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INVITED CENTENNIAL ARTICLE

REVIEW

Petrology on Mars†

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ABSTRACT

Petrologic investigations of martian rocks have been accomplished by mineralogical, geochemical, and textural analyses from Mars rovers (with geologic context provided by orbiters), and by laboratory analyses of martian meteorites. Igneous rocks are primarily lavas and volcaniclastic rocks of basaltic composition, and ultramafic cumulates; alkaline rocks are common in ancient terranes and tholeiitic rocks occur in younger terranes, suggesting global magmatic evolution. Relatively uncommon feldspathic rocks represent the ultimate fractionation products, and granitic rocks are unknown. Sedimentary rocks are of both clastic (mudstone, sandstone, conglomerate, all containing significant igneous detritus) and chemical (evaporitic sulfate and less common carbonate) origin. High-silica sediments formed by hydrothermal activity. Sediments on Mars formed from different protoliths and were weathered under different environmental conditions from terrestrial sediments. Metamorphic rocks have only been inferred from orbital remote-sensing measurements. Metabasalt and serpentinite have mineral assemblages consistent with those predicted from low-pressure phase equilibria and likely formed in geothermal systems. Shock effects are common in martian meteorites, and impact breccias are probably widespread in the planet's crustal rocks. The martian rock cycle during early periods was similar in many respects to that of Earth. However, without plate tectonics Mars did not experience the thermal metamorphism and flux melting associated with subduction, nor deposition in subsided basins and rapid erosion resulting from tectonic uplift. The rock cycle during more recent time has been truncated by desiccation of the planet's surface and a lower geothermal gradient in its interior. The petrology of Mars is intriguingly different from Earth, but the tried-and-true methods of petrography and geochemistry are clearly translatable to another world.

Keywords: Mars, petrology, igneous, sedimentary, metamorphic, rock cycle, Invited Centennial article, Review article

INTRODUCTION

When the *American Mineralogist* published its first issue a century ago, the notion of irrigation canals on Mars constructed by sentient beings was just falling out of favor, and no geologist contemplated the likelihood of ever studying martian rocks. Even in the modern spacecraft era, martian petrology has proved to be challenging. Nonetheless, significant progress has been made in determining the mineral identities and modal proportions, rock textures, and geochemical compositions that are necessary to characterize the petrology of the martian crust.

Mars rovers have, so far, analyzed rocks from four surface sites. Rover instruments can provide substantial information required for in situ petrologic characterization, but with significant limitations. Some minerals have been identified by visible/near-infrared reflectance spectroscopy (e.g., Bell et al. 2008), but commonly only one spectrally dominant mineral at a time, and complete mineral assemblages remain elusive. The thermal infrared emission spectra of minerals add linearly, so coexisting phases can be deconvolved (e.g., Ruff et al. 2008), provided they have diagnostic spectra and are sufficiently abundant. Spectroscopy from orbiting spacecraft has also been an effective mineralogic tool (e.g., Bibring et al. 2006; Christensen et al. 2008; Murchie et al. 2009; Carter and Poulet 2013; Ehlmann and Edwards 2014), but with the same limitations. Other techniques using instruments on rovers have provided more specific mineral determinations. Mössbauer spectra have allowed the identification of some Fe-bearing phases (e.g., Morris and Klingelhöfer 2008). X-ray diffraction shows great promise (e.g., Vaniman et al. 2014), but only a few rocks have been analyzed so far. Microscopic imagers provide textural information (e.g., Herkenhoff et al. 2008; Blaney et al. 2014), although many rock surfaces are weathered or coated with dust. Geochemical analyses of major and minor elements in rocks are carried out by α-particle X-ray spectrometers (APXS) (e.g., Gellert et al. 2006; Schmidt et al. 2014), but measurements can be compromised by dust contamination.

Martian meteorites (McSween and Treiman 1998; McSween 2008) allow more complete petrologic investigations, although

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the locations on Mars from which they came (and thus geologic contexts) are unknown. The times when they were launched from Mars by impacts are estimated by summing their cosmic-ray exposure ages, which measure the time spent in space, and their terrestrial ages, also determined from cosmogenic nuclides. The launch ages form clusters that usually consist of a single lithology (Fig. 1), suggesting that each cluster represents a different sampling site on Mars, and non-clustered meteorites may represent additional sites. The meteorites thus sample many more locations than have been visited by rovers. However, the meteorites are biased compositionally and chronologically, probably because young, coherent igneous rocks are most likely to survive launch during impacts, so they are not representative of the whole martian crust (McSween et al. 2009).

Despite these caveats, some firm conclusions about martian petrology are emerging. Data from remote-sensing and martian meteorites indicate that the planet's crust is dominated by basalt and related ultramafic rocks. Ancient sedimentary rocks, both clastic and chemical, have become the focus of rover exploration, spurred in part by the search for evidence of liquid water and, by extension, extraterrestrial life. Thermally metamorphosed rocks have only been identified from orbital spectroscopy, although many meteorites have been metamorphosed by shock. This paper synthesizes what we have learned about martian petrology and reveals gaps in knowledge that will hopefully be filled by the time of the next centennial.

SOURCES OF PETROLOGIC DATA

Mars rovers

Mars Pathfinder first analyzed rocks on the martian surface. The APXS-analyzed rocks had andesitic compositions (Rieder et al. 1997; McSween et al. 1999; recalibrated by Brückner et al. 2008; Foley et al. 2008), although alteration of rock surfaces likely accounts for their silica-rich nature. Because of this compositional uncertainty, we will not base any conclusions on these rocks.

The Mars Exploration Rovers (MER) Spirit and Opportunity landed in Gusev Crater and Meridiani Planum, respectively. Each rover carried an APXS for geochemistry, a miniature thermal emission spectrometer (MiniTES) and Mössbauer spectrometer (MB) for mineralogy, a panoramic camera (PanCam) with color filters and microscopic imager (MI) for imaging texture, and a rock abrasion tool (RAT) for brushing or griding rock surfaces. Spirit operated for six years, analyzing basalts on the floor of Gusev Crater and altered volcanic and volcaniclastic rocks in the Columbia Hills and at Home Plate (Squyres et al. 2004a, 2006a, 2007). Opportunity has operated for 10 years (and is still in operation at this writing), traversing >40 km and characterizing sedimentary rocks exposed in progressively larger craters (Squyres et al. 2004b, 2006b, 2009, 2012). Opportunity also analyzed one igneous sample, Bounce Rock (presumably ejecta from a distant crater), that resembled martian meteorites (Zipfel et al. 2011).

The Mars Science Laboratory (MSL) Curiosity rover landed in Gale Crater in 2011. Its instruments include an APXS, a laser-induced breakdown spectrometer (ChemCam) for element detection and textural imaging of rocks a few meters away, a powder X-ray diffractometer (CheMin) for mineralogy, a panoramic camera (MastCam) and a microscopic imager (MAHLI) for studying textures, mass spectrometers and gas chromatographs (SAM) capable of analyzing organic molecules and stable isotopes, and a rock-sampling device for brushing rock surfaces, scooping or drilling samples, and delivering them to CheMin and SAM. Curiosity has operated for more than one year (at this writing), working its way across the floor of Gale Crater, and has arrived at the base of an interior peak (informally called Mt. Sharp) of exposed strata. During its traverse, it has analyzed various sedimentary and igneous rocks (Blaney et al. 2014; Grotzinger et al. 2014; Sautter et al. 2014a; Schmidt et al. 2014; Stolper et al. 2013).

APXS measurements sample only the outer few tens of micrometers and thus are susceptable to dust contamination. MER and MSL APXS data vary in quality, depending on the extent to which the analyzed rock surfaces contained adhering dust. In this paper, I have attempted to use the best available APXS analyses, relying on data published in scientific literature. Additional data are archived in the NASA Planetary Data System, but are not plotted here. ChemCam data are normally reported as element ratios, and many elements are not analyzed; these data are useful for mineral identification but not for bulk-rock chemistry.

Mars orbiters

Remote sensing by orbiters does not provide sufficient data for petrologic characterization, but is very useful in identifying critical minerals used to develop geologic context. For some rock compositions, orbital spectroscopy provides the only data available. I will make reference to global geochemical maps by the γ-ray spectrometer (GRS) (Boynton et al. 2008) on Mars Odyssey, thermal emission spectrometer (TES) data (Christensen et al. 2008) from Mars Global Surveyor, and visible/near-infrared spectrometry from the Observatoire pour la Mineralogie, l'Eau,

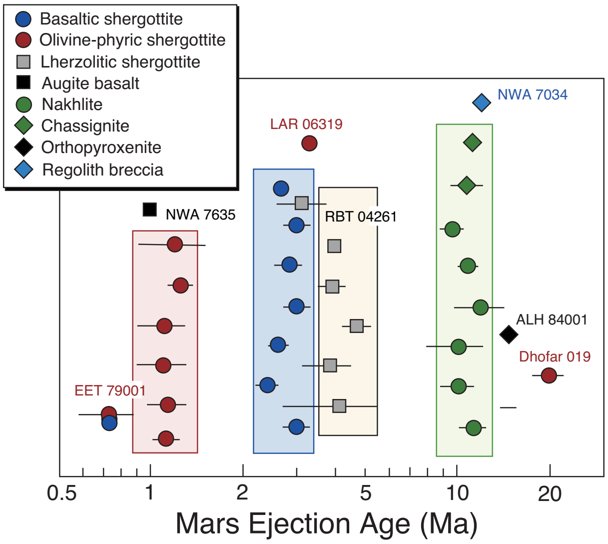

FIGURE 1. Meteorites with the same Mars ejection age usually have the same petrologic classification. Each clump of ages is interpreted as a distinct launch (impact) event at a separate location. Updated from McSween (2008).

les Glaces et l'Activite (OMEGA) (Bibring et al. 2006) on Mars Express and from the compact reconnaissance imaging spectrometer (CRISM) (Murchie et al. 2009) on Mars Reconnaissance Orbiter.

