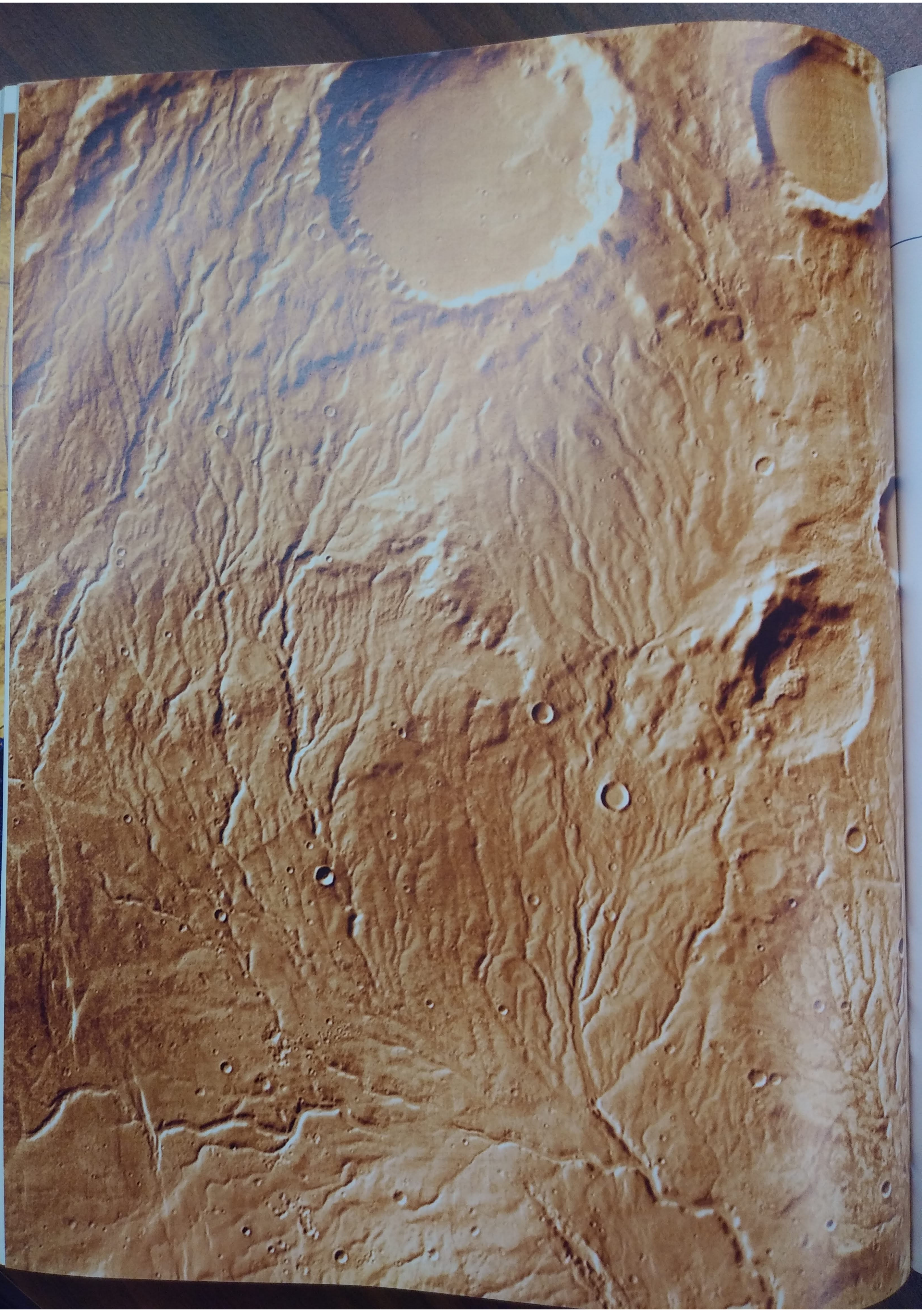

15

Physical and Chemical Changes: Weathering, Sedimentology, Metamorphism, and Mass Wasting

Physical weathering of rocks on bodies other than the Earth occurs mostly through impact fragmentation, producing regoliths. The lunar regolith is finer-grained and contains more agglutinates than asteroidal regoliths, indicating its greater maturity. Mars exhibits both physical and chemical weathering, and its sedimentary deposits superficially resemble those on Earth. However, its basalt-derived sediments differ from those formed from felsic protoliths on Earth, and evaporation of its aqueous fluids is dominated by sulfates, distinct from terrestrial evaporites that are mostly carbonates and halides. On the surfaces of airless bodies, recondensation of vapor produced by micrometeorite impacts accounts for spectral changes, known as space weathering. In the interiors of carbonaceous chondrite asteroids, isochemical reactions of rocks with cold aqueous fluids produced by melting of ice have altered their mineralogy. Thermal metamorphism of dry chondritic asteroids has modified all but near-surface rocks. Hydrothermal metamorphism on Mars, likely associated with large impacts, has produced low-grade mineral assemblages in metabasalts and serpentinites. Conditions at Venus' surface are severe enough to cause thermal metamorphism, and reactions with rocks may control the composition of the atmosphere. Because all bodies have gravity, some sloping topography, and some unconsolidated materials, mass wasting is among the most common processes modifying planetary surfaces.

15.1 Petrologic Changes and the Rock Cycle

Igneous, sedimentary, and metamorphic rocks comprise the Earth's crust and interior. The processes that account for this petrologic variety can be summarized by the familiar rock cycle (Figure 15.1). Melting produces magmas that crystallize to form igneous rocks. Rocks on the surface are weathered and eroded, producing unconsolidated sediments that are transported, deposited, and subsequently lithified during diagenesis to form sedimentary rocks. Deeply buried sedimentary and igneous rocks are transformed by heat and pressure into metamorphic rocks. Plate tectonic processes recycle these rocks back into the mantle, where melting occurs, regenerating the rock cycle.

Many of the rocks we encounter on other planets or collect as meteorites have also been modified from their original igneous (or primitive, in the case of chondrites) states. Fragmentation by impacts is the dominant form of physical weathering for most extraterrestrial bodies. Impact-comminuted sediments cover the surfaces of other bodies and may become solidified to form sedimentary rocks. Chemical weathering is less common on other planets, because of the requirement for liquid water. Thermal metamorphism occurs within the deep interiors of other bodies, but metamorphic rocks are rarely exposed because of the lack of tectonic uplift mechanisms. However, shock metamorphism by meteor impacts (discussed in Section 11.5) is pervasive in extraterrestrial rocks; although this is not commonly illustrated in the rock cycle, it is an important part of the cycles on other planets (Figure 15.1). The rock cycle is truncated on planets other than our own, because the lack of plate subduction does not allow recycling of rocks back into the deep interior, where melting occurs. In this chapter, we will explore the petrologic processes that modify the rocky materials that comprise extraterrestrial bodies.

All bodies, large and small, have some topographic relief. Gravity acting on unstable slopes results in downslope

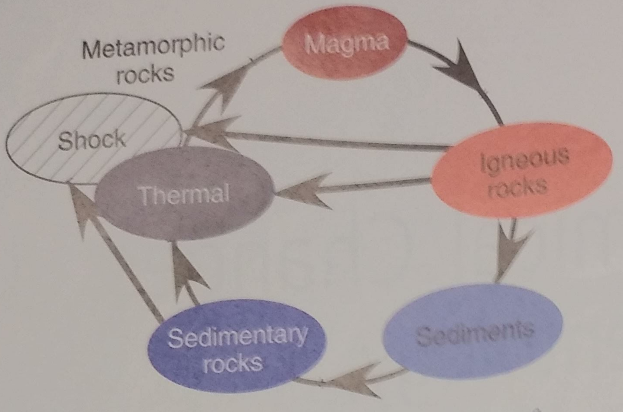

Figure 15.1 The Earth's rock cycle, with the addition of shock metamorphic rocks that are pervasive on other planetary bodies.

movements. We will also consider how surfaces are modified by this physical process.

15.2 Regoliths: Physical Weathering

On Earth, various physical weathering processes break down surface rocks into sediments. On other planets, however, the most effective physical weathering process, by far, is comminution by meteor impacts. As noted in Section 8.5.4, thermal stresses on airless bodies can also cause fracturing of surface rocks. Fragmentation produces an unconsolidated surface layer, called **regolith**. Soil scientists sometimes distinguish regolith from "soil" – by their definition, soil must contain an organic component, a distinction lost on most planetary scientists who use the terms interchangeably.

Surface regoliths on other bodies are generally fine-grained, and grade downward into larger transported blocks, and even deeper into fractured crust (Figure 15.2); collectively, the disturbed outer stratigraphy is the megaregolith. Micrometeorite impacts account for most of the pulverization of rocks, and larger meteor impacts slowly churn and mix ("garden") the regolith.

15.2.1 The Lunar Regolith

Our knowledge of planetary regoliths is based mostly on *Apollo* astronauts' field observations and on laboratory studies of regolith samples returned from the Moon (McKay et al., 1991; Lucey et al., 2006). The thickness of the lunar regolith, as estimated from penetrating craters, ranges from 4–5 m in maria regions to 10–15 m in older highlands regions. Regolith thickness correlates with the density of impact craters and the age of the underlying rocks, indicating its progressive development over time. At most lunar sites where core samples or scoops of soil were taken (Figure 15.3a), the regolith is remarkably homogeneous and becomes highly compacted below depths of ~10 cm. The needs of future lunar explorers have focused considerable interest on the geotechnical properties of the regolith.

