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Geologic mapping of tectonic planets

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Abstract

Geological analysis of planets typically begins with the construction of a geologic map of the planets' surfaces using remote data sets. Geologic maps provide the basis for interpretations of geologic histories, which in turn provide critical relations for understanding the range of processes that contributed to the evolution. Because geologic mapping should ultimately lead to the discovery of the types of operative processes that have shaped a planet surface, geologic mapping must be undertaken in such a way as to allow such discovery. I argue for modifications in current planetary geologic mapping methodology that admit that tectonic processes may have contributed to the formation of a planet surface, and I emphasize a goal of constraining geologic history rather than determining global stratigraphy. To this end, it is imperative that secondary (tectonic) structures be clearly delineated from material units; each record different aspects of planet surface evolution. Neglecting such delineation can result in geologic maps and interpreted geohistories in which both the spatial limits and the relative ages of material units and suites of secondary structures are incorrect. Determination of absolute time is fundamentally difficult to constrain in planetary studies. In planetary geology the only means to estimate absolute age is the density of impact craters on a surface. Crater density surface ages are more akin to terrestrial εNd average mantle model ages, which reflect the average time at which all of a rock's components were extracted from the Earth's mantle. Rocks, or planetary surfaces, with very different geohistories could yield the same average model age. Dating tectonic events or determining rates of tectonic events is even more difficult.

Keywords: mapping; planets; Venus; tectonics; structural geology

1. Introduction

Advances in space science technology and an increasing number of missions have revealed unprecedented views of planet surfaces, which form the fundamental data sets for construction of extraterrestrial geologic maps. Geologic maps provide the basis for interpreting geologic histories, which in turn provide critical relations for understanding the range of processes that contributed to the evolution of planets and their satellites. The purpose of geologic mapping is to determine the geologic history of a region and to incorporate that history into an increasingly larger area of study. The larger goal of understanding geologic histories is to understand planetary processes - that is, to understand how a planet works, spatially and temporally. The method of investigation must not sacrifice one's ability to constrain geo-

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logic history, and thus sacrifice one's ability to understand planetary processes - the fundamental research goal. Many planetary geologists currently employ the geologic mapping methodology outlined by Wilhelms [1,2]. The method evolved in the 1960s with the nascent space program and draws largely from geological analysis of the relatively tectonically inactive Moon and Mars. The method emerged at a critical time - prior to widespread acceptance of plate tectonics, and a widely accepted view of a dynamic Earth. As evidence of this Wilhelms ([1], p. 219) states: 'A major goal of planetary geologic mapping, like terrestrial mapping, is to integrate local stratigraphic sequences ('columns') of geologic units into a stratigraphic column applicable over the whole planet'. Although this method, referred to herein as the 'global stratigraphic method', may have proved useful for tectonically quiescent planets, it requires modification for application to tectonically active planets.

Planetary geologic mapping aimed at determining a global stratigraphy is fundamentally flawed because such a method assumes, a priori, that such a stratigraphy exists. However, as stated by Gilbert [3], 'scientific research consists of the observation of phenomena and the discovery of their relations'. In order for a planet to develop a global stratigraphy, it must have evolved by globally synchronous and spatially continuous processes. If a planet indeed evolved through global processes, a global stratigraphy could be discovered through study of local geologic histories, and successively broader correlation of these geologic histories. If one assumes a global stratigraphy, but such does not exist, any 'discovered' global stratigraphy must be either grossly incorrect, or so broadly blurred as to achieve apparent global synchroneity. The former derails scientific progress, and the latter greatly inhibits understanding of planetary processes because critical details of local, regional and global planetary processes are lost [3].

Although one might expect that the geologic history of a nontectonic planet is both less complex and simpler to determine than that of a tectonic planet, neither is necessarily the case. In fact, because tectonic planets can preserve both geological material units and secondary (tectonic) structures, the potential exists to determine more detailed geologic histories, and therefore to understand more detailed geological process(es) than for nontectonic planets. The surface record of a nontectonic planet may lead one to propose an erroneously simple history. Because tectonic planets can record a more detailed history, study of such planets can result in inherently more testable geologic histories than nontectonic planets.

Thus any planetary geologic mapping methodology should allow that tectonic processes may have played a role in planet evolution, and, as such, should emphasize geologic history rather than global stratigraphy. Section 2 of this contribution reviews the historical development of stratigraphic methodology on Earth and illustrates how various dating methods worked to invalidate a search for terrestrial global stratigraphy; flaws in the global stratigraphic method are illustrated through a geohistory experiment. The body of the paper outlines definitions, mapping principles, and proposed method modifications aimed at discerning geohistory; this method is 'tested' using the same experiment. A brief discussion of absolute age dating methods with particular application to Venus and implications for tectonic planets concludes the paper. Whereas Wilhelms [1] used mostly lunar examples, Venusian examples are used herein. The NASA Magellan mission (1989–1993) resulted in high-resolution global data including synthetic aperture radar (SAR) imagery, altimetry, emissivity, and gravity sets that can constrain geologic histories. Ford et al. [4] provide an extensive treatment of Magellan data analysis and cautions. Although Earth and Venus followed different evolutionary paths, the methods for understanding local and global geological processes share the same philosophical underpinnings. For Venus we have only remotely collected data sets, which adds to requisite cautions and resulting challenges.

2. Background

In the late 1700s to early 1800s an important goal of terrestrial geology was the construction of a 'Standard Stratigraphic Column'. A.G. Werner, following J. G. Lehmann and C. Füchsel and the law of superposition, believed that stratified rocks occurred in an invariable order; rock units were characterized by their lithology and 'correlation' was established by lithologic similarity and sequential order - that is, the age of rocks everywhere was presumed to be directly related to their lithologic character. Werner divided rocks into five progressively younger groups: primitive, transitional, layered, transported, and volcanic rocks [5]. He believed that all rocks, except volcanic rocks (which were rare and unimportant), formed in water, and that their universal sequence recorded the Earth's gradual history; each rock group reflected a globally extensive change. Early formed crystalline rocks (primitive) precipitated from a deep primeval ocean; as sea level fell, transitional rocks (mostly graywackes) formed by mechanical derivation from earlier formed rocks and continued precipitation. Further subsidence produced widespread fossiliferous layered rocks (and related basalt); transported rocks developed as sea level fell yet further; finally volcanic rocks erupted locally - the result of heat from subterranean burning coal.

