NASA

Technical Memorandum 78051

COMPARATIVE PLANETOLOGY: SIGNIFICANCE FOR TERRESTRIAL GEOLOGY

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JANUARY 1978

National Aeronautics and
Space Administration

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(NASA-TM-78051) COMPARATIVE PLANETOLOGY: SIGNIFICANCE FOR TERRESTRIAL GEOLOGY (NASA) 18 p HC A02/MF A01 CSCL 08G

N78-32634

Unclas

G3/46 33092

TM 78051

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INTRODUCTION

The term "comparative planetology" was apparently first used by George Gamow in his popular classic "Biography of the Earth" (1948), but as a science such studies had to await the era of spacecraft exploration of the inner solar system. A major milestone in that exploration was reached with the successful landing of both Viking spacecraft on the surface of Mars during the summer of 1976. Earlier major events in this study of the terrestrial planets included the Mariner 10 triple flyby of Mercury, the highly successful Mariner 9 orbital mission to Mars, numerous Mariner and Venera spacecraft directed to Venus, and the manned and unmanned lunar missions which have returned 850 pounds of the Moon's surface to the Earth. The knowledge accumulated from these and related programs presents a broad picture of planetary and solar system evolution; it is a picture into which the Earth fits very well. The age of payoff for understanding the Earth through studies of other planets has arrived, and we present below one example where the comparative approach has provided invaluable insight into one of the most fundamental problems in the development of the Earth: the early evolution of the crust.

THE EARTH IN CONTEXT

It is now generally recognized that the Moon's geologic evolution stopped nearly 3 billion years ago. The lunar surface is therefore a fossilized record of the early processes that shaped its relatively simple surface. The Earth's evolution has been by contrast dynamic and apparently continuous for the last 4.5 billion years; so great is its activity that the Earth has effectively erased the record of what was happening 3 and 4 billion years ago. Perhaps observation of the Moon's early development can constrain the modeling of the Earth's first evolutionary period.

Or can it? Is there any reason to believe that the evolution of the Earth was at anytime similar to that of the Moon or Mars? Do the large size and mass of the Earth mean that its evolutionary processes were radically different from those of the small terrestrial planets? Two observations suggest that the Earth should be regarded not as an anomalous object but merely as the large end member of a sequence of terrestrial planets, a sequence in which increasing size means increasing geologic development and complexity. The first of these observations is that the complexity of the surface features of the terrestrial planets increases with size. As shown in Table I, the Moon is a relatively simple object, whose surface has been dominated largely by impact processes and subsequent volcanic flooding. While these same characteristics apply to a large part of the martian surface, Mars also shows evidence of shield volcanism, crustal warping and rift-style tectonics. These latter features are even more common on the larger Earth, which is the only planet which also has the folds and thrusts of active plate motions.

The second observation is that of the basic crustal structure of the terrestrial planets: all show a two-fold division into low density highlands (on the Earth, continents) and higher

TABLE I

Comparative Data for Terrestrial Planets

Planet	Diameter (km)	Mass (Earth=1)	"New/Old" Crust[1]	Complexity of Crustal Development[2]
Moon	3,476	0.01	30/70	Simple: Impact deformation, basaltic flooding
Mercury	4,864	0.05	?	Simple: Impact deformation, basaltic flooding
Mars	6,738	0.11	40/60	Intermediate: Shield volcanism, uplift, rifting
Venus	12,118	0.81	?	? Shield volcanism (?), rifting (?)
Earth	12,756	1.00	60/40	Complex: Moving plates, spreading, thrusting, folding

[1] Ratio of maria/highlands or continents/ocean basins.
[2] Only the most advanced geologic processes are listed.

density mare (on the Earth, oceanic) type crust. There is a progressive change in this crustal dichtomy with size of the planet, as shown in Table I. Larger planets have a larger fraction of the higher density (in general also the newer) crust. 60% of the Earth's surface is oceanic crust less than 200 million years old. On the Moon the surface is nearly 70% highland crust whose age probably exceeds 4 billion years. Larger planets apparently produce more young high density crust with time than do smaller bodies, and the increase is relatively smooth with increasing size or mass of the planet. While this relation will be better established when more accurate ages are available for the young plains of Mars and Mercury, the implication that the Earth is simply the largest member of the terrestrial sequence is clear.

