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Planetary tectonics: introduction

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Summary

The geocentric realm of tectonics changed with the dawn of robotic exploration of the other bodies of the solar system. A diverse assortment of tectonic landforms has been revealed, some familiar and some with no analogues to terrestrial structural features. In this chapter, we briefly introduce some of the major topics in the book. The chapters review what is known about the tectonics on Mercury, Venus, the Moon, Mars, the outer planet satellites, and asteroids. There are also chapters that describe the mapping and analysis of tectonic features and review our understanding of the strength of planetary lithospheres and fault populations.

1 Introduction

At the most basic level, tectonics concerns how landforms develop from the deformation of crustal materials. The root of the word "tectonics" is the Greek word "tektos," meaning builder. The building of tectonic landforms is in response to forces that act on solid planetary crusts and lithospheres. Tectonic landforms in turn provide a wealth of information on the physical processes that have acted on the solid-surface planets and satellites.

Until little more than a century ago, the study of tectonics and tectonic landforms was limited to those on the Earth. This changed in the early 1890s when G. K. Gilbert began to study the lunar surface with a telescope. He described sinuous ridges in the lunar maria and interpreted them to be anticlinal folds (see Watters and Johnson, Chapter 4). This marked the beginning of the scientific investigation of

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tectonic landforms on planetary surfaces. In the decades that followed, during the era when planetary exploration was limited to telescopic observations, the Moon was the only other object in the solar system that was known to have tectonic landforms.

In the 1960s, with the first successful launches and operations of lunar and interplanetary spacecraft, a new era of planetary exploration began. The Mariner 4 spacecraft returned the first high-resolution (~3 km/pixel) images of the surface of Mars in 1965. In one of the 22 images, a poorly defined linear feature that occurs in the area of a mapped "canal" was identified and interpreted to be evidence of escarpments associated with an eroded rift valley. Higher resolution images from subsequent missions (Mariner 9 and the Viking Orbiters) revealed the areas imaged by Mariner 4 were on the western and southern flanks of the Tharsis volcanic and tectonic province. The linear feature was actually a segment of Sirenum Fossae, a prominent extensional trough that is part of the Tharsis radial graben system (see Golombek and Phillips, Chapter 5; and Tanaka *et al.*, Chapter 8).

Since the 1960s, an armada of exploratory spacecraft have identified widespread evidence of tectonism on all the terrestrial planets, most of the satellites of the outer planets, and on a number of asteroids. Tectonic landforms on large and small solid bodies in the solar system are as ubiquitous as impact craters. They express crustal deformation across a very large range in length-scale, from a few tens of kilometers up to several thousand kilometers (see Schultz *et al.*, Chapter 10; Watters and Nimmo, Chapter 2; and Watters and Johnson, Chapter 4). Deformation occurs in a wide range of crustal materials, from silicates to water ice to exotic ices, and exhibits local, regional, and global distributions.

The chapters in this book explore the diversity and similarity of tectonic landforms known to exist in the solar system. The characterization of tectonic landforms, methods of mapping the spatial distribution and bounding the age of structures and deformed terrains, the relationship between individual faults and fault populations, the kinematics and mechanics of crustal deformation, the thermal and mechanical properties of deformed lithospheres, and models for the origin and evolution of tectonic stresses are all described.

2 Terrestrial planets

The foundation for the interpretation of tectonic landforms on the terrestrial planets, and also on icy satellites in the outer solar system, is inexorably rooted in our understanding of tectonic landforms and processes on the Earth. On our planet, the vast majority of tectonic landforms occur within the context of plate tectonics. The largest scale tectonic landforms on Earth are the direct result of the relative motion of the lithospheric plates. Thus, most of Earth's tectonic landforms can be described as localized, occurring in or near current or past plate margins. Ironically, the plate tectonics paradigm was gaining acceptance during the same period, the 1960s to 1970s, when the exploration of the Moon and other terrestrial planets was gaining momentum. Yet, the large-scale manifestations of plate tectonics – mountain belts, spreading centers, and ocean trenches – now appear to be unique to the Earth.

