ABSTRACT: The last decade of Mars exploration produced a series of discoveries that provide compelling evidence for the existence of sedimentary rocks on Mars. Previously, Mars was regarded principally as a volcanic planet, the dominant surface processes of which were eruption of lavas and pyroclastic deposits, although early studies did recognize valley networks, enormous outflow channels, and the required transport of sedimentary materials to the northern plains of Mars. In contrast, our new view of Mars shows a rich history of interactions between water and the surface, with weathering, transport, and deposition of sediments by water as well as eolian processes. Surprisingly thick accumulations of stratified rocks extend back into the Noachian Era—the oldest of which were likely formed over 4 billion years ago, making these rocks much older than any sedimentary rocks preserved on Earth.

Some sedimentary rocks were formed and deposited locally, whereas others accumulated as vast sheets that can be correlated for hundreds of kilometers or farther. Local deposits were formed in alluvial fan, deltaic, sublacustrine fan, and lacustrine environments in addition to deposits that fill canyons and valleys possibly carved during catastrophic floods. These former deposits indicate more gradual erosion and sedimentation, perhaps even involving meteoric precipitation, and they provide support for the notion of element conditions on early Mars. In contrast, rapid erosion and sedimentation may have occurred within large, regional outflow channels thought to have resulted from outbursts of groundwater. Regionally extensive sedimentary deposits have less obvious origins, but the presence of hydrated sulfate minerals indicates that some of these deposits may have formed as lacustrine evaporites, particularly in the Valles Marineris network of open and closed basins. Others may have involved eolian reworking of previously deposited sulfates, or perhaps aqueous (groundwater) alteration of previously deposited basaltic sediments. Another major type of regionally extensive sedimentary deposit occurs as meter-scale stratification with highly rhythmic organization. These deposits occur in several places in the Arabia Terra region of Mars and are also observed at the top of a 5-km-thick stratigraphic section in Gale Crater. The significant lateral continuity of relatively thin beds, their distribution over broadly defined highs as well as lows, and the lack of strong spectral absorption features indicate that these rocks may be duststones, formed by weak lithification of fine particles that settled from the Martian atmosphere. The most ancient sedimentary deposits on Mars may be dominated by stacked, impact-generated debris sheets, similar to those seen on the Moon, and may include impact melts.

In the absence of plate tectonics, it appears that the flux of sediment on Mars has declined over time. Early on, primary sediments may have consisted mainly of impact- and volcanic-generated particles that would have been transported by fluvial and eolian processes. Chemical weathering of fragmented bedrock in the presence of circum-neutral pH fluids would have generated clay minerals and carbonates, though the latter are surprisingly rare; weathering under more acidic conditions generated dissolved salts that precipitated as sulfates, halides, and oxides. With time, Mars is regarded to have evolved from a rather wet planet, in which chemical weathering by circum-neutral pH fluids was common, to a regime in which more acidic chemical weathering took place and, eventually, to a cold, dry environment dominated by physical weathering. As the flux of impactors and volcanism declined, and as the planet's hydrologic cycle decreased in vigor, the formation of sedimentary rocks also declined. Today the Martian highlands appear to be in a net state of erosion, and outcrops of sedimentary rocks are exposed as a result of wind-driven denudation. This erosion is likely balanced by deposition of sediments in the Martian lowlands.

Orbiter observations of depositional framework, bed-scale textural/morphologic attributes, and mineralogy provide the basis for an "orbital facies" classification scheme. Orbital facies include Massive Breccia (MBR); Complexly Stratified Clay (CSC); Laterally Continuous Sulfate (LCS); Laterally Continuous Heterolithic (LCH); Distributary Network (DNW); and Rhythmite (RHY). These orbital facies are observed in several key reference sections, and their succession allows for correlation between widely separated regions of Mars, leading to a more refined understanding of environmental history. The oldest terrains on Mars are dominated by MBR and CSC facies, whereas younger terrains are characterized by LCS, DNW, and RHY facies. However, some occurrences of clay-bearing DNW and LCH facies may be contemporaneous with large sulfate deposits of the LCS facies, which are typically regarded as Hesperian in age. This indicates that the climatic evolution of Mars may be more complex than a simple global alkaline–acidic transition and that important regional variations in aqueous geochemistry and the relative roles of surface waters and groundwaters may be preserved in the Martian sedimentary record.

KEY WORDS: Mars, sedimentology, stratigraphy, facies
INTRODUCTION

The previous decade witnessed several milestones in the history of sedimentary geology. In the year 2000, the first high-resolution image-based evidence for the occurrence of sedimentary rocks on Mars was published (Malin and Edgett 2000), and in 2004 the Opportunity rover provided in situ confirmation of their existence (Squyres 2004). The discipline of extraterrestrial sedimentary geology was revitalized and is now undergoing significant growth, not just as a result of discoveries on Mars, but also as a result of the discovery of Saturn’s extraordinary moon Titan (Hayes et al. 2008, Rubin and Hesp 2009).

The uninterrupted exploration of Mars over the past ~15 years has dramatically unveiled the rich record of sedimentary rocks on Mars at increasing levels of resolution (Fig. 1). Beginning with the Mars Orbiter Camera (MOC) on the Mars Global Surveyor (MGS) orbiter, sedimentary rocks were discovered to be widespread on the red planet. The MOC camera provided images with a resolution of about 1.5 to 12 m/pixel and showed clear evidence for sand dunes, alluvial fans, deltas, and vast “layered terrains” with strata covering hundreds to thousands of kilometers (Malin et al. 2010). Following MOC, the High Resolution Imaging Science Experiment (HiRISE) camera on the Mars Reconnaissance Orbiter (MRO) spacecraft has provided a dramatic increase in spatial resolution and currently images Mars at a stunning scale of about 25 cm/pixel, including three-channel false color (McEwen et al. 2010).

The HiRISE camera provides detail of the surface of Mars that is unparalleled even for parts of Earth, and the data are good enough to show, for example, that some sand dunes—previously thought to be relict and immobile—exhibit evidence of movement when imaged sequentially from year to year (Bridges et al. 2010). The MRO spacecraft also hosts the Context Camera (CTX), which images the surface at a lower spatial resolution of ~2.3 m/pixel. More recently, the High Resolution Imaging Science Experiment (HiRISE) camera on the Mars Reconnaissance Orbiter (MRO) spacecraft has provided a dramatic increase in spatial resolution and currently images Mars at a stunning scale of about 25 cm/pixel, including three-channel false color (McEwen et al. 2010).

The HiRISE camera provides detail of the surface of Mars that is unparalleled even for parts of Earth, and the data are good enough to show, for example, that some sand dunes—previously thought to be relict and immobile—exhibit evidence of movement when imaged sequentially from year to year (Bridges et al. 2010). The MRO spacecraft also hosts the Context Camera (CTX), which images the surface at a lower spatial resolution of ~2.3 m/pixel. More recently, the High Resolution Imaging Science Experiment (HiRISE) camera on the Mars Reconnaissance Orbiter (MRO) spacecraft has provided a dramatic increase in spatial resolution and currently images Mars at a stunning scale of about 25 cm/pixel, including three-channel false color (McEwen et al. 2010).

The combination of extremely high-resolution HiRISE images with the moderate-resolution (but greater coverage) CTX images has been revolutionary in allowing detailed, local observations to be properly placed in their regional context.

The MOC, HRSC, CTX, and HiRISE cameras provide a wealth of data of interest to sedimentary geologists, and it would be possible to fill a volume with descriptions of just the surficial deposits formed during the most recent phases of Martian history. Indeed, there has been much attention given to these younger deposits, particularly those of eolian origin. Therefore, it is the goal of this special publication to more specifically examine the record of the ancient sedimentary rocks of Mars. Orbiter-based visible, near-infrared, and thermal infrared spectral data and ground-based rover data provide information on the composition and petrogensis of these ancient sedimentary rocks as well as information on their physical textures and spatial distribution. Integration of all available data sets indicates a new view of the environmental evolution of Mars that goes beyond the limited paradigm of cold/dry vs. warm/wet. Mineralogical inferences based on visible–near-infrared reflectance data hypothesize a time-dependent evolution from an early environment conducive to formation and deposition of clay-rich deposits, to a younger environment conducive to formation of sulfate-rich sediments, to even-younger strata that generally lack hydrous minerals and that may be dominated by finely ground unaltered basalt and anhydrous Fe–oxides (Bibring et al. 2006). For the first time, we have evidence for a diverse sedimentary record that likely spans billions of years of history and evidence that proxies of environmental change are embedded within this record.

The view that global records of stratigraphy and mineralogy combine to inform evaluation of local processes is now a major driver in selection of landing sites for next-generation rovers (Grotzinger 2009, Grant et al. 2011). Sedimentary geology has rapidly become an important tool for understanding Mars, particularly where understanding past surface processes, habitability, and potential for preservation of organics is important.

In many respects, these alien sedimentary rocks seem very Earth-like: they show a variety of styles and thicknesses of bedding; they exhibit simple to complex stratigraphic geometries; they show patterns of variability that relate to depositional position within basins, in which source-to-sink transport pathways can be traced; in some places they form thicknesses that exceed 5 km; they have expressions that indicate deposition from mass-flow, traction, and suspension transport; and they bear evidence of complex diagenetic histories. Even cyclic or quasi-periodic meter-scale deposits are present. But for all of these visual similarities, there are also aspects of the Martian sedimentary record that are very different from those of Earth. These differences include the lack of evidence for deposition within subsiding basins; the abundance of sulfate deposits not associated with carbonates; deposits of likely wind-blown dust that vastly exceed in scale anything known from Earth; the potential for preservation of very old strata formed primarily by impact-related processes; and the possible dominance of strata formed of eolian rather than subaqueous origin, opposite to what we see on Earth. One remarkable observation is that the oldest strata on Mars are likely older than the oldest rocks on Earth. This last point is important, as it serves as a constant reminder that Mars is not Earth, its history has been different, and there may be sedimentary rock types, facies, and processes on Mars for which the Earth provides no suitable analog. Though we should be guided by our knowledge gained from the study of Earth, we must take care to not impose our terrestrial biases too strongly on the interpretation of Mars, lest we obscure a novel perspective.

In the middle of the last century, the Precambrian record was viewed as a frontier of sedimentary geology. Compared to Phanerozoic Earth history, our understanding of Precambrian Earth history was greatly limited as a result of our access to only the coarsest age constraints, the absence of fossils for use in correlation, poor preservation of strata due to deformation, and restriction of outcrops to outliers lacking regional context. It is hard to not see the sedimentary rock record of Mars in a similar light today, although admittedly through an even darker lens. The original locations of the few meteorite samples we have from Mars are unknown, and it is not possible for us to walk the outcrops; but the planet is mapped at a scale of which we can be envious even on Earth, and the absence of plate tectonics has resulted in minimal deformation and metamorphism of strata. The obvious differences between...
FIG. 1.—Images of layers in Juventae Chasma showing changes in orbiter camera resolution from the Viking orbiters (mid-1970s) to the HiRISE camera (mid-2000s). Development of the MOC represents a milestone in that its resolution was fine enough that sedimentary deposits were finally obvious. Most stratification on Mars is revealed at this scale of 3 to 6 m, although HiRISE images reveal further detail at scales of 25 cm/pixel. (A) Viking MDIM (~200 m/pixel); (B) THEMIS daytime infrared mosaic (100 m/pixel); (C) MOC Narrow Angle (~3 m/pixel); (D) HiRISE (25 cm/pixel); (E) MOC NA E0202546 (4.33 m/pixel). Subset box in (C) corresponds to this image. (F) HiRISE ESP_020470_1755 (25 cm/pixel). Subset box in (D) corresponds to this image.
exploring Mars and the Precambrian Earth notwithstanding, it is hard
to not feel a great sense of excitement in studying the data returned
from Mars orbiters and rovers. Intriguingly, we may have much to learn
about geologic processes during the most ancient times on Earth by
studying our neighbor, Mars. Each new set of observations promises
fresh insight into an extraordinary time in the evolution of our solar
system, when Earth and Mars set on different courses in the evolution
of surface environments of terrestrial planets.

This volume comprises a set of articles that chronicle some of these
events in the evolution of Mars. The articles presented here illustrate
Martian sedimentary processes, including weathering, sediment
transport, and deposition. Other articles describe potential terrestrial
analogues, including consideration of microbial habitats. A third group of
articles develop the case for unique Martian processes that lack clear
analogues—modern or ancient. Finally, an atlas of HiRISE images has been
prepared that provides the reader with a sense of what can be observed from orbit—a representative subset of potential study
areas, very few of which have been examined in detail.

HISTORY OF DISCOVERY

The first suggestion that Mars may have a sedimentary record was
provided by Carpenter (1948). He acknowledged the role of wind on
Mars and suggested that the smoother surface of Mars (as compared to
that of the Earth’s moon) might well result from abrasion of topography
by the sediment-laden wind, acting over millions of years. Interestingly,
he did not expect that such a process would directly contribute to the
accumulation of compacted sediments to form rocks because of the
suggested absence of water.

In the 1970s, images of the Valles Marineris canyon system from the
Mariner 9 and Viking orbiters provided the first strong indication that
layered rocks, possibly sedimentary, could be present on Mars.
Furthermore, it was recognized that such materials could provide
windows into past surface environments (Blasius et al. 1977, Malin
1979, Lucchitta and Ferguson 1983, Nedell et al. 1987, McKay and
Nedell 1988, Goldspiel and Squirey 1991, Komatsu et al. 1993,
Williams and Zimbelman 1994, Forsythe and Zimbelman 1995),
including those that might be habitable for microbes (McKay and
Stoker 1989). What were less clear were the texture and composition of
sediments that might compose these layers. Different workers
interpreted the layered terrains of Mars—in and beyond Valles
Marineris—in various ways, with ideas spanning from the more
common suggestion of volcanic ignimbrites (Scott and Tanaka 1982)
or volcanic tephra (e.g., Chapman and Tanaka 2002) offset by more
provocative ideas, including lacustrine deposits (Lucchitta and
Ferguson 1983, Williams and Zimbelman 1994, Cabrol and Grin
2001) or even carbonates (McKay and Nedell 1988). More recently,
astrobiologists pointed out the potential for sedimentary rocks to exist
on Mars, though no unambiguous examples were identified (Farmer
and Des Marais 1999). Despite the limited data and clear indications
for extensive volcanism on Mars, members of the terrestrial
sedimentary geology community held the hope that sedimentary rocks
were present on Mars and emphasized the need to search for Mars-
derived sandstone meteorites (Ashley and Delaney 1999).

Before and following the arrival of the MGS orbiter, an important
discussion regarding the Martian layered terrains centered on
interpretation of hardness, and therefore their degree of lithification.
In many cases, cliffs of layered materials can be seen weathering
without producing talus, an observation first made by Malin (1976,
1979). This tended to discount a volcanic origin of the layers as stacked
lavas or ignimbrites, though poorly consolidated tephra remained a
possibility. This was further supported by MGS Thermal Emission
Spectrometer (TES) data, which indicated that certain types of layered
terrains were characterized by relatively low thermal inertia, suggestive
of poorly lithified materials. One particular outcrop, known as “White
Rock” and located in Pollack Crater, has attracted much attention as a
result of this property (compare McCalley [1974], Thomas [1984], and
Ruff et al. [2001]). In contrast, basalts and most other volcanic or
pervasively lithified materials would be expected to exhibit relatively
high thermal inertia (Christensen et al. 2001, Putzig et al. 2005).
Finally, in many cases these layered deposits were observed to be light-
toned, often being described as “white” as a result of their appearance
in grayscale images (Williams and Zimbelman 1994), further
reinforcing the possibility of sediments and/or sedimentary rocks on
Mars. In some instances these light-toned layered deposits were
interpreted as lacustrine deposits (Forsythe and Zimbelman 1995).
It was clear at that time that Mars had a distinctive record of layered
materials that was not easily interpreted as lava flows, as had been the
case on the Moon (Head 1982). Estimates of the physical properties
of these deposits, such as thermal inertia, were important in making
the case that these layered materials were likely sedimentary rocks (e.g.,
Christensen et al. 2003), and this point is examined further below.

The Mariner 9 and Viking orbiters are credited with the observation
of deep channels incised into bedrock, accepted by many to have been
formed during catastrophic discharge of subsurface groundwater.
In addition to these large “outflow channels” (e.g., Sharp and Malin
1975), other more highly branched networks with greater saturation
densities, referred to as “valley networks,” were also observed in those
early images (e.g., Carr 1996). The apparent densities of these valley
networks are even more pronounced in later MOC and recent HiRISE
data, and some have been interpreted to represent periods of meteoric
precipitation (e.g., Hynek and Phillips 2003, Mangold et al. 2004,
Barnhart et al. 2009). During the Mariner 9–Viking era, much
emphasis was placed on outflow channels and valley networks, though
some authors did provide evidence for sediment-bearing polar ice
deposits (Cutts 1973). Over the past decade, strong evidence has been
provided for the existence of ancient “source-to-sink” networks, in
which drainage networks that cut into bedrock can be traced down
topographic gradients to fewer numbered or even single channels, and
then further downslope into sedimentary deposits represented by
terminal distributary networks, including alluvial fans (Moore and
Howard 2005), deltas (Wood 2006), and even sublacustrine fans (Metz
et al. 2009a).

The observation of distributary networks from orbit, and the logical
inference that they form sediments and/or sedimentary rocks of fluvial
origin, has been relatively straightforward, and there is strong
consensus for this process. This is also true for liquid water as the
transport medium of choice (but see Hoffman [2000] for a different
view). In contrast, the case for a sedimentary origin of the vast layered
terrains that are not obviously related to any eolian, fluvial, or other
aquaese processes has been more difficult. Initial studies (Malin and
Edgett 2000, Edgett and Malin 2002) emphasized regional stratigraphy
more than petrogenesis, and a compelling case was made that these
layered deposits were younger than the rocks of the older, more
extensively cratered southern highlands.1 Evidence was found in key
locations that showed the physical onlap of these younger strata on
older bedrock. Furthermore, the recognition that these sediments
accumulate over a substantial interval of time was provided through
the identification of craters that were once buried but that are now
being exhumed and exposed at the surface. The significance of this
discovery cannot be underestimated in that it indicates that Mars, in the
absence of plate tectonics, still has a rock cycle: older rocks are
exposed to weathering, erosion, and transport as sediments that
accumulate to some considerable thickness (kilometers in places), but
which are then subjected to erosion themselves and reworked to form a
second generation of sediments. However, whereas the extent of these
processes distinguishes Mars from the Moon, they still fall short of

Studies by Malin and Edgett also indicate the possibility that the ancient cratered
terrains, or older bedrock, may be composed of stratified rocks in some cases.
providing an easy comparison to the tectonically driven rock cycle of Earth.

The composition of inferred sedimentary rocks on Mars was often assumed to be basaltic, likely involving little chemical weathering. This interpretation, which prevailed until the middle of the past decade, arose primarily because of the absence of clear spectroscopic data indicative of weathering by-products, such as carbonates and clay minerals (e.g., Christensen et al. 2001). Some evidence for chemical weathering was provided by the observation of sulfur enrichment in the soils observed by the Viking landers, the Sojourner rover, and the few locations of hematite enrichment observed by the TES instrument. In addition, studies of the Martian meteorites indicate a relatively low degree of weathering in subsurface environments on Mars that has produced clays, carbonates, sulfates, and halides (Velbel, this volume).

