CONSTRAINING MARTIAN SEDIMENTATION VIA ANALYSIS OF STRATAL PACKAGING, INTRACRATER LAYERED DEPOSITS, ARABIA TERRA, MARS

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Linda C. Kah, Major Professor

We have read this thesis and recommend its acceptance:

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CONSTRAINING MARTIAN SEDIMENTATION VIA ANALYSIS OF STRATAL PACKAGING, INTRACRATER LAYERED DEPOSITS, ARABIA TERRA, MARS

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ABSTRACT

Craters within Arabia Terra, Mars, contain hundreds of meters of layered strata showing systematic alternation between slope- and cliff-forming units, suggesting either rhythmic deposition of distinct lithologies or lithologies that experienced differential cementation. Hypothesized origins of these intercrater layered deposits include lacustrine, aeolian, volcanic airfall, and impact surge deposition. On Earth, rhythmically deposited strata can be examined in terms of stratal packaging, wherein the interplay of tectonics, sediment deposition, and change in base level results in predictable patterns with respect to changes in the amount of space available for sediment accumulation. Fundamental differences between tectonic regimes of Earth and Mars demand that packaging of layered strata primarily reflects changes in sediment influx and base level. Analysis of stratal packaging may therefore help us understand the relative roles of these parameters, and provide crucial constraint on martian depositional models.

Rhythmic stratal patterns in Becquerel Crater (7°W 22°N) have been attributed to astronomical forcing of regional climate. A clear depositional model, however, has yet to be presented. Here, we reanalyze strata of Becquerel Crater and compare results with two additional crater successions. Results indicate that, by contrast with Becquerel Crater, strata within Danielson Crater (7°W 8°N) and an unnamed crater (Crater X; 1.2°W 9°N) do not record hierarchical packaging readily attributable to astronomical effects, and suggest that regional climate forcing may not be readily applied as a paradigm for all intracrater deposition. Similarities in depositional style in these three craters, however, may be linked by a model for sediment accumulation—with potential links to regional climate—wherein episodic melting of ground ice raised local base level, stabilized aeolian sedimentation, and resulted in differential
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1. Introduction

Layered geologic units have been recognized on Mars since the 1971 Mariner 9 mission (Malin and Edgett, 2000 and references within). Since then, images and data from both orbital missions and planetary rovers show evidence of layering nearly everywhere bedrock of ancient cratered highlands is exposed. Occurrences of layered deposits include those within cratered interiors (Edgett, 2002; Venechuck et al., 2006; Fassett and Head, 2007; Oehler et al., 2007; Wilson et al., 2007; Ferguson and Christensen, 2008; Lewis et al., 2008; D’Arcangelo et al., 2009; Carter et al., 2010; Hill et al., 2010), intercrater terrain (Christensen et al., 2000; Edgett and Malin, 2000; Hynek and Phillips, 2008), chaotic terrain (Sharp et al., 1973; Sowe et al., 2008), and chasm interiors (Komatsu et al., 1993; Gendrin et al., 2005; Catling et al., 2006; Quantin et al., 2010). Low-resolution imagery from Mariner 9 (100-1000 meters/pixel) and Viking (100-300 meters/pixel) missions resulted in the interpretation of layered deposits as mantling units that draped pre-existing cratered substrate (Moore 1990; Fassett and Head, 2007). Later high-resolution images (0.5-20 m/pixel) revealed thin-bedded strata to be an integral part of the martian substrate that records a complex history of deposition, cratering, infilling, burial, erosion, and exhumation (Edgett and Malin, 2002; Edgett, 2005).

No clear, identifiable source region has been identified for most of the layered strata observed on the surface of Mars (Malin and Edgett, 2000). The lack of identifiable sedimentary sources has led to numerous hypotheses regarding the lithology and depositional environment for these deposits. Proposed hypotheses include: (1) subaqueous deposition in lacustrine or oceanic-scale systems (Edgett and Parker, 1997; Malin and Edgett, 2000; Cabrol et al., 2001; Edgett and Malin, 2002; Beyer and McEwen, 2005; Edgett, 2005); (2) aeolian deposition (Squyers et al., 2004; Benison and Bowen, 2006), likely associated with a regional groundwater system (Squires
et al., 2004; Grotzinger et al., 2005; Grotzinger et al., 2006; Andrews-Hanna et al., 2010); or (3) air fall deposition from either pyroclastic ejecta (Moore 1990; Hynek et al., 2003; Fassett and Head, 2007) or impact-related surge deposits (Knauth et al., 2005; Burt et al., 2008; Hynek and Phillips, 2008).

The potential for widespread aqueous activity during early (Noachian to Hesperian) martian history has resulted in substantial research aimed at understanding the history of habitable environments on Mars (Atreya et al., 2006; Tosca et al., 2008). A combination of imagery, mineralogic spectra and data, and elemental data from the Mars Reconnaissance Orbiter and recent landers have provided evidence suggesting that sedimentary processes have been active throughout martian history (Grotzinger et al., 2005; Squyers and Knoll., 2005; Grotzinger et al., 2006; Benison and Bowen, 2006; Squyers et al., 2006; Metz et al., 2009). For example, Meridiani Planum has been identified as a region of past aqueous activity from the presence of sulfate-rich evaporite minerals interpreted to have formed in a playa setting that experienced both groundwater flow and surficial runoff (Benison and Bower, 2006; Grotzinger et al., 2006; Andrews-Hanna et al., 2010). Additionally, valley networks and associated distributary fans entering into Eberswalde Crater (Fassett and Head, 2005; Ponderelli et al., 2008), Holden Crater (Malin and Edgett, 2003), and into unnamed craters in the Nili Fossae region (Fassett and Head, 2005) provide evidence that surficial runoff and ponding of surface waters may have occurred globally.

Recently, research regarding the interpretation of ancient martian environments has moved from interpretation of isolated geomorphic or geochemical features to the potential planetary-scale implications of regional aqueous activity (Lewis et al., 2008; Andrews-Hanna et al., 2010; Farien 2010). Andrews-Hanna et al. (2010), for instance, suggested that layered rocks
at Meridiani Planum were part of a regionally extensive zone of groundwater upwelling that was active for up to 200 million years. Similarly, Lewis et al. (2008) suggested that rhythmic layering in Becquerel Crater reflect astronomical forcing of martian climate and its influence on depositional conditions. The implication of both of these studies is that sedimentary patterns on Mars should have broad regional application in terms of our understanding of martian climate and the evolution of sedimentary processes.

The next step in furthering our understanding of martian sedimentation is to determine whether this evolving paradigm of regional climate and environmental evolution can be traced to other stratal deposits, or whether a broader paradigm for sedimentation on Mars is needed to explain the variety of deposits and their depositional profiles. Layered deposits in craters of Arabia Terra provide a unique opportunity to further explore depositional processes during early martian history. Intracrater deposits in Arabia Terra contain hundreds of meters of light-toned, finely bedded layers. These deposits are commonly eroded into mounds with stair-stepped morphologies that alternate between slope- and cliff-forming units, suggesting repetitive or rhythmic deposition of distinct lithologies or a single lithology that experienced differential diagenesis (Fig. 1). In Arabia Terra, the majority of layered deposits are contained within craters, although a distinct class of craters preserves layered strata existing above crater rims (Malin and Edgett, 2000).

To further understand depositional conditions responsible for the accumulation of layered sediment on Mars, it is necessary to first determine the range of variability in stratal packaging. Herein, we present a reanalysis of strata within Becquerel Crater and compare features of stratal packaging with that of two additional craters showing very different stratal morphologies: Danielson Crater (7°W, 8°N), and an unnamed crater at 1.2°W, 8.9°N (herein called Crater X).
Figure 1: Examples of layered strata exposed in craters of Arabia Terra. Deposits contain hundreds of meters of strata that, despite differences in broad erosional morphology, show systematic alternation between cliff- and slope-forming units. A) Subframe of MOC2-1342; Becquerel Crater, 21.5°N, 8.2°W; B) Subframe of MOC2-348; Unnamed Crater at 8°N, 7°W; image is 3 km wide. C) Subframe of MOC2-1563; Schiaparelli Basin, 3°S, 343.3°W. Each image is 3 km wide, and lateral continuity and uniformity of layers is interpreted to reflect depositional or diagenetic periodicity.
Multiple, detailed stratigraphic columns from each crater are used to analyze component and cycle thickness, to identify stratigraphic patterns, and to construct potential models for sediment deposition.

The goal of this study is to explore sedimentary environments of the Arabia Terra region and use details of sedimentary deposition to infer their importance in terms of better understanding the early history of Mars. By analyzing stratal packaging of intracraterr layered deposits, we can begin to define the driving forces for sedimentation in these three craters, and explore whether these forces may have been acting locally or regionally. Ultimately, because changes in stratigraphic packaging reflect a combination of sediment input and its interaction with various controls on accommodation space, this analysis will extend our understanding of martian sedimentary environments and geologic history.
2. Geology of Arabia Terra

Arabia Terra is a relatively low elevation, high albedo, densely cratered province within the martian southern highlands that lies close to the crustal dichotomy (Fig. 2A). Arabia Terra represents the largest portion of ancient cratered crust in the martian northern hemisphere, with quantitative crater densities indicating a dominantly Noachian age (Hartmann, 2005). The occurrence of buried and partially to fully exhumed craters within regional strata of Arabia Terra has been shown to record the presence of progressively older substrates to the north (Edgett, 2005). This interpretation further implies that intracrater fill in the Arabia Terra region may have occurred across a broad expanse of Noachian, and potentially early Hesperian, time.

The broadly circular shape of the Arabia Terra region has previously been inferred to represent the primary aerial extent of a large depositional basin of either impact (Dohm et al., 2007) or tectonic (Anderson et al., 2008) origin. After initial basin formation, layered strata accumulated within the basin (Anderson et al., 2008; Hynek and Phillips, 2008; Malin and Edgett, 2001). Later uplift (Anderson et al., 2008; Phillips et al., 2001) and erosional incision (Hynek and Phillips, 2001) exposed these ancient successions. Currently, substantial dust coverage marked by regionally low thermal inertia (Christenson et al., 2001) has obscured much of the region.

Several lines of evidence suggest that Arabia Terra may have had a long-lived aqueous history. Laterally continuous strata across the region (Edgett, 2005) and inferred shoreline terraces along the crustal dichotomy (Parker et al., 1989; Perron et al., 2004) suggest the possibility of deposition associated with a persistent aqueous basin to the north, and denudation of highland material to the south of Arabia Terra resulting from long-term fluvial activity (Hynek and Phillips, 2001; Hynek and Phillips, 2008). Additionally, impact crater morphologies
Figure 2. A) Global topographic map of the surface of Mars, modified from Smith et al., 1999. Dashed white line shows the approximate position of the crustal dichotomy, which separates northern lowland from southern highland terrains; white box shows area of Arabia Terra. B) Detail of Arabia Terra with localities of Becquerel (A), Danielson (B), and unnamed Crater X (C).
(Anderson et al., 2008) and the localized presence of hydrated mineral deposits within intracratater deposits (Fialips et al., 2005) suggest the possibility of a persistent volatile-rich substrate (Anderson et al., 2008).

2.1. Craters

Three craters were examined for this study, Becquerel Crater, Danielson Crater and Crater X (Fig. 2B; Table 1). All three craters are in western Arabia Terra, between 0° and 10°W. Craters were chosen for analysis based on: (1) relation to Becquerel Crater (assuming similarity of age with proximity; Edgett, 2005), (2) existence of visible layered strata, and (3) current availability of HiRISE stereo pair images.

Table 1: Geographical information for craters analyzed in this study.

