

tion of carbonate both suggest aqueous alteration, most plausibly on a planetesimal surface, of material produced earlier, possibly in the nebula. A similar origin has also been inferred for all other major minerals in CI chondrites (21). Such mineralization does not appear compatible with an origin directly in the nebula. Therefore, the I-Xe age determined for the Orgueil magnetic separate (5) apparently records alteration on a parent body rather than nebular condensation (22). Thus, aqueous activity, chondrule formation, and planetesimal differentiation all occurred within a period of 16×10^6 years, the "sharp isochronism" (23). Aqueous alteration apparently took place in a system that was closed, at least to nonvolatile elements, because the elemental abundances determined by bulk analyses of CI chondrites closely match solar elemental abundances (10).

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2. A magnetic separate, consisting mostly of magnetite, from the Orgueil CI meteorite gave a ^{129}Xe retention age of 4×10^6 years prior to the Bjurböle standard (5). This was the oldest age recorded at that time and was interpreted as dating the era of nebular condensation, linking that event to the nucleosynthesis of ^{129}I (5). An apparently older age, by 6×10^6 years, has since been reported for the chondrite Arapahoe [R. J. Drozd and F. A. Podosek, *Earth Planet. Sci. Lett.* **31**, 15 (1976)].
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and sulfates are only occasionally found in contact with their presumed precursor, pyrrhotite.

20. An identical orientation relationship to that suggested here is found when magnetite is produced by thermal decomposition of siderite (FeCO_3) despite loss of more than half of the oxygen from the carbonate lattice [J. D. Bernal, D. R. Dasgupta, A. L. Mackay, *Clay Miner. Bull.* **4**, 15 (1959)].
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Sulfur Volcanoes on Io

Abstract. Widespread volcanism on Jupiter's satellite Io, if it occurred over the age of the solar system, would quickly reduce the inventory of most common volatiles needed to drive such volcanism. One exception is the volatile element sulfur. It is therefore postulated that sulfur is the driving volatile for Ionian volcanism. Its presence is consistent with a carbonaceous-chondrite-like bulk composition for the original material that formed Io 4.5 billion years ago. The ubiquity of sulfur on Io today demonstrates the importance of this element in the processes that formed its surface.

In a recent report Peale *et al.* (1) examined the dissipation of tidal energy in Jupiter's satellite Io and predicted that "widespread and recurrent surface volcanism would occur, leading to extensive differentiation and outgassing" of that body. Recent photographs of Io by Voyager 1 appear to confirm this prediction (2).

If such extensive outgassing has occurred over 4.5 aeons, as would seem to be implied by the model of Peale *et al.* (assuming the Galilean satellites have occupied their current positions over the age of the solar system), then one would expect the outgassing of Io to have been completed long ago.

For example, let us assume Io started with the composition of a very volatile-rich C1 carbonaceous chondrite—20 percent water and 5 percent carbon by mass. This is similar to the composition proposed by Fanale *et al.* (3). On eruption, gases such as H_2O and CO_2 will be at roughly 1000°C ; their molecules will have mean velocities of 1.4 and 0.9 km/sec, respectively, compared to the escape velocity of material from Io into Jupiter orbit, which can be as low as 1.78 km/sec. [Such escape is trajectory-dependent; the average escape velocity is

2.0 km/sec (4).] Thus one would expect much of the H_2O to escape immediately. More importantly, the molecules that did not escape would be subject to dissociation and ionization by solar ultraviolet (UV) radiation (5) and their products would be quickly lost by Jeans escape or the sweeping action of Jupiter's magnetic field. Thus one can assume that any H_2O or CO_2 outgassed by a volcanic event would be lost to the system. To lose an entire Io inventory of such volatiles, assuming an initial C1 composition, one would have to erupt these gases at the rate of 10^8 g/sec.

This is of the same order as the volatile loss for a single Earth volcano. The Laki flow in Iceland erupted 15 km^3 of material over 7 months, or 2×10^9 g of material per second (6). The average rate for most Earth lavas is about an order of magnitude less; however, eruption rates an order of magnitude greater have been estimated for a section of the Columbia River plateau (7). Estimates of the volatile content of Earth lavas have ranged from 0 to 50 percent; best estimates for the solubility of water in magma at kilobar pressures are 10 percent (6). Thus one large Earth volcano with a volatile content of 10 percent could degas a very vol-

atile-rich Io over 4.6 aeons. In fact, the Peale *et al.* theory suggests many such volcanoes. Furthermore, if Io had the composition of a type C3 carbonaceous chondrite, it would have an order of magnitude less volatiles, and thus the volatile depletion problem would be that much more serious. Such a composition seems more likely than a C1 composition, on theoretical grounds (8).