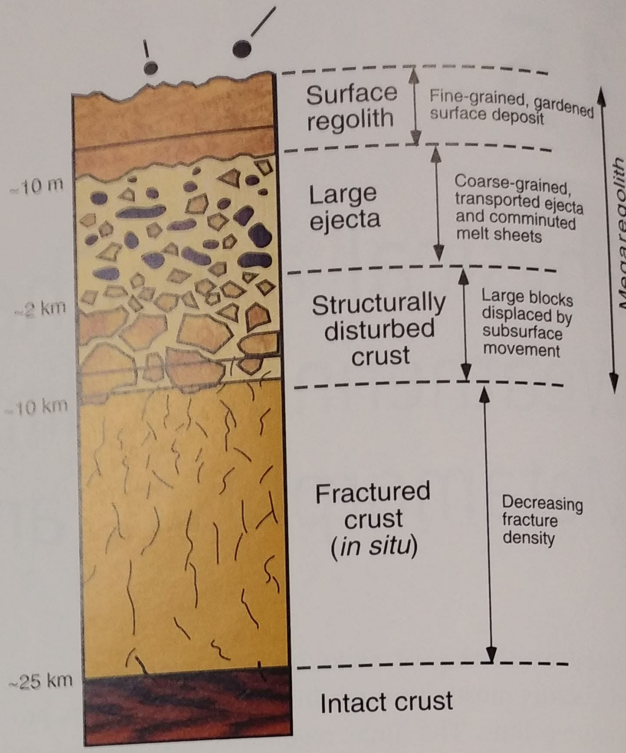

Figure 15.2 Vertical profile of the Moon's regolith.

The surface regolith is extremely fine-grained (Figure 15.3b), with particle sizes varying down to silt (typically 60–80 μm). Over time, crushed particles can become aggregated by impact-produced melts, forming glass-welded clusters of clastic grains called **agglutinates** (Figure 15.3c). The textural "maturity" of the regolith is determined by the balance between two opposing impact processes, one destructive and the other constructive with respect to particle size.

Bulk chemical analyses of regolith at the various sites can be understood in terms of mixing only a few components (highlands anorthosite, mare basalt, and KREEP; see Box 10.1). The regolith is a mixture of mineral grains, rock fragments, and agglutinates (Figure 15.3d), the abundance of the latter increasing with soil maturity. Lunar surface soils contain implanted hydrogen from the solar wind and have been irradiated by cosmic rays, which produced particle tracks and cosmogenic isotopes in target mineral grains.

The *Apollo* sample collections also contain numerous regolith breccias (Figure 15.3e,f) – lithified soils that constitute the Moon's only sedimentary rocks. The

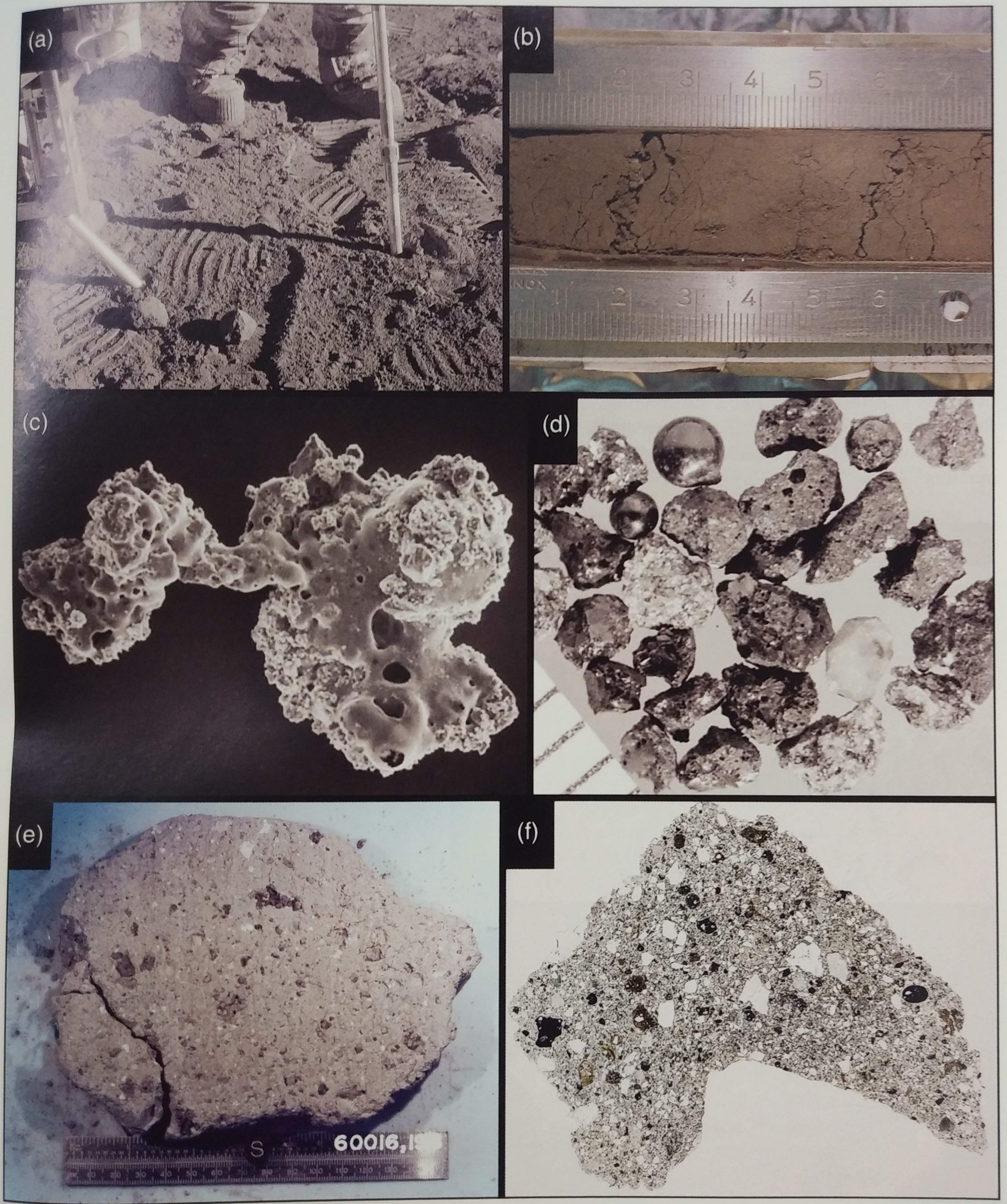

Figure 15.3 Lunar regolith. (a) Astronaut collecting a regolith core sample at the *Apollo 12* landing site. (b) Portion of an *Apollo 11* regolith core sample. (c) Agglutinate, composed of glass-bonded clastic particles. (d) *Apollo 17* soil particles consist of mineral grains (white grain is plagioclase), rock fragments including volcanic beads (spheres), and agglutinates (vesicular particles). (e) *Apollo 16* regolith breccia. (f) Thin section of regolith breccia shown in (e). NASA images.

induration of loose regolith into coherent rock results from compaction and cementation by impact melts.

15.2.2 Asteroid Regoliths

Regoliths have been imaged on the surfaces of asteroids and other small bodies like the moons of Mars. These tend to be blocky and thinner than regoliths on larger bodies (Figure 15.4a), which retain more impact fragments and have longer lifetimes against collisional disruption. Small asteroids may be covered by just a meter or so of regolith, but the regolith thickness on Vesta, the second-most massive asteroid, is estimated at greater than 1 km in places, as revealed in craters and landslides (Figure 15.4b). Models suggest that the irregular shapes and complex gravitation fields of asteroids lead to unequal global distributions of regoliths, including infilling of valleys, a prediction borne out by the discovery of ponds of dust on asteroid surfaces.

Petrologic studies of meteorite regolith breccias indicate that they are less fragmented and contain fewer agglutinates than lunar soils. In other words, asteroid regoliths are less mature. Howardites (Figure 15.4c), representing the regolith of asteroid Vesta, show significant differences in the mixing ratios of different igneous components. Depending on the size of impacts, these breccias can sample otherwise unobtainable rocks; for example, a few howardites contain small clasts of mantle rocks (Hahn et al., 2018). Howardites also contain tiny fragments of exogenic carbonaceous chondrite, the source of localized concentrations of hydrogen (in the form of hydrated phyllosilicates) discovered by the *Dawn* spacecraft.

Chondritic and achondritic breccias are common, and some of them must represent regoliths. However, not all breccias reside on the surface. The lack of agglutinates makes distinguishing regolith breccias from other fragmental rocks challenging, but cosmic ray tracks and implanted solar wind are diagnostic.

Figure 15.4 Regoliths on asteroids and Mars. (a) Coarse blocks in the regolith of asteroid Itokowa. *Hyabusa* spacecraft, image ~25 m across. (b) *Dawn* image of thick regolith on asteroid Vesta. (c) Dag 844 howardite, a sample of the vestan regolith. (d) Mars regolith, showing tracks of the Spirit rover. NASA and JAXA images.

BOX 15.1 SPACE WEATHERING

The effects of **space weathering** on the visible/near-infrared spectra of the Moon are lowering of albedo (darkening), increasing reflectance with increasing wavelength (reddening), and reduction in the depth of absorption bands (flattening). Lunar igneous rocks do not show these spectral effects, so space weathering is understood to be a characteristic of the surface regolith. Relatively young craters on the Moon expose bright materials that darken and redden over time through space weathering.