In contrast to Earth, tectonism on Mercury, Venus, the Moon, and Mars is generally more distributed in character. Rather than a lithosphere comprised of a mosaic of individual plates that can shift and move relative to one another, the lithospheres of the other terrestrial planets and Earth's Moon behave largely as a single continuous shell. This is particularly puzzling in the case of Venus, a tectonically dynamic planet almost identical to the Earth in size and bulk density (see McGill *et al.*, Chapter 3). The relatively small sizes of the Moon and Mercury might be expected to work against the development of plate tectonics as a dominant interior cooling mechanism given the tenet that a planet's tectonic vigor and longevity scale approximately with its volume. On Mercury, contractional deformation (i.e., surface-breaking thrust faults) is broadly distributed in the regions of the planet imaged by spacecraft, possibly caused by contraction of the lithosphere from interior cooling (see Watters and Nimmo, Chapter 2). Tectonism on the Moon, on the other hand, is generally localized in the mare impact basins, attributed to subsidence and flexure-related deformation (see Watters and Johnson, Chapter 4). The bimodal distribution of topography and crustal thickness on Mars is strikingly similar to that on the Earth. However, tectonics on Mars, a planet intermediate in size between Mercury and Earth, occurred predominantly in the Tharsis volcanotectonic province and in only a few other major areas (see Golombek and Phillips, Chapter 5). Thus, each of the terrestrial planets and Earth's Moon exhibit a distinctive style of tectonics, expressing different interior structures, different mechanisms of heat loss, and different paths of crustal evolution.

2.1 Mercury

Mercury has many unusual characteristics that make it stand out in the spectrum of terrestrial planets in the solar system. As first in order from the Sun, Mercury is located in a harsh environment, exposed to intense solar radiation, flares, and tidal forces. It is the smallest terrestrial planet, about one-third the size of the Earth and only slightly larger than Earth's Moon. Yet, Mercury's mean density is comparable to that of the Earth, indicating that the proportion of its core volume to that of its mantle and crust is much larger than that of the other terrestrial planets.

Chapter 2 by Watters and Nimmo describes tectonic landforms imaged by Mariner 10 in three flybys of Mercury during the mid 1970s, along with some newly discovered tectonic landforms imaged by the MESSENGER spacecraft in its first flyby of Mercury. New images and data obtained by MESSENGER in two future flybys of Mercury and during the orbital phase of the mission will revolutionize our understanding of this intriguing planet.

Landforms indicative of both crustal shortening and extension are evident on Mercury. The number and scale of tectonic landforms was one of the surprising aspects of Mercury first revealed by Mariner 10. Lobate scarps are the most widely distributed tectonic landforms, interpreted as thrust faults that cut the oldest intercrater plains and the youngest smooth plains (see Watters and Nimmo, Chapter 2). Associated with lobate scarps are tectonic landforms known as high-relief ridges. Their maximum relief can exceed 1 km. In some cases, high-relief ridges transition along-strike into lobate scarps, suggesting they too are an expression of crustal shortening. Wrinkle ridges are another common tectonic landform on Mercury. These complex, positive relief structures occur predominantly in smooth plains in the interior of the Caloris impact basin and in the exterior smooth plains to the east. Wrinkle ridges, another result of crustal shortening, are structural anticlines formed by thrust faulting and folding.

Also surprising is the near absence of extensional landforms outside the interior smooth plains materials of the Caloris basin. Extensional deformation of the interior smooth plains is expressed by a complex and widespread network of basin radial and basin concentric troughs formed by graben that crosscut the wrinkle ridges within the Caloris basin. These extensional troughs appear to be among the youngest endogenic features known on Mercury. The origin of the stresses that form the graben are likely due to exterior loading of the Caloris basin or lateral crustal flow causing uplift of the basin floor (see Watters and Nimmo, Chapter 2).

