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Image resolution and evaluation of genetic hypotheses for planetary landscapes

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Abstract

The spatial resolution of image data tends to constrain the horizontal length scale of genetic hypotheses that are addressable by those data. No 'simple' formula exists when image resolution is sufficient to test a given geomorphic process, which is dependent on what characteristics are diagnostic of the particular process. Genetic hypotheses should be formulated along the lines of the "multiple working hypotheses" concept as described in a classic paper by Chamberlin [J. Geol. 5 (1897) 837]. An essential element of a viable working hypothesis is a clear indication of the characteristics predicted by, or a consequence of, the hypothesis. An untestable hypothesis is not an effective working hypothesis. The history of the study of lunar sinuous rilles is outlined as an illustration of the influence of image resolution and the formulation of genetic hypotheses on the subsequent advancement of understanding of the problem. Sinuous rilles on Venus and Mars, and controversial sinuous ridges on Mars are also reviewed. In the lunar case, the three-order-of-magnitude improvement in spatial resolution provided by Lunar Orbiter photographs over Earth-based telescopic photographs did *not* result in definitive examination and elimination of published hypotheses for the formation of sinuous rilles. Topographic data obtained from cartographically controlled Apollo orbital photographs, along with important observations and samples obtained by the astronauts on the lunar surface, did test and exclude several hypotheses. The formulation of a genetic hypothesis, including testable consequences of that hypothesis, is a greater determinant of its ultimate utility to the scientific community than is the image resolution available at any given time. Published by Elsevier Science B.V.

Keywords: Earth; Planetary landscape; Genetic hypothesis

1. Introduction

Morphologic features distinguishable in images represent the primary source of information available for interpreting the geologic and geomorphic history of planetary surfaces. The size, shape, and orientation of visible features provide clues to the processes that contributed to the formation of the terrain. Geomorphologists are challenged to assess the relative importance of a host of different agents that may, or may not, contribute to the history of the present surface. Image data are among the most complex data sets available; often the potential of the spatial and textural detail is not fully appreciated in the initial analyses. This paper explores some of the ramifications of the spatial resolution of image data to geomorphologic studies of planetary landscapes and the importance of well-formulated hypotheses to

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the advancement of knowledge on the origin of landforms. The goal is to illuminate some of the problems and successes encountered during previous analyses of planetary data, to maximize the utility of geomorphic studies undertaken in the future.

Planetary (or extraterrestrial) geomorphology broadens the classical study of the form or shape of landforms on Earth to encompass the vast array of landscapes recently revealed by spacecraft exploration (Baker, 1993). The varied surfaces now available for geomorphic study greatly expand the environmental regimes in which landforms must be examined and evaluated, providing numerous 'natural laboratories' to test the basic physical principles involved in the processes that have acted upon these surfaces. Planetary studies generally suffer from the inability to field-check hypothesized genetic processes on the actual landform under study, but this should not restrict the utility of interpretations derived from the study of planetary landscapes when potentially significant limits to the hypotheses are clearly identified. Differences in spatial resolution for the image data used in planetary studies holds promise and peril for improving our general understanding of the origin of landforms on planetary surfaces. The task facing planetary geomorphologists is to maximize the application of old and new data to the evaluation of genetic hypotheses, clearly identifying how best to test all viable hypotheses.

The discussion starts with a brief review of the relevant terms encountered in descriptions of image resolution and the significance behind the concept of multiple working hypotheses. Next, examples from the literature of planetary geomorphology are explored in an attempt to identify strengths and weaknesses encountered in the remote study of landforms. The information gained from the examples is then discussed in terms of how future studies in planetary geomorphology might enhance the usefulness to the science community at large.

2. Background

2.1. Spatial resolution

The spatial resolution of an image establishes the limiting size of the target surface area that contributes to the brightness recorded in an image. Spatial resolution is often expressed as *ground resolution*, which corresponds to the smallest distance on the target surface that can be resolved as a separate point in an image (Mutch et al., 1976, p. 328). Ground resolution is equivalent to detection resolution, where the presence of an object can be detected but the object cannot be classified (Masursky et al., 1970). Digitally transmitted images have a limiting size that is related to the individual picture elements (pixels), which comprise the scene. The ground resolution of a pixel equals the product of the angular size of the pixel (on the detector) and the slant range, the distance from the detector to the imaged area on the target. Photographic products have a limiting resolution that is a function of the grain size of the light-sensitive materials within the film and the optics of the camera system. While not directly equivalent to the pixel size of a digital system, the photographic resolution of a film/camera system can be measured with special targets such as closely spaced pairs of lines (Masursky et al., 1970).

Terrain features must be larger than the ground resolution of either a digital or photographic system to be recognized in an image. *Identification resolution* is the size of a feature that can be identified from its shape (Masursky et al., 1970). Identification resolution varies for different features, depending on how much shape information is required for identification. A relatively simple shape, such as a circular impact crater, typically requires from four to six pixels to be properly identified (Mutch et al., 1976, p. 328). The resolution information provided for spacecraft data is usually expressed as the ground resolution for the imaging system, but the reader should be cognizant that individual landforms identifiable in the images will of necessity be many times larger than the ground resolution.

Lighting conditions have a particularly strong effect on the morphologic information obtainable from images. An empirical study carried out prior to the first Lunar Orbiter mission to the Moon quantified the inherently subjective effect of lighting conditions on the resolution of a photographic system (Keene, 1965): objects of varying size and shape (all with comparable reflectance properties) were photographed at differing illumination angles, then viewers categorized each photograph as to no detection,

detection, or identification. The results are summarized as functions of the object size and the illumination angle, equivalent to the sun elevation above the horizon (Fig. 1). Detection and identification are substantially improved near the terminator where low illumination angles produce strong shadows that enhance the visibility of subtle surface features. Conversely, when the illumination angles are large (near local noon on the surface), the detection and identification resolutions are substantially larger than for the same features viewed near the terminator.

The Lunar Orbiter spacecraft were placed in orbits such that at perilune, when slant range was a minimum, the lunar surface was illuminated with sunlight incident from 10° to 30° above the local horizon (Levin et al., 1968). Similarly, the panoramic cameras flown on the last three Apollo missions were optimized for photography at 20° illumination (Head and Lloyd, 1971). Some Apollo crews used special high-speed black and white film in a hand-held Hasselblad camera to obtain near-terminator photographs where the solar illumination angle ranged from 4° (Fig. 2) to as little as 0.5°. The near-terminator photographs highlighted many subtle geologic features not evident at higher illumination angles (Figs. 2 and 3; Head and Lloyd, 1971, 1972), and also provided the first observational evidence that impact-erosive mechanisms reduce the maximum interior slope of lunar impact craters to about

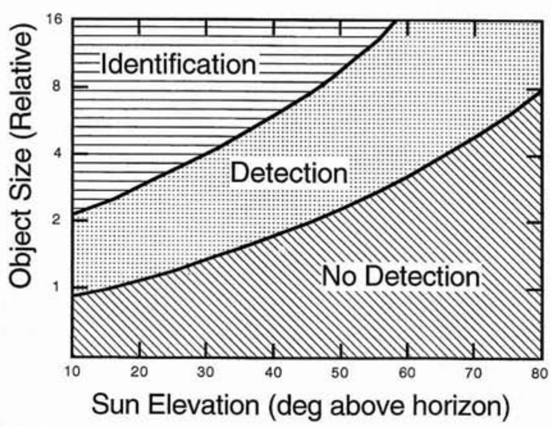

Fig. 1. Detection and identification resolution as a function of insolation angle, measured from horizontal. The vertical axis is a relative scale, referenced to an object visible at 10° illumination. Adapted from Masursky et al. (1970), fig. 8.

1° (Soderblom, 1972). To preserve flexibility for a variety of lighting conditions, digital imaging systems usually are not optimized for operation in the extreme near-terminator region.

Planets with atmospheres have an additional geomorphic complication. Particulates in the atmosphere, or even the atmosphere itself, can degrade the visibility of surface features (i.e., Van Blerkom, 1971). For example, Kahn et al. (1986) demonstrated that atmospheric haze increased the identification resolution for Viking Orbiter images of Mars, effectively eliminating most fine-scale textural information from images during hazy conditions. At Venus, the atmospheric influence reaches a maximum, effectively hiding the entire surface from view at visual wavelengths. Synthetic Aperture Radar (SAR) enabled the Magellan spacecraft to image over 98% of the venusian surface at a ground resolution of 120 to 300 m (Senske et al., 1993), but with the new consideration that the images record the interaction of the surface with 12-cm-wavelength radar signals rather than with sub-micron visual wavelengths.

2.2. Multiple working hypotheses

The mental system utilized for feature identification is likely as important as the physical limitations of the camera system used for obtaining image data. The intellectual model used by researchers in any scientific analysis can have a profound influence on the interpretations derived from that analysis. The methodology and motivation for the use of multiple working hypotheses was eloquently summarized in a classic paper by Chamberlin (1897), published under the general heading of "Studies for Students". Chamberlin's arguments are just as valid for the researchers of today as they were a century ago:

"Three phases of mental procedure have been prominent in the history of intellectual evolution thus far. These three phases may be styled the method of the ruling theory, the method of the working hypothesis, and the method of multiple working hypotheses. It is a too frequent habit to hastily conjure up an explanation for every new phenomenon that presents itself. Interpretation leaves its proper place at the end of the intellectual procession and rushes to the fore-

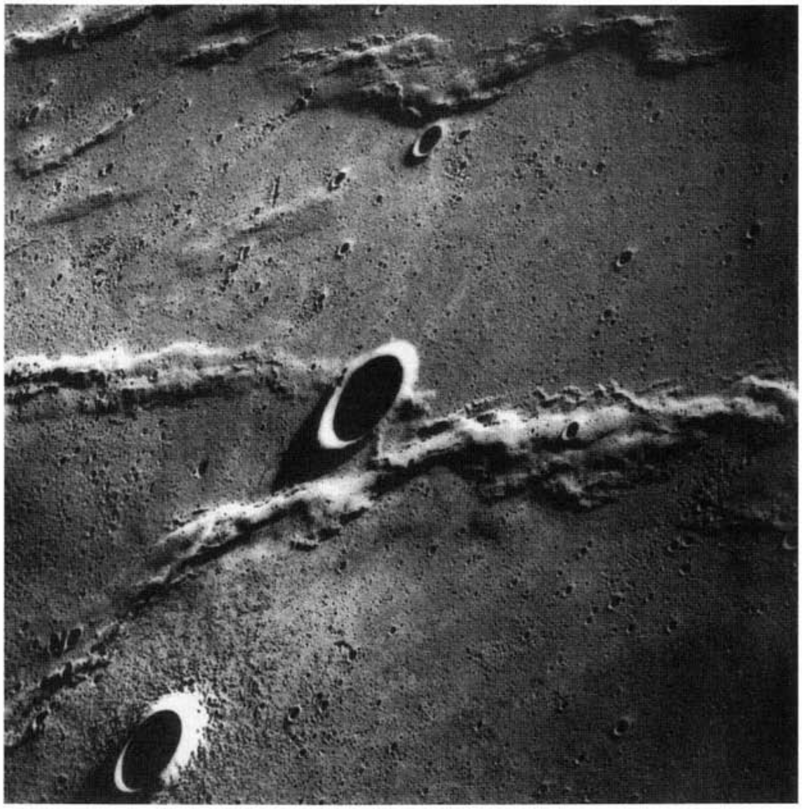

Fig. 2. Near-terminator oblique photograph of wrinkle ridges on Oceanus Procellarum. Note the subtle features visible on and around the ridges at an illumination angle of approximately 4°. Lichtenberg B Crater (lower left) and Naumann G Crater (center) are about 6 km in diameter. Apollo photograph AS15-98-13354.