Martian meteorites

Meteorites from Mars are recognized by the composition of trapped martian atmospheric gas in impact-melted glasses, distinctive bulk oxygen isotopic compositions, and Fe/Mn ratios in pyroxenes (McSween 1984). Shergottites are subdivided into basaltic, olivine-phyric, and lherzolitic varieties, corresponding to basalt, basalt with olivine megacrysts, and olivine-pyroxene cumulate, respectively. Nakhlites and chassignites are cumulates of augite and olivine, respectively, and ALH 84001 is an orthopyroxene cumulate. A new variety, augite basalt, has so far only been described in abstracts. NWA 7034 and other samples paired with it (NWA 7475, 7533, 7906, 7907, 8114) are the only sedimentary rocks—regolith breccias—in the martian meteorite collection. Compilations of the petrology and geochemistry of martian meteorites are given by Lodders (1998), McSween and Treiman (1998), Treiman (2005), Bridges and Warren (2006), and McSween and McLennan (2013).

PETROLOGY OF MARTIAN IGNEOUS ROCKS

Geochemical analyses of surface rocks by MER APXS (tabulated by Brückner et al. 2008) and of martian meteorites indicate that Mars is dominated by igneous rocks with basaltic compositions and products of limited fractional crystallization (McSween et al. 2009) (Fig. 2). GRS global maps of silica abundance (Boynton et al. 2008) are consistent with this finding (GRS boxes in Fig. 2). The andesitic composition determined for Mars Pathfinder rocks is illustrated in Figure 2, although this is likely an altered composition as no abrasion of surface rinds prior to measurement was possible.

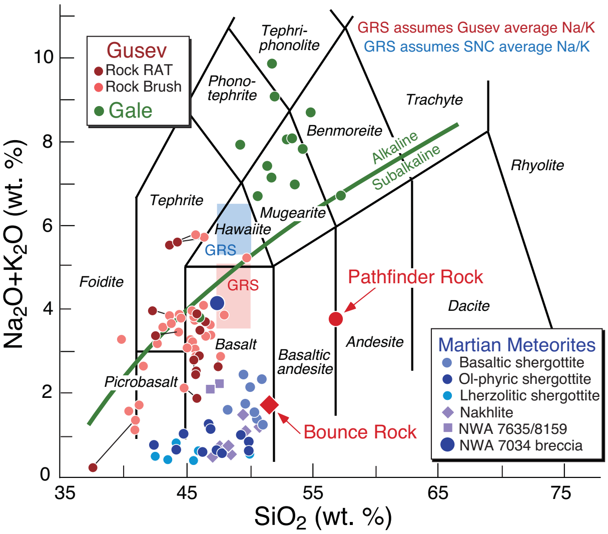

FIGURE 2. Geochemical classification of martian igneous rocks in Gusev and Gale craters analyzed by rovers (SO_3- and Cl-free), and of martian meteorites. Bounce Rock is a Meridiani igneous sample similar in composition to shergottites; the Mars Pathfinder rock composition is likely to be an altered surface coating. Global average GRS data (colored boxes) are consistent with basaltic compositions; GRS cannot determine Na contents, so two assumptions are made for Na/K. Updated from McSween et al. (2009).

Distinguishing volcanic, volcaniclastic, and sedimentary float rocks on Mars is not always obvious, as the textural features normally attributed to these rock classes may not be visible at the scale of rover observations. This debate extends to interpretations of orbital data as well (Ehlmann and Edwards 2014). Moreover, alteration overprints on igneous rocks can further complicate their identification. The reader should note that some misclassifications may occur in the following igneous rock descriptions.

Rocks analyzed by rovers

Gusev Crater has become the most thoroughly studied igneous province on Mars. Basalts encountered by the Spirit rover on the Gusev plains are float. Although a large volcano, Apollinaris Patera, of comparable age to the basaltic plains is located north of Gusev Crater, putative flow paths through a breach in the crater wall would require lavas to flow uphill, so a local magma source beneath the crater is favored (Lang et al. 2010). Petrologically related volcanic rocks occur mostly as float on the Columbia Hills, sitting on older outcrops of altered igneous rocks (Squyres et al. 2006a).

Basaltic rocks in Gusev (McSween et al. 2004, 2006a) are highly oxidized, mildly alkaline (McSween et al. 2006b), and generally silica undersaturated (Fig. 3), as reflected in the abundance of olivine (up to 20–30%). The modal mineralogies of Gusev volcanic rocks have been determined from modeling Mössbauer data for Fe-bearing minerals combined with CIPW norms calculated from APXS bulk chemistry for other minerals (McSween et al. 2008). Modes for Humphrey (basalt), Irvine (basalt), Wishstone (tephrite), and Backstay (trachybasalt) are illustrated in Figure 4. The textures of these lavas are porphyritic or aphanitic (Figs. 5a and 5b) and sometimes vesicular (Fig. 5c). Bedded volcaniclastic rocks occur at Home Plate (Squyres et al. 2007).

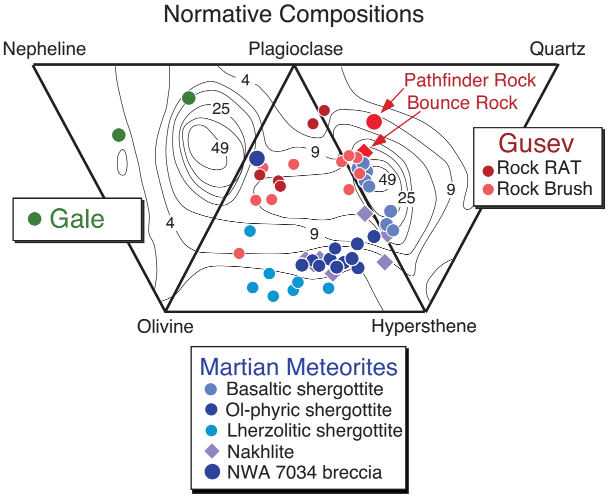

FIGURE 3. Normative compositions of selected martian igneous rocks. Contours represent global rock abundances on Earth (McBirney 2007). Updated from McSween et al. (2009).

As in Gusev, the igneous rocks encountered in Gale Crater by the Curiosity rover are float. Some controversy exists about whether some are fine-grained volcanic rocks or first-generation sedimentary rocks; these lithologies also constitute most of the clasts in conglomerates. Their source is undetermined, perhaps transported from the crater walls or thrown in as ejecta (Schmidt et al. 2014).

APXS analyses of aphanitic volcanic rocks analyzed in Gale are strongly alkaline (Fig. 3), with volcanic compositions that include hawaiite (Bathurst_Inlet) and mugearite (Jake_M) (Stolper et al. 2013; Schmidt et al. 2014), as well as other compositions (Grotzinger et al. 2015). These rocks are characterized by especially high contents of K and Fe. The CIPW normative mineralogies of Bathurst_Inlet and Jake_M contain orthoclase, and Jake_M contains nepheline (Fig. 4). ChemCam analyses have distinguished fine-grained monzonitic rocks with elongated feldspar phenocrysts (Fig. 5d) and coarse-grained, granular dioritic rocks (Sautter et al. 2014a, 2014b). The coarse-grained rocks contain augite, sodic plagioclase, and orthoclase, although no modes or norms have been reported.

Highly fractionated (felsic) rocks are uncommon on Mars. Earlier reports of widespread andesites, based on TES thermal emission spectra, are now reinterpreted as partly altered basalt (e.g., Michalski et al. 2005). Spectroscopic searches for quartz, easily identified in TES data, have been unsuccessful; a lone detection of quartzofeldspathic rocks (Bandfield et al. 2004) has been reinterpreted as altered amorphous silica rocks (Ehlmann et al. 2009). A GRS-derived global silicon map shows abundances ranging from 18–23 wt%, corresponding to 39–50 wt% SiO_2 (Boynton et al. 2008). This silica range overlaps those of