Although Werner played a major role in elevating geology as a science, general correlations based on lithology were shown to be grossly incorrect by W. Smith in 1815 with the recognition of fossils and faunal assemblages, rather than lithology, as tools of correlation [5]. Index fossils, which occur in widely separated rock layers, commonly with different lithologies, provided the first means to define regionally extensive timelines. The utility of index fossils results from their widespread geographic distribution and rapid evolutionary changes. Faunal assemblages provided clear evidence that similar lithologic units could be diachronous, and that lithologically dissimilar units could be synchronous. By the early 1800's the three major stratigraphic principles had emerged: (1) the law of superposition - oldest layers at the bottom; (2) uniformitarianism - the present is the key to the past; and (3) the law of faunal succession - fossils provide temporal constraints independent of lithology. From these principles, the Standard (stratigraphic) Column evolved into rock units (lithology) and time units (faunal assemblages).

Williams [6] and the USGS [7,8] objected to the rigid parallelism of time and rock units [9], arguing that the boundaries of rock units need not be, and typically are not, everywhere the same age, and therefore cannot serve as time units. They advocated a dual and separate classification system similar to what is generally accepted today: (1) numerous local rock units based on local sections, independent of time, and (2) relatively few universal time units based on fossils, independent of lithology. The 1933 Stratigraphic Code, however, ignored these arguments, implying exact parallelism of rock and time units. Through debate, influenced in part by the advent of radiometric age dating, the geologic time scale has emerged with a two-fold classification based on relative faunal ages and absolute radiometric ages. The last $\sim$200 Myr of Earth's history is further defined by a detailed magnetic polarity time scale correlated by radiometric dates. The geologic time scale is continually being refined [10,11]; time scales differ mostly in details specific to region or 'time slice'. Therefore, although the original divisions of type geologic sections were based on stratigraphic relations of beds (i.e., material units), correlations of distinct strata are necessarily based on a comparison of fossils (and/or radiometric ages), not lithology ([12], p. 165). Thus rock-stratigraphic units should be defined as lithologic units, without regard to time. These units must be kept distinct from time markers (e.g., fossils) that are used in correlating local sections with each other and with the standard chronology (i.e., the geologic time scale) ([9], p. 293).

In summary, although some unique rock units mark specific parts of Earth's history (e.g., banded iron formations), rock type is generally useful only as a local stratigraphic marker, and lithology cannot be uniquely associated with time. Thus terrestrial geologic units record physical lithospheric processes, not time. Terrestrial timekeepers are either recorders of broadly unidirectional changes within the biosphere or isotopic systems, or they result from changes within the Earth's internal dynamo (paleomagnetism). Each of these timekeeping systems is mostly independent from lithospheric processes recorded by stratigraphic sequences, intrusions, and tectonic events. It is the lack of correlation of these systems with material units that allows geologists to unravel terrestrial lithospheric histories and processes.

The plate tectonics revolution finalized the demise of any search for terrestrial global stratigraphy. Plate tectonics (e.g., [13]) led to a highly mobile view of the Earth, following earlier theories of continental drift [14], and recognition that geologic environments vary greatly in time and space. The plate tectonics revolution resulted from technological and scientific advances in bathymetric and magnetic data collection, aided by faunal and absolute ages of oceanic crust, leading to the realization that the ocean basins are much younger than the continents, rather than older, as previously assumed. This realization opened the door for plate tectonics - a mechanism that successfully explained the hotly debated theory of continental drift [15,16]. Conceptually, a global stratigraphic column cannot be reconciled with recycling of surface units at convergent margins or with formation of new crust at divergent margins. Studies aimed at discovering a global stratigraphy would contribute little to understanding Earth processes. Some may argue that seismic stratigraphy might reveal a global stratigraphy; however, seismic stratigraphy is generally restricted to relatively young marine strata not greatly disrupted by tectonic processes. Because much of Earth's history involves both continents and tectonism such a stratigraphy could never be truly global, nor could it record the bulk of Earth's rich history. Thus, global stratigraphy on any planet is a dangerous assumption.

3. Geologic mapping

One goal of planetary geologists, like terrestrial geologists, is to unravel geologic histories in order to understand planet processes. Determination of the geologic history of a particular region commonly begins with construction of a geologic map, which, for solid planets, begins with identification and differentiation of geologic (material) units and geomorphic features [1]. Geomorphic features can include primary structures (formed during unit emplacement), secondary (or tectonic) structures, or erosional features (commonly primary structures related to reworking of preexisting geologic units by wind, water, or ice (or analog equivalents)). Planet surfaces record the dominant processes that operated during their evolution. Mercury and Moon record widespread evidence of impact processes, whereas secondary structures are rare. Mars displays evidence of impact and widespread erosional and depositional processes, and localized volcanic processes; evidence for tectonic structures is relatively rare. New evidence of early (>3.5 Ga) linear magnetic anomalies in Mars' southern highland suggests that tectonic processes may have been important in early Mars evolution [17]. Venus shows abundant volcanic and tectonic features; sedimentary and erosional features are rare given the high surface temperature ($\sim475°C$) and lack of surface water. Earth provides examples of all of the above processes.

Data types and resolution vary from planet to planet. Earth has the most varied data sets, but not the most areally extensive. New planetary missions and advances in technology and scientific knowledge result in new data. The ability to differentiate material units and tectonic elements requires a working knowledge of available data sets; such can be gained from planet- and mission-specific literature.

Venus' geologic units (or material units; e.g., volcanic flows, aeolian deposits, crater deposits) are typically differentiated in Magellan data by patterns in SAR, emissivity, or root mean square (RMS) slope data that reflect primary features such as lobate flows, mottling, or homogeneity. The first-order task in mapping material units is to determine their spatial distribution and to examine contact relations between adjacent units [1]. Several problems must be kept in mind. Available data might inhibit unique distinction between different material units, or may result in division of a single geologic unit into two apparently different units. For example, spatially separate lava flows may show similar radar, emissivity, or RMS slope characteristics and hence one might conclude (incorrectly) that these units are time correlative.

