# 10

# Plains: smooth and intercrater

## 10.1 WILL THE UNSEEN SURFACE OF MERCURY BE COVERED WITH PLAINS?

As soon as the first pictures of Mercury were available from Mariner 10, it was realized that the surface was largely covered with plains. The plains were obviously heavily cratered and from this it was inferred that they were emplaced early in Mercury's history. About 60% of the imaged portion of Mercury is plains, and if this proves true for the unexplored side, then plains are the most abundant terrain on Mercury. The other 40% consists of large craters, basin rim structures, and the hilly and lineated terrain. Mercury's plains differ from the Moon's plains in two important respects (recall that the lunar maria are plains consisting of basaltic lava flows). First of all, Mercurian plains are much more widespread than at the Moon, and second, they appear to have a higher albedo than those on the Moon.

## 10.2 MERCURY HAS TWO TYPES OF PLAINS

The Mercurian plains are usually divided into two general types:

(1) intercrater plains; and
(2) smooth plains. This division is largely based on differences in crater abundances and mode of occurence between the two types. Intercrater plains are much more heavily cratered than smooth plains, and are, therefore, older. They occur in the Mercurian highlands between clusters of craters (Figures 10.1, 10.2 and 10.3). Like the lunar maria, smooth plains are relatively young and largely confined to the interior and/or exterior of impact basins and large craters (Figure 10.4).

Plains can have various origins. They can be caused by erosion and deposition similar to Earth's plains. They can also be formed by impact ejecta mantling such

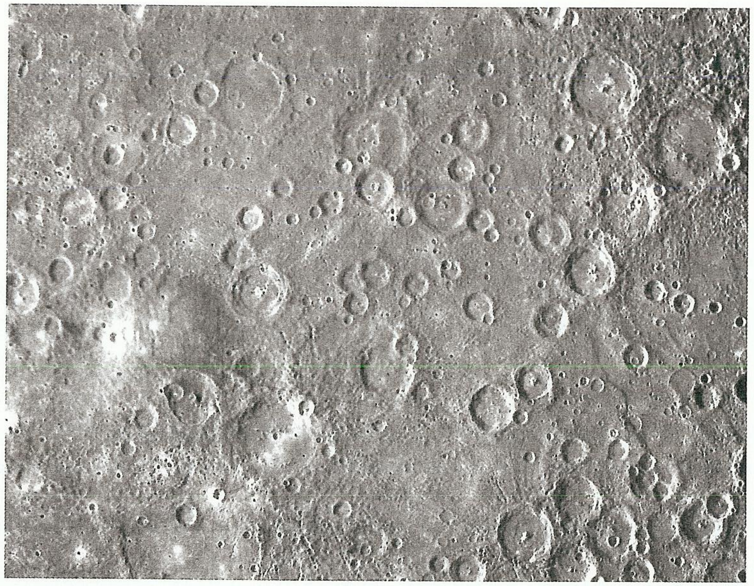

**Figure 10.1.** This photomosaic shows large areas of intercrater plains between heavily cratered areas. Intercrater plains dominate Mercury's highlands.

as some highland plains on the Moon. Most plains are the result of volcanism that has produced enormous flood basalt deposits, such as those on the Moon, Venus, Earth, and Mars. The origin of Mercury's plains is still uncertain, but current evidence seems to favor a volcanic origin for most.

## 10.3 THE INTERCRATER PLAINS, SOME DETAILS

### 10.3.1 Distribution, age, and morphology

About 45% of the surface viewed by *Mariner 10* is occupied by intercrater plains. They occur between and around clusters of large craters in the heavily cratered highlands of Mercury.

In many cases the superposed small craters occur in chains or clusters suggesting they are secondary craters from the larger craters and basins that make up the highlands. The high crater density indicates that these plains predate the smooth plains and that they constitute one of the oldest surfaces on the planet. They apparently span a range of ages contemporaneous with the period of heavy bombardment. They partially bury some large craters (Figure 10.3) and the ejecta blankets of others, but other large craters and their ejecta are superposed on the plains. The older and intermediate age craters seem to be more affected by intercrater plains formation than the younger fresh craters which are the ones that contribute most to the superposed secondary cratering. Figure 10.4 (colour section) shows paleogeologic maps by Martha Leake of Mercury's incoming side as viewed by Mariner 10. They show that intercrater plains were emplaced during the formation of older class 5 through class 3 craters and that the volume of plains generally decreases as age decreases. Secondary craters superposed on the intercrater plains appear to be derived mainly from the younger class 1–3 craters and class 4 basins of the heavily cratered terrain. Patches of plains emplaced during the formation of the young class 1 and 2 craters are equivalent to smooth plains. These relationships strongly suggest the intercrater plains were emplaced during the period of heavy bombardment, and that the volume of these plains decreased as the impact rate declined. In fact, the formation of intercrater plains and smooth plains may not represent two distinct episodes of plains formation. Instead they may represent a more-or-less continuous period of plains formation lasting from sometime during the period of heavy bombardment to the emplacement of the youngest smooth plains. Absolute dating of intercrater plains based on their crater densities suggests that they formed between 4.0 and 4.2 billion years ago (see Chapter 9), but they may have continued as smooth plains to at least 3.8 billion years ago.

