
Classification and Characterization of Planetary Landforms

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Introduction

Revealing Earth's history is like trying to solve a 4D jigsaw puzzle whose three-dimensional pieces are in continual motion that mixes and destroys the records of the past. Although the methods of terrestrial geology are more diverse and allow more detailed investigations than planetary geology, its subject is also more complex. Most of the planets and moons appear to have a simpler history, with most of the known solid-surface bodies shaped principally by impacts. Even the most complex known extraterrestrial worlds lack plate tectonics and, consequently, all landforms and climatic changes related to the supercontinent cycle. The majority of planetary bodies show very old surfaces with apparent ages on the scale of billions of years. Deciphering their history from only what the surface displays seems to be a realistic task. There are only a few worlds whose surfaces are young or very young (Venus, Io, Europa), where no record of previous times is preserved on the surface.

The classical approach in earth science was to move from local to global scale, whereas in planetary sciences, on the contrary, global-scale features are identified first, and investigation progresses toward local scales.

In the following, we present an outline of the basic methods that were developed in the planetary geological community to best describe and interpret surface features. We present several theoretical models and practical methodologies on how to work with visual information, particularly with photogeological data and with types and tokens. These models are not just theoretical but practical methodologies also, based on terrestrial practice.

An additional aim of this book is to explore the philosophical foundations of the methods commonly used in planetary geology.

Our knowledge of the geology of solid-surface solar system bodies is derived from several sources: different types of spaceborne and in situ remote sensing data with varying 2D or 3D spatial and temporal resolution; models based on these data (some combined with terrestrial observations); lunar rock and regolith samples; and lunar, martian, and asteroidal meteorites ejected

from unknown geographical locations. The remote sensing data rarely reveal active processes or recent surface changes: Such rare examples are the volcanoes of Io; geyser-like eruptions of Europa, Enceladus, and Triton; or several phenomena on Mars: recently formed small impact craters, gullies, landslides, rockfalls, albedo features related to aeolian activity (e.g., dust devil tracks, wind streaks), defrosting, and sublimation features (e.g., dune spots, south polar residual cap features). Most other observed features are traces of past processes whose type, age, and dynamics (speed, intensity, and duration) are revealed through the interpretation of forms, context, crater counting, stratigraphical relations, spectra, etc.

The Types and Scales of Geological Objects and Their Perception

Remotely sensed features on the solid surfaces of planets and moons of our solar system include structures (landforms or topographical features), terrains (relief types), more complex physiographic provinces (landscapes), features identified at wavelengths extending from visible to radio waves (e.g., Albedo Feature, Thermal Infrared Feature, Radar Feature), inferred or spectrally defined material units, and their patterns.

Direct landings on some of those surfaces have expanded the observational database with sample returns (from the Moon) and in situ microscopic exploration (on Mars). Even so, the vast majority of planetary observations still involve features at much coarser scales. Therefore, most problems concerning the classification and characterization of planetary features are related to these coarse-scale surface observations.

Nested Hierarchies

As finer-scale observations become available, integrating them into a spatial hierarchy of regional distinctions in a scale-sensitive manner becomes ever more useful. Those attempting photogeological analyses of a landform or unit in high-resolution imagery need to situate it into a wider regional context.

An example of a nested hierarchy of physiographic regions is the *division—province—section* hierarchy proposed by Fennemann in 1916 to describe the physical geography of the United States (Fenneman 1916). The trichotomy has been expanded to the global and local scales and elaborated, not always consistently, by authors of several geomorphology and physical geography textbooks as the “orders of relief” scheme (e.g., Bridges 1990, pp. 4–6; Christopherson 2003; Garrard 1988, p. 9). Rodrigue (2012, 2009) developed an analogous scheme for the geography of Mars. One key objective was the construction of a vivid mental map of another planet using such surface manifestations as topographic contrast and landforms. The scheme consists of five levels.

The first order of relief refers to Mars’ striking crustal dichotomy, while the second order describes large, visually conspicuous features that can be

used to organize a mental map of Mars (the polar ice caps, the great impact basins, Tharsis and Elysium rises, the “Blue Scorpion” centered on Syrtis Major Planum, the Thaumasia Block, Valles Marineris, and the Chryse Trough). The third order comprises large terræ, plana, and planitiæ. The fourth order describes landforms, terrains, and units at the landscape level seen from orbiter-based sensors, while the fifth order constitutes features visible at the scale of lander and rover activities or as small sections of high-resolution orbiter imagery. Such a progressively finer scale and detailed framework for regional subdivision of a planetary surface should be portable to other solar system bodies.

Delineation of Landforms and Landscapes

When defining a *landform* – either (proto)type or individual particular (token) at a certain place – it must be taken into account that the landform boundaries may be fuzzy, arbitrary, or made up of transitional units. If one zooms into a landform, the landform itself will disappear just to give rise to landforms of a finer scale. Eventually, one reaches individual grains or the bedrock, the basic building blocks of landforms. (This is spectacularly illustrated by the final sequence of images before the landing of a space probe). Landforms have temporal boundaries as well, having a lifetime and an evolutionary path (whose progress can be charted stratigraphically). They may also transform into another landform (type) either abruptly or gradually.

Classification of landforms may be based on rules, one prototype (type example or type locality), or several exemplars (Jaimes and Chang 2000). In many cases, named landform types are defined morphologically by a specific set of *other landforms* (e.g., an impact crater is the sum of a cavity, a raised rim, and an ejecta blanket), of multiple landforms (e.g., double crater), as a spatial position, e.g., contact between surface features (e.g., shoreline), or genetically by a particular type of formative event or process (e.g., a hypervelocity impact) that produces a variety of geological changes on the surface and subsurface. An actual landform, however, is a result of a very complex series of geological, surface, and/or subsurface events (that may have a typical sequence and duration) in specific conditions and specific, often complex, materials (e.g., Căpitan and van de Wiel 2011). Such events may produce a predictable set of adjacent, genetically associated, landforms of different temporal and spatial scales.

Landforms may thus be defined as relief features developed at the interfaces between the lithosphere and one or more of the atmosphere, the hydrosphere (and on planets with life, the biosphere), or space on airless planetary bodies. Processes may form features at a characteristic scale or at any size (Evans 2003). For example, impact structure types are in general scale dependent (small craters have different morphology from large craters), but a particular crater type within a given size range is scale independent: they are similar until a size threshold is reached. Secondary faults are completely scale independent: They have similar morphology at all scales (Schulson 2001).

Table 1 Scale terms and corresponding diameters of landforms as used in some studies

	Antarctic dry valley landforms: Marchant and Head (2007)	Rised rim depressions: Burr et al. (2009)	Terrestrial landscape ecology: Delcourt and Delcourt (1988)	Soil survey: NSSH (2008)	Yingst et al. (2011)	Volcanic landforms in Venus radar: (Ford et al. 1989)
Megascale			>1,000 km			km-100s km
Macroscale	>250 m		100–1,000 km			–
Mesoscale	1 to ~250 m	100 m	1–100 km			m-100s m
Microscale	<1 m		<1 km	Features too small to delineate at survey scales	Lens-scale (resolved by a hand lens)	cm-m (surface roughness)

The terminology of landform scales is flexible: The actual sizes that correspond to the terms of relative scales depend on the focus of attention (Table 1).

Physiographic provinces (e.g., Moore et al. 1985) in the Fenneman sense of landform hierarchy broadly correspond to the term “landscapes” or the “third order of relief.” They are used as major terrain mapping units and can be defined as “broad or unique groups or clusters of natural, spatially associated features” (NSSH 2008).

Since emphasis is put on the presence of groups of features, the definition of these provinces seems relatively straightforward once the geological units, terrains of related levels of topographic contrast, and individual landforms have been unambiguously identified. Identification depends on consistent definitions of underlying concepts. The following discussion explores various realizations of the geological Unit.

Working with Visual Information

The conceptual framework developed for indexing visual information (Jaimes and Chang 2000) can be directly applied to photogeological analysis. These authors distinguish two parts of the analysis: (1) Syntax is description based on pure perception without considering the meaning of what is perceived; (2) Semantics deals with the meaning, requires prior knowledge that may well be abstract and subjective, and corresponds to the interpretation in photogeological analysis.

Low-level perceptual features in any image, including those that represent planetary surfaces, include spectral sensitivity (color, albedo), frequency sensitivity (texture, characterized by roughness, directionality, and contrast), as well as temporal and spatial dimensions (area and shape). The arrangement of elements in an image is called global composition, but it only deals with basic *elements* (lines, circles, etc.) and not with *objects*, whose identification would require prior knowledge.

In geology, the next level could be the three-dimensional (topographical) description of the scene in general and its identified topographic elements (e.g., flat, knob, depression). From the description, it is straightforward to move to semantics (generic, specific, and abstract levels of interpretation). The generic level is the identification of the terrain units based on the description above.

Features in the landscape can be categorized into types. Once objects in the landscape have been defined and classified, their arrangement (spatial distribution) can be analyzed. Associations of geological objects in space and time can be identified stratigraphically.

The highest, abstract, level of visual analysis concerns what the *objects* represent. This includes formation models, identification of the possible controls and driving forces, and processes that have shaped the specific features and the landscape that they occupy.

Identification of Geologic Units

Wilhelms (1990) defines a geologic unit as a “discrete three-dimensional body of rock . . . formed relative to those of the neighboring units (1) by a discrete process or related processes and (2) in a discrete timespan.” Although planetary geological units are observed and defined by their surface manifestations, it is important to remember that they are not solely surface features but may involve materials that underlie the surface, defining how that surface appears.

Wilhelms (1990, p. 214) emphasizes the distinction between the origin of a unit’s constituents (materials) and the origin of its emplacement as a three-dimensional rock body.

Generally, the definition of a “unit” in planetary geology puts special emphasis on its morphological attributes in addition to its other independently observed characteristics (color, grain size, mineralogy, contact relations, etc.). This is reflected in the term “morphostratigraphic unit” (Ivanov and Head 2011).

Fundamental rock units observed on the surface are called *formations* that can be combined into *groups* and divided into *members*. In a more general context, the term *material unit* is used, sometimes described as *tectonostratigraphic unit* or *terrane*.

Material and Structural Units

Ivanov and Head (2011) distinguish between *material*, *structural*, and *structural–material* units in mapping Venus. According to these authors, *material units* (e.g., smooth plains) are usually much less deformed, and priority in their definition is given to the characteristics of the primary material. Structural units (e.g., groove belts), however, are formed by the tectonic deformation of older materials, sometimes quite varied, and their definition is based on the character and density of tectonic structures.

Primary and Secondary Units

Hansen (2000) also argues for a clear delineation of tectonic structures from material units for the purposes of mapping planets that have been tectonically active so that each of them records different aspects of planet surface evolution. In her view, “secondary structures absolutely cannot constitute a part of a material unit(s) descriptor or characteristic” because it “implies that the material unit and the structural element reflect a single geologic event,” and this implication then becomes embedded in the data, the geological map. In addition to geologic (material) units, Hansen (2000) distinguishes two groups of geomorphic features that can help in the determination of geologic history: (1) *primary structures* formed during unit emplacement (these generally include erosional features related to syngenetic or penecontemporaneous (immediate postdepositional) reworking of geologic units) and (2) *secondary structures* formed after material emplacement or deposition, e.g., sedimentary (e.g., nodule, sedimentary dike) and tectonic (e.g., faults, fractures, folds) structures, which may result from subaerial exposure, weathering, and dissolution. Some structures, such as joints, may be primary (formed during the formation of the rocks) or secondary (formed later). Secondary structures have no intrinsic relation with conditions of the unit emplacement environment.

In the planetary domain, where ground truth is almost always unavailable, these “secondary” characteristics are therefore seen as the only objective way of defining such units. Such a view, however, fails to recognize the fundamentally stratigraphical nature of all such structural-tectonic observations, the only truly objective method of reconstructing past geological events (see Tectonic mapping of planetary surfaces and landforms).

Spectral and Other Units

Stephan et al. (2010) defined spatial units based on spectral characteristics, referring to them as *spectral class units* (or classes) in order to distinguish them from conventional geological “units.” Spectral characteristics reflect compositional and physical surface properties that cause changes in (1) overall albedo, (2) the local slope of the spectral continuum at a given wavelength, (3) the existence of absorption signatures, and (4) their spectral parameters, i.e., wavelength position, shape, and band depth. Page (2010b) discussed, by martian example, the problems that arise when the *elemental composition* of planetary spectral units is taken for the *lithology* (or *rock type*) of inferred geological units (see Page 2015, this volume, chapter “[Spectral Mapping of Planetary Landforms and Geological Units](#)”).

The definition of spatial units may be based on various specific aspects, e.g., the biotic effects on topography (Dietrich and Perron 2006) or landing site selection criteria, etc.

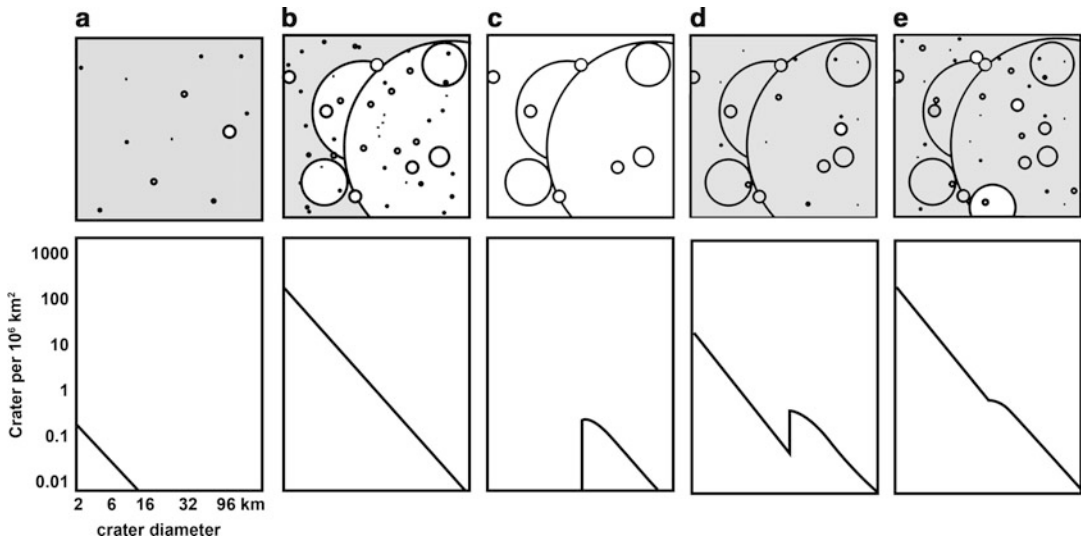


Fig. 1 Time sequence of crater size–frequency distribution. Regions in white represent newly formed (resurfaced) units. *Upper row*: terrain view; *bottom row*: crater size–frequency diagrams (After Hartmann and Wood 1971) (see also Fig. 10 in Buried Crater). (a) Young surface with few small craters produced randomly at constant rate. (b) Older terrain near saturation. (c) The terrain is resurfaced by a material that completely buried smaller shallow craters, but larger and deeper ones

(rim and/or cavity) protrude from the cover: Small craters are obliterated preferentially. (d) The terrain is re-cratered. The two characteristic ages can be observed together. (e) The surface resaturates with smaller craters. Since the cratering record shows a constant cratering rate from ~ 3.5 Ga and an exponentially increasing rate before that time, younger terrains cannot be saturated even in Ga time scales

Chronostratigraphical Units

Units can be defined by their resurfacing history and age, which can be determined (or estimated) from crater counting (crater size–frequency distribution) in terrains where sufficient numbers of primary impact craters are found (e.g., Baldwin 1964; Hartmann and Wood 1971; Michael and Neukum 2010; Fig. 1).

A time sequence of surface units can also be determined from their cross-cutting relationships (e.g., Hoppa et al. 2001; Fig. 2).

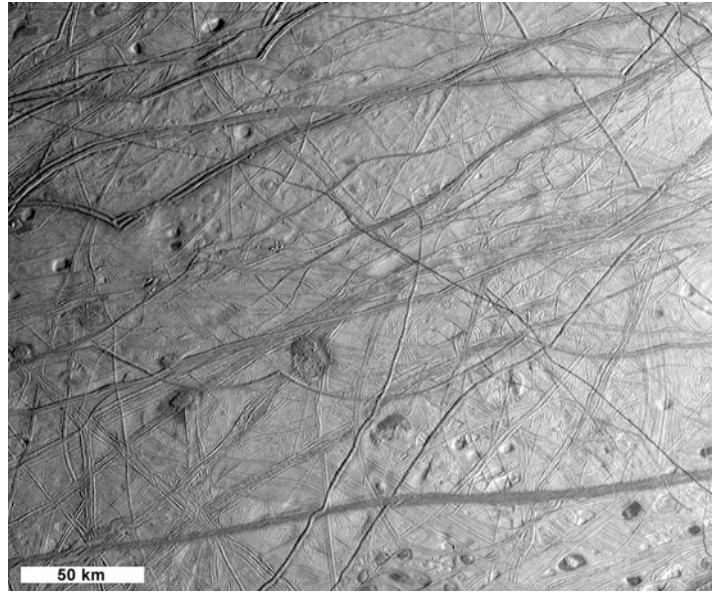
In any case, somewhat independently of the approach used for their definition, units will be defined in planetary geology based on their spatial homogeneity. This suggests uniform formation and modification (resurfacing) histories within a unit.

However, “spatial homogeneity” may still be a subjective parameter even at the highest spatial resolutions, and impact crater counts must be stratigraphically controlled if they are to have any meaning at the geological-unit level.

Types and Tokens

Landform expression varies with the scales of both observation and deposition (i.e., local-regional-global), across single or multiple planetary bodies.

Fig. 2 Portion of the surface of Europa. This view shows bands, ridges, and oval lenticulae. Their relative-age can be determined from their stratigraphic position. Detail of 15ESREGMAP01 Galileo mosaic. Cf. Fig. 1 in Bright Plains (Icy Moons) (NASA/JPL/ASU)



Thus, when dealing with the definition of landforms it is important to distinguish between categories of features and the individual entities which instantiate these categories. We use the concept of types and tokens (after Peirce 1906) to describe the tangible objects encountered at planetary surfaces, a token instantiating a parent type, Olympus Mons an instance of the type “volcano”, and so on. This typology is more than a naming convention as it allows standards or points of reference to be constructed. Where an object, structure or landform is considered to be representative of a whole or a wider class, then it becomes the Type example, e.g., the Caloris Basin on Mercury is the stratigraphical type section for mercurian chronology, or the crater Copernicus which typifies the class of lunar rayed-craters. Such classification can only approximate the continuity of nature, the boundary between types and tokens not always clear, and serves as much to facilitate descriptive communication as constrain object origins and processes. Types and tokens are difficult to confuse when dealing practically with the real world because tokens are tangible objects whereas types exist as abstractions (Mark and Smith 2004). The problem of categories – types, classes, shared properties – that are exemplified by many individual particulars is called the problem of universals in philosophy (e.g., Agassi and Sagal 1975). This is the subject of *landform ontology*, which deals with feature classification and its standardization, and is defined as “a formal specification of a shared conceptualization” (Borst 1997). The philosophical problem of universals is manifested in the example of Smith and Mark (2003), who pose the following question: “Do mountains exist?”

This problem of landform ontology may seem to be rather theoretical, but these studies are driven by the practical considerations of making digital

terrain analysis more effective. For this very reason, Deng (2007) developed five categories of landforms that can help define “kinds” of landforms from perspectives beyond description and origin, allowing us to approach questions regarding “what landforms really are” and “how they exist”: (1) *bona fide landform objects*: “real” landforms that are the least dependent on human definition (e.g., summits, active and wetted stream channels) that serve as conceptual cores of (2) *prototypical objects* (e.g., peak area, valley, basin); (3) *semantic landforms* that have no bona fide references, whose delimitation as categories relies on multiple possibilities of definition (e.g., steep slope or pristine crater; more complex examples are bedrock channels and rock glaciers); (4) *landform classes* (e.g., north-facing steep-slope cells); and (5) *multiscale objects* (e.g., flatland next to a channel).

Where specific environmental and/or geological conditions are present, similar landforms can be developed: several tokens in the same type. Such conditions may be present globally or only locally, on one or multiple bodies in our solar system. Thus, some landform types may be common on one planet but not found on another (e.g., coronae on Venus or coral reefs on Earth). Some landforms may be hosted in a *material unit* that may be only locally emplaced, but they may also be globally distributed hosting several different feature types in different locations depending on local conditions (e.g., dark or friable deposits on Mars).

On the other hand, the same landform type may be comprised of different materials in different bodies (e.g., dunes of snow, silicate, organic material, etc.).

The presence of an atmosphere may largely affect the resulting (multifinal) forms from similar primary driving forces (e.g., the shape of impact or volcanic ejecta deposits).

To classify these as one type, we have to select a finite number of defining parameters and ignore all others. If one would take *all* parameters into account, types could not exist.

Some characteristically unique landforms that have been found only in one locality constitute types, each having only one token of its kind (e.g., an annular dark mantle deposit on the moon). There may also be several landform types that exist only in theoretical models for which individual examples await discovery.

Naming Landform Types

Geological terms of feature types are generally different from “descriptor terms” used in the official geographic names of these features. Opinions in the planetary science community are divided regarding classification schemes, especially where related to features observed at relatively fine scales. One group of scientists prefer to use nongenetic, sometimes descriptive, names (e.g., Type 1 or Hilly and Lineated), whereas other researchers tend to use more traditional or terrestrially oriented nomenclature despite often strong and potentially misleading genetic implications of such usage

exist. Examples of the latter approach include calling a low, flat hill with radiating flow-like features a “shield volcano” or referring to “complex impact craters” when any circular, terraced depression is being described. A good example of the dichotomy of opinions from this volume is the martian feature type called “triangular scars” by some and “meters-thick avalanche scars” by others.

“Names, definitions and classification suggest that there is an independent *basis* for these names or schemes,” argues Berthling (2011) for the power of scientific terms, in this case “rock glacier.” However, a name for a landform may not necessarily refer to something that exists even if it is formally defined, Berthling (2011) remarks. For example, “Rock Glaciers” are defined by one school applying a morphological description, whereas another uses a genetic, process-based definition. So when speaking of “rock glaciers,” the same term is applied but refers to two different concepts that may include different surface features or none at all. This may give way to the use of terms for practically undefined feature types that Cox (2007) calls “name magic.” Berthling (2011) claims that a morphological definition “communicates words instead of concepts or everyday concepts instead of scientific ones.” The issue of morphological versus genetic definition is even debated on Earth, where direct measurements of landforms are possible in most cases.

Tanaka et al. (2005) considered morphology, albedo, terrain type (lowlands vs. highlands), or any other physical characteristics in martian geologic map unit names (e.g., channel, aeolian, or surficial materials) “highly variable and suspect as definitive criteria for unit identification.” These authors instead identified and delineated map units based on relative age and geologic relations, which makes the mapped units incongruent with units defined by physical characteristics. They named their geologic units after appropriate toponyms (for example, Isidis Planitia unit).

On the other hand, usage of a terrestrially oriented nomenclature is advantageous because it establishes a direct link with current understanding of many processes that have been extensively studied in our own backyard. Even so, extensive adoption of this approach is not devoid of problems (Malin et al. 1992). Genetic terms should be avoided if there is no well-understood mechanism to create a particular feature or when it leads to unfounded speculation in contexts that go beyond the original intention of the definition (Malin et al. 1992). Unwarranted speculation might promote onset of a mythical style of thinking (Dickinson 2003). Consequently, the choice of geographic ontology is a critical point in avoiding mythical thinking.

Using the vocabulary of logic (Copi and Cohen 1994), the characteristic aspect of mythical thinking is the selective assignment of truth values to some of the premises used in the interpretation of observations. Sometimes, this occurs in a very subtle form but nevertheless favoring an *a priori* accepted conclusion. Consequently, to avoid mythical thinking, it is extremely important to have definitions leading to classification schemes that are as unbiased as possible yet at the same time allow us to recognize meaningful aspects that can be interpreted genetically (Cañón-Tapia 2010). For this reason, the classification and definition of landforms in a planetary context deserve closer inspection.

The Science and Technique of Geographic Description

Feature Characterization and Classification

Aristotle's requirements of a definition are "(1) the denomination of the closest class (*genus proximus*) to which the object to be defined belongs, and (2) a list of specific differences (*differentia specifica*) by which that object differs from other objects belonging to the same class." (Ross 1927, cited by Szakács 2010). When applied to landforms, failure to fulfill either of these two requirements might lead to artificial groupings of landforms. Artificial groupings in turn may lead to a distorted, preconceptualized view of given landform types. Landform types thus are redefined as separate classes instead of morphological end-members or groups of individual landforms. As Collins and Nimmo (2009) noted, citing the example of chaos areas on Europa, a particular classification "can sometimes draw arbitrary distinctions between types of chaotic terrain when there is a *continuum of morphology* observed" (*italics from us*).

An exemplary classification scheme is that of the layered ejecta types (Barlow et al. 2000). In contrast, the current classifications of small cones and mounds on Mars or the classification of lunar craters before the twentieth century are examples of premature and overcomplicated systems. At the "early" stages of observations, we may not have sufficient data or tools to be able to determine, which characteristic can be considered *genus proximus* and which ones are *differentia specifica* for a given group of landforms. This learning and effective assignment of characteristics develops simultaneously with the *recognition* of significant boundaries between typical (shared) and individual characteristics within a particular landform type. Consequently, since the origin of a large part of planetary landforms is not well understood, the theory and explicit practice of using multiple working hypotheses (Chamberlin 1897) should be a commonly used method in any planetary geologic investigation.

Limits of Knowledge

Another aspect that needs to be taken into consideration in planetary studies of landforms is related to the source of *information available* to create a particular classification scheme. For instance, whereas landform classification on Earth is based on lithology, morphology, structure, and, where possible, inferred origin process(es), classification systems on other bodies rely primarily on imaging surface data at a particular resolution (Levy et al. 2008). For some of the bodies, topographic data are also available at different resolutions.

Another complicating factor is that features may appear different under different illumination conditions (angle of incidence of the solar radiation; radar illumination and view angles) that emphasize or mask certain characteristics of the feature (e.g., albedo or relief) (Figs. 3, 4, and 5) (e.g., Neish et al. 2012).

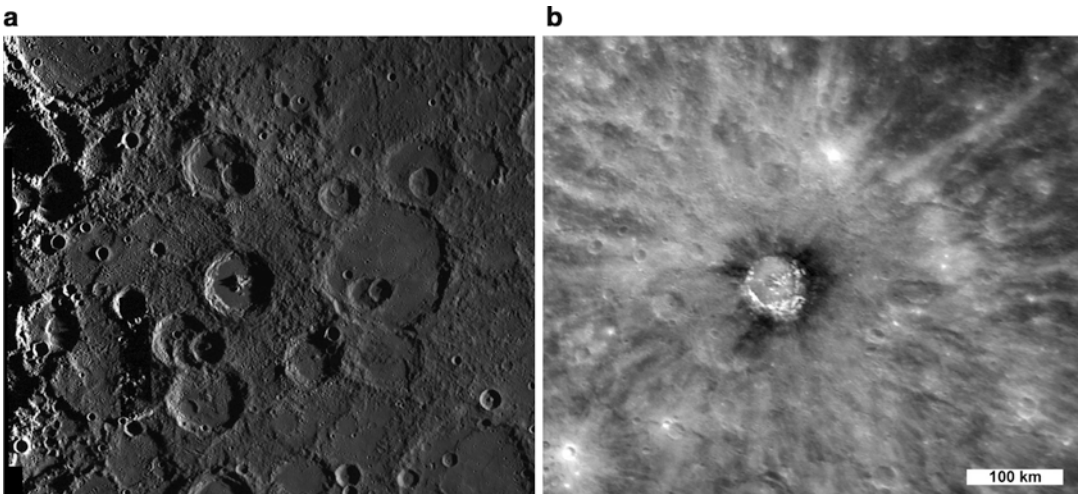


Fig. 3 Comparison of Mercury's 74 km diameter Bashō crater under two different illumination conditions. (a) Image taken under high solar incidence angle when the sun was near the local horizon (*low sun*). This image

emphasizes topographic features. (b) Image taken under low solar incidence angle (*high sun*). This image shows albedo features like the crater rays. MESSENGER MDIS, based on PIA16343 (NASA/JHUAPL/CIW)

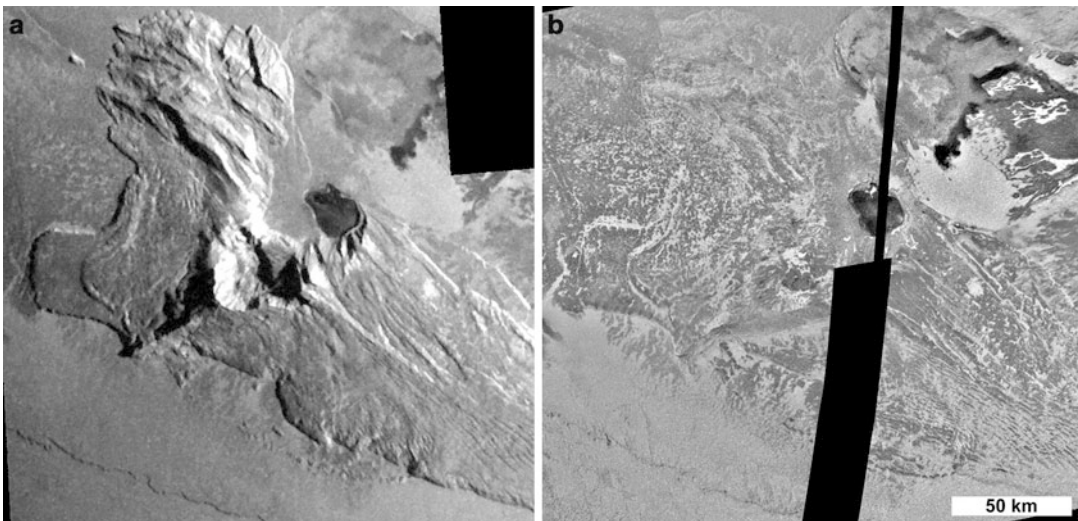
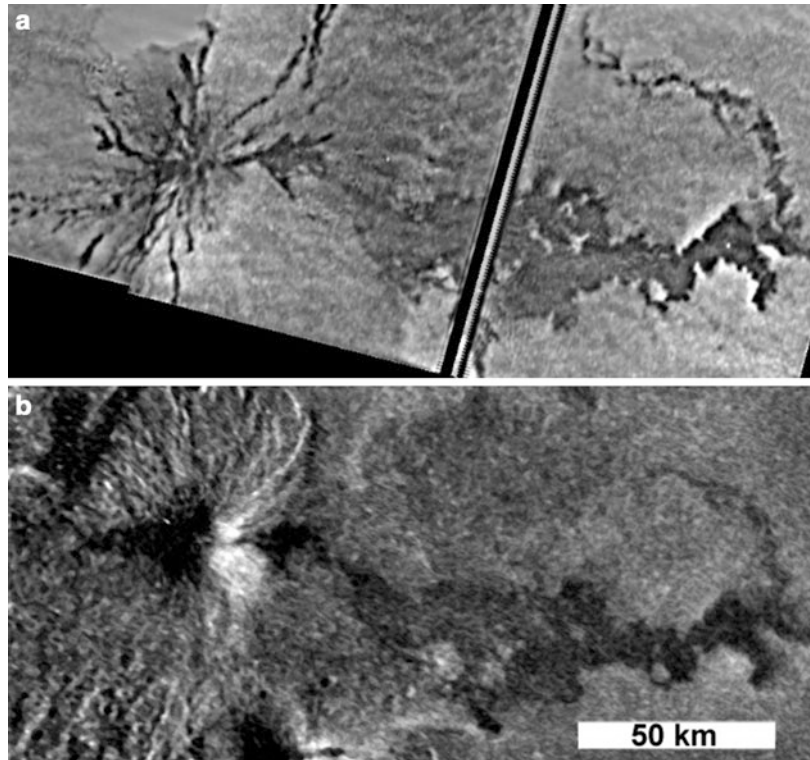


Fig. 4 Galileo views of the 9-km-high Tohil Mons, Io. (a) Low-sun view, PIA03600 (NASA/JPL/University of Arizona). (b) high-sun view, I27ISTOHIL_01 (NASA/JPL/ASU)

Daytime and nighttime infrared images emphasize different thermophysical aspects of the same feature or they may even show different features of the same area (Fig. 6).

Different landforms and terrains may appear similar when viewed at low resolution (e.g., Zimbelman 2001), and similar landforms observed at different spatial or spectral resolutions or illumination conditions may be classified into separate groups. High-resolution images may reveal new topographic details in landforms previously described as smooth.

Fig. 5 Comparison of Zamama Tholus A and its lava flows on Io under two different illumination conditions. (a) High-sun view, Galileo Orbit I24 Mosaic I24ISZAMAMA02. (b) Low-sun view, Galileo Orbit I32 Mosaic I32ISTERM02 (NASA/JPL/ASU)



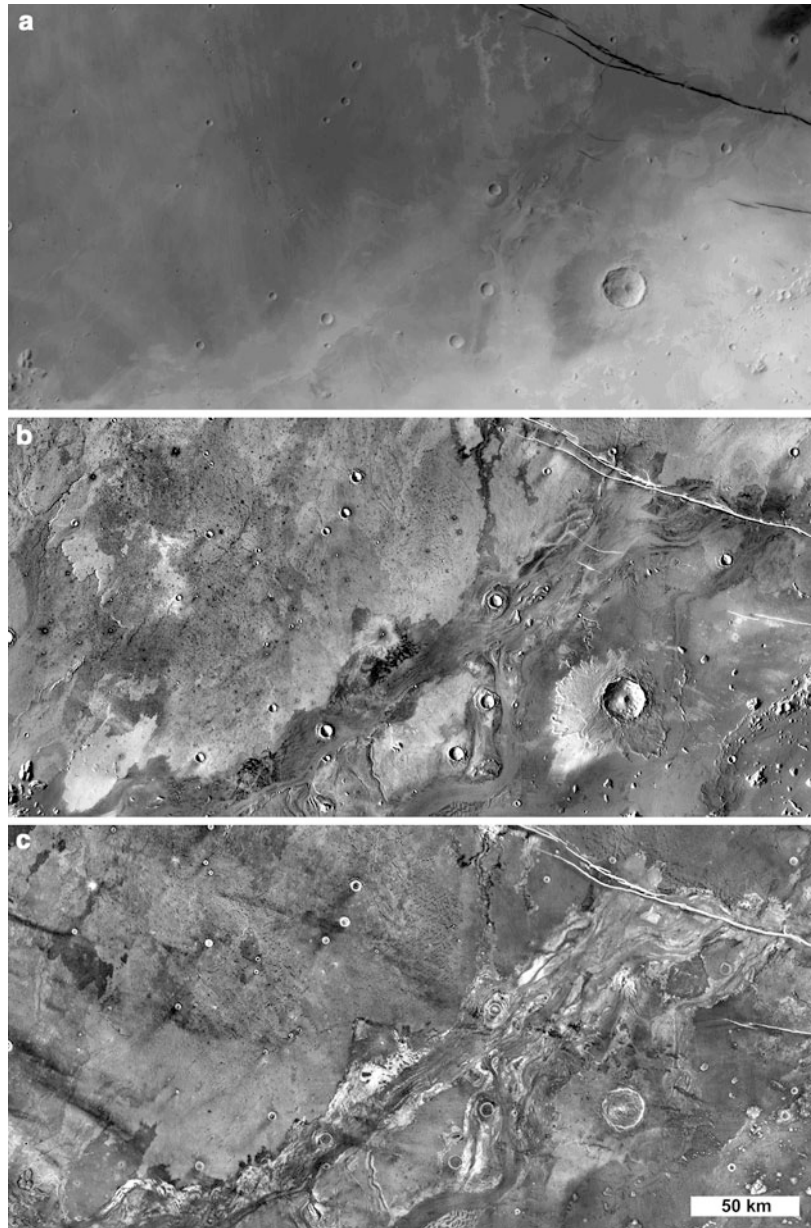
This kind of observational uncertainty is reflected by the cautious practice of officially naming features seen at a resolution that is insufficient for proper (topographic) identification only by descriptive albedo names (e.g., by the terms *macula*, *facula*, etc.). In this case, the inherent observational uncertainty does not have a particularly negative consequence. Unfortunately, the resolution-related uncertainty may lead to confusion of a more dramatic nature. This is illustrated by the discussions concerning the use of terms such as *lenticulae* and *chaotic terrains* (on Europa), the different scales of grooves on Ganymede, or the various features of “basketball terrain” on Mars that are appreciable only as a function of the resolution of the images. Such confusion expresses the modifiable areal unit problem (MAUP), which is defined by the unavoidable error inherent in aggregation and scaling. It manifests itself here in the sense of different spatial resolutions of the sensors on which planetary geology depends (Marceau and Hay 2000).

Thus, image resolution, the conditions for its acquisition, and the spectral range of the image become crucial factors in landform identification.

All of these issues have been found in various degrees during the exploration of the surfaces of the several planets and moons with which we have become acquainted in recent years.

As these examples illustrate, even when great efforts in planetary geology are put into the objective description of features observed at a lower scale, there are many factors that introduce a measure of subjective interpretation.

Fig. 6 Three views of the Athabasca Valles region on Mars centered 9°N, 155°E. (a) visible albedo view (MOC); (b) daytime infrared view (THEMIS); (c) nighttime infrared view (THEMIS). Warmer regions appear *bright*; colder regions appear *dark* in the infrared images. In the daytime infrared image, sun-facing slopes are warmer and appear *bright*. During the daytime, *dark*, fine-grained sand heats up more quickly than dusty regions and rocks. At night, sand quickly cools, whereas rock outcrops and lava flows cool more slowly and become warmer (in the image: *brighter*) than the surrounding. There are no shadows in the nighttime infrared image because there is no sunshine at night. The nighttime IR image shows the thermophysical properties of the surface cover (NASA/JPL/MSSS/ASU)



Consequently, it is necessary to turn our attention to the role played by interpretation in the definition of landforms and terrains.

The Science, Technique, and Philosophy of Geologic Interpretation

The methods of geologic inquiry and the methods of planetary surface interpretation are comparable to Hume's principles of association that

describe how our mind (unintentionally) works. Hume (1739:I/1/IV) claims that ideas, derived from sensory perception, can be connected in three ways: (1) resemblance (moving from an image to the actual object cf. methods of photointerpretation-based comparative planetology), (2) contiguity in time or place (moving from one event to another that happened at the same period cf. methods of stratigraphy, e.g., global correlation of strata), and (3) cause or effect (cause is an event not observable now; only its effect is; cf. process geomorphology).

Comparative Planetology

Comparative planetology is “the study of the differences and similarities among planets and satellites” (Veverka 1985). Comparative research can be conducted on a qualitative or quantitative basis.

While the first goal (identification of similarities) is reached by paying attention to simple rules during the “description” of observations, the second goal (identification of processes) is harder to reach. Knowing the “formation” of a given landform or any other planetary feature will always be based on interpretation and extrapolation (unless directly observed). Thus, formation models address issues concerning a) what processes formed the landform, b) what happened during the process of formation (landform and landscape development), and c) why these events occurred (driving mechanisms) at several levels (on the surface or subsurface or in space).

Certain limiting conditions need to be taken into account somewhat arbitrarily in the temporal and spatial extent of formation models. Failure to introduce some constraints concerning the reasons that ultimately initiated the processes at hand might lead the search right back to the big bang if one does not stop in time. Formation models that extend that far back in time might well be ultimately correct, but they turn out to be rather cumbersome to handle, making it preferable to use alternative models that are easier to grasp if more modest in ambition. At the same time, it is this temporal element that is the essence of the stratigraphical method, following the “thread” of time from present to past to constrain events (and thereby origin). Page (2015, this volume) details this different route to geological understanding grounded in the principles of terrestrial stratigraphy, where origin may be inferred without the need to ascribe *cause*. The stratigraphic approach proceeds free of all but the most basic of hypotheses: that geological events can be ordered in space and time (Page 2015).

