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The geology of Mars: new insights and outstanding questions

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1.1 Introduction

The major dynamic forces shaping the surfaces, crusts, and lithospheres of planets are represented by geological processes (Figures 1.1–1.6) which are linked to interaction with the atmosphere (e.g., eolian, polar), with the hydrosphere (e.g., fluvial, lacustrine), with the cryosphere (e.g., glacial and periglacial), or with the crust, lithosphere, and interior (e.g., tectonism and volcanism). Interaction with the planetary external environment also occurs, as in the case of impact cratering processes. Geological processes vary in relative importance in space and time; for example, impact cratering was a key process in forming and shaping planetary crusts in the first one-quarter of Solar System history, but its global influence has waned considerably since that time. Volcanic activity is a reflection of the thermal evolution of the planet, and varies accordingly in abundance and style.

The stratigraphic record of a planet represents the products or deposits of these geological processes and how they are arranged relative to one another. The geological history of a planet can be reconstructed from an understanding of the details of this stratigraphic record. On Mars, the geological history has been reconstructed using the global Viking image data set to delineate geological units (e.g., Greeley and Guest, 1987; Tanaka and Scott, 1987; Tanaka *et al.*, 1992), and superposition and cross-cutting relationships to establish their relative ages, with superposed impact crater abundance tied to an absolute chronology (e.g., Hartmann and Neukum, 2001). These data have permitted reconstruction of the geological history and the relative importance of processes as a function of time, and determination of the main themes in the evolution of Mars. Three major time periods are defined: Noachian, Hesperian, and Amazonian. Although absolute ages have been

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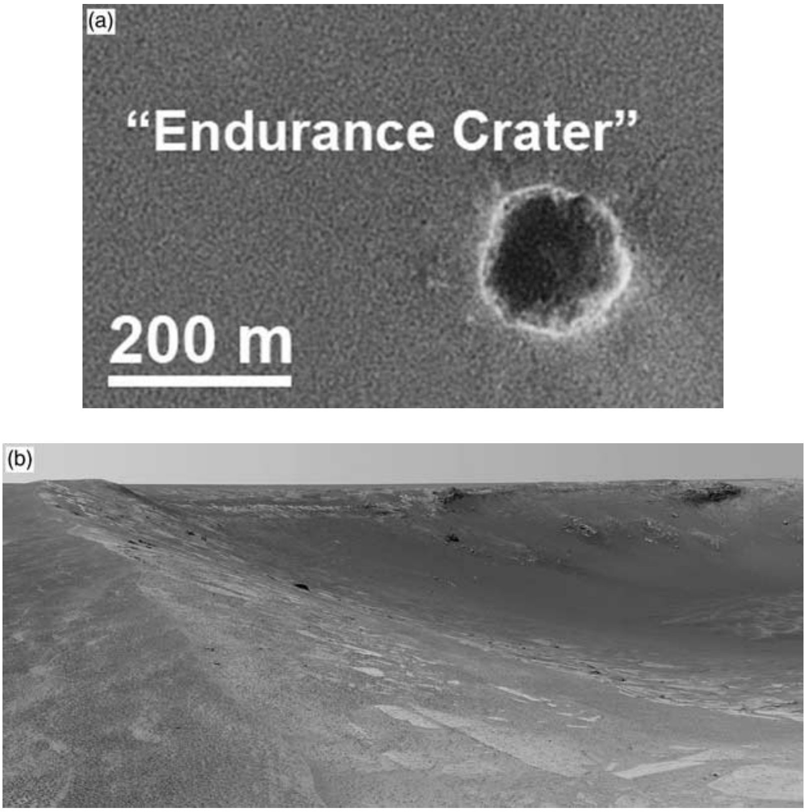

Figure 1.1. Impact crater landforms and processes. (a) NASA's Mars Exploration Rover Opportunity landed on Jan. 24 on a small bowl crater within the Meridiani Planum region later nicknamed "Eagle Crater." After about two months of examining rocks and soils within that crater, the rover set out toward a larger crater informally named "Endurance." During an extended mission following its three-month prime mission, Opportunity finished examining Endurance (1b), and explored a type of landscape to the southeast called "etched terrain" where additional deposits of layered bedrock are exposed. The underlying image for the map was taken from orbit by the Mars Orbiter Camera (MOC) on NASA's Mars Global Surveyor. (NASA/JPL/MSSS). (b) This image taken by the panoramic camera on the Mars Exploration Rover Opportunity shows the interior of the impact crater known as "Endurance." The exposed walls provide a window to what lies beneath the surface of Mars and thus what geologic processes occurred there in the past. While recent studies of the smaller crater nicknamed "Eagle" revealed evidence for an ancient evaporating body of salty water, that crater was not deep enough to indicate what came before the water. Endurance explored this question in the rocks embedded in vertical cliffs. Endurance is ~130 m across. Images such as these bridge the gap between orbital views and sample analysis and provide an important scale perspective when using terrestrial analogs. (NASA/JPL/Cornell).