<table>
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<th>Becquerel</th>
<th>Danielson</th>
<th>Crater X</th>
</tr>
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<tbody>
<tr>
<td>Coordinates</td>
<td>7°W, 22°N</td>
<td>7°W, 8°N</td>
<td>1.2°W, 8.9°N</td>
</tr>
<tr>
<td>Diameter</td>
<td>167 km</td>
<td>67 km</td>
<td>30.2 km</td>
</tr>
<tr>
<td>Local intercrater plane elevation</td>
<td>-1862 m</td>
<td>-1862 m</td>
<td>-1561</td>
</tr>
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Becquerel Crater is the northernmost and largest of the craters analyzed in this study (Table 1). Danielson Crater is 775 km south of Becquerel Crater. Crater X is 350 km east and 56 km north of Danielson Crater, and 350 km east and 737 km south of Becquerel Crater. Edgett (2005) proposed that the age of exposed substrate increases northward across Arabia Terra. Therefore, Becquerel Crater may be arguably older than Danielson Crater and Crater X. However, the low regional slope of basement strata (Hynek and Phillips, 2008), and the relatively similar elevation of the three craters support a broadly similar position within the
regional stratigraphic framework. Meridiani Planum, dated as Noachian-Hesperian in age is 1350 km to the south. Therefore, keeping with the notion that bedrock gets older as move northward in the northern highlands, further suggests a late Noachian to early Hesperian age for intracrater strata within craters of Arabia Terra.
3. Strata and stratal packaging

3.1. Implications of layering

Bedding is a fundamental characteristic of sedimentary rocks and represents layers of lithologic, textural, or structural unity that can be clearly distinguished from under and overlying layers (Christie-Blick and Driscoll, 1995). Lower and upper bedding planes reflect abrupt changes in depositional conditions, such as sediment influx, energy of flow, sediment cohesion/cementation, and sediment erosion (Christie-Blick and Driscoll, 1995). Therefore, bedding within a sedimentary package records sedimentological response to changes in the depositional process. Similarly the concept of bedding can be broadened to include post-depositional layering resulting from changes in diagenetic conditions (Chan et al., 2010).

Whereas the formation of bedding occurs in response to change in depositional conditions, the accumulation of bedding reflects a combination of: (1) accommodation space—the vertical space available for sediment deposition at any point in time, (2) sediment input—either detrital sedimentation or in-situ precipitation, and (3) base level—the level above which deposition is temporary and erosion occurs (Jervey, 1988). In order for sediment to be deposited, there must be vertical space available to fill. On Earth, changes in accommodation space are determined by the dynamic interplay of basin subsidence or uplift, changes in base level, and changes in the rate or source of sediment input (Curray, 1964; Posamentier and Allen, 1999; Coe et al., 2002; Fig. 3A).

In terrestrial marine environments, changes in the first two of these parameters, accommodation space and sediment input, largely reflect a combination of sea level (i.e., eustasy) and tectonics (Jervey, 1998). High sea level, for instance, provides subaqueous accommodation space (Fig. 3A), and can restrict terrigenous regions susceptible to erosion. By
contrast, tectonic subsidence or uplift can act to either increase or decrease accommodation space at the same time as potentially decreasing or increasing sediment supply, respectively.

Base level, however, is the most important concept for understanding sediment accumulation in nearshore to non-marine environments. Base level is a conceptual equilibrium surface that separates the regions of potential sediment to accumulate from the potential for sediment to erode (Boggs, 2000). In marine environments, base level is coincident with relative sea level, and is therefore rarely distinguished from eustasy. In non-marine subaqueous (i.e., lacustrine) environments, base level is defined by the intersection of the ground water table with the topographic substrate. In such environments, increase in accommodation space is attributed to an increase in the available volume of water within the groundwater reservoir (Fig. 3B). Similarly, in a subaerial environment, although aeolian deposition may be controlled ultimately by air pressure, it is the position of a subsurface water table that defines base level and therefore the maximum thickness of subaerially deposited sediment not susceptible to deflation and continued transport (Fig. 3C).

The position of base level is therefore critical in determining accommodation space, particularly in non-marine depositional environments where accommodation space and base level vary, and thus the maximum amount of sediment that has the potential to accumulate at any point in time. The rate of change of base level, relative to sedimentary input, then becomes critical in determining the hydrodynamic environment of deposition. In a subaqueous environment, assuming sediment input sufficient to fill available accommodation space, depositional packages reflect amount of accommodation space and base level position, with increase in thickness as accommodation space increases and thinning as accommodation space decreases. In the case of aeolian deposition, if sediment input is sufficient to fill accommodation
Figure 3: Controls on accommodation space, not to scale. A) Marine environment. Eustasy and tectonics are the first-order controls on accommodation space. The purple arrow represents initial accommodation space. An increase in either eustatic sea level or tectonic subsidence results in a rise in relative sea level and an increase in accommodation space, shown by red arrow. B) Subaqueous, terrestrial (i.e. lacustrine) environment. Position of the water table and its intersection with the substrate topography controls accommodation space. Purple arrow indicates initial accommodation space. An increase in the size of the groundwater reservoir increases accommodation space, shown by red arrow. C) Terrestrial subaerial environment. Position of the water table determines potential for aeolian accumulation (modified from Havholm and Kocurek, 1994). Purple arrow represents initial position of the water table. With an increase in the position of the water table, caused by subsidence or absolute water table rise, new preservation space is created, shown in the red arrow. All sediment above the new water table will be susceptible to erosional deflation.
space, base level will control the maximum amount of sediment that escaped deflation, and package thickness will directly reflect the base level position.

### 3.2. Implications of stratal packaging

Earth and Mars are sibling planets; each has a substantial atmosphere, weathered surfaces, massive volcanoes, and chemically and thermally evolved interiors (Prinn and Fegley, 1987). The consistency of basic physical properties that control the behavior of fluids and solids and the conservation of mass and energy requires, therefore, that the stratigraphic architecture of sedimentary deposits on Mars should be similar to that of Earth (Grotzinger et al., 2005). Opportunity’s investigation of layered strata at Meridiani Planum showed that not only are sedimentary patterns of Mars and Earth are similar, but that these deposits are structurally and geochemically analogous to those deposited in terrigenous aeolian environments (Grotzinger et al., 2005).

Mars and Earth, however, differ fundamentally with respect to their tectonic regimes and potential aqueous surface conditions, which should have a substantial influence on local to regional scale accommodation space. Earth is tectonically active and basin subsidence, which is controlled by the isostatic response of the crust to changes in thickness, thermal regime, or tectonic or sedimentary loading, is a first-order factor in the accumulation of tremendous thickness of strata (Alavi, 1994). By contrast, Mars has been tectonically extinct for most of its history (Barlow, 2008). Recently, late Amazonian volcanotectonic fissures have been identified at Cerberus Fossae (Berman and Hartman 2002; Burr et al., 2002; Head et al., 2003). However, basin development on Mars occurs largely through impact cratering, and its thick crust (Zuber, 2000) inhibits subsidence. As a result, tectonic subsidence and uplift play little role in the
control of accommodation space on Mars. Earth has also had liquid water throughout its geology history (Wilde et al., 2000), and eustatic sea level change is a primary factor in the production of accommodation space (Jervey, 1988). By contrast, the occurrence and extent of aqueous conditions is highly debated for Mars. Geomorphologic, sedimentological, and geochemical evidence (Parker et al., 1993; Malin and Edgett, 2000; Squyers et al., 2004; Poulet et al., 2005; Bibring et al., 2006) indicate that liquid water has been present on or near the Martian surface at different times in the planet’s history. The presence of a volatile rich substrate is supported, as well, by a broad range of landforms indicative of ground ice or permafrost development (eg., Baker, 2001; Dohm et al. 2007). Therefore, without tectonics, aqueous fluctuations are the primary driver of sediment accumulation and stratal packaging.

Martian and terrestrial differences in tectonic regime and potential aqueous reservoir characteristics are critical to arguments regarding accommodation space. Without accommodation changes based on sea level or regional subsidence, relative base level is strictly determined by the equilibrium position of the aqueous surface. A growing body of evidence supports that much of the aqueous reservoir on Mars exists within the subsurface (Malin and Edgett, 2000; Andrews-Hanna et al., 2007, 2010, and references therein), and suggests that sediment accumulation on Mars depends largely on changes in the size or behavior of this largely subsurface aqueous reservoir. Stratal packaging on Mars should therefore reflect the relationship between sediment supply and the generation of accommodation space via changes in local or regional aqueous base level by either position of the water table or surficial aqueous position.

If quantity of sediment influx is sufficient to fill available accommodation space, stratal packages can potentially show thickening upward, thinning upward, stochastic, or cyclic
packaging. Thickening upward packaging likely reflects an increase in accommodation space resulting from an increase in local or regional water volume, whereas thinning upward packages typically reflect a net decrease in accommodation space associated with a loss of local or regional water volume. Cyclic packaging reflects a hierarchy of processes that results in a net gain or loss of water volume (Vail et al., 1977; Schwarzacher, 2000). By contrast, stochastic packaging is likely to represent either random changes in accommodation space, or stratal deposition and lithification that is non-sedimentary in origin (e.g. impact ejecta deposits, volcanic deposition).

In addition to an understanding of the origins of accommodation space, the determination of stratal packaging on Mars also requires some fundamental assumptions regarding the nature of the strata being measured. Observed from orbit, the primary geomorphic pattern reflected in layered strata is a stair-stepped pattern, with a recessively weathered interval, commonly blanketed by windblown dust, capped by a more resistant interval (Fig. 4). In this study, as well as earlier examinations of stratal packaging (Lewis et al., 2008), measurements of stratal thickness are taken from the top of the resistant cap to the top of the next successive resistant cap. These measurements, therefore, should not be identified as “beds”, as in Lewis et al. (2008). Rather, these recessive/resistant couplets may represent: (1) two distinct beds of different composition, lithology, cementation, grain size, etc., (2) single initial lithology with differential cementation of lower and upper portions, or (3) a single depositional package composed of multiple beds of varying thickness, lithology, or cementation that are too thin to be distinguished via orbital imagery.

Layered intervals such as those observed in intracrater deposits of Arabia Terra, can form within a number of different depositional environments. In subaqueous deposition, a
recessive/resistant couplet may be essentially analogous to a parasequence on Earth (Van Waggoner et al., 1988). In this scenario, individual beds that comprise the couplet reflect varying hydrodynamic energies, wherein the lower recessive interval represents deeper-water (lower-energy) deposits that form characteristically fine-grained and thinly bedded deposits, and the upper resistant interval represents shallow-water (high-energy) deposits that are characteristically coarser-grained and more thickly bedded. Terrestrially, this is seen in glacial lakes by sedimentary varves, with fine grained layers representing low energy conditions, and sand/silt layers higher energy, forming a couplet (Ridge and Larson, 1990). By contrast, in an aeolian depositional environment, where sedimentary deposition is characteristically more uniform in its grain size, couplets likely result from preferential cementation of the sedimentary package via evaporation of ambient pore fluids and mineral precipitation at the air water interface (Havholm and Kocuek, 1994). Terrestrially, continental ephemeral salt lakes with periodic flooding from subsurface groundwater deposits salt precipitates such as halite, gypsum, dolomite, iron oxides, and jarosite (Benison and Bowen, 2006; Stivaletta et al., 2008).
Figure 4: Intracrater layered deposits of Becquerel Crater (21.5N 8.2W). A) Subframe of MOC2-1342; north is to the lower left rotated to display a view up the stratigraphic section. Over 750 meters in total thickness, the 400 meters shown here contains over 150 distinct couplets. Although details of individual beds that comprise these couplets are frequently obstructed by dust cover, the benched erosional expression of couplets is clear. Within this section, 16 distinct “bundles” are identified, each containing 7-14 couplets. B) Plan view of HiRISE image PSP_001546_2015, showing topographic context for A (modified from Lewis et al., 2008).
4. Data and methods

4.1. Sources of data

4.1.1. Mars Global Surveyor

Mars Global Surveyor (MGS) was launched on November 7, 1996 and inserted into Mars orbit on September 12, 1997 (Malin and Edgett, 2001), becoming the first successful US mission launched to Mars since the Viking mission in 1976. MGS was a global mapping mission that carried a suite of science instruments for studying the entire martian surface, atmosphere, and interior. After nearly a decade of discovery, MGS went silent in November 2007 after a battery failure.

