REVISITING THE POST-*GALILEO* MODEL OF THE IONIAN ROCK CYCLE.

L. P. Keszthelyi[1], W. L. Jaeger, A. S. McEwen[2], M. T. Bland[1], and [1]USGS Astrogeology Science Center, Flagstaff, AZ 86001 (laz@usgs.gov), [2]University of Arizona, Lunar and Planetary Laboratory, Tucson, AZ 85721.

Introduction: After the *Galileo* mission, a self-consistent model of Io's rock cycle that fit a number of apparently contradictory observations was constructed [1]. Here we revisit this model after 15 years to consider if it continues to be useful and identify aspects that are most in need of refinement.

Observational Constraints: Any model for the Ionian rock cycle must be compatible with the extreme tidal heating and resulting volcanic and tectonic activity observed on Io. Io's current volcanic heat flux is at least 10^{14} W [2], equal to ~700 km^3 of erupted lava per year. If Io has been this active for ~4 Gy, the erupted volume is >10^{12} km^3, 100 times the total volume of Io. It is also equivalent to a mean global resurfacing rate of >1 cm/y. The lack of any observed impact craters indicates that the resurfacing is indeed global, with no significant part of Io undergoing resurfacing at less than >1 mm/y [3].

Global geologic mapping [4] found the level and style of activity across Io to be remarkably uniform with vast plains interrupted by lava lakes, lava flows, and tectonic massifs. What is not seen is noteworthy: there is no evidence for planetary-scale heterogeneities like the hemispheric dichotomy on Mars or continents/oceans on Earth. Mountain ranges are notably absent and rift zones are not seen. Even regional anomalous terrains such as the ancient tessera on Venus are not found. Detailed statistical studies have found a possible subtle anti-correlation between areas with higher concentrations of mountains and higher concentrations of volcanic centers [5,6], but the overall picture is one of globally distributed active volcanism and tectonism.

However, when examined in detail, it is evident that the geologic activity is highly focused. Active eruptive centers and tectonic massifs make up only a few % of the surface of Io [4]. Furthermore, there is a statistically significant tendency for eruptive centers and mountains to be adjacent to each other [7]. Still, lava flows and plume deposits do extend >>100 km from their vents, covering approximately 30% and 20% of Io, respectively [4].

Compositional observations are few, but the morphology and eruption temperatures are consistent with mafic to ultramafic compositions. With mountains up to 17-km tall lifted by thrust faults, Io's lithosphere must be at least a few tens of kilometers thick in many locations [8]. Sulfur and other volatiles are too weak to support the steep and tall patera walls and mountain sides so silicates must dominate below a mantle of sulfurous volatiles [9, 10].

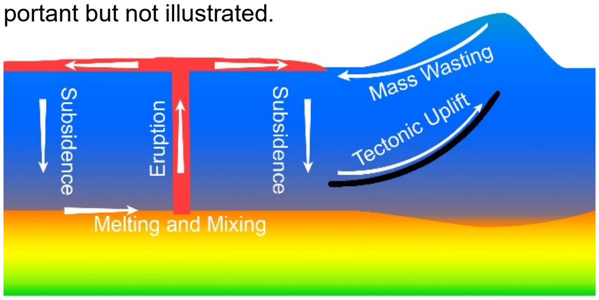
Derived Constraints: Inferences drawn from these observations provide a second tier of constraints on the Ionian rock cycle. The extreme volcanic activity would lead to extreme geochemical differentiation with low-temperature felsic lavas [10] unless there is complete recycling of the crust [11]. The high heat flow would require a conductive lithosphere only a few kilometers thick, but a thick cold lithosphere is possible if heat is transported primarily by the volcanic heat pipe process [12]. A consequence of the rapid global resurfacing is subsidence and compression that increases rapidly with depth, exceeding the strength of rock at a depth of only a few km [7]. This stress field is inimical to the ascent of magma but is locally relieved by thrust faults like those associated with mountain uplift. However, since the spacing between mountains suggests that such faults are a miniscule fraction of Io's lithosphere, magma is expected to accumulate in the upper asthenosphere.