The arrival of the Opportunity rover at the surface of Meridiani Planum in 2004 dramatically changed this view. After 7 years of observations it is now clear that on the order of 10 to 20 m of rocks composed of windblown sulfate–silicate sands existed in this region, reworked rarely by sulfate-rich stream flows, and that they have been subjected to salt-rich diagenetic fluids during burial. Contemporaneous with these discoveries, the Mars Express orbiter was returning a wealth of data in 2004. In addition to high-resolution images acquired by HRSC, the visible–near-infrared Observatoire pour la Minéralogie, l’Eau, les Glaces et l’Activité (OMEGA) spectrometer began to map the Martian surface at high spectral resolution and revealed the widespread presence of clay minerals and sulfate salts in the ancient crust (Bibring et al. 2005, Gendrin et al. 2005, Poulet et al. 2005). Together, these orbital and in situ measurements have revolutionized the way we view water–rock interactions on Mars. The initial findings of the OMEGA instrument have since been confirmed by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument on the MRO, which has provided a significant improvement in spatial resolution (Murchie et al. 2007). Just as the number of hydrous minerals detected on Mars continues to increase (e.g., Mustard et al. 2008), so too does the evidence for the formation and preservation of sedimentary rocks formed in a variety of possible depositional environments.

**DISTRIBUTION OF SEDIMENTARY ROCKS ON MARS**

**Geologic Timescale**

In considering the distribution of sedimentary rocks on Mars it is important to review how age constraints are achieved. The geologic timescale for Mars is based entirely on the density distribution of impact craters, which in very broad terms constrains the age of geomorphic surfaces (e.g., Hartmann and Neukum 2001). With the exception of the Martian meteorites, rocks, per se, cannot be directly dated; the ages of Martian rocks are inferred from the ages of surfaces that expose rocks of all types. The older the surface, the greater the frequency of craters in general and the frequency of larger craters in particular.

A relative timescale based on crater density distribution is converted into an absolute timescale via comparison to the surface of the Moon (Binder 1966, Hartmann 1966, Öpik 1966, Ivanov 2001). Lunar crater density distributions for different terrains were known to vary in relative age (e.g., lowlands vs. highlands), and some of these different surfaces were sampled by Apollo astronauts who returned rocks to Earth for geochronometric calibration. Once dated, the rocks provided a constraint on the maximum age of the surface from which they were sampled. A first-order approach would be to apply the impact density distributions calibrated for the Moon to Mars, accounting for the flux of bolides to Mars and the influence of higher gravity on crater excavation diameters (smaller bolides produce larger impact craters on the Moon; Ivanov 2001). In addition, Mars differs significantly from the Moon in that it has an atmosphere, and in the very ancient past this atmosphere may have been more substantial. Driven by the dynamics of the atmosphere, surface processes that cause erosion and sedimentation (e.g., eolian, fluvial) will all tend to degrade craters through erosion of their uplifted margins and infilling of their interiors. In this manner, the distribution of craters on surfaces will become modified, and relative to the Moon, some surfaces on Mars may appear younger than their true age (Hartmann and Neukum 2001). In some cases sediment accumulation rates may have been high enough that craters became fully buried, giving rise to the important concept of a "cratered volume" rather than a "cratered surface" (Malin and Edgett 2000, Edgett and Malin 2002). To obtain the correct age for the corresponding surface one would need to sum all the craters in the sedimentary succession for a given area. Therefore, crater counts of surfaces may instead reflect exposure ages or crater retention ages rather than absolute depositional ages.

With these caveats in mind, a geologic timescale for Mars has been erected and is used on a routine basis for discussion of the ages of rocks and terrains on Mars. The three principal subdivisions are known as the Noachian (4.5–3.6 Ga), Hesperian (3.6–2.6 Ga), and Amazonian (2.6 Ga–present) eras, for which the Noachian–Hesperian boundary has uncertainties of ≥0.1 Gyr and the Hesperian–Amazonian boundary has uncertainties of ±0.6 Gyr (Tanaka and Hartmann 2008). In recent years, global mineralogical mapping from orbit has been interpreted to indicate an evolution in weathering and production of hydrated minerals with stages that roughly correspond to the three principal subdivisions mentioned above (Fig. 2) (Bibring et al. 2006). The Noachian Era appears to have been marked by circum-neutral pH aqueous alteration that generated clay minerals; the Hesperian Era witnessed generation of sulfates, some under apparently acidic conditions; and the Amazonian Era was dominated by formation of anhydrous ferric oxides in a slow superficial weathering regime without liquid water (Bibring et al. 2006, McLennan and Grotzinger 2008, Murchie et al. 2009b).

**Global Distribution**

As a first pass it is useful to examine the global distribution of inferred sedimentary rocks on Mars. In general, most strata inferred to be of sedimentary origin (i.e., not including polar ice or lava plains) are restricted to more equatorial latitudes, residing between 50°N and 50°S. The global distribution of Martian sedimentary strata is shown in Figure 3. All of the localities discussed in this article are shown in Figure 4.

Figure 3 was constructed by compiling observations from MOC,
Fig. 3.—Distribution of inferred sedimentary rocks on Mars plotted on a Mars Orbiter Laser Altimeter (MOLA) elevation map. White dots correspond to stratified deposits observed in HiRISE images. Black dots correspond to MOC images with words such as “light-toned” or “layered” deposits in the formal image description tag. Note the concentration of stratified rocks in the walls of major canyon systems such as Valles Marineris (high concentration of dots in center–left part of image) as well as in Sinus Meridiani (~0°E, 0°N).

Fig. 4.—Reference map showing important localities discussed in this article. Base map is MOLA topography. Note the strong contrast in elevation between the northern lowlands and the more ancient southern highlands. Black arrow shows downslope transport direction within ULM fluvial system.
CTX, and HiRISE data sets, building on earlier efforts based only on MOC data. However, even this current effort is limited to a small fraction of the available data, consisting of examination of 7016 HiRISE images, of which 2045 images exhibit possible sedimentary strata (white circles in Fig. 3). A first pass was made to search for bedrock; all images that contained bedrock were then examined for stratification; then, if stratified, an attempt was made to distinguish if the rocks are volcanic lava flows or sedimentary, including possible pyroclastic volcanic deposits. In addition to the examination of HiRISE data, the MOC image database was searched for images whose description tag contained words such as “layered terrain,” “layers,” “strata,” or “light-toned deposits,” with the thought that many of these images may contain sedimentary strata (black circles in Fig. 3), although visual inspection of each image is still required for confirmation. Here, 1388 potential sedimentary rock targets were identified.

Our initial work (and that of Malin et al. [2010], their fig. 16) indicates that the stratified deposits of Mars are located globally, although many are found in mid-equatorial regions (Fig. 3). We note that the apparent paucity of clearly stratified deposits in the mid- to high-latitude regions of Mars may be a result of overprinting and obscuration by ice-related processes known to occur in these regions under current climate conditions. Airfall deposition of ice–dust mixtures that mantle the surface (Mustard et al. 2001), relaxation of topography due to possible creep of ground ice (Squyres and Carr 1986), and widespread deposition of ice during high-obliquity “ice ages” (Head et al. 2003) are all believed to occur at these latitudes, and all could act to cover or erase stratified outcrops. Therefore, the apparent increase in stratified deposits for near-equatorial regions may represent the effect of ice-related processes at higher latitudes on a cold and dry Mars over the past several billion years rather than an inherent distribution in depositional environments conducive to formation of sedimentary strata on ancient Mars. However, recent studies have shown that some of these geologically young latitude-dependent ice–dust deposits (Mustard et al. 2001) also exhibit layering (Schon et al. 2009), raising the question of whether or not such processes may ultimately contribute to the formation of stratified rocks at these latitudes.

Many of the interpreted sedimentary deposits depicted in Figure 3 are not in close enough proximity to currently identified volcanoes to explain their deposition exclusively via volcanism. Nevertheless, it should be possible to recognize likely volcanic lava flows if they are present (see, for example, Milazzo et al. [2009]). In some cases, the nature of the stratified deposit is such that a definitive case for a sedimentary deposit may be made (Malin and Edgett 2003). In other cases the evidence is suggestive but not compelling (Malin and Edgett 2000). However, in many cases it is not possible to distinguish one from the other with a high degree of confidence based on initial study. Therefore, we have developed additional criteria that, with further testing and evaluation, may become helpful in distinguishing classes of sedimentary rocks in addition to distinguishing lava flows from sedimentary rocks. These criteria are also used in helping to define the categories of sedimentary rocks illustrated in the atlas of Beyer et al. (this volume).

Based on preliminary work, we recognize the following broadly defined attributes that usefully characterize particular types of strata. These include tone/albedo (MOC, HRSC, CTX, HiRISE grayscale and false color), apparent thickness of stratification and presence of apparent rhythmic beds, weathering character (rough, blocky vs. smooth), larger-scale textures and patterns (e.g., polygonal or reticulated), and spectral signature, as seen in visible–near-infrared (VNIR) and thermal infrared data. The spectral signature attribute includes the distinct lack of absorption features associated with mafic or hydrous minerals, most often attributed to modern dust cover, but possibly also associated with a distinct class of sedimentary rocks suggested to be composed of ancient lithified dust (Bridges and Muhs, this volume). These attributes are shared between sequences of strata across widely separated regions of Mars. For example, compare the light-toned, apparently thickly bedded, rough to blocky weathering deposits of the lower part of the ∼5-km-thick mound in Gale Crater (Fig. 5A) with the light-toned, rough to blocky weathering deposits of an ∼2-km-thick mound in Juventae Chasma (Fig. 5B). Both of these stratigraphic successions are also known to contain hydrated sulfates based on mapping using OMEGA and CRISM reflectance spectra (Gendrin et al. 2005, Milliken et al. 2010). This type of stratified rock can be contrasted with the medium-toned, smooth-weathering, apparently thinly bedded and rhythmic deposits in the upper part of the mound in Gale Crater (Fig. 5C) and with similar deposits in Beagle Crater (Fig. 5D). In both cases these latter deposits have been shown to be thin-bedded (beds are at least as thin as a few meters) and have a statistically significant rhythmic thickness distribution (Lewis et al. 2008a, Lewis 2009).

It is possible to subdivide the Martian layered terrains with probable sedimentary origins based on these characteristics. However, classification reaches its fullest potential if regional topographic/structural context is considered as well. To be clear, the analysis of sedimentary rocks on Mars is still in a very immature stage, and therefore these generalizations must be approached with appropriate caution. As such, this represents the beginning of an effort to build an objectively defined stratigraphy for parts of Mars, with the hope that interregional correlations might eventually be possible. The regional- to local-scale sedimentary terrain types we define here include (1) underfilled basins; (2) overfilled craters; (3) chasm and canyon systems; (4) plains-covering deposits; and (5) very ancient strata. In addition, Beyer et al. (this volume) also recognize the polar ice caps as examples of sedimentary strata, including well-developed stratal geometries (Kocurek and Ewing, this volume); however, these are not discussed further here. The following section briefly describes a few members in each of these five categories. These examples are by no means exhaustive, but rather they provide an overview of the diversity of sedimentary rocks and depositional environments that exist on Mars.

**Underfilled Basins**

Topographic depressions created by tectonic extension, subterranean collapse, or impact events have acted as significant sediment traps on Mars. Specifically, it has been known for decades that many craters in the Martian southern highlands exhibit clear evidence for partial infilling, presumably the result of volcanic or sedimentary processes (see Craddock et al. 1997, Malin and Edgett 2000, Craddock and Howard 2002 [and references therein]). These craters, as well as other topographic basins on Mars, are quite variable in terms of the amount of material they preserve. One class of these features, which we refer to as “underfilled basins,” exhibits limited sediment accumulation in the sense that accommodation space in the crater or basin still remains significant. In other words, these basins, most of which are impact craters, contain sediments or sedimentary rocks but lack evidence for having been filled close to or beyond their rims. Many craters within this category exhibit flat floors (e.g., Chapman et al. 1968, McGill and Wise 1972, Craddock et al. 1997), and the interior deposits lack clear geomorphic evidence for a unique depositional mode, making a sedimentary origin ambiguous. However, in a number of rather spectacular cases the geomorphology of these deposits indicates that fluvial systems were an important agent for sediment transport and that at least a fraction of the sediment filling many of these basins is externally derived.

Sedimentary deposits at the termini of some of these fluvial...
networks include alluvial fans, deltas, and stratified units for which the mode of emplacement is uncertain (Fig. 6). In the ancient and topographically high southern hemisphere of Mars, well-developed drainage networks often lead to single-strand channels that route to the margins of craters and then incise through the crater rim, sometimes grading laterally into wedge-shaped alluvial deposits (Howard et al. 2005). Many examples of these alluvial fans have been documented (Howard et al. 2005), but there are fewer examples of well-defined deltas. Fan-shaped features, possibly deltas, have been identified in a number of locations (e.g., Di Achille et al. 2006a, 2006b; Hauber et al. 2009), and those lying outside of craters that face the northern plains of Mars and along the topographic dichotomy boundary have been inferred to constitute evidence of a northern ocean (Di Achille and Hynek 2010). However, these latter features do not show clearly defined channel networks indicative of distributary networks (Fig. 6A). The thickness of these alluvial deposits is at least tens if not hundreds of meters, as projected above the flat-lying, possibly lacustrine strata that they apparently overlie (Grant et al. 2008). Clay minerals have been detected in some of these deposits, with the strongest clay signatures occurring in the lowermost (possibly lacustrine) strata. The presence of clay minerals in the surrounding crater wall indicates that at least some of these clays are detrital, having been transported from the crater wall to their current location by fluvial systems (Milliken and Bish 2010). The strata in Holden Crater also record a late-stage, high-energy flooding event, caused when the southwestern portion of the crater rim was breached by water that had ponded in the adjacent Uzboi Vallis (Grant et al. 2008). This event, possibly akin to the Lake Bonneville flood on Earth (Jarrett and Malde 1987), formed large subaqueous dunes that contain meter-sized blocks and whose paleocurrent direction is aligned with Uzboi Vallis (Grant et al. 2008).

**Holden Crater:** The ~150-km-diameter Holden Crater (26°S, 326°E; Fig. 4) hosts well-developed alluvial fans along the interior margins of the crater wall. As with other alluvial fans on Mars, these examples typically exhibit a cone-shaped morphology, are tens of kilometers in length, and have gradients of a few degrees (Howard et al. 2005). Holden Crater provides a representative example, with numerous fans coalescing to form long bajadas (Grant et al. 2008). Fans typically radiate from deep, extensively dissected alcoves in the crater wall and are best expressed along the western and southwestern walls. Differential eolian abrasion of these alluvial systems has produced inverted topography of distributary channel networks (Fig. 6A). The thickness of these alluvial deposits is at least tens if not hundreds of meters, as projected above the flat-lying, possibly lacustrine strata that they apparently overlie (Grant et al. 2008). Clay minerals have been detected in some of these deposits, with the strongest clay signatures occurring in the lowermost (possibly lacustrine) strata. The presence of clay minerals in the surrounding crater wall indicates that at least some of these clays are detrital, having been transported from the crater wall to their current location by fluvial systems (Milliken and Bish 2010). The strata in Holden Crater also record a late-stage, high-energy flooding event, caused when the southwestern portion of the crater rim was breached by water that had ponded in the adjacent Uzboi Vallis (Grant et al. 2008).
Fig. 6.—Sedimentary deposits in several underfilled basins. (A) Holden Crater, showing alluvial fan deposits within crater-fringing bajada. (B) Eberswalde Crater, showing a well-preserved delta. (C) Jezero Crater, with only partially preserved delta or alluvial fan. (D) Southwest Melas Basin within the larger Melas Chasma, where a topographic depression (not a crater) is filled with possible sublacustrine fan sediments. See text for discussion. Inset maps show location of images.
Eberswalde Crater: Deltaic deposits are very well developed in Eberswalde Crater (24°N, 327°E; Fig. 4), showing a remarkable degree of preservation (Malin and Edgett 2003). In Eberswalde Crater (Figs. 6B), which sits along the northern rim of Holden Crater, the deltaic feature is approximately 100 m thick and may largely preserve its original extent (Lewis and Aharonson 2006, Pondrelli et al. 2008). The delta comprises six distinct lobes that have prograded on the order of 17 km from their apex (Bhattacharya et al. 2005, Wood 2006) and represents an estimated 6 km$^3$ of sediment (Jerolmack et al. 2004). The geometry of the deposit features flat topset strata, comprising distinct meandering channels that are fronted by more steeply dipping strata interpreted as clinolomata (Lewis and Aharonson 2006, Pondrelli et al. 2008). Clay-bearing sediments apparently comprise the bottomset strata (Milliken and Bish 2010), and though their abundance is unknown, their presence is consistent with the inferred increase in the relative proportion of fine-grained sediment that a deltaic facies model would predict. Though the deltaic origin of these strata is generally agreed upon, estimates for the duration of deltaic deposition and associated surface runoff range widely, from ~10 years (Jerolmack et al. 2004) to >100,000 years (Bhattacharya et al. 2005). Eberswalde Crater pre-dates the formation of Holden Crater, as evidenced by the presence of ejecta from Holden Crater that resides in Eberswalde. It has recently been suggested (Grant and Wilson 2011) that the fan deposits in both of these craters are much younger than previously recognized, possibly Hesperian or younger. If true, the Eberswalde Delta may be somewhat anomalous in that it would thus postdate the major period of valley network formation, which had largely ceased by the Early Hesperian (Fassett and Head 2008a).

Jezero Crater: On the opposite side of the planet, the inferred deltaic deposits at Jezero Crater (18°N, 78°E; Fig. 4) have received significantly less attention. There are two distinct deposits, but each is significantly eroded, and their original maximum extent is not known. Accordingly, it is difficult to distinguish between a deltaic vs. alluvial fan origin. In contrast to Eberswalde, Jezero Crater has a significant outlet channel on the opposite side of the crater, from which the delta is developed, indicating a significant history of discharge and throughput; estimates of duration are similar to that calculated for Eberswalde (Fassett and Head 2005). The present upper surface of the deltas/alluvial fans is below the elevation of the outlet breach, indicating that the crater was underfilled at the time at which deposition ceased. However, postdepositional eolian deflation could have reduced the lateral extent as well as the thickness of strata associated with the fluvial deposits. Both deposits are estimated to collectively represent 5 km$^3$ of sediment. The western deposit is shown in Figure 6C. It has a thickness of 50 to 100 m and extends outward for ~10 km from its apex. Distributary channels are clearly truncated, however, indicating a greater primary extent (Fassett and Head 2005). This erosional truncation reveals the internal layering of the deposit, and spectroscopic data indicate clay minerals are concentrated in the delta relative to the surrounding region (Ehlmann et al. 2008a).

Melas Chasma: Distributary networks representing terminal sediment sinks also are present in topographic depressions other than craters. One well-studied region is an enclosed basin, hereafter referred to as the "southwest Melas Basin" (10°S, 283°E), which resides within the larger Melas Chasma in the Vallis Marineris canyon system (Figs. 4, 11A). Similar to the underfilled craters, there is no clear evidence that the entire basin was ever filled with sediment. Furthermore, in contrast to the deposits that are exposed in the broader Vallis Marineris system (see below), the morphologic characteristics of the Melas deposits place tighter constraints on their origin. Specifically, on the floor of this basin exists a well-preserved deposit (Fig. 6D) that has been interpreted to represent a set of sublacustrine fans (Metz et al. 2009a).

The highlands surrounding the basin and fans are marked by dense, highly organized valley networks (Mangold et al. 2004). Because the heads of the valleys occur at different elevations, including near the tops of wall rock ridgelines, they have been interpreted to have been fed by meteoric precipitation (Mangold et al. 2004, Quantin et al. 2005). These valleys drain into a subcircular closed depression within the Melas Basin that is interpreted to have been filled by a body of standing water (Quantin et al. 2005). The basin contains numerous light-toned, flat-lying layers that can be traced over several kilometers. Four fans have been identified in the southwest Melas Basin, two in the western part of the basin and two in the eastern part of the basin (Metz et al. 2009a). One of these, shown in Figure 6D, is particularly well preserved and appears to preserve most of its primary extent and finest scale distributaries. This fan has unique morphologic features, including multiple lobes with dendritic finger-like terminations that branch off at high angles in the downstream direction (up to 90° to the overall transport direction). The mean branching angles for the fingers are 75°, with a median of 80° (Metz et al. 2009a).

