CAUTIONS FOR ASSSUMPTIONS IN PLANETARY GEOLOGIC MAPPING.

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Introduction: The Space program emerged in the 1960's and with it, the ability to observe planetary bodies in our solar system. Advances in space technology and the quality and number of missions continue to provide incredible views of planet surfaces. Geological maps, constructed through observation of planet surfaces, form a fundamental basis for interpreting geological histories which in turn form the basis for understanding operative planetary processes. Because geological maps form a critical interim step in any planetary analysis it is important that the method of map construction be as free as possible of imbedded assumptions such that geological relations can be discovered [1]. The first planetary geologic maps were made of the Moon, a relatively tectonically inactive planet. Since then the Magellan mission (among others) has revealed evidence of the tectonic and volcanic evolution of Earth's dynamic sister planet Venus. Images of other planets reveal similar activity, if not similar processes. Planetary mapping methodology emerged prior to widespread acceptance of terrestrial plate tectonics, and with a stated goal of the discovery of global stratigraphy [2]. Given appreciation for the dynamics of terrestrial geological processes, and high-resolution planet imagery, it is useful to reexamine geological mapping methodology. Geological maps should attempt to delineate material units, primary structures, and secondary (tectonic) structures with an aim to unravel local and regional geohistories [3]. Because material units and secondary structures record different geologic events it is imperative that secondary structures not be used to define material units.

Geologic mapping: Because a geologic map is used to provide critical constraints to lead us to understand processes of planet evolution, and therefore provide clues to planetary dynamics, it is important that maps allow discovery, rather than assumption, of geologic relations. Geologic mapping of solid planets begins with differentiation of geologic (material) units and geomorphic features [2]. Geomorphic features can include primary structures (formed during unit emplacement), secondary (tectonic) structures, or erosional features—commonly primary structures related to reworking of preexisting geologic units by wind, water, or ice (or analog equivalents). Primary structures can provide clues to unit properties or emplacement processes; they can be unit descriptors. Because secondary structures (fractures, folds, etc.) formed after unit deposition or emplacement they record time(s) and process(es) distinct from the unit(s) they deform; secondary structures cannot be part of unit descriptors. Inclusion of secondary structures in a unit descriptor implies that the unit and the structure reflect a single geologic event; this implication becomes an assumption imbedded in the geologic map and in any studies based on that map. Although one might expect that the history of a nontectonic planet is both less complex and simpler to determine than that of a tectonic planet, neither is necessarily true. Ironically, tectonic planets have the potential to record more detailed geohistories (and thus provide more detailed clues for planet analysis) than nontectonic planets because tectonic planets can preserve both material units and secondary structures. Differences in the formation of material units and secondary structures can be used to one's mapping advantage in order to constrain spatial and temporal relations of both material units and secondary structures. The surface record of a nontectonic planet may lead one to propose a simple, but inherently untestable, geohistory. The greater the spatial and temporal resolution in geohistory that can be gleaned from remote data sets, the more rigorous the constraints imposed on models of planetary processes, and thus the more likely that a model that meets those many constraints will reflect real processes. Differences in character of material units and suites of secondary structures can be employed in a complimentary fashion to extract information from two-dimensional data sets; such constraints would not be available for nontectonic planets. Both the cautions and the utility of secondary structures relate, in part, to their three-dimensional character, their dependence on rheology, and their potential for reactivation, as outlined in numerous excellent structural geology textbooks.

Secondary structures and relative time. Relative temporal relations can be derived from stratigraphic analysis (strata without mechanical disruption), cross-cutting relations (strata and tectonism), and mechanical analysis (mechanical disruption). In the case of a nontectonic planet only stratigraphic analysis can be used to determine geohistory. In the case of tectonic planets the later two (discussed here) can add critical information. Once formed, a secondary structure has the potential to be a material weakness, including after deposition or emplacement of a younger material unit. Whether or not a structure forms a weakness that is later reactivated depends on the character of the structure, interaction with younger material units, and orientation with respect to future (younger) principal stresses [4]. Documentation of structural reactivation requires detailed geologic mapping with clear delineation of material units and secondary structures. Such delineation can lead to documentation of a rich geohistory of material units and time.