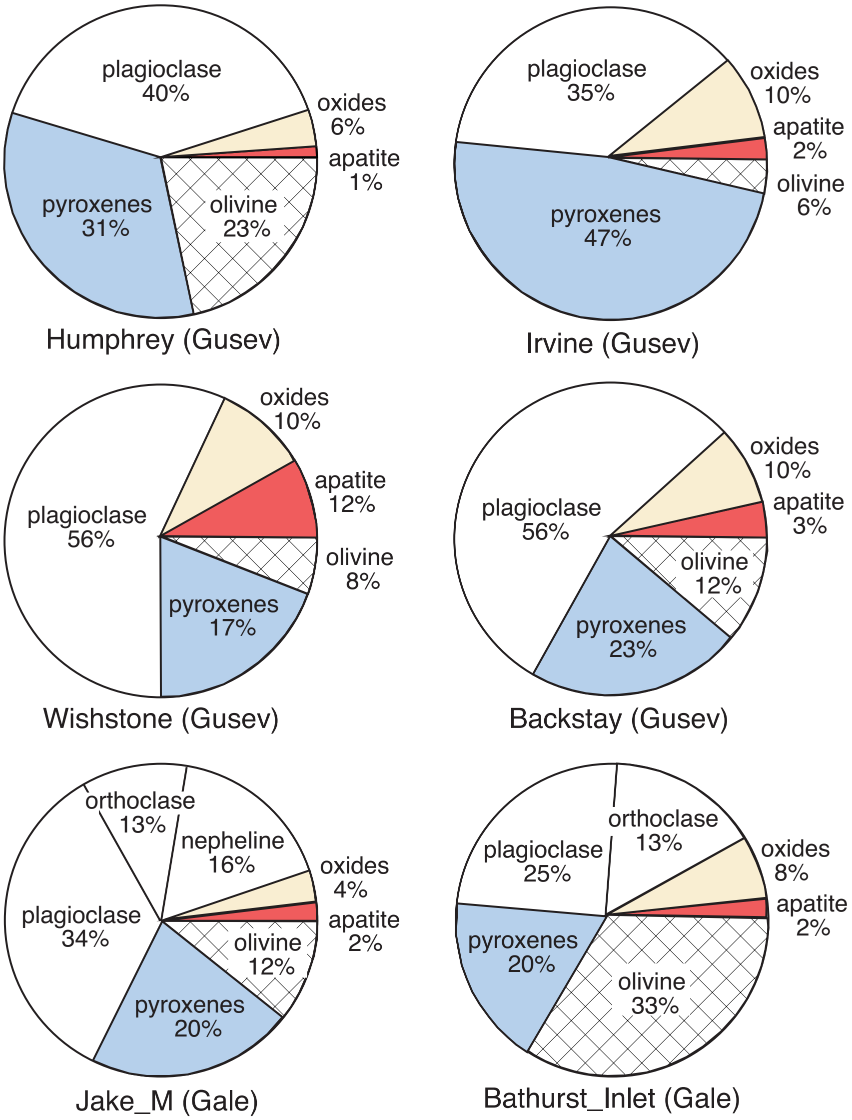

FIGURE 4. Modal mineralogy of selected Gusev igneous rocks (McSween et al. 2008), and normative mineralogy of two rocks from Gale crater (Stolper et al. 2013; Schmidt et al. 2014). Humphrey and Irvine are basalts, Wishstone is a tephrite, Backstay is a trachybasalt, Jake_M is a mugearite, and Bathurst_Inlet is a hawaiite.

basaltic rocks analyzed in Gusev and of martian meteorites (see below), and suggests no exposures of rocks more felsic than basaltic andesite occur anywhere, at least at the coarse (~450 km) GRS spatial resolution. However, at finer resolution one dacite flow has been identified from TES spectra (Christensen et al. 2005), and feldspathic rocks have been noted from CRISM and OMEGA spectra (Carter and Poulet 2013; Wray et al. 2013) and encountered by the Curiosity rover as noted above (Sautter et al. 2014a). Monzonite clasts occur in a martian meteorite breccia as well (Humayun et al. 2013).

Martian meteorites

The specific locations on Mars from which martian meteorites derive are unknown. However, several young rayed craters have been found in the Tharsis and Elysium volcanic regions and appear to be plausible launch sites for these meteorites (Tornabene et al. 2006).

Shergottites are basalts and gabbros formed from subalkaline magmas. Their compositions are distinct from those of Gusev rocks (Figs. 2 and 3). Basaltic shergottites (e.g., Stolper and McSween 1979; Rubin et al. 2000) are composed of pigeonite, augite, plagioclase (transformed into maskelynite by shock), and accessory Fe-Ti oxides, phosphates, zircon, baddelyite, and ferrosilite (sometimes decomposed to silica and fayalite) (Fig. 6a). Pyroxenes have Mg-rich cores, interpreted as entrained cumulus grains, with Fe-rich overgrowths. Olivine-phyric shergottites (e.g., Goodrich 2003; Greshake et al. 2004) contain those same phases, plus olivine megacrysts (5–28%) (Fig. 6b). The megacrysts in olivine-phyric shergottites have been variously interpreted as xenocrysts, phenocrysts, or antecrysts. Lherzolitic shergottites (e.g., McSween et al. 1979; Usui et al. 2010) are composed of olivine, orthopyroxene, augite, maskelynite, and chromite. The "lherzolitic" term is probably a misnomer, because mineral proportions vary widely in these heterogeneous rocks, and are hard to quantify from thin sections. As more lherzolitic shergottites have been found, characterization suggests that they may be more properly classified as olivine gabbros; some sections consist of olivine poikilitically enclosed by pyroxene, and other sections of the same meteorites are gabbroic.

Shergottites can be either enriched or depleted in incompatible trace elements, and enriched shergottites contain more radiogenic Sr and Nd isotopes (e.g., Symes et al. 2008). These geochemical characteristics are illustrated in Figure 7a, where meteorites with high-La/Yb ratios are enriched, and ε^{143}Nd decreases with enrichment. The enriched shergottites are also more highly oxidized than depleted shergottites (e.g., Wadhwa 2001; Herd et al. 2002) (Fig. 7b). The depleted shergottites are interpreted to reflect the compositions of their mantle source; it

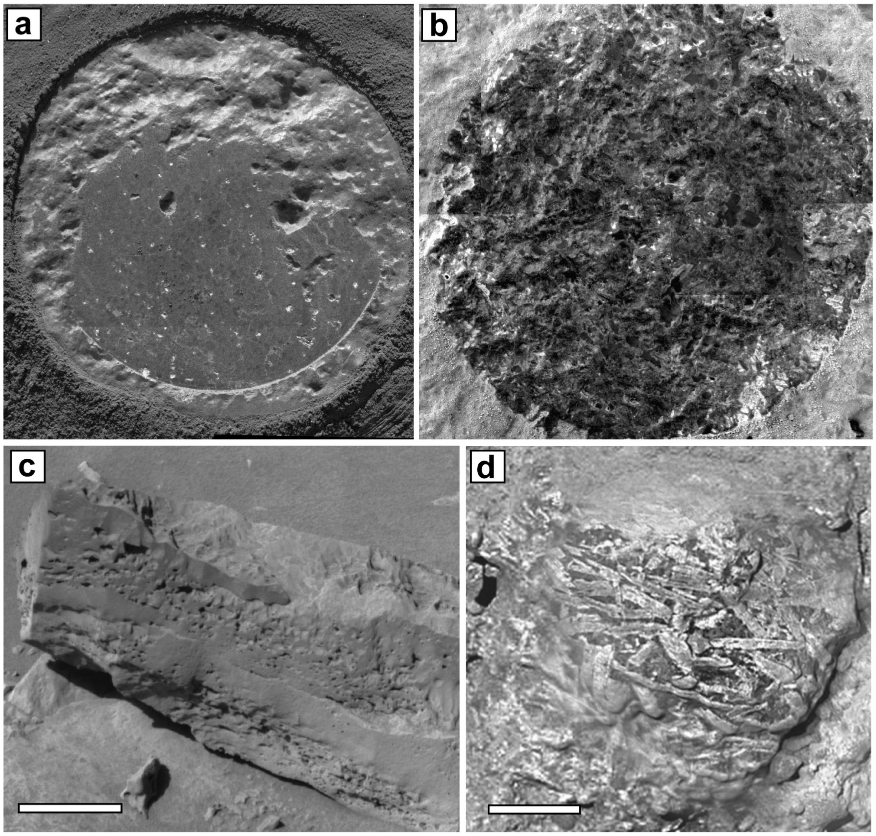

FIGURE 5. Images of igneous rocks obtained by Mars rovers. (**a**) Spirit Microscopic Imager view of RAT-ground Gusev basalt (Mazatzal), showing dark olivine phenocrysts and white alteration veins. RAT hole is 30 mm across. (**b**) Spirit RAT-brushed view of Champagne, showing fine-grained, vesicular texture. Scale as in **a**. (**c**) Vesicular basalt on the Gusev crater plains. Scale bar is 2 cm. (**d**) Curiosity image of elongated feldspar phenocrysts in an igneous rock (Harrison) from Gale crater. Scale bar is 6 mm.

is unclear whether the enriched shergottites represent melts of metasomatized mantle or magmas that have assimilated crust. Although the shergottites are nearly anhydrous, several lines of evidence suggest that their parent magmas were hydrous and lost water during ascent or eruption (e.g., McSween et al. 2001; McCubbin et al. 2012).

Two other martian meteorite types, nakhlites (e.g., Day et al. 2006; Treiman and Irving 2008) and chassignites (e.g., Johnson et al. 1991; Beck et al. 2006), are clinopyroxenites and dunites, respectively, and their cumulus augites and olivines (Fig. 6c) crystallized from mildly alkaline, dry parent basaltic magmas. Nakhlites consist of augite (70–80%), olivine (9–17%), and mesostasis (8–20%) containing Fe-Ti oxides, sulfides, and sprays of sodic plagioclase and K-feldspar (Treiman 2005). Their textures are dominated by elongate, aligned augite crystals. The cores of the olivines are xenocrysts (Goodrich et al. 2013). The nakhlites have been interpreted to have formed in a single thick flow or sill, and they can be placed in approximate stratigraphic order based on petrographic differences related to cooling rate and thermal annealing (e.g., Mikouchi et al. 2003); however, this interpretation does not take into account complexities in the internal dynamics of flows. Most nakhlites have experienced minor aqueous alteration, which produced iddingsite and other alteration phases (Hallis and Taylor 2011). Chassignites consist of olivine (90–92%), augite (3–5%), feldspar (2%), and chromite (2–5%), with accessory Fe-Ti oxides, sulfides, and phosphate. Their textures are dominated by subhedral olivine crystals, sometimes poikilitically enclosed by augite. The petrologic relationship between nakhlites and chassignites is unclear, but they have the same crystallization and Mars ejection ages.

