Mineralogy of the Martian Surface

Bethany L. Ehlmann[1,2] and Christopher S. Edwards[1]

[1]Division of Geological & Planetary Sciences, California Institute of Technology, Pasadena, California 91125; email: ehlmann@caltech.edu, cedwards@caltech.edu

[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

Annu. Rev. Earth Planet. Sci. 2014. 42:291–315

The *Annual Review of Earth and Planetary Sciences* is online at earth.annualreviews.org

This article's doi:
10.1146/annurev-earth-060313-055024

Keywords

Mars, composition, mineralogy, infrared spectroscopy, igneous processes, aqueous alteration

Abstract

The past fifteen years of orbital infrared spectroscopy and in situ exploration have led to a new understanding of the composition and history of Mars. Globally, Mars has a basaltic upper crust with regionally variable quantities of plagioclase, pyroxene, and olivine associated with distinctive terrains. Enrichments in olivine (>20%) are found around the largest basins and within late Noachian–early Hesperian lavas. Alkali volcanics are also locally present, pointing to regional differences in igneous processes. Many materials from ancient Mars bear the mineralogic fingerprints of interaction with water. Clay minerals, found in exposures of Noachian crust across the globe, preserve widespread evidence for early weathering, hydrothermal, and diagenetic aqueous environments. Noachian and Hesperian sediments include paleolake deposits with clays, carbonates, sulfates, and chlorides that are more localized in extent. The late Hesperian to Amazonian mineralogic record of water is sparser, though sulfates and silica in some locations indicate local availability of ground and surface waters even in the most recent geologic epoch.

1. INTRODUCTION

A record of the evolution of Mars is preserved in the rocks and sediments exposed at its surface. Minerals can fingerprint many processes that build the martian rock record. The past decade of exploration has seen a tremendous increase in the level of detail accessible about our neighboring planet and its history, driven by three factors: (*a*) a focused effort to acquire compositional data, which offers a new lens through which to decipher the history of the planet and complements photographic morphologic data available since the Mariner and Viking missions; (*b*) observations of the surface at increasingly high spatial and spectral resolution, provided by the ever-increasing capabilities of orbital instruments; and (*c*) in situ exploration and small-scale measurements by rovers and landers. The composition of Mars is revealed through infrared spectroscopic instruments that have mapped mineralogy on the surface and from orbit, supplemented by chemical measurements from orbiters and landers and in situ data from Mössbauer spectroscopy of Fe-bearing minerals and X-ray diffraction (XRD).

A striking mineralogic feature of the so-called Red Planet has been observed for millennia: the distinctive reddish hue of the surface, imparted by ferric oxides and oxyhydroxides in Mars dust (e.g., Singer 1982). Reddish, fine-grained (<5 μm) dust is ubiquitous on the surface of Mars, and a continuous dust cover obscures large portions of the planet from further probing by remote sensing. However, dust cover is incomplete, and beneath the dust of Mars lie bedrock and sediments of distinctive composition. Early spectroscopic and lander data showed large volcanic provinces composed of basalt and a surface that was hydrated (OH, H_2O), with possible traces of other alteration minerals (e.g., Banin et al. 1992, Soderblom 1992).

Early observations also showed terrains of different ages. Delineation of time periods by surface crater density statistics establishes a temporal framework for determining surface age and time-ordering Mars history into Noachian (>3.7 Ga), Hesperian (3.7–3.1 Ga), and Amazonian (<3.1 Ga) epochs (e.g., Hartmann & Neukum 2001, Nimmo & Tanaka 2005). There is only one independent radiometric date for surface materials, however (Farley et al. 2014). Temporal uncertainties in the lunar impact record, extrapolation of the lunar crater production rate to Mars, and overprinting processes that destroy craters result in uncertainties of hundreds of millions of years on the absolute age of martian terrains. Nevertheless, superposition and crosscutting geologic relationships between units, coupled with crater statistics, allow relative ages to be discerned.

Over the past fifteen years, there has been a vast increase in the amount of data about Mars, importantly including information on composition. Many minerals have been discovered, mapped in association with particular geologic units, and used to understand geologic processes (**Table 1**). Key points of similarity and departure between the histories of Mars and Earth have become apparent. First, as was originally inferred from telescopic and early spectrometer data, Mars has a basaltic crust. Unlike Earth, with its plate tectonics–driven compositional dichotomy between silica-enriched continental crust and iron- and magnesium-enriched oceanic crust, Mars's composition is more homogeneous and more similar to terrestrial oceanic crust. Second, and remarkably, early crust dating from the first billion years of Mars's history (∼50% of the surface) preserves a rich chemical record of multiple, diverse aqueous environments varying in space and time across the surface. The modern record of Mars, in contrast, testifies to infrequent and less intensive interaction of the crust with water. Finally, "think local, not global" is an important emerging theme. Like Earth, Mars is a large planet, and although there are global trends in evolution, one can no longer speak of homogeneously varying conditions. However, local-scale observations do constrain regional-scale processes, placing important constraints on the evolutionary history of Mars.

Study of the composition of Mars has a long history. Infrared spectroscopic measurements in the 1960s–1980s by Earth-based telescopes and results from the 1989 ISM (Infrared Spectrometer for

Table 1 Minerals detected on Mars from landed and orbital data sets[a]

	Class	Group/mineral/phase	Formula
Primary	Framework silicates	Olivines	$(Mg, Fe)_2SiO_4$
		Orthopyroxenes	$((Mg, Fe)_{0.95+x}, Ca_{0.05-x})Si_2O_6$
		Clinopyroxenes	$(Ca, Mg, Fe)Si_2O_6$
		Plagioclase feldspars	$(Ca, Na)(Al, Si)AlSi_2O_8$
		Alkali feldspars	$(K, Na)AlSi_3O_8$
	Sulfides	Pyrrhotite[b]	$Fe_{1-x}S$
		Pyrite/marcasite[c]	FeS_2
	Oxides	Magnetite[d]	$Fe_{3-x}Ti_xO_4$
		Ilmenite[d]	$FeTiO_3$
Secondary	Oxides	Hematite	Fe_2O_3
		Goethite[d]	$FeO(OH)$
		Akaganeite[b]	$Fe(O, OH, Cl)$
	Phyllosilicates (clay minerals)	Fe/Mg smectites (e.g., nontronite, saponite)	$(Ca, Na)_{0.3-0.5}(Fe, Mg, Al)_{2-3}(Al, Si)_4O_{10}(OH)_2 \cdot nH_2O$
		Al smectites (e.g., montmorillonite, beidellite)	$(Na, Ca)_{0.3-0.5}(Al, Mg)_2(Al, Si)_4O_{10}(OH)_2 \cdot nH_2O$
		Kaolin group minerals (e.g., kaolinite, halloysite)	$Al_2Si_2O_5(OH)_4$
		Chlorite	$(Mg, Fe^{2+})_5Al(Si_3Al)O_{10}(OH)_8$
		Serpentine[e]	$(Mg, Fe)_3Si_2O_5(OH)_4$
		High-charge Al/K phyllosilicates (e.g., muscovite, illite)	$(K, H_3O)(Al, Mg, Fe)_2Al_xSi_{4-x}O_{10}(OH)_2$
	Other hydrated silicates	Prehnite	$Ca_2Al(AlSi_3O_{10})(OH)_2$
		Analcime	$NaAlSi_2O_6 \cdot H_2O$
		Opaline silica ($n > 0$), quartz ($n = 0$)	$SiO_2 \cdot nH_2O$
	Carbonates	Mg/Ca/Fe carbonates	$(Mg, Fe, Ca)CO_3$
	Sulfates	Kieserite ($MgSO_4 \cdot H_2O$); szomolnokite ($FeSO_4 \cdot H_2O$); Fe(II)-, Fe(III)-, and Mg-polyhydrated sulfates	$(Fe, Mg)SO_4 \cdot nH_2O$
		Gypsum ($n = 2$), bassanite ($n = 0.5$), anhydrite[b] ($n = 0$)	$CaSO_4 \cdot nH_2O$
		Alunite	$KAl_3(SO_4)_2(OH)_6$
		Jarosite	$KFe_3(OH)_6(SO_4)_2$
		Not a named mineral	$Fe^{3+}SO_4(OH)$
	Chlorides	Chlorides	e.g., NaCl, $MgCl_2$
	Perchlorates	Perchlorates[f]	e.g., $(Mg, Ca)(ClO_4)_2$

[a] For those minerals not discussed within the text, references are provided as footnotes. Several phases were not included as their detections are more tentative, subject to additional data to confirm: chromite (Morris et al. 2008), dehydrated copiapite (Bishop et al. 2009), talc (Viviano et al. 2013), vermiculite, margarite, epidote, mordenite, thomsonite, clinoptilolite, gismondine, and riebeckite (Carter et al. 2013).

[b] Vaniman et al. 2014; [c] Morris et al. 2008; [d] Morris et al. 2006; [e] Ehlmann et al. 2010; [f] Hecht et al. 2009.

Table 2 Instruments for measuring mineralogy, since 1990

Years of operation	Instrument name (abbreviation)	Full instrument name	Location	Key characteristics	Reference
1997–2006	TES	Thermal Emission Spectrometer	Orbit	Thermal infrared point spectroscopy (∼6–50 μm; 3 × 6 km spots)	Christensen et al. 2001
2001–present	THEMIS	Thermal Emission Imaging System	Orbit	Thermal infrared multispectral imaging (6.7–14.8 μm; 7 bands; 100-m pixels)	Christensen et al. 2004
2004–2011 (Spirit) 2004–present (Opportunity)	Mini-TES	Miniature Thermal Emission Spectrometer	Rover	Thermal infrared point spectroscopy (landed; 5–29 μm; 20 mrad; i.e., 20-cm spots at 10 m)	Christensen et al. 2003
2004–present	OMEGA	Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité	Orbit	Visible/near-infrared imaging spectroscopy (0.4–5.0 μm; 200–2,000 m/pixel)	Bibring et al. 2005
2006–present	CRISM	Compact Reconnaissance Imaging Spectrometer for Mars	Orbit	Visible/near-infrared imaging spectroscopy (0.4–4.0 μm; 18–200 m/pixel)	Murchie et al. 2007
2004–2011 (Spirit) 2004–present (Opportunity)	MB	Mössbauer Spectrometer	Rover	Arm-based in situ Mössbauer spectroscopy (^{57}Co source; ∼1.4-cm footprint)	Klingelhöfer et al. 2003
2011–present (Curiosity)	CheMin	Chemistry and Mineralogy	Rover	Delivery of powdered sample for X-ray diffraction ($2\theta = 5$–50)	Blake et al. 2012

Mars) instrument on the Russian Phobos-2 mission are detailed in Bibring et al. (1989), Soderblom (1992) and Banin et al. (1992) in the 1992 *Mars* volume (Kieffer et al. 1992), and Murchie et al. (2000). Bell's (2008) *The Martian Surface* also provides an excellent instrument-by-instrument summary of findings of Mars missions since the 1997 Mars Global Surveyor mission. McSween & Treiman (1998) and Nyquist et al. (2001) provide a synthesis of the mineralogy of the Mars meteorites, an important topic, which is not treated further here due to space limitations. Herein, we focus in particular on summarizing the current state of knowledge about the mineralogy of the martian surface, integrating the key results from orbiting and landed missions of the past 15 years (**Table 2**). Exploration is a continuing process: With three orbiter missions and two rovers on the surface still operational we expect—indeed hope—this review will serve as a foundation for and be superseded by new discoveries. We begin with a description of techniques employed to date to identify minerals, then review sequentially the primary composition of Mars and the environments of secondary alteration indicated by the mineralogic record.

2. MEASURING THE MINERALOGY OF MARS

On Earth, mineralogy of prepared samples is commonly measured in the laboratory by light and electron microscopy or XRD of prepared samples. Of the seven landed Mars missions to date, only three have carried tools for direct, in situ measurement of mineralogy. Each of the 2004 Mars Exploration Rovers, Spirit and Opportunity, carried a Mössbauer spectrometer, which enables identification of the iron-bearing mineral phases by measuring quadrupole splitting and the isomer shift during the emission and absorption of gamma rays (Klingelhöfer et al. 2003). The first XRD, which uses diffracted X-rays to determine crystal structure, is just now beginning measurements as part of the payload on the 2012 Curiosity rover (Blake et al. 2012). For landed investigations, measurements of elemental chemistry or temperature of gas release upon pyrolysis have commonly been key, if not sole, tools for determining composition.

