Chapter 6: **Surfaces of terrestrial objects: volcanism & other endogenic processes**

- basic rocks and minerals
- types of volcanism
- other endogenic processes that modify surfaces of planetary bodies
- sample questions

Basic rocks and minerals

Rocks are assemblages of minerals. Minerals are solids, often inorganic (i.e., not usually containing carbon), sometimes having an orderly crystalline structure, sometimes glassy or amorphous. Whether the minerals in a rock are crystals or glassy depends both on the chemistry of the particular molecule(s) in the mineral and on the rate at which it cooled; rapid cooling doesn't give the molecules time to line up neatly in a crystal lattice. Some minerals have a fixed molecular form – silica or quartz, for instance, is SiO_2. Others are variable, in the sense that one or more atoms or ions can fit into a given location in a crystal lattice. Feldspars, for instance, may be written as $(K,Na,Ca)AlSi_2O_8$, indicating that K, Na, and Ca can substitute for each other in the same location in an aluminum silicate. Farther out in the solar system, roughly beyond the asteroid belt, it's cold enough that molecules that on Earth would be gases or liquids – e.g., H_2O, CH_4 – will more likely form ices and in effect function as the rock-forming minerals.

Rocky / icy planetary bodies do not all start with exactly the same compositions; as one obvious distinction, objects farther out in the solar system are expected to be enriched in volatiles relative to inner solar system objects. That said, chondrites, the most primitive / least processed meteorites, give clues to the primordial composition of the terrestrial objects. Earth's mantle rock (predominantly peridotite, composed mostly of the minerals olivine and pyroxene) is close to chondritic in composition, with the exception that a substantial percentage of the iron and nickel have sunk to the core. The most abundant elements in the lithospheres of rocky bodies in our solar system are O, Si, Al, Fe, Ca, Na, K, and Mg.

Common minerals

Searching for minerals online will produce a plethora of images. One page with a nice collection of images of two dozen common minerals is the following: http://www.blinn.edu/STEM/Geology/faculty/Minerals_Web_Page/index.htm.

Ices. Water ice, H_2O, is the most abundant, found in the pole caps on Earth and Mars and dominating the surfaces of the moons of the outer solar system. Nitrogen is likely to be found as ammonia, NH_3, ice in the high cirrus in Jupiter's atmosphere or mixed with water ice in the interiors of Jovian moons. Farther out, e.g., on Triton or Pluto, we find N_2 ice. Carbon may be found attaching itself either to oxygen, as CO or CO_2, or to hydrogen, as in methane, CH_4. Titan's surface conditions are near the triple point for methane; without a protective atmosphere, though, methane surface ice should only be stable farther out, as in on Triton or Pluto (where it could be mixed with the nitrogen ice). Methane clathrate hydrate is a compound in which methane molecules are trapped (forming a "clathrate") in a crystalline form of water (the "hydrate" part of the name). On Earth it's stable at temperatures less than ~2 C, and is found in deep lake or ocean sediments or high-latitude shallow continental rocks. We expect to find both methane and ammonia trapped in water ice on many outer solar system moons. Pure water ice will be rock solid on Saturn's moons and more distant bodies. Adding salts or ammonia can depress the freezing point of water by as much as 100 K, making cryovolcanism possible in the outer solar system.

Silicates. Many of the rock-forming minerals in Earth's crust are silicates, built around the basic tetrahedral shape of SiO_4, i.e., a silicon bonded to four oxygens that form the points of the tetrahedron. In *quartz*, SiO_2, each oxygen atom is part of two tetrahedra, resulting in the Si:O ratio of 1:2. Quartz has a relatively low density, ~2.6 g/cm^3. It's one of the last minerals to crystallize from a cooling magma but because of its low density it is common on the surface of the Earth. Quartz, or silica, is a major constituent of sand, is important in modern microelectronics and in the glass in your windows, just a few among many applications. Quartz is not always clear – for example, radiation damage or impurities such as adding iron atoms can make it purple, producing what we call amethyst.

Feldspars, mentioned above, have densities of ~2.6 – 2.8 g/cm^3 and are the most common set of minerals in lunar and terrestrial surface rocks. Feldspars are a group of silicates containing aluminum and a combination of potassium, sodium, and calcium atoms. Orthoclase feldspars are the more potassium-rich minerals; the end member, i.e., the mineral with no sodium or calcium, has the formula $KAlSi_3O_8$. Plagioclase feldspars are the calcium- and sodium-rich members of the group, ranging from albite ($NaAlSi_3O_8$) to anorthite ($CaAl_2Si_2O_8$). With their relatively low densities it makes sense that feldspars would float to the surface of a magma and accumulate at the surfaces of terrestrial planets.

Pyroxenes tend to be a bit denser than feldspars, ranging from ~2.8 to ~3.7 g/cm^3. In pyroxenes the silicon-oxygen tetrahedra are chained together such that each set of one silicon plus four oxygens shares two of its oxygens with another group, with the result that the ratio of Si:O is 1:3. The pyroxenes have the general form $XY(Si,Al)_2O_6$, where X and Y represent various possible metal ions, such as Ca, Na, Fe, Mg, Al, and Ti. The most abundant pyroxenes in Earth's crust have the form $(Ca,Na)(Mg,Fe,Al,Ti)(SiAl)_2O_6$, broadly called augite. Pyroxenes are also found in meteorites. The magnesium end member of the pyroxene group, $MgSiO_3$, is enstatite, found in a rare class of meteorites and possibly identified on the surfaces of asteroids 16 Psyche and 21 Lutetia.

Two groups of silicates that are slightly less dense than pyroxenes are *micas* and *amphiboles*. Micas form in sheets and tend to flake easily. In amphiboles the silicate tetrahedra form double chains, resulting in crystals with needle-like or prism-like shapes. Both micas and amphiboles show up in igneous and metamorphic rocks (described below) and both make up several percent of Earth's crustal minerals.

Olivine, $(Mg,Fe)_2SiO_4$, is denser, roughly 3.3 – 4.4 g/cm^3, meaning that it will tend to sink in a magma. Olivine is abundant in Earth's mantle, and, we presume, in the mantles of other rocky planetary bodies. It is present in meteorites and lunar samples. Olivine is often greenish, and in gem quality is called peridot.

Hydrous aluminum silicates are *clays*, found in eroded sediments on Earth and Mars. Clay minerals also show up in the spectra of the surfaces of Ceres and some of the more distant asteroids.

Carbon and carbonates. On Earth, elemental carbon is typically found either as graphite or, after having been subjected to high pressure, as diamond. Carbonates are composed of molecules containing CO_3 and on Earth are typically found in sedimentary rocks (more below). Many marine organisms form shells of $CaCO_3$; when these creatures die, their shells contribute to the sediments collecting on the ocean floors. In the outer solar system we often find objects with dark, slightly reddish surfaces. Solar ultraviolet radiation makes organic molecules such as methane or ethane (C_2H_6) break apart and reform into gooey darker molecules collectively called *tholins*, which seem to be responsible for the dark brown-red surfaces of these outer solar system objects.

Iron Oxides. Although iron oxides may be gray or brown rather than reddish, one reason Mars is reddish is because it is literally rusty, with the surface rocks containing a noticeable fraction *magnetite* (Fe_3O_4). Magnetite is also found in lunar rocks and some meteorites. *Hematite* (Fe_2O_3) can be either gray or reddish and on Earth is often formed in association with water. The fact that we've found hematite on Mars, often in small spheres, suggests that there was standing water on Mars when the hematite formed.

Sulfur. Several commonly occurring minerals contain sulfur. Elemental sulfur and sulfur dioxide (SO_2) provide the garish range of yellows on the surface of Io. On Earth we find $CaSO_4$, both with and without attached water molecules. (Gypsum is $CaSO_4{\cdot}2H_2O$; anhydrite is $CaSO_4$, no water.) Common sulfides are often relatively heavy: PbS (galena, density ~7.6 g/cm^3), FeS_2 (pyrite, ~5 g/cm^3), $CuFeS_2$ (chalcopyrite, ~4.2 g/cm^3), and FeS (troilite, ~4.6 g/cm^3). Troilite is found in meteorites and may be present in predominantly iron-nickel planetary cores, acting to lower their overall density – elemental iron has a density of ~7.8 g/cm^3 and nickel ~8.9 g/cm^3, so the addition of some sulfur would lower the core density.

Halides. Halides generally means molecules containing a halogen atom, something from that penultimate column in the periodic table. Two that in particular would count as minerals are halite or common salt (NaCl) and fluorite (CaF_2). Fluorite in its clear form is useful for lenses because it doesn't exhibit much chromatic aberration and because it will transmit more IR and UV than regular glass. Fluorite often includes other atoms as impurities that give it a broad range of colors.

Rocks and rock types

Rocks are typically divided into three types indicating the nature of their formation. *Igneous* rocks form from the cooling of molten magma. Little bits and pieces of rock often get deposited as sediment, e.g., sinking to the bottom of a lake or sea. Applying enough pressure to cement these bits together produces *sedimentary* rock. Rock that's been subjected to high pressure and / or high temperature and / or new chemicals may be modified from a prior form, producing *metamorphic* rock. In addition to some of the images below, the "Rock Library" at http://mars.nasa.gov/mer/classroom/schoolhouse/rocklibrary/ has many good images of various rock samples.

Igneous rock. What sort of rock we get from a molten magma depends on the composition of the original melt and how quickly it cools. One principal distinction is whether the magma cools and solidifies underground or erupts onto the surface as lava. If it cools underground it's called *intrusive* or plutonic. Intrusive rocks are likely to cool relatively slowly, resulting in the formation of larger crystals and an overall coarse-grained appearance for the rock, which we can then see when subsequent erosion of overlying layers exposes the now-solid intrusive rock to the surface and to our examination. *Extrusive,* volcanic, rocks erupted as fluid lava and cooled after arriving on the surface. Rapid cooling produces smaller crystals and a fine-grained appearance. Very fast cooling can produce a rock with no crystals at all, effectively a glass; obsidian is an example of extrusive rock that cooled very rapidly. Readers who are familiar with the Pacific Northwest may have noticed the general sorts of rocks on, for instance, the east slopes of the Cascade Range or the eastern Columbia River gorge. Much of the rock that makes up the Cascades (not counting the volcanoes) is intrusive and coarse-grained granite is common. The Columbia River gorge cuts through flood basalts and the rock is typically darker and fine-grained. The following two images are typical examples of granite and basalt.

Figure 6.1: Granite
http://mars.nasa.gov/mer/classroom/schoolhouse/rocklibrary/source/biotite_hornblende_granite.html

Figure 6.2: Basalt
http://mars.nasa.gov/mer/classroom/schoolhouse/rocklibrary/source/basalt.html

Let's get into a bit more detail. Igneous rocks don't all contain the same proportion of silicates. Those with relatively more silicates tend to be lighter in color and less dense and generally called granitic.