front. Too often a theory is promptly born and evidence hunted up to fit in afterward. The habit of precipitate explanation leads rapidly on to the birth of general theories. In support of the general theory, there may not be any further evidence or investigation than was involved in the first hasty conclusion. But the repetition of its application to new phenomena, though of the same kind, leads the mind insidiously into the delusion that the theory has been strengthened by additional facts. The moment one has offered an original explanation for a phenomenon which seems satisfactory, that moment affection for his intellectual child springs into existence, and as the explanation grows into a definite theory his parental affections cluster about his offspring and it grows more and more dear to him. There springs up also unwittingly a pressing of the theory to make it fit the facts and a pressing of the facts to make them fit the theory.

The working hypothesis differs from the ruling theory in that it is used as a means of determining facts rather than as a proposition to be established. The hypothesis is a mode rather than an end. Conscientiously followed, the method of the working hypothesis is an incalculable advance upon the method of the ruling theory; but [one should note] the ease with which the hypothesis becomes a controlling idea. To avoid this grave danger, the method of multiple working hypotheses is urged. In developing the multiple hypotheses, the effort is to bring up into view every rational explanation of the phenomenon in hand and to develop every tenable hypothesis relative to its nature. The right use of the method requires the impartial adoption of all alike in the

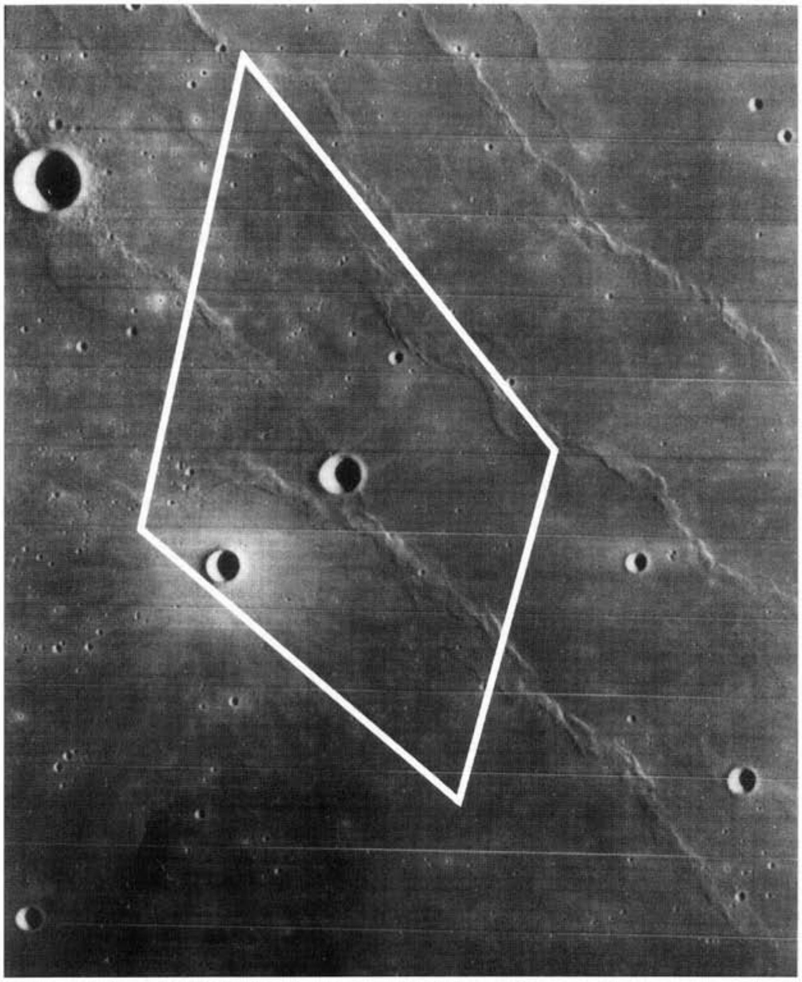

Fig. 3. Portion of Lunar Orbiter photograph IV-163H1, showing wrinkle ridges on Oceanus Procellarum and the location of Fig. 2 (lines). Illumination angle is approximately 19°. Area shown is about 70 km wide.

working family. The investigator proceeds with a certain natural and enforced erectness of mental attitude to the inquiry, knowing well that some of his intellectual children must needs perish before maturity, but yet with the hope that several of them may survive the ordeal of crucial research, since it often proves in the end that several agencies were conjoined in the production of the phenomena. An adequate explanation often involves the coordination of several causes. The full solution therefore involves not only the recognition of multiple participation but also an estimate of the measure and mode of each participation."

The very nature of geomorphic problems involves using the shape of the landscape to infer the previous land surface and the active processes that generated the present landforms. It is rarely true that a single process can fully explain the development of an array of landforms in a particular location. Similarly, planetary landforms often result from several processes active on the surface under study, working at a variety of time scales. The concept of "equifinality" or "polygeneticism" for similar-appearing landforms derived from different origins demonstrates the necessity of maintaining an open mind when formulating working hypotheses of genetic processes. The multiple hypotheses do not need to be established by testing (as in an analytical laboratory), but the consequences of the hypotheses should lead to some observable characteristics that can be sought in future studies. The great value of incorporating new ways of viewing the facts is well demonstrated in many studies of Quaternary geology and geomorphology (Baker, 1996a,b).

The terrestrial geomorphologist can supplement the landform shape with information on the soil and bedrock susceptibility to erosion, the rates of erosion and deposition for various active processes, climate data indicative of the environmental conditions, and a variety of other information sources to aide in evaluating the processes responsible for the present landforms. The planetary geomorphologist seldom has abundant quantitative information of surface conditions in a study area to supplement the geomorphic analysis of surface landforms. This paucity of field data often causes planetary geomorphic problems to appear overly dependent upon access to higher resolution imaging data to test hypotheses. At times, the limited available information may entice researchers to embrace a 'ruling theory' rather than the ideal of multiple working hypotheses. Geomorphic problems from three planetary surfaces are used next to explore how image resolution was (or was not) helpful in resolving the genetic mechanisms responsible for certain distinctive landforms.

3. Examples from three planets

Planetary exploration during the past 25 years has produced an enormous wealth of information about the solar system. Photographs and digital images have revealed a bewildering array of landforms, some very similar to terrestrial landforms like shield volcanoes or sand dunes, and others that have been much more difficult to classify. The history of some controversial landforms are reviewed next, in an effort to learn what new information has been most helpful in advancing the state of knowledge for these features.

3.1. Moon

The enormous effort exerted to deliver astronauts to the lunar surface, and return them safely to Earth, stimulated an explosion of new information about the Moon. Study of some lunar features (e.g., impact craters) resulted in fundamental advances in our understanding of processes that are active on all planetary surfaces (Melosh, 1989). One specific lunar feature—sinuous rilles—provides insight into how genetic hypotheses were addressed as new information became available from increasingly sophisticated missions to the Moon. Sinuous rilles are narrow trenches with a meandering plan view, which distinguishes them from straight, arcuate, and irregularly branching rilles (Quaide, 1965). These distinctive lunar landforms have received considerable scientific attention for many decades (see summaries in Mutch, 1970, pp. 190–196; Short, 1975, p. 103; Basaltic Volcanism Study Project, 1981, pp. 755–756; Heiken et al., 1991, pp. 99–101). The largest lunar sinuous rilles are easily visible through Earth-based telescopes, but spacecraft photographs revealed that only 16% of the rilles are between 100 and 340 km in length, whereas more than 75% of the rilles are between 10 and 100 km in length (Schubert et al., 1970).

3.1.1. Telescopic studies

Earth-based telescopes have two physical causes that limit the sharpness of the image they can produce: diffraction and atmospheric blurring (Jastrow and Thompson, 1972, p. 43). The very nature of light itself causes diffraction to be the ultimate physical limit to the separation of two points that can be detected with optical devices. The size of the lens or mirror determines the physical limit established by diffraction. The largest telescopes, such as the 200″ (5 m) Hale telescope on Mt. Palomar, have a diffraction-limited resolving power of about 0.02″ of arc (Menzel, 1964, p. 312), which would translate to a ground resolution of 40 m at typical lunar distances. The turbulent atmosphere of Earth, however, causes blurring that is much more significant than the diffraction limit. Atmospheric blurring varies from night to night, but on average it can effectively erase any photographed lunar feature that is less than 1 km in size, independent of the telescope dimension (Jastrow and Thompson, 1972, p. 48). Visual observations may achieve some improvement over this limit under favorable circumstances but the effective ground resolution for photographic plates, the principle data source for published lunar geomorphic studies prior to the advent of spacecraft data, can be considered to be approximately 1 km.

Telescopic photographs of the Moon led to several proposed mechanisms for the origin of the sinuous rilles (summarized in Cameron, 1964; Mutch, 1970, pp. 190–196). One of the oldest proposed mechanisms is that of aqueous erosion, where the rille meanders are considered to be analogous to terrestrial river channels (Pickering, 1904, pp. 42–43; Frisoff, 1960, pp. 159–160). The water required for this mechanism was consistent with a proposed model that advocated an extensive lunar hydrosphere early in the history of the Moon (Gilvarry, 1960). Published alternative mechanisms for sinuous rille formation included collapsed lava tubes or lava channels (Baldwin, 1963), erosion by pyroclastic flows (Cameron, 1964), and a combination of faulting and subsidence (Quaide, 1965). Cameron (1964) and Quaide (1965) cite the Hadley Rille (Fig. 4) as an example of their proposed mechanism: Cameron argues it was eroded by a volcanic glowing avalanche (nuee ardente) originating from a craterlet at the rille source; Quaide states that "the details of the morphology do not support this idea" and concludes instead that "the Hadley Rille is merely a sinuous tensional fracture along which volcanic activity has been localized". Unfortunately, no specific characteristics were provided as potential ways to test the hypotheses.