The Melas fans appear morphologically similar to deltas and submarine fans; however, the details of the morphology and their position in the basin indicate that they likely formed in a sublacustrine environment (Metz et al. 2009a). The combination of low slope, channel branching geometry, presence of distinctive small-scale lobes, and position near the center (rather than near the margin of a topographic basin) show that the Melas fans are distinct from previously identified fluvial features on Mars. Estimates of fan formation timescales indicate that they formed in a minimum of 10$^5$ to 10$^6$ years, and, thus, a stable body of water must have been present for at least this long.

Overfilled Craters

One of the most fascinating types of stratified deposits on Mars involves sequences of rocks, often hundreds and sometimes thousands of meters thick, whose upper parts approach or even exceed the elevation of the margins of the crater in which they are preserved. Therefore, the entirety of these deposits could not simply have accumulated in local topographic lows. As depocenters, these craters are probably best regarded as random sediment traps, and the more significant question has to do with how sediment accumulated up to and possibly beyond the rims of these older craters over such large regions.

These deposits are often preserved as mounds within large (>100-km-diameter) craters, sometimes with a "moat" occurring between the mound and crater walls. Their origin is uncertain, and some workers have argued that because the deposits form the shape of a mound today they may have been deposited as a mound (e.g., Rossi et al. 2008). However, inspection of layers in digital terrain models shows that thicknesses remain constant toward the margins of these mounds, indicating that the mounds are erosional remnants of deposits that were once more laterally extensive; i.e., there is no evidence for thinning and downlap toward the margins of the mound. In this sense they may be similar to outliers of terrestrial Proterozoic cratonic cover rocks that overlie older Archean basement and have been eroded to small remnants. These outliers were once thought to be isolated minibasins, but subsequent work (e.g., Ware and Hiscott 1985, Rainbird et al. 2003) revealed that they are erosional remnants of once-laterally continuous strata. By analogy, it is startling to consider that parts of Mars may have once been covered with regionally extensive successions of sedimentary rocks that have been stripped away over the course of billions of years by eolian abrasion, only to leave isolated remnants behind as evidence of their existence (Malin and Edgett 2000).

Gale Crater: There are several examples that illustrate this curious relationship of intracraterr strata that exceed the height of portions of
their bounding crater rim. One of the most interesting is Gale Crater (5°S, 137°E; Fig. 4), an ~155-km-diameter Noachian Age crater located along the geomorphic and topographic boundary that separates the ancient heavily cratered southern highlands from the younger and topographically smoother northern lowlands. The crater contains a remarkably thick, ~5-km succession of stratified rocks that form a mound, the maximum elevation of which is similar to that of the southern crater rim but that is several kilometers higher than the degraded northern rim (Fig. 7A) (Anderson and Bell 2010, Thomson et al. 2011). The mound exhibits no volcanic landforms (e.g., lava flows, vents, cones), and, thus, the rocks are considered to be sedimentary in origin (Malin and Edgett 2000, Anderson and Bell 2010, Milliken et al. 2010, Thomson et al. 2011). Other researchers have interpreted the strata as being volcanic ash, lacustrine (Cabrol et al. 1999), eolian, spring mound (Rossi et al. 2008), or ancient polar deposits (Schultz and Lutz 1988).

The mound in Gale Crater can be divided into two formations based on visible images (Milliken et al. 2010). The Lower formation is composed of parallel beds that dip gently to the northwest at 2 to 4° and that vary in thickness, albedo, and surface texture, whereas strata in the Upper formation appear relatively homogeneous, dip more steeply toward the north–northeast, and have fewer impact craters. In addition, the Lower formation exhibits a net transition from clay–sulfate to sulfate–oxide mineral assemblages and is separated from the overlying Upper formation by an erosional unconformity. Superposition and crater statistics indicate that strata in the Lower formation lie along the

Fig. 7.—Sedimentary deposits in overfilled craters. Subsets are from HiRISE images. (A) Gale Crater, in which strata form a mound over 5 km in thickness that exceeds the elevation of the northern crater rim. Subset is PSP_008002_1750. (B) Terby Crater; note large mesas formed of stratified deposits. Subset is PSP_002572_1520. (C) Crommelin Crater, showing central mound formed of stratified deposits. Subset is PSP_001876_1850. (D) Henry Crater, in which strata form a significant mound, the peak elevation of which coincides with elevation of the crater rim. Subset is PSP_006569_1915. See text for discussion.
Fig. 8.—Overfilled to partially filled craters of Arabia Terra, including THEMIS nighttime infrared and OMEGA hydration responses. (A) Regional topographic map showing locations of craters that exhibit various degrees of infilling. Small white arrows point to partially filled/exhumed craters. Large white arrow points to an unnamed crater, shown in B, C, and D. Large black arrow points to Henry Crater, shown in E, F, and G. (B) THEMIS nighttime infrared image; yellow and red tones indicate higher thermal inertia relative to surroundings, consistent with large particles or bedrock. (C) H$_2$O content map derived from OMEGA data; yellow and red tones indicate $\geq$4 wt. % H$_2$O; note that this crater does not exhibit an increase in hydration associated with the stratified mound; black arrow marks location of D. (D) Close-up of strata in central mound of crater (HiRISE PSP_003655_1885). (E) THEMIS nighttime infrared image; color scale same as B. (F) H$_2$O content map...
Noachian–Hesperian time-stratigraphic boundary (Thomson et al. 2011), whereas beds in the Upper formation, which lack signatures indicative of hydrous minerals, are thinner, more regularly spaced, and are clearly younger. In addition to the hydrated mineralogy, a broad array of geomorphic features indicates the activity of water within Gale Crater (Anderson and Bell 2010).

The observed stratigraphic trends are consistent with the rocks at Gale Crater recording a global transition from a climate favorable for clay formation to one more favorable to forming sulfates, succeeded by younger strata that lack evidence for hydrated minerals (Milliken et al. 2010). These transitions may represent the progressive “drying out” of Mars from early clement conditions to water-limited acidic and oxidizing conditions, and ultimately to the cold, dry climate of today in a single stratigraphic sequence. As such, the Gale mound constitutes an important “reference section” for establishing the chronostratigraphic history of Mars.

Terby Crater: Terby Crater (28°S, 74°E; Fig. 4), located along the northern rim of the giant Hellas Impact Basin, forms a basin 175 km in diameter. The crater is flat-floored, indicating significant infill, and is marked by three significant linear mesas—or ridges—of stratified deposits (Wilson et al. 2007). These ridges are equivalent in elevation to the crater’s northern rim but are several kilometers higher than the degraded southern rim (Fig. 7B). Layers are generally flat in all three ridges and form successions that are several kilometers thick. As is the case at Gale Crater, many of the layers are of uniform thickness when traced laterally (Ansan et al. 2011), indicating that they are erosional remnants of once–more extensive deposits.

Strata in Terby are suggested to be either fine grained or lacking in pervasive cementation as a result of the lack of talus at the base of slopes. Blocks produced by erosion and collapse of outcrop faces via mass wasting are generally not apparent in orbital images. This is particularly interesting given Terby’s latitude and proximity to Hellas, which is in a region that has been subject to ice-related processes for the past several hundred million years or longer (e.g., Head et al. 2003, Crown et al. 2005). Freeze–thaw cycles might be expected to increase physical weathering at Terby and produce large boulders along the steep walls of the mounds, yet such boulders are oddly absent.

In general, the modes of deposition for the strata in Terby are not known, although both lacustrine and eolian loess-like processes have been invoked (Wilson et al. 2007, Ansan et al. 2011). Most recently, recognition of locally steeper dips has indicated the presence of clinoforms, equated with deltaic progradation (Ansan et al. 2011). These transitions may represent the progressive “drying out” of Mars from early clement conditions to water-limited acidic and oxidizing conditions, and ultimately to the cold, dry climate of today in a single stratigraphic sequence. As such, the Gale mound constitutes an important “reference section” for establishing the chronostratigraphic history of Mars.

Henry Crater/Arabia Terra: One of the larger examples of these mound-forming intracrater deposits is found in Henry Crater (11°N, 337°E; Figs. 4, 8A), which is also ~170 km in diameter (Figs. 7D, 8A). Similar to Crommelin Crater, the mound in Henry Crater also reaches an elevation equivalent to its rim, again indicating a process of deposition that exceeds simple filling of a topographic depression (Malin and Edgett 2000). The mound is estimated to be on the order of 1500 to 2000 m thick (Andrews-Hanna et al. 2010), and, as with other crater-filling mounds in Arabia, the Henry mound is well-bedded with strata on the order of a few meters to tens of meters thick. As with other examples of mounds that fill craters, the deposit has been deeply eroded to form a “moat” around its base.

Much of the mound in Henry Crater (and much of Arabia Terra) is covered with dust, making compositional identification via orbital spectroscopy difficult. However, analysis of OMEGA data has shown that small exposures of bedrock in Arabia Terra have increased water contents, consistent with the increased H\textsuperscript{+} signal seen throughout the region by the Mars Odyssey Gamma Ray Spectrometer (Feldman et al. 2004). This indicates that hydrous minerals may be present in some of the strata in Arabia Terra. Though not all overfilled craters exhibit this property (Fig. 8B–D), small and relatively dust-free outcrops in Henry Crater do exhibit an apparent increase in hydration, as observed in the OMEGA data (Fig. 8E–G). Visual inspection indicates that the bedding in the Henry Crater mound may also be rhythmic, consistent with a climate-based control on sedimentary accumulation. However, derived from OMEGA data; color scale same as C; note that this crater does exhibit an increase in hydration associated with some portions of the stratified mound; black arrow marks location of G. (G) Close-up of strata in central mound (HIRISE PSP_008072_1905). For reference, typical dusty regions on Mars exhibit 2 to 4 wt. % H\textsubscript{2}O, as seen by OMEGA (Milliken et al. 2007).
this has yet to be confirmed using time-series analysis (cf. Lewis et al. 2008a, Lewis 2009).

**Becquerel Crater/Arabia Terra:** Becquerel Crater (22°N, 353°E; Fig. 4) also preserves a mound (Fig. 9A), but its elevation is considerably below the rim of the crater; the highest part of the stratigraphic succession lies over a kilometer beneath the highest elevation of the crater rim. Becquerel Crater has a width of ~170 km in diameter, similar to the Henry Crater. Although the mound is much lower in elevation than the crater rim, the similarity of the deposits that form the mound, combined with the range of erosion elevations for mounds in other craters of Arabia Terra—from overfilled to underfilled—warrant its inclusion in the overfilled crater category. Importantly, the analysis of bed thickness distributions makes it a kind of "type section" for this style of deposit.

The stratification at Becquerel shows striking differential resistance to erosion that has produced a distinctive "staircase" weathering pattern (Fig. 9B, C), likely reflecting changes in facies or cementation patterns within the rocks (Lewis et al. 2008a). Furthermore, these strata are characterized by a distinctive cyclicity in bedding thicknesses. Lewis et al. (2008a) analyzed the distribution of bed thicknesses at a number of locations, including Becquerel, and found a roughly 10:1 ratio of frequencies over several hundred meters of section, for a total of at least 10 bundles (Fig. 9B, C). Individual beds here have a mean thickness of 3.6 ± 1 m, and the bundles are 36 ± 9 m thick. This ~10:1 thickness ratio indicates cyclicity in environmental conditions, possibly as a result of astronomical forcing due to obliquity variations. If deposition were forced by orbital variation, the stratigraphic succession at Becquerel may have been deposited over tens of millions of years, although the true age is poorly constrained.

**Danielson Crater/Arabia Terra:** Another spectacular example of rhythmic bedding in a mound-forming deposit occurs in Danielson Crater, also located in Arabia Terra (8°N, 353°E; Fig. 4). This crater has received little study, although much of the crater floor is covered by these intriguing rhythmic strata (Fig. 10). Bedding in the center of the crater seems to be relatively flat-lying, in contrast to bedding at the margin of the crater, which steepens significantly, dipping inward toward the center of the crater (Fig. 10B). It could be that this change in dip is a result of simple compaction of thicker deposits toward the center of the crater.

**Chasm and Canyon Systems**

One of the more amazing discoveries from the Mariner 9 mission was the presence of enormous east–west trending canyons east of the Tharsis volcanic complex and just south of the equator (McCauley et al. 1972, Sharp 1973). Now known as the Valles Marineris, these canyons were created primarily by tectonic forces associated with the formation of the Tharsis rise, with later modification by collapse, fluvial, and eolian processes. Studies of the regional tectonic setting indicate multiple periods of extension, uplift, and collapse to form the graben and canyon systems found throughout the region, with variations (Lewis et al. 2008a). HiRISE image PSP_001546_2015 is shown draped over digital stereo topography. Scale bars, 100 m (both horizontal and vertical). (C) Plan view of HiRISE image PSP_001546_2015, showing context for B; north is down. Numbers mark the boundaries between successive bundles, defined by variations in topography. Figure constructed by Kevin Lewis using DEM made by K. Lewis and T. Suer.
Fig. 10.—Rhythmic strata in Danielson Crater (8°N, 353°E; Fig. 4) in the Arabia Terra region. (A) In addition to clear effects of structural deformation, note the remarkable uniformity of bed thickness and the lateral persistence of bedding. This indicates a possible climate control on sediment accumulation (Lewis et al. 2008a). HiRISE image PSP_002733_1800. (B) HiRISE DEM showing orientation of deformed strata and rhythmic bedding. The nose of the main ridge is shown at the top of the image in A and is about 500 m wide. Figure based on DEM made by K. Lewis and T. Suer.
formation extending from the Early Noachian until the Early Amazonian (Tanaka and Davis 1988; Schultz 1998). Today the Valles Marineris system consists of both interconnected, open canyons and isolated, closed basins (Fig. 11A). In many instances the interiors of these chasms contain thick sequences of layered deposits, more commonly referred to as “Interior Layered Deposits” (e.g., Lucchitta et al. 1994), or ILD. The ILD are generally light-toned compared to surrounding terrains and reach thicknesses of up to several kilometers. In some cases, the maximum elevations of the ILD approach the same elevations as the surrounding plains, raising the possibility that their lateral (and possibly vertical) extent was once much greater.

Stratification is visible at the subkilometer to meter scale in many of the deposits, and the prevailing view has been that the ILD postdate canyon formation. In some locations the ILD show evidence of onlapping the surrounding wallrock (e.g., Metz et al. 2009a), which is often characterized by spur-and-gully morphology; but in many cases the stratigraphic relationships are unclear as a result of debris cover along the contacts. In other cases, it has been shown that light-toned deposits are exposed within the walls of some chasms in the Valles Marineris (Malin and Edgett 2000, Montgomery and Gillespie 2005), which indicates that light-toned deposits may underlie the surrounding plains traditionally interpreted as thick stacks of lava flows (e.g., McEwen et al. 1999). Other evidence indicates that some ILD were formed in older ancestral basins, the topographic boundaries of which are no longer visible today (Lucchitta et al. 1994, Schultz 1998), and although not the predominant hypothesis, the ambiguity in stratigraphic relationships between some ILD and the canyon walls leaves open the possibility that some of these deposits may pre-date canyon formation.

The origin of the ILD is a major unresolved question in Martian geology, and volcanic ash, subaqueous volcanism; and fluvial, eolian, and lacustrine processes have all been invoked (e.g., Peterson 1981, Nedell et al. 1987, McKay and Nedell 1988, Lucchitta et al. 1992). Spectral data have revealed the presence of sulfate salts (Gendrin et al. 2005, Bishop et al. 2009, Roach et al. 2010), indicating that at least some fraction of it is sourced from the surrounding light-toned ILD. The original extent of the ILD in Candor is unknown.

**Candor Chasma:** Candor Chasma (6°S, 289°E; Fig. 4) lies in the north-central portion of the Valles Marineris and hosts several kilometers-thick ILD (Fig. 11A–C). Crude layers were visible in these deposits even from Mariner 9 and Viking images, but MOC and HiRISE data have revealed that they are also stratified at the meter to decimeter scale (e.g., Malin and Edgett 2000, Okubo 2010). OMEGA and CRISM data indicate that these strata are composed at least in part of polyhydrated sulfates (likely Mg-varieties such as hexahydrate, MgSO₄·6H₂O), kieserite (MgSO₄·H₂O), and crystalline ferric oxides (Gendrin et al. 2005, Birbing et al. 2007, Mangold et al. 2008, Murchie et al. 2009a, Roach et al. 2010). At longer wavelengths, TES data have revealed the presence of gray (specular) hematite (Christensen et al. 2001), similar to the signatures observed for Sinus Meridiani. Despite this knowledge of the composition of the ILD, whether these minerals are detrital or authigenic is not known, and the depositional environment of the sediments is also ambiguous. However, similarities in composition to strata examined by the Opportunity rover in Sinus Meridiani have led to the interpretation that they are eolian sediments cemented by sulfates during interaction with groundwater (Bibring et al. 2007, Murchie et al. 2009a). It is also possible that the Candor ILD formed as primary lacustrine evaporites, accumulating in one of the planet’s great topographic depressions. In either scenario, these thick ILD would postdate the formation of Candor Chasma, which is supported by the apparent onlap of ILD onto the surrounding wallrock.

In contrast to most ILD and other stratified deposits within Valles Marineris, the western region of Candor contains strata that have experienced extensive deformation (Fig. 11C, D). Deposits surrounding the westernmost ILD exhibit significant folding and faulting (Okubo et al. 2008, Metz et al. 2010, Okubo 2010), and the structural geometries are consistent with thin-skinned deformation (Metz et al. 2010). Although the abundance of sulfates and other salts within these deposits is unknown, their mere presence may have facilitated deformation of these units. Indeed, it has even been suggested (Montgomery et al. 2009) that vast salt deposits might underlie the entire region east of Tharsis (the Thaumasia Plateau) and were responsible for the opening of Valles Marineris via gravity gliding along a regionally extensive detachment surface localized within the salt. Locally within western Candor, strike-and-dip measurements derived from 1 m/pixel digital elevation models indicate that undeformed strata in this region dip toward the basin interior and that folds in the deformed zones have a gentle plunge of ~5° (Metz et al. 2010, Okubo 2010). The deformed rocks exhibit meter- to decameter-scale stratification, and bedding is often accentuated by the presence of wind-blown, dark-toned sediment that has accumulated in troughs formed by eroded layers. In some locations this dark material exhibits strong sulfate and Fe-oxide signatures (Murchie et al. 2009a), indicating that at least some fraction of it is sourced from the surrounding light-toned ILD. The original extent of the ILD in Candor and the terminal sink for the sediment eroded from them are not known.

**Juventae Chasma:** Juventae Chasma is a large basin that lies to the northeast of Candor Chasma, at 4°S, 299°E; Juventae Chasma is the source for the large Maja Valles outflow channel that empties into Chryse Planitia. A small outlet channel along the northern margin debouches into a separate smaller basin, and together these two basins are lower in elevation than the surrounding regions. Therefore, although Juventae may not technically be a closed basin today, this appears to have been the case in the past. Juventae contains at least four distinct ILD (Catling et al. 2006) that are known to contain hydrated sulfates (Gendrin et al. 2005, Bishop et al. 2009). Layering is apparent in several of these ILD, even in low-resolution images, as a result of differential erosion that has produced stair-step topography (see Fig. 1). However, meter- to decameter-scale stratification (Fig. 11E) is also apparent in high-resolution MOC and HiRISE images (e.g., Chapman et al. 2003, Catling et al. 2006, Bishop et al. 2009). As with other ILD, the depositional environment(s) of these sediments is poorly constrained. Detailed studies indicate that these light-toned deposits, which are possibly ~3 to 6 km thick, were once much more laterally extensive and that they may be eroding at a rate of ~1 km/Gyr (Catling et al. 2006). Origins consistent with these observations have included, but are certainly not limited to, precipitation of evaporites in bodies of standing water, accumulation of wind-blown sulfates (McLennan and Grotzinger 2008), and volcanic sulfate aerosols deposited with ice during high-obliquity cycles (Catling et al. 2006).