The Mars Orbiter Camera (MOC), carried by MGS, produced approximately 250,000 images of the surface of Mars. Three instruments were used to produce these images: a narrow angle camera that produced, high-resolution grayscale images (typically 1.5 to 12 m per pixel) and red and blue wide angle cameras for context images (240 m per pixel) and daily global imaging (7.5 km per pixel). Images are publicly available through Malin Space Science Systems (www.msss.com) and databases such as Planetary Data Systems (PDS) and JMARS. For this study, high-resolution images from the narrow-angle lens camera were used to identify craters containing layered deposits.

The Mars Orbiter Laser Altimeter (MOLA) created the most accurate global topographic map of any planet in the solar system to date. A 1064 nm laser altimeter operating at 10 Hz transmitted infrared laser pulses towards Mars and measured the time of flight to determine the distance from the MGS spacecraft relative to martian surface. Derived elevations have an average precision of less than 40 cm in the vertical dimension (Smith et al., 2001), with horizontal resolution from hundreds of meters in equatorial regions to a few meters at the poles.
(Smith et al., 2001). For this study, gridded MOLA data retrieved from JMARS was used in the
initial construction of topographic profiles through the craters.

4.1.2. Mars Reconnaissance Orbiter

Mars Reconnaissance Orbiter (MRO), the most recent orbiter of Mars, was launched on
August 12, 2005 and reached Mars on March 10, 2006. On board MRO are three cameras, a
spectrometer, radiometer, and radar that provide data about the surface, subsurface and
atmosphere of Mars to Earth at a rate 10 times that of previous missions.

The Context Camera (CTX) provides large-scale views of the martian terrain. From 400
km above Mars, CTX takes gray scale images, 30 km wide, of terrain at a resolution of 6 m per
pixel. Currently, approximately 35% of the martian surface has been imaged with this camera.
Images are publicly available through Planetary Data Systems (PDS) and JMARS. In this study,
CTX images were used for detailed crater mapping.

The High Resolution Imaging Science Experiment (HiRISE) aboard MRO offers high-
resolution views of Mars, capable of revealing features as small as 0.25 m, with stereo image
pairs providing a vertical precision of greater than 25 cm per pixel. HiRISE images are publicly
available though Planetary Data Systems (PDS), the University of Arizona, and JMARS. In this
study, HiRISE images were used to identify details of intracrater deposits, and stereo image pairs
were used for construction of Digital Elevation Models (created by Matt Chojnaki of the
University of Tennessee in association with the United States Geological Survey in Arizona).
HiRISE DEMs were used to extract elevation data for depositional couplets at a higher resolution
than that available with MOLA (which has broader coverage, but poorer vertical and spatial
resolution, especially in equatorial regions).
4.2. Methods

4.2.1. Reconstruction of stratigraphic sections from orbital data

An extensive survey of high-resolution images (MOC, CTX, HiRISE) as well as published literature (Malin and Edgett, 2000; Edgett and Malin, 2002; Fassett and Head, 2007; Oehler et al., 2007; Chung et al., 2008) was used to identify craters within Arabia Terra that contain layered strata. Based on image coverage of both crater and layered intracrater deposits, three craters were chosen for final analysis: Becquerel Crater (8°W, 22°N), Danielson Crater (7°W, 8°N), and Unnamed Crater (Crater X; 1.2°W, 9°N).

CTX images were used to map each crater to identify distinct geologic units. Detailed geologic mapping allows determination of the broader sedimentary context of intracrater deposits. Units were distinguished based on their albedo, observed stratigraphic and structural discontinuities, and other visual differences such as erosional expression. The following units were mapped in each crater: (1) light-toned layered deposits (layers 1m-20m in thickness), (2) crater rim deposits and regional strata which the crater impacted, (3) crater floor and, (4) low-albedo, surficial dunes and/or detritus.

HiRISE DEMs of a portion of layered deposits in each crater were used to identify bedded intervals, compute dips, and determine stratigraphic thicknesses. Details of individual layers, or beds, are typically obstructed in regions with high dust cover. Benched erosional expression of strata, however, is easily recognized. Recessive/resistant couplets are commonly highlighted by the presence of secondary, low-albedo material that mantles the less indurated, lower interval of the couplet (Fig. 4).

Orientation and dip directions of recessive/resistant couplets was determined by selecting three points along the contact between a resistant interval and the overlying recessive interval.
(i.e. the top of resistant interval) and extracting three-dimensional coordinates from the DEMs. The dip corresponding to the plane was calculated using traditional 3-point problem methodology (Fig. 5). In each crater, measurements were taken of 51 intervals and average was calculated to estimate the regional dip.

Couplet thicknesses were determined using a series of geometric equations (Fig. 6). Changes in elevation ($|E|$) and pathway distance ($P$) of couplet boundaries were extracted from HiRISE DEMs. Using a combination of regional dip ($^\circ D$), elevation ($|E|$) and pathway distance ($P$), the true stratigraphic thickness ($T$) of each identifiable couplet was calculated. In flat lying strata, reconstruction of stratigraphic thickness is simple because stratigraphic position corresponds directly to elevation. In cases of dipping strata, it is necessary to correct for dip, strike, topographic slope, and topographic position.
Figure 5. Three point problem methodology for determining strike and dip of plane. A) Map view of hypothetical three sedimentary layers. Trace a distinct contact and mark three intersections of the contact with local topography (shown as red, yellow, and blue circles). B) Determine elevations of intersections (A, B, and C), as well as distances between points (AB, BC, AC). Interpolate elevation between B and AC to determine the strike. C) Transpose intersections onto cross section, to scale, of elevation perpendicular to strike. Using this, determine true dip by measuring angle.
Figure 6: Geometric determination of stratigraphic thickness (T). Distance along horizontal pathway (P) and change in elevation (E) between pathway endpoints are retrieved directly from DEMs; dip of bed (D) is calculated as a standard three-point problem; distance of ground travel along pathway (P), dip of topographic surface from horizontal pathway (α), and angle between bed dip and the topographic surface (β) are calculated geometrically. Four examples here show A) Horizontal topography with dipping beds; B) a rise in elevation over dipping beds; C) a drop in elevation less than dip of underlying beds; and D) a drop in elevation greater than dip of underlying beds.
4.2.2. Analysis of stratigraphic sections

Stratigraphic sections were used to identify potential patterns in stratal packaging. In order to identify stratigraphic patterns such as systematic changes in thickness, calculated couplet thicknesses were plotted as both a stratigraphic sections and as couplet thickness vs. distance up section. To assess relative rates of sediment accumulation, cumulative couplet thickness up-section is plotted against couplet number. Linear trends indicate uniform conditions of sedimentation, or a constant rate of sedimentation (Schwarzacher, 2000), whereas a change in slope represents a change in accumulation rate.

Visually traceable couplets were also analyzed for lateral change in thickness using a two-sample t-test, in order to assess if bed thickness varied regionally across the basin. The t-statistic is calculated using:

\[
    t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}
\]

where \( t \) is the t-statistic, \( \bar{x} \) is sample average, \( s^2 \) is sample standard deviation, and \( n \) is sample size. Using calculated t-statistic to find the p-value, statistical similarity of thickness can be assessed. Using a 95% confidence interval, where p-value is greater than 0.05, we accept the null hypothesis, \( H_0 \), which implies no statistical difference in couplet thickness between successions. If p-value is less than 0.05, we accept the alternative hypothesis \( H_a \), and implies that couplet thicknesses changes from succession-to-succession.
5. Results

5.1. Visual Description of Layers

Observed intracraterr layered deposits range in their occurrence from a single mound (Becquerel Crater; Fig. 7A) to multiple individual mounds (Crater X, Fig. 7C), to extensive covering of the crater floor and up the walls (Danielson Crater; Fig. 7B). Visual, topographic, and geographic data were retrieved from HiRISE stereo pairs and their DEMs (Table 2). In each of these craters, exposure of intracraterr strata provides clear evidence of post-depositional erosion and removal of sedimentary material. The depositional origin of this material, however, is less well understood. In each case, the crater rim is fully intact (Fig. 7), indicating aeolian transport rather than a fluvial source for sediment, and suggesting potential aqueous input via groundwater migration. In addition to light-toned, finely bedded layered deposits, dark-toned debris material composing dunes is common in all craters (Fig. 7), and represents more recent sediment deposition in the craters. Exposures within Crater X are unique in that the interior contains two discrete sedimentary packages (Fig. 7C). A lower unit consists of five discrete layers, less than 100 m in total thickness. Unconformably overlying this basal package occurs more typical, thinly bedded, light-toned layers found in the other craters.

<table>
<thead>
<tr>
<th>Location</th>
<th>Image 1</th>
<th>Image 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Becquerel</td>
<td>PSP_001546_2015</td>
<td>PSP_001955_2015</td>
</tr>
<tr>
<td>Danielson</td>
<td>PSP_002733_1880</td>
<td>PSP_002878_1880</td>
</tr>
<tr>
<td>Crater X</td>
<td>PSP_002047_1890</td>
<td>PSP_001902_1890</td>
</tr>
</tbody>
</table>
Figure 7: Contexual geomorphic map (Appendix 1) and corresponding hypothesized cross sections (vertically exaggerated) of Becquerel Crater (A), Danielson Crater (B), and Crater X (C). In each crater, mapped units are overlain on composite CTX images. Mapped units include crater rim and regional strata into which the crater impacted (yellow), light-toned layered deposits (red), lower layered deposits (purple), low albedo debris and/or dunes (green), and unknown or dust-covered units (blue), which are suspected to be exposed crater floor. In cross-section, grey represents impacted material and dashed lines represent unknown depths and relationships of units. In Becquerel Crater (A), light toned layered deposits occur in a single mound, whereas in Danielson Crater (B) and Crater X (C), they cover broad expanses of the crater floor.
Layered deposits in Becquerel Crater occur in a single mound in the southern part of the crater (Fig. 7A) and contain approximately $340.3 \text{ km}^3$ of layered strata. The mound contains up to 4 km of layered strata. The lower portion of the mound is best exposed on the northern regions and consists of alternating dark and light-toned banding that can be traced visually for distances up to 13 km (Fig. 8). Faulting and jointing, which creates vertical offset of couplets up to 20 m, are common (Fig. 8). Couplets occur in bundles (cf. Lewis et al., 2008), defined by systematic differences in topographic expression, wherein the resistant upper half-couplet is less pronounced in the lower portion of the bundles, and more pronounced in the upper portion of the bundles (Fig. 9). As many as 10 bundles can be recognized in the northern portion of the mound before the expression of layering is disrupted by a combination of irregular erosional expression and dust coverage (Fig. 8).

Distinctive bundling of couplets is not observed in Danielson Crater (Fig. 10) or Crater X (Fig. 11). In Danielson Crater, hundreds of meters of exposed strata—from the crater floor to the walls of the crater (Fig. 7B)—show stacked couplets of strikingly uniform erosional expression. Strata are exposed regionally within a low-relief intracrater surface, as well as in a series of NE-SW trending, elongate hills (Fig. 10). Common faulting, which trends NE-SW—largely parallel to hill orientation—displaces couplets up to 10 m vertically.