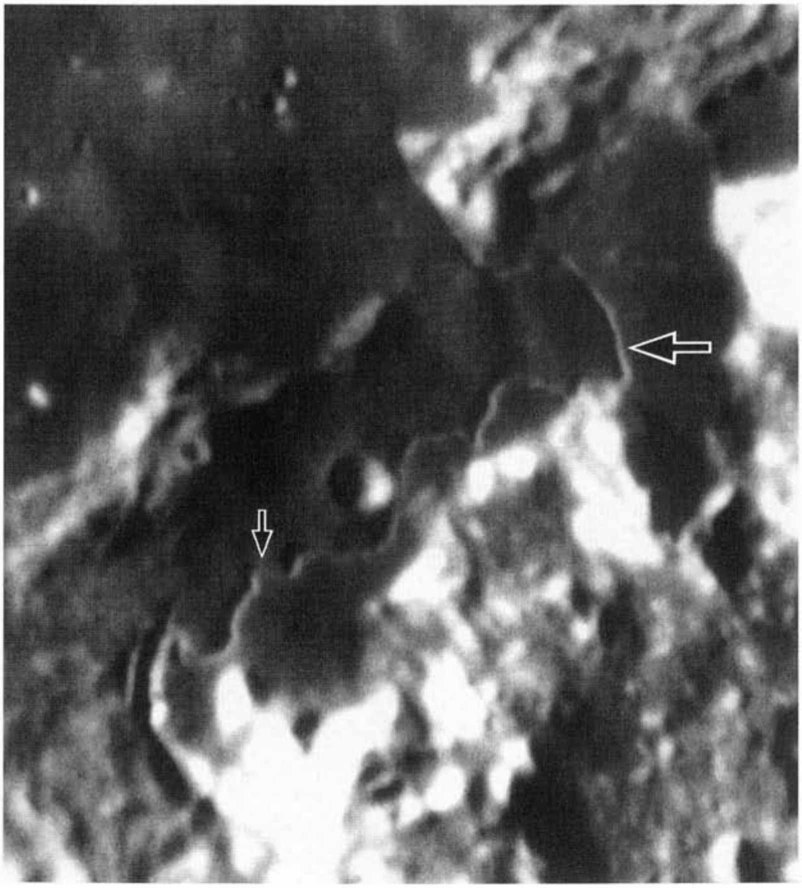

Fig. 4. Telescopic view of Hadley Rille area on the Moon, centered on lat. 25°N, long. 3°E. Effective ground resolution is slightly better than 1 km. Compare with the Apollo orbital view in Fig. 6. Small arrow shows the location of the views in Fig. 5; large arrow shows the location of the ground views in Figs. 7 and 8. Area shown is about 58 km wide. Modified from a portion of Lick Observatory photograph L35.

3.1.2. Lunar orbiter

The advent of spacecraft data from the Moon had intriguing consequences for studies of the formation of sinuous rilles. The primary objective of the Lunar Orbiter program was to locate smooth, level areas within 5° of the equator between 45°E and 45°W and to confirm their suitability as manned landing sites for the Apollo missions (Kosofsky and El-Baz, 1970). Five spacecraft achieved this objective between August, 1966, and August, 1967, with high resolution photographs of 1 to 3 m ground resolution in the Apollo zone, along with coverage at various resolutions for much of the rest of the Moon (Mutch, 1970, pp. 40–45). Photographic film was developed in lunar orbit, scanned by an on-board electron gun and photomultiplier tube, and transmitted as an analog signal for reconstruction on the ground (Kosofsky and El-Baz, 1970).

Strange as it may seem in the post-Apollo era, the Lunar Orbiter photographs were interpreted by several researchers to provide strong evidence for the aqueous origin of the sinuous rilles. Urey (1967) listed distinctive morphologic characteristics of sinuous rilles revealed in high resolution Lunar Orbiter photographs, described the problems they posed for mechanisms other than the flow of water on the surface, and concluded that the evidence was "overwhelming" for water as the agent producing the sinuous rilles, possibly during a temporary lunar atmosphere caused by a large comet impact. Gilvarry (1968) built on Urey's results, using Surveyor (robotic lander) and Lunar Orbiter results to present "observational evidence for sedimentary rocks" as the major component of lunar mare materials. The need for a temporary lunar atmosphere was removed by the proposal that the "mature meanders in lunar sinuous rilles" formed through "surface erosion by water... under a pressurizing ice cover in the absence of a lunar atmosphere" (Lingenfelter et al., 1968), an ice-covered river being capable of eroding a sinuous rille in about 100 years. The complete near-side coverage by Lunar Orbiter IV at a uniform ground resolution of 100 m was used to map the distribution of sinuous rilles, which revealed that more than 80% occurred on the margins of mare basins or craters with mare-type floors (Peale et al., 1968). Morphological characteristics again were interpreted to exclude non-aqueous mechanisms such as ash flows and lava drainage channels, leading to the conclusion that "the distribution of sinuous rilles is the only available and unambiguous indicator of the location of subsurface volatiles" on the Moon (Peale et al., 1968). The improved resolution of the Lunar Orbiter photographs provided 'overwhelming' and 'unambiguous' support, to some at least, for an aqueous origin for the sinuous rilles.

The Lunar Orbiter data resulted in significantly different interpretations from other investigators. Oberbeck et al. (1969) described a sinuous ridge comprised of coalesced elongate craters in northern Oceanus Procellarum as an example of an incompletely collapsed lava tube, pointing out similarities between the lunar example and a terrestrial lava tube. Calculations showed that a lava tube roof may be stable up to 500 m in width under lunar gravity (Oberbeck et al., 1969). In an interesting experimental study, Schumm (1970) used subsurface gas emission in granular material of variable thickness to reproduce the sinuosity and the partially cratered aspect of lunar sinuous rilles, one of which was Hadley Rille. Schumm's conclusions are particularly illuminating:

> These experiments... increase the number of working hypotheses available to the astrogeologist. During experimentation the venting of gas through granular material produced craters, crater clusters, crater chains, troughs, and sinuous channels by fluidization of the test material. Of course, other agencies can produce these or similar features, and, therefore, as on the Earth, each lunar topographic feature should be interpreted with several alternatives in mind.

No numerical modeling was published on the sinuous rille problem prior to Apollo, but this probably is a result of the limited computing capability readily available at the time. Any form of modeling is most helpful when it broadens the range of mechanisms considered rather than simply reinforcing a 'ruling theory' mindset.

3.1.3. Apollo

The Apollo missions produced several crucial pieces of information for the sinuous rille problem, but even the visit of astronauts to Hadley Rille left some issues unresolved. Each Apollo mission returned many hundreds of photographs taken with handheld Hasselblad cameras. Photographic coverage of the lunar surface was enhanced substantially by the Scientific Instruments Module (SIM bay) in the orbiting Command-Service Module on the final three Apollo missions. The SIM bay contained two mapping cameras specifically designed to obtain cartographically controlled photographs of the illuminated terrain beneath the spacecraft. The Metric Camera obtained concurrent wide angle (25–30 m ground resolution) stereo photographs of the lunar surface, photographs of star fields, and laser eleva-

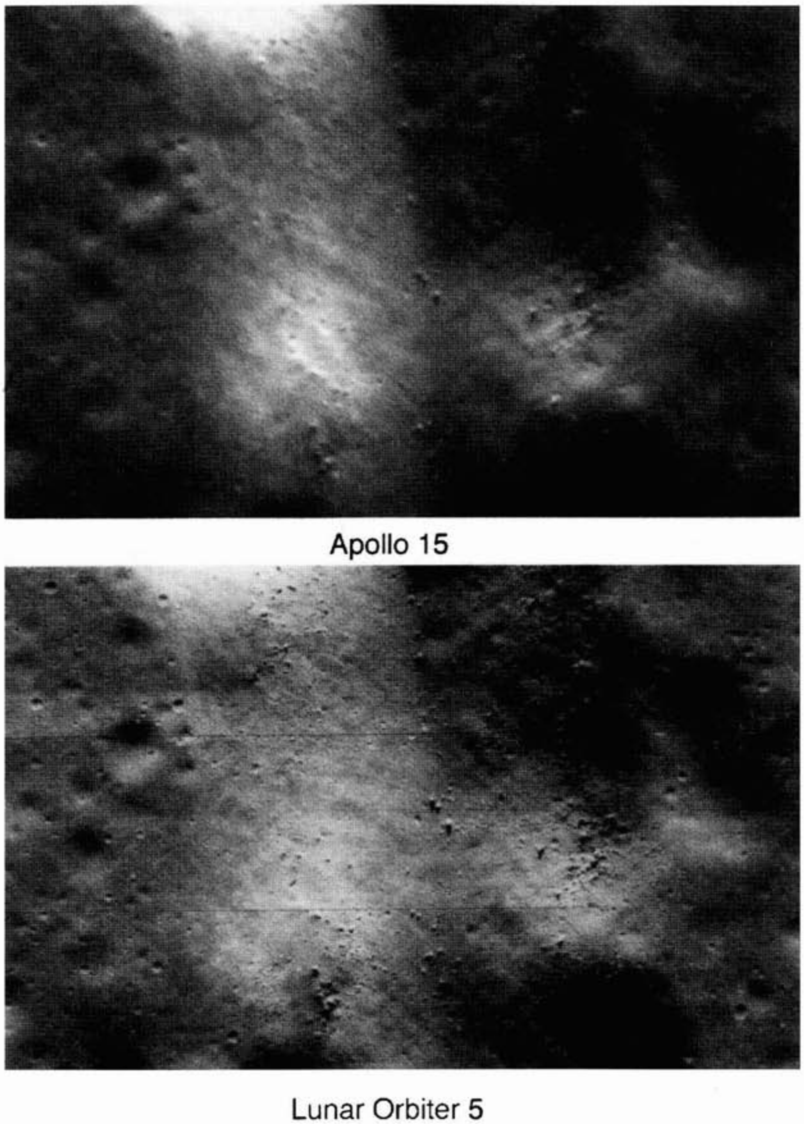

Fig. 5. Detail of Hadley Rille. See Fig. 4 for location on the rille. Blocks up to 30 m in diameter have rolled to the bottom of the rille. The two views were taken nearly 6 years apart, under similar illumination conditions of about 20°. When viewed stereoscopically, no changes in boulder positions are detectable. Top view, portion of Apollo 15 Panoramic frame 9432, with an effective ground resolution of about 5 m. Bottom view, portion of Lunar Orbiter V frame 105H2, with an effective ground resolution of about 2 m. The rille is about 1.5 km wide in this area.

tion measurements; the Panoramic Camera obtained high resolution (2 m ground resolution) stereo strips intermixed with the Metric Camera frames (Masursky et al., 1978, pp. 5–15). Here we focus on results obtained for the Hadley Rille, where Panoramic photographs have similar ground resolution and illumination as high resolution Lunar Orbiter photographs (Fig. 5), and Metric Camera photographs provide excellent stereo coverage of the Appenine Front region (Fig. 6).

