints shown in Figure 16a. Because the geometry of subsurface units in these examples provides no indication of a process-based depositional interpretation of the stratigraphic units, more complex stratigraphic models, though plausible, would likely be an over-interpretation of the available data and thus speculative. Although some “layer cake” models may be valid representations of the subsurface geology, in situ observations of the bedrock outcrop and surficial deposits present at the three waypoints in Gale crater suggest that a more appropriate model for the subsurface of Aeolis Palus is that shown in the schematic in Figure 16b. In this model, the fundamental principles of stratigraphy still hold, but lithologic units exposed at the surface are mapped and interpreted in the context of the fluvial depositional system suggested for Bradbury Rise by the in situ analysis of *Williams et al.* [2013], *Grotzinger et al.* [2014], and *Vasavada et al.* [2014]. Such a model for the subsurface stratigraphy is likely closer to reality for fluvial depositional systems than the layer cake model presented in Figure 16a, but its construction was only suggested from ground-based interpretations of the outcrops exposed throughout Aeolis Palus.

6. Implications for mapping future landing sites on Mars

High-resolution orbital images have been incredibly important for increasing recent understanding of the geological diversity of the martian surface and have made a positive impact on surface mission landing site selection and surface operations. But this study shows that even 25 cm/pixel HiRISE images mapped at a 1:500 scale will provide limited to no information about the small-scale textural characteristics of an outcrop, including grain size, lithology, or internal structures (e.g., bedforms and fine-scale bedding characteristics), that are critical for making depositional interpretations even as fundamental as sedimentary versus volcanic. The vertical viewing geometry of orbital imaging systems can also limit the amount of geologically significant information gleaned from outcrop exposures observed in orbital data, particularly because three-dimensional outcrop exposures are difficult to observe in orbital data. Yet orbital images provide a breadth of surface coverage and the local-to-regional context for detailed rover observations that the limited visual range and horizontal viewing geometry of a ground-based rover cannot provide, highlighting how complementary the combined approach of orbiter and rover-image based analysis can be.

Developing more complex and detailed process-based models for the depositional history of martian landing sites through the integration of detailed orbital facies mapping and analysis of rover images is critical for making better-informed predictions of where Curiosity or future rovers might concentrate effort and resources to find preserved evidence of past habitable environments, organic matter, or other biosignatures. Ground-based rovers are needed to measure small-scale textural characteristics of rock outcrops, such as grain size, lithology, sedimentary structures, bedding style, and allow the exploration of three-dimensional outcrop exposures that are essential for paleoenvironmental reconstructions. Detailed orbital mapping of

high-resolution image datasets like that carried out in this study aids in the planning and execution or rover measurements on daily or monthly operational timescales and provides critical context for these measurements at a finer-scale than that typically employed in regional or global orbital map investigations.

As critical as the integration of orbiter and rover data is for understanding the past depositional processes and paleoenvironments on the surface of Mars, the reality is that rover and landed missions to Mars are rare and the majority of the planet can only be studied with orbital data sets. Although it may not be practical to map large areas of the martian surface at the 1:500 scale (or finer) employed for the waypoint study areas here, for locations on Mars considered of interest for future rover or even human missions, the analysis of high resolution orbital image datasets through fine-scale orbiter image-based mapping efforts are important for mission planning purposes as well as predicting in advance the diversity of rock outcrops and deposits that will be encountered.

This study highlighted some of the considerable challenges that persist with geologic interpretations of the highest resolution orbital images currently available of the martian surface, but future airborne or orbital imaging systems designed to image at even higher resolutions could help resolve the limitations of existing orbital geologic interpretations. Imaging at the ~1-5 cm/pixel scale would afford the ability to recognize finer distinctions in outcrop texture that could significantly aid in the depositional interpretation of orbital facies and the recognition of locally and regionally significant geologic contacts.

7. Conclusions

The Curiosity rover stopped at the Darwin, Cooperstown, and Kimberley waypoints during its traverse from Yellowknife Bay to the base of Aeolis Palus. This study presents detailed orbital facies maps for each waypoint based on HiRISE images and provides a comparison between orbital facies mapping and geologic mapping based on images from the Curiosity rover Mastcam M-100 and MAHLI cameras. The results of the orbiter and rover-based comparison are as follows:

(1) Orbital facies mapping is generally useful for distinguishing between in-place bedrock outcrop and unconsolidated surficial deposits.

(2) Orbital facies mapping can be used to identify distinct geologic contacts if outcrop exposure is good and adjacent facies exhibit differences in brightness, color hue, surface texture, or resistance to erosion.

(3) The remote sensing properties used to define orbital facies and the geologic interpretations that result from these observations can be non-unique and biased by a mapper's interpretation of how distinct those properties are. This leads to challenges in accurately correlating spatially distinct orbital facies.