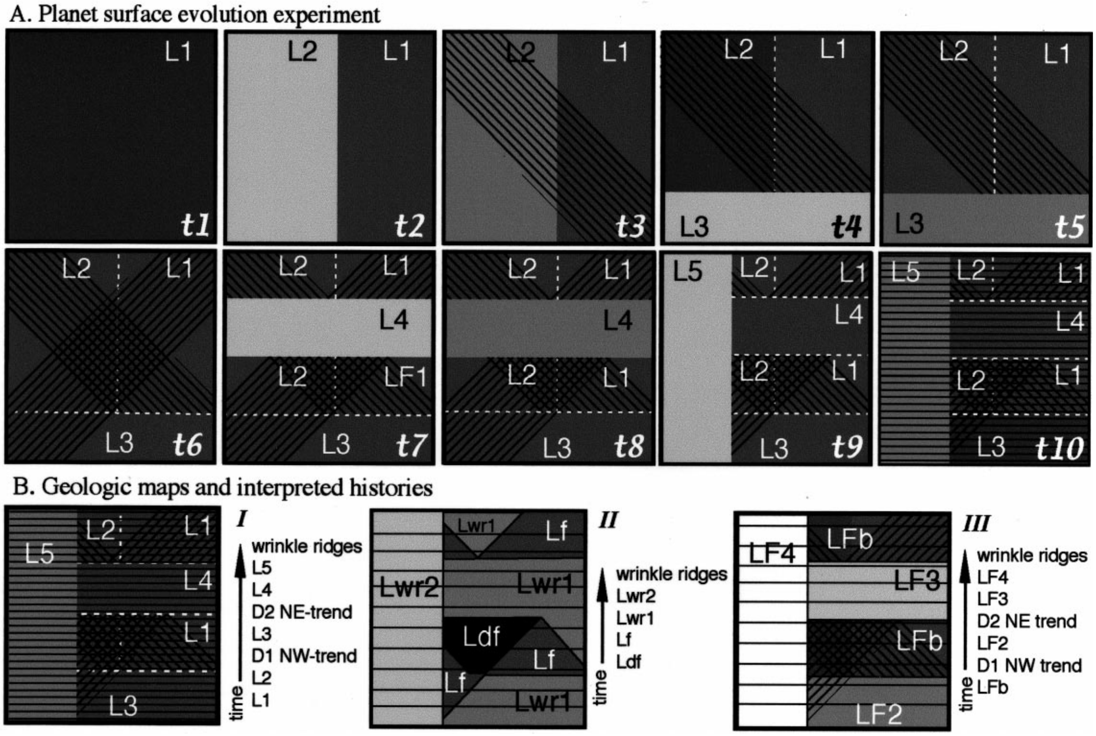

Fig. 1. Geologic history experiment of a simple 10-time-step surface evolution. Sequential flood-lava flows (L1–5) darken with time [19] over three time steps; dotted lines mark flow boundaries; closely spaced black lines indicate suites of secondary structures (fractures, faults, folds); horizontal lines mark wrinkle ridges. B: Geologic maps and resultant histories determined by: (I) experiment; (II) global stratigraphic method (unit definition includes secondary structures: f, fracture; df, densely fractured; wr, wrinkle ridged), and (III) geohistory method.

Alternatively, a single volcanic flow unit emplaced within a single eruptive event may have both pahoehoe and aa flow facies and show different radar and RMS slope signatures, and therefore they might be interpreted (incorrectly) as temporally distinct geologic units. Lumping versus splitting of material units depends in part on the understanding of process-dependent facies changes (e.g., metamorphic, volcanic, sedimentologic, stratigraphic, magnetic). Fundamentally, these potential problems are no different from those encountered in terrestrial mapping, although on Earth one has more tools to address the problem.

Lithologic similarity of units is not required, nor is it sufficient, for correlation ('correlation' infers temporal equivalence ([5], p. 7;[9], p. 271). Terrestrial correlation requires either faunal or radiometric age data, or both. By contrast, correlations of material units in planetary geology are based, to date, solely on surface crater densities; this method requires numerous assumptions, resulting in gross correlations at best [1,18]. Crater density ages are most robust for planets with high crater densities (very old surfaces). The more localized a planet's surface processes, the less robust are crater density surface ages.

Unidirectional timekeeping systems that are distinct from geologic units are absolutely necessary for correlation studies - without such tools, proposed correlations are simply unsupported assumptions. For example, prior to the advent of geochronometric techniques all terrestrial gneissic terrains were mapped as 'Precambrian' (because they were consistently interpreted as the oldest local rock unit, and they lacked fossils), leading some workers to interpret the Precambrian as a time of global 'gneissification', with further implications for early Earth processes. Geochronometric data clearly indicate that gneissic terrains are diachronous, ranging in age from billions to millions of years old; thus concepts of global correlation and gneissification have been discarded. Prudent planetary geologists will not assume temporal correlation of spatially separate terrains that appear, based on remote data, to comprise similar material units.

The construction of a geologic map is partly fact and partly an interpretation, and interpretations typically include operating assumptions. One must be mindful of assumptions implicit in any method and be careful to ensure that the assumptions do not hamper discovery. A simple experiment allows us to test geologic mapping methods. Fig. 1A illustrates a simplified ten-step (t_1–t_{10}) magmatic and tectonic geohistory of a local 'field area'. In the experiment all material units are emplaced as low viscosity lava flows (L1–5) with straight boundaries. Flow surfaces progressively degrade with time as reflected by a change in radar character and RMS slope data, mimicking flow units on Venus [19]. If flows do not degrade with time, some temporal resolution may be lost because old and young flows might be indistinguishable. Flows reach a steady-state surface signature after three time-steps and are no longer distinguishable from earlier flows. Two linear fracture zones form at distinct times (t_3 and t_6); fractures parallel the trend of their respective fracture zones. Late wrinkle ridges overprint all preexisting material units.

