AN INVESTIGATION OF EXTENSIVE TIDALLY HEATED SUPER-EARTHS (SUPER-IOS) USING A SULFUR SOLUBILITY MODEL OF GLIESE 876 d. Steven M. Battaglia[1], Marco E. Castillo[1], and Christine A. Knudson[1], [1]Department of Geology and Environmental Geosciences, Northern Illinois University, Davis Hall 312, Normal Road, DeKalb, IL, 60115 (Corresponding Email: battagls1@gmail.com).

Introduction: A super-Earth is an extrasolar planet with a mass between 1–10$M_{\oplus}$ [1]. The mass of a super-Earth does not imply its bulk composition and current remote sensing capabilities limits us from directly probing an exoplanetary surface. Therefore, super-Earth compositions remain unknown. Current models of planetary formation and evolution predict two types of super-Earth compositions: (i) an Earth-like silicate planet or (ii) a global water world overlying a subsurface high-pressurized ice [2,3]. A terrestrial super-Earth is likely to sustain active-lid tectonics and thus maintain surficial volcanism [4]. This volcanism may be extensive if a super-Earth orbits close to its host star and has undergone significant tidal heating since its formation [5]. The amount of tidal evolution is likely analogous to Jupiter's volcanically active satellite, Io, where large amounts of silicate and sulfurous eruptions cover its surface from the interior melting [6]. Such a tidally heated super-Earth with a surface heat flux larger than Io's (>2 Wm^{-2}) is called a "super-Io" [7]. Sulfur plays a critical role in ionian volcanism and thus sulfurous compounds on a super-Io may be relevant in determining volcanic-surficial environments of tidally heated super-Earths.

Here, we investigate the behavior of sulfurous compounds in super-Io magmas using a sulfur solubility model to constrain the possible surface environments of terrestrial super-Earths. Our model of a super-Io is developed under the following assumptions: (1) its silicate composition is Earth-like (terrestrial), (2) its interior is tidally heated similar to Io, and (3) it is undergoing active resurfacing. We use our model for Gliese 876 d as a supposition that it represents the behavior of other super-Io exoplanets.

Gliese 876 d: Gliese 876 d is a super-Earth fifteen light-years away with an estimated mass of ~7.5$M_{\oplus}$ and a gravitational acceleration of ~1.9–3.3g assuming a planetary radius of ~1.4$R_{\oplus}$ [8]. Planet d orbits Gliese 876 in less than two days with a semi-major axis of ~0.02AU. This short revolution and close proximity suggests Gliese 876 d has endured generous tidal deformation during its evolution and may be of geologic interest [5]. The substantial tidal heating melts the interior of planet d and advances silicate magma towards the surface assuming a terrestrial composition. Therefore, a considerable amount of reoccurring ascending magmas may produce extensive surface volcanism and sustain active-lid tectonics.

We assume the tidal deformation and resulting melting of Gliese 876 d are correlative to ionian volcanism and thus consider it a super-Io. Magmas on the surface of Io are likely of basaltic composition [9]. We therefore model the sulfur solubility on Gliese 876 d for a basaltic melt.

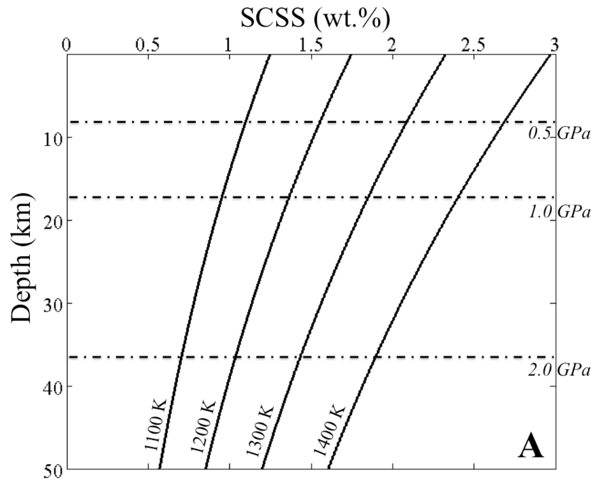
Sulfur Solubility Model: The sulfur concentration *S* at sulfide saturation (*SCSS*) for a silicate melt is given by [10]:

$$\ln(S\ in\ ppm)_{SCSS} = a - \frac{b}{T} - c\frac{P}{T} + d\ln(MFM) - e\,(MFM)(X_{H2O}) + f\ln(X_{H2O}) + g\ln(X_{FeO}) \quad (1)$$

where a–g are constants, T is the temperature in K, P is the pressure in bars, *MFM* is the modified fractional melt value, and X is the compositional mole fraction of the given compounds (H_2O, FeO) in the silicate melt.

We adopt a *MFM* value of 7.0 for a basaltic melt that contains 9 wt.% FeO and 1 wt.% H_2O, and a constant density of 2900 kg m^{-3} [10]. We model *SCSS* against depth for a basaltic melt on Gliese 876 d using Eq. 1 under the gravitational constraints stated above and the temperature range 1100–1400K.