Equifinality and Terrestrial Analogues

“Unambiguous identification” is a principal problem in planetary geology as it is easy to think that visual analogy is sufficient to establish origin or genesis.

Additional aspects, which should be taken in consideration when making geological interpretations, include the use of terrestrial analogues and the concept of “equifinality” (von Bertalanffy 1950, 1969) according to which a

closed system cannot behave in an equifinal way – arrive at the same – equilibrium – result from different initial starting positions. Geologic systems are open systems where different geologic processes acting in different environments may result in similar-looking (equifinal) landforms (Langhans et al. 2012; Washburn 1970). In a geologic context, equifinality can be called form convergence or polygeneticism.

In comparative planetology, however, it is a basic general assumption that the same processes result in landforms displaying similar morphology regardless of the body or materials involved. So, terrestrial morphological analogues can be helpful – although not conclusive – in the identification of formative processes of similar-looking extraterrestrial landforms whose origin and properties are not known.

The use of terrestrial analogues was first described by Gilbert (1886).

Plan View, Cross Section, and Size

The history of the interpretation of lunar craters shows the pitfalls of superficial similarities. For centuries, they were generally believed to be volcanoes based on their planform shape as seen through a telescope. However, Wegener (1921/1975), using the method of comparative planetology, analyzed their cross-sections and pointed out that “the similarity of the forms are totally superficial. [...] The forms [of terrestrial volcanoes and lunar craters] are fundamentally different; therefore, their origins also should be different.”

Size differences between apparently similarly shaped terrestrial and planetary features should also be taken into account in the interpretation. On the one hand, landforms produced by similar processes may have different *characteristic sizes*, e.g., due to different fluid densities (e.g., dunes on Venus, Earth, and Mars and underwater), different gravity (e.g., craters), different duration of the formation process (e.g., shield volcanoes), etc. On the other hand, giant polygons of Mars resemble mud cracks, columnar joints, or frost wedge polygons on Earth but “are orders of magnitude larger than these potential Earth analogues, leading to severe mechanical difficulties for genetic models based on simple analogy arguments” (McGill and Hills 1992).

Similarly, terrestrial experiments at scales different from planetary analogues (in sizes or, for impact process studies, in velocities) may lead to false conclusions. G. K. Gilbert’s experiments with low-velocity impacts (Gilbert 1893) or Walter Bucher’s experiments with frozen water-filled spherical Christmas tree ornaments are examples (Bucher 1924). “A planet may behave differently,” caution Mutch et al. (1976, p. 234). There is a tension, however, between the concept of equifinality and the practical assumptions underlying the use of terrestrial analogues in extraterrestrial contexts.

Eliminative Induction and Multiple Working Hypotheses

The method of *eliminative induction* (Bacon 1620) in this context gets closer to the origin of a landform by systematically ruling out what it cannot be. The

concept of strong (systematic formal method of) inference, which builds a logical tree of exclusions, was introduced by Platt (1964) to explain why some scientific fields experience more rapid advances (Kuhn 1962) than others. This combines Baconian eliminative induction with iterative experiment coupled with the method of multiple working hypotheses (Chamberlin 1897). In this analytic method, competing hypotheses are explored by crucial experiments sharp enough to eliminate one or more of these hypotheses. Karl Popper points out the importance of falsification: “it must be possible for an empirical scientific system to be refuted by experience” (Popper 1959). Feyerabend (1975, 1993, pp. 20–23) remarked that even science includes ideological elements. In planetary science, such may be initial qualitative interpretations based on visual analogy, which are later cemented by quantitative means, but this does not make the initial identification any more certain and can often only serve to bury the inconsistencies beneath other data. Indeed, in the planetary domain, such visual analogy can only ever inspire hypotheses – it can never test them (Page 2010a). These initial interpretations are analogous to the “natural interpretations” of Bacon and Feyerabend. Feyerabend proposed the method of counterinduction, i.e., making hypotheses inconsistent with well-established facts, observations, and experimental results. This method builds on a conceptual system that is external in relation to “reality” as we know it (Feyerabend 1975) and thus may be useful in testing widely accepted initial interpretations (see, e.g., the mantle plume debate at <http://www.mantleplumes.org/>).

An early example of the use of the scientific method in astrogeology was Alfred Russel Wallace’s examination of Percival Lowell’s Mars paradigm. Wallace claimed that Mars’ climate does not allow the existence of water and life. Contrary to Lowell’s approach, he proposed purely geologic explanations for the then identified surface features including canals and oases. (It is somewhat ironic in this context that Wallace accepted the actual existence of these features (Wallace 1907), which later turned out to be false assumptions (Canal, Mars)).

Observational Constraints

Collins and Nimmo (2009) distinguished between hard and soft constraints when applying Chamberlin’s method of multiple working hypotheses. According to these authors, any viable theoretical model devised to explain the formation of any landform must be able to explain a set of “hard” constraints from observation (the Strong Inference of Platt (1964)). Consistency with stratigraphical principles can be the “hardest” geoscientific constraint of all (at least in a planetary environment, where both lithology and ground-truth are unavailable) (Page 2015, this vol.). In addition, there are “soft” observational constraints: These may be either real constraints or observational biases, misinterpretations, or misclassifications of feature types. Soft constraints are especially salient issues in planetary science with its dependence on remotely sensed data and images. Models that are able to explain these observations will be considered most successful. Thus, after

setting the critical hard constraints, the models can be compared to the hard and soft observational constraints one by one, ultimately winnowing multiple working hypotheses into one or few.

The observations on which interpretations are based may further be classified as “extrinsic,” providing information about processes (transport, emplacement, erosion), or “intrinsic,” those that inform about the lithology, morphology, and material properties of the deposit (Mandt et al. 2008). To some extent, both intrinsic and extrinsic observations are hard constraints, but in some cases, it might be important to have this fine subdivision of observation types.

As for the soft observational constraints, one should consider that interpretation does not depend solely on the characteristics of the landform itself. In many cases, the interpretation of a single feature or a feature type seen in a particular area is part of a wider context in which the environment of the landform also has to be interpreted. For example, sinuous ridges might be interpreted as unusual lava flows once their context is interpreted as volcanic, but they might be interpreted as eskers if the context is that of a degrading ice sheet. Soft constraints might also include the training, experience, and predilections that the observer brings to the observation and analysis. That is, the scientist is also part of the “soft constraints” given that each of us comes to a study marked by our backgrounds and the things they sensitize us to.

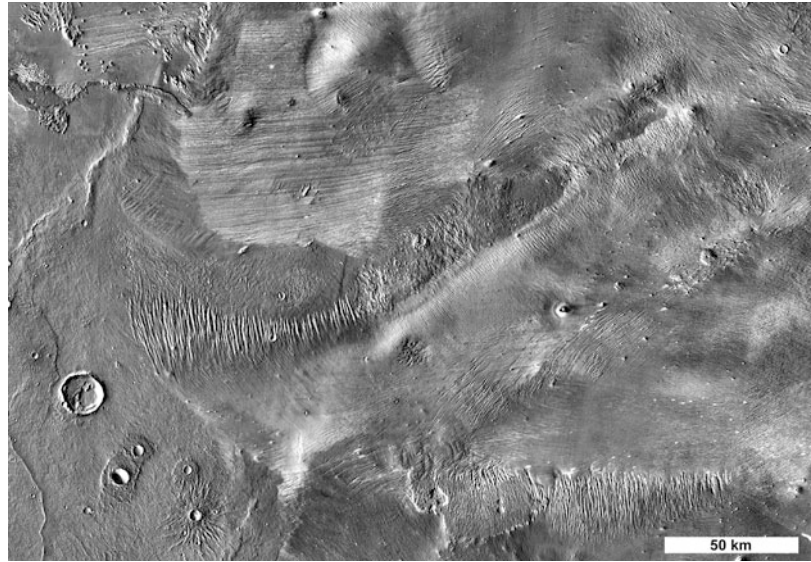
Distribution Patterns

Another example of a soft observational constraint can be identified by noting that in addition to individual and geologic context parameters, there are some features that occur in groups and that they may be identified by their characteristic distribution pattern (e.g., grouping, whether random, regular, clustered, dispersed, or linear; multiple or single; and other parameters such as direction, proximity, etc.) (Jaimes and Chang 2000; Bruno et al. 2006). For example, distribution patterns might help with identification of pitted cones on Mars that may form in several unrelated or related environments (volcanic or periglacial or both) whose morphologies are comparable but whose grouping pattern is different (Dickson and Head 2006; Bishop 2008).

If a variety of morphologies (and/or sizes) of the – supposedly – same landform type is observed in a cluster or at close proximity following the method of multiple working hypotheses, different geologic models should be evaluated. The possible model should be able to explain *all* observed morphologies (and/or sizes), their spatial distribution, and geologic setting (including stratigraphic relations – sequence of events (Page and Murray 2006) – and consistency with assumed (paleo)climatic conditions). (One of the main arguments against the volcanic origin of lunar craters was that their distribution is very different from that of terrestrial volcanoes (Wegener 1921/1975)).

The model may suggest that different morphologies result from different processes or that they result from the same process but are at different

Fig. 7 Amazonian, predominantly aeolian, landscape in Zephyria Planum, Mars. THEMIS day IR (NASA/JPL/ASU) See also Fig. 6 for another complex Amazonian landscape and Fig. 1 in ice contact delta for complex glaciofluvio-lacustrine-impact landscape



evolutionary or erosional stages (de Pablo and Komatsu 2009). Thus, the interpretation of an assemblage of features (the landscape) (Figs. 7, 8) must be based on the observed individual features and feature types, but the models of origin of both individual features and landscape should be consistent with each other (Gathan and Head 2004).

At a much larger scale, the distribution patterns of a specific type of landform can reflect processes that take place at some depth beneath the surface of the planet. For example, the global distribution of volcanism can reveal patterns concerning the existence of plate tectonic boundaries on Earth or of mantle plumes on other planets (Cañón-Tapia and Mendoza Borunda 2014; Cañón-Tapia 2014).

Formation Models

Finally, even if all elements are seemingly consistent with a model or a system of various models (paradigm), the interpretation might still not be valid because models are based on a finite number of observations and parameters. Classic examples of misinterpretation include the lunar meandering valleys being interpreted as carved by water (► [Rille](#)) (with the first opponent being Beer and Mädler (1838, p. 46)) and lunar craters as derived from volcanic or magmatic processes (► [Impact Structure](#); ► [Mare, Volcanic](#)). Both fit into an incorrect paradigm that explained the origin of numerous types of lunar features seemingly coherently.

The discovery of a new feature or observation or the introduction of a new parameter in the model may be inconsistent with the previous working hypothesis. If new evidence falsifies several models, it indicates a possible

Fig. 8 Lunar landscape shaped by tectonic, volcanic, and impact processes. Lunar Orbiter IV-187-H2 centered 14.97°S, 89.06°W (NE Mare Orientale), the Moon (NASA/LPI)



need for a paradigm shift in that particular field. Since it is very clear that the observational database is far from complete in the case of planetary geology, most problems in comparative planetology can, should, and must be approached by using multiple working hypotheses. Shakespeare's famous quote "There are more things in heaven and earth, Horatio/ Than are dreamt of in your philosophy" is indeed justified at almost every first planetary flyby. Many successful spacecraft missions induce profound changes in surface evolution models. The new concepts can be usually applied to any planetary body, not only the target(s) of the particular mission.

What neither human creativity nor spacecraft observations can provide may be delivered by computational models that simulate the behavior of a potentially existing complex system.

In addition, Collins and Nimmo (2009) note that the principle of parsimony (also known as Occam's razor) should also be taken into consideration although oversimplified models have their own drawbacks. For instance, the existence of meteorites or the continental drift (later plate tectonics) model were initially rejected as victims of Occam's razor (e.g., Gernert 2007).

Local-Scale Interpretations

Two specific examples illustrate several problems faced in planetary geology and the form in which new observations can influence previous interpretations. Both underscore how photogeological interpretation of a material from its texture and albedo may be misleading.

The first concerns lunar geology, and the second relates to Mars.

The *Cayley Formation*, a smooth plains unit within the lunar highlands with a higher albedo than the maria, was interpreted to have been deposited as siliceous (hence bright) lavas or volcanic tuffs (Wilhelms and McCauley 1971; Taylor and McLennan 2009, p. 53 and references therein). Due to the apparent volcanic origin, the Apollo 16 landing site was therefore selected to sample the Descartes and Cayley Formations. Upon landing on the Cayley plains in 1972, however, it became apparent to the astronauts that this formation consisted instead of anorthositic impact breccias. This suggested that these plains were (fluidized) debris sheets and that they resulted from emplacement of impact ejecta rather than lavas (Eggleton and Schaber 1972; Head et al. 2009 and references therein).

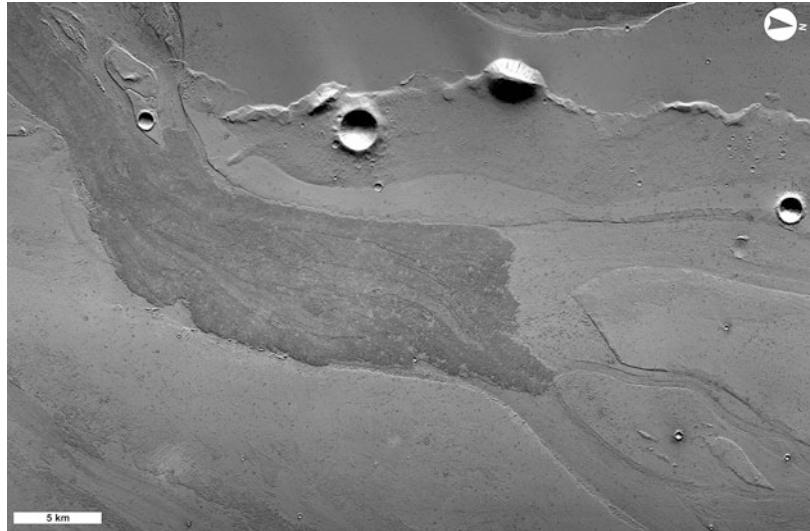
An opposite misinterpretation occurred in the *Gusev Crater formation*, Mars. According to the initial interpretation, the surface materials of Gusev Crater are sediments transported by Ma'adim Vallis and deposited within the crater. This sedimentary interpretation was the basis for its selection as the landing site for Mars Exploration Rover (MER) Spirit. However, results of Spirit later showed that the plains surrounding the landing site are instead composed of picrite basalt lavas unaltered by aqueous processes (van Kan Parker 2010). The original, entirely sedimentary interpretation of the Spirit landing site was reinterpreted as unsustainable in the light of new evidence from the rover, and an important volcanic component had to be added to the model. Experience at this site suggests that similar volcanic processes may have operated also in other ostensibly fluvial channels. This ambiguity could explain in part why landers sent to investigate sites of ancient flooding on Mars have predominantly found lavas at the surface (Jaeger et al. 2007).

Similarly, Athabasca Valles outflow channel (Mars) shows features that may be interpreted as aqueous flood or lava flood related. Athabasca Valles and Marte Vallis (Fig. 9) show the morphological characteristics of young outflow channels (whose origin is also not well understood but generally accepted as being aqueous flood carved features).

Features shown in high-resolution images of Athabasca Valles have been interpreted as evidence of the presence of a thin drape of lava and explosive cones formed by interaction between lava and heated groundwater (Jaeger et al. 2007) (► [Platy material](#)). However, Page (2008) maintains that this volcanic interpretation is inconsistent with deposit geometry and that putative volcanic features are secondary and postdate the surface by many millions of years (see separate chapter by Page (2015), this volume, for reference to this specific case). For detailed discussion platy material.

The volcanic or fluvial nature of deeply incised and adjacent construction leveed channels in the Cerberus Plains are similarly debated (Thomas

Fig. 9 The terminus of an inferred lava flow in one of the Marte Vallis outflow channels at 17.94 °N, 185.51 °E (Keszthelyi et al. 2008) (CTX image P03_002027_1979 (NASA/JPL/MSSS))



2013). For further discussion on classic lunar examples of water / alluvial deposit (Neison 1876:52) versus lava (Gilbert 1893) debate (Elger 1895), see rille and mare.

Similar difficulties arise at micro scales when interpreting in situ rock samples from morphology alone, e.g., on landing site images. Koehler et al. (1998) noted that “rectangular ‘Flat Top’-like candidate ‘sediments’ proved to be massive basalt; possible conglomerates with ‘outwashed pebbles’ proved to be vesicular basalt.”

Even in situ human observations – as on Earth – may lead to false interpretations. Hadley Rille on the Moon was originally interpreted as a lava channel with multiple lava flows – this was evidenced by local observations of at least two layers of rock (interpreted as multiple flows) and a shallow ridge at the rill’s edge (interpreted as levee). A reinterpretation, however, concluded that the same observations are also consistent with a collapsed lava tube that formed within a thick inflated lava flow. In this interpretation, layers of rock are interpreted as resulting from inflation and the ridge as a line of tumuli or pressure ridge (Keszthelyi 2008).

Global-Scale Interpretations

In a global context, views on the structures of the upper crusts of several planetary bodies and their inferred geological histories have been challenged during the last decades. These challenges involve proposed changes in the procedures of geologic mapping.

Shoemaker and Hackman (1962) applied the geological principle of stratigraphical superposition to the moon, at that time restricted to the relation of surface features as seen through telescopes, a historical–geological approach refined over 200 years of terrestrial geological inquiry. Confirmation of the validity of this approach resides in the fact that our understanding of the

geological history of the lunar surface has remained largely unchanged for half a century as a result of the stratigraphical methods of these investigators, whereas nonstratigraphical attempts at understanding planetary geologic history have resulted in many controversies.

In a global context, Wilhelms (1990), following Shoemaker and Hackman, set as a major goal of planetary geological mapping “to integrate local stratigraphic sequences (‘columns’) of geologic units into a stratigraphic column applicable over the whole planet,” similar to the goal of terrestrial mapping.

Hansen (2000), however, calls attention to the fact that this “global stratigraphic method” was originally developed for the tectonically inactive moon (and for Mars, which was thought to be similar at that time) “prior to widespread acceptance of plate tectonics” on Earth. Hansen (2000) proposes that this approach is only useful for tectonically inactive planets because global stratigraphy is only developed when the planet has “evolved by globally synchronous and spatially continuous processes,” which may not be the case for tectonically active bodies. This is especially the case on those planets where the ages of the units cannot be safely determined (e.g., on Venus) and, therefore, they cannot be correlated. Hansen proposes that in such cases, the “geohistory method” should be used. This method “has the stated goal of determining the geochronology of local regions and progressively assembling those histories into testable models of planet evolution.” The geohistory approach is heavily based on a separate study of geomorphic features and geological material units as well as the differentiation of primary from secondary structures because “secondary structures and material units record different events within a geohistory.” In this model, relative-age constraints are provided by cross-cutting relations (overprint, inclusion, embayment).

In fact, both Wilhelms’ and Hansen’s approaches involve stratigraphical study of local regions built up into a regional–global system where possible, a system of inquiry that is independent of the planetary body in question (Page, this volume).

Directional and Nondirectional Models of Venus

The construction of the possible geologic history of Venus is a good example that shows the importance of mapping concepts. On Venus, two opposing end-member models of its geological history have been developed based on two different mapping methods and assumptions. Constructing the geological map of Venus, Ivanov and Head (2011) used the “global stratigraphical method” and assumed a “directional history” in which certain geological processes are typically confined to a particular time period. Their mapping results support the catastrophic resurfacing hypothesis, which emerged from initial (Magellan) mission reports and was accepted by much of the planetary community “after limited debate” (Hansen and Young 2007). Hansen (2000) proposed that the “geohistory method” should be used instead and assumed a nondirectional geological history in which certain geological processes can occur repeatedly in the planet’s history (Guest and Stofan 1999; Hansen 2000, 2007).

In the *global (catastrophic/episodic/synchronous) resurfacing or directional history* model, Venus experienced a global volcanic resurfacing event about half a billion years ago (Head et al. 1992) and has progressed through a series of stages, each characterized by a particular style of volcanic activity (Addington 2001). Rock-stratigraphic units represent globally quasynchronous geological events (Basilevsky and Head 1996), and thus, this stratigraphical column is also viewed as a sequence time-stratigraphic unit.

Widespread and voluminous volcanism followed the era of tectonism. It was initialized by the formation of small shields (Shield Plains) and continued with the generally globally synchronous emplacement of the material of the lower unit of wrinkle ridge plains. Later, the emplacement style changed to more localized eruptions forming the lava material of the upper unit of wrinkle ridge plains. Subsequently, wrinkle ridges formed in these volcanic plains (Ivanov and Head 2011). During these events, a 2.5 km thick flood lava unit emplaced at 500 ($\sim 750 \pm 350$) Ma over a period of 10–100 My covered almost all preexisting terrains, as reflected in the near-random distribution of impact craters (Schaber et al. 1992). In this model, most of the craters are pristine: There are only a few partially flooded (Embayed Crater) and a few faulted (tectonized) craters (Deformed Crater) on Venus, which suggests that crater removal processes must have completely obliterated or covered preexisting craters (Hansen and Young 2007).

In the *equilibrium (evolutionary/diachronous) resurfacing or nondirectional history* model, lava emplacement takes place continuously in different locations and at different times, eventually covering almost the whole surface. Similar sequences of features occurring at different locations may be of different age (Guest and Stofan 1999). Geological activity occurred as local deposits of less than 400 km in diameter (Phillips et al 1992). Volcanic plains represent extremely low volumes of lava globally distributed over tens of millions of km² (Hansen 2007), and preflood surfaces are covered by only a thin (10s-100 m thick) layer of lava. Impact crater density and morphology indicate that elevated plateaus believed to be representatives of ancient preflood surfaces in the global resurfacing model do not correlate spatially with Venus's oldest surfaces. Crater studies suggest that lowland regions, representative of the hypothesized flooded surface in the other model, correlate with some of the oldest surfaces. Although craters buried by significant lava layers have not been identified (Hansen and Young 2007), Herrick and Rumpf (2011) suggest that the majority of craters is not at the top of the stratigraphical column (Shield Plains).

A More Dynamic Model for Mars

According to the traditional geological concept, lunar surface materials could be interpreted as a variety of volcanic and brecciated deposits underlying distinctive surface morphologies (as discussed above in the Cayley plains' case). The nature of the upper crust of Mars was initially thought to be similar to the moon but with an atmosphere through which agents of geological and geomorphological change acted upon a previously heavily cratered surface.

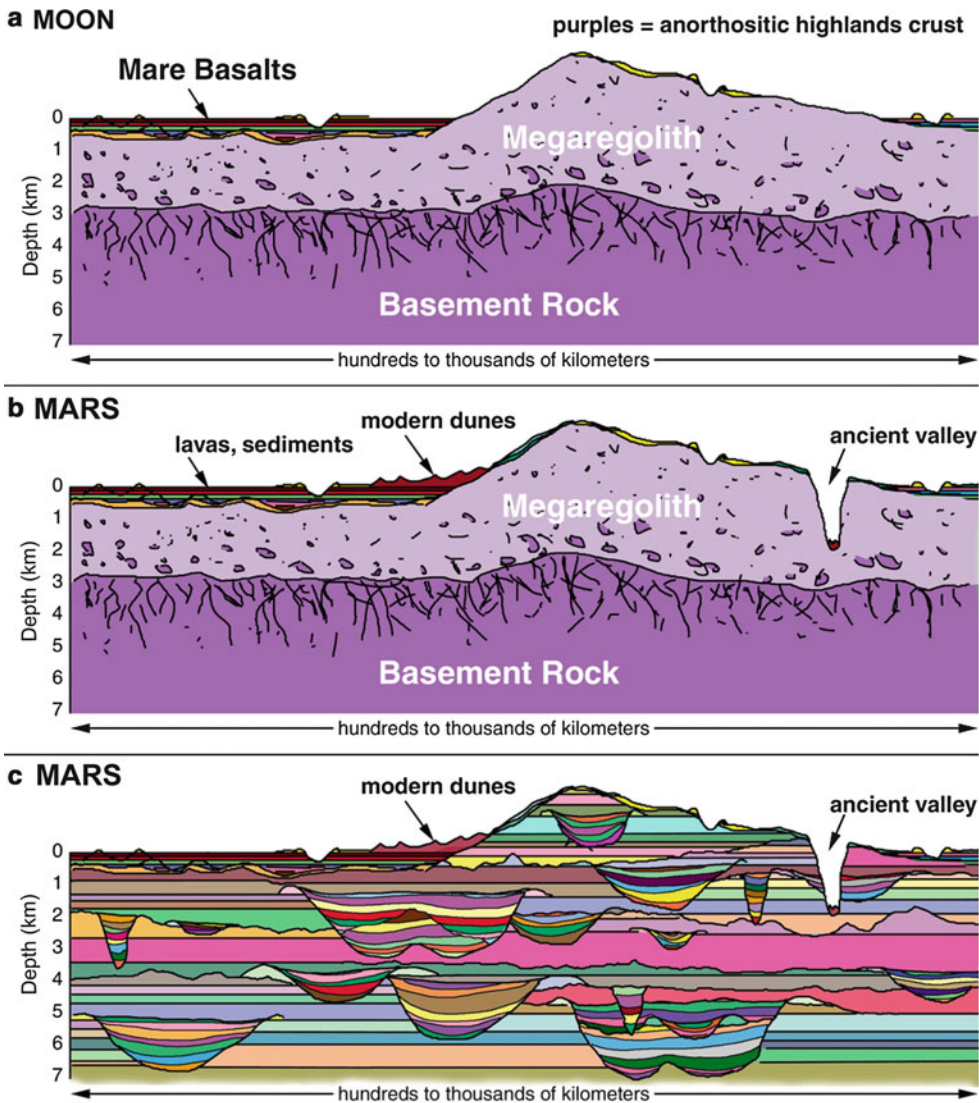


Fig. 10 Simplified model of (a) the lunar upper crust and (b, c) two different interpretations of the Martian upper crust: (b) idealized model from the 1990s, (c) post-MGS model (After Fig. 14 from Malin et al. 2010). The difference between the inferred lunar and Martian stratigraphies is the presence of numerous erosional unconformities (wavy jagged lines) on Mars. They are inferred from process models and otherwise unobserved. The inferred

presence and migration of groundwater further complicates underground geology (Michalski et al. 2013). While such nonconformities undoubtedly exist on Mars, they also exist on the moon (e.g., between the megaregolith and the mare basalts); the absence of an atmosphere and fluvial activity on the moon affect the *processes* of deposition and emplacement but do not affect the *methods of inquiry* into them

In contrast to this approach, it is now generally recognized that many martian landforms consist of reworked materials. Their different surface texture may be attributed to recent erosion and deposition rather than to the conditions of their formation. Consequently, the stratigraphical units suggested by the traditional geological concept may not be identifiable (Căpitan and van de Wiel 2011).

This new model was crystallized following the analyses of MGS MOC images (Malin and Edgett 2001; Malin et al. 2010) that showed abundant subsurface layering with filled, buried, and interbedded impact craters and valleys (Fig. 10).

It was recognized that erosion surfaces are important elements of the martian surface, where landforms previously entombed within geological units can be exhumed. Craters and other landforms on an erosion surface, therefore, can form two populations: those that were previously buried and are now exposed and those formed on the erosion surface during or after erosion (Kite et al. 2013).

Furthermore, long-wavelength surface elevations of apparently old terrains may not reflect paleotopography: Uplift or subsidence may have occurred over billions of years while leaving surface landforms relatively unchanged. Thus, “a paleoequipotential surface does not necessarily have to fit well a present-day equipotential surface” (Ruiz et al. 2004) that complicates identification of paleoshorelines from present-day topographical data (Ruiz et al. 2004).

From a terrestrial geological point of view, some models of martian surface evolution appear to be very simple, and new data show that they may indeed be oversimplified.

Conclusion

Ultimately, all the lunar, martian, and venusian examples described above clearly illustrate that in the context of planetary geology, every new influx of data can lead to drastic changes in the interpretation of an existing observational database. Interpretation is largely dependent on the methods and information used in the investigation. New missions and new data-processing techniques shift the methods and information available, sometimes forcing drastic changes in interpretation. The above examples indicate that the rocky bodies of the solar system still have surprises in store. Many unusual, unexpected features or perhaps entirely new feature types await discovery. Those discoveries may include not only features with a well-defined physical existence but also a somewhat less tangible type of conceptual knowledge that goes beyond the boundaries of a single planet. Actually, this type of knowledge constitutes the backbone of science. The possibility offered by planetary geology to revitalize the structure of knowledge itself is precisely what makes this branch of science extremely attractive to young, or not so young, inquisitive scientists.

References

- Addington EA (2001) A stratigraphic study of small volcano clusters on Venus. *Icarus* 149:16–36
- Agassi J, Sagal PT (1975) The problem of universals. *Philipp Stud* 28(4):289–294

- Bacon F (1620) *Novum organum scientiarum*, Book II. English: The works, vol VII-I. Taggard and Thompson, Boston, 1863
- Baldwin RB (1964) Lunar crater counts. *Astron J* 69:377–392
- Barlow NG et al (2000) Standardizing the nomenclature of Martian impact crater ejecta morphologies. *J Geophys Res* 105(E11):26733–26738
- Basilevsky AT, Head JW (1996) Evidence for rapid and widespread emplacement of volcanic plains on Venus: stratigraphic studies in the Baltis Vallis region. *Geophys Res Lett* 23(12):1497–1500. doi:10.1029/96GL00975
- Beer W, Madler JH (1838) Survey of the surface of the Moon. *Edinb New Philos J* 25:38–67
- Berthling I (2011) Beyond confusion: rock glaciers as cryo-conditioned landforms. *Geomorphology* 131:98–106
- Bishop MA (2008) Higher-order neighbor analysis of the Tartarus Colles cone groups, Mars: the application of geographical indices to the understanding of cone pattern evolution. *Icarus* 197:73–83
- Borst WN (1997) Construction of engineering ontologies for knowledge sharing and reuse. PhD thesis, University of Twente, Enschede, CTIT Ph. D-series no 97–14
- Bridges EM (1990) *World geomorphology*. Cambridge University Press, Cambridge
- Bruno BC, Fagents SA, Hamilton CW, Burr DM, Baloga SM (2006) Identification of volcanic rootless 27 cones, ice mounds, and impact craters on Earth and Mars: using spatial distribution as a remote sensing tool. *J Geophys Res* 111(28). doi:10.1029/2005JE002510
- Bucher WH (1924) The pattern of the Earth's mobile belts. *J Geol* 32:264–290
- Burr DM, Bruno BC, Lanagan PD, Glaze LS, Jaeger WL, Soare RJ, Wan Bun Tseung J-M, Skinner JA Jr, Baloga SM (2009) Mesoscale raised rim depressions (MRRDs) on Earth: a review of the characteristics, processes, and spatial distributions of analogs for Mars. *Planet Space Sci* 57:579–596
- Cañón-Tapia E (2010) Origin of Large Igneous Provinces: the importance of a definition. In Cañón-Tapia E, Szakács A (eds) *What is a volcano?* Geological Society of America special paper, vol 470. Geological Society of America, pp 77–101. doi:10.1130/2010.2470(06)
- Cañón-Tapia E (2014) Insights into the dynamics of planetary interiors obtained through the study of global distribution of volcanoes II: tectonic implications from Venus. *J Volcanol Geotherm Res* 281:70–84
- Cañón-Tapia E, Mendoza-Borunda R (2014) Insights into the dynamics of planetary interiors obtained through the study of global distribution of volcanoes I: empirical calibration on Earth. *J Volcanol Geotherm Res* 281:53–69
- Căpitân RD, van de Wiel M (2011) Landform hierarchy and evolution in Gorgonum and Atlantis basins, Mars. *Icarus* 211(1):366–388
- Christopherson RW (2003) *Geosystems: an introduction to physical geography*, 5th edn. Prentice Hall, Upper Saddle River
- Collins G, Nimmo F (2009) Chaotic terrain on Europa. In: Pappalardo RT, McKinnon WB, Khurana K (eds) *Europa*. University of Arizona Press, Tucson, pp 259–282
- Copi IM, Cohen C (1994) *Introduction to logic*. Macmillan, New York, 729 p
- Cox NJ (2007) Kinds and problems of geomorphological explanation. *Geomorphology* 88:46–56
- de Pablo MA, Komatsu G (2009) Possible pingo fields in the Utopia basin, Mars: geological and climatic implications. *Icarus* 199(1):49–74
- Delcourt HR, Delcourt PA (1988) Quaternary landscape ecology: relevant scales in space and time. *Landsc Ecol* 2(1):23–44
- Deng Y (2007) New trends in digital terrain analysis: landform definition, representation, and classification. *Prog Phys Geogr* 31(4):405–419
- Dickinson WR (2003) The place and power of myth in geoscience: an associate editor's perspective. *Am J Sci* 303:856–864. doi:10.2475/ajs.303.9.856
- Dickson J, Head JW (2006) Evidence for an Hesperian-aged south circum-polar lake margin environment on Mars. *Planet Space Sci* 54:251–272
- Dietrich WE, Perron JT (2006) The search for a topographic signature of life. *Nature* 439(7075):411–418. doi:10.1038/nature04452
- Eggerton RE, Schaber GG (1972) Cayley formation interpreted as basin ejecta. In: *Apollo 16 preliminary science report*, vol 315. NASA Special Publication, pp 29–7–29–16

- Elger TG (1895) The Moon – a full description and map of its principal physical features. George Philip & Son, London
- Evans IS (2003) Scale-specific landforms and aspects of the land surface. In: Evans IS, Dikau R, Tokunaga E, Ohmori H, Hirano M (eds) Concepts and modelling in geomorphology: international perspectives. pp 61–84
- Feyerabend P (1975/1993) Against method, 3rd edn. Verso, London
- Ford JP, Blom RG, Crisp JA, Elachi C et al. (1998) Spaceborne radar observations. A guide for Magellan radar-image analysis. JPL Publication 89-41, Pasadena
- Garrard AJ (1988) Rocks and landforms. Routledge, London
- Gathan GJ, Head JW III (2004) Regional drainage of meltwater beneath a Hesperian-aged south circumpolar ice sheet on Mars. *J Geophys Res* 109:E07006. doi:10.1029/2003JE002196
- Gilbert GK (1886) The inculcation of scientific method by example. *Am J Sci* 31:284–299
- Gilbert GK (1893) The moon's face. A study of the origin of its features, vol XII. Bulletin of the Philosophical Society, Washington, DC, pp 241–292
- Guest JE, Stofan ER (1999) A new view of the stratigraphic history of Venus. *Icarus* 139:55–66
- Hansen VL (2000) Geologic mapping of tectonic planets. *Earth Planet Sci Lett* 176:527–542
- Hansen VL (2007) LIPs on Venus. *Chem Geol* 241:354–374
- Hansen VL, Young DA (2007) Venus's evolution: a synthesis. In: Cloos M, Carlson WD, Gilbert MC, Liou JG, Sorensen SS (eds) Convergent margin terranes and associated regions: a tribute to W.G. Ernst. Geological Society of America special paper, vol 419. Geological Society of America, pp 255–273. doi:10.1130/2006.2419(13)
- Hartmann WK, Wood CA (1971) Moon: origin and evolution of multi-ring basins. *Moon* 3:3–78
- Head JW et al (2009) Volcanism on Mercury: evidence from the first MESSENGER flyby for extrusive and explosive activity and the volcanic origin of plains. *Earth Planet Sci Lett* 285(3–4):227–242
- Head JW, Crumpler LS, Aubele JC, Guest JE, Saunders RS (1992) Venus volcanism: classification of volcanic features and structures, associations, and global distribution from Magellan data. *J Geophys Res* 97(E8):13153–13197. doi:10.1029/92JE01273
- Herrick RR, Rumpf ME (2011) Postimpact modification by volcanic or tectonic processes as the rule, not the exception, for Venusian craters. *J Geophys Res* 116, E02004. doi:10.1029/2010JE003722
- Hoppa GV, Tufts BR, Greenberg R, Hurford TA, O'Brien DP, Geissler PE (2001) Europa's rate of rotation derived from the tectonic sequence in the Astypalaea region. *Icarus* 153:208–213
- Hume D (1739/2000) A treatise of human nature. Oxford University Press, Oxford
- Ivanov MA, Head JW (2011) Global geological map of Venus. *Planet Space Sci* 59:1559–1600
- Jaeger WL, Keszthelyi LP, McEwen AS, Dundas CM, Russell PS (2007) Athabasca Valles, Mars: a lava-draped channel system. *Science* 317:1709–1711
- Jaimes A, Chang S-F (2000) A conceptual framework for indexing visual information at multiple levels, vol 3964. IS&T/SPIE Internet Imaging, San Jose, pp 2–15
- Keszthelyi L (2008) Inflated pahoehoe at Rima Hadley. *Lunar Planet. Sci. XXXIX*, abstract #2339, Houston
- Keszthelyi L, Jaeger W, McEwen A, Tornabene L, Beyer RA, Dundas C, Milazzo M (2008) High Resolution Imaging Science Experiment (HiRISE) images of volcanic terrains from the first 6 months of the Mars Reconnaissance Orbiter Primary Science Phase. *J Geophys Res* 113, E04005. doi:10.1029/2007JE002968
- Kite ES, Lucas A, Fassett CI (2013) Pacing early Mars river activity: embedded craters in the Aeolis Dorsa region imply river activity spanned $\geq(1\text{--}20)$ Myr. *Icarus* 225:850–855
- Koehler U, Hiesinger H, Hauber E (1998) Terrestrial analogs to the MPF landing site: investigation of morphologies of sander in northern Iceland. 29th Lunar Planet. Sci., abstract #1938, Houston
- Kuhn T (1962) The structure of scientific revolutions. University of Chicago Press, Chicago
- Langhans MH, Jaumann R, Stephan K et al (2012) Titan's fluvial valleys: morphology, distribution, and spectral properties. *Planet Space Sci* 60:34–51

