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 has been tectonically mapped. However, even this amount of mapping is sufficient to constrain certain tectonic models.

11.1.1 Fault types and mechanics

There are three basic types of faults: 1) normal, 2) thrust, and 3) transverse (Figure 11.1). Each is formed by a different stress regime. A convenient way to visualize these regimes is to consider the stresses as directed along three principal axes at right angles to each other. One axis is the maximum principal stress, another is the intermediate principal stress, and the third is the minimum principal stress. The orientation of these principal stress axes with respect to the surface determines the type of fault that forms. Faults form at an angle between the maximum and minimum stress axes and parallel the to intermediate stress axis. If the type of fault is known, then the orientation of the principal stresses can be inferred.

If the crust of a planet is stretched or pulled apart it is in tension. When this occurs the lateral or confining pressure is eased, and the weight of the rocks acting vertically exerts the greatest stress on the crust. In this case, the maximum stress axis is perpendicular to the surface, and the minimum and intermediate stress axes are parallel to the surface. If the maximum stress exceeds the strength of the rocks, then the crust will fracture. It will break along a fault plane that is inclined at a steep angle between the maximum and minimum stress axes and parallel to the intermediate stress axis. One block will move downward along a fault plane sloping toward the down-dropped block. This type of fault is called a normal fault. It is also called a tension fault because it forms when the crust is under tension. Another term for this type of fault is gravity fault because the maximum stress is vertical and due to the force of gravity acting on the rocks. Often this type of fault forms troughs where a section of the crust slides downward between two oppositely facing normal faults. In this case it is called a graben.

The opposite situation occurs when the crust is pushed together or compressed. Here the stress field is reversed with the maximum stress axis parallel to the surface and the minimum stress axis vertical. Again the crust breaks along a fault plane inclined at an angle between the maximum and minimum stress axes and parallel to the intermediate stress axis. In this case, however, one block is pushed or thrust over another block along a gently sloping fault plane that dips beneath the overthrust block.

The third type of fault forms when both the maximum and minimum stress axes are parallel the surface and the intermediate stress axis is perpendicular. Again the fault plane forms at an angle between the maximum and minimum stress axes, but in this case the fault plane is vertical and one block slides past the other with little vertical movement. This type of fault is rare/absent on the Moon, Mars, and Mercury, rare on Venus, but relatively common on Earth where they form one of the plate boundaries called transform faults. The San Andreas fault of California is a well-known example of a transverse fault, that forms the boundary between the Pacific and North American tectonic plates.

In summary, normal faults result from tension that pulls the crust apart and causes crustal lengthening. Thrust faults are due to compression that pushes the crust together, causing crustal shortening. In transverse faulting two segments of the crust slide by each other and the surface area is conserved (neither crustal lengthening or shortening) (Figure 11.1).

