

## CRUSTAL STRUCTURE AND IGNEOUS PROCESSES IN A CHONDRITIC IO;

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Liquid sulfur can form when metal-free C1 or C2 chondrites are heated [1]. It may be obtained either by direct melting of native sulfur in disequilibrated C1 or C2 chondrites or by incongruent melting of pyrite and other sulfides in thermodynamically equilibrated rocks of the same composition. Hence, Lewis [1] considered C2 chondrites to be the best meteoritic analog for Io's bulk composition. Metal-bearing C3 and ordinary chondrites are too chemically reduced to yield liquid sulfur and are not thought to represent plausible analogs of Io's bulk composition. An important aspect of Lewis' work [1] is that  $\text{CaSO}_4$  and  $\text{MgSO}_4$  are predicted to be important in Io. Real C1 and C2 chondrites contain averages of, respectively, 11% and 3% by mass of salts (plus water of hydration) [2]. The most abundant chondritic salts are magnesium and calcium sulfates, but other important components include sulfates of sodium, potassium, and nickel and carbonates of magnesium, calcium, and iron. It is widely accepted that chondritic salts formed by low-temperature aqueous alteration. Even if Io originally did not contain salts, it is likely that aqueous alteration would have yielded several percent sulfates and carbonates. In any event, Io probably contains sulfates and carbonates.

This report presents the results of a model of differentiation of a simplified C2 chondrite-like composition that includes 1.92%  $\text{MgSO}_4$ , 0.56%  $\text{CaSO}_4$ , 0.53%  $\text{CaCO}_3$ , and 0.094% elemental sulfur [2]. The temperature of the model is gradually increased; ensuing fractional melting results in these components extruding or intruding at gravitationally stable levels in Io's crust. Relevant phase equilibria were reviewed by [3]. A deficiency of high-pressure phase equilibria renders the present model qualitative.

Figure 1 shows the modeled evolution of Io's crust. The most abundant chondritic sulfate, epsomite ( $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ), melts incongruently in several stages, leaving progressively more dehydrated residua. During stage 1, occurring near 321 K, epsomite yields an aqueous solution containing 33%  $\text{MgSO}_4$  plus solid hexahydrite ( $\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$ ). During stage 2, hexahydrite decomposes at 341 K to an aqueous solution of 37%  $\text{MgSO}_4$  plus residual kieserite ( $\text{MgSO}_4 \cdot \text{H}_2\text{O}$ ). This liquid is denser than the stage 1 crust, so it presumably intrudes beneath the early formed stage 1 crust. During stage 3, elemental sulfur melts at 392 K and intrudes beneath the stage 2 sulfate layer. During stage 4, kieserite melts and produces a very dense solution containing up to 87%  $\text{MgSO}_4$ ; this liquid intrudes beneath the sulfur layer. After stage 4 is complete, Io's mostly anhydrous silicate-rich mantle still contains anhydrite ( $\text{CaSO}_4$ ) and carbonates (mainly  $\text{CaCO}_3$ ). During stage 5, a dense carbonate-anhydrite melt intrudes and possibly mixes with the stage 4 layer.

After stage 5, the layered sulfate-carbonate crust contains 42% water, including some water ice in the surface layer, and pure sulfur resides at a depth of nearly 50 km. To produce an object resembling Io, some process is required to thoroughly desiccate Io's crust. As the crust dries, the sulfate-rich residual solids become denser than sulfur and consequently sink. Sinking sulfates eventually displace sulfur, which rises to the surface. After stage 6, anhydrous carbonates and sulfates reside beneath the sulfur in a layer averaging 25 km thick. Presumably the sulfate-carbonate layer is differentiated, but for simplicity it is depicted in Fig. 1 as a homogeneous layer. Stage 6 might reflect Io's present crustal structure. The modeled thickness of pure sulfur on Io is about 1 km. This layer might be substantially thicker than modeled, perhaps several kilometers, if incongruent fusion of sulfides contributed additional sulfur or if Io was initially composed of C1 chondrite-like material.