In Crater X, layered strata are found both covering the crater floor and up the walls of the (Fig. 7C). Well-exposed strata occur primarily in small, discrete mounds (Fig. 11). Much of the crater is obscured by substantial dust coverage, which affects exposures of strata outside of discrete mounds, thereby allowing only layers in mounds to be used to reconstruct stratigraphic columns. Similar to Danielson Crater, couplets within Crater X show strikingly similar erosional expression, with no apparent bundling (Fig. 11).
Figure 8: Portion of HiRISE stamp PSP_001546_2015 showing layered deposits in Becquerel Crater. Purple lines delineate bundles of couplets (cf. Lewis et al. 2008); red lines highlight examples of faults that offset couplets; green arrow shows stratigraphic up. Seven full bundles are exposed in this photo before the pattern is obscured by dust coverage and irregular erosional expression.
Figure 9: Close-up of a single stratal bundle in Becquerel Crater. Purple lines represent bundle boundaries; white circles represent individual couplets. Ten couplets are in the bundle here. Couplets in the lower portion of the bundle are less pronounced, and become more pronounced upsection. Note, stratigraphic up is toward the base of the picture.
Figure 10: Portion of HiRISE stamp PSP_002733_1880 showing layered strata in Danielson Crater. Green arrow shows stratigraphic up. Layered strata are exposed both along the low-relief crater floor (couplets highlighted in purple) and in elongate mounds (highlighted with blue lines). Despite different erosional expression, couplets show a strikingly uniform rhythmicity. Faulting is abundant (red), trending both NE-SW and NW-SE, offsetting couplets.
Figure 11: Portion of HiRise stamp PSP_002047_1890 showing layered strata in Crater X. Light toned, finely bedded deposits are best exposed in small mounds on the crater floor. At most, mounds contain 12 couplets, which are striking in their uniformity of erosional expression. More continuous layered strata in the eastern and northern parts of the crater are obscured by extensive dust coverage.
5.2. Dip Measurements

Dips of 51 bedding planes were calculated for each crater. Results are summarized in Table 3 (See Appendix 2 for detailed data)

Table 3: Dip measurements at each location in Arabia Terra

<table>
<thead>
<tr>
<th></th>
<th>Minimum Dip</th>
<th>Maximum Dip</th>
<th>Mean Dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Becquerel</td>
<td>0.3°</td>
<td>5.5°</td>
<td>1.5 ± 0.2°</td>
</tr>
<tr>
<td>Danielson</td>
<td>0.6°</td>
<td>26.3°</td>
<td>13.8 ± 1.1°</td>
</tr>
<tr>
<td>Crater X</td>
<td>0.0°</td>
<td>6.9°</td>
<td>1.6 ± 0.2°</td>
</tr>
</tbody>
</table>

Calculations of stratal dip show approximately sub-horizontal bedding (maximum dips <<10°) in the study regions from Becquerel Crater and Crater X (Table 3). Dips of couplets in these craters show a tight distribution, indicating that parallel bedding dominates the study region (Fig. 12). Strike and dip directions, however, are variable in both craters, which is expected with limited resolution and near horizontal dips.

Dips measured within Danielson Crater have a larger range than those observed in Becquerel or Crater X (Table 3; Fig. 13), demands that dips are not parallel through the study area dips. Regional block faulting, which appears across the Danielson Crater study area, appears to have resulted in the differential rotation of blocks. When dips are calculated across fault blocks (Fig. 13), it becomes clear that much of the variation in measured dip angles reflects rotation of fault blocks. In a small geographical region, calculations of stratal dips range from 0.1° to 10.2°, averaging 4.1 ± 0.7° SW (Fig. 13). These couplets have widely variable strikes, mostly oriented NW-SE (Fig. 13). With the limited resolution, it is expected that such low dipping strata would have variable strike directions.
Figure 12: Regional dip frequencies for Becquerel Crater, Danielson Crater and Crater X. Dips of both Becquerel Crater and Crater X are tightly clustered, indicating a predominance of parallel bedding. The dips of Danielson Crater are widely distributed, suggesting bedding is affected by post-depositional faulting and differential rotation of fault blocks.
Figure 13: Sample of dip measurements in Danielson Crater, showing average strikes and dips in different regions (Appendix 3). Dips range from $0.7^\circ$ to $10.2^\circ$. Dips corresponding with the central hill are greater than regional strata, whereas the eastern hill has similar dip to regional strata, but very different strike. Differences between regional strata and hills suggest that regional faulting has resulted in uplift and differential rotation of fault blocks as opposed to erosional differences.
5.3. Stratigraphic Measurements

A total of 424 couplets were measured for stratigraphic thickness, with results summarized in Table 4 (See Appendix 4 for detailed data). For each couplet, measurements to derive stratal thickness were taken from the top of the resistant cap to the top of the next successive resistant cap.

Table 4: Stratigraphic measurements for each location in Arabia Terra.

<table>
<thead>
<tr>
<th></th>
<th>Number of couplets</th>
<th>Total Thickness (m)</th>
<th>Range of Thickness (m)</th>
<th>Average Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BECQUEREL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 (blue)</td>
<td>51</td>
<td>230</td>
<td>1.43-8.02</td>
<td>3.76 ± 0.19</td>
</tr>
<tr>
<td>2 (green)</td>
<td>74</td>
<td>257</td>
<td>1.34-7.47</td>
<td>3.47 ± 0.16</td>
</tr>
<tr>
<td>3 (red)</td>
<td>51</td>
<td>235</td>
<td>1.42-7.85</td>
<td>3.86 ± 0.19</td>
</tr>
<tr>
<td><strong>DANIELSON</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 (yellow)</td>
<td>35</td>
<td>220</td>
<td>2.01-12.51</td>
<td>6.27 ± 0.47</td>
</tr>
<tr>
<td>2 (red)</td>
<td>53</td>
<td>404</td>
<td>1.22-19.37</td>
<td>7.63 ± 0.54</td>
</tr>
<tr>
<td>3 (green)</td>
<td>52</td>
<td>445</td>
<td>2.14-24.84</td>
<td>8.50 ± 0.59</td>
</tr>
<tr>
<td>4 (blue)</td>
<td>32</td>
<td>284</td>
<td>2.37-19.58</td>
<td>8.68 ± 0.66</td>
</tr>
<tr>
<td><strong>CRATER X</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 (red)</td>
<td>7</td>
<td>105</td>
<td>10.5-17.5</td>
<td>15.08 ± 0.88</td>
</tr>
<tr>
<td>2 (orange)</td>
<td>10</td>
<td>179</td>
<td>11.82-25.54</td>
<td>18.06 ± 1.32</td>
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<tr>
<td>3 (yellow)</td>
<td>7</td>
<td>78</td>
<td>2.49-14.71</td>
<td>11.18 ± 1.55</td>
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<tr>
<td>4 (l. green)</td>
<td>4</td>
<td>64</td>
<td>9.55-15.55</td>
<td>12.88 ± 0.98</td>
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<tr>
<td>5a (green)</td>
<td>9</td>
<td>102</td>
<td>4.62-17.72</td>
<td>11.44 ± 1.53</td>
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<tr>
<td>5b (l. blue)</td>
<td>7</td>
<td>95</td>
<td>9.31-18.61</td>
<td>13.61 ± 1.23</td>
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<tr>
<td>6 (blue)</td>
<td>7</td>
<td>83</td>
<td>3.76-18.92</td>
<td>11.89 ± 2.05</td>
</tr>
<tr>
<td>7 (purple)</td>
<td>5</td>
<td>82</td>
<td>12.54-22.67</td>
<td>16.40 ± 2.04</td>
</tr>
<tr>
<td>8 (pink)</td>
<td>6</td>
<td>76</td>
<td>6.87-16.49</td>
<td>12.59 ± 1.66</td>
</tr>
<tr>
<td>9 (teal)</td>
<td>7</td>
<td>76</td>
<td>6.60-13.74</td>
<td>10.82 ± 0.89</td>
</tr>
<tr>
<td>10 (brown)</td>
<td>7</td>
<td>63</td>
<td>4.68-15.03</td>
<td>8.97 ± 1.26</td>
</tr>
</tbody>
</table>

In Becquerel Crater, a total of three successions were measured for stratigraphic thickness (Fig. 14A). At most, only 8 bundles were measured in each individual succession (Fig. 14A), representing a maximum of 257 m (Table 4). All couplets can be visually traced between laterally adjacent successions in Becquerel Crater (Fig. 14A), allowing construction of a
composite succession of 9 couplets, representing 381.6 m of strata (Fig. 15). Over lateral
distances of ~3 km, there is little measured difference in couplet thickness (Fig. 14), which is supported by a statistical two-sample T-Test at 95% confidence interval yielding p-values of 0.07 and 0.23 for BECQ1-BECQ2 and BECQ2-BECQ3 respectively.

A total of four successions in Danielson Crater were analyzed for stratigraphic thickness (Table 4; Fig. 14B). Unlike in Becquerel Crater, successions in Danielson Crater are not laterally continuous, but rather have small regions of overlap that allow construction of a single composite stratigraphic column, 968 m in thickness (Fig. 16). Although lack of correlative beds inhibits analysis of lateral change in couplet thickness, mean thicknesses are similar in each of the individual measured sections (Table 4).

Stratigraphy was reconstructed for 11 mounds in Crater X (Fig. 14C). Substantial erosion of strata between mounds and presence of wind blown sediment between the mounds obscures correlation of strata between individual mounds (Fig. 14C). Sub-horizontal bedding, however, (Table 3) allows reconstruction of relative stratigraphic position from couplet elevation (Fig. 17). Using these geographic relationships, it is observed that mathematically correlative couplets are laterally similar in stratigraphic thickness between mounds (Fig. 17).
Figure 14: Measured successions of strata in Arabia Terra. In all three, purple lines represent traceable couplets between successions. A) Three successions were measured in Becquerel Crater: BECQ1 (blue), BECQ2 (green), and BECQ3 (red). Filled circles represent divisions between inferred bundles. BECQ1 is 1.1 km away from BECQ2, with minor faulting and disturbance occurring between them, and BECQ 2 is 1.8 km from BECQ3, with major faulting and disturbance between the two. B) Four successions were measured in Danielson Crater: DAN1 (yellow), DAN2 (red), DAN3 (green), and DAN4 (blue). Due to abundant faulting and dust coverage, many couplets cannot be traced between successions. Image is rotated 180° to display stratigraphic up. C) Eleven mounds are analyzed in Crater X: 1 (red), 3 (yellow), 4 (light green), 5A (green), 5b (light blue), 6 (blue), 7 (purple), 8 (pink), 9 (teal), and 10 (brown). Mound 2 (orange) is not pictured here, and occurs ~7 km north of the pictured region. Dark sediment occurs between mounds, obscuring direct correlation between mounds.
Figure 15: Comparison of stratigraphic sections in Becquerel Crater. Purple lines highlight bundle boundaries, and correlate these layers between adjacent bundles. Within each bundle, the same numbers of couplets are observed in each succession.
Figure 16: Comparison of stratigraphic sections in Danielson Crater. Purple lines correlate couplets between adjacent bundles, with dashed lines indicating couplets that cannot be directly correlated between successions due to dust and/or faulting. Successions do not represent laterally continuous strata, therefore we are with this diagram unable to clearly identify if correlative couplets are similar in thickness.
Figure 17: Correlation of mounds in Crater X based on elevation. Mound 1 represents the lowermost strata, and Mound 9 the uppermost. Grey solid lines represent visual correlation of couplets, whereas dotted lines suggest some possible couplet correlations based on elevation data. Correlated couplets are of similar thickness between lateral mounds.
5. 4. Half Couplet Measurements

Couplets were divided into lower and upper ‘cap’ units to measure stratigraphic thickness of half-couples; results are summarized in Table 5 (Appendix 5). As previously described, each couplet consists of a recessive and resistant interval, where the recessive interval is the lower unit, and the resistant is the upper, or cap, unit.

Table 5: Half-couplet measurements for each location in Arabia Terra.

<table>
<thead>
<tr>
<th></th>
<th>Becquerel</th>
<th>Danielson</th>
<th>Crater X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Couples measured</td>
<td>17</td>
<td>16</td>
<td>13</td>
</tr>
<tr>
<td>Lower average thickness (m)</td>
<td>2.23 ± 0.33</td>
<td>8.48 ± 0.34</td>
<td>6.70 ± 0.49</td>
</tr>
<tr>
<td>Upper average Thickness</td>
<td>1.46 ± 0.14</td>
<td>4.61 ± 0.22</td>
<td>7.21 ± 0.44</td>
</tr>
</tbody>
</table>

The upper ‘cap’ unit is, on average, thinner than the lower unit for both Becquerel and Danielson Crater (Table 5; Fig. 18). Supporting p-values <0.05 for each indicate the two units are statistically different in stratigraphic thickness. In Becquerel couplets, the upper cap units are on average 1.46 m in thickness, where the cap unit is substantially thicker, averaging 2.23 m (Fig. 18A; Table 5). With the exception of couplets that define individual bundles, the lower, recessive intervals of Becquerel couplets are all either equal to, or greater than, thicknesses of the upper cap units (Fig. 18A). Lower, recessive units in Danielson Crater show a similar trend where, with the exception of 1 couplet, all lower units are thicker than upper units for each couplet (Fig. 18B). No systematic differences in half couplets are observed up section in either crater; upper ‘cap’ units remain thinner than recessive, lower units with the exception of those defining bundles in Becquerel, where cap units are thicker or equal to thickness of the lower unit.

