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Notes

The geologic evolution of Venus: Insights into Earth history

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Through the clever use of stereo radargrammetric techniques on images from the Magellan mission to Venus in the 1990s, combined with recent quantitative analyses of magma reservoirs on Earth, McGovern et al. (2014, p. 59 in this issue of *Geology*) resolve an important outstanding question dating from that era: What forces are responsible for the graben extending radially from large shield volcanoes? They show that, in addition to radial dike emplacement, the larger graben are readily accounted for by magma reservoir inflation, providing new insight into processes of magma ascent and eruption on Venus, and their relation to globally interconnected rift systems on Earth's sibling planet. This new contribution serves as a reminder of the importance of Venus to our understanding of geological processes and history on Earth, and the need for new data to resolve some of the most fundamental problems in comparative planetology.

HISTORY OF VENUS EXPLORATION

The liftoff of Sputnik in 1957 launched a vigorous international program of planetary exploration and the field of comparative planetology. How do our neighboring terrestrial (Earth-like) planets look, and what insights can they provide in understanding our own planet? Early missions to the Moon, Mercury, and Mars showed that these terrestrial planets with one-half or less the diameter of Earth looked very different from Earth. Their high surface area/volume ratio lets them conduct internal heat to the surface efficiently and cool rapidly, becoming "one-plate planets" with thick, stable lithospheres. Their surfaces preserve evidence of geological processes from the first half of solar system history. Intensely pockmarked by impact craters and resurfaced by volcanism, they reveal the roles of external forces (early accretion and high impact flux) and internal thermal evolution (conduction, convection, hot spot formation, magmatism, advection, and surface volcanism).

But what about Venus, similar to Earth in size, density, and position in the Solar System? Is it Earth-like, with a young surface, plate tectonics, and tracks of hot-spot volcanoes, or like the smaller planets, with a heavily cratered surface? When imagination outstripped data, Venus was thought to have an Earth-like hot swampy surface, but we now know that its CO₂ atmosphere, sulfuric acid clouds, surface temperatures hot enough to melt lead, and very slow and retrograde rotation, are nothing like Earth.

What about its surface and interior geology? Venera (Soviet Union) atmospheric probes and landers showed that the surface was littered with generally basaltic rocks and patchy soils (Hunten et al., 1983). A radar altimeter on the Pioneer Venus (PV, United States) orbiter (1978) provided a global topographic map, with a resolution of ~100 km, low by today's standards. Its analysis showed many Earth-like features: evidence for continent-like highlands with marginal linear mountain belts, broad Iceland-like rises and plateaus, circular basins, and very long, linear lowlands, but with a global hypsometry different from that of current Earth. Instead of the latter's bimodal distribution of global topography, the hypsometry of Venus was unimodal, skewed to higher elevations. Increasingly higher-resolution radar data provided additional evidence for Earth-like features. One of the rises in the PV data (Beta Regio) was cleaved by a rift zone, surmounted by volcanoes. The mountain belts surrounding a large continent-like plateau (Ishtar Terra) were composed of multiple parallel linear features analogous to Earth's folded mountain belts. Often-circular features (coronae) were not impact structures, but complex deformation zones, more consistent with internal deformation origins.

Higher-resolution radar imaging and more coverage were needed to find out whether Venus was Earth-like.

In 1983, Soviet Union orbiters Venera 15 and 16 surveyed the northern hemisphere (~30% of Venus), with radar imaging resolution of 1–2 km (Barsukov et al., 1992), showing that many highlands consist of very highly deformed terrain (tesserae), and that organized linear folded mountain belts surround highland plateaus. Large volcanoes exist in abundance, but show little evidence for hot spot traces or convergent plate boundaries. Coronae looked like the fingerprints of mantle processes. Most remarkably, there were few impact craters, indicating an age on the order of only hundreds of millions of years.

These results raised significant, fundamental questions: Where is the ancient billions-of-years-old continent-like terrain on Venus? What is the average age of the surface? Is Venus characterized by Earth-like plate tectonics, or do its thermal regimes suggest another manifestation of plate tectonics? Is internal heat transferred mainly by conduction, advection, or plate tectonics? Are the fold belts global and if so, where is the corresponding extension and divergence? These questions guided the 1989 United States Magellan mission to Venus.

THE MAGELLAN MISSION PROVIDES GLOBAL COVERAGE

Over the course of four years, Magellan obtained near-global radar images (120–280 m resolution) and altimetry coverage. Planetary scientists catalogued features and mapped their distribution (Saunders et al., 1992). Coronae were globally distributed, commonly in linear zones, and debate about their origin ranged between mantle upwelling and downwelling. Wide linear rift zones extended for thousands of kilometers, connecting broad topographic rises with associated volcanoes, but total extension appeared limited, and no transitions to ocean basins were observed. Crustal shortening was present in folded mountain belts and linear deformation ridges, but no global patterns emerged. Surprisingly, no integrated patterns of divergence and convergence were seen, and there were no transform faults and offset divergent plate boundaries, strongly suggesting that there are no Earth-like plate tectonics on Venus. Were the highly deformed tesserae-covered plateau highlands built by mantle upwelling that underwent relaxation, or did they represent crustal thickening due to mantle downwelling? Hundreds of large shield volcanoes dot the surface, commonly associated with volcanic rises, but not organized into linear chains. Relatively featureless volcanic plains cover ~40% of the surface, deformed by wrinkle ridges like their lunar counterparts. Tens of thousands of small shield volcanoes cover the surface, and large viscous-appearing, pancake-like domes hinted at more evolved magma compositions.