Apollo landings that preceded the Apollo 15 mission to the Hadley–Apennine region provided important results that influenced the interpretation of orbital data. Prior to Apollo 15, Greeley (1971) used the chemical and physical characteristics of mare lavas to augment his analysis of the geomorphology and topography of Hadley Rille, in conjunction with terrestrial lava tube analogs. The poorly sorted and compacted regolith encountered at all Apollo sites lessened the likelihood of an aqueous origin for Hadley Rille, and the regional setting on basaltic mare favored lava effusion in tubes rather than the fortuitous fracture orientation required for fluidization by outgassing. Greeley (1971) concluded that Hadley Rille resulted from a roofed lava tube; meteoroid bombardment collapsed nearly all roof sections and caused slumping of the rille rim, leaving blocks up to 30 m within the rille, which are visible on both Lunar Orbiter and Panoramic photographs (Fig. 5).

Direct examination of Hadley Rille by the Apollo 15 crew strongly influenced ideas about sinuous rilles. Surface photographs showed outcrops of massive, layered rocks in the upper wall of the rille (Fig. 7), but talus and mass-wasted material (Fig. 8) covered virtually all of the rille interior (Swann et al., 1972). Important field results include eroded vesicular zones in blocks at the edge of the rille (possibly correlative with discontinuous horizontal partings visible in the bedrock outcrops), pahoehoe-like surfaces on some mare blocks, crescentic ribs on one

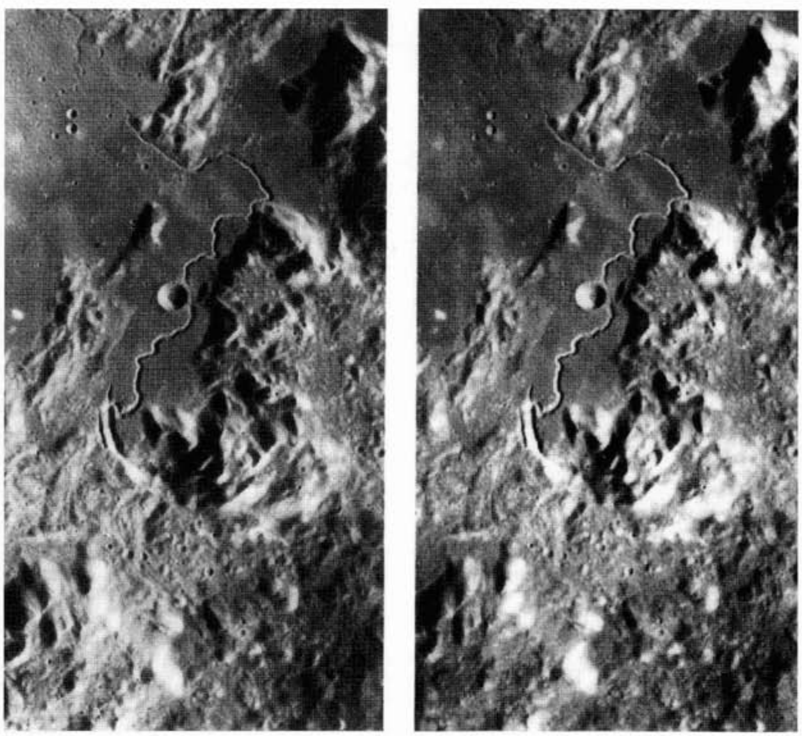

Fig. 6. Stereo view of Hadley Rille, from Apollo Metric Camera frames. Each frame has approximately 30 m ground resolution. Vertical relief is highly exaggerated, to emphasize subtle elevation changes. Each view shows an area about 93 km wide, with north to the top. Left frame, portion of Apollo photograph AS15-M3-1136. Right frame, portion of Apollo photograph AS15-M3-1134.

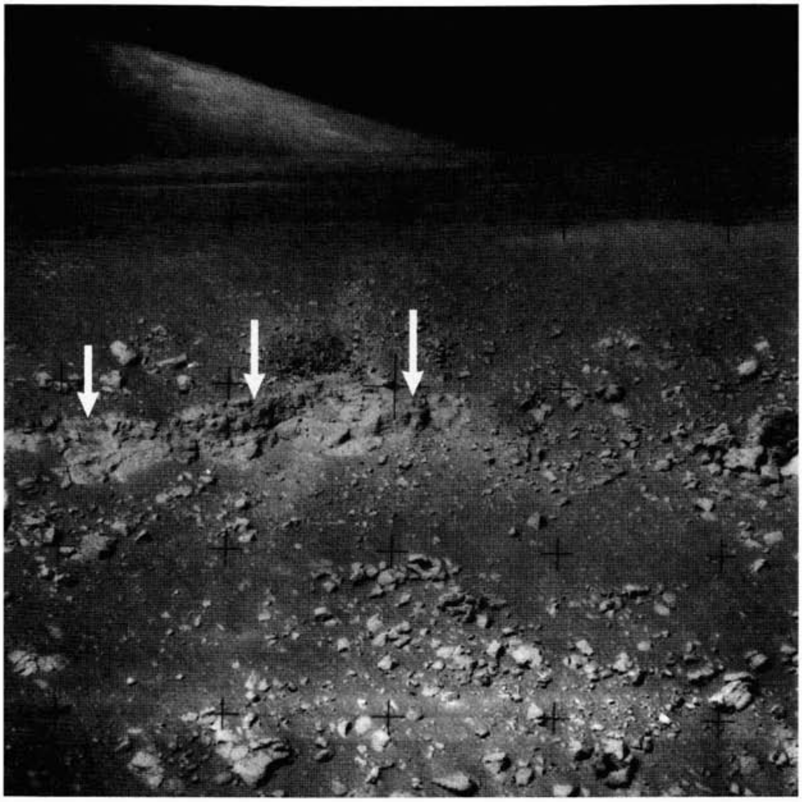

Fig. 7. Surface view of the eastern wall of Hadley Rille, taken by the Apollo 15 astronauts. Arrows indicate bedrock outcrops visible near the top of the rille wall, just below a steep break in slope. The tallest bedrock exposure is about 10 m high. Apollo Hasselblad photograph AS15-89-12115.

talus block similar to pahoehoe festoons, and irregular column-like vertical joints in some outcrops resembling columnar jointing, all of which support a lava emplacement for Hadley Rille within the layered volcanic plains in the Imbrium basin, possibly as a drainage outlet for late-stage mare lavas (Howard et al., 1972).

Apollo samples provided definitive data for the various aqueous hypotheses proposed for sinuous rilles. The Apollo 15 samples in particular (Head, 1976), and all Apollo samples in general (Heiken et al., 1991, p. 150), provided no evidence for indigenous water in any lunar materials. Some samples showed a 'rust' colored alteration which was initially suspected of resulting from lunar water, but detailed isotopic studies of the lunar rust confirmed that it was caused by contamination by terrestrial water vapor after the samples were returned to Earth (Taylor et al., 1973). The complete lack of chemical evidence for the presence of water in the lunar environment effectively eliminates all aqueous hypotheses.

Observations of massive bedrock layering in the rille wall and the nature of the basalts sampled from the edge of the rille provided strong evidence against fluidization and erosion by ash flow at Hadley Rille, while supporting an interpretation associated with the deposition of mare lavas (Head, 1976; Basaltic Volcanism Study Project, 1981, p. 756). Topographic information derived from Metric Camera photographs (Fig. 6) demonstrated that Hadley Rille is deepest where it is widest, in contrast to river channels, but consistent with the collapsed lava tube hypothesis (Howard et al., 1972). The Apollo results generally strengthened the analogy of terrestrial lava channels and tubes for lunar sinuous rilles (Oberbeck et al., 1969; Greeley, 1971; Cruikshank and Wood,

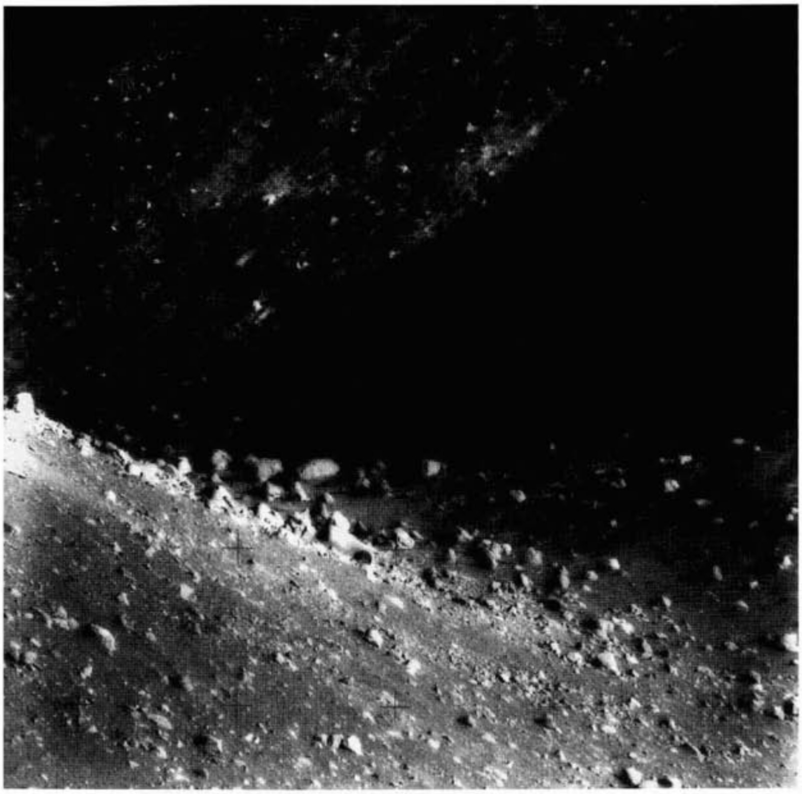

Fig. 8. Surface telephoto view of talus and boulders in Hadley Rille, taken by the Apollo 15 astronauts. View is looking north–northeast. The lower portions of the rille wall are completely covered by talus. The largest block on the rille floor is about 15 m across. Apollo Hasselblad photograph AS15-84-11287.