The newly recognized augite basalts (Agee et al. 2014) consist of augite and plagioclase with minor olivine and oxides. The compositions of NWA 7635 and 8159 are shown in Figure 2. They are chemically similar to nakhlite intercumulus melt, but trace element and age differences preclude them being basalts complementary to the nakhlite suite (Herd et al. 2014).

ALH 84001 (Mittlefehldt 1994), famous for its purported evidence for martian life (McKay et al. 1996), is an orthopyroxene cumulate (Fig. 6d). It has been brecciated and annealed, and zoned Mg-Ca-Fe carbonate globules were precipitated in fractures by fluids. Its basaltic parent magma was isotopically similar to shergottites (Lapen et al. 2010).

NWA 7034 (Agee et al. 2013), NWA 7533 (Humayun et al. 2013), and other paired meteorites (i.e., stones that were part of the same pre-atmospheric meteoroid) are sedimentary breccias (as described below), composed partly of igneous clasts. The igneous lithologies include basalt, mugearite, and trachyandesite (Santos et al. 2013, who prefer volcanic terminology), or gabbro, monzonite, and norite (Humayun et al. 2013, who prefer plutonic terminology). Textures range from subophitic to granoblastic. These rocks are alkaline and resemble the igneous lithologies in Gusev and Gale craters (the bulk composition of NWA 7034 is

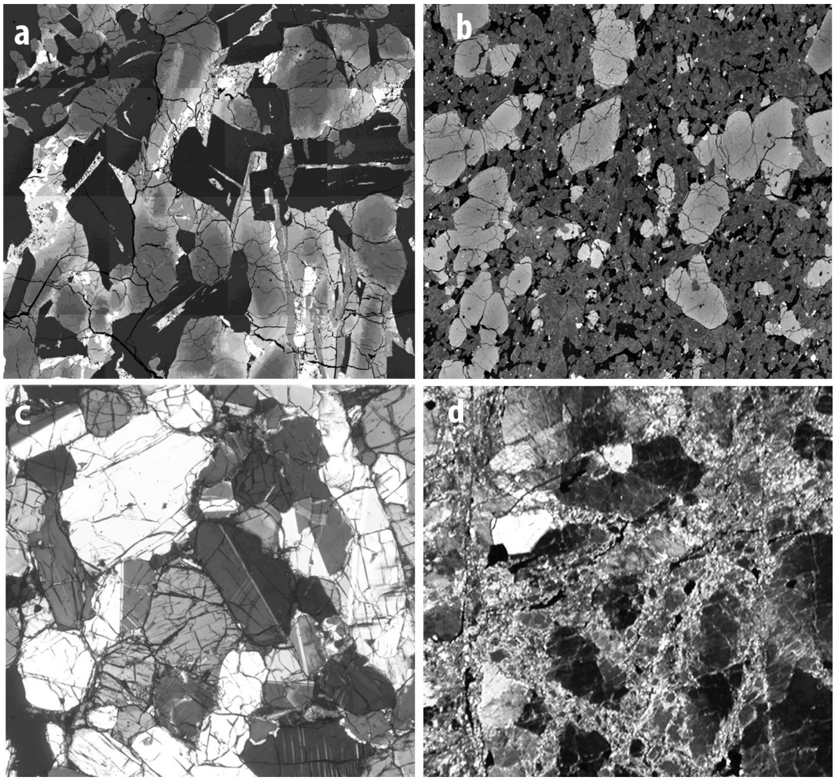

FIGURE 6. Microscopic images of martian meteorites. (**a**) Basaltic shergottite QUE 94201 showing intergrown zoned pyroxenes (gray to white) and maskelynite (dark). Backscattered electron (BSE) image, 5 mm across. (**b**) Olivine-phyric shergottite SAU 005 showing olivine megacrysts in groundmass of pyroxenes and glass. BSE image, 5 mm across. (**c**) Nakhlite Lafayette showing cumulus augite and minor olivine. Transmitted light (X polars), 20 mm across. (**d**) ALH 84001 orthopyroxenite showing brecciated texture. Transmitted light (X polars), 70 mm across.

shown in Fig. 2). Igneous minerals identified include plagioclase (38%), low-Ca pyroxene (25%), clinopyroxenes (pigeonite and augite, 18%), Fe-Ti oxides (10%), alkali feldspars (sanidine and anorthoclase, 5%), apatite (4%), and trace zircon and pyrite.

The compositions of olivines and pyroxenes in martian meteorites are generally more ferroan than in terrestrial basalts, and plagioclase tends to be more sodic: the ranges for olivine, pyroxene, and plagioclase, respectively, are Fo_{66-79}, En_{32-77}, and An_{39-70} in shergottites, Fo_{15-42}, En_{37-62}, and An_{23-40} in nakhlites, and Fo_{68-80}, En_{49-56}, and An_{30-80} in chassignites (Treiman 2005; Bridges and Warren 2006). Mars rocks analyzed by rovers have similar mineral compositions: normative olivine, pyroxene, and plagioclase compositions from Gusev rocks are Fo_{42-73}, En_{44-64}, and An_{16-47} (McSween et al. 2008). These differences in martian and terrestrial mineral compositions reflect bulk compositional differences between the planets. Bulk martian meteorites are rather Al-poor and P-rich, leading to late crystallization of plagioclase and to abundant phosphates. Feldspars (and Al) are more abundant in Gusev rocks than in the meteorites, but phosphates are abundant in both.

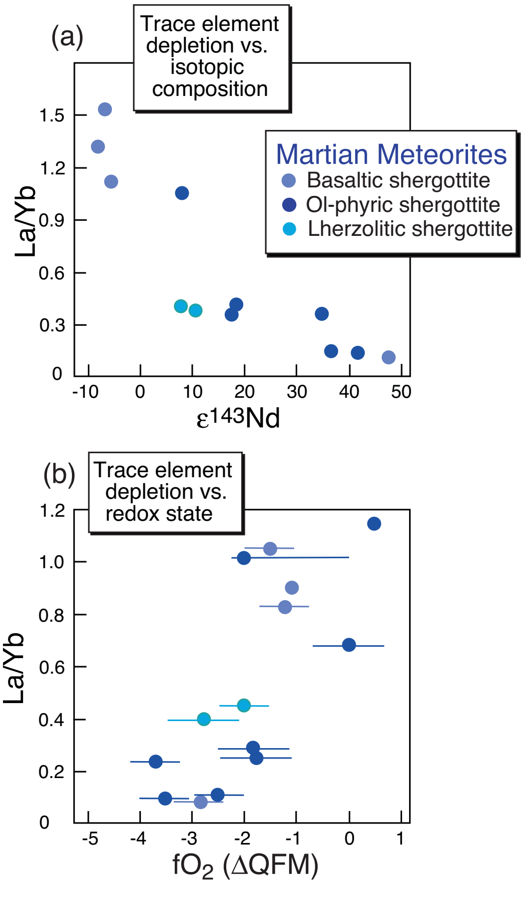

FIGURE 7. Geochemical correlations among shergottites, arising from geochemically depleted and enriched source regions. (**a**) Bulk ratios of light (La) to heavy (Yb) rare earth elements (normalized to chondrite) correlate with (**a**) radiogenic isotope compositions such as ε^{143}Nd, and (**b**) oxidation state as measured by Fe-Ti oxide oxybarometry. Modifed from McSween and McLennan (2013).

Trace element patterns in bulk martian meteorites are shown as a spider diagram in Figure 8. All these meteorites show depletions in Rb and K, which are highly incompatible, but not in adjacent incompatible elements. These alkali elements are soluble in aqueous fluids, although Ba, Sr, and U are as well and do not show consistent depletions. Nakhlites are enriched in incompatible trace elements and, unlike the shergottites, they show depletions in Zr and Hf. These elements are also depleted in terrestrial basalts affected by fluids and suggest alteration of the nakhlite source region. Trace elements are not normally analyzed by APXS (exceptions are Zn, Br, and Ni in Gusev rocks, as well as Ge in Gale rocks), so systematic comparisons with meteorite data are not yet possible. However, orbital average GRS measurements of K and Th (Taylor et al. 2006) are consistent with the highest values in shergottites. ChemCam on the Curiosity rover has measured Li, Rb, Sr, and Ba in individual minerals (Ollila et al. 2014), but bulk-rock data cannot be determined from these analyses.