The geologic map and 'true' geohistory are shown in Fig. 1B. Geologists cannot typically observe the evolution of a planet surface; instead they must attempt to reconstruct the surface history by observation of the final surface (Fig. 1A–t_{10}). Geologists organize observations through construction of geologic maps. Map methodology influences the product and the interpreted geologic history. Given that we know the history of our experimental field area, we can use it to test mapping methods.

3.1. Global stratigraphic method

The global stratigraphic method has the stated goal ([1], p. 219) of determining local sequences of geologic units and integrating these into a coherent 'global stratigraphy'. It allows secondary structures ('post-depositional modifications' ([1], p. 214) to be included in the definition of a material unit (Wilhelms ([1], p. 227) states: 'Structures and structural patterns should be related to specific rock or time-rock units and therefore to the evolutionary history of the planet'). But this practice assumes a known evolutionary history of a planet independent of, and prior to, mapping secondary structures - reminiscent of Werner's assumed stratigraphic sequences, geologic history, and geologic processes. Determination of global stratigraphy becomes the overriding goal and its existence cannot be challenged.[1]

Consider a geologic map of the experimental field area constructed using the global stratigraphic method allowing secondary structures to be part of a material unit description (Fig. 1B, II) (e.g., [20–23]). The resulting map and history are quite different from the actual sequence of events (Fig. 1B, I). Wrinkle ridge formation is the youngest event, and the boundaries of the youngest flow unit (Lwr2 [L5]) are correctly defined. (Many workers do not actually distinguish the formation of material units and wrinkle ridges [20–23], despite wrinkle ridge spacing of more than 50 times image resolution). However, neither the spatial distribution nor the relative ages of Lwr1, Lf, or Ldf bear any relation to reality. Lwr1 combines all units not affected by a fracture event and not covered by L5 (parts of L1, L2, L3 and L4; t_1, t_2, t_4, and t_7). Lf combines parts of

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[1] Evidence that this goal colors Wilhelms' method is provided in his topical discussion order; he discusses unit correlation (7.2.3) and time-rock units (7.2.4) prior to structures and structural units (7.2.5). Although Wilhelms admits that structures commonly cut several rock units, and although he argues that the Stratigraphic Code does not allow for mapping of units based solely on their structural modification, in the same paragraph he states (p. 227): 'Where the rock units of a highly faulted or otherwise deformed terrain are recognizable, they should be mapped as separate rock units. Sometimes, however, the deformed rock units are not recognizable. In this case it is better to map the structural unit as 'fractured plains material' than to ignore the presence of the structures in order to adhere strictly to the code'. This allows secondary structures to characterize a material unit.

material units L1, L2, L3, and L5 (t_1, t_{10}, t_4 and t_9), and it combines fracture events 1 (t_3) and 2 (t_6). Ldf includes parts of L1 and L2 (t_1 and t_2) and both fracture events (t_3 and t_6). Ldf is defined, therefore, solely based on its deformation features. The youngest interpreted material unit (Lwr2) is differentiated from the next older unit, Lwr1, only based on gray scale (radar character), which would not exist if the experiment were allowed to run one more time-step. In that case Lwr1 and Lwr2 would be mapped as a single material unit, combining parts of the oldest and youngest lava flow units (L1–5). The proposed geohistory is grossly incorrect and any processes interpreted from the purported geohistory must also be incorrect.

3.2. Geohistory method

The geohistory method has the stated goal of determining the geochronology of local regions and progressively assembling those histories into testable models of planet evolution. It allows that geologic histories record tectonic processes. The method begins as Wilhelms [1] outlined, with differentiation of material units and geomorphic features, but it also requires differentiation between primary and secondary structures. Material units are determined in the manner and with the cautions detailed by Wilhelms [1], and outlined briefly above. Geomorphic features, generally three-dimensional shapes or landforms, can be either primary or secondary structures. Geomorphic features can be differentiated on Venus by radar effects resulting from local topography, or altimetry if sufficiently large (tens to hundreds of kilometers). Primary structures commonly provide clues to material unit properties or emplacement processes (e.g., flow morphologies reflecting flow viscosity) because they formed during unit emplacement; in addition, they can be unit specific and used as a material unit descriptor. Secondary or tectonic structures 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 they deform. Secondary structures absolutely cannot constitute a part of a material unit(s) descriptor or characteristic. Using secondary structures to describe a material unit implies that the material unit and the structural element reflect a single geologic event; this implication becomes embedded in the data (geologic map) and its viability cannot be tested later. In mapping secondary structures one seeks to understand geometry, kinematics (movement and timing), and ultimately dynamic processes (driving forces). The pitfalls and complexities of such analyses are many; a few cautions are discussed briefly.

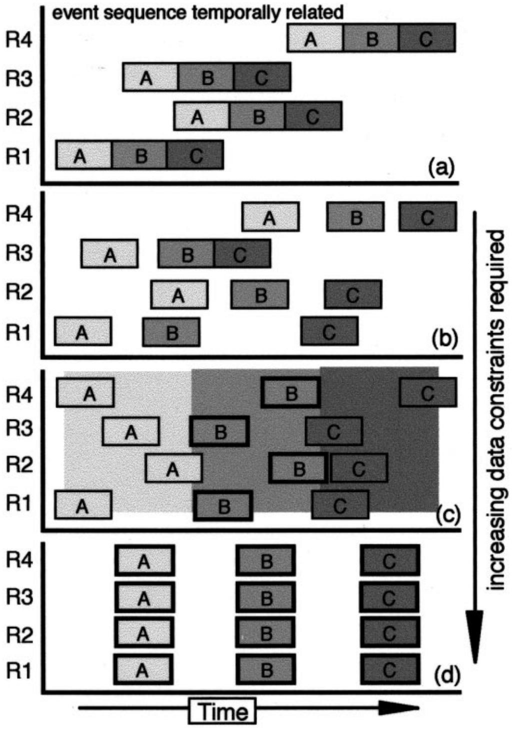

Fig. 2. Idealized models of the surface evolution of a theoretical planet. Three arbitrary events (A, B, and C in which age of A > B > C) and four arbitrary regions (R1–R4) illustrate spatial and temporal relations of events: (a) A, B, and C are genetically linked (must be independently demonstrated), but not necessarily global synchronous; (b) the broadest of interpretations in which A, B, and C are spatially and temporally unrelated - the most conservative interpretation lacking absolute ages; (c) a minimum of four specific absolute ages (bold boxes) could indicate that at R1–R4 A precedes B, which precedes C; (d) interpretation following the global stratigraphic method - requires at least 12 specific absolute ages (bold boxes) to document.