Global tectonic stresses on Mercury may have arisen from a number of sources. Cooling of Mercury's interior is thought to have resulted in global contraction and widespread thrust faulting. Tectonic stresses may also have occurred from slowing of Mercury's rotation by despinning due to solar tides, and relaxation of an early equatorial bulge. A combination of global contraction and tidal despinning or a combination of global contraction and the formation of the Caloris basin have also been suggested. Mantle convection may have also been a source of stress. Each model predicts distinctive spatial and temporal distributions of lobate scarps, and therefore a global investigation of Mercury's tectonic landforms is needed for these models to be fully evaluated.

2.2 Venus

Venus also occupies a distinctive place in the spectrum of terrestrial planets in the solar system. In some ways it is strikingly similar to the Earth, but the difference between Venus and Earth are equally perplexing. The two planets could pass as twins with respect to diameter and bulk density. However, Venus and Earth have little in common when it comes to the composition and pressure of their atmospheres, their surface temperatures, and their tectonics. Chapter 3 by McGill *et al.* describes the tectonic landforms and terrains on Venus.

The exposed surface of Venus is relatively young, with the total population of impact craters of less than 1000 (see McGill *et al.*, Chapter 3). Although volcanic plains are the dominant terrain on Venus, features analogous to spreading centers, subduction zones, oceanic transform faults, and other diagnostic plate-boundary signatures found on Earth are absent. This suggests that Earth-like plate tectonics has not developed on Venus, at least during the recent period of time preserved in the crust (less than ~700 Ma; McGill *et al.*, Chapter 3; see Figure 8.1 in Tanaka *et al.*, Chapter 8).

Even in the absence of plate tectonics, Venus displays a surprising number of tectonic landforms and terrains. McGill *et al.* (Chapter 3) describe the several classes of tectonic terrains on Venus that include plains, tesserae, coronae, and chasmata. The expansive plains of Venus display a diverse suite of tectonic landforms, including wrinkle ridges, fractures and graben, polygonal terrains, ridge belts, fracture belts, and broad-scale uplifts and ridges. Some of these landforms are also associated with either coronae (large subcircular volcanotectonic complexes) or chasmata (lithospheric rift valleys). Coronae vary greatly in size, topographic relief, and in the extent of associated volcanism, and are generally associated with distinctive curvilinear fracture and graben systems. They are thought to have formed over thermal mantle plumes and may account for a significant fraction of the total planetary heat loss on Venus, thus replacing plate tectonics as the dominant interior heat loss mechanism. The large-scale graben that make up chasmata can have kilometer-scale relief and may be thousands of kilometers long. Tesserae are complex terrains consisting of multiple sets of ridges or graben that intersect at high angles, indicating a sequence of polyphase folding and extension over broad regions of Venus.

McGill *et al.* (Chapter 3) discuss the two principal hypotheses for the timing of the formation of the tectonic terrains. One hypothesis proposes that similar tectonic landforms formed at the same time globally, while the competing hypothesis postulates that tectonic landforms formed at different times in different places. In the absence of plate tectonics and liquid water, the tectonic history of Venus could conceivably involve a combination of both scenarios. An important question is how Venus and Earth, with nearly the same bulk properties, evolved into two distinctly different planets. Significant differences in tectonic evolution are predicted by geophysical models that involve a high-viscosity crust, asthenosphere, and mantle due to a lack of liquid water, motivating tests of these models constrained by the tectonic landforms.

2.3 The Moon

Among the diverse bodies in the solar system that display evidence of tectonism, Earth's Moon stands out because most of the tectonic landforms are found in and around the nearside lunar maria, impact basins subsequently flooded by basalt. Chapter 4 by Watters and Johnson describes the tectonic landforms that have been recognized on the Moon. The major tectonic landforms are wrinkle ridges, that occur exclusively in mare basalts, and rilles, narrow troughs that occur along basin margins and the adjacent highlands. Lunar rilles are the result of extension, formed by graben. The lunar farside, however, is not without tectonics. Lobate scarps are tectonic landforms that occur primarily in the farside highlands (Watters and Johnson, Chapter 4). Lunar lobate scarps are small-scale landforms relative to the nearside wrinkle ridges and rilles. They, like wrinkle ridges, are the surface expression of thrust faults.