Consequently, much knowledge of Mars mineralogy relies on data collected remotely, using infrared spectroscopic tools (e.g., Farmer 1974, Clark 1995; **Table 2**). In thermal infrared spectroscopy (TIR, defined here as 5–50 μm; 2,000–200 cm^{-1}), molecular lattice vibrations lead to distinctive minima, diagnostic of composition, in electromagnetic radiation thermally emitted from the surface. These include variations in silica polymerization that determine the position and shape of the Si-O stretch (~10 μm; 1,000 cm^{-1}) and absorptions by structural components of sulfates, carbonates, iron oxides, and aluminosilicates. Similarly, in the visible and near-infrared wavelengths (VNIR, defined here as 0.4–5 μm; 25,000–2,000 cm^{-1}), sunlight reflected from the surface of Mars is diminished at certain wavelengths by absorptions that are diagnostic of the surface composition. Vibrational absorptions from 1 to 5 μm are overtones of those in the TIR and provide the ability to identify minerals with OH, H_2O, or CO_3. Absorption of energy by electrons of transition metal elements, most commonly iron, produces distinctive spectral features from 0.4 to 2 μm for olivines, pyroxenes, Fe-bearing glasses, and Fe oxides such as hematite and goethite. IR spectroscopy can operate at all standoff distances; however, there is a trade-off between spatial resolution and detectability of discrete phases. The larger the footprint of the measurement on the surface, the less likely that a small outcrop or deposit of unique composition can be identified. High spectral resolution allows for better discrimination of similar phases and classes of minerals, and different wavelength regions exhibit different sensitivities to particular minerals. Steadily increasing spatial and spectral resolution and examination with multiple wavelength ranges have driven discoveries over the past decade.

Unique minerals or phases, identified on Mars and widely accepted or replicated by multiple authors, are described in the below overview and listed in **Table 1**. Because of the nonuniqueness of some spectral features, overprinting of potential minor phases' spectral features by features in major phases, and/or confounding effects of instrument noise, not all detections reported in the past decade are included (see the **Table 1** footnotes for a list of tentative identifications); exploration remains ongoing and future data may yet confirm these.

3. PRIMARY IGNEOUS MINERALOGY

TIR and VNIR spectroscopy of regions with low dust cover, mostly within the southern highlands, have confirmed initial data indicating the essentially igneous and basaltic nature of the upper martian crust (Christensen et al. 2000b, Ruff & Christensen 2002, Bibring et al. 2005). Nonetheless, spatial variations in mineralogic composition provide insight into the changing nature of the igneous processes—e.g., heterogeneous composition of source regions, fractional crystallization, and crustal assimilation—that have shaped the planet over time. The surface of Mars can be grouped into a few major distinctive types of igneous terrains that have variable spectral properties in TIR and VNIR data sets, driven by differences in the relative proportions of olivine, clinopyroxenes, orthopyroxenes, feldspars, and high-silica phases such as silicate glasses, zeolites, and sheet silicates (Rogers & Christensen 2007, Poulet et al. 2009). Plagioclase and clinopyroxene are the dominant minerals of most of the southern highlands. The northern plains exhibit the lowest pyroxene abundance and highest concentration of high-silica phases. The oldest Noachian crust of Mars shows enrichments in low-calcium pyroxene and olivine relative to younger Hesperian lava provinces (Mustard et al. 2005). To date, alpha-particle X-ray spectroscopy data from the landing sites have confirmed these observations with basaltic rocks and sands found by Pathfinder, Spirit, Opportunity, and Curiosity, albeit with some important local variations with more alkali-rich rocks (McSween et al. 2006a, 2009; Stolper et al. 2013; Sautter et al. 2014). [Note that initial reports of andesite from Mars Pathfinder were revised after data recalibration (Foley et al. 2003).] The composition of the youngest voluminous volcanics covering the surfaces of the large volcanos of the Olympus Mons province is more difficult to discern due to high dust cover in this part of the planet. The most important aspects of primary mineralogic diversity are addressed below.

3.1. Spectral Properties of the Southern Highlands Versus Northern Lowlands

In both TIR and VNIR spectroscopic data, there is a distinctive difference in large-scale surface spectral properties that roughly coincides with the topographic and age dichotomy between the southern highlands and northern lowlands. Thermal emission data from dust-free areas of the northern lowlands, particularly Acidalia and Utopia Planitiae, do not possess the distinctive spectral properties imparted by pyroxene in the Si-O stretch (10 μm; 1,000 cm^{-1}) and at lower wavenumbers but rather have a sharper Si-O absorption characteristic of high-silica phases (**Figure 1**) (Bandfield et al. 2000, Wyatt & McSween 2002, Kraft et al. 2003). Originally, these northern plains units were hypothesized to represent andesitic to basaltic andesite volcanic units, dominated by plagioclase and high-silica primary glasses (Bandfield et al. 2000); however, the products of aqueous alteration, including phyllosilicate-rich altered basalt (Wyatt & McSween 2002) or silica-rich amorphous coatings (Kraft et al. 2003), were also consistent with the data. Analysis of VNIR data likewise shows spectral differences between the low-dust areas of the southern highlands and northern lowlands, characterized by a downward slope toward higher wavelengths in the north, consistent with the presence of thin or fine-grained coatings but no widespread hydrated silicates (Mustard et al. 2005). Numerous moderate-sized craters in Acidalia Planitia, ∼3 to 30 km in diameter, expose olivine-bearing rock units in their walls and ejecta, indicating that mafic/ultramafic igneous materials are present at shallow depths beneath the surface of the northern plains (Salvatore et al. 2010). Thin oxidative coatings on the surfaces of basalt (Salvatore et al. 2013) or leached rinds of iron-bearing glass (Horgan & Bell 2012) generated by weathering processes are also consistent with VNIR spectral properties and with the TIR observations. Collectively, these data point to basaltic materials constituting the bulk of the northern plains but with a distinctive style of sedimentation or weathering in the northern lowlands that affects the uppermost surface.

3.2. Olivine Enrichments: Implications for Igneous Processes

The abundance of olivine varies, in some regions reaching >20%. Olivine compositions range from Fe-rich to Mg-rich ($\sim Fo_{40}$–Fo_{90}) and have been globally mapped (**Figure 2**) (Koeppen & Hamilton 2008, Ody et al. 2013). Olivine-enriched rocks have also been found by rovers. At Gusev crater (**Figure 1**), rocks examined in the basaltic plains contain 20–30% intermediate-composition olivine in phenocrysts (McSween et al. 2006b), and the Comanche outcrop in the Columbia Hills contains 40% olivine (Morris et al. 2010).

A striking feature in the global distribution of olivine-rich units is enrichment circumferential to the largest ancient impact basins. For example, west of the Isidis impact basin, in and around the Nili Fossae, a region with olivine-enriched bedrock (>20%) is found in fractured Noachian-aged bedrock, unconformably draping older crust and cut by tectonic graben (Hoefen

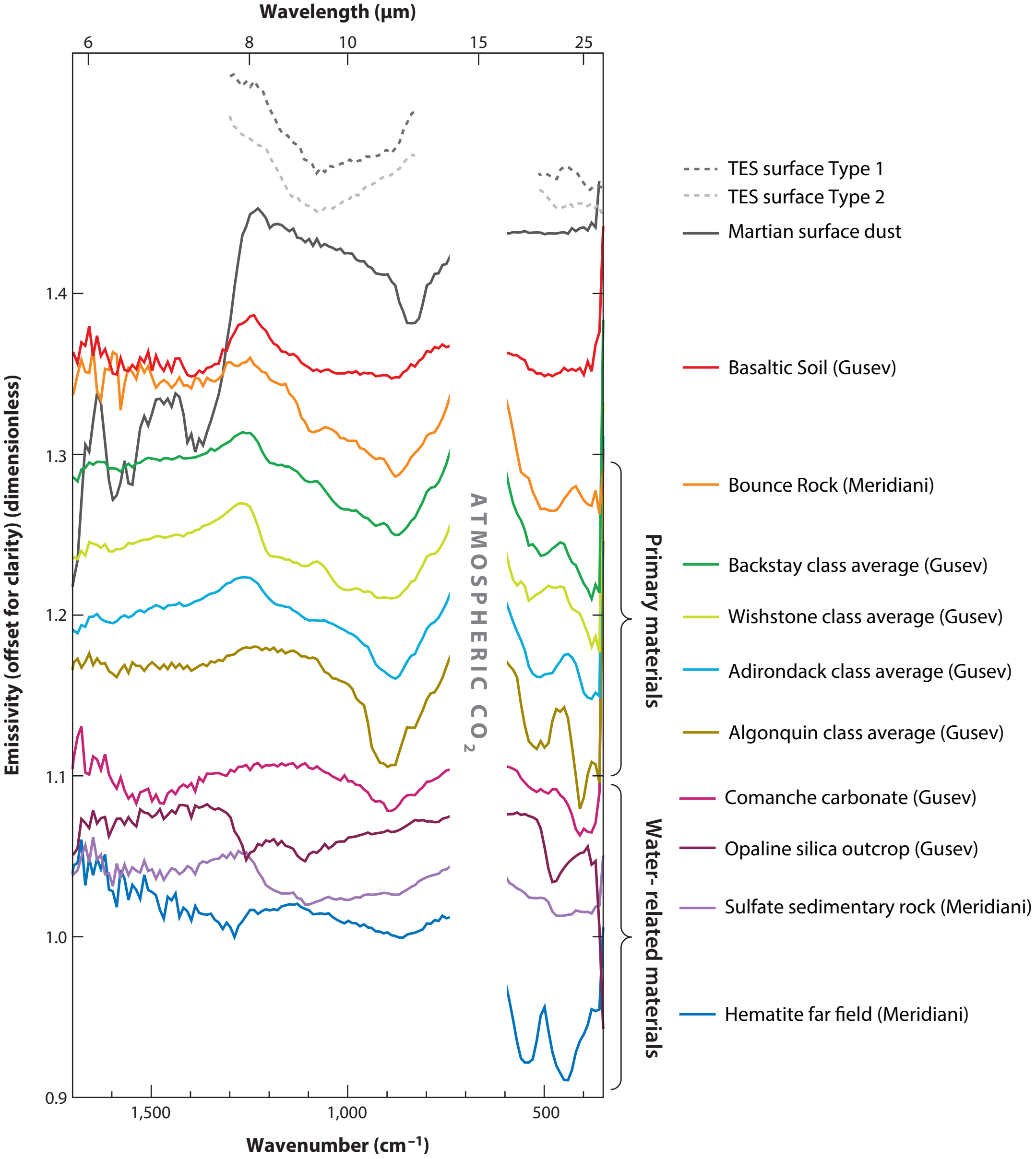


Figure 1

Summary of the major compositional variability observed by thermal infrared spectroscopy. The greatest regional differences observed from orbit by TES are between basaltic Type 1 terrains and more silicic Type 2 terrains. At small scales, greater spectral variability can be observed from rock unit to rock unit by TES and Mini-TES (*solid lines*). Identified Mini-TES primary igneous materials have compositions that range from typically basaltic (Gusev Soil, Bounce Rock) to alkaline volcanic (e.g., Backstay class) to picritic basalts (Adirondack class) and olivine-dominated clastic rocks (Algonquin class). Rocks altered by aqueous processes have been found, including those with carbonate, opaline silica, sulfate, and hematite.

et al. 2003; Hamilton & Christensen 2005; Mustard et al. 2007, 2009). Similar olivine-enriched units are found south of the Isidis basin in Libya Montes (Tornabene et al. 2008). These circumferential deposits have been proposed to represent igneous intrusions (Hoefen et al. 2003); upper-mantle-sourced cumulates that settled from impact melt (Mustard et al. 2007, 2009); or fluid, komatiitic-type lavas (Hamilton & Christensen 2005, Tornabene et al. 2008).