THE SIMPLE PLANETS

There remain many unanswered questions about the Moon, not the least of which is the nature of its origin. But the combination of ground-based observations, analysis of samples returned from six manned and three unmanned landings, and the photography and geochemistry from orbiting spacecraft serve to reveal a picture of lunar history that in many ways is far more complete than that of the Earth. This becomes obvious when it is realized that nearly all of the rocks returned from the Moon predate 99% of the material found on the Earth.

Several reconstructions of lunar history are available in the literature; all agree on the major events that shaped the crust of this small planet (see, e.g., Taylor, 1976; El-Baz, 1975). The earliest of these was the formation of the global, plagioclase-rich low density crust. Formed by igneous processes between 4.4 and 4.6 billion years ago, this crust remains today as the battered highlands which cover nearly 70% of the Moon, and provides indisputable evidence of an early differentiation for at least the outer parts of the Moon. The scientific importance of this conclusion can not be overstated, for it overturned the earlier popular view that the Moon was a cold, undifferentiated body. The relative importance of accretional versus radioactive heating in this differentiation is not yet established, but the important point remains: if a volatile-poor body as small as the Moon could become differentiated early in its history, than any larger body of roughly the same composition must likewise have been as thoroughly melted and separated as the Moon (Lowman, 1976). In particular, differentiation at a very early stage must be considered a fundamental part of the Earth's evolution.

Spectral analysis of asteroids and meteorities has led to the conclusion that some asteroids, in particular Vesta, are also differentiated (see review by Chapman, 1976a). The above conclusion is therefore strengthened, and early melting and consequential crustal evolution by igneous processes should be a common part of the evolutionary histories of all the terrestrial planets.

The highland crust of the Moon has not remained untouched to the present. Early intense impact cratering has thoroughly brecciated, melted, and mixed the surface. Especially