The timing of tectonic events on the Moon suggests an interplay between periods of extension and compression. The crustal extension that formed the basin-localized graben ceased at ~3.6 Ga (see Figure 8.1 in Tanaka *et al.*, Chapter 8), while crustal shortening in the maria continued to ~1.2 Ga ago (Watters and Johnson, Chapter 4). The much earlier termination of extension on the Moon may have occurred when compressional stresses from global contraction were superposed on the basin-localized extensional stress, marking a shift from net expansion of the lunar interior to net contraction. Lobate scarps may be the youngest tectonic landforms on the Moon, forming less than 1 Ga ago. Young lobate scarp thrust faults indicate late-stage compression of the lunar crust.

One of the important accomplishments of the Apollo missions was deployment of a seismic network on the Moon. The deepest moonquakes (~800–1000 km) are spatially associated with nearside maria (Watters and Johnson, Chapter 4). These deep moonquakes may be related to the effects of impact basin formation and the production of mare-filling basalts. Shallow-depth moonquakes, some of which may occur within the lunar crust, are also associated with the nearside maria. This suggests that some moonquakes may be associated with nearside lunar faults and that the Moon may still be tectonically active.

Lunar gravity data show that many of the maria have large positive anomalies indicative of mass concentrations ("mascons") due to the mare basalts on an impact-induced thinned lithosphere. Watters and Johnson (Chapter 4) note that the shoulders of the positive anomalies, that are spatially correlated with basin-interior wrinkle-ridge rings in some maria, suggest a pan- rather than a bowl-shaped mare-fill geometry. Models for the origin of stresses in mascons suggest that the spatial distribution of the wrinkle ridges and rilles is best fit by a relatively uniform thickness of mare basalts. Watters and Johnson (Chapter 4) conclude that the stresses and the estimated contractional strain expressed by the lobate scarps are consistent with thermal history models that predict a small change in lunar radius over the last 3.8 Ga.

2.4 Mars

Mars is intermediate in size in the spectrum of the terrestrial planets. By comparison with smaller bodies, the Moon and Mercury, the size of Mars appears to have been favorable to sustain tectonic activity throughout much of its geologic history. Although smaller in size than Venus and the Earth, Mars has some of the largest tectonic landforms and the most intensely deformed terrains in the solar system. Golombek and Phillips (Chapter 5) describe the principal tectonic landforms and provinces on Mars.

Two large-scale physiographic provinces dominate the planetary landscape, and their development and evolution are directly responsible for, or have influenced the formation of, most of the tectonic landforms on Mars (Golombek and Phillips, Chapter 5). These are the Tharsis province and the highland–lowland dichotomy. The highland–lowland dichotomy boundary separates the sediment-covered northern lowland plains from the more rugged and heavily cratered southern highlands. The Tharsis province is a broad, topographic rise superimposed on the dichotomy boundary in the western hemisphere. Its massive volcanoes and large expanses of volcanic plains are punctuated by a vast array of extensional and compressional fault populations that include the striking Valles Marineris rift system.

Extensional tectonic landforms on Mars vary greatly in scale, from narrow fractures and graben to rift valleys up to 100 km wide and kilometers deep. The most common compressional tectonic landform on Mars is wrinkle ridges. These anticlines occur in broadly distributed plains units in the Tharsis province, and elsewhere in the highlands and the northern lowlands. Another common compressional tectonic landform is lobate scarps. Many of the lobate scarps on Mars occur in the highlands along the dichotomy boundary in the eastern hemisphere. Large-scale ridges, landforms that can have up to several kilometers in relief, have also been identified on Mars.