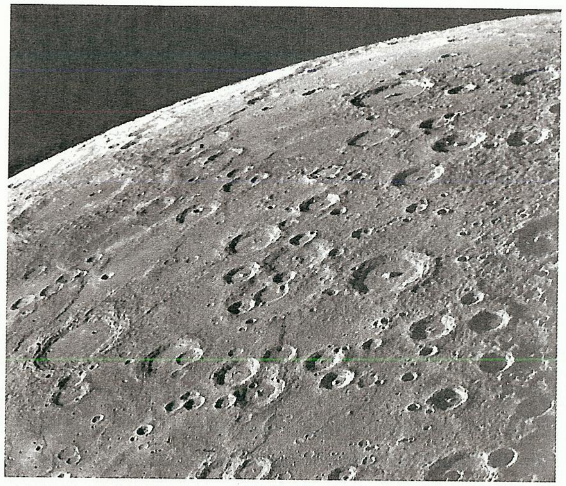

**Figure 10.2.** This image of the Mercurian highlands shows large areas of intercrater plains. The large scarp near the planet's limb is a thrust fault.

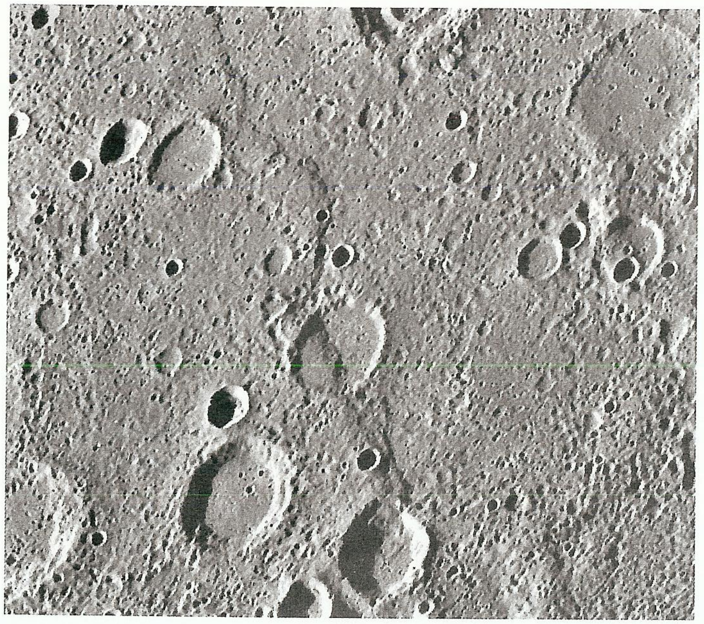

**Figure 10.3.** A high-resolution image of the intercrater plains. It shows an abundance of small craters that are mostly secondary impact craters from younger primary impact craters. Also shown are intercrater plains that have flooded a large crater (70 km) in the upper right-hand corner of the image.

### 10.3.2 Crater degradation by intercrater plains

The crater/size frequencey distribution indicates that a substantial fraction of the craters less than 50 km in diameter have been destroyed by intercrater plains formation. There is a significantly smaller abundance of craters less than 50 km diameter on the Mercury highlands compared to the lunar highlands, showing a systematic loss of craters relative to the Moon, where there are very few intercrater plains (see Chapter 9). This is exactly what would be expected if Mercury's intercrater plains were formed during the period of heavy bombardment with smaller craters buried first, followed by larger craters as the plains continued to be deposited (Figures 10.3 and 10.4, colour section). Intercrater plains form level, to gently rolling surfaces with a high density of craters greater than about 15 km diameter. This high crater denisty gives these plains a rough appearance and attests to their great age.