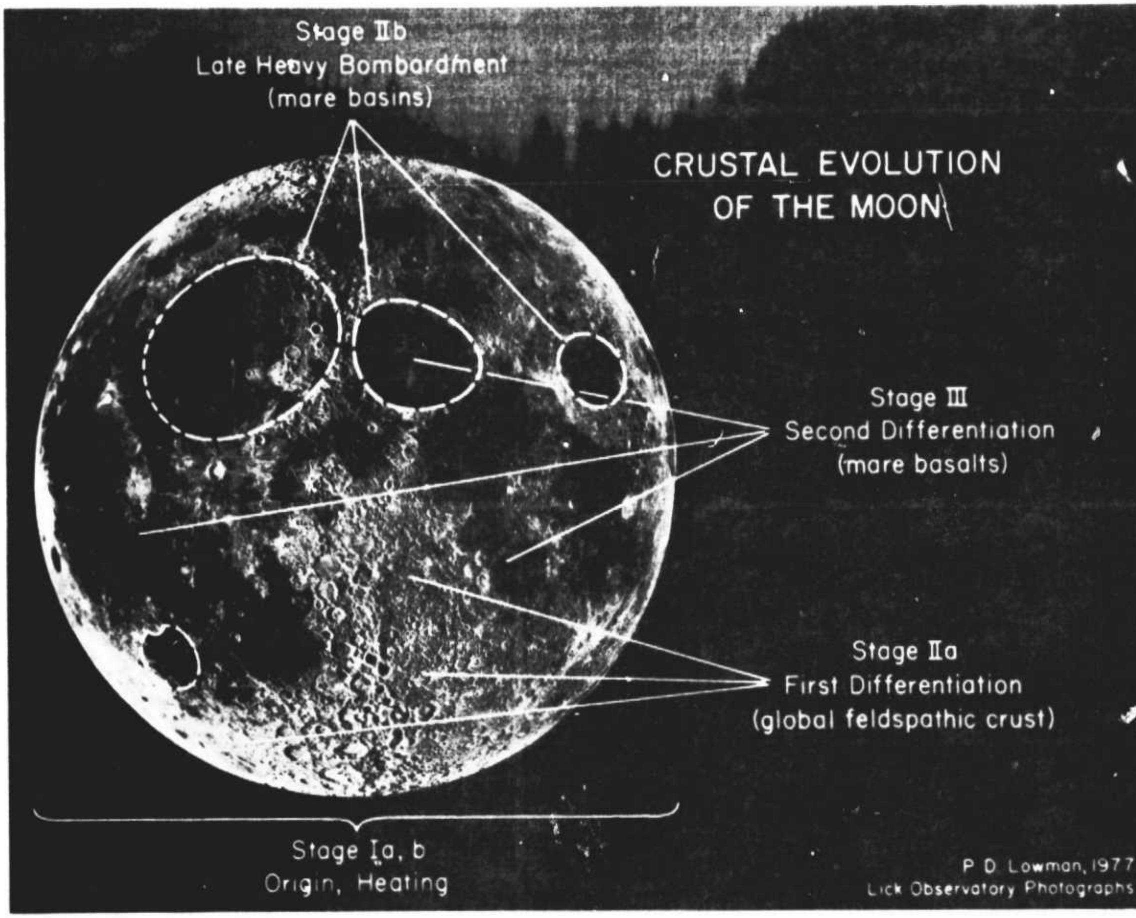

Figure 1.: CRUSTAL EVOLUTION OF THE MOON was brief and simple. The major products of that evolution are shown (after Lowman, 1976). The highlands are the remains of a once global crust produced by the Moon's "first differentiation." Modification of this crust by basin-forming impact cratering was followed by eruption of dark mare basalts, representing a second period of differentiation (or partial melting).

important for lunar history were the formation of the large lunar basins such as Imbrium, Orientale, Nectaris and others. Whether these represent the final sweep-up of the accretional process, or a special flux of objects deflected into the inner solar system is undecided and an area of intense current study (Wetherill, 1975, 1976; Chapman, 1976b). In either case the Earth must also have been pounded by similar objects (Frey, 1977a). On the Moon this basin formation not only created topographic differences of several kilometers, but provided sites for the concentration of the later erupting mare basalts (see below). More significantly these intense impacts battered, heated and scattered the lunar surface, resetting the radiometric clocks in what some have called the "lunar catacylsm" (Tera et al., 1974; see also Hartmann, 1975). Few whole rocks older than 4 billion years survive, but some older dates are seen in fragments of lunar breccias and soils. Lunar history is much more complete following the Orientale impact that signaled the end of this phase of severe external modification of the Moon's crust.

The largest lunar basins on the near side became the sites for eruptions of iron-rich basalts, derived from depths of several hundred kilometers, several tens of millions of years following the impacts (Taylor, 1975). These basalts most likely represent a second differentiation by partial melting of the cumulates left from the "magma ocean" from which was derived the original crust. The period of mare flooding was long, continuing to 3.1 billion years ago in the returned samples. Hundreds of individual flows have been mapped on high resolution images, and in some locations the volcanism may have lasted to 2.7 billion years ago (see El-Baz, 1975). But the major activity ended about 3 billion years ago; with the termination of the mare flooding the active portion of lunar history was over. For the next 3 billion years, during which more and more of terrestrial geologic evolution becomes preserved, the Moon remained a fossilized record of an early and quickly done evolution. Minor volcanic events, declining impact cratering, and mass wasting have little changed the crust. The Moon's evolution, in broad outline, was comparatively simple.

But how representative was the evolution of the Moon? Are the processes which operated there common ones that might be expected to affect the Earth, Mars, Mercury and Venus, or are they some expression of the Moon's rather unique location in the solar system?

The uncertainties of the general nature of lunar evolution were dispelled by the first detailed images of the planet Mercury transmitted from Mariner 10. Revealed was a surface which, despite the large differences in the size, mass, bulk density and location of the planets in the solar system, showed Mercury to be like the Moon not only in its development but also in the extent of its evolution. Highlands, ray craters, maria, giant impact basins are all common to the two planets (Trask et al., 1975). Spectral studies suggest similarities in surface composition. Only the large, one-sided scarps are unique to Mercury; these have been interpreted as thrusts caused by crustal shortening in response to cooling of Mercury's large iron core (Strom et al., 1975).

