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SUMMARY

Although our knowledge of the Moon and the terrestrial planets is incomplete and each has evolved differently, some general conclusions can be stated. The evolution of planetary surfaces depends on the interplay of four types of geologic processes: (1) impact cratering, (2) volcanism, (3) tectonism, and (4) interaction with the atmosphere and hydrosphere. The relative roles of the different processes vary with time, the size of the planetary body, and with atmospheric conditions at the surface.

IMPACT CRATERING

The Moon, Mercury, and Mars all have heavily cratered surfaces, which record a period of intense bombardment early in their histories. Since these bodies span the entire range of inner planet distances (0.38–1.5 AU), there can be little doubt that both Venus and Earth were also subjected to the same bombardment. Absolute ages of returned lunar samples demonstrate that, at least for the Moon, the period of heavy bombardment ended about 3.8 billion years ago. Presumably it ended at about the same time on all the terrestrial planets. On Earth, the record of early, heavy bombardment has been entirely erased because of high rates of volcanism, deformation, erosion, and burial. The oldest areas of Earth's surface, the Precambrian shields, are mostly 1 to 3 billion years old; the oldest rocks so far dated are 3.8 billion years old. The shields retain numerous old impact scars but even these post-date the heavy bombardment. Information on Venus is still inadequate to determine the extent to which its cratering record has been preserved, but radar images show large circular features which have been interpreted as impact craters and basins.

The shapes of the crater size/frequency distribution curves for the heavily cratered regions of the Moon, Mercury, and Mars are similar, suggesting that the population of objects responsible for the heavy bombardment was the same throughout the inner solar system. Conversely, the shapes of the size/frequency distributions of the younger craters that are superposed on the lunar maria and Martian plains are similar to each other but somewhat different from those of the highlands, which suggests a different population of objects may have caused the later craters. The origin of the two populations of impacting bodies is uncertain. Orbit dynamical studies suggest the period of heavy bombardment may be due to (1) the impact of a long-lived tail of accretional remnants left over from the formation of the terrestrial planets, or (2) the impact of fragments of large planetesimals perturbed into the inner solar system by the outer planets and tidally disrupted by close approaches to Earth or Venus. The present orbits of comets and Apollo and Amor asteroids have orbits that cross those of the terrestrial planets and these objects must have been dominant contributors to the cratering record in the inner solar system, at least during the last 3.8 billion years. If these families of objects were also responsible for the period of heavy bombardment, then their flux rates must have been orders of magnitude higher before 3.8 billion years ago than at present.

No matter what the origin of the impacting objects, cratering has clearly had major effects on the surfaces of all the terrestrial planets. Mercury, the Moon, and Mars reveal direct evidence that impacts excavated large volumes of material and fractured deeply into the lithosphere, redistributing material over broad areas and providing foci for later volcanic activity. Similar catastrophic events must also have occurred widely on Earth and Venus during the first 600 million years of their histories, perhaps causing early separation of continental and oceanic areas on Earth, and profoundly influencing the style of deformation. Impacts probably continued to affect geologic and biologic evolution on Earth after 3.8 billion years ago, although to a far lesser extent than before, as suggested by recent debate over the nature of the Cretaceous-Tertiary boundary.

VOLCANISM

The style, mode of occurrence, and duration of volcanism vary considerably among the terrestrial planets. Volcanism on Earth occurs primarily at plate boundaries or in intraplate areas over mantle hot spots. At divergent boundaries, intrusion and eruptions occur along the mid-oceanic ridges as the plates separate. The eruptions are mostly basaltic and formed all the oceanic crust during the last 250 million years. Volcanism at convergent boundaries is more varied, including eruptions of volatile-rich andestic and rhyolitic materials in addition to basalts. Pyroclastic activity is far more common than at divergent junctions, and a greater variety of volcanic landforms are produced. The magmas at convergent junctions are generated, at least in part, by partial melting of the descending plate as it slides beneath the leading edge of the opposing plate. Hot spot volcanism in the interior of plates gives rise primarily to large basaltic shield volcanoes (particularly in oceanic areas) whose sizes are governed by the thickness of the lithosphere and the rate of plate motion relative to the fixed hot spot. Flood basalts are located primarily at the margins of continents where they form extensive plains derived from voluminous fissure eruptions. They appear to be associated with extensive deep-seated fracturing that accompanies breakup of continental plates.

Volcanism on the Moon is dominated by flood basalts primarily in impact basins on the nearside. These lavas originated at subcrustal depths and apparently worked their way through an essentially passive, but fractured crust without storage in shallow magma reservoirs. The concentration of maria on the nearside is probably related to a thinner crust there as indicated by the offset of the center of mass from the center of figure. The thinner crust may be the result of an enormous impact that occurred before most of the more prominent impact basins formed. A thicker farside lithosphere probably prohibited extensive volcanism there except in the deepest basins. Absolute ages of returned samples show that volcanism lasted from at least 3.0–4.0 billion years ago; crater densities suggest that it may have continued to 1 to 2 billion years ago in some areas. After that time, cooling and lithospheric thickening precluded further volcanic activity. The lack of large shield volcanoes suggests that localization of melting in discrete hot spots within the mantle was not important on the Moon.