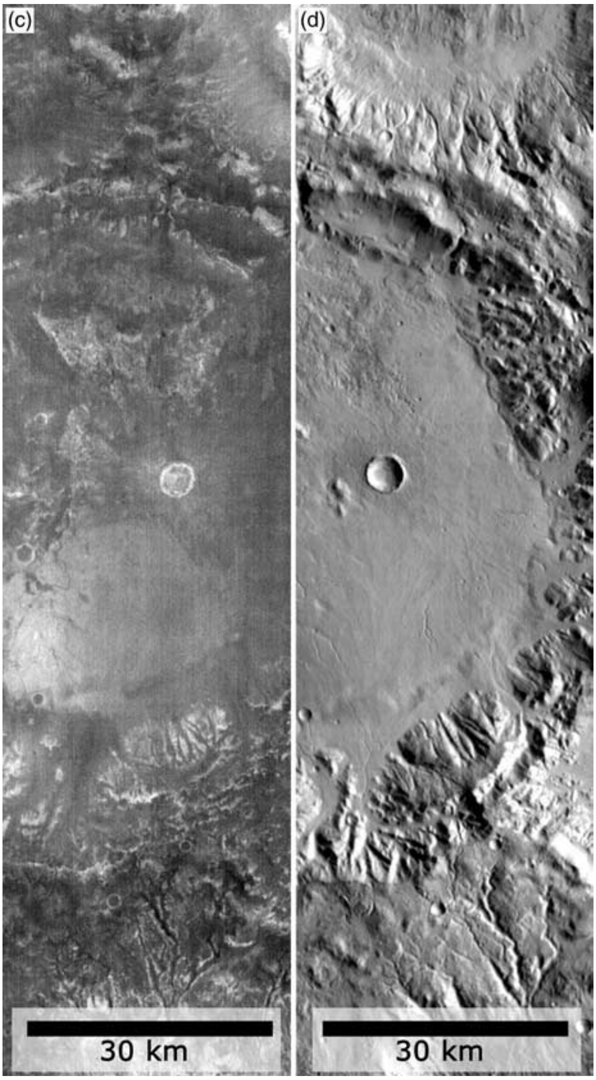

Figure 1.1. (cont.) (c) Nightime THEMIS IR image of a ~90 km diameter impact crater along the northeastern margin of Hellas Basin. Bright areas on the surface are warmer than dark areas. Bright areas along the rim of the crater (and along the rim of the smaller superposed crater in the center of the image) are likely to be exposed bedrock that show a higher thermal inertia than the surrounding soil. Image: I07269009 (ASU). (d) Daytime THEMIS IR image of the same crater in 1c. Surface temperature readings are largely dependant on solar reflectance during the day, so small-scale variations in surface composition are not as easily detected, but morphology is enhanced. This combination provides important additional information in interpreting the surface process and geologic history. Image: I07987004 (ASU).

