A Jökulhlaup-like Model for Secondary Sulfur Flows on Io. Steven M. Battaglia[1,2], [1]University of Illinois, Dept. of Geology, Natural History Bldg, 1301 W. Green St., Champaign, IL 61801, [2]Northern Illinois Univ., Dept. of Geology, 312 Davis Hall, Normal Rd., DeKalb, IL, 60115 (email: battagls1@gmail.com)

Introduction: Io is a very volcanically active body in the solar system with high temperature basaltic to ultramafic eruptions occurring over the entire surface of the satellite [1-5]. Early studies suggests that sulfur volcanism exists as a primary role in Io's dynamic crustal evolution [6-9]. Since these early studies, observational evidence and theoretical modeling has strengthened the mode of resurfacing to be dominated by widespread silicate-volcanism. Yet, it has been postulated that secondary sulfur-dominated eruptions may still endure on Io's surface and could be analogous to terrestrial volcanic processes [10].

The secondary sulfurous eruptions would consist of remobilized surficial sulfur deposits melted by the heat from nearby high-temperature silicate eruptions, as observed to occur on Earth. These subsequent eruptions could take the form of flows or sputters that emanate from the edges of lava lakes and hotspots (or, in the case of Io, paterae) (Fig. 1). Although these eruptions have only been calculated to be possible on Io's surface based on surface imagery of thermal erosion channels and terrestrial-drawn comparisons, there is currently no analog to Earth's hydro-tectonic processes to better develop the model of secondary sulfurous-dominated flows that radiate from an Io hotspot.

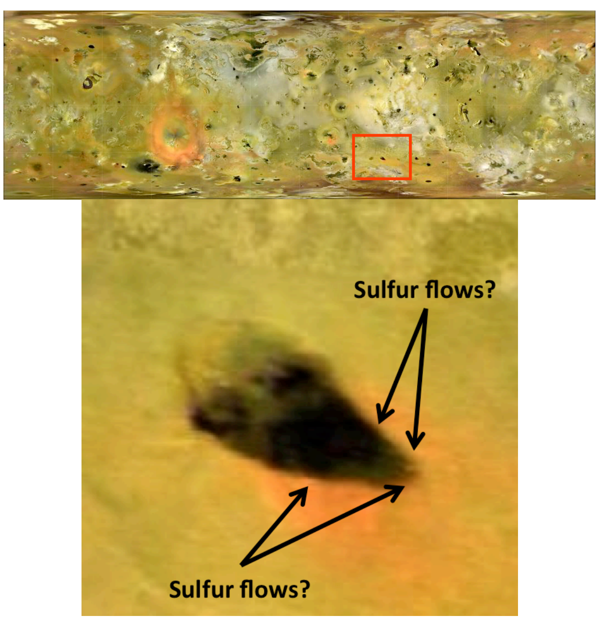

Fig. 1: Malik Patera (region in red box on Io surface map) with possible sulfur flows emanating from the edges of the paterae floor in thermally-eroded channels on the ionian surface. (Image Credit: NASA)

Silicate Volcanism and Volatile Sulfur: A volcanically active body such as Earth or Io suggests a magmatic distillation process that works to concentrate volatiles in or near surface reservoirs. On Earth, this is the combined hydrologic and tectonic cycle, whereas on Io it is a combined cycling of sulfur and resurfacing of volcanically-derived silicate material. This concept was supported from a sulfur solubility model of Pele's magma supply that demonstrated sulfur is likely to be concentrated in the upper crust of Io similar to water in terrestrial volcanism [11]. Therefore, volatile sulfur plays a crucial role in both primary and secondary volcanic processes on Io as water does on Earth.

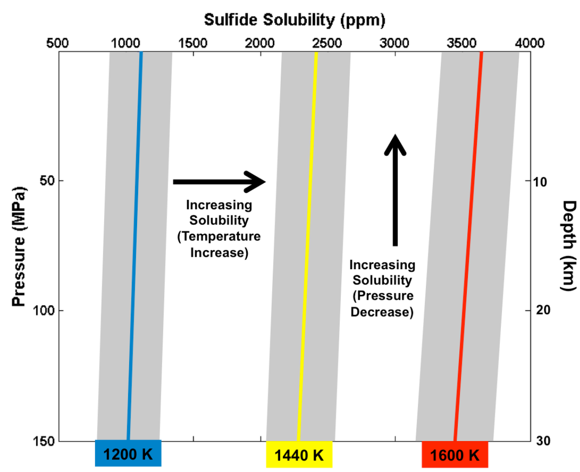

Fig. 2: Sulfur concentration at sulfide solubility (SCSS) in the crust (~30 km) of Io using the updated sulfur solubility model by [12] for magma temperatures at 1200K, 1440K, and 1600K. Sulfide solubility is in parts per million, ppm. (See [11] for model methodology.)

