CRYSTALLIZATION KINETICS, VISCOUS FLOW AND THERMAL HISTORIES OF LUNAR BRECCIAS 15286 AND 15498. D. R. Uhlmann and L. C. Klein, Dept. of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Mass. 02139.

A kinetic analysis was presented at the Sixth Lunar Science Conference (1) which offers notable promise for elucidating the thermal histories of clastic or fragmental lunar breccias. This analysis is based on the suggestion that these breccias formed by a process of viscous sintering, rather than by a shock lithification process, and uses a combined treatment of crystallization and viscous sintering to derive information about the thermal histories. It was applied (1, 2) to a highly vitric soil breccia, 70019, and to a highly crystalline brecciated basalt, 79155. It was found that the analysis was capable of providing a close estimate of the cooling history of the 70019 composition, but could provide an upper limit for the cooling rate of the 79155 composition.

Because of the immediate applicability of the kinetic analysis to highly vitric breccias (low-grade in Warner's (3) classification scheme), it was decided to investigate two lunar breccias with substantial glass content in the matrices before undertaking further studies of breccias with largely-crystalline matrices. The two breccias chosen for study were Lunar Compositions 15286 and 15498. The first is a vesicular microbreccia weighing 34.6 g. which was collected at Station 6 on the Apennine Front. It appears to have broken off from a larger rock, and exhibits clear evidence of devirtification (primarily around vesicles) in a largely-glassy matrix. Sample 15498 is a large soil breccia, weighing about 2340 g., which was collected at Station 4 on the south rim of Dune Crater. It shows evidence of internal deformation and fracturing, but little evidence of recrystallization; and the matrix is more than 70 pct. glass. The compositions of the glassy matrix in the two breccias, determined using an electron beam microprobe, are shown in the Table below.

Table I

Compositions (wt. pct.) of Breccia Materials Investigated

15286		15498
46.1	SiO_2	48.2
1.6	TiO_2	2.0
14.3	Al_2O_3	19.8
14.2	FeO	8.4
12.5	MgO	7.5
10.4	CaO	13.0
0.8	Na_2O	0.9

The elucidation of thermal histories using the kinetic treatment of breccia formation requires detailed information about the viscous flow and crystallization behavior of the respective matrix materials. The data on viscous flow and crystallization behavior were in both cases obtained over wide ranges of temperature on synthetic materials prepared from reagent grade

© Lunar and Planetary Institute • Provided by the NASA Astrophysics Data System

raw material powders. The techniques of preparing the samples and measuring the viscosity have been described in detail elsewhere (4). The measurements of the crystal growth rates, also carried out over wide ranges of temperature, were carried out using techniques similar to those in previous studies of other lunar compositions (5, e.g.). The furnace in which the crystallization runs were carried out was provided with a gas-mixing system, using $CO-CO_2$ mixtures, and an electrolyte cell similar to those used previously by Lofgren et al. (6, e.g.). The provision of a controlled atmosphere in the crystallization furnace was considered important because of the possible effects of Fe-oxidation state on the rates of nucleation and crystal growth. Such effects, reflected in changes of observed textures in crystallized bodies with changes in oxygen fugacity, were noted by Lofgren et al. (6). In particular, they suggested that decreases in the oxygen fugacity reduced the iron content of the melt by causing the precipitation of metallic iron. This change in melt composition raised the liquidus composition of their materials, thereby affecting the rates of crystal nucleation and growth.

It was not considered necessary to provide a closely-controlled oxygen fugacity for the measurements of liquid viscosity--but simply an atmosphere of low oxygen activity--because of the results obtained by Cukierman and Uhlmann on Lunar Composition 15555 (7). Even for this composition containing 22.5 wt. pct. FeO, it was found that small changes in the oxidation state from one of low Fe^{3+} concentration (for Fe^{3+}/total Fe ratios of 0.26 or less) has a negligible effect on the measured viscosity. Since the two breccia matrix compositions investigated here have much smaller iron concentrations (14.2 and 8.4 wt. pct. respectively) than the 15555 composition, no significant effect of variations in oxygen activity over the low range was anticipated.