- Levy JS, Head JW, Marchant DR (2008) Mars thermal contraction crack polygon classification and distribution: morphological characterization at HiRISE resolution. *Lunar Planet Sci XXIX*, abstract #1171, Houston
- Malin MC (1992) Mass movements on Venus: preliminary results from Magellan cycle 1 observations. *J Geophys Res* 97:16337–16352
- Malin MC, Edgett KS (2001) Mars Global Surveyor Mars Orbiter Camera: interplanetary cruise through primary mission. *J Geophys Res* 106(E10):23429–23570
- Malin MC, Edgett KS, Cantor BA, Caplinger MA et al (2010) An overview of the 1985–2006 Mars Orbiter Camera science investigation. *Mars* 5:1–60. doi:10.1555/mars.2010.0001
- Mandt KE, de Silva SL, Zimbleman JR, Crown DA (2008) Origin of the Medusae Fossae Formation, Mars: insights from a synoptic approach. *J Geophys Res* 113, E12011
- Marceau DJ, Hay GJ (2000) Remote sensing contributions to the scale issue. *Can J Remote Sens* 25(4):357–366
- Marchant DR, Head JW III (2007) Antarctic dry valleys: microclimate zonation, variable geomorphic processes, and implications for assessing climate change on Mars. *Icarus* 192:187–222
- Mark DM, Smith B (2004) A science of topography: from qualitative ontology to digital representations. In: Shroder JF, Bishop MP (eds) *Geographic information science and mountain geomorphology*. Springer-Praxis, Chichester, UK, pp 75–100
- McGill GE, Hills LS (1992) Origin of giant Martian polygons. *J Geophys Res* 97(E2):2633–2647. doi:10.1029/91JE02863
- Michael GC, Neukum G (2010) Planetary surface dating from crater size–frequency distribution measurements: Partial resurfacing events and statistical age uncertainty. *Earth Planet Sci Lett* 294:223–229
- Michalski JR, Cuadros J, Niles PB, Parnell J, Rogers AD, Wright SP (2013) Groundwater activity on Mars and implications for a deep biosphere. *Nat Geosci* 6:133–138
- Montgomery DR, Som SM, Jackson MPA, Schreiber BC, Gillespie AR, Adams JB (2009) Continental-scale salt tectonics on Mars and the origin of Valles Marineris and associated outflow channels. *GSA Bull* 121(1–2):117–133
- Moore JM, Horner VM, Greeley R (1985) The geomorphology of Rhea: implications for geologic history and surface processes. *J Geophys Res* 90(S02):C785–C795. doi:10.1029/JB090iS02p0C785
- Mutch TA, Arvidson RE, Head JW III, Jones KL, Saunders RS (1976) *The geology of Mars*. Princeton University Press, Princeton
- Neish CD, Prockter LM, Patterson GW (2012) Observational constraints on the identification and distribution of chaotic terrain on icy satellites. *Icarus* 221(1):72–79
- Neison E (1876) *The Moon and the condition and configuration of its surface*. Longmans, Green, London
- NSSH (2008) National soil survey handbook, part 629. Glossary of landform and geologic terms 430–VI-NSSH
- Page DP, Murray JB (2006) Stratigraphic and morphologic evidence for pingo genesis in the Cerberus plains. *Icarus* 183:46–54
- Page DP (2010a) Resolving the Elysium Controversy: an open invitation to explain the evidence. *Planet Space Sci* 58:1406–1413
- Page DP (2010b) Contribution of Mars Odyssey GRS and Mars Reconnaissance Orbiter CRISM at Elysium Planitia: a case of mistaken identity. *Planet Space Sci* 58:1404–1405
- Page DP (2015) The geology of planetary landforms. In: Hargitai H, Kereszturi Á (szerk) *Encyclopedia of planetary landforms*. Springer, New York
- Phillips R, Raubertas RF, Arvidson RE, Sarkar IC, Hertick RR, Izenberg N, Grimm RE (1992) Impact craters and Venus resurfacing history. *J Geophys Res* 97:15923–15948
- Pierce CS (1906) Prolegomena to an apology for pragmatism. *Monist* 16:492–546
- Platt JR (1964) Strong inference. *Science* 146:347–353
- Popper KR (1959) *The logic of scientific discovery*. Basic Books, New York
- Rodrigue CM (2009) Orders of relief and the regional geography of Mars. Paper presented at the Association of American Geographers, Las Vegas, 22–27 Mar 2009. Available via <http://www.csulb.edu/~rodrigue/mars/aag09/marsrelief09aag.html>
- Rodrigue CM (2012) Geography 441/541, the geography of Mars. <http://www.csulb.edu/~rodrigue/mars/>. Accessed 7 Oct 2012

- Ruiz J, Fairén AG, Dohm JM, Tejero R (2004) Thermal isostasy and deformation of possible paleoshorelines on Mars. *Planet Space Sci* 52(14):1297–1301
- Schaber GG, Strom RG, Moore HJ, Soderblom LA, Kirk RL, Chadwick DJ, Dawson DD, Gaddis LR, Boyce JM, Russell J (1992) Geology and distribution of impact craters on Venus: what are they telling us? *J Geophys Res* 97:13256–13301
- Schulson EM (2001) Fracture on ice on scales large and small. In: Dempsey JP, Shen HH (eds) IUTAM symposium on scaling laws in ice mechanics and ice dynamics, Fairbanks, pp 161–170
- Shoemaker EM, Hackman RJ (1962) Stratigraphic basis for a lunar time scale. In: Kopal Z, Mikhailov ZK (eds) *The Moon*. Academic, pp 289–300
- Smith B, Mark DM (2003) Do mountains exist? Ontology of landforms and topography. *Environ Plann B Plann Des* 30:411–427
- Stephan K, Jaumann R, Wagner R, Clark RN, Cruikshank DP et al (2010) Dione's spectral and geological properties. *Icarus* 206:631–652
- Szakács A (2010) From a definition of volcano to conceptual volcanology. In: Cañón-Tapia E, Szakács A (eds) *What is a volcano?* Geological Society of America special paper, vol 470. Geological Society of America, pp 67–76. doi:10.1130/2010.2470(05)
- Tanaka K, Skinner J, Hare T (2005) Geologic map of the northern plains of Mars. Scientific investigations map, 2888. U.S. Geological Survey
- Taylor SR, McLennan SM (2009) *Planetary crusts: their composition, origin and evolution*. Cambridge University Press, Cambridge, UK
- Thomas RJ (2013) Identification of possible recent water/lava source vents in the Cerberus plains: stratigraphic and crater count age constraints. *J Geophys Res Planets* 118:789–802. doi:10.1002/jgre.20071
- Veverka J (1985) *Planetary geology in the 1980s*. NASA Office of Space Science and Applications, Washington, DC
- von Bertalanffy L (1950) The theory of open systems in physics and biology. *Science* 111(2872):23–29
- von Bertalanffy L (1969) *General system theory: foundations, development, applications*. Revised edition. Penguin University Books, George Braziller, New York, 296 pp
- Wallace AR (1907) *Is Mars habitable? A critical examination of Professor Percival Lowell's book "Mars and its canals," with an alternative explanation*. Macmillan, London/New York
- Washburn AL (1970) An approach to a genetic classification of patterned ground. *Acta Geographica Lodziensia* 24:437–446
- Wegener A (1921/1975) The origin of lunar crater [Die Entstehung der Mondkrater]. *Moon* 14:211–236, Translation
- Wilhelms DE (1990) Geologic mapping. In: Greeley R, Batson RM (eds) *Planetary mapping*. Cambridge planetary science series, vol 6. Cambridge University Press, Cambridge, UK, pp 208–260
- Wilhelms DE, McCauley JF (1971) Geologic map of the near side of the Moon. USGS miscellaneous investigations series, map I-703
- Yingst RA, Schmidt ME, Lentz RCF, Janzen JL, Kuhlman KR (2011) A Mars-oriented image database of hand lens-scale features and textures: the 1996 Skeiðarársandur jökulhlaup example. *GSA special papers*, vol 483. Geological Society of America, pp 301–315
- Zimbelman JR (2001) Image resolution and evaluation of genetic hypotheses for planetary landscapes. *Geomorphology* 37(3–4):179–199

The Geology of Planetary Landforms

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Time is always time and place is always and only place.

(T.S. Elliot 1932)

The Encyclopedia of Planetary Landforms is a comprehensive compendium of the landforms that populate the surfaces of the rocky planets and moons of our Solar System, and the various (and often numerous) hypotheses that are proposed for their formation. The methods of study of these landforms are also varied, but are form analogical in the main, based on visual similarity to known landforms on Earth. In seeking to understand these geomorphological features in terms of geological units and origin, this volume necessarily treads a path between geography and geology.

In an encyclopedia dedicated to planetary landforms, one might ask why it is necessary to study geological units. However, any analysis of a landform or terrain type that goes beyond the descriptive to *identify* a landform always carries an assertion of geological origin. For instance, identifying a surface feature as a “rootless cone” implies an explosive, volcanic origin, while “alluvial fan” denotes both a particulate, sedimentary substrate, and aqueous activity. Clearly, if the landform identification is incorrect, then the inferred geology will also be in error. As such identifications are frequently the basis for other, superposed theories (e.g., interpreting impact crater distributions or surface spectra in the context of an inferred substrate, or associating a particular terrain type with meteorites of unknown provenance), the geological element of such landform identifications must be as secure as possible.

The difficulty with interpretive geomorphology is the scope for *form convergence* (or equifinality (von Bertalanffy 1950)), where different processes operating in different substrates yield visually identical landforms. An example of this convergence is presented in Fig. 1, showing a terrestrial rootless cone (Fig. 1a) alongside an intrusive frost mound (Fig. 1b). As can be seen, there is nothing to distinguish these two landforms visually despite their mutually exclusive volcanic and periglacial origins. Given these two terrestrial analogues, interpretation of the visually comparable martian landform of Fig. 1c immediately faces a problem, with a 50 % chance of misidentification (increasing to 100 % if both analogues are false), and it is not uncommon in planetary geology for entire assemblages of landforms to have multiple interpretations of origin. Genetic interpretation of planetary landforms is fraught with difficulty as a consequence, a situation that is not improved by crater-chronological or spectral observations, both of which often assume the geology inferred from those landform identifications.

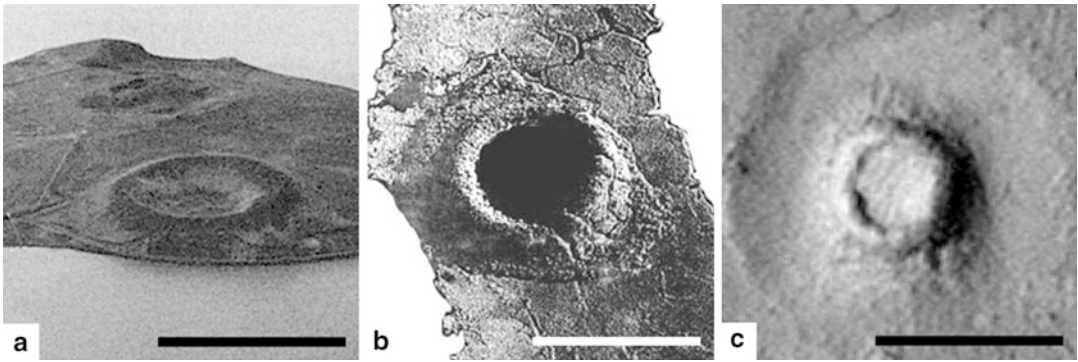


Fig. 1 Form convergence in terrestrial and martian landforms. (a) Rootless cone, Myvatn, Iceland (Fagents et al. 2002: Fig. 6, Geological Society, London). Ground patterns surrounding cone are pathways. (b) Pingo, Prudhoe Bay, Canadian Arctic (Geophysical Institute,

University of Alaska, Fairbanks). (c) Cone of indeterminate origin, Athabasca Valles, Mars (HiRISE PSP_002661_1895) (NASA/JPL/University of Arizona). Note poly-hexagonal pattern of surfaces surrounding b-c. Scale bars = 75 m (all)

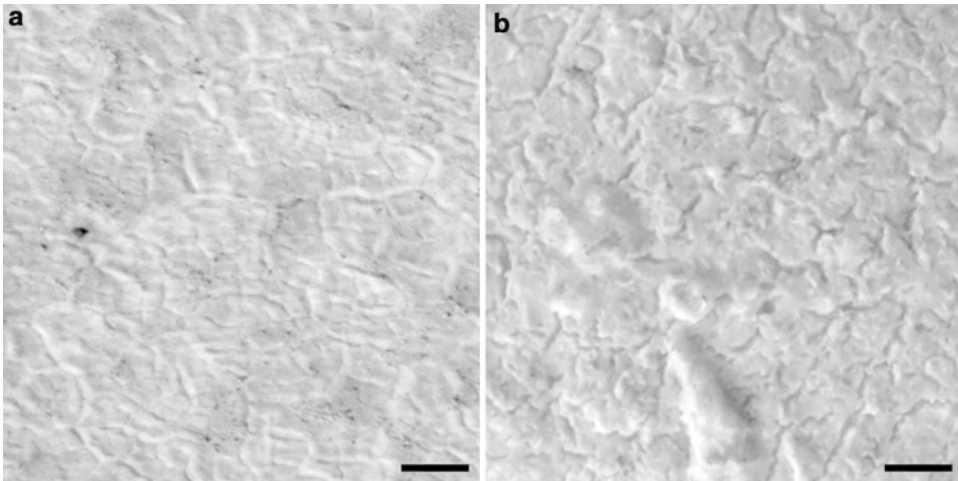
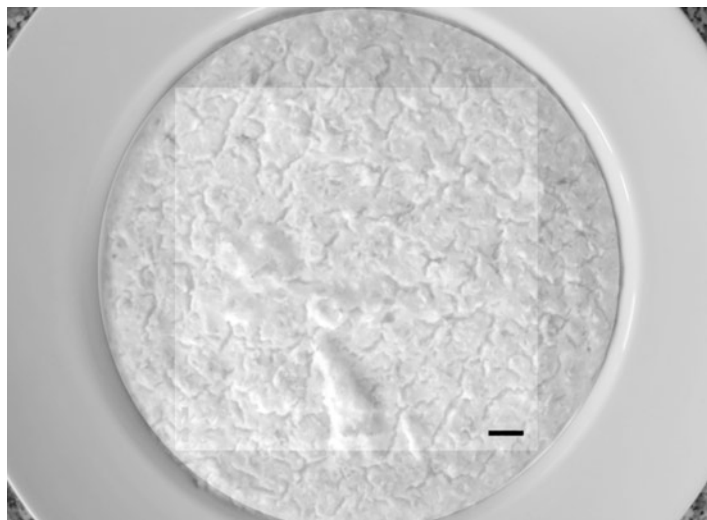


Fig. 2 Form convergence in terrestrial and martian landforms. Scale bars 5 m and 1 cm, respectively. (a) Polygonally-fractured surface at Phoenix Lander site, considered to be the product of thermal contraction in water-ice-rich substrate. HiRISE PSP_008301_2480, 25 cm/px, North to top (NASA/JPL/University of

Arizona). (b) Polygonally-fractured surface in the author's breakfast (porridge oats). Fractures observed to form on cooling if water replaces milk in cooking, an observation serendipitously grounded in running out of milk and a preference for cooler porridge (Photo by author)

The degree to which physical resemblance can deceive the observer is illustrated by the polygonized surfaces of Fig. 2. The visual correspondence between these two surfaces, one from Mars and one from Earth, although striking, is misleading, for where one is the surface of Mars' northern plains, the other is the surface of cooled porridge oats (context, Fig. 3). The process of polygonization in both cases is probably similar – shrinkage resulting from volatile loss – but the serious point is the scope for error that exists in

Fig. 3 Context for Fig. 2, scale bar = 1 cm. Bowl of cooled porridge oats showing polygonized surface (Photo by author)



comparative morphology. One might argue that this comparison illustrates no more than self-organization in different media. However, the fact that similar landforms can form in completely different substrates is very much the point – that form analogy is no way to inquire into the origin of planetary surfaces where our inferences cannot be tested by “ground truth.”

If determination of landform origin is our ultimate goal, then planetary landforms cannot be considered in isolation of the geology that they express, geomorphology only functional in the terrestrial environment because of our ability to test initial assertions of landform origin *in situ*. The inability to do this with the large majority of planetary observations thus makes it mandatory that we understand these landforms in terms of geological units. The following text discusses how the concept of *time*, as inferred from deposit geometry and impact crater distributions, can help define units and landforms in the planetary environment where information on lithology (or rock type) is unavailable.

Geological units are stratigraphical entities defined in three-dimensional space by the nature of their contacts with other units. Just as the spatial dimensions of a geological unit are a function of the passage of time during its formation, so too is every landform formed at a certain point in time (or over a particular time period), a depositional event the geometry of which constrains origin. This temporal element is the essence of *stratigraphy*, and a simple test of the validity of any unit or landform designation on any planetary surface – if our mapped “units” or landform identifications do not make stratigraphical sense in terms of observed relative-age, then they are somewhere in error. Where temporal discontinuities occur within geological materials, as inferred stratigraphically, then this signifies a Unit boundary that serves to constrain the origin of the landforms within, or crossing, those units. The *lithostratigraphical unit* is the basic unit of geological mapping, classified directly on the lithological

characteristics of rocks, and “time” in terms of age-of-formation (e.g., 100 Ma, 1 Ga¹) plays little part in establishing such units. However, this is not the case for the *relative-age* inferences of deposit geometry, the contact relations of which act as a guide for unit definition. This distinction is important for planetary geology, and returned to repeatedly in this entry, as units and landforms on other planets are often defined on the basis of absolute-age alone (i.e., as determined by impact crater counts) with the relative-age relations of those units and craters largely unexplored.

Beyond those few areas studied *in situ* by landed or roving expeditions, the remote sensing of planetary surfaces does not afford information on lithology (Page 2010a). Here, we must use another means to distinguish one body of rock (or sediment) from another and the relative-age relations of deposit geometry are the most objective way of doing so². We are hampered in this by the two-dimensional nature of planetary imaging, lacking the 3-D, sectional view of the substrate that is the mainstay of terrestrial geological inquiry. As such, planetary geology is often viewed as a “data poor” discipline (e.g., Keszthelyi et al. 2004) that becomes an exercise in the geography and geomorphology of landscape. However, we should not assume that three-dimensional inferences cannot be drawn from two-dimensional data or that we need engage in one-dimensional thinking.

For the terrestrial geologist, determination of geological history is just that – a “historical” sequence of events defined by relative-age, without recourse to the causes involved. Yet how can we know “what happened” (and “what happened next”) on other planets without first understanding the nature of the landforms and surfaces affected? The terrestrial approach to determination of geological history is to study rocks at the points of their intersections, as illustrated by Fig. 4. In geometrical terms, this graphic shows the intersection of three non-coincident planes, “A,” “B,” and “C,” a real-world example being the intrusion of one rock into another (e.g., the emplacement of igneous dykes into country rock). The geological significance of this relationship is threefold:

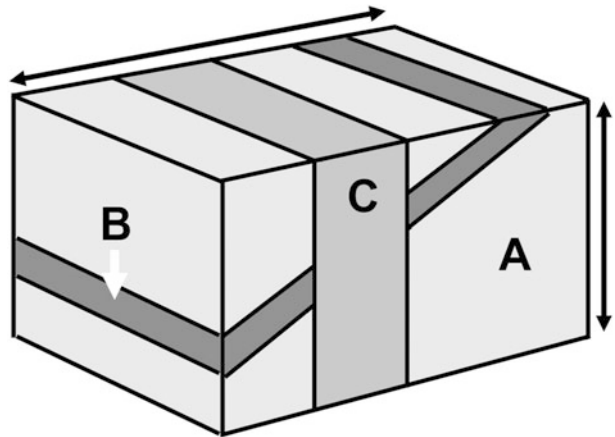
- (i) It defines the order of events – “C” must have formed later than “B,” which formed later than “A” – a unique, unidirectional time line that requires no measurement.
- (ii) It is unaffected by tectonism.
- (iii) It is independent of interpretation.

Whether we are dealing with the emplacement of a salt-dome, an igneous body or a mineralizing fracture fill, the geological history of events is the same and fixed, a relationship that is unaffected by tectonism (invert, rotate, or fault the Fig. 4 graphic through any

¹The terms “Ga,” “Ma,” and “ka” refer to billions, millions, and thousands of years in age, respectively (Ma = Mega annum, or million years).

²Allowing stratigraphical units to be established without regard for the genetic or causal interpretation of their surfaces (International Subcommission on Stratigraphic Classification 1976).

Fig. 4 Principle of cross-cutting relations demonstrated by three intersecting planes “A,” “B,” and “C.” Horizontal and vertical arrows correspond to the land surface and depth in the subsurface, respectively. Note how there is only one possible order of formation (see text) and how this “event history” is only evident in vertical section



desired angle, and the “ $A \rightarrow B \rightarrow C$ ” sequence of events does not change). The significance of (iii) for planetary geology is that it is independent of lithology, removing the need to *identify* surfaces or terrain types before we can understand their history in an environment where we cannot subject our inferences to ground truth.

This principle of “cross-cutting relations” is the most important of the four principles of stratigraphical geology, comprising *stratigraphical superposition*, *original horizontality*, *cross-cutting relations*, and *original continuity*. Application of these principles is how geologists establish geological units on Earth, but they also allow constraints to be placed on planetary landform origins by determining what is and is not possible as a result of a particular deposit geometry. In order, these principles state that the lowest deposit in a succession is also the oldest (assuming no folding or overturning), that the deposit that cuts another is the later formed (as in the $A \rightarrow B \rightarrow C$ event sequence above), and that geological materials extend laterally in space, their former presence inferred where separated by erosion (e.g., as in the case of identical strata either side of a valley or river channel).

However, Fig. 4 is a subsurface view whose geometry is only apparent in section, a perspective not readily available to the planetary observer. How then to apply this principle to the two-dimensional surfaces of planetary bodies that are the subject of this volume? Given physical detachment from the object of study, some relative-age reference point must be established. What is needed is a surface landform whose identity and age relative to the substrate can both be taken as a given and against which the origin of other landforms can be gauged by observation of their contact relations. Just such a landform exists – the impact crater. *Impact craters* are abundant, easily recognized, and possessed of a number of characteristics that collectively are not found in any other landform (the presence of a raised rim around a bowl-shaped excavation with a surrounding blanket of ejecta derived from the

impact event). Impact craters are post-depositional by definition³; as such, any landform that cross-cuts a crater must itself be post-depositional, and have formed post-impact: a definitive “time marker” that can be used to constrain the origin of landforms and geological units.

The following section describes how impact craters can be used to define the relative ages of surface landforms and terrains. Later sections show how this relative chronology adds a new dimension to the absolute chronology of crater counts, the application of stratigraphical principles to unit and landform definitions presented in the context of two case studies from the recent planetary research literature. The examples given are 10^7 – 10^8 km²-scale surfaces with multiple interpretations of origin and simultaneously the chronostratigraphical referent for both planets. Sections on tectonic and spectral mapping of planetary surfaces, and strength of inference in planetary geology, follow.

Impact Craters and Relative Age

The martian impact craters of Figs. 5, 6 illustrate the characteristic features of this landform photographically (Fig. 5a-b) and in inferred section (Fig. 5A-A', B-B'). Note how material ejected from the crater basin forms a surrounding rim that thins out laterally to form the ejecta blanket, the rim raised above the surrounding terrain (by ~ 0.07 crater diameters, a scaling relationship between rim height and diameter that is applicable to all simple impact craters (Pike 1977)). These excavation products are emplaced ballistically and are destructive of pre-existing surface texture. That is, nothing within the interior of the resulting basin survives impact, with no recorded examples of such survival anywhere in the Solar System (Melosh 1989). An example of this behavior is seen in Fig. 5a, where a later impact has obliterated all trace of the original crater rim. For the D 130-m crater of Fig. 5b, the rim will be ~ 10 m high at its crest and any landform here must be post-depositional in origin to account for its presence in post-impact ejecta above the pre-impact surface. Even if one supposes the crater-crossing surface polygonization in Fig. 5b to be an original feature that extends to depth, accounting for its presence in the crater floor thereby, any landform that passes continuously from the surrounding substrate, over the rim, and into the interior (arrowed in Fig. 5b, blocked red in Fig. 5B-B') must have formed post-impact.

Such crater-crossing features abound on Mars, this process of *stratigraphical superposition* evident across one-fifth of equatorial longitude (Page et al. 2009) in an entire assemblage of constructional and degradational landforms, all equally indicative of post-impact activity

³The impact status of martian “ring-mold” craters are considered in detail in Addendum: “Isochrons, diachrons, and landform identification.”

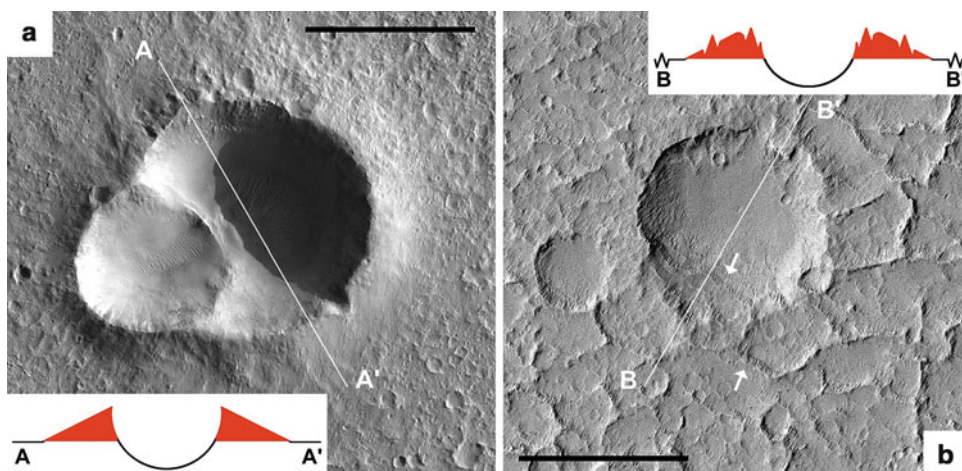


Fig. 5 Impact craters in Terra Cimmeria (a) and Amazonis Planitia (b) showing age relations relative to later-formed landforms. Scale bars 1 km and 150 m, respectively, both images from HiRISE at 25 cm/pixel and 2.5 m/px. Insets show inferred sections along lines A-A' and B-B' (vertical scale exaggerated for clarity). (a) Impact crater superposed upon larger, earlier-formed crater. Note obliteration of preexisting crater structure by

later impact (see text), HiRISE AEB_000002_0000, 33°S/146°E. (NASA/JPL/University of Arizona) (b) Polygonal sculpture cross-cutting impact crater on SW side. Note presence of sculpture on crater floor (*upper arrow*), continuous with that outside crater (*lower arrow*) = unambiguous indicator of relative age, PSP_008382_1980, 18°N/197°E (NASA/JPL/University of Arizona)

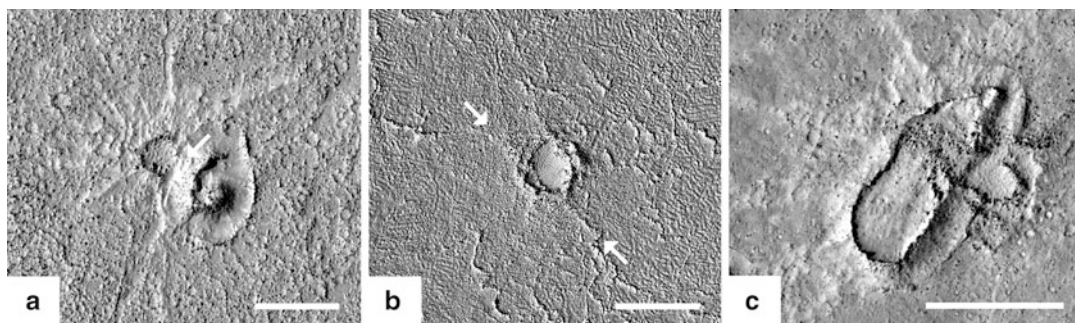


Fig. 6 Landforms in polygonal terrain in Athabasca Valles showing secondary age-relations relative to impact craters, cf. Fig. 5b. (a) Pitted cone within raised, hexagonal collapse structure; wall of collapse structure transects impact crater rim (*arrowed*) = landform postdates impact cratering, cf. Fig. 11b). (b) Surface-ridging sweeps over crater rim (*ridge front arrowed*) = landform postdates impact cratering. (c) Low-velocity, secondary impact cratering obliterates wall of pitted cone, illustrating

destructive nature of the impact process, cf. a. Note well-preserved rays of craters a and c, characteristic of secondary impacts from the primary impact crater “Zunil” to the west. All images from HiRISE at 25 cm/px. PSP_003571_1880 (a), 7.5°N/153°E, PSP_002371_1890 (b), 9°N/156°E, PSP_002661_1895 (c), 9.5°N/156°E. North to top, scales = 100 m (NASA/JPL/University of Arizona)

(Page and Murray 2006; Page 2008). Moreover, because the superposing landforms are destructive of crater texture (e.g., Figs. 5b and 6a), we can infer that they are intrusive, i.e., formed from *within* by some process operating in the subsurface. The cross-cutting, relative-age relations of

the landforms in Figs. 5 and 6 parallel those of Fig. 4, showing “what happened, and what happened next,” a geological history of events determined without knowledge of substrate lithology or hypotheses of genesis.

Yet what use is this for establishing unit and landform origins, beyond demonstrating that some unidentified (and perhaps unidentifiable) landforms on Mars form post-depositionally? Well, it follows from these relative-age relations that the superposing landforms cannot be *primary* (or syn-depositional) in origin because they postdate a landform that is itself *secondary* (or post-depositional) in origin – the impact crater. That is, we have a way to constrain the origin of landforms or surfaces without first having to identify them or know what they are. For instance, lava flows and their associated landforms have their geomorphological characteristics established in the time it takes them to crystallize; thereafter, they are only subject to modification by erosion or burial. In contrast, periglacial landforms and landscapes are the product of continuous, often repetitious (i.e., *time-transgressive*, or *diachronous*), constructional and degradational processes resulting from the action of intrusive ground ice (French 1996); as such, they interact stratigraphically with post-depositional structures, such as impact craters, in a way that lava flows or other layered deposits cannot. The implications of this time-transgressive activity for landform identification and age-determination are considered in the Addendum: *Isochrons, diachrons, and landform identification*.

In an environment where multiple genetic hypotheses abound (the terrain in Figs. 5b and 6 variously regarded as lava, the surface of an extant “frozen ocean,” outflow channel effluent or periglacialized sediment), this stratigraphical approach is inherently more objective than geomorphic interpretation and “fruitful” in pointing to the testable consequences of our inferences, telling us “*what to look for or where to look next*” (Johnson 1933). This generative aspect of stratigraphical-historical method is illustrated in the subsequent sections “Mapping Mars by Isochrons” and “Strength of inference and geomyth in Planetary Geology.”

Mapping Geological Units, Landforms, and Structures by Absolute Age

In common with the Earth and Moon, a geochronological timescale has been established for Mars⁴. In increasing order of age, the equatorial deposits of the Elysium-Amazons plains (Figs. 1c, 5b, 6, 9, and 20) are Late Amazonian in age, with the older Utopia plains to the north of Late Hesperian age and the older-still cratered highlands to the south Noachian in age. The Ma-Ga ages of these surfaces are derived by *crater counts*, a chronology based on the observed and modeled flux of asteroidal impactors arriving at the surfaces

⁴A timescale also exists for Mercury [see Tanaka et al. (2010) for an introduction], but Venus has no such system at present because of the inferred resurfacing of the planet c. 500 Ma (see later Section: “Tectonic mapping of planetary surfaces and landforms”).

of the terrestrial planets and the calibrated early crater-record of Earth's Moon⁵. The result is a terrestrial-like system of immaterial (*geochronological*) time units divided into material (*chronostratigraphical*) rock units, the Late Amazonian Epoch containing deposits of the upper Amazonian Series, and so on.

Following terrestrial practice, planetary chronologists look for synchronous surfaces to record the “production function” of impactors arriving at planetary surfaces at one specific moment of time (Ivanov et al. 2002). By assuming an ideal-case “blank slate” where a planetary surface erased by some process begins to accumulate craters (before the processes of crater loss change the population of these craters), the resultant crater size-frequency distribution (SFD) provides a measure of the passage of time from which a system of crater isochrons is derived. These isochrons are then used to date other, more distant surfaces in an act of correlation. Examples of such synchronous surfaces are the lunar Orientale Basin, which erased a large area near the base of the Imbrian (Wilhelms et al. 1987), the emplacement of mare basalts (Hartmann et al. 1981), Eratosthenian-aged craters (Wilhelms et al. 1987), and rayed craters (which have a limited lifetime and thus mark an approximate time-horizon) such as those of the lunar Copernican (Wilhelms 1990). For Mars, the plains-forming deposits of the Elysium-Amazons region are assumed to be just such a “pristine” surface (Hartmann and Berman 2000; Hartmann and Neukum 2001) whose contained craters are reflective of the impactor population that created them, a region that now forms the planetary stratotype.

Crater counts are also used as a geological mapping tool at the Formation (lithostratigraphical) level (Tanaka et al. 2005) by reasoning that the more heavily cratered a surface is, the older that surface must be. Ideally (assuming no major crater-loss), observed differences in crater density will correspond to surfaces of different age, allowing a basic stratigraphy to be erected. This relative stratigraphy would have both surface and sub-surface components, with the potential to define geological units in three dimensions. However, where mapping is based on the absolute age of a crater count, its meaning depends entirely on whether we count across surfaces formed at the same time. If a count is made across multiple geological surfaces (of potentially different ages), then the significance of both mapping and count at the Unit level is effectively zero as the derived chronology is not that of a single surface accumulating craters but that of a quite different, and nonexistent, temporal composite. For example, the largest craters on the North American continent, the Sudbury and Barringer impact structures, vary in age from 40 ka to 2 Ga, a result that tells us little about the age or origin of any particular geological unit. Counts are made across a similar 10^7 km²-scale area of the martian equator, asserting this to

⁵Calibrated for large craters between 4.0 and 3.0 Ga only. The Earth–Moon system has been bombarded by both asteroids and comets over Solar System history (Bottke et al. 2002). However, the contribution of comets to impact crater formation in the inner solar system either replicates the wavy SFD seen for asteroids or is relatively insignificant (Ivanov et al. 2002).

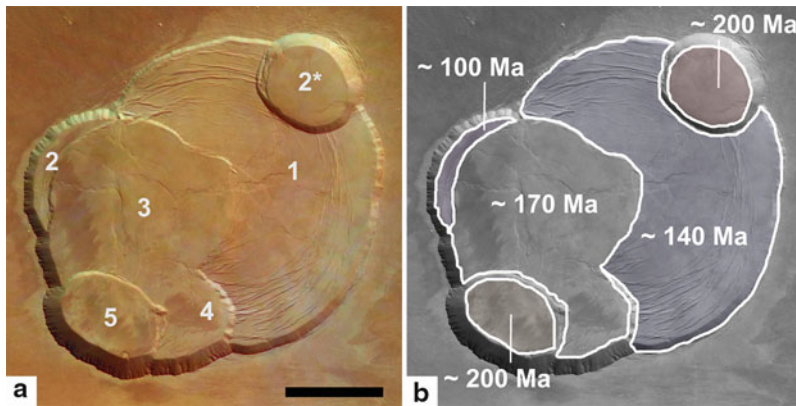


Fig. 7 Relative- and absolute-age chronologies of sequential caldera collapse on Olympus Mons, Mars. **(a)** Caldera complex at volcano summit, with collapse history as determined stratigraphically (see text for explanation). HRSC composite image. (ESA/DLR/FU Berlin

(G. Neukum)). **(b)** Caldera complex with calculated absolute-age assignments of Neukum et al. (2004). Colored, outlined regions show areas of crater counts. North to top, Scale bar = 20 km

be flood lava (Hartmann and Berman 2000) emplaced on a timescale of days (Jaeger et al. 2010). Were these simply regional studies then such conclusions would not affect unit definitions generally. However, this region is the chronological Type Area for the entire planet, these counts said to offer “...a fundamental geological tool to interpret not only ages, but also the nature of geological processes altering the surface of Mars” (Hartmann and Werner 2009).

Given the random nature of impact cratering, large areas of terrain must be counted to provide statistically meaningful results, for which many of the landforms described in this volume will be too small. Relate landforms to geological units stratigraphically and count craters *within* those units, however, and we have a way to date these smaller features as well as constrain their origin. This geological approach to geochronology, grounding calculated absolute age in observed relative-age, is a central theme of the landform analyses described in this entry.

To illustrate the importance of deposit geometry for age determination of units and landforms, let us consider Olympus Mons – the largest volcano in the Solar System. Figure 7 shows the caldera complex at the summit of this massif, a series of nested collapse structures formed by syn-/post-eruptive subsidence of the vent into the underlying magma chamber. Because these features cross-cut one another, they can be analyzed stratigraphically, the relative chronology of collapse derived thereby. Each collapse event is marked on Fig. 7a sequentially (“1” being the earliest and “5” the latest). Any crystalline rock that undergoes subsidence as support is withdrawn from beneath will be subject to both tension and compression over its surface. The circumferential and radiating extensional and compressional features (*graben* and *wrinkle ridges*, respectively) visible within the perimeter of calderas “1” and “3” are signs of just such syn- or post-collapse tectonism, and allow us to further constrain the history of events where these

structures intersect other calderas. Now consider the derived, absolute chronology of caldera collapse (Fig. 7b), as determined by crater counts.

On the basis of crater counts, caldera collapse starts at 140 Ma (“1”). The next events that clearly cross-cut “1” occur 40 million years later and 60 million years *earlier* than “1,” at 100 and 200 Ma respectively (“2” and “2*”).⁶ The next event (“3”) that cross-cuts the 100 Ma-aged “2” occurs another 70 million years earlier, at 170 Ma. The final event (“5”) that cross-cuts the 170 Ma-aged “3” is 30 million years earlier still, at 200 Ma (“5”). Thus the history of collapse begins 140 Ma ago, with an intermediate stage at 170 Ma and ends at 200 Ma – it runs “backwards” in time, and cannot be correct⁷. Just as a fossil found in rocks of an early geological period cannot be the descendant of the one found in a later geological period, so too must the derived chronology of a crater count be consistent with the stratigraphy of the rocks in which the craters are counted. This inconsistency between observed and calculated ages has been suggested to be the result of resurfacing by lava flows or tectonism, burying or erasing part of the crater record post-accumulation (Neukum et al. 2004; Werner 2009)⁸.

The point of this exercise is to demonstrate the primacy of observed relative-age as a check of calculated absolute age. Absent these relative-age observations, we would be unaware that the derived chronology in Fig. 7b is incorrect, and as the following sections will show, not all age anomalies are so obvious. As landform identifications and crater counts often carry a denotation of geology (“...a fundamental geological tool to interpret not only ages, but also the nature of geological processes altering the surface of Mars”), they must first make stratigraphical sense if the identifications and derived ages are to be robust. Accept the dates of the surfaces in Fig. 7b at face value, and these cannot be the series of sequential collapse structures that deposit geometry clearly shows them to be.

⁶The duplication of “2” does not imply that these events are the same age; merely that they both postdate “1.” Because their age relative to one another cannot be established, they are shown as “2” and “2*.” A further stage of collapse (“4”) is shown whose age relative to “3” can be established by virtue of the fact that it cross-cuts the circumferential graben associated with the caldera formation of “2” and “3.” This penultimate stage was not shown by Neukum et al. (2004), so is not present in Fig. 7b. The reduced counting area of subtracting “4” from “3” would make “3” even older (by increasing crater density per unit area), making this “backwards chronology” even more acute.

⁷Caldera “1” should be older than “2*” (in the NE) and is not, “3” should be younger than “1” and is not, “2” (in the W) should be older than both “3” and “5” and is not, and “5” should be younger than each of “3,” “2,” and “1” and also is not. None of these relative-age assignments is reflected in the absolute ages of the impact crater counts.

⁸No such “resurfacing” events are evident in the crater SFD, which is steep and isochron-following at all measured crater diameters (see Fig. 1e of Neukum et al. 2004 and Fig. 7 of Werner 2009) with none of the inflections that would indicate such processes, the 5,200 km² combined area of the calderas sufficient to provide good crater statistics for the <1 km diameter of the craters counted. The interaction between tectonism and impact craters is considered further in a later section (“Tectonic mapping of planetary surfaces and landforms”).

Certainly, the observation of a power-law decay in impact crater populations indicates a universal mechanism of production independent of the particular way or environment in which formation proceeds and in this respect impact crater chronology is independent of geology. However, whilst impactor *production* is independent of surface geology, the spatial composition of the resulting crater population is not. Such craters only have the potential to yield “true ages” if we first map out synchronous surfaces formed at one specific moment of time (Ivanov et al. 2002) (and even then, the derived ages may be misleading, as in Fig. 7b); to do otherwise is to have isochrons that move up and down through the geological column – a construct without temporal meaning. However, count impact craters in the context of observed relative-age and calculated absolute age may be tested to the degree to which this accords with the mapping of units and their constituent landforms. If the relative-age relations point to temporal discordance (or non-conformity) in the rock record, then this should be reflected in the crater SFD. In the following sections, we will explore this relationship between crater numbers, deposit geometry and landform identifications with two case studies from Mars and Mercury, where a hypothesized geology has modified an established chronology (Mars) and impact crater counts have been used to erect geological units (Mercury).