Secondary structures typically form lineaments in two-dimensional data sets such as SAR, although they are three-dimensional planes (e.g., faults) or curvilinear shapes (e.g., folds). First order issues concerning secondary structures include: character (paired, anastomosing, linear), orientation, length and width, density or spacing, wavelength, continuity, spatial distribution and patterns, and spatial relations with material units. The spatial distribution of secondary structures is not typically correlative with the spatial limits of material units. This general lack of spatial association provides evidence that secondary structures and material units record fundamentally different processes or parts of processes. Secondary structures result from stresses associated with planetary processes, whereas material units record the distribution (or redistribution) of planet material. Thus, secondary structures and material units record different events within a geohistory, and thus, different aspects of geological process(es). A greater ability to delineate material units and secondary structures in time and space leads to a more detailed geohistory and a more detailed understanding of operative processes.

Geohistory analysis requires relative time constraints. Although faunal succession can help to correlate spatially separate terrestrial regions, in general, similar sequences of geologic events recorded in spatially separate regions do not provide any a priori evidence for correlation. Despite this limitation, local relative temporal constraints - gleaned from stratigraphic and crosscutting relations, and mechanical analysis - are critical to understanding fundamental aspects of planetary processes. Stratigraphic analysis deals mainly with strata in the absence of tectonism; cross-cutting relations involve both material units and tectonic structures; mechanical analysis relates to timing among tectonic structures as determined by material rheology - largely a function of composition and physical conditions during tectonism. Each has its limits and benefits. Because proposed geohistories must be able to accommodate temporal relations determined through each of these somewhat independent means, robust geohistory analysis will employ as many methods as possible because geohistories are fundamentally built on consistency and compatibility arguments.

Stratigraphic relations address local stacking of geologic units with older below younger units, and assume original deposition as roughly horizontal. Stratigraphic analysis is based the three principles mentioned above: (1) superposition, (2) uniformitarianism, and (3) faunal succession. Stratigraphic analysis assumes that tectonism has not omitted or repeated the stratigraphic section. Stratigraphic analysis requires a means to test this assumption, as well as to correlate strata of separate regions (e.g., 3 above). Means of correlation are rare (presently absent?) for many planets. In addition, given two-dimensional remote data sets, it can be difficult to robustly determine the stacking order, and thus unit superposition [24]. The presence of secondary structures, however, might be used to constrain the relative temporal relations between two or more stratal units.

Crosscutting relations can provide relative age constraints for material units and secondary structures. The younger unit or secondary structure may overprint the older unit(s) or secondary structure(s); younger units might contain clasts of an older unit, or a younger unit may embay topographic features associated with an older structural element. If tectonism occurred between the emplacement of material units, tectonic pattern distribution may allow determination of the spatial distribution of the younger unit, the area affected by the tectonic process, and firm relative temporal constraints between the two material units. Temporal constraints are gained by comparison of material unit patterns with structural patterns. For example, assuming horizontal deposition, if a material unit preferentially occupies synformal fold valleys, and hence the contact between material units correlates with fold crests or troughs, the material unit that fills the synformal valleys was emplaced after folding - and folding postdates formation of the folded unit(s). If the contact between material units is not spatially correlative with the fold crests or troughs, both material units likely formed prior to folding. In addition, we must be mindful that a geologic environment might not favor formation or preservation of crosscutting relations. For example, if the processes or crustal section one is studying formed below a planet surface, no 'classic' crosscutting relations involving surface material units would be possible (e.g., temporal constraints on S–C shear zone fabrics [33]). At the surface 'classic' cross-cutting relations will be preserved if and only if material units deposited on the surface formed continuously during the tectonic evolution and were variably distributed across the map area. If a material unit has completely covered a surface of interest, the record of earlier geologic history is commonly lost to the remote investigator.

Some understanding of structural topography (three-dimensional character) can also be gained by detailed mapping of a 'lava-line', or the embayment patterns marked by the boundary between deformed crust and flood lava flows. The 'shoreline' defined by flows can provide a detailed picture of topographic highs and lows. Comparison of the lava line and structural orientations near the 'shoreline' can provide strong constraints on the detailed topography defined by secondary structures that predated the lava flow.

Mechanical analysis of relative age addresses the interaction and development of tectonic structures, and depends, in part, on kinematic analysis. Kinematic analysis endeavors to identify distinct structural elements, and to address geometrical, rheological and temporal relations recorded by each suite of elements with the goal of understanding the deformation history. Kinematic analysis involves several, typically iterative, tasks: (1) identify and differentiate structural suites; (2) determine geometry, orientation, and spatial distribution of each suite; (3) determine temporal relations between and among structural suites, recognizing that they could have formed synchronously, that they could be partially or wholly reactivated, and that determination of temporal relations requires knowledge of material properties and deformation mechanisms, and (4) develop a kinematic model that accommodates documented constraints. Structural principles and their range of applications, the topic of many textbooks and numerous journal articles, are discussed here only in the broadest terms.

Identification and differentiation of structural elements is a first, and critical, step. It is imperative that secondary structures be delineated from primary structures and mapped independent of material units. Further, if distinct structural elements are not differentiated, subsequent geometric and temporal analysis may be flawed. Primary structures, genetically (and thus temporally) related to unit emplacement, may prove useful as mapping criteria, and provide clues to unit emplacement processes. In contrast, secondary structures record tectonic processes; they postdate emplacement of units they deform. In some situations the character, orientation, and distribution relative to an associated material unit will indicate whether structural elements are primary or secondary. If a suite of structures is difficult to identify as primary or secondary, it is generally best to map the suite as secondary because this interpretation can be tested with continued mapping. If the structures are mapped as primary, this implies temporal equivalence with the 'host' material unit, an interpretation that becomes embedded in the material unit description and thus impossible to test with continued mapping.