If both the smooth and intercrater plains on Mercury are volcanic deposits, then volcanic activity was more extensive than on the Moon, and the rate of highland volcanism was higher. The morphology of these deposits and the apparent lack of large volcanic constructs suggests, however, that the style of volcanism was similar on the two bodies. The more extensive volcanic activity postulated for Mercury as compared with the Moon may be related to the formation of Mercury's enormous core, which would have greatly raised internal temperatures and thus caused extensive melting and global expansion. This, in turn, caused tensional fracturing in the thin lithosphere, thereby allowing easy access of magma to the surface. Albedo and color suggest that the Mercurian volcanic deposits are depleted in iron and titanium relative to lunar lavas possibly as a result of more thorough melting and differentiation. How long volcanism persisted on Mercury is unclear; it almost certainly was confined to very early in the planet's history and may have been of shorter duration than on the Moon.

Volcanism on Mars has been dominated by two main types of activity: the formation of lava plains and the building of shield volcanoes. Other types of activity, possibly of a more pyroclastic nature, may have also occurred. Large areas of the northern plains and some intercrater areas of the southern highlands appear to have been flooded by basalts. Unlike the Moon, these plains are not necessarily contained within impact basins and in this respect are more akin to the intercrater plains on Mercury. Large shield volcanoes occur principally in the Hellas, Elysium, and Tharsis regions. The largest and youngest are associated with the Tharsis uplift where they reach heights of about 24 km above their surroundings. The enormous size of the shields is probably the result of a thick lithosphere and the lack of plate tectonics. A thicker lithosphere on Mars, as compared to Earth, results in greater hydrostatic pressures in the magma source regions, which can force magma to higher levels on Mars; while in the absence of plate tectonics the shields remain fixed over the hot spots to allow more lava to accumulate in the same area. Volcanism appears to have persisted throughout most of Martian history although at a progressively declining rate. It was widespread during the first half of the planet's history, forming intercrater plains in the cratered uplands and extensive lava plains elsewhere. During the second half of the planet's history, volcanism was restricted to the main volcanic provinces of Tharsis and Elysium. The most recent volcanism appears confined to the large shield volcanoes in and around Tharsis.

The history of volcanic activity on Venus is still uncertain. At least one mountain mass (Beta Regio) has two components (Rhea and Theia Mons) with shapes like shield volcanoes and one has a summit depression. Both mountains are rough at radar wavelengths, and chemical analyses by Venera spacecraft near the flanks of Beta Regio indicate a basaltic composition. Whether or not floor basalts or forms of more sialic volcanism are also present is not known.

TECTONICS

Each planet has had a distinctive tectonic history. Geologic activity on Earth is at present dominated by plate tectonics. The lithosphere is divided into plates that move relative to one another at rates mostly in the range of 1–15 cm/yr. At divergent junctions, along the crests of mid-oceanic ridges, new lithosphere forms as the plates move apart. Tensional tectonics dominate at these junctions, the most obvious manifestation being the enormous rift valleys along the ridge crests. At most convergent junctions are subduction zones where one plate slides beneath the other and is consumed in the hot mantle below. Mainly compressional tectonics occur at these junctions, creating the linear mountain chains that dominate the topography of the continents and many ocean margins. At other boundaries the plates may move by one another along transform faults, so that each plate is conserved. Plate tectonics has controlled the evolution of Earth's surface for at least the last 500 million years, and possibly for most of its history.

Neither interconnected ridges nor linear mountain chains have been observed on any other planet but Earth. On the Moon, most crustal deformation results from basin subsidence due to loading of the lithosphere by high density flood basalts. Tensile stresses have produced concentric graben at the margins of basins and compressive concentric wrinkle ridges in the interior of basins. Crustal deformation probably ceased shortly after emplacement of most of the mare basalts had been accomplished, around 3 billion years ago.

The tectonic framework of Mercury is unique among the terrestrial planets and is characterized by the widespread (probably global) distribution of thrust or reverse faults. These faults appear to be a manifestation of crustal shortening primarily caused by core/lithosphere cooling aided by planet despinning early in Mercury's history. Thermal history models suggest that extensive melting, global expansion, and tensional fracturing resulted from core formation, although the surface lacks evidence from this early period. Thus, Mercury's tectonic activity appears to be largely the result of formation of the large iron core, and activity probably terminated early in the planet's history.

The tectonics of Mars is dominated by the Tharsis bulge. Radial fractures (mostly graben) centered on Tharsis affect nearly an entire hemisphere, and compressional wrinkle ridges occur around the bulge periphery. Tharsis is also the site of the most recent volcanic activity and a large positive gravity anomaly. Deformation appears to have been most intense during the first half of Martian history but continued to the present at a lower level. Volcanism and faulting took place simultaneously. This extraordinary long period of deformation implies a stable stress system was sustained over much of Martian history. The stresses appear to be caused by the presence of the bulge, that is, by its topography and gravity anomaly rather than the mechanics of its formation. The bulge may have resulted from overturn in the mantle during core formation.