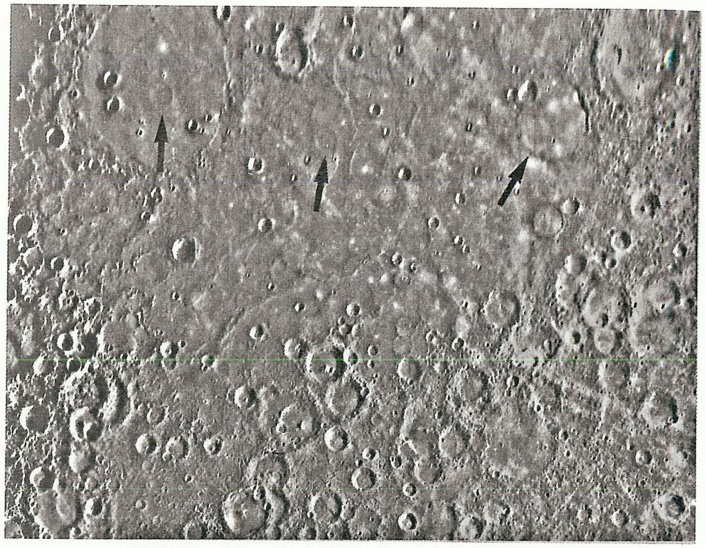

**Figure 10.5.** This photomosaic shows a large area of smooth plains that occurs in the north polar region and appears to fill the ancient Borealis basin about 1500 km in diameter. The plains also fill the younger Goethe basin (340 km diameter) located in the upper left corner of the photomosaic. Some craters that have been flooded by smooth plains are indicated by arrows.

## 10.4 SMOOTH PLAINS, SOME DETAILS

### 10.4.1 Distribution, age, and morphology

Smooth plains cover almost 15% of the imaged portion of Mercury. About 90% of the smooth plains are associated with older large impact basins, but they also fill smaller basins and large craters (Figures 10.5, 10.6, 10.7 and 10.8). There are two large concentrations of smooth plains on the explored side of Mercury. One fills and surrounds the 1300 km diameter Caloris basin. The other occupies a large highly degraded impact basin about 1500 km diameter called the Borealis basin (Figure 10.5). Smooth plains have the lowest crater density, and are, therefore, the youngest geologic unit on Mercury.

The smooth plains on Mercury appear similar in morphology and mode of occurrence to the lunar maria. Craters within the Borealis, Tolstoj, and other basins have been flooded by smooth plains. Furthermore, the crater densities on the floors of these basins are significantly less than those on the terrains immediately surrounding the basins (Figures 10.5 and 10.8). These observations alone indicate

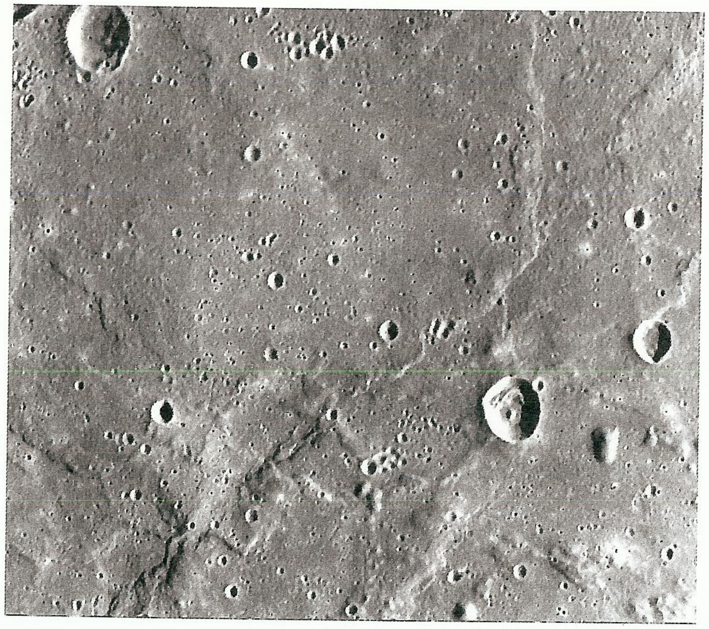

Figure 10.6. Most of the area in the image is covered by smooth plains that surround the Caloris basin. A ridge similar to a lunar wrinkle ridge crosses the middle of the image. Wrinkle ridges are compressional tectonic features.

that smooth plains are younger than the basins they occupy and cannot be impact melt that resulted from the impacts that formed the basins. Smooth plains filling smaller craters and basins could be impact melt, however.

Based on the shape of the crater size/frequency distribution and the fairly high crater density (Figure 9.20), the smooth plains probably formed near the end of heavy bombardment. They may have an average age of about 3.8 billion years, or several hundred million years younger than the intercrater plains laid down during the period of heavy bombardment. This means they are, on average, older than the flood basalt lavas that consitute the lunar maria.

