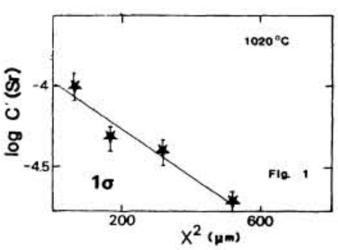
Possible Isotopic Resetting Mechanisms in Shergottite Meteorites

R. O. Colson, L. Nyquist, G. McKay, and F. Horz: Johnson Space Center, Houston, Tx 77058

Accurate determination of the chronology of the shergottites is important in that it places constraints on the thermal history of the Shergottite parent body. This is of special interest since this parent body may be Mars [1]. However, ages determined from Rb-Sr, Sm-Nd, and K-Ar isotopic systematics are not always concordant [2]. This work determines diffusion coefficients of Sr in plagioclase and considers various models of resetting in an effort to constrain the origin of the Rb-Sr discordance.

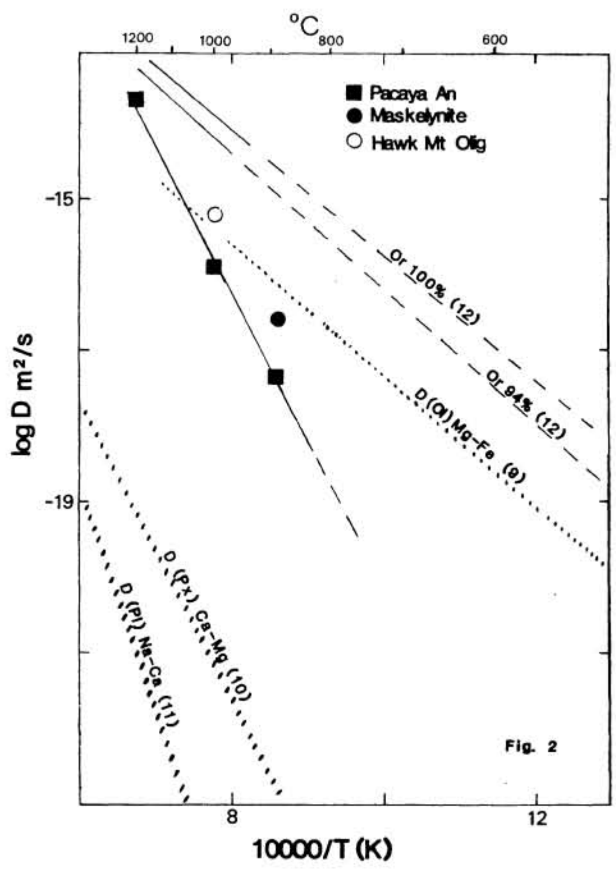
Diffusion coefficients are being determined in Pacaya Anorthite (unshocked and shocked to 244 GP resulting in conversion to maskelynite) and Hawk Mountain oligoclase (AN_{24}) by sandwiching fused Sr and Ba nitrates between polished faces of isochemical samples and heating in air at various temperatures for various times. Diffusion coefficients were determined by linear regression of the diffusion profile to the equation $\ln C = \text{const} - x^2/4Dt$ where C = concentration, x = distance from crystal edge, t = time, and D = diffusion coefficient. A typical diffusion profile is shown in Fig. 1. Diffusion coefficients are plotted versus temperature in Fig. 2.



Estimates of resetting rates were calculated using these and published diffusion coefficients assuming that plagioclase crystals can be considered as spheres 300 μm in diameter. For the calculations, concentrations of isotopes at the surface of the spheres were held constant at bulk rock values. It was assumed that Sr exchange between plagioclase and the Rb rich reservoirs (mesostasis) was controlled by diffusion in plagioclase.

This study considers the following possible mechanisms of resetting of Rb-Sr systematics in shergotty:

1. Bulk diffusion of Sr in Plagioclase, including the effects of variable composition.
2. Sr diffusion in Plagioclase enhanced at low temperatures by dislocations or maskelynization induced by a shock event.
3. A change in the equilibrium distribution of Sr between phases, perhaps induced by the impact, which results in a diffusive mass flow of Sr between phases.
4. Resetting caused by a mass injection between phases or a greatly enhanced diffusion during the moments of the impact.



The discordant ages indicate that some sort of disturbance must have occurred in the Shergottites, but how this might occur is unclear and the possibility of its occurrence has been contested. In particular, it has been suggested that mineral zoning in the Shergottites indicates that significant isotopic resetting has not taken place [4].