Darker, denser, lower-silicate rocks are generally called basaltic. Granitic and basaltic refers to general classes of rocks, not just granite and basalt themselves. The dark lunar maria are basalts. *Gabbro* is a typical intrusive rock with a composition similar to basalt. Gabbros are found, for instance, in the lunar highlands. *Rhyolite* is a typical extrusive rock with a composition similar to granite and is often a product of highly explosive volcanic eruptions. Plutonic *diorite* and volcanic *andesite* are intermediate in silica content. *Ultramafic* rocks, high in olivine, are less common on Earth's crust today than they might have been earlier in Earth's history. Here's a table showing these rock types.

Igneous rock types	Felsic, high SiO_2, light-colored	intermediate	Mafic, high Mg, Fe, dark-colored	Ultra-mafic, most dense
Intrusive, plutonic, coarse-grained	Granite	Diorite	Gabbro	Peridotite
Extrusive, volcanic, fine-grained	Rhyolite	Andesite	Basalt	Komatiite

Granitic rocks, with their concentrations of lightweight silicates (especially quartz and feldspar) are formed after repeated meltings. Different minerals solidify at different temperatures and low-density minerals will float to the surface of a melt, but it may normally take more than one melting to produce granitic rocks. In the process of terrestrial plate tectonics, surface rocks are subducted, melted, and chemically fractionated. Without plate tectonics we don't expect to see on other planets anything like the huge provinces of granitic rocks that make up the continental crust on Earth.

Minerals with higher proportions of iron and magnesium and calcium (i.e., mafic) are among the first to crystallize from a cooling magma. Quartz and other minerals high in silicon, sodium, aluminum, and potassium are among the last. The Bowen reaction series, based on work by petrologist Norman Bowen in the 1910s and 20s, shows the sequences of which minerals crystallize at what temperatures, as in this figure:

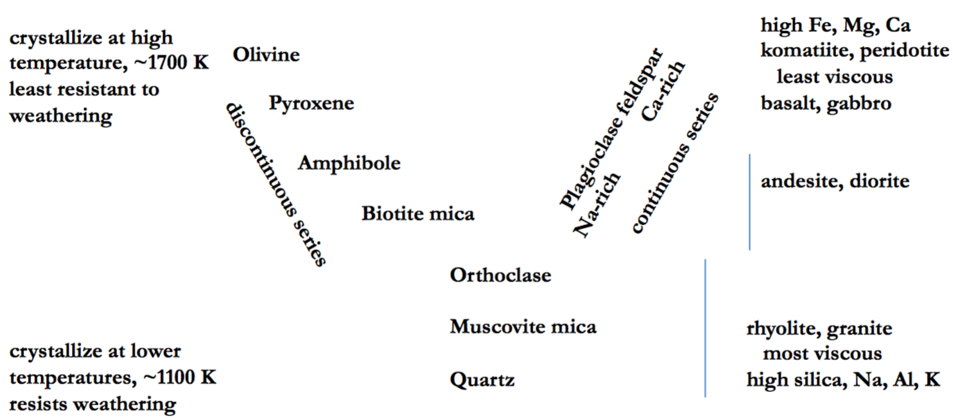


Figure 6.3: Bowen reaction series

Imagine starting with a magma of roughly upper mantle – peridotite – composition. As it begins to cool, the first minerals to crystallize will be olivine and anorthite (Ca-rich feldspar). There are now three possibilities. First, the magma could erupt volcanically and we'd have an ultramafic lava. Komatiites, named after a river in South Africa, are ultramafic, high-olivine rock that erupted on Earth as very hot, very fluid lavas a very long time ago, in most cases over 3 billion years ago when the Earth's mantle was hotter than today. A second possibility is that, lacking an eruption, the crystals could stay in suspension in the melt, interacting chemically with the rest of the melt, and with the olivine, in particular, getting converted into pyroxenes. An eruption at this point produces normal basalt; if it cools underground, we have a gabbro. But crystals such as olivine are heavier than the surrounding melt and likely to sink – fractionate –

so the third possibility is that the first crystals to form separate from the remaining melt and that the melt, now with a slightly different composition, continues to cool and more felsic minerals will crystallize.

Erupting magma varies in viscosity in proportion to the temperature and silica content of the magma. Hot, very low viscosity komatiitic lavas are capable of flowing long distances and it's possible that the *sinuous rilles* on the surface of the Moon, which look as though they were carved by rivers, may have been carved out by komatiite lava flows. Terrestrial basaltic lavas are several tens of thousands of times more viscous than water; rhyolitic lavas can be several tens of millions of times more viscous than water.

In the case of cryovolcanism, the magma is ice. As noted above, ice here doesn't mean pure water ice but any icy mix of water, ammonia, salts, etc., which has a lower freezing point than pure water. If you have made ice cream in an old-fashioned churn or have put salt on an icy sidewalk you are probably already familiar with the concept of salt lowering the freezing point of water. Consider a mixture of two substances, such as water and salt, in which we may vary the percentage of each of the two constituents. There will be an optimum composition at which the freezing point will be the lowest possible. Add too little salt to your water ice and you won't melt all the water ice; add too much salt, and you will already have melted the water and have excess chunks of salt. The *eutectic point* is that optimal point at which the freezing temperature is the lowest. The following sketch shows the eutectic point for a generic mix of two components, 1 and 2, which could be water and salt or two rocky minerals or two types of nickel-iron crystals; there are many planetary applications for this concept.

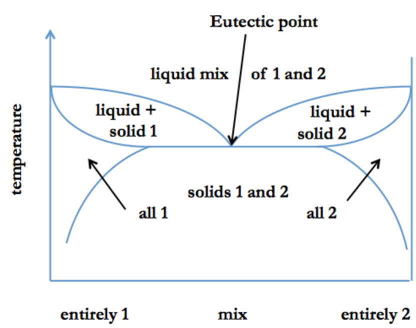


Figure 6.4: Eutectic point

A water-salt mix of about 23% salt will have a freezing point that's ~20 °C lower than the freezing point of pure water.

Partial melting of a water-salt-ammonia mix, i.e., the mantle "rock" of an icy outer solar system object, will produce both some fractionation as water ice crystals freeze out and a magma that's enriched in ammonia. This is similar to a mantle peridotite partially melting and producing some olivine crystals and a basaltic lava.

There are two additional processes responsible for partially melting mantle rock to produce magma beyond what we considered in our discussion of interiors and the heat needed to differentiate an object. First, note that solid-state convection happens in the mantle. What this means is that rock that is close to but not quite melted can be low enough viscosity to move, or that some components of the rock are melted and can move through the cracks of the more solid bits. As a mass of warm mantle material rises it experiences less and less pressure. At some point *decompression melting,* i.e., a phase change, happens. Deeper down, under more pressure, the material was more likely to be solid; less pressure, less likely to be solid. In other words, we don't need to add heat to produce magma – it will suffice to reduce pressure.

On Earth another important process is hydration-induced melting. At a subduction zone one tectonic plate sinks beneath another, carrying with it the sediments that have accumulated at the plate boundary. Those sediments are often rich in water and other volatiles. At depth, that water is squeezed out of the hydrated minerals, interacts with the surrounding mantle rock and proceeds to lower the melting point of the whole assemblage of rock enough to contribute significantly to the production of magma.

Magma also rises in plumes of hot rock from deep in the mantle. Volcanically active hot spots on Earth, such as the one that underlies the south-east end of the Hawaiian island chain (as well as many other volcanic islands in the Atlantic and south Pacific oceans), seem to sit atop deep-rooted plumes that some geophysicists argue rise from the very base of the mantle. As a non-terrestrial example, Olympus Mons may be sitting atop the Martian equivalent of a deep mantle plume.

Sedimentary rock. At the surface of a planetary body rock will interact with such gases and fluids as may be present and the surface rocks experience weathering and erosion. Mechanically, rocks may be abraded by wind-blown sand or water or micrometeorite impacts. Rocks may experience seasonal effects; e.g., on Earth, water may seep into cracks in warm weather and then freeze and expand in the winter, leading to larger cracks. Small grains are carried off, mostly downslope, by wind and water, aided by gravity. Additional weathering happens chemically. On Earth, for instance, carbon and water interact in our atmosphere to form a weak carbonic acid, which falls to the surface when it rains. The carbonic acid contributes to dissolving the rock. Streams and rivers carry ions – e.g., of Ca, Mg, K, Na – to the ocean. Once in the ocean the calcium in particular will combine with dissolved carbonate to form the calcium carbonate shells of corals, barnacles, and other such organisms, which, once they die, will sink to the seafloor.

Bits and pieces of rock are tumbled and broken and transported downstream by rivers, grains of sand are blown across the desert, shells sink to the bottom of the ocean. If this sediment is cemented together new rock forms. *Evaporites* form when the liquid carrying solid bits evaporates. On Earth, moving water may have picked up salts, the water reaches the end of its journey, stagnates, evaporates, and the salts are left behind. This process seems to have happened on Mars, also, increasing the evidence that Mars once had much more liquid surface water than it does today. *Shale* and *sandstone* are sedimentary rocks composed of fine and coarse grains, respectively. On Earth the grains are rounded, indicative of time spent being tumbled and abraded as the grains were carried by wind or water. The following images illustrate a sandstone and a finer-grained shale.

Figure 6.5: Sandstone
http://mars.nasa.gov/mer/classroom/schoolhouse/rocklibrary/source/gray_sandstone.html

Figure 6.6: Shale
http://mars.nasa.gov/mer/classroom/schoolhouse/rocklibrary/source/oil_shale.html

Grain sizes may or may not be uniform. The Spokane-Missoula (or Bretz) floods swept across eastern Washington at the end of the last ice age as ice dams near Missoula ruptured, emptying massive glacial lakes down the Columbia River. The floodwaters backed up tributaries, stalled there, and dropped their loads of sediment. Larger rocks settle first and finer sediments later, resulting in graded beds rather than single beds of uniform grain size. Each layer in the Touchet beds, exposed near Walla Walla, represents an individual flood:

Figure 6.7: Touchet beds; photo by AKD.

