**GEOPHYSICAL MAPPING AND MONITORING OF ACTIVE PLANETS ($GM^2AP$).**

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**Introduction:** Data collected during the initial reconnaissance of the inner solar system (through the mid-1990s) indicated ages for terrestrial planet surfaces (other than the plate tectonics-endowed Earth) of order $10^9$ years, suggesting dead or at best dormant planets. However, data obtained during the last two decades, combined with careful re-analysis of previous datasets, point to substantial present-day activity at Venus and Mars. For example, Venus Express instruments have uncovered signatures of geologically recent [1] and even possibly active [2] volcanism on that planet. A re-examination of Magellan SAR images of dark-floored craters [3] suggested a mean surface age for Venus of around 150 Ma. This result was followed up by a re-calibration of the Venus impactor distribution curve giving a comparably young surface age [4]. At Mars, paleotopographic analysis indicates that a substantial portion of the Olympus Mons volcanic edifice was emplaced within the last 210 Myr [5]. Estimates of heat flux from the interior of Mars are consistent with the possibility that secular cooling is minimal or even negative (i.e., Mars is heating up) [6].

These results justify a re-examination of tectonic and volcanic activity on Venus and Mars. Findings of substantial ongoing volcano-tectonic activity on these “one-plate planets” [7] provide strong motivation to create in-depth programs of geophysical sensing and monitoring, in order to figure out how planets work beyond the singular plate tectonic setting of Earth, and also for evaluating hazards to humans exploring Mars.

**Motivation:Volcano-tectonic activity levels.**

*Hawaii:* Large basaltic volcanic edifices formed at intraplate volcanic settings (“hotspots”) on Earth are the best analogs for large volcanoes on Mars and Venus. At Hawaii, extensive instrumentation provides detailed records of seismic activity. A catalog of 7022 earthquakes spanning 45 years, with moment magnitudes $M_0$ ranging from 3.2. to 6.6 [8], can be used to derive the Gutenberg-Richter (G-R) frequency-magnitde relation for the Island of Hawaii, expressed as $\log(N) = a - bM_0$, where $N$ is the number of earthquakes with magnitudes greater than or equal to $M_0$, and $a$ and $b$ are constants [9]. By this analysis, (Fig. 1), one earthquake with $M_0$ 4.9 or greater can be expected every year. Under the assumption that the mechanisms of seismicity for edifice building are similar across the planets, we use the same $b$ for all planets [10] and scale $a$ according to estimates of magmatic volume flux rates $dV/dt$ at the various planets. Over the 80 Myr history of the Hawaiian-Emperor volcanic chain, $dV/dt$ is around 1.7 x $10^{-2}$ $km^3$/yr [11].

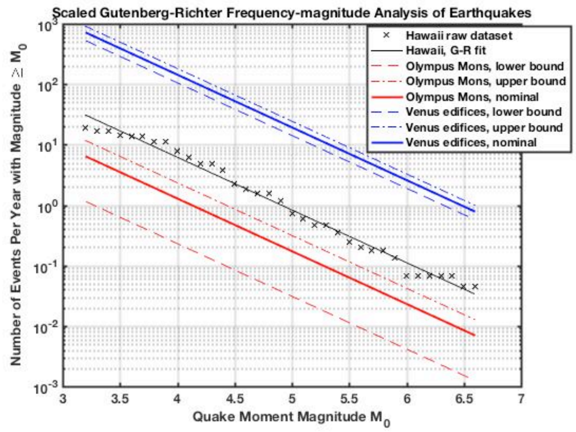


**Figure 1.** Frequency of seismic events with moment $\geq M_0$ as a function of $M_0$. Black ‘x’s show raw data for Hawaii [8], and the black line shows the best-fit G-R relation ($a$ = 5.93 and $b$ = 0.872), scaled to the duration of the seismic catalog to give rates. Red lines show nominal and bounding G-R relations for quakes at Olympus Mons, Mars; blue lines show them for volcanic edifices on Venus.

*Mars:* Paleotopography at Olympus Mons [5] yields estimates of $dV/dt$ for the last 210 Myr ranging from 6.33 x $10^{-4}$ to 6.43 x $10^{-3}$ $km^3$/s. Taking the mean of these values and scaling $a$ by the ratio of $dV/dt$ values for Mars and Hawaii yields a rate of at least 1 quake of $M_0$ = 4.1 or greater per year (Fig. 1).