Half couplet measurements differ in Crater X. Couplets in two discrete layered mounds, Mound 1 and Mound 5a, reveal upper and lower units to be similar in thickness (Table 5; Fig.
18C). A two-sample T-Test with 95% Confidence Interval yields a P-Value greater than 0.48, thus acceptance of the null-hypothesis: there is no statistical difference in thickness of lower and upper units in couplets. This pattern is visually similar in all other mounds, suggesting that Crater X couplets are all similar in their construction.
Figure 18: Measured half-couplets and their stratigraphic thickness for Becquerel Crater, Danielson Crater, and Crater X. In each, blue represents the resistant, lower unit, whereas red indicates upper, recessive, cap units. Dashed lines represent average half-couplet thicknesses, and purple stars in Becquerel indicate boundaries of bundles. A) In Becquerel Crater, the upper cap units average 1.4 m in thickness, with the exception of bundles, where thickness increases to average of 2.6 m. The lower units are all greater than or approximately equal to upper unit thickness. B) A similar trend is seen in Danielson where upper units are thinner than lower units. C) Half couplet thicknesses in Crater X are similar in thickness between upper and lower units.
5.5 *Stratigraphic Trends*

Variations in couplet thickness are displayed in histograms of couplet thickness (Fig. 19). Couplet thicknesses are clustered around the mean value for both Becquerel Crater and Danielson Crater (Fig. 19). In all craters, the majority of couplet thicknesses fall within 2 standard deviations, or 95% of the mean value (Fig. 19). The distribution of couplet thicknesses for each crater is consistent with a normal distribution via a Kolmogrov-Smirnov test with 99% confidence.

Trends in stratigraphic thickness were investigated using composite stratigraphic successions for each crater. In Becquerel, Danielson, and Crater X, when couplet thicknesses are plotted up section against couplet count, a decreasing trend is observed in thicknesses up section (Fig. 20). Regression coefficients are 0.02, 0.06, and 0.16 for Becquerel, Danielson, and Crater X respectively (Fig. 20). Weak regression coefficients indicate couplet thicknesses have no dependence up section. Therefore, the overall thinning up section trend is not significant.

Couplet thicknesses vary upsection relative to the mean (Fig. 21). In Becquerel Crater, couplet deviations from the mean range from approximately -2 to 3 m relative to the mean of 3.62 m (Fig. 21A). Within bundles, both thickening and thinning up section trends are observed. In bundles 1 and 6, couplets show a thickening up section trend (Fig. 21A). In many bundles (4, 5, 7, 8), couplets are the thickest at their base, and then drop in thickness followed by a rise up section within the bundle, with thickness not reaching that of the base. In other bundles, couplets vary up section, alternating between greater than or less than the mean value.

Compared to Becquerel Crater, couplets in Danielson Crater deviate more from the mean. Deviations range from approximately -6 to 12 m relative to the mean of 7.68 m (Fig. 21B). No
observable trends are observed in couplets up section. Couplet thicknesses vary up section, alternating between greater than or less than mean value (Fig. 21B).

Similarly to Danielson Crater, couplets in Crater X deviate more from the mean than is observed in Becquerel Crater (Fig. 21). The span of range of deviations for Crater X is 12 from mean of 12.4 m (Fig. 21C). As observed in Danielson Crater, no clear stratigraphic trends are observed in Crater X (Fig. 21C). Couplets thicken from the base up section 3 couplets, then vary, clustered around the mean, before thinning up section the last 4 couplets (Fig. 21C).
Figure 19: Couplet thickness for analyzed craters in Arabia Terra. Purple solid lines indicate mean, purple dashed lines indicate median, and green lines indicate 2 standard deviations, or 95%. A) Becquerel Crater ($\mu=3.19; \text{median}=3.06; \sigma=1.27$). B) Danielson Crater ($\mu=4.45; \text{median}=3.92; \sigma=2.10$). C) Crater X ($\mu=11.71; \text{median}=12.56; \sigma=2.97$). Data is broadly normally distributed for all three craters.
Figure 20: Composite stratigraphic thicknesses for analyzed craters in Arabia Terra. No clear trend toward either couplet thickening or thinning is observed for Becquerel, Danielson, or Crater X. $R^2 = 0.02$ (Becquerel), 0.06 (Danielson), 0.16 (Crater X)
Figure 21: Deviations from mean couplet thickness ($\mu$) for analyzed craters in Arabia Terra. Black line indicates mean value. In Becquerel Crater (A) dashed grey lines and alternating color differences represent bundles, which are numbered. Thickening up section trends occur in bundles 1 and 6, and no thinning up section trends are observed. B) Danielson Crater. Thicknesses vary up section, alternating between thinner and thicker than mean value. C) Crater X. No trend is observed up section, couplet thicknesses are primarily clustered around the mean, with the upper 4 couplets thinning to the top of the succession.
5. 6. Rates of Accumulation

Data from the composite stratigraphic sections of Becquerel Crater, Danielson Crater and Crater X are used to examine relative rates of accumulation in the craters. Each couplet represents a successive step in sedimentation, as time is unknown. Following Schwarzacher (2000), cumulative curve of sediment increments can be used to relate accumulated sediment to time assuming increments along the x-axis represent equal intervals. Based on slope, Crater X has the highest relative rate of accumulation, whereas Becquerel Crater the lowest (Fig. 22; Table 6).

Table 6: Slope measurements of accumulated thickness at each location in Arabia Terra.

<table>
<thead>
<tr>
<th></th>
<th>Slopes Overall</th>
<th>Slopes Lower Unit</th>
<th>Slopes Upper Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Becquerel Crater</td>
<td>3.7</td>
<td>1.9</td>
<td>1.4</td>
</tr>
<tr>
<td>Danielson Crater</td>
<td>7.8</td>
<td>8.4</td>
<td>4.5</td>
</tr>
<tr>
<td>Crater X a</td>
<td>12.9</td>
<td>7.7</td>
<td>7.0</td>
</tr>
<tr>
<td>Crater X b</td>
<td></td>
<td>6.6</td>
<td>6.9</td>
</tr>
</tbody>
</table>

In Crater X, the slope of accumulation against couplet count produced a nearly straight line (Fig. 22). There is no noticeable change in slope up section, indicating that relative rates of sediment accumulation were stable or constant during deposition. Accumulated thicknesses alternate in cycles of shallow to steep slope up section in both Becquerel and Danielson Carter (Fig. 22), indicating recognizable change in accumulation rates for both craters.

Distinct changes in slope between bundles are observed in Becquerel Crater (Fig. 22). Within each bundle, slopes are low, and increase up section within the bundle (Fig. 22). For bundle 1 in Becquerel Crater, the slope is 2.5 over the first 6 couplets, and then increases to 4.8 (Fig. 22). This trend occurs in all couplets indicating that during deposition of a bundle,
sediment is accumulated initially at a lower rate, and transitions to relatively higher accumulation rate.

Differences in relative rate of accumulation are also observed between lower and upper units of couplets. In Becquerel Crater and Danielson Crater, the lower units show greater accumulation than upper ‘cap’ units (Fig. 23). Accumulation of the thicker recessive units, overall, in both craters, was faster than that of the thinner, capping resistant units. Little to no difference is observed between accumulation of upper and lower units in Crater X (Fig. 23), therefore accumulation of recessive and resistant units was nearly uniform.
Figure 22: A. Accumulated couplet thickness vs. couplet count for analyzed craters in Arabia Terra. Purple brackets in Becquerel indicate bundle boundaries. B. shows a magnification of trends within bundle 1 of Becquerel Crater; this pattern is repeated in each successive bundle. Slopes between the three vary, with Crater X having the highest relative accumulation rate, and Becquerel having the lowest. There are few fluctuations in the line for Crater X, indicating a continuous relative rate of sediment accumulation. For Danielson and Becquerel there are numerous fluctuations, indicating changes in amount of accumulation per couplet. Between each bundle in Becquerel, a change in slope occurs. Slope is not consistent within the bundle, seen in upper box. It starts shallow, with a slope of 2.5, and at couplet 6 the slope steepens to 4.8. This indicates that initially there is a lower amount of accumulation per couplet which transitions to a relatively higher accumulation rate upsection within the bundle.
Figure 23: Accumulation for half-couplets for Becquerel Crater, Danielson Crater, and Crater X. In each, the blue circles represent the lower, resistant unit in the couplet, and red represents upper, resistant ‘cap’ units. In Becquerel Crater (A) and Danielson Crater (B), the slopes for lower units are steeper than that of the upper unit, indicating higher rates of sediment accumulation represented by the lower half-couplet relative to the upper half-couplet. In Crater X (C), filled circles represent Mound A and open circles represent Mound B. Slopes between upper and lower units are similar in both Mound A and Mound B.
6. Interpretations and Discussion

6.1. Potential Depositional Models

With no clear sediment source for any craters, it is unknown if sediment deposited in Becquerel Crater, Danielson Crater, and Crater X results from a common source, or whether deposition occurred independently within each basin. Several modes of deposition have previously been hypothesized as occurring in the Arabia Terra region. Thinly-layered deposits within craters has lead many to suggest impact craters may represent lacustrine basins with sedimentary layers that are fluvial or subaqueous in origin (Grin and Cabrol, 1997; Malin and Edgett, 2000; Fassett and Head, 2005). A lacustrine depositional scenario is consistent with models for Eberswalde Crater (Malin and Edgett, 2003; Fassett and Head, 2005; Ponderelli et al., 2008), Holden Crater (Malin and Edgett, 2003) and Nili Fossae craters (Fassett and Head, 2005). A shallow water environment, such as a lake, would produce relatively thin, horizontal, planar layers with lateral variability dependent on lake-basin type. In an open, overfilled, fluvial-lacustrine system, deposits are closely related to river input systems, with couplet development driven predominantly by shoreline progradation and delta-channel avulsion (Bohacs et al., 2000). Alternatively, in a closed basin or underfilled, system, couplets represent rising of base-level, and individual wetting or flooding events causing pooling of water (Bohacs et al., 2000).

Aeolian deposition associated with local to regional groundwater fluctuations would be consistent with findings at the Burns Formation, Meridiani Planum, where strata analyzed by the Opportunity rover are interpreted as a wetting-upward succession recording an increase in the influence of ground and surficial fluids (Squyers et al., 2004; Grotzinger et al., 2005; McLennen et al., 2005; Beyer and Benison, 2006; Grtoxinger et al., 2006). Layered deposits at Meridiani Planum are interpreted as formed in a playa setting, where groundwater evaporation resulted in
evaporative cementation of aeolian-derived sediments (Grotzinger et al., 2005; McLennan et al., 2005; Arvidson et al., 2006; Andrews-Hanna et al., 2010). In an interdune or playa sedimentation scenario, sediments are transported and deposited dominantly by aeolian processes, such as dune migration (Grotzinger et al., 2005).

Another hypothesized depositional model for intracrater sedimentary deposition in Arabia Terra involves subaerial deposition with no apparent aqueous component, such as airfall deposition of volcanic or impact related ejecta (Beyer and McEwen, 2005; Knauth et al., 2005; Burt et al., 2008; Hynek and Phillips, 2008). Layered deposits can be formed from volcanic processes with multiple episodes of activity pulses (Fisher and Schmincke, 1984; Barley, 1993; Wohletz, 1998; Malin and Edgett, 2000; Knauth et al., 2005). On Earth, pyroclastic units with thicknesses exceeding a few centimeters are rare except within tens of kilometers of their respective source. On Mars, lower gravity and lower atmospheric pressure may cause broader deposits of fine tephra (Wilson and Head, 1994), resulting in airfall deposition that drapes over pre-existing topography and has the ability to form massive, kilometer-thick units with potentially repeated, layered beds (Knauth et al., 2005; Malin and Edgett, 2000). Airfall deposition of atmospheric impact ejecta mimics volcanic airfall and is likely to be indistinguishable from orbit. Finally, both volcanic and impact processes can result in surging density currents that sweep across the substrate, (Knauth et al., 2005). Whereas a density-surge model is capable of forming layered deposits, these deposits would be local in their distribution and would be expected to thin dramatically away from their source. Intense impact cratering, such as during the heavy bombardment, on a planet with an atmosphere and abundant substrate volatiles, could result in a great abundance of ejecta material (Burt et al., 2008; Hynek and Phillips, 2008). In both volcanic and impact airfall, however, thickness of individual
stratigraphic layers would be expected to be stochastic, unlike rhythmic deposition observed at Becquerel Crater or uniform thickness of deposits observed elsewhere.