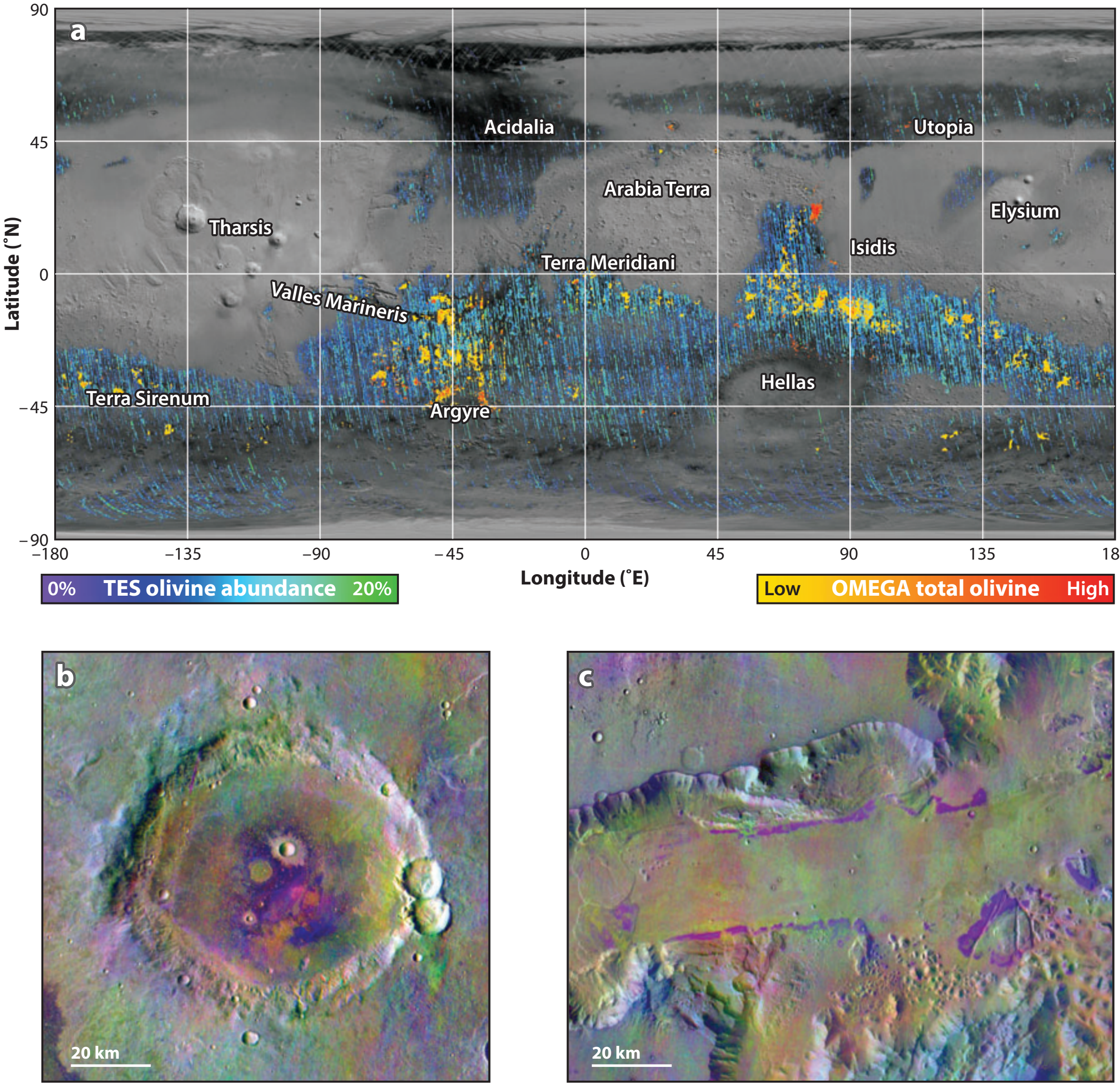


Figure 2

(*a*) Global olivine distribution from TES (Koeppen & Hamilton 2008) and OMEGA (Ody et al. 2013). The purple to green tones are the total olivine abundance for all compositions derived from TES deconvolution results. The yellow to red tones are olivine spectral indices, correlated with 1-μm absorption band strength and derived from OMEGA data for locations where olivine is detected. Coincident locations of olivine enrichment point to excavation of materials by impact or lavas of distinctive composition. THEMIS decorrelation stretch of bands 8, 7, and 5 exhibiting olivine enrichments (magenta/purple tones) (*b*) in late Noachian–early Hesperian crater floor volcanics (53°E, 22°S) (Edwards et al. 2014) and (*c*) in the Ganges/Eos Chasmata mid-Noachian olivine-rich layer (40.5°E, 8°S) (Edwards et al. 2008).

Isidis regional basin–circumferential deposits are especially well studied, but they are not unique. Olivine-enriched materials are also found circumferential to Argyre and Hellas (Koeppen & Hamilton 2008, Buczkowski et al. 2010, Ody et al. 2013). The circumbasin olivine-rich rocks contain the highest-Mg olivines on Mars (~Fo_{90}; Koeppen & Hamilton 2008) and may indicate tapping of lower-crust or upper-mantle material by these large, early basin-forming impacts.

Elsewhere, olivine-bearing lavas (>15%) are found in the bottom of impact craters and exposed in the eroded walls of channels (Rogers et al. 2005, Edwards et al. 2009, Rogers et al. 2009, Rogers & Fergason 2011, Edwards et al. 2014). These olivines are relatively more Fe enriched (~Fo_{50}–Fo_{70}) relative to olivine associated with the largest basins. In general, these lavas are mid-Noachian to Hesperian. The largest such exposure crops out in Ganges and Eos Chasmata near the bottom of the stratigraphic sequence observable in Valles Marineris. This exposure is a contiguous thick unit inferred to represent primitive lavas that flowed on the martian surface for >1,000 km and may signal the initiation of volcanism in the Tharsis province (Edwards et al. 2008). Punctuated eruptions from minimally fractionated mantle sources created widespread, large olivine-rich flows during the first billion years of Mars history across the planet but were rare to absent during later periods.

3.3. Evolved Compositions

Although the crust of Mars is broadly basaltic, locally more evolved silicic compositions have been reported. The largest of these are dacitic lavas within the Nili Patera caldera complex of Syrtis Major (**Figure 3**) (Christensen et al. 2005). The multiple flows, extending over tens of square kilometers, are among the youngest of the Syrtis Major flows and likely represent the products of local fractional crystallization. Exposures of granitoid rocks had also been reported on Mars (Bandfield et al. 2004, Bandfield 2006); however, further analysis demonstrated that these deposits are hydrated silica and quartz that formed during hydrothermal alteration or diagenesis of mafic crustal materials (Ehlmann et al. 2009, Smith & Bandfield 2012). A small outcrop of Fe-bearing feldspar has been detected in Xanthe Terra along a fluvially eroded part of a crater wall (Popa et al. 2010), and more recently, additional small exposures have been reported in a few isolated locations across the southern highlands (Carter & Poulet 2013, Wray et al. 2013). The geologic context of these felsic exposures is not clear and may be local igneous intrusions. Interestingly, the Curiosity rover has also found anomalously (for Mars) alkali-rich float rocks at its landing site in Gale crater, both fine-grained alkali basalts known as mugearites (Stolper et al. 2013) and coarse-grained alkali feldspar–bearing lithologies (Sautter et al. 2014) that indicate a nearby region of more felsic crust, formation from partial melting, or an alkali-rich mantle source. Within the Columbia Hills, Gusev crater, the Spirit rover also encountered alkaline volcanic rocks, substantially enriched in plagioclase relative to pyroxene and olivine (McSween et al. 2006a). The timing and nature of processes producing more evolved compositions remain a subject for future investigations.

4. SECONDARY ALTERATION OF THE CRUST

Superimposed on the primary composition of Mars are the effects of secondary processes: physical weathering and erosion to mix and distribute materials, anhydrous oxidation, and chemical weathering and alteration by interaction with liquid water. In particular, for the latter, the diversity in secondary minerals discovered in the past decade (**Table 1**; **Figures 4** and **5**) defies simple grouping by phase but rather points to specific types of alteration environments varying spatially and temporally.

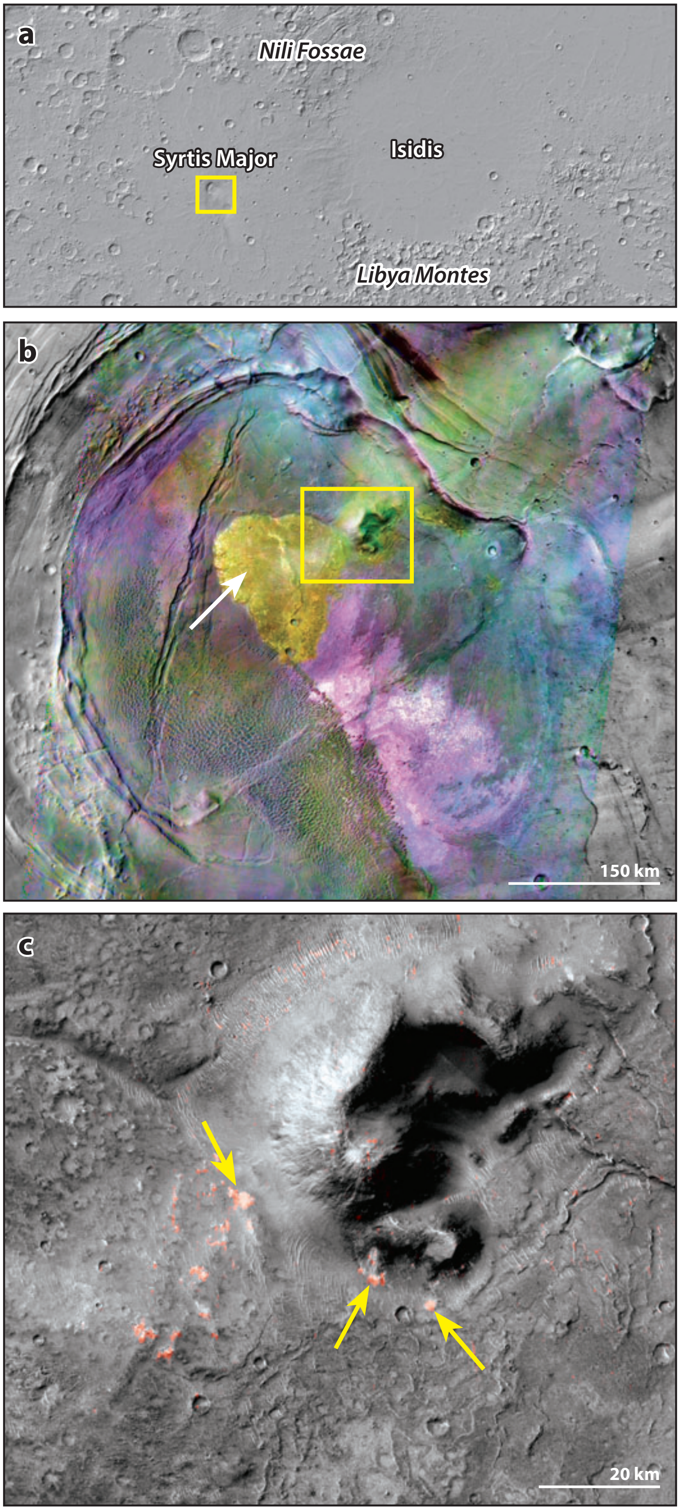


Figure 3

(*a*) Location of the Nili Patera caldera (9°N, 67°E) on a topographic hillshade map. (*b*) THEMIS decorrelation stretch mosaic of bands 8, 7, and 5 (11.79, 11.04, and 9.35 μm, respectively) overlaid on a CTX image for context. Yellow tones identify a late-stage dacite lava flow (*white arrow*), likely formed by differentiation of magmas. Magenta/purple tones identify olivine-bearing deposits. (*c*) CRISM 2.2-μm band depth map overlaid on a CTX image. Small deposits of hydrated silica (*yellow arrows*) identified by CRISM on and around the volcanic cone formed during the Hesperian or later from alteration by volcanic vapors and/or waters (Skok et al. 2010).

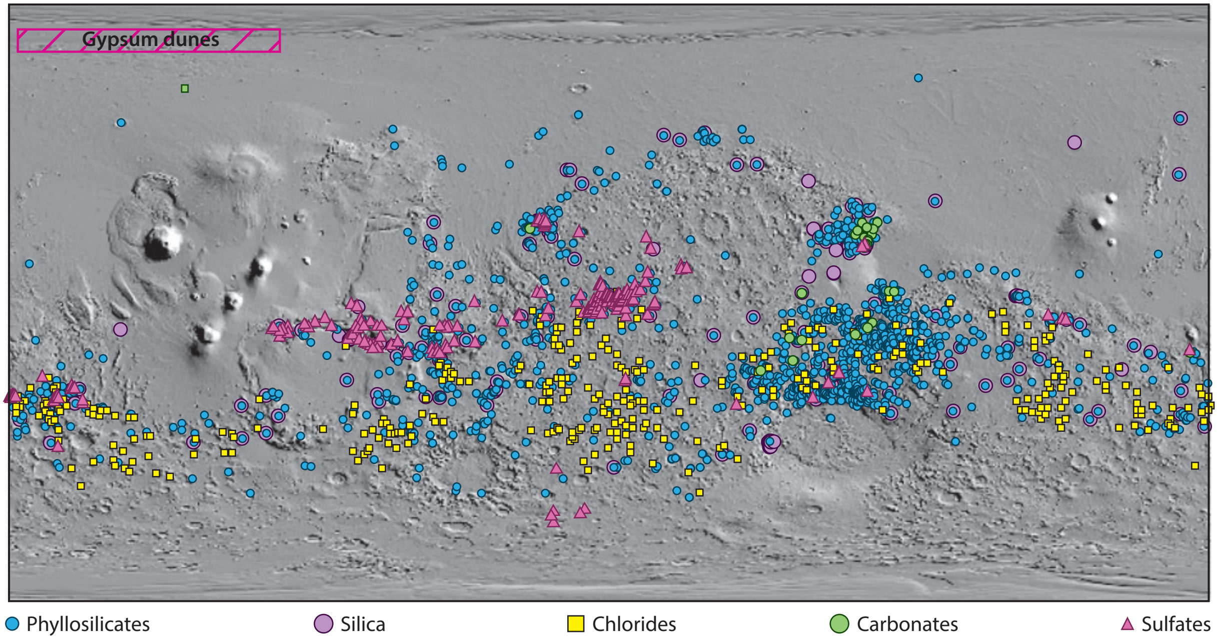
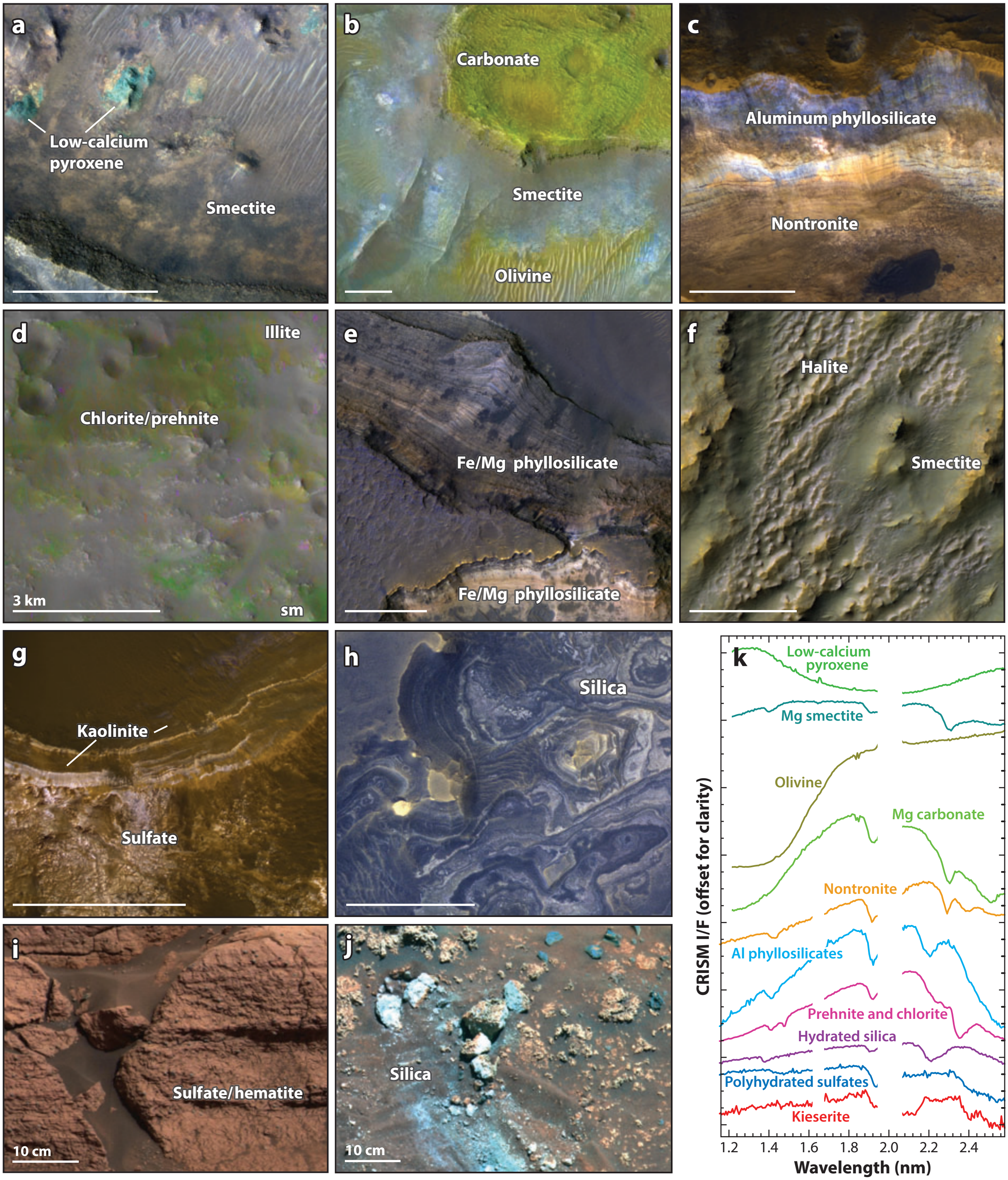