This large iron core distinguishes the interior of Mercury from that of the Moon. As Bruce Murray has said: "Mercury is like the Moon on the outside, but like the Earth on the inside." The exterior implies that lunar and mercurian crustal evolution were remarkably similar (Murray et al., 1975). It is now clear that the Moon is not some solar system freak but a typical terrestrial planet whose aborted evolution was controlled by its small size. The formation of a global crust, bombardment by basin-forming objects and subsequent flood volcanism seem to be a natural part of the evolution of these small and simple worlds.

INTERMEDIATE PLANETS

Mars is nearly twice the size of the Moon, but the first closeup pictures of its surface from Mariner 4 in 1965 suggested a very Moon-like world. Had these been representative of the entire planet, Mars would have been a primitive world and little comparison with the Earth would have been possible. Mariner 9 showed that despite a surface dominated by lunar-type structures, Mars is really a hybrid planet (Masursky, 1973; Carr et al., 1973). In many ways Mars looks like a Moon trying to become an Earth. Shield volcanoes exist which dwarf the largest comparable features on the Earth. These alone indicate an Earth-like development for some parts of Mars, but also demonstrate the effect of the mobility of the Earth's surface on constructional volcanics. Carr (1973) has suggested that the large size of the martian shields is due to the lack of horizontal transport of the martian lithosphere. As a result, volcanic piles continue to grow in a given location rather than as a string of volcanoes along a moving plate, such as the Emperor Seamount Chain.

The Martian shield volcanoes are proof of an evolution more advanced than that of the Moon, an evolution influenced by the deep interior of the planet. There are other expressions of this deep influence. Large crustal swells or uplifts exist which span a range of ages, as judged from their isostatic state (Phillips and Saunders, 1974). Again these are large compared with most terrestrial crustal domes. The extensional rifting of the Valles Marineris and Echus Chasma systems was accompanied by vast outpourings of volcanic plains, similar to the early stages of rift development in East Africa. Most of the major tectonic features, which include three large crustal swells and ten or so rift canyons, are confined to a single hemisphere on Mars. Even in the active sector, however, there is no evidence for spreading or plate motion. There are in fact no plates on Mars; the rifting of the martian lithosphere has been too sluggish to form isolated blocks. There is also no evidence for past plates or plate motion in the form of terrestrial type folded mountains or Andean type volcanics. Mars is best described as undergoing (or having undergone) incipient plate tectonics. The planet bears the unmistakable signature of the earliest parts of the Wilson Cycle, but no indication that the cycle ever ran to completion anywhere on the planet.

It is fortunate that a planet with the size and mass of Mars exists within the solar system, for that world clearly demonstrates that modern terrestrial evolutionary processes can develop on a world which initially evolved as did the Moon. Heavily cratered highlands, the