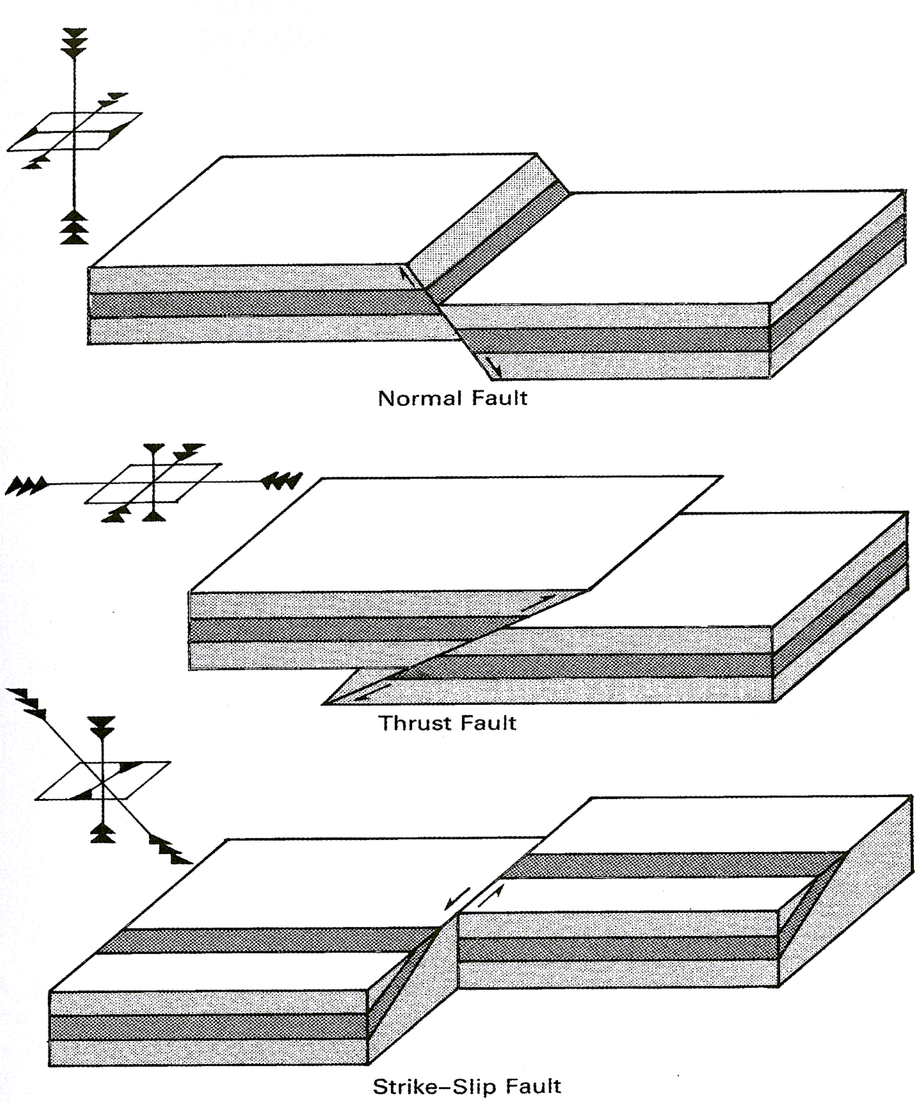


Figure 11.1. These diagrams show the three basic types of faults and the orientation of the stress field that causes them. Normal faults caused by tension are rare on Mercury, and strike–slip faults have not been confirmed. Thrust faults which are very common on Mercury form the lobate scarps. Normal faults represent crustal lengthening, thrust faults represent crustal shortening, and area is conserved for strike slip faults (from Strom, 1987).

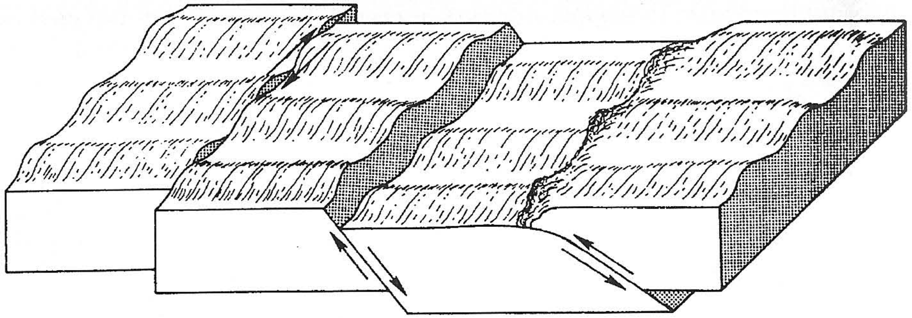


Figure 11.2. The three types of faults exhibit different surface expressions; see text for explanation (from Strom, 1987).