Geochronology and petrogenesis

The igneous rocks analyzed in Gusev and Gale Craters are older (early Hesperian, ~3.65 Ga and <~3.7 Ga, respectively), based on crater counting (Parker et al. 2010; Thomson et al. 2011) than most martian meteorites (Nyquist et al. 2001; Righter et al. 2014): shergottite ages are 170–475 Ma (late Amazonian), nakhlites/chassignites are ~1.3 Ga (middle Amazonian), and the newly recognized augite basalts are ~2.4 Ga (early Amazonian). The orthopyroxenite ALH 84001 is much older, ~4.1 Ga (Noachian) (Lapen et al. 2010), and zircons in the NWA 7533 breccia give ages of ~4.4 and ~1.4 Ga (Humayun et al. 2013; Yin et al. 2014), the former corresponding to Pre-Noachian time. Although an ancient age (~4.5 Ga) has been suggested for shergottites (Bouvier et al. 2008) based on Pb-Pb chronology, most workers (e.g., Nyquist et al. 2001; Borg and Drake 2005; Symes et al. 2008; Shafer et al. 2010) accept younger, typically concordant ages indicated by other radioisotope systems such as ^{87}Rb-^{87}Sr, ^{147}Sm-^{143}Nd, ^{176}Lu-^{176}Hf, and ^{40}Ar-^{39}Ar.

The Y-980459 olivine-phyric shergottite and several basaltic rocks (Humphrey and Fastball) in Gusev Crater are thought to

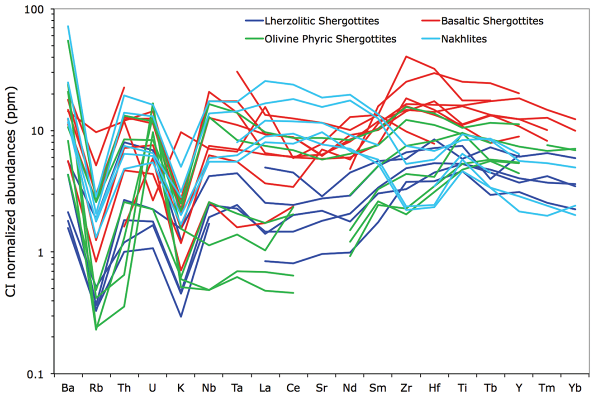

FIGURE 8. Spider diagram of trace element abundances in martian meteorites, plotted as a function of incompatability (decreasing from left to right). Modified from McSween and McLennan (2013).

represent primary magma compositions. Phase equilibria experiments indicate that these rock compositions represent multiply saturated magmas with olivine + orthopyroxene ± spinel at 1.0–1.2 GPa, corresponding to depths of 85–100 km (Musselwhite et al. 2006; Monders et al. 2007; Filiberto et al. 2010). This mineral assemblage is predicted as a partial melting residue for the Mars upper mantle. Other shergottites have fractionated compositions and contain some cumulus phases, and their crystallization paths have been determined by experiments (Stolper and McSween 1979; McCoy and Lofgren 1999). MELTS models indicate that the tephrites and trachybasalts in Gusev Crater (Fig. 2) could have been produced by fractionation of hydrous Gusev basalt (Humphrey) magma at varying pressures (McSween et al. 2006b; Udry et al. 2014a). Alternatively, Schmidt and McCoy (2010) suggested a two-stage melting model, in which tephrites and trachybasalts were generated first, followed by melting of the depleted source to form Humphrey-like basalts. The highly alkaline mugearite in Gale crater could also have formed by fractionation of hydrous magma at high pressure (Stolper et al. 2013) and may require a metasomatized mantle source (Schmidt et al. 2014).

Not as much is known about the origin of nakhlite and chassignite magmas, because of the difficulty in determining parent magma compositions of these cumulate rocks. Attempts to estimate their parent magmas have been based on trapped melt inclusions (e.g., Johnson et al. 1991; Stockstill et al. 2005; Goodrich et al. 2013), with experiments or MELTS modeling to determine their crystallization paths. Some nakhlite melt inclusions are K-rich and can fractionate to produce alkaline magmas (Goodrich et al. 2013). An estimated parental melt composition for Chassigny is also similar to those of Gusev basalts (Filiberto 2008).

The difference in rock compositions (alkaline vs. tholeiitic) between old rocks on the martian surface and young martian meteorites is striking and suggests global magmatic evolution through time. However, Noachian rocks have not been definitely sampled. Several explanations for this difference in composition have been offered, including melting and fractionation at different pressures (Baratoux et al. 2011), under different redox conditions (Tuff et al. 2013), or with different water contents (Balta and McSween 2013).

PETROLOGY OF MARTIAN SEDIMENTARY ROCKS

The martian crust contains a rich variety of sedimentary rocks, including both clastic rocks (sandstone and siltstone, shale and mudstone, and conglomerate) and chemically deposited rocks (mostly evaporitic sulfate, and some carbonate). The clastic rocks differ fundamentally from most terrestrial sediments, in that they are derived from basalt, rather than from felsic rocks like those that dominate the Earth's continental crust (McLennan and Grotzinger 2008). Clay-bearing rocks and sulfates have been studied mostly from orbital OMEGA and CRISM spectra (e.g., Murchie et al. 2009). Correlation of crustal age with mineralogy has led to a mineral-based timeline for Mars (Bibring et al. 2006), defined by an early warm and wet (or alternatively cold and intermittently wet) period characterized by clay formation, followed by a period of increased aridity conducive to the deposition of Ca-, Mg-, and Fe-bearing sulfates, and succeeded by the current cold and dry period dominated by the formation of iron oxides. These periods were also marked by fluids with varying pH. Meridiani rocks analyzed by the Opportunity rover formed during the middle (acidic) period (Hurowitz et al. 2006), but after a long trek to Endeavor crater that rover has now encountered subjacent clay-bearing strata (Arvidson et al. 2014) formed under neutral to slightly basic pH conditions.

The molar A-CNK-FM diagram, where A = Al_2O_3, CNK = $CaO + Na_2O + K_2O$, and FM = $FeO_{Total} + MgO$ (Fig. 9), provides a means of quantifying chemical changes in rocks and estimating alteration mineralogy. This diagram is especially useful for sediments derived from basaltic rocks, and has been applied to martian sedimentary rocks (e.g., Hurowitz and McLennan 2007). Analyzed sedimentary rock compositions from Meridiani and Gale and altered rocks from Gusev plot fairly close to this face of the projection, so this diagram provides a reasonably accurate representation of their geochemistry. The compositions of sedimentary rocks are very similar to basalt at the same locations, pointing to their igneous provenance and lack of chemical changes during weathering. The rocks in Figure 9 form a nearly linear array, with some dispersion resulting from mixing of sulfate or clay. The resulting trend is notably unlike terrestrial basaltic sedimentary rock compositions, which extend toward the A-FM side. This linear trend has been interpreted to reflect dissolution of olivine under acidic weathering conditions (Hurowitz and McLennan 2007) or physical sorting of olivine and other minerals during transport (McGlynn et al. 2012). However, the Opportunity rover has recently found evidence of leaching processes in some altered martian rocks (Arvidson et al. 2014). Also indicated on Figure 9 are the approximate compositions of minerals in the basaltic protolith and some common sedimentary minerals. Most of these rocks plot between clay and sulfate, although detrital igneous minerals are important constituents.

Rocks analyzed by rovers

The best-characterized martian sedimentary sequence is the late Noachian to early Hesperian-age Burns formation, analyzed in Meridiani by the Opportunity rover. Three facies, representing eolian dunes, sand sheets, and subaqueous interdune sands

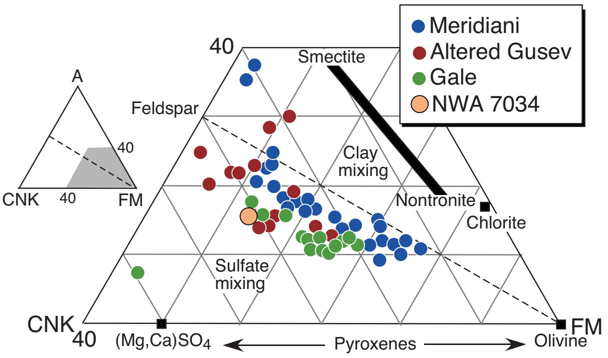

FIGURE 9. A-CNK-FM diagram showing compositions of martian sedimentary and altered rocks. Modified from McGlynn et al. (2012), with additional analyses of Meridiani rocks (Arvidson et al. 2014), Gale crater rocks (McLennan et al. 2014), and the NWA 7034 regolith breccia (Agee et al. 2013).

were recognized in Endurance Crater (Fig. 10) by Grotzinger et al. (2005). Three facies can be recognized from sedimentary structures and textures (Figs. 11a and 11b), including festoon cross-bedding, planar stratification, ripples, and a deflation surface. Burns Formation rocks are impure evaporitic sandstones, composed of altered siliciclastic materials of basaltic origin, cemented by evaporitic precipitates. Diagenetic overprints (McLennan et al. 2005) resulting from a fluctuating water table include the formation of hematite-rich concretions ("blueberries"), soft sediment deformation, and crystal molds from dissolution of a soluble evaporate mineral. Weakly indurated strata with similar stratigraphy were encountered in subsequently visited larger craters in Meridiani (Squyres et al. 2009, 2012).

The mineral assemblage of Meridiani sandstones was modeled by fitting chemical (APXS) and mineralogical (Mössbauer) trends (Clark et al. 2005). A derived mineral assemblage for Merdiani rocks, consisting mostly of subequal amounts of sulfate, silica, and igneous detritus (feldspar and pyroxene), is illustrated in Figure 12.