## 10.5 ORIGINS OF PLAINS

Two radically different origins of the Mercurian plains have been proposed. One hypothesis considers both the smooth and intercrater plains to be impact ejecta deposits from large basins, similar to the Cayley plains on the Moon. The other hypothesis considers both plains units to be volcanic deposits. In the past, the origin of plains on Mercury has been controversial, but a re-evaluation of the *Mariner 10* color data together with earlier stratigraphic analyses favor a volcanic origin, particularly for the smooth plains.

Figure 10.7. High-resolution image of the smooth plains. The smallest crater that can be seen is about 200 m across. These plains surround the Caloris basin.

The problem with determining the origin of the plains is the dearth and relatively low quality of the available data. The mode of formation of any plains unit is difficult to determine because there are usually not many landforms that are diagnostic of their origin. For instance, the origin of plains on the Moon was very controversial when only relatively low-quality earth-based telescopic observations were availible. That is about where we stand for Mercury at the present time. However, the great advantage now is that we can draw on our past experiences with the Moon.

### 10.5.1 Mercury's smooth plains as impact basin ejecta deposits or impact melt

On the Moon just beyond the continuous ejecta blankets of fresh impact basins lie small areas of light smooth plains. These deposits are fluidized basin ejecta that flowed beyond the continuous ejecta blanket and buried some pre-existing craters. At greater distances occur patches of gently rolling light plains that fill craters and other low areas in the lunar highlands. Except for their small areal extent, they resemble to some degree the intercrater plains of Mercury. *Apollo 16* returned samples from one of these areas that proved to be impact breccias, probably from the Imbrium basin.

Under this hypothesis, the smooth plains surrounding the Caloris basin are smooth ejecta deposits from the basin. The interior smooth plains filling the Caloris basin would be impact melt under this hypothesis. Other smooth plains filling older basins would be either impact melt or ejecta deposits from other basins. Furthermore, the intercrater plains would be the same type of ejecta deposits as the Cayley plains on the Moon and would have been formed early in Mercury's history during the period of heavy bombardment. The similar albedos of smooth and intercrater plains has been used as an arguement in favor of an impact origin. This hypothesis for plains formation implies there has been no volcanism on Mercury's explored side.

### 10.5.2 Mercury's smooth plains as volcanic deposits

There are several severe problems with the impact ejecta/melt hypothesis. Lunar light plains ejecta deposits only cover about 5% of the entire Moon's surface. In contrast, Mercurian smooth plains cover about 15% of the imaged side, which may be representative of the planet as a whole. It is difficult to explain why Mercury's smooth plains, if ejecta deposits, are more widely distributed than on the Moon when the ballistic range is much less. For example, the smooth plains surronding the Caloris basin extend outward from the rim in a more-or-less continuous deposit for more than 2000 km in some areas. No such extensive ejecta deposits occur around lunar craters of comparable size. Since the ballistic range on Mercury is about half that for the Moon, the ejecta blankets should be closer to the rim on Mercury, as observed for smaller craters. Furthermore, the surface gravity on Mercury is 2.3 times stronger than the Moon's so flow of ejecta deposits beyond the continuous ejecta blanket should be much more restricted on Mercury for comparable impact melt viscosities. Also, large fresh craters greater than 200 km diameter do not show a proportionately larger amount of smooth plains surrounding them. They, instead, show ejecta deposits consisting of narrow, continuous deposits with numerous clusters and strings of secondaries right up the the crater rims.

There are several aspects of the large expanses of smooth plains that indicate they are volcanic in origin. One observation that is very damaging to the ejecta hyposthesis is the observation that the smooth plains are younger than the basins they occupy or surround. Ejecta deposits and impact melt are part of the impact process, and, therefore, are the same age as the basin to which they are associated. In the interiors of the large Tolstoj and Borealis, basins, smooth plains have embayed older craters on their floors indicating that the plains are younger than the basins they occupy (Figures 10.5 and 10.8). Crater counts on the smooth plains surrounding the Caloris basin and on Caloris ejecta deposits show they are of different ages, therefore, these smooth plains cannot be ejecta deposits from Caloris. Furthermore, there appears to be a slight difference in albedo between the Caloris smooth plains and the intercrater plains, with the smooth plains being slightly darker. Earth-based radar observations show that the annulus of smooth plains surrounding Caloris is strongly down-bowed like the lunar maria. On the Moon this is due to the weight of the volcanic iron-rich basalts. Also, several irregular rimless depressions on the floors of the Caloris and Tolstoj basins appear to have a volcanic origin (Figure 10.8 and Figure 9.12). *Mariner 10* enhanced color images show that the boundary of smooth plains within the Tolstoj basin is also a color boundary suggesting a different composition from the surrounding material. However, color differences could indicate age difference due to varying amounts of space weathering or even textural differences such as grain size or porosity. The youth of smooth plains relative the the basins they occupy, their great areal extent, the presence of a sharp color boundary in at least one case, and other stratigraphic relationships indicate that the majority of smooth plains are volcanic deposits which erupted about 3.8 billion years ago.