(4) Process-based interpretations based on orbital image observations alone should be made cautiously for landscapes such as Bradbury Rise, which lack clear paleogeomorphic landforms or topography indicative of a particular depositional process.

(5) Stratigraphic architecture interpreted from orbital maps is often represented as "layer cake" models, but these models are inconsistent with Curiosity rover observations of the ancient sedimentary environments explored in Gale crater. Integration of orbiter and rover image-based observations is needed to construct more sophisticated stratigraphic or depositional models.

(6) Fine-scale orbital mapping of future candidate landing sites, actual landing sites, and field investigation traverse paths like that presented in this study, integrated with rover image-based observations enables better-informed predictions of where ground-based rover missions might concentrate effort and resources to find preserved evidence of past habitable environments, organic matter, or other biosignatures.

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1013 **Tables**

1014 **Table 1. Curiosity rover waypoints during the Bradbury Rise traverse**

Waypoint	Arrival Sol	Departure Sol	Curiosity Rover Geology Investigation
Darwin	392	401	Remote sensing (Mastcam and Chemcam) and Contact Science (APXS and MAHLI)
Cooperstown	441	443	Remote sensing (Mastcam and Chemcam) and Contact Science (APXS and MAHLI)
Kimberley	574	631	Remote sensing (Mastcam and Chemcam), Contact Science (APXS and MAHLI), Dust Removal Tool (DRT), Drill, CheMin, SAM

1015 **Figures**

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1017 **Figure 1.** MSL Curiosity landing ellipse (yellow ellipse), Bradbury Landing, Curiosity's landing
1018 site (yellow star), and the location of Bradbury Rise annotated on a shaded relief HiRISE stereo
1019 image-derived topographic map of the Peace Vallis Fan, Aeolis Palus, and Aeolis Mons.
1020 Contours represent 10 meter intervals. Inset figure shows Gale crater in THEMIS Day IR.

Figure 2. (a) Mosaic of HiRISE images PSP_009505_1755, PSP_010573_1755, ESP_018854_1755, and PSP_009149_1750) showing the Curiosity rover traverse across Bradbury Rise and the locations of the Darwin, Cooperstown, and Kimberley waypoints in relation to Bradbury Landing (yellow star), Yellowknife Bay, and the base of Aeolis Mons. HiRISE images of the (b) Darwin (PSP_010573_1755), (c) Cooperstown (PSP_010573_1755), and (d) Kimberley (ESP_018854_1755) waypoints. Curiosity's traverse is traced by the white line.

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1031 **Figure 3.** Previous orbiter image-based mapping of the Darwin, Cooperstown, and Kimberley waypoints by *Grotzinger et al.* [2014]

1032 compared to this study's orbital maps. The rover traverse is traced by the white line in the HiRISE color images (top row).

Figure 4. (a) Orbital facies map of the Darwin waypoint and (b-c) cross-section interpretations representing A to A' displayed with a vertical exaggeration of 6.5x. The rover's location when the mosaic in Figure 6 was acquired is just north of the mapping area displayed here, and the area between the two dashed red lines marks the ground coverage of this mosaic in plan view. The Darwin contact science location shown in Figure 7 is indicated by the blue dot, and is outlined by the blue boxes in (b) and (c).

Figure 5. Representative examples of bedrock lithologies and surficial deposits observed in the M-100 rover mosaics of the (a-c) Darwin, (d-f) Cooperstown, and (g-i) Kimberley waypoints. Scale bar = 50 cm. Darwin: (a) undifferentiated sandstone and conglomerate, (b) conglomerate, (c) sand. Cooperstown: (d) platy sandstone, (e) vuggy sandstone, (f) dark float consisting of boulders and cobbles. Kimberley: (g) south-dipping resistant and recessive sandstones, (h) bedded sandstone, (i) undifferentiated sand and float.

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(a) Darwin Waypoint Sol 389 Mastcam M-100 Mosaic

(b) Darwin Orbital Facies

Key
Smooth Dark
Boulder Hummocky
Smooth Hummocky
Resistant Cratered Outcrop
Bright Outcrop

(c) Darwin Rover Image-Based Geology

Key
Conglomerate
Undifferentiated Conglomerate and Float
Undifferentiated Sandstone and Conglomerate
Platy Sandstone
Sandstone
Dark Fine-Grained Float
Misc. Float
Sand
Undifferentiated Sand and Float

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1050 **Figure 6.** Rover mosaic of the Darwin waypoint. (a) Sol 389 Mastcam M-100 Mosaic, The blue box outlines the outcrop shown in

1051 Figure 7 on which the stratigraphic column in Figure 15a is based. White tick marks represent 10° intervals in azimuth. (b) Mosaic

1052 annotated with mapped orbital facies, (c) Mosaic annotated with rover image-based geology observations.

