

EVOLUTION OF SULFUR TO THE SURFACE OF IO

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The excitement surrounding the discovery of volcanism involving species of sulfur on Io has spawned many studies on the means by which sulfur species may drive eruptions. Far less attention has been directed towards understanding how sulfur species were concentrated on the surface of Io in the first place. This is no trivial problem: iron has a very strong affinity for sulfur over a wide range of oxygen and sulfur fugacities, leading to the formation of iron sulfides which are dense and, on a planetary scale, might be expected to concentrate in the interiors of planets rather than at the surfaces.

Using thermodynamic data to predict the production and mobility of S and SO<sub>2</sub>, Lewis (1) found that temperatures > 1200 K and a very restricted range of oxygen fugacity are required. At lower fO<sub>2</sub>, pyrite forms, and at higher fO<sub>2</sub> MgSO<sub>4</sub> forms, immobilizing the sulfur components. Consolmagno (2) suggested that carbon in chondritic composition may react with water to form methane, which is lost to the surface, leaving behind oxygen which increases fO<sub>2</sub> to the value where sulfur liquid can form and SO<sub>2</sub> pressures build to significant values.

If presently-anhydrous Io once contained H<sub>2</sub>O, an alternate model for transport of sulfur species to the surface may be developed. This model requires no special chemical conditions, and may be considered as an extension of the model for petrologic evolution of Europa suggested by Ransford et al. (3) and Finnerty et al. (4). It bears similarities to the evaporite model of Fanale et al. (5). The extension is justified because of the similar diameters of the two satellites, because the density contrast between them may be accounted for if Europa has the bulk composition of Io with the addition of 5 to 6 wt% H<sub>2</sub>O, and because tidal dissipation in Io results in the internal generation of about 100 times as much heat as in Europa.

In the Europa model, it is assumed that accretion temperatures did not exceed 500 to 600 C. Either by direct accretion, or by reaction with anhydrous silicates as the interior warms by decay of radioisotopes, any H<sub>2</sub>O would have to be incorporated in hydrous silicates (e.g. serpentine). Such hydrous silicates decompose to free H<sub>2</sub>O fluid + anhydrous silicates only when temperatures exceed 500 to 600 C, nearly independent of pressure. Thus, as the interior warms due to radioactive decay, the migration upwards through the interior of the satellite of the 500-600 C isotherm coincides with the upwards migration of a dehydration front. Ultimately a thermal steady state is reached with the 500-600 C isotherm located at 200 to 250 km depth. In Europa, with 5 to 6 wt% H<sub>2</sub>O, almost all H<sub>2</sub>O will be trapped in hydrated silicates in the 200-250 km layer between the 500-600 C isotherm and the surface. It is extremely unlikely that a thick (>100 km) layer of free H<sub>2</sub>O exists in Europa.

The dehydration reactions by which H<sub>2</sub>O is evolved upwards during the thermal evolution of a hydrous chondritic planet proceed with large increases in volume. Serpentinites and other rocks with a large proportion of hydrous minerals become very weak and brittle in the presence of free water. This provides a mechanism for pervasive fracturing of a hydrated crust. Free H<sub>2</sub>O will vigorously convect in such a porous medium (6,7).

In the extension of this model to Io, it is supposed that a similar evolutionary sequence is followed. But, because of the generation of

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additional heat in Io due to tidal dissipation, the 500-600 C isotherm will migrate very near to the surface (8,9,2). Any H<sub>2</sub>O that accreted into Io will be evolved to the surface.

On Earth, the principle mode of sulfur species transport is via hydrothermal solutions as dissolved metal sulfides (10). The solubility of sulfur species in water in experiments is less than 640 ppmw (11), with 13 ppmw or less measured in fluid inclusions in ore deposits (12). The accumulation of significant concentrations of sulfide ore minerals on Earth requires the deposition of sulfides from large volumes of water passing through a particular region. The water may be recycled between the source region and the developing ore body via convection.

Metal sulfides, principally iron sulfides, may have been deposited on the surface of Io by a similar mechanism. During the later stages of thermal evolution, water circulating through a fractured, porous crust would dissolve sulfides and redeposit them at higher levels in the crust as temperature and pressure of the hydrothermal fluid drops. The thickness of the crustal layer that bears hydrothermal fluids would steadily decrease as the 500-600 C isotherm approaches the surface, eventually stripping the sulfides from the crust and depositing them on the surface.

Io is presently anhydrous and, although spectral and other data do not preclude concentrations of iron on the surface (D.B. Nash, JPL, pers. com. 1983), it is unlikely that iron sulfides presently reside on the surface. However, the same mechanisms that can cause the loss of H<sub>2</sub>O from the surface (13) leads to oxidation of metal sulfides to form elemental sulfur and SO<sub>2</sub>. For comparable concentrations of H<sub>2</sub> and O in the paleoatmosphere of Io, as might be formed by thermal dissociation of H<sub>2</sub>O or by photodissociation of H<sub>2</sub>O in the intense radiation environment of Io, H is lost by Jeans escape at a rate two orders of magnitude faster than O. Metal sulfides break down to S + metal oxides (which may enter into silicate phases), and further oxidation produces SO<sub>2</sub>. Silicates and oxides, being denser than sulfur, will most likely be buried under a sulfur layer.

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