1972). Theoretical studies of thermal erosion by lava flows revealed that lunar sinuous rilles may be significantly widened during prolonged flow (Hulme, 1973; Carr, 1974), helping to explain the order of magnitude difference between most lunar sinuous rilles and most terrestrial collapsed lava tubes (Head, 1976). The planimetric shape of lunar sinuous rilles obtained from Apollo data compares favorably with the shape of terrestrial collapsed lava tubes when using Fourier analysis (Oberbeck et al., 1969). These studies led to the lava channel/tube origin as the most widely supported explanation for the sinuous rilles (Head, 1976; Basaltic Volcanism Study Project, 1981; Heiken et al., 1991).

3.2. Venus

The Magellan mission to Venus has revealed the nearest planetary neighbor of Earth in unprecedented detail. Magellan radar (SAR) images covered more than 98% of the surface of Venus, a planet only slightly smaller than the Earth, with an effective ground resolution ranging from 120 to 300 m (Senske et al., 1993). The interaction of radar signals with a solid surface has important differences from the shadowing, high-lighting, and albedo information which provides textural detail to optical images (Ford et al., 1993). It is unlikely that information from another spacecraft will significantly improve upon the Magellan resolution in the near future, so genetic hypotheses developed from Magellan images will need to be tested with those data. Discussion is limited here to venusian landforms that have many similarities to the lunar sinuous rilles (Fig. 9).

Several channel and valley landforms were identified in the Magellan SAR images, but here we concentrate on simple channels that include (1) sinuous rilles that closely resemble lunar counterparts

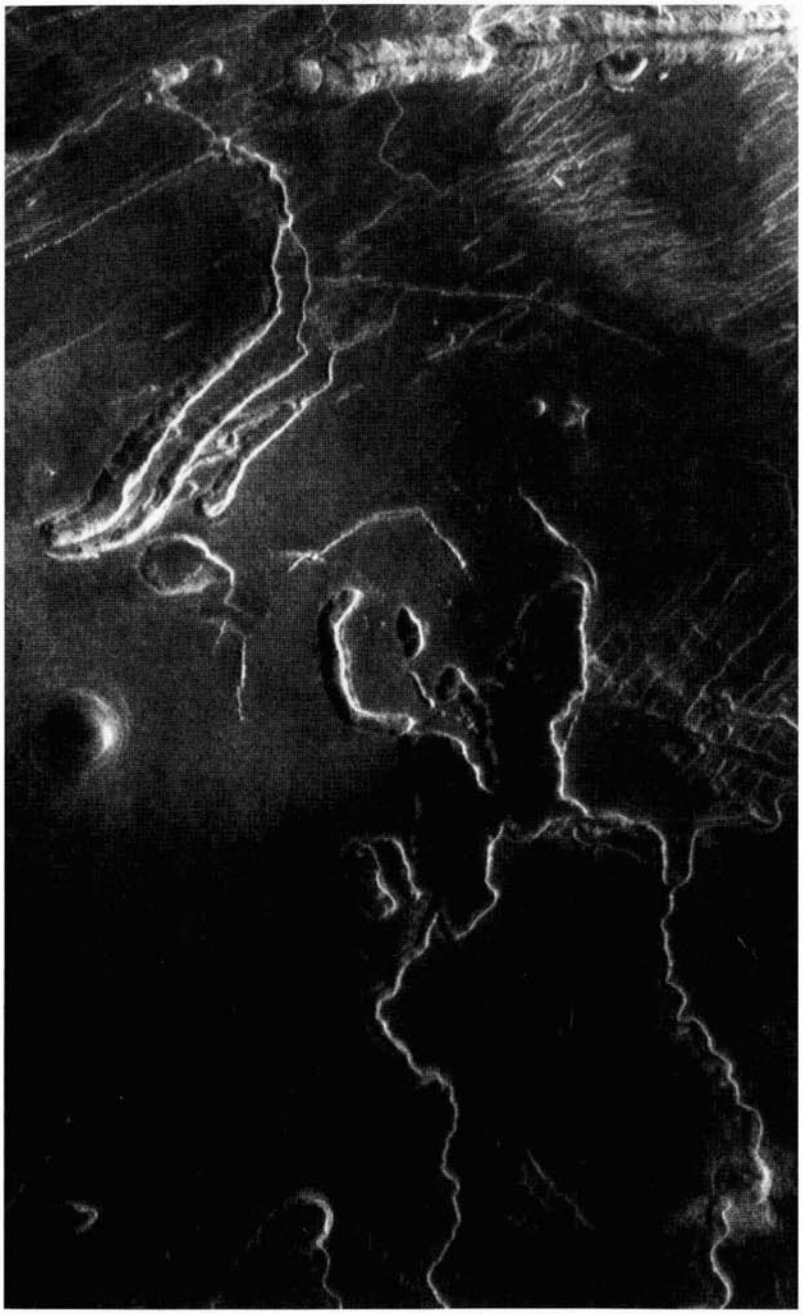

Fig. 9. Venusian sinuous rilles north of Ovda Regio. Image is centered on lat. 11.4°S, long. 89.7°, with north to the top. These rilles are similar to lunar sinuous rilles. Width of Magellan SAR image is about 135 km. Portion of Magellan F-MIDR 10S087, after Baker et al. (1992a,b), fig. 4a.

and (2) a newly recognized long sinuous form of high width-to-depth ratio and remarkably constant width (Head et al., 1991; Baker et al., 1992a). Venera 15/16 SAR images, with 1 to 2 km ground resolution, failed to detect many such channels on the northern quarter of the planet (Barsukov et al., 1985; Basilevsky et al., 1986). The current high temperatures and pressures at the surface of Venus do not allow for the stability of liquid water, although some theories suggest that water may have been stable early in the history of Venus (Kasting and Toon, 1989). The impact crater record on Venus, however, implies an age of several hundred million to possibly 1 billion years (Basilevsky et al., 1987; Phillips et al., 1992; Schaber et al., 1992), effectively eliminating water as a viable fluid for the erosion of the channels.

Venusian sinuous rilles form a deep single channel 1 to 2 km wide which narrows and shallows toward its terminus, located several tens to hundreds of kilometers from circular to elongated collapse regions (representing possible source regions) ranging to tens of kilometers in diameter (Baker et al., 1992a; Komatsu et al., 1993). The new sinuous landforms, termed canali (Fig. 10), have relatively constant down-channel widths (1 to 5 km) and are typically longer than 500 km, with one exceptional case that is traced for 6800 km (Komatsu et al., 1992). The venusian sinuous rilles and the canali are interpreted to result from the erosion of some flowing fluid, with the intriguing situation that several low-viscosity fluids are candidates for multiple hypotheses for the fluid-erosive origin: ultramafic or highly alkaline mafic silicates, carbonatite, and sulfur (Baker et al., 1992a; Komatsu et al., 1993). A simple model incorporating channel flow and radiative cooling suggests that tholeiitic lavas cannot sustain a superheated and turbulent state for the long distances required by several observed canali, which tends to support a more exotic fluid like carbonatite or sulfur for the erosional genesis of canali (Komatsu et al., 1992). Here we have the interesting situation where channel geometry does not uniquely constrain the flowing fluid, but channel lengths place limits on the physical properties of fluids that can remain erosive and fluid over length scales that are planetary in scale. Future research oriented toward a better understanding of these exotic fluids could aid in the evaluation process.

3.3. Mars

The advent of spacecraft missions to Mars, beginning with 22 frames returned by Mariner 4 in 1965,

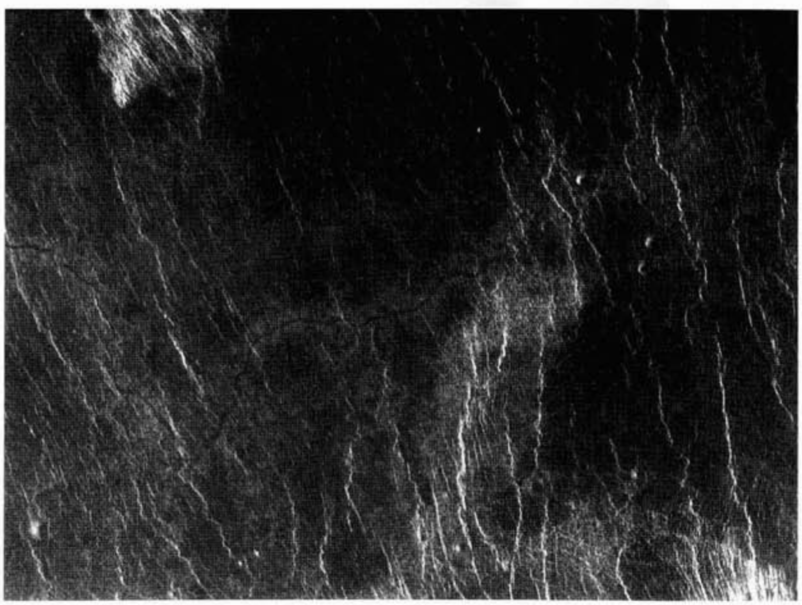

Fig. 10. Venusian canali in Helen Planitia. Image is centered on lat. 49.0°S, long. 269.9°, with north to the top. Canali crosses ridged plains and displays variable sinuosity wavelengths in different reaches. Width of Magellan SAR image is about 290 km. Portion of Magellan F-MIDR 50S272, after Baker et al. (1992a,b), fig. 6.

has provided images of Mars with increasing resolution: the best ground resolution obtained from U.S. missions to Mars was 730 m/pixel for Mariner 4, 950 m/pixel for the Wide Angle camera and 95 m/pixel for the Narrow Angle camera on Mariners 6 and 7, 400 m/pixel for the Wide Angle camera and 40 m/pixel for the Narrow Angle camera on Mariner 9, and 8 m/pixel for the Viking Orbiter cameras (Masursky et al., 1970; Carr et al., 1972; Snyder, 1979). The new information returned by each mission led to an astounding array of geomorphic hypotheses proposed to explain the complex landforms on Mars. Martian sinuous channels and the more controversial sinuous ridges are considered next.