For example, a region could illustrate the following relationships between volcanic flows (F), tectonism, and time (t). An early flow unit (Fa, t1) is fractured (t2); the unit is locally covered by a second flow (Fb, t3); later contraction leads to local wrinkle ridge formation through mechanical reactivation (and structural inversion) of filled fractures (t4). Wrinkle ridges do not form where fractures in Fa are not filled by Fb (i.e., Fa is not covered), nor where Fb is presumably too thick (strong) to accommodate wrinkle ridge formation. That is, wrinkle ridges do not form where Fb is either too thin or two thick. Thus fracture distribution and orientation helps delineate the boundary between Fa and Fb; this contact together with local and regional topographic reflects the thickness of Fb (relations that cannot be determined directly from SAR imagery). The orientation, distribution, and timing of wrinkle ridges provide independent, but consistent and compatible clues to the variable thickness of Fb, as well as the local history. In addition, one might be able to postulate the mechanical layer thickness of Fa during the fracture formation event given that structural wavelength (e.g., fracture spacing) is related in part to mechanical layer thickness [5]. Furthermore, one must understand that wrinkle ridge spacing reflects fractures that cut Fa, rather than the thickness of Fb.

A lack of delineation of secondary structures from flow units would lead to a much simpler (but less robust, less constrained, and less useful) geohistory: emplacement and fracturing of an early flow (Ff, t1), followed by emplacement and wrinkle ridge formation of a younger flow (Fwr, t2). Such an analysis would not provide clues to Fb thickness. Furthermore, one might propose (incorrectly) that Fa formed after Fb because it lacks wrinkle ridges, and one might postulate (incorrectly) a thickness of Fb as related to wrinkle ridge spacing.

Other examples taken from tessera terrain record rich geohistories in which tectonism and volcanism are intimately related in time and space.

Absolute time. Absolute time also plays a critical role in understanding planetary processes. Just as relative geologic history must be discovered, so too must we discover, not assume, absolute time constraints. Unfortunately, as critical as absolute time is to our understanding of planetary processes, the more detailed the history we are able to unravel, the less potential we have to determine absolute time—not because detailed history inhibits quantitative time determination, but because currently the only available method to date planet surfaces is through crater density dating. However, crater density dating techniques are statistical and, as such, require large numbers of craters on any one surface. Young surfaces, or small surfaces, cannot yield crater counts high enough to be statistically valid on even highly cratered planets, and on planets without large numbers of craters even relatively large surfaces are not large enough [6,7]. Furthermore, crater density dating results in determination of an average model surface age, analogous to an average mantle model age gained from εNd analysis [8]. Surfaces with completely different histories can yield the same model surface age [9]; without prior knowledge of the surface history (including absolute age distribution) the actual age of a surface age is unconstrained. We need to discover a means to constrain absolute time akin to radiometric age dating in which individual minerals record cooling through known closure or blocking temperatures. Such techniques have only recently been discovered for terrestrial application, and continue to be refined. Use of crater density ages as if they robustly constrain time can only lead to the assumption, not the discovery, of geologic histories and the responsible planetary processes.

Summary: Planetary geology holds endless challenges to understanding the workings of planetary bodies within our solar system and beyond. The data sets are remote, typically two-dimensional, and, of course, never quite as high-resolution as we might like. Despite these challenges, planetary data sets allow us a means to view planets in ways that we cannot view the Earth. We must be ever mindful of the real limitations of the data, yet continually challenge ourselves to be creative in the means in which we tickle detailed information out of these remarkable data sets. The construction of a geologic map is partly fact and partly interpretation. Interpretations typically include operating assumptions. One must be mindful of assumptions implicit in any method and ensure that assumptions do not hamper discovery. Clear delineation of secondary structures from material units greatly increases ones ability to unravel the geological history of a planet region. We should view our constructed geohistory interpretations with a healthy skepticism that requires consistency and compatibility of model histories with observations. Because proposed geohistories must be able to accommodate temporal relations determined through stratigraphic analysis, cross-cutting relations and mechanical analysis, the careful planetary geologist will entertain the possibility that tectonism may have been important in a planet's evolution, and thus employ as many methods as possible to constrain history. Geohistories are fundamentally built on consistency and compatibility arguments—arguments that are forever open to challenge by additional observations [1].

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