Golombek and Phillips (Chapter 5) review two predictive models for the gravity field and topography associated with Tharsis: elastic spherical-shell loading and plume-related uplift of a lithospheric shell. In elastic spherical-shell loading models, Tharsis constitutes a massive lithospheric load supported by membrane (bending) stresses in a rigid lithospheric shell. In plume-related models, the long-wavelength topography of Tharsis supported by a mantle plume and associated radial dikes are responsible for forming the graben system. Outside of the Tharsis province, the broad distribution of wrinkle ridges on Mars indicates widespread contractional deformation across the planet. While stresses from the Tharsis load appear to have had a global influence, many wrinkle ridges in the eastern hemisphere highlands and in the northern lowlands are not obviously related to Tharsis, implying additional controls on the planet's tectonic history. Golombek and Phillips (Chapter 5) suggest that a globally isotropic contractional strain event, modulated by Tharsis stresses in the western hemisphere, can account for the distribution and orientation of wrinkle ridges.

3 Small bodies of the solar system

It might be expected that the large number of smaller bodies of the solar system would not display evidence of tectonics, simply because their size would limit the number of mechanisms that generate significant stress in larger bodies. However, a surprising number of small bodies have tectonic landforms. Small bodies, defined as objects with radii less than about 200 km, include the satellites of some planets, along with many of the known asteroids, cometary nuclei, and Kuiper-belt objects. In the spectrum of objects in the solar system, they are the remnants of the building blocks of the planets and larger satellites, and perhaps fragments of large bodies that were disrupted. A variety of spacecraft have now imaged small satellites, asteroids, and cometary nuclei, providing insight into tectonic processes on these bodies. Perhaps the most dramatic to date was the Near Earth Asteroid Rendezvous (NEAR) mission. After orbiting 433 Eros, the NEAR Shoemaker spacecraft touched down on the asteroid. Thomas and Prockter (Chapter 6) describe tectonic landforms that have been discovered on the solar system's small bodies.

The most common tectonic landforms on small bodies are grooves, troughs, and ridges. Although these landforms deform the regolith of the bodies, the underlying fractures and faults are likely rooted in more competent substrate materials (Thomas and Prockter, Chapter 6). The scale of tectonic landforms on small bodies varies as greatly as their size. Grooves are generally small-scale features that vary morphologically from linear, straight-walled depressions to rows of coalesced pits, and are common tectonic landforms on Gaspra, Ida, Eros and Phobos. Grooves likely result from extension, expressed by collapse of the regolith into near-vertical subsurface fractures or cracks. Troughs are larger-scale landforms than grooves, typically exhibiting greater widths and depths. An example is Calisto Fossae, which is made up of some of the largest tectonic landforms on Eros. Calisto Fossae and troughs on other small bodies are extensional landforms formed by graben. Ridges are positive-relief landforms found on Eros and Gaspra. One of the most striking examples of these is Rahe Dorsum on Eros, an asymmetric ridge that extends over a significant portion of the length of the asteroid. Rahe Dorsum appears to be the surface expression of thrust faulting.

Thomas and Prockter (Chapter 6) review models for the origin of structure-forming stresses on small bodies. Internal thermal activity on small bodies, although limited, may have been significant enough to induce tectonic stresses. External thermal stresses are created by temperature variations due to short- and long-period changes in rotation or distance from the Sun. Significant stress can also be induced externally from collisions with other small bodies. Sufficiently high-velocity impacts will result in stresses that far exceed the yield strengths of the small body, leading to the growth of tectonic landforms. Another external source of stress is tidal forces, which are induced by close encounters of small bodies with larger bodies and planets.

4 Outer planet satellites

The satellites of the outer planets (Jupiter, Saturn, Uranus, and Neptune) are diverse bodies that rival the inner planets and Earth's Moon in size and the range of tectonic complexity. Jupiter's moon Ganymede, and Saturn's moon Titan, are both larger than the planet Mercury. Water ice, rather than silicates, is the dominant constituent of the near-surface crusts of most of the larger outer planet satellites. Jupiter's Io is a notable exception: its widespread volcanism and isolated giant mountains present a sharp contrast to the icy satellites. Most of the tectonic landforms on the outer planet satellites are indicative of crustal extension. Landforms that express crustal shortening are rare. Collins *et al.* (Chapter 7) describe the vast array of familiar to enigmatic tectonic landforms on Io and the icy satellites. Just a few examples of these are summarized below.