Original OMEGA-based interpretations of the composition of the ILD indicated that the lower strata in one of the mounds contained kieserite (MgSO₄·H₂O) and were overlain by gypsum-bearing strata (Gendrin et al. 2005). If formed by direct precipitation via evaporative concentration, this mineral sequence is hard to explain because of the
Fig. 11.—Sedimentary deposits in Valles Marineris. (A) Overview of central Valles Marineris; MOLA elevation on THEMIS daytime infrared mosaic. (B) Close-up of strata in Melas Chasma, HiRISE image ESP_019442_1700. (C) Close-up of deformed (folded) strata in west Candor, HiRISE image PSP_001918_1735. (D) Close-up of brecciated and deformed strata in west Candor. HiRISE image ESP_001372_1730. (E) Close-up of finely stratified ILD in Juventae Chasma, HiRISE image PSP_006915_1760. CRISM data indicate that sulfates are present in all locations.
high solubility of kieserite and the low solubility of gypsum: the sequence should be the opposite of what is observed if given a simple, single-stage evaporation process. However, more recent analysis using higher-resolution CRISM data has shown that the identification of gypsum was likely an artifact during processing of the OMEGA data in this region. Monohydrated sulfates have been confirmed in the CRISM data (kieserite and possibly the Fe-sulfate zomolnokite, FeSO₄·H₂O), and polyhydrated sulfates consistent with Mg and Fe varieties (but not gypsum) have also been identified (Bishop et al. 2009). The variation in hydration states of sulfates may reflect hydration–dehydration reactions that occur as these phases are exposed to the atmosphere by continual erosion. The hydrated Mg- and Fe-sulfate minerals are particularly sensitive to changes in relative humidity, and thermodynamic calculations and laboratory studies have predicted that changes in the hydration states of these sulfates (e.g., between monohydrated and polyhydrated states) should occur on Mars (Vaniman et al. 2004, Hasenmueller and Bish 2005, Bish and Scanlan 2006, Vaniman and Chipera 2006, Chipera and Vaniman 2007). However, such changes have not yet been observed for a given sulfate deposit, even after several years of repeat observations by OMEGA and CRISM, implying that the rates of these reactions are too slow to be observed on these timescales (Roach et al. 2010). Regardless, the diversity of hydrated sulfates in the sedimentary rocks of Juventae provides an interesting location for further testing of this hypothesis. As with other ILD additional measurements of the strike, dip, and stratal geometries of layers within these units would help to place further constraints on their mode(s) of emplacement.

**Plains Covering Deposits**

At several locations on Mars, outcrops of regional extent show clear evidence of stratification, are laterally continuous on a scale of hundreds of kilometers, and form the bedrock beneath broad plains. These strata lack signs of accumulation in an obvious topographic depression. Exposures occur along relatively high plateaus, such as the rim of Valles Marineris, as well as in lower regions, such as Arabia Terra and Sinus Meridiani. What is important about these regions is that these strata seem to represent sequences that blanket large regions of the planet and that in some cases (e.g., Sinus Meridiani) achieve substantial thickness, on the order of many hundreds of meters. Though the paleotopography of these regions on Mars is unknown, it is clear that they were sinks for sediment accumulation.

**Plains Surrounding Valles Marineris**: The plains immediately adjacent to the Valles Marineris are predominantly Hesperian in age, though some Noachian terrains are exposed along the far eastern portions (e.g., south of Eos Chasma) and north and south of eastern Candor Chasma (Scott and Tanaka 1982). Historically, these plains were interpreted as sequences of lava flows, and many exhibit compression ridges (Scott and Tanaka 1982). However, examination of high-resolution images has revealed the presence of very thinly bedded deposits of alternating light- and dark-toned strata in some locations along the margins of these plains. These deposits consist of submeter- to meter-thick beds, and the well-stratified portions of these sequences are typically ~60 m thick (Weitz et al. 2010). Analysis of CRISM data has shown that these deposits contain opaline silica and hydrated Fe-sulfates, consistent with acidic alteration of basalt or deposition in acidic fluids (Milliken et al. 2008). In addition, some of these deposits exhibit inverted channels and drainage networks, indicating that fluvial processes were related to their emplacement (Milliken et al. 2008; Weitz et al. 2008, 2010). Similar fluvial networks observed in other plains regions adjacent to Valles Marineris have been interpreted as evidence for precipitation-driven runoff (Mangold et al. 2004), and in all cases these deposits and features are interpreted to postdate the primary period of valley network formation, which was prior to the Early Hesperian (Fassett and Head 2008a).

The best examples of this category of sedimentary plains deposits occur along the western rim of Juventae Chasma (~4°S, 296.5°E; Fig. 4) and the southern rim of Ius Chasma (~8.3°S, 275.1°E; Fig. 12A–D). In some locations these deposits occur between ridges, although whether they onlap the ridges or instead represent erosional windows into the subsurface is not always clear. Furthermore, although these deposits are typically the locally highest stratigraphic unit, they often recede beneath a thin, dark capping unit when traced farther away from the canyon rim. The origin of this capping unit (eolian?, volcanic?, pedogenic?), its thickness, and whether or not it has a similar origin to the regionally extensive volcanic Hesperian plains are currently unclear. Therefore, these opal- and sulfate-bearing strata may be restricted to the edges of the canyon system, where they sit atop Hesperian-age lava flows. Alternatively, they may be regionally extensive but commonly obscured by the thin dark capping unit, or they may represent a sedimentary sequence that sits within a stack of Hesperian lava flows. If either of the latter two scenarios are correct, then the full extent of these sediments may be much greater than currently recognized, exposed only near the edges of the canyons, where erosion has been more extensive. Regardless of their age and origin, the finely stratified nature of these deposits, the presence of mineral phases that require water for their formation, and the association with fluvial features imply aqueous activity and alteration much more recently in Mars’ history than previously thought (Milliken et al. 2008, Weitz et al. 2010). This supports growing geomorphic evidence for localized valley incision during the Late Hesperian or even Amazonian, as is also observed in the Margaritifer Terra region (Grant and Wilson 2011) and in the Newton and Gorgonum basins (Howard and Moore 2011).

**Sinus Meridiani**: Sinus Meridiani is a large low-albedo region centered roughly near 0° longitude, 0° latitude (Fig. 4). Outcrops are represented by cliff-forming, light-toned stratified deposits covering a region somewhat larger than the Colorado Plateau (∼300,000 km²), and the northern part of Sinus Meridiani is particularly well exposed and free of mantling dust, silt, and sand (Edgett and Malin 2002). A variety of origins for these strata have been proposed, including lacustrine, palaeoporal deposits (dust), eolian dust/dune, volcaniclastic, and other subaqueous environments (summarized in Edgett and Malin [2002]).

Edgett (2005) estimated the thickness of the strata at Sinus Meridiani to be >800 m, composed of four distinct units. Differentiation of these units is based on geomorphic style (plains vs. ridge forming), tone/albedo, and the presence of buried/inverted channels. The section shows extensive exhumation, exposing inverted channels as well as numerous buried craters. The presence of craters, formed and buried at the time of sediment accumulation and subsequently exposed during erosion and exhumation (Fig. 12E, F), is strong evidence for a Martian cycle of sedimentation followed by erosion (Malin and Edgett 2000, Edgett and Malin 2002). Toward the upper part of this succession, in a region called Meridiani Planum, are the outcrops encountered by the Opportunity rover (Edgett 2005). On the ~7-km traverse from Eagle to Endurance to Erebus to Victoria craters, outcrops were observed and studied systematically using the rover payload (Squyres et al. 2004; Grotzinger et al. 2005, 2006; Metz et al. 2009b; Squyres et al. 2009; Hayes et al. 2011; Edgar et al. [this volume]); the bulk of these sediments are of eolian origin.

The Burns formation is the informal name given to the portion of the succession examined in outcrop by Opportunity, which revealed a succession of well-sorted, moderately indurated sandstones (Fig. 13A) preserved immediately beneath the surface of the Meridiani plains. Detailed stratigraphic measurements (Fig. 14) and sedimentological observations (Fig. 13) indicate that eolian and local subaqueous processes deposited these sedimentary rocks as part of an interstratified
Fig. 12.—Sedimentary deposits formed on the plains surrounding the Valles Marineris and other broad open tablelands of Mars. (A) CTX mosaic showing light-toned outcrops along the plains south of Ius Chasma; some light-toned deposits contain opaline silica. (B) Close-up of opal-bearing units in plains adjacent to Ius Chasma; arrow in A marks location; HiRISE image PSP_002459_1715. (C) CTX mosaic showing light-toned outcrops along the plains west of Juventae Chasma; some light-toned deposits contain opaline silica and/or Fe-sulfates. (D) Close-up of opal- and sulfate-bearing units; location marked by arrow in C; HiRISE image PSP_003434_1755. (E) CTX mosaic showing light-toned outcrops in eastern Sinus Meridiani including large exhumed crater. (F) Close-up of finely stratified light-toned units in a filled and exhumed crater; location marked by arrow in E; HiRISE image PSP_001981_1825.
FIG. 13.—Sedimentary facies and textures in the Burns formation, Meridiani Planum. (A) Microscopic Imager (MI) image showing distinct grains that form lamination (“Flatrock,” Eagle Crater), indicating that most of the Burns formation was composed of sandstones, the grains of which were derived from reworked evaporites. Grains range in size from 0.1 to 1.0 mm, are moderately well rounded, and are well sorted into discrete laminae. The excellent size sorting on the scale of individual laminae is strongly indicative of “translatent” strata, formed by sediment transport within migrating eolian impact ripples (see Grotzinger et al. [2005] for more details). Fabric preservation, which reveals discrete grains, is rare as a result of cementation recrystallization; preservation is best where early cementation was minimal, permitting grains to weather in positive relief. Compare with Figure 13B, which shows the effects of increasing cementation. The image (1M131912465) was
Eolian dune facies are characterized by the occurrence of large-scale, cross-bedded, well-sorted sandstones (Grotzinger et al. 2005, Metz et al. 2009b, Hayes et al. 2011, Edgar et al. [this volume]). This facies is interpreted to represent a migrating dune system of unknown extent that was deposited under dry conditions, such that the sediment was noncohesive and thus transported in migrating dune fields. Bedset thicknesses indicate moderately large dunes in excess of 4 m (Fig. 13H). Eolian sand sheet facies are characterized by planar-laminated to low-angle cross-stratified, well-sorted sandstones (Grotzinger et al. 2005, Metz et al. 2009b). This type of stratification (Fig. 13F) results from sediment limitation, forming low-relief bedforms produced by migrating impact ripples. In Endurance Crater, the contact between the dune and overlying sand sheet facies marks the boundary between the lower and middle stratigraphic units (Fig. 13G). This important stratigraphic boundary, termed the “Wellington contact,” is interpreted to be a deflation surface formed where the groundwater capillary fringe limited erosion of previously deposited dune sediments (Grotzinger et al. 2005).

Wet to evaporitic interdune facies are characterized by centimeter-scale trough cross-lamination, diagnostic of subaqueous current transport in the lower flow regime (Grotzinger et al. 2005, 2006). At Endurance, Eagle, and Erebus craters, this facies marks where the groundwater table breached the surface and wind-driven subaqueous currents transported the sediment. Centimeter-scale trough cross-lamination (Fig. 13D) is particularly well developed at Erebus Crater, where additional features indicative of desiccation also are present (Grotzinger et al. 2006). The sediments that form these ripples were likely transported by brines with potentially high viscosities (Lamb et al., this volume). Prism cracks (Fig. 13E) are interpreted to have formed during multiple wetting and drying events, and soft sediment deformation features are consistent with sediment liquefaction. Stratigraphic sections studied by Opportunity are exposed in the walls of craters, and, therefore, intact bedrock is usually capped by a unit of impact breccia (Fig. 13I). The presence of ferric sulfates (i.e., jarosite) in the rocks of Meridiani Planum indicates interaction with or deposition by acidic fluids, where the acidity may have been generated by the oxidation of Fe(II)-rich water as it emerged from the subsurface (Huwowitz et al. 2010). Indeed, global hydrologic models predict that groundwater would emerge in the Sinus Meridiani region (Andrews-Hanna et al. 2007), and terrestrial studies of acid–saline lakes may prove useful for constraining the origin of acidic brines on Mars (see Bowen et al., this volume).

**Medusae Fossae Formation:** Perhaps one of the most enigmatic sedimentary deposits on Mars is the Medusae Fossae Formation (MFF). The MFF is a large discontinuous deposit that straddles the equator between 130 and 230°E longitude and that is flanked by Noachian- and Hesperian-aged plains units. The deposit can be as thick as several kilometers, although locally it can be significantly thinner, and it has an estimated volume of $1.4 \times 10^6$ km$^3$ (Bradley et al. 2002). An Amazonian age has traditionally been assigned to the MFF (Scott and Tanaka 1986), though recent analysis of superposition by Hesperian lavas, as seen in higher resolution images, has indicated that it may have been emplaced in the Hesperian (Kerber and Head 2010). The deposit is extremely variable in its morphology, but major textural characteristics indicate that it is poorly cemented, easily eroded, and wind scoured. The friable nature of the deposit is likely a contributing factor in the interpreted young age, as determined by crater counting; many craters have been eroded, and the Amazonian age may reflect an exposure age that is much younger than its depositional age (Kerber and Head 2010).

Large portions of the surface are characterized by yardangs, and stratification is developed at a variety of scales; <10-m beds are visible only at MOC or HiRISE resolution, and these occurrences are locally restricted (Bradley et al. 2002). However, this stratification is not visible in SHARAD shallow sounding radar data, indicating that the upper several hundred meters of the deposit have a high porosity and that this region is rather
Fig. 14.—Stratigraphy of the Burns formation exposed at Burns cliff and within Eagle Crater, Meridiani Planum. Names and letters on the left side denote the approximate stratigraphic locations of key rocks and targets. Sedimentological interpretations of the three stratigraphic units are shown on the right-hand side of the column. See text for further discussion. From Grotzinger et al. (2005).
homogeneous (low permittivity contrast) or has discontinuous bedding.

The ultimate origin of the deposit is still unknown, but volcanic airfall, ignimbrites, or eolian dust are leading hypotheses (Bradley et al. 2002, Mandt et al. 2008, Kerber and Head 2010). Alternatively, radar data indicate that the dielectric properties of the deposit are also consistent with the presence of significant amounts of water ice (Watters et al. 2007), possibly indicating a formation mechanism similar to the polar layered deposits (Schultz 1988). To date, spectral data have revealed no unique or diagnostic mineral signatures associated with the MFF, adding further mystery to its origin. Of the sedimentary deposits discussed here, the MFF may be the leading candidate for a thick sequence of volcanic ash on Mars. The general absence of well-defined, meter-scale stratification developed across a significant fraction of the aerial extent of each deposit helps differentiate the MFF from the spectrally bland but well-bedded deposits that fill and sometimes overtop the craters of Arabia Terra (see preceding discussion, “Overfilled Craters”). As discussed above, these latter deposits are regarded as possible eolian dust deposits as a result of their highly rhythmic bedding (Lewis et al. 2008a, Lewis 2009). However, Lewis (2009) examined the bed thicknesses of several stratified deposits within the MFF and found that these regions did in fact exhibit a periodic thickness of 3 m. Given that the majority of the MFF does not exhibit this style of bedding, this raises the possibility of facies variability in time or space, such that massive deposits may substitute for rhythmic deposits.

Another intriguing attribute of the MFF is the numerous fluvial features that mark its surface, many of which are inverted (Burr et al. 2009). These features indicate that erosion, transport, and redeposition of the MFF sediments by fluvial systems have played an important role in its history, and although the primary depositional mechanism(s) of the MFF remains uncertain, it is clear that subsequent reworking has formed fluvial deposits (Burr et al. 2009, Kerber and Head 2010).

Very Ancient Strata

Some of the stratified deposits on Mars that have captured significant attention over the past several years are those preserved as part of the most ancient Noachian crust. It is widely believed that Mars, like the Moon, was subject to a period of intense bombardment and impact crater formation from 4.1 to 3.8 Ga. The size and number of impact events during the Late Heavy Bombardment imply that much of the preexisting crust would have been destroyed and that vast regions of the planet would have been covered by impact ejecta. Therefore, it may be somewhat surprising that any sedimentary sequences of appreciable thickness formed prior to this period would remain visible from orbit today. Indeed, much of the ancient Noachian crust in the southern highlands of Mars lacks clear stratification at the scale of tens and hundreds of meters. However, Noachian stratified rocks, possibly of sedimentary origin, have been identified in a handful of instances. These regions typically contain some of the strongest spectral signatures of clay minerals observed on Mars, and their mineralogical diversity is striking. On Earth, deciphering the original depositional environments of such ancient rocks, which have been subjected to billions of years of postdepositional geologic processes, can be daunting. The same is true for Mars, although the volume of stratified crust preserved from the earliest days of the planet is much greater than for Earth. Furthermore, the fraction of volcanic vs. sedimentary rocks, the possible depositional environments of any sedimentary rocks, and alteration conditions of these strata continue to be a subject of significant debate.

Mawrth Vallis: The Mawrth Vallis outflow channel, located near \(23^\circ N, 341.5^\circ E\) (Fig. 4), is a very old flood channel that empties into the northern lowlands of Mars. The channel incises bedrock formed of stratified rocks up to several hundred meters in thickness (Loizeau et al. 2007, Michalski and Noe Dobrea 2007). Orbital images show that these rocks are stratified at the meter to decameter scale, typically light-toned, significantly eroded, and heavily cratered (Fig. 15A–C). They span a region measuring \(>80,000 \text{ km}^2\) and are assigned an Early to Middle Noachian age (4.1–3.8 Ga) (Michalski and Noe Dobrea 2007), implying they were emplaced during or prior to the Late Heavy Bombardment.

In addition to being some of the oldest possible sedimentary rocks yet observed, these rocks also exhibit some of the strongest clay mineral signatures detected on Mars (Poulet et al. 2005, Loizeau et al. 2007, Michalski et al. 2010). The rocks at Mawrth Vallis exhibit a broad-scale bipartite mineralogic stratigraphy in which Fe/Mg-rich smectitic clays persist for \(>100 \text{ m}\) in thickness and ultimately transition upslope to more Al-rich clays (e.g., kaolinite, montmorillonite), possibly mixed with opaline silica (Poulet et al. 2005, Bishop et al. 2008, Michalski et al. 2010, Noe Dobrea et al. 2010). The thickness of the Al-rich zone is variable as a result of erosion, but locally it can measure up to 50 m (Loizeau et al. 2007). It is not clear whether this mineralogical transition (Fig. 16A) is linked to variations in primary depositional environments or whether it cuts across primary bedding, which would indicate a diagentic origin for at least the Al-rich rocks. However, this mineralogical sequence is observed elsewhere in the surrounding region, and studies have indicated that the Al-bearing phases at the top of the succession are due to diagenetic overprinting, leaching, or pedogenesis (e.g., Noe Dobrea et al. 2010). The entire succession is unconformably overlain by an erosionally resistant, dark-toned capping unit of unknown origin (Michalski and Noe Dobrea 2007, Noe Dobrea et al. 2010).