Figure 4

Global distribution of the major classes of aqueous minerals on Mars. Phyllosilicates (compilations by Ehlmann et al. 2011 and Carter et al. 2013) occur in almost every region where Noachian crust is exposed. The distributions of other secondary minerals are more regional and/or patchy. Silica detections compiled by Carter et al. (2013). Chlorides compiled by Osterloo et al. (2010). Carbonate-bearing rock detections reported by Ehlmann et al. (2008b) and reviewed in Niles et al. (2013) (square indicates Phoenix lander soil carbonate). Sulfate detections are amalgamated from Murchie et al. (2009a), Milliken et al. (2010), Ackiss & Wray (2012), and Carter et al. (2013), edited to remove locations with ambiguity regarding hydrated silicates.

4.1. Sands and Soils

The composition of sands and soils records the local bedrock composition, sedimentary and impact-induced transport, mixing, and, potentially, chemical alteration. A global soil—i.e., a globally transported and homogenized fine fraction—has been inferred from the similar chemistry of unconsolidated materials at landing sites but remains to be tested with in situ mineralogic analysis. Locally, like the basaltic terrains of Mars, the detailed mineralogy of aeolian bedforms can be variable (Tirsch et al. 2011). Regolith materials typically appear relatively depleted in olivine relative to in-place rock, potentially due to chemical weathering (Bandfield & Rogers 2008, Bandfield et al. 2011). However, some dunes are olivine enriched (>20%), for example at Nili Fossae, likely because of bedrock locally enriched in olivine (Mustard et al. 2009). Sands within the Rocknest bedform at Gale crater are composed of 22% olivine ($\sim\mathrm{Fo}_{60}$; Blake et al. 2013). Within Gusev crater, coarse olivine grains were observed to armor bedforms in and around the Columbia Hills (Arvidson et al. 2008). At Meridiani, dunes are commonly armored by hematite grains, derived from physically weathered concretions (Arvidson et al. 2006). In and around the northern plains are dunes and interdunes enriched in gypsum that results from mineralization and rock-water interactions locally or from erosion of gypsum-bearing materials in the polar cap (Langevin et al. 2005, Fishbaugh et al. 2007, Horgan et al. 2009, Massé et al. 2010). At some landing sites, carbonate and perchlorate are found in soils (Boynton et al. 2009, Hecht et al. 2009), while others include sulfates and silica (Yen et al. 2005, Ruff et al. 2011). Thus, although the soils of Mars are


a
Low-calcium
pyroxene
Smectite
b
Carbonate
Smectite
Olivine
c
Aluminum phyllosilicate
Nontronite
d
Illite
Chlorite/prehnite
3 km
sm
e
Fe/Mg phyllosilicate
Fe/Mg phyllosilicate
f
Halite
Smectite
g
Kaolinite
Sulfate
h
Silica
i
Sulfate/hematite
10 cm
j
Silica
10 cm
k
Low-calcium
pyroxene
Mg smectite
Olivine
Mg carbonate
Nontronite
Al phyllosilicates
Prehnite and chlorite
Hydrated silica
Polyhydrated sulfates
Kieserite
CRISM I/F (offset for clarity)
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Wavelength (nm)

mostly basaltic in nature, local variations in mineralogy are reflected in the composition of aeolian bedforms and regolith.

4.2. Mars Dust: An Alteration Product?

The precise composition of Mars's finest-grained (<5 μm) material, globally dispersed reddish dust, has been something of an enigma: VNIR data show a strong Fe^{3+} absorption but lack the absorptions of well-crystalline oxides, favoring instead a phase such as palagonite or poorly crystalline nanophase iron oxides (Morris et al. 2000). The dusty surfaces of Mars are hydrated in both VNIR and TIR data, and some features suggest the presence of a hydrated silicate such as a zeolite (Ruff 2004). TES spectra of dust lofted in the atmosphere suggest dominantly plagioclase and framework hydrated silicates along with lesser amounts of olivine, pyroxenes, and sulfates (Hamilton et al. 2005). Magnesium carbonate (<4 wt%) has also been reported (Bandfield et al. 2003). Rover-based data show that the dust is magnetic, enriched in nanophase Fe(III), and depleted in olivine relative to the soils, although olivine and pyroxene still constitute over half of the iron-bearing minerals (Goetz et al. 2005, Morris et al. 2006). Sulfur and chlorine, along with zinc, are also enriched in the dust, which indicates, respectively, some degree of aqueous alteration and a meteoritic component (Yen et al. 2005). The Curiosity rover has not yet measured dust alone, but the finest (<150 μm) fraction from a sand ripple contains a high proportion of poorly crystalline phases (Blake et al. 2013). Short-range ordered phases may dominate Mars dust, rather than well-crystalline igneous or secondary minerals. Collectively, the data indicate physical comminution of primary rocks and soils to form the dust fraction along with oxidation but limited interaction with liquid water.

4.3. Hydration and Alteration of the Bulk Crust

A significant discovery of the past decade was the globally widespread occurrence of hydrated silicates, dominantly clay minerals, in the Noachian crust of Mars. They were originally detected in a few large outcrops in the southern highlands (Bibring et al. 2005, Poulet et al. 2005), and subsequent higher-resolution orbital data have shown additional exposures that are small but widespread, numbering in the thousands and found in locations where Noachian crust is exposed (**Figure 4**) (Mustard et al. 2008, Murchie et al. 2009a).

Occurrences of clay minerals can be divided into three types: in-place stratigraphies of multiple clay-bearing units perhaps formed by in situ alteration; central peaks, walls, and ejecta of impact

←

Figure 5

Mars's aqueous environments as seen by HiRISE and CRISM false color IR images and composites. (*a*) Rocks disrupted by the Isidis impact and exposed 500 m deep in the Nili Fossae trough contain low-calcium pyroxene breccia blocks (*green*) partially altered to Fe/Mg smectite and contained within a smectite-bearing matrix. (*b*) An eroded stratigraphy in Nili Fossae with Mg carbonates (*green*) formed by alteration of an eroded olivine-rich unit that in turn overlies Mg-smectite clays (*blue*). Ridges indicate conduits of subsurface fluid flow. Olivine is also enriched in sand dunes. (*c*) Aluminum phyllosilicates overlie nontronite-bearing sediments at Mawrth Vallis and may have formed by top-down, near-surface leaching. (*d*) Prehnite, chlorite, and illite are associated with the ejecta of small craters north of Syrtis Major and indicate excavation of hydrothermally altered materials. (*e*) Sedimentary beds in the Holden crater fan deposit host Fe/Mg phyllosilicates. (*f*) Chloride salt, possibly halite, overlies older smectite clay–bearing knobs in a shallow depression near 205°E, 33°S. (*g*) Interbedded sulfate- and kaolinite-bearing sediments in Columbus crater paleolake deposits. (*h*) Silica as seen from orbit in layered units around Valles Marineris. (*i*) Sulfate- and hematite-bearing sediments imaged by Pancam at Meridiani have concretions and vugs formed by episodic fluid influx and precipitation and dissolution of minerals. (*j*) Silica rocks and encrustations observed by Pancam in rocks and soils in the Columbia Hills. Scale bar is 200 m unless otherwise indicated. (*k*) CRISM visible/shortwave-infrared spectra of ancient Mars terrains show mineralogic diversity. Data are not shown at the 1.65-μm CRISM filter boundary or within the 2.0-μm atmospheric CO_2 absorption.

craters; and units in sedimentary basins with clay minerals (Ehlmann et al. 2011, 2013). In the geographically largest exposures of stratigraphies of clay minerals, the lowermost stratigraphic units are composed of hundreds of meters of Fe/Mg phyllosilicate–bearing basaltic materials with morphologies ranging from brecciated to layered (**Figure 5*a–c***). In Mawrth Vallis, the composition of the clays is Fe smectite, i.e., nontronite (Poulet et al. 2005, Bishop et al. 2008), whereas in Nili Fossae, more magnesian smectites are detected (Ehlmann et al. 2009). In both locations, stratigraphically above the Fe/Mg smectite–bearing units are aluminum phyllosilicates, kaolinite in Nili Fossae, and a diverse collection of kaolinite, beidellite, montmorillonite, and hydrated silica in Mawrth Vallis (**Figure 5*c***) (Bishop et al. 2008, 2011; Loizeau et al. 2010). This stratigraphy of Al phyllosilicate over Fe/Mg phyllosilicate has also been reported in Vallis Marineris (Murchie et al. 2009a) and in numerous small outcrops across the southern highlands (Carter et al. 2013). It likely results from more acid alteration and/or enhanced leaching later in Mars history (late Noachian–early Hesperian) that affected the uppermost crustal units (Ehlmann et al. 2009, 2011).

Impact craters provide exposures of the deep Noachian crust of Mars. As is true in other geologic settings, Fe/Mg smectites are the most common hydrated silicate, but chlorite minerals are also commonly found, and several craters host prehnite, illite/muscovite, serpentine, opaline silica, and analcime (**Figure 5*d***) (Ehlmann et al. 2009, 2011; Carter et al. 2013). These assemblages point to higher-temperature alteration processes—in the case of prehnite, 200–400°C. Because hydrated silicates are found not only in central peaks of impact craters but also in walls and far-flung ejecta, these materials are thought to mostly represent excavated, deeply buried crust that experienced subsurface hydrothermal alteration at temperatures ranging from ambient up to 400°C (Ehlmann et al. 2009, 2011). The association between clay minerals and craters is global and linked with the excavation of Noachian crust. For example, clay minerals are not widespread in the Hesperian and Amazonian units of the northern plains but are found associated with the largest impact craters, which excavate through Hesperian plains to Noachian bedrock (Carter et al. 2010). A few craters have been proposed to be sites of post-impact hydrothermal activity (Marzo et al. 2010, Loizeau et al. 2012, Mangold et al. 2012). In situ exploration of Noachian-aged Endeavor crater by the Opportunity rover shows extensive Fe/Mg-clay-altered bedrock and fracture fill as well as centimeter-scale-width veins of silica- and aluminum-rich materials and gypsum; the veins are interpreted to be zones of post-impact fluid alteration (Arvidson et al. 2014).