The crust of Europa records a long-lived and complex history of tectonic activity. Common tectonic landforms there include troughs, ridges, bands, and undulations. Troughs on Europa are linear to curvilinear in plan form and often V-shaped in cross section, and are interpreted to be tension fractures analogous to terrestrial crevasses. Ridges are the most common landform on Europa. They often occur in pairs forming a double ridge with a medial trough. Numerous hypotheses have been proposed for Europa's ridges, many involving extensional stresses generated by mechanisms such as tidal squeezing, volcanism, dike intrusion, or diapirism. The diversity of hypotheses attests to the continuing difficulty in interpreting this exotic structural landform.

Another unusual tectonic landform on Europa is bands, which are polygonally shaped areas with sharp boundaries formed by crustal extension that appear to be offset laterally and displaced from adjacent bands. Bands can be reconstructed geometrically by using rigid-block rotations to restore originally contiguous landforms, suggesting significant strike-slip motion on the body. Subtle shading variations in high-resolution Galileo images revealed undulations comprised of alternating zones of small-scale ridges and troughs. These undulations are interpreted to be folds with bending-related fractures along the inferred anticlinal rises and compressional ridges in the synclinal valleys. Such folds may accommodate some part of Europa's widespread crustal extension.

A principal source of tectonic stress on Europa arises from nonsynchronous rotation which causes a shift in the moon's surface relative to its fixed tidal axes. Diurnal tidal variations also induce a daily rotating stress field in the icy crust that changes the orientation of cracks developing in response to stresses from nonsynchronous rotation.

One of Saturn's smaller satellites, Enceladus, has some of the most remarkable tectonic landforms found to date on icy bodies. The south polar region of Enceladus has a series of subparallel troughs flanked by ridges. Informally described as "tiger stripes," these features are likely associated with thermal anomalies and active plumes of water vapor (Collins *et al.*, Chapter 7). Arcuate scarps in the south polar region are interpreted to be evidence of thrust faults. In contrast to the south polar region, the more ancient north polar cratered terrain appears undeformed. The deformation on Enceladus is likely to have arisen from a number of sources, including tidally induced stress, diapirs in a subsurface ocean, crustal subsidence, poleward reorientation, and ice shell thickening above a subsurface ocean.

The largest of Neptune's moons is Triton. Although its crust is thought to be composed mainly of water ice or ammonia hydrate ice, evidence of other exotic ices has been found. The dominant tectonic landform on Triton is double ridges similar to those found on Europa. These sinuous features are characterized by continuous, along-strike depressions that are flanked by ridges. The stresses that formed these ridges may reflect tidally induced shear heating generated during the highly eccentric phase of Triton's orbital evolution. Triton has one of the most puzzling surface features known on icy bodies, the "cantaloupe terrain." Quasi-circular shallow depressions with raised rims give the appearance of a cantaloupe rind. This terrain may result from diapirism and gravity-driven overturn due to an instability caused by more dense ices emplaced on less dense ice layers.

5 Structural mapping on planetary bodies

Tectonic landforms on planetary bodies beyond the Earth have been identified and analyzed using remote sensing data. By and large, the tectonic landforms discussed in this book have been characterized using images and topographic data obtained by spacecraft observations. The attributes of a dataset determine what scales and aspects of tectonic landforms can be identified and mapped. Tanaka *et al.* (Chapter 8) describe the principal datasets and methods utilized in the recognition and geologic mapping of tectonic landforms. Chapter 8 and the two that follow contain material that connects the previous chapters, providing a synthesis of concepts and processes common to planetary tectonics on any object in the solar system.