Mapping Mars by Isochrons

Planetary chronologists define an *isochron* as the SFD of all craters created over a specified period, such as 100 Ma or 1 Ga (Hartmann 2005). This isochron is not tied to a single surface, but it does make assumptions about the nature of that surface, in the case of the lavas of Mars’ Elysium-Amazons plains (Fig. 8) that this is a relatively homogenous stratigraphical unit containing a gradual accumulation of craters reflective of the impactor population that created them (Hartmann and Neukum 2001). This definition of an isochron differs from that of geology, where isochrons are derived from units of the same age. Impact crater chronology, however, accepts that crater counts will sample surfaces of different ages, and the counts are often interpreted in the context of the morphology of the surface cratered (e.g., Hartmann and Berman 2000; Dundas et al. 2010). For instance, because the “pristine” young plains of this region are regarded as young lava flows (Plescia 1990; McEwen et al. 2005), and therefore possessive of a Production Population of impact craters (Hartmann and Neukum 2001), this area has become the reference for crater chronology globally, such surfaces providing a “perfect surface” for recording the production function distribution of impact craters and a test of assumed production function (i.e., isochron) shape (Hartmann and Neukum 2001, p. 175).

In recent years, a number of observations have emerged that provide just such a test, the SFD in this region departing from the steep slope at small-crater diameter (Hartmann and Berman 2000; Burr et al. 2002; Berman and Hartmann 2002; Page et al. 2009) that the asteroidal and lunar production

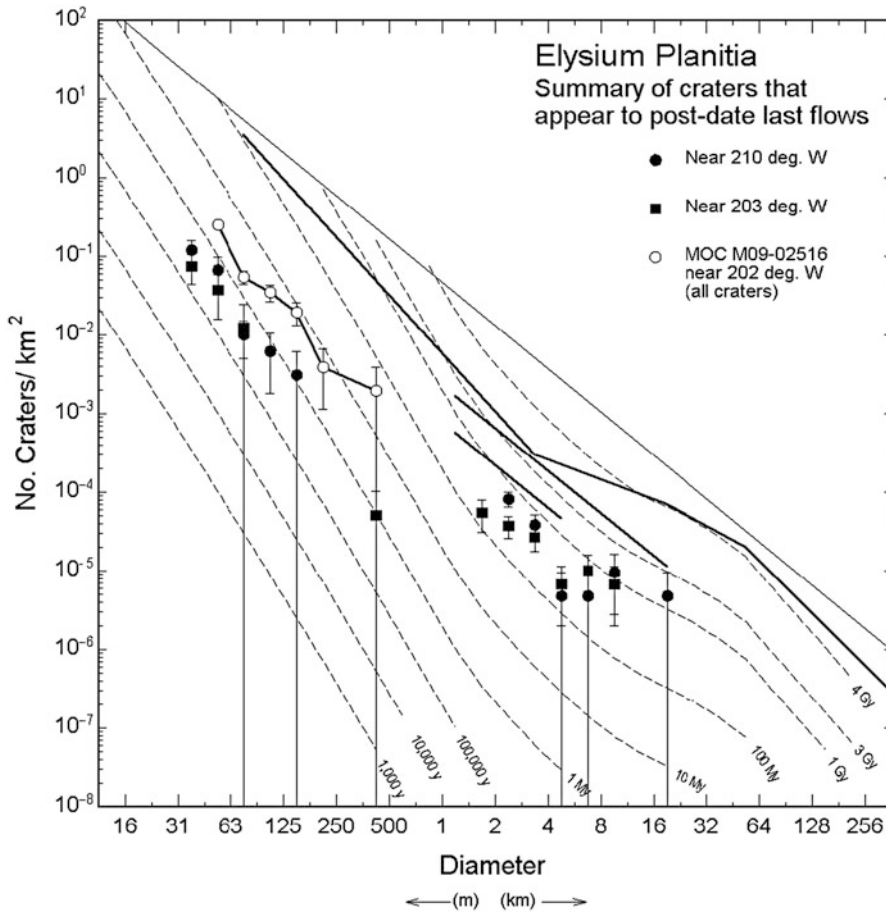


Fig. 8 Crater counts in Elysium (Data from Hartmann and Berman (2000), reproduced with permission). *Dashed lines* are isochrons (1,000 years, 100 Myr, etc.). *Inflected bold line* marks onset of saturation equilibrium (where

crater density is such that each new crater erases a preexisting one and accurate ages can no longer be derived). Two smaller *bold lines* define boundaries of the Amazonian, Hesperian, and Noachian (*bottom to top*)

functions (PF) would both suggest (König et al. 1977; Moore et al. 1980; Wilhelms et al. 1987; Neukum et al. 2001; Ivanov et al. 2002). As this departure from the PF has become steadily clearer, a number of changes to isochron shape have resulted (Berman and Hartmann 2002; Hartmann 1999, 2005), depressing the isochrons at small crater diameter by a factor of 10 to remain consistent with the SFD observed in these deposits, the latest iteration of these isochrons now “...a much better fit between the isochron shapes and SFDs on young, pristine plains of Mars” (Hartmann 2006)⁹.

⁹The latest change to the isochrons involves a correction for the loss of small cosmic projectiles in the martian atmosphere (the “Popova effect” (see Hartmann 2005)). This issue is considered in more detail in Addendum: “Isochrons, diachrons, and landform identification”.

In this interpretation, each point in Fig. 8 is connected by an assumed uniformity of process, specifically the build-up of a stack of lavas over 100s of Ma (Hartmann and Berman 2000; Hartmann and Neukum 2001). The idea is that craters formed at different times all follow the distribution defined by these isochronal lines, but it is clear from the spread in the plotted data that surfaces of widely different age are being sampled, the age-averaging effect of counting on surfaces formed over such a long time period apparent in the resulting crater SFD, which does not follow any single isochron but cuts across them at a shallow slope, yielding an age range of a few-100 ka to a few Ga (the aforementioned temporal composite covering many geological horizons and time periods)¹⁰.

The difficulty with an isochron that includes all of the craters created over a 100 Ma or 1 Ga period is that it is almost guaranteed to sample multiple surfaces (no terrestrial geological structure having a 10^8 – 10^9 -year history). The real issue, however, and the reason for inclusion in this entry, is not chronological but one of landform identification. In its lack of stratigraphical constraint and presumed independence of geology, crater counting can drive our perception of landform origin when dealing with both simple and geologically complex surfaces. Examples of such “simple” surfaces are considered in the case studies of Mars, Mercury and Venus. A fourth, geometrically complex study is presented in the addendum to this entry (*Isochrons, diachrons, and landform identification*).

As suggested earlier, stratigraphical method points to the testable consequences of our inferences, so what can it tell us about the volcanic model described above? The cross-cutting relations of the landforms in this terrain (Figs. 5b and 6) indicate a dynamic, non-lithified substrate rather than solid rock, and a “time gap” between impact cratering and landform genesis that should be reflected in the crater SFD if the assertion of a time-transgressive geology is valid – a consequential assertion that is confirmed by the impact crater distribution in Fig. 9. This figure shows a 20-fold difference in impact crater density between the two surface morphologies in these deposits, as revealed for the first time by HiRISE. The younger of these two surfaces (5 Ma, blue plot) is the polygonal terrain that is host to the post-depositional landforms of Figs. 1c, 5b, 6, and 20 – a 10^8 -year hiatus between formation of

¹⁰The tabulated crater Production Function on the terrestrial planets (a log-incremental SFD representation based on the number of craters/km²) is an assemblage of data selected to represent one specific moment of time (Ivanov et al. 2002): in the case of the lunar reference, the average time of lunar mare surface formation. Here the condition for a synchronous (isochronous) surface is satisfied by the fact that most lunar mare basalt samples have a narrow range of ages (i.e., 3.2–3.5 Ga (Stöffler and Ryder 2001)), the age variation represented by a factor of 1:1. In contrast, the martian reference has a very wide range of ages (i.e., ~200 ka to 2 Ga [Fig. 8]), a 1:10,000 age-variation equivalent to roughly half of the entirety of all geological time. No craters of the size formed by the $D > 40$ km impactor fraction derived from the observed asteroidal PF (Ivanov et al. 2001) are present in this terrain, and the $D < 250$ m craters in this figure lack any defined planetary PF (because the lunar mare are saturated by impacts below this diameter (Hartmann and Gaskell 1997)). This leaves the few-100 m to few-10s of km crater fraction seen in this figure – a distribution whose slope is effectively horizontal.

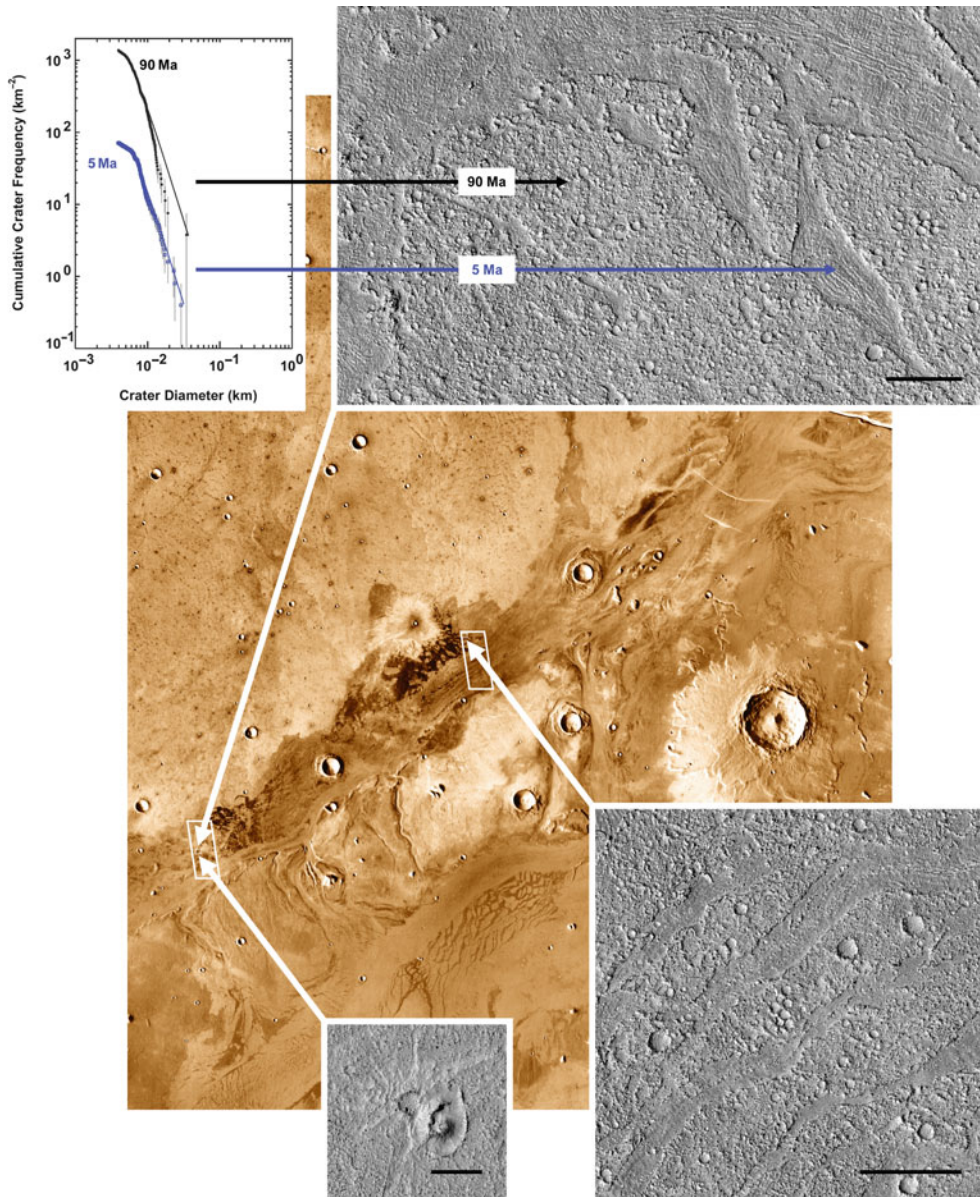


Fig. 9 Terrain in Athabasca Valles showing non-conformity in platy and polygonal, inter-plate terrains. *Insets:* HiRISE PSP_003571_1880 (image as for Fig. 6a) and PSP_003083_1890, 25 cm/px, North to top,

8°N/153°E. Scale bars = 100 m (NASA/JPL/University of Arizona). Background: THEMIS 100 m/px infrared mosaic (NASA/JPL-Caltech/Arizona State University)

these two morphologies that mirrors the relative age gap between cratering and landform growth in Figs. 5b and 6.

Many of the smaller impact craters in this region are thought to be of secondary-ejecta origin, derived from the large primary impact Zunil (McEwen et al. 2005). Such projectiles do not fall randomly but lie in fields centered around the primary crater, posing a significant problem for dating.

The lower velocity of such impacts has led to the suggestion that the age difference in Fig. 9 is more apparent than real, the inferred “material properties” of the substrate limiting crater formation in the lower crater-density regions (Dundas et al. 2010). However, these dm-scale secondaries are readily identified by their well-preserved rays (two examples shown in Fig. 6a, c) and are visibly destructive of surface texture (Fig. 6c), confirming both the post-depositional origin of the landforms that cut them and that substrate properties do not control crater formation. There is thus cause to believe that the majority of the craters on Fig. 9 are of primary origin and that the age difference is both real and robust¹¹.

Such temporal discordance (or *non-conformity*) in the terrestrial rock record signifies a geological-unit boundary, and so it is for Mars also, the division between the surface morphologies in Fig. 9 as clear as could be wished for in remotely-sensed data, being reflected in each of land form, relative-age *and* absolute age. In this case study, I have emphasized the significance of observed relative-age for landform interpretation and derived absolute age. In this, the order of events is plain because of the temporal nature of the inference, reasoning back from present to past (rather than from presumed “cause” to “effect”), landform development postdating impact cratering which itself postdates deposition of the substrate, a system of relative-age-based inquiry that anticipates – and finds – absolute-age confirmation in the highest-resolution crater counts now available from HiRISE.

Interpreting an Image Stratigraphically

In the previous section, we saw how the relative-age observations of deposit geometry and small-crater distributions can be brought together to determine geological history. However, this is not to suggest that spatial resolution at any given time is the principal determinant of geological understanding (e.g., Zimbelman 2001). Indeed, it is the simplicity of relative-age observations that makes these largely independent of image resolution, with many of the observations described in this account equally apparent at regional scales or in lower-resolution imagery. One such “low-level” stratigraphical observation of the polygonized terrain across Elysium-Amazons is shown in Fig. 10.

This figure moves to eastern Amazonis Planitia to show the same platy, polygonal terrain in vertical section. Two stratified deposits of polygonally patterned ground are seen stacked one upon the other, courtesy of a number of erosional voids or “windows” in the topmost unit. The underlying stratum

¹¹In this respect, it is notable that where the terrain over Fig. 9 is bulk counted as a relatively homogenous stratigraphical unit (Hartmann and Neukum 2001), the derived SFD cuts across the isochrons (Fig. 8); where it is counted on the basis that it is a single lava-flow surface of uniform age (Dundas et al. 2010), the crater population on half of the visible surface must be discarded; where it is counted as the separate units indicated by relative-age, the SFD is steep and without any roll over, in agreement with the asteroidal and lunar SFDs.

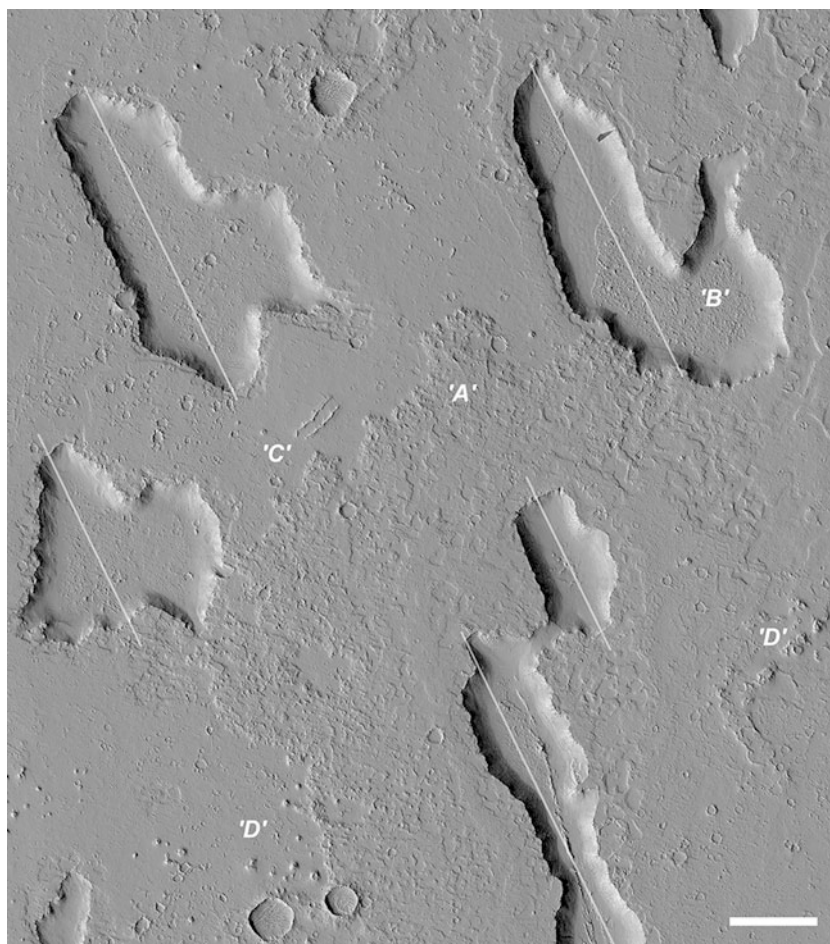


Fig. 10 Erosional voids in Amazonis plain. Ridged, polygonally patterned terrain (“A”) in upper unit, also visible (through voids) in lower unit (“B”). Yardangs (“C”), pitted cones (“D”). Note consistent NNW-SSE

alignment of voids (strike marked in *white*). HiRISE PSP_002712_1925, North to top, 25 cm/px, 13°N/204°E. Scale bar = 500 m (NASA/JPL/University of Arizona)

visible through these voids displays all of the characteristic landforms of this terrain: the ridged, platy rafts, polygonal, inter-plate regions, and the pitted cones (cf. Figs. 1c, 5b, 6, and 9). This same landform assemblage is also present in the overlying unit, indicating that both deposits are the same¹², a circumstance that allows us to place further constraints on landform origin as a result of this deposit geometry.

Deposition of the underlying unit in Fig. 10 clearly predates that of the overlying one (*the principle of stratigraphical superposition*), thus void formation in the upper unit cannot be related to emplacement of the lower unit. Neither can these voids be collapse features, as such features would still

¹²A frozen-oceanic origin for this terrain is not readily explained by these stratigraphical observations, as the floating, platy “pack-ice” element of such a water body would be confined to its uppermost surface, not repetitious and stratified to depth, as in Fig. 10.

contain the collapsed material, whether that collapse occurred during emplacement of the overlying unit or much later. Although a structural control on void formation is a possibility, there is no consistent subsurface lineament that would act as its locus. Moreover, while such a control could affect the orientation of these features, it is hard to see how this could also affect their uniform shape. The voids must therefore be erosional, an aeolian control on their formation suggested by the consistent NW-SE alignment of these features, their long axes perpendicular to the katabatic winds that descend from Olympus Mons, 800 km to the NE (Spiga and Forget 2009). An origin as “deflation hollows” formed by wind scour of unlithified sediment is further suggested by the yardangs aligned parallel with the southwesterly wind current from this large topographical high. Wind can abrade but not quarry rock (Smithson et al. 2002) and rocks do not simply dissolve into thin air, so this terrain, covering 50,000 km² of the surface west of Olympus, must be sedimentary in origin, such degradation consistent with the unconsolidated, particulate substrate inferred from deposit geometry (Figs. 5 and 6).

Testing Stratigraphical Method and Hypothesis Generation

Our stratigraphical observations of polygonized terrain at the martian equator have revealed widespread vertical and lateral time-transgressive activity in these deposits, the surface populated by intrusive, late-stage landforms (Figs. 5b, 6), varying in relative-age over short distance (Fig. 9), and suffering regional-scale deflation (Fig. 10). Collectively, these observations speak of a particulate, volatile-rich substrate that is active on geologically recent timescales¹³.

For the geologist, these temporal observations indicate a non-lithified substrate across this region. However, there are many facets to planetary scientific inquiry, and others would draw attention to the visual similarity of some of these landforms to lithified lava surfaces or the basaltic spectral signal that is returned from these deposits (see later section “[Spectral Mapping of Planetary Landforms and Geological Units](#)”). What then distinguishes stratigraphical observations from those that a non-geologist might find more compelling or straightforward? Indeed, could these collective observations be no more than the self-consistency and confirmation biases that affect form-analogical methods of inquiry? The answer is that stratigraphical observation always suggests its own test.

Recall that the unconsolidated substrate in Fig. 10 contains the same conical landforms as Figs. 1c and 6a, supporting the active, non-rocky origin for these landforms suggested by deposit geometry, the age relations of

¹³Given the volatile-rich substrate suggested by the landform assemblage in these deposits, it is distinctly possible that the voids are ablation hollows rather than simple deflation hollows.

those landforms pointing to the action of intrusive ground ice. If true, then these same conical landforms should also occur in other particulate, volatile-rich terrains on Mars. One such terrain, uniformly agreed to be of unconsolidated, ice-rich origin are the Viscous Flow Features (VFF) that occur on south-facing crater walls in Mars' southern hemisphere (Milliken et al. 2003).

Looking here (Fig. 11), we find the same post-depositional cones with surrounding hexagonal moats seen in Fig. 6a. These identical conical landforms at the equator and in the southern highlands converge not only in form but also seemingly in process of formation given that both show secondary age-relations to the substrate. As such, only one of the competing hypotheses of cone genesis at the martian equator (Fig. 1) can be correct. Do we propose that the impact crater in Fig. 6a (reproduced here as Fig. 11c) deflected around this conical landform (Jaeger et al. 2008) and that the surrounding hexagonal rims are tilted lava plates (Keszthelyi et al. 2010) when these same landforms and age relations are found in icy deposits on crater walls in the southern highlands, or do we recognize these for the active landforms on a young, dynamic substrate that deposit geometry shows them to be?

Such eliminative induction is ideally suited to the unknowns of remotely sensed geology, but little furthers planetary science if it never reaches any conclusion regarding origin. The conical landforms at Mars' equator have been suggested to be intrusive frost mounds (or "pingos") based on analogy to cold-climate landforms on Earth (Burr et al. 2005). Their discovery within icy viscous-flow features provides further support for this hypothesis, their position at the distal front of such features providing the hydraulic head for pingo genesis, the material forming the VFF inferred to be a potential source of the water that carved the gullies observed to cut such viscous flows (Milliken et al. 2003).

So far we have seen how individual landforms can be analyzed stratigraphically. The method may lack the appeal of an encompassing genetic hypothesis but it is strictly objective. Such hypotheses as a result along the way (e.g., the intrusive-ice origin suggested by the age relations) may alter with new data, but the relative-age observations that are their basis should not. In the next section, we take a lower-resolution (kilometer-scale) look at the stratotypic area of Mercury's Caloris basin, showing how the same basic stratigraphical principles allow us to build up a detailed view of events there.

Age Evidence for Late-Stage Volcanism on Mercury

Since the Apollo-era discovery that the Cayley plains on the Moon are impact ejecta rather than volcanic, a major issue in planetary geology has concerned the relative importance of volcanism in plains formation (Strom et al. 2008). *Messenger* mapping is suggested to have resolved this debate for Mercury, differences in the numbers of craters superposed on the rim of the hemisphere-sized crater Caloris and surrounding plains showing the latter

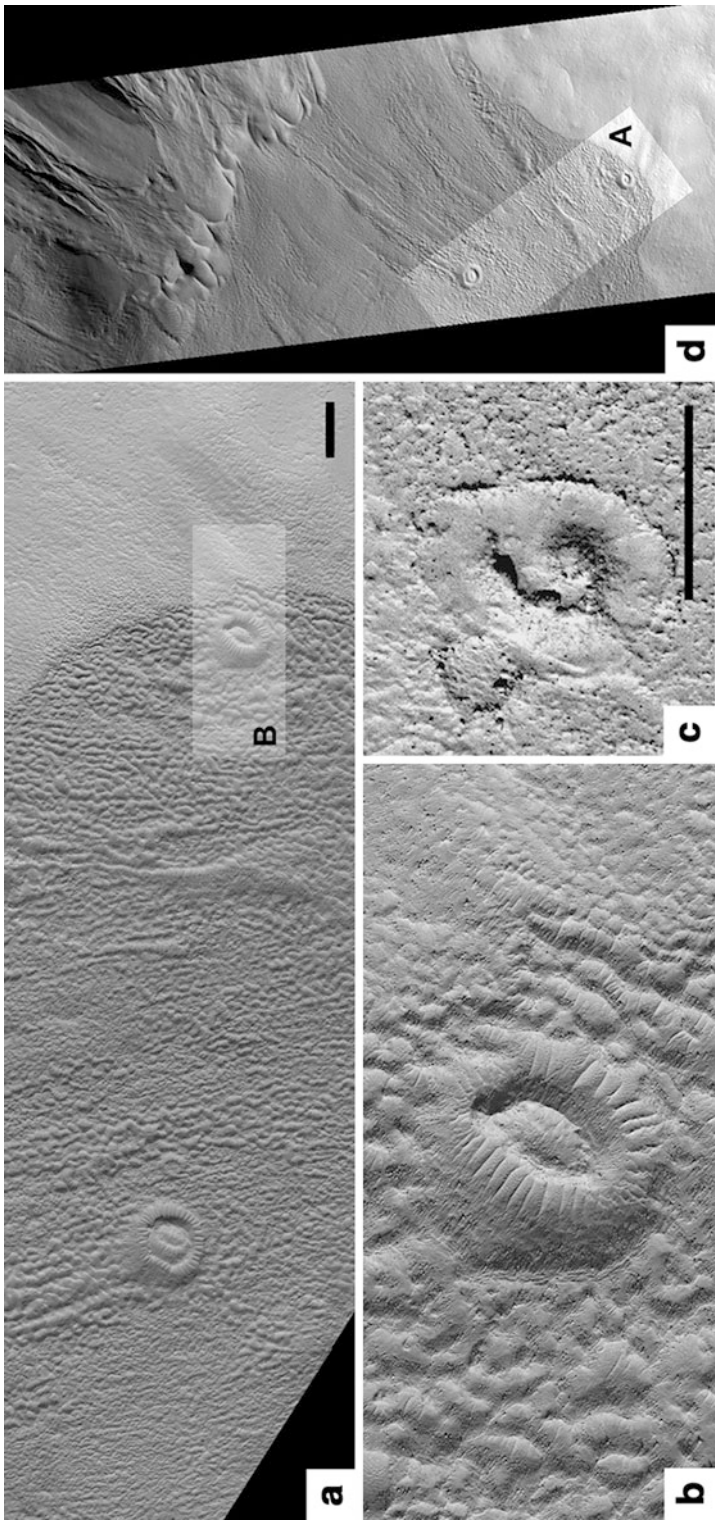


Fig. 11 (a) Cones formed within Viscous Flow Feature in south-facing crater (context **d**, at *right*), cf. Fig. 6a (reproduced here as **c** for comparison). (b) Detail of rightmost cone of (a). Context frames oriented NNW toward solar illumination, showing these cones to be positive-relief features within a hexagonal, raised-rimmed “moat,” just as for the cone of (c). HIRISE PSP_007499_1385, 25 cm/px, scale bars = 100 m. 41.4°S/196°E (NASA/JPL/University of Arizona)

to be younger, and thus not impact related (Fassett et al. 2009). In common with the Mars case study, the landforms of the circum-Caloris plains are inferred to be the product of plains-forming volcanism. Yet, long-standing doubts remain about the volcanic origin of Mercury's surface based on the lack of obvious constructional landforms, such as shield volcanoes, and non-lunar bulk composition (Wilhelms 1976), bolstered more recently by Fe-poor compositional measurements (Solomon et al. 2008), and one of the major goals of *Messenger* is to investigate the history of volcanism on Mercury (Head et al. 2007).

The Mars case study emphasized the need for stratigraphically controlled impact crater counts prior to their use in landform identification. The point – and relevance for Mercury – is that the meaning of a crater count depends on where (and on what basis) we draw geological Unit boundaries. The Caloris basin and surrounding Odin plains are described by *Messenger* investigators as “...a chronostratigraphical marker for the geological history of Mercury” based on the number of superposed impact craters (“...the primary argument that the Odin Formation was not emplaced as ejecta from Caloris coming from crater size-frequency data” (Fassett et al. 2009)). A study of deposit geometry here, in an area of the stratigraphical column where origin and chronology are both uncertain, is thus useful.

Figure 12 (from Fassett et al.) shows the Caloris impact basin in context, with type examples of Caloris Group materials arranged radially, B-F, from proximal rim/montes (B) to distal secondary ejecta (F). While the nature of these surfaces was determined during *Messenger* fly-bys and will become clearer during the upcoming, higher-resolution orbital phase, it is fortunate that it is the middle section of Caloris stratigraphy (“D,” orange) whose origin is at question, as the bounding of this unit suggests the investigative path. The Caloris stratigraphy is summarized on the following page, younging outward and bottom to top, uncertainty regarding the nature of the Odin Formation notwithstanding:

As the existence of *cn* and *co*, *m* as discrete entities (separate from *co*) is debated, we can narrow this stratigraphy down to ***cm***, ***co***, and ***cvl-cvs*** (i.e., the proximal rim/montes, medial circum-Caloris plains, and distal radiating ejecta sculpture/secondaries, respectively), i.e.,:

3. ***cvl-cvs*** (Van Eyck Formation: distal ejecta [“E”-“F”])
2. ***co*** (Odin Formation: circum-Caloris plains; medial ejecta OR lava plains [“D”])
1. ***cm*** (Caloris Montes Formation: impact crater rim; proximal ejecta [“B”])

This simplified sequence presents the Caloris stratigraphy from the impact center out (1 → 3, B → F). The impact status of “1” and “3” is known, with the impact/lava origin of “2” uncertain. However, impact crater formation is a geologically instantaneous event (*the principle of original continuity*), so the geometry of the various deposits can provide a stratigraphical test of landform

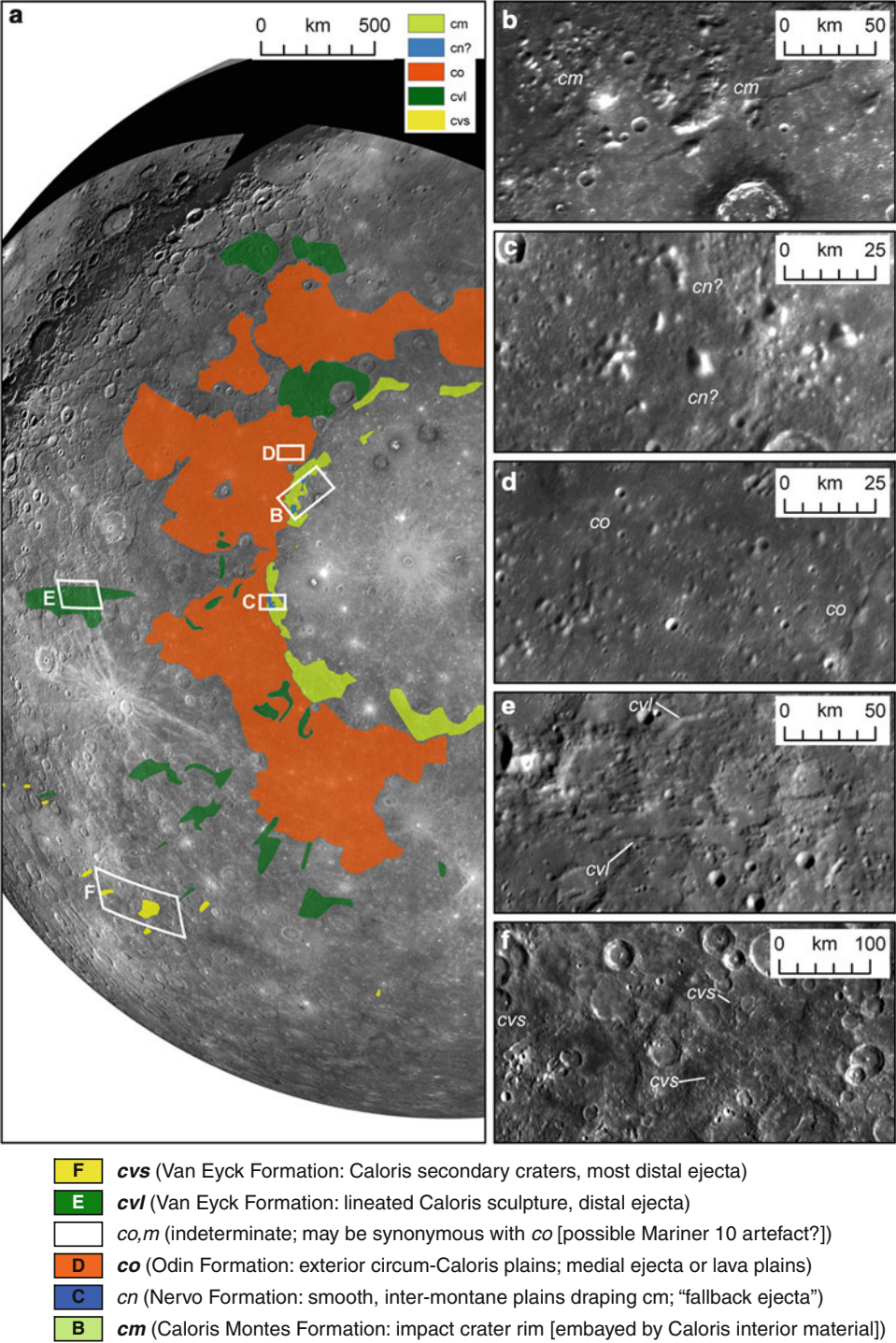
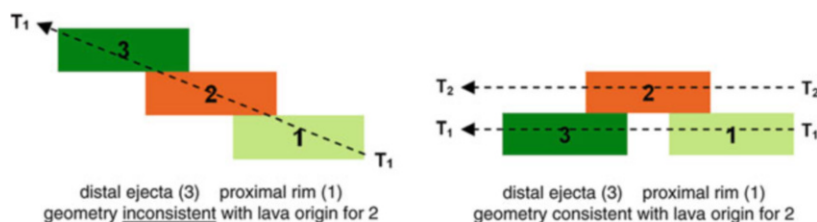


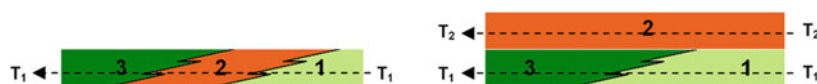
Fig. 12 Context map of distribution of Caloris Group materials (a) and Type examples (b–f) from *Messenger* data (From Fassett et al. (2009), reproduced with permission). (b) Caloris Montes Formation (*cm*); (c) Nervo

Formation (*cn*). (d) Odin Formation (*co*). (e, f) Van Eyck Formation: lineated (*cvl*) and secondary crater facies (*cvs*). Unit legend above (note that legend is only stratigraphical insofar as it has been established by crater counts)

origin *independent* of the chronology of superposed craters. Thus, if 2 is post-impact lava, then it should nowhere be overlain by the distal ejecta facies of 3, as in the block graphic below left, as 3 is impact related and structurally distinct from all other terrain. Similarly, if 2 *is* impact related, then the whole sequence should young outwards, showing a linear progression of overlaid units, proximal to distal.



This “building-block” stratigraphy is an obvious oversimplification, most geological deposits grading into one another laterally, as in the block graphic below. The intent here is not to offer a particular view of Caloris structure but to illustrate by stratigraphical means what is possible in terms of landform origin. Thus if deposits “1” and “3” are related along time T_1 at left (e.g., by impact), then “2” cannot have been formed by a different process (e.g., by volcanism). By the same token, where geometry is different, as in T_1 and T_2 at right, then these different processes *are* possible. In this relative-age respect, one detail of the Caloris mapping of Fig. 12 stands in support of the proposed volcanic origin and will be returned to after the following discussion of the crater-mapping data.



If one surface has a much lower impact crater density than another, then the question of where to draw the geological lines between them might seem to be a minor one, particularly where related to an obvious division like the Caloris rim. However, one aspect of the count data associated with Fig. 12 is significant, both in terms of the counts and the geological mapping that is based upon them. Fassett et al. present counts for the Caloris rim, outer (and inner) plains, and distal ejecta facies (i.e., “1,” “2,” and “3” in our simplified stratigraphy), re-plotted here as Fig. 13. Whilst it is to be expected that the inner plains (Fig. 13a, blue trace) are younger than the basin that they fill, let us explore the evidence presented for the assertion, now widely held, that the outer Odin plains (“2,” *co*, Fig. 13b orange and black traces) are younger than Caloris’ rim.

We again simplify stratigraphy by concentrating on the counts of the Caloris rim and Odin Formation (the lime-green and orange plots in Fig. 13a, b, respectively [“1” and “2” in our block graphics]).

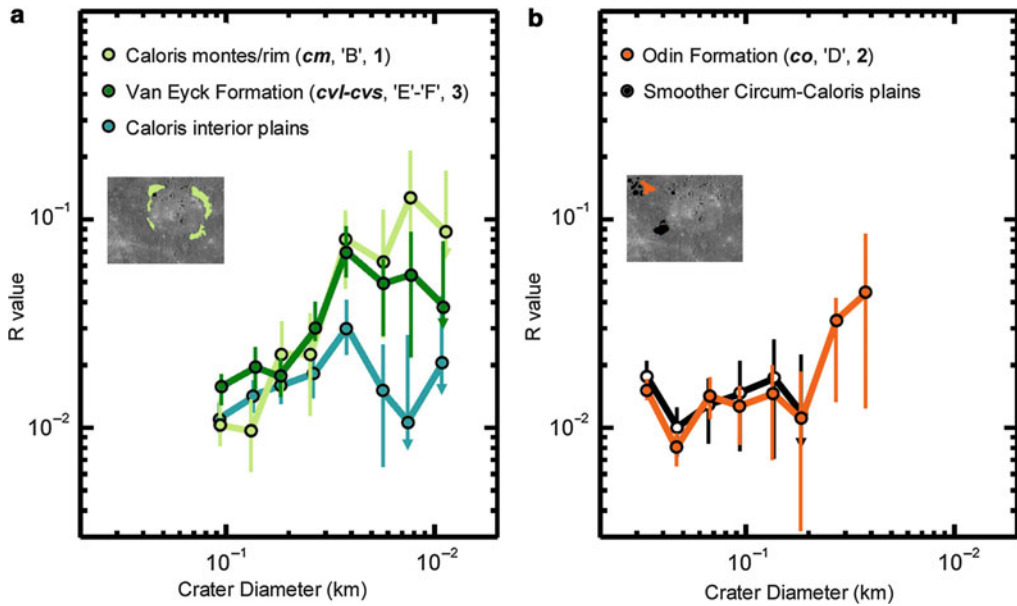


Fig. 13 Count data (R-plots) of various Caloris Group materials of Fassett et al. (2009). (a) Counts for Caloris rim (Caloris Montes Formation, lime-green), sculpted ejecta (Van Eyck Formation, dark green), and interior plains (blue). Count area of Caloris Montes inset. (b) Counts for

Odin Formation (orange) and smooth plains (black), the “knobby” and “smooth” facies respectively of the circum-Caloris Plains. In both cases, plot colors match those of the block graphics in preceding text. Count areas of Odin Formation and smooth-plains inset (Figures by author)

For both plots, the SFDs overlap or fall within the error bars at all diameters common to both units. For instance, at the minimum and maximum crater diameters common to rim and plains (i.e., $D = 10$ and 40 km, Figs. 13a, b), crater density is similar, 10^{-2} km² and 10^{-1} km², respectively, a similarity that is even clearer when rim and plains data are presented on the same plot (Fig. 14a). Figures 13 and 14a show that the craters on the Caloris rim extend to larger diameters than those in the surrounding plains, ~ 100 km vs. 40 km (Fig. 13a, cf. Fig. 13b), and it is these larger, less-frequently formed craters that are more significant for age determination, supporting the asserted age difference. Yet it is here that the “where” of drawing geological boundaries comes into play. As Figs. 15 and 16 show, the large crater Raditladi ($D = 250$ km) occupies the plains region between the two plains count areas (of Fig. 13a). Fassett et al. draw the SW boundary of the Odin Formation along the margin of the Raditladi ejecta blanket (Figs. 12a, 15 and 16b), but as the high-resolution MDIS mosaic of Fig. 16c reveals, the secondary crater clusters radiating out from Raditladi cross these plains. While the boundary of the Odin Formation has been drawn to exclude these ejecta, this superposition clearly indicates that formation of this large impact crater *postdates* emplacement of the plains, an exclusion with implications for derived age and the geological history of the Caloris basin.