*Venus:* Findings of a young(er) Venus surface age [3,4] greatly enhance predicted rates of volcanism. Estimates of $dV/dt$ associated with 145 large volcanoes on Venus [12], under the assumption of a surface age of 150 Ma [3,4], yields nominal $dV/dt$ = 3.95 x $10^{-1}$ $km^3$/yr, more than an order of magnitude greater than the Hawaiian-Emperor flux and comparable to Earth’s total intraplate volcanic flux [13]. Scaling the Hawaiian G-R relation to Venus edifices (alone) yields a prediction of at least one quake with $M_0 \geq 6.5$ per year.

**Monitoring: Instruments and Missions.**

*Seismic.* Above and beyond globally oriented Mars seismic experiments like InSight [14] and successor networks, a dedicated Olympus Mons Seismic Network modeled on networks at active volcanoes on Earth [15] would allow elucidation of structures related to lithospheric flexure [16], volcanic spreading [17], and perhaps even signals (tremor) related to magma movement and emplacement [18]. 20 years of monitoring should give at least one mag. 5.6 quake and ~ 20 $M_0 \geq 4.1$ quakes to study. Such results would provide insights into the processes that controlled Martian volcanic evolution and crustal structure that are not likely to be available at any other site on the planet.

New evidence of geologically recent or even ongoing volcano-tectonic activity on Venus [1,2] provides strong motivation for seismic monitoring (see also Fig. 1), and while surface temperature conditions are extreme, progress on high-$T$ electronics offers some hope of long-duration seismometers in the 2030-50 timeframe [19]. If the volcanic edifice volume flux for Venus is indeed comparable to Earth's intraplate flux, then even relatively short-duration seismic stations should find numerous large-magnitude events to study (Fig. 1). Surface monitoring could also be augmented by long-duration (buoyant) aircraft platforms.

*InSAR.* Interferometric Sythetic Aperture Radar (InSAR) techniques allow detailed analyses of fault and volcano deformation [20]. These analyses require repeat-pass orbital imaging of sites, which is straightforward to accomplish at rapidly rotating planets like Earth or Mars, but which presents challenges at a slowly rotating one like Venus, resulting in 243-day long cycles [e.g., 21]. A pair or even constellation of InSAR-capable spacecraft in staggered orbits [22] could mitigate the slow-rotation constraint, allowing shorter repeat-pass time baselines.

*Gravity.* Gravity data provide fundamental constraints on planetary interior structure [23], including time-dependent signals related to volatile cycles, such as polar cap/atmosphere exchange [24] and terrestrial water storage [25]. There are several mission mode options for next-generation gravity investigations of Mars and Venus. GRACE/GRAIL-type dual-satellite gravity missions using Ka-Band Doppler or laser-interferometer tracking [26,27] offer substantial advantages in precision and resolving power over traditional Doppler tracking, as do single-satellite gravity gradiometry missions [28]. Technological advances in gradiometry technology [29] offer orders of magnitude improvements in sensitivity over current instruments.

For Mars, while Doppler gravity tracking from MGS/ODY/MRO was sufficient to detect signals from polar cap volatile cycles [24], improvements from dual-satellite or gradiometry measurements would resolve Mars' $CO_2$ cycle at greatly improved resolution. Further, detection of subsurface water flow cycles on Mars (if present) would be a spectacular leap forward. Volatile cycles of this sort are not relevant to Venus. However, Venus' atmosphere perturbs gravity mapping from orbit by causing atmospheric drag at the satellite altitude and also through perturbations induced by the variability and motion of the atmosphere. These have likely contributed to irregularities and errors in the mapping of the gravity field of Venus using Magellan data, contributing to spuriously low or erratically variable gravity/topography correlations on Venus [30]. New gravity missions with high sensitivity and uniform coverage, that include methods for accounting for non-conservative force-induced accelerations on the spacecraft (for example, using precision accelerometers as on GRACE [26]), could allow the gravity field of Venus to be properly resolved, as well as producing data relevant to atmospheric studies.

*Groundstation Science.* A positioning satellite network at Mars would enable precision GPS-type observations [31] from fixed ground stations, and also allow autonomous rover/astronaut navigation. The GPS-like stations could be arranged in local networks to monitor deformation of volcanic edifices or signatures of surface or subsurface mass exchange. These ground stations would also deploy gravimeters, seismometers, heat-flow sensors, and strain meters.

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