Results: The *SCSS* increases with a decrease in pressure for a basaltic magma on Gliese 876 d at isothermal conditions analogous to the behavior of sulfur in silicate melts on Earth and Io. However, an increase in planetary mass decreases the *SCSS* at depth (Fig. 1). Gliese 876 d is more massive than Earth and Io. Thus, the *SCSS* is lower in shallow magma reservoirs on Gliese 876 d in comparision to terrestrial and ionian melt reservoirs. On Io, the *SCSS* is higher in near-surface reservoirs than Earth because of the low planetary mass, which may be contributing to the immense amount of sulfur expelling from Io's subsurface and the residual sulfur on the surface. Since Gliese 876 d is a super-Earth with a terrestrial composition, we expect sulfur in silicate magmas on other super-Earths to demonstrate a similar behavior. Our model indicates that the *SCSS* for super-Io silicate magmas is different from the observed silicate melts in the solar system.



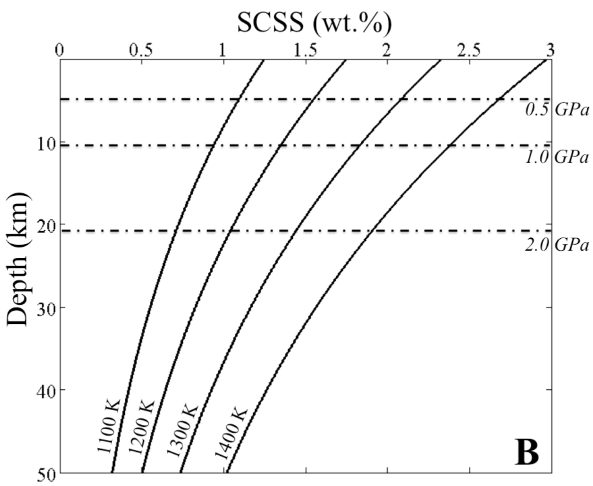


Fig. 1: *SCSS* to a depth of 50 km for Gliese 876 d at magma temperatures 1100, 1200, 1300, and 1400K. Solid lines represent the *SCSS* at depth under isothermal conditions. Dashed lines represent the depths at pressures 0.5, 1.0, and 2.0 GPa. Graph A (upper) models *SCSS* for a minimum gravity of 1.9*g* and Graph B (lower) models *SCSS* for a maximum gravity of 3.3*g*.

Discussion: As on Earth, excess sulfur in the primitive mantle was likely extracted from early magma oceans during core formation [11] and any immiscible Fe-sulfide liquids that have formed during melting would be negatively buoyant and fractionate from rising silicate melt [12]. Ascending magmas are not expected to exsolve sulfide liquid from the negative pressure dependence of the sulfur solubility and the incremental decreases in temperature from adiabatic expansion. These magmas may assimilate crustal materials producing a sulfide melt from those assimilated materials. However, crustal assimilation of sedimentary and organic material is unlikely to occur on a super-Io under our initial assumptions. Any sulfide melt produced on a super-Io from crustal assimilation is thus preexisting silicate- or sulfur-rich country rock within the upper crust.

Magmatic sulfur expels to the surface as magma cools and degasses from residence in shallow magma reservoirs when vaporous sulfur separates from the magmas during cooling. The sulfur vapor diffuses from assimilated silicate- or sulfur-rich materials in the magma. Our model indicates super-Io magma chambers are shallower than those on Earth suggesting a shorter cooling residence time from assimilation to degassing. A shorter crystallization period for magma ascending in a shallow chamber implies rapid overturning and extensive near-surface volatile degassing similar to the conditions on the early Earth and present-day Io. However, the sulfur vapor expelled onto the surface of a super-Io will condense into a liquid from the high surface temperature instead of a solid. Other degassed volatile compounds lighter than sulfur such as H_2O, CO_2, and SO_2 are not likely to be retained on the surface and may produce a venusian-like atmosphere with a superrotating atmospheric jet [13,14].

Conclusions: Our sulfur solubility model of Gliese 876 d indicates that sulfurous compounds on super-Ios are likely to be concentrated in the upper crust. The rapid magma overturning from short-cooling residency in shallow reservoirs corresponds to an active-lid plate tectonic regime similar to the conditions on the early Earth and present-day Io. The extensive volatile degassing may produce global cloud cover and a greenhouse atmosphere that would ultimately warm the surface to extreme temperatures.

We conclude that an extensive tidally heated super-Earth, or super-Io, (i) sustains active-lid tectonics that may resemble crustal processes of the early Earth, (ii) contains an ionian sulfur-rich crust, (iii) may have liquid sulfur residing on its surface, and (iv) may retain a venusian atmosphere from exsolved magmatic gases. Future studies investigating super-Ios could provide direct analogs to Io, Venus, and the early-Earth.

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