Loose sediment in moving water may get pushed by currents into ripples or waves of sand. When that sediment consolidates it may retain the record of its watery formation as layers in the rock. The top of these sediment layers may be slightly eroded and more waves of sediment subsequently deposited in new layers, possibly at an angle to the first layers. Images from the Mars Curiosity rover show this sort of cross-bedding on Mars. The following image was taken in 2014 of a sedimentary rock the Curiosity team informally nicknamed "Whale Rock":

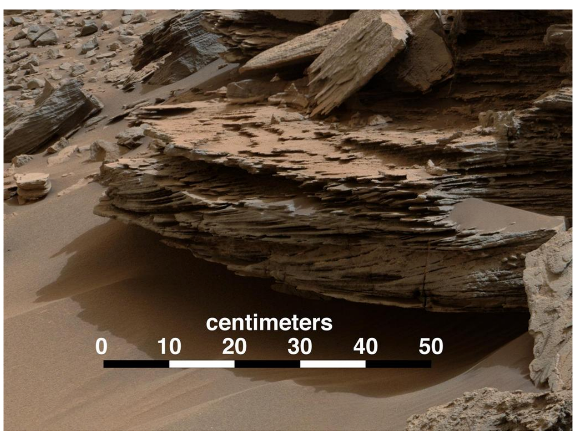


Figure 6.8: Cross-bedding at "Whale Rock"

http://mars.nasa.gov/msl/multimedia/images/?ImageID=6871
NASA / JPL / Malin Space Science Systems

Metamorphic rock. Various processes may act to alter a rock without necessarily totally remelting it. The rock may be buried and subjected to high pressure or to heat, either of which could change the phase of its constituent minerals. Rocks may also be modified chemically, e.g., by exposure to subterranean water. Exposure to hot magma, e.g., could induce both thermal and chemical changes. Rocks that are produced by these processes that act to change the crystal structure and / or composition, and then subsequently exposed by erosion or tectonism for us to examine, are called metamorphic rocks. Some examples: quartzite started out as sandstone, slate was originally shale, and marble began its life as limestone ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$):

Figure 6.9: Dolomitic limestone

http://mars.nasa.gov/mer/classroom/schoolhouse/rocklibrary/source/dolomitic_limestone.html

Figure 6.10: Dolomite marble

http://mars.nasa.gov/mer/classroom/schoolhouse/rocklibrary/source/dolomite_marble.html

As another example, a biotite granite + pressure could become a biotite gneiss:

Figure 6.11: Granite

http://mars.nasa.gov/mer/classroom/schoolhouse/rocklibrary/source/biotite_granite.html

Figure 6.12: Gneiss

http://mars.nasa.gov/mer/classroom/schoolhouse/rocklibrary/source/biotite_gneiss.html

Types of volcanism

Volcanism on Earth ranges from effusive, for example lava oozing out of vents on Mt. Etna or Kilauea, to explosive, for example Mt. St. Helens hurling ash and other *pyroclastic* materials high into the air and, at the extreme end of the scale, the eruptions of Toba, in Sumatra (~75,000 years ago) and Yellowstone (~640,000 years ago being the most recent). Here is an image of lava flowing down the sides of a cone called Pu`u `O`o on the southern side of Kilauea in 1986 and, on the right, an image from Mt. St. Helens' 1980 eruption.

Figure 6.13: Pu`u `O`o eruption; photo by J.D. Griggs.
http://hvo.wr.usgs.gov/hazards/dds24167_photocaption.html

Figure 6.14: Mount St. Helens, Oman/Combs, May 18 1980.
http://www.nps.gov/features/yell/slidefile/geology/volcanicsigneous/Images/10485.jpg

A number of highly destructive natural disasters are associated with explosive pyroclastic eruptions. The bronze age Minoan town of Akrotiri was destroyed by the explosion of the volcanic island of Thera (or Santorini) in the Aegean Sea in approximately 1627 B.C.E. Archaeological excavations into the thick volcanic debris have revealed a city with sophisticated frescoes, paved streets, three-story buildings, and an advanced drainage system. It has been suggested that this city's destruction might be linked to the legends of a lost city of Atlantis. The image below left is a satellite view down into the collapsed caldera. The right image shows layers of ash and lava along the caldera walls.

Figure 6.15: Santorini, Greece
ASTER Science team
http://visibleearth.nasa.gov/view.php?id=55717

Figure 6.16: Santorini; Dimitris Sakellariou, Hellenic Center for Marine Research
http://oceanexplorer.noaa.gov/explorations/06greece/background/geology/media/santorini_caldera_wall.html

Explosive rhyolite eruptions can send huge quantities of ash high into the air. They can also create pyroclastic flows, where the hot pulverized erupting material and entrained boulders is so dense that it flows along the ground like a fluid. The 1902 eruption of Mount Pelée, on the island of Martinique, sent pyroclastic flows surging down the volcano's sides, overwhelming the city of Saint-Pierre. Estimates are that the flow moved through the town at ~150 m/s. Nearly all of the 29,000-plus residents died.

Fluid basalt lava flows are certainly capable of doing damage as well. Lava from Kilauea destroyed many roads and structures in 2018.

The image at the left shows lava from Kilauea swallowing a road in May 2018; a lava fountain is visible in the background.

Very fluid, ropy, lava flows such as this are known as pāhoehoe. Pāhoehoe flows erupt at ~1,100 – 1,200 °C. Lava flows that are ~100 degrees cooler and more viscous are fragmented and clinkery and called ʻaʻā.

Figure 6.17: 2018 Kilauea eruption; U.S Geological Survey https://volcanoes.usgs.gov/volcanoes/kilauea/kilauea_multimedia_15.html

Figure 6.18: An ʻaʻā flow plowing its way over an earlier pāhoehoe flow on Kilauea.

https://volcanoes.usgs.gov/vsc/glossary/aa.html

Lava flows can develop a relatively cool, somewhat flexible, insulating crust. Beneath the crust the lava stays molten and can flow for long distances. If the flow is fairly narrow a lava tube may develop. If the eruption stops and the tube empties out, we're left with a long cave or, if the roof subsequently collapses, possibly a rille.

Figure 6.19: Here, the roof of an active lava tube on Kilauea has partially collapsed. The volcanologists in the image were making measurements to estimate the rate of lava flow.

Below is a small collapsed lava tube near Bend, Oregon.

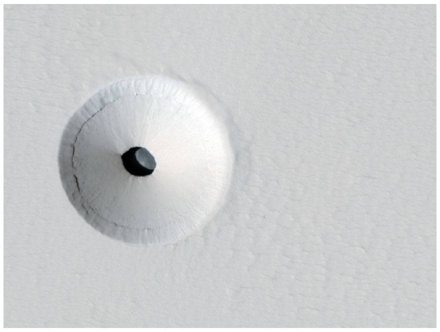
Kilauea lava tube photo 21 October 1970.
https://volcanoes.usgs.gov/volcanoes/kilauea/kilauea_gallery_53.html

Figure 6.20: Small lava tube near Lava Lands Visitor Center, Bend Oregon.
Photo by AKD.

Figure 6.21:
Hadley rille, visited by the Apollo 15 astronauts, may be a collapsed lava tube.

https://www.hq.nasa.gov/alsj/a15/AS15-85-11449.jpg

There are features on other terrestrial bodies that may also be indicative of collapsed lava tubes or surfaces having collapsed at the top of now-drained magma chambers. Here, for instance, is a pit crater on Mars. The central hole is about 35 meters in diameter and the cave below it must be at least 20 m deep,



based on the Sun angle and the shadows. It lies on the flanks of one of Mars' volcanoes, Pavonis Mons.

Figure 6.22: Pit crater on Mars
NASA / Mars Reconnaissance Orbiter
http://apod.nasa.gov/apod/ap120718.html

How far lava can flow depends both on how fluid the lava is, i.e., temperature and composition, and how much gravity it's experiencing, both in terms of the steepness of the slope at the eruption site and the gravitational acceleration of the particular planet or moon. The longest active lava flow known is on Io. In the following image the flow named Maui extends to the right for ~250 km. Amirani, the flow heading north / up is even longer, at ~330 km. In this Galileo spacecraft image you can also see a whiteish oval of sulfur dioxide frost around the main vent. Infrared observations show multiple, changing, hotspots along these flows, showing that this is an active eruption site.

Figure 6.23: Amirani – Maui flows on Io – Galileo spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA02506

Hot, fast-moving lava flows can create valleys with features that resemble those formed by water erosion on Earth. Here's an example from Mercury.

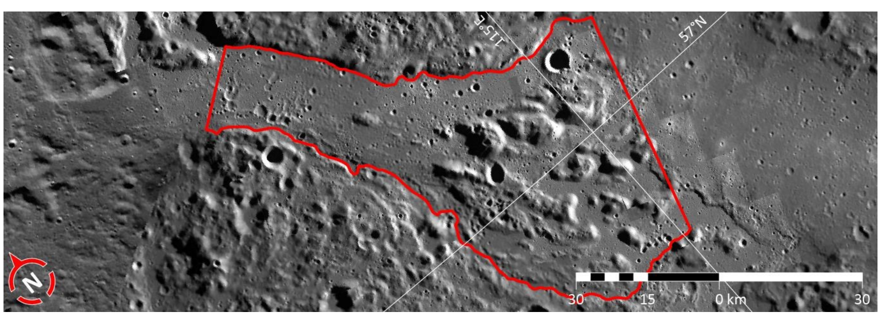


Figure 6.24: Angkor Vallis – MESSENGER spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA17026

A lava flow that develops a flexible crust may inflate in thickness, possibly to a thickness of many meters. That propensity to inflate and insulate the hot lava inside the crust, coupled with large eruption rates, may help explain the immense flows of the continental flood basalts such as the Columbia River basalts, which erupted in more than 350 individual flows primarily from ~16.7 to 15.6 million years ago.

Figure 6.25: Basalt flows near the Spalding, Idaho, Nez Perce National Historical Park Visitors' Center.

Photo by AKD.

The Columbia Basin basalt eruptions may have been fed by the mantle hot spot now lying below Yellowstone National Park. The basalts cover more than 200,000 km^2, as shown in the following USGS map:

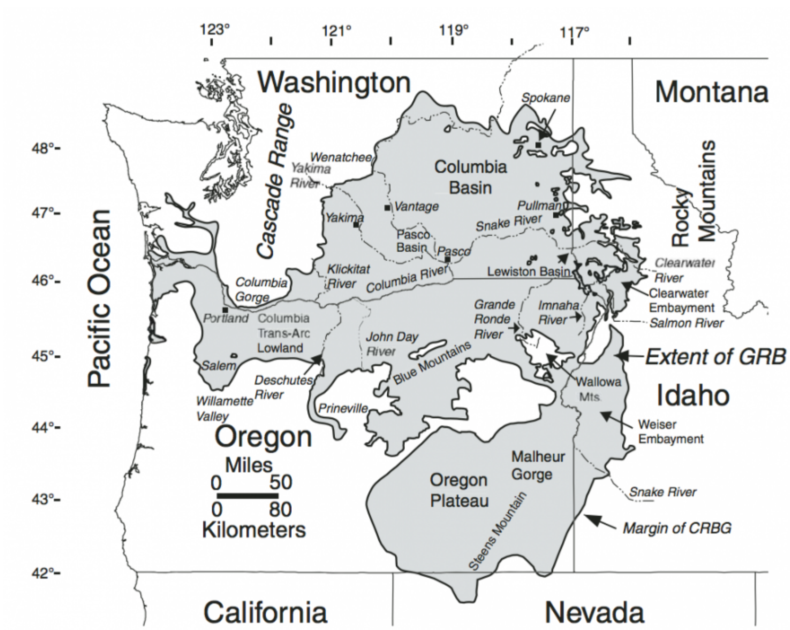


Figure 6.26: Extent of the Columbia Basin basalts

http://volcanoes.usgs.gov/observatories/cvo/cvo_columbia_river_basalt.html
Barry et al. 2013; USGS

The motion of the hotspot, or, the motion of the North American plate across the top of the hotspot, more recently can be traced in the ages of the eruptions of lava it left behind. The following shows the approximate location of the hotspot over the last 15 million years. The path of the Snake River follows the hotspot trail for approximately the past 10 million years. The hotspot now sits under Yellowstone, where we see evidence of a mix of super-sized explosive eruptions and less violent effusive and explosive eruptions over the past two million years. The geysers, hot springs, and burbling mud pots of Yellowstone National Park are indicators of the hot magma lying below.