In no cases is stochastic layering indicated by the vertical distribution of couplet thicknesses (Fig. 19, 20), therefore airfall by volcanic or impact ejecta is considered an unlikely model to describe layered strata deposited in craters of Arabia Terra. Additionally, with no recognizable fluvial networks surrounding (or deltas within) the craters analyzed for this study, we consider the possibility of a fluvial delivery for deposition to be unlikely. The most likely generation of layered strata in craters of Arabia Terra is therefore considered to be a combination of aeolian transport and deposition, with in situ mineral precipitation, within a closed-basin lacustrine and aeolian environment (Bohacs et al., 2000).

In the absence of significant tectonic loading or thermal subsidence in Arabia Terra, the depth of crater from its rim to floor represents the maximum accommodation space available for sediment fill. In Becquerel, Danielson and Crater X, maximum sediment thickness does not exceed the crater rim (Fig. 7), suggesting that sediment accumulation was confined to intracrater regions. This may not, however, always be the case. Examples of craters with intracrater sedimentary mounds that exceed the height of the crater rim (Malin and Edgett, 2000) and the occurrence of intercrater strata that successively buried both craters and crater fills (Edgett, 2005) argues that maximum accommodation space across Arabia Terra exceeded, at least episodically, crater basins. Andrews-Hanna et al. (2010) proposed a model that linked intra- and intercrater layered deposits in Arabia Terra and Meridiani Planum, and argued that accommodation space normally would have exceeded crater depths. In order for intra and intercrater deposits to result from identical depositional mechanisms, aeolian activity must have continuously redistributed sand and dust across the surface of Mars, and have been stabilized by
groundwater upwelling. Even under arid conditions inferred for the early Hesperian, such a scenario requires continual growth of a groundwater reservoir in order to transmit fluids through an increasingly thick sediment pile. In this scenario, early groundwater upwelling (and evaporative cementation of the sediment pile; cf. evaporative cementation of sediment via acidic groundwater flow at Meridiani Planum, McLennan et al., 2005) would be limited to the largest and deepest impact craters. Only once the craters were filled would the groundwater-driven playa expanded laterally over the intercrater plains. Aerially exposed deposits would be susceptible to aeolian deflation (Havholm and Kocurek, 1994), leaving behind thick intracrater deposits and isolated remnants of deposits in the form of pedestal craters or other plains-covering deposits.

If we confine discussion only to intracrater sediment accumulation, observed strata could represent either: (1) incomplete filling of accommodation space by sediment whose input alternated in such a way to produce apparent couplets, or (2) a progressive increase in base level, representing fluctuation in local or regional water table that was completely filled by available sediment input. In terms of aqueous input as determining base level, two different scenarios are possible: (1) a simple scenario with constant aqueous level from groundwater or precipitation, or (2) a more complex scenario with rising aqueous levels again from either groundwater or precipitation.

In the first scenario, a constant aqueous level defines both accommodation space and base level (Fig. 3B). Therefore, sediment input would be the primary control on stratal packaging. Either continuous or pulsed sediment input with stable accommodation space and base level would yield progressive hydrodynamic sorting from bottom to top of the succession. If input is fluvial, a strong edge-to-center gradient in grain size would result in fluctuating shorelines
(Bohacs et al, 2000; Boggs 2001). If sediment is derived via clastic transport mechanisms, deposition would need to be pulsed to produce observed couplets, otherwise a continual fill would occur. With no change in aqueous position, as more sediment is deposited, available accommodation space decreases, therefore preserving a progression of deep to shallow environments, which would be expected to both thicken and coarsen upward.

The second scenario, wherein each couplet represents a complete filling of accommodation space and production of new accommodation space, implies fluctuating base level. This scenario is consistent with the model proposed by Andrews-Hanna et al. (2010). Initially, accumulation of aeolian sediment must outpace water table rise to allow the formation of a dry aeolian sequence (Havholm and Kocurek, 1994). A rise in the water table then acts to cohesively retain aeolian sediment, and a deflation surface forms as sediment is removed down to the level of the capillary fringe of the water table. If the water table continues to rise above the depositional surface, wet interdunes and playas are developed, and fluvial/lacustrine type deposits may accumulate (Havholm and Kocurek, 1994; Bohacs et al, 2000; Boggs 2001).

Evaporation at the aqueous interface also permits mineral precipitation, which results in the formation of the more resistant, and presumably more highly cemented, upper half of the sedimentary couplet. Repeated fluctuation of the water table, or continuous upwelling with periods of enhanced aridity and mineral precipitation, then has the potential to create stacked couplets, which may grow substantially thick, even in topographically elevated regions (Havholm and Kocurke, 1994).

In all craters, the similarity in couplet structure from the bottom to top of the successions suggests that the total accommodation space in the basin was never more than what is preserved by the thickness of a single, or perhaps a bundle of, couplets. If accommodation space were
substantially greater than the amount of sediment deposited during formation of a single couplet, strata would be expected to record a clearer differentiation in couplet structure and thickness between the base and the top of the succession. In this scenario, couplets deposited near the base of the succession—under greater total accommodation space—would be expected to be thicker and to show little or no cementation, whereas couplets deposited near the top of the succession—under lesser total accommodation space—would be expected to be thinner and show a potentially much greater degree of cementation in the upper half-couplet (Jervey, 1988; Van Wagnon et al., 1988; Boggs, 2001). The absence of these features thereby demands that the aqueous interface must have continued to rise in concert with the filling of accommodation space within the crater.

At the level of this investigation, lacustrine and aeolian environments cannot readily be differentiated without observation of sedimentary structures, grain size analysis, and mineralogy. In terms of aqueous input, both scenarios require a rise of the air-water interface from either ground- or surface-water sources. The fundamental controls on lake strata are balance of accommodation space and sediment and water supply (Bohacs et al., 2000). Mixed lacustrine/aeolian environments occur on Earth, where a basin can switch from over filled to balanced filled to underfilled depending on the amount of pooled water (Lambiase, 1990; Bohacs et al., 2000). For example, the Green River Formation records deposition that is, at times, fluvial, overfilled, balanced, and underfilled (Bradley, 1964; Roehler, 1992; Bohacs et al., 1996; Bohacs et al., 2000). In addition, different lake types can also coexist in adjacent basins (Bradley, 1964). An overfilled basin occurs when the rate of sediment and water consistently exceeds accommodation. Changing climatic conditions (or tectonics) may cause the basin to become underfilled, characterized by accommodation outstripped water and sediment supply,
resulting in persistently closed basin hydrology with deposits of ephemeral lakes or brine pools
and playas interspersed with lakes (Bohacs et al., 2000).

An increasing groundwater scenario causing aeolian and lacustrine conditions would be
consistent with observations from MER-B sites (Grotzinger et al., 2005; Grotzinger et al., 2006;
Beyer and Benison, 2006). Sediment deposition fills or exceeds base level and evaporation at
the aqueous interface drives lithification of the upper sediment package, resulting in formation of
a complete depositional couplet. Each couplet, therefore, represents complete filling of
accommodation space, and deposition of successive couplets requires production of additional
accumulation space. With no active tectonic forces to cause subsidence, accommodation space
thereby must be produced due to increasing aqueous input. Therefore, layered strata likely
reflect a combination of aeolian and in situ aeolian or lacustrine deposition within a balanced
filled to underfilled environment, with sediment accumulation driven by fluctuation of an air-
water interface within a ground- or surface-water reservoir.

6. 2. Implications of a Cold, Wet Mars

A depositional model consistent with Andrews-Hanna et al. (2010) requires a progressive
rise of the air-water interface from either ground- or surface water sources. A prolonged,
progressive rise of an aqueous interface from long-term groundwater upwelling is proposed as
the outcome of a precipitation-evaporation-driven hydrologic cycle operating under warm
and arid conditions. (Andrews-Hanna et al., 2010). In this scenario, precipitation in equatorial
latitudes recharged aquifers, driving groundwater flow. Sediment infilling occurred either as
partial fill of a crater or depression until the water table ceased to rise and the flux of
groundwater to the surface terminated, or complete infill of sediment with the rising water table intersecting the surface throughout the surrounding area (Fig. 24). Evaporation of the groundwater at the sediment surface would have precipitated sulfate salts, cementing materials in place. This model thus demands continual aggradation of the aqueous surface, with parallel rise in the regional water table, in order to deposit and cement thick sedimentary successions (Fig. 24). A waning hydrologic cycle in early Hesperian would then cause precipitation and evaporation rates to decrease, dropping water table below the surface. Sedimentary deposits across Arabia Terra would therefore be left above the water table, allowing net deflation of the region (Andrews-Hanna et al., 2010).

A mechanism for sediment accumulation that requires long-term groundwater upwelling also requires surface temperatures across low to mid-latitudes to have been above freezing for long periods of time, facilitating both precipitation induced recharge of aquifers and groundwater evaporation at the surface (Andrews-Hanna et al., 2010). This model utilizes an initial mean water table depth, which lies below the surface of most of the planet. Currently, the martian water table lies at or near the surface at interiors of giant impact basins north of the dichotomy boundary (Andrews-Hanna et al., 2007), within the Valles Marineris canyon system, and across Meridiani Planum and portions of the Arabia Terra region. Because Arabia Terra lies at a topographic levels above Meridiani Planum, if a progressively rising water table is responsible for deposition and lithification of layered sedimentary outcrops, an ever increasing liquid groundwater reservoir would be necessary. As a result, the increasing groundwater volume would certainly result in widespread subaqueous conditions in the northern highlands throughout the early Hesperian.
Figure 24: Long-term groundwater upwelling model for intracrater sediment deposition (modified from Andrews-Hanna et al., 2010; not to scale). A) Aeolian sediment accumulated in crater. Water table is below crater bottom. Sediment is unconsolidated and susceptible to deflation and transport. B) Precipitation induced groundwater recharge causes water table to rise, infiltrating deposited sediment in the crater. Evaporation of groundwater at the sediment surface precipitates sulfate salts, cementing the material in place. C) Continued sediment deposition and aggradation of the sediment interface is accompanied by a parallel rise in the water table, allowing additional couplets to accumulate.
Whereas Andrews-Hanna et al. (2010) presents an intriguing mechanism for the formation of thick stratal packages, there has been much contention as to the extent to which early Mars was warm and wet (Baker et al., 1991; Phillips et al., 2001; Christenson et al., 2004). Evidence for liquid water across the most ancient terrains of Mars has perpetuated the argument that the early martain climate was substantially different than at present, capable of sustaining long-term warmer and wetter periods, if only episodically, in an Earth-like hydrological cycle (Phillips et al., 2001; Andrews-Hanna et al., 2007). Recently, an alternative scenario has been proposed by Fairen (2010), suggesting that cold, saline, and acidic solutions—which would have been stable liquids on a sub-zero surface of Mars—may have formed the basis of a hydrogeological cycle in a water-enriched, but thermally-depleted planet. In this model of a cold, wet Mars, episodic increases in surface temperature would cause ice water to melt and allow the formation of confined crustal aquifers of liquid water with primary groundwater recharge by precipitation of snow (Farien, 2010). This hydrologic cycle, proposed by Farien (2010), was plausibly active only on an early Mars, where a substantially dense atmosphere permitted the local formation of high temperatures required to trigger evaporation and snowfall. Mean surface temperatures in the order of 245-255 K have been suggested to result in the flow of 15-35% of the planetary water inventory in liquid form during the Noachian (Farien, 2009). It is proposed that surface temperatures in the Hesperian were likely higher than today, but did not rise to levels comparable to those achieved in the Noachian, thereby depleting the potential for evaporation and activity of surficial fluids and increasing retention of volatiles within the martian crust. Assuming a mean global temperature of 225-245K, only 5-15% of the surface water inventory may have been liquid in the Hesperian (Farien, 2009).
A cold, wet model for Noachian to Hesperian environments on Mars must be considered when exploring models for the origin of depositional packages. The previous warm-wet conditions implied by Andrews-Hanna et al. (2010) have numerous implications, greatest being an ever increasing groundwater reservoir. Continual upwelling of groundwater would result in wide-spread aqueous conditions in the northern hemisphere, such as an ocean. Whereas there has been substantial speculation regarding the potential for oceanic conditions on Mars y, with the crustal dichotomy representing a shoreline (Zuber et al., 2000; Perron et al., 2007; Di Achill and Hynek, 2010; Tim Parker, much earlier), these ideas remain highly controversial. Furthermore, there is no consistent agreement that early Mars was significantly warmer than present day (Farien, 2009; Farien, 2010).