Planetary geologic mapping relies on spacecraft data and generally lacks ground truth. One of the cornerstones of planetary structural mapping is imaging. Spacecraft-borne imaging systems are usually designed to obtain images in the visible and infrared part of the electromagnetic spectrum. The spatial resolution and image quality are governed by the characteristics of the camera(s), the mission parameters, and the properties of the planetary target. Images recorded on film were replaced by digital images obtained by vidicon cameras. Charge-coupled device (CCD) cameras are the current standard for planetary imaging. Multiple images are combined into mosaics that can provide regional and even global-scale image maps. Essential to the identification and morphologic analysis of tectonic landforms is slope information, where brightness variations are related to the slope orientation and incident angle. Albedo variations of surface materials may also highlight tectonic landforms and aid in their geologic interpretation.

An important alternative to passive visible and infrared imaging is radar. Radar uses the microwave part of the spectrum and is capable of obtaining image and altimetry data independent of solar illumination or atmospheric density. Factors that influence radar return are surface slope, surface roughness, and the electrical properties of the surface materials. For objects in the solar system with dense, opaque (at visible wavelengths) atmospheres such as Venus and Titan, radar has been utilized to obtain images of their surfaces. The synthetic aperture radar (SAR) instrument on the Magellan spacecraft returned a global set of high-resolution images of the surface of Venus, revealing the planet's complexly deformed terrains.

Another of the cornerstones of planetary mapping is topography. Accurate characterization of the morphology and the structural relief of tectonic landforms are often impossible without topographic data. Topography is also critical to estimates of strain and in quantitatively evaluating kinematic and mechanical models for tectonic features (see Tanaka *et al.*, Chapter 8; and Schultz *et al.*, Chapter 10). As well as an important adjunct to imaging, topography has been used to identify and define the extents of tectonic landforms not clearly resolved in images. Topography of planetary bodies has been obtained from a variety of sources. Methods to derive topographic data from images includes shadow measurements, photoclinometry (shape from shading), and stereo imaging. Earth-based radar altimetry and radar interferometry are also an important independent source of topographic data. Finally, radar and laser altimeters on orbiting spacecraft have been used to obtain global topographic datasets.

Structural and tectonic maps are invaluable in deducing the tectonic evolution of a body. Combined with appropriate analysis techniques, such maps can provide insight into the timing of deformation, sources of stress, the mechanical properties of deformed materials, and the thermal and interior evolution of the body. Tanaka *et al.* (Chapter 8) review the major tectonic landforms identified and mapped on the terrestrial planets, the Moon, and the satellites of the outer planets.

6 Planetary lithospheres

The mechanical properties of a lithosphere have a major influence on the tectonic processes that shape it. As in the analysis of most planetary tectonic landforms, the understanding of planetary lithospheres is strongly dependent on the understanding of mechanical properties of Earth's lithosphere. This is informed primarily by experimental investigations of the properties of minerals and rocks at elevated temperatures and pressures. Recent experimental studies have focused on the question of the rock strength of other terrestrial planets and outer planet satellites. Kohlstedt and Mackwell (Chapter 9) review work on lithospheric mechanical properties of the planets Venus and Mars, along with Jupiter's moons Europa, Ganymede, and Io.

The exotic tectonic landforms on Europa and Ganymede are intimately related to the rheological properties of their water-ice crustal shells that likely overlie mantles of liquid water. These properties also determine the ability of an icy body to retain tectonic landforms. Deformation of ice, like other crystalline materials, occurs by diffusion of ions or diffusion creep and propagation along grain boundaries or dislocation creep. Modeling that incorporates dislocation creep, which is sensitive to grain size, predicts topography at wavelengths consistent with Ganymede's grooved terrain. Relaxation models for Ganymede suggest that crater topography can survive for billions of years, as observations suggest (Kohlstedt and Mackwell, Chapter 9).

Water, even in very small amounts, also has a major influence on the rheological properties of the silicate lithosphere of Earth. The influence of water or "water weakening" is likely all but absent, however, on some of the other terrestrial planets. The lithosphere of Venus, for example, is expected to be completely dehydrated because of the high surface temperatures and widespread volcanic activity (Kohlstedt and Mackwell, Chapter 9). The high strength of basaltic rocks under dry conditions means that most of the strength of Venus's lithosphere is in the crust. Such a strong crust is capable of supporting topography for periods of tens of millions of years. A low-strength contrast between the Venusian crust and mantle predicted by experimental work suggests that lithospheric deformation there is likely strongly coupled to mantle convection, unlike the Earth that has a wet, weak asthenosphere. Thus, regional- and global-scale tectonics on Venus may directly reflect mantle processes.