Figure 6.27: Yellowstone hotspot locations in millions of years before present.

Underlying imagery from NASA GSFC / LaRC / JPL MISR Team.
http://eoimages.gsfc.nasa.gov/images/imagerecords/4000/4597/

PIA04361_lrg.jpg

Volcanic eruptions can create a wide range of structures. *Shield volcanoes*, such as those in Hawaii, are built by repeated fluid eruptions. The low-viscosity lava can travel considerable distances and build up gently sloping mountains. The following image is a map of the island of Hawaii, looking toward the northwest. Kilauea is the several eruptions in the foreground (multiple eruptions don't tend to happen all at once); Mauna Loa is on the left, below Hualalai, and Mauna Kea upper right, below Kohala.

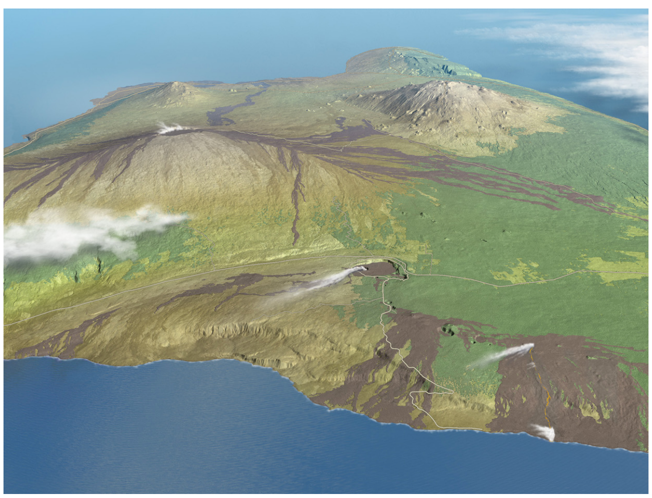


Figure 6.28: Hawaiian shield volcanoes

http://www.nps.gov/hfc/carto/wallpapers/InsetStandard/hawaii_volcanoes_1920x1440_I.jpg

Olympus Mons, on Mars, is a shield volcano. The base diameter is ~624 km; the scarp (cliffs) around the lower edge are 6 km high.

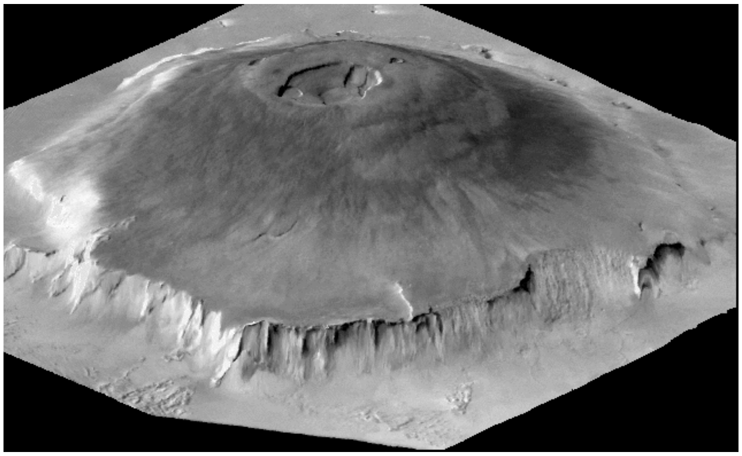
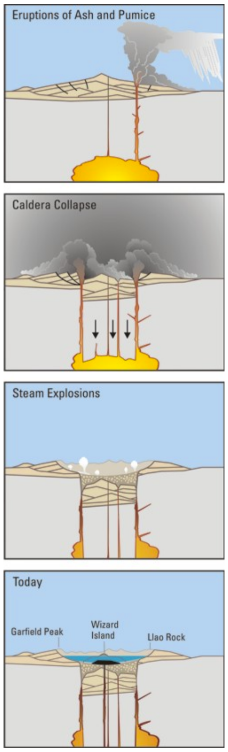


Figure 6.29: Olympus Mons
http://mars.jpl.nasa.gov/gallery/atlas/images/3dom.jpg

Stratovolcanoes, or composite volcanoes, are, as their name suggests, built up of many layers, or strata. The mountains are built of layers of both effusive and explosive eruptions. They tend to be steeper than shield volcanoes, at least near the vents, and may have calderas, formed when a magma chamber empties and the top of the volcano collapses. Mount St. Helens is a stratovolcano. Crater Lake, in Oregon's Cascades, fills the collapsed caldera at the top of Mount Mazama. Mount Mazama last erupted approximately 7,700 years ago. Wizard Island, in Crater Lake, is a *cinder cone* that formed after the formation of the caldera. Similarly, there's a dome continuing to build in the crater at the top of Mount St. Helens. The following three images are of Crater Lake. The first image shows the lake and cinder cone that is Wizard Island. On the left in the second panel is a USGS illustration of the likely steps in the formation of Crater Lake and on the right a map of the caldera.

Figure 6.30: Crater Lake with the Wizard Island cinder cone. Photo by AKD.



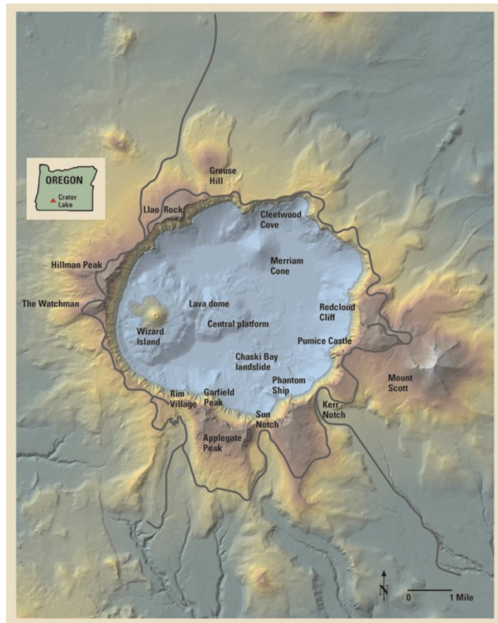


Figure 6.31 a): Crater Lake / Mount Mazama history; b) current topography
http://pubs.usgs.gov/fs/2002/fs092-02/

Here are images of Mount St. Helens before its 1980 eruption and of the growing lava domes in the crater at the top. The dome in the foreground formed in the immediate aftermath of the 1980 eruption; the volcano was quite for nearly 20 years and reawakened in 2004, creating the newer dome in the middle of the image. In November 2004 the rock labeled "whaleback" was moving at ~35 feet per day.

Figure 6.32: Mount St Helens, 1980
https://volcanoes.usgs.gov/volcanoes/st_helens/st_helens_gallery_23.html

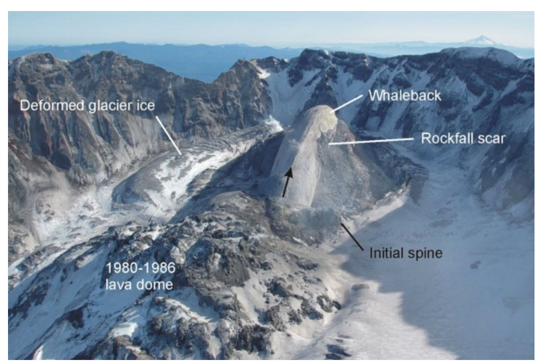


Figure 6.33: Mount St. Helens crater, Feb. 2005.
http://pubs.usgs.gov/fs/2005/3036/fs2005-3036.html

Think back to the interiors chapter for a moment: the state of Hawaii is moving across the top of a mantle hotspot; the active Cascade range volcanoes parallel the edge of the subducting Juan de Fuca plate. Different types of volcanoes result.

Math note: How high can a volcano be expected to grow? Here is a sketch of a volcano with a magma chamber below:

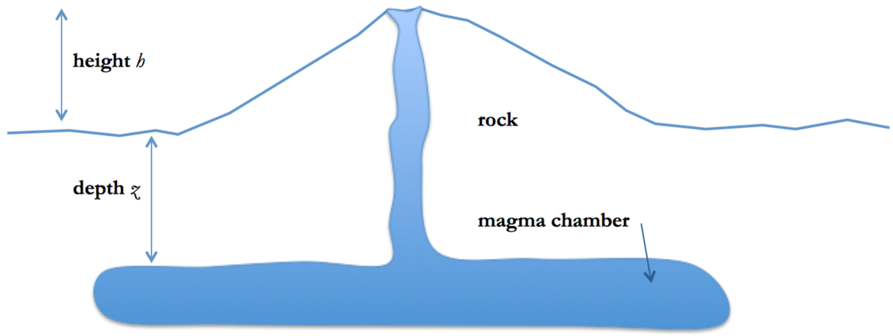


Figure 6.34: Volcano height

The overlying layers of rock are exerting pressure on the magma in the chamber. The magma can rise no higher than the level at which the pressure on the magma chamber equals the pressure at that depth due to the weight of the column of magma. At that point we have achieved hydrostatic equilibrium. Let z be the depth of the magma chamber and h be the maximum height of the volcano. The rock has a density ρ_{rock} which we assume is larger than the density of the magma, ρ_{magma}. The pressures at the depth of the magma chamber are due to the force of gravity per unit area acting on the mass of rock and of magma:

$$P = \rho_{magma}\, g\, (z+h) = \rho_{rock}\, g\, z,$$

where g is the appropriate gravitational acceleration for the terrestrial object in question. Solve for the height:

$$h = \frac{\rho_{rock} - \rho_{magma}}{\rho_{magma}} \cdot z = \frac{\Delta\rho}{\rho_{magma}} \cdot z.$$

Lunar magmas don't have many volatiles and so might not be very different in density from the average density of the surrounding rock, perhaps with a density of ~2.96 g/cm^3 compared with a rock density of ~3.0 g/cm^3. At the end of the Late Heavy Bombardment (about 3.8 billion years ago; more on that in the cratering chapter), i.e., at a time when a volcano might form and not subsequently get obliterated by impacts, a lunar magma chamber might have been 150 km deep. That would give a volcano height of

$$h = (0.04 / 3) \cdot 150 \text{ km} = 2 \text{ km},$$

meaning that it's not unreasonable for us not to see tall lunar volcanoes.

Some magma chambers don't succeed in producing mountains but erupt into low disks, forming features such as those called "pancake domes" on Venus. The following image is a three-dimensional rendering of radar images of pancake domes in an area called Alpha Regio on Venus. The domes are ~25 km across and only ~750 m high.