11.1.2 Topographic expression

Each type of fault has a different topographic expression. Normal faults or grabens form linear or arcuate scarps or troughs that vertically displace the topography they transect; their scarps are generally steep with sharp crests. Transverse faults are very straight, show little vertical relief, and laterally displace the landforms they transect. Thrust faults vertically displace the surface, but their crests are rounded because the fault plane dips beneath the overthrust block, producing an overhang that is unstable and collapses under its own weight. The surface trace is usually sinuous, because the fault plane slopes at a low angle and forms a meandering path as it cuts across different elevations. Thrust faults also push one portion of the surface over another so that landforms are shortened (Figure 11.2).

11.2 MERCURY'S LOBATE SCARPS

One of *Mariner 10*'s most important discoveries was the observation of long, sinuous cliffs or scarps that traverse Mercury's surface for hundreds of km. They were termed lobate scarps because they are characterized by rounded and lobed fronts that wind across the surface. Their lengths vary from about 20 km to over 500 km, and they can reach heights of about 1.5 km or more. Earth-based radar has determined heights of 700 m and widths of over 70 km for some of these scarps. Also, shadow, photoclinometry and several stereoscopic measurements have provided some good topographic determinations. The scarps transect a variety of terrain including craters, intercrater plains and smooth plains. Landforms that are transected by these scarps are displaced, indicating they are indeed faults. Similar faults occur on the Moon and other terrestrial planets.

11.2.1 Thrust faults

Mercury's lobate scarps have a surface expression exactly the same as that expected of thrust faults (Figures 11.3 and 11.4). They are sinuous scarps with rounded crests that in some cases greatly distort the craters they transect. One outstanding example is Guido d'Aresso crater whose rim is cut by a thrust fault named Vostok. The northeast part of this crater has been thrust over the southwestern part, causing a shortening of the crater's diameter and a 10 km horizontal offset of its rim (Figure 11.5).

