OBSERVATIONS OF INDUSTRIAL SULFUR FLOWS AND IMPLICATIONS FOR IO

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The possibility of sulfur flows on the Jovian satellite Io has been discussed by several investigators [1-3]. Although the primary problem is lack of sufficient information to resolve the issue, interpretations of existing data are hampered by poor knowledge of the thermal properties and rheologic behavior of sulfur flows, especially under conditions present on Io. Relatively few natural sulfur flows occur on Earth [4-8] and only one has been seen in active flow [4]. However, recent observations of industrial sulfur flows, which are much larger than are possible to produce experimentally, may provide important information concerning natural sulfur flows on both Earth and Io.

Sulfur is mined by the Frasch process which involves drilling wells into sulfur-rich limestone or salt domes and melting the sulfur with water heated to ~ 165° C. Liquid sulfur is then pumped from the well and transported in molten form to processing plants where it is either stored as a liquid or cooled and solidified in ~ 100 m by 100 m vats with walls composed of solidified sulfur about 5 m thick and 15 m high. Liquid sulfur (99.6 % pure) at ~ 130° C is poured onto the vats at a rate of ~15 metric tons/minute (~ 7.5 m^3/min), with each "pour" totalling about 500 metric tons (~ 250 m^3 of liquid sulfur). Although this results in a total flow thickness of only 6-9 cm upon cooling, the flow is emplaced as extremely complex, thin (~ 1 cm) multiple flow units.

The flows advance in unconfined lobes and channels. Unconfined flow lobes spread rapidly, and as the flow cools and/or the local flow rate decreases, a crust forms simultaneously over the entire flow surface. Crustal flow lobes are very plastic and deform easily as flow continues beneath the crust. Breakouts along flow margins are common. Flow margins can be identified in the solidified sulfur, the surface of which is smooth and relatively featureless. Channelized flows exhibit marginal levees composed of cooling sulfur (Figure 1). Small aggregates of crystals, froth due to turbulence, and crustal plates are commonly observed on the surfaces of both channelized and unchannelized flows. Crystals and small plates collect and aggregate in slow-moving and quiescent areas of channels and along their margins and can be incorporated into fast-moving regions of flows. Crustal plates can be rafted together to form continuous and discontinuous ("sulfur lava tubes") crusts overlying the channels. Breakouts occur at channel margins and flow over levees to form additional channelized flows and lobes. Channels with crustal plates can be identified in the solidified deposits by their surface morphology (Figure 2).

Samples of overturned crust (1-2 cm thick) exhibit growth of acicular crystals 1-3 cm long into the molten sulfur; crystal growth is apparently enhanced in areas of ponded flow. Cross-sections through numerous flow units viewed in the excavated vat walls indicate that crystal growth occurs both downward from the crust and upward from the base of the flow. Crystal size apparently increases toward flow interiors. Similar features, including surface morphologies and interior structure, were noted on the natural Mauna Loa sulfur flow [9].

In one instance a "pour" was observed after a heavy rainfall which left puddles of standing water ~ 5 cm deep on the vat surface. When molten sulfur entered a puddle, the mode of flow emplacement was drastically altered; the flow advanced by thin overlapping "fingers" of sulfur (< 1 cm in diameter and commonly ~ 15 cm long). When the local flow rate decreased, molten sulfur cascaded from the top of the flow vertically into the water forming beads and "sulfur stalactites." However, while these morphologies were observed in cross-section, the flow surfaces of the solidified deposits were smooth and relatively featureless. Nevertheless, the interaction of molten sulfur and volatiles and the resultant change in flow emplacement should be considered in the analysis of both terrestrial and Ionian sulfur volcanism.

For several "pours" a thermocouple array was used to monitor the cooling of flows. Temperatures up to ~ 109° C were recorded for dark reddish-brown molten sulfur. Previous correlations [10,11] of color with temperature indicate that below ~ 160° C liquid sulfur should be yellow to orange in color whereas dark reddish-brown sulfur is representative of much higher temperatures (> ~180° C). This apparent temperature inconsistency requires further attention and could be quite important for consideration of sulfur flows on Io because color transitions along flows have been used as evidence for the existence of sulfur flows on Io [11].