These spectral changes are attributed to tiny inclusions of nanophase iron metal, which occur in agglutinates and on the surfaces of soil particles (Figure 15.5). These minute blebs of metal are formed when iron-bearing minerals are vaporized during micrometeorite impacts, and the iron is subsequently recondensed from vapor in its native form.

Even thin atmospheres can screen out micrometeorites, so we would not expect space weathering on Venus or Mars. Curiously, though, Mercury exhibits no spectral effects, despite absence of an atmosphere. Mercury's surface rocks are nearly devoid of iron, as judged from its spectrum. Although energetic micrometeorite impacts should produce more melt and vapor than on the Moon, there is no source for condensable iron.

Many asteroids, particularly the abundant S-types, show darkening and spectral reddening, relative to the spectra of ordinary chondrites thought to be derived from them. For many years, this inability to match meteorite and asteroid spectra was a conundrum, but space weathering on asteroid surfaces now provides an explanation. As further evidence, a gradation between the spectra of chondrites and near-Earth S-type asteroids has been documented, and recent craters on the surface of asteroid Gaspra show no space weathering.

Despite its compositional similarity to the Moon, asteroid Vesta does not show the spectral effects of space weathering. Impact velocities in the asteroid belt are slower and consequently produce less vaporization, perhaps accounting for this difference. Also, the lower gravity on asteroids suggests more extensive overturn of regoliths, so there should be less exposure to micrometeorite impacts. Indeed, examination of howardites from Vesta shows virtually no nanophase iron, although other shock effects are common.

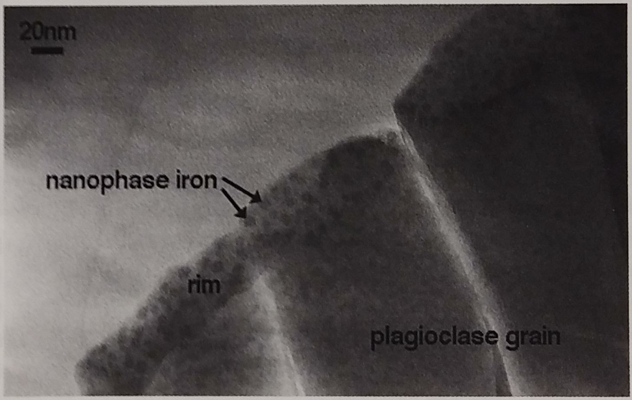

Figure 15.5 Transmission electron microscope (TEM) image of a space-weathered rim of glass containing nanophase iron on grains of lunar plagioclase. Image from NASA.

15.2.3 The Martian Regolith

Besides impacts, the martian surface has been affected by sedimentary processes that are familiar from terrestrial experience. Aqueous and aeolian processes are described in Chapters 13 and 14, and chemical weathering is considered in Section 15.3. Here we focus on physical weathering.

Since Mars' crust is dominated by basaltic volcanism, it should not be surprising that its regolith consists largely of basaltic minerals, in contrast to Earth, where sediments are mostly derived from felsic rocks (McLennan and Grotzinger, 2008). Soils, dominated by sand-sized particles, on modern Mars are transported and sometimes swept into dunes by winds. Most soils are covered by fine dust, which is revealed by rover tracks (Figure 15.4d). Basaltic detritus comprises two-thirds of these soils, with the remainder being chemically altered materials (McSween et al., 2010). The physical properties (grain sizes and shapes) of excavated soils, as determined from rover microscopic images (McGlynn et al., 2011), match those of crushed rock and are consistent with derivation by impacts. In contrast, the physical sorting of surface soils indicates reworking by aeolian activity.

The only martian sedimentary rock occurring as a meteorite is NWA 7034 (and a few meteorites paired with it that broke up during its plunge through the atmosphere). This rock is an ancient regolith breccia (Figure 15.6), composed of basaltic fragments and

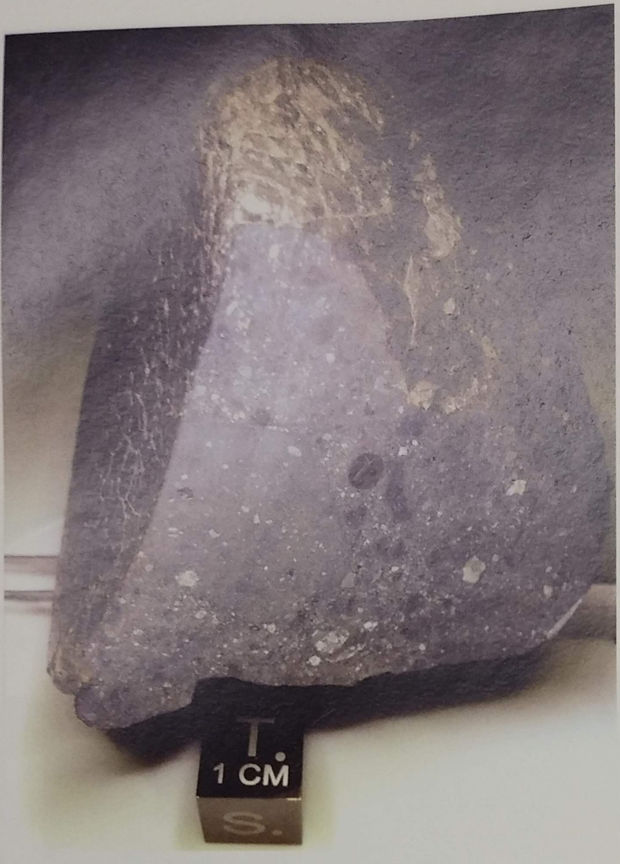

Figure 15.6. Cut surface of the NWA 7034 martian meteorite, illustrating its brecciated texture. Photograph courtesy of Carl Agee. Reprinted with permission.

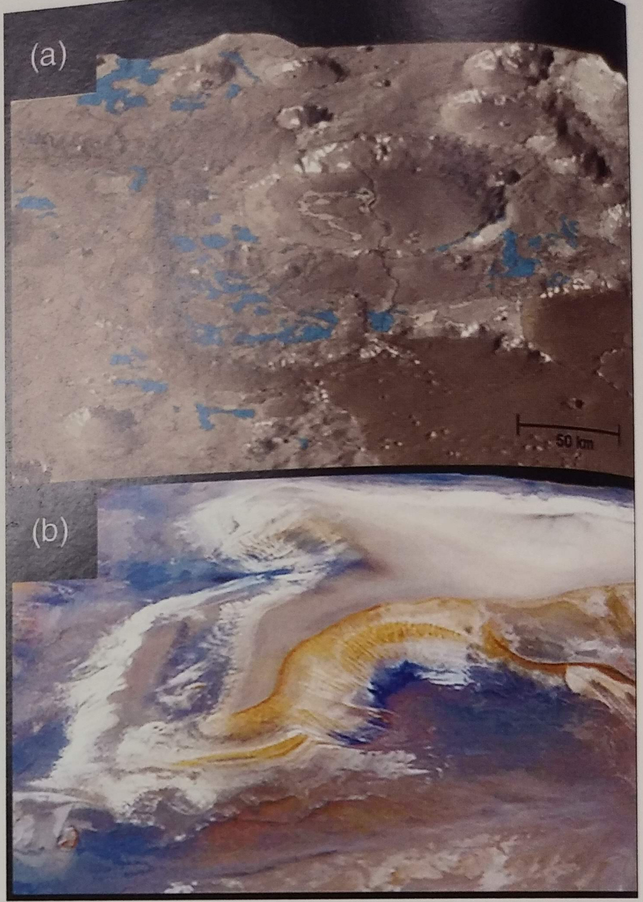

Figure 15.7 Aqueously altered rocks on Mars. (a) Phyllosilicates (blue) around Mawrth Vallis. (b) Layered sulfate deposits (brown) in Candor Chasma. Both images are colorized to show minerals mapped by *Mars Express* OMEGA. ESA and NASA images.

impact-melted clasts. Less coherent sedimentary rocks on Mars are unlikely to survive impact ejection.

15.3 Chemical Weathering and Aqueous Alteration

The Earth has the only planetary surface where liquid water is common and persistent and where chemical weathering is pervasive. Consequently, reactions of minerals with aqueous fluids are generally more common underground than on planetary surfaces. Water flowed or ponded on the surface of ancient Mars, allowing some chemical weathering, but any aqueous reactions on other planets or asteroids occurred in the subsurface by interaction with groundwaters. For asteroids, we do not use the term "chemical weathering" and instead talk about "aqueous alteration."

15.3.1 Chemical Weathering on Mars

Because Mars had surface water, at least in its distant past (see Box 15.2), chemical weathering occurred. This process likely produced the amorphous material, clay minerals (Figure 15.7a), silica, hematite, and other phases that comprise portions of Noachian rocks. Examples of martian rocks that have experienced chemical weathering (Grotzinger et al., 2005, 2014) include sandstones, siltstones, and shales encountered by the Curiosity rover in paleolake deposits in Gale crater. The igneous detritus in these rocks is associated with amorphous material, and sometimes silica and clays, and is typically cemented by evaporative salts (sulfates, chlorides, and carbonates) or hematite.