The data on growth rate and viscosity were combined to construct time-temperature-transformation (TTT) curves corresponding to various degrees of crystallinity, and in particular to the degree of crystallinity observed in the matrices of the two breccias. In both cases, the nucleation frequencies required in the kinetic analysis were calculated from the measured viscosities using the classical theory of homogeneous nucleation. In these calculations, a nucleation barrier of 60 kT at a relative undercooling, ΔT_r, of 0.2 was assumed. Here $T_r = \Delta T/T_E$, where ΔT is the undercooling and T_E is the liquidus temperature. The use of classical nucleation theory and the range of the assumed nucleation barrier are in accord with the results obtained by Klein and Uhlmann on Lunar Composition 70019. These results are reported elsewhere in the present volume (8).

In pursuing the model of breccia formation by viscous sintering, the viscosity data were also used to estimate the times required at various temperatures to achieve a substantial degree of sintering, such as that observed in the matrices of the breccias. The Frenkel model of viscous sintering (9) was used in effecting these estimates. In treating the competing process of crystallization, continuous cooling (CT) curves were constructed from the TTT curves following the procedure described previously (1). These curves were constructed for both linear and logarithmic cooling conditions. From the CT curves corresponding to the degrees of crystallinity observed in the matrices

© Lunar and Planetary Institute • Provided by the NASA Astrophysics Data System

BRECCIAS 15286 AND 15498

Uhlmann, D.R. et al.

of the breccias, it has been possible to estimate the rates at which the lunar samples cooled. Using the model described previously (1) for viscous sintering under conditions of continuous cooling, it has been possible to estimate the minimum temperature at which the particles of the matrix came in contact.

The information obtained in this way about the conditions of formation of the two samples can be usefully combined with other data on the same breccias to provide a more complete picture of their histories. In the 15286 sample, for example, Wosinski et al. (10) found many Fe or Fe-Ni inclusions (3 to 25 μm in size) in the regions of devitrification and smaller metallic particles (< 1 μm in size) in the glassy regions. The presence of the metallic particles was associated with subsolidus reduction.

As an example of relevant data on the 15498 material, Pearce et al. (11) reported that the breccia has a stable natural remanent magnetization. The magnetic properties were associated with the presence of single domain iron particles, 0.015 to 0.03 μm in size. The small size of these particles suggests that the sample did not spend much time above about 800 C subsequent to their formation.

The results of the present investigation indicate how the kinetic treatment of breccia formation by viscous sintering can be used to deduce useful information about the thermal histories of lunar breccias. When combined with information provided by other techniques, the kinetic analysis can provide notable insight into the conditions of formation of the samples.

References

1. D.R. Uhlmann, L. Klein, P.I.K. Onorato and R.W. Hopper, 1975, Proc. Lunar Sci. Conf. 6th, p. 693-705.
2. L. Klein, P.I.K. Onorato, D.R. Uhlmann and R.W. Hopper, 1975, Proc. Lunar Sci. Conf. 6th, p. 579-593.
3. J. L. Warner, 1972, Proc. Lunar Sci. Conf. 3rd, p. 623-643.
4. M. Cukierman, P. M. Tutts and D.R. Uhlmann, 1972, Proc. Lunar Sci. Conf. 3rd, p. 2619-2626.
5. G. Scherer, R.W. Hopper and D.R. Uhlmann, 1972, Proc. Lunar Sci. Conf. 3rd, p. 2627-2637.
6. G. Lofgren, C.H. Donaldson, R.J. Williams, C. Mullins and T.M. Usselman, 1974, Proc. Lunar Sci. Conf. 5th, p. 549-567.
7. M. Cukierman and D.R. Uhlmann, 1974, J. Geophys. Res. 79, p. 1594-1598.
8. L. Klein and D.R. Uhlmann, "The Kinetics of Lunar Glass Formation, Revisited", Companion paper, Lunar Science VII.
9. J. Frenkel, 1945, J. Phys. (USSR) 9, p. 385-391.
10. J. F. Wosinski, J. P. Williams, E. J. Korda and G. A. Geiger, 1973, Proc. Lunar Sci. Conf. 4th, p. 383-388.
11. G. W. Pearce, W. A. Gose and D. W. Strangway, 1973, Proc. Lunar Sci. Conf. 4th, 1973, p. 3045-3076.

© Lunar and Planetary Institute • Provided by the NASA Astrophysics Data System