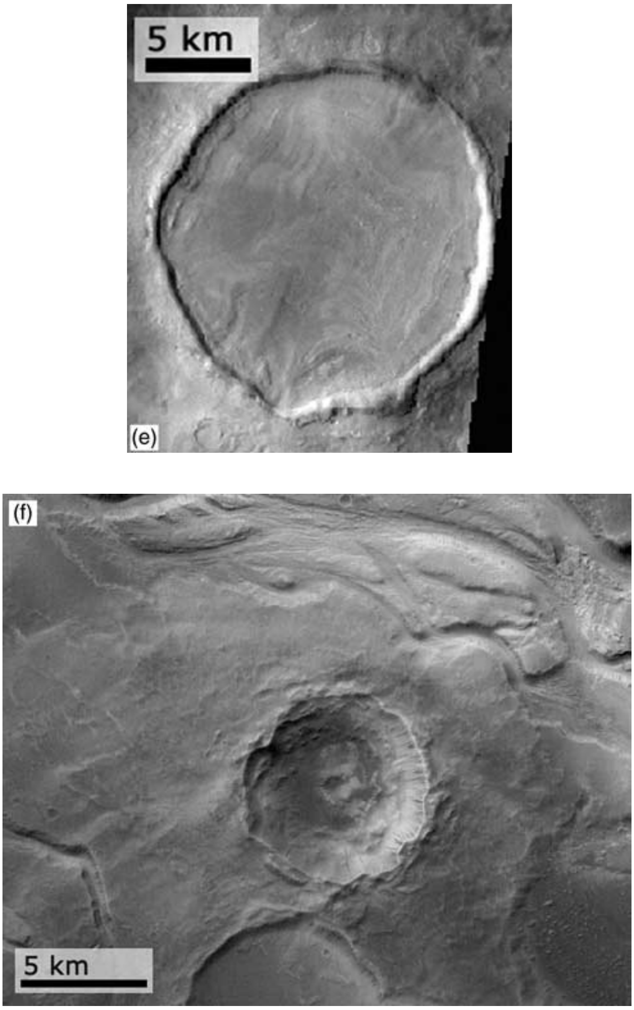

Figure 1.1. (cont.) (e) THEMIS Visible image V03679003 of a highly modified impact crater in the Adamas Labyrinthus region, within Utopia Planitia, at 43.9° N, 101.7° E. (ASU). (f) High Resolution Stereo Camera on board the Mars Express spacecraft took this image of an impact crater to the west of Mangala Valles and just south of its northern reaches (top of image), at 15° S, 205° E. (ESA). (g) The Haughton meteorite impact crater, on Devon Island, Nunavut, in the Canadian high arctic, is 20 km in diameter and formed 23 million years ago. It is one of the highest-latitude terrestrial impact craters known on land (75°22’ N, 89°41’ W) and is the only crater on Earth known to lie in a polar desert environment similar to that of Mars. Terrestrial analogs such as these provide important information on the nature of impact cratering and modification processes on Mars (see marsonearth.org; Image: obtained via GSFC by Landsat 7, bands 4, 3, and 2).

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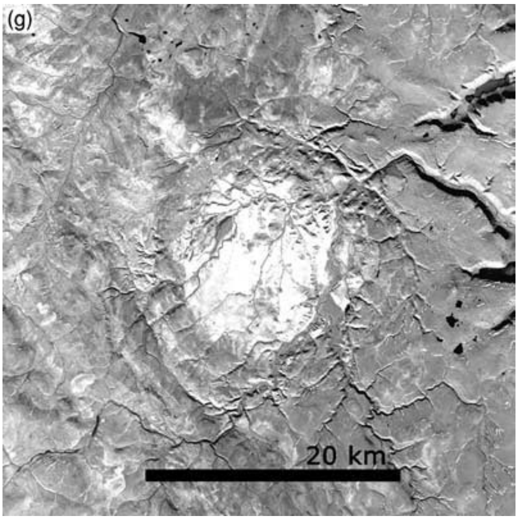


Figure 1.1. (cont.)

assigned to these periods (e.g., Hartmann and Neukum, 2001) (Noachian, ~4.65–3.7 Gyr; Hesperian, ~3.7–3.0 Gyr; Amazonian, ~3.0 Gyr to present), lack of samples from Mars whose context and provenance are known means that these assignments based on crater densities are dependent on estimates of cratering rates and thus are model dependent. Further confidence in these assignments must await a better understanding of the flux in the vicinity of Mars and radiometric dating of returned samples from known units on the surface of Mars.

Confidence in understanding the nature of the geological processes shaping planetary surfaces is derived from: (1) data: the amount and diversity of planetary data at hand, (2) terrestrial analogs: the level of understanding of these processes on Earth and their applicability, and (3) physical modeling: the manner in which planetary variables modulate and modify the processes (e.g., position in the Solar System, which influences initial state, composition, and solar insolation with time; size, which influences gravity and thermal evolution; and presence and nature of an atmosphere, which influences dynamic processes such as magmatic explosive disruption, ejecta emplacement, lava flow cooling, eolian modification, and chemical weathering). On Mars, our understanding of the geological history at the turn of the century was derived largely from the framework provided by the comprehensive coverage of the Mariner and Viking imaging systems (e.g., Mutch *et al.*, 1976; Carr, 1981; Scott and Tanaka, 1986; Greeley and Guest, 1987; Tanaka and Scott, 1987; Tanaka *et al.*, 1992).