Sinuous channels on Mars have most of the properties already described for the lunar sinuous rilles. The term 'channel' has been applied to valleys on Mars, because of much greater diversity in groundplan and detailed morphology than the lunar sinuous rilles and, perhaps, as a consequence of observational and theoretical analyses that indicate water was present throughout the history of Mars. The martian sinuous channels were first documented during the Mariner 9 mission in 1971–1972 (Masursky et al., 1972; Milton, 1973), and the hypotheses for origin were derived primarily from the extensive lunar sinuous rille literature. Viking images greatly expanded the available coverage of the martian sinuous channels (Fig. 11), and various other valley features on the planet (Baker et al., 1992b). Unlike the lunar situation, many of the channels on Mars display geomorphic features clearly indicative of fluid flow (Baker, 1982; Baker et al., 1992b). The sinuous channels on Mars that are most similar in groundplan and overall dimensions to the lunar sinuous rilles are interpreted to result from volcanic flow within channels or tubes, like the post-Apollo view of the lunar sinuous rilles (Carr, 1974). The erosive character of the flowing turbulent lava is considered to be significant on Mars (Carr, 1974), consistent with the proposal for thermal erosion during sinuous rille formation on the Moon (Hulme, 1973). Terrestrial analogs

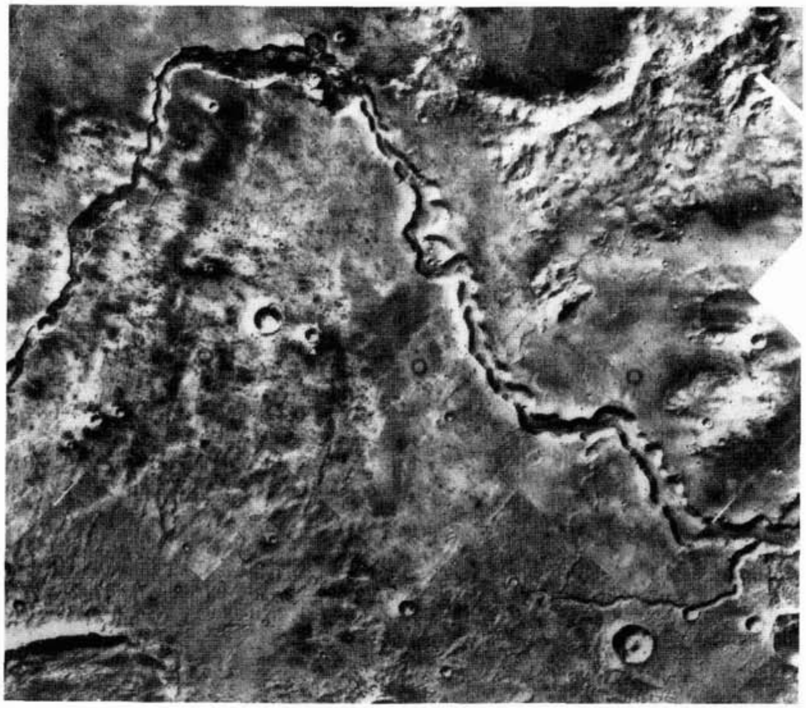

Fig. 11. Martian sinuous channel, showing a portion of Bahram Vallis. As with lunar and venusian sinuous rilles, this channel has few tributaries, a flat floor, and cuspate walls. North is to the right of the top. The figure covers an area about 127 km wide. Portion of mosaic of Viking Orbiter images, JPL mosaic 211-5189.

have been examined for comparison to sinuous channels on Mars (Carr and Greeley, 1980, pp. 109–125), following the procedure applied to lunar sinuous rilles (Oberbeck et al., 1969; Greeley, 1971; Cruikshank and Wood, 1972). The martian features do not appear to have altered the outcome of the lunar sinuous rille investigations, although a wide variety of alternative hypotheses have been proposed for the various forms of channels on Mars (Baker et al., 1992b).

Considerable controversy surrounds some unusual sinuous ridges observed in Viking images of the martian mid-latitudes. These distinctive landforms consist of long (several tens to hundreds of kilometers), narrow (hundreds of meters to a few kilometers) ridges with broad sinuous bends and localized sections of anastomosing ridge complexes (Fig. 12; Kargel and Strom, 1992). Proposed origins for these features include wrinkle ridges and lava flows (Viking Orbiter Imaging Team, 1980, p. 136; Tanaka and Scott, 1987), exhumed igneous dikes (Viking Orbiter Imaging Team, 1980, p. 136; Carr, 1984, pp. 231–232), exhumed clastic dikes (Ruff and Greeley, 1990), linear sand dunes (Parker et al., 1986; Ruff and Greeley, 1990), fluvial or lacustrine spits or bars (Parker et al., 1986), inverted stream topography (Howard, 1981), and glacial eskers (Viking Orbiter Imaging Team, 1980, p. 136; Howard, 1981; Carr, 1984, pp. 231–232; Parker et al., 1986; Tanaka and Scott, 1987; Ruff and Greeley, 1990; Metzger, 1991; Kargel and Strom, 1992). Kargel and Strom (1992) point out that eskers are the only feature common to all analyses, but it should also be noted that most authors do not conclude that eskers are the most

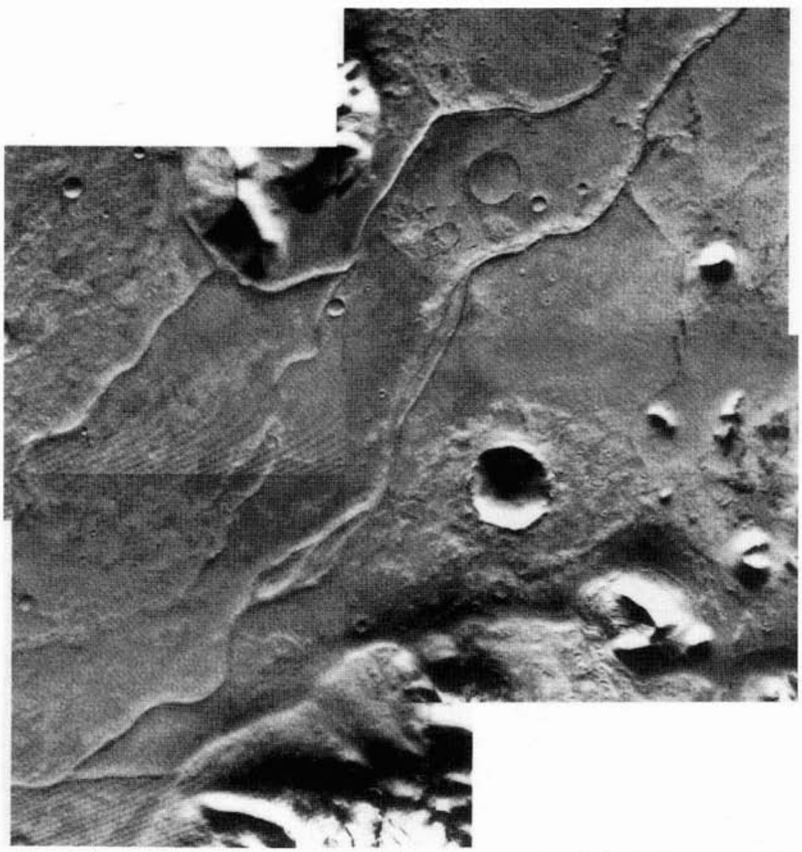

Fig. 12. Martian sinuous ridges in Argyre Planitia. The ridges extend for many tens to hundreds of kilometers, with anastamosing sections in places (lower left). Mosaic of Viking Orbiter frames 567B30-33, with a ground resolution of 49 m/pixel and an illumination angle of 13°. North is slightly left of the top. The mosaic covers an area about 108 km wide.

probable explanation. An informal working group was established, comprised of various researchers actively studying these perplexing features, with the goal of documenting the significant characteristics of each hypothesis for use by the science community.

The esker hypothesis probably draws the strongest reaction from most researchers because, as a direct consequence, it has strong implications for the recent history of Mars. Several authors have noted the superposition relationships among the ridges and the surroundings, most of which imply that the ridges are among the most recent landforms emplaced in the vicinity. A glacial origin for the ridges would then indicate substantial ice masses were present in the martian mid-latitudes late in martian history, which has been incorporated into a broader proposal for the hydrologic cycle on Mars (Baker et al., 1991; Kargel and Strom, 1992). This scenario is a significant departure from recent views of water on Mars, which include massive water release into the northern plains during the formation of the large outflow channels at an intermediate stage of martian history (Carr, 1986; Clifford, 1993). Most other proposed origins for the sinuous ridges involve a martian environment not substantially different from the current climate.

The best Viking images of the sinuous ridges have a ground resolution of 47–50 m/pixel, with an illumination angle of about 13° (Fig. 12). This leads to an identification resolution of 250–300 m under the favorable illumination conditions (see Fig. 1). It is not clear that any of the proposed hypotheses predict the presence of features on this scale, raising doubts that diagnostic morphologic characteristics can help to test between the proposed hypotheses. However, Viking images can provide non-geomorphic information, which could provide tests for some of the hypotheses. For example, the topographic information around the Hadley Rille proved to be particularly helpful in evaluating some of the hypotheses for sinuous rille formation. Photoclinometric measurements may provide local relative elevations which could test between some hypotheses (e.g., flow-related processes would most likely favor particular gradient directions whereas aeolian or tectonic processes could result in widely varying local slopes). This is just one example of how available image data may still yield new information that could help to discriminate between possible hypotheses.

4. Discussion

Several genetic hypotheses have now been reviewed for distinctive landforms on different planetary surfaces. How did available image resolution factor into the development of the hypotheses? High spatial resolution does not automatically translate into diagnostic tests for genetic hypotheses.

The evolution of ideas about the origin of lunar sinuous rilles seems to have progressed nearly independently of the image resolution available. Hypotheses originally developed from telescopic studies (with a ground resolution of 1–2 km) were elaborated upon through the advent of high-resolution Lunar Orbiter photographs (with ground resolutions from a few to tens of meters) but without the elimination of any major competing concept. The “ruling theory” as described by Chamberlin (1897) seems to have been more prevalent at this time than one would have hoped. The Apollo orbital data had a ground resolution comparable to (or even worse than) the Lunar Orbiter data but, more importantly, the topographic information obtained from the cartographically controlled cameras provided quantitative results essential to testing certain hypotheses. It is not known how the hypotheses would have fared from acquisition of the orbital data alone, without the accompanying crucial information derived from landing missions. Clearly, several important constraints on the formation of sinuous rilles came from piloted exploration, through detailed observations on the surface and through sample analysis. Surface exploration is substantially more complex (and expensive) than improved orbital resolution. A substantial improvement in resolution provided by Lunar Orbiter, however, still failed to provide definitive evidence regarding proposed origins for the sinuous rilles, let alone any new hypotheses. Must we necessarily wait for surface studies before geomorphic hypotheses can be tested adequately? Such a conclusion would be a serious misinterpretation of the examples discussed above.