Sulfur Solubility Model—Updated: Since sulfur solubility modeling is one of the limited methods to estimate the quantity of sulfur in Io's magmas, the same methodology as used in [11] is applied here. However, an updated sulfur solubility equation is used [12] that is based on more recent petrological experiments of terrestrial magmas to better approximate the sulfur concentrations in Io's melts. Fig. 2 is the result of the sulfur concentration at sulfide solubility (SCSS) of Io's magmas to a depth of 30km (~150MPa) for varying magma temperatures (1200K, 1440K, 1600K).

The model indicates the SCSS in Io's melts will increase from either (i) an increase in magma temperature or (ii) a decrease in pressure from melt ascension. The concentration of volatile sulfur in the near surface of Io may be excessive and can exist as an insoluble sulfide liquid or undergo recycling through resurfacing and burial, analogous to the water cycle on Earth. Thus, the resulting implications from the model are in agreement with the previous findings of sulfur's solubility for Io's melts and it also suggests that the sulfur concentrations in the upper crust could be larger than previously evaluated.

Secondary Sulfur Flows: Sulfurous deposits in Io's upper lithosphere, which exists as either an insoluble sulfide melt or as a remobilized volatile, have a high probability to accumulate in subpaterae chambers. The sulfur is likely to be in its liquid phase from being within the vicinity of an upwelling magma source. An assembly of liquid sulfur beneath a lava lake or patera floor may have no direct flowpath to pour outward toward the surface because of continuous resurfacing and burial of silicate material, therefore leading to an increase in pressure.

The accumulation of liquid volatiles near a thermal hotspot is similar to geothermal heating beneath glaciers on Earth. One particular location with subglacial geothermal heating, where an increase of pressure from subglacial meltwater can occur, is in Iceland. Such heating and pressure escalation can eventually lead to a flooding event called a *jökulhlaup*.

Jökulhlaups (Subglacial Outburst Floods): A jökulhlaup, which in Icelandic translates directly as "glacier run," describes the event in which a large amount of water from one of Iceland's glaciers bursts outward toward the ocean from a buildup of subglacial basin pressure [13-14]. Geothermal heating from below the glacier causes meltwater to accumulate in subglacial basins. Once there is a significant amount of water, a tunnel valley opens in the ice blockage of the glacier and can discharge excess water, sometimes as a violent outflow or a turbulent flow. This leads to strong erosion of the valley floor and sends a torrent of water outward towards the ocean. The turbulent floodwaters that is released from the glacier and subsequent damage to the landscape or infrastructure are two of the fundamentals of jökulhlaups.

Subpaterae Outburst Floods of Sulfur: Similar to a jökulhlaup, large concentrations of excess sulfur beneath a lava lake or hotspot may undergo a surge in pressure and could eventually spurt through to the surface as a turbulent flow. Fig. 3 is a proposed illustration of the subpaterae outburst flooding of sulfur on Io.

Subsidized sulfur in the ionian crust may undergo a phase change from solid to liquid if near the vicinity of an upwelling magma source. This is analogous to subglacial meltwater basins forming from geothermal heating beneath ice. On Io, overburden of silicate and

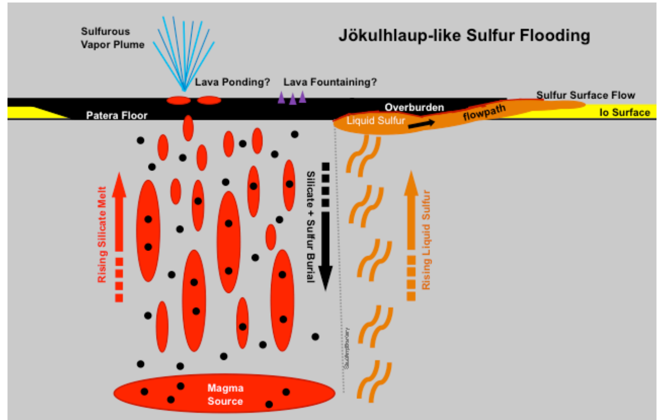

Fig. 3: Illustration of a jökulhlaup-like flood of liquid sulfur from beneath an Io patera to the surface. Heated subsidized sulfurous and silicate material occur near an upwelling magma source. Liquid sulfur rises to an accumulation chamber beneath the patera floor or lava lake. Increasing pressure from liquid sulfurous materials may eventually exceed the overburden force and open a channel to spew its excess sulfur outward as a short-lived turbulent flow.

sulfurous materials can contain secondary liquid sulfur in subpaterae that could congregate and escalate the basin pressure if there is no open flowpath to the surface. Once pressure and sulfur concentration exceeds the overburden force of the paterae floor, the sulfur liquid can spew onto the surface, outward and away from the hotspot, as a secondary turbulent flow.

This process of subpaterae sulfur outburst floods (*brennisteinihlaups*, or "sulfurous runs," if maintaining Icelandic nomenclature), like jökulhlaups on Earth, would be short-lived and may suggest why there are limited observations of secondary sulfur flows on Io. Nonetheless, the complexity of Io's active volcanism and large sulfur concentrations in the upper crust leaves the possibility for secondary sulfur volcanism to be occurring in Io's present dynamic state.

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