GLOBAL GEOLOGICAL MAPPING OF VENUS: IDENTIFICATION OF CHALLENGES AND OPPORTUNITIES FOR FUTURE VENUS MAPPING.
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Introduction and Background: A global geologic map of Venus was compiled [1] at a scale of 1:10 M, using Magellan radar image and altimetry data, supplemented by Venera-15/16 radar images. The map (Fig. 1) covers the entire surface of Venus (460 10^6 km^2), 90% of the surface area of Earth. The associated documentation [1] outlined the history of Earth and planetary geological mapping to illustrate the importance of utilizing the dual stratigraphic classification approach to geological mapping. On the basis of this well-established approach, thirteen distinctive units and a series of structures and related features were identified on the surface of Venus. Included were discussions of 1) the history and evolution of the definition and characterization of these units, 2) exploration and assessment of alternative methods and approaches that have been suggested, and 3) an outline of the pathway from the sequence of mapping of small areas, to regional and global scales. As seen in Fig. 1, the contribution outlined the specific definition and characterization of these units, mapped their distribution, and assessed their stratigraphic relationships.

On the basis of these data, [1] then compared local and regional stratigraphic columns and compiled a global stratigraphic column, defining rock-stratigraphic units, time-stratigraphic units, and geological time units. Superposed craters, stratigraphic relationships and impact crater parabola degradation were used to assess the geologic time represented by the global stratigraphic column. On the basis of these data and the unit characteristics, [1] interpreted the geological processes that were responsible for their formation, and then, on the basis of unit superposition and stratigraphic relationships, interpreted the sequence of events and processes recorded in the global stratigraphic column.

The earliest part of the history of Venus (Pre-Fortunian) predates the observed surface geological features and units, although remnants may exist in the form of deformed rocks and minerals. The observable geological history of Venus was subdivided into three distinctive phases (Fig. 1). The earlier phase (Fortunian Period, its lower stratigraphic boundary cannot be determined with the available data sets) involved intense deformation and building of regions of thicker crust (tessera). This was followed by the Guineverian Period. Distributed deformed plains, mountain belts, and regional interconnected groove belts characterize the first part and the vast majority of coronae began to form during this time. The second part of the Guineverian Period involved global emplacement of vast and mildly deformed plains of volcanic origin. A period of global wrinkle ridge formation largely followed the emplacement of these plains. The third phase (Atlian Period) involved the formation of prominent rift zones and fields of lava flows unmodified by wrinkle ridges, often associated with large shield volcanoes and, in places, with earlier-formed coronae. Atlian volcanism may continue to the present. About 70% of the exposed surface of Venus was resurfaced during the Guineverian Period and only about 16% during the Atlian Period. Estimates of model absolute ages (Fig. 1) [2] suggest that the Atlian Period was about twice as long as the Guineverian and, thus, characterized by significantly reduced rates of volcanism and tectonism. The three major phases of activity documented in the global stratigraphy and geological map [1], and their interpreted temporal relations [1,2], provide a basis for assessing the geological, atmospheric and geodynamical processes operating earlier in Venus history [e.g., 3-5] that led to the preserved record [1]. In addition, detailed analysis of the preserved volcanic [6] and tectonic [7] records permit a more in-depth understanding of the recent geological history, the associated geological processes [8-10] and the major unknowns and questions that can be addressed with continuing geologic mapping at a wide range of scales. Below we list some of compelling questions (see also [11]) and opportunities for future geological mapping.

Some Fundamental Questions for Future Geological Mapping of Venus:

1. Is there evidence for extensive pyroclastic activity? When, where and how abundant?: This question is of critical importance for determining the history of the present atmosphere and links to the potential volatile content of eruptive magmas.

2. What is the relationship of coronae, novae, arachnoids, and shield volcanoes in space, time and altitude?: Are these apparently disparate features related in origin, in space, in time? This is a critical question to assess the nature and evolution of mantle dynamics (e.g., mantle plumes, broader mantle upwellings, etc.) and how this might have changed with time.

3. What constraints does the distribution and volume of volcanic plains of different ages place on the origin and evolution of the atmosphere?: Estimates of the areal coverage, embayment relationships, thickness, and volumes of units of extrusive volcanic origin is key to assessing the input of magmatic volatiles into the atmosphere.

4. How does the current atmospheric environment influence the ascent and eruption of magma?: Clearly, the very high Venus atmospheric pressure inhibits magmatic gas exsolution, concentration and explosive volcanic eruptions. Is there any evidence for widespread pyroclastic deposit in the past and could such deposits signal the presence of a very different, lower-atmospheric-pressure environment?

5. What is nature and relationships of festoons and pancake domes?: Are they silica-rich volcanism, viscous magmatic foams, or both? How do they differ in terms of their age and geologic setting?

6. How do tessera patterns of deformation compare among the different occurrences and how do similarities and differences inform us about tessera origin (e.g., lateral collision, upwelling, downwelling etc.)?: In order to span the gap between the preserved geologic record (e.g., [1]) and the earlier "cryptic" history, this question requires detailed and comprehensive geologic mapping.

7. How much strain is represented by deformational features in the tessera, and how does this vary in space and time?: These are critical issues in understanding earlier "cryptic" Venus history and the transition to the current record (see details in [10]). Detailed geologic mapping of deformation features in the tessera and integrations across different tessera occurrences is essential.

8. What is the history of topography on Venus and how does this inform us about the Venus thermal and geodynamic evolution?: When and how did the current topography form and what are the relative roles of Pratt and Airy isostacy? How can geologic mapping and topography be combined to address this question?

9. What are the criteria for recognizing tectonically modified impact craters in the tessera and can additional craters be recognized?: Do any tessera elements represent much more ancient terrain dating back into the "cryptic" period of Venus history? Can we develop additional criteria for recognizing tectonically and volcanically modified craters and comprehensively map the tessera in search for any evidence of these?

10. What are the relationships of gravity highs and recent volcanism?: Where on Venus is the most likely recent geological deformation and volcanism [12]? How do these relate to the several positive gravity anomalies suggesting active mantle upwelling?

11. How can we distinguish between tectonic and volcanic features and processes?: Graben and fractures of tectonic origin abound on Venus, but some are radial and concentric to coronae, and related central volcanic features. How many of these are due to near-surface dikes of volcanic origin? Which have associated pits, domes and flows?

12. What is the relationship between rift zones and the major lobate flows that originate there?: Detailed documentation of the relationships (time and space) is essential to understand the global rifting system and implications for mantle convective patterns.

References: [1] Ivanov & Head, 2011, PSS 59, 1559; [2] Kreslavsky et al., 2015, Icarus 250, 438; [3] Bullock & Grinspoon, 1996, JGR, 101, 7521; [4] Way et al., 2016, GRL, 43, 8376; [5] Way & Del Genio, 2020, JGR, 125; [6] Ivanov & Head, 2013, PSS 84, 66; [7] Ibid, 2015, PSS 113, 10; [8] Head & Wilson, 1986, JGR 91, 9407; [9] Gaillard & Scaillet, 2014, EPSL 403, 307; 9. [10] Hanmer, 2020, ESR 201, 103077; [11] Byrne et al., 2019, LPSC 50, 2853; [12] Shalygin et al., 2015, GRL 42, 4762.

Fig. 1. Left top, geologic map; bottom left, stratigraphic column; Right top, interpreted 3 phases of geologic evolution and events (1). Right bottom, buffered impact crater density data (2).