In contrast to Venus, an early wet Mars may have contributed to a lithosphere that was relatively weak. In addition, however, the Fe content of Martian mantle rocks is thought to be about twice that of Earth's mantle. Experimental data indicate that mantle strength decreases with increasing Fe content. Water-related weakening is also greater in Fe-rich rocks than in Fe-poor rocks. A weak early Martian mantle may have contributed to mantle dynamics controlled by stagnant-lid convection rather than plate tectonics (Kohlsted and Mackwell, Chapter 9). This would have resulted in interior heat loss through widespread volcanic activity and possibly through crustal delamination. The Tharsis volcanotectonic province and the crustal dichotomy may then be expressions of this stagnant-lid mode of interior cooling.

7 Planetary fault populations

The primary window into the state of stress in crustal materials of a planetary body, past and present, is its fault populations. Fault populations also express the magnitude of strain and reflect the mechanical properties and strength of the deformed rocks. The characteristics of faults, such as their length, height, displacement, and spacing are dependent on each other. Thus, knowledge of some of these characteristics can provide insight into the relationships of other characteristics and permit quantification of the fault-related deformation. Schultz *et al.* (Chapter 10) review the stress states in a planetary lithosphere, the characteristics of fault populations, the structural topography generated by faulting, and methods of determining strains from planetary fault populations.

The state of stress in the Earth's crust, as determined from *in situ* stress measurements, is generally compressive and controlled in magnitude by the frictional resistance of the fractured crust. Stress differences that are sufficiently greater than the lithostatic stress result in faulting. These values provide a basis for defining the stress states and failure criteria for the crusts and lithospheres of other planetary bodies.

Individual faults in a population can occur as isolated or linked structures in a wide range of sizes and geometrical configurations. Statistical analysis reveals a consistent scaling relationship between the maximum displacement and fault length. This relation describes, in part, how faults grow because displacement accumulates with lateral and/or down-dip growth of the fault (Schultz *et al.*, Chapter 10). The displacement–length (D/L) ratio describes the rate of displacement accumulation relative to the fault length. Analysis of multiple fault populations on the Earth and other terrestrial planets indicates that each population has a particular D/L ratio that is controlled by factors such as planetary gravity, lithology, and three-dimensional fault geometry.

Linkage of initially isolated faults is an important process in fault growth. As the faults grow and interact, shear stress around the relay zone increases, and transfer of displacement on the segments results in an increase in the displacement gradient at the ends of the faults. The interaction of fault segments can result in an increase of the D/L ratio by linkage of the temporarily over-displaced fault segments. After a period of fault displacement recovery, the resulting linked segmented fault can have the D/L ratio of single isolated faults. One of the exciting frontiers in the study of planetary fault populations is the recent identification of vertical restriction of faults on Mars by mechanical stratigraphy in the crust or lithosphere, which influences fault lengths, spacing, topography, and strain magnitudes in both space and time.

8 Conclusions

In this introduction to the chapters that follow, only a small number of the many and diverse aspects of planetary tectonics are highlighted. The planets, satellites, and small bodies of our solar system have a remarkable collection of tectonic landforms. Just as remarkable are the similarities and differences in the tectonics of bodies with silicate and non-silicate crusts. Water, whether enriched or absent in the crustal material of a terrestrial planet, or as the major constituent in the icy crust of an outer planet satellite, has an extraordinary influence on the style and magnitude of deformation. The sources of tectonic stresses are also remarkably diverse, arising from everything from interior heat loss, external tidal influences, or collisional interactions with other objects. We hope the following chapters will both inform and stimulate interest in planetary tectonics. Each chapter has been peer-reviewed and revised accordingly.