TRACE-ELEMENT FRACTIONATION DURING CRYSTALLIZATION OF THIN THOLEIITIC LAVA FLOWS  Larry A. Haskin, Marilyn M. Lindstrom, Dept. of Earth and Planetary Sciences and McDonnell Center for Space Sciences, Washington University, St. Louis, MO 63130 and Michael A. Dungan, Lunar Science Institute, Houston, TX 77058.

Variations in trace-element concentrations and relative abundances, interpreted on the basis of predictions of simple partial melting and fractional crystallization models, have been used as criteria for determining the number of parent magmas for lunar basalts (e.g., 1,2). Such use of trace elements has usually led to assumptions of more sources than apparently required by petrographic, major-element, and isotopic data. A recent compilation of data for terrestrial basalts showed that simple interpretations of trace-element data overestimate the number of sources for terrestrial basalts (3). Variation in concentration for incompatible elements is known to depend in part on concentrations of mesostasis in analyzed samples (e.g., 4), although relative abundances (element ratios) for incompatible elements among samples with different quantities of mesostasis may be less variable (2,3). Movement of the late stage liquid has been credited with small changes in alkali and REE contents in an 11 meter thick Icelandic tholeiite (5,6). In the present study of two flows of Servilleta basalt we show that incompatible element concentrations and, in some cases, ratios vary in a systematic way according to the portions of the flows sampled. These variations are sufficient to affect even conservative use of trace-element criteria in classifying lunar basalts (e.g., 2).

Fig. 1 shows REE abundances relative to average "massive interior" basalt for each flow. Compositional ranges for the massive interior samples (which constitute the bulk of each flow) are narrow. Average massive interior for these flows is slightly LREE enriched relative to the average for 18 Servilleta flows sampled but well within their range. In comparison, bottoms of flows are depleted in LREE, Hf, Ba, Sr, Rb, Zr, and Nb; they are not significantly enriched in any trace element analyzed (which includes Sc, Co, Cr, Th, Zn, and Ni in addition to the above). Samples from vesicle pipes have REE concentrations higher than those of massive interiors but identical relative REE abundances except Eu, which is depleted. Also, Sc, Hf, FeO, Na2O, Th, Ba, Sr, Rb, Zr, and Nb are enriched in these materials but Co, Cr, and Ni are depleted. The sample from the uppermost few cm of RG-44 is enriched relative to massive interior in LREE, Ba, Rb, Th, and possibly Nb and Zr and is depleted in Cr, Ni, and perhaps FeO. These characteristics are shared to a lesser extent by a sample taken 80 cm from the flow top.

Servilleta basalts (7) are being studied in conjunction with the LSI Basaltic Volcanism Project. They comprise the bulk of the volcanic valley fill underlying the Taos Plateau (N.M.) in the northern Rio Grande rift. Monotonously similar olivine tholeiitic lavas are exposed to some 300 m depth in the Rio Grande Gorge. Individual flows extend for several km but in thickness rarely exceed 10 m and average 2-5. Servilleta shield volcanoes have very gentle slopes. The vesicular pahoehoe flows show many features in outcrop indicative of high fluidity.

All analyzed samples are evolved with cotectic mineralogy and ~20%
olivine and plagioclase phenocrysts. Flow margins range texturally from quenched, glassy rinds to dense ophiitic basalt. Within interiors of even thin flows coarse-grained dikttyaxitic texture (ave. grain size ≤4mm) has developed. Interstitial to aggregates of plagioclase laths (1-6mm long) exhibiting synnusis and to equant olivine grains are large poikilitic clinopyroxene crystals and fine-grained mesostasis. Mesostasis is concentrated near abundant triangular vugs supported by randomly oriented plagioclase laths.

Associated with flow interiors are concentrations of mesostasis-rich material localized along vesicle-rich, horizontal, planar fractures and vertical, cylindrical pipes. These pipes and fracture fillings typically form an interconnected system with pipes emerging from bases or terminating at tops of fractures. Pipes range from 1-20 cm in diameter; fracture fillings rarely exceed 3-5 cm thickness. Pipes contain the same mineralogy as adjacent massive interior but textural relationships indicate crystallization at greater undercooling with mineral phases more strongly zoned. Pipes appear to form by migration of late stage, vapor-rich liquid from massive interiors to tension cracks after sufficient solidification to form the framework of dikttyaxitic matrix.

An explanation of trace-element compositions is offered in terms of fractional crystallization models and petrological and geochemical evidence on the manner in which the flows solidified. The starting point for modeling is the liquid with uniformly distributed olivine-plagioclase glomero-crysts. This liquid composition is taken to be that of massive interior basalt, corrected for phenocrysts, which exclude incompatible elements and include some Sr, Eu, Ni, Co, and Cr. Massive interiors comprise at least 80% of flow mass and thus approach average flow composition closely. (Flows were not studied for lateral variation but low dispersion among 18 flows indicates that lateral variations cannot be large.)

1.) Crystallization proceeded until newly formed solid plus phenocrysts comprised ~85% and residual liquid ~15% of the massive interiors. Phenocrysts excluded, this corresponds to ~80% solidification of starting liquid. To cover uncertainties in fraction of residual liquid a crystallization range of 70% to 90% was used in modelling. D values of 0.1, 0.15, and 0.25 for La, Yb, and Eu, for fractional crystallization (eq. 8, 10; 8) yield 2.4 - 3.7 ppm La, 0.57 - 0.80 ppm Yb, and 0.51 - 0.72 ppm Eu in the solid and 43 - 114 ppm La, 6.3 - 14.6 ppm Yb, and 3.4 - 7.5 ppm Eu in the residual liquid.

2.) Material from each vesicle pipe is enriched in mesostasis and in REE (except Eu), Hf, Ba, Rb, Zr, Nb, and Th to the same extent, relative to massive interior. This means those elements are mainly in the residual liquid portions of