Another way to assess the mineralogy of sandstones is by comparison with unconsolidated sand (soil). Soil mineralogy for Mars has been estimated by modeling Mössbauer data to determine the proportions of Fe-bearing minerals, combined with normative mineralogy calculated from APXS chemistry and the abundance of alteration minerals determined from Mini-TES spectra (McSween et al. 2010). Sediments at both Gusev and Meridiani are mixtures of unaltered basaltic minerals (70–83%) plus silica, Fe-oxides, clay, sulfate, and chloride, collectively interpreted as an altered component unrelated to the detrital basaltic debris. Similarly, X-ray diffraction analysis of Rocknest sand at Gale indicated a composition of 74% basaltic minerals (plagioclase, olivine, pyroxene, oxides) with minor alteration phases and ~25% amorphous material (Bish et al. 2013).

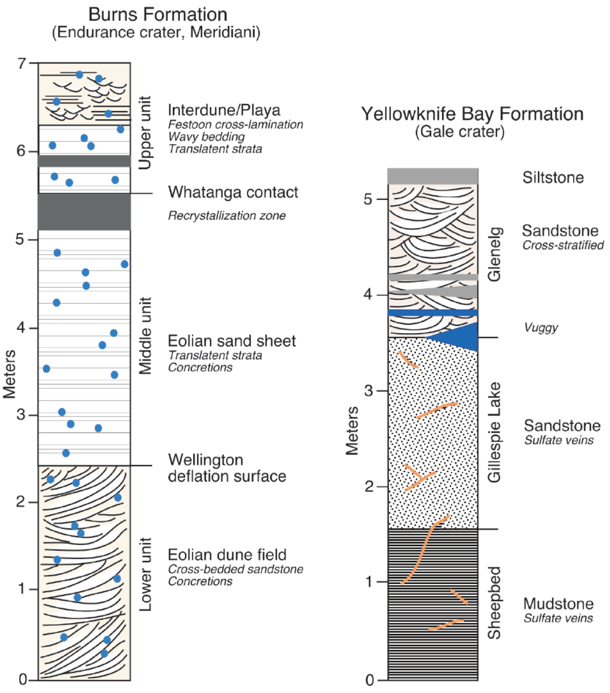

FIGURE 10. Stratigraphy and sedimentary interpretation of the Burns Formation (Meridiani) in Endurance crater (redrawn from Grotzinger et al. 2005) and the Yellowknife Bay Formation in Gale crater (redrawn from Grotzinger et al. 2014). Blue dots in Burns strata indicate concretions (blueberries); orange lines and blue areas in Yellowknife strata are sulfate veins and vugs, respectively.

Once Opportunity reached Endevour Crater (Squyres et al. 2012), it encountered fine-grained layered rocks containing spherules ("newberries," compositionally distinct from blueberries and possibly formed by impact), and overlain by impact breccias. These rocks occur stratigraphically below Burns formation rocks that characterize Meridiani Planum. The older (Noachian) rocks are cut by gypsum veins and contain clay minerals (Arvidson et al. 2014). Orbital CRISM spectra (Wray et al. 2009) had earlier shown the presence of smectite, best matched by nontronite. PanCam spectra suggest that the clay forms thin veneers on the rocks and is not a depositional phase. APXS-measured chemistry for these rocks is not noticeably different from rocks at other locations, although several rocks have elevated Al (Fig. 9), possibly reflecting clay formed by nearly isochemical alteration.

Many rocks analyzed by the Spirit rover in the Columbia Hills of Gusev Crater are sedimentary or volcaniclastic. Because of considerable chemical diversity and structural complexity, these rocks have not been studied as extensively as the Meridiani rocks (McLennan and Grotzinger 2008). The rocks are generally basalt-derived detritus, cemented by sulfate and silica. A few rocks containing significant amounts of carbonate (Morris et al. 2010) have been discovered. The rock Comanche, interpreted as an olivine cumulate, is estimated to contain 26% secondary Mg-Fe carbonate, as well as amorphous material of unknown origin (Fig. 12), based on modeling Mini-TES, Mössbauer, and APXS spectra. Rocks at Home Plate, a layered butte, are altered pyroclastic rocks, succeeded by cross-bedded sandstones that may consist of reworked pyroclastic materials (Squyres et al. 2007). Some of the layered rocks contain up to 90% silica, with elevated Ti, and are interpreted to have been leached by hydrothermal fluids (Squyres et al. 2008).

Sedimentary rocks in Gale crater have been analyzed by the Curiosity rover, and exploration is ongoing. The early Hesperian Yellowknife Bay formation (Grotzinger et al. 2014) is a coarsening-upward succession of mudstone to sandstone (Figs. 10 and 11c). A K-Ar age for the mudstone is 4.21 ± 0.35 Ga (Farley et al. 2014), confirming the antiquity of the detrital crater rim component of this rock. The Yellowknife Bay rocks are laminated to massive. Mudstone facies, in particular, contain various diagenetic features, including concretions (Stack et al. 2014) and mineralized fractures (Siebach et al. 2014), that suggest active precipitation in the depositional environment. Diagenetic phases, such as Ca-sulfate veins, crosscut both fine- and coarse-grained lithologies, indicating emplacement during later diagenesis. The bulk chemistry of Yellowknife Bay rocks (McLennan et al. 2014) is broadly similar to sedimentary rocks in Gusev and Meridiani (Fig. 2), reflecting their basaltic provenance with no evidence for chemical fractionation. Contents of Fe are highly variable, and sandstones of the Glenelg member (Fig. 10) are Fe-cemented (Blaney et al. 2014). Unlike the Burns Formation, in which the basaltic protolith was altered before deposition and was cemented with sulfate, the basaltic detritus in Gale sedimentary rocks was not appreciably chemically weathered and the rocks contain very few chemical precipitates. Alteration of these rocks occurred during diagenesis of water-saturated sediment rather than by weathering in the sediment source region (Grotzinger et al. 2015). The modal mineralogy of Sheepbed mudstone, the stratigraphically lowest member of the Yellowknife Bay formation, was determined by X-ray diffraction (Vaniman et al. 2014). The rock is a disequilibrium assemblage of basaltic minerals, with smectitic clay, amorphous material (including allophane-like material), and other alteration minerals (Fig. 12).

As Curiosity continued its traverse to Gale's central mountain (Mt. Sharp), it obtained analyses of the Windjana sandstone. Its composition is alkaline, like the Gale igneous rocks, and its modal mineralogy (Fig. 12) has a high proportion of detrital igneous minerals (Grotzinger et al. 2015). Conglomerates (Fig. 11d) have also been encountered during Curiosity's traverse (Williams et al. 2013).

Missing from the rocks analyzed so far by Mars rovers are massively layered MgFe-, and Ca-sulfates, layered Al- and FeMg-phyllosilicates, and chloride deposits, all observed in remote sensing data (e.g., Bibring et al. 2006; Murchie et al. 2009; Osterloo et al. 2010). Although sulfate cements and veins occur in Gusev and Gale sedimentary rocks, these differ petrologically from the massive evaporitic deposits.

Martian meteorites

The only martian sedimentary meteorites studied so far are the paired samples NWA 7034 and NWA 7533. The bulk composition of NWA 7034 is similar to igneous rocks in Gusev Crater (Fig. 2). These regolith samples are polymict breccias (Fig. 13), composed of igneous detritus (described above) and impact-melted clasts in a fine-grained matrix partly altered by aqueous processes (Muttik et al. 2014). Some large "pebbles" have breccia-within-breccia textures, and their rounded outlines suggest that they were transported sedimentary rocks (McCubbin et al. 2014). These pebbles contain metamict zircons that give ages of ~1.4 Ga (Yin et al. 2014), much younger than the ~4.4 Ga (Pre-Noachian) ages of zircons in the igneous clasts (Humayun et al. 2013; Yin et al. 2014), and suggest that the host breccia was assembled after 1.4 Ga.

PETROLOGY OF MARTIAN METAMORPHIC ROCKS

Shock metamorphism

Most martian meteorites have suffered shock metamorphism to varying degrees, although the nakhlites show minimum shock effects. Shock in basaltic shergottites has transformed plagioclase into diaplectic glass (maskelynite), and veins of impact melt crosscut some meteorites (Stöffler et al. 1986). Impact-melt pockets may also contain high-pressure polymorphs—stishovite and post-stishovite (from tridymite) and hollandite