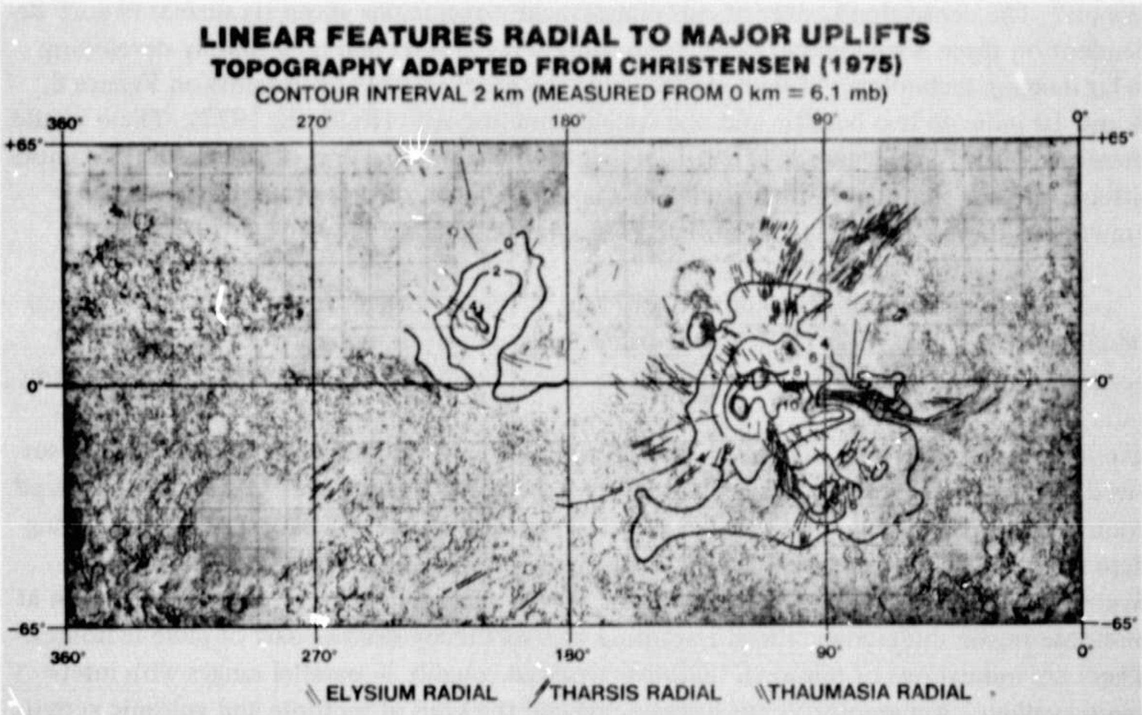

Figure 2. CRUSTAL EVOLUTION OF MARS advanced somewhat beyond that of the Moon. The ancient martian crust has been modified not only by basin-forming impacts and mare-type flooding, but also by crustal uplift and associated tectonic fracturing. Shown are contours outlining the major crustal domes (after Christenson, 1975), and major groups of fractures radial to these uplifts (adapted from Hartmann, 1973; Carr, 1974; Frey, 1977).

product of an initial differentiation, can be significantly modified first by asteroid-sized impacts and basaltic flooding, then by uplift and extension (presumably due to mantle convection). Given enough internal heat, spreading should follow rifting. The modern activity of the Earth seems a natural evolution for a very large planet that at one time, early in its development, experienced the same processes which are revealed in the preserved surface features of the smaller, more sluggish Moon, Mercury and Mars.

What of Venus, which in size and mass is more nearly an "Earth" than any of the other planets? The dense cloud cover of this planet make conclusions about its surface history dependent on three Soviet lander images and gamma ray studies and on a rapidly developing radar imaging technology. Taken at face value the geochemical experiments on Venera 8, 9, and 10 indicate two basaltic and one roughly granitic sites (Keldysh, 1977). There would therefore seem to be evidence of a crustal dichotomy similar to that of the Earth (in composition). No conclusions about the relative amounts of each of these rock types can be drawn, but there is good indication that Venus has undergone extensive differentiation.

There is evidence in the radar imagery that Venus is both an active and evolved planet (Malin and Saunders, 1977). This conclusion follows even though only a relatively small percentage of the surface has been imaged to date; even this limited coverage reveals a wide variety of structures indicative of a varied and complex history. Large but shallow crater-like features demonstrate that a significant fraction of a presumably ancient surface has survived, but also that erosion and deposition have modified this surface. Olympus Mons-sized conical features exist which may be similar to very large shield volcanoes. A 1400 km long depression or trough bears similarities to the Valles Marineris and the East African Rift System in scale and rough topographic form. If the analogy is correct, then Venus has in at least one region undergone crustal fracturing of a sort recognized as part of plate tectonics. There are indications of tensional features, arranged roughly in parallel ranges with intervening valleys. Apparently Venus has experienced the kind of tectonic and volcanic activity that operated on Mars and continues to modify the Earth. The extent of this development is not known, but the persistence of very ancient terrain on the cloud-shrouded planet suggests that geologic activity on Venus has failed to completely rework or mask the surface, as it has on the Earth.