4.4. Paleolake and Playa Sediments

The surface of Mars is pockmarked with craters and depressions that serve as depositional centers for sediments eroded from surrounding terrains. A recent discovery has been the association of Fe/Mg clay minerals with fluviodeltaic deposits in multiple paleolakes including Jezero, Holden, and Eberswalde craters (**Figure 5*e***) (Ehlmann et al. 2008a, Grant et al. 2008, Murchie et al. 2009a, Dehouck et al. 2010, Milliken & Bish 2010). The clay mineralogy detected within the basins is spectrally similar to the clay mineralogy of the surrounding highlands, consistent with a detrital origin. However, in many locations, the sedimentary clay-bearing deposits are found with other minerals, particularly salts not found in nearby highlands. Hundreds of irregular depressions across the southern highlands host chloride minerals (Osterloo et al. 2008, 2010), which sometimes unconformably overlie eroded clay-bearing knobs (**Figure 5*f***) (Glotch et al. 2010). Several craters in the Terra Sirenum area of Mars host flat-lying sediments, which include clay minerals and sulfate minerals, including gypsum, and polyhydrated Mg sulfates, as well as the acid sulfates jarosite and alunite (**Figure 5*g***) (Swayze et al. 2008, Wray et al. 2011). These occur within closed basins and are thought to represent evaporite sediments from acid lakes. Gale crater, the landing site for the 2012 Mars Science Laboratory Curiosity rover, also hosts a sequence of nontronite, crystalline hematite, and sulfates in the sediments of Mount Sharp (Milliken et al. 2010, Fraeman et al. 2013). Curiosity's first year of exploration yielded discovery of Fe/Mg smectites in fine-grained sedimentary rocks within Yellowknife Bay, cut by veins of diagenetic calcium sulfates (Grotzinger et al. 2014, Vaniman et al. 2014).

4.5. The Groundwater Story: Sulfates and Crystalline Ferric Oxides

What controls the distribution of evaporite salts? In some cases, there appears to be a clear relationship between areas of predicted groundwater upwelling (Andrews-Hanna et al. 2010) and locations of orbital detections of sulfate minerals including at Terra Sirenum, Meridiani Planum, and Aram Chaos (Murchie et al. 2009a, Roach et al. 2010a, Wray et al. 2011). The Opportunity rover has explored in situ a hematite-enriched unit detected by TES and associated with Hesperian sedimentary units, finding Mg/Ca/Fe sulfates, hematite, silica, and some residual primary phases from basalt (**Figure 5*i***) (Christensen et al. 2000a, Clark et al. 2005, Glotch et al. 2006). Subsequently, orbital VNIR imaging showed that the Hesperian sedimentary rocks with hematite and polyhydrated and monohydrated sulfates overlie Noachian units with clays (Gendrin et al. 2005; Arvidson et al. 2005, 2006; Wiseman et al. 2010). The environmental interpretation, based on in situ textural analysis at fine scale, is that the sediments were deposited in a playa setting in which episodic groundwater upwelling led to formation of shallow lakes between aeolian bedforms (Grotzinger et al. 2005). Vugs and spherical nodules of hematite are evidence of multiple episodes of diagenetic precipitation and dissolution of secondary mineral phases (**Figure 5*i***) (McLennan et al. 2005). The association between hematite and hydrated sulfates is one observed elsewhere on the planet, including the Valles Marineris system and chaos units (Bibring et al. 2007, Roach et al. 2010a). These deposits are all Hesperian aged. The presence of jarosite at Meridiani (Klingelhöfer et al. 2004, Tosca et al. 2005); jarosite and alunite in the Terra Sirenum basins (Swayze et al. 2008, Wray et al. 2011); and $Fe^{3+}SO_4(OH)$ at Aram Chaos (Lichtenberg et al. 2010) indicates that waters were acidic ($pH < 4$) at some locations.

4.6. Younger Alteration in the Valles Marineris System and Around Volcanoes

The Valles Marineris canyon system is unique in both the diversity and the relatively young age of some of its aqueous deposits. The system initiates in the Noctis Labyrinthus area, a chaos region in the Tharsis volcanic dome. Within Noctis Labyrinthus, a suite of alteration minerals have been mapped, including kaolin and hydrated silica minerals on the trough floor; Fe smectite in sediments on the walls; and an array of polyhydrated sulfates, jarosite, and other ferric sulfate hydroxides (Thollot et al. 2012). This alteration, which occurred from the Hesperian onward, postdates that in most other places on Mars, possibly driven by hydrothermal circulation. Within the broader troughs of Valles Marineris, a 6-km sequence of minerals is exposed. The deeper units include mafic lavas and dikes with olivine and low-calcium pyroxene as well as certain discrete rocky units altered partially to chlorite and Fe/Mg smectites (McEwen et al. 1999, Murchie et al. 2009a, Flahaut et al. 2012). Near the top of the canyon walls are Fe/Mg smectites, overlain by Al smectites, as occurs elsewhere on Mars (Murchie et al. 2009a). Within the canyon are many several-kilometers-high sedimentary layered deposits, which contain kieserite, szomolnokite, and polyhydrated Fe/Mg sulfates (Gendrin et al. 2005, Murchie et al. 2009b, Bishop et al. 2009), as well as local topographic lows with sulfate and an enigmatic "doublet material" (a phase with absorptions at 2.21 and 2.27 μm), which may represent the products of acid leaching of smectites (Roach et al. 2010b). Finally, Hesperian to Amazonian finely layered sediments on the plateaus surrounding the canyon are fluvially dissected and partially altered to opaline silica and jarosite (**Figure 5*b***) (Milliken et al. 2008, Weitz et al. 2011). That the alteration to hydrated minerals persists into the late Hesperian is anomalous and may be related to the proximity of regionally important volcanic activity. Among the youngest hydrated silicates on Mars are hydrated silica deposits on the flanks of the Hesperian Nili Patera caldera (**Figure 3**) (Skok et al. 2010) and in soils and rocks around the explosive volcanic feature Home Plate in the Columbia Hills of Gusev crater, in one instance paired with pyrite/marcasite (**Figure 5*j***) (Morris et al. 2008, Squyres et al. 2008, Ruff et al. 2011). The soils and rocks of Gusev crater near Home Plate also contain Fe(III) sulfates, which may be geologically recent, in select locations (Morris et al. 2006, 2008).

4.8. The Carbonate Puzzle

Mg/Fe carbonates have been detected associated with the large, Noachian olivine-enriched units west of the Isidis basin and in a few impact craters scattered throughout the southern highlands (**Figure 4**) (Ehlmann et al. 2008b, Niles et al. 2013). The Spirit rover also encountered Mg/Fe/Ca carbonates in the Columbia Hills Comanche outcrop, associated with rocks containing olivine and silica (**Figure 1**) (Morris et al. 2010). Collectively, these data indicate neutral to alkaline aqueous alteration in these locations whereby dissolution of olivine promoted the formation of particularly Mg/Fe-rich carbonates. Mg carbonates have also been reported in martian dust (Bandfield et al. 2003) and Ca carbonates in soils at the Phoenix landing site (Boynton et al. 2009). However, the presence of carbonate-bearing rocks appears to be geographically restricted (**Figure 4**).

In light of widespread near-surface aqueous alteration in the past and the CO_2-rich composition of the Mars atmosphere, one might expect carbonate deposits to dominate the record. Laboratory data indicate that small quantities of carbonate could form as thin films under present-day martian conditions (Booth & Kieffer 1978), and clay-carbonate assemblages are common in terrestrial settings and were predicted for Mars (Pollack et al. 1987). In light of the lack of massive, widespread carbonate, one possibility is that most alteration to form hydrated silicates occurred in the subsurface, out of contact with the atmosphere (Ehlmann et al. 2011). Another is that interaction with acidic waters inhibited carbonate formation or preservation (Bullock & Moore 2007). Whether or not carbonate commonly co-occurs at low abundances (undetectable from orbit) associated with clay minerals provides a means of distinguishing between these hypotheses but remains to be tested by future in situ exploration.

5. FUTURE SCIENCE AND EXPLORATION

There remain numerous puzzles and key questions about the mineralogy of Mars that build upon the discoveries above. For example, the oldest Noachian crust of Mars is basaltic, but the relative proportions of bedrock from lavas, ash from explosive volcanism, impact breccias, sediments, and chemically weathered material are subjects of ongoing work (e.g., McEwen et al. 1999, Bandfield et al. 2013). What are the proportions and configurations of igneous intrusions? Do any remnants of the primary crust, formed during differentiation, remain, as is the case for the Moon (e.g., Skok et al. 2012)? It is not yet known whether the widespread olivine-enriched basalts host xenoliths and are a probe of mantle composition or host phenocrysts that result from crystallization from magma.

The global nature of mineral formation by liquid water during the first billion years has been a key discovery, and it appears that large deposits of phyllosilicates are found only in the Noachian crust (e.g., Bibring et al. 2006). However, the extent of alteration (e.g., wt% clay mineral) is less well known, and there is considerable spatiotemporal variability in the details of the mineralogy. Were most clay minerals formed in the subsurface or at the surface? What controls the distribution of chlorides, sulfates, and carbonates at large scale (**Figure 4**) as well as at local scale in soils? Were most later Mars environments acidic, or have local conditions always exerted strong control on fluid pH and thus on minerals formed? Does the confluence in timing of lake basin sediments and

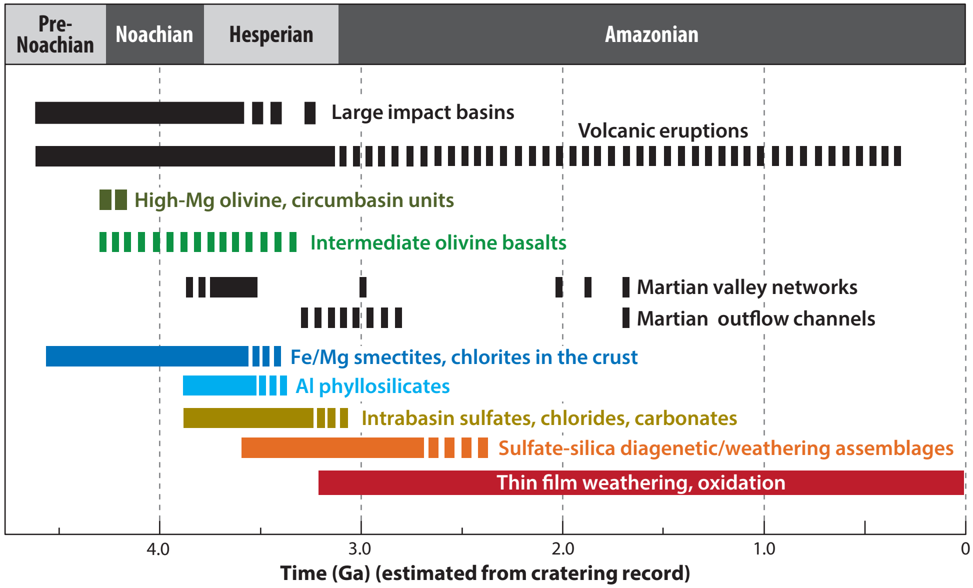


Figure 6

Timeline of the major processes affecting the mineralogic composition of Mars and the ages of large-scale compositional units.

aluminum clay minerals in units dating from near the Noachian–Hesperian boundary indicate a late Noachian climate optimum or preservation bias (**Figure 6**) (e.g., Ehlmann et al. 2011)?

Compositions of some important Mars surface units remain unknown. Dust cover in the summit regions of Mars's highest volcanoes, where the youngest (<500 Ma) flows lie (Werner 2009), has confounded even the 18 m/pixel scale now enabled by CRISM. Likewise, no mineralogically diagnostic IR spectral signatures are associated with mantling layers in the north and south polar regions (Mustard et al. 2001), the sedimentary materials of the Medusae Fossae formation (Kerber & Head 2010), or the banded sedimentary deposits, termed rhythmites, that fill a few highlands craters and are thought to record changes in climate due to orbital forcing (Lewis et al. 2008). Moreover, the most recent, Amazonian potential fluvial features (Malin & Edgett 2001, McEwen et al. 2011) have no unique spectral signatures indicative of precipitated salts. Some phases mapped spectrally on Mars have not yet been definitively attributed to a mineral or mineral assemblage. This includes the "doublet" material found throughout Valles Marineris (Roach et al. 2010b). Some phyllosilicate minerals have absorption band characteristics that do not match well samples measured on Earth, perhaps because of different chemical composition or perhaps because the physiochemical properties are distinctive due to the pressure and temperature conditions of the Mars environment (Morris et al. 2011). An outstanding question is to what degree Fe/Mg phyllosilicates are Fe/Mg smectites versus intermediate products on the diagenetic sequence from smectite to chlorite, illite, or other higher-temperature clays (Milliken & Bish 2010). Conversely, it is intriguing that a phase, $Fe(III)OHSO_4$, can be mapped from orbit around Mars but is not classified as a mineral because it does not occur naturally on Earth (Lichtenberg et al. 2010).