The tectonic framework of Venus is poorly understood. Extensive rifting has occurred, primarily in Aphrodite Terra and Beta Regio, but the rifts do not form a planet-wide network as on Earth. There are also continent-like masses, large mountains, and escarpments, but linear mountain chains or deep linear trenches have yet to be identified. Most of the Venus surface consists of rolling plains with a rather high density of possible impact craters which suggests an ancient surface. These limited data imply a more stable surface than on Earth and no present plate tectonics.

INTERACTION WITH THE ATMOSPHERE AND HYDROSPHERE

Among the terrestrial planets only Earth, Mars, and Venus have significant atmospheres. On Earth the atmosphere has a marked effect on the surface, mainly through the action of water which plays an essential role in two major processes: (1) weathering, the chemical breakdown of rock-forming minerals into mineral assemblages in equilibrium with surface conditions, and (2) gradation, the reduction of surface relief by erosion of the highs and deposition in the lows. The two processes are mutually dependent in that erosion exposes new surfaces to weathering, and weathering makes the surfaces more susceptible to erosion. The rates of erosion and weathering on Earth are so high, compared to most other geologic processes, that on the continents the small scale relief is almost everywhere dominated by the effects of dissection, mainly by water. Only at the larger scales does the imprint of primary processes of tectonism and volcanism dominate.

The Martian surface also retains abundant evidence of interaction with the atmosphere and hydrosphere. Vast sand seas surround the poles, debris blankets appear to have been repeatedly deposited and stripped away at high latitudes, the old terrain is everywhere dissected by valley networks, flood features are present in places, and numerous features suggest the action of ground-ice. Nevertheless, the rate of interaction appears to be orders of magnitude less than on Earth. An ancient cratered surface is well preserved over extensive areas. Where fluvial erosion has occurred its effects are small, having generally been insufficient to erode away the craters. On young surfaces (<2.5 billion years) erosion is almost imperceptible, except at high latitudes. Similarly, weathering has occurred as suggested by probable presence of clay minerals in the regolith, but without erosion to continually re-expose fresh material, weathering is likely to proceed far more slowly than on Earth. The relatively modest role of water in the evolution of the Martian surface results from its instability under the climatic conditions that prevailed for most of the planet's history.

Evidence of the nature of surface-atmosphere interaction on Venus is sparse, but since temperatures are too high for liquid water to exist, rates of interaction may be low. This viewpoint is supported by preservation of a seemingly ancient cratered surface on the planet. However, some interaction must occur. Winds are sufficient to move loose debris; the surface probably reacts with carbon dioxide in the atmosphere; and chemical activity of water at the surface may be comparable to Earth, despite the extremely low humidity. Moreover, early conditions may have been significantly different from those at present, and liquid water could have been stable at one time.

PLANETARY EVOLUTION

During accretion, around 4.6 billion years ago, the growing planets were heated by impacts and compression. Ultimately, internal temperatures reached the melting temperature of iron (or iron oxide or sulfide). The melted iron-rich materials then began gravitating toward the center, thereby releasing large amounts of energy and causing pervasive melting of the silicates of the interior. This in turn led to extensive outgassing and separation of aluminum and silicon rich materials to form the crust. These events probably all took place within the first few hundred million years, during which the planet continued to be heavily bombarded by interplanetary debris.

By the time the impact rates started to decline, around 3.8 billion years ago, each planet had a rigid crust able to retain a record of the impacts. Also by this time, Mercury and the Moon had lost any volatiles that had outgassed. The subsequent history of each planet depended to a large extent on the balance between heat dissipation and heat production by radioactive decay. Internal activity on the smaller, more efficient heat dissipators, Moon and Mercury, declined rapidly. Activity on the somewhat larger Mars declined more slowly, while activity on the much larger Earth was sustained at a high level. By this reasoning internal activity on Venus should have continued.

Two circumstances caused Earth to evolve along a path radically different from the other planets. First was development of plate tectonics and second was maintenance of conditions at the surface such that liquid water is stable. Why these two circumstances should have coincided only on Earth is unclear. Plate tectonics and the action of water have caused relatively rapid recycling of Earth's near-surface materials, partly through ingestion of the entire lithosphere at subduction zones and the re-emergence of the materials close to the surface as volcanic and plutonic rocks, and partly through mixing within the lithosphere by the processes of weathering, erosion, transport, burial, and metamorphism. No comparable recycling occurs on Mars, Moon, or Mercury; their surfaces are orders of magnitude more stable than Earth's. The extent to which the Venusian surface materials have been recycled is unclear. Water is now unstable at the surface and most evidence suggests that there are no plate tectonics. But our perception of the style of current geologic activity on Venus is still very vague. Moreover conditions could have been very different in the past.

Thus, Earth is a dynamic planet on which is preserved a rich and diverse record from the recent geologic past, but only a poor record from the first half of its history. In contrast, the other terrestrial planets, with the possible exception of Venus, preserve a rich record from their early history, after which time their surfaces remained essentially unchanged.