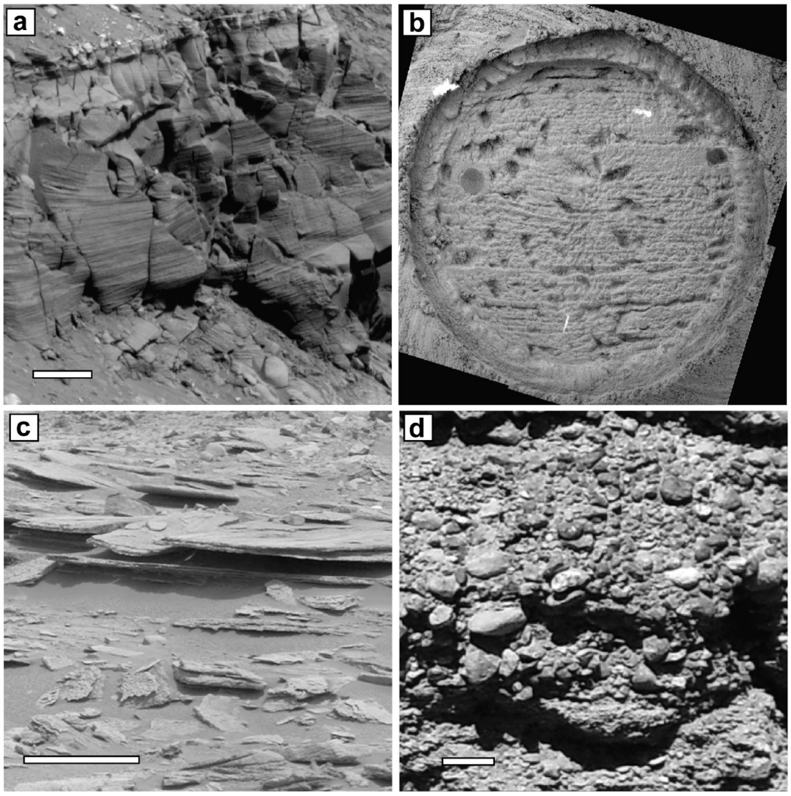

FIGURE 11. Images of sedimentary rocks obtained by Mars rovers. (**a**) Opportunity image of cross-bedded sandstones of the Burns Formation in Victoria crater, Meridiani. Scale bar is 1 m. (**b**) Microscopic view of RAT-ground Burns Formation sandstone, showing layering, crystal molds, and round concretions ("blueberries"). RAT hole is 30 mm across. (**c**) Curiosity image of layered mudstone (Shaler) in Gale crater. Scale bar is 10 cm. (**d**) Conglomerate in Gale crater. Scale bar is 2 cm.

(from plagioclase) (El Goresy et al. 2004). Atmospheric gas implanted into pockets of impact melt in shergottites provides the most persuasive evidence that these meteorites are from Mars (Bogard and Johnson 1983).

Olivine megacrysts in many olivine-phyric shergottites are stained brown, which is attributed to shock oxidation (Ostertag et al. 1984). The olivine-phyric shergottite Tissint is the most severely shocked martian meteorite. It contains a wide variety of high-pressure polymorphs in melt pockets, including ringwoodite (from olivine), akimotoite, majorite, and silicate perovskite (from pyroxene), lingunite (from plagioclase), tuite (from merrillite), and stishovite (from tridymite) (Baziotis et al. 2013). These phases correspond to localized shock conditions of ~25 GPa and ~2000 °C.

ALH84001 has also been highly shocked (Treiman 1998; Greenwood and McSween 2001), and some of the features originally attributed to martian life apparently resulted from impact vaporization and condensation (Bradley et al. 1996; Golden et al. 2004). The NWA 7034 and NWA 7533 regolith breccias contain significant amounts of impact melts, some clast-laden (Humayun et al. 2013) and some completely melted (Udry et al. 2014b). Shock effects may be widespread in martian rocks; however, these effects are more common in lunar meteorites than in returned lunar samples. On Mars breccias are ubiquitous, and Newsom et al. (2015) identified possible shatter cones, impact spherules, and other evidence suggestive of impact melting at Gale crater.

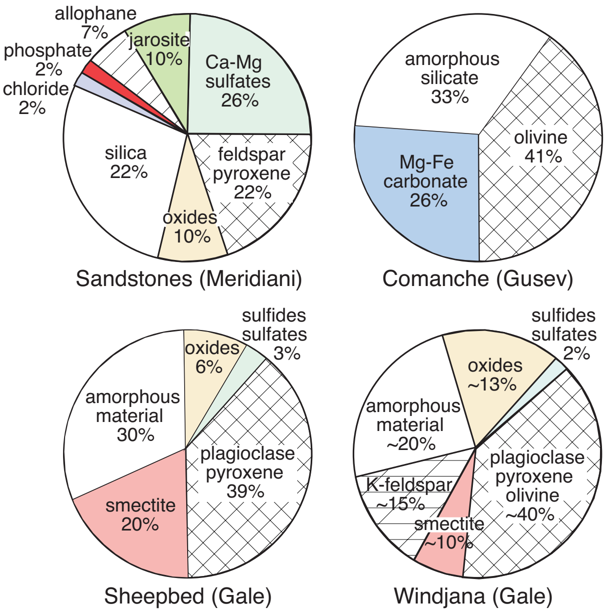

FIGURE 12. Modal mineralogy of martian sedimentary rocks, determined by different methods as explained in the text: Meridiani sandstones (Clark et al. 2005), Commanche carbonate-bearing rock from Gusev (Morris et al. 2010), Sheepbed mudstone (Vaniman et al. 2014) and Windjama sandstone (Grotzinger et al. 2015) from Gale. Windjama mode is approximate, as no numerical values were reported.

Thermal or hydrothermal metamorphism

Thermal or hydrothermal metamorphism was most likely to have occurred in ancient (Noachian) rocks, because radiogenic heat production was five times greater than the present-day value (Hahn et al. 2011). Before exploring Mars for metamorphic rocks, it would be helpful to predict likely diagnostic mineral assemblages. The Noachian gradient has been estimated at ~12 °C/km (McSween et al. 2014) based on the GRS-measured abundances of radiogenic heat-producing elements (U, Th, K) in the present crust and correction for radioactive decay over time (Hahn et al. 2011). This gradient is likely to be a lower limit, as gradients estimated from other constraints on Noachian heat flow range from 14–20 °C/km (McSween et al. 2014, and references therein). These gradients in the crust of Mars, where pressure increases less rapidly with depth than on Earth, would produce temperatures and pressures corresponding to the following low-grade metamorphic facies: zeolite, prehnite-actinolite, and pumpellyite-actinolite.

Based on the inference that the crust of Mars is basaltic, we can predict the mineralogy of low-grade metabasalts from molar ACF diagrams, where $A = Al_2O_3 + Fe_2O_3 - Na_2O - K_2O$, $C = CaO - 3.3\ P_2O_5$, and $F = MgO + FeO + MnO$ (Fig. 14). The compositions of basaltic rocks for which we have complete major element analyses (martian meteorites, and basalts from Gusev and Gale) are projected onto this diagram (McSween et al. 2014). The three triangles show predicted mineral assemblages for the various facies. The diagnostic assemblages for most of these

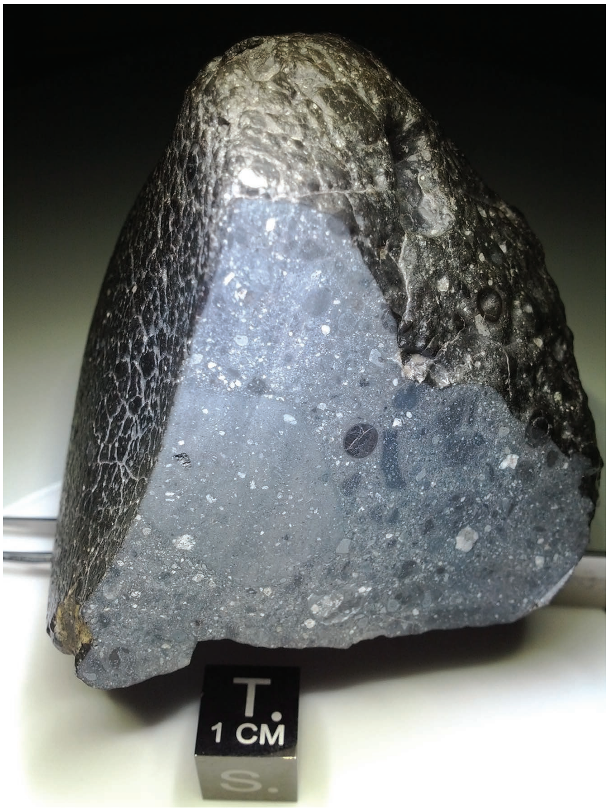

FIGURE 13. Cut surface of the NWA 7034 meteorite, a regolith breccia. Photograph courtesy of Carl Agee.

metabasalts are chlorite + actinolite + one of the following: laumontite, prehnite, or pumpellyite. Olivine-phyric and lherzolitic shergottites plotting outside of the triangles defined by those minerals would contain chlorite + actinolite + serpentine or talc. In addition, sodic plagioclase (albite) or analcime, and possibly silica could occur. Ultramafic rocks at these metamorphic grades should produce serpentine, or talc + magnesite, depending on fluid composition.

Of the diagnostic metamorphic minerals for metabasalts suggested by these plots, only prehnite, chlorite, and analcime have been positively identified in CRISM and OMEGA spectra (Ehlmann et al. 2009; Carter et al. 2013), although unspecified zeolite spectra could include laumontite, and pumpellyite has been suggested based on radiative transfer modeling (Poulet et al. 2008). The apparent absence of actinolite in the spectra is perplexing; however, we do not know the chemical compositions of martian metabasalts, so there is no certainty that they should contain enough actinolite to be detected spectrally. Additionally, TES spectral deconvolutions in the best-studied Noachian terrane (Nili Fossae) indicated the presence of albite (Milam et al. 2010), and silica, analcime, and Fe,Mg smectite have been recognized from visible/near-infrared spectra (Elhmann et al. 2009). The spectra of ultramafic rocks in Nili Fossae indicate either serpentine, magnesite, and possibly talc (Ehlmann et al. 2008, 2009, 2010; Viviano et al. 2013), as predicted for this metamorphic grade.