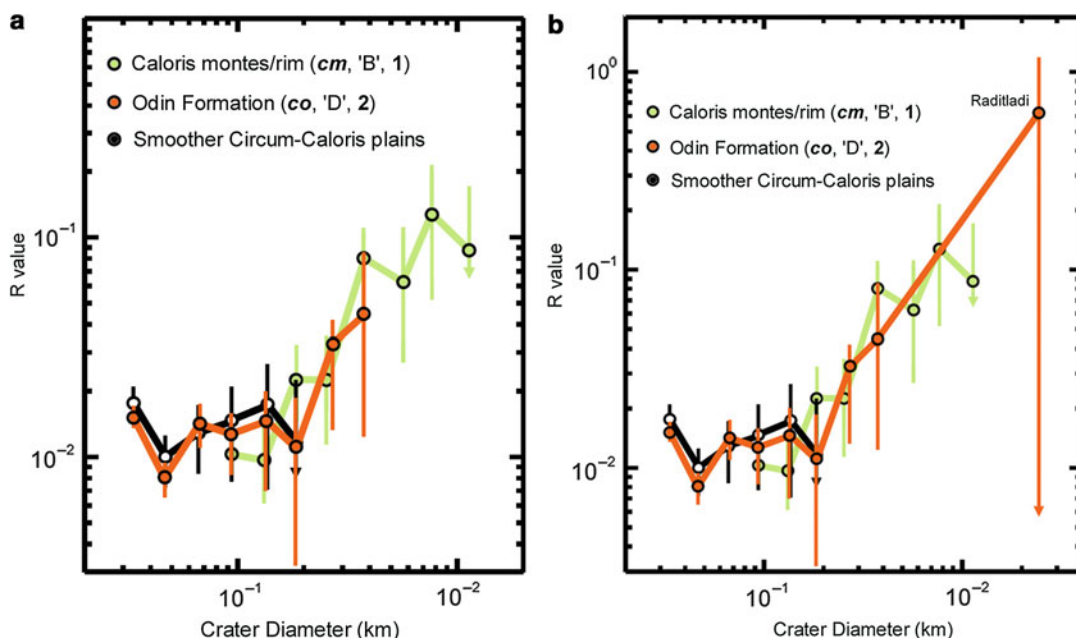


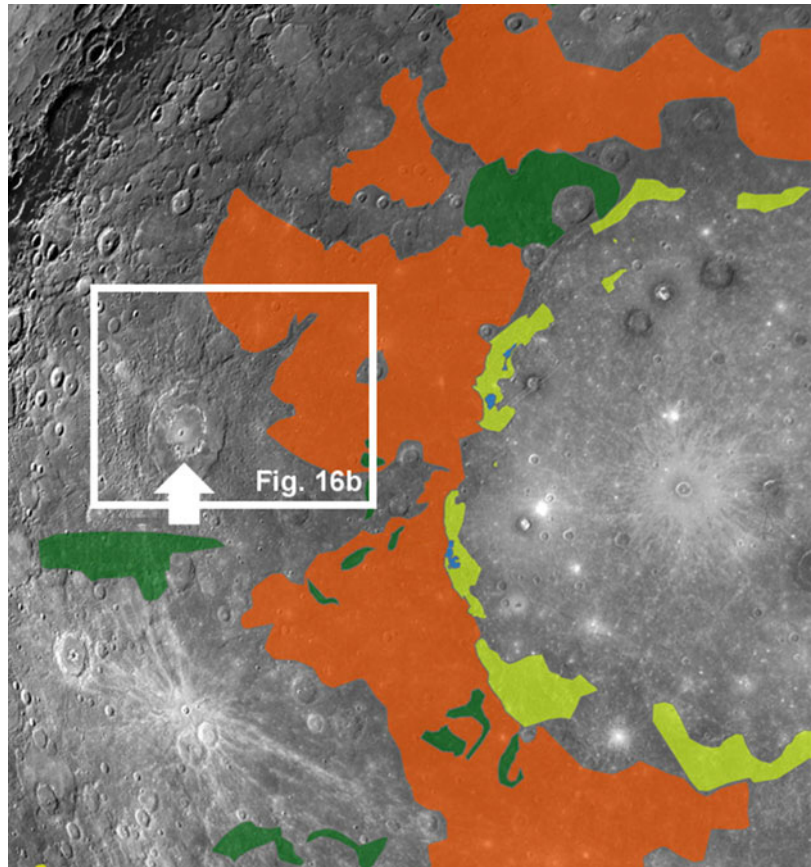
Fig. 14 (a) R-plots from Figs. 13a, b (Caloris Montes and Odin Formation) overlaid. (b) R-plot of (a) extended to include Raditladi ($D \sim 250$ km) in count – see text for

explanation. Vertical lines through each point on plot are error bars (those where the bin contains a single crater are denoted by an arrow, e.g., Raditladi) (Figures by author)

To visualize what this means for derived age, we can extend the Fig. 13b count by adding this 250 km crater to the data¹⁴. Figure 14b shows the result of adding Raditladi to the R-plot of Fig. 14a, the age for the count area at $D > 100$ km now *greater* than for the Caloris rim (equally apparent when plotted cumulatively, where the SFD at $D > 100$ km is between 10^{-4} and 10^{-5} km², greater than the 10^{-5} to 10^{-6} km² of the Caloris rim). Whilst one might question the chronological significance of a single (albeit large) crater, the assertion that one terrain is younger than another effectively rests on *not* counting such craters, and, as Fig. 16 shows, the boundary of the Odin Formation is mapped to exclude that part of the plains bearing the ejecta from this crater. One possible reason for excluding Raditladi is the uncertainty surrounding its absolute age, its size suggesting that it is very old (forming at the end of the Late Heavy Bombardment, >3.8 Ga). Yet, the order-of-magnitude lower crater density (than the circum-Caloris plains) on

¹⁴Extending the count area by the area of the Raditladi crater and ejecta blanket ($\sim 200,000$ km²), and using the production and chronology functions for Mercury of Ivanov et al. (2001) and Neukum et al. (2001). The Odin Formation is composed of dense areas of km-scale knobby terrain surrounded by smooth plains (orange and black plots, Fig. 13b). The crater SFD in these two regions shows no statistically significant difference in crater density at $D < 22$ km, and Fassett et al. (2009) map these as the same geological unit. As such, Raditladi may be added to the counts of either smooth or knobby terrain, the decision made to add this crater to the latter (Fig. 14b).

Fig. 15 Context map of Caloris basin and Odin Formation (detail of Fig. 12). *Raditladi* arrowed



its floor and ejecta suggest that it is anomalously young, formed within the last 1 Ga (Strom et al. 2008). However, whether young or old, this crater must be included in the counts because its ejecta cross the Odin Formation, this Formation therefore at least as old as this crater. As such, the age data that show the Odin plains to be younger than the Caloris rim – and the principal evidence for a volcanic, non-impact origin – now become less clear.

What else do the relative-age observations of stratigraphy say here? As suggested previously, one detail of the Caloris mapping (of Fig. 12) stands out – that the sculpted ejecta of the Van Eyck Formation (*cvl*, “3,” “E,” dark green) is repetitious, bounding the Odin Formation (*co*, “2,” “D,” orange) on both sides, as shown in Fig. 17a. Note that this geological repetition is observed (Fig. 17b), not simply inferred from the crater SFD. This geometry is consistent with an unrelated (lava) origin for *co*, one deposit overlying another, as in the right-hand graphic at T_1 – T_2 . As mapped in Fig. 12, the spatial arrangement of these deposits argues against a uniform (i.e., ejecta) origin for the whole, supporting the conclusion of a later-formed lithology. It remains the case, however, that the boundary of the Odin Formation is drawn to omit an age-significant object based on inferred absolute age, an

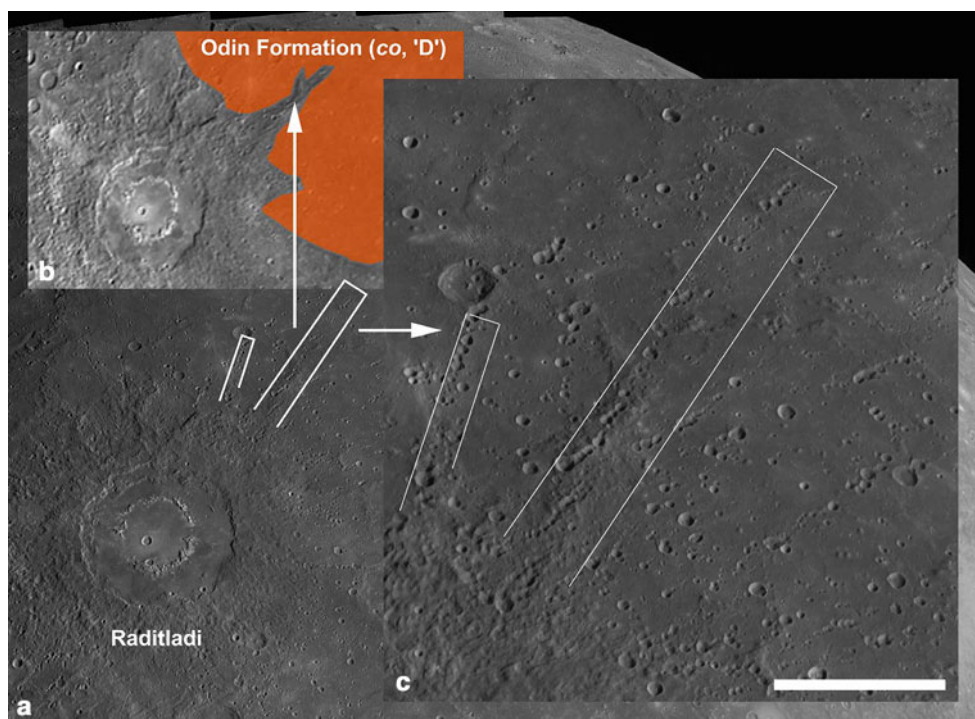


Fig. 16 Secondary ejecta from Raditladi impacting smooth plains of Odin Formation, “B” (thus postdating the plains), the surface geology (“C”) no different within

or without mapped unit boundary. Scale bar = 100 km (Image: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington)

unnatural unit boundary without apparent reflection in the geology of the surface cratered (Fig. 16c).

Figure 16 illustrates another aspect of the relative-age utility of impact craters (cf. Fig. 5) and how such use differs from a crater count. Thus it is not the SFD of the secondary craters that cross the plains in this figure that is significant, but the observation that they *do* cross these plains: a clear indication of relative age that is more useful in deciphering geological history than aggregate “absolute” ages based on bulk counts and model isochrons – a true isochron in the geological sense that makes Raditladi younger than the Odin plains that its ejecta superpose. That it is secondary-ejecta that give the age relation (where such craters are often regarded as “contamination” (McEwen et al. 2005; Plescia 2005b)) only emphasizes this point. While the non-uniform production of secondary craters (i.e., ejecta from a primary impact elsewhere on the surface) precludes the 1:1 correspondence of crater density with absolute age (unlike primary craters (Strom et al. 2008)), this is not the case for *relative*-age – a discrete, geometrical observation of the age relations of an impact crater, relative to the substrate, that is independent of the source, nature, velocity, or size of the impacting projectile.

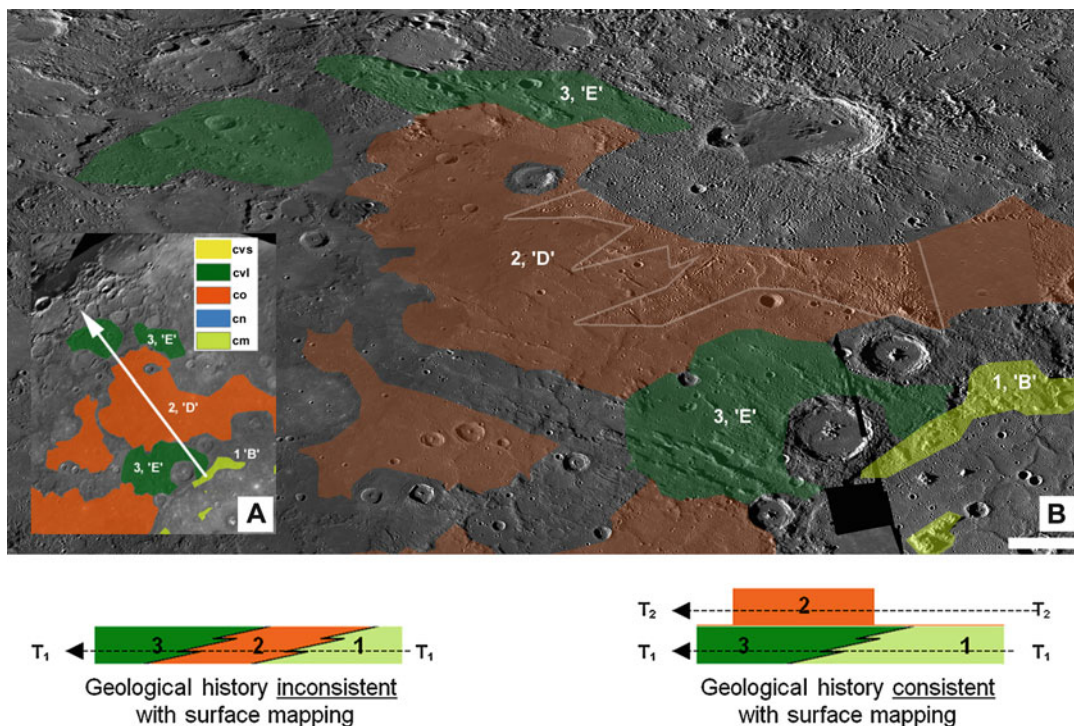
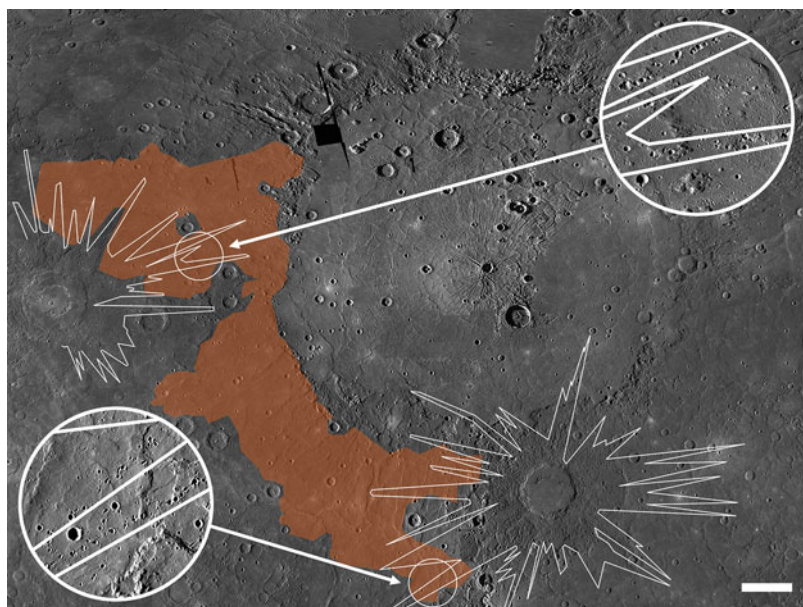


Fig. 17 (a) Northwest margin of Caloris basin from Fig. 12 with path of Caloris ejecta indicated by arrow. Note repetitious stratigraphy (i.e., 1,3,2,3), inconsistent with impact origin for "D" ("2," co, orange). (b) Perspective

view of terrain in 250 m/px *Messenger* MDIS imagery showing mapped units related to surface. Secondary ejecta chains from large crater at upper-right crossing Odin Formation (2, "D") highlighted. Scale bar = 100 km

Because planetary scientists cannot map geological boundaries stratigraphically (by observed differences in lithology), mapping by crater SFDs across surfaces of varying morphology has become the norm, acting as a proxy for relative-age. However, we must under such circumstances allow the boundary to go where the combined observations of land-form and crater density lead – if we permit the boundary to avoid (or the counts to ignore) objects of clear age significance, such as Raditladi, then such boundaries lose any geochronological significance that they might otherwise have had. Consider then that there is another, equally large crater (Mozart, D 225 km) superposed on the southern rim of Caloris whose ejecta also cross the Odin Formation, both as mapped in eastern Caloris by Mariner 10 and in the west by *Messenger* (Fig. 18). While we might conceive of one large and anomalously young impact event (Raditladi) occurring within the vicinity of Caloris in geologically recent times, a second such event (Mozart) is harder to justify. Thus, while there is some stratigraphical justification for a later-formed deposit in the plains between the repetitious outcrops of Van Eyck Formation to the NE of Caloris (Fig. 17), the crater SFD arguments for the existence of such a deposit are only valid insofar as the boundary of the Odin Formation is allowed to avoid any large craters (or their ejecta) that would make that

Fig. 18 Secondary ejecta from the craters Raditladi (upper-left) and Mozart (lower-right) crossing plains of Odin Formation, these large craters therefore postdating these plains. Orange stipple between these two craters shows southerly mapping of Odin Formation of Fassett et al. (2009), 250 m/px detail of secondary-crater chains inset. Scale = 200 km



Formation older. Yet another such ($D \sim 200$ km) crater is evident in Fig. 17b, its ejecta reaching from one side of the Odin Formation to the other¹⁵.

So where does this leave us in our quest to understand the origin (and age) of the deposits surrounding Caloris? On the one hand, the crater-SFD evidence of a later-formed lithology is supported by observations of repetitious impact stratigraphy to the NE (Fig. 17). On the other hand, the presence of ejecta chains from three 200-km-scale impacts crossing the circum-Caloris plains (Figs. 16–18) argues against the possibility that these plains are very much younger than Caloris. In this respect, there is a lack of consensus among the various *Messenger* mission papers regarding the nature of the Odin Formation. Fassett et al. (2009) come down on the side of volcanism, based on crater distributions, whereas Murchie et al. (2008) see “...an outlying darker annulus consists of rolling ejecta deposits (the Odin Formation), which grade into radially lineated plains and overlapping secondary craters.” Head et al. (2009) describe how the density of craters on these plains indicate that they were emplaced after Caloris formed and are “...not contemporaneous ejecta,” Strom et al. (2008) detailing how the circum-Caloris plains “...exhibit a crater density ~ 40 % less than on interior plains and are thus volcanic and not Caloris impact ejecta.” In contrast, Denevi et al. (2009)

¹⁵There is no sign that any of the Odin-crossing secondary ejecta chains radiating out from Raditladi, Mozart, or the unnamed crater in Fig. 17b are embayed by later deposition anywhere along their length, questioning whether there has been any post-Caloris resurfacing. Any resurfacing thick enough to mask the crater SFD of the underlying Caloris ejecta would be thick enough to bury these much-smaller secondary craters. Thus these secondary-crater chains and the large impacts from which they are derived must postdate the Odin plains.

describe the Odin Formation as ejecta, as inferred from albedo, color and spectral-reflectance data.

Historically, Mariner 10 observations noted the concentric alignment of the Odin “knobby” facies with the Caloris rim, Schaber and McCauley (1980) and Greeley and Guest (1983) considering this facies to be basin ejecta mantled by plains materials. Areas of lunar Cayley plains (of presumed volcanic but confirmed ejecta origin) also display younger ages than adjacent basin ejecta (Wilhelms et al. 1987), only adding to the difficulty of terrain identification by crater counts. Although some consider the “Caloris Question” to be settled, stratigraphical analysis indicates that there is much still to know here in regard to both origin and age, particularly if the deposits of the Caloris Group are to serve as the planetary age-referent in the way that the deposits of the Elysium plains have on Mars.

As on Mars, Mercury illustrates the point that the meaning of a crater count depends where (and on what basis) we draw unit boundaries, in the latter case the most relative-age-significant objects not part of the chronology – or the mapping based upon that chronology (a choice to exclude craters that can produce different results from the same data (Chapman 2011))¹⁶. Stratigraphical principles illustrated geometrically (Figs. 4 and 17), by crater/landform relations (Figs. 5, 6), and by the examples of Olympus Mons (Fig. 7), Elysium (Fig. 9), and Raditladi (Fig. 16) all show that calculated absolute-age should be grounded in observed relative-age if landform identifications and derived ages are to be robust. In a remotely sensed environment, absent ground truth, this is the most objective way to interpret geological units and the various landforms that are their surface expression.

Tectonic Mapping of Planetary Surfaces and Landforms

The tectonic study of other planets goes back three decades to the earliest, low-resolution fly-bys of Venus, Mars, and Mercury. Increasing data has allowed these studies to move from the theoretical to the empirical, but reconstructing past tectonic events remains difficult and controversial (Bird 1986). In the Mars case study, we saw how geomorphic analysis of planetary surfaces is limited by the need to identify landforms and terrains as a first step in inquiry (and how stratigraphical observation bypasses this limitation). It is surprising to learn then that this issue also affects tectonic analyses because of the difficulty of determining whether a particular feature or terrain type *is* tectonic in origin. A third case study of

¹⁶The material forming the ejecta of a large crater such as Raditladi is excavated from considerable depth and is no more part of the surface geological unit that it cross-cuts than is an igneous intrusion from below. However, the ejecta of such craters carries unambiguous (and isochronous) age information relative to surrounding geological units that inform map construction. If the decision to include any primary impact in the counts is a matter of choice, however, then it is hard to see how terrain identification by crater SFDs can ever be objective.

the most tectonically studied of Solar System bodies – Venus – considers the use of tectonic methods in planetary mapping, before going on to discuss the variety of tectonic structures found on the planets, moons, satellites, and asteroids of our Solar System.

All but a small number of the thousands of circular, rimmed structures or *coronae* that populate the surface of Venus are of disputed origin, being considered as either of exogenic, impact origin (Vita-Finzi et al. 2005; Hamilton 2005), or endogenic, volcanotectonic origin (Jurdy and Stoddard 2007; Stofan and Smrekar 2005)¹⁷. Because it involves landforms that may or may not be impact related, this dispute is central not just to our understanding of surface chronology but the entire path of venusian geological evolution, most of the material exposed at the surface generally thought to have formed within the last 20 % of Solar System history with a total crater population numbering <1,000 and no significant clues to conditions on the planet during earlier epochs (McGill et al. 2010).

Plains form the dominant terrain type on Venus, constituting ~80 % of the planet's surface with four major classes of tectonic landforms and terrains – volcanic rises, crustal plateaus and tesserae, chasmata, and coronae – forming the residue. The plains are host to wrinkle ridges, ridge belts (or dorsa), fractures and graben, the tesserae occurring both on crustal plateaus and as inliers (i.e., older terrain) within the plains. Tesserae are often cross-cut by at least two sets of ridges or fractures at high angles to each other, these structures truncated at their contact with the surrounding plains, pointing to multiple, temporally distinct phases of deformation. The coronae range up to ~2,600 km in diameter and are considered in the endogenic model to be tectonic constructs formed over thermal plumes in the mantle. The chasmata are large graben structures (fault-bounded subsidence blocks) that form major rift systems, being associated with volcanic rises or cutting across the plains, and a major issue in venusian geology remains whether the various terrain types are globally synchronous or if they formed at different times in different places, as on Earth (McGill et al. 2010).

This divergence of opinion regarding coronal origin drives models of planetary evolution (i.e., Venus either preserves an ancient, impact-accretionary surface or is the site of young, widespread mantle-plume activity) as well as our ability to date surface features by crater counts, the absence of impact craters implied by the endogenic model forming the principal evidence for widespread volcanic resurfacing on Venus, ~500 Ma (Ivanov and Head 2001). While the majority of researchers working with Venus data clearly differentiate between craters and coronae, proposing each to have distinct morphologies and distributions inconsistent with the opposing view (e.g., Stofan et al. 1985, 2001; Jurdy and Stoddard 2007; Stofan and Smrekar 2005, cf. Vita-Finzi et al. 2005; Hamilton 2007), questions remain with both of these interpretations. For instance, why are coronae interiors, on average,

¹⁷A third suggestion is that these circular features are transitional exogenic-endogenic structures, Nikoleava et al. (1986) advancing a process of coronae formation in which impact-weakened lithosphere acts as a source for lava which then mantles the crater.

less heavily cratered (Jurdy and Stoddard 2007) if they are indeed the site of ancient impacts and why do coronae tend to be more densely distributed in and near rift zones (Phillips and Hansen 1994) if they are not endogenic? On the other hand, one must ask why coronae display an SFD consistent with an impact origin (Vita-Finzi et al. 2005) if plume-sourced, the presence of numerous, few-hundred km scale examples within Scarpellini quadrangle pointing to an upwelling scenario early in venusian history without parallel anywhere else in the Solar System.

In *Geologic mapping of tectonic planets*, Hansen (2000) outlines a methodology for making extraterrestrial geological mapping more objective. As in the current account, some of the difficulties intrinsic to the use of crater counts in geological mapping are described and a tectonic-geohistorical method of analysis is advanced. This method is described only in the context of the tectonic planets of its title and is applied only to Venus. The landform selected for this analysis is the *wrinkle ridge*, a compressional-deformational feature produced by the directional stresses applied by later-stage surface movements, a structure well-documented on the Moon and the terrestrial planets beyond Earth.

Wrinkle ridges were first identified on the Moon (Gilbert 1893), where their preponderance in the basaltic lunar mare led to a presumed origin in volcanism (Strom 1972; Watters 1988). Their distribution radial to basin-fills and inferred planetary stress fields, propagation into the lunar highlands and association with extensional graben resulted in the further conclusion that wrinkle ridges are tectonic features, the discovery of comparable landforms on Mars, Venus, and Mercury leading to the identification of tectonically active volcanic facies in each case. This volcanic-tectonic association is seen in the wrinkle ridging and graben collapse within the Olympus Mons caldera of Fig. 7, terrain that is clearly both volcanic and has been affected by tectonism, and similar volcanotectonic terrains are identified in Mercury's circum-Caloris plains and basin interior (Watters et al. 2009a, b).

The presence of circular wrinkle ridges formed over buried impact craters supports an origin in volcanism, reflecting the emplacement, loading and subsequent relaxation of a lava pile (Head et al. 2009). However, the compressive stress field acting on smooth plains is also thought to result from compressional stresses associated with global interior cooling and contraction (Watters et al. 2005). The pattern of graben that cross-cut the ridges within and around Caloris contrasts sharply with the spatial and temporal distribution of tectonic features within and proximal to basins on the Moon, where wrinkle ridges occur in the basin interiors and graben are found outside of mare basins (McGill 1971; Strom 1972). Superposition relationships of lunar graben suggest that they are restricted to the older mare deposits, whereas wrinkle ridges deform both older and younger mare basalts (Boyce 1976; Hiesinger et al. 2003). Cross-cutting relations between ridges and graben in Caloris indicate that extension postdates contraction of the floor, in contrast to the sequence of stresses implied for lunar basins, indicating processes not seen on the Moon (Watters et al. 2009b).

Thus wrinkle ridges can range from primary, syn-depositional features confined to a specific lithology, to secondary, post-depositional features

with local- to planetary-scale formational mechanisms, and this has led to questions over their utility in mapping volcanic units (Goudy 2002). However, as with genetic identification of landforms, this is only an issue if we first classify wrinkle ridges as tectonic and it is their very generality of occurrence that makes them stratigraphically (rather than tectonically) useful. That ridges formed by mantle-driven tectonism are not easily distinguished from those that result from lithology-specific, syn-depositional deformations and basin subsidence in regional-scale deposits is of no consequence if they are treated as stratigraphical-geometrical entities.

Hansen emphasizes tectonic mapping because of a perceived problem with the translation of terrestrial stratigraphical method to the planetary domain, both generally and as articulated by Wilhelms (1990). In advocating this tectonic approach, stratigraphy is presented as the lithological ordering of material geological units to the exclusion of the geometrical principles that define this core element of geological inquiry. Yet, when we speak of the superposition relations of lunar graben, the cross-cutting relations between compressional and extensional features in Caloris, or the chasmata and tesserae that cut across Venus' plains and are cross-cut in turn by multiple sets of ridges and fractures or truncated at their contact with the surrounding plains, we are making *stratigraphical* (i.e., relative-age) assignments that are independent of these landforms' tectonic origin.

As such, Hansen's suggestion that "*...stratigraphic analysis deals mainly with strata in the absence of tectonism*" is at odds with basic geological practice, the observation that a fault always postdates deposition of the strata that it cuts a stratigraphical one (i.e., the principle of cross-cutting relations), and a fault is clearly a tectonic feature. While "*...stratigraphic relations address local stacking of geologic units with older below younger units, and assume original deposition as roughly horizontal*", they principally describe the points-of-contact between those units rather than their stacking, e.g., intrusive deposits, which may intersect other strata at any angle (including vertically). To illustrate this distinction, a study of coronae along chasmata could show whether the former are endogenic by virtue of the fact that intrusive structures will cross-cut underlying strata in reverse age order – a way that impact processes cannot. The allied notion that "*...geometry, no matter how carefully defined, cannot uniquely constrain relative timing*" belies the precise degree to which the relative-age of geological surfaces can be constrained geometrically. Indeed, deposit geometry is the *only* process whereby relative timing may be established, and we need only refer back to the examples of Figs. 5 and 7 to see the unique and unidirectional series of events that is derived geometrically. Stratigraphy is central to *all* geological inference because its principles apply to all geological materials at any scale and are portable to any planet, the crystallization history of minerals in thin-section derived in the same way as the chronology of caldera collapse on Olympus Mons. In its study of the spatiotemporal deformation of such materials, tectonism assumes these stratigraphical principles – it is not distinct from them.

It is true that "*...given two-dimensional remote data sets, it can be difficult to robustly determine the stacking order, and thus unit superposition*", but

this does not admit of the possibility of 3-D geometrical inference from 2-D data. Thus, whether we take an early view of planetary cratering and propose that such craters as in Fig. 5a formed volcanically, or a later one that recognizes their impact origins, there is no doubt that the larger crater predates the smaller – a robust, three-dimensional inference drawn from two-dimensional data (one that does not change even if such craters are later found to form by a third, as yet undocumented process). Superposition concerns more than unit stacking-order and has a subsurface component also, whether visible or inferred.

This distinction between stratigraphical- and tectonic-mapping is not merely a philosophical one, as certain tectonic processes may be confined to a particular period of geological time on different planets (or not present at all, e.g., the absence of large-scale strike-slip faults on Venus), restricting the generality of tectonic analysis as a primary mapping index. For instance, wrinkle-ridging on Venus appears to be the product of just such a temporally restricted (recent) time-frame based on the observation that these structures intersect so few of its randomly spaced impact craters (Hansen 2000). While this youth may be a product of repeated, wholesale resurfacing that obliterates impact craters and wrinkle ridges alike, a tectonic approach to mapping will also be affected by this restriction by only being applicable in terrains of a certain age. That so few of Venus' craters are visibly modified by this resurfacing (McGill et al. 2010) suggests that the tectonism is truly young¹⁸.

This temporal confinement of tectonic processes has a spatial component also, the large impact craters Caloris and Raditladi host to the only known extensional tectonic features on Mercury (Strom et al. 1975; Melosh and McKinnon 1988; Watters et al. 2005), as represented by a complex of cross-cutting circumferential wrinkle ridges and radiating graben. The age relations between ridges and graben are consistent in both eastern and western halves of the Caloris basin; where the two types of features intersect, wrinkle ridges are always cut by, and thus predate, the graben. The rim of concentric massifs forming Caloris' rim is not cut by these graben, the latter obscured by the crater rim (Murchie et al. 2008). These collective age relations indicate that graben formation postdates the ridged plains and that the Caloris impact event postdates the graben, a geological history (summarized below, 1–3, oldest to youngest) that questions why extensional features on Mercury that predate (thus are unrelated to) impact are nevertheless restricted to large impact basins.

1. Compressional deformation of plains, forming wrinkle ridges
2. Extensional deformation of ridged plains, forming graben
3. Formation of Caloris, obscuring graben

¹⁸Unless most coronae are actually ancient and/or tectonized impact craters, in which case tectonism has been ongoing throughout venusian history (the aforementioned temporal-restriction of wrinkle-ridging likewise affected by the endogenic/exogenic status of coronae).

Both the lithospheric flexure and subsidence that result from basaltic loading and the loss of support as magma chambers empty will lead to compression in basin interiors and extension at their margins, and the origin of the planetary wrinkle ridge/graben association may reside in such processes. Such a model would explain the central wrinkle ridging and circumferential graben formation in the Olympus Mons caldera (Fig. 7), but not the distribution of tectonic landforms within Caloris, a complex pattern of deformation unlike that found in any other basin in the Solar System.

This temporal element to tectonism is similarly evident on the most studied of terrestrial planets, Mars. Formation of the martian crustal dichotomy and the Tharsis plateau are thought to have occurred very early in the planet's history (Dohm et al. 2001, 2007; Frey et al. 2002; Watters et al. 2007), the latter resulting in a vast system of graben and wrinkle ridges that span the entire western hemisphere (Anderson et al. 2001). Yet, these ancient structures are well preserved, partly due to the slow rates of erosion and deposition promoted by the thin martian atmosphere (Schultz 1999) but also as a result of the general lack of subsequent deformational events (Tanaka et al. 2010).

Nor is this time-limited tectonism confined to the terrestrial planets, being evident on the surfaces of other bodies in the Solar System. For instance, Ganymede, the majority of whose surface is dominated by tectonic features, the youngest of which is nominally 2 Ga in age (Zahnle et al. 2003), or the Saturnian moon Iapetus, where a minor episode of ancient tectonic activity formed a single, spatially restricted (if major) feature of possible tectonic origin. Then there are those satellites without widespread tectonic activity, such as Titan, an apparently active world that is erasing craters from its surface at a geologically rapid rate (Porco et al. 2005) but which displays no evidence of active, internally driven tectonic processes (or whose erosion and/or deposition is so effective at erasing or masking tectonic features that the nature of its tectonics cannot clearly be determined (Collins et al. 2010)). In contrast, the gas-giant moons Enceladus and Europa are both active, heavily deformed bodies with a geological history stretching from billions of years ago to the present day. If the identification and differentiation of tectonic elements is “...a first, and critical, step in planetary geological mapping” (Hansen 2000, p. 535), then it is clear that while some of these worlds could be comprehensively mapped, others could only be partially mapped and a few not mapped at all.

Some descriptions of planetary tectonism present their observations stratigraphically (e.g., on Mercury (Watters et al. 2009b) and the asteroid Vesta (Buczkowski et al. 2012)), and I would argue that this approach has all the objective benefits for studies of tectonically active worlds, such as Venus, that it has for more quiescent bodies, such as Mars. Consider that the biggest questions in Venus' geological evolution – the existence of mantle plumes, the nature of its tectonic and heat-loss mechanisms, the age of its surface, the evidence for global resurfacing and the inferred decline in geological activity thereafter – all hinge upon the endogenic/impact origin of coronae. For all the quantitative analysis of which tectonic studies are capable, this amounts to a difference of opinion regarding landform origin. Given the seemingly

non-random distribution of coronae, with two-thirds located within and along chasmata (Stofan et al. 2001), a study of these two landform types at their stratal intersections could contribute much to our knowledge of venusian geology and chronology.

Hansen makes the case for tectonic mapping thus: “...*Secondary or tectonic structures (are) formed after material unit deposition or emplacement (e.g., fractures, faults, folds, wrinkle ridges), and thus record time (s) and process(es) distinct from the material unit that they deform.*” Yet, as we have seen for wrinkle ridges on Venus and the Moon, this primary/secondary distinction is not a given for process, time, lithology or place. Tectonism in a particular deposit or series of deposits can be extrinsically controlled (e.g., by mantle processes), confined to either a specific time period (e.g., Ganymede, Iapetus), substrate (e.g., subsidence in volcanically-loaded basins), or location (e.g., extensional features on Mercury) and is “facies controlled” to a degree, being determined by the rheology of the deformed material. In some cases (e.g., coronae), even the identification of tectonic landforms is a non-trivial matter, with different identifications yielding vastly different geohistories. Moreover, Earth, Mars, Venus, and Mercury may each have their own distinct tectonic regimes.

As such, the utility of tectonic mapping as a replacement for stratigraphical techniques must remain open to question. Indeed, given that tectonic analysis assumes the principles of stratigraphy in its methods, it is debateable whether there is any need for a formal division between the two.

Spectral Mapping of Planetary Landforms and Geological Units

With five spectrometers in orbit around Mars (offering complete planetary coverage at 100-m spatial resolution) and one orbiting Mercury, we can also map landforms spectrally. These instruments¹⁹ image the surface at a variety of visible near-infrared, infrared, and hyperspectral thermal infrared wavelengths, but for our geological purposes their observations fall into two classes: compositional and thermophysical. The first of these relates to the chemical composition of the materials in which gamma ray, neutron, and infrared radiation signals are produced, the second to the thermophysical properties of the surface that govern temperature variation in response to solar heating.

These spectral observations provide information on substrate mineralogy, particle-size, and porosity on local to global scales, information unavailable

¹⁹The Thermal Emission Spectrometer (TES), the Thermal Emission Imaging System (THEMIS), the Gamma Ray Spectrometer (GRS), the Observatoire pour la Mineralogie, l'Eau, les Glaces et l'Activité (OMEGA), the Compact Reconnaissance Imaging System (CRISM), and the Mercury Atmospheric and Surface Composition Spectrometer (MASCS), onboard Mars Global Surveyor, Mars Odyssey, Mars Express, Mars Reconnaissance Orbiter, and Mercury Messenger, respectively.

from visual imagery. However, interpretation of surface spectra requires that we first understand the distinction between two very different properties of surface materials – *composition* and *lithology*. Elemental composition, in sum, may allow us to make inferences regarding surface mineralogy, e.g., a preponderance of the elements that go to make up mafic minerals (i.e., Fe, Al, Ti, Ca, Mg, K, Na, Ar) might indicate a basaltic substrate. Where we can see through the spectrally homogenous dust that blankets Mars' lower latitudes (more anon), the returned spectrum is indeed igneous (Bandfield 2002), moderate-resolution thermal infrared (THEMIS) spectra of Mars' Elysium plain hinting at a basaltic composition for this region (Wilcox and Hamilton 2005). Yet, any number of lithologies can be basaltic in composition and appear spectrally identical as a consequence. A sand-grade deposit may be dominated by volcanic rock fragments (giving a basaltic spectrum as a result), but this does not mean that sandstones issue from volcanoes, or that they are synonymous with lava flows. Equating lithogenesis with petrogenesis ("what is made" with "what it is made from") is scientifically risky, as it is easy to believe that we strengthen a weak class of evidence, like surface morphology, with observations from a less-interpretive class, like chemistry (a situation not unlike the assumed rigor of an impact crater count).