Geometric analysis requires three-dimensional exposure, or, in the case of remotely sensed two-dimensional data, a means to constrain three-dimensional geometry. For two-dimensional data geometric models are commonly non-unique, and in many cases unique geometric determination is a nontrivial exercise. Furthermore, geometry, no matter how carefully defined, cannot uniquely constrain relative timing. Geometric constraints are necessary but not sufficient for kinematic analysis; relative temporal constraints are also required.

Relative temporal clues can be gleaned from interactions between material units and structural suites, or from rheological considerations. In each case, temporal constraints depend on deformation or emplacement mechanisms. For example, determining the relative age of a layer-parallel body requires knowledge of whether it was emplaced as a volcanic flow unit or an intrusive sill; independently determined temporal data could favor one mechanism over the other, or detailed observation might indicate the mechanism and hence constrain the relative timing. Unfortunately, commonly the deformation mechanism is precisely what one is attempting to understand; hence the iterative nature of kinematic analysis.

Knowledge of rheology and rheologic structure can provide clues about deformation mechanisms. Clues to rheology can be gained from the wavelength of regularly spaced structural elements such as folds, fractures, joints, or boudins - relations that can commonly be extracted from two-dimensional data sets. Empirical, analytical, and analog modeling studies consistently illustrate that a dominant wavelength:thickness ratio (l:d) exists for both contractional and extensional structures, with average l:d ∼5.5 for folds, ∼2–6 for brittle extensional features, and up to 10–20 for ductile extensional features, respectively (e.g., [25,26]). Layer instability analysis can constrain planet layer thickness during deformation [27,28] that can, in turn, provide clues for deformation mechanisms and timing [29].

Clues to the dip, relative timing, and depth of structures might be inferred from their spacing, their interactions with topography, and/or their interaction with other suites of structures. Steeply dipping structures cut across topography; shallow dipping structures follow topography. Terminated fractures are typically younger than through-going fractures, because a through-going fracture acts as a free surface that blocks propagation of younger fractures [30,31]. However, a younger fault could truncate an earlier formed fracture (or fault), resulting in a similar 'T' geometry but with opposite temporal relations. Interpreting temporal relations from crossing fractures can be more difficult: if an older through-going fracture is filled, it might no longer act as a free surface, allowing younger fractures to propagate across it. In addition, if a young fracture initiates at a greater depth than an old fracture, it may propagate beneath and around the older fracture. Fracture spacing can provide an independent constraint on timing because fracture spacing reflects, in part, the depth of the fracture set [29–31]. Two intersecting fractures could form synchronously under the right conditions [32].

Temporal constraints derived from crosscutting relations or mechanical analysis must also consider possible structural reactivation-renewed slip along previously formed mechanical discontinuities. Early formed secondary structures can be reactivated any time after their formation given favorable conditions. Reactivation can occur after deposition or emplacement of a younger material unit that covers the previously formed tectonic structure; thus preliminary temporal analysis may be misleading. Once formed, a secondary structure has the potential to be a material weakness. Whether or not a pre-existing structure forms a weakness that could be later reactivated depends on the character of the structure and on its orientation with respect to future (younger) principal stresses [34]. Careful mapping with attention to delineation of material units and secondary structures can provide evidence of reactivation.

Because all geologic features are three-dimensional, geologic mapping should include the construction of cross-sections and block diagrams in order to explore possible three-dimensional relations [1]. Cross-sections and block diagrams provide a critical reminder that geologic elements are spatially three-dimensional; they also help to identify unstated assumptions, previously unrecognized problems or solutions, and they encourage workers to ask additional questions of the data.

Using these principles we can construct a geologic map of the experimental field area (III of Fig. 1B). The resulting map correctly delineates each lava flow unit (LF4 [L5], LF3 [L4], LF2 [L3]), except LFb, which combines L1 and L2 as an undifferentiated basal unit. The geohistory also matches 'reality' except for the lumping of L1 and L2 into a basal lava flow unit (LFb). This method results in robust determination of both the spatial and relative temporal relations of all post-L2 events (t_2–t_{10}), from which it is possible to hypothesize processes responsible for surface formation. Further degradation of flow surfaces ($t_{11...}$) would result in the combining of LF3 and LF4 into a single young flow unit. This simplified experiment does not consider three-dimensional relations that could provide additional clues to geohistory and hence, operative processes. Additional clues might also be gleaned from mechanical analysis of tectonic structures.

4. Absolute time

Even if one is able to determine a unique sequence of geologic events within a specific field area, several critical questions with regard to planetary processes remain unconstrained, perhaps the most pressing of which deals with absolute time. The absolute time required for terrestrial processes is commonly debated for two fundamental reasons: (1) its importance, and (2) its difficulty to constrain. Methods for measuring absolute time are continually improving. In the late 1800s the Earth was considered to be ~100 Myr old based on stratigraphic arguments, salinity calculations, and cooling models of the Earth and Sun. The discovery of radioactive decay and development of radiometric techniques tentatively established Earth's age as 2 byr old by the 1930s. Once the age of the Earth was relatively well established, efforts to determine absolute time were directed toward the geologic time scale and determining rates of tectonic processes [35]. Rate determination requires the ability to date both the onset and cessation of an event. Currently available dating techniques can date specific minerals, or, in the case of planetary studies, surfaces comprised of material units. Tectonic processes typically result in secondary structures, the dating of which requires bracketting by two datable material units. The accuracy relates, in part, to how closely the material units temporally bracket the tectonic event in question. This process is nontrivial even on Earth.