Some metamorphic rocks in Nili Fossae were excavated by impacts, suggesting that metamorphism occurred in the subsurface at depths of perhaps 5–8 km, as inferred from crater diameter/depth relations. Noachian geothermal gradients based solely on heat-producing radioactive elements are not high enough to produce the observed mineral assemblages at these depths, so additional heat supplied by geothermal sources seems likely (Ehlmann et al. 2011; McSween et al. 2014). Impact craters on Earth commonly develop hydrothermal systems, and hydrothermal metamorphism could have produced these martian rocks.

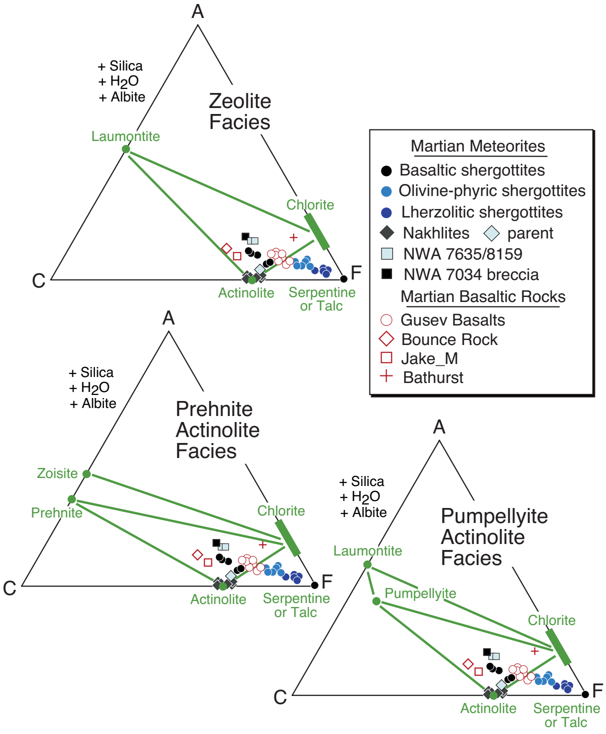

FIGURE 14. ACF diagrams predicting the mineralogy of thermally metamorphosed martian basaltic rocks at zeolite, prehenite-actinolite, and pumpellyite-actinolite facies conditions. Modified from McSween et al. (2014).

In addition to Nili Fossae, metamorphic minerals have also been identified in other Noachian terrains, especially in excavated rocks in the central peaks and ejecta blankets of craters. A global spectroscopic survey (Carter et al. 2013) reported 85 occurrences of prehnite, 268 of chlorite, 94 of serpentine or talc, 152 of unspecified zeolites, and 5 of epidote (the latter indicating greenschist facies conditions).

MARTIAN ROCK CYCLES

The rock cycle (Fig. 15, top) has proven to be a convenient, albeit simplified way to relate igneous, sedimentary, and metamorphic rocks on Earth. The terrestrial version does not include shock metamorphism, but that has been added here because impact processes have played such an important role in altering rocks on Mars. The absence of plate tectonics, and in particular subduction, on Mars prevents cycling of crustal rocks back into the mantle, the subsidence of depositional basins, as well as flux melting that produces felsic magmatism. The lack of uplift resulting from plate collisions also limits erosion to produce sediments.

Two hypothesized martian rock cycles, representing different ages, are illustrated at the bottom of Figure 15. In Noachian and early Hesperian time, igneous processes were important, as inferred from the NWA 7034 and ALH 84001 meteorites and

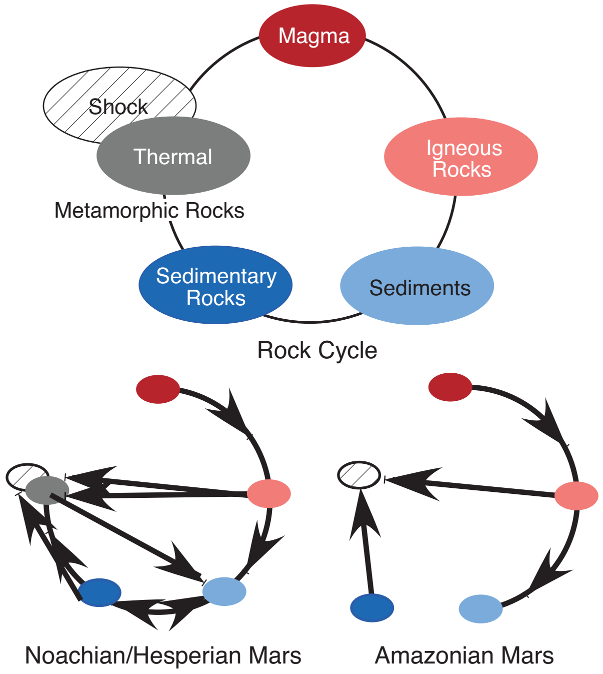

FIGURE 15. The rock cycle (**top**), and inferred rock cycles for Mars at different time periods (**bottom**).

seen in volcanic rocks in Gusev and Gale Craters. Chemical and physical weathering of surface rocks produced sediments, which were transported and deposited by flowing (probably intermittent) water, as evidenced in Meridiani and Gale rocks. Chemical alteration and precipitation of evaporative salts may have followed different pathways during the Noachian and Hesperian periods, however, depending on a change in the pH of aqueous fluids from near-neutral to acidic (McLennan and Grotzinger 2008). Groundwater-driven diagenesis and hydrothermal activity further altered igneous and sedimentary rocks. Burial of surface rocks by subsequent volcanism or the deposition of sediments or impact ejecta over time exposed subsurface rocks to increased pressure and temperature (perhaps aided by hydrothermal cells), causing metamorphism. Continuing impacts may have caused shock metamorphism in any of these materials. Although impacts certainly produced some melts, these were not on the scale of subduction zone magmatism and differed compositionally (impact melts tend to represent complete, rather than partial melting, and form from mafic crustal rather than ultramafic mantle sources).

During Amazonian time, the martian rock cycle was likely truncated substantially. Volcanism has continued, but has become localized in a few provinces like Tharsis and Elysium. The absence of surface water means that sediments were produced by physical weathering (including impacts) and transported and deposited primarily by winds. Few fluids were available to promote diagenesis or metamorphism. It is unclear to what extent modern sediments (soils) can be lithified into sedimentary rocks. Earlier-formed sedimentary rocks, as well as igneous rocks, have continued to suffer shock metamorphism, but the low-geothermal gradient in modern Mars probably precludes thermal metamorphism, at least in the accessible crust.

IMPLICATIONS

Geochemical, mineralogical, and textural analyses of rocks by rovers, coupled with laboratory studies of martian meteorites and inferences from orbital remote sensing data, have provided information with which the rocks of Mars can be characterized. The petrology of Mars is intriguingly different from that of our own planet, but the application of tried-and-true petrographic and geochemical methods has been instrumental in the geologic exploration of another world.

- The martian crust is composed mostly of igneous rocks of basaltic composition, along with ultramafic cumulates. Ancient basaltic rocks analyzed by Mars rovers and sampled by one meteorite are more alkaline than young martian meteorites. Further evidence of and explanation for this apparent magmatic evolution over time is needed.
- Source regions were compositionally distinct, and magmas derived from them have inherited differences in trace element patterns, radiogenic isotopic compositions, and oxidation states. The extent of mantle heterogeneity, as well as the possible magmatic assimilation of crust, are open questions.
- Fractional crystallization of basaltic parent magmas at different depths, likely with varying water contents, produced trachyte, trachybasalt, hawaiite, and mugearite melts, as well as cumulate pyroxenites and dunites. Felsic (silica-rich) igneous rocks are unknown, but feldspar-rich rocks occur locally. Magma fractionation has produced different suites of rocks than on Earth.
- Sedimentary clastic rocks range from ancient clay-rich mudstone to sandstone and conglomerate, derived from basaltic protoliths and retaining significant igneous detritus and similar bulk compositions. Volcaniclastic rocks are also common. Chemical rocks include evaporative sulfate and carbonate, and sulfates, silica, and Fe oxides are common cements. What factors, in addition to distinct protoliths, have controlled the nature of surface materials on Mars requires further exploration.
- Depositional, diagenetic, and hydrothermal processes in martian rocks have terrestrial analogs, but evolving global environmental conditions (from wetter, neutral-pH, to drier, acidic, and finally to desiccated, highly oxidized) have produced distinctive sedimentary rocks and altered igneous rocks. Although the broad picture seems clear, the transitions between environments are confusing.
- Shock metamorphism has affected most martian meteorites. Although the effects of impacts are likely to have been pervasive in rocks on Mars, only breccias have been clearly documented from spacecraft data.
- Hydrothermally altered or metamorphosed rocks have been inferred from diagnostic minerals in orbital spectra, consistent with predictions from phase equilibria in metabasalt and serpentinite. Until metamorphic rocks are analyzed from the ground or as meteorites, metamorphic processes on Mars will remain speculative.
- The martian rock cycle during Noachian and early Hesperian time was similar in some respects to that of Earth. However, the absence of plate tectonics precluded high-pressure metamorphism and flux melting associated with subduction, as well as sedimentary deposition in subsided basins and rapid erosion resulting from tectonic uplift. The Amazonian rock cycle can hardly be called that, as recent geologic activity on Mars has been limited.

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