The venusian canali provide an illustration of how non-imaging results can have a profound impact on hypothesized geomorphic agents. The modeling of Komatsu et al. (1992) may not be the optimum method for evaluating the flow potential for all fluid materials, but it was sufficient to lessen the likelihood of mafic silicate lavas as the causal agent for the very long canali. Are silicate lavas eliminated entirely from geomorphic hypotheses for Venus? Certainly not, given that the lunar-like sinuous rilles on Venus are smaller features where such lavas could still be the operative eroding fluid. Similarly, the martian sinuous channels that are comparable in size and groundplan to the lunar sinuous rilles are strong candidates for emplacement by lava flows or tubes, but that does not eliminate other geologically plausible fluids (such as mudflows) from also being active in some cases. Still, the removal of even one candidate material is a definite increase in the knowledge base about a given planet.

A non-verbalized assumption may exist that if only one could see a feature with more detail, one would automatically understand how it formed. The lunar sinuous rilles are an excellent case in point that an increase in resolution of three orders of magnitude does not guarantee that alternative genetic hypotheses will be tested adequately. Improved resolution will always reveal intriguing new details about a planetary surface, as in the case for Mars where a surface texturally 'smooth' at 57 m/pixel was shown to be covered with aeolian dune forms when imaged at 8 m/pixel (Zimbelman, 1987). Such new detail, however, may not, in certain cases, relate to a geomorphic process that acts on a much larger scale (Squyres, 1989). Testing of hypothesized genetic processes is facilitated if researchers include specific statements regarding observable characteristics. A proposed mechanism that is not testable is not a useful working hypothesis if it cannot be evaluated further in some manner. Attention to this concept would go a long way toward providing ways to evaluate existing hypotheses and still encourage the generation of new alternative hypotheses where applicable.

New image data sets anticipated in the near future provide the opportunity for additional tests to be proposed for some genetic processes. The successful completion of multispectral mapping of the entire lunar surface by the Clementine spacecraft represents an opportunity to evaluate existing ideas about the lunar surface, with the important addition of global topographic information (Nozette and Garrett, 1994). The loss of the Mars Observer (MO) and Russian Phobos spacecraft were serious blows to studies of Mars, but the reflight of several MO instruments on the Mars Global Surveyor (MGS) spacecraft provides another chance to evaluate many published and new hypotheses.

The Mars Orbiter Camera (MOC) provides 1.5 m/pixel ground resolution images at 2 p.m. local Mars time (Malin et al., 1991, 1992, 1998). The roughly 60° illumination angle of the planned MGS mapping orbit should increase the detection and identification resolutions by factors of 4 and 16, respectively, over the ground resolution available at optimal illumination (see Fig. 1). Tests utilizing MOC data should incorporate this effect into plans for possible target landforms. MOC was designed to examine "geological processes that operate on short time scales" (Malin et al., 1991, 1992), consistent with its very high spatial resolution. Researchers can learn from the sinuous rille example and should not assume that high spatial resolution can provide tests to hypotheses that were not formulated for application at a surficial scale. Important genetic tests can also be applied to complimentary data sets, such as the detailed topographic data for Mars from the Mars Orbiter Laser Altimeter (Zuber et al., 1992; Smith et al., 1998) and compositional data from the Thermal Emission Spectrometer (Christensen et al., 1992; 1998). The strength of these tests will be more dependent upon the effort placed into the development of new working hypotheses (in the Chamberlin sense), with their associated testable consequences, than on the precise ground resolution utilized. Such working hypotheses will help to keep the evaluation of genetic agents out of the insidious trap of the "ruling theory". New ideas and the critical evaluation of existing hypotheses are fundamental to the advancement of knowledge of the complex surfaces encountered throughout the solar system.

5. Summary

Improved spatial resolution is not automatically the best test for geomorphic hypotheses. While improved resolution will certainly reveal more detail about the surface, that detail may not relate directly to the geomorphic agent under study. Whereas improved application of geomorphic principles (particularly careful attention to the concept behind multiple working hypotheses) should help to test existing hypotheses and to generate viable alternative hypotheses. The careful formulation of a genetic hypothesis, including as many testable consequences of that hypothesis as possible, is a greater determinant of its ultimate utility to the scientific community than the specific image resolution available at a given time.

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References

Baker, V.R., 1982. The Channels of Mars. Univ. of Texas Press, Austin, 198 pp.

Baker, V.R., 1993. Extraterrestrial geomorphology: science and philosophy of Earthlike planetary landscapes. Geomorphology, 7, 9–35.

Baker, V.R., 1996a. Hypotheses and geomorphological reasoning. In: Rhoads, B.L., Thorn, C.E. (Eds.), The Scientific Nature of Geomorphology. Wiley, New York, pp. 57–85.

Baker, V.R., 1996b. The pragmatic roots of American Quaternary geology and geomorphology. Geomorphology, 458, 1–19.

Baker, V.R., Strom, R.G., Gulick, V.C., Kargel, J.S., Komatsu, G., Kale, V.S., 1991. Ancient oceans, ice sheets and the hydrological cycle on Mars. Nature, 352, 589–594.

Baker, V.R., Komatsu, G., Parker, T.J., Gulick, V.C., Kargel, J.S., Lewis, J.S., 1992a. Channels and valleys on Venus: preliminary analysis of Magellan data. J. Geophys. Res., 97, 13421–13444.

Baker, V.R., Carr, M.H., Gulick, V.C., Williams, C.R., Marley, M.S., 1992b. Channels and valley networks. In: Kieffer, H.H. (Ed.), Mars. Univ. of Arizona Press, Tucson, pp. 493–522.

Baldwin, R.B. et al., 1963. The Measure of the Moon. Univ. of Chicago Press, Chicago, 488 pp.

Barsukov, V.L., Basilevski, A.T., Kuzmin, R.O., Markov, M.S., Kryutchkov, V.P., Nikolaeva, O.V., Pronin, A.A., Sukhanov, A.L., Chernaya, I.M., Burba, G.A., Bobina, N.N., Shashkina, V.P., 1985. Main types of structures of the northern hemisphere of Venus. Sol. Syst. Res., 19, 1–9.

Basaltic Volcanism Study Project, 1981. Basaltic Volcanism on the Terrestrial Planets. Pergamon, New York, 1286 pp.

Basilevsky, A.T., Pronin, A.A., Ronca, I.B., Kryuchkov, V.P., Sukhanov, A.L., Markov, M.S., 1986. Styles of tectonic deformations on Venus: analysis of Venera 15 and 16 data. Proc. Lunar Planet. Sci. Conf. 16th. J. Geophys. Res., vol. 91, pp. D399–D411.

Basilevsky, A.T., Ivanov, B.A., Burba, G.A., Chernaya, I.M., Kryuchkov, V.P., Nikolaeva, O.V., Campbell, D.B., Ronca, L.B., 1987. Impact craters of Venus: a contribution of the analysis of data from the Venera 15 and 16 spacecraft. J. Geophys. Res., 92, 12869–12901.

Cameron, W.S., 1964. An interpretation of Schroter's Valley and other lunar sinuous rilles. J. Geophys. Res., 69, 2423–2430.

Carr, M.H., 1974. The role of lava erosion in the formation of lunar rilles and martian channels. Icarus, 22, 1–23.

Carr, M.H., 1984. Mars. In: Carr, M.H. (Ed.), The Geology of the Terrestrial Planets. NASA SP, vol. 469, U.S. Gov. Printing Office, Washington, pp. 207–263.

Carr, M.H., 1986. Mars: a water-rich planet? Icarus, 68, 187–216.

Carr, M.H., Greeley, R., 1980. Volcanic features of Hawaii: a basis for comparison with Mars. NASA SP, vol. 403, U.S. Gov. Printing Office, Washington, 211 pp.

Carr, M.H., Baum, W.A., Briggs, G.A., Masursky, H., Wise, D.W., Montgomery, D.R., 1972. Imaging experiment: the Viking Mars Orbiter. Icarus, 16, 17–33.

Chamberlin, T.C., 1897. The method of multiple working hypotheses. J. Geol., 5, 837–848.

Christensen, P.R., Anderson, D.L., Chase, S.C., Clark, R.N., Kieffer, H.H., Malin, M.C., Pearl, J.C., Carpenter, J., Bandiera, N., Brown, F.G., Silverman, S., 1992. Thermal emission spectrometer experiment: Mars observer mission. J. Geophys. Res., 97, 7719–7734.

Christensen, P.R., Anderson, D.L., Chase, S.C., Clancy, R.T., Clark, R.N., Conrath, B.J., Kieffer, H.H., Kuzmin, R.O., Malin, M.C., Pearl, J.C., Roush, T.L., Smith, M.D., 1998. Results from the Mars Global Surveyor Thermal Emission Spectrometer. Science, 270, 1692–1698.

Clifford, S.M., 1993. A model for the hydrologic and climatic behavior of water on Mars. J. Geophys. Res., 98, 10973–11016.

Cruikshank, D.P., Wood, C.A., 1972. Lunar rilles and Hawaiian volcanic features: possible analogues. Moon, 3, 412–447.

Ford, J.P., Plaut, J.J., Weitz, C.M., Farr, T.G., Senske, D.A., Stofan, E.R., Michaels, G., Parker, T.J., 1993. Guide to Magellan image interpretation. JPL Publ., 93-24, Pasadena, 148 pp.

Frisoff, V.A., 1960. Strange World of the Moon. Basic Books, New York, 189 pp.

Gilvarry, J.J., 1960. Origin and nature of lunar surface features. Nature, 188, 886–891.

Gilvarry, J.J., 1968. Observational evidence for sedimentary rocks on the Moon. Nature, 218, 336.