Few things would seem more obvious than that basalt should emit a basaltic spectrum, yet "basaltic" and *basalt* (i.e., a lava flow) are not the same thing geologically. A real-world example of the spectral parallel between detrital particulates and bedrock may be found in Earth's Antarctic Dry Valleys, the most Mars-like of terrestrial analogue sites. Here, dolerite (a shallow-intrusive igneous rock compositionally equivalent to basalt) yields mafic soils whose spectral shape and absorption features are similar to the parent bedrock (Salvatore et al. 2010) – mafic soils that few would mistake for lava flows, yet whose spectra provide no clue to their sedimentary nature (Page 2010a).

This geological distinction between basaltic particulates and basalt rock may seem of little relevance to the aim of deriving surface composition, but it concerns the most abundant composition detected on the terrestrial planets and is a distinction that often goes unrecognized in the search for supporting evidence of a particular landform origin. For instance, GRS neutron counts at the martian equator have been compared with elemental abundances to determine a general overview of the geology of this region, concluding that the local maximum of neutron emission is consistent with lava (Diez et al. 2009). However, nothing in such data speak of rock type or even mineralogy, only chemical composition as expressed by elemental abundance (the weighted sum of all chemical elements), yet the derived basaltic *composition* nevertheless becomes basalt *lava*.

Non-recognition of this distinction is common in spectral investigations, irrespective of scale. Whether the sub-km footprint of GRS or the decameter resolution of CRISM, the inferential leap is the same – chemistry is equated with geology, and origin is inferred. Thus CRISM spectra of the basalt lava that floors Gusev crater, the mafic sands of the "El Dorado" ripple field within that crater, and the surface in Elysium were all

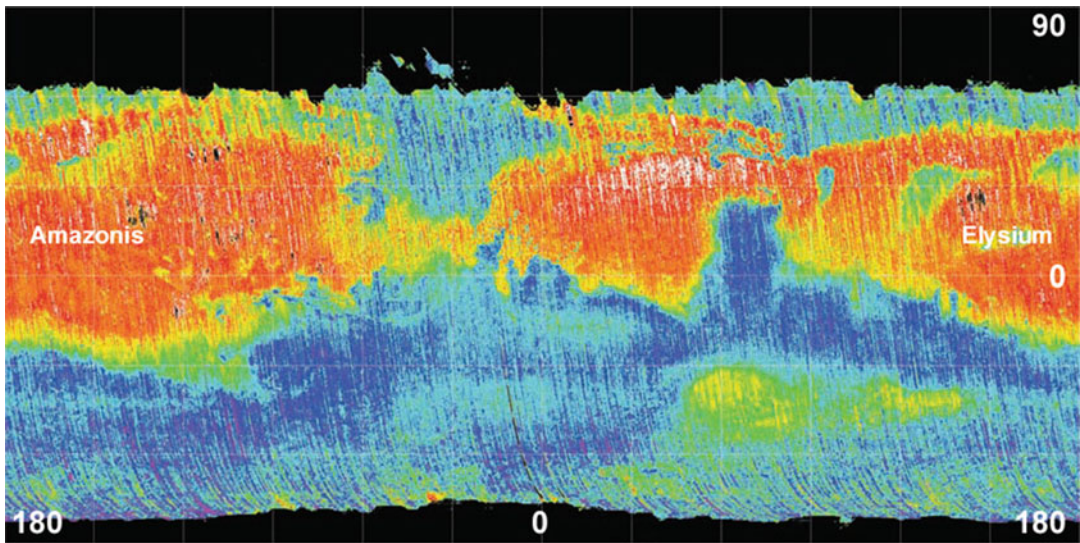


Fig. 19 Mars global dust-cover map (From Ruff and Christensen (2002), reproduced with permission). Orange-red colors indicate areas of dust cover, blue-purple dust-free. Note uniform dust-cover across equator

compared, the spectral similarity between the three described as “*unmistakable*”, citing this as one line of evidence pointing to a mafic-ultramafic lava composition for the Elysium region (Jaeger et al. 2010). The spectral similarity is indeed striking (Fig. 5, *ibid.*), but what do we establish geologically by such ‘*unmistakable*’ parallels when the analysis cannot distinguish between sand dunes and solid rock? By highlighting the identical spectra to be had from sand, lava flows, and the Elysium plain, we show that compositional spectra are diagnostic of bulk chemistry, and perhaps even mineralogy, but are non-diagnostic of lithology. If caution is advised in the conclusions drawn from chemical compositional data, then analysis of the thermophysical properties of planetary surfaces presents another, and quite different, set of challenges for the observer.

Despite the multiplicity of orbiting spectrometers, the composition of almost half of Mars’ surface remains elusive due to a pervasive cover of dust. Just a few-10s of μm of dust completely obscures any underlying thermal infrared signal, rendering instruments like the TES and THEMIS ineffective. Moreover, any compositional information that can be gleaned from this dust is largely irrelevant to the composition of the underlying surface because of the global nature of dust storm transport (Wilcox and Hamilton 2005), the Elysium plain lying within a large, equatorial “blind spot” (Fig. 19), clearly visible in published maps of emissivity and thermal inertia (Ruff and Christensen 2002; Putzig et al. 2005). Thermal inertia (TI) is the primary physical property that governs the daily thermal response of the surface to solar heating and is of particular relevance here because it is a bulk property that provides information about the material *beneath* the surface, varying by a factor of 20 for different surface materials on Mars (i.e., from $100 \text{ J/m}^2 \text{ Ks}^{1/2}$ for silt to $2,000 \text{ J/m}^2 \text{ Ks}^{1/2}$ for basalt (Jakosky et al. 2000)).

Physically, it is most closely related to the thermal conductivity of the surface, which varies with grain size, porosity, and degree of induration, the thickness of the layer that contributes to the derived value of TI equal to the penetration depth of the diurnal thermal wave (~ 20 cm in rock). Using high-resolution TES data to identify areas of particulate basalt within Elysium, Rogers and Christensen (2003) found the plains around 9° – 14° N/ 149° – 162° E (the area of Fig. 9) to have thermal inertial values (250 to >300 J/m² Ks^{1/2}) indicative of particle sizes in the range of silt to coarse sand (200 – 800 μ m). Nowhere were values consistent with bedrock (i.e., $\sim 2,400$ J/m² Ks^{1/2} (Jakosky 1979)).

While the low thermal inertia of this region of Mars supports an origin in particulate, basaltic regolith [e.g., see Appendices of Page (2007) and Page et al. (2009)], the source of the basaltic spectrum cannot be determined unequivocally. There are two possible scenarios of origin: (i) it represents a local basaltic eruption within the Elysium province (e.g., Plescia 1990) or (ii) it is a basaltic erosional product derived from elsewhere (e.g., Carr 1981; Greeley and Guest 1987). On purely spectral grounds, neither scenario can be distinguished²⁰.

This lithological indeterminacy limits the utility of spectral analysis as a means of landform analysis, as the absence of a particular spectrum is often ascribed to “spectral masking.” A pertinent example is the shergottitic spectral signal expected from the repeated, random ejection of the shergottite meteorites from the martian surface. Data from the TES describe two broad spectral signatures distributed north–south of the planetary dichotomy: a surface type 2 (ST2) that (variously) defines the surface composition of the northern plains as andesitic (Bandfield et al. 2000) or aqueously altered basaltic (Wyatt and McSween 2002) and a basaltic surface type 1 (ST1) in the southern highlands. The shergottitic spectrum, however, is nowhere detected on the martian surface, even at the 10-km scale (e.g., Bandfield et al. 2000; Christensen et al. 2000; Hamilton et al. 2003). Spectral masking by fine dust can be invoked for the low latitudes, but large areas of the surface show no such masking, are basaltic in composition (i.e., ST1), yet lavas that fit martian meteorite spectra are conspicuous by their absence (unlike the Moon, where lunar meteorites find their match in surface spectra (Korotev (2005), and references therein)). While some variability exists among the shergottites, their mineralogy is sufficiently similar to classify them unambiguously as a distinctive group that is distinguishable from TES-derived basaltic spectra (Hamilton et al. 2003). The “andesitic” ST2 spectral type that characterizes much of the northern plains is also absent as a chemical signature in the shergottites, so neither of the igneous compositions detected from orbit corresponds to these meteorites – the only “hard” geological samples that we have of the martian surface.

The so-called Shergottite Paradox (Nyquist et al. 1998) asks why this rock type should be repeatedly sampled by impact, but also poses the question why other martian basalt types (such as ST1 and ST2) that *are* identified spectrally

²⁰The observation that the polygonally patterned terrain in this area suffers regional-scale aeolian deflation (Fig. 10) and is therefore more likely to be particulate and sedimentary than solid rock provides geological support for the second of these scenarios.

should not also be returned. The inferred lavas of Fig. 9 remain for many the source of these meteorites (e.g., Keszthelyi et al. 2000; Plescia 2005a; Hartmann 2005; McEwen et al. 2005; Jaeger et al. 2007), their identity hidden by “dust mantling,” but a more geologically consistent scenario is that all of the shergottites were excavated from depth.

This lithological indeterminacy of different lithologies having the same spectral signature on Mars and Earth is duplicated on Mercury, where the ostensibly different geology of the volcanic circum-Caloris plains and the rim massifs of that crater are not distinguished spectrally. The origin of this spectral similarity between Odin plains and Caloris’ rim remains unknown; both units may have the same composition, or the rim materials may be a physical mixture of an originally heterogeneous target whose spectral signature matches that of the exterior plains (Watters et al. 2009b). Alternatively, these plains may be impact related, as suggested by the crater SFD when larger craters within these plains are taken into account (see section “[Age Evidence for Late-Stage Volcanism on Mercury](#)”).

Recall the question of the source of voluminous flood volcanism on Mercury, a planet with no large shields, and whether this has any bearing on the seeming absence of ferroan silicates at the surface. Compositionally, the contribution that Fe and Ti might be expected to make to mercurian surface spectra is unclear, as interpretation of neutron data is model dependent, with different spectral results for each fly-by. Nevertheless, a presumed dominantly-volcanic planet that lacks any measurable degree of FeO as silicate (Solomon et al. 2008) or whose iron is only present in the form of Fe-Ti oxides, such as ilmenite (Lawrence et al. 2010), is puzzling in equal measure. Interestingly, elements with much greater neutron absorption than Fe and Ti, such as Cl, are also reported for Mercury. Abundant Cl is not expected in non-hydrated silicates, so it is concluded that some combination of Fe, Ti, Gd, and Sm as non-silicate phases is driving measured neutron absorption (Lawrence et al. 2010), contrasting with the idea that much of Mercury’s iron may have been sequestered to the core. Observe then that another area of presumed flood volcanism – the martian case study region of Elysium – also shows high Cl neutron absorption (Diez et al. 2009), consistent with geological observations of a volatile-rich, particulate igneous regolith. Could Mercury’s elemental composition signal a similar geology, an erosive remnant of anorthositic²¹ basement, perhaps?

Strength of Inference and “Geomyth” in Planetary Geology

On both Mars and Mercury, volcanic resurfacing of a wide plains region has been proposed based on crater SFDs in areas of the stratigraphical column where lithology is effectively unknown. Only in the case of Mercury does

²¹“Anorthositic” is here given in its mineralogical sense, as an example of an iron-poor igneous rock, with no connotations of planetary differentiation or a lunar-like “magma ocean.”

the proposed volcanic history find any support in stratigraphical observation²². If the evidence for a landform hypothesis is found fundamentally wanting, why then does it persist? Dickinson (2003) describes it thus: “...*The characteristic style of mythic thinking is to place special emphasis on a selective conjecture, based typically on the initial observation or recognition of a phenomenon, which is thereafter given privileged status over alternate interpretations*”. The consensus view regarding the Mars case study region is suggested to be an example of this mythic thinking, a geological worldview so established that observation is made consistent with theory rather than the other way around.

This allusion to “myth” is not a matter of one interpretation being right and one wrong, but a question of valid inference and how one should “do” geology in a non-terrestrial environment absent ground truth. Geology is an “open-system” science (von Bertalanffy 1950) that lacks the rigid, theory-based framework of physics. While there are a number of principles at the geologist’s disposal, there is no “law” that requires that a landform or terrain of a certain appearance or elemental composition must have a particular origin²³. This does not mean that rigorous, systematic inquiry is beyond geology’s purview, but ours is not a “predictive” science in the generally accepted sense because we deal with the past – the *experiment* is long over, and we have the *result* (the rock record) before us. Unlike all other experimental science, geological inference runs backward in time, from observed present to inferred past, and is “retrodictive” (or abductive (Peirce 1896)) rather than predictive. We may study a lava flow, a rock glacier, or an alluvial plain on Earth and make testable predictions regarding the conditions of formation of such surfaces. Beyond Earth, however, we do not have the luxury of such certainty of identity or origin. The point is that we do not really “prove” things in planetary geology, only disprove them – getting closer to what “is” by progressively ruling out what is not, a process of *falsification* (Popper 1963) that is common to all scientific endeavor.

To do otherwise, to start from a particular geological standpoint and then explain away or disregard disconfirming observations is how geomorphs are created. Thus, so certain is the idea that the surface of Fig. 9 represents a rapidly emplaced flood lava that the discovery that the two surface morphologies have different ages is explained by proposing that the contained impact craters do not contain age information at all, reflecting instead the effect of undocumented “material properties” on crater formation across a single surface of uniform age, rendering the less-cratered regions immune to impact (Dundas et al. 2010). Jaeger et al. (2010) describe emplacement of this surface as a single event, detailing how “...*careful mapping finds that the Athabasca Valles flood lava is the product of a single eruption ... emplaced turbulently over a period of only a few to several weeks*” (“...3 to 17 days” the result given), a model said to be “...*concordant with all of the available data*”, including stratigraphical

²²This volcanic resurfacing based on impact crater SFDs is also inferred for Venus.

²³Calling into question the geomorphic and spectral assumptions that are often the parameters for numerical models of geological origin.

relationships, describing how instantaneous emplacement has produced a single lithology “...at a distinct time horizon (i.e., a lithochronostratigraphic unit)”. However, such a scenario makes no sense in terms of geological time, whether this be the relative chronology of deposit geometry or the absolute ages of the crater chronology, the difference between formation on a timescale of “days” and 10s of Ma amounting to a billion-fold error in age estimation. Even if, as seems likely, some fraction of the crater population in this figure is secondary in origin, these two surfaces need only diverge in age by about a century to be incompatible with this model. While the boundaries of lithostratigraphical units may cut across synchronous surfaces when traced laterally (i.e., they may be time transgressive), such diachroneity cannot occur in extrusive crystalline rocks (i.e., lava flows) and cannot explain this 10⁸-years discordance. This is the product of theory-driven observation, where data are gathered and inferences drawn in the context of a conclusion preconceived – calculated absolute age *ungrounded* in observed relative-age.

The cautions against such an approach are many, Chamberlin (1897) describing the danger when “...*Interpretation leaves its proper place at the end of the intellectual procession and rushes to the forefront*”, or Gilbert (1886) who admonishes us to “...*discriminate the phenomena observed from the observer’s inference in regard to them*”. Peirce (1896) had the measure of this, asking “...*what is a likely hypothesis? It is one which falls in with our preconceived ideas. But these may be wrong*”. More recently, Platt (1964) reminds us to formulate hypotheses “...*sharp enough to be capable of disproof*”, a “strong inference” mode of inquiry championed by Dickinson (2003) as an antidote to mythic reasoning, whereby inductive inferences are succeeded at once by deductive predictions designed deliberately to test each inductive leap for potential disproof, an approach that ensures that such inferences “...*do not grow inadvertently into untested geomyths having more durability than ultimate utility*”.

If the most important test of any hypothesis or theory is its usefulness and accuracy in predicting phenomena before they are observed (Suppes 1957), then it might seem that the geologist can establish little by working in reverse, retrodictively, reconstructing past from present. However, the observations of deposit geometry, free from any explanatory element, allow a number of inferences and generalizations to be made regarding landform or terrain origin that give rise to testable consequences. To illustrate, let us look at this approach in stages as applied in the martian case study area over the past decade:

Initial observation:

1. It is observed (in 2006) that ostensibly volcanic cones on Mars cross-cut impact craters (Fig. 6a) and would therefore seem to be secondary (or post-depositional) in origin (Page and Murray 2006).

Assertion:

2. Unless the superposition in 1 is a local anomaly or an artifact of image resolution, this should not be a single instance.

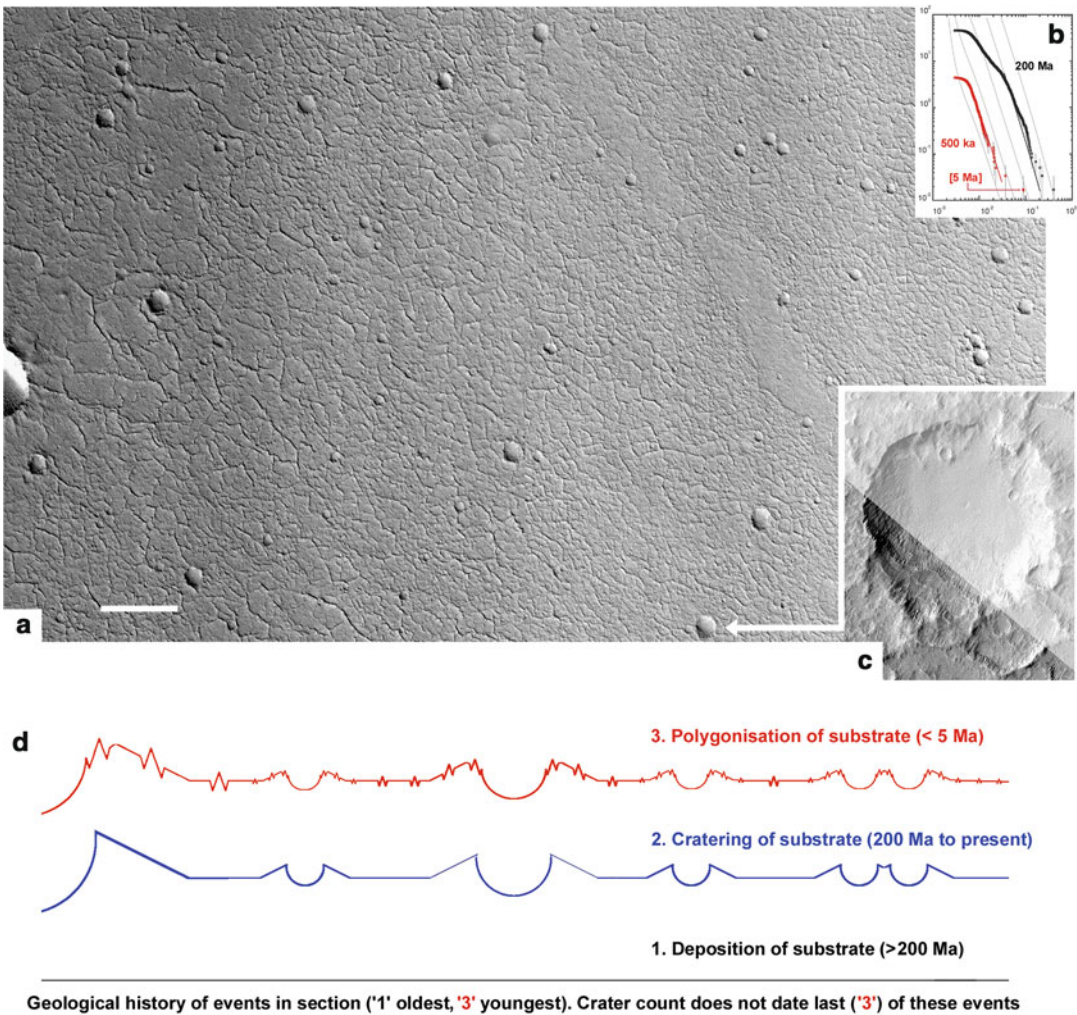


Fig. 20 Composite view of crater population in polygonized terrain in Amazonis plain. (a) Context view showing every crater to be visibly polygonized. (b) Crater count (black plot) of this surface yielding an ~200 Ma absolute age. Craters that cross-cut polygonization plotted in red. Bulk count through multiple stratigraphical levels (black) results in a crater SFD that cuts across isochrons (cf. Fig. 8, main text), as compared with stratigraphically controlled, post-polygonization count (red, m-scale craters counted in HiRISE) which is steep and isochron-following (cf. blue count of polygonal ground in Elysium

[Fig. 9, main text]). (c) Detail of polygonized crater showing destructive nature of process (veiled at upper right to show effect of polygonization on crater detection, rim at lower left almost invisible). (a) MOC S09-02331 (NASA/JPL/MSSS), (b–c) HiRISE PSP_008092_1980, 18°N/197°E, scale bar = 300 m, resolution 3.19 m/px and 25 cm/px, respectively. Isochrons, L–R = 100 ka, 1, 10, 100 Ma, and 1 Ga. (NASA/JPL/University of Arizona). (d) Stylized cross-section through a terrain showing geological “history of events”

Test, confirmation, and generalization:

3. Finding the same superposition of impact craters among multiple and varying landforms in 2007–2008 (Figs. 5b and 6a, b, main text, Fig. 20a, Addendum), it is concluded, on the basis of deposit geometry, that the

entire assemblage is secondary and that accepted explanation of a static, lithified surface across this region is deficient (Page 2007, 2008).

Consequential assertion:

4. Because the superposing landforms of 1–3 populate both “platy” and polygonal terrain types in these deposits, there should be a time-transgressive component to the plates also (despite their multi-kilometer scale) if the general assertion of post-depositional origin in 1–3 is valid.

Further test:

5. This inference drives the search for further age anomaly, with attention paid to impact craters at plate margins. Finding this anomaly (in 2009) in HiRISE images showing large crater-density differences between contiguous platy and polygonal terrain types (Fig. 9, main text), the conical landforms cutting across both, every landform in these deposits is now shown to have a strong time-transgressive element (Page et al. 2009).

Further test II:

6. From the first stratigraphical observations, the diachronous nature of the landforms in these deposits has suggested a particulate rather than rocky substrate (Page 2007; Page et al. 2009) – a lithological inference supported by the regional-scale deflation of these deposits (Fig. 10 (Page, this volume)): a process known only from sedimentary terrains.

Further test III and genetic hypothesis:

7. The secondary age-relations of the crater-crossing cones give rise to a hypothesis of origin in intrusive ground ice. Again, this should not be a single instance if true, and these same landforms should also occur in ice-rich terrains elsewhere on Mars. These post-depositional cones with encircling, hexagonal moats have now been found in Viscous Flow Features on crater walls in the southern highlands (Fig. 11 (Page, this volume)), supporting both this hypothesis of origin and its stratigraphical basis. Form convergence states that the visual similarity between such landforms may only be superficial, but when both show the same post-depositional age relations to the substrate, then there is a cause to suspect a common origin.

The first thing to note here is how hypotheses of origin are the *culmination* of stratigraphical inquiry rather than the beginning – observations seeking an explanation, rather than a hypothesis in search of supporting facts. Since we are concerned with visual observations, it might seem that analysis has no role to play during data collection, but stratigraphical analysis vs. genetic

interpretation at this point makes for two very different geological outcomes (i.e., icy sediment vs. solid lava). Thus, while a genetic hypothesis of explosive volcanism may be competent to explain the form (if not the relative-age relations) of the conical landforms in Mars' equatorial plains, it is quite *incompetent* to explain the presence of these same landforms in the VFF on crater walls in the southern highlands.

In 1–7 above, we reason backwards temporally, following the signs of secondary origin from observed present to inferred past by tracing the thread of “time” through the system. The only hypothesis of the unguided observations of stages 1–2 is the tentative null hypothesis that accepted explanation of an isochronous, lithified surface in this region is deficient. The renewed observations of stages 3–5 is directed observation that knows what else to look for, and hence how and where to look next in test of the assertions of stages 2 and 4. Directed observation has another great value – it is apt to lead to discoveries wholly unanticipated at the outset of inquiry. Such unanticipated discoveries that nevertheless find full explanation in the final hypothesis have exceptionally high value as confirmation of that hypothesis (Johnson 1933). The discovery at stage 5 is of this kind. At this point, there is sufficient information to test competing hypotheses of genesis (i.e., flood lava, frozen ocean, periglaciatic outflow channel effluent, finding in favor of the last of these).

Note in stage 4 that there was no idea at the time of what kind of age anomaly was sought – simply that one must exist in these largest of landforms if the wider suggestion of a dynamic, post-depositional landscape were valid – a test of the reasoning in 1–3. When found, it was so unambiguous yet so unanticipated in its expression that here was an example of the “explanatory surprise” characteristic of *Consilience* (Whewell 1840; Peirce 1878; Gould 2003): an observation aligned with the general thesis of an active, time-transgressive landscape, yet of an independent class (visible differences in crater density), a geohistory sustained by the subsequent discoveries of stages 6–7.

This process of iterative induction, with each deduction tested for validity, is what was meant by the earlier statement that “...*stratigraphical observation always suggests its own test*”. It is in the very nature of geological evidence – unobserved events, unknown conditions, and preservational biases – that this method of inquiry has developed. In a discipline defined as much by what has been lost from the record as what remains, what could be more prejudicial to inquiry than the need to *classify* landforms as a first step? Stratigraphical-historical method places no such constraint on us.

Geological inference is a straightforward matter whose rigor lies in its simplicity, but I suggest that an overly simplistic view of geological practice, tied up in the view that planetary imaging is a fundamentally two-dimensional affair (and thus the province of geomorphology), has driven decades of geoscientific inquiry at the martian equator down the wrong path. I have tried in this account to show how and why this has happened, and to present a guide to the objective, geologically valid interpretation of planetary landforms and terrains so that it might be avoided in future investigations.

Conclusions, Recommendations, and Using This Encyclopedia

If we are to use photographic imagery to study landforms on the surfaces of other planets (such imagery “. . . *the primary source of information available for interpreting the geologic and geomorphic history of planetary surfaces*” (Zimbelman 2001)), then it is vital that we have a structural element to our inquiries. We do not add rigor to an interpretive geomorphology by crater-counting or spectrally-analyzing the surface, as these methods easily become contingent upon that geomorphic interpretation (as on Mars), their quantitative nature blinding us to the fragile genetic assumptions of the surfaces that they seek to constrain. Indeed, what end genetic hypothesis when most landforms have competing identifications and interpretations that cannot be distinguished by this method? On form-convergence grounds, all such identifications are inadmissible as evidence of origin because they are non-unique, and vary depending on the point of view of the observer who, in the case of Mars, considers these to be the signs of flood volcanism, outflow channel effluent, or inundation by oceanic quantities of water, and interprets their observations solely in that context. These competing interpretations cannot be “multiple working hypotheses” (Chamberlin 1897) when the genetic identifications are both source of the hypotheses *and* evidence for them (Page 2010b).

It is fair to say that there is no single discovery or issue in planetary geology where morphology-led inquiry has *not* resulted in controversy, e.g., the Elysium question (lava, sediment, ocean), the origin of the Vastitas Borealis (ditto) and Medusae Fossae Formations (ignimbrite, ash-fall, buried ice-sheet, aeolian materials), sinuous-rilles on the Moon (lava tubes vs. fluvial channels), or the decades-long dispute regarding the origin of venusian coronae, a debate which continues for the lack of any terrestrial analogue (highlighting another aspect of morphogenetic method – what to do when there *is* no analogue). There is no counter-example in planetary geology where stratigraphical inquiry has led to similar controversy. Indeed, our understanding of the geological history of the lunar surface has remained largely unchanged for over half a century as a result of the stratigraphical methods of early investigators (e.g., Wilhelms et al. 1987).

If the primary evidence for landform origin in the planetary domain comes from crater counts, then the exercise becomes a subjective one, as we selectively count, blanket count or even discount part of the crater population altogether in support of an inferred origin, regional-scale volcanic resurfacing on Mercury, Venus, and Mars all proposed on the distribution, absence, or expected number of impact craters. The student of remotely sensed geology should never lose sight of the fact that we are reconstructing the *past*, in which the passage of time is implicit and a “thread” that can be traced back through the rock record by stratigraphical means. If impact craters are used to their fullest potential as indicators of absolute- *and* relative-age, then our identifications become truly rigorous, one means of age estimation tested by another (the relative-age observations described herein lacking any obvious metric, but still geometrically based). Crater counts are empirical enough, but if we choose

what to count (and what not), then we are theory building and on the path to geomyth.

When using this encyclopedia, the reader is encouraged to consider the landforms herein not just in terms of hypotheses of formation but also their relations with the surface vis-à-vis relative-age (particularly on those planets where tectonic activity is suspected), a method of inquiry that goes back two centuries to the very inception of geology as a science. In a traverse across the Scottish Highlands, James Hutton (1788) was able to piece together the history of the various plutonic, metamorphic, and sedimentary rocks based on the geometry of their intersections. He inferred that the Caledonian granites were younger than the “Primitive” (metamorphic) basement that they intrude, with the numerous faults and intrusive dykes younger than the Old Red Sandstone that they cut. By determining the age of one rock relative to another, Hutton produced a geological “history of events” for rocks whose origins he did not know²⁴, a history that remains unchanged to this day²⁵.

Two centuries on, geology is no longer Earth-bound as we seek to understand the surface evolution of our nearest planetary neighbors. It is fortunate then that deposit geometry may be discerned from space with rather less difficulty than rock type (Page 2007, 2010b), employing a directional, temporal logic that is practiced by all geologists as a matter of course, whether they be determining the crystallization history of minerals under the microscope, the stratigraphy of an outcrop in the field, or the order of undefined events on a distant planetary surface.

Addendum: Isochrons, Diachrons, and Landform Identification

In the preceding text, we saw how the observations of deposit geometry and impact crater chronology can be brought together to constrain landform origin. In this, I suggested that *time transgression* (or *diachroneity*) is a phenomenon that goes unrecognized in planetary chronology. Examples of this behavior were presented, positing a non-depositional hiatus (or disconformity) in the deposits of the martian stratotype. Here we will explore the practical implications of this phenomenon for dating surface landforms by crater counts and the ongoing evolution of the martian isochron system.

Unconformities – erosional or non-depositional breaks in the rock record – are ubiquitous features of terrestrial stratigraphy. Many are not immediately apparent as such, lacking the obvious discordance of the classical “angular unconformity” where a steeply dipping erosional surface is

²⁴The genesis of “Primitive” and granitic rocks was uncertain in Hutton’s time, with many believing granite to be an aqueous precipitate. Note here how there is no methodological distinction between tectonic (faults) and material (intrusions) observations in such inquiry – it is all simply stratigraphical (cf. Hansen 2000)).

²⁵A methodology that could hardly be more applicable to the remotely sensed – and often controversial – geology of other planets.

truncated by later-formed, flat-lying bedding. However, they may still be there and the time-gap represented by such significant events as erosion or non-deposition can be far greater than the time periods represented by the deposits bounding such gaps, a temporal hiatus that crater counts effectively (if inadvertently) disguise. The import of diachroneity is illustrated by the fact that it breaks one of the central tenets of impact crater chronology – that a surface can never be younger than its crater population. It has always been assumed that a surface with a certain number of impact craters (of a certain diameter) has a minimum “absolute” age, i.e., that crater density is always virtually proportional to age (Hartmann 2005, p. 303). Both the number of craters and the age derived can be distorted by erosion or burial, such that a surface can always be older than we think (based on the observation that a surface cannot have less craters than we currently see, but could well have had more in the past), but it can never be *younger*. Thus we can rank surfaces on any planet in order of age by noting that the more impact craters it has, the older that surface must be (Hartmann 1999).

Geologically, this is an unsafe assumption. Consider Fig. 20a, a composite view of polygonized terrain in Amazonis Planitia (from which Fig. 5b in the main text is taken) with an age of ~ 200 Ma (Fig. 20b, black plot). Now note how this polygonization cross-cuts the entire impact crater population, reaching over rim crests and into crater floors (Fig. 20c). This intrusive activity is an example of *time transgression*, and its chronological consequences are considerable. As 100 % of the craters visible in this figure are affected by this superposition, a process affecting craters large and small, the recency of this activity can be no more than a few percent of the age determined by counting all of these craters, i.e., a few Ma, rather than the apparent surface age of ~ 200 Ma. Put another way, is there a 200-Ma accumulation of impact craters visible in this figure? Yes. Are the landforms forming this surface 200 Ma old as a result? No – intrusive polygonization of this surface is almost 100x younger than tallying craters would lead us to believe. Where a 95 % confidence limit is regarded as statistically significant, consider the value of a >95 % error if the result is to be an “absolute” age.

Just as the recency of an igneous intrusion is not determined by dating the surface intruded, so is it that the activity in Fig. 20 is not dated simply by counting all of these craters. Identical behavior is observed in the terrestrial environment, where intrusive frost mounds (or “pingos”) are forming today in 150-Ma-aged Jurassic sediments (Ross et al. 2005). To focus only on the age of the substrate in this example is to overlook the entirety of post-Jurassic time.

Time-transgressive geological activity also has a spatial component, as expressed in the terrestrial rock record by laterally migrating sedimentary systems. A martian example of such sedimentary diachroneity is presented below.

Lineated Valley Fill and Lobate Devris Aprons (hereafter, LVF) occur at northern mid-latitudes on Mars and are, like VFF, thought to be formed of ice and wind-borne dust (Head et al. 2006), an interpretation sustained by radar soundings that indicate ice at depth (Holt et al. 2008). LVF is host to a unique kind of impact structure, the “ring-mold crater” that occurs exclusively on this terrain-type (Kress and Head 2008). Figure 21 illustrates the two principal

features of this landform: the softened crater rim and concentric, “oyster-shell” morphology, both of which are attributed to viscous relaxation, impact armor, or impact into an icy substrate (Mangold 2003). In terms of deposit geometry, however, these impact interpretations are inconsistent with the observation that the ring-mold interior is *stratified*, indicating a sedimentary origin.

Evidence of this sedimentary origin is presented in Fig. 21d, showing the ring-mold structure to be a basin-fill product of LVF emplacement within preexisting impact craters. This figure shows laterally-aggrading LVF progressively filling an impact basin from east to west (i.e., right to left), the easternmost half of the crater displaying the characteristic rim-softening and layered, “oyster-shell” interior, while the unaffected western half preserves the sharp rim and empty interior of a typical impact crater. A HiRISE DTM²⁶ of this terrain (Fig. 21e) shows topography to fall by ~215 m moving E-W across the image, consistent with the inferred direction of deposition and the view that LVF, like VFF, is formed by downslope movement of material (Milliken et al. 2003).

While many of these basins are clearly of impact origin, the crater element of ring-mold craters *underlies* – and therefore *predates* – the LVF. These ring-mold structures must form by both surface and subaerial (i.e., airfall) sedimentary means, as there are many instances (e.g., Fig. 21b) with no obvious source of surface sediment supply. In every case, however, the presence of a stratified deposit filling the crater and embaying the rim indicates that LVF deposition postdates that crater, the depositional age of which is not constrained by counting that crater.

As such, ring-mold craters are of little use for surface dating unless counted stratigraphically. Indeed, given that they form almost 80 % of the total crater population in these deposits (Kress and Head 2008), bulk counts of such craters must greatly overestimate surface age on local scales, the LVF currently dated to 90–300 Ma (Head et al. 2006; Baker et al. 2010). There are many craters superposed upon the LVF that are possessed of the empty, bowl-shaped interior expected from impact processes, and it is these craters, devoid of interior ring-mold deposits, that date this terrain. When counts are made of such craters (Fig. 21d, inset, blue plot), the LVF yields a surface age on the order of a few-100 ka²⁷ – the same age as their VFF counterpart at southern mid-latitude.

The laterally-aggrading LVF of Fig. 20 is effectively sandwiched between two $D \sim 1$ -km impact craters, one (“T₁”) stratigraphically below the flow, and

²⁶This terrain has not been stereo-imaged by HiRISE, so this DTM is constructed by draping HiRISE ESP_016707_2180 over MOLA data (tracks ap10966, ap10942 and ap10183), the correspondence between the image and the apex of the topographical high at 1,900 m confirming the accuracy of registration.

²⁷Although the extensive pitting of the LVF surface in Fig. 21c suggests that sublimation has played a significant role in modifying this surface, a complete, full-resolution HiRISE crater count of this surface (Fig. 21d inset, blue plot) shows a steep, isochron following SFD below $D \sim 30$ m and does not support the assertion of crater loss below $D 150$ m (Baker et al. 2010); indeed, this is the maximum crater diameter found on this surface when stratigraphically lower RMCs are not added to the counts, suggesting that the LVF in Deuteronilus Mensae is truly young.