The smectite clays on Mars come in two varieties: dioctahedral $(Mg, Fe)^{2+}$ clays are nontronites, and trioctahedral $(Al, Fe)^{3+}$ clays are saponites. Nontronite does not form in cold, limited-water environments, so these clays likely formed by hydrothermal processes in the subsurface. Saponites likely formed during weathering on the surface during intermittent warm and wet periods (Bishop et al., 2018). Ehlmann et al. (2011a) mapped the global distributions of clays formed by these competing processes.

In addition to clastic rocks, Mars has chemical sediments, mostly layered sulfate evaporates (Gendrin et al.,

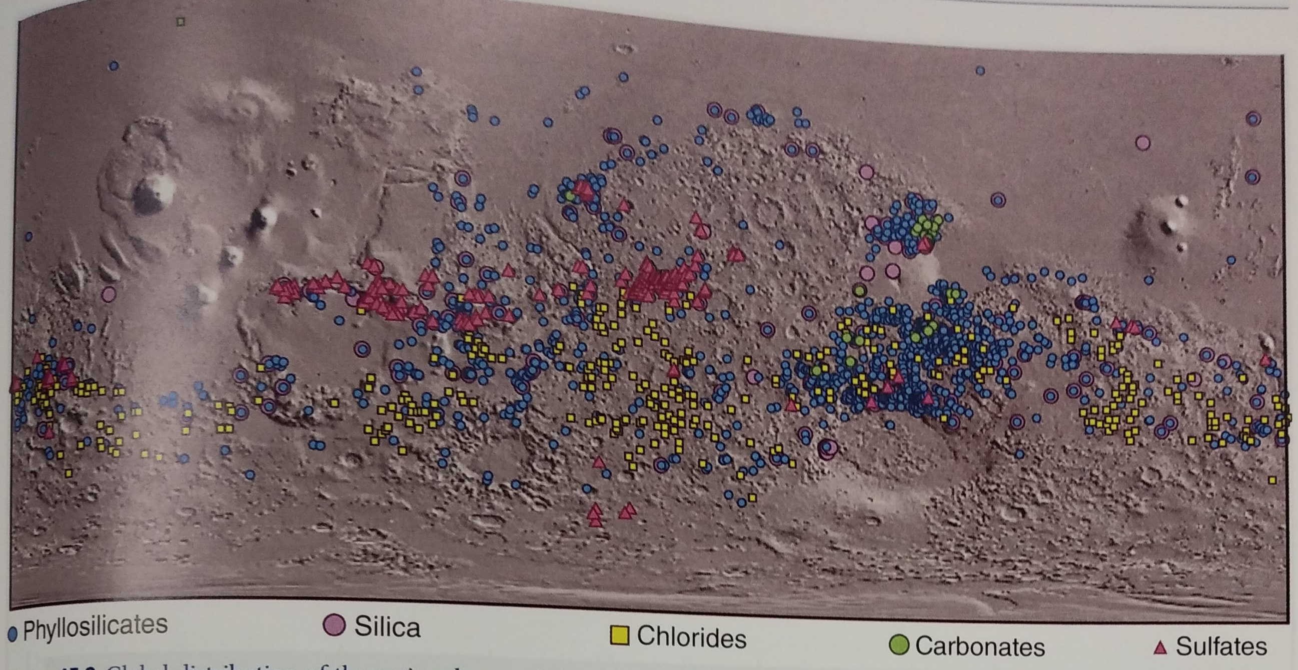

Figure 15.8 Global distribution of the major classes of alteration minerals on Mars. Modified from Ehlmann and Edwards (2014).

2005) identified in orbital spectra (Figure 15.7b). Chlorides (Osterloo et al., 2008) and small amounts of carbonates also occur. These ancient rocks demonstrate that chemical weathering occurred when water was more prevalent early in Mars' history; in contrast, Mars during the last several billion years has been dominated by physical weathering and aeolian processes.

The global distribution of the major classes of alteration minerals on Mars (Ehlmann and Edwards, 2014) is shown in Figure 15.8. These minerals are detected wherever Noachian crust is exposed.

We can summarize the effects of chemical weathering on Mars using the molar A-CNK-FM diagram (Figure 15.9) where $A = Al_2O_3$, $CNK = CaO + Na_2O + K_2O$, and $FM = FeO + MgO$. Rover-analyzed sedimentary rocks from Meridiani, Gusev, and Gale are chemically similar to basalts at the same locations, pointing to their volcanic provenance and to limited chemical change. Although mineralogic evidence for chemical weathering is widespread on Mars, bulk geochemical data do not show the leaching of water-soluble elements characteristic of open system alteration. The martian sedimentary rocks form a nearly linear array on this diagram, interpreted to reflect either some dissolution of olivine during acidic chemical weathering (Horowitz and McLennan, 2007) and/or physical sorting of olivine and other minerals during transport (McGlynn et al., 2012). The martian trend is distinct from terrestrial basaltic sediments, which migrate toward the A–FM join as CNK-rich soluble minerals are removed during weathering under neutral to slightly basic conditions.

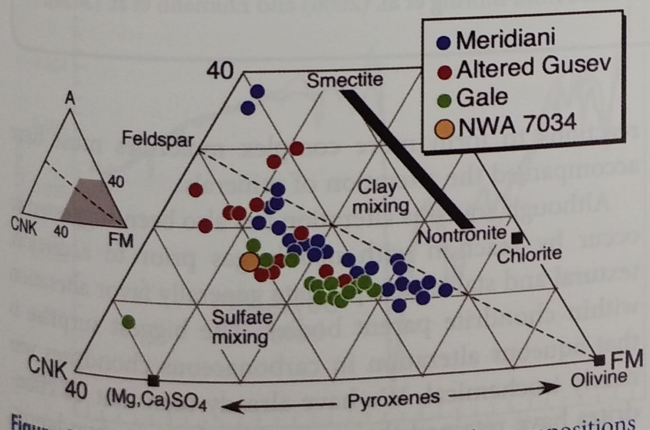

Figure 15.9 A–CNK–FM diagram illustrating the compositions of martian sedimentary rocks analyzed by rovers and the NWA 7034 meteorite. Reproduced with permission: Harry Y. McSween (2015) Petrology on Mars, *American Mineralogist*, v. 100, i. 11–12, p. 2380–2395.

Aqueous weathering processes are also recorded in many martian basaltic meteorites. Small amounts of clays, salts, and carbonates, as well as stable isotope data, indicate limited alteration of these igneous rocks (Leshin and Vicenzi, 2006).

15.3.2 Asteroids: Cosmic or Cosmuck?

Carbonaceous chondrites have experienced aqueous alteration (unlike other chondrite classes which experienced thermal metamorphism, as described below). Their parent bodies originally accreted mixtures of anhydrous rock with H_2O ice, which melted when heated by ^{26}Al decay. The presence of ice moderated large temperature increases, so for the most part these aqueous fluids were

BOX 15.2 A WEATHERING CHRONOLOGY FOR MARS

The observation that clay minerals were widespread in Mars' Noachian terrains has prompted the popular hypothesis that early Mars was warmer and wetter than later periods. This was followed in the Hesperian by precipitation of spatially restricted sulfate deposits, resulting from the evaporation of discharged groundwaters. Thus, early Mars is commonly thought to have been dominated by chemical weathering. In the Amazonian the martian surface became desiccated, characterized by iron oxides and dominated by physical weathering. A chronology for Mars based on these abundant weathering products (bottom of Figure 15.10) was developed by Bibring et al. (2006).

Although some crater lakes certainly existed for a time, e.g., in Gale crater (Grotzinger et al., 2014), the existence or persistence of widespread surface water on early Mars is now questioned. Substantial Noachian clay formation is recognized to have occurred in the subsurface by reaction with hydrothermal groundwaters (Ehlmann et al., 2011a). If those clays did not form on the surface by chemical weathering, they cannot be used as evidence of climate change. Instead, cold, arid conditions with only transient surface water may have characterized early (and later) Mars, limiting the amount of chemical weathering. This accords better with the difficulty for models to produce enough greenhouse warming and to explain what happened to a thick early atmosphere.