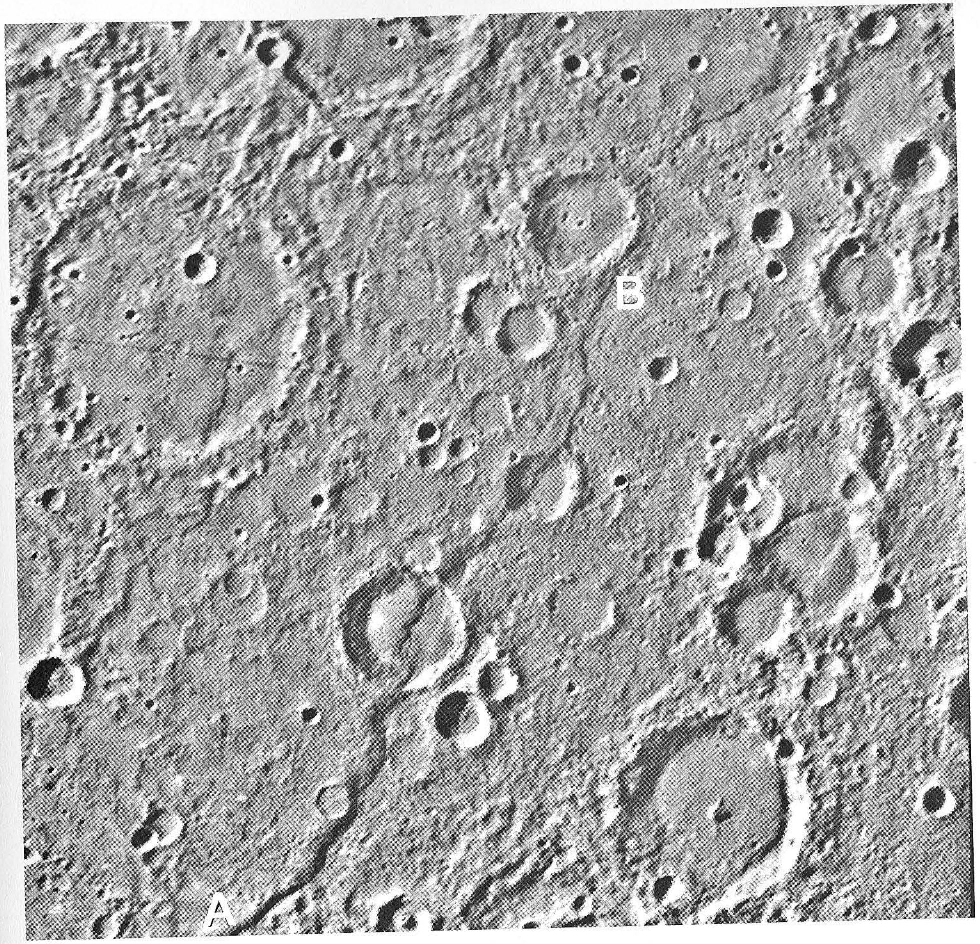


Figure 11.3. This is Discovery fault that traverses Mercury's surface for about 400 km from A to B. It is one of the largest viewed by *Mariner 10*, and reaches about 1.5 km high.

11.2.2 Distribution and age

Where topographic analysis is possible, lobate scarps are found on all types of terrains and in almost all regions viewed by *Mariner 10*. They appear to be evenly distributed in the equatorial, mid-latitude and polar regions of the explored part of Mercury. Lobate scarps also show no preferred orientation, although there is a slight

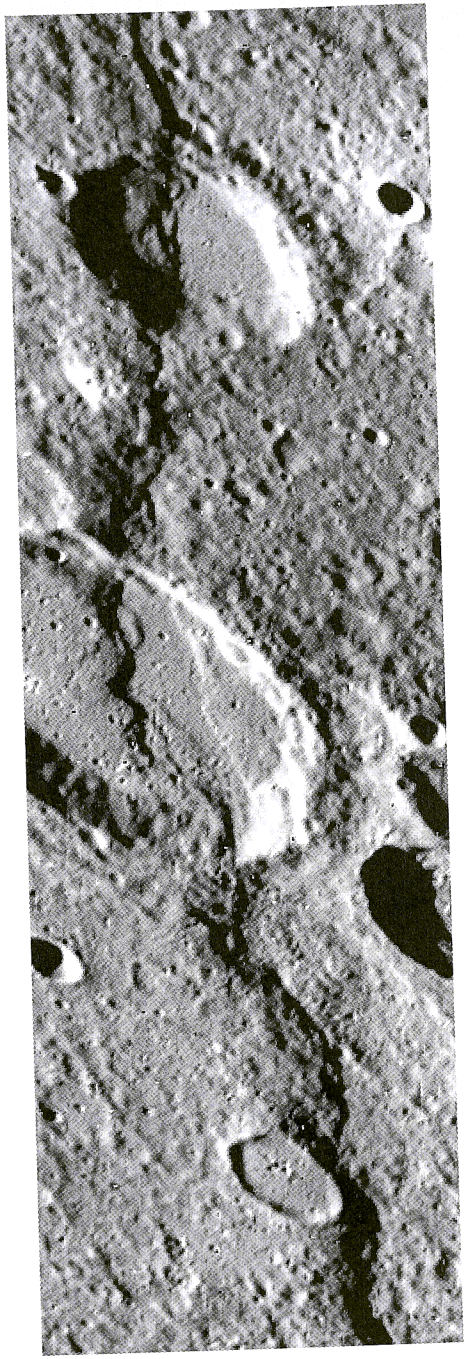


Figure 11.4. This high-resolution image of Discovery fault was taken by *Mariner 10* on its third encounter with Mercury.