**Figure 10.8.** Smooth plains fill the ancient Tolstoj impact basin 400 km in diameter. The arrows point to craters that have been flooded by the smooth plains indicating they are younger than the basin. The "A" indicates the location of a rimless, elongate depression that may be volcanic.

Recent ground-based imaging has captured Mercury images at moments of excellent atmospheric stability showing albedo differences between regions on the

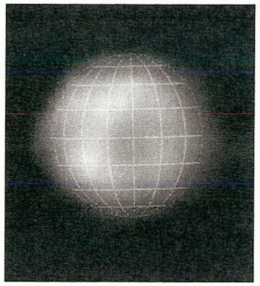

**Figure 10.9.** Good contrast between bright and dark regions is in this ground-based image of Mercury. The image was captured by Frank Melillo with his Celestron 8 inch Starlight Express and commercially available CCD imaging camera from his backyard in Holtsville, NY. Tim Wilson, another amateur Mercury observer prepared the latitude and longitude grid for the image for better identification of surface features. The grid lines are separated by 22.5° in latitude and 30° in longitude, with the central meridian at 158° longitude. The dark regions coincide with the smooth plains, above, and to the west of Tolstoj.

surface (see Figure 1.7 and 1.8). Amateur observers are also taking advantage of imaging Mercury with relatively inexpensive and very capable instrumentation. Some images show definite albedo differences across the surface, some associated with bright impact craters, also associated with radar bright features. Darker regions may be examples of smooth plains. A ground-based image of Mercury is shown in Figure 10.9. The image was obtained with a back-yard Celestron telescope and imaging CCD from Holtsville, NY. A grid has been overlain to permit knowledge of the proper latitudes and longitudes on the planet and permit identification of surface features. The vertical line in the center of the image is the 158° longitude. The large darker albedo region coincides with a large expanse of smooth plains replete with wrinkle ridges and embayed craters. The region encompasses smooth plains surrounding the Caloris basin. It includes Tir Planitia on the west, Odin Planitia, spanning the meridian, and Budh Planitia to the east. The large, smooth plains in the interior of Tolstoj are in the lower portion of the dark region just west of the central meridian. This observation is corroborated by *Mariner 10* image photometric studies of the smooth plains surrounding the Caloris basin. They indicate that these smooth plains are slightly darker than the adjacent intercrater plains.

Definitive volcanic landforms are rare on Mercury, but one must keep in mind that *Mariner 10* resolution and coverage is only about the same as Earth-based telescopic resolution and coverage of the Moon before the advent of spacecraft exploration. At this resolution, there are few identifiable volcanic landforms on the Moon although most of the frontside is covered by volcanic deposits. There are, however, some irregularly shaped rimless pits on smooth plains that have been interpreted to be volcanic. They are similar to volcanic rimless pits on the Moon and shown in Figure 10.8 and 9.12.

These combined observations strongly suggest that most of the smooth plains have a volcanic origin. The distribution of the smooth plains is, in fact, very similar to the lunar volcanic maria; both are associated with large impact basins and have about the same areal distribution. This further indicates that they were emplaced in a similar fashion.

### 10.5.3 Mercury's intercrater plains as volcanic deposits

The origin of intercrater plains is considerably more difficult to interpret. Similar arguments can be made for the volcanic origin of Mercurian intercrater plains as are made for smooth plains. They cover about 45% of the imaged side of Mercury, but there is no evident source basins from which impact deposits could be derived. On the Moon small patches of intercrater-like plains occur in the highlands but they only constitute about 3% of the Moon's entire surface. The origin of these lunar deposits is still debatable but, unlike the Mercurian deposits, they at least can be indentified with possible source basins.

As discussed in Chapter 9, the frequency of the interior morphologies of craters on the smooth plains, the lunar maria, and the intercrater plains are the same, but differ signifantly from that of the lunar highlands. This suggests that the intercrater plains have physical properties (strength and cohesiveness) similar to the lunar maria volcanic deposits and probably those of the volcanic smooth plains (see Figure 9.3). In other words, they are much more similar to coherent igneous rock than the lunar highlands megabreccia.