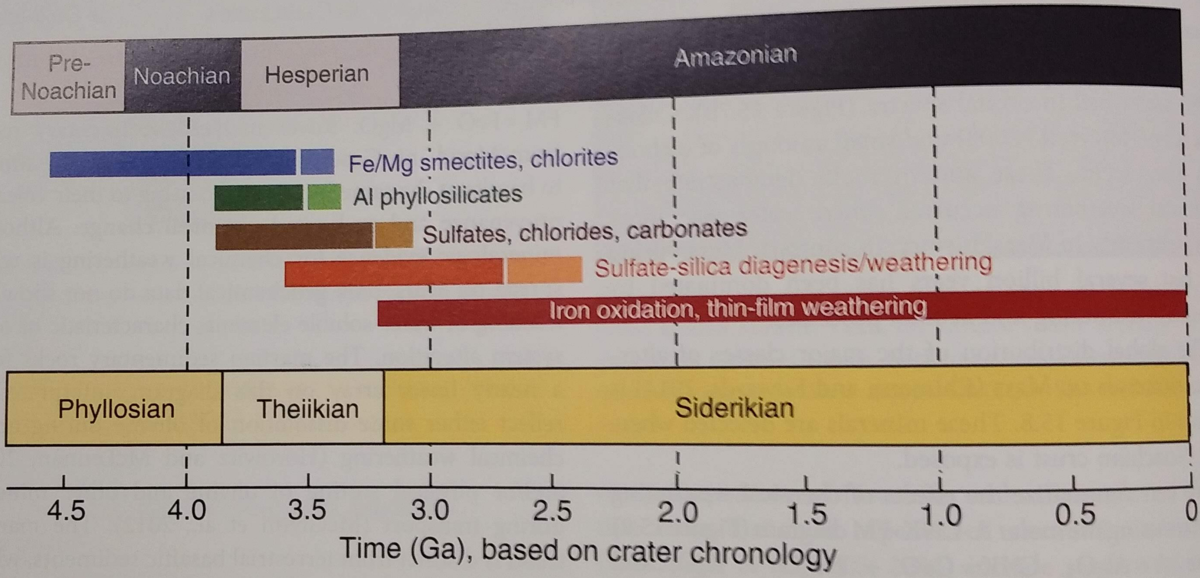

Figure 15.10 Mars chronology based on weathering products. Modified from Bibring et al. (2006) and Ehlmann et al. (2014).

fairly cold, generally 0 to 100 °C. The original chondritic minerals – mostly olivine, low-calcium pyroxene, and metal – were highly reactive and formed a variety of secondary minerals. The earliest-formed minerals were cronstedtite (Fe-serpentine) and tochilonite (interlayered $Mg(OH)_2$ and FeS) (Figure 15.11a). As alteration progressed, these phases were converted to antigorite (Mg-serpentine), clay minerals (smectites), magnetite, sulfates, and carbonates (Brearley, 2006; Howard et al., 2011). In chondrites, all these alteration minerals are fine-grained, requiring analysis by electron microscopy (Figure 15.11b). Organic matter is also an important constituent of these meteorites, and its association with phyllosilicates suggests reactions to form more complex molecules must have accompanied the alteration of minerals.

Although aqueous alteration has also been suggested to occur by reaction with nebula gas prior to accretion, textural and stable isotopic data generally favor alteration within chondrite parent bodies. The biggest surprise is that aqueous alteration in carbonaceous chondrites was nearly isochemical. We have already seen that CI chondrites have retained their solar-like element abundances despite having the appearance and mineralogy of congealed mud puddles. In contrast, terrestrial alteration by fluids typically causes significant chemical changes (metasomatism).

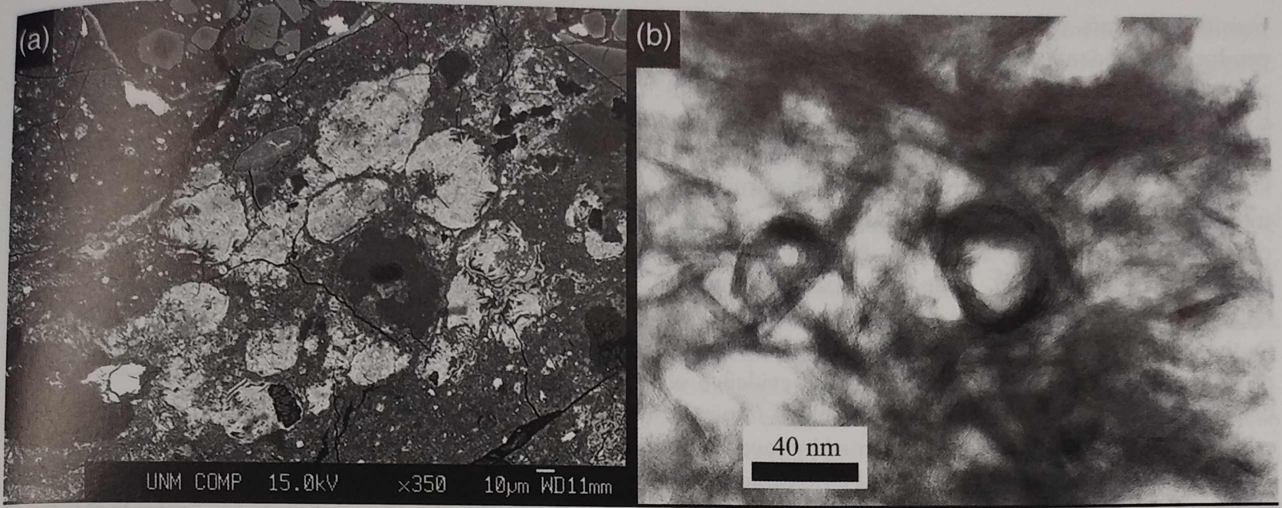

Figure 15.11 Aqueously altered CM carbonaceous chondrites. (a) Cronstedtite and tochilinite (light-colored clots in backscattered electron image). (b) Hollow serpentine tubes (TEM image). Images courtesy of Adrian Brearley. Reprinted with permission.

Dwarf planet Ceres is a carbonaceous chondrite-like body that has experienced pervasive alteration. Ceres' spectrum is similar to carbonaceous chondrites, but it has some distinct absorption bands. The spectrum, as measured by the *Dawn* spacecraft (Figure 15.12), consists of Mg-serpentine, ammonia-bearing clay, magnetite, and carbonate. Ammonia, perhaps produced by heating organic matter or incorporated as nitrogen-bearing ices, apparently exchanged with alkalis in clay minerals, and alteration produced more abundant carbonates than are found in carbonaceous chondrites. Unlike other carbonaceous asteroids, Ceres is differentiated, with an altered crust containing as much as 40 percent ice, and a coating of altered mineral grains representing a lag deposit formed when ice sublimated. Several other massive carbonaceous asteroids have similar spectra to Ceres, implying that larger bodies suffered more extensive aqueous alteration than smaller ones.

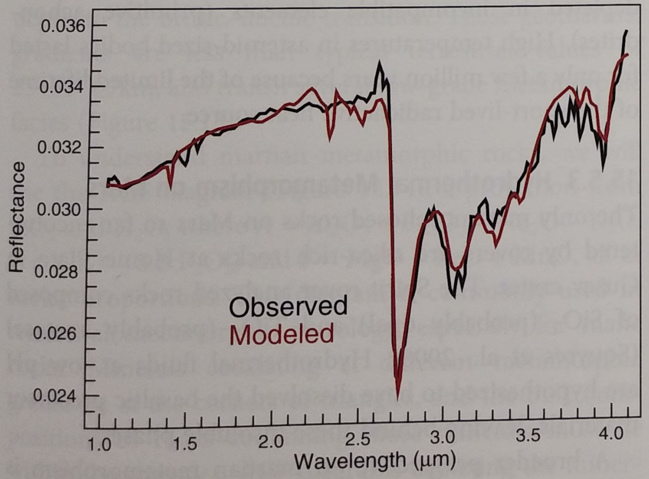

Figure 15.12 Reflectance spectrum of Ceres, compared with a modeled mixture of Mg-serpentine, ammoniated clay, magnetite, and carbonate. Modified from De Sanctis et al. (2015).

15.4 Sedimentary Petrology on Other Worlds

The dominant sedimentary rocks on extraterrestrial rocky bodies, excepting Mars, are breccias physically weathered by impacts. Whether on bodies of asteroidal, lunar, or planetary size, impact processes have pulverized target rocks, scattered and deposited the fragments as ejecta, and cemented the buried clasts with small amounts of impact melt. These rocks are classified as "fragmental" or "melt" breccias, depending on the proportions of unmelted versus melted material. "Regolith" breccias represent lithified materials that have spent time on the surface, as opposed to breccias from the deeper megaregolith that were buried. Regolith breccias can be distinguished by the presence of implanted solar wind gases and cosmogenic nuclides formed by irradiation.

Chondrites, which comprise most asteroids, are in effect cosmic sedimentary rocks (see Box 4.1). Chondrules and metal grains were sorted by mass in the nebula prior to or during accretion, so that any one chondrite has a restricted range of particle sizes. The aqueous alteration processes that affected carbonaceous chondrites mostly occurred at low temperatures and could be analogous to diagenesis. Lithification of chondrites results from shock or cementation by precipitates from aqueous fluids.

We have previously discussed the erosion, transport, and deposition of sediments by aeolian (Chapter 13) and aqueous (Chapter 14) agents. These processes are only manifest on Mars, where current or past conditions have produced abundant sedimentary rocks. However, sedimentary petrology on Mars differs fundamentally from that on Earth (McLennan and Grotzinger, 2008). The planet's basaltic surface composition gives rise to particulate debris that is distinct from that arising from the intermediate to felsic rocks of the Earth's crust. Martian clastic rocks commonly retain the chemistry of their basaltic protoliths, even after chemical weathering. Quartz sands are unknown, and feldspars are more stable in the Mars environment than on Earth. Many clastic rocks are cemented by sulfates, and other evidence of diagenesis (i.e., concretions, casts of dissolved minerals, criss-crossing veins) has been documented by rovers. The evolution of evaporating fluids derived by weathering of basalt is different from terrestrial experience (Tosca et al., 2005), producing Ca-, Mg-, and Fe-sulfates with lesser chlorides and carbonates. Even though clastic and chemical sediments are absent from the martian meteorite collection, rover missions have provided exquisite microscale observations and *in situ* measurements that reveal a great deal about the petrology and stratigraphic context of sedimentary rocks on Mars (Chapter 17).