A groundwater-driven accumulation of strata could occur within a predominantly frozen groundwater reservoir, envisioned for a cold, wet early Mars. In a cold, wet scenario, differential wind speed and pressure over craters would result in the production of temporary accommodation space within individual craters for deposition of aeolian sediment (Fig. 25). With even minor warming, melting of ground ice near the martian surface would occur. This active, liquid groundwater layer would percolate downward into the crater, pool within aeolian sediments, and act to stabilize these sediments. It is unlikely that melting would occur in the crater substrate, however, because aeolian sediments would have insulated the crater floor from solar heat input (Quayle et al., 2002). During these warm yet potentially arid intervals, evaporation at the aqueous interface would have driven cementation and formation of a depositional couplet. Melt water exceeding the thickness of aeolian sediment would result in short term lacustrine deposition, and any sediment deposition above this interface would have been susceptible to deflation. Cooling climate and re-freezing of the active hydrological layer
would reestablish impermeable conditions necessary to sustain deposition of another aeolian layer (Fig. 25). Subsequent warming intervals would drive establishment of another active layer, and development and accumulation of another depositional couplet.

On Earth, mixed aeolian/lacustrine environments are common in cold and arid environments, such as the McMurdo Dry Valleys, Antarctica. The dry valleys area is a polar desert with a mean annual temperature below freezing and extremely low humidity (Wharton et al., 1995). Lakes of the Antarctic dry valleys are ancient systems, with lakes in the Taylor Valley existing for at least 300,000 years and perhaps much longer (Barrett and Hambrey, 1992; Hendy, 2000). Whereas today all the dry valleys lakes are perennially ice covered, this has not always been the case. Changes in lake level have resulted from the response of the hydrological regime to both local and regional/local climate forcing (Hendy, 2000; Doran et al, 2002). In addition to highstands, sediment data from Antarctic lakes indicate that they have gone through a number of drainage events over at least the last 14,000 years, at times existing only as saline pans or playas with, at most, 1-3 m of water (Lyons et al., 1998, 1999).

On Mars, Amazonian–aged permafrost and glacial conditions have been identified by presence of geomorphic features (Head et al., 2006; Dickson et al., 2008; Fastook et al., 2008). However, it is unknown as to how far back into martian history cold climate may have occurred. Geomorphic and sedimentological evidence for liquid water flowing and ponding over the surface of the planet has led many authors to propose a warm and wet climate for Noachian-Hesperian (Pollack et al., 1987; Baker et al., 1991; Phillips et al., 2001). However, recently, Chapman et al. (2010) described two episodes of fluvial-glacial activity from Noachian-Hesperian-aged regions within Echus Chasma and Kasei Valles based on observation of glacial
eskars, ridges, and gullies. These observations support hypothesis proposed by Fraien that liquid water and ponding does not necessarily negate the presence of a cold climate (2009, 2010).
Figure 25: Ground-ice/melt model for intracrater sediment deposition. A) Aeolian sediment temporarily accumulates in crater; subsurface pore and fracture networks are ice-filled. Sediment is unconsolidated and susceptible to deflation. B) During warmer climates, melting of near-surface ground ice creates an active groundwater layer. Groundwater percolates into the crater, pooling at the sediment/ice interface. Evaporation drives mineral precipitation and sediment lithification at the aqueous interface, forming a sedimentary couplet; extraneous sediment is susceptible to deflation. C) Cooler climate caused active layer, as well as potential sediment pore fluids, to re-freeze, allowing initiation of a subsequent depositional stage.
6.3 Application of Ground-Ice/Melt Model to Stratal Packaging

A cold, wet environment with a ground-ice/melt model for couplet formation has the ability to form stratal patterns observed for Becquerel, Danielson, and Crater X. Couplet thicknesses differ among the three craters (Table 4), indicating different depositional conditions between the craters. The most pronounced difference between the craters is the quasi-periodic bundling in Becquerel Crater (Fig. 8, 9) that is not observed in either Danielson Crater (Fig 10) or Crater X (Fig. 11). Bundling in Becquerel Crater is consistent with Milankovitch forcing as suggested by Lewis et al. (2008). On Earth, cyclic forcing mechanisms occur at diurnal, annual, or orbital frequencies (House, 1995). The thickness of couplets in Becquerel Crater, averaging 3.47 m (Table 4) suggests that an annual depositional rate is unlikely; therefore orbital cyclicity provides a more reasonable deposition rate, estimated to be 100 microns per year (Lewis et al., 2008). The obliquity of Mars oscillates with a period of ~120,000 years, and is modulated on a time scale of 1.2 and 2.4 million years (Laskar et al., 2004).

The obliquity of Mars has a large effect on global climate. The tilt of the planet’s spin axis ranges over tens of degrees and can have a strong effect on climate, changing the mean annual insolation even at low latitudes by 10% or more (Lewis et al., 2008). Minor changes in regional to global climate would result from increased heat input to the martian surface. Increased heat input would potentially activate the ground-ice, allowing liquid water to flow into craters. Because saline, acidic fluids can occur at temperatures as low as 225K (Farien, 2010), such a model of orbitally driven climate change is consistent even with a model of a cold early Mars. In terms of the ground-ice/melt model presented here, warming that occurred as a result of orbital forces could cause melting and stabilization of sediment in the crater, with subsequent
evaporation resulting in cementation. Bundling of depositional packages, as observed in Becquerel crater, may thus represent waxing and waning of climatic cycles through several obliquity modulation cycles (Laskar et al., 2004; Lewis et al., 2008).

Although bundling of couplets is not identified within Danielson or Crater X, it is possible that their formation was also the result of orbital forcing driving melting ground-ice. One possibility is that differences in crater depth or crater size relative to the extent of melt during warm-periods resulted in differential preservation of an orbital signal. For example, a large and deep crater like Becquerel may have received a larger enough amount of melt-water to record even small-scale changes in climate. As a result, the sedimentary succession was capable of recording both periods and modulations of the orbital climate record. By contrast, Danielson and Crater X may have only received substantial melt-water influx during the most intense or most prolonged changes in orbital climate parameters, with remaining modulations reflected by ‘missed beats’. The potential for ‘missed beats’ in climate-sediment cycles described by “Sandler’s Rule,” which defines that even as cyclicity within stratigraphic packages may indicate cyclicity in time, the absence of cyclicity in the stratigraphic record does not necessarily indicate the absence of cyclicity in time (Schwarzacher 1975). In terrestrial depositional systems, Goldhammer et al. (1990) demonstrated the potential for ‘missed beats,’ and hypothesized that if rhythmic sedimentation in shallow marine strata of the Dolomite Alps was the product of astronomically-forced oscillation of Triassic sea level, they should expect to find evidence of these rhythms in other Triassic platform carbonates. However, the regular repetition of five-part megacycles was found to be the exception, rather than the norm in Triassic cyclic platform deposits. Goldhammer et al. (1990) termed complete five-part megacycles “Goldilocks”
megacycles, and hypothesized their formation only under conditions suitable for every fifth-order sea-level oscillation to be registered in the sedimentary record (Fig. 26).

Such “Missed beats” are typically the result of either local tectonic forcing or differences in the relative amplitudes of high-frequency sea-level oscillations (Goldhammer et al., 1990). It is therefore reasonable to apply the concept of “missed beats” to a ground-ice/melt model for intracrater sediment accumulation. On Mars, orbital forcing is of climate has been recognized in layering within current polar ice (Phillips et al., 2008), as well as in the accumulation of low-latitude ice accumulation (Fastook et al., 2008). Whereas orbital forcing may demand regional climatic change, it does not necessarily imply that each crater record the same extent of liquid influx. Development of the sedimentary package will depend, in part, on the original crater size and depth, the presence of accumulated strata within the crater, the amount of new aeolian sediment within the crater at any given time, and the position of the sedimentary substrate with respect to the ground-water table and the amount of liquid water that infiltrates the crater during periods of ground-ice melting. In turn, the extent of melt-water formation will be a function of both the extent and duration of warmer conditions, wherein greater extent of ground-ice melting will result in more extensive fluid infiltration. Ultimately, the relative positions of the aqueous and sedimentary interfaces will affect both depositional processes (e.g., lacustrine vs. playa deposition) and the degree to which evaporation at the aqueous interface affects cementation and sediment stabilization.

Differences in depositional packages amongst these craters may also potentially result from their relative age. Following arguments of progressively greater substrate age northward in Arabia Terra (Edgett, 2005), Becquerel Crater is likely to be older than both Danielson Crater and Crater X. Differences in depositional style may thus reflect either a different modulation of
the orbital parameters, or generally warmer surface temperatures earlier in the Noachian (Farien, 2010). Within Becquerel, differential cementation upward within stratal bundles of couplets likely reflects increased aridity and mineral precipitation during modulations of the orbital climate cycle, and less distinct couplets of the lower portion of the bundle may represent either decreased duration of arid cycles or increased temperature and groundwater flow that resulted in the development of poorly lithified, dominantly lacustrine couplets. In the later Noachian to Hesperian, potentially lower global temperatures (Farien, 2010) may have reduced the ability for climate modulations to result in substantial ground-ice melting. In this case, substantial active layer flow may have occurred only during the warmest periods of the orbital cycle, resulting in substantial “missed beats”.

The ground-ice/melt model presented here is consistent with the observations of stratal packaging, as well as with previous interpretations of astronomical forcing of sedimentary packages (Lewis et al., 2008), and supports the potential for mixed aeolian and lacustrine deposition on a cold, wet Mars. While we concentrate on the application of this model to intracrater layered deposits, it may also be applicable to intercrater deposition, or layered deposits that extend crater rim, following the model proposed by Andrews-Hanna et al (2010). Once craters fill with sediments, melted ground-ice, instead of percolating into the crater (Fig. 25), would potentially rise and expand laterally over the intercrater plains.
Figure 26: Preservation of orbitally-driven climate cycles in the sedimentary record. A) “Goldilocks” cyclicity occurs when subsidence rates, sedimentary input, and total accommodation space are suitable every period and modulation of an orbital cycle to be preserved in the sedimentary record by a distinct bed. B) In the theory of “Missed beats”, an identical record of orbital forcing, may not be preserved in the sedimentary record, resulting in an incomplete record of orbitally-driven climate cycles.
Figure 27: Extended ground-ice/melt model for both intracrater and intercrater sediment deposition. A-B) During warm climates, melting of near-surface ground ice creates an active groundwater layer, percolating into the crater. Evaporation drives mineral precipitation and sediment lithification at the aqueous interface, forming sedimentary couplet. Cooler climate causes active layer to refreeze, allowing initiation of next depositional stage. C) Process of A-B continues until crater fills with couplets. D) Sediment is deposited laterally over crater and intercrater plains. E) Warming occurs, possibly causing melting of near-surface ground ice. However, aeolian sediment may insulate ground ice, thereby keeping it frozen. F) Liquid ground ice causes water table to rise, expanding laterally over the intercrater plain sediments, with evaporation occurring at the liquid-atmosphere interface, cementing sediments.
6.4. Global implications

Sediment-water interaction on a cold, wet early Mars can potentially explain a wide range of the global morphological diversity that is recorded in sedimentary strata. Furthermore, geographical differences in melting of ground-ice, by either astronomically driven changes in solar input or localized heating from volcanic or extraterrestrial impact, could be reflected in a range of depositional environments from fluvial, to lacustrine, to playa, to spring mounds (Bohacs et al., 2000). A cold, wet early Mars theory is also consistent with fluid compositions inferred from sulfate-hematite deposits within Aram chaos, in the westernmost portion of Arabia Terra (Lichtenberg et al., 2009). Furthermore, a cold, volatile-rich mars subjected to periodic melting would also be consistent with formation of Chaos terranes and dramatic outflow flooding that have been inferred from morphological analysis of the martian surface (REF).