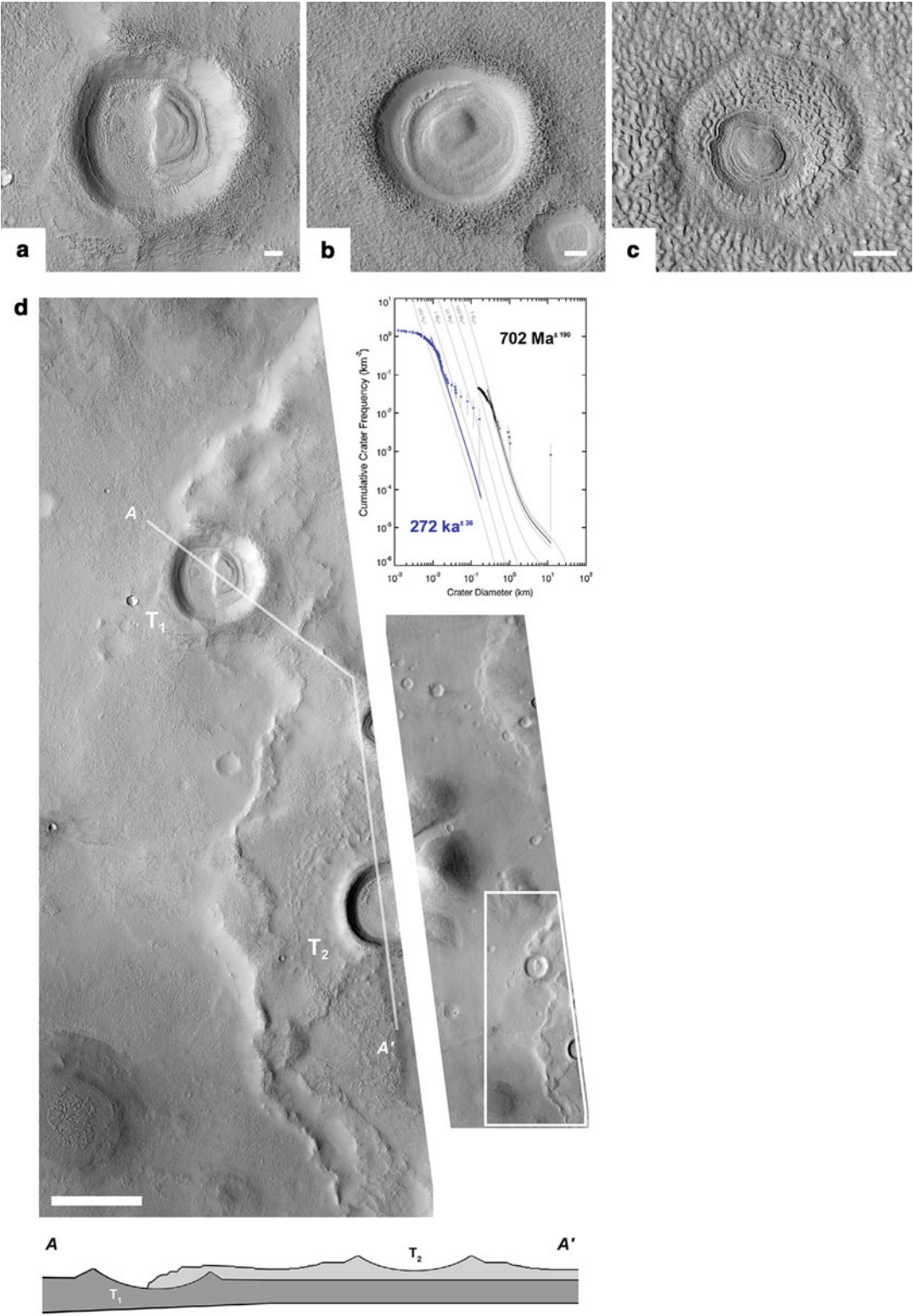


Fig. 21 (continued)

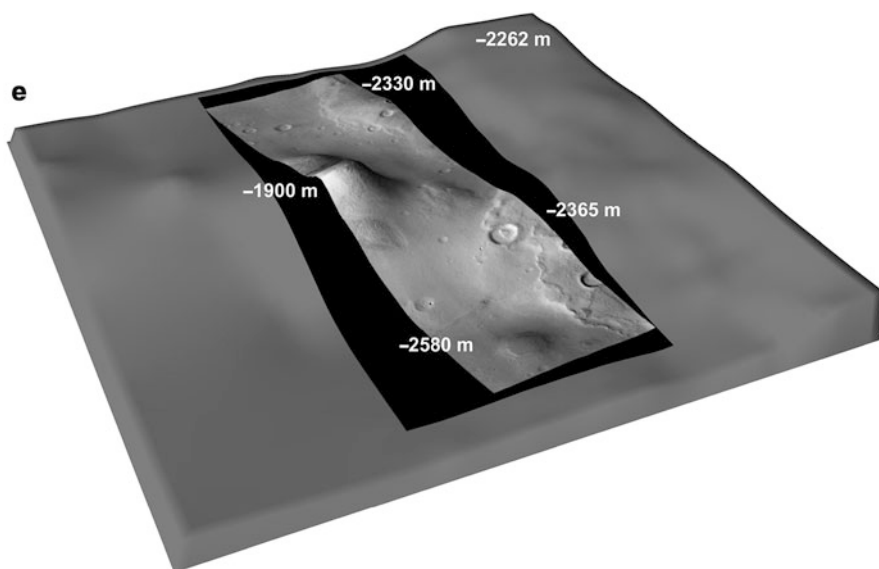


Fig. 21 “Ring-mold” craters (RMC) in LVF in Nilosyrtris and Deuteronilus Mensae. (a) Partly formed RMC showing sedimentary origin by lateral accretion (see text and d for context). Note softening of crater rim on the right and unaffected rim on the left (b) RMC displaying characteristic layered interior-fill. (c) RMC, showing near-complete fill of basin interior. This A-B-C sequence is tentatively suggested to show the evolution of this landform: an impact basin progressively filled by LVF of clastic, sedimentary origin (“A”), a basin filled with LVF with a softened though still-discernible crater rim (“B”), and an impact basin completely filled with extensively pitted, thamnastroid LVF, whose rim is almost completely effaced by deposition (“C”). Scale bars = 100 m. (a) ESP_016707_2180, 29 cm/px, 38°N/69°E; (b) ESP_017867_2195, 59 cm/px, 39°N/78°E; c: PSP_009799_2205, 60 cm/px, 40°N/24°E (All images NASA/JPL/University of Arizona). Ring-mold

craters and surface-age in Nilosyrtris Mensae. (d). Main image: context view of a, showing lobate LVF flows moving east–west (*right* to *left*) across surface of HiRISE ESP_016707_2180, and in inferred cross-section (A–A’, horizontal scale compressed for clarity). Inset plot shows crater counts of HiRISE CTX B18_016707_2192 in *black* and PSP_009799_2205 (i.e., Fig. 21c) in *blue*. See text for discussion of crater data. Isochrons (*gray symptotic lines*) from *left* to *right* = 100 kyr, 1 Myr, 10 Myr, 100 Myr and 1 Gyr. Scale bar = 1 km (NASA/JPL/University of Arizona). (e) Digital Terrain Model (DTM) of HiRISE ESP_016707_2180 superposed upon MOLA 128 px/degree topographical data. Elevations of two LVF flow lobes in d and surrounding topographical highs and low shown in meters below Mars datum. *Vertical scale* exaggerated 500 % (NASA/JPL/MOLA Science Team, NASA/JPL/University of Arizona)

of ring-mold form, and the other (“ T_2 ”) upon the flow, as indicated by superposition of radial ejecta atop the flow. Crater T_1 was obviously present before lateral emplacement of the overlying flow that partially fills it, and crater T_2 visibly postdates this flow by virtue of superposing it with impact ejecta.

A time-transgressive lithology formed on long-order cycles would form thick, laterally extensive sequences that vary in age regionally. A lower-resolution HiRISE CTX view of the Fig. 21d terrain shows the crater-superposing flows to extend N-S for >100 km, a count of craters at $D \geq 150$ m (Fig. 21e inset, black plot) yielding an age of ~ 700 Ma: a 2,000-fold age variation across the Deuteronilus-Nilosyrtris region. Further HiRISE coverage will reveal whether such an age is realistic, or if this 700 Ma terrain is a mélange of younger deposits, such as are exposed in Deuteronilus Mensae.

This simple stratigraphical observation – that the ring-mold morphology is post-depositional in origin and that the largest such craters underlie the LVF

(i.e., that LVF deposition transgresses time) – is absent in the literature, yet it is one that is of overwhelming importance for the origin of this terrain, its contained landforms, and our understanding of Mars climatic and geological history. A simplistic, “layer-cake” view of vertical succession takes no account of such diachronous stratigraphies, where surface age is decoupled from bulk crater statistics, the features we seek to date postdating the very indicators used for measurement. Consider craters stratigraphically, however, and impact crater chronology has the potential to exceed terrestrial levels of chronostratigraphical-geochronological resolution.

Martian impact crater chronology is based on lunar impact crater chronology, a system calibrated by absolute dating from Apollo and Luna sample return, but Mars is not the Moon in one major (and unanticipated) respect. There is increasing evidence for recent surface activity on Mars – and in more than just an erosive capacity, endogenic activity forming “new” surfaces within the substrate at a time far removed from deposition – activity that crosses the time boundaries (or isochrons) of crater statistics. This stratigraphical issue becomes a theoretical one when we consider that the surfaces affected by this dynamism are those “blank slate” surfaces that are used to inform and refine the martian PF.

In crater-count terms, such time transgression invalidates the assumption that a heavily cratered surface is a necessarily “old” surface. This diachroneity is easy to detect when expressed in crater-density differences, as in Fig. 9 (main text), or laterally, as in Fig. 21, but is subtler when expressed vertically, as in Fig. 20²⁸. The non-conformity in these figures is not captured by counting these craters nor by the allied concept of “crater-retention age,” where erosional loss of craters is inferred from the shape of the resulting crater SFD. Nothing about the crater numbers indicates the hidden breaks in the record, the geochronological utility of counting every visible crater (Hartmann et al. 1999, p. 586) substantially reduced. This analysis is not merely conceptual, as the way that we count these craters depends on our identification of the landforms therein. See the polygonal landforms in Fig. 20 as syn-depositional “cooling fractures” in lava, and the surface can be dated by standard crater-chronological methods. Recognize the polygonization as post-depositional, as determined stratigraphically, and the landform interpretation not only changes but the absolute age of polygonization also changes

²⁸It is said that sediment accumulation rates on Mars may have been high enough for impact craters to become fully buried, giving rise to the concept of the crust as a “cratered volume” rather than a “cratered surface” (Malin and Edgett 2000; Edgett and Malin 2002). As such, crater counts of surfaces may instead reflect exposure ages or crater-retention ages rather than absolute depositional ages (Grotzinger and Milliken 2012). Geologically, the “cratered volume” does not seem a particularly important concept because it will be the norm on the rocky planets of the inner Solar System. Certainly, there is no reason why a planet with an active erosional (thus depositional) cycle should only have “cratered surfaces” or why these should not evolve over time to become a “cratered volume” – this is simply the process of stratification in action, whether those cycles be volcanic, aeolian, or aqueous in nature. While this concept marks a growing awareness of the importance of stratigraphy for surface chronology, the problems of dating the landforms and terrains at the upper bound of such “cratered volumes” concern rather more than the exposure or retention ages that result from exhumation or crater losses.

(as it visibly postdates every crater). This is similarly the case for the “ring-mold” features of Fig. 21, where age significance is derived from a landform interpretation – a landform that is not strictly an impact structure and whose chronological significance relates to an earlier geological period. Thus we see how landform identification and impact crater counts are intimately intertwined, the quantitative rigor of the latter, often seen as a test of landform origin (“...a fundamental geological tool to interpret not only ages, but also the nature of geological processes altering the surface of Mars” (Hartmann and Werner 2010)), dependent on the inferred origin of the surface cratered.

One might ask whether the endogenous activity in Fig. 20 really matters – after all, the craters are still visible. As stated previously, to derive the impactor production SFD below D 40 km²⁹, one must assume that the surface cratered was once a “blank slate,” such that the craters observed today directly reflect the size spectrum of the impacting projectiles (Ivanov et al. 2002). It is this assumption that the diachronous surface of Fig. 20 affects. This surface is not the “ideal case” (of a surface accumulating craters before crater degradation processes change the population of those craters) because the intrusive activity is *destructive* of crater texture. Cover the unpolygonized fraction of the $D \sim 150$ m crater of Fig. 20c and the crater becomes invisible, the rim at lower left all but gone. We cannot know how many craters may have been lost to this process, but it does accord with the documented deficiency of craters in the small-crater branch of the SFD in these deposits (e.g., Hartmann and Berman 2000; Burr et al. 2002; Page et al. 2009). This deficiency has been central to a decade of refinement of the martian crater PF³⁰, the latest iteration of this system now “...a much

²⁹The impactor PF above D 40 km is derived observationally from the asteroidal database (astorb.dat). The sub-40 km PF is derived from a combination of observations of the crater SFD on presumed “blank-slate” surfaces and models of impactor production (e.g., the polynomial function of Neukum and the de-biased asteroidal population (Bottke et al. 2002)) and crater loss (e.g., the “Popova effect”).

³⁰The most recent modification to the isochrons results from the “Popova effect,” a model prediction that the crater population below 5 m will be reduced by ~ 90 % by atmospheric filtering (see Hartmann (2005), Table 2), a correction that has been built into the isochron system. In this context, cm-scale HiRISE observations of terrain in Elysium (Fig. 9, main text) show that the crater SFD remains steep and isochron-following down to the measurement limit (of a few-m), with an abundance of m-scale craters (formed by cm-scale impactors). If the SFD of bulk counts on composite surfaces in Elysium did not show such pronounced roll over at small crater diameters (Fig. 8, main text), would this model have been incorporated into the isochron system? Models of atmospheric filtering of incoming impactors are not new, and it was not so long ago that impact craters below $D = 50$ m were not thought to form on Mars as a consequence of atmospheric break-up of bolides (Carr & Viking Orbiter Team 1980; Barlow 1997). This model was eventually abandoned as an artifact of the resolution-limited look of the time, 4 m/px MOC imagery testing this prediction and finding no cut-off down to D 16 m (Hartmann et al. 1999). The ~ 16 m MOC resolution limit (i.e., 4 pixels across) for detection of circular features has now been improved by HiRISE, showing abundant, isochron-following impact crater formation at m-scale. Any difference between the lunar and martian small-crater SFD resulting from possible martian atmospheric effects (or greater loss of high speed ejecta from the atmosphere-less Moon), however, remains to be demonstrated (Hartmann (2005), cf. Popova et al. (2003)), Neukum and Ivanov (1994) seeing no difference in the crater SFD on these two bodies (see footnote 30)

better fit between isochron shapes and SFDs on young, pristine plains of Mars". Given the requirement for "blank-slate" surfaces to derive the crater PF and an isochron system refined with an isochronous lava target in mind, the chronological influence of this diachronous activity is significant.

This inconsistency between the expected and observed crater SFD has been highlighted by a number of workers, where the consequential refinements to the isochron system, the nature of the martian PF at small crater-diameter, and even the validity of the entire isochron system itself have all been called into question (McEwen et al. 2005; Plescia 2005b; Malin et al. 2006). In no case have these age inconsistencies been connected with the geology of the Type region on which this chronology rests. A robust theory, well corroborated by calibration from lunar sample return and observations of the present-day martian cratering rate errs at small-crater diameter because of a conception of geology that sees synchronous surfaces where only diachronous, unconformity-bound ones exist. The assumed fidelity of surfaces formed of isochronous lavas builds this deficiency of craters into the system, being seen as a reflection of the number of impactors arriving at the martian surface, the isochrons changed accordingly – despite the fact that the Moon and Mars are bombarded by the same impactor population³¹, the lunar reference showing no such flattening at comparable (Copernican-Amazonian) age (König et al. 1977; Moore et al. 1980; Neukum et al. 2001; Ivanov et al. 2001).

All of this has practical implications for the way that landform ages are calculated on Mars. As Fig. 22 shows, the effect of the changes to the isochrons is to significantly decrease the number of craters required for a surface to be of a certain age – 10 to 100 times less for a 1 Ma-old surface at the 16 m crater diameter shown (Fig. 22, black squares). What is not immediately apparent is that a surface previously dated at 1 Ma using the 1999 isochron iteration (i.e., a surface containing between 10 and 100 craters/km² ["A"]) would now be given an age 10–100 times *greater* for the same density of craters using the 2004 iteration ["B"]. These modifications change the chronological significance of the data gathered in a terrain that dynamically alters the crater population, and do so at those diameters where this alteration has its greatest effect, this small-crater fraction where data for the lunar PF are lacking, the measurable data for the lunar mare steep-branch applicable only down to $D \sim 250$ m, the maria saturated with craters below that size (Hartmann and Gaskell 1997).

Of course, craters are counted across the full diameter range, not just at this small size, but there are few if any craters larger than 100 m on the youngest terrains that are of most interest for studies of recent surface activity on Mars (Mustard et al. 2001; Milliken et al. 2003), such as the VFF of Fig. 11. Clearly, if our stratigraphical understanding of the surface cratered is incomplete, then the potential for skewing chronological inferences based on the crater SFD is great, with scope for age-mis correlation planet-wide. These inferences then feed back into the geology, the deviations from the expected SFD used to

³¹Neukum and Ivanov (1994) arguing that the crater SFD is empirically the same on both the Moon and Mars (after allowing for scaling).

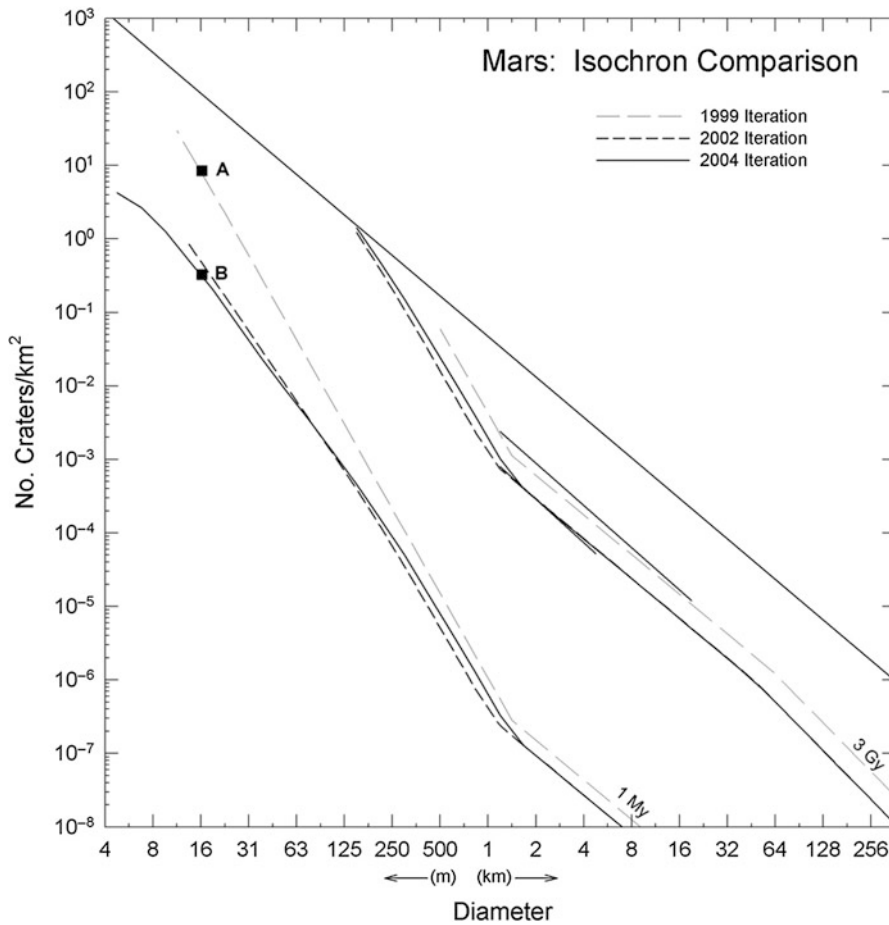


Fig. 22 Evolution of the martian isochron system over the past decade. Points “A” and “B” described in the text. Base figure available online at <http://www.psi.edu/epo/isochrons/chron04b.html>

expand geology in a circular argumentation that defines chronology on the basis of an assumed geology and then derives a geological history on the basis of that chronology. Neither is this just a problem for Mars, as linking the histories of individual planets and the Moon provides the framework for understanding the chronology of the entire Solar System (Barlow et al. 2007).

Observed anywhere else in the Solar System, the difference in crater density in Fig. 9 (main text) would indicate units of separate age. Yet because this surface is considered to have been deposited in a “geological instant” (Jaeger et al. 2010; Dundas et al. 2010), the crater population must be reinterpreted to remain consistent with that interpretation by positing that different areas of a single lithology can prohibit 95 % of craters in the observed diameter range from forming. Such efforts to protect this hypothesis from refutation compromise a dating technique unique in geochronology – that surfaces can be dated visually is a powerful tool, quite unlike anything in terrestrial geology (were we to try dating a random, unfossiliferous geological Formation on Earth by visual means, we would not get very far). Controversial

suggestions have a role in the advancement of science by questioning assumptions and paradigms, but this proposal makes selective observations in the service of a single genetic hypothesis – one whose defining landforms are all shown to be younger than their host geology and form in such disparate deposits as presumed lava flows and Viscous Flow Features. If we permit landforms to arbitrarily disobey the principles of superposition, sanction the spread in derived ages by postulating burial of craters by lava as circumstances require, else allow undefined material properties to render parts of those same landforms immune to impact, then this hypothesis becomes too flexible to evaluate by geological observation, and we have gone beyond empiricism.

Such advocacy science has a serious corollary for planetary geology. If we are free to ignore part of the impact crater population when it does not result in the distribution expected, then we undermine the very basis for dating planetary surfaces by crater counts, reliant as this is on the assertion that impact cratering is independent of lithology. If it is not, then we have no valid basis for deriving surface ages from the crater SFD on any planetary body other than the Moon (which we have visited, and whose lithology has been confirmed), as a lithology-dependent impact crater population is no longer an independent measure of the passage of time.

It was suggested in Introduction that crater counts made across multiple geological horizons will have zero age-significance at the Unit level (as such counts include craters formed many millions of years before the surface we wish to date). This is exemplified by diachronous geological units such as Figs. 20 and 21, where a standard count does not date the upper-bound of these surfaces *at all*. Discriminate one horizon from another by observed relative-age, however, and stratigraphically controlled crater counts can provide absolute-age information unavailable from an isochronous count, a surface assumed to be static and 200 Ma in age (Fig. 20b, black plot) shown to be dynamic and active within the last few hundred ka when craters are counted stratigraphically (Fig. 20b, red plot). This relative-age constraint is not simply a geological “rule-of-thumb”, separate from the business of impact crater chronology, but a fundamental aspect of the accurate determination of surface age. Conceptually, some see surface dating by crater counts as inherently stratigraphical in nature, a story to be read in “cratered volumes” (e.g., Malin et al. 2006; Grotzinger and Milliken 2012), while others view that stratigraphy is something to be derived *from* a crater count, such crater data considered to have “...*the potential to clarify geological processes and timescales, and even to investigate vertical structure and/or processing within the stratigraphic column*” (Hartmann and Werner 2010). To the geologist, it is a given that chronology derives from geology, for only unique rock-types may be defined by their age.

A return to the original stratigraphical basis for this dating method (Gilbert 1893; Shoemaker and Hackman 1962; Wilhelms et al. 1987) would contribute much, making crater counting the “safe” way (Neukum et al. 2001) to date planetary surfaces that it is currently believed to be. The landform analyses that are the subject of this encyclopedia could only benefit from such unfettered inquiry, but to employ such reasoning one must first allow that there is more to surface chronology than just crater numbers and more to landform analysis than surface morphology and analogies of form.

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References

- Anderson RC, Dohm JM, Golombek MP, Haldemann A, Franklin BJ, Tanaka K, Lias J, Peer B (2001) Significant centers of tectonic activity through time for the western hemisphere of Mars. *J Geophys Res* 106:20563–20585
- Baker DMH, Head JW, Marchant DR (2010) Flow patterns of lobate debris aprons and lineated valley fill north of Ismeniae Fossae, Mars: evidence for extensive mid-latitude glaciation in the Late Amazonian. *Icarus* 207:186–209
- Bandfield JL (2002) Global mineral distributions on Mars. *J Geophys Res* 107(E6):5042. doi:10.1029/2001JE001510
- Bandfield JL, Hamilton VE, Christensen PR (2000) A global view of martian surface compositions from MGS-TES. *Science* 287:1626–1630
- Barlow NG, Schenk P, Bierhaus EB (2007) Issues in planetary chronology. *Eos, Trans AGU* 88(18):199
- Barlow NG (1997) Mars. *Encyclopedia of Planetary Science*. Springer, New York, pp 430–432. doi:10.1007/1-4020-4520-4_237
- Berman DC, Hartmann WK (2002) Recent fluvial, volcanic, and tectonic activity on the Cerberus plains of Mars. *Icarus* 159:1–17
- Bird P (1986) Tectonics of the terrestrial planets. In: Kivelson MG (ed) *The solar system: observations and interpretations*, Rubey volume 4. Prentice Hall, Englewood Cliffs, pp 176–206
- Bottke WF, Morbidelli A, Jedicke R, Petit JM, Levison HF, Michel P, Metcalfe TS (2002) Debaised orbital and absolute magnitude distribution of the near Earth objects. *Icarus* 156:399–433
- Boyce JM (1976) Ages of flow units in the lunar nearside maria based on Lunar Orbiter IV photographs. *Proc Lunar Planet Sci Conf* 7:2717–2728
- Buczowski DL et al (2012) Large-scale troughs on Vesta: a signature of planetary tectonics. *Geophys Res Lett* 39, L18205. doi:10.1029/2012GL052959
- Burr DM, Grier JA, McEwen AS, Keszthelyi LP (2002) Repeated aqueous flooding from the Cerberus Fossae: evidence for very recently extant, deep groundwater on Mars. *Icarus* 159:53–73
- Burr DM, Soare RJ, Wan Bun Tseung J-M, Emery JP (2005) Young (late Amazonian), near-surface, ground ice features near the equator, Athabasca Valles, Mars. *Icarus* 176:56–73
- Carr MH (1981) *The surface of Mars*. Yale University Press, New Haven, 232 p
- Carr MH, Viking Orbiter Team (1980) *Viking Orbiter View of Mars* (Spec Pub 441, NASA, Washington, DC)
- Chamberlin TC (1897) The method of multiple working hypotheses. *J Geol* 5:837–848
- Chapman CR (2011) *Lunar Cratering Processes*. Southwest Research Institute University of Colorado. http://isotope.colorado.edu/~geol5700/week_14b.pdf
- Christensen PR, Bandfield JL, Smith MD, Hamilton VE, Clark RN (2000) Identification of a basaltic component on the Martian surface from Thermal Emission Spectrometer data. *J Geophys Res* 105:9609–9621
- Collins GC, McKinnon WB, Moore JM, Nimmo F, Pappalardo RT, Prockter LM, Schenk PM (2010) Tectonics of the outer planet satellites. In: Watters TR, Schultz RA (eds) *Planetary tectonics*. Cambridge University Press, Cambridge, UK
- Denevi BW et al (2009) The evolution of Mercury's crust: a global perspective from MESSENGER. *Science* 324:613–618
- Dickinson WR (2003) The place and power of myth in geoscience: an associate editor's perspective. *Am J Sci* 303:856–864. doi:10.2475/ajs.303.9.856

- Diez B, Feldman WC, Mangold N, Baratoux D, Maurice S, Gasnault O, d'Uston L, Costard F (2009) Contribution of Mars Odyssey GRS at central Elysium Planitia. *Icarus* 200:19–29
- Dohm JM, Ferris JC, Baker VR, Anderson RC, Hare TM, Strom RG, Barlow NG, Tanaka KL, Klemaszewski JE, Scott DH (2001) Ancient drainage basin of the Tharsis region, Mars: potential source for outflow channel systems and putative oceans or paleolakes. *J Geophys Res* 106:32943–32958
- Dohm JM, Baker VR, Maruyama S, Anderson RC (2007) Traits and evolution of the Tharsis superplume, Mars. In: Yuen DA, Maruyama S, Karato S-I, Windley BF (eds) *Superplumes: beyond plate tectonics*. Springer, London, pp 523–537
- Dundas CM, Keszthelyi LP, Bray VJ, McEwen AS (2010) The cratering record of young platy-ridged lava on Mars: implications for material properties. *Geophys Res Lett* 37, L12203. doi:10.1029/2010GL042869
- Edgett KS, Malin MC (2002) Martian sedimentary rock stratigraphy: outcrops and interbedded craters of northwest Sinus Meridiani and southwest Arabia Terra. *Geophys Res Lett* 29:2179
- Fagents SA, Lanagan P, Greeley R (2002) Rootless cones on Mars: a consequence of lava-ground ice interaction. *Geol Soc (Lond)* 202:295–317. doi:10.1144/GSL.SP.2002.202.01.15, Special Publications 200.
- Fassett CI et al (2009) Caloris impact basin: exterior geomorphology, stratigraphy, morphometry, radial sculpture, and smooth plains deposits. *Earth Planet Sci Lett* 285:297–308
- French H (1996) *The periglacial environment*, 2nd edn. Longman, Essex
- Frey H, Roark JH, Shockey KM, Frey EL, Sakimoto SHE (2002) Ancient lowlands on Mars. *Geophys Res Lett* 29:1384. doi:10.1029/2001GL013832
- Gilbert GK (1886) The inculcation of scientific method by example. *Am J Sci* 31:284–299
- Gilbert GK (1893) The Moon's face, a study of the origin of its features. *Philos Soc Washington Bull* 12:241–292
- Goudy CL (2002) Wrinkle ridges of Hesperia Planum, Mars: implications for the evolution of ridged plains. State University of New York, Buffalo, p 260. doi:oclc/50442101
- Gould SJ (2003) *The Hedgehog, the Fox, and the Magister's Pox*. Harmony Books, New York
- Greeley R, Guest JE (1983) *Geologic map of the Shakespeare quadrangle of Mercury (H-3)*. Map I-1408, Misc Investigations Ser, US Geological Survey, Denver
- Greeley R, Guest JE (1987) *Geologic map of the eastern equatorial region of Mars*, US Geol Surv Misc Invest Map, I-1802-B, scale:15,000,000
- Grotzinger J, Milliken RE (2012) The sedimentary record of Mars. In: Grotzinger J, Milliken RE (eds) *Mars sedimentology*. SEPM Special Publication, vol 102, pp 1–48
- Hamilton WB (2005) Plumeless Venus preserves ancient impact-accretionary surface. In: Foulger GR, Natland JH, Presnall DC, Anderson DL (eds) *Plates, plumes, and paradigms*, vol 388, Geological Society of America Special Paper, pp 781–814
- Hamilton WB (2007) *An alternative Venus*: Geological Society. America Special Paper 430, p 879–914
- Hamilton VE, Christensen PR, McSween HY Jr, Bandfield JL (2003) Searching for the source regions of martian meteorites using MGS TES: integrating martian meteorites into the global distribution of igneous materials on Mars. *MAPS* 38(6):871–885
- Hansen VL (2000) Geologic mapping of tectonic planets. *Earth Planet Sci Lett* 176:527–543
- Hartmann WK (1999) Martian cratering VI: Crater count isochrons and evidence for recent volcanism from Mars Global Surveyor. *Meteorit Planet Sci* 34:167–177
- Hartmann WK (2005) Martian cratering. 8. Isochron refinement and the chronology of Mars. *Icarus* 174:294–320
- Hartmann WK (2006) Using martian craters to derive chronologic information. *Planetary Chronology Workshop 2006*, # 601.
- Hartmann WK, Berman DC (2000) Elysium Planitia lava flows: Crater count chronology and geological implications. *J Geophys Res* 105:15011–15026
- Hartmann WK, Gaskell RW (1997) Planetary cratering 2: studies of saturation equilibrium. *Meteorit Planet Sci* 32:109–121

- Hartmann WK, Neukum G (2001) Cratering chronology and the evolution of Mars. In: Kallenbach R, Geiss J, Hartmann WK (eds) *Chronology and evolution of Mars*. Space science review, vol 96. Kluwer Academic, Norwell, pp 165–194
- Hartmann WK, Werner SC (2010) Martian Cratering 10. Progress in use of crater counts to interpret geological processes: examples from two debris aprons. *Earth Planet Sci Lett* 294(3):230–237
- Hartmann WK et al. (1981) Chronology of planetary volcanism by comparative studies of planetary cratering. In: *Basaltic volcanism on the terrestrial planets*, Chapter 5. Pergamon Press, pp 1049–1127
- Hartmann WK et al (1999) Evidence for recent volcanism on Mars from crater counts. *Nature* 397:686–689
- Head JW, Marchant DR, Agnew MC, Fassett CI, Kreslavsky MA (2006) Extensive valley glacier deposits in the northern mid-latitudes of Mars: evidence for late Amazonian obliquity-driven climate change. *Earth Planet Sci Lett* 241:663–671. doi:10.1016/j.epsl.2005.11.016
- Head JW, Chapman CR, Domingue DL, Hawkins SE III, McClintock WE, Murchie SL, Prockter LM, Robinson MS, Strom RG, Watters TR (2007) The geology of Mercury: the view prior to the MESSENGER mission. *Space Sci Rev* 131:41–84
- Head JW et al (2008) Volcanism on Mercury: evidence from the first Messenger flyby for extrusive and explosive activity and the volcanic origin of plains. *Earth Planet Sci Lett* 285:227–242
- Hedberg HD (ed) (1976) *International stratigraphic guide – a guide to stratigraphic classification, terminology, and procedure*. Wiley, New York
- Hiesinger H, Head JW III, Wolf U, Jaumann R, Neukum G (2003) Ages and stratigraphy of mare basalts in Oceanus Procellarum, Mare Nubium, Mare Cognitum, and Mare Insularum. *J Geophys Res* 108:5065. doi:10.1029/2002JE001985
- Holt JW et al (2008) Radar sounding evidence for buried glaciers in the Southern mid-latitudes of Mars. *Science* 322:1235–1238
- Hutton J (1788) *Theory of the Earth*. *Trans R Soc Edinb* 1:209–304
- International Subcommission on Stratigraphic Classification (ISSC), 1976. *International Stratigraphic Guide - A guide to stratigraphic classification, terminology, and procedure* (H.D. Hedberg, ed.), John Wiley and Sons, New York, 200 p
- Ivanov MA, Head JW (2001) Global geological map of Venus. *Planet Space Sci* 59:1559–1600
- Ivanov BA, Neukum G, Wagner R (2001) Distributions of planetary impact craters and asteroids. In: Marov H (ed) *Collisional processes in the solar system*. Kluwer, Dordrecht, pp 1–34
- Ivanov BA, Neukum G, Bottke WF, Hartmann WK (2002) The comparison of size–frequency distributions of impact craters and asteroids and the planetary cratering rate. In: Bottke WF, Cel-lino A, Paolicchi P, Binzel RP (eds) *Asteroids III*. University of Arizona Press, Tucson, pp 89–101
- Jaeger WL, Keszthelyi LP, McEwen AS, Dundas CM, Russell PS (2007) Athabasca Valles, Mars: a lava-draped channel system. *Science* 317:1709–1711
- Jaeger WL, Keszthelyi L, McEwen AS, Titus TN, Dundas C, Russell PS (2008) Response to comment on “Athabasca Valles, Mars: a lava-draped channel system”. *Science* 320:1588c
- Jaeger WL, Keszthelyi LP, Skinner JA, Milazzo MP, McEwen AS, Titus TN, Rosiek MR, Galuszka DM, Howington-Kraus E, Kirk RL (2010) Emplacement of the youngest flood lava on Mars: a short, turbulent story. *Icarus* 205:230–243
- Jakosky BM (1979) The effects of nonideal surfaces on the derived thermal properties of Mars. *J Geophys Res* 84:8252–8262
- Jakosky BM, Mellon MT, Kieffer HH, Christensen PR, Varnes ES, Lee SW (2000) The thermal inertia of Mars from the Mars Global Surveyor Thermal Emission Spectrometer. *J Geophys Res* 105:9643–9652
- Johnson D (1933) Role of analysis in scientific investigation. *Geol Soc Am Bull* 44:461–493
- Jurdy DM, Stoddard PR (2007) The coronae of Venus: impact, plume or other origin? In: Foulger GR, Jurdy DM (eds) *GSA Specific Paper #430, Plates, Plumes, & Planetary Processes*, 859–878

- Keszthelyi LP, Jaeger WL, Dundas CM, Martinez-Alonso S, McEwen AS, Milazzo MP (2010) Hydrovolcanic features on Mars: preliminary observations from the first Mars year of HiRISE imaging. *Icarus* 205:211–229. doi:10.1016/j.icarus.2009.08.020
- Keszthelyi L, McEwen AS, Thordarson T (2000) Terrestrial analogs and thermal models for martian flood lavas. *J Geophys Res* 105:15027–15049
- Keszthelyi L, Burr DM, Herkenhoff K, Gaddis L (2004) Systematic rock classification in a data-poor environment: application to Mars. *Lunar Planet Sci XXXV*, abstract #1633, Houston
- König B, Neukum G, Fechtig H (1977) Recent lunar cratering: absolute Ages of Kepler, Aristarchus. *Tycho Lunar Planet Sci VIII*:555–557
- Korotev RL (2005) Lunar geochemistry as told by lunar meteorites. *Chemie Erde* 65:297–346
- Kress AM, Head JW (2008) Ring-mold craters in lineated valley fill and lobate debris aprons on Mars: evidence for subsurface glacial ice. *Geophys Res Lett* 35, L23206. doi:10.1029/2008GL035501
- Lawrence DJ et al (2010) Identification and measurement of neutron-absorbing elements on Mercury's surface. *Icarus* 209:195–209
- Malin MC, Edgett KS (2000) Sedimentary rocks of early Mars. *Science* 290:1927–1937
- Malin MC, Edgett KS, Posiolova LV, McColley SM, Noe Dobrea EZ (2006) Present-day impact cratering rate and contemporary gully activity on Mars. *Science* 314:1573–1577
- Mangold N (2003) Geomorphic analysis of lobate debris aprons on Mars at Mars Orbiter Camera scale: evidence for ice sublimation initiated by fractures. *J Geophys Res* 108(E4):8021. doi:10.1029/2002JE001885
- McEwen AS et al (2005) The rayed crater Zunil and interpretations of small impact craters on Mars. *Icarus* 176:351–381
- McGill GE (1971) Attitude of fractures bounding straight and arcuate lunar rilles. *Icarus* 14:53–58
- McGill GE, Stofan ER, Smrekar SE (2010) Venus tectonics. In: Watters TR, Schultz RA (eds) *Planetary tectonics*. Cambridge University Press, Cambridge, UK
- Melosh HJ (1989) Impact cratering: a geologic process, vol 11, *Oxford Monographs on Geology and Geophysics*. Oxford University, New York
- Melosh HJ, McKinnon WB (1988) The tectonics of Mercury. In: Vilas F, Chapman CR, Matthews MS (eds) *Mercury*. University of Arizona Press, Tucson
- Milliken RE, Mustard JF, Goldsby DL (2003) Viscous flow features on the surface of Mars: observations from high resolution Mars Orbiter Camera [MOC] images. *J Geophys Res* 108:5057
- Moore HJ, Boyce JM, Hahn DA (1980) Small impact craters in the lunar regolith-their morphologies, relative ages, and rates of formation: the Moon and the Planets, vol 23, no 2, pp 231–252
- Murchie SL et al (2008) Geology of the Caloris basin, Mercury: a new view from MESSENGER. *Science* 321:73–76
- Mustard JF, Cooper CD, Rifkin FK (2001) Evidence for recent climate change on Mars from the identification of youthful near-surface ground ice. *Nature* 412:411–414
- Neukum G, Ivanov BA (1994) Crater size distributions and impact probabilities on Earth from lunar, terrestrial-planet, and asteroid cratering data. In: Gehrels T (ed) *Hazards due to comets and asteroids*. University of Arizona Press, Tucson, pp 359–416
- Neukum G, Ivanov BA, Hartmann WK (2001) Cratering records in the inner solar system in relation to the lunar reference system. In: Kallenbach R, Geiss J, Hartmann WK (eds) *Chronology and evolution of Mars*, vol 96, *Space Sci Rev*. Kluwer, Norwell, pp 55–86
- Neukum G, Jaumann R, Hoffmann H, Hauber E, Head JW, Basilevsky AT, Ivanov BA, Werner SC, van Gasselt S, Murray JB, McCord T (2004) Recent and episodic volcanic and glacial activity on Mars revealed by the high resolution stereo camera. *Nature* 432:971–979
- Nikoleva OV, Ronca LB, Bazilevskiy AT (1986) Circular structures on the plains of Venus as indicating geological history. *Geochem Int* 23(9):1–11
- Nyquist LE, Borg LE, Shih CY (1998) The Shergottite age paradox and the relative probabilities for martian meteorites of differing ages. *J Geophys Res* 103:31445–31455