Newly recalibrated *Mariner 10* images bear strongly on the origin of Mercury's plains deposits. The recalibrated image mosaics show the complete ultraviolet-orange color data for the region near Kuiper crater. The data are interpreted in terms of visible color reflectance for iron-bearing silicate regoliths. Based on the albedo and color ratios (UV/orange), the content of opaque minerals and soil maturity were estimated. Many differences across the surface are dramatically displayed in Figure 10.10 (colour section). Smooth plains units near the Rudaki crater show distinct color boundary embayment relationships that correspond to previously mapped plains boundaries. This strongly indicates that these plains have a different composition, age, or grain size and porosity than the surroundings and are probably deposited as volcanic flows (Figure 10.10). It is not possible to determine from the ratioed images whether the plains are basaltic, but the morphology suggests that they were formed from a relatively fluid lava, one example of which is basalt. This area also shows two areas of spectrally blue material with high opaque indecies, low albedos and diffuse boundaries. Since there are no impact craters associated with this material they could be more mafic pyroclastic deposits. Kuiper and Muraski craters show a very low opaque mineral index which may indicate they have excavated into an anorthositic crust. These observations strongly indicate Mercury is compositionally heterogeneous and that volcanism has contributed to plains formation. This is strengthened by Earth-based spectrographic data which was discussed in detail in Chapter 8.

## 10.6 MODES OF VOLCANIC PLAINS FORMATION

### 10.6.1 Earth, Mars, and the Moon

The form that volcanism takes is highly dependent on the composition of the lava, and the volume and rate at which it is erupted. The more silica a magma contains in proportion to its *bases* (iron (Fe), magnesium (Mg), calcium (Ca), sodium (Na), etc.) the higher its viscosity. Silica forms tetrahedra which are bound together in the liquid. This tetrahedral network resists the change of shape of the liquid, and, therefore, restricts its freedom to flow. With a large content of bases, chaining of tetrahedra is less extensive and flow is easier.

On Earth, lavas rich in Si, aluminum (Al), Na, and potassium (K) and poor in Fe and Mg are extremely viscous and form short, thick flows or domes. They usually contain large amounts of gas (primarily water vapor and carbon dioxide [$CO_2$]) that can be released explosively to form extensive ash deposits. This type of volcanism can form two major volcanic landforms, composite volcanoes (also called stratovolcanoes) and ash flow plains. Composite volcanoes are composed of alternating layers of lava (usually andesite) and ash that form large conical mountains like Fujiyama in Japan. Ash flows are enormous volumes of ash that are erupted from the flanks of composite volcanoes resulting in their collapse and formation of calderas.

Lavas rich in Fe and Mg and with $SiO_2$ content varying from about 45–57% are very fluid. These basaltic lavas are composed of plagioclase feldspar, olivine and pyroxene. But each of those three constituents comes in multiple compositions and crystalline structures. Thus one basalt may be different chemically and mineralogically from another even though they share a similar broad mineralogy of pyroxene, plagioclase feldspar, and olivine. Basalt eruptions can produce either huge domical mountians with summit calderas, called shield volcanoes, or extensive plains called plateau or flood basalts. On Earth, shield volcanoes are formed over mantle plumes whose positions are stable beyond the timescale of plate tectonics. Therefore, plates move over these plumes to produce chains of shield volcanoes. The Hawaiian Islands with its huge shield volcano Mauna Loa is the best known example. Large shield volcanoes also occur on Mars and Venus, but none occur on the Moon and none have been observed on Mercury.

Flood basalts on Earth are also thought to be associated with unusually large mantle plumes called superplumes. They are the result of voluminous fissure eruptions of basalt that produce extensive plains covering thousands of square kilometers. The fissures that give rise to these flows are usually covered by the lava so the sources of the flows are rarely visible. Large deposits of flood basalts occur in India, Brazil, Africa, and the United States. In the United States, the Columbia River flood basalts cover about 220,000 km$^2$ of Washington, Oregon, and Idaho. Individual flows average about 25 m thick, and the estimated volume of these deposits totals 195,000 km$^3$.They were erupted about 15 million years ago. Flood basalt eruptions are the most common type of volcanism on Mars, Venus, and the Moon. There, they produce vast areas of thick basaltic lava plains. The lunar maria, the plains of Venus, and the intercrater plains and much of the Northern Plains of Mars are probably flood basalt deposits. Martian meteorites all have a basaltic composition, as do the returned *Apollo* mare samples. The lunar maria are flood basalts that were erupted over a period of more than one billion years. They cover about 17% of the surface with an estimated volume of 10 million km$^3$. Some individual lava flows have traveled more than 350 km. Venus flood basalts cover about 70% of the planet.