15.5 Metamorphism

Metamorphism in Earth's crust occurs under varying pressure–temperature conditions, depending on the local geothermal gradient. The various conditions define the metamorphic facies. H_2O is a common participant or catalyst in metamorphic reactions, and CO_2 is important in some metamorphic systems. Fluids and elevated pressure and temperature play similar roles on other planets.

15.5.1 Thermal Metamorphism on the Surface of Venus

The high surface temperature and elevated pressure (~465 °C, 92 bar) on Venus are equivalent to greenschist facies metamorphic conditions. Consequently, rocks on the planet's surface likely have metamorphic mineral assemblages. However, the virtual absence of H_2O would preclude formation of the hydrous minerals that characterize greenschist facies rocks on Earth. Iron in silicate minerals is predicted to become oxidized to form hematite or magnetite.

The mineralogy of venusian surface rocks and regolith may be controlled by reactions with atmospheric gas. It is also possible that such reactions with minerals may even regulate the atmospheric composition (Fegley et al., 1997). Thermodynamic models suggest that the reaction calcite + silica = wollastonite + CO_2 should occur if the reactants are present, and this reaction could buffer the pressure of carbon dioxide, the dominant atmospheric component. Hydrochloric acid may be controlled by the reaction HCl + nepheline = albite + Cl-sodalite, and hydrofluoric acid by the reaction HF + K-feldspar + enstatite = fluorophlogopite + silica + H_2O. Sulfur dioxide could be affected by the reaction SO_2 + calcite = anhydrite + CO.

15.5.2 Thermal Metamorphism in the Interiors of Asteroids

Most chondrites have experienced early thermal metamorphism, caused by the heat generated from ^{26}Al decay. The degree of metamorphism is incorporated into the chondrite classification scheme as "**petrologic type**" (refer back to Figure 4.8). As noted in Chapter 4, during progressive thermal metamorphism, chondrule textures become blurred by recrystallization, and chemical zoning in minerals is homogenized. Asteroids undergoing metamorphism are thought to adopt the onion shell configuration (see Figure 5.15), in which the intensity of metamorphism – petrologic type – increases toward the center. Heating by ^{26}Al decay occurs faster than the heat can conduct outward, so the thermal profile is preserved. Onion shell bodies are probably not common now, as collisions have disrupted them and they have been gravitationally reassembled as rubble piles.

Thermal metamorphism has occurred in anhydrous asteroids (e.g., ordinary chondrite parent bodies). Without ice melting to inhibit large temperature increases, the temperatures inside dry asteroids can reach 1000 °C or higher. Some chondritic asteroids even experienced partial melting, producing magmas that crystallized in plutons or volcanic flows (achondrites) and leaving behind residues depleted in incompatible elements (primitive achondrites). High temperatures in asteroid-sized bodies lasted for only a few million years because of the limited lifetime of the short-lived radioactive heat source.

15.5.3 Hydrothermal Metamorphism on Mars

The only metamorphosed rocks on Mars so far encountered by rovers are silica-rich rocks at Home Plate in Gusev crater. The Spirit rover analyzed rocks composed of SiO_2 (probably opal) and TiO_2 (probably anatase) (Squyres et al., 2008). Hydrothermal fluids at low pH are hypothesized to have dissolved the basaltic precursor materials, leaving behind these insoluble phases.

A broader perspective on martian metamorphism is provided by hundreds of spectral detections of metamorphic minerals by orbiting spacecraft. These minerals

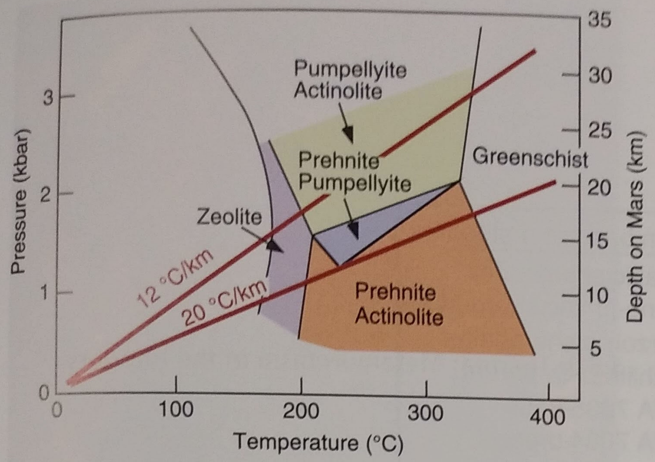

Figure 15.13 Pressure–temperature diagram illustrating geothermal gradients calculated for Mars during Noachian time, along with boundaries for low-grade metamorphic facies. Modified from McSween et al. (2015).

include chlorite and other clays, serpentine, zeolites, prehnite, and epidote (Carter et al., 2013). They occur most commonly on central peaks or in ejecta of craters, implying formation deeper in the crust.

Predicted pressure–temperature conditions in the martian crust are summarized in Figure 15.13 (McSween et al., 2015). The 12 °C/km geothermal gradient is calculated from measurement of radioactive heat-producing elements (potassium and thorium, with an assumed uranium value) in the modern Mars crust by the gamma ray spectrometer on the *Mars Odyssey* orbiter. Heat production was five times greater in the Noachian, before significant decay of these radioisotopes, so this gradient was corrected for the relevant half-lives. The 20 °C/km gradient in Figure 15.13 is the maximum based on heat flow estimated from thickness of the lithosphere and depth to the brittle–ductile transition. These geothermal gradients are less than typical terrestrial values of 25–30 °C/km, and transit several low-grade metamorphic facies (Figure 15.13).

To understand martian metamorphic rocks, we will use the ACF diagram (Figure 15.14), a projection from SiO_2 and H_2O, where $A = Al_2O_3 + Fe_2O_3 - Na_2O - K_2O$, $C = CaO - 3.3\ P_2O_5$, and $F = MgO + FeO + MnO$, all in molar proportions. This diagram is commonly used in terrestrial metamorphic petrology, especially for mafic rocks. Minerals coexisting at different metamorphic grades lie at the corners of triangles, and the bulk compositions of rocks containing those minerals must lie within the triangles. ACF diagrams depicting the mineralogies of low-grade metamorphic facies are illustrated in Figure 15.14 (McSween et al., 2015). Also plotted are the bulk compositions of martian meteorites and basaltic rocks analyzed by Mars rovers. Metamorphism of basaltic rocks plotting closer to F should produce chlorite + actinolite + serpentine, or talc, and rocks plotting farther from F should form chlorite + actinolite + laumontite, prehnite, or pumpellyite.

Orbital spectra from the Nili Fossae region indicate the occurrence of prehnite + chlorite (Ehlmann et al., 2011b), although neither actinolite nor any other amphibole has been identified. Laumontite has also not been specifically identified, but unspecified zeolites with similar spectra occur, and modeling suggests pumpellyite could be present. Serpentine and talc have also been noted. The Nili Fossae region has a Noachian age, and its metamorphism appears to have been caused by hydrothermal fluids circulating below abundant large craters.

15.6 Mass Wasting

Regolith and sediments occur on the surfaces of bodies throughout the Solar System. Unconsolidated materials on sloping terrains tend to move under the force of gravity. This process is called **mass wasting** – the movement of masses of regolith or rock debris downslope. Such movements can take a range of forms, including fast motions such as falls, slides, and flows, and slow motions such as creep. The speed and morphology of the mass wasting depends on composition, pre-existing weaknesses, and other factors. The shape of the mass-wasting feature depends on the shape of pre-existing planes of weakness, which may be parallel to the land surface, producing planar slides, or concave up, producing rotational slides or slumps. Materials can also be weakened by weathering and especially by the presence of liquids, which increase pore pressure and reduce friction.

Tectonic structures such as extensional faults have high relief, and so provide an opportunity for slope failure, as do the walls of impact craters. Because all planetary bodies have gravity and at least some topographic relief, if only from impact craters, mass wasting is probably the most common surficial process in the Solar System (after impact cratering, of course!).

Impacts not only often host mass-wasted material, but they commonly trigger mass-wasting events, as do tectonic movements. Rainfall is also a common trigger on Earth. Liquid has also clearly prompted mass wasting on Mars in the past and perhaps on Titan under present-day conditions. However, differentiating dry and wet mass-wasted deposits can be challenging.