COMPARATIVE PLANETOLOGY AND TERRESTRIAL GEOLOGY

There seems to be a pattern in the evolutionary development of the smaller terrestrial planets: the larger the planet the more its ancient Moon-like surface has been modified by Earth-like tectonics and volcanics. This pattern can be extrapolated to the Earth, at least qualitatively, with little difficulty. In actual fact the detailed study of the smaller planets suggests a scenario which may be the solution to one of the most basic problems in terrestrial crustal evolution: the origin of the fundamental dicohtomy of high density (oceanic) and low density (continental) crust.

THE ORIGIN OF CONTINENTS. . . . . .

Two extreme views exist. Continents are either (a) the remnants of some original, primordial sialic material differentiated early in the Earth's history, or (b) the slowly accumulating masses growing over time by gradual but irreversible differentiation of the mantle. A compromise is possible: continents could grow over time by the lateral accretion of orogenic belts about early-formed sialic nuclei. Support for the slow-grow view comes from two principle sources. First, the oldest known granitic rocks are intrusive into still older basic (oceanic) crust and are not themselves true primordial crust. Second, Moorbath (1975) and others find geochemical evidence in strontium isotopes of the gradual separation of continental crust from the mantle. But granites may appear isotopically juvenile if they have been recycled through the mantle (Armstrong, 1968). Also, the oldest known foldbelts formed on sialic (later reactivated) crust, suggesting that some form of low density material existed prior to the earliest known orogenies. Finally, thermal history models (Hanks and Anderson, 1969; others subsequently) and Archaean geochemical data (Shaw, 1972; Hargraves, 1976) both suggest an early rapid differentiation of the Earth.

Comparative planetology likewise supports the view that low density crust formed rapidly and early. It is almost inescapable that the Earth formed hot; a differentiation at least as complete as that of the Moon is difficult to avoid. The resulting crust would have been sialic, probably of intermediate bulk composition, and most likely of global extent (Lowman, 1976). An original global crust could not have been granitic unless it was very thin, as the resulting decayed heat flow would be unacceptably high today (Frey, 1977b; compare Hargraves, 1976). It is more likely that the modern granites have been derived by partial melting or "redifferentiation" of an intermediate (perhaps andesitic) original crust (Lowman, 1977). In this view the modern continents are the reworked remnants of the original crust, not crust generated slowly over the Earth's history.

. . . . . OCEAN BASINS . . . . .

The crustal dichotomies of the smaller terrestrial planets can be traced back to the late heavy bombardment which produced the large basins seen on the Moon, Mercury and Mars. While impact craters do not survive from this epoch on the Earth, this planet could not have escaped the basin-formation which occurred nearly 4 billion years ago on the Moon. Scaling for the larger gravitational cross-section of the Earth shows that, although large basins cover only about 40% of the lunar surface, at least 50% (and perhaps 70%) of the Earth's original crust would have been disrupted and converted into shallow basins at that time (Frey, (1977a). Redistribution of crustal mass by the impacts would have created a major topographic dichotomy in the early (global) crust: highlands would have been separated from basin floors by 3-4 kilometers following isostatic adjustment. This assumes an original depth of some 12-13 kilometers for a 1000 kilometer wide basin, using Baldwin's (1963) formulas. Greater depths are possible, perhaps likely.

The lithosphere of the Earth should have been significantly thinner 4 billion years ago (even before impact thinning) due to greater heat production by radioactive elements. The pressure drop from impact excavation would have triggered partial melting at even shallower depths, producing a basaltic liquid which would have risen rapidly through the intensely fractured sub-basin lithosphere. The largest basins would have been flooded in a very short time, concentrating high density crust in the low-lying 50% of the Earth's surface (Frey, 1977a). It seems likely that a crustal dichotomy similar to that of the Moon or Mars and superficially akin to the modern one was established on the Earth by about 3.9 billion years ago, as a direct result of the basin-forming late heavy bombardment. The true significance of these external influences would have been impossible to assess without the detailed evidence gathered from the other terrestrial planets. Indeed, the effects of this important period go beyond the establishment of the Earth's crustal dichotomy.