As with all clay minerals detected on Mars, it is also unclear if the Fe/Mg-smectites at Mawrth Vallis are detrital, authigenic, or diagenetic; if the latter is true, then the clay minerals could be much younger than the rocks in which they reside. Regardless of these complexities, it is clear that these strata are very ancient, and their compositional diversity indicates changes in fluid chemistry, parent rock composition, and/or depositional environment. The potential for the Al- to Mg/Fe-clay transition to record the surface weathering process on ancient Mars is particularly intriguing as it would imply the persistent stability of water in the near-surface.

Despite their strong mineral signatures and great areal extent, the modes of emplacement for these rocks are also poorly constrained. Though interpreted as sedimentary in origin (Michalski and Noe Dobrea 2007), the rocks may represent fluvial, lacustrine, altered volcanic ash, eolian, or impact deposits (Loizeau et al. 2007; Michalski and Noe Dobrea 2007; Bishop et al. 2008; Michalski et al. 2010; Noe Dobrea et al. 2010; D Sumner, personal communication, 2011). An origin for some strata, through accretion of impact deposits, is indicated by the occurrence of buried impacts and their adjacent ejecta (Fig. 17). In addition, examination of stratal geometries indicates that impact breccias may form a significant part of the section (Sumner 2010; D Sumner, personal communication, 2011), similar to the stratification present in the Fra Mauro Formation at Silver Spur in the lunar highlands (Lindsay 1972, Cadogan 1981). Primary bedding truncations form depressions that are overlain by draping (not onlapping) layers (Fig. 16B). Such features may have formed by scour and draping related to impact surge deposition, and stratigraphically bound breccias may represent impact deposits. In addition, lenticular pods of breccia are also present, nearly parallel to bedding, and may represent injectities (Fig. 16C). However, rover-based observations of small-scale features such as accretionary lapilli will likely be required to confirm an impact surge origin for these deposits (see Fralick et al., this volume). Postdepositional tectonic overprinting includes extensive low-angle faulting (Fig. 16D) and small block rotation/imbrication (Fig. 16E); in other cases, trains of disharmonic waveforms are present (Fig. 16F). Finally, these already-complex relationships may be
Fig. 15.—Very ancient (Noachian) rocks of Mars. (A) CTX mosaic of Noachian-aged light-toned strata surrounding Mawrth Vallis. Note light-toned outcrops within large crater (Oyama Crater) in lower left of image. (B) False-color close-up of strata exposed in a crater wall in Mawrth Vallis; strata contain clay minerals and other hydrous (sulfate?) minerals; location marked by arrow in A; HiRISE image ESP_016829_2040. (C) False-color close-up of light-toned strata exposed near Mawrth Vallis; rocks contain Al-, Mg-, and Fe-bearing clay minerals; location marked by arrow in A; HiRISE image PSP_001929_2050. (D) CTX mosaic of Noachian-aged units in the Nili Fossae region; the region of lower topography (trough) is a large graben on the western edge of the Isidis Impact Basin. (E) False-color close-up of stratified rocks and breccia exposed in the Nili Fossae trough; rocks in this region contain a variety of clay minerals; location marked by arrow in D; HiRISE image.
overprinted by pervasive high-angle conjugate joint sets (Fig. 16G) and brecciation that obscure primary stratatal geometries and earlier low-angle deformation features.

It is important to note that many of these complex stratatal geometries are observed within a one-crater radius of the edge of Oyama Crater, though similarly complex geometries are also observed farther away in the floor of Mawrth Vallis itself (Fig. 15A). However, strata even farther away from the rim of Oyama, north of Mawrth Vallis, show evidence of noticeably lower strain and may better preserve primary stratification.

**Nili Fossae**: In addition to strata surrounding Mawrth Vallis, rocks exposed within and adjacent to the Nili Fossae region (22°N, 75°E; Fig. 4) are interpreted to represent ancient, aqueously altered crust (Mangold et al. 2007; Mustard et al. 2007, 2009; Ehlmann et al. 2009). Nili Fossae consists of several large concentric grabens that lie to the northwest of the large Isidis Impact Basin, which is centered near 13°N, 88°E. The fossae (grabens) are believed to have formed as a result of tectonic readjustment after the Isidis Impact event at approximately 3.9 Ga, and they cut through and expose several hundred meters of ancient Noachian crust. Unlike the rather uniform and relatively flat stratigraphy found near Mawrth Vallis, the rocks in and around Nili Fossae often exhibit evidence of extreme brecciation and ductile deformation in addition to decameter-scale stratification (Fig. 15D–F). This region of Mars also hosts the widest range of hydroxyl minerals yet observed on Mars, including Mg/Fe-smectite, chlorite, illite/muscovite, kaolinite, zeolite (analcime), sulfates, carbonate, serpentine, prehnite, and opal (Ehlmann et al. 2009). Breciated zones have been interpreted as impact breccia deposits, and the large clasts within these units can exhibit layering and often exhibit mafic spectral signatures (primarily pyroxene) or absorptions consistent with Mg/Fe-clay minerals, as determined from CRISM data (Mustard et al. 2009). In addition to these breccias, some of the strata have experienced ductile deformation, possibly as a result of the Isidis Impact (Mustard et al. 2009) (Fig. 15F).

Despite these complexities, certain outcrops within this region exhibit clear stratification and are consistent with a sedimentary origin. The lowermost strata observed in vertical section in this region exhibit very strong visible–near-infrared absorptions attributed to Mg/Fe-clay minerals (e.g., Mangold et al. 2007, Mustard et al. 2007). These clay-rich units are often succeeded by either olivine-rich deposits, which appear to drape preexisting topography (Mustard et al. 2009), or thin deposits containing kaolinite (Ehlmann et al. 2009). The olivine unit has been interpreted as possible impact melt from the Isidis Basin, which would imply that the strata beneath this unit pre-date that event (Mustard et al. 2007). In some locations the olivine is mixed with Mg/Fe-carbonate, indicating that a period of aqueous alteration occurred after the Isidis Basin had formed (Ehlmann et al. 2009). Such aqueous activity is also supported by the presence of the Jezero delta/alluvial fan complex, which is found to the east of the fossae and also postdates the Isidis Impact event. The stratigraphy of Nili Fossae is rather complex, which is not unexpected for ancient crust that has experienced Late Heavy Bombardment. Nevertheless, this region is intriguing in that it appears to contain aqueously altered Noachian-age igneous, sedimentary, and possibly metamorphic rocks, many of which are covered by younger, unaltered Hesperian lava flows. The preponderance and diversity of hydrous minerals at Nili Fossae, the spatial distribution of those phases, the presence of high-temperature phases (e.g., prehnite), and the proximity to the Isidis Impact Basin have led to the hypothesis that the ancient crust in this region may have been overprinted by impact-induced hydrothermal alteration (e.g., Ehlmann et al. 2009, Mustard et al. 2009). Mg/Fe-clay minerals are found in smaller deposits throughout the ancient southern highlands (Bibring et al. 2006) and they, like those at Nili, may be the result of deep crustal alteration (Murchie et al. 2009b). However, the environments of formation of the stratified clay-bearing rocks at Nili remain unknown, and further research is needed to determine which, if any, of the sections at Nili still preserve information related to ancient sedimentary environments.

**ORIGINS OF MARTIAN STRATA**

The foregoing descriptions make clear that there should be several modes of sedimentation on Mars. For this discussion we exclude pyroclastic deposits, although eruptions on Mars are likely capable of transporting material over much greater distances than on Earth (Wilson and Head 1994), and pyroclastic deposits are most certainly present in the Martian stratigraphic record. Based on surface geomorphology, as observed from orbit, the most obvious transport mechanism is via fluvial networks, often as alluvial fans but occurring locally as meandering rivers in deltas or across plains. In outcrop (e.g., the Burns formation) we see clear evidence for wind-driven bedload transport of sand, and planet-wide dust storms indicate that eolian transport of sediment occurs on a global scale. It is also possible that the upper part of the ~2-m-thick “Home Plate” deposit in Gusev Crater, studied by the Spirit rover, involved eolian reworking of sand-sized volcaniclastic sediments (Lewis et al. 2008b). However, the amount of outcrop collectively studied by the Opportunity and Spirit rovers is trivial. Opportunity’s investigation of the Burns formation established the environmental significance of the uppermost part of the sequence at Meridiani Planum, but it represents only ~2% of the estimated thickness of the sequence (~20 m out of >800 m). This limitation of in situ investigations by rovers highlights the importance and necessity of interpretation based on orbital data in order to understand sedimentary rocks and processes on Mars in a regional and global context. The following section describes the primary modes by which sediment may be transported, concentrated, and converted to rock on Mars, informed largely by orbital observations.

**The Role of Surface Water: Fluvial Networks and Source to Sink**

As described above, many regions in the ancient southern highlands of Mars exhibit extensive fluvial networks. Crater counts indicate that the majority of the fluvial or “valley” networks on Mars were carved during the Noachian period and that valley network formation had largely ceased by the Early Hesperian (Fassett and Head 2008a). It also has been estimated that their formation potentially stripped several thousands of meters of material from the surface of the southern highlands, further evidence for extensive aqueous sediment transport on ancient Mars (Hynek and Phillips 2001). This apparently widespread fluvial activity declined over time, possibly associated with the loss of atmospheric volatiles and associated drop in atmospheric pressure and temperature; only localized fluvial bedrock incision is observed on Late Hesperian and younger surfaces (e.g., Carr 1996, Mangold et al. 2004, Fassett and Head 2008a, Grant and Wilson 2011, Howard and Moore 2011). However, recent crater-counting studies based on new high-resolution images have shown that smaller,
Fig. 16.—Complex stratal geometries at Mawrth Vallis, in the vicinity of the proposed landing ellipse for the Mars Science Laboratory. Location shown in Figure 15A. (A) HiRISE false-color image showing uneven, laterally discontinuous stratification. Transition from beige color in lower part of image to blues and yellows shown in upper part of image corresponds approximately to the Fe–Mg phyllosilicate to Al–phyllosilicate transition. Black boxes show regions highlighted in Figure 16C–G. (B) Stratal truncation surface is overlain by draping strata that contour truncation surface. Location is from axis of Mawrth Vallis, shown in Figure 15A. (C) Pod of breccia appears stratigraphically bound within layered sequence. Note how upper layers bend around pod, indicating a possible origin through injection. (D) Possible low-angle fault, marked by black arrows, penetrates succession, causing offset of strata. (E) Deformation by rotation and/or imbrication of blocks of...
but still substantial, regions of Mars have experienced overland flow, fluvial incision, and channel network formation during Late Hesperian to Amazonian times, indicating a late pulse of fluvial activity (Grant and Wilson 2011, Howard and Moore 2011).

Extensive fluvial erosion of the southern highlands generated significant amounts of sediment. In some cases there was enough to fill >10-km-diameter craters with several hundred meters of material (Craddock and Howard 2002). Eroded landscapes, including the inner walls of craters, achieved channel densities approaching terrestrial values (Irwin and Howard 2002, Mangold et al. 2004). The environment that created such significant erosion and sediment transport is still debated, but many agree that widespread, although episodic, precipitation likely occurred in association with runoff and groundwater seepage (Hynek and Phillips 2003, Howard et al. 2005, Irwin et al. 2008).

One of the longest and largest source-to-sink systems on Mars has its source along the northern rim of the Argyre Impact Basin (50°S, 318°E; Fig. 4) and extends all the way to the northern lowlands, inferred to be the terminal sink. The total length of the outflow system, from where Uzboi Vallis begins near the rim of Argyre to where the outflow system discharges onto the northern plains at Chryse Planitia, is over 4000 km (see Fig. 18). It is hypothesized that fine-grained sediments transported through this and other outflow systems accumulated along the fringe of the northern lowlands, where their burial triggered subsurface mud diapirism (Oehler and Allen, this volume).

A series of valleys and basins, known as the Uzboi–Ladon–Morova network (ULM), link Argyre with the northern lowlands (Fig. 18A). Several ancient craters along this network are interpreted to have once been lakes, and younger craters within the ULM system may also have hosted lakes when their formation blocked the large drainage network (Grant et al. 2008, Grant and Wilson 2011). These impact basins are regarded as significant local sinks for sediments, including clay minerals (Mil liken and Bish 2010). The ancient, heavily eroded Ladon and Holden basins are the largest potential lake basins in the ULM system (Fig. 18B), although younger craters such as the Holden and Eberswalde craters also likely hosted lakes (Fig. 18C). Sedimentary, clay-bearing strata of possible lacustrine origin are preserved throughout Ladon Basin, in terraces in Ladon Vallis (Fig. 18D), and in Eberswalde and Holden craters (Milliken and Bish 2010).

For many locations on Mars the sedimentary record captured within craters and other depressions defines complete erosional–depositional systems, albeit at much smaller scales than the hemispheric-scale system described above. In the Melas Chasma Basin we see a diverse set of geomorphic elements that ranges from the fluvially incised source region in the surrounding highlands to sediment sinks at progressively lower elevations formed by the alluvial fans, shoreline/ delta, and sublacustrine fans in the topographically lowest part of the basin (Fig. 19). On Earth, sediments are moved from their source in the surrounding mountainous areas to their sink in depositional areas by the sediment transport system (Allen 2008). On Mars, fluvial incision of bedrock (Fig. 19A), interpreted by some to be caused by runoff from precipitation, drains the ridges and plains bordering topographic depressions that form sedimentary basins (e.g., Mangold et al. 2004, Howard et al. 2005, Quantin et al. 2005, Grant et al. 2008). Sediments generated during erosion of the upland areas were transported by fluvial drainage systems and formed classic cone-shaped alluvial fans (Fig. 19B) along basin margins, where confined channel flow emerged onto the fan surface (Howard et al. 2005, Quantin et al. 2005).

The preservation of sediments in these fringe alluvial fans depends on whether there is accommodation space available to store the sediment over the long term. Accommodation space can be generated when the graded profile of these streams moves upward in response to a rise in base level or to uplift of the source area (Viseras et al. 2003). The amount of sediment permanently stored in the alluvial fans is likely small compared to the total flux of sediment in the system (Allen 2008). Sediments that passed through the alluvial fans could then be deposited as shoreline deposits if bodies of standing water were present. Clinoforms also developed in some Martian sedimentary basins, which could record a potential shoreline or the upslope channel levee part of a sublacustrine fan (Dromart et al. 2007). In other cases clinoforms are associated with delta progradation (e.g., Eberswalde Delta; Lewis and Aharonson 2008). At Melas Chasma, observed clinoforms (Fig. 19C) give way farther down the topographic profile to a sublacustrine fan (Fig. 19D), very similar in morphology to the Mississippi submarine fan. This ultimate topographic low in the system then provides the terminal sink for the sediments.

In all cases, such as Melas Chasma, these interpretations invoke a significant assumption—that the various elements of the geomorphic system are all the same age. If these features have different ages, then the linkages between elements in the sediment transport system would not necessarily hold. However, even if some of these elements are not the same age, they still represent pieces of the sediment transport system. For example, cross-cutting relationships indicate that there are several generations of valley networks preserved in the ridges surrounding the small basin in Melas Chasma (Quantin et al. 2005). It is not possible to determine which generation of the drainages may have fed the depositional fans currently preserved in the bottom of the basin. Similar to the valley networks, perhaps the currently exposed clinoforms overlie a set of older buried clinoforms that are the same age as the depositional fan. As sediments were transported into the basin, the depositional system could have responded with retrogradation, aggradation, or progradation of the sediment depocenter farther into the basin; these dynamic responses depend on how the incoming sediment flux balances with basin subsidence and lake level (Flemings and Grotzinger 1996, Hodgson et al. 2006).

The Role of Groundwater

Widespread accumulation of sedimentary rocks in regions such as Arabia Terra and Sinus Meridians may have been facilitated by regional groundwater flow, which would have driven oscillations in the water table (Grotzinger et al. 2005, Andrews-Hanna et al. 2010). In turn, such a process could have promoted accumulation of largely wind-blown strata, either as saltation-driven sand sheets or suspended dust that settled during intervals of decreased wind velocities (Fig. 20A). Evaporation of emerging groundwater, possibly brines, would have resulted in the precipitation of evaporites and cementation of eolian sediments. This cementation mechanism could have driven the accumulation of strata, perhaps even above the rims of large craters, if the regional groundwater table rose to sufficiently high elevations.

Arabia Terra is a unique region of Mars wherein elevation values define a broadly depressed surface relative to the southern highlands of Mars (Hynek and Phillips 2001). Groundwater could have sourced from the highlands and would have emerged downgradient, trapping sediments and inducing evaporite sedimentation in Arabia Terra and similar regions (Andrews-Hanna et al. 2010). Such a process could
Fig. 17.—Strata exposed on the gently sloping wall of a crater in the Mawrth Vallis region. Location is the west wall of the impact crater marked in Figure 15A. North is to the right in A and B. (A) Strata in this location have been faulted, and some regions contain localized breccia, likely generated by impacts. (B) An important feature of the strata is an inferred buried impact crater (white arrow). Note dark stratigraphic unit pierced by impact depression that is also marked by overturned strata along right margin (to the upper right of white arrow). Younger strata onlap the margins of this paleo-crater, and bounding strata may represent reworking of impact-derived detritus. HiRISE image ESP_018820_2035.
lead to significant infilling or even overfilling of craters to form extensive stratigraphic sheets (Fig. 20B). Subsequent lowering or drying up of the groundwater system would result in stripping of the section by eolian abrasion. Over very long timescales, this transition from a wet period driven by changes in regional or global groundwater levels to a dry period of eolian denudation could reflect the transition from wet to dry Mars during the Hesperian.

Evidence for groundwater at a local scale is provided by stratigraphic relationships and textural and geochemical data in the Burns formation (Grotzinger et al. 2005, McLennan and Grotzinger 2008). At a more regional scale, evidence for groundwater is provided by fractures filled with possible cements in a number of locations (Okubo and McEwen 2007, Okubo et al. 2009, Anderson and Bell 2010). In addition, rounded, amphitheater-headed canyons that incise the plains along the rim of Valles Marineris are morphologically similar to classic groundwater-sapping features observed on Earth, leading to the hypothesis that similar processes operated on Mars (Pieri 1980). However, recent studies have indicated that such features may instead be carved by catastrophic floods (Lamb et al. 2008). Other evidence for regional groundwater includes the “chaos” terrains of Mars, which are large regions of brecciation and collapse, similar to karst topography and believed to have formed by melting of ground ice (Sharp 1973) or by dissolution of soluble rocks by emerging groundwaters (Carr 1979, Spencer and Croft 1986, Spencer and Fanale 1990). Finally, recent studies of inferred lakes developed in “open” basins—craters or topographic depressions with both an inlet and outlet channel—have indicated that the volume of water in some of these inferred lakes was much greater than can be explained by surface runoff from the surrounding watershed, implying that groundwater played a significant role (Fassett and Head 2008b). It is interesting to note that many of these inferred groundwater-fed paleolakes are located in Arabia Terra, the same region that hosts many of the overfilled craters discussed above (Fig. 8) (Fassett and Head 2008b). Therefore, an active groundwater system may be a crucial component for lithification and net accumulation of thick, crater-filling sedimentary deposits, such as those observed in Henry Crater and elsewhere in this region (e.g., Fig. 20).

Light-Toned Layered Deposits and Their Origins

In addition to the presence of stratification, many of the interpreted sedimentary rocks on Mars are apparent in orbital images because they are light-toned. However, caution must be used with such descriptions. Many images of the Martian surface are acquired as single-band, grayscale images. When processed, these images are often stretched to be more visible at different wavelengths. Therefore, deposits often only appear light-toned or dark-toned when compared to their surroundings. In addition, the true albedo values at visible wavelengths are rarely reported for features observed in MOC, HiRISE, or CTX images. Therefore, deposits that appear “light-toned” in one image may have a true albedo that is higher, equal, or lower than “light-toned” deposits from another image. Indeed, nearly all of Mars is relatively dark in that albedo values are typically <0.35, and most regions are <0.25 (where the highest possible albedo value is 1, meaning 100% of incident light is reflected from the surface). It is also useful to keep in mind that Mars is the “Red Planet,” and deposits that appear light-toned or white in grayscale images are often light-orange, reddish, or brownish tones in true color.