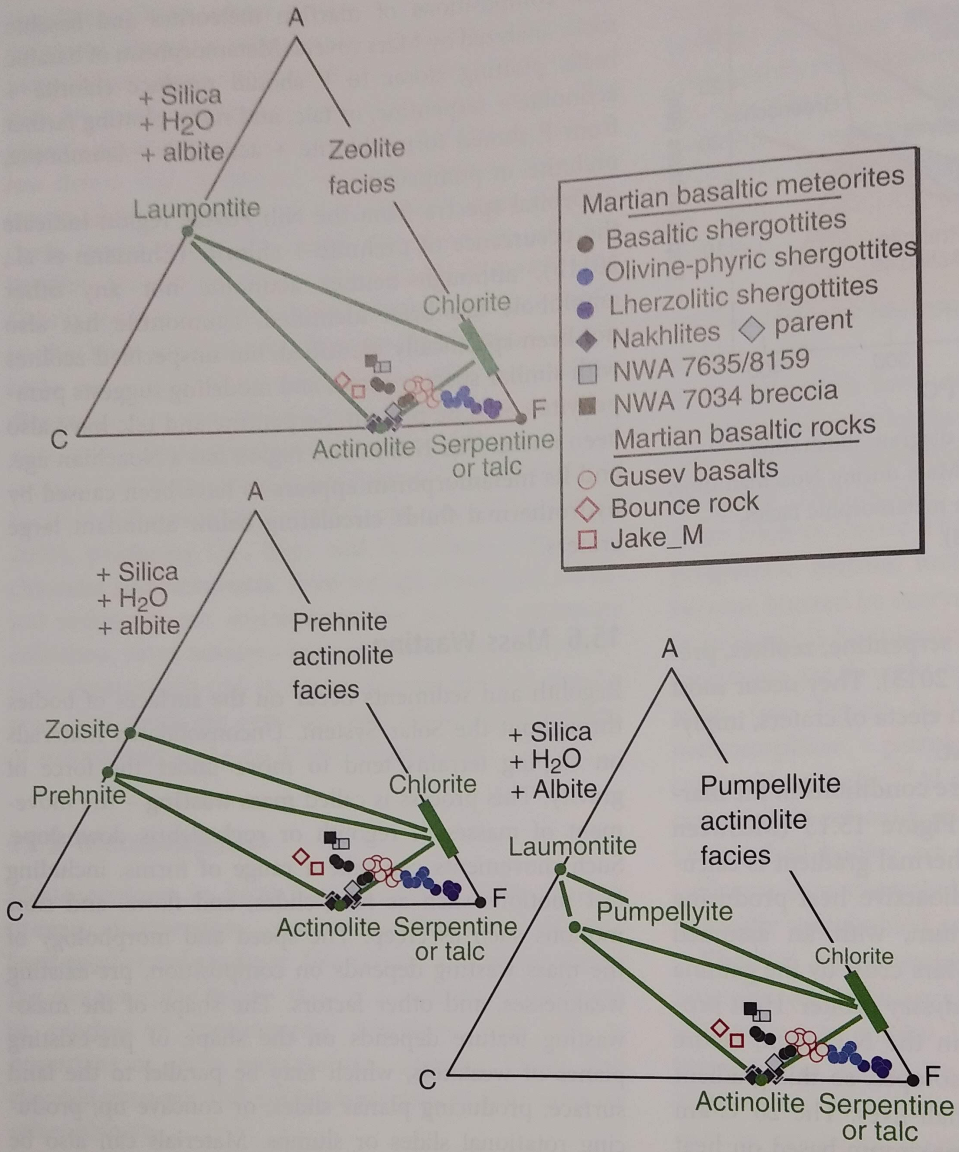

Figure 15.14 ACF diagrams showing mineral assemblages for metabasalts in various metamorphic facies. Bulk chemical compositions of martian meteorites and of basaltic rocks analyzed by Mars rovers are projected onto this diagram. Modified from McSween et al. (2015).

The significant topographic relief of Mars provides a ready context for mass wasting. As a striking example, the ~10 km deep canyon Valles Marineris, formed by global-scale extension related to the uplift of Tharsis, exhibits extensive landslide deposits (Figure 15.15a). These martian landslides have a greater areal extent and longer run-out distance than would be expected from the landslide scar height – a measure of their original potential energy – and are interpreted to have been fluidized by ice or even by acoustic energy from the rocks banging together (Watkins et al., 2015). Although rare on Earth, long-run-out landslides represent a prominent geomorphic process in Valles Marineris, perhaps because of its steep escarpments. Long avalanches have also been detected on Iapetus, a moon of Saturn, where the cause for the exception extent of icy deposits is localized heating during run-out. Because of Titan's low gravity, avalanches might also be extensive.

The flanks of volcanoes are also subject to slope failure, and mass wasting is now recognized as a significant part of volcano evolution. The high scarps around Olympus Mons result from collapse and gravity slide of the outer flanks of

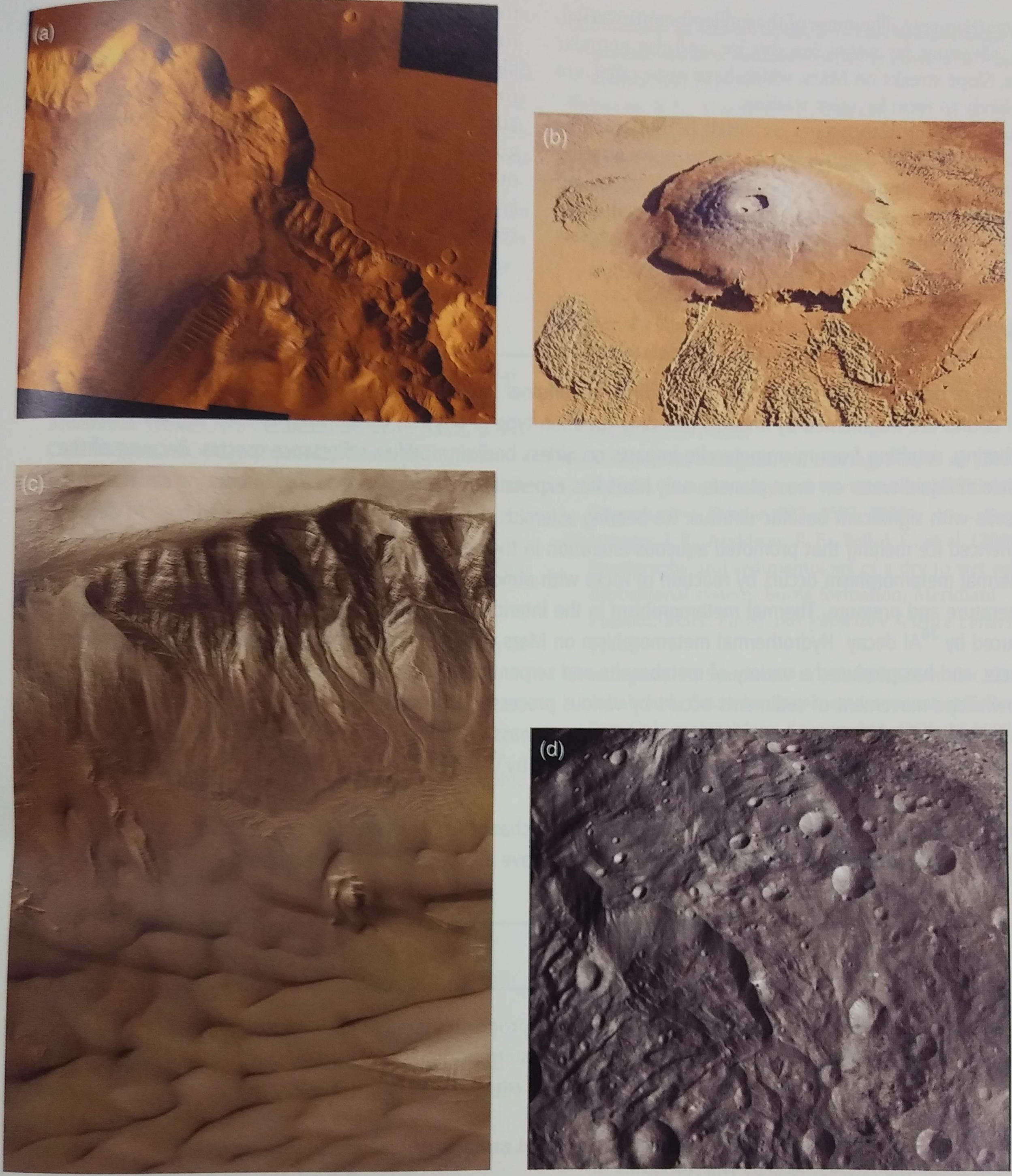

Figure 15.15 Examples of mass wasting. (a) Numerous landslides on graben walls in Valles Marineris, Mars. (b) Collapse of the flanks of Olympus Mons has produced high bounding scarps and rugged debris deposits. (c) Martian "gullies" on a crater wall. (d) Landslides on a fault scarp on asteroid Vesta. NASA images.

the shield, and huge debris deposits surround the volcano (Figure 15.15b). The landslides could have been triggered by marsquakes or stresses induced by the growing volcano.

Martian "gullies" (Figure 15.15c) are also examples of mass wasting, at a much smaller scale (McEwen et al., 2011). These features are characterized by an upper alcove and a depositional apron, linked by a channel. They occur on the walls of craters, generally 30° poleward in each hemisphere. The gullies are very young features, and repeated observations show changes over the course of a martian year. The cause of the gullies is controversial, with advocates for water, ice, dry ice, and dry granular flows. Slope streaks on Mars, which have some relief, are also likely to form by mass wasting.

Mass wasting also occurs on small bodies, such as the asteroid Vesta. Figure 15.15d shows mass wasting along a high-standing scarp, interpreted to be an extension fault. The ridged or stepped morphology of the deposits at the bottom of the scarp suggests their emplacement by rotational sliding, involving rotation backward – toward the cliff – of coherent blocks during their downward movement. In the surrounding impact craters, streaks along the crater walls attest to another type of mass wasting, namely by granular flow. Mass-wasting deposits rest on top of other units, so they are relatively younger, which is typical for units formed by surficial processes that rest on bedrock related to older processes.

Summary

A variety of geologic processes modify rocks from their original forms. Rocks on the surfaces of planets, the Moon, and small bodies are fragmented by impacts (the only common type of physical weathering) to form regoliths. Space weathering, resulting from micrometeorite impacts on airless bodies, modifies reflectance spectra. Because of the absence of liquid water on most planets, only Mars has experienced chemical weathering, producing sedimentary rocks and soils with significant basaltic detritus. Ice-bearing asteroids (carbonaceous chondrites) heated by ^{26}Al decay experienced ice melting that promoted aqueous alteration in their interiors.

