FURTHER STUDIES ON THE PHENOMENON OF SHOCK-IMPLANTED GASES

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In recent shock loading experiments that implanted noble gases into a basalt target (1,2), we demonstrated that such gas implantation occurs readily, that the quantity of gas implanted increased with increasing shock pressure as well as ambient gas pressure, and that the implanted gas showed no obvious isotopic or elemental fractionation (except for post-shock Ne loss). Shock appears to be a reasonable mechanism to explain the occurrence of Martian atmospheric gases in shocked phases of the EETA79001, shergottite meteorite. We have extended these studies to include higher shock pressures on basaltic and monomineralic targets, and a comparison of diffusion properties of volume-correlated radiogenic Ar with shock-implanted Ar. Our main objective is to characterize the implantation phenomenon.

Implantation efficiency is defined as the ratio of measured quantity of noble gas implanted into the sample to the calculated quantity of gas present in pore spaces at the time of shock. The implantation efficiency for powdered samples increases from 0.5% at 2 GPa to a "plateau" of 50% or more for shock pressures of 20-59 GPa. The implantation efficiency for solid basalt disks increases from 5% at 20 GPa to nearly 100% at 59 GPa. Monomineralic, powdered targets of diopside, oligoclase (An29), and labradorite (An67) shocked at 20 GPa gave nearly identical pressure-normalized concentrations of Ar, both to one another and the basalt powder shocked at the same pressure. This observation indicates that the shock process occurs with similar efficiency regardless of the specific mineral species involved.

Diffusion Characteristics: From measurements of gas released during stepwise temperature extractions in the laboratory, we can estimate the ease of diffusion of the shock-implanted gas, and thereby make some inferences as to the type of mineral lattice sites it occupied. The ease of gas diffusion was determined by calculating the parameter D/a² (diffusivity divided by the square of the grain radius) and the activation energy, Q, from the relation of D/a² as a function of temperature. Because not all such Arrhenius plots were linear, we also estimated relative diffusion by measuring the temperature at which 50% of the total amount of a given noble gas had been released. Ar released from powdered basalt samples generally gave linear Arrhenius plots and showed that values of activation energy, Q, and the temperature of 50% gas release both were strongly proportional to shock levels between 2 and 59 GPa (Fig.1). For pure powdered minerals we noted the following. Unshocked oligoclase released 50% of its radiogenic Ar at 880°C, whereas oligoclase shocked to 20 GPa in vacuum released 50% of its radiogenic Ar at 550°C. Oligoclase shocked to 20 GPa in a noble gas mix also released 50% of the shock-implanted Ar at 550°C. These observations indicate that the shock process significantly increases the susceptibility of radiogenic Ar to diffusion, probably as a result of mechanical fracturing of grains, but that no obvious difference in diffusivity exists between radiogenic Ar and shock-implemented Ar in shocked grains (Fig.2). Furthermore, little difference in Ar diffusivity was seen between radiogenic Ar and shock-implemented Ar for two samples of laboradorite shocked to 20 GPa.

Stepwise temperature releases and Arrhenius plots for implanted Kr and Xe commonly suggest two components for shock-implanted gas. One component releases at relatively low temperatures and has a low activation energy of about 10 kcal/mole. The second component, releasing most of the total gas at higher temperatures, shows a much higher activation energy. As expected, the heavier the molecular weight of the noble gas, the more resistance it shows to diffusion. Ne shows a very low resistance to diffusive loss, particularly at low shock levels.
Implantation mechanism: From these results we suggest that gas implantation occurs along fractures and freshly generated free surfaces in a shocked grain. Upon pressure release, shocked materials have lower densities (3), and X-ray studies reveal a progressive breakdown of crystals into ever decreasing domain sizes as peak pressure is increased (4). Because the gas pressure in a sample void will be similar to the shock pressure, and the microcracks will be large compared to molecular sizes, gases will be driven into these disturbed lattices without substantial mass fractionation. At low shock levels, e.g., <10 GPa, the gas driven into these sites has a relatively low activation energy for diffusion because most of the gas is surface-trapped in relatively large fractures that connect with grain surfaces. However, the activation energies for gas diffusion increase substantially with shock levels, even after the point where the efficiency of gas implantation has reached nearly 100%. This fact suggests that some form of rapid "annealing" of defects occurs upon release of shock compression, and that this process increases with increasing shock. Closing of these defects leaves the shock-implanted gas in a volume-correlated site with similar diffusion properties to volume-correlated radiogenic Ar in shocked materials. Such lattice defects may also be shear planes that close upon release of shock pressure, or lattice defects that rotate and isolate small, gas-containing voids.


Fig. 1 (left) Effect of shock level on Ar diffusion properties; both activation energy (kcal/mole) and the temperature (°C) for release of 50% of the Ar are shown. Fig. 2 (right) Temperature (°C) of 50% Ar release for oligoclase (unshocked, shocked in vacuum, shocked in a gas mix), labradorite (shocked in vacuum and in a gas mix), and diopside (shocked in a gas mix); all shock runs were at 20 GPa.