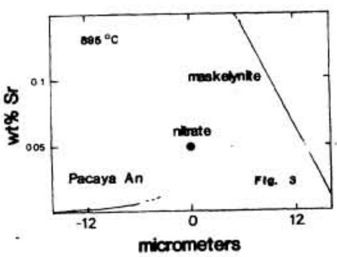
Calculations based on the Sr diffusion data obtained for this study show that the presence of either major or trace element zoning in plagioclase or pyroxene does not preclude diffusive resetting of Rb-Sr isotopic systematics. As seen from Fig. 2, Sr diffuses at a faster rate in plagioclase than the major elements in pyroxene or plagioclase, at almost any temperature. We suggest that the existence of the major element zonation imposes a trace element zonation as well. The force driving diffusion is activities, not concentrations, and activities of trace elements have a strong dependence on major element compositions [e.g. 5]. The gradient in trace element activities imposed by the variation of major element compositions across the crystal results in the diffusive generation of a trace element zonation even if none had originally existed.

However, interdiffusion in olivine is much higher than in either plagioclase or pyroxene. At 1000°C, calculations indicate that zoning will be about 75% homogenized after 1 year. This is less time than required for Sr isotopic resetting. Therefore, if resetting at 1000°C, as suggested as an upper limit for EETA 79001 [4], has taken place, some mechanism for either enhancing Sr diffusion or suppressing diffusion in olivine must be postulated.

Several factors are potentially important in enhancing Sr diffusion in plagioclase. Enhanced diffusion or mass injection might occur during the impact itself and leave mineral zoning intact. Increased diffusion rates have been reported during deformation [6] and impact [7] with diffusion rates increasing many orders of magnitude. However, diffusion times during impact must be very short (microseconds?) and significant diffusion likely does not occur during the impact itself.

No resetting would take place if phases were fluidized by the impact and injected into each other as this is simple mechanical mixing. However, fine disseminations of one phase into another could enhance resetting due to subsequent diffusion. No such disseminations have been reported in Shergotty.

Another factor which might influence the rate of isotopic resetting while leaving major elements little changed is a net flow of Sr into or out of a phase. For example, if there is a net flow of Sr from plagioclase into pyroxene, the degree of resetting may be greater after a given diffusion time. This flow might be induced when energy states of ions in crystals are changed by an increase in dislocations or maskelynite during an impact.



To test this possibility, polished maskelynite of Pacaya anorthite composition was placed against a polished face of unshocked Pacaya anorthite with a layer of molten Ba and Sr nitrate between. It was assumed that the surface of each would approximate equilibrium with the nitrates. The results are shown in Fig. 3. Though the experiment is too crude to hope that this represents a precise partition coefficient, it can be seen that Sr concentration is over an order of magnitude higher in the maskelynite than in the unshocked sample.

Despite the apparent large magnitude of this effect, calculations indicate that it is not large enough to change the resetting rate by more than about 30%. Although a rock might be reset more quickly (or more slowly) due to this effect, it is not enough of a change to account for the preservation of olivine zonation unless the effect on other phases, such as pyroxene, is of even greater magnitude.

Therefore isotopic resetting with retention of olivine zoning can only be explained by invoking the speculated effects on diffusion of shock induced dislocations or maskelynization or the effects of increasing Na content of the plagioclase. It has been shown previously that the effects of shock can enhance diffusion in plagioclase [8], and the effect of increasing Na (Hawk Mt Oligoclase) is seen in Fig. 2.

Calculations based on the preliminary results in Fig. 2 suggest that, at 900 to 1000°C, resetting of Sr isotopes cannot take place without significant homogenization of olivine even for high Na plagioclase or maskelynite. However, the effect of maskelynization on diffusion is expected to increase with decreasing temperature and it is possible that at 400°C, suggested as a maximum temperature for Shergotty, Sr diffusion in plagioclase may be much greater than the rate of major element homogenization in olivine. This is currently being tested.

[1]Becker R.H. and Pepin R.O. (1984) EPSL 69, 225-242 [2]Shih C.-Y. et al. (1982) GCA 46, 2323-2344 [3]Nyquist L. et al. (1979) GCA 43, 1057-1074 [4]Jones J.H. (1986) GCA 50, 969-977 [5]McKay G., Wagstaff J., and Yang S.-R. (1986) GCA 50, 927-937 [6]Cohen M. (1970) Trans J.I.M. 11, 145-151 [7]Bekrenev A.N. and Fedorov B.N. (1984) Fiz. Khim. Obrab. Mater. 5, 136-137 [8]Ostertag R. and Stoffler D. (1982) PLPSC 13th JGR 87 supplement, A457-A463 [9]Buening D.K. and Buseck P.R. (1973) JGR 78 [10]Brady J.B. and McCallister R.H. (1983) Am Min 68, 95-105 [11]Grove T.L., Baker M.B., and Kinzler R.J. (1984) GCA 48, 2113-2121 [12]Misra N.K. and Venkatasubramanian V.S. (1977) GCA 41, 837-838.