Greeley, R., 1971. Lunar Hadley Rille: considerations of its origin. Science, 172, 722–725.
Head, J.W., 1976. Lunar volcanism in space and time. Rev. Geophys. Space Phys., 14, 265–300.
Head, J.W., Lloyd, D.D., 1971. Near-terminator photography. Apollo 14 Preliminary Science Report. NASA SP, vol. 272, U.S. Gov. Printing Office, Washington, pp. 297–300.
Head, J.W., Lloyd, D.D., 1972. Near-terminator photography. Apollo 15 Preliminary Science Report. NASA SP, vol. 289, U.S. Gov. Printing Office, Washington, WA, pp. 25-95–25-101.
Head, J.W., Campbell, D.B., Elachi, C., Guest, J.E., McKenzie, D.P., Saunders, R.S., Schaber, G.G., Schubert, G., 1991. Venus volcanism: initial analysis from Magellan data. Science, 252, 276–288.
Heiken, G., Vaniman, D., French, B.M., 1991. Lunar Sourcebook: A User's Guide to the Moon. Cambridge Univ. Press, New York, 736 pp.
Howard, A.D., 1981. Etched plains and braided ridges of the south polar region of Mars: features produced by basal melting of ground ice? Reports of the Planetary Geology and Geophysics Program. NASA TM-84211, pp. 286–288.
Howard, K.A., Head, J.W., Swann, G.A., 1972. Geology of Hadley Rille. Proc. Third Lunar Sci. Conf. Geochem. Cosmochem. Acta. Sup. 3, vol. 1, pp. 1–14.
Hulme, G., 1973. Turbulent lava flow and the formation of lunar sinuous rilles. Mod. Geol., 4, 107–117.
Jastrow, R., Thompson, M.H., 1972. Astronomy: Fundamentals and Frontiers. Wiley, New York, 404 pp.
Kahn, R.E., Guinness, E., Arvidson, R., 1986. Loss of fine-scale surface texture in Viking Orbiter images and implications for the inferred distribution of debris mantles. Icarus, 66, 22–38.
Kargel, J.S., Strom, R.G., 1992. Ancient glaciation on Mars. Geology, 20, 3–7.
Kasting, J.F., Toon, O.B., 1989. Climate evolution on the terrestrial planets. In: Atreya, S.K., Pollack, J.B., Matthews, M.S. (Eds.), Origin and Evolution of Planetary and Satellite Atmospheres. Univ. of Arizona Press, Tucson, pp. 423–449.
Keene, G.C., 1965. Lunar Orbiter Photo Study Z-3841. Eastman Kodak, Rochester, NY, p. 137.
Komatsu, G., Kargel, J.S., Baker, V.R., 1992. Canali-type channels on Venus: some genetic constraints. Geophys. Res. Lett., 19, (13), 1415–1418.
Komatsu, G., Baker, V.R., Gulick, V.C., Parker, T.J., 1993. Venusian channels and valleys: distribution and volcanological implications. Icarus, 102, 1–25.
Kosofsky, L.J., El-Baz, F., 1970. The Moon as Viewed by Lunar Orbiter. NASA SP, vol. 200, U.S. Gov. Printing Office, Washington, 152 pp.
Levin, E., Viele, D.D., Eldrenkamp, L.B., 1968. The Lunar Orbiter missions to the Moon. Sci. Am., 218 (5), 58–78.
Lingenfelter, R.E., Peale, S.J., Schubert, G., 1968. Lunar rivers. Science, 161, 266.
Malin, M.C., Danielson, G.E., Ravine, M.A., Soulanille, T.A., 1991. Design and development of the Mars Observer camera. Int. J. Imaging Syst. Tech., 3, 76–91.
Malin, M.C., Danielson, G.E., Ingersoll, A.P., Masursky, H., Veverka, J., Ravine, M.A., Soulanille, T.A., 1992. Mars Observer camera. J. Geophys. Res., 97, 7699–7718.
Malin, M.C., Carr, M.H., Danielson, G.E., Davies, M.E., Hartmann, W.K., Ingersoll, A.P., James, P.B., Masursky, H., McEwen, A.S., Soderblom, L.A., Thomas, P., Veverka, J., Caplinger, M.A., Ravine, M.A., Soulanille, T.A., Warren, J.L., 1998. Early views of the Martian surface from the Mars Orbiter Camera of Mars Global Surveyor. Science, 279, 1681–1685.
Masursky, H., Batson, R., Borgeson, W., Carr, M., McCauley, J., Milton, D., Wildey, R., Wilhelms, D., Murray, B., Horowitz, N., Leighton, R., Sharp, R., Thompson, W., Briggs, G., Chandeysson, P., Shipley, E., Sagan, C., Pollack, J., Lederberg, J., Levinthal, E., Hartmann, W., McCord, T., Smith, B., Davies, M., De Vaucouleurs, G., Leovy, C., 1970. Television experiment for Mariner Mars 1971. Icarus, 12, 10–45.
Masursky, H., Batson, R., McCauley, J., Soderblom, L.A., Wildey, R.L., Carr, M.H., Milton, D., Wilhelms, D., Smith, B.A., Kirby, T.B., Robinson, J.C., Leovy, C.B., Briggs, G.A., Young, A.T., Duxbury, T.C., Acton, C.H., Murray, B.C., Cutts, J.A., Sharp, R.P., Smith, S., Leighton, R.B., Sagan, C., Veverka, J., Noland, M., Lederberg, J., Levinthal, E., Pollack, J.B., Moore, J.T., Hartmann, W.K., Shipley, E.N., De Vaucouleurs, G., Davies, M.F., 1972. Mariner 9 television reconnaissance of Mars and its satellites: preliminary results. Science, 175, 294–305.
Masursky, H., Colton, G.W., El-Baz, F., 1978. Apollo over the Moon: a view from orbit. NASA SP, 362, 255 pp.
Melosh, H.J., 1989. Impact Cratering: A Geologic Process. Oxford Univ. Press, New York, 245 pp.
Menzel, D.H., 1964. A Field Guide to the Stars and Planets. Houghton Mifflin, Boston, 397 pp.
Metzger, S.M., 1991. A survey of esker morphometries, the connection to New York state glaciation and criteria for subglacial melt–water channel deposits on the planet Mars. Lunar and Planetary Science, vol. XXII, Lunar and Planetary Institute, Houston, pp. 891–892.
Milton, D.J., 1973. Water and processes of degradation in the martian landscape. J. Geophys. Res., 78, 4037–4047.
Mutch, T.A., 1970. Geology of the Moon: A Stratigraphic View. Princeton Univ. Press, Princeton, NJ, 324 pp.
Mutch, T.A., Arvidson, R.E., Head, J.W., Jones, K.L., Saunders, R.S., 1976. The Geology of Mars. Princeton Univ. Press, Princeton, NJ, 400 pp.
Nozette, S., Garrett, H.B., 1994. Clementine mission offers a new look at the Moon and a Near-Earth asteroid. Trans. Am. Geophys. Union, 75 (14), 161–165.
Oberbeck, V.R., Quaide, W.L., Greeley, R., 1969. On the origin of lunar sinuous rilles. Mod. Geol., 1, 75–80.
Parker, T.J., Pieri, D.C., Saunders, R.S., 1986. Morphology and distribution of sinuous ridges in central and southern Argyre. Reports of the Planetary Geology and Geophysics Program. NASA TM-88383, U.S. Gov. Printing Office, Washington, pp. 468–470.
Peale, S.J., Schubert, G., Lingenfelter, R.E., 1968. Distribution of sinuous rilles and water on the Moon. Nature, 220, 1222.
Phillips, R.J., Raubertas, R.F., Arvidson, R.E., Sarkar, I.C., Her-

rick, R.R., Izenberg, N., Grimm, R.E., 1992. Impact craters and Venus resurfacing history. J. Geophys. Res., 97, 15923–15948.

Pickering, W.H., 1904. The Moon. Doubleday, Page, and Co., New York, 103 pp.

Quaide, W.L., 1965. Rilles, ridges and domes—clues to maria history. Icarus, 4, 374–389.

Ruff, S.W., Greeley, R., 1990. Sinuous ridges of the south polar region, Mars: possible origins. Lunar and Planetary Science, vol. XXI, Lunar and Planetary Institute, Houston, pp. 1047–1048.

Schaber, G.G., Strom, R.G., Moore, H.J., Soderblom, L.A., Kirk, R.L., Chadwick, D.J., Dawson, D.D., Gaddis, L.R., Boyce, J.M., Russel, J., 1992. Geology and distribution of impact craters on Venus: what are they telling us? J. Geophys. Res., 97, 13257–13301.

Schubert, G., Lingenfelter, R.E., Peale, S.J., 1970. The morphology, distribution, and origin of lunar sinuous rilles. Rev. Geophys. Space Phys., 8, 199–224.

Schumm, S.A., 1970. Geol. Soc. Am. Bull., 81, 2539–2552.

Senske, D.A., Saunders, R.S., Stofan, E.R., 1993. A global geologic map of Venus: characterization of landforms and stratigraphy. Trans. Am. Geophys. Union, 74 (43), 379.

Short, N.M., 1975. Planetary Geology. Prentice-Hall, Englewood Cliffs, NJ, 361 pp.

Smith, D.E., Zuber, M.T., Frey, H.V., Garvin, J.B., Head, J.W., Muhleman, D.O., Pettengill, G.H., Phillips, R.G., Solomon, S.C., Zwally, H.J., Banerdt, W.B., Duxbury, T.C., 1998. Topography of the northern hemisphere of Mars from the Mars Orbiter Laser Altimeter. Science, 279, 1686–1692.

Snyder, C.W., 1979. The extended mission of Viking. J. Geophys. Res., 84, 7917–7933.

Soderblom, L.A., 1972. The process of crater removal in the lunar maria. Apollo 15 Preliminary Science Report. NASA SP, vol. 289, U.S. Gov. Printing Office, Washington, pp. 25-87–25-91.

Squyres, S.W., 1989. Urey prize lecture: water on Mars. Icarus, 79, 229–288.

Swann, G.A., Bailey, N.G., Batson, R.M., Freeman, V.L., Hait, M.H., Head, J.W., Holt, H.E., Howard, K.A., Irwin, J.B., Larson, K.B., Muehlerger, W.R., Reed, V.S., Rennilson, J.J., Schaber, G.G., Scott, D.R., Silver, L.T., Sutton, R.L., Ulrich, G.E., Wilshire, H.G., Wolfe, E.W., 1972. Preliminary geologic investigation of the Apollo 15 landing site. Apollo 15 Preliminary Science Report. NASA SP, vol. 289,, pp. 5-1–5-112.

Tanaka, K.L., Scott, D.H., Geologic map of the polar regions of Mars. U.S. Geol. Surv. Misc. Invest. Map I-1802-C, scale 1:15,000,000.

Taylor, L.A., Mao, H.K., Bell, P.M., 1973. "Rust" in the Apollo 16 rocks. Proc. Lunar Sci. Conf. 4th., pp. 829–839.

Urey, H.C., 1967. Water on the Moon. Nature, 216, 1094.

Van Blerkom, D.J., 1971. The effect of haze on the visibility of martian surface features. Icarus, 14, 235–244.

Viking Orbiter Imaging Team, 1980. Viking Orbiter views of Mars. NASA SP, vol. 441, 182 pp.

Zimbelman, J.R., 1987. Spatial resolution and geologic interpretation of Martian morphology: Implications for subsurface volatiles. Icarus, 71, 257–267.

Zuber, M.T., Smith, D.E., Solomon, S.C., Muhleman, D.O., Head, J.W., Garvin, J.B., Abshire, J.B., Bufton, J.L., 1992. The Mars observer laser altimeter investigation. J. Geophys. Res., 97, 7781–7798.