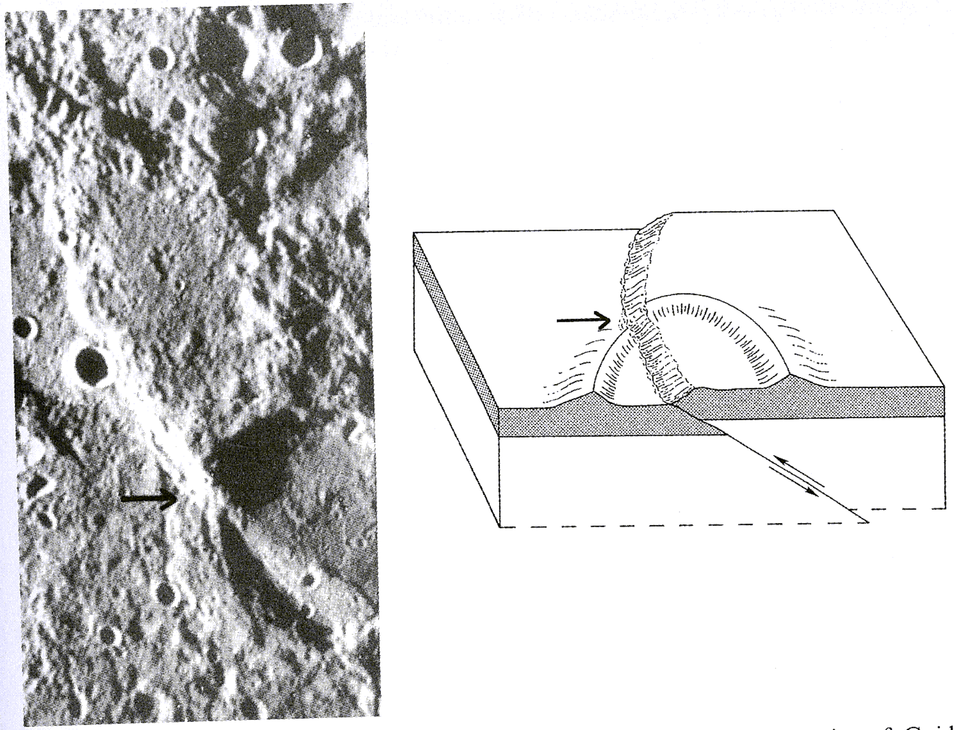


Figure 11.5. This image shows Vostok scarp (130 km long) displacing the rim of Guido d'Arezzo crater by about 10 km (arrow). The diagram on the right illustrates how the thrust fault has shortened the diameter leading to the horizontal offset (arrow). Guido d'Arezzo crater is 65 km diameter.

tendency for N 45° W and N 45° E directions. The more-or-less random distribution of thrust faults on the explored part of Mercury suggests that they may, in fact, be similarly distributed across the entire surface of the planet. If this turns out to be the case, then the planet experienced a period of global compression, and a net decrease in surface area since the compression began.

The time of formation of lobate scarps can be estimated from the age of the thrust faults relative to various terrain units. The scarps cut across the intercrater plains and all relatively old degraded craters in the highlands. There is no instance on the explored side where intercrater plains embay a thrust fault. Craters that disrupt faults are all relatively young with fresh-appearing morphology. These structural relationships suggest that the onset of scarp formation (compression and planet contraction) occurred after intercrater plains formation and at a time when the period of heavy bombardment was declining. If the period of heavy bombardment was a cataclysmic event, then scarp formation occurred after this event which ended about 3.8 billion years ago. The age of the scarps relative to smooth plains formation is more difficult to assess. They are very common on the plains within and surrounding the Caloris basin, but these scarps are probably related to subsidence of the basin floor and surroundings. The areas of smooth plains in the uplands appear to be somewhat deficient in lobate scarps compared to the surrounding terrains. However, these areas are rather small and it could be that the seeming paucity is not real. Future explorations will be needed to solve this problem. It appears that the tectonic framework represented by the lobate scarps began relatively late in Mercurian geologic history; possibly about 3.8 billion years ago.