The rapid formation of a plastic crust, plus the apparently durable nature of the observed crusts, may also have important implications for the behavior of potential sulfur flows on Io. As solid sulfur is denser than liquid [10], it has been suggested that a solid crust may tend to break up and sink into the melt [12]. Such ephemeral crusts would allow relatively rapid cooling of the underlying liquid, effectively limiting flow dimensions. However, observations of extensive crusts (both "fixed" and free-floating) on flows in the vats suggest that similar crusts could occur on Io. Solid sulfur has excellent insulating properties [10] and the formation of durable crusts could significantly reduce heat loss from a flow, hence increasing the length achievable by a crusted sulfur flow. Some flow units on Io extend several hundred km [1,3]; if these are composed of sulfur, such crustal insulation would be essential.

Observations of industrial sulfur flows have provided important insights into the flow properties of molten sulfur. Continued studies and further analysis of existing data including the development of a thermal model for sulfur flows will allow a more complete understanding of terrestrial sulfur flows so that the possibility of sulfur flows on Io can be examined from a more informed perspective.

References

[1] Sagan, C., 1979, *Nature 280*, 750-753.
[2] Schaber, G., 1981, *Icarus 43*, 302-333.
[3] Pieri, D., et al., 1981, *NASA TM-84211*, 41-43.
[4] Watanabe, T., 1940, *Japanese J. Geol. Geogr. 17*, 289-310.
[5] Banfield, A., 1954, *Canadian Mining and Metallurgical Bull. 47*, 769-775.
[6] Colony, W., and Nordlie, B., 1973, *Econ. Geol. 68*, 371-380.
[7] Skinner, B., 1970, *Pacific Sci. 24*, 144-145.
[8] Naranjo, J., 1985, *Nature 313*, 778-780.
[9] Greeley, R., et al., 1984, *Icarus 60*, 189-190.
[10] Theilig, E., 1982, *NASA CR-3594*, 34 pp.
[11] Pieri, D., et al., 1984, *Icarus 60*, 685-700.
[12] Fink, J., et al., 1983, *Icarus 56*, 38-50.

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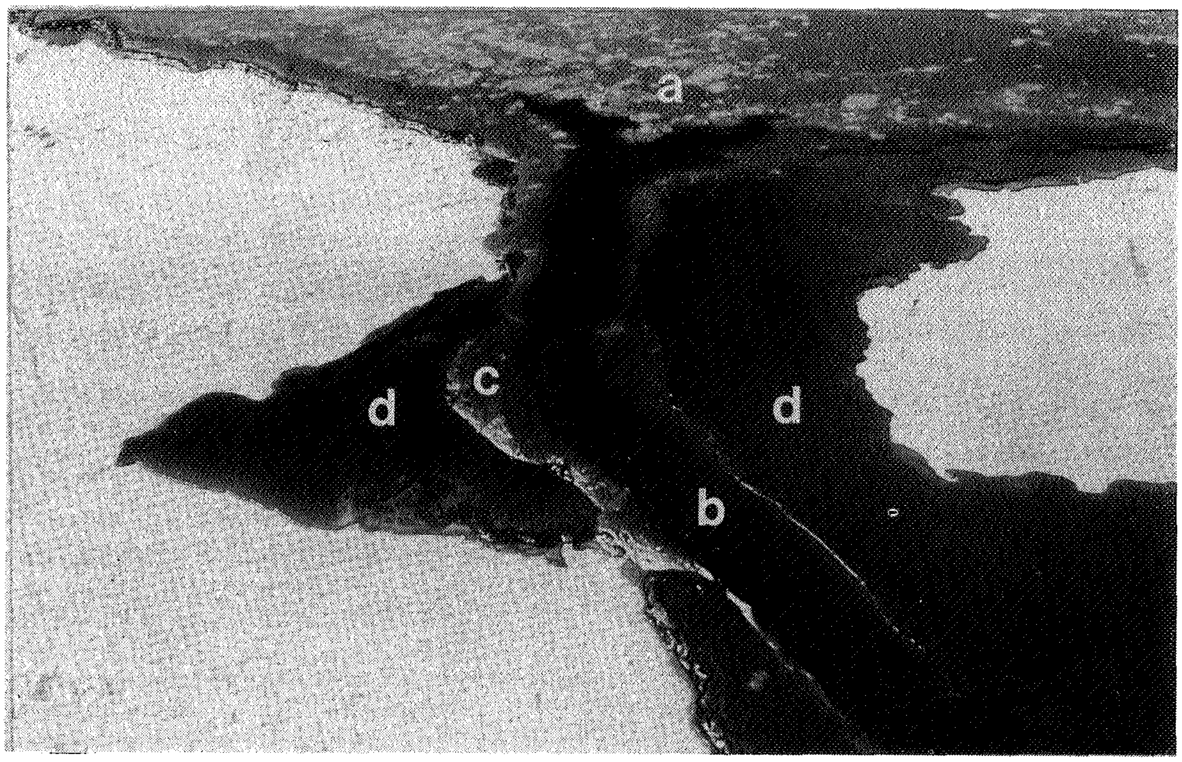