Workers must be ever mindful of the potential problems with absolute age determinations. The most robust of geohistories will be built upon a relative temporal framework punctuated with robustly determined absolute age constraints. Correlation of different regions with similar relative geologic histories or a sequence of geologic events is not valid in the absence of an independent time marker (Fig. 2). 'Correlations' based only on similar relative geohistories assume - but do not document - global synchroneity, following Werner. Fig. 2 illustrates interpretations of three theoretical geologic events (A, B and C) identified in four spatially separate regions (R1–R4). At each location, A predates B, which predates C. The three events could be completely unrelated, or they could record a common geologic process. If the events are unrelated, documentation of global synchroneity of all three events would require documentation of the absolute age of each event in each region (a minimum of 12 absolute ages). If one could establish that events A–C record the same type of sequential geologic process at each location, then synchroneity might be established with only four absolute age determinations of the same phase of the A–C sequence at each of the four locations. (Of course this does not establish that the A–C sequence is globally synchronous, only that the sequence occurred at the same time at these four locations). Lacking absolute age data, the similar sequence of events at each location in no way requires, or even suggests, synchroneity. Although an interpretation of global synchroneity of each of the three events might be the simplest model to envision (e.g., Werner), such a result actually requires the most highly constrained model of planet evolution and the most detailed supporting data. For example, continental rifting results in a common succession of rock types and deformation, the sequence of which reflects the fundamental process of rifting; but the stages of continental rifting need not occur synchronously in different locations, and the more general interpretation is that they do not. To establish that continental rifting in separate locations was indeed globally synchronous would require individual absolute age constraints for each location. Establishing global synchroneity requires detailed data sets including numerous independently determined absolute ages.

Determination of absolute time is fundamentally difficult to constrain in planetary studies. Because absolute time and rates are so critical to understanding the process one must be particularly vigilant about the robustness of all absolute ages used to constrain models. Significantly incorrect temporal data are much worse than no temporal data at all. In planetary geology the only means to estimate absolute age is the density of impact craters on a surface [18]. In the best of circumstances this might allow one to constrain the absolute age of a particular surface. This technique requires several assumptions (in addition to an assumed impactor flux rate), and ages are only as valid as the assumptions.

Although crater density might place limited absolute age constraints on Lunar and Martian surfaces, the assumptions inherent in this dating technique must be critically evaluated for Venus and other tectonic planets. Venus hosts ~950 relatively evenly globally distributed impact craters [36,37]. The statistics of small numbers require that any datable surface on Venus be greater than 20 000 000 km^2 [38] - a region larger than North America. Additionally one must assume that the entire surface developed quickly (that is, that it formed synchronously). These assumptions are circular. Furthermore, surface ages estimated by this method cannot be extrapolated in the same way as radiometric dates, which typically record the cooling of specific minerals through known closure temperatures. Crater density surface ages are more akin to terrestrial εNd average mantle model ages, which reflect the average time at which all of a rock's components were extracted from the Earth's mantle. Rocks with very different geohistories could yield the same average mantle model age [39]. Similarly, crater density determinations yield average surface model ages, and therefore surfaces with extremely different geohistories could yield the same crater density; a surface could be comprised of many units with a wide range in ages, or a single unit with the mean crater density age, or an infinite number of other possibilities [40,41].

Several workers have used crater density in attempts to discern relative or absolute ages of geomorphic provinces across Venus [42–44]. These studies should be reevaluated with regard to issues of crater ages [40,41], and the implications of these studies should not be incorporated into models without careful consideration of the underlying assumptions. These studies lack robustness because the true mean crater density is poorly constrained, and any crater density can be accommodated by a host of rate functions ranging from simple to complex; thus, currently, crater counts offer little constraint on the relative time of duration of geologic units on Venus [41].

Dating tectonic events or determining rates of events are even more perilous. In addition to the significant problems outlined above, one must be able to robustly establish whether each individual crater is younger or older than the relevant secondary structures. This is difficult because both secondary structures and impact craters are spaced elements - that is, they do not occur everywhere, even within a surface that predated their formation.

In the case of dating tectonic elements on Venus the best candidate might be wrinkle ridges, because their distribution broadly correlates with global gravity–topography relations, indicating that wrinkle ridge formation might have been restricted to a somewhat narrow (recent) timeframe [45]. Any attempt to test this hypothesis requires unique determination of the relative ages of individual wrinkle ridges and impact craters. Although most Venusian impact craters are well preserved, various features distinguish relatively young (fresh) from relatively old (degraded) impact craters (Fig. 3A). Radar-bright (rough) floored craters with halo deposits are young, whereas radar-dark (flood-lava-filled) floored craters with little or no halo deposits are old; in addition, impact crater formation and interior flooding represent two distinct events [46]. Most craters with interior fill lack evidence of flooding from outside the crater [36,47], and thus at least one possible model for crater filling is flooding from below (Fig. 3B (see also [48])). Impact craters and wrinkle ridges must each postdate the surfaces they deform. Therefore, if a surface hosts craters and wrinkle ridges, both craters and wrinkle ridges are younger than the surface material unit(s). How much younger is unconstrained. Furthermore, given that interior flooding postdates crater formation (impact), and that craters and wrinkle ridges are spaced, unique determination of crater–wrinkle ridge temporal relations is rarely possible. In SAR data, material units or tectonic elements are delimited by brightness, a function of roughness and orientation relative to incident radar. Because it is impossible to determine unique relative temporal relations between spatially overlapping radar bright crater ejecta or radar bright crater interiors with radar-bright wrinkle ridges (Fig. 3C, k,l), the relative ages of wrinkle ridges and young craters (lacking interior radar-dark fill)