More minerals may yet be found unique to Mars. The XRD instrument on Curiosity, complemented by other payload instruments, should provide some of the most precise mineralogic and chemical data ever obtained for Mars for the materials in Gale crater. An important lesson from the past decade and a half of remote sensing is the synergy between orbital and rover-based exploration. Progressively higher spatial resolution mineralogy from orbit has been the enabler of many new discoveries, best illustrated by the thousands of new phyllosilicate exposures and mineral identifications enabled by the factor-of-ten increase in spatial resolution and modest increase in spectral resolution provided by CRISM over previous IR spectrometers. While data from landed investigations will never be acquired for large sections of the planet, the locations where landed data intersect orbital data allow local insights learned at the lander scale to be applied to regional and global investigations possible only from orbit. The rovers at Meridiani, Gusev, and Gale have also shown that Mars gets more interesting the closer one looks. Sulfates, silica, and carbonates of the Columbia Hills were detected on the ground at small scale, by the data from Mini-TES (**Figure 1**), showing that the basaltic hills held a history of processes not resolved spatially from orbit. Similarly, at Gale crater, the sediments of Yellowknife held phyllosilicates and centimeter-scale gypsum veins that were not seen from orbit, but the exposures could be sampled by the rovers. Although from orbit major components of an assemblage can sometimes be discerned with confidence, it remains for landed exploration to characterize complete assemblages and use all geologic tools to discern the paleoenvironmental conditions.

Looking ahead to future mission opportunities, advancing detector and instrument technology to higher spatial and spectral resolution capabilities would enable new discoveries from orbit. The rovers sent to the surface so far have visited only three of the dozen or so distinctive aqueous paleoenvironments related to water and distinguished by secondary mineral assemblages. Mars's largest volcanic units also remain unsampled. Sampling these is a key objective for furthering studies of Mars mineralogy and understanding of planetary processes. In the meantime, laboratory-based studies with analog samples on Earth continue to increase the quality and quantity of phases in terrestrial spectral libraries and provide a testing ground for new, improved ways of analyzing the rich collection of data sets on martian mineralogy.

SUMMARY POINTS

1. Mars has a basaltic upper crust with regional variations in the relative abundances of plagioclase, pyroxene, and olivine minerals that indicate spatiotemporal changes in magma composition and generation.
2. The presence of >1,000-km-diameter impact basins with enrichment in high-Mg olivine indicates excavation of the upper mantle or high-temperature lavas emplaced following impact.
3. Many Noachian and Hesperian lavas on Mars are enriched in intermediate-Mg-number olivine.
4. Evolved rocks are rare but are found locally, indicating local-scale igneous fractional crystallization of magmas, differences in their source compositions, or other differences in igneous processes.
5. Clay minerals are widespread where there is exposure of Noachian crust, implying global aqueous alteration processes at neutral to alkaline pH early in Mars history. Some portion of this alteration was hydrothermal and some was near-surface weathering.
6. Paleolakes existed in late Noachian–early Hesperian Mars, roughly coincident with the timing of enhanced near-surface weathering inferred from aluminum clay formation, and some basins host sedimentary clay minerals and precipitated salts (sulfates, chlorides, carbonates). Salinity and pH differed regionally, as did the relative importance of detrital and precipitated sediments, as indicated by varied mineral assemblages.

7. Groundwater played an important role in formation and diagenesis of clay minerals, and its upwelling produced large deposits of sulfates, hematite, and chlorides.
8. Many (but not all) hydrated mineral assemblages from the Hesperian have acid sulfate minerals such as iron and aluminum sulfates, implying more acidic conditions later in Mars history in some locations.
9. Carbonate-bearing rocks associated with olivine have been detected, and carbonate is present in small quantities in dust and soil; however, controls on its present-day distribution are incompletely understood.
10. The northern plains record a distinctive style of aqueous alteration, involving amorphous coatings or weathering rinds, possibly of volcanic glasses.
11. Amazonian units do not generally have crystalline alteration minerals, implying substantially less water and aqueous alteration late in Mars history.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

The authors thank numerous individuals. Phil Christensen, Woody Fischer, Andy Knoll, Dick Morris, Scott Murchie, Deanne Rogers, and James Wray provided early reviews that improved this manuscript, as did formal review comments provided by an anonymous reviewer. Steve Ruff provided the Mini-TES data and Anouck Ody provided the global OMEGA olivine distribution data used in this manuscript. John Carter provided his hydrated mineral detections.

LITERATURE CITED

Ackiss S, Wray J. 2012. Hydrated sulfates in the southern high latitudes of Mars. *Lunar Planet. Sci. Conf. Abstr.* 43:2434

Andrews-Hanna JC, Zuber MT, Arvidson RE, Wiseman SM. 2010. Early Mars hydrology: Meridiani playa deposits and the sedimentary record of Arabia Terra. *J. Geophys. Res.* 115:E06002

Arvidson RE, Poulet F, Bibring J-P, Wolff M, Gendrin A, et al. 2005. Spectral reflectance and morphologic correlations in eastern Terra Meridiani, Mars. *Science* 307:1591–94

Arvidson RE, Poulet F, Morris RV, Bibring J-P, Bell JF III, et al. 2006. Nature and origin of the hematite-bearing plains of Terra Meridiani based on analyses of orbital and Mars Exploration rover data sets. *J. Geophys. Res.* 111:E12S08

Arvidson RE, Ruff SW, Morris RV, Ming DW, Crumpler LS, et al. 2008. Spirit Mars Rover Mission to the Columbia Hills, Gusev Crater: mission overview and selected results from the Cumberland Ridge to Home Plate. *J. Geophys. Res.* 113:E12S33

Arvidson RE, Squyres SW, Bell JF III, Catalano JG, Clark BC, et al. 2014. Ancient aqueous environments at Endeavour crater, Mars. *Science* 343. doi: 10.1126/science.1248097

Bandfield JL. 2006. Extended surface exposures of granitoid compositions in Syrtis Major, Mars. *Geophys. Res. Lett.* 33:L06203

Bandfield JL, Edwards CS, Montgomery DR, Brand BD. 2013. The dual nature of the martian crust: young lavas and old clastic materials. *Icarus* 222:188–99

Bandfield JL, Glotch TD, Christensen PR. 2003. Spectroscopic identification of carbonates in the martian dust. *Science* 301:1084–87

Bandfield JL, Hamilton VE, Christensen PR. 2000. A global view of martian volcanic compositions. *Science* 287:1626–30

Bandfield JL, Hamilton VE, Christensen PR, McSween HY Jr. 2004. Identification of quartzofeldspathic materials on Mars. *J. Geophys. Res.* 109:E10009

Bandfield JL, Rogers AD. 2008. Olivine dissolution by acidic fluids in Argyre Planitia, Mars: evidence for a widespread process? *Geology* 36:579–82

Bandfield JL, Rogers AD, Edwards CS. 2011. The role of aqueous alteration in the formation of martian soils. *Icarus* 211:157–71

Banin A, Clark BC, Wanke H. 1992. Surface chemistry and mineralogy. See Kieffer et al. 1992, pp. 594–625

Bell J III. 2008. *The Martian Surface—Composition, Mineralogy, and Physical Properties*. New York: Cambridge Univ. Press

Bibring J-P, Arvidson RE, Gendrin A, Gondet B, Langevin Y, et al. 2007. Coupled ferric oxides and sulfates on the martian surface. *Science* 317:1206–10

Bibring J-P, Combes M, Langevin Y, Soufflot A, Cara C, et al. 1989. Results from the ISM experiment. *Nature* 341:591–93

Bibring J-P, Langevin Y, Gendrin A, Gondet B, Poulet F, et al. 2005. Mars surface diversity as revealed by the OMEGA/Mars Express observations. *Science* 307:1576–81

Bibring J-P, Langevin Y, Mustard JF, Poulet F, Arvidson R, et al. 2006. Global mineralogical and aqueous Mars history derived from OMEGA/Mars Express data. *Science* 312:400–4

Bishop JL, Gates WP, Makarewicz H, McKeown NK, Hiroi T. 2011. Reflectance spectroscopy of beidellites and their importance for Mars. *Clays Clay Miner.* 59:378–99

Bishop JL, Noe Dobrea EZ, McKeown NK, Parente M, Ehlmann BL, et al. 2008. Phyllosilicate diversity and past aqueous activity revealed at Mawrth Vallis, Mars. *Science* 321:830–33

Bishop JL, Parente M, Wietz CM, Noe Dobrea EZ, Roach LH, et al. 2009. Mineralogy of Juventae Chasma: sulfates in the light-toned mounds, mafic minerals in the bedrock, and hydrated silica and hydroxylated ferric sulfate on the plateau. *J. Geophys. Res.* 114:E00D09

Blake DF, Morris RV, Kocurek G, Morrison SM, Downs RT, et al. 2013. Curiosity at Gale Crater, Mars: characterization and analysis of the Rocknest sand shadow. *Science* 341:1239505

Blake DF, Vaniman D, Achilles C, Anderson R, Bish D, et al. 2012. Characterization and calibration of the CheMin mineralogical instrument on Mars Science Laboratory. *Space Sci. Rev.* 170:341–99

Booth MC, Kieffer HH. 1978. Carbonate formation in Marslike environments. *J. Geophys. Res.* 83:1809–15

Boynton WV, Ming DW, Kounaves SP, Young SMM, Arvidson RE, et al. 2009. Evidence for calcium carbonate at the Mars Phoenix landing site. *Science* 325:61–64

Buczkowski DL, Murchie S, Clark R, Seelos K, Seelos F, et al. 2010. Investigation of an Argyre basin ring structure using Mars Reconnaissance Orbiter/Compact Reconnaissance Imaging Spectrometer for Mars. *J. Geophys. Res.* 115:E12011

Bullock MA, Moore JM. 2007. Atmospheric conditions on early Mars and the missing layered carbonates. *Geophys. Res. Lett.* 34:L19201

Carter J, Poulet F. 2013. Ancient plutonic processes on Mars inferred from the detection of possible anorthositic terrains. *Nat. Geosci.* 6:1008–12

Carter J, Poulet F, Bibring J-P, Mangold N, Murchie S. 2013. Hydrous minerals on Mars as seen by the CRISM and OMEGA imaging spectrometers: updated global view. *J. Geophys. Res. Planets* 118:831–58

Carter J, Poulet F, Bibring J-P, Murchie S. 2010. Detection of hydrated silicates in crustal outcrops in the northern plains of Mars. *Science* 328:1682–86

Christensen PR, Bandfield JL, Clark RN, Edgett KS, Hamilton VE, et al. 2000a. Detection of crystalline hematite mineralization by the Thermal Emission Spectrometer: evidence for near-surface water. *J. Geophys. Res.* 105(E4):9623–42

Christensen PR, Bandfield JL, Hamilton VE, Ruff SW, Kieffer HH, et al. 2001. Mars Global Surveyor Thermal Emission Spectrometer experiment: investigation description and surface science results. *J. Geophys. Res.* 106(E10):23823–71

Christensen PR, Bandfield JL, Smith MD, Hamilton VE, Clark RN. 2000b. Identification of a basaltic component on the martian surface from Thermal Emission Spectrometer data. *J. Geophys. Res.* 105(E4):9609–22

Christensen PR, Jakosky BM, Kieffer HH, Malin MC, McSween HY Jr, et al. 2004. The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey mission. *Space Sci. Rev.* 110:85–130

Christensen PR, McSween HY Jr, Bandfield JL, Ruff SW, Rogers AD, et al. 2005. Evidence for magmatic evolution and diversity on Mars from infrared observations. *Nature* 436:504–9

Christensen PR, Mehall GL, Silverman SH, Anwar S, Cannon G, et al. 2003. The Miniature Thermal Emission Spectrometer for the Mars Exploration Rovers. *J. Geophys. Res.* 108(E12):8064

Clark BC, Morris RV, McLennan SM, Gellert R, Jolliff B, et al. 2005. Chemistry and mineralogy of outcrops at Meridiani Planum. *Earth Planet. Sci. Lett.* 240:73–94

Clark RN. 1995. Reflectance spectra. In *Rock Physics & Phase Relations: A Handbook of Physical Constants*, ed. TJ Ahrens, pp. 178–88. AGU Ref. Shelf 3. Washington, DC: AGU

Dehouck E, Mangold N, Le Mouélic S, Ansan V, Poulet F. 2010. Ismenius Cavus, Mars: a deep paleolake with phyllosilicate deposits. *Planet. Space Sci.* 58:941–46

Edwards CS, Bandfield JL, Christensen PR, Fergason RL. 2009. Global distribution of bedrock exposures on Mars using THEMIS high-resolution thermal inertia. *J. Geophys. Res.* 114:E11001

Edwards CS, Bandfield JL, Christensen PR, Rogers AD. 2014. The formation of infilled craters on Mars: evidence for widespread impact induced decompression of the early martian mantle? *Icarus* 228:149–66

Edwards CS, Christensen PR, Hamilton VE. 2008. Evidence for extensive olivine-rich basalt bedrock outcrops in Ganges and Eos chasmas, Mars. *J. Geophys. Res.* 113:E11003

Ehlmann BL, Berger G, Mangold N, Michalski JR, Catling DC, et al. 2013. Geochemical consequences of widespread clay mineral formation in Mars' ancient crust. *Space Sci. Rev.* 174:329–64

Ehlmann BL, Mustard JF, Fassett CI, Schon SC, Head JW III, et al. 2008a. Clay minerals in delta deposits and organic preservation potential on Mars. *Nat. Geosci.* 1:355–58

Ehlmann BL, Mustard JF, Murchie SL. 2010. Geologic setting of serpentine deposits on Mars. *Geophys. Res. Lett.* 37:L06201

Ehlmann BL, Mustard JF, Murchie SL, Bibring J-P, Meunier A, et al. 2011. Subsurface water and clay mineral formation during the early history of Mars. *Nature* 479:53–60

Ehlmann BL, Mustard JF, Murchie SL, Poulet F, Bishop JL, et al. 2008b. Orbital identification of carbonate-bearing rocks on Mars. *Science* 322:1828–32

Ehlmann BL, Mustard JF, Swayze GA, Clark RN, Bishop JL, et al. 2009. Identification of hydrated silicate minerals on Mars using MRO-CRISM: geologic context near Nili Fossae and implications for aqueous alteration. *J. Geophys. Res.* 114:E00D08

Farley KA, Malepsin C, Mahaffy P, Grotzinger JP, Vasconcelos PM, et al. 2014. In situ radiometric and exposure age dating of the martian surface. *Science* 341:1247166

Farmer VC. 1974. The layer silicates. In *The Infra-Red Spectra of Minerals*, ed. VC Farmer, pp. 331–64. London: Mineral. Soc.