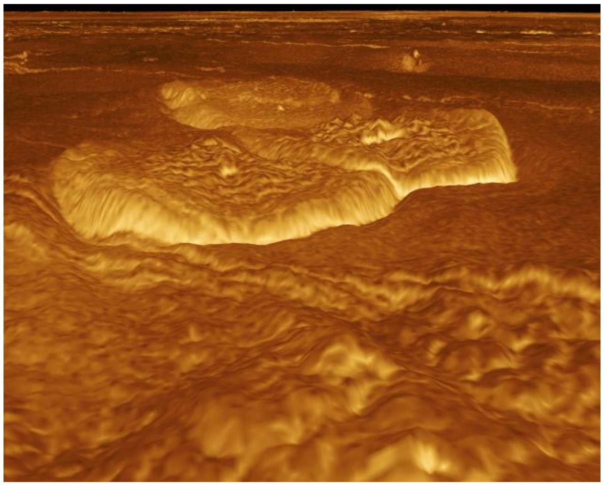


Figure 6.35: Pancake domes on Venus / Magellan http://photojournal.jpl.nasa.gov/catalog/PIA00246

Ahuna Mons, a 4-ish km-high mountain on Ceres, is only lightly cratered, suggesting that it's a young feature, perhaps only a few hundred million years old. Its slopes are streaked with high-albedo material that appear to be salts. This feature, discovered in images taken by the Dawn spacecraft, might have been created in a cryvolcanic eruption of muddy salty water.

It's tough to see through Titan's hazy atmosphere but there are features on its frigid surface that certainly resemble volcanoes. The following is a false-color infrared image of Titan showing in the inset a structure that appears, at least possibly, to be a cryovolcano. Here the lava would be an icy mix, likely of water and ammonia. Much farther out and much much colder, there are also at least two lightly cratered features on Pluto whose age and shape also suggest cryovolcanic origins.

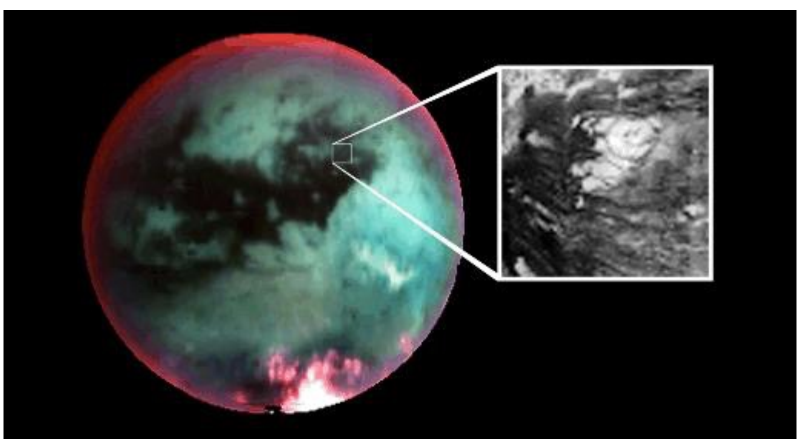


Figure 6.36: Titan cryovolcanism. NASA / Cassini spacecraft
https://photojournal.jpl.nasa.gov/catalog/PIA07965

There is less ambiguity about volcanic activity on Io. In the following image we see a depression ~100 km long which looks as if the crust collapsed above a now-empty magma chamber. On the right is a shield volcano sitting next to bright high-sulfur lava flows from a vent just to the west / left of the shield volcano. Infrared observations show that these lava flows are active, although not as hot as silicate lavas would be.

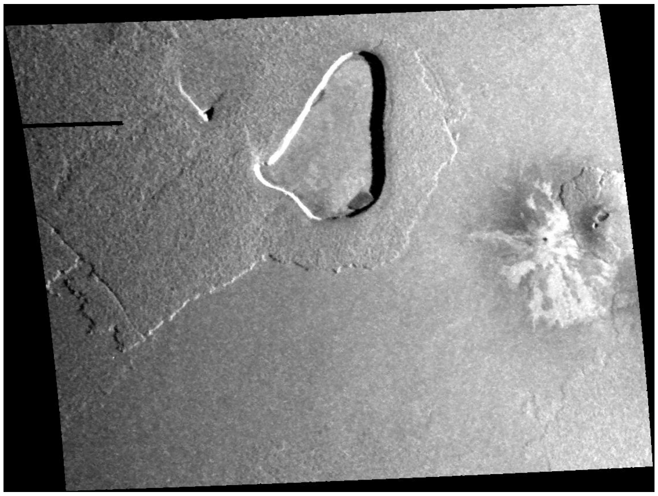


Figure 6.37: Volcanic depression and shield volcano on Io. NASA / Galileo spacecraft.
http://photojournal.jpl.nasa.gov/catalog/PIA03532

The region near Io's north pole named Tvashtar provides an example of hotter eruptions. Note that in the left-hand image the caption says "fire fountain sketch". That's because the lava was so hot (~1150 K) and bright that it saturated the camera and NASA artists filled in the orange color based on other images.

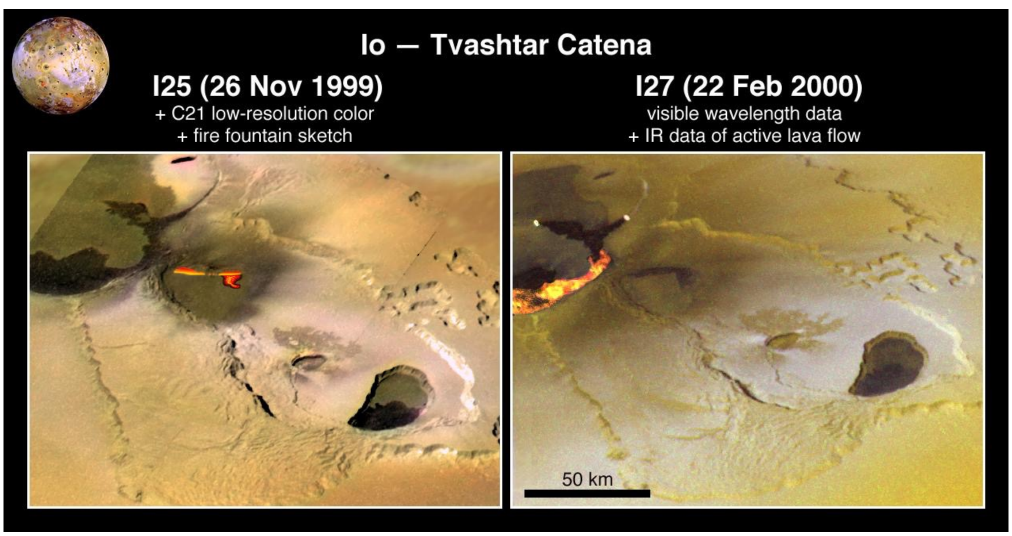


Figure 6.38; NASA / Galileo spacecraft.
http://photojournal.jpl.nasa.gov/catalog/PIA02584

Some of the more explosive eruptions on Io create plumes of material that rise over 100 km in Io's low gravity. The following shows two plumes that were actively erupting when the Galileo spacecraft captured this image. The plume on the limb is called Pillan Patera and seems to be relatively new. It crested out at ~140 km altitude. Near the terminator we are looking down on Prometheus, a volcano that's been consistently erupting since at least 1979; the red is the shadow cast by its erupting plume.

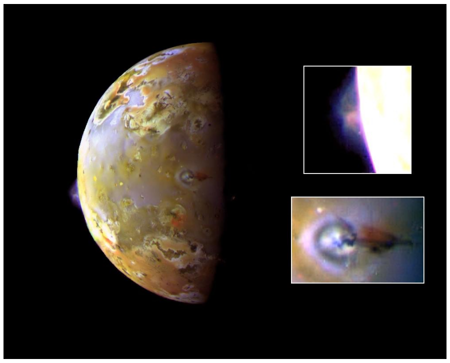


Figure 6.39: Volcanic plumes on Io. NASA / Galileo spacecraft.
http://photojournal.jpl.nasa.gov/catalog/PIA00703

As on Earth, Io exhibits eruptions that are more effusive and eruptions that are more explosive, although plumes and flows are not mutually exclusive – Prometheus, for example, has plume eruptions but its output is dominated by flows.

Geysers, or hydrothermal eruptions, on Earth tend to occur near active volcanic regions, which makes sense because hot magma is a source of energy to heat the water that the geyser ejects. Iceland, which sits atop the Mid-Atlantic Ridge spreading zone, has a high level of hydrothermal activity, as does Yellowstone, where several hundred geysers, such as the one below, are active in any given year.

Figure 6.40: Ebony Geyser, Yellowstone National Park

http://www.nps.gov/features/yell/slidefile/thermalfeatures/geysers/norris/Page.htm

Geysers on icy moons are mostly vapor because the pressure is too low for stable liquids.

Triton displays jets or plumes or geysers, although in this case they may be driven by sunlight heating pockets of volatiles beneath the moon's icy surface. The volatiles turn to gas and vent explosively, carrying dark particles with them. The plume from the vent gets carried downwind and the particles gradually settle out, leaving streaks.

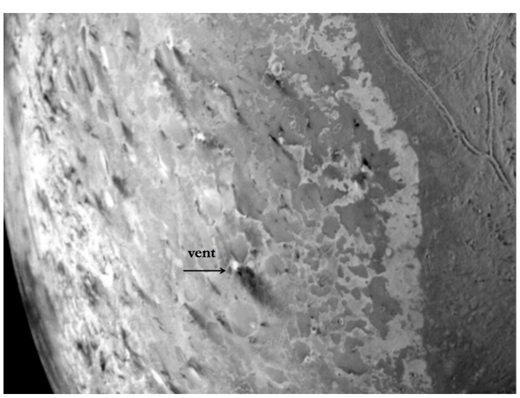


Figure 6.41: Geyser near Triton's south pole. NASA / Voyager 2 spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA00059

Rather than being discrete jets or plumes, it's possible that Enceladus' watery geyser-like eruptions maybe be curtains that stretch for some distance along fractures in the icy surface. The right-hand panel in the following image is a simulation of curtain eruptions showing that a waviness in the curtain could create the illusion of jets.

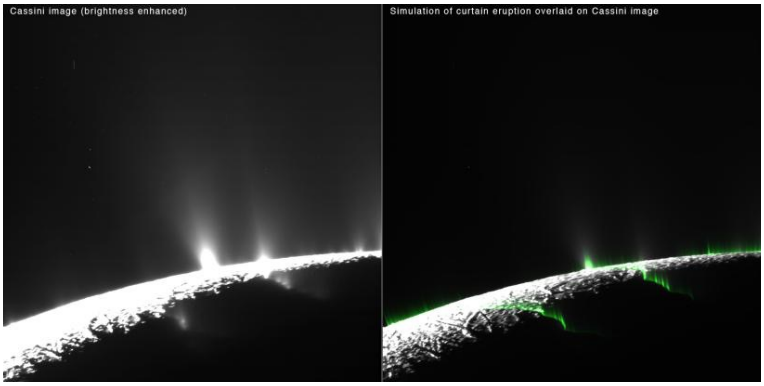


Figure 6.42: Curtain eruptions on Enceladus
NASA / Cassini spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA19061

Many rocky / icy objects have large regions that appear to have been flooded by volcanic material, although in the absence of extensive close-range observation it can be hard to determine the mechanism responsible for the emplacement of the flood material. The most familiar of these are the basalt flows that make up the lunar *maria* (singular: mare), so-called because to the eye the dark patches on the Moon resemble seas. Most, but not all, of the lunar maria are associated with large impact basins, but we don't have a definitive answer to the question of whether large impacts were the cause of the lava flows or whether the lava came from unrelated vents and flooded preexisting basins. Observations of variations in surface gravity by the GRAIL (Gravity Recovery And Interior Laboratory) spacecraft suggest that the largest basin, Oceanus Procellarum, is ringed by rift valleys that could be the source of the lava.