Figure 1. Molten, channelized sulfur flow over solidified sulfur vat surface. Shown are (a) crusted over, unconfined flow lobe from which channel originates, (b) uncrusted channelized flow, (c) partially solidified marginal levees, and (d) breakout flows from the channel margin. Field of view is approximately the same size as in Figure 2.

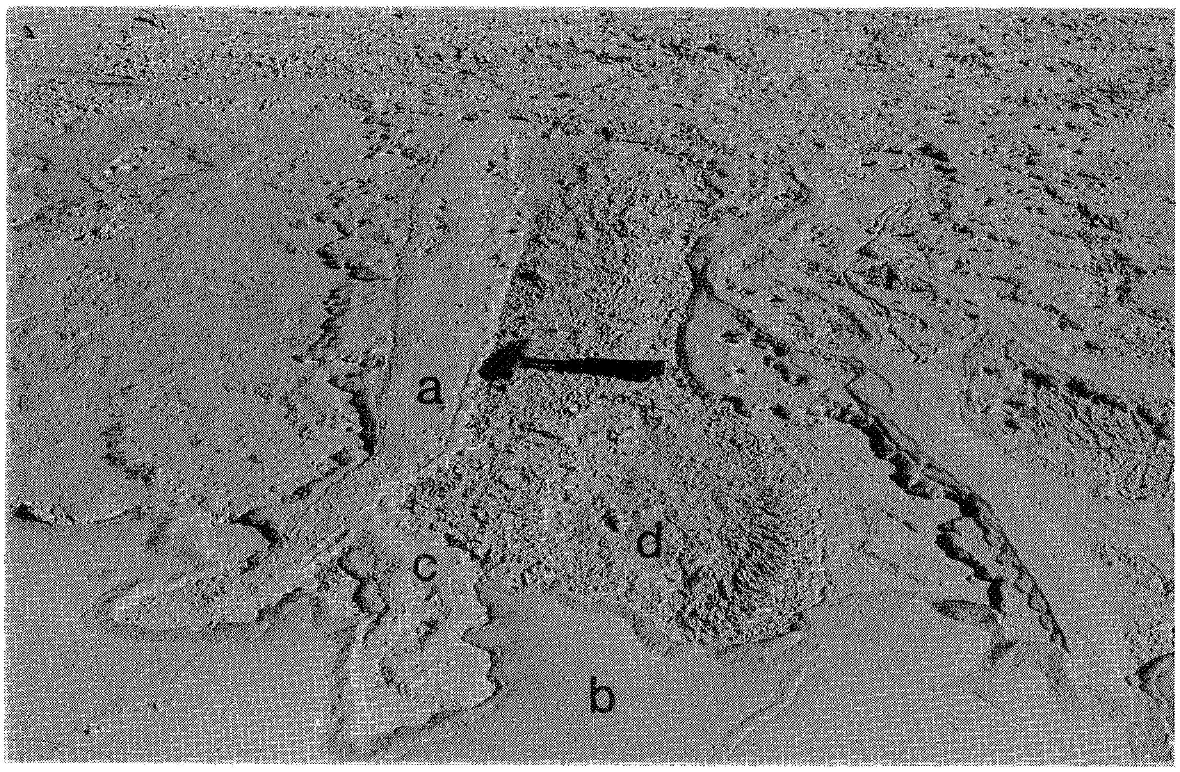

Figure 2. Portion of surface of solidified sulfur vat showing (a) a channelized flow with crustal plates, (b) an unconfined flow, (c) a breakout flow over a channel levee, and (d) rough surface texture with plates and flow lineaments.