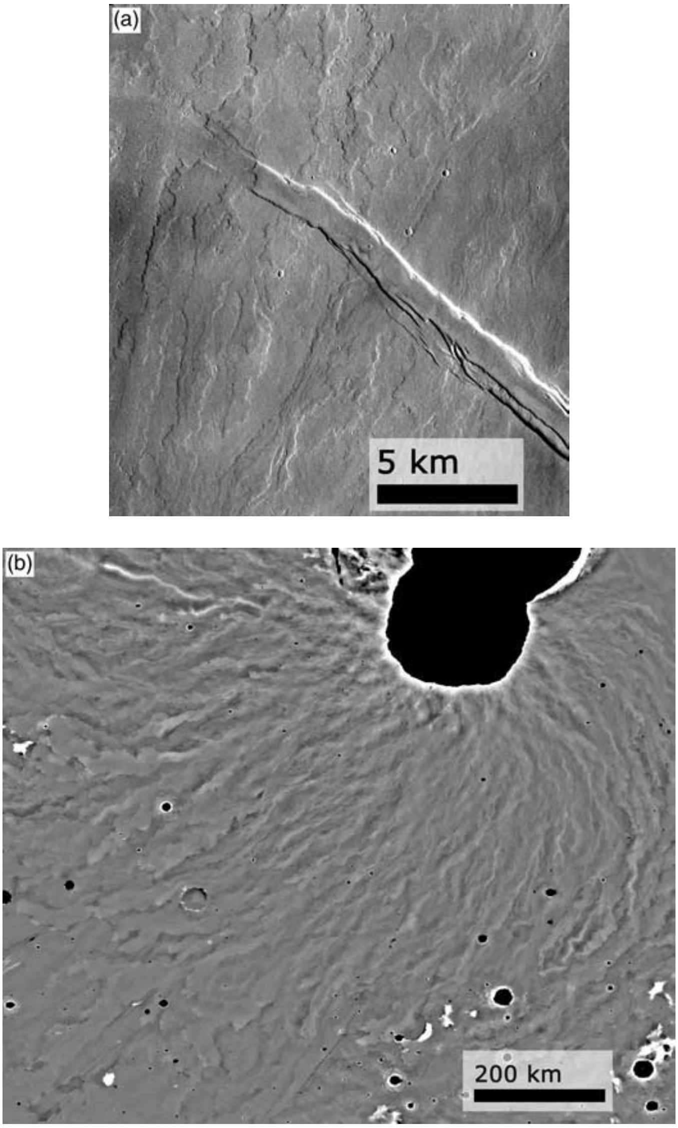
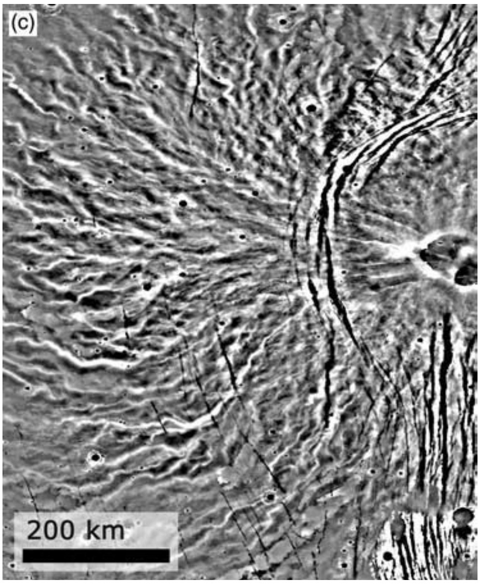


Figure 1.2. Volcanic landforms and processes. (a) Lobate lava flows from Olympus Mons. The relative timing of these volcanic flows and the formation of the structural feature can be deduced by which flows are cut by the fracture and which flows fill and cross the fracture. (THEMIS V02064003; ASU) (b) Lava flows of Arsia Mons, the southernmost of the Tharsis Montes. In this MOLA detrended altimetry data image, the regional topographic slope has been removed and individual lava flows become highlighted. The blacked out area represents the flanking rift zone (lower lobe) and the summit edifice and caldera (upper portion of blacked out area). These new data and modes of presentation provide important tools in the mapping and comparison of lava flows to terrestrial analogs.