Despite these complications, many of the sedimentary deposits on Mars have the intriguing attribute that they are brighter or “light-toned” at visible wavelengths when compared to their surroundings. The juxtaposition of such deposits against the darker basaltic compositions that typify the Martian crust can be striking. Indeed, this was one of the primary reasons that the enigmatic “White Rock” feature in Pollack Crater (discussed above) was so surprising when first imaged by Mariner 9. Most of the crust of Mars is basaltic (e.g., Taylor and McLennan 2009), and many of the bedrock exposures, sand dunes, and other sediments are relatively dark, as would be expected for basaltic compositions. Therefore, the identification of light-toned rocks, and light-toned stratified bedrock in particular, immediately raises the possibility that nonbasaltic compositions may be present. On a planet with a CO2-rich atmosphere and a clear history of aqueous processes, identification of bright sedimentary deposits sustains hope that hypothesized large carbonate deposits may one day be recognized (compare Kahn [1985] with Milliken et al. [2009] and Michalski and Niles [2010]). Although local occurrences of carbonates have been detected both from orbit (Ehlmann et al. 2008b) and in situ (Boytont et al. 2009, Morris et al. 2010), large carbonate deposits are conspicuously absent; rather, many large, light-toned deposits are known to contain sulfates (Gendrin et al. 2005). This has raised the possibility that Mars and its sedimentary record may have been dominated by a sulfur cycle rather than a carbon cycle (McLennan and Grotzinger 2008; McLennan, this volume).

Although the origin of White Rock is still ambiguous, we now know that it is merely one of many examples of light-toned sedimentary deposits on Mars (Malin and Edgett 2000). Orbital spectroscopy provides a means by which to characterize the composition of these and other deposits, and an increase in the spatial resolution and wavelength range of instruments on Mars missions over the past decade has fundamentally changed our knowledge of their possible origins. Many light-toned deposits identified in high-resolution visible images (MOC, HiRISE, CTX) were below the kilometers/pixel spatial resolution of the TES instrument on MGS. The Thermal Emission Imaging Spectrometer (THEMIS) instrument on Mars Odyssey acquires images at much greater spatial resolutions (~100 m/pixel), but its limited spectral resolution makes unique identification of compositions difficult. However, by combining data from these two thermal infrared systems it has been shown that some small light-toned deposits contain chloride salt (Osterloo et al. 2008). As discussed above, the advent of even higher spatial and spectral visible–near-infrared spectrometers in orbit around Mars has provided greater insight into the compositions, and thus the processes, that may have formed light-toned deposits.

As with TES, the rather coarse spatial resolution of data acquired by the visible–near-infrared OMEGA spectrometer (often several kilometers/pixel) precluded mineralogical identification in many of the smaller or thinly bedded light-toned deposits. However, the OMEGA data were revolutionary in that they revealed the widespread presence of hydrous minerals in regionally extensive intermediate- and light-toned deposits, including clay minerals in very ancient strata (e.g., Mawrth Vallis; Poulet et al. 2005) and sulfate salts in plains covering deposits (e.g., Sinus Meridiani; Gendrin et al. 2005). The large and often light-toned ILD in Valles Marineris were also found to contain hydrated sulfates and Fe-oxides (Gendrin et al. 2005, Le Deit et al. 2008, Mangold et al. 2008). In addition to these areally extensive deposits of light-toned strata, higher spatial resolution OMEGA data (~250 m/pixel) revealed the presence of hydrous minerals in some smaller light-toned deposits, hinting at the rewards that higher spatial resolution spectral data would offer. These rewards were realized in 2006 when the visible–near-infrared CRISM instrument on the MRO spacecraft began to return images in 544 channels over the 0.35 to 4–μm wavelength region at a maximum resolution of ~18 m/pixel.

Studies utilizing CRISM data have built on those based on OMEGA data to show that many of the light-toned deposits identified on Mars contain hydrous minerals and that the diversity of hydrous minerals is much greater than previously recognized (Mustard et al. 2008, Murchie et al. 2009b). Specifically, the high-resolution CRISM data have revealed previously unrecognized occurrences of clay minerals in spatially restricted light-toned outcrops of the Eberswalde and Jezero deposits (Ehlmann et al. 2008a, Milliken and Bish 2010), opaline silica in thinly bedded strata adjacent to Valles Marineris (Milliken et al. 2008a).
FIG. 18.—The Uzboi–Ladon–Morava (ULM) fluvial–lacustrine transport system. (A) MOLA elevation on THEMIS day infrared mosaic, showing the low elevation of the ULM system relative to the surrounding ancient highlands. The ULM system was once through-going from the northern rim of the Argyre Impact Basin to Chryse Planitia at the edge of the northern lowlands, but it was blocked at one point by the formation of Holden Crater (see C). Much of the channel system exhibits evidence for sedimentary fill and multiple episodes of incision. (B) Close-up of the ancient Ladon Basin, which has been filled with sediment of an unknown thickness that is known to contain clay minerals (Milliken and Bish 2010); numerous fluvial features are found along the heavily degraded rim and wall. (C) Close-up of Eberswalde Crater, Holden Crater, and the more ancient Holden Basin; breach of Uzboi Vallis into Holden Crater is visible in the southwest portion of the image;
The occurrence of hydrous minerals in these and other light-toned deposits implies that these strata record a much more complex geologic history than do the typical lava flows associated with Martian volcanism. However, in many (perhaps most) cases the origin of these minerals is unclear. Are they secondary minerals produced by in situ surface alteration of primary mafic minerals? Were they precipitated directly out of bodies of standing water? Do they occur as pore-filling cements formed by fluctuating groundwater levels, or are they precipitated out of bodies of standing water? Answering questions such as these is critical in order to determine the origin of the light-toned deposits in which some of these minerals reside, but such questions are exceedingly difficult to answer when limited to orbital data. In the case of the light-toned sulfate and hematite-bearing rocks detected from orbit in Sinus Meridiani, the Opportunity rover was able to perform in situ investigations to place tighter constraints on their origin, as discussed above. But what, if anything, does this imply about light-toned, sulfate-bearing rocks identified elsewhere on Mars? The transition between light- and dark-toned rocks in Sinus Meridiani examined by Opportunity was shown to result in part from the presence of a diagenetic contact that cuts across bedding (see Whatanga contact in Fig. 14; Grotzinger et al. 2005). The true relationship between the dark–light tone transition and actual bedding is not apparent from orbital images. Elsewhere on Mars, many light-toned strata are overlain, underlain, or interbedded with dark-toned strata, and although the sharpness of these contacts often appears to represent bedding, it cannot be ruled out that these transitions are not bedding contacts at all, but rather the result of overprinting by diagenesis.

A major step forward in determining the origin of light-toned deposits would be to determine the mineral abundances in these rocks and whether the alteration and secondary minerals in each deposit are detrital, authigenic, or diagenetic. Using the sulfate-bearing ILD in Valles Marineris as an example, the determination that sulfates comprise 30% of the rocks would be consistent with pore-filling cements, possibly indicating an origin similar to the sulfate-cemented sandstones in Meridiani Planum. However, if the rocks are determined to contain more sulfate than can be accommodated in pore space (i.e., >30%), then direct precipitation from a body of standing water may better explain their origin. Unfortunately, the process of deriving accurate mineral abundances from VNIR data can be highly nonlinear, and the uncertainties based on current models are rather large and poorly constrained for fine-grained sediments (though recent attempts at modeling OMEGA data have been made by Poulet et al. [2008]). Additional laboratory experiments and modeling are needed for this possibility to reach its full potential.

Similarly, determining whether hydrous minerals, especially clay minerals, in a given rock are detrital or authigenic can be challenging when examining the terrestrial rock record, and the problem could be intractable for Mars when limited to orbital data. Clay minerals detected in the bottomsets of the Eberswalde Delta are spectrally similar to clay mineral signatures in the surrounding watersheds, indicating that at least some of the clays in the delta are detrital (Milliken and Bish 2010). However, the presence of neoformed clays in the deltaic strata cannot be ruled out. Similarly, whether the strong clay mineral signatures at Mawrth Vallis represent concentration of transported, fine-grained sediment or in situ alteration of primary mafic deposits such as volcanic ash remains unknown (Loizeau et al. 2007, Michalski and Noe Dobrea 2007, Bishop et al. 2008). Despite these ambiguities, it is clear that light-toned stratified deposits on Mars are diverse in their mineralogy and were likely formed in a wide range of depositional environments, even though the context and evidence for a specific environment are not always clear from orbit.

We conclude our discussion on light-toned deposits by noting that there is not a one-to-one correlation between detections of hydrous minerals and light-toned strata. In fact, many occurrences of clays and sulfates on Mars are not associated with light-toned materials at all, and some occur in rocks that lack clear stratification altogether. The converse is also true, in that not all light-toned rocks on Mars exhibit spectral signatures diagnostic of hydrous or mafic minerals. Even the enigmatic White Rock deposit itself, which is intermediate- to light-toned when compared to its immediate surroundings, appears to be spectrally bland (Ruff et al. 2001). The origin and composition of such deposits remain unknown, but one possibility is that they represent deposits of poorly lithified dust, or “duststones” (Bridges and Muhls, this volume).

Martian Duststones

The striking red color of Mars is due primarily to the ubiquity of fine-grained, Fe-oxide–bearing dust that coats much of the surface in a layer that is optically thick at visible wavelengths, though possibly only several hundreds of micrometers thick by measurement (Fig. 21). Significant amounts of dust are mobilized by typical local and regional winds and also by global dust storms. Several decades of spacecraft observations have shown that bright and dark regions on Mars are not necessarily fixed; some dark regions become coated with dust over time, and other regions are blown free of dust (Christensen 1988, Geissler 2005, Szwest et al. 2006, Fenton et al. 2007). Indeed, it is safe to say that eolian transport of dust has played a significant role in the Martian sediment cycle for hundreds of millions and possibly billions of years (Bridges and Muhls, this volume). Dust-sized particles (2–5 μm; Kahn et al. 1992, Lemmon et al. 2004) are constantly transported across the surface, and it is estimated that 2.9 x 10^{12} kg/yr is exchanged between the surface and atmosphere (Pollack et al. 1977). Rover measurements have shown that the major constituents of this material are consistent with pulverized, unaltered basalt (Goetz 2005, Hamilton and Christensen 2005). Perhaps this is not unexpected on a planet where liquid water has apparently been unstable or meta-stable in the near-surface for several billion years, but the lack of abundant liquid water does not preclude the possibility that this dust can make a significant contribution to the rock record. One final point about these dust particles is that they may become aggregated to form larger silt- or sand-sized particles that may then become transported by saltation as well as suspension (Herkenhoff et al. 2008a, Sullivan 2008). Aggregation of these particles may be stimulated by electrostatic forces or weak cementation during gas exchange and condensation in soils.

Accumulation and compaction of dust, perhaps aided by precipitation of salts from thin films of water along grain boundaries, could form weakly lithified strata. If composed primarily of dust, these

Note that the formation of Holden Crater blocked water flow through the larger ULM system. (D) Close-up of finely stratified and clay-bearing outcrops exposed in a terrace in Ladon Vallis where it enters Ladon Basin along the southern rim; location marked by arrow in B; HiRISE image PSP_006637_1590.
Fig. 19.—Cartoon of the Melas Basin source-to-sink system (after Metz et al. 2009a). (A) Upper reaches of the system show a well-developed tributary network cut into bedrock (HiRISE image PSP_005452_1700) that passes downslope into (B) an alluvial fan complex (CTX image B10_013561_1704_XN_09S076W). This passes farther downslope into a set of (C) clinoforms, the origin of which—although uncertain—could represent a deltaic or shoreline deposit (HiRISE image PSP_008735_1700). The terminal sediment sink (D) is represented by a set of inferred sublacustrine fans (HiRISE image PSP_007667_1700). The accompanying images come from successively lower geomorphic/sedimentologic positions within the Melas Basin.
“duststones” may be akin to terrestrial mudrocks with regard to their particle size, but they would be inherently different in that they would be dominated by physically, and not chemically, weathered particles (Bridges and Muhs, this volume). Unlike on Earth, the clay size fraction of dust on Mars may be lacking in actual clay minerals, if it has any at all. Therefore, Martian duststones may be hard to identify on Mars based solely on mineralogy, as derived from spectral observations. In fact, the apparent lack of unique spectral signatures may be one of their defining characteristics. Strata such as those at the top of the Gale Crater mound and in some craters in Arabia Terra are rhythmically bedded (Lewis et al. 2008a, Lewis 2009) and are often spectrally “bland.” Their VNIR spectra are often equivalent to that of typical Martian dust, and they lack absorption features diagnostic of hydrous minerals. This could be caused by the presence of a thin dust cover, but it could also indicate that these rocks are composed of material that is compositionally equivalent to Martian dust.

Rocks such as these could be duststones that capture information about the dry climate of the past several billion years in the Martian rock record. The amount, source regions, lofting, and transport distance of dust can be directly related to atmospheric properties. Thus,
if some Martian strata are composed largely of this material, then these rocks could act as ancient climatically sensitive deposits (Lewis et al. 2008a). As such, this type of stratified sedimentary rock, with its distinct set of characteristics, may also have a distinct origin. The nature and origins of these duststones are discussed in greater detail by Bridges and Muhs (this volume). The essential point is that Mars may have produced significant quantities of fine-grained sediments early in its history as a result of impact fracturing of bedrock, in addition to volcanism. Over time, the flux of both sediment sources would have been reduced. Remobilization by winds and subsequent deposition would have created duststone deposits wherever circulation patterns preferred net accumulation over geologically significant timescales. Today, this process may still be in effect, albeit at much lower rates and with a depocenter represented by the northern plains of Mars.

Lithification, Burial, and Diagenesis

An important question in sedimentary geology is how sediments undergo conversion to rock. On Earth, the circulation of pore fluids upon burial creates the geochemical environment in which most lithification occurs (in addition to diagenetic transformations). The pore space in sedimentary rocks of Precambrian age is often entirely occluded. In contrast, the absence of both an atmosphere and subsurface water on the Moon insures that 4.4 billion–year-old impact-generated deposits have not been cemented by aqueous processes (Carrier et al. 1991). Mars, it seems, is somewhere in between.

There is evidence that some cementation and lithification have occurred on Mars, perhaps pervasively over broad regions, but there is little evidence that this has ever occurred as completely as on Earth. Diverse observations constitute evidence for cementation and lithification of Martian sediments. These include preservation of resistant, cliff-forming outcrops of stratified light-toned materials (Malin and Edgett 2000); occurrence of hydrous minerals in outcrops of stratified light-toned materials (Gendrin et al. 2005); thermal inertia of stratified materials (Christensen et al. 2001, Putzig et al. 2005, Fergason et al. 2006, Edwards et al. 2009); and observation ofprobable cements and diagenetic fronts in outcrop (Grotzinger et al. 2005; McLennan and Grotzinger 2005; Squyres et al. 2007; Metz et al. 2009b; Edgar et al., this volume). Of these, the thermal inertia values for globally distributed layered deposits may best capture the degree of regional or global lithification. Interestingly, the majority of thermal inertia values for the Martian surface, including many light-toned layered deposits, are lower than would be expected for completely lithified rock, indicating relatively low rock densities (Fergason et al. 2006, Edwards et al. 2009) and possibly higher preserved porosities. TES-derived thermal inertia values for White Rock, for instance, were shown to be inconsistent with either loose dust or well-cemented bedrock (Ruff et al. 2001). Similarly, thermal inertia values for stratified deposits in Hebes Chasma are too low to be consistent with well-lithified rock and are more consistent with poorly cemented or highly porous eolian or volcanic sediments (Fergason et al. 2006). The general paucity of high thermal inertia surfaces on Mars (Edwards et al. 2009) is supported by the absence of rock fall talus adjacent to cliff-forming outcrops, which is observed for many light-toned stratified deposits in Gusev Crater and are more consistent with poorly cemented or highly porous eolian or volcanic sediments (Fergason et al. 2006).

The general paucity of high thermal inertia surfaces on Mars (Edwards et al. 2009) is supported by the absence of rock fall talus adjacent to cliff-forming outcrops, which is observed for many light-toned stratified deposits in Gusev Crater and are more consistent with poorly cemented or highly porous eolian or volcanic sediments (Fergason et al. 2006).

Direct observations by Opportunity and Spirit indicate that stratified outcrops formed of granular materials contain pore-filling materials, interpreted to represent cements or cemented matrix sediment. However, deposits at both Meridiani Planum and Home Plate (an outcrop in Gusev Crater) exhibit textural evidence for the presence of significant porosity (McLennan et al. 2005; McLennan and Grotzinger 2008); possible volcaniclastic sediments in Gusev Crater may possibly have been remobilized by winds and subsequent deposition would have created duststone deposits wherever circulation patterns preferred net accumulation over geologically significant timescales. Today, this process may still be in effect, albeit at much lower rates and with a depocenter represented by the northern plains of Mars.

Fig. 21.—Dust on Mars can form irregularly shaped aggregates of silt- to sand-sized particles. These aggregates are easily crushed and molded by the ~1-N contact force generated by the Mössbauer plate. The image spans approximately 31 mm in width. Microscopic Imager image 2M147677362IIF8800P2976M2F1 taken on sol 240 by the Opportunity rover (see Herkenhoff et al. 2008b).
spectral data indicate that the ILD contain highly soluble Mg-sulfates (Gendrin et al. 2005, Mangold et al. 2008, Murchie et al. 2009a), raising the possibility that some of these rocks may have been dissolved and recrystallized after their initial formation. In addition, even a low, early geothermal gradient of 12 °C/km (McSween et al. 2011) would imply temperatures conducive to diagenesis and mineral transitions at the great depths experienced by strata at the base of kilometers-thick ILD in Valles Marineris or clays at the base of the Gale Crater mound.

The detection of clay minerals on Mars, and specifically smectites (Poulet et al. 2005), is of particular interest in this context. On Earth, the vast majority of smectites are ultimately converted to illite or chlorite during burial diagenesis. The extent and rate of reaction depend on factors such as time, temperature, and fluid chemistry, and intermediate products include mixed-layered illite/smectite or chlorite/smectite (see Srodon [1999]) for a review on terrestrial mixed-layered clays). The oldest sequences on Earth may be on the order of 600 million years old (Bristow et al. 2009), yet the vast majority of clays on Mars are believed to have formed over 3.5 billion years ago (Bibring et al. 2006). This raises the questions of whether or not mixed-layered clays are present on Mars and to what extent burial diagenesis may have occurred in clay-bearing sedimentary rocks (McSween et al. 2011, Milliken et al. 2011). Given the interpreted age of the clay minerals, time is not a limiting factor, and it is unlikely that temperature is a limiting factor for clays at the base of thick sequences, such as in Gale Crater. Therefore, a lack of mineralogic evidence for diagenesis may indicate that chemical sediments on Mars are juvenile and have had little if any interaction with water since their formation (Tosca and Knoll 2009). However, recent analyses of CRISM data indicate that mixed-layered chlorite/smectite, and thus diagenesis, may indeed be more common on Mars than was previously recognized (Milliken et al. 2011). Ultimately, the role and extent of diagenesis on Mars remains an open question, yet it is an extremely important one when assessing the preservation potential of organic compounds in Martian sediments, especially given the often destructive effects of diagenesis.