While the quantitative aspects of this scenario are very sensitive to the exact types of material accreted by Io, the qualitative aspects are not so sensitive. Qualitatively, the model depends on accretion by Io of material containing salts (such as C1 or C2 chondrites) or on post-accretion formation of salts by aqueous alteration. The model also depends on a workable mechanism to remove water from Io, because all likely salt-rich planetesimals are expected to contain also at least several percent water. If Io initially had accreted a significant amount of water ice, this water would have to be removed. One possible mechanism involves impact erosion by comets, which could account for loss of as much water as occurs in the icy mantles of Ganymede and Callisto (Eugene Shoemaker, personal communication, 1992). Smaller amounts of water may have been sputtered by charged particles. If water loss occurred primarily by impact erosion, then the current prevalence of sulfur volcanism on Io imposes a time constraint on impact erosion. While water was extruded, sulfur may have been "protected" in a rocky core and then lost; only after impact erosion had subsided might sulfur have been extruded and still have remained on Io's surface. According to a scenario modified from that illustrated by Figure 1, Io underwent

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early low-temperature aqueous differentiation to form layers B and C; then impact erosion stripped these briny ice layers; then a higher temperature phase of differentiation occurred, when sulfur extruded onto an impact-battered surface; then, finally, molten carbonates and sulfates intruded beneath the sulfur.

Io's sulfur volcanism may be driven by magmatic processes in the sulfate-carbonate layer. The peritectic temperature for  $\text{MgSO}_4$ -rich compositions in the system  $\text{MgSO}_4\text{-Na}_2\text{SO}_4\text{-CaSO}_4$  is 696 K [4]. Addition of carbonates and minor sulfate components probably reduces the peritectic to  $\sim 450\text{-}550$  K. Intrusion of molten salts could cause extensive melting of Io's sulfurous upper crust. The temperatures are high enough that a wide range of liquid sulfur allotropes could be erupted, thus accounting for the yellow, orange, red, and black flows photographed by the Voyager spacecraft [5]. It is also possible that high mountain peaks on Io are composed of carbonate-sulfates rather than silicates, as is commonly supposed.

References. [1] Lewis, J.S., 1982, *Icarus*, 50, 103-114. [2] Burgess, R., I.P. Wright, and P.T. Pillinger, 1991, *Meteoritics*, 26, 55-64. [3] Kargel, J.S., 1991, *Icarus*, 94, 368-390. [4] Mukimov, S.M. and Z.I. Filipova, 1949, *Trudy Inst. Khim., Akad. Nauk Uzbek. SSSR, Inst. Khim., No. 2, Obshchaya i Neorg. Khim.*, 1949, 123-132. [5] Sagan, C., 1979, *Nature*, 280, 750-753.