...... and PLATE TECTONICS

The evolutionary development of Mars shows that plate-type tectonic processes (uplift and rifting) have also been important in modifying a small part of the Moon-like surface of that planet. A closer look at the post-impact effects of basin formation suggests a very rapid evolution to a plate-type environment (Frey, 1977b). The impacts should not only have triggered partial melting below the basin, but should have also significantly steepened the thermal gradients in the sub-basin lithosphere by exposing hotter layers. This would have enhanced the convection that must have existed below the lithosphere (McKenzie and Weiss, 1975). Combined with the greatly thinned and highly fractured nature of the sub-basin lithosphere, rapid rifting of the newly flooded basin floor was highly likely. The resulting "plates" would have been many and small and rapidly moving to dissipate the high heat flow of the early Earth (compare Burke et al., 1976). This early period of plate development is best described as "microplate tectonics" (Frey, 1977b), and is a direct consequence of the late heavy bombardment. Because subductable high density crust was already present, plate motion through spreading and subduction should have followed rifting almost immediately. The gradual slowing of plate motions over time (as the Earth cools) would lead to less and less violent collisions between the highland blocks, gradually stabilizing these into larger and larger units. The earliest period of fast microplate tectonics provided an environment for the extensive reworking and redifferentiation (Lowman, 1977) of the early continental crust, perhaps explaining why so little of the early Archaean has been preserved.

In any discussion of plate tectonics, comparison of the Valles Marineris system on Mars with terrestrial rifts is suggested. Like those on the Earth, the martian system of extensional canyons is associated with crustal uplift and extensive volcanic flooding in the Tharsis region (Hartmann, 1973; Carr, 1974). But triple junctions are not obvious, there are no clearly isolated blocks or plates, and there is no evidence for spreading anywhere on Mars (Frey, 1977b; Sharp, 1973). The uplifts and rifts of the Valles Marineris and Echus Chasma systems are indicative of incipient plate development; the lack of complete Wilson Cycle tectonics or even of complete plate formation is likely due to the relatively rapid thickening

Figure 3. CRUSTAL EVOLUTION OF THE EARTH is even further advanced, and continues dynamically today. This Landsat view shows a uniquely terrestrial tectonic feature: the folded mountains of Pennsylvania. The sinuous ridges at the upper left were produced by differential erosion on folds resulting from plate motions.

of the martian lithosphere successfully competing with a sluggish internal activity (Johnston et al., 1974). As such the martian example may be a good description of future terrestrial rifting as internal motions diminish and the lithosphere becomes thicker with the loss of heat from the Earth.

CONCLUSIONS

The study of the smaller, less-developed terrestrial planets provides a framework within which a better understanding of the early history of the Earth can be obtained. We are fortunate to have these clues, for there is no reliable record of terrestrial tectonics and crustal evolution on this planet back beyond about 3.5 billion years. Most of the important early processes–including those that led to the establishment of the original crustal dichotomy and the onset of plate tectonics–all occurred in the remote past of the early Archaean whose trace has been obliterated by the subsequent dynamic activity of the Earth. Without the progressive complexity in development which is so obvious in the smaller planets it would be almost impossible to accurately describe earliest Earth history. With these constraints it is possible to construct a plausible early development out of which the present evolutionary style naturally falls.

Nor is this the only example of comparative planetology providing the necessary information for Earth studies. Atmospheric physics and evolution have greatly benefited from the isotopic analysis of the atmosphere of Mars by Viking. It is now clear that the earlier martian atmosphere was significantly more massive than the present one. This conclusion supports a similar suggestion based on totally independent and less quantitative indicators. The inferred constraints for the degassing history of Mars will be useful in describing the evolution of the Earth's atmosphere as well. Study of climate variations is now aided by the accumulating data indicating massive changes in the martian climate. In these and many other ways the comparative studies now available are providing more complete theories and fewer false starts in the study of the Earth than has ever been possible before.

The lesson of the smaller planets has been that not only is the Earth understandable, but readily so, when viewed in the proper context as the largest, most evolved of the terrestrial planets. This context would be impossible to exploit without the data derived from the missions to the Moon and planets, and represents a giant leap forward in the science of planetology. The exploration of space has indeed been the exploration of the Earth as well.