MINERALOGY AND STRATIGRAPHY: TOWARD A GEOLOGIC TIMESCALE

Martian Mineral Stratigraphy

On Earth, the great majority of stratified rocks are of sedimentary origin and have formed as a result of accumulation of loose particles, including precipitated minerals. Stratigraphic studies traditionally have focused on the correlation of spatially separated successions of sedimentary rocks for the purpose of establishing a temporally comprehensive record of Earth history—the geologic timescale. The geologic timescale has two components: a relative timescale based on correlation of stratigraphic successions and an absolute timescale based on geochronologic calibration of key tie points that link those successions (Gradstein et al. 2004). Correlation commonly is achieved by delineating temporal trends in the successions of fossils, chemical markers, and magnetic properties. Radiometric age determination of volcanic rocks interspersed with sedimentary rocks provides absolute age control for even the oldest successions of terrestrial strata. Advances in U-Pb zircon dating have revolutionized calibration of the Precambrian timescale so that events may now be constrained to ±10^5 years (Bowring et al. 2007).

For Mars, the same principles apply; a relative sequence of superimposed and cross-cutting rocks (terrains with distinct properties) is established (Scott and Tanaka 1986, Greeley and Guest 1987, Nimmo and Tanaka 2005), and this record is then calibrated in “absolute” time using crater counting (Hartmann and Neukum 2001). In comparison to Earth, the geologic timescale for Mars is far less well resolved. This stems from a lack of precision with both the ordering of events (relative component) and the absence of direct geochronologic calibration of those events (absolute component). In contrast to lunar rocks returned by the Apollo program, age-dating of Martian meteorites provides little help because the locations on Mars from which these rocks come are unknown. For the near future, there is little prospect for an improved measurement scheme for absolute dating of strata on Mars. In contrast, the past decade of global mapping and the ongoing MRO mission offer the chance for a significant improvement in the relative component of the Martian geologic timescale. This will likely improve precision in understanding the relative order of regional geomorphic and compositional terrains on Mars. New high-resolution data (e.g., HiRISE) provide the capability to produce a high-fidelity relative timescale for individual sedimentary deposits that was previously not possible. In turn, this could enable correlation within more highly deformed terrains, which remains problematic.

Most recently, our understanding of the geologic history of Mars has taken a fresh turn as a result of the discoveries by ongoing missions such as Mars Express and MRO. Mars may have a distinct history of aqueous events that left distinct time-dependent patterns embedded within the rock record (Fig. 22), and recent studies have attempted to classify deposits based on distinct mineral assemblages, as observed from orbit (e.g., Murchie et al. 2009b). A rising paradigm is that the long-term environmental evolution of Mars is captured in its history of mineral assemblages (Bibring et al. 2006). In this hypothesis, Mars began as a planet characterized by aqueous alteration of impact-brecciated, primary ancient crust under pH conditions that were conducive to the formation of clay minerals. Subsequently, it transitioned to a drier and more acidic environment that resulted in the formation of vasty extensive bedded sulfate minerals, and ultimately it transitioned to a dry and cold planet dominated by the accumulation of anhydrous iron oxides, as is observed today (Bibring et al. 2006, Murchie et al. 2009b). The foundation for this hypothesis is the apparent temporal separation of these mineral assemblages. Phyllosilicates are most commonly found in Noachian-age terrains, sulfates are primarily associated with younger Hesperian terrains, and anhydrous Fe-oxides are dominant in Amazonian terrains; Bibring et al. (2006) refer to these “mineralogical” time periods as the phyllosian, theiikian, and siderikian, respectively (Figs. 2, 22).

In order for this model for hydrous environmental evolution to be correct, the age of the observed alteration minerals must be closely related in age to the strata in which they now reside, and the observations themselves must stand up to independent testing. This is a delicate proposition given the difficulty in assessing the age of alteration minerals relative to their parent rocks, but it strongly motivates research aimed at evaluating the evolutionary record and testing the ordering and environmental history of stratified deposits. Though new for Mars, the importance of unique mineral assemblages in defining environmental breakpoints in the geologic timescale is not without precedent. It is in exactly this mode that the geologic history of Earth was established, for example, based on recognition of the temporal restriction of Precambrian banded iron formation; distinct mineral deposits with profound environmental significance, in that case signaling progressive oxygenation of Earth’s atmosphere and oceans (Knoll et al. 2004). In the course of construction of the Phanerozoic geologic timescale the mineralogic name “Cretaceous” (from the Latin “creta,” for chalk) was applied to that period of time in which chalks were noted to be particularly abundant.

The determination of similar patterns in the geologic history of Mars offers the same promise of insight into early environmental evolution, and one of the goals of future research will be to continue to work

---

6As used by the Mars community of scientists, the term “geomorphic” connotes all surface textural properties of rocks on Mars, including stratal geometries and scales of bedding of sedimentary rocks, in addition to its more traditional use on Earth, where emphasis is placed mostly on terrain surface morphology.
toward establishing the relative chronology of different types of stratified deposits. In this context, we now highlight several localities on Mars that could provide key reference sections for refining the Martian geologic timescale.

**Orbital Facies and Environmental History**

The categories of Martian sedimentary rocks described above (underfilled basins, overfilled craters, chasma/canyon deposits, plains covering deposits, very ancient strata) were defined based on their large-scale geomorphic context. Similarly, Murchie et al. (2009b) recently discussed and defined 10 classes of deposits on Mars based primarily on mineral assemblages indicative of aqueous alteration. However, the preceding discussion makes it clear that both the mineral assemblages in the Martian sedimentary rock record as well as their bedding-scale textural attributes are important distinguishing attributes for classification. Together, mineralogy and texture/morphology provide critical information about petrogenesis; in turn, this informs our understanding of depositional environments and paleoclimate, the water–rock ratios involved in diagenesis, aqueous geochemistry, and how these factors have changed throughout the history of the planet. We now integrate the textural/morphologic and mineralogical aspects of Martian sedimentary strata to define several distinct “orbital facies.”

Similar to terrestrial facies defined on the basis of outcrop observations (Walker and James 1992) or Martian facies defined on the basis of rover-based in situ observations (Grotzinger et al. 2005), these “orbital facies” are defined and characterized by distinctive attributes of deposits observed from orbit. However, in contrast to terrestrial and Martian facies schemes derived from outcrop-scale observations, these
orbital facies cannot offer the same resolution of insight into past depositional or diagenetic processes. As a result of the inherent limitations of orbital data, the specific depositional environment(s) or formation conditions of the rocks in question are often unknown; thus, these conditions need not be unique to each orbital facies. Rather, each orbital facies represents a rock type or group of rock types that exhibits similar attributes in visible images (texture/morphology) and/or VNIR data (mineralogy). We discuss below the major orbital facies that we have identified on Mars and their relationships to what we believe are key stratigraphic sections (“reference” sections). Because the characteristics we use to define these orbital facies are primarily objective, we do not assume a priori that certain orbital facies are restricted in either time or space, and key sections may contain more than one orbital facies. Indeed, our goal is to determine which orbital facies are present in the different reference sections. Coupled with the inferred age of these reference sections, we can then attempt to determine whether or not certain orbital facies are restricted to specific time intervals or whether there are spatial transitions in dominant orbital facies for a constant time interval. We now briefly describe each orbital facies (see Table 1); this is followed by a discussion of several stratigraphic reference sections (or regions) on Mars that could act as key tie points for refining the Martian geologic timescale.

**Massive Breccia (MBR):** This orbital facies consists of rock units that contain breccia blocks with diameters commonly in the range of <1 to ~100 m that are present in a finer-grained matrix. Units are massive and marked by poorly expressed layering that occurs at a scale of tens of meters in thickness; ductile deformation, including recumbent folding, may also be present. These units are variable in their tonality, laterally discontinuous, and are known to contain mafic and/or clay minerals. Though the definition of this facies does not assume an origin, many such deposits have been interpreted as impact breccias. The reference section for this orbital facies can be found in the walls of the Nili Fossae (~73.6°E, 20.0°N; see Mustard et al. [2009] for examples).

**Complexly Stratified Clay (CSC):** The defining characteristics of this orbital facies are units that exhibit generally thin (often <10-m), light-toned layers that are known to contain clay minerals. The composition of clay minerals can be variable (e.g., Mg-, Fe-, or Al-rich varieties). The reference section for this orbital facies is within and adjacent to the landing ellipse that was proposed for Mars Science Laboratory (MSL) near Mawrth Vallis (~29°N, 341°E), although other examples can be found within Mawrth Vallis itself as well as in the surrounding plains (e.g., Poulet et al. 2005, Michalski and Noe Dobrea 2007) (Fig. 16A).

Though the areal extent of the clay-bearing rock body is significant (>80,000 km²), the strata themselves are generally discontinuous when traced over hundreds of meters to kilometer-length scales. Stratigraphic geometries can be very complex as a result of primary erosional truncation as well as postdepositional deformation (Fig. 16B–G). In the case of Mawrth Vallis, and as discussed above, many of the observed complex stratigraphic geometries are proximal to Oyama Crater, whereas deposits farther from Oyama exhibit less strain and may better preserve primary stratification. We propose that the latter examples constitute a less-deformed subsurface of the CSC orbital facies. Future mapping could determine which is more dominant. We cannot tell at this time if the inferred lower strain of the CSC subsurface is simply due to distance from Oyama Crater or rather relates to variability within a facies mosaic created by Noachian impact-induced erosional, depositional, and subsequently overprinting deformational events. The risk of impacts predicted during Late Heavy Bombardment implies that all such processes may have been happening more or less simultaneously on Mars at that time.

**Laterally Continuous Sulfate (LCS):** Highly variable bed thickness (~1 to ~100 m), presence of sulfate minerals often associated with Fe-oxides, and great lateral and/or vertical extent of layering are the primary characteristics of this facies. Planar bedding is the dominant primary stratigraphic geometry observed (this excludes postdepositional deformation). Units are commonly light-toned, etched and wind-scoured, and friable. Units formed by this orbital facies can be exposed over hundreds of kilometers and can approach several kilometers in thickness. Apparent massive beds may be the result of amalgamation of thinner beds or may be due to the resolution limitations of orbital images. Type examples can be found in the ILD of Valles Marineris (e.g., Gendrin et al. 2005) and in Sinus Meridiani (e.g., Edgett et al. 2007).

**Laterally Continuous Heterolithic (LCH):** This facies consists of units that exhibit thin, cliff-forming beds (~1 to <10 m) and that can be traced laterally for tens to hundreds of kilometers. Planar bedding is the dominant primary stratigraphic geometry observed. In contrast to the laterally continuous clay and sulfate strata, units in this facies can contain opal, sulfates, or clay minerals or can lack spectral signatures indicative of hydrous minerals. In addition to the thin bedding, another defining characteristic of layers in this facies is their variated tonality. Strata vary from light-toned to very dark-toned vertically through a section, sometimes bed by bed. Type examples include opal-/sulfate-bearing strata along the plains west of Juventae Chasma (Milliken et al. 2008, Weitz et al. 2010) and clay-bearing strata in Ladon Vallis (Milliken and Bish 2010) (compare Fig. 12B, D and Fig. 18D).

**Distributary Network (DNW):** Units in the “distributary network” orbital facies are characterized by moderately thick layers (commonly 5–20 m), the tonality of which ranges from light to moderately dark. These layers can contain clay minerals, carbonate, or other hydrous minerals, but many examples also lack spectral evidence for hydrous phases. The defining aspect of this facies is the occurrence of depositional bodies in clear association with distributary channel systems. In addition, nonplanar stratigraphic geometries are present and may include well-developed clinoforms with slopes in excess of several degrees. This facies includes alluvial fan, deltaic, and sublacustrine fan deposits. Type examples include Holden Crater (alluvial fans; Grant et al. 2008), Eberswalde Crater (delta; Malin and Edgett 2003), Jezero Crater (delta; Fassett and Head 2005, Ehlmann et al. 2008), and the southwest Melas Basin (sublacustrine fan; Metz et al. 2009a).

**Rhythmite (RHY):** Primary attributes of the “rhythmite” facies are very thin (~1–5 m) beds that exhibit a repeatable thickness (are rhythmic) within a vertical sequence and that often lack spectral signatures indicative of sulfate, clay, or other hydrous phases. Planar bedded stratigraphic geometries dominate, perhaps uniquely so. Visible–near-infrared spectra are similar to typical Martian dust, indicating that these units are either composed of dust or covered by an optically thick veneer of dust. Type localities include craters within Arabia Terra (e.g., Bucquoyel Crater; Lewis et al. 2008a) and the Upper formation of the Gale Crater mound (Lewis 2009, Milliken et al. 2010).

**Key Reference Sections**

**Mawrth Vallis and Nili Fossae:** The ancient Noachian crust of Mars contains a multitude of outcrops of clay mineral-bearing rocks (Bibring et al. 2006, Mustard et al. 2008, Murchie et al. 2009b), and the two largest expanses of clay-bearing terrains on Mars are found in the regions surrounding Mawrth Vallis and Nili Fossae (Poulet et al. 2005). The section at Mawrth Vallis is dominated by the CSC facies, whereas rocks at Nili are best characterized as MBR orbital facies and local occurrences of the CSC orbital facies (Fig. 23). At Mawrth, much of
<table>
<thead>
<tr>
<th>Orbital facies name:</th>
<th>Massive Breccia</th>
<th>Complexly Stratified Clay</th>
<th>Laterally Continuous Sulfate strata</th>
<th>Laterally Continuous Heterolithic strata</th>
<th>Distributary Network</th>
<th>Rhythmite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abbreviation</td>
<td>MBR</td>
<td>CSC</td>
<td>LCS</td>
<td>LCH</td>
<td>DNW</td>
<td>RHY</td>
</tr>
<tr>
<td>Stratification</td>
<td>Discontinuous stratification on hundreds of meters–to kilometer-length scale; large breccia blocks in massive matrix; ductile deformation including recumbent folding; massive layering</td>
<td>Discontinuous stratification on hundreds of meters–to kilometer-length scale; forms successions up to a few hundred meters in thickness; stratified breccia; thin bedding; irregular bedding associated with buried impact craters</td>
<td>Beds extend laterally for &gt;10 km; forms successions that can exceed hundreds of meters in thickness; bed thickness highly variable; easily eroded</td>
<td>Laterally extensive for tens to hundreds of kilometers; forms successions up to ~100 m in thickness; thin and variegated (alternating light/dark) bedding; cliff-forming</td>
<td>Close association with bedrock channels and upstream contributory networks; deposits traceable over 1 km to tens of kilometers; beds locally discontinuous</td>
<td>Extreme lateral continuity of bedding, &gt; tens of kilometers; forms successions in excess of hundreds of meters; uniform bed thickness distributions; apparent lack of hydrous minerals</td>
</tr>
<tr>
<td>Dominant mineralogy</td>
<td>Mafic, clay minerals</td>
<td>Clay minerals</td>
<td>Sulfates, Fe-oxides</td>
<td>Opal, sulfates, clay minerals</td>
<td>Clay minerals, anhydrous phases</td>
<td>Anhydrous phases</td>
</tr>
<tr>
<td>Representative bed thickness</td>
<td>&gt;10 m to massive</td>
<td>&lt;10 m</td>
<td>&lt;10 m to tens of meters</td>
<td>&lt;10 m</td>
<td>&lt;20 m</td>
<td>1 to ~5 m typically</td>
</tr>
<tr>
<td>Tonality</td>
<td>Variable</td>
<td>Generally light</td>
<td>Generally light</td>
<td>Light to dark</td>
<td>Light to moderately dark</td>
<td>Light to intermediate</td>
</tr>
<tr>
<td>Reference locality</td>
<td>Nili Fossae</td>
<td>Mawrth Vallis</td>
<td>Sinus Meridians; ILD; Gale Lower formation</td>
<td>Ladon Vallis; plains surrounding Valles Marineris</td>
<td>Eberswalde Crater; Holden Crater</td>
<td>Becquerel; Gale Upper formation</td>
</tr>
<tr>
<td>Example figures</td>
<td>Figure 15E, F</td>
<td>Figure 15B, C</td>
<td>Figures 5A, B; 11; 12F; 13</td>
<td>Figures 12A–D; 18D</td>
<td>Figure 6</td>
<td>Figures 5C, D; 9; 10</td>
</tr>
</tbody>
</table>
Fig. 23.—Correlation of stratigraphic reference sections on Mars at a regional to global scale. Orbital facies identified in each section are also noted. Oldest (Noachian) sections are dominated by MBR and CSC facies, whereas younger (Hesperian–Amazonian) sections are dominated by LCS and RHY orbital facies. However, important outcrops of clay-bearing DNW facies are also present in post-Noachian terrains and may be contemporaneous with LCS and RHY facies (e.g., stratigraphic section for ULM system). See text for detailed description and discussion of orbital facies and key sections. Angled lines indicate that one or more units may be present at a given stratigraphic position (e.g., dark flood deposits and dark capping unit at the top of the ULM section). This figure is purely schematic; individual sections and units are not to scale.
the section is heavily fractured and affected by low-angle to high-angle faulting, possibly as a result of post depositional impact events. In addition, depositional breccias related to impact processes may be present, but they appear to be uniform in mineralogical composition. In contrast, MBR units at Nili Fossae include polymict breccias with both mafic and clay-rich clasts (some of which are themselves stratified) and highly deformed zones, all capped by younger (Hesperian) lava flows (e.g., Mustard et al. 2009). At Mawrth Vallis, parallel stratal geometries with significant lateral continuity indicate that a CSC subfacies is present, but it is not yet clear if this subfacies also exists in the Nili Fossae region.

It is intriguing that these rocks, which are among the oldest on the planet, also host the strongest clay–mineral signatures observed from orbit, indicating that alteration by circum-neutral pH fluids was widespread on ancient Mars. The mineralogy and age of both locations indicates early conditions that were favorable to the formation of smectitic clay, but overlying mineral assemblages indicate that later environmental conditions may have differed between these two regions. As discussed above, the original depositional environment(s) of any possible sedimentary rocks, other than impact deposits, in these regions are currently unconstrained, although much of the stratigraphy is believed to have formed over ~3.6 Gyr ago in the Noachian Era. The ambiguity in the origins of these deposits is not unexpected given their antiquity, the effects of the Late Heavy Bombardment, and the limitations of orbital data. Furthermore, it seems that any future work on the stratigraphy of these sites will have to wrestle with palinspastic reconstruction of overprinting deformation events in order to reconstruct primary depositional geometries. However, it is clear that these regions are important stratigraphic tie points because they likely record global processes that were occurring on early Mars: large and small impact events, deformation, erosion, and aqueous alteration of primary crust. Sedimentation by processes other than impacts may have occurred but has not yet been documented. Indeed, the Noachian rock record of Mars may largely be a product of aqueous alteration of primary basaltic crust punctuated and significantly overprinted by impact events. The orbital facies in the stratigraphic reference sections at both Mawrth Vallis and Nili Fossae likely record these events.

**Sinus Meridiani:** Strata at Sinus Meridiani, the upper part of which includes the 10 to 20 m of the Burns formation examined by **Opportunity**, are dominated by the LCS facies (Fig. 23). Orbital data indicate that these rocks contain sulfate and Fe-oxide minerals, and rover observations have shown that at least part of this section occurs as sulfate-cemented sandstones with hematite concretions. The strata examined by **Opportunity** also indicate formation and/or alteration under acidic conditions, although the extent to which this is true for other rocks in Sinus Meridiani and other regions exhibiting the LCS orbital facies remains unknown. We note that the dominance of the LCS orbital facies in this region does not require or imply that all of the rocks have a similar origin (i.e., reworked sulfate-cemented sandstones). The LCS orbital facies within this region may also include hypothesized evaporites from playa lakes (Grotzinger et al. 2005, McLennan et al. 2005) or sulfate-bearing rocks formed in other environments, such as the alternative (hydrothermal) explanation for the Burns formation provided by McCollom and Hynek (2005).