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1055 **Figure 7.** (a) Annotated Mastcam M-34 mosaic acquired on sol 390 showing the location of
1056 Darwin contact science activities represented by the stratigraphic column in Figure 15a. (b)
1057 MAHLI image 0394MH0001900010104439C00 of the Altar Mountain pebble conglomerate
1058 target acquired on sol 394. (c) MAHLI image 0396MH0001700000104468R00 of the Bardin
1059 Bluffs very coarse sandstone acquired on sol 394.

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Figure 8. (a) Orbital facies map of the Cooperstown waypoint and (b) cross section interpretation representing A to A' displayed with a vertical exaggeration of 13x. The red dot in (a) marks the rover's location when the mosaic in Figure 10 was acquired, and the area between the two dashed red lines marks the ground coverage of this mosaic in plan view. The location of the Cooperstown contact science activities shown in Figure 11 is indicated by the blue dot in (a) and outlined by the blue box in (b).

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Figure 9. Striations of the bright striated outcrop orbital facies visible in the HiRISE color mosaic at the (a-b) Cooperstown and (c-d) Kimberley waypoints. (a) Un-annotated close-up of striations within the bright striated outcrop facies at the Cooperstown waypoint. Dashed black line outlines the southeastern corner of the Cooperstown mapping area shown in Figure 8. (b) Same image as (a) with striations traced in white. (c) Un-annotated close-up of striations within the bright striated outcrop facies at the Kimberley waypoint. (d) Same image as (c) with striations traced in white.

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1089 **Figure 10.** Rover mosaic of the Cooperstown waypoint. (a) Sol 438 Mastcam M-100 Mosaic, The blue box shows the portion of the
 1090 Darwin outcrop shown in Figure 11 and represented by the stratigraphic column in Figure 15b. White tick marks represent 10°
 1091 intervals in azimuth. (b) Mosaic annotated with mapped orbital facies, (c) Mosaic annotated with rover image-based geology
 1092 observations.

Figure 11. (a) Annotated Mastcam M-100 mosaic acquired on sol 439 showing the Cooperstown outcrop represented by the stratigraphic column in Figure 15b. (b) MAHLI image 0443MH0003290000200185R00 taken near the Renssalaer target acquired on sol 443.

Figure 12. (a) Orbital facies map of the Kimberley waypoint and (b) cross section interpretation representing A to A' displayed with a vertical exaggeration of 9x. The red dot indicates the rover's location when the mosaic in Figure 13 was acquired, and the two dashed red lines mark the ground coverage of this mosaic in plan view. The blue dot indicates the Windjana contact science and drill location shown in Figure 14 that was used to construct the stratigraphic section in Figure 15c. Since the cross-section does not cross this location, no annotation of the section is shown in (b). (c) Portion of a Mastcam M-100 mosaic obtained on Sol 595 showing the rover's view of the contact mapped in HiRISE between the bright striated outcrop facies and the bright bedded outcrop facies.

(a) Kimberley Waypoint Sols 580 and 582 Composite Mastcam M-100 Mosaic

(b) Kimberley Orbital Facies

(c) Kimberley Rover Image-Based Geology

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Figure 13. Rover mosaic of the Kimberley waypoint. (a) Sol 580 Mastcam M-100 Mosaic. The

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white box outlines the outcrop shown in Figure 14. White tick marks represent 10° intervals in

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azimuth. (b) Mosaic annotated with mapped orbital facies. (c) Mosaic annotated with ground-

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based rover geology observations.

Figure 14. (a) Annotated Mastcam M-34 mosaic of Mount Remarkable acquired on sol 603 showing the outcrop represented by the stratigraphic column in Figure 15c. (b) MAHLI image 0612MH0001930000203350R00 of the very-fine sandstone at the Winjana brushed target acquired on sol 612. (c) MAHLI image 0585MH0002970010202808C00 of a coarse-grained south-dipping sandstone bed taken near the Square Top target (location not shown in this mosaic) on sol 585. (d) MAHLI image 0601MH0003810000203227R00 of the coarse granule sandstone of the Liga target (location not shown in this mosaic) acquired on sol 601.

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1124 **Figure 15.** Stratigraphic columns showing mapped orbital facies interpreted as stratigraphic units compared with equivalent rover
 1125 observations of bedrock lithology for (a) Darwin, (b) Cooperstown, and (c) Kimberley.

Figure 16. Schematic cross-sections showing (a) Bradbury Rise stratigraphy interpretation derived from orbital mapping, and (b) the ground-based fluvial/alluvial depositional interpretation of Bradbury Rise. The topography shown in both profiles is derived from a HiRISE DTM. Sections in (a) and (b) are displayed with a vertical exaggeration of 22x.