- Page DP (2007) Recent low-latitude freeze–thaw on Mars. *Icarus* 189:83–117
- Page DP (2008) Comment on “Athabasca Valles, Mars: a lava-draped channel system”. *Science* 320:1588b
- Page DP (2010a) Resolving the Elysium Controversy: an open invitation to explain the evidence. *Planet Space Sci* 58:1406–1413
- Page DP (2010b) Contribution of Mars Odyssey GRS and Mars Reconnaissance Orbiter CRISM at Elysium Planitia: a case of mistaken identity. *Planet Space Sci* 58:1404–1405
- Page DP, Murray JB (2006) Stratigraphical and morphological evidence for pingo genesis in the Cerberus plains. *Icarus* 183:46–54
- Page DP, Balme MR, Grady MM (2009) Dating martian climate change. *Icarus* 203:376–389
- Peirce CS (1878) Deduction, induction, and hypothesis. *Pop Sci Mon* 12:470–482
- Peirce CS (1896) The scientific attitude and fallibilism. In: Buchler J (ed) *The philosophy of peirce: selected writings*. Routledge and Keegan Paul, London, pp 42–59 (1940)
- Phillips RJ, Hansen VL (1994) Tectonic and magmatic evolution of Venus. *Annu Rev Earth Planet Sci* 22:597–654
- Pike RJ (1977) Size-dependence in the shape of fresh impact craters on the moon. In: Pepin RO, Merrill RB, Roddy DJ (eds) *Impact and explosion cratering*. Pergamon, New York, pp 489–509
- Platt JR (1964) Strong inference. *Science* 146:347–353
- Plescia JB (1990) Recent flood lavas in the Elysium region of Mars. *Icarus* 88:465–490
- Plescia JB (2005a) Cerberus Plains – source for the young SNCs? *Lunar Planet Sci XXX*, abstract #1627, Houston
- Plescia JB (2005b) Small-diameter martian craters: applicability for chronology—or not. *Lunar Planet Sci XXXVI*, abstract #2171, Houston
- Popova O, Nemtchinov I, Hartmann WK (2003) Bolides in the present and past martian atmosphere and effects on cratering processes. *Meteorit Planet Sci* 38:905–925
- Popper K (1963) *Conjectures and refutations: the growth of scientific knowledge*. Routledge, London
- Porco CC et al (2005) Imaging of Titan from the Cassini spacecraft. *Nature* 434:159–168
- Putzig NE, Mellon MT, Kretke KA, Arvidson RE (2005) Global thermal inertia and surface properties of Mars from the MGS mapping mission. *Icarus* 173:325–341
- Rogers D, Christensen PR (2003) Age relationship of basaltic and andesitic surface compositions on Mars: analysis of high-resolution TES observations of the northern hemisphere. *J Geophys Res* 108:5030
- Ross N, Harris C, Christiansen H, Brabham P (2005) Ground penetrating radar investigations of open system pingos, Adventdalen, Svalbard. *Nor J Geogr* 59(2):129–138
- Ruff SW, Christensen PR (2002) Bright and dark regions on Mars: particle size and mineralogical characteristics based on Thermal Emission Spectrometer data. *J Geophys Res* 107:5127
- Salvatore MR, Wyatt MB, Mustard JF, Head JW, Marchant DR (2010) Near-infrared spectral diversity of the Ferrar Dolerite in Beacon Valley, Antarctica: implications for martian climate and surface compositions. *Lunar Planet Sci XXXXI*, abstract #2290, Houston
- Schaber GG, McCauley JF (1980) Geologic map of the Tolstoj quadrangle of Mercury (H-8). Map I-1199, Misc Investigations Ser, US Geological Survey, Denver
- Schultz RA (1999) Understanding the process of faulting: selected challenges and opportunities at the edge of the 21st century. *J Struct Geol* 21:985–993
- Shoemaker EM, Hackman RJ (1962) Stratigraphic basis for a lunar time scale. In: Kopal Z, Mikhailov ZK (eds) *The Moon*. Academic, pp 289–300
- Smithson P, Addison K, Atkinson K (2002) *Fundamentals of the physical environment*, 5th edn. Routledge, London
- Solomon SC et al (2008) Return to Mercury: a global perspective on Messenger’s first Mercury flyby. *Science* 321:59–62
- Spiga A, Forget F (2009) A new model to simulate the Martian mesoscale and microscale atmospheric circulation: validation and first results. *J Geophys Res* 114, E02009. doi:10.1029/2008JE003242
- Stofan ER, Smrekar SE (2005) Large topographic rises, coronae, large flow fields, and large volcanoes on Venus: evidence for mantle plumes? In: Foulger GR, Natland JH, Presnall

- DC, Anderson DL (eds) *Plates, plumes, and paradigms*, Geological Society of America. Special Paper, vol 388, pp 841–861
- Stofan ER, Head JW, Grieve RAF (1985) Classification of circular features on Venus, in 1984 Report of planetary geology and geophysics program: NASA, pp 103–104
- Stofan ER, Tapper SW, Guest JE, Grinrod P, Smrekar SE (2001) Preliminary analysis of an expanded corona database for Venus. *Geophys Res Lett* 28:4267–4270
- Stöffler D, Ryder G (2001) Stratigraphy and isotope ages of lunar geologic units: chronological standard for the inner solar system. In: Kallenbach R, Geiss J, Hartmann WK (eds) *Chronology and evolution of Mars*, vol 96, *Space Science Review*. Kluwer, Norwell, pp 9–54
- Strom RG (1972) Lunar mare ridges, rings and volcanic ring complexes. *Mod Geol* 2:133–157
- Strom RG, Trask NJ, Guest JE (1975) Tectonism and volcanism on Mercury. *J Geophys Res* 80:2478–2507
- Strom RG, Chapman CR, Merline WJ, Solomon SC, Head JW (2008) Mercury cratering record viewed from MESSENGER's first flyby. *Science* 321:79–81
- Suppes P (1957) *Introduction to logic*, 1st edn. Dover Publications, New York
- Tanaka KL, Skinner JA, Hare TM (2005) Geologic map of the Northern Plains of Mars. USGS miscellaneous investigation series MAP I-2888
- Tanaka KL, Anderson R, Dohm JM, Hansen VL, McGill GE, Pappalardo RT, Schultz RA, Watters TR (2010) Planetary structural mapping. In: Watters TR, Schultz RA (eds) *Planetary tectonics*. Cambridge University Press, Cambridge, UK
- Vita-Finzi C, Howarth RJ, Tapper SW, Robinson CA (2005) Venusian craters, size distribution, and the origin of coronae. In: Foulger GR, Natland JH, Presnall DC, Anderson DL (eds) *Plates, plumes, and paradigms*, Volume Special Paper 388, Geological Society of America, pp 815–823
- von Bertalanffy L (1950) The theory of open systems in physics and biology. *Science* 111:23–29
- Watters TR (1988) Wrinkle ridge assemblages on the terrestrial planets. *J Geophys Res* 93:10236–10254
- Watters TR, Nimmo F, Robinson MS (2005) Extensional troughs in the Caloris basin of Mercury: evidence of lateral crustal flow. *Geology* 33:669–672
- Watters TR, McGovern PJ, Irwin RP III (2007) Hemispheres apart: the crustal dichotomy on Mars. *Annu Rev Earth Planet Sci* 35:621–652
- Watters TR, Solomon SC, Robinson MS, Head JW, Andre SL, Hauck SA, Murchie SL (2009a) The tectonics of Mercury: the view after Messenger's first flyby *Earth Planet. Sci Lett*. doi:10.1016/j.epsl.2009.01.025
- Watters TR, Murchie SL, Robinson MS, Solomon SC, Denevi BW, André SL, Head JW (2009b) Emplacement and tectonic deformation of smooth plains in the Caloris basin. *Mercury Earth Planet Sci Lett* 285:301–3119
- Werner SC (2009) The global martian volcanic evolutionary history. *Icarus* 201:44–68
- Whewell W (1840) *The philosophy of the inductive sciences, founded upon their history*. Cambridge University Press, Cambridge, UK
- Wilcox BB, Hamilton VE (2005) Themis observations of compositional variation in Elysium Planitia. *Lunar Planet Sci XXXVI*, abstract #1557, Houston
- Wilhelms DE (1976) Mercurian volcanism questioned. *Icarus* 28:551–558
- Wilhelms DE (1990) Geologic mapping. In: Greeley R, Batson RM (eds) *Planetary mapping*. Cambridge University Press, New York, pp 208–260
- Wilhelms DE, McCauley JF, Trask NJ (1987) The geologic history of the Moon. *US Geol Survey Prof Paper* 134.
- Wyatt MB, McSween HY (2002) Spectral evidence for weathered basalt as an alternative to andesite in the northern lowlands of Mars. *Nature* 417:263–266
- Zahnle K, Schenk P, Levison H, Dones L (2003) Cratering rates in the outer solar system. *Icarus* 163:263–289
- Zimbelman JR (2001) Image resolution and evaluation of genetic hypotheses for planetary landscapes. *Geomorphology* 37:179–199

Feature Classes

Aeolian Features

Entries that discuss feature types entirely or partly formed by aeolian processes:

Aeolian Deposits	Longitudinal Dunes (or Linear Dunes)
Aeolian Dust Deposits	Lunette
Aeolian Ripple	Megabarchan
Aeolian Sand Deposits	Megadune
Barchan	Megaripple
Barchanoid Ridge	Microdune
Bedform	Nebkha
Blowout Dune and Hollow	Niveo-Aeolian Deposits
Climbing Dune	Obstacle Dunes and Obstacle Marks
Current Crescent and Scour Flute	Parabolic Dune
Dark Deposits (Mars)	Periodic Bedrock Ridge (Mars)
Dark Splotch (Albedo Feature)	Polar Layered Deposits
Dome Dune	Polar Spiral Troughs (Mars)
Drift Deposit (Aeolian)	Rectilinear Dune
Drop Dune	Reticulate Ridges
Dune	Reticulate Terrain (Mars, Hellas)
Dune Apron	Reversing Dune
Dune Convoy	Ridge in Current Shadow
Dune Field Patterns (Aeolian)	Ripple
Dune System	Sand Patch
Dust Devil Track	Sand Ramp
Echo Dune	Sand Sheet
Emissivity Parabola	Sastruga
Erg	Scour Marks
Falling Dune	Seif Dune
Frame Dune	Snow Megadune
Frost Streak (Mars)	Source-Bordering Dune
Indurated Dune (Mars)	Star Dune
Interdune	Streamer
Large Dark Dune	Transverse Aeolian Ridge (TAR)
Lee Dune	Transverse Dunes
	Transverse Ridge
	Ventifact (Faceted Rock)
	Wall Dune
	Wedge Dune
	Whaleback Dune

Wind Streak
Yardang
Zibar

Albedo Features

Entries that discuss features identified by their albedo:

“Drainage Pattern” (Trojan Satellites of Saturn)
Albedo Dichotomy or Color Dichotomy
Albedo Feature
Cryptic Region
Dark Splotch (Albedo Feature)
Lenticula
Lineament
Mid-Latitude Dark Linear Feature (Titan)
Mottled Terrain (Europa)
Red Spot (Moon)
Wispy Terrain

Collapse Features

Entries that discuss features entirely or partly formed by collapse, catastrophic outflow, or loss of volatiles:

Caldera
Central-Pit Crater
Chaotic Crater Floor (Mars)
Chaotic Terrain (Mars)
Chaotic Terrain (Venus)
Clusters of Small Closely-Spaced Pits in Ejecta Related Deposits
Hollows (Mercury)
Pit Crater
Pit Crater Chain, Pit Chain
Skylight

Deposits

Entries that discuss features entirely or partly formed by the accumulation of nonmagmatic material on the surface.

Bright Plains (Icy Moons)
Bright Plains (Io)

Delta
Diffuse Deposit (Io)
Distributary System Deposits
Dorsa Argentea Formation
Dust Pond
Ejecta Deposit
Emissivity Parabola
Faint Dark Halo
Festoon (Sedimentary)
Fine-Ejecta Halo
Friable Layered Deposits
Lag Deposit
Lateral Accretion Patterns
Latitude Dependent Mantle (in HiRISE) (with No Stratigraphically Associated Periglacial Landforms)
Latitude Dependent Mantle (in MOC) (with Stratigraphically Associated Periglacial Landforms)
Light Toned Deposit
Mud Volcano
Niveo-Aeolian Deposits
Perched Crater
Plume Deposit (Types)
Polar Layered Deposits
Pyroclastic Deposits
Radar-Dark Parabola
Sedimentary Rocks (Mars)
Spherule
Splotch (Radar)
Stealth Feature (Radar, Mars)
Subaqueous Fan
Valley Terrace
Volcaniclastic Deposits

Desiccation Features

Entries that discuss feature types entirely or partly formed by desiccation:

Contraction Crack
Crater Floor Polygons (Mars)
Desiccation Crack Polygon
Giant Polygons (Mars)
Polygonal Patterned Ground
Synaeresis (Syneresis) Crack Polygons
Shrinkage Crack Polygon

Liquefaction and Fluidization Features

Entries that discuss feature types entirely or partly formed by liquefaction or fluidization:

Clastic Dike
Crater Outflow
Double Layer Ejecta
Flow
Lateral Spread
Layered Ejecta
Light Plains (Moon)
Multiple Layer Ejecta
Pancake Ejecta
Rampart Ejecta
Slide

Features of Diverse, Complex or Uncertain Origin

Entries that discuss feature types that formed by multiple processes, or can be produced by several different processes or whose origin is not well understood and debated:

Albedo Dichotomy or Color Dichotomy
Albedo Feature
Balanced Rock
Banded Terrain (Mars, Hellas)
Basal Scarp
Boulder Field
Bright Plains (Icy Moons)
Cantaloupe Terrain
Cavernous Weathering Features
Chaotic Terrain (Europa)
Circumferential Depression
Columnar Joints
Crater Floor Polygons (Mars)
Dark Dune Features
Desert Pavement
Equatorial Features
Equatorial Ridge (Lapetus)
Fretted Channel
Fretted Terrain
Grooves (Irregular Body)
Gutta

Honeycomb Terrain (Mars, Hellas)
Hummocky Terrain
Interior Layered Deposit
Karst-Like Landforms
Knobby Terrain
Light Toned Deposit
Lineament
Linear Ridge Types (Various Origins)
Lowland (Mars)
Martian Hemispheric Dichotomy
Mesoscale Positive Relief Landforms (Mars)
Mid-Latitude Dark Linear Feature (Titan)
Moat (Type)
Pedestal Rock
Pit
Pit Crater
Plateau Degradation Landforms
Polar Chasms (Mars)
Polar Undulations (Mars)
Pond, Lake, Sea and Ocean
Radar Feature
Regolith
Streamlined Island
Surficial Crust
Terrace
Tongue-Shaped and Arcuate Ridges Inside
 Depressions (Mars)
Transition Topography (Mars)
Tree Bark Texture

Features of Earth

Entries that discuss feature types that are found only on Earth and have no unambiguous planetary analogs proposed:

Brim
Grounding Line System
Lunette
Marine-Target Crater
Nebkha
Nunatak
Oceanic Impact (Water Cavity)
Parabolic Dune
Seamount
Snow Megadune
Wet Patch (Antarctica)
Whaleback Dune
Zibar

Features of Europa and Other Icy Moons

Entries that discuss feature types that are only found on Europa and other icy moons or are characteristic features there. Not body-specific feature types are not listed.

Band (Europa)
 Bright Plains (Icy Moons)
 Chaotic Terrain (Europa)
 Cycloid (Europa)
 Double Ridge (Europa)
 Faulted Band (Europa)
 Fracture (Europa)
 Lenticula
 Lineated Band (Europa)
 Mottled Terrain (Europa)
 Ridge (Icy Moons)
 Ridge Complex (Europa)
 Ridged Band (Europa)
 Single Ridge (Europa)
 Smooth Band (Europa)
 Triple Band (Europa)
 Wedge Shaped Band (Europa)

Features of Ganymede or Callisto

Entries that discuss feature types that are only found on Ganymede or Callisto:

Anomalous Dome Crater
 Central Dome Crater
 Furrow (Icy Moon)
 Groove (Ganymede)
 Multiring Structure, Valhalla Type
 Palimpsest
 Penepalimpsest

Features of Io

Entries that discuss feature types that are only found on Io or are characteristic features of Io. Not body-specific feature types are not listed.

Bright Plains (Io)
 Diffuse Deposit (Io)

Eruptive Center (Io)
 Layered Plains (Io)
 Mountain (Io, Tectonic)
 Steep Sided Dome (Io)
 Volcanic Mountain (Io)

Features of Mars

Entries that discuss feature types that are only found on Mars or are characteristic features of Mars. Not Mars-specific impact crater types and other ubiquitous or not body-specific features are not listed.

“Brain Terrain”
 Amphitheater-Headed Valley (Mars, Earth)
 Arcuate Ridge Set
 Banded Terrain (Mars, Hellas)
 Basal Scarp
 Boulder-Halo (Crater)
 Canal (Mars)
 Canyon Lake (Mars)
 Central Mound Crater (Ice Associated)
 Chaotic Crater Floor (Mars)
 Chaotic Terrain (Mars)
 Combination Ejecta
 Crater Floor Polygons (Mars)
 Cryptic Region
 Dark Deposits (Mars)
 Dark Dune Features
 Dorsa Argentea Formation
 Drop Dune
 Dune Crestline Pit
 Excess Ejecta Crater
 Fan-Shaped Deposit (Tharsis, Mars)
 Fretted Channel
 Fretted Terrain
 Friable Layered Deposits
 Frost Streak (Mars)
 Giant Polygons (Mars)
 Glacier-Like Form
 Gully
 Highland Patera
 Honeycomb Terrain (Mars, Hellas)
 Indurated Dune (Mars)
 Interior Layered Deposit
 Lacustrine Features (Mars)

Large Dark Dune
 Latitude Dependent Mantle (in HiRISE) (with No Stratigraphically Associated Periglacial Landforms)
 Latitude Dependent Mantle (in MOC) (with Stratigraphically Associated Periglacial Landforms)
 Light Toned Deposit
 Linear Gullies (Mars)
 Lineated Valley Fill
 Lobate Debris Apron
 Low Shield Volcano (Mars)
 Low-Aspect-Ratio Layered Ejecta
 Lowland (Mars)
 Martian Hemispheric Dichotomy
 Mesoscale Positive Relief Landforms (Mars)
 Outflow Channel (Mars)
 Paleoshoreline
 Pancake Ejecta
 Pedestal Crater (Mars)
 Perched Crater
 Periodic Bedrock Ridge (Mars)
 Peripheral Peak Ring (crater)
 Pitted Pedestal Crater
 Polar Cavi (Mars)
 Polar Chasms (Mars)
 Polar Layered Deposits
 Polar Spiral Troughs (Mars)
 Polar Undulations (Mars)
 Radially Striated Ejecta (Mars)
 Rectilinear Dune
 Recurring Slope Lineae
 Residual South Polar Cap Features
 Reticulate Ridges
 Reticulate Terrain (Mars, Hellas)
 Ring Furrow
 Ring-Mold Crater
 Rubble Piles on Patterned Ground (Mars)
 Runoff Channel
 Scalloped Terrain
 Seasonal Cap Spring Sublimation Related Phenomena (Mars)
 Seasonal Polar Fan-Shaped Deposits (Mars)
 Sedimentary Rocks (Mars)
 Slope Lineae
 Slope Streak (Mars)
 Solifluction-Like Lobes (Mars)

Spider
 Stealth Feature (Radar, Mars)
 Tholus (Mars)
 Thumbprint Terrain
 Tongue-Shaped and Arcuate Ridges Inside Depressions (Mars)
 Transition Topography (Mars)
 Transverse Aeolian Ridge (TAR)
 Triangular Scar (Mars)
 Valley Network (Mars)
 Viscous Flow Features (Mars)
 Wall Dune
 Wedge Dune

Features of Mercury

Entries that discuss feature types that are only found on Mercury or are characteristic features of Mercury. Impact craters and other ubiquitous or not body-specific feature types are not listed.

Antipodal Terrain
 High Reflectance Plains (Mercury)
 Hollows (Mercury)
 Intercrater Plains
 Pit-Floor Crater

Features of Mid-sized and Small Outer Solar System Satellites

Entries that discuss feature types that are only found on the mid-sized and small satellites of the outer Solar System.

“Drainage Pattern” (Trojan Satellites of Saturn)
 Corona (Miranda)
 Equatorial Features
 Equatorial Great Circle (Rhea)
 Equatorial Ridge (Lapetus)
 Tiger Stripe Fractures (Enceladus)
 Wispy Terrain
 Y-Shaped Discontinuity

Features of the Moon

Entries that discuss feature types that are only found on the Moon or are characteristic features of the Moon. Not Moon-specific impact crater types and other ubiquitous or not body-specific feature types are not listed.

Concentric Crater (Moon)
 Crater Wall Flow-Like Features (Moon,
 Asteroids)
 Dark Mantle Deposit (Annular)
 Dark Mantle Deposit (Regional)
 Light Plains (Moon)
 Lunar Swirl
 Mare (Moon)
 Mare Dome (Moon)
 Mesoscale Positive Relief Landforms
 (Moon)
 Nonmare Dome
 Orientale Type Multiring Basin
 Randgebirge
 Red Spot (Moon)
 Thalassoid
 Tranquillitatis Type Mare Basin

Features of Small Bodies

Entries that discuss feature types that are only found on small bodies moons or are characteristic features there.

Crater Wall Flow-Like Features (Moon,
 Asteroids)
 Dust Pond
 Grooves (Irregular Body)

Features of Titan

Entries that discuss Titan-specific feature types.

Amphitheater-Headed Valley (Titan)
 Flooded Valley (Titan)
 Lacustrine Features (Titan)
 Mid-Latitude Dark Linear Feature (Titan)
 Mountain (Titan)

Radar-Bright Valley (Titan)
 Valley (Single, Titan)
 Valley Network (Titan)
 Valley-Like Features (Titan)

Features of Triton

Entries that discuss feature types that are only found on Triton.

Cantaloupe Terrain
 Gutta

Features of Venus

Entries that discuss feature types that are only found on Venus or are characteristic features of Venus. Impact craters and other ubiquitous or not body-specific feature types are not listed.

Amphitheater-Headed Valley (Venus)
 Arachnoid
 Canali (Venus)
 Chaotic Terrain (Venus)
 Circumferential Lineament System (Venus)
 Corona (Venus)
 Corona-Nova
 Crater Cluster (Atmospheric Breakup)
 Crater Outflow (Venus)
 Crater-Associated Radar-Dark Diffuse Features
 Crustal Plateau (Venus)
 Deformation Belt (Venus)
 Densely Lineated Plains (Venus)
 Emissivity Parabola
 Festoon (Lava)
 Fine-Ejecta Halo
 Fracture Belt (Venus)
 Graben System
 Gridded Plains (Venus)
 Intermediate Volcano (Venus)
 Layered Ejecta
 Linear Lineament System (Venus)
 Lobate Plains (Venus)
 Microdune
 Modified Dome (Venus)
 Nova
 Outflow Channel (Venus)

Radar Anomaly (Venus)
 Radar-Dark Parabola
 Radially-Patterned Intermediate Volcano
 Ribbon Tessera
 Ridged Plains (Venus)
 Shield Field (Venus)
 Small Volcano (Venus)
 Splotch (Radar)
 Steep Sided Dome (Venus)
 Tessera
 Topographic Domains (Venus)
 Valley Network (Venus)
 Volcano (Venus)

Fluvial Features

Entries that discuss feature types entirely or partly formed by fluvial processes:

Alluvial Fan
 Amphitheater-Headed Valley (Mars, Earth)
 Amphitheater-Headed Valley (Titan)
 Anastomosing Pattern
 Avulsion Channel
 Braided Pattern
 Channel
 Channel Pattern
 Crater Breach
 Crevasse Splay
 Cutoff Chute
 Delta
 Deltas, Rías & Estuaries
 Drainage Pattern
 Flooded Valley (Titan)
 Floodplain
 Gully
 Inverted Channel
 Lateral Accretion Patterns
 Levee (Fluvial)
 Meander
 Meander-Bend Cutoff
 Outflow Channel (Mars)
 Outwash Plain
 Radar-Bright Valley (Titan)
 Ría
 Runoff Channel
 Sapping Valley

Sinuous Ridge
 Valley (Single, Titan)
 Valley Network (Mars)
 Valley Network (Titan)
 Valley Terrace
 Valley-Like Features (Titan)

Fluvial or Volcanic Features

Entries that discuss feature types that can be produced either by fluvial or volcanic processes:

Anastomosing Pattern
 Avulsion Channel
 Braided Pattern
 Channel
 Channel Pattern
 Crater Breach
 Crevasse Splay
 Cutoff Chute
 Delta
 Drainage Pattern
 Inverted Channel
 Levee
 Meander
 Meander-Bend Cutoff
 Outflow Channel (Mars)

Glacial Features

Entries that discuss features entirely or partly formed by glacial processes:

“Brain Terrain”
 Arcuate Ridge Set
 Central Mound Crater (Ice Associated)
 Concentric Crater Fill
 Crevasse (Glacier)
 Cryptic Region
 Drumlin
 Esker
 Fan-Shaped Deposit (Tharsis, Mars)
 Glacial Clast
 Glacier
 Glacier-Like Form
 Glaciofluvial Valley
 Grounding Line System

Ice Cauldron
 Ice-Contact Delta
 Jökulhlaup Deposit
 Kettle Hole
 Lineated Valley Fill
 Lobate Debris Apron
 Moraine-Mound Complexes
 Nunatak
 Ogive (Glacial)
 Piedmont Glacier
 Platy Material
 Polar Cap
 Polar Cavi (Mars)
 Ring-Mold Crater
 Rock Glacier and Debris-Covered Glacier
 Sublimation Landforms
 Tool Marks
 Trimline
 Viscous Flow Features (Mars)

Square brackets signify a descriptor term approved but not assigned to any feature as to 2014.

[Astrum, astra]
 [Collis], colles
 [Flumen], flumina
 [Lenticula, lenticulae]
 [Reticulum, reticula]
 [Unda], Undae
 Arcus, [arcūs]
 Catena, catenae
 Cavus, cavi
 Chaos, [chaoses]
 Chasma, chasmata
 Corona, coronae
 Dorsum, dorsa
 Facula, faculae
 Farrum, farra
 Flexus, [flexūs]
 Fluctus, fluctūs
 Fossa, fossae
 Insula, [insulae]
 Labes, [labēs]
 Labyrinthus, [labyrinthi]
 Lacuna, [lacunae]
 Lacus, [lacūs]
 Large ringed feature
 Linea, lineae
 Lingula, lingulae
 Macula, maculae
 Mare, [maria]
 Mensa, mensae
 Mons, montes
 Oceanus, [oceani]
 Palus, [paludes]
 Patera, paterae
 Planitia, [planitiae]
 Planum, [plana]
 Plume
 Promontorium, [promontoria]
 Regio, [regiones]
 Rima, rimae
 Rupes, rupēs
 Scopulus, scopuli
 Serpens, [Serpentes]
 Sinus, [sinūs]
 Solitudo, [solitudines]
 Sulcus, sulci
 Terra, [terrae]

Historic Terms

Entries about now-obsolete concepts or classification terms.

Canal (Mars)
 Dark Splotch (Albedo Feature)
 Randgebirge
 Runoff Channel
 Thalassoid
 Triple Band (Europa)
 Walled Plain

IAU Descriptor Terms

Terms used as generic element in the names of features (toponyms) on planets, satellites and small bodies named and approved by the International Astronomical Union (IAU) Working Group for Planetary System Nomenclature (WGPSN).

Note: “Descriptor terms are intended to represent morphological characteristics, not geological origin. The WGPSN does not endorse any specific scientific hypotheses when assigning descriptors.” (<http://planetarynames.wr.usgs.gov/DescriptorTerms>).

Tessera, tesserae
 Tholus, tholi
 Vallis, valles
 Vastitas, [vastitates]
 Virga, virgae

Impact Ejecta Features

Entries that discuss feature types entirely or partly formed by impact ejecta:

Bumblebee Ejecta
 Butterfly Ejecta
 Combination Ejecta
 Crater Outflow (Venus)
 Crater-Associated Radar-Dark Diffuse Features
 Dark Halo Crater (Impact, Optical)
 Double Layer Ejecta
 Fine-Ejecta Halo
 Layered Ejecta
 Light Plains (Moon)
 Low-Aspect-Ratio Layered Ejecta
 Multiple Layer Ejecta
 Offset Ejecta
 Pancake Ejecta
 Radar-Dark Parabola
 Radial Ejecta
 Rampart (Ejecta)
 Single Layer Ejecta
 Uprange Forbidden Zone

Impact Features

Entries that discuss feature types entirely or partly formed by impact:

Anomalous Dome Crater
 Antipodal Terrain
 Boulder-Halo (Crater)
 Bright Halo Crater (Impact)
 Brim
 Bumblebee Ejecta
 Buried Crater
 Butterfly Ejecta
 Central Dome Crater
 Central Mound (Secondary) Crater
 Central Peak Crater
 Central-Pit Crater

Circular Graben
 Circular Thin Area
 Combination Ejecta
 Compaction Crater
 Complex Crater
 Complex Crater (Low Gravity)
 Concentric Crater (Moon)
 Conical Crater
 Crater
 Crater Chain (Impact, Primary)
 Crater Chain (Type)
 Crater Cluster (Atmospheric Breakup)
 Crater outflow (Venus)
 Crater Ray
 Crater Rim
 Crater Wall
 Crater-Associated Radar-Dark Diffuse Features
 Craterlet
 Dark Halo Crater (Impact, Optical)
 Deformed Crater (Tectonized)
 Degraded Basin
 Double Layer Ejecta
 Doublet Crater
 Ejecta (Impact)
 Ejecta Deposit
 Elliptical Crater
 Elliptical Crater (Oblique Impact)
 Equatorial Great Circle (Rhea)
 Eroded Crater
 Excess Ejecta Crater
 Flat Floored Crater
 Fine-Ejecta Halo
 Fractured Floor Crater
 Ghost Crater
 Heavily Cratered Terrain
 Herringbone Pattern
 Host Crater
 Impact Basin
 Impact Melt Flow
 Impact Melt Pond
 Impact Structure
 Inverted Crater
 Irregular Crater
 Land-Target Crater
 Layered Ejecta
 Low-Aspect-Ratio Layered Ejecta
 Marine-Target Crater
 Microcrater

Microcratered Rock
 Modified Crater
 Multiple Crater
 Multiple Crater (Category)
 Multiple Layer Ejecta
 Multiring Structure, Valhalla Type
 Nested Crater
 Oceanic Impact (Water Cavity)
 Offset Ejecta
 Orientale Type Multiring Basin
 Palimpsest
 Pancake Ejecta
 Parent Crater
 Peak-Ring Structure
 Pedestal Crater (Mars)
 Penepalimpsest
 Penetration Funnel (Hypervelocity)
 Penetration Pit (Low-Velocity)
 Perched Crater
 Peripheral Peak Ring (Crater)
 Pitted Pedestal Crater
 Polygonal Crater
 Protobasin
 Quasi-circular Depression
 Radar-Dark Parabola
 Radial Ejecta
 Radially Striated Ejecta (Mars)
 Rampart (Ejecta)
 Randgebirge
 Ricochet Crater
 Ring Furrow
 Ringed Peak-Cluster Basin
 Ring-Mold Crater
 Satellite Crater
 Secondary Crater
 Secondary-Crater Chain
 Secondary-Crater Cluster
 Secondary-Crater Field
 Septum
 Sesquinary Crater
 Shatter Cone
 Simple Crater
 Single Layer Ejecta
 Softened Crater
 Splotch (Radar)
 Terraced Crater (Platform)
 Thalassoid
 Tranquillitatis Type Mare Basin

Transitional Crater (Simple to Complex)
 Uprange Forbidden Zone
 Walled Plain

Lacustrine, Marine and Coastal Features

Entries that discuss feature types entirely or partly formed by standing liquid bodies:

Canyon Lake (Mars)
 Crater Lake
 Delta
 Deltas, Rías & Estuaries
 Estuary
 Flooded Valley (Titan)
 Lacustrine Features (Mars)
 Lacustrine Features (Titan)
 Lake, Sea and Ocean (Hydrological)
 Paleoshoreline
 Ría
 Shoreline Landforms (Terrestrial Analogs)
 Subaqueous Fan
 Terrace
 Terraced Crater (Platform)

Magmatic Features

Entries that discuss feature types entirely or partly formed by magmatic processes:

Crust (Type)
 Diapir (Mantle)
 Dike (Igneous)
 Magmatic Intrusion Structure
 Lake and Ocean (Magmatic or Cryomagmatic)

Mass Movement Features

Entries that discuss feature types entirely or partly formed by mass wasting:

“Drainage Pattern” (Trojan Satellites of Saturn)
 Basal Scarp
 Boulder Track
 Brim

Colluvial Deposit
 Crater Wall Flow-Like Features (Moon, Asteroids)
 Creep
 Fall
 Flow
 Lateral Spread
 Linear Gullies (Mars)
 Lobate Debris Apron
 Mass Wasting
 Modified Dome (Venus)
 Peripheral Peak Ring (Crater)
 Recurring Slope Lineae
 Rock Avalanche
 Slide
 Slope Lineae
 Slope Streak (Mars)
 Terraced Crater Wall (Mass Wasting)
 Topple
 Triangular Scar (Mars)
 Wall Morphologies

Nival Features

Entries that discuss feature types entirely or partly formed by snow:

Niveo-Aeolian Deposits
 Polar Undulations (Mars)
 Protalus Features
 Sastruga
 Snow Features
 Snow Megadune

Other Features

Unclassified entries:

Cave
 Contraction Crack
 Dust Pond
 Highland
 Karst
 Kipuka
 Lunar Swirl
 Pareidolia
 Radar Anomaly (Venus)

Rock Arch
 Slopes
 Surface Roughness
 Thermal Infrared Feature
 Topographic Domains (Venus)

Periglacial Features

Entries that discuss features entirely or partly formed by periglacial processes:

“Sublimation-Type Polygon”
 Blockfield (Periglacial)
 Boulder-Halo (Crater)
 Central Mound Crater (Ice Associated)
 Colluvial Deposit
 Composite-Wedge Polygon
 Crater Floor Polygons (Mars)
 Creep
 Cryokarst
 Earth Hummock
 Ice Wedge Polygon
 Latitude Dependent Mantle (in HiRISE) (with No Stratigraphically Associated Periglacial Landforms)
 Latitude Dependent Mantle (in MOC) (with Stratigraphically Associated Periglacial Landforms)
 Nonsorted Circle
 Nonsorted Patterned Ground
 Patterned Ground
 Periglacial Landforms
 Permafrost
 Pingo
 Ploughing Boulder
 Polygonal Patterned Ground
 Polygon-Junction Pits
 Retrogressive Thaw Slump
 Rubble Piles on Patterned Ground (Mars)
 Sand-Wedge Polygon
 Scalloped Terrain
 Shrinkage Crack Polygon
 Solifluction Landforms
 Solifluction-Like Lobes (Mars)
 Sorted Patterned Ground
 Striped Terrain
 Sublimation Landforms

Thermal-Contraction Crack Polygons
(Permafrost)
Thermokarst Landforms
Thumbprint Terrain
Tongue-Shaped and Arcuate Ridges Inside
Depressions (Mars)
Water Track
Wet Patch (Antarctica)

Polar Spiral Troughs (Mars)
Recurring Slope Lineae
Residual South Polar Cap Features
Seasonal Cap Spring Sublimation Related
Phenomena (Mars)
Seasonal Polar Fan-Shaped Deposits (Mars)
Spider
Thermokarst Landforms

Selective Erosion Features

Entries that discuss features entirely or partly formed by differential erosion:

“Brain Terrain”
Inverted Channel
Inverted Crater
Pedestal Crater (Mars)
Pedestal Rock
Periodic Bedrock Ridge (Mars)
Plateau Degradation Landforms
Reticulate Terrain (Mars, Hellas)
Ring Furrow
Rock Arch
Spur-and-Gully
Yardang

Sublimation Features

Entries that discuss features entirely or partly formed by sublimation:

“Cryokarst”
“Sublimation-Type Polygon”
Ablation Hollow
Circumferential Depression
Dark Dune Features
Denivation Features
Desiccation Crack Polygon
Dune Crestline Pit
Excess Ejecta Crater
Gutta
Lag Deposit
Layered Plains (Io)
Linear Gullies (Mars)
Pitted Pedestal Crater
Polar Chasms (Mars)

Tectonic Features

Entries that discuss features entirely or partly formed by tectonic processes:

Band (Europa)
Canyon
Circular Graben
Circumferential Lineament System (Venus)
Clastic Dike
Corona (Miranda)
Corona (Venus)
Corona-Nova
Crustal Plateau
Crustal Plateau (Venus)
Cycloid (Europa)
Deformation Belt (Venus)
Deformed Crater (Tectonized)
Densely Lineated Plains (Venus)
Disharmonic Folds
Double Ridge (Europa)
Fault
Faulted Band (Europa)
Fissure Vent
Fracture
Fracture (Europa)
Fracture Belt (Venus)
Furrow (Icy Moon)
Giant Polygons (Mars)
Graben
Graben System
Gridded Plains (Venus)
Groove (Ganymede)
Grooves (Irregular Body)
High-Relief Ridge
Joint
Lava Cooling Polygon
Lava Polygon (Large)

Lava Polygon (Small)
 Lineament Grid
 Linear Lineament System (Venus)
 Linear Rille
 Lineated Band (Europa)
 Lobate Scarp
 Mountain (Io, Tectonic)
 Mountain (Titan)
 Mountain Belt
 Normal Fault
 Pit-Floor Crater
 Radiating Lineament System
 Reverse Fault
 Ribbon Tessera
 Ridge (Icy Moons)
 Ridge Complex (Europa)
 Ridged Band (Europa)
 Ridged Plains (Venus)
 Secondary Fault
 Single Ridge (Europa)
 Smooth Band (Europa)
 Strike-Slip Fault
 Tessera
 Tiger Stripe Fractures (Enceladus)
 Triple Band (Europa)
 Wedge Shaped Band (Europa)
 Wispy Terrain
 Wrinkle Ridge
 Wrinkle Ridge Plains
 Wrinkle-Ridge Ring
 Y-Shaped Discontinuity

Volcanic Features: Flows and Airfalls

Entries that discuss features entirely or partly formed by volcanic flows and pyroclastic falls:

Amphitheater-Headed Valley (Venus)
 Bright Plains (Io)
 Canali (Venus)
 Coulée
 Crater Breach
 Cryovolcanic Features
 Dark Mantle Deposit (Annular)
 Dark Mantle Deposit (Regional)
 Diffuse Deposit (Io)
 Festoon (Lava)

High Reflectance Plains (Mercury)
 Inflated Lava Flow
 Intercrater Plains
 Lake and Ocean (Magmatic or Cryomagmatic)
 Large Igneous Province
 Lava Channel
 Lava Coil
 Lava Flow
 Lava Lake
 Lava Tube
 Lava-Fed Delta
 Levee (Lava)
 Lobate Plains (Venus)
 Mare (Moon)
 Ogive (Volcanic)
 Outflow Channel (Venus)
 Plume Deposit (Types)
 Pressure Ridge
 Pyroclastic Deposits
 Red Spot (Moon)
 Shield Plain
 Sinuous Rille
 Thermal Erosion Channel
 Tumulus
 Volcanic Plain
 Volcaniclastic Deposits

Volcanic Features: Volcanic Constructs and Others

Entries that discuss locations of volcanic activity and positive or negative relief features entirely or partly formed by volcanic processes:

Arachnoid
 Aureole Deposit (Olympus Mons)
 Basaltic Ring Structure
 Caldera
 Cinder Cone
 Composite Volcano
 Corona (Venus)
 Cryovolcanic Features
 Dark Halo Pit or Bright Halo Pit
 Dome (Volcanic)
 Eruptive Center (Io)
 Geyser
 High Reflectance Plains (Mercury)

Hydrovolcanic Feature
 Intermediate Volcano (Venus)
 Large Shield Volcano
 Lenticula
 Low Shield Volcano (Mars)
 Maar
 Mare Dome (Moon)
 Mesoscale Positive Relief Landforms (Moon)
 Modified Dome (Venus)
 Mottled Terrain (Europa)
 Nonmare Dome
 Nova
 Open Vertical Volcanic Conduit
 Pyroclastic Cone
 Radially-Patterned Intermediate Volcano
 Radiating Lineament System
 Rootless Cone and Rootless Vent
 Seamount
 Shield Field (Venus)
 Shield Volcano
 Shield Volcano (Io)
 Small Volcano (Venus)
 Spatter Cone
 Steep Sided Dome (Io)
 Steep Sided Dome (Venus)
 Subglacial Volcano
 Tholus (Mars)

Tindar
 Tuff Cone
 Tuff Ring
 Tuya
 Volcanic Cone
 Volcanic Mountain (Io)
 Volcanic Rise
 Volcano
 Volcano (Venus)

Weathering Features

Entries that discuss feature types entirely or partly formed by weathering:

Balanced Rock
 Cavernous Weathering Features
 Desert Pavement
 Fluvial Clast
 Glacial Clast
 Lag Deposit
 Microcratered Rock
 Pedestal Rock
 Spur-and-Gully
 Ventifact (Faceted Rock)
 Weathering Features