Fishbaugh KE, Poulet F, Chevrier V, Langevin Y, Bibring J-P. 2007. On the origin of gypsum in the Mars north polar region. *J. Geophys. Res.* 112:E07002

Flahaut J, Quantin C, Clenet H, Allemand P, Mustard JF, Thomas P. 2012. Pristine Noachian crust and key geologic transitions in the lower walls of Valles Marineris: insights into early igneous processes on Mars. *Icarus* 221:420–35

Foley CN, Economou TE, Clayton RN, Dietrich W. 2003. Calibration of the Mars Pathfinder alpha proton X-ray spectrometer. *J. Geophys. Res.* 108(E12):8095

Fraeman AA, Arvidson RE, Catalano JG, Grotzinger JP, Morris RV, et al. 2013. A hematite-bearing layer in Gale Crater, Mars: mapping and implications for past aqueous conditions. *Geology* 41:1103–6

Gendrin A, Mangold N, Bibring J-P, Langevin Y, Gondet B, et al. 2005. Sulfates in martian layered terrains: the OMEGA/Mars Express view. *Science* 307:1587–90

Glotch TD, Bandfield JL, Christensen PR, Calvin WM, McLennan SM, et al. 2006. Mineralogy of the light-toned outcrop at Meridiani Planum as seen by the Miniature Thermal Emission Spectrometer and implications for its formation. *J. Geophys. Res.* 111:E12S03

Glotch TD, Bandfield JL, Tornabene LL, Jensen HB, Seelos FP. 2010. Distribution and formation of chlorides and phyllosilicates in Terra Sirenum, Mars. *Geophys. Res. Lett.* 37:L16202

Goetz W, Bertelsen P, Binau CS, Gunnlaugsson HP, Hviid SF, et al. 2005. Indication of drier periods on Mars from the chemistry and mineralogy of atmospheric dust. *Nature* 436:62–65

Grant JA, Irwin RP III, Grotzinger JP, Milliken RE, Tornabene LL, et al. 2008. HiRISE imaging of impact megabreccia and sub-meter aqueous strata in Holden Crater, Mars. *Geology* 36:195–98

Grotzinger JP, Arvidson RE, Bell JF III, Calvin W, Clark BC, et al. 2005. Stratigraphy and sedimentology of a dry to wet eolian depositional system, Burns formation, Meridiani Planum, Mars. *Earth Planet. Sci. Lett.* 240:11–72

Grotzinger JP, Sumner DY, Kah LC, Stack K, Gupta S, et al. 2014. A habitable fluvio-lacustrine environment at Yellowknife Bay, Gale Crater, Mars. *Science* 343:1242777

Hamilton VE, Christensen PR. 2005. Evidence for extensive olivine-rich bedrock in Nili Fossae, Mars. *Geology* 33:433–36

Hamilton VE, McSween HY Jr, Hapke B. 2005. Mineralogy of martian atmospheric dust inferred from thermal infrared spectra of aerosols. *J. Geophys. Res.* 110:E12006

Hartmann WK, Neukum G. 2001. Cratering chronology and the evolution of Mars. *Space Sci. Rev.* 96:165–94

Hecht MH, Kounaves SP, Quinn RC, West SJ, Young SMM, et al. 2009. Detection of perchlorate and the soluble chemistry of martian soil at the Phoenix lander site. *Science* 325:64–67

Hoefen T, Clark RN, Bandfield JL, Smith MD, Pearl JC, Christensen PR. 2003. Discovery of olivine in the Nili Fossae region of Mars. *Science* 302:627–30

Horgan BH, Bell JF III. 2012. Widespread weathered glass on the surface of Mars. *Geology* 40:391–94

Horgan BH, Bell JF III, Noe Dobrea EZ, Cloutis EA, Bailey DT, et al. 2009. Distribution of hydrated minerals in the north polar region of Mars. *J. Geophys. Res.* 114:E01005

Kerber L, Head JW. 2010. The age of the Medusae Fossae Formation: evidence of Hesperian emplacement from crater morphology, stratigraphy, and ancient lava contacts. *Icarus* 206:669–84

Kieffer HH, Jakosky BM, Snyder CW, Matthews MS, eds. 1992. *Mars.* Tucson: Univ. Ariz. Press

Klingelhöfer G, Morris RV, Bernhardt B, Rodionov DS, de Souza PA, et al. 2003. Athena MIMOS II Mössbauer spectrometer investigation. *J. Geophys. Res.* 108(E12):8067

Klingelhöfer G, Morris RV, Bernhardt B, Schröder C, Rodionov DS, et al. 2004. Jarosite and hematite at Meridiani Planum from the Mössbauer spectrometer on the Opportunity rover. *Science* 306:1740–45

Koeppen WC, Hamilton VE. 2008. Global distribution, composition, and abundance of olivine on the surface of Mars from thermal infrared data. *J. Geophys. Res.* 113:E05001

Kraft MD, Michalski JR, Sharp TG. 2003. Effects of pure silica coatings on thermal emission spectra of basaltic rocks: considerations for martian surface mineralogy. *Geophys. Res. Lett.* 30:2288

Langevin Y, Poulet F, Bibring J-P, Gondet B. 2005. Sulfates in the north polar region of Mars detected by OMEGA/Mars Express. *Science* 307:1584–86

Lewis KW, Aharonson O, Grotzinger JP, Kirk RL, McEwen AS, Suer TA. 2008. Quasi-periodic bedding in the sedimentary rock record of Mars. *Science* 322:1532–35

Lichtenberg KA, Arvidson RE, Morris RV, Murchie SL, Bishop JL, et al. 2010. Stratigraphy of hydrated sulfates in the sedimentary deposits of Aram Chaos, Mars. *J. Geophys. Res.* 115:E00D17

Loizeau D, Carter J, Bouley S, Mangold N, Poulet F, et al. 2012. Characterization of hydrated silicate-bearing outcrops in Tyrrhena Terra, Mars. *Icarus* 219:476–97

Loizeau D, Mangold N, Poulet F, Ansan V, Hauber E, et al. 2010. Stratigraphy in the Mawrth Vallis region through OMEGA, HRSC color imagery and DTM. *Icarus* 205:396–418

Malin MC, Edgett KS. 2001. Mars Global Surveyor Mars Orbiter Camera: interplanetary cruise through primary mission. *J. Geophys. Res.* 106(E10):23429–570

Mangold N, Carter J, Poulet F, Dehouck E, Ansan V, Loizeau D. 2012. Late Hesperian aqueous alteration at Majuro crater, Mars. *Planet. Space Sci.* 72:18–30

Marzo GA, Davila AH, Tonrabene LL, Dohm JM, Fairen AG, et al. 2010. Evidence for Hesperian impact-induced hydrothermalism on Mars. *Icarus* 208:667–83

Massé M, Bourgeois O, Le Mouélic S, Verpoorter C, Le Deit L, et al. 2010. Martian polar and circum-polar sulfate-bearing deposits: sublimation tills derived from the North Polar Cap. *Icarus* 209:434–51

McEwen AS, Malin MC, Carr MH, Hartmann WK. 1999. Voluminous volcanism on early Mars revealed in Valles Marineris. *Nature* 397:584–86

McEwen AS, Ojha L, Dundas CM, Mattson SS, Byrne S, et al. 2011. Seasonal flows on warm martian slopes. *Science* 333:740–43

McLennan SM, Bell JF III, Calvin WM, Christensen PR, Clark BC, et al. 2005. Provenance and diagenesis of the evaporite-bearing Burns formation, Meridiani Planum, Mars. *Earth Planet. Sci. Lett.* 240:95–121

McSween HY Jr, Ruff SW, Morris RV, Bell JF III, Herkenhoff K, et al. 2006a. Alkaline volcanic rocks from the Columbia Hills, Gusev crater, Mars. *J. Geophys. Res.* 111:E09S91

McSween HY Jr, Taylor GJ, Wyatt MB. 2009. Elemental composition of the martian crust. *Science* 324:736–39

McSween HY Jr, Treiman AH. 1998. Martian meteorites. In *Planetary Materials*, ed. J Papike, pp. 6-01–6-54. Rev. Mineral. 36. Washington, DC: Mineral. Soc. Am.

McSween HY Jr, Wyatt MB, Gellert R, Bell JF III, Morris RV, et al. 2006b. Characterization and petrologic interpretation of olivine-rich basalts at Gusev Crater, Mars. *J. Geophys. Res.* 111:E02S10

Milliken RE, Bish DL. 2010. Sources and sinks of clay minerals on Mars. *Philos. Mag.* 90:2293–308

Milliken RE, Grotzinger JP, Thomson BJ. 2010. Paleoclimate of Mars as captured by the stratigraphic record in Gale Crater. *Geophys. Res. Lett.* 37:L04201

Milliken RE, Swayze GA, Arvidson RE, Bishop JL, Clark RN, et al. 2008. Opaline silica in young deposits on Mars. *Geology* 36:847–50

Morris RV, Golden DC, Bell JF III, Shelfer TD, Scheinost AC, et al. 2000. Mineralogy, composition, and alteration of Mars Pathfinder rocks and soils: evidence from multispectral, elemental, and magnetic data on terrestrial analogue, SNC meteorite, and Pathfinder samples. *J. Geophys. Res.* 105(E1):1757–817

Morris RV, Graff TG, Achilles CN, Agresh DG, Ming DW, Golden DC. 2011. Visible and near-IR reflectance spectra of Mars analogue materials under arid conditions for interpretation of martian surface mineralogy. *Lunar Planet. Sci. Conf. Abstr.* 42:2757

Morris RV, Klingelhöfer G, Schröder C, Fleischer I, Ming DW, et al. 2008. Iron mineralogy and aqueous alteration from Husband Hill through Home Plate at Gusev Crater, Mars: results from the Mössbauer instrument on the Spirit Mars Exploration Rover. *J. Geophys. Res.* 113:E12S42

Morris RV, Klingelhöfer G, Schröder C, Rodionov DS, Yen A, et al. 2006. Mössbauer mineralogy of rock, soil, and dust at Gusev crater, Mars: Spirit's journey through weakly altered olivine basalt on the plains and pervasively altered basalt in the Columbia Hills. *J. Geophys. Res.* 111:E02S13

Morris RV, Ruff SW, Gellert R, Ming DW, Arvidson RE, et al. 2010. Identification of carbonate-rich outcrops on Mars by the Spirit rover. *Science* 329:421–24

Murchie S, Arvidson R, Bedini P, Beisser K, Bibring J-P, et al. 2007. Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on Mars Reconnaissance Orbiter (MRO). *J. Geophys. Res.* 112:E05S03

Murchie S, Kirkland L, Erard S, Mustard J, Robinson M. 2000. Near-infrared spectral variations of martian surface materials from ISM imaging spectrometer data. *Icarus* 147:444–71

Murchie SL, Mustard JF, Ehlmann BL, Milliken RE, Bishop JL, et al. 2009a. A synthesis of martian aqueous mineralogy after 1 Mars year of observations from the Mars Reconnaissance Orbiter. *J. Geophys. Res.* 114:E00D06

Murchie S, Roach L, Seelos F, Milliken R, Mustard JF, et al. 2009b. Evidence for the origin of layered deposits in Candor Chasma, Mars, from mineral composition and hydrologic modeling. *J. Geophys. Res.* 114:E00D05

Mustard JF, Cooper CD, Rifkin MK. 2001. Evidence for recent climate change on Mars from the identification of youthful near-surface ground ice. *Nature* 412:411–14

Mustard JF, Ehlmann BL, Murchie SL, Poulet F, Mangold N, et al. 2009. Composition, morphology, and stratigraphy of Noachian crust around the Isidis basin. *J. Geophys. Res.* 114:E00D12

Mustard JF, Murchie SL, Pelkey SM, Ehlmann BL, Milliken RE, et al. 2008. Hydrated silicate minerals on Mars observed by the Mars Reconnaissance Orbiter CRISM instrument. *Nature* 454:305–9

Mustard JF, Poulet F, Gendrin A, Bibring J-P, Langevin Y, et al. 2005. Olivine and pyroxene diversity in the crust of Mars. *Science* 307:1594–97