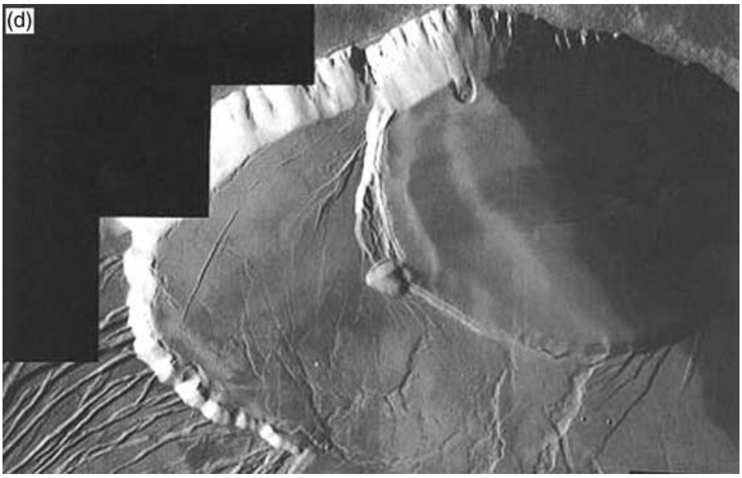


Figure 1.2. (cont.) (c) The western part of the summit and flank of Alba Patera, a massive shield volcano in the northern part of Tharsis. The MOLA detrended topographic representation shows the western part of the summit caldera and edifice, concentric faults, and the extensive western lava flow complex. (d) Multiple calderas on the summit of Olympus Mons, the largest volcano on Mars. Sequential collapse of the calderas can be assessed from the cross cutting relationship, with the youngest being in the top right. The surfaces of the caldera floors are flooded by lavas and then further deformed by wrinkle ridges and graben. Width of the caldera in the upper right is ~30 km. (THEMIS Visible image I04848014) (ASU)

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Newly acquired data sets (Mars Global Surveyor, Mars Odyssey, Mars Exploration Rovers, and Mars Express) and increased understanding of terrestrial analogs and their application are fundamentally and irrevocably changing our view of Mars and its geologic history. Global high-resolution topography, comprehensive high-resolution images, thermal mapping of rock and soils types and abundance, enhanced spectral range and resolution, mapping of surface and near-surface water and ice, probing of shallow crustal structure, mapping of gravity and magnetic anomalies, roving determination of surface geology, physical properties, geochemistry and mineralogy, astrobiological investigations, and sounding of the subsurface are some of the ways our understanding is changing. In this contribution, the current view of the geology of Mars is summarized, some key outstanding questions are outlined, and an assessment is made as to where changes from new data and a better understanding of terrestrial analogs is likely to take us in the near future.

1.2 Geological processes and their importance in understanding the history of Mars

1.2.1 Impact crater landforms and processes

Impact craters (Figure 1.1) occur on virtually all geological units and in the cases of older units, such as the heavily cratered uplands, basically characterize and shape the terrain (Figure 1.1c,d), forming the first-order topographic roughness of the Martian uplands (Smith *et al.*, 1999; Kreslavsky and Head, 2000). Several large basins (Hellas, Argyre, Isidis, Utopia) dominate regional topography and crustal thickness. Impact craters cause vertical excavation and lateral transport of crustal material, and future sample return strategies will call on this fact to gain access to deeper crustal material. Ejecta deposit morphologies in younger craters (e.g., Barlow *et al.*, 2000; Barlow and Perez, 2003) provide important clues to the nature of the substrate and also reveal the nature of the impact cratering process, particularly in reference to Martian gravity conditions, presence of an atmosphere, and icy substrates. Impact melts and ejected glasses are also likely to be important (Schultz and Mustard, 2004). Older impact craters provide clues to the types of modification processes operating on landforms (e.g., Pelkey and Jakosky, 2002; Pelkey *et al.*, 2003; Forsberg-Taylor *et al.*, 2004) (Figure 1.1c–f). Impact craters can also be sites of long-term geothermal activity due to heating and impact melt

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emplacement, and can serve as sinks for ponded surface water (e.g., Carr, 1996; Rathbun and Squyres, 2002).

The number of impact craters forming as a function of time, the flux, is a critical aspect of impact crater studies as it provides a link to absolute chronology provided by radiometrically dated samples returned from well-characterized lunar surfaces. Tanaka (1986) described the crater density of a range of stratigraphic units on Mars, and Ivanov and Head (2001) discussed a conversion from lunar to Martian cratering rates, which set the stage for correlation of crater density with absolute age on Mars. Hartmann and Neukum (2001) show that, in agreement with Martian meteorite ages, significant areas of late Amazonian volcanic and other units have ages in the range of a few hundred million years, while most of the Noachian probably occurred before 3.7 Gyr ago. In the less reliably dated intermediate periods of the history of Mars, Hartmann and Neukum (2001) use the Tanaka *et al.* (1987) tabulation of areas (km^2) resurfaced by different geological processes in different epochs, to show that many processes, including volcanic, fluvial, and periglacial resurfacing, show much stronger activity before ~3 Gyr ago, and decline, perhaps sharply, to a lower level after that time.