### 10.6.2 Terrestrial magmas and temperature

The way in which the many forms and composition of minerals combine is complicated and the subject of *petrology*. The most *refractory* magmas are those rich in Mg. A refractory substance is one that freezes at a high temperature and must be raised to a high temperature to melt. When Fe is added to the magma the melting point is lowered slightly because FeO is less refractory. High temperature magmas contain Fe, Mg, and other refractory elements like Titanium (Ti). High Mg basalts are the most refractory. When such magmas are flowing they are very fluid. As the Na, and K abundance increases the Fe may decrease. On Earth, magma bearing significant Na and/or K cools to form alkali basalt. But there are also volcanic rocks on Earth of the high alkali type that extruded from relatively high in the magma chamber at relatively low temperatures after the deeper magma chambers have cooled and crystalized removing much of the Fe and Mg from the magma mix. Such magmas may be rich in alkali metals such as Na, K, Lithium (Li), and low in Fe and Mg. The silica content of such magmas may be less than in typical Fe and Mg-bearing magmas, especially if the Al content is enriched. In this case alumino silicate lavas may result. As the aluminum and alkali abundances increase, the $SiO_2$ content will decrease (some of the silica combines with the aluminum) forming feldspathoid lavas that are more viscous, but may still flow for distances of many km across the surface. The more *viscous* feldspathoid lavas remain liquid at lower temperatures than the high temperature Mg-rich basalts. Table 10.1 lists the extrusion melting point, viscosity, and liquid density of some common lavas.

Other more or less exotic conditions may produce lava flows of compositions that have less common names and are of less common occurrence on Earth. Ash flows are also very fluid and, as mentioned in Section 10.6.1, may cover large surface areas.

Water in magma has two effects:

(1) If a hot magma is coming from a deep resevoir and contains considerable water it becomes very explosive when pressure is released suddenly, producing pyroclastic cinders, beads and glasses.
(2) Water also reduces *viscosity* and is associated with volcanic lavas that flow long distances. A fluid medium to high temperature iron bearing magma is produced that can spread over considerable distances but still build a shield type volcano. Probably many lava flows on the flanks of the Olympus Mons volcano on Mars

**Table 10.1.** Melting points, viscosities, and denities of some common lavas.

| Rock Type | Extrusive Melting Point (°C) | Extrusive Viscosity (Poise) | Liquid Density (g/cm3) |
|---|---|---|---|
| Lunar Basalt (~40% $SiO_2$) | 1300–1400 | 10 | 2.7 |
| Olivine Basalt (~45% $SiO_2$) | 1100–1200 | 100–1000 | 2.7 |
| Tholeiitic Basalt (~50% $SiO_2$) | 1100–1200 | 1000–10,000 | 2.6 |
| Andesites (~62% $SiO_2$) | 1000–1100 | $10^6$–$10^7$ | 2.4 |
| Rhyolites (~75% $SiO_2$) | 800–900 | $10^{10}$–$10^{11}$ | 2.2 |

were formed by relatively water-rich basalts, perhaps of medium temperature coming from mid-level resevoirs, rich in iron. However, on the Moon the mare lavas are highly depleted in volatile elements and lack water. The very low viscosity of lunar basaltic lava (10 poise compared to 100–1000 poise for terrestrial olivine basalt) is the result of a relatively low abundance of $SiO_2$ (40%) and a high abundance of Fe, Ti and Mg, not water content.

### 10.6.3 What type of volcanism occurred on Mercury?

There is no morphological evidence for silica-rich volcanism on Mercury, nor is there any evidence for plate tectonics. The morphology of apparent volcanic plains is similar to flood basalts on the Moon and other terrestrial planets. This suggests that they were emplaced in a fluid condition. No large volcanic constructs are evident, as occur on Mars, Venus, and Earth, which further suggests the plains were erupted in large volumes from widely distributed sources, presumably fissures. From this evidence it is inferred that the plains are the Mercurian equivalent of flood basalts. Because of spectral evidence presented in Chapter 8, it is likely that basalts are of the Mg-rich or alkali-rich variety rather than the Fe-rich basalts common on Earth and the Moon. Spectroscopic measurements of Mercury's surface and of the thin atmosphere suggests that some of the smooth plains may be more alkali-rich than one would expect of a typical Mg-rich flood basalt especially around and in Caloris basis where enhancements of emissions from neutral potassium in the exosphere have been observed.

If the origin of both the intercrater and smooth plains is volcanic, then Mercury has experienced a period of volcanism much more extensive than that on the Moon. This would be consistent with thermal models that predict a thermal history with heating and melting a larger volume on Mercury than the Moon.