One must therefore find another volatile material to drive the volcanism observed on Io. Such a substance must be able to be recycled into the interior of Io (if volcanism spews material at the rate of 10^9 g/sec per volcano, then the whole mass of Io would have been processed ten times, given six such volcanoes). It also should be cosmochemically reasonable. Such an element is sulfur.

Hydrated calcium and magnesium sulfates make up 22 percent of typical C1 material (which translates to a sulfur content of 5.5 percent by weight for C1's), and troilite makes up 7 percent of the mass of a typical C3 composition (giving an abundance of 2.5 percent by weight for sulfur). Other heavy volatiles, such as sodium, are at least an order of magnitude less abundant. Various sulfur compounds such as SO_2 and H_2S are common constituents of terrestrial volcanoes, and these have been suggested as being present in the Ionian volcanic gas (2). Presumably all these volatiles could have been present in Io originally; indeed, the presence of water may have been necessary to oxidize FeS, in the presence of FeO, producing magnetite and H_2S . However, once the entire planet had been outgassed for the first time, only S_2 would remain. The destruction by solar UV of the other gases, with the subsequent loss of oxygen and hydrogen, suggests that the driving gas in Ionian volcanoes at the present time must be elemental sulfur. Finally, sulfur has been suggested as a likely surface material of Io (2, 9).

At the surface temperature of Io (100 K) sulfur will be in a crystalline state with a negligible vapor pressure ($< 10^{-9}$ bar); at lithostatic pressures deep within the interior it will be in the liquid or supercritical fluid phase. However, near the surface where gases in the rock become in contact with the surface ambient pressures, the hydrostatic rather than the lithostatic pressure confines the gas. On Io this pressure is close to that of a vacuum. Even at 1 atm, crystalline sulfur vaporizes at 444°C . Under Io conditions, it is clear that fluid sulfur in contact with magma will vaporize when the rising magma approaches the surface of the planet. The dominant

molecule in the gas phase above 1000°C should be S_2 ; the vapor pressure of sulfur at this temperature is on the order of 1 kbar.

On eruption, S_2 gas should cool quickly and condense on the surface before destruction by solar UV can take place. Once on the surface, it could be recycled into the planet either by deep convection of the lithosphere, as suggested by Peale *et al.* (1), or by simple diffusion and percolation (similar to groundwater on Earth), coming in contact with rising magma at relatively shallow depths.

Such percolation will be possible once the sulfur is liquid. Assuming that the sulfur on the surface is at 100 K and that the thermal gradient is 1300 K in 18 km, as suggested by Peale *et al.* (1), this sulfur would have to be buried to a depth of 4 km to reach its melting temperature. Given the eruption rate of 2×10^9 g/sec as before, the entire surface of Io would be buried to this depth in less than 10 million years. The lithostatic pressure at this point is 250 bars; the vapor pressure of sulfur at 400 K is 10^{-5} bar. Thus volcanism will not occur until this liquid sulfur comes in contact with rising hot magma.

Quantitative calculations on the role of sulfur in the eruption process will depend on knowledge of the actual thermal gradient within Io and the lithospheric stresses on the surface and measurements of the number and size of the eruptions themselves. With such measurements, it should be possible to test various models of the interior and thermal structure of Io—for example, to determine the mechanical properties of the crustal material, the depth at which

sulfur comes in contact with the ambient surface atmospheric pressure, and whether the upper lithosphere of Io is convecting. The ability to test such models will be important not only in understanding the interior of Io, but also in determining the strengths and weaknesses of competing modeling techniques that may be applicable to the other terrestrial planets.

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Samarium-Neodymium Systematics in Kimberlites and in the Minerals of Garnet Lherzolite Inclusions

Abstract. *The initial ratios of neodymium-143 to neodymium-144 in kimberlites ranging in age between 90×10^6 to 1300×10^6 years from South Africa, India, and the United States are different from the corresponding ratios in the minerals of peridotite inclusions in the kimberlites but are identical to the ratios in the basaltic achondrite Juvinas at the times of emplacement of the respective kimberlite pipes. This correlation between the kimberlites and Juvinas, which represents the bulk chondritic earth in rare-earth elements, strongly indicates that the kimberlite's source in the mantle is chondritic in rare-earth elements and relatively primeval in composition.*

Kimberlites are almost always found in stable continental regions and are reported from southern Africa, Siberia, North America, Brazil, India, and Australia. They most commonly occur as vertical, narrow pipelike bodies (diatremes), or as thin dikes, but rarely as sills. The diatremes may have an average

diameter of 300 m at the present-day erosion level; the diatremes narrow down gradually with depth until they become indistinguishable from fissures that cut the deepest known basement structures.

Kimberlite has an inequigranular, porphyritic texture; the porphyritic texture is due to relatively large crystals of oli-