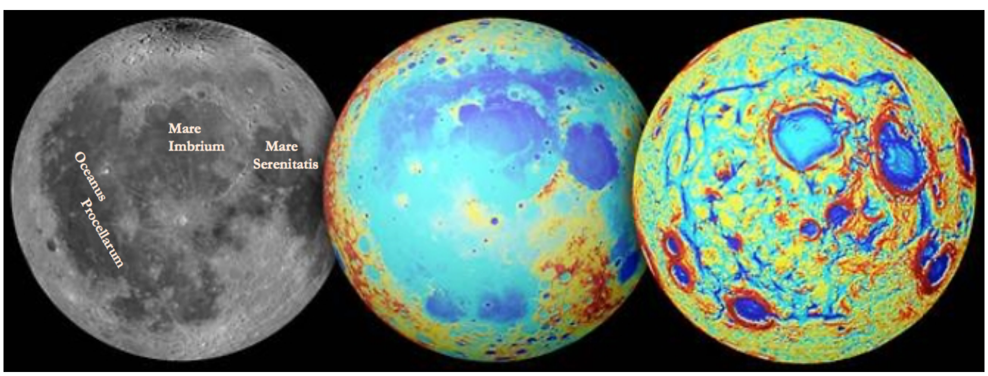


Figure 6.43: Lunar topography (center) and gravity gradients (right).
NASA / GSFC / JPL / Colorado School of Mines / MIT – Grail spacecraft
http://www.nasa.gov/press/2014/october/nasa-mission-points-to-origin-of-ocean-of-storms-on-earth-s-moon/#.Vh6tHbwq-RB

Mare basalts tend to be lower in volatiles relative to terrestrial basalts (e.g., almost no water or minerals containing hydrogen). Some, the KREEP basalts, are enhanced in potassium (K), rare-earth elements, and phosphorus (P). There are relatively few maria on the lunar farside and they seem to be older than the near-side maria. The best ages, ranging from ~3 to ~4 billion years, are from radiometric dating of Apollo rock samples, all of which are from the near side. Ages of lunar samples that show evidence of impact melting tend to support a model of the history of the solar system in which terrestrial objects experienced a period of *late heavy bombardment* about 3.9 billion years ago, i.e., several hundred million years after the formation of the solar system. Does that mean that the Moon experienced major impacts at a time when it was still warm enough inside for molten material to be near enough to the surface to flood following the impacts? Perhaps, although not all studies of the formation of the solar system and its impact history agree that there must have been a period of late heavy bombardment *and* some of the mare basalt ages are quite a bit younger than 3.9 billion years. As stated above, we don't have a firm picture of the relationship between major impacts and maria.

Understanding flooded basins is certainly no easier any place else in the solar system, where we lack rock samples to date. Triton has flooded basins in its northern hemisphere. Like the lunar maria, these basins have few impact craters, suggesting that they are relatively young, although how young is debatable.

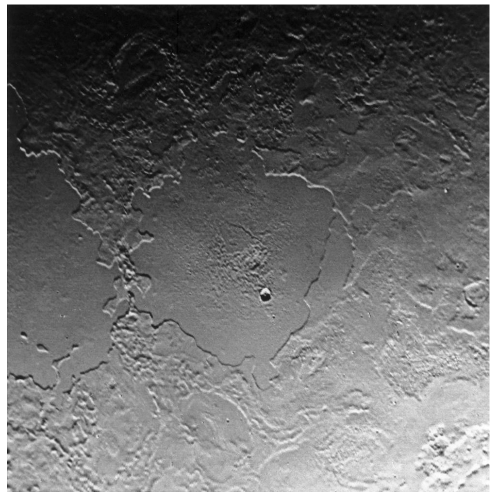


Figure 6.44: Flooded basin on Triton; this image spans ~500 km.

NASA / JPL – Voyager 2 spacecraft
https://photojournal.jpl.nasa.gov/catalog/PIA01538

As the lava filling these basins cools it may sag, shrink, and fold, leading to the formation of *wrinkle ridges*. The following image is of a relatively smooth plain in Mercury's northern hemisphere. Near the center is a flooded "ghost" crater. The prevailing interpretation is that this region was flooded by lava.

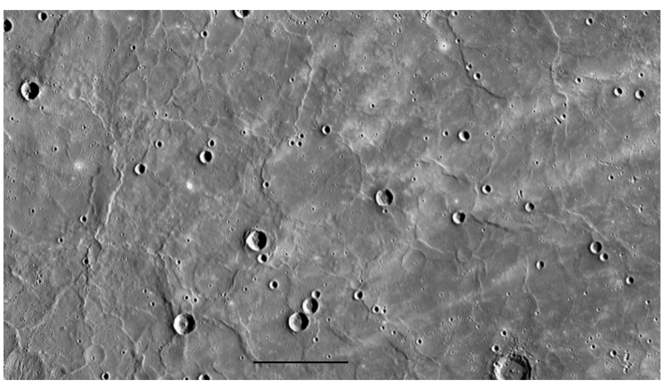


Figure 6.45: Volcanic plains, flooded craters, and wrinkle ridges on Mercury. The bar at the bottom is 100 km long.

NASA / JHU APL / Carnegie Inst. – MESSENGER spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA19415

Volcanic regions often show fractures around the edges. The following image is of a structure on Venus called a *corona*, thought to be formed when magma pushes the crust up a bit but then cools or drains away, leaving the central dome to subside, still surrounded by a round ridge or crown.

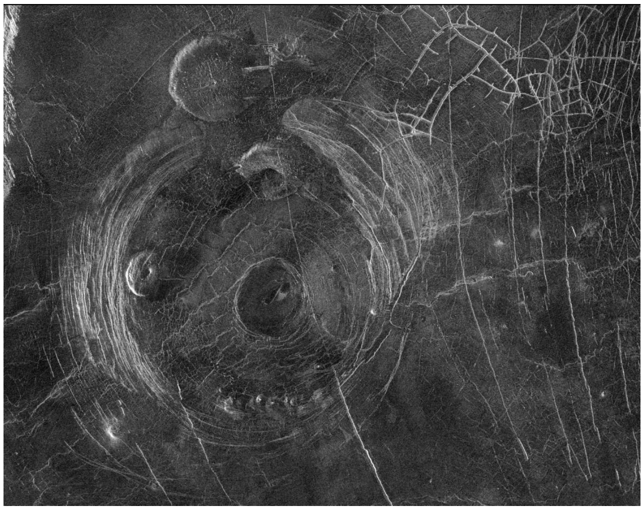


Figure 6.46: Fotla Corona on Venus. The region in this radar image is ~300 km across. The two low round features, just north of the corona and just inside on the west / left are pancake domes.

NASA / JPL – Magellan spacecraft.

http://photojournal.jpl.nasa.gov/catalog/PIA00202

The cracks and wrinkles are tectonic features, formed when part of the crust shifts with respect to adjacent crust. There are three possible relative directions for such slippage: adjacent crust can move apart and form extensional features, move together and form compressional features, or move sideways. Geologists distinguish three main types of faults: normal (extensional), thrust or reverse (compressional), and slip-strike or transform (sideways). Here are sketches of these possibilities:

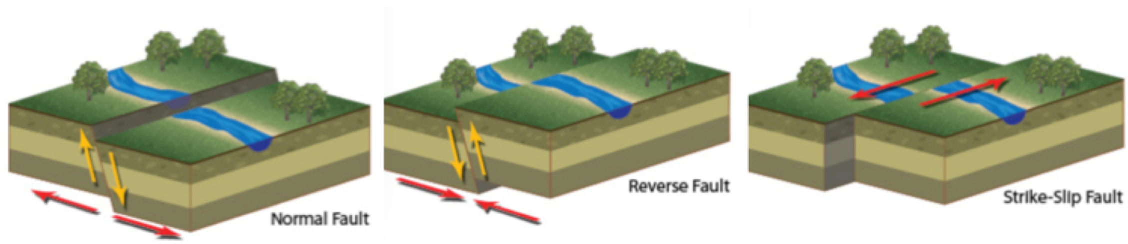


Figure 6.47: Types of faults
http://www.srh.noaa.gov/jetstream/tsunami/plates.htm

The ground can move quite a bit during an earthquake. In January 1700 an earthquake, estimated at greater than magnitude 8, along the Cascadia subduction zone (where the Juan de Fuca plate is sinking beneath the western edge of the North American plate) caused the ground along the coast of the Pacific Northwest to drop by ~2 meters. Trees inundated with salt water died and coastal marshes were swamped by sand from a tsunami surge. The event can be dated because Japanese observers recorded a tsunami not associated with any Japanese earthquakes at a time that corresponds to the approximate dates from First Nations oral traditions and biological dating of the dead trees. Earthquake magnitudes are reported on a logarithmic scale; the scale currently in use is based on the log of the amount of mechanical work done by a quake and assigns similar magnitudes as earlier scales. It's not clear exactly how strong the 1700 quake was, but it is clear that subduction zone earthquakes can exceed magnitude 8 – the 2001 earthquake in southern Peru was 8.4; the Sumatra-Andaman quake of 2004 registered 9.1, created tsunami waves 30 meters high, and killed over 200,000 people in low-lying regions around the Indian Ocean. Several cities and towns along the coast of the Pacific Northwest are at risk should such an event recur along the Cascadia subduction zone.

Sometimes it's easy to see which way the ground has moved. Here, as an example, is a slip-strike fault just south of the Tien-Shan mountains in Xinjiang province in western China. The various sedimentary layers (reddish, greenish, cream) were laid down at different times and in different depths of water. Thrusting, e.g., as the Indian subcontinent plowed into Asia, and erosion have created ridges and opened what were once horizontal layers to view. The Piqiang Fault runs perpendicular to those ridges for about 70 km. The adjacent sides of the fault are offset by ~3 km in the area captured in this image.

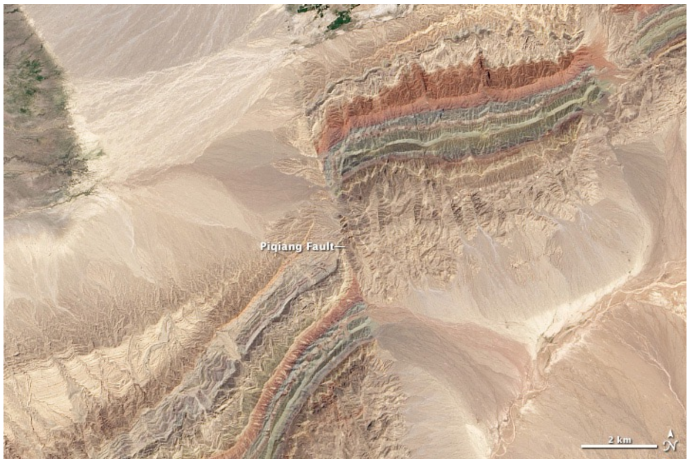


Figure 6.48: Piqiang slip-strike fault.