Most surprising, however, was the confirmation that few impact craters exist on Venus: only ~1000 were seen, giving an astonishingly young average age for the Venus surface of ~750 m.y. (McKinnon et al., 1997). No older, more-heavily cratered areas (analogous to Earth continents) could be found, and a debate ensued whether the distribution of impact craters could be distinguished from *completely spatially random*. Geologists looked for craters heavily modified by volcanism and tectonism, to find the most geologically active and perhaps oldest areas, but few were found.

THE CONUNDRUM OF VENUS

Many features on Venus (folded mountain belts, rift zones, tesserae) were like Earth, but there were few signs of Earth-like plate tectonics,

so that Venus seemed to have a single lithospheric plate that was losing heat conductively and advectively. But the cratering record presented a conundrum. First, the average age of the surface was <20% of the total age of the planet, and second, the average was *not* a combination of very old and very young surfaces, such as Earth's continents and ocean basins. Third, the lack of variability in crater density, and of a spectrum of crater degradation, meant that all geological units might be about the same age. This implied that the observed surface of Venus must have been produced in the past hundreds of millions of years, possibly catastrophically, with very little volcanic or tectonic resurfacing since then! Suddenly, Venus was not like Earth, nor like the Moon, Mars, or Mercury.

Many hypotheses attempted to explain these dramatic results, with little progress to consensus (Bougher et al., 1997). Some called on recent tectonic and volcanic catastrophic resurfacing, followed by relative quiescence (Schaber et al., 1992), with mechanisms including vertical crustal accretion and catastrophic depleted mantle layer overturn (Parmentier and Hess, 1992) and episodic plate tectonics (Turcotte, 1993). Others called for a change in mantle convection style related to planetary thermal evolution, or a transition from mobile lid to stagnant lid regime (Herrick, 1994).

In parallel, it was not clear how to interpret the geological record. The relative ages of geologic units could not be worked out using crater densities, and two approaches and interpretive paradigms were explored. In one, dubbed the non-directional mode, each area was viewed as having a separate, independent geological sequence, analogous to Wilson cycles on Earth (Guest and Stofan, 1999). Others mapped the stratigraphic columns in different areas, looking for global patterns in thermal and geological evolution (Basilevsky and Head, 1998). Neither approach could be completely tested and validated without global mapping, not an easy task for an Earth-sized planet.

GLOBAL GEOLOGIC MAPPING

Quadrangle mapping at the scale of 1:5M, more regional thematic mapping, and the compilation of a global geological map led to more detailed definition of geological units and structures, an analysis of their stratigraphic relationships (embayment, cross-cutting, etc.), and the extension of map units across the surface, to distinguish between a relatively random non-directional geological history, and the possibility of more global trends in geological and thermal evolution. Well-established (Wilhelms, 1990) but sometimes debated (Hansen, 2000) planetary mapping techniques were used to define geologic units, and mapping was conducted for ever larger areas, most recently to the entire globe (Ivanov and Head, 2011) where geological units can be stratigraphically traced planet wide. The global map shows that the past history (a few hundreds of millions of years) of Venus can be divided into three phases, with different volcanic and tectonic styles. In the oldest, *global tectonic regime*, intensive tectonism represented by the tesserae and plateau-like topographic highs was accompanied and immediately followed by plains deformation and initial coronae activity. In the intermediate, *global volcanic regime*, tens of thousands of small shield volcanoes formed, followed by vast outpourings of flood lavas filling the lowlands and covering most of the planet, and continued minor subsidence and deformation caused formation of contractional wrinkle ridges on the volcanic plains. In the third, *network-rifting and volcanism regime*, limited focused rift zones formed. Combined crater densities indicated that the first two phases (intense tectonic deformation followed by vast lava outpourings) occurred over a short period of time, whereas the third phase (local rifting and limited volcanism) occupied the vast majority of the observable geologic history of Venus.

THE PRESENT AND THE FUTURE

This recent global geologic mapping provides new impetus to revisit the hypotheses from the 1990s proposed to account for the unusual geological history of Venus. As shown by the results of McGovern et al., the time is ripe for a renaissance in Venus science; new, more robust geological and geodynamic models can be tested using the extensive geological mapping. New eyes and approaches are needed to look at old data.

It has been over 20 years since the Magellan mission. Improved technology now makes possible very high-resolution orbital imaging, sophisticated atmospheric probes, and long-lived landers and rovers. No less compelling are the insights to be gained about Earth. Did catastrophic resurfacing lead to plate tectonics in Earth history? Is Earth's plate tectonic heat transfer mode linked to the presence of water, relative to Venus? What are the consequences of the formation of the Moon on Earth? What can the formative years of Earth history and the smaller terrestrial planets tell us about the missing ~80% of Venus history? Under what conditions, and when in the future, might Earth undergo a catastrophic resurfacing or a transition from mobile lid to stagnant lid convection? Do the emerging differences between Venus and Earth presage similar differences in other solar systems? International cadres of scientists and space agencies are readying the next phase of Venus exploration to address these critical questions.

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