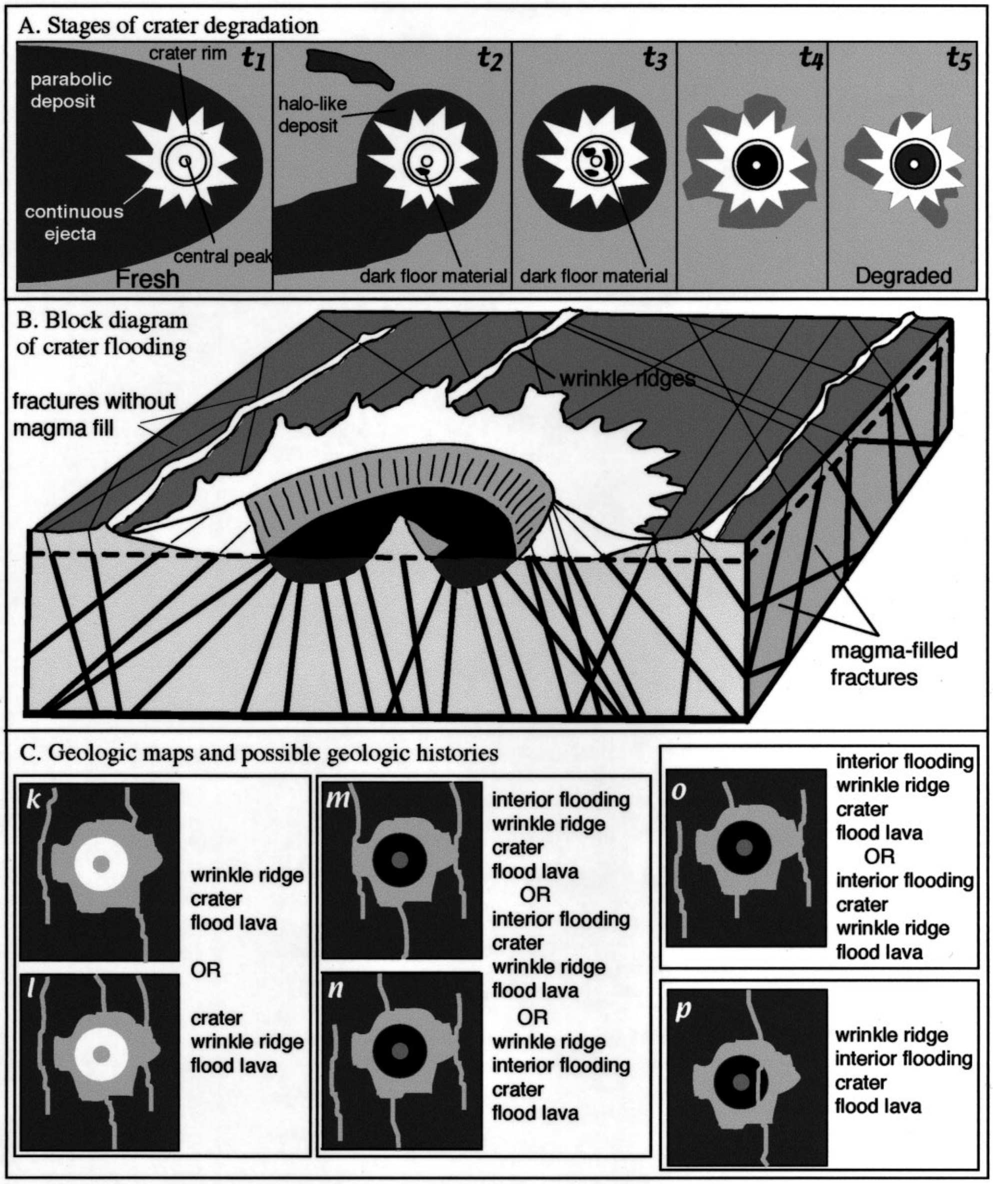

Fig. 3. (A) Crater degradation model illustrating sequential stages of crater morphology [46]; radar-dark crater fill (presumably lava flows) are temporally distinct from impact event. (B) Block diagram of subsurface crater flooding to some pressure surface level. (C) Geologic maps (k–p) and resultant geologic histories illustrating possible crater–wrinkle ridge temporal relations (oldest below youngest).

is indeterminate. For craters with flooded interiors (Fig. 3C, m–p), one must consider three distinct geologic events following formation of the base surface. The relative age of wrinkle ridge–crater formation can only be determined in the infrequent case in which a wrinkle ridge cuts, and therefore postdates, the radar-dark crater fill (Fig. 3C, p). In that case, the wrinkle ridge postdates the crater, but it also postdates crater flooding - therefore an indeterminate period of time elapsed between crater and wrinkle ridge formation. In another rare case one might argue that an individual wrinkle ridge spans the width of a filled crater (Fig. 3C, o), and that it is likely (but not required) that the wrinkle ridge predated crater flooding; however, the wrinkle ridge could have formed either before or after the impact event. In each other case the order of crater formation, crater flooding, and wrinkle ridge formation are indeterminate (Fig. 3C, k–n). Thus, in only one unique case out of six can the relative age between individual crater and wrinkle ridge formation be determined (Fig. 3C, p). This unique case allows only determination of wrinkle ridge formation after crater formation and flooding. Therefore, absolute age constraints (much less rates) of tectonic processes on Venus are not currently possible.

Some prominent current tectonic models for Venus fall victim to these uncertainties. For example, models that propose early globally extensive high strain deformation resulting in formation of global tessera represent a non-unique interpretation of limited data sets lacking temporal constraints [20–23,49,50]. These models, conceptually similar to abandoned terrestrial Precambrian gneissification models, assume global distribution and synchroneity of tessera, as well as high strain during tessera formation; yet, none of these assumptions are documented, and are, in fact, inconsistent with detailed structural analysis [29,51,52].

5. Summary

Construction of a geologic map is a critical first step in unraveling geologic history for any solid planet. Because geologic mapping is itself an interpretation that results in a database to be used for interpretation of geologic processes, mapping must be conducted in such a fashion as to ensure that any operative process can be discovered - that is, the mapping method must not predetermine the geologic map. Any method should allow that tectonic processes could be important in the evolution of a planet surface. It is imperative that secondary structures be distinguished from material units because material units and secondary structures record different 'time slices' in the evolution of a planet surface and reflect different aspects of planetary processes. Clear differentiation of primary and secondary structures might not be critical for tectonically inactive planets; however, one should not assume tectonic inactivity on uninvestigated planets. For Venus and other tectonic planets, failure to clearly differentiate secondary structures from material units leads to erroneous interpreted geologic histories, and can inhibit recognition of critical aspects of the planet's history and therefore critical aspects of planetary evolution processes. In addition, time is a fundamental factor in understanding processes of planet evolution in general, and tectonic processes in particular. Time must be robustly constrained, and cannot be assumed. To assume time is to assume fundamental aspects of the processes one is attempting to understand.

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