NASA / Landsat
http://earthobservatory.nasa.gov/IOTD/view.php?id=82853

Sometimes it is less easy to reconstruct the jigsaw puzzle. The surface of Europa is a good example. The icy crust has split often. Warmer, more ductile ice, sometimes darker colored, wells up and fills in the gashes. Sometimes the gashes are narrow and the new ice creates ridges; sometimes the adjacent sides of the fault line move apart more, sometimes they slip sideways with respect to each other, and sometimes, given enough space, blocks will rotate on the mushy layers below. Here's an example of a complicated section of Europa's surface. This region is ~238 x 225 km.

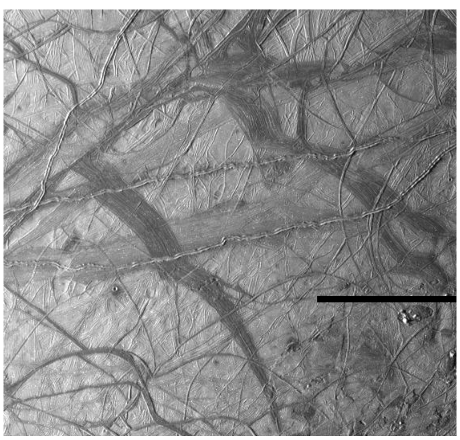


Figure 6.49: Faults, ridges, bands, etc., on Europa

NASA / JPL – Galileo spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA00518

Other endogenic processes that modify surfaces of planetary bodies.

The general term for the unconsolidated solid material on the surface of a rocky / icy object is *regolith*. On Earth we are more likely to say "soil", but that could imply the presence of organic material. On the Moon, the regolith is micrometeorites and small broken bits of lunar surface rock. Such unconsolidated material is going to tend to slide downhill. It may do so all at once, as in a landslide, perhaps nudged loose by an earthquake or, on Earth, by too much rain reducing the normal level of surface tension holding the grains together. Earth isn't the only place we see landslides. Here, for example, is an image of a landslide at the edge of a crater, which is itself near the edge of a larger impact basin, on the low-albedo side of Iapetus.

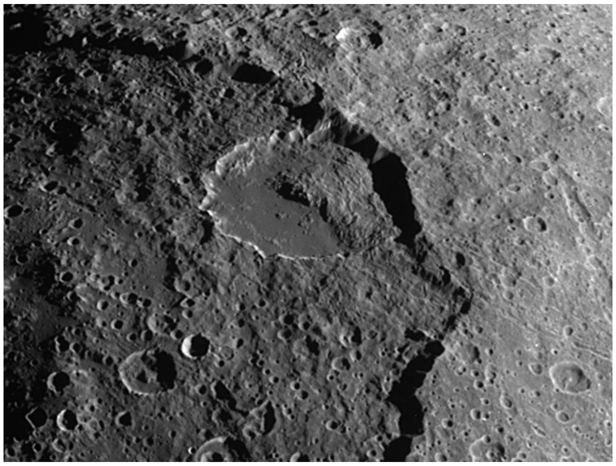


Figure 6.50: Landslide on Iapetus
The scarp (cliff) is ~15 km high; the flat crater into which the slide slid is ~120 km diameter.

NASA / JPL / Space Science Inst. – Cassini spacecraft

http://photojournal.jpl.nasa.gov/catalog/PIA06171

Unconsolidated grains can be piled up, at least a bit. Imagine pouring sand onto a table – the sand will form a cone. The steepest angle that the cone edge can make with the horizontal is called the *angle of repose*. Try to pile the grains into a steeper cone and they will slump. If the grains are angular, rather than rounded, or they are otherwise inclined to stick together, the angle of repose will be steeper. (E.g., for smooth rounded grains it might be 25° whereas for rough particles it might be 45°.) Gravity matters a bit; we see slides on Mars, for instance, with a more gentle slope than we would expect on Earth.

Wind can move at least the smaller grains around. Mars' atmosphere normally carries a good bit of dust, particles on the order of 1-2 μm size. Often near perihelion Mars will experience planet-wide dust storms that can last for months. NASA's Mariner 9 space probe arrived at Mars in November 1971, the first spacecraft to go into orbit around a planet other than Earth. If it hadn't gone into orbit the mission would not have been able to accomplish much – the spacecraft arrived at Mars in the midst of the largest dust storm humans had ever seen, a storm large enough to obscure totally the surface of Mars. Gradually the dust settled and the tops of the Tharsis volcanoes came into view. After about two months the majority of the surface was clear and Mariner 9 could get on with its science projects. The following pair of images shows Hubble Space Telescope views of Mars under normal conditions and dust storm conditions.

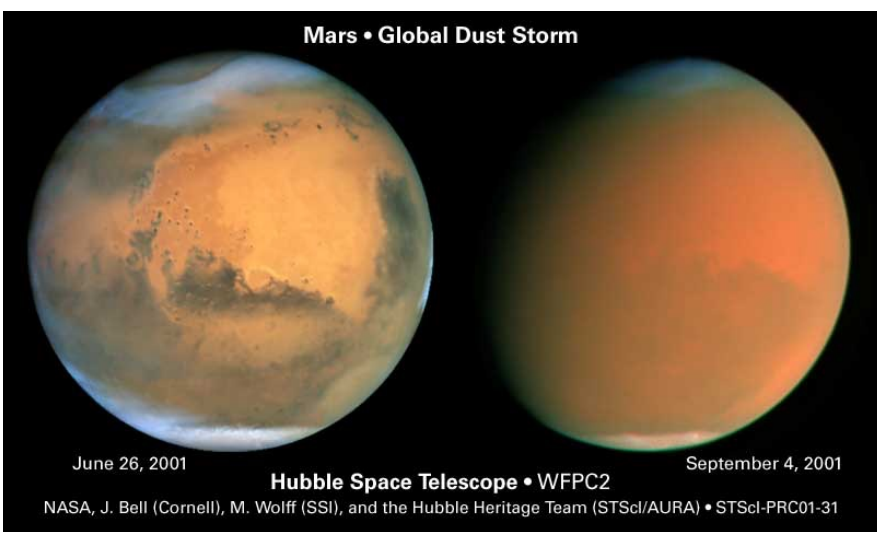


Figure 6.51; http://hubblesite.org/image/1101/news_release/2001-31

On many rocky / icy objects wind can move dust or sand grains with enough force to be a source of erosion or abrasion for rock. *Aeolian processes* are those by which wind and wind-borne particles alter the landscape, so-called for Aeolus, the Greek god who served as keeper of the winds. Larger dust grains may not get picked up or blown very far but rather make short hops, not getting more than perhaps a meter from the ground. This process is called *saltation*. Saltating grains can hit rock with enough force to pit the surfaces of rock or in some cases undercut them. A *ventifact* is a structure created by this sort of sand blasting. Here are two examples, imaged by the Mars Curiosity Rover:

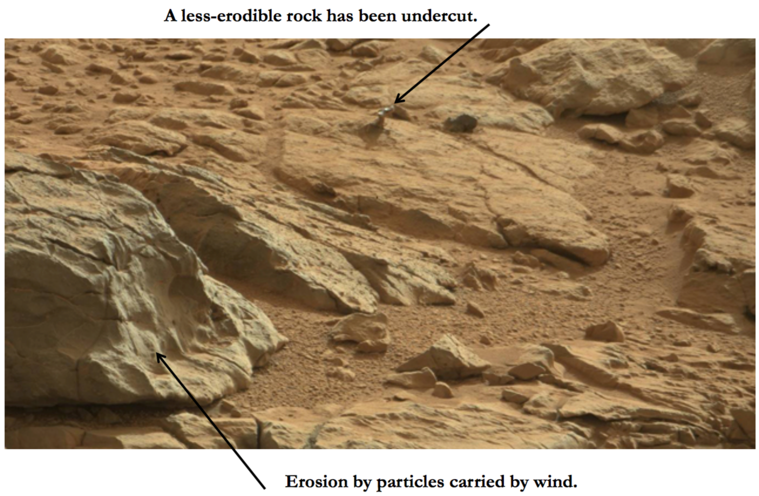


Figure 6.52: Ventifacts on Mars

NASA / JPL / Malin Space Sci Systems – Mars Curiosity Rover

http://www.jpl.nasa.gov/news/news.php?feature=3687

Grains can pile up in streaks or dunes, whose shape and orientation give us some indication of the direction of the prevailing winds. Dunes have been seen on Mars and dune-like structures are also seen on Titan, Pluto, Venus, and possibly even on comet 67P / Churyumov-Gerasimenko.

Figure 6.53: Dunes in Endurance Crater, Mars
NASA / JPL / Cornell – Opportunity Rover
http://photojournal.jpl.nasa.gov/catalog/?IDNumber=PIA06754

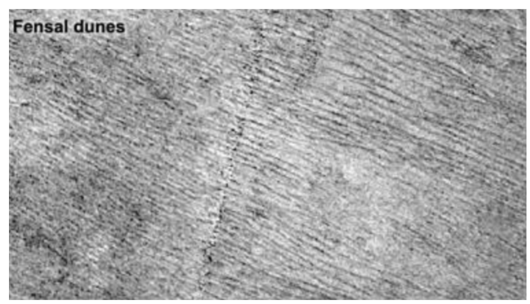


Figure 6.54: High-latitude dunes on Titan
NASA / JPL – Cassini spacecraft radar image
http://photojournal.jpl.nasa.gov/catalog/PIA15225

Mars' polar ice caps are a mix of water ice, carbon dioxide, and dust. The water ice stays; the CO_2 ice comes and goes with the seasons, sublimating in spring and freezing out again in winter. Dust that blows in during the summer can get covered by ice in the winter. Dust that stays on the surface increases the absorption of sunlight and that in turn influences how much ice disappears how rapidly. The end result is that Mars' polar ice caps show layered deposits. Because the tilt of Mars' axis has changed much more over the history of the planet than Earth's has, Mars' seasons have at times been much more extreme than they are today. It's possible that the layering in the polar deposits underlies the water ice. Perhaps someday we will have the capacity to drill down through these several kilometer deposits and trace the history of Mars' climate.