Future sample return missions must focus on the acquisition and return for radiometric dating of key geologic units that can be characterized in terms of the impact cratering flux. This step is of the utmost importance in establishing the geologic and thermal evolution of Mars, and the confident interplanetary correlation that will reveal the fundamental themes in planetary evolution. Characterization of impact craters at all scales on Mars is important to obtain a much more firm understanding of the cratering process. Currently there are uncertainties in the nature of the excavation process that influence the size frequency distribution and thus the dating of surfaces. The role of volatiles in the process of excavation, ejecta emplacement, and immediate landform modification is poorly understood. New high-resolution data on the topographic, physical properties, and mineralogic characteristics of impact craters and their deposits are beginning to revolutionize our understanding of the cratering process on Mars (Malin and Edgett, 2001), and radar sounding and surface rovers will add significantly to this picture. Until this improved picture emerges, the full potential of impact cratering as a "drilling" and redistribution process cannot be realized. Terrestrial analogs (Figure 1.1) must play a critical role in contributing to this new understanding and the documentation of Earth impact craters in a host of different geological and climate

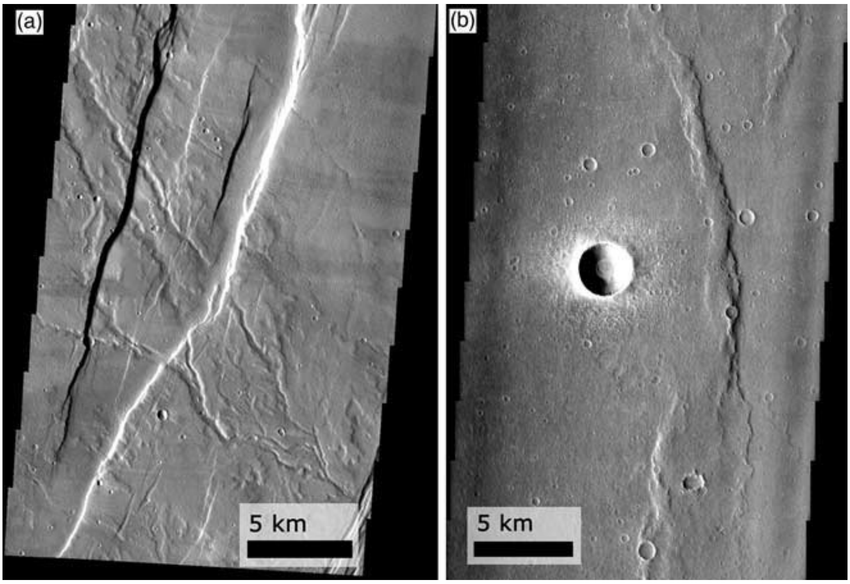

Figure 1.3. Tectonic landforms and processes. (a) Tantalus Fossae, a graben system, along the eastern flank of Alba Patera. Note that the lava flows and channels are cut by the graben. (THEMIS Visible image V02625006) (ASU) (b) Ridged plains of Lunae Planum located between Kasei Valles and Valles Marineris in the northern hemisphere of Mars. Wrinkle ridges are seen along the eastern side of the image. The broadest wrinkle ridges in this image are up to 2 km wide. A 3 km diameter young fresh impact crater is also seen; the sharp well-defined crater rim and the ejecta blanket contrasts with older more degraded impacts (Figure 1.1) and is indicative of a very young crater that has not been subjected to significant erosional processes. (THEMIS image V01388007) (ASU)

environments on Earth (submarine, desert, polar, temperate) is beginning to provide new insight (e.g., Barlow *et al.*, Chapter 2 in this volume).

1.2.2 Volcanic landforms and processes

Early Mars space missions (Mariner 9, Viking) showed clearly the importance of volcanic processes in the history of Mars (Figure 1.2). The huge shield volcanoes of the Tharsis and Elysium regions, extensive lava plains (Figure 1.2a–c), and low-profile constructs (paterae), permitted mapping and characterization of the extent, timing, and styles of volcanism on Mars (Greeley and Spudis, 1978; Mouginis-Mark *et al.*, 1992; Greeley *et al.*, 2000a). Currently and in the near future, new high-resolution images