### 10.6.4 Compositions of Mercury's plains

As discussed in Chapter 8, telescopic observations of Mercury have found Mercury's surface is low or lacking in FeO. However, there is evidence for pyroxene (both orthopyroxene and clinopyroxene) and alkali elements. At first, these two observations may seem incompatible. But there are at least two ways in which these different types of volcanics could both be located and observed in the intercrater plains on Mercury. (1) There could have been an early volcanic event from deep within Mercury at the time the Fe was differentiating into the core of the planet with the Mg-rich fluid material covering great extents over Mercury's surface. Then in the late part of the heavy bombardment another volcanic episode could have begun where more shallow lavas, rich in alkalis and lower in $SiO_2$ and containing Ca-bearing pyroxene and feldspathoids were released in localized regions. Such basalts are called tephrite. (2) Another possibility is that following the early volcanism of Mg-rich basalts volcanism stopped. Near the end of the heavy bombardment or even later, excavation by impact cratering uncovered the highly differentiated alkali-rich material and exposed it at the surface in one or more locations. In fact, an anorthisitic crust may be overlain by basalts of varying composition. As mentioned earlier, *Mariner 10* recalibrated color ratioed images suggest Kuiper and Muraski craters may have excavated into such material. This material could be anorthosite. Anorthosite is a bulk rock formed from fractional crystallization as discussed earlier. It is composed of at least 90% plagioclase feldspar and up to 10% pyroxene. As we saw in Chapter 8, a spectrum from Mercury shows great similarity to a spectrum from a lunar breccia composed of 90% plagioclase feldspar and 10% pyroxene. The Mercury spectrum was from the intercrater plains. It appears from mid-IR spectroscopy that the feldspar in Mercury's intercrater plains may be more Na-rich than that of the lunar anorthosite which is generally Ca-rich. It is also interesting to note that when imaging the Na in Mercury's thin atmosphere, enhanced emission of Na was observed over the Kuiper/Muraski crater complex. The Na could be baking out of Na-bearing plagioclase feldspars that have been relatively recently excavated.

### 10.6.5 Mercury's smooth plains composition

Several mid-IR spectra have been obtained from 205–240° giving evidence for low Si and, perhaps mafic mineral content. This region is west of the smooth plains in and north of Tolstoj on the unimaged side of the planet. Other spectroscopic evidence for low Si content is just east of 15° longitude, again on the side unimaged by *Mariner 10*.

A low-Si (undersaturated in silica) and alkali-rich signature is consistant with feldspathoidal-bearing basalts and the high K abundance observed over the smooth plains in a near Caloris basin. Smooth plains are also formed from impact melt on the floors of craters formed in energetic impacts. The differentiation of these melts may have resulted in unusul compositions, especially if the target material was low in FeO and rich in alkalis. The earth-based spectra may, at least, in part represent these compositions.

The sophisticated spectrographs on the *MESSENGER* spacecraft will determine the chemical composition at high spatial resolutions. This, combined with other geological data, should greatly help characterize these plains units and finally answer the puzzling questions that remain regarding the geochemical make-up and history of Mercury's surface.

# 11

# Tectonics

Crustal deformation (tectonics) occurs on Mercury, the other terrestrial planets, and the Moon. Crustal deformation is the result of stresses in the outer layers of a planet that are produced by thermal and/or mechanical processes. This deformation forms characteristic structures (faults and/or folds) that reveal the nature and direction of the stresses responsible for their formation. Mercury appears to have a tectonic framework which is unique in the Solar System.

## 11.1 FAULTING

In order to understand the causes and history of crustal deformation, three major characteristics must be determined: 1) the type of deformation must be identified. This can be accomplished by studying the morphology of the structures and the way they displace or deform the surface. 2) the distribution and orientation of the structures, and the time they formed must be determined. This procedure involves plotting the structures on a map, measuring their orientation, and observing their age relative to other landforms (for example, faults that cross craters or other terrain are younger than the craters and terrain. Conversely, if a fault is disrupted by a crater or is partially buried by plains, then it is older than those landforms). 3) the nature and distribution of the stresses that caused the deformation must be inferred from the types of structures, their distribution, and the pattern they form.

Unfortunately, not all of these characteristics can now be determined for Mercury. Since only about half the planet has been explored we do not know the global distribution of the tectonic features. To make matters worse, only about 25% of the surface was viewed at sun angles low enough to undertake terrain analysis. Therefore, tectonic features that occur in areas viewed at high sun angles are probably not discernable. So, in essence, only about 25% to 30% of the planet