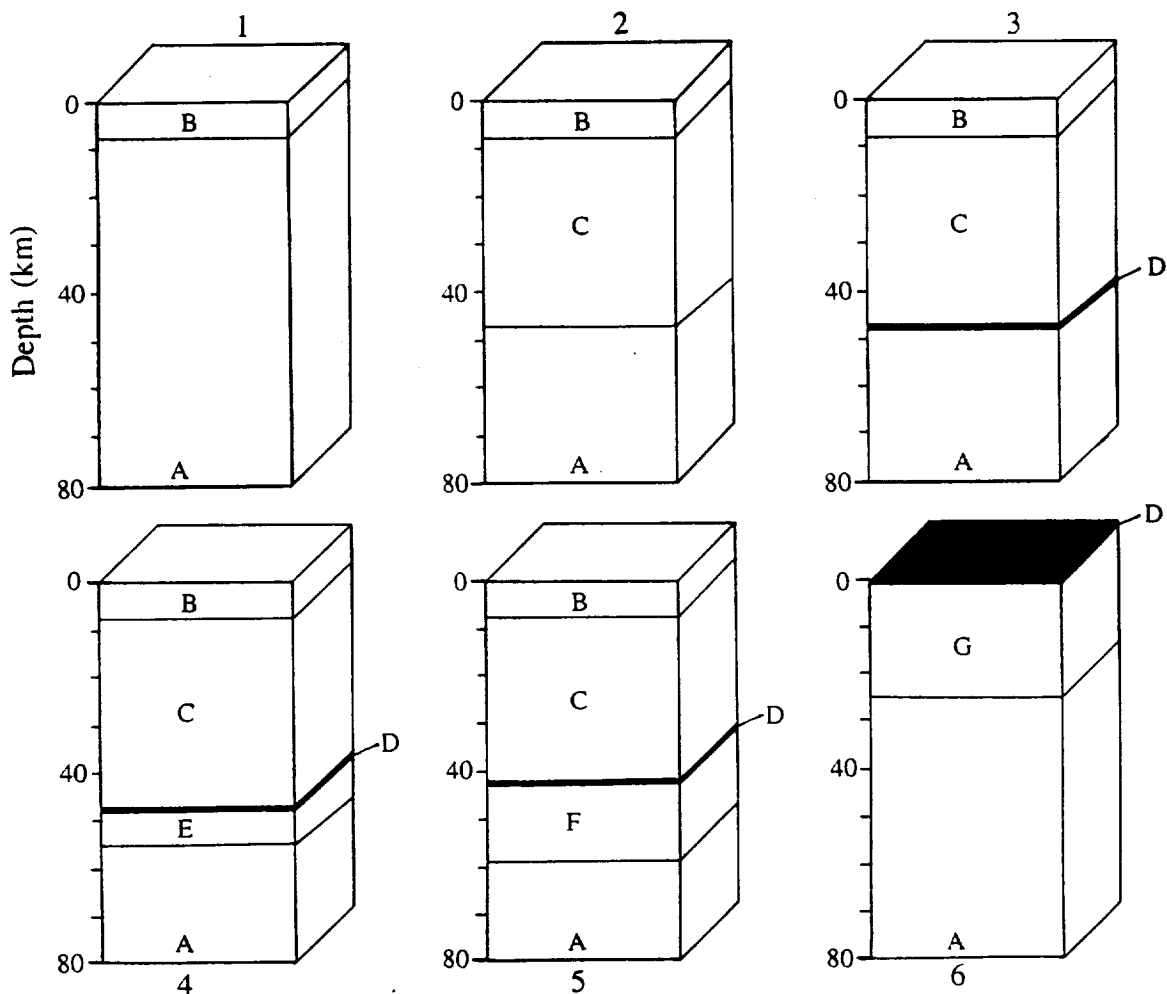


Figure 1. Model showing the evolution of Io's crust during melting stages 1-6. Properties and compositions of rock units are as follows: A, Silicate-rich mantle. B, 33%  $\text{MgSO}_4$  + 67%  $\text{H}_2\text{O}$ , density =  $1.44 \text{ g cm}^{-3}$ , melting temperature = 321 K. C, 37%  $\text{MgSO}_4$  + 63%  $\text{H}_2\text{O}$ , density =  $1.53 \text{ g cm}^{-3}$ , melting temperature = 341 K. D, Sulfur, density =  $2.07 \text{ g cm}^{-3}$ , melting temperature = 392 K. E, 87%  $\text{MgSO}_4$  + 13%  $\text{H}_2\text{O}$ , density =  $2.46 \text{ g cm}^{-3}$ . F,  $\text{MgSO}_4$  +  $\text{CaSO}_4$  +  $\text{CaCO}_3$  +  $\text{H}_2\text{O}$ . G, Anhydrous sulfate-carbonate layer, density  $\sim 2.7 \text{ g cm}^{-3}$ , melting point  $< 696$  K.