11.2.3 The shrunken planet

With certain assumptions, the amount of decrease in surface area can be estimated from the total length and height of the scarps, and the inclination of the fault planes. The amount of horizontal displacement or crustal shortening along a thrust fault is simply the length of the fault multiplied by the vertical displacement divided by the tangent of the fault plane inclination. The lengths of the faults are readily measured. The vertical displacement is probably close to the heights of the scarps, but these heights are more difficult to measure. Scarp heights have been measured from the shadows they cast or by some Earth-based radar profiles. They appear to range in height from a few hundred meters to maybe as much as 2 km for Discovery Rupes. Furthermore, the faults often have a rounded crest which is higher than the height that is casting the shadow. In these cases the heights are a minimum. In the calculations it is assumed that the average height of the scarps is about 0.5–1 km. The inclination of the fault plane is considerably more difficult to estimate. On Earth thrust faults have fault plane inclinations ranging from about 45° (high-angle reverse faults) to about 25° for most thrust faults. However, for thrust faults the angles can vary widely and the faults can be imbricated. This means that they can be made up of a series of low-angle fault planes. In fact, the Vostok scarp appears to show several layers which could be individual fault planes of an imbricated thrust fault. The sinuous morphology of the Mercurian faults is much more compatible with thrust faults than high-angle reverse faults. Therefore, it is much more likely that the fault planes dip at angles closer to 25° than 45°. If it is assumed that the average fault plane inclination is 25° and that the average vertical displacement is from 500 m to 1 km, then the amount of crustal shortening can be estimated. It also must be assumed that the number and lengths of the faults measured on about 25% of the surface is representative of the other 75%. With these uncertainties in mind, the surface area lost because of crustal shortening is estimated to be about 31,000 to 63,000 km^2. This implies that Mercury's diameter has decreased by about 1–2 km since the onset of compression. Although there is much uncertainty involved in these estimates they are probably good to within about a factor of 2. The age of the faults suggests the global contraction began about 3.8 billion years ago. This places constraints on Mercury's thermal history and other tectonic models.

If the assumptions used for these calculations, particularly the global distribution of thrust faults, prove to be true from future explorations, then Mercury is truly unique in the Solar System. No other planet or satellite has had its entire crust shortened and its diameter decreased from tectonic activity. The cause of this contraction is probably cooling of its crust and mantle, and, particularly, its enormous iron core.

11.2.4 Thrusting, lithospheric and crustal thickness

Mechanical modeling of Discovery Rupes gives some idea of the faulting parameters, and the thickness of the lithosphere at the time of faulting. Based on *Mariner 10* stereo images that cover the area of Discovery Rupes, the maximum height is about 1.5 km. Furthermore, there appears to be a parallel trough about 40 km wide located 90 km behind the scarp. The trough is interpreted to be a syncline that defines the dimension of the upper plate of the thrust fault. Mechanical modeling suggests that the fault plane inclination is about 30–35° with a displacement of about 2 km. The depth of faulting is estimated at about 35–40 km which should be the thickness of the lithosphere at the time of faulting ~3.8 billion years ago. If the limiting isotherm for Mercury's crust is about 300–600°C and it occurred at a depth of 40 km, then the corresponding heat flux at the time of faulting was about 10–40 W/m^2, which is less than old terrestrial oceanic lithosphere. Since Mercury has long-wavelength topography only certain combinations of crustal thickness and thermal structure are possible. This together with the faulting data suggests that the concentration of radiogenic elements in the crust and mantle of Mercury is at least 80% that Earth's value, and that the present thickness of the crust is about 100–200 km.

11.3 OTHER TECTONIC STRUCTURES

Although thrust faults dominate the tectonic framework of Mercury, there are other tectonic structures that are much less prominent or have a much more limited distribution.

11.3.1 Grabens and normal faults

At least the side viewed by *Mariner 10* is remarkably free of structures indicative of tension. Only the grabens and valleys (probably also grabens) on the floor of the Caloris basin and the jumbled terrain of the hilly and lineated terrain are due to tensional stresses. However both of these structural provinces are either the direct or indirect result of the Caloris basin impact. The grabens on the floor of the Caloris basin are probably due to an uplift of the floor following the formation of the interior plains and its ridges. The hilly and lineated terrain was caused directly by seismic waves generated by the Caloris basin impact and focused at the antipodal region (see Chapter 9).