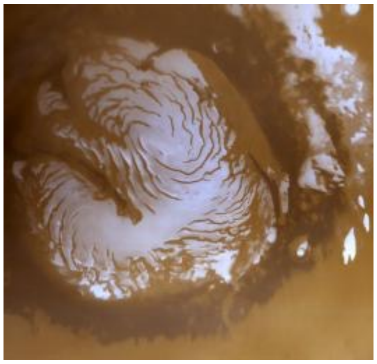


Figure 6.55: Mars' North polar cap in summer; NASA / JPL / MSSS – Mars Global Surveyor
http://photojournal.jpl.nasa.gov/catalog/PIA02800

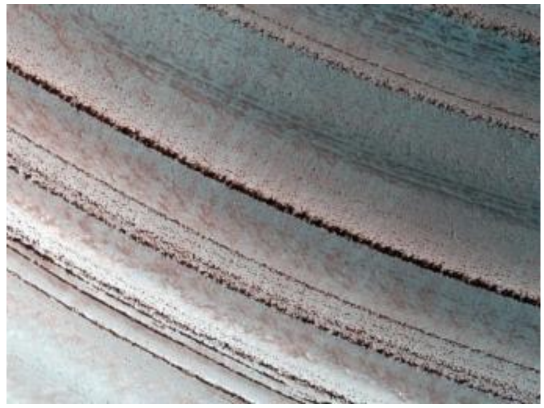


Figure 6.56: Martian north polar layered deposits; this image spans ~ 1 km. NASA / JPL / U. of AZ – Mars Reconnaissance Orbiter
http://photojournal.jpl.nasa.gov/catalog/PIA12997

Even prior to drilling, though, we can gain some insights into the structure of the pole caps using ground-penetrating radar, such as the MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) instrument aboard the European Space Agency (ESA) Mars Express spacecraft. Observations using MARSIS verified the existence of layers of water ice interspersed with dust to a depth of roughly 1.5 km at Mars' south polar cap. In July 2018 ESA scientists reported higher-resolution data highly suggestive of a layer of liquid water, or at least very water-rich sediments, under that south polar ice cap. The bright radar reflection extends over a region about 20 km wide, and although it's not clear how thick the layer is, it must be at least on the order of a meter. If the liquid layer is thicker it might resemble terrestrial lakes buried under the ice in Antarctica. The largest of these is Lake Vostok, which is among the top ten largest lakes on Earth; it just happens to be buried under ~4 km of ice. For those of you interested in astrobiology, accessing the water in Lake Vostok provides a model site for developing the techniques, and identifying the challenges, that might be useful to understand should we get to the point of trying to drill through the ice on Europa or Enceladus. If the liquid layer on Mars is more extensive, i.e., if there is a groundwater layer on Mars that extends beyond the poles, water might break through to the surface through deep-seated cracks, perhaps associated with craters. If further observations lend support to that hypothesis, that could be quite useful should we actually send humans to Mars one day.

Water or similar liquids can also of course move larger chunks of sediment and erode planetary surfaces. One consequence that you have probably seen is that cobbles, rocks tossed along by a stream, are rounded. The once-angular edges have been abraded away from years of knocking against other rocks. Appealing to what we see happen on Earth, the rounded cobbles on Titan strongly suggest that there has been liquid flowing on the surface at some time. The following image from the surface of Titan shows rounded cobbles several centimeters in diameter, some of which appear to have been undercut by flowing liquid; it's possible that fluid accounts for the lack of cobbles across the middle of the region shown here. Since this is Titan, we expect these "rocks" to be water ice.

Figure 6.57: Cobbles and a possible streambed on the surface of Titan.

NASA / JPL / ESA / U. of AZ – Cassini mission Huygens probe.
http://photojournal.jpl.nasa.gov/catalog/PIA07232

Flowing water creates a variety of erosional features on Earth. Comparison of erosive features on Mars with terrestrial erosion is an important tool in understanding the history of water on Mars. As an example, let's look in a bit more detail at the Spokane-Missoula floods that carved the "channeled scablands" of Eastern Washington at the end of the last ice age. These catastrophic floods, each releasing on the order of 2,000 km^3 of water, followed the failure of ice dams on the Clarks Fork River that had created glacial Lake Missoula. The floodwaters carved channels or coulees which are much more rectangular in cross-section than valleys carved by glaciers, which create rounded, U-shaped valleys, or meandering rivers, which create V-shaped valleys that widen over time as the rivers change course. The water cut the channels back, toward the headwaters, in many cases leaving falls such as the one along the route the Palouse River follows. The floods carried large boulders, often riding on rafts of ice. Turbulence created potholes, which eroded local bedrock. The rocks eventually got dropped as "erratics" a long ways from their origins.

Figure 6.58: Palouse Falls, left, and looking downstream, below.

National Park Service
http://parkplanning.nps.gov/document.cfm?parkID=531&projectID=37903&documentID=54445

The floodwaters followed the paths of least resistance, often resulting in anastomosing, or braided channels. More resistant rock left lenticular (lens-shaped) islands. Smaller grains in the sediment collected in dunes, giant ripples of sand up to ~15 m high. It was a tough sell in the 1920s when J. Harlen Bretz proposed cataclysmic flooding as a mechanism for sculpting the channeled scablands. No one alive had seen a flood of this magnitude. Seen from space, it makes a bit more sense. In the following image the scablands are the brown and tan region south of the label.

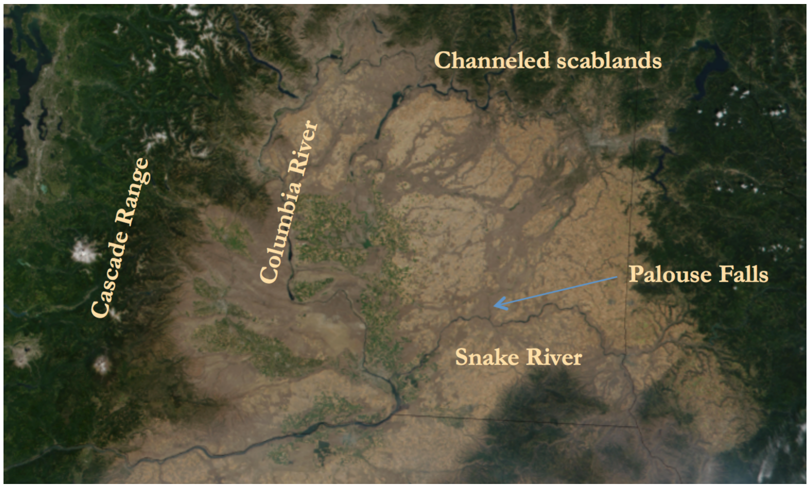


Figure 6.59: Channeled scablands, Eastern Washington

NASA / Jacques Descloitres, MODIS
http://eoimages.gsfc.nasa.gov/images/imagerecords/56000/56573/Washington.A2001223.1920.250m.jpg

We see features with similar morphologies in Martian *outflow channels*. There is an image of Kasei Vallis in the Planetary_Overview chapter; in the image below are two more channels. Not all of the features on Mars that resemble those we know to have been created by liquid water on Earth were necessarily created by water. Collapsed lava tubes can look resemble aqueous features; it's also possible that seasonal carbon dioxide frost cycles could carve some Martian gullies.

In addition to flowing liquid or windblown dust, chemistry happens, i.e., minerals at the surface interact with atmospheric gases as part of what are broadly called geochemical cycles. Harold Urey was one of the first to point to the importance of such reactions on Earth. Specifically, CO_2 gas interact with silicate minerals in reactions such as the following: $MgSiO_3 + CO_2 \rightarrow MgCO_3 + SiO_2$. In this example, enstatite reacts with carbon dioxide to form magnesium carbonate and quartz. High temperatures will drive this reaction to the left; the presence of water, in other words, dissolving CO_2 in water to make a weak carbonic acid, will drive it toward the right.

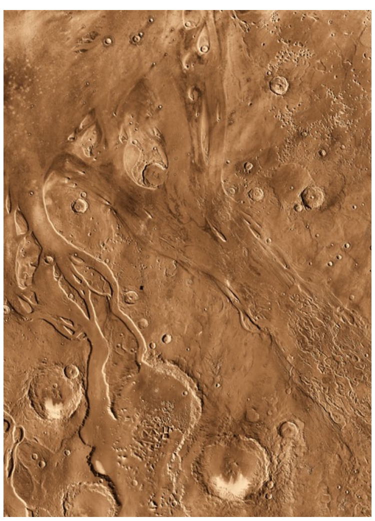


Figure 6.60: Tiu Vallis, left, and Ares Vallis, right, in Mars' southern hemisphere. Note the lenticular islands, top center.

NASA / JPL / ASU – Mars Odyssey
https://mars.jpl.nasa.gov/odyssey/gallery/martianterrain/aresoutflow.html

Much of Earth's CO_2 got incorporated into carbonate rocks. On Venus, where the temperature is high and there is no ocean to dissolve CO_2, conditions favor the left-hand side of the reaction. Venus' CO_2 is in its atmosphere; Earth's mostly isn't. We have two very different planets even though their total amounts of CO_2 are nearly the same.

Life leaves its mark on Earth's surface as well. We have already mentioned seashells of calcium carbonate contributing to sedimentary rocks. Think back farther, to the beginnings of life on Earth. Prior to the advent of life, free oxygen was not a significant component of our atmosphere or oceans. Once life got started, oxygen started to build up, at first in the oceans where it combined with dissolved iron, creating iron oxides such as magnetite and hematite. These sank and became part of the layers of sedimentary rock, creating what are now called the banded iron formations. The earliest of these are 3.7 billion years old; most date from around 2.4 billion, a time called the great oxygenation event. As an example, here are two images of a red, iron-oxide-rich formation in Western Australia dating from 2.5 billion years ago.

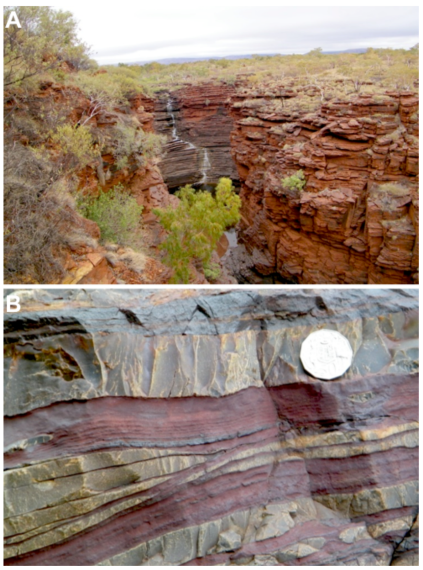


Figure 6.61: Brockman Iron Formation in Western Australia's Karajini National Park.
a) Joffre Falls. b) Close-up showing banding.

NASA Astrobiology Institute / A. D. Czaja
http://astrobiology.nasa.gov/media/txp_files/2010%20Czaja%20project%20report.pdf

Sample questions

1. Explain / define
   - a) eutectic point
   - b) igneous, sedimentary, metamorphic
   - c) why basalt is more fine-grained than granite
   - d) Bowen reaction series
   - e) sinuous rille
   - f) pyroclastic eruption
   - g) shield volcano
   - h) ʻaʻā vs. pāhoehoe
   - i) KREEP
   - j) types of geologic faults
   - k) regolith
   - l) saltation
   - m) channeled scablands
   - n) banded iron formation

2. Ch 6a & b refers to several solar system objects in addition to the Earth, especially Mars and Io. Describe a few interesting volcanic features of each of these two objects.

3. Where in the solar system do we find evidence of surface features sculpted by aeolian processes?

4. There are roughly 10 active volcanoes on Io at any given time; there are several different types of eruptions but on average any given volcano could erupt roughly 10 km^3 of lava per year. Models vary, but it's not unreasonable to assume that the upper 3 km or so of Io are regularly involved in eruptions and the ongoing resurfacing of Io. At this rate, and assuming that the lava flows spread evenly over Io's surface, how long would it take to bury the entire surface 3 km deep?

5. Olympus Mons is ~600 km wide and rises ~25 km above the surrounding plains. Assume that its shape is conical and that it erupted lava continuously at a rate of 0.5 km^3 / yr. How long would it take to build a mountain this size?

Answers to selected problems are on the next page:

4. About 300,000 years.

5. About 4.7 million years.