The Post-*Galileo* Model: The model presented after the end of the *Galileo* mission (Fig. 1) [1] is a refinement of previous results [7,8,11-14]. Mafic/ultramafic magma (1st or 2nd generation mantle melts) erupt at the surface or are emplaced as shallow sills to form lava flows and patera-filling lakes that spread laterally for tens to hundreds of kilometers. The lavas cool and are buried by subsequent flows. The lava then descends and is subjected to ever-increasing compression. These stresses fracture the rock and collapse the pore spaces. Because of the speed of lithospheric subsidence, the descending rocks are not subjected to significant heating until near the base of the lithosphere. Here the rock can follow one of two different paths.

In the first path, it can continue to descend and be conductively heated from the tidally heated asthenosphere. As the degree of partial melting reaches a few percent, the crustal rock weakens and becomes asthenosphere. The initial melt struggles to ascend back up through the lithosphere that is in compression. As the degree of partial melting continues to increase the zone of melting grows. At high degrees of partial melting, the residual solid from the crust should be denser than mantle melts and mechanical mixing between the crust and mantle becomes plausible. The tall column of magma also becomes buoyant enough to break through zones of weakness in the lower lithosphere and reach the surface in energetic and sustained eruptions.

In the second path, the cold rock is uplifted from the lower lithosphere along a thrust fault and incorporated into a tectonic mountain. The mountain is destroyed by mass wasting processes and the debris is eventually covered by lava flows and is again driven downward.

Figure 1. Cartoon of Ionian rock cycle. On the left is the classic volcanic heat pipe where successive lava flows are buried and subside. On the right is the cycle including the formation and destruction of mountains. The role of tectonics in opening pathways for the magma is important but not illustrated.



This model makes some interesting predictions, some of which have been tested. For example, the widespread high degree of partial melting in the asthenosphere should produce a global interconnected zone of high electrical conductivity, consistent with magnetometer data from Io [15]. In contrast to the Earth, the model predicts that the lithosphere/asthenosphere boundary falls within the crust instead of within the mantle. Also, the magma is fed from a global reservoir and will ascend rapidly through the lithosphere [16], leading to a limited opportunity for assimilation of wall rock and to a dearth of mid-crustal magma chambers where magma evolution would be expected. This leads to an expectation of highly uniform lava compositions.

Alternative Models? In essence, the post-Galileo rock cycle described above just provides some geologic detail to the volcanic heat pipe process. Thus any true alternate model would have to provide a fundamentally different mechanism for explaining the way heat is delivered to the surface of Io. No such mechanism has appeared in the peer-reviewed literature, but this has not precluded ideas from circulating less formally.

For example, it has been occasionally suggested that Loki and other paterae on Io represent foundered crustal blocks or may be modified impact craters. In this scenario, the lava lakes in paterae would be windows to a magma ocean below. With a large portion of Io's heat flux explained in this fashion, the volcanic heat pipe is no longer needed, and a thin lithosphere is to be expected. While this idea might address many of Io's volcanic features, it fails to explain the tectonic features and can therefore be rejected.

Volcanologist and geophysicists studying Io often make assumptions based on intuition gained from Earth with its lithosphere extending into the mantle, an asthenosphere with only minimal partial melting except over mantle upwellings, and a plumbing system with a network of dikes, sills, and magma chambers. These assumptions are largely based on the terrestrial association between vigorous volcanism and extensional tectonics. But it is not valid for a lithosphere that is almost globally under intense compression, as required by the volcanic heat pipe model.

Future Work: While no real alternative model has arisen in recent years, there are major unanswered questions about the Ionian rock cycle. Perhaps the most glaring is the manner in which crustal recycling takes place at the base of the lithosphere. The complex mechanical and petrologic interactions between a partially molten crust and a partially molten mantle have not been investigated in any detail. The lateral heterogeneities introduced by magma conduits that tap this zone and the cold roots of mountains that intrude into it are essential to include in the analysis. The importance of perturbations caused by mantle convection is an open question.

The second, predominantly tectonic, path in the Ionian rock cycle is also under-studied. The role of sulfur and other volatiles in this cycle is unknown but may be extremely important. A more detailed understanding of the kinematics of the interaction between local areas of subsidence and uplift could reveal important new insights into the geology of Io.

We end by noting that research along these lines would have implications far beyond a single odd-ball satellite of Jupiter. Understanding the rock cycle on Io will provide new insight into how ocean worlds like Europa work [17] and how terrestrial planetary bodies transition from a magma ocean to a single-plate or to plate tectonics [18].

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