Thermal metamorphism occurs by reaction of rocks with atmospheric gas on the surface of Venus, owing to its high temperature and pressure. Thermal metamorphism in the interiors of anhydrous asteroids resulted from the heat produced by ^{26}Al decay. Hydrothermal metamorphism on Mars was likely caused by groundwater heated by large impacts, and has produced a variety of metabasalts and serpentinites.

Downslope movement of sediments occurs by various processes as a result of gravity. Unstable slopes can form by tectonic activity, volcanism, or cratering, and the resultant mass wasting has sculpted the surfaces of large and small planetary bodies. The materials on slopes can be weakened by weathering and, on bodies with past or present volatile cycles, by the presence of fluids.

Aqueous fluids and elevated temperatures have produced changes in rocks on bodies large and small. In the following chapter, we will consider whether those conditions might have allowed life to arise beyond the Earth.

Review Questions

1. What is regolith, and how do its constituents and properties change with maturity?
2. Why is chemical weathering so limited in Solar System bodies?
3. What kinds of metamorphic rocks have been found on Mars? What do we surmise about metamorphism on Venus?
4. What is the heat source for thermal metamorphism and aqueous alteration on asteroids, and what accounts for one process or the other?
5. What is space weathering?
6. What kinds of planetary surface features are subject to mass wasting? What factors facilitate mass wasting?

SUGGESTIONS FOR FURTHER READING

Brearley, A. J. (2006) The action of water. In *Meteorites and the Early Solar System II*, eds. Lauretta, D. S., and McSween, H. Y. Tucson, AZ: University of Arizona Press, pp. 587–624. This is a comprehensive review of aqueous alteration in meteorites.

Ehlmann, B. L., and Edwards, C. S. (2014) Mineralogy of the martian surface. *Annual Reviews of Earth and Planetary Science*, **42**, 291–315. This paper provides an overview and global perspective of the distribution of minerals formed by chemical weathering and hydrothermal metamorphism on Mars.

McKay, D. S., Heiken, G., Basu, A., et al. (1991) The lunar regolith. In *Lunar Source Book: A User's Guide to the Moon*, eds. Heiken, G., Vaniman, D., and French, B. M. Cambridge: Cambridge University Press, pp. 285–386. The nature of the Moon's regolith is described in detail in this chapter.

McLennan, S. M., and Grotzinger, J. P. (2008) The sedimentary rock cycle of Mars. In *The Martian Surface Composition: Composition, Mineralogy, and Physical Properties*, ed. Bell, J. F. Cambridge: Cambridge University Press, pp. 541–577. A thoughtful summary of the differences between martian and terrestrial sedimentary rocks.

McSween, H. Y. (2015) Petrology on Mars. *American Mineralogist*, **100**, 2380–2395. This paper summarizes the petrology of igneous, sedimentary, and metamorphic rocks on Mars.

REFERENCES

Bibring, J.-P., Langevin, Y., Mustard, J. F., et al. (2006) Global mineralogical and aqueous Mars history derived from OMEGA/Mars Express data. *Science*, **312**, 400–404.

Bishop, J. L., Fairen, A. G., Michalski, J. R. et al. (2018) Surface clay formation during short-term warmer and wetter conditions on a largely cold ancient Mars. *Nature Astronomy*. DOI: 10.1038/x41550-017-0377-9.

Brearley, A. J. (2006) The action of water. In *Meteorites and the Early Solar System II*, eds. Lauretta, D. S., and McSween, H. Y. Tucson, AZ: University of Arizona Press, pp. 587–624.

Carter, J., Poulet, F., Bibring, J.-P., et al. (2013) Hydrous minerals on Mars as seen by the CRISM and OMEGA imaging spectrometers: updated global view. *Journal of Geophysical Research*, **118**, 831–858.

De Sanctis, M. C., Ammannito, E., Marchi, S., et al. (2015) Ammoniated phyllosilicates with a likely outer solar system origin on (1) Ceres. *Nature*, **528**, 241–245.

Ehlmann, B. L., and Edwards, C. S. (2014) Mineralogy of the martian surface. *Annual Reviews of Earth and Planetary Science*, **42**, 291–315.

Ehlmann, B. L., Mustard, J. F., Murchie, S. L., et al. (2011a) Subsurface water and clay mineral formation during the early history of Mars. *Nature*, **479**, 53–60.

Ehlmann, B. L., Mustard, J. F., Clark, R. N., et al. (2011b) Evidence for low-grade metamorphism, diagenesis, and hydrothermal alteration on Mars from phyllosilicate mineral assemblages. *Clays & Clay Minerals*, **59**, 359–377.

Fegley, B., Klingelhoefer, G., Lodders, K., et al. (1997) Geochemistry of surface–atmosphere interactions on Venus. In *Venus II*, eds. Bougher, S. W., Hunten, D. M., and Phillips, R. J. Tucson, AZ: University of Arizona Press, pp. 591–636.

Gendrin, A. N., Mangold, N., Bibring, J-P., et al. (2005) Sulfates in martian layered terrains: the OMEGA/Mars Express view. *Science*, **307**, 1587–1590.

Grotzinger, J. P., Arvidson, R. E., Bell, J. F., et al. (2005) Stratigraphy and sedimentology of a dry to wet eolian depositional system, Burns formation, Meridiani Planum, Mars. *Earth and Planetary Science Letters*, **240**, 11–72.

Grotzinger, J. P., Sumner, D. Y., Kah, L. C., et al. (2014) A habitable fluvio-lacustrine environment at Yellowknife Bay, Gale crater, Mars. *Science*, **343**. DOI: 10.1126/science.1242777.

Hahn, T. M., Lunning, N. G., McSween, H. Y., et al. (2018) Mg-rich harzburgites from Vesta: mantle residua or cumulates from planetary differentiation? *Meteoritics & Planetary Science*, **53**, 514–546.

Horowitz, J. A., and McLennan, S. M. (2007) A 3.5 Ga record of water-limited, acidic conditions on Mars. *Earth and Planetary Science Letters*, **26**, 432–443.

Howard, K. T., Benedix, G. K., Bland, P. A., et al. (2011) Modal mineralogy of CM chondrites by X-ray diffraction (PSD-XRD): part 2. Degree, nature and settings of aqueous alteration. *Geochemica et Cosmochimica Acta*, **75**, 2735–2751.

Leshin, L. A., and Vicenzi, E. (2006) Aqueous processes recorded by martian meteorites: analyzing martian water on Earth. *Elements*, **2**, 157–162.

Lucey, P., Korotev, R. L., Gillis, J. J., et al. (2006) Understanding the lunar surface and space–Moon interactions. In *New Views of the Moon*, eds. Jolliff, B. L., Wieczorek, M. A., Shearer, C. K., and Neal, C. R., Chantilly, VA: Mineralogical Society of America, pp. 83–219.

McEwen, A. S., Ojha, L., Dundas, C. M., et al. (2011) Seasonal flows on warm martian slopes. *Science*, **333**, 740–743.

McGlynn, I. O., Fedo, C. M., and McSween, H. Y. (2011) Origin of basaltic soils at Gusev crater, Mars, by aeolian modification of impact-generated sediment. *Journal of Geophysical Research*, **116**, E00F22.

McGlynn, I. O., Fedo, C. M., and McSween, H. Y. (2012) Soil mineralogy at the Mars Exploration Rover landing sites: an assessment of the competing roles of physical sorting and chemical weathering. *Journal of Geophyical Research*, **117**, E01006.

McKay, D. S., Heiken, G., Basu, A., et al. (1991) The lunar regolith. In *Lunar Source Book: A User's Guide to the Moon*, eds. Heiken, G., Vaniman, D., and French, B M. Cambridge: Cambridge University Press, pp. 285–386.

McLennan, S. M., and Grotzinger, J. P. (2008) The sedimentary rock cycle of Mars. In *The Martian Surface Composition: Composition, Mineralogy, and Physical Properties*, ed. Bell, J. F. Cambridge: Cambridge University Press, pp. 541–577.

McSween, H. Y., McGlynn, I. O., and Rogers, A. D. (2010) Determining the modal mineralogy of martian soils. *Journal of Geophysical Research*, **115**, E00F12.

McSween, H. Y., Labotka, T. C., and Viviano-Beck, C. E. (2015) Metamorphism in the martian crust. *Meteoritics & Planetary Science*, **50**, 590–603.

Osterloo, M. M., Hamilton, V. E., Bandfield, J. L., et al. (2008) Chloride-bearing materials in the southern highlands of Mars. *Science*, **319**. DOI: 10.1126/science.1150690.

Squyres, S. W., Arvidson, R. E., Ruff, S., et al. (2008) Detection of silica-rich deposits on Mars. *Science*, **320**, 1063–1067.

Tosca, N. J., McLennan, S. M., Clark, B. C., et al. (2005) Geochemical modeling of evaporation processes on Mars: insight from the sedimentary record at Meridiani Planum. *Earth & Planetary Science Letters*, **240**, 122–148.

Watkins, J. A., Ehlmann, B. L., and Yin, A. (2015) Long runout landslides and the long-lasting effect of early water activity on Mars. *Geology*, **43**, 107–110.