11.3.2 Linear structures

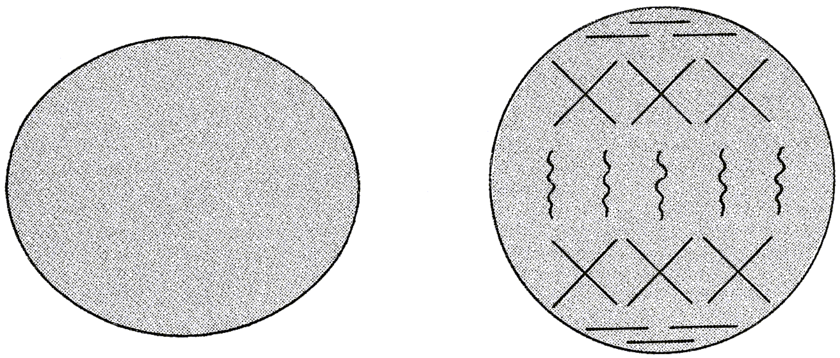
Another less prominent set of linear features may have a tectonic origin. They consist of linear portions of crater rims and linear ridge-like structures. These lineations trend in two main directions, northeast and northwest, with a weaker north–south direction. This may represent an ancient fracture pattern formed very early in Mercury's history. The much younger valleys in the hilly and lineated terrain also trend in the same two main directions. They may have formed along fractures of this system when the region was disrupted by the Caloris impact-generated seismic waves.

The linear portions of crater rims may have formed by slumping or preferential excavation along zones of weakness associated with a pre-existing fracture pattern. These linear rims occur on more degraded older craters as well as the younger ones. This indicates that the fractures were present before the old craters, and, therefore, established very early in Mercurian history.

11.3.3 Despinning fault pattern

Mercury may have rotated much faster just after its formation and was subsequently slowed by tidal forces until it was captured into the present 3:2 spin–orbit resonance. During this time of rapid rotation centrifugal forces would have produced an asymmetric shape with flattened poles and bulging equator. As Mercury slowed and the centrifugal forces decreased, its shape would have become more spherical.

When changing from a flattened sphere (oblate spheroid) to a sphere, the bulging equatorial regions would have contracted and the flattened polar regions would have expanded proportionally (Figure 11.6). This process would have produced a stress pattern leading to a unique tectonic framework. The contracting equatorial region would have produced east–west directed compressional stress, with the expanding polar regions inducing north–south directed tensional stresses. In the equatorial regions north–south oriented thrust faults would form and east–west directed normal faults would form in the polar regions. At mid-latitudes this interplay of stresses would produce northeast and northwest trending transverse fractures.



Rapid Rotation

Slow Rotation

Figure 11.6. This diagram shows the tectonic consequence of despinning Mercury from a higher rate. At a higher spin rate Mercury might have flattened poles as shown at the left. As the rotation slowed, it would have become more spherical, causing stresses above the fracture limit. The resulting tectonic framework is show in the right diagram where north–south thrust faults occur in the equatorial region, orthogonal strike–slip faults in mid-latitudes, and east–west normal faults in the polar regions. This type of tectonic framework is not seen on Mercury (from Strom, 1987).

This mechanism, however, cannot account for the present tectonic framework of lobate scarps for four reasons. Firstly, the lobate scarps are just as abundant in the polar regions as in the equatorial regions. Secondly, no normal faults (tension) are found in the polar regions. Thirdly, the lobate scarps have a more-or-less random orientation, and, Fourthly, they are relatively young features that post-date the lineament system. However, the northeast and northwest systems of ancient lineations may be the remnants of a transverse fracture system caused by planetary despinning. The ancient age of this fracture pattern indicates that, if this despinning occurred, it did so very early in Mercury's history, probably before the formation of intercrater plains and many of the older craters.