A cold, wet early Mars has substantial astrobiological implications. In order to retain long-term habitable environments, it is often considered that water on Mars must be available for extended periods of time. On Earth, however, viable microorganisms and biosignatures have been identified in Antarctic permafrost (Schaefer et al., 2000), perennially ice-covered Antarctic lakes (Priscu et al., 1998; Sattley and Madigan, 2006; Laybourn-Parry, 2009), and cold-methane springs in Arctic permafrost (Niederberger et al., 2009; Niederberger et al., 2010), suggesting that habitability is equally as plausible for a cold, wet Mars.
7. Conclusions

Different stratigraphic patterns observed in three craters in Arabia Terra confirms previous studies that sedimentation is locally forced (Malin and Edgett, 2000). However, similar geomorphic depositional styles indicate a need for a regional, if not global, depositional model. With no stochastic stratal patterns, we reject previous hypotheses that layered deposits were formed from pyroclastic airfall of volcanic or impact ejecta (Moore 1990; Hynek et al., 2003; Fassett and Head, 2007; Knauth et al., 2005; Burt et al., 2008; Hynek and Phillips, 2008). In addition, with no recognizable fluvial networks entering the craters, nor systematic differences between characteristics of couplets from base to the top of the succession, we reject the possibility of fluvial input into deep-water lakes (Edgett and Parker, 1997; Malin and Edgett, 2000; Cabrol et al., 2001; Edgett and Malin, 2002; Beyer and McEwen, 2005; Edgett, 2005). Therefore, intracratered layered strata reflect a combination of aeolian and in situ aeolian or lacustrine deposition within a closed basin, balanced filled to underfilled environment, with sediment accumulation driven by fluctuation of an air-water interface within a ground- or surface-water reservoir.

With available imagery of intracrater layers in Arabia Terra, lacustrine and aeolian environments cannot currently be differentiated. The composition and mineralogy in Arabia Terra cannot be ascertained from Mars orbit; data from the Thermal Emission Spectrometer on the Mars Global Surveyor indicates that all of Arabia Terra is significantly dusty. Even with the best resolution images currently available, sedimentary structures such as cross bedding or mud cracks that may indicate specific environment of deposition are not observed. Regardless, both aeolian and lacustrine scenarios demand a progressive rise of air-water interface from either
ground- or surface water sources in order to progressively increase accommodation space completely filled by available sediment input without the presence of tectonics.

Previously proposed depositional environment with ever increasing groundwater reservoir (Andrews-Hanna et al., 2010) has numerous implications for widespread flooding and climatic conditions. Therefore, we propose a new scenario in which groundwater-driven accumulation of strata could occur within a predominantly frozen groundwater reservoir envisioned for a cold, early Mars. Within a frozen groundwater reservoir, minor warming from astronomically driven changes in solar input melts the ground ice near the martian surface, percolating into the crater, stabilizing accumulated sediments. Evaporation at the aqueous interface would drive cementation and formation of a depositional couplet, whereas melt water exceeding aeolian sediment thickness would result in short term lacustrine deposition; therefore supporting the potential for mixed aeolian and lacustrine deposition on a cold, wet Mars. In addition, our ground-ice/melt model is consistent with previous interpretations of astronomical forcing of sedimentary packages, where absent bundling of couplets in Danielson and Crater X is the result of missed beats due to progressive decreasing temperatures through the Noachian and early Hesperian.
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Appendix 1

Explanation for Dip calculations and measurements for all craters (Attachment 2)

1. Three points of elevations (A, B, C) were determined by choosing three locations along a couplet boundary and reading elevation from HiRISE DEMs in ENVI software.

2. Line Segments AB, BC and AC were determined by measuring distances between points of elevations from HiRISE DEM in ENVI.

3. Line Segment AB’ was determined by interpolating between Elevation A and Line Segment BC.

4. Dip was calculated by transposing intersections onto cross section to scale of elevation perpendicular to strike and measuring angle.
Appendix 2

Explanation of Dip calculations and measurements for small section of Danielson Crater

(Attachment 3)

1. Three points of elevations (A, B, C) were determined by choosing three locations along a
coupel boundary and reading elevation from HiRISE DEMs in ENVI software.
2. Line Segments AB, BC and AC were determined by measuring distances between points of
elevations from HiRISE DEM in ENVI
3. Line Segment AB’ was determined by interpolating between Elevation A and Line Segment
   BC.
4. Dip was calculated by transposing intersections onto cross section to scale of elevation
   perpendicular to strike and measuring angle.
5. *Color notation refers to mapped sections denoted on Fig. 13*
Appendix 3

Explaination for Couplet stratigraphic thickness calculations and measurements for all craters

(Attachment 4)

1. Succession/Mound refers to which succession or mound within specified crater measurements refers.

2. Path refers to which part of the succession measurements refer to.

3. Distance upsection (m) provides the distance of measured point from beginning of succession, measured from HiRISE DEM in ENVI

4. E refers to elevation, which was determined by reading the elevation from HiRISE DEM in ENVI

5. Slope was calculated using the following equation:

\[ \text{slope} = \frac{\Delta E}{\Delta \text{Distance}} \]

where \( \Delta E \) is the change in elevation, and \( \Delta \text{Distance} \) is change in distance upsection.

6. \( \theta \) is the angle of the slope, calculated using the following equation:

\[ \theta = \tan^{-1}(\text{slope}) \]

7. P is the pathway distance, or distance between two points of elevation, which was determined from measuring distance between two points of elevation from HiRISE DEM in ENVI

8. \( \Delta E \) is the change in elevation over specified pathway distance (P)

9. \( |\Delta E| \) is the absolute value of \( \Delta E \)

10. H is the hypotenuse, or distance between pathway distance and \( \Delta E \), calculated using the following equation:
\[ H' = \sqrt{\Delta E^2} + P^2 \]

where \( \Delta E \) is the change in elevation and \( P \) is the pathway distance.

11. \( \alpha \) is dip of topographic surface from horizontal pathway, calculated using the following equation:

\[ \alpha = \tan\left(\frac{|\Delta E|}{P}\right) \]

where \( \Delta E \) is the change in elevation and \( P \) is the pathway distance.

12. \( D \) is the angle of regional dip, previously calculated using traditional three point problem methodologies (Appendix 1)

13. Scenario denotes the relationship between elevation and dip, where no change indicates a horizontal topography with dipping beds, rise indicates a rise in elevation over dipping beds, and drop indicates a drop in elevation less than dip of underlying beds.

14. \( \beta \) is angle between bed dip and the topographic surface, calculated using the following equations, which differ depending on relationship between elevation and dip:

\[ \beta_{\text{rise}} = \alpha + D \]
\[ \beta_{\text{dip}} = D - \alpha \]

where \( \alpha \) is dip of topographic surface from horizontal pathway, and \( D \) is dip.

15. \( T \) is the true stratigraphic thickness of a couplet, calculated using the following equations, which differ depending on relationship between elevation and dip:

\[ T_{\text{no change}} = P \times \sin D \]
\[ T_{\text{rise}} = H \times \sin \beta \]
\[ T_{\text{dip}} = H \times \sin \beta \]

where \( P \) is pathway distance, \( D \) is dip, and \( H \) is hypothenuse.
Appendix 4

Explanation for Half couplet stratigraphic thickness calculations and measurements for all craters

(Attachment 5)

1. Distance upsection (m) provides the distance of measured point from beginning of succession, measured from HiRISE DEM in ENVI.

2. E refers to elevation, which was determined by reading the elevation from HiRISE DEM in ENVI.

3. Slope was calculated using the following equation:

\[
\text{slope} = \frac{\Delta E}{\Delta \text{Distance}}
\]

where \(\Delta E\) is the change in elevation, and \(\Delta \text{Distance}\) is change in distance upsection.

4. \(\theta\) is the angle of the slope, calculated using the following equation:

\[
\theta = \tan^{-1}(\text{slope})
\]

5. P is the pathway distance, or distance between two points of elevation, which was determined from measuring distance between two points of elevation from HiRISE DEM in ENVI.

6. \(\Delta E\) is the change in elevation over specified pathway distance (P).

7. \(|\Delta E|\) is the absolute value of \(\Delta E\).

8. H is the hypotenuse, or distance between pathway distance and \(\Delta E\), calculated using the following equation:

\[
H' = \sqrt{|\Delta E|^2 + P^2}
\]

where \(\Delta E\) is the change in elevation and P is the pathway distance.
9. $\alpha$ is dip of topographic surface from horizontal pathway, calculated using the following equation:

$$\alpha = \tan^{-1}\left(\frac{|\Delta E|}{P}\right)$$

where $\Delta E$ is the change in elevation and $P$ is the pathway distance.

10. $D$ is the angle of regional dip, previously calculated using traditional three point problem methodologies (Appendix 1)

11. Scenario denotes the relationship between elevation and dip, where no change indicates a horizontal topography with dipping beds, rise indicates a rise in elevation over dipping beds, and drop indicates a drop in elevation less than dip of underlying beds.

12. $\beta$ is angle between bed dip and the topographic surface, calculated using the following equations, which differ depending on relationship between elevation and dip:

$$\beta_{\text{rise}} = \alpha + D$$
$$\beta_{\text{dip}} = D - \alpha$$

where $\alpha$ is dip of topographic surface from horizontal pathway, and $D$ is dip.

13. $T$ is the true stratigraphic thickness of a couplet, calculated using the following equations, which differ depending on relationship between elevation and dip:

$$T_{\text{nochange}} = P \times \sin D$$
$$T_{\text{rise}} = H \times \sin \beta$$
$$T_{\text{dip}} = H \times \sin \beta$$

where $P$ is pathway distance, $D$ is dip, and $H$ is hypothenuse.

14. Upper/Lower refers to if the measurement is for the upper portion of a couplet, or the lower.
VITA

Sarah Beth Cadieux was born in New Haven, CT, to the parents of Peggy O’Malley and Douglas Cadieux. She is the eldest of two children, with a younger brother Theodore. She attended Bristol Elementary School and Newfound Memorial Middle School in Bristol, NH and continued to Concord Senior High School in Concord, NH. After graduation in 2004, she began college at Mount Holyoke College in South Hadley, MA where she was first introduced to Geology. At Mount Holyoke, Sarah studied abroad at the University of Otago in Dunedin, New Zealand, and spent a January session in the Bahamas studying Carbonate Sedimentology. Over the summer of 2007, she conducted her first independent research project with Dr. Alan Warner on Paleolimnology of Lake Wyola in Shutesbury, MA. After, she conducted her senior thesis with Dr. Bosiljka Glumac of Smith College, entitled “Carbon-Isotope Stratigraphy of Upper Cretaceous Deposits of the Dalmatian Island of Brac, Croatia”. Sarah obtained her Bachelors of Arts degree from Mount Holyoke in June of 2008 in Geology and Biogeochemistry. She accepted a National Science Foundation GK-12 fellowship at the University of Tennessee, Knoxville in the Department of Earth and Planetary Science in Fall 2008. Sarah graduated with a Masters of Science degree in Geology in May 2011. She is continuing her education with a Doctorates of Geology at Indiana University in Bloomington IN, focused on Biogeochemistry and Astrobiology.