
Introduction. The very low Ti green glasses from the Apollo 15 site have intrigued scientists for over 20 years. Their primitive composition has been used to understand magmatic processes and the structure of the moon. The compositional variability observed in the Apollo 15 glass population has long been a point of debate. Initial studies did not recognize the compositional diversity in the glasses. Stolper et al. [1] documented the major element variability and concluded it could not be produced by magmatic processes and therefore concluded that these glasses must be of impact origin. Subsequent studies confirmed a volcanic origin for the glass population and attempted to elucidate magmatic processes to account for its compositional variability. Models that have been proposed for these glasses include (1) the crystallization of single or multiple phases (olivine, pyroxene, Fe metal, immiscible sulfide) [e.g., 2,3], (2) the incompatible behavior of Ni and Co during multiple phase crystallization at extremely low fO2 [4], and (3) magma or source mixing [5,6,7]. All of these models have problems. Type (1) models appear not to be consistent with recent trace element studies on the glasses [7], model (2) is dependent on the debatable incompatible behavior of Ni and Co, and in models of type (3) the origin and nature of mixing models are somewhat unconstrained. This study compares the Apollo 15 green glasses with the very low Ti picritic glasses from other landing sites.

Analytical Procedures. Electron microprobe techniques and criteria established by Delano [3] were used to identify the very low Ti glasses of volcanic origin. Glasses were identified from the Apollo 11, 14, 15, 16 and 17 landing sites. The glasses were then analyzed for REE, Ba, Sr, V, Cr, Ti, and Zr using ion microprobes. Most of these analyses were accomplished using the ion microprobe at Woods Hole Oceanographic Institute (WHOI). Additional glass analyses were performed at the ion microprobe facility at the University of New Mexico. The ion microprobe is a microbeam technique which allows analysis of individual electron microprobe spots on a glass bead and multiple analyses of a single bead. In addition, this technique is not hampered by weighing errors, equating microprobe spots with bulk analysis, and contamination by deposits on bead surfaces or in cracks as is the case with INAA techniques.

Results. Fig. 1 illustrates the relative major element relationships among the more Mg-rich members of each suite of glasses (TiO2 = 0.25 to 1.10 wt. percent). As illustrated in numerous major [1,2] and trace element [4,5,6,7] studies of the A-15 green glasses, MgO is (+) correlated to SiO2. Co is (+) correlated to incompatible elements such as REE, Y, Zr, and Ba (Fig. 2) [5,6,7]. Fig. 2 compares the very low Ti glasses from the Apollo 11, 14, 16, and 17 sites with the Apollo 15 glasses. In these plots of incompatible elements versus Co, the Apollo 11, 16, and 17 glasses plot near the Apollo 15 glasses. The Apollo 14 glasses define a compositional range that far exceeds that observed in the Apollo 15 glasses. These compositional similarities and differences are also reflected in a plot of Sr versus Ba (Fig. 3).

Discussion. The Co versus incompatible element diagrams (Fig. 2) illustrates several points. (1) The compositional range observed in the very low Ti glasses far exceeds that of the Apollo 15 glasses. This wide range in composition cannot be accounted for by fractional crystallization or partial melting under any extreme P or fO2. This indicates that compositional heterogeneity in the lunar mantle accounts for the complexity of the glass population. Therefore, compositional heterogeneity in the mantle can account for the variability observed in the Apollo 15 glasses. (2) There are two different types of trajectories in Fig. 2 (A and B). A is a result of the incorporation of a KREEP component either through assimilation or during melting (Fig. 3). B may be a mixing trajectory resulting from local compositional variability in the cumulate pile due to the sequence of crystallization, the amount of intercumulus melt, and the extent of recrystallization and volcanic processes. As illustrated in Fig. 4, these variables may result in the co-linearity of compatible and incompatible elements.

Conclusions. The wide range in trace element characteristics exhibited by the very low Ti glasses from the various Apollo landing sites indicates that the lunar mantle is itself variable and can yield a wide range of compositionally distinct very low Ti picritic magmas. Therefore, it is not surprising that the compositional variability observed in the Apollo 15 Green glass is a result of mantle inhomogeneities.


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A15 GREEN GLASS. C.K. Shearer and J.J. Papike

Figure 1. Plot of SiO2 wt% versus MgO/(MgO + FeO) (Mol.%) for the more Mg glasses of the various very low Ti glass suites.

Figure 2. Plot of Zr versus Co for the very low Ti picritic glasses.

Figure 3. Plot of Ba versus Sr for the very low Ti picritic glasses. A mixing line between A15 glasses and KREEP is superimposed on diagram.

Figure 4. The diagram illustrates highly simplified evolutionary paths for two end-member cumulate sources with differing amounts of intercumulate melt. Mixing between these two hypothetical cumulates have the potential to produce hybrid mantle sources. Upon melting, these sources may produce basalts with the compositional variability exhibited by the A15 glasses.