We also note that several craters in northern Sinus Meridiani exhibit strata that appear to be rhythmically bedded (intracrater deposits unit of Hynek et al. [2001]), although their power spectrum has not yet been computed, as was done for beds in Bucquerei, other Arabia Terra craters, and the top of the mound at Gale Crater (Lewish et al. 2008a, Lewis 2009). Nevertheless, it is possible that the sulfate- and hematite-bearing plains in Meridiani Planum are over lain by a section of the RHY orbital facies, similar to the RHY deposits in Arabia Terra (Fig. 23). However, Hynek et al. (2001) noted that the stratigraphic relationships between these intracrater deposits in northern Sinus Meridiani and the hematite-bearing plains is unclear and that the former may be erosional remnants of the latter. If true, deposits formed of the LCS and RHY orbital facies at Sinus Meridiani could indicate time-equivalent, lateral changes in orbital facies.

**Interior Layered Deposits:** Similar to what is observed at Sinus Meridiani, the ILD in Valles Marineris are dominated by the LCS orbital facies, and rocks are known to contain sulfates and Fe-oxides (Fig. 23). Though we classify strata in these two regions as the same orbital facies, the definitions of our orbital facies (Table 1) and the limits of orbital data preclude us from determining their origin. However, the similarity in mineralogy to rocks at Meridiani Planum has led others to hypothesize that these deposits have a common origin (e.g., Bibring et al. 2007, Murchie et al. 2009a). Specular (gray) hematite and other Fe-oxides (e.g., red hematite) are associated with other rocks in Sinus Meridiani and the hematite-bearing plains is unclear and that the ILD in Valles Marineris. Future work that helps prove they are indeed lag deposits like those at Meridiani Planum (e.g., Jerolmack et al. 2006) or that shows the presence of diagenetic contacts within the ILD would help support their interpretation as sulfate-cemented sandstones.

We note that the ILD are distinct from Sinus Meridiani in that the deposits are significantly thicker (up to several kilometers) and occur in well-defined basins; thus, their depositional setting is quite different. In addition, the LCS orbital facies in the ILD exhibit a wide range of morphologic and textural characteristics at meter to decameter scales, many of which have not yet been observed in this orbital facies at Sinus Meridiani, indicating that a single depositional-diagenetic environment may be an oversimplification. It is important to recognize that sulfates formed at the top of a sedimentary succession at Sinus Meridiani have the opposite stratigraphic relationship to those formed in the ILD at the time-equivalent, lateral changes in orbital facies.

Despite these possible differences, the ILD and Sinus Meridiani deposits are likely both Hesperian in age, indicating that the LCS orbital facies was widespread during this time period.

**Uzboi–Ladon–Morava System:** This system is complex and involves at least intermittent events of channel incision and sedimentation beginning in Noachian time and possibly extending through to early Amazonian time (Grant and Parker 2002, Grant and Wilson 2011). Therefore, strata deposited at various positions along the network, and at various points in time, have the potential to overlap in age with very different orbital facies exposed at other reference sections.

Bedrock incision and depositional infilling of the oldest parts of the ULM system, including Holden Basin, Ladon Basin, and Ladon Vallis, likely began during late Noachian time or earlier (Grant and Parker 2002). Outcrops in Ladon Basin and exposed terraces at the northern end of Ladon Vallis contain Mg/Fe-phyllosilicates and vary widely in their tonality; thus, they are classified as the LCH orbital facies. The specific mode of emplacement for these valley and basin-filling deposits remains somewhat ambiguous, but their mineralogy is consistent with weathering, transport, deposition, and/or alteration by circum-neutral pH fluids at this time. This through-going transport network was later blocked by the impact event that formed Holden Crater, but the initial formation of the ULM system and its early activity as a possible sediment conveyor to the northern lowlands may have been contemporaneous with the uppermost parts of the reference sections at Mawrth Vallis and Nili Fossae, and all three sections are dominated by clay minerals rather than sulfates.

Recent studies have shown that alluvial fan/lacustrine deposits in
Holden Crater and deltaic deposits in Eberswalde Crater, which we classify as DNW orbital facies, may be much younger than previously recognized, having formed in Hesperian or even younger times (Grant and Wilson 2011). These younger ages would place these deposits in the era proposed to represent the time of peak sulfate formation on Mars (Bibring et al. 2006). However, these ULM strata are known to contain clay minerals (Grant et al. 2008, Milliken and Bish 2010), whereas sulfates and other salts are conspicuously absent (Milliken et al. 2009). The presence of such phases (clays) and the absence of others (sulfates) in aqueous deposits with ages possibly equivalent to the LCS orbital facies in the ILD and Meridiani deposits (Fig. 23) poses a significant challenge to the hypothesis invoking “global” acidic environments that arose during the Late Noachian–Early Hesperian (e.g., Bibring et al. 2006, Murchie et al. 2009b).

Considering their broader context, the sulfate deposits in the ILD and at Meridiani Planum likely formed in the presence of groundwater, or locally emergent groundwater (playa lakes). In contrast, the deposits characterized by the DNW orbital facies in the ULM system formed largely as a result of surface runoff and sediment transport, although groundwater may have been important in the upper reaches of contributory networks. Therefore, it is possible to invoke a difference in pH between locally emerging groundwater in the lowlands of Mars and surface water (especially if meteoric precipitation occurred) in the highlands of Mars. This may also help explain why Hesperian alluvial fan and deltaic systems (e.g., Holden and Eberswalde craters) were able to transport and deposit clay minerals without destroying them, as would be expected for smectitic clays interacting with acidic fluids. If correct, this would also account for the absence of observed sulfates in these strata.

Regardless of their origin, the rocks within the ULM system provide an important reference section on Mars because they may contain the longest temporal record of clay mineral formation, transport, and deposition on the planet, stretching from the Noachian (LCH orbital facies in Holden Basin, Ladon Basin, Ladon Vallis) to the Hesperian–Early Amazonian (DNW orbital facies in Holden and Eberswalde craters). If the inferred young ages of the latter deposits are correct, then this occurrence of clay-bearing DNW and LCH orbital facies would stand in marked contrast to the more commonly observed LCS or RHY orbital facies characteristic of post-Noachian terrains (Fig. 23).

Arabia Terra: The Arabia Terra region of Mars hosts many overfilled and underfilled crater deposits that, unfortunately, are commonly covered with veeners of dust that can obscure spectroscopic determination of their composition (Fergason and Christensen 2008). However, as discussed earlier, in some cases dust is absent or limited enough to allow the hypothesis that these deposits may be formed of dust and not simply covered by dust. Specific locations of “key sections” in the vast Arabia Terra region include the deposits in Danielson, Crommelin, and Bécquerel craters, discussed above. The distinct rhythmic layering (Lewis et al. 2008a) and often “bland” spectral signatures of these deposits lead us to classify them as the RHY orbital facies.

Many of these RHY deposits have been heavily eroded as a result of their weak lithification, which has undoubtedly affected the number of impact craters visible on their surfaces. However, these deposits are clearly younger than the craters in which they reside, indicating a likely Hesperian or possibly Early Amazonian age. Although some of these RHY deposits exhibit an increase in H$_2$O absorption features at near-infrared wavelengths, most of them appear to lack clay, sulfate, or other common hydrous minerals (Fig. 8). Therefore, the composition of these rocks is consistent with deposition in a dry environment.

Based on their mineralogical and physical stratigraphy we assign a younger chronostratigraphic age to the RHY-dominated deposits relative to the LCS-dominated rocks of the ILD and Sinus Meridiani deposits (Fig. 23). In support of this hypothesis we note that examples of the RHY orbital facies are restricted to relatively young terrains. Furthermore, in at least one place the RHY orbital facies occurs—in a single continuous section—stratigraphically above LCS orbital facies (Gale Crater); possibly another place is Sinus Meridiani, where RHY orbital facies may fill a crater formed in LCS orbital facies. Finally, to date no examples of the RHY orbital facies have been observed in Noachian-age deposits. Therefore, the RHY orbital facies may be limited in geologic time, possibly to the last several billion years, when the planet had dried and was dominated by transport and accumulation of anhydrous dust. However, its formation does not appear to be limited in space, as examples of the RHY orbital facies are found in widely separated regions of the planet (Lewis 2009).

The Section at Gale Crater: We conclude our list of key reference sections on Mars by examining the ~5-km-thick mound in Gale Crater. This deposit is likely the thickest continuously exposed single succession of sedimentary rocks on the planet (Milliken et al. 2010). The succession cannot, however, record continuous accumulation as it contains at least one significant erosional unconformity (Malin and Edgett 2000). Although the absolute ages of the deposit are not well constrained, the lower part of the mound may date to the Noachian–Hesperian chronostratigraphic boundary, and the upper part of the mound may be as young as Amazonian (Thomson et al. 2011). Albeit discontinuously, the mound in Gale may therefore record significant events in the environmental evolution of Mars (Anderson and Bell 2010, Milliken et al. 2010, Thomson et al. 2011).

The Lower formation, located beneath the significant unconformity (see Milliken et al. 2010), is best classified as LCS orbital facies, with a thin interval of CSC orbital facies near the base. In contrast, the Upper formation is composed at least in part of the RHY orbital facies (Fig. 22). The CSC facies at the base of Gale, however, is most similar to the minimally deformed subfacies observed at Mawrth as a result of its lateral continuity. This interval is on the order of tens of meters thick, and although the abundance of clay minerals are unknown, they are spectrally the dominant hydrous phase in these beds, possibly mixed with lesser amounts of sulfates (Milliken et al. 2010). Through recognition of CSC orbital facies (minimally deformed subfacies) it is proposed that the lower-most strata in the Lower formation at Gale may be contemporaneous with the youngest rocks at the Nili Fossae and Mawrth Vallis reference sections and the lower-most parts of the section at the Sinus Meridiani reference section. Indeed, most of the Lower formation at Gale is the same orbital facies (LCS) as the deposits in Sinus Meridiani, and these rocks may have formed contemporaneously. That said, the outcrop facies at Gale may differ significantly from the outcrop facies of the Burns formation at Meridiani, and we reiterate that not all occurrences of an orbital facies need to have the same petrogenetic origin. Testing this hypothesis will be one of the principal objectives of the MSL science investigation at Gale.

In a similar fashion, the RHY orbital facies at the top of the Gale mound may be equivalent in time to the RHY-dominated deposits observed in Arabia Terra, though more robust crater counts are needed to test this hypothesis. The mound at Gale is intriguing in that it captures several different orbital facies and, remarkably, may in a single section record the global transitions from clay to sulfate to anhydrous Fe-oxide stages of Mars’ environmental evolution, effectively chronicling the “drying out” of Mars (Milliken et al. 2010).

Synthesis: The extent to which any of the key reference sections described above record local vs. regional or global-scale environmental conditions is currently poorly understood. Many reference sections, independently constrained in time to avoid circular reasoning, would be required to build a more confident history of the environmental evolution of Mars. But there must always be a beginning, and as a group the reference sections discussed above provide a well-defined
starting point. The most ancient rocks on Mars, dating to the Noachian Era, are dominated by the CSC and MBR orbital facies and record extensive aqueous activity on a young planet that was still experiencing a significant flux of impactors. Younger Hesperian rocks in many places are dominated by the LCS orbital facies, and the presence of Fe-sulfates in some of these locations indicates a very acidic environment. However, local occurrences of clay-bearing DNW orbital facies also are observed in rocks deposited at this time, indicating that regional differences in aqueous geochemistry were important and are preserved in the Martian rock record. The youngest sedimentary rocks on Mars may consist dominantly of the RHY orbital facies and may support the traditional hypothesis that eolian processes have dominated the rock cycle on a cold, dry Mars for the past several billion years. Fortunately, possible duststones in the RHY facies may contain much information about the Martian atmosphere and climate over this time. It is our hope that future work will continue to identify important mineralogical and morphological key reference sections on Mars to build on what is presented here, providing a framework with which to understand the evolution of climate and geologic processes through time.

**SUMMARY**

1. Mars has a surprising diversity of sedimentary rocks. From orbit, these rocks are distinctive in their stratification, depositional morphology, mineral composition, tone/albedo variations, and thermal inertia. These attributes combine to form distinct classes of inferred sedimentary rocks. In many cases it is impossible to confirm their mode(s) of origin because of non-uniqueness; origins for those with distinctive morphologies are best known (deltas, alluvial fans, lacustrine fans); followed by eolian deposits, the large-scale cross-bedding of which can in some cases be observed even from orbit—and which are confirmed by in situ rover observations. Lacustrine deposits are largely inferred based on context, most commonly expressed as flat, continuous layers in topographic low. Regionally extensive sulfate deposits, some of which are kilometers thick, indicate precipitation as evaporites; reworking by wind and precipitation of cements from groundwater brines may have helped them attain their great thickness. Regionally extensive sheets of flat-lying strata that apparently lack hydrated mineral signatures may represent “duststones” formed by prolonged settling of dust from the atmosphere, although regionally extensive volcanic ash deposits could have similar stratigraphic expression.

2. The oldest sedimentary rocks on Mars are likely older than the oldest rocks (gneisses) on Earth. The absence of plate tectonics on Mars has resulted in impressive preservation of the earliest records of aqueous processes on a terrestrial planet. However, the sedimentary record of Mars is fundamentally different from that of Earth in several ways. Mars is a basaltic planet, and so the provenance of sedimentary materials, including particulate detritus and the geochemistry of fluids from which chemical constituents precipitate, reflects mafic compositions rather than intermediate to felsic compositions. Furthermore, Mars seems to have progressed from a very early (primarily Noachian) stage, in which aqueous alteration was dominated by circum-neutral pH reactions that formed clay minerals, to a later (primarily Hesperian) stage, in which alteration occurred at lower pH. This stage of alteration—hypothesized as acidic and global in extent, and therefore very different from terrestrial weathering—saw high mobility of Al and Fe, resulting in the formation of exotic sulfate minerals deposited in volumes unknown on the Earth. Mg-, Ca-, Fe-, and Al-sulfates likely dominate Martian evaporite deposits. During late Hesperian—Early Amazonian time Mars may have seen a last pulse of significant water, expressed as bedrock-incising fluvial channel networks, before arriving at its current dry state, which has been dominated by eolian and ice-related processes for the past ~2 billion years.

3. The absence of plate tectonics on Mars leads to critical differences between Earth and Mars with regard to the character of the stratigraphic record. Most (all?) sedimentary deposits on Mars formed in preexisting topographic depressions created either by impact events or by faulting associated with the development of the Valles Marineris rift system. To date, there is no evidence for the syndepositional subsidence that is so common on Earth. Consequently, most stratal geometries are very flat or otherwise exhibit simple downlap and onlap associated with the infilling of crater basins. Rare examples of more complex stratal geometries have been observed in Melas Chasma and Eberswalde Crater, likely associated with progradation of shoreline/deltaic sediment wedges. Again, the lack of tectonics results in only rare exposures of stratigraphic cross sections that can be observed at only slight off-nadir angles by orbiting cameras; this bias tends to emphasize flatter stratal geometries.

4. Source-to-sink systems can be well defined on Mars. For aqueous transport systems, the source regions can exhibit very densely spaced fluvial networks, analogous to those observed on Earth, and consistent with meteoric precipitation and overland flow. In other cases, particularly for the largest systems on Mars, the source regions are more consistent with emerging groundwater, particularly where networks and outflow channels originate in “chaos” regions (brecchia, collapse features). Distributary networks are represented by alluvial fans, possible debris flow fans, deltas, and sublacustrine fans. In contrast, eolian systems are poorly defined. Source regions can only be imagined, but as such are regarded to be the cratered highlands of Mars, where impact-generated sediments would have been available for transport. In the early history of Mars, both chemical and physical weathering also would have been important in the generation of fine-grained materials. Later in the history of Mars, physical weathering processes became dominant, and erosion of basaltic yielded quantities of unaltered olivine and pyroxene that form the eolian bedforms and soils observed across the surface of Mars today. The sinks for fine-grained eolian materials might have been vast duststone deposits, the abundance of which decreased through time as impact, volcanic, and weathering byproducts all decreased in importance. Today these deposits are in a state of net erosion. Eolian deposits formed by traction processes are less evident, though both Opportunity and Spirit have observed cross-bedded eolianites, and some stratified outcrops observed from orbit exhibit large-scale cross-stratification and have preserved large-scale bedforms most simply interpreted as eolian traction deposits. These tend to occur at high stratigraphic positions (paleoelevations) in their respective sections.

5. Integrating regional setting, bed-scale physical properties, and mineral assemblages as observed from orbital data leads to identification of distinct “orbital facies” that can be identified in different key reference sections on Mars. These orbital facies may not be restricted in time, and none appear to be restricted in space—beyond the apparent general limitation of most sedimentary rocks occurring at lower latitudes. Several key reference sections exhibit multiple orbital facies developed in a stratigraphic context that allows potential correlation to other locations. The most ancient strata preserved on Mars are dominated by MBR and CSC orbital facies. In contrast, younger strata in key reference sections are dominated by LCS orbital facies and RHY orbital facies. This transition is largely consistent with an apparent widespread, perhaps global, transition from clay-forming to sulfate/Fe-oxide–forming conditions followed by the desiccation of Mars. However, important occurrences of post-Noachian clay-bearing orbital facies (e.g.,
Barnhart CJ, Howard AD, Moore JM. 2009. Long-term precipitation and late-
channels suggest a long-lived Noachian crater lake on Mars. Geophysical
Research Letters 32:L10201.

Coupled ferric oxides and sulfates on the Martian surface. Science 317:1206–
1210.

ACKNOWLEDGMENTS

This article has benefited from many discussions with our colleagues on Mars missions led by Ken Edgett (MOC, CTX), Mike Malin (MOC, CTX), Alfred McEwen (HiRISE), Scott Murchie (CRISM), Steve Squires (MER), and also the MSL team. Interactions and presentations given at MSL Landing Site workshops and the First International Conference on Mars Sedimentology and Stratigraphy were key sources of knowledge and inspiration. Individually, we would like to thank Ken Edgett and Mike Malin for sharing their knowledge of sedimentary rocks on Mars, including early articles that speculate on the presence of possible sedimentary rocks; John Grant and Tim Parker for their insights into the evolution of crater lakes and the ULM fluvial network; Gary Kocurek, Dave Rubin, and Rob Sullivan for discussions of eolian systems; Kevin Lewis and Katie Stack for insights into Mars bed thickness distributions; Dawn Summer and Horton Newsom for their work on impact processes and stratigraphy; David Bish for fruitful discussions relating to clay minerals and diagenesis on Mars; and Joel Hurowitz and Scott McLennan for insights into Martian geochemistry. Support for writing this work was provided the National Aeronautics and Space Administration Astrobiology Institute and the Mars Exploration Rover and Mars Science Laboratory projects. We thank Ken Edgett, Sangeev Gupta, Dawn Sumner, and Brad Thomson for their helpful reviews of the manuscript. Jennifer Griffis is thanked for help in figure construction and compiling all of the observations on which Figure 3 is based.

REFERENCES

Anderson RB, Bell JF III. 2010. Geologic mapping and characterization of Gale
Crater and implications for its potential as a Mars Science Laboratory landing site. Mars 5:76–128.
Andrews-Hanna JC, Phillips RJ, Zuber MT. 2007. Meridiani Planum and the
Andrews-Hanna JC, Zuber MT, Arvidson RE, Wiseman SM. 2010. Early Mars
hydrology: Meridiani playa deposits and the sedimentary record of Arabia
Ansan V, Loizeau D, Mangold N, Le Mouelic S, Carter J, Poulet F, Dromart G,
S, Mustard JF, Neukum G. 2011. Stratigraphy, mineralogy, and origin of
Arvidson RE, Gooding JL, Moore HJ. 1989. The Martian surface as imaged,
orbital facies, improved estimates of relative ages based on crater
counts using new high-resolution images, detailed geologic mapping, and correlation of strata. In implementing this integrated approach we can hope to decipher the geologic and environmental history of Mars.