Mustard JF, Poulet F, Head JW, Mangold N, Bibring J-P, et al. 2007. Mineralogy of the Nili Fossae region with OMEGA/Mars Express data. 1. Ancient impact melt in the Isidis Basin and implications for the transition from the Noachian to Hesperian. *J. Geophys. Res.* 112:E08S03

Niles PB, Catling DC, Berger G, Chassefiere E, Ehlmann BL, et al. 2013. Geochemistry of carbonates on Mars: implications for climate history and nature of aqueous environments. *Space Sci. Rev.* 174:301–28

Nimmo F, Tanaka K. 2005. Early crustal evolution of Mars. *Annu. Rev. Earth Planet. Sci.* 33:133–61

Nyquist LE, Bogard DD, Shih C-Y, Greshake A, Stoffler D, Eugster O. 2001. Ages and geologic histories of martian meteorites. *Space Sci. Rev.* 96:105–64

Ody A, Poulet F, Bibring J-P, Loizeau D, Carter J, et al. 2013. Global investigation of olivine on Mars: insights into crust and mantle compositions. *J. Geophys. Res. Planets* 118:234–62

Osterloo MM, Anderson FS, Hamilton VE, Hynek BM. 2010. Geologic context of proposed chloride-bearing materials on Mars. *J. Geophys. Res.* 115:E10012

Osterloo MM, Hamilton VE, Bandfield JL, Glotch TD, Baldridge AM, et al. 2008. Chloride-bearing materials in the southern highlands of Mars. *Science* 319:1651–54

Pollack JB, Kasting JF, Richardson SM, Poliakoff K. 1987. The case for a wet, warm climate on early Mars. *Icarus* 71:203

Popa C, Esposito F, Mennella V, Colangeli L. 2010. Occurrence of anorthosite on Mars in Xanthe Terra. *Eur. Planet. Sci. Congr. Abstr.* 5:EPSC2010-589

Poulet F, Bibring J-P, Mustard JF, Gendrin A, Mangold N, et al. 2005. Phyllosilicates on Mars and implications for early martian climate. *Nature* 438:623–27

Poulet F, Mangold N, Platevoet B, Bardintzeff J-M, Sautter V, et al. 2009. Quantitative compositional analysis of martian mafic regions using the MEx/OMEGA reflectance data. 2. Petrological implications. *Icarus* 201:84–101

Roach LH, Mustard JF, Lane MD, Bishop JL, Murchie SL. 2010a. Diagenetic hematite and sulfate assemblages in Valles Marineris. *Icarus* 207:659–74

Roach LH, Mustard JF, Swayze G, Milliken RE, Bishop JL, et al. 2010b. Hydrated mineral stratigraphy of Ius Chasma, Valles Marineris. *Icarus* 206:253–68

Rogers AD, Aharonson O, Bandfield JL. 2009. Geologic context of bedrock exposures in Mare Serpentis, Mars: implications for crust and regolith evolution in the cratered highlands. *Icarus* 200:446–62

Rogers AD, Christensen PR. 2007. Surface mineralogy of martian low-albedo regions from MGS TES data: implications for crustal evolution and surface alteration. *J. Geophys. Res.* 112:E01003

Rogers AD, Christensen PR, Bandfield JL. 2005. Compositional heterogeneity of the ancient martian crust: analysis of Ares Vallis bedrock with THEMIS and TES data. *J. Geophys. Res.* 110:E05010

Rogers AD, Fergason RL. 2011. Regional-scale stratigraphy of surface units in Tyrrhena and Iapygia Terrae, Mars: insights into highland crustal evolution and alteration history. *J. Geophys. Res.* 116:E08005

Ruff SW. 2004. Spectral evidence for zeolite in the dust on Mars. *Icarus* 168:131–43

Ruff SW, Christensen PR. 2002. Bright and dark regions on Mars: particle size and mineralogical characteristics based on Thermal Emission Spectrometer data. *J. Geophys. Res.* 107(E12):5119

Ruff SW, Farmer JD, Calvin WM, Herkenhoff KE, Johnson JR, et al. 2011. Characteristics, distribution, origin, and significance of opaline silica observed by the Spirit rover in Gusev crater, Mars. *J. Geophys. Res.* 116:E00F23

Salvatore MR, Mustard JF, Head JW, Cooper RF, Marchant DR, Wyatt MB. 2013. Development of alteration rinds by oxidative weathering processes in Beacon Valley, Antarctica, and implications for Mars. *Geochim. Cosmochim. Acta* 115:137–61

Salvatore MR, Mustard JF, Wyatt MB, Murchie SL. 2010. Definitive evidence of Hesperian basalt in Acidalia and Chryse planitiae. *J. Geophys. Res.* 115:E07005

Sautter V, Fabre C, Forni O, Toplis MJ, Cousin A, et al. 2014. Igneous mineralogy at Bradbury Rise: the first ChemCam campaign at Gale crater. *J. Geophys. Res. Planets* 119:1–17

Singer RB. 1982. Spectral evidence for the mineralogy of high-albedo soils and dust on Mars. *J. Geophys. Res.* 87:10159–68

Skok JR, Mustard JF, Ehlmann BL, Milliken RE, Murchie SL. 2010. Silica deposits in the Nili Patera caldera on the Syrtis Major volcanic complex on Mars. *Nat. Geosci.* 3:838–41

Skok JR, Mustard JF, Tornabene LL, Pan C, Rogers D, Murchie SL. 2012. A spectroscopic analysis of martian crater central peaks: formation of the ancient crust. *J. Geophys. Res.* 117:E00J18

Smith MR, Bandfield JL. 2012. Geology of quartz and hydrated silica–bearing deposits near Antoniadi Crater, Mars. *J. Geophys. Res.* 117:E06007

Soderblom LA. 1992. The composition and mineralogy of the martian surface from spectroscopic observations: 0.3 μm to 50 μm. See Kieffer et al. 1992, pp. 557–93

Squyres SW, Arvidson RE, Ruff S, Gellert R, Morris RV, et al. 2008. Detection of silica-rich deposits on Mars. *Science* 320:1063–67

Stolper E, Baker M, Newcombe M, Schmidt M, Treiman A, et al. 2013. The petrochemistry of Jake_M: a martian mugearite. *Science* 341:1239463

Swayze G, Ehlmann B, Milliken R, Poulet F, Wray J, et al. 2008. Discovery of the acid-sulfate mineral alunite in Terra Sirenum, Mars, using MRO CRISM: possible evidence for acid-saline lacustrine deposits? *Eos Trans. AGU* 89, Fall Meet. Suppl., Abstr. P44A-04

Thollot P, Mangold N, Ansan V, Le Mouélic S, Milliken RE, et al. 2012. Most Mars minerals in a nutshell: various alteration phases formed in a single environment in Noctis Labyrinthus. *J. Geophys. Res. Planets* 117:E00J06

Tirsch D, Jaumann R, Pacifici A, Poulet F. 2011. Dark aeolian sediments in martian craters: composition and sources. *J. Geophys. Res.* 116:E03002

Tornabene LL, Moersch JE, McSween HY Jr, Hamilton VE, Piatek JL, Christensen PR. 2008. Surface and crater-exposed lithologic units of the Isidis Basin as mapped by coanalysis of THEMIS and TES derived data products. *J. Geophys. Res.* 113:E10001

Tosca NJ, McLennan SM, Clark BC, Grotzinger JP, Hurowitz JA, et al. 2005. Geochemical modeling of evaporation processes on Mars: insight from the sedimentary record at Meridiani Planum. *Earth Planet. Sci. Lett.* 240:122–48

Vaniman DT, Bish DL, Ming DW, Bristow TF, Morris RV, et al. 2014. Mineralogy of a mudstone at Yellowknife Bay, Gale crater, Mars. *Science* 343:1243480

Viviano CE, Moersch JE, McSween HY. 2013. Implications for early hydrothermal environments on Mars through the spectral evidence for carbonation and chloritization reactions in the Nili Fossae region. *J. Geophys. Res. Planets* 118:1858–72

Weitz CM, Milliken RE, Grant JA, McEwen AS, Williams RME, et al. 2011. Mars Reconnaissance Orbiter observations of light-toned layered deposits and associated fluvial landforms on the plateaus adjacent to Valles Marineris. *Icarus* 205:73–105

Werner SC. 2009. The global martian volcanic evolutionary history. *Icarus* 201:44–68

Wiseman SM, Arvidson RE, Morris RV, Poulet F, Andrews-Hanna JC, et al. 2010. Spectral and stratigraphic mapping of hydrated sulfate and phyllosilicate-bearing deposits in northern Sinus Meridiani, Mars. *J. Geophys. Res.* 115:E00D18

Wray JJ, Hansen ST, Dufek J, Swayze GA, Murchie SL, et al. 2013. Prolonged magmatic activity on Mars inferred from the detection of felsic rocks. *Nat. Geosci.* 6:1013–17

Wray JJ, Milliken RE, Dundas CM, Swayze GA, Andrews-Hanna JC, et al. 2011. Columbus crater and other possible groundwater-fed paleolakes of Terra Sirenum, Mars. *J. Geophys. Res.* 116:E01001

Wyatt MB, McSween HY Jr. 2002. Spectral evidence for weathered basalt as an alternative to andesite in the northern lowlands of Mars. *Nature* 417:263–66

Yen AS, Gellert R, Schröder C, Morris RV, Bell JF III, et al. 2005. An integrated view of the chemistry and mineralogy of martian soils. *Nature* 436:49–54

Annual Review of Earth and Planetary Sciences
Volume 42, 2014

Contents

Indexes

Errata

An online log of corrections to *Annual Review of Earth and Planetary Sciences* articles may be found at http://www.annualreviews.org/errata/earth

Annu. Rev. Earth Planet. Sci. 2014.42:291-315. Downloaded from www.annualreviews.org
Access provided by University of Arizona - Library on 01/15/15. For personal use only.

ANNUAL REVIEWS
It's about time. Your time. It's time well spent.

New From Annual Reviews:

Annual Review of Statistics and Its Application
Volume 1 • Online January 2014 • http://statistics.annualreviews.org

Editor: **Stephen E. Fienberg,** *Carnegie Mellon University*
Associate Editors: **Nancy Reid,** *University of Toronto*
Stephen M. Stigler, *University of Chicago*

The *Annual Review of Statistics and Its Application* aims to inform statisticians and quantitative methodologists, as well as all scientists and users of statistics about major methodological advances and the computational tools that allow for their implementation. It will include developments in the field of statistics, including theoretical statistical underpinnings of new methodology, as well as developments in specific application domains such as biostatistics and bioinformatics, economics, machine learning, psychology, sociology, and aspects of the physical sciences.

Complimentary online access to the first volume will be available until January 2015.

TABLE OF CONTENTS:

- *What Is Statistics?* Stephen E. Fienberg
- *A Systematic Statistical Approach to Evaluating Evidence from Observational Studies,* David Madigan, Paul E. Stang, Jesse A. Berlin, Martijn Schuemie, J. Marc Overhage, Marc A. Suchard, Bill Dumouchel, Abraham G. Hartzema, Patrick B. Ryan
- *The Role of Statistics in the Discovery of a Higgs Boson,* David A. van Dyk
- *Brain Imaging Analysis,* F. DuBois Bowman
- *Statistics and Climate,* Peter Guttorp
- *Climate Simulators and Climate Projections,* Jonathan Rougier, Michael Goldstein
- *Probabilistic Forecasting,* Tilmann Gneiting, Matthias Katzfuss
- *Bayesian Computational Tools,* Christian P. Robert
- *Bayesian Computation Via Markov Chain Monte Carlo,* Radu V. Craiu, Jeffrey S. Rosenthal
- *Build, Compute, Critique, Repeat: Data Analysis with Latent Variable Models,* David M. Blei
- *Structured Regularizers for High-Dimensional Problems: Statistical and Computational Issues,* Martin J. Wainwright
- *High-Dimensional Statistics with a View Toward Applications in Biology,* Peter Bühlmann, Markus Kalisch, Lukas Meier
- *Next-Generation Statistical Genetics: Modeling, Penalization, and Optimization in High-Dimensional Data,* Kenneth Lange, Jeanette C. Papp, Janet S. Sinsheimer, Eric M. Sobel
- *Breaking Bad: Two Decades of Life-Course Data Analysis in Criminology, Developmental Psychology, and Beyond,* Elena A. Erosheva, Ross L. Matsueda, Donatello Telesca
- *Event History Analysis,* Niels Keiding
- *Statistical Evaluation of Forensic DNA Profile Evidence,* Christopher D. Steele, David J. Balding
- *Using League Table Rankings in Public Policy Formation: Statistical Issues,* Harvey Goldstein
- *Statistical Ecology,* Ruth King
- *Estimating the Number of Species in Microbial Diversity Studies,* John Bunge, Amy Willis, Fiona Walsh
- *Dynamic Treatment Regimes,* Bibhas Chakraborty, Susan A. Murphy
- *Statistics and Related Topics in Single-Molecule Biophysics,* Hong Qian, S.C. Kou
- *Statistics and Quantitative Risk Management for Banking and Insurance,* Paul Embrechts, Marius Hofert

Access this and all other Annual Reviews journals via your institution at www.annualreviews.org.

ANNUAL REVIEWS | Connect With Our Experts

Tel: 800.523.8635 (US/CAN) | Tel: 650.493.4400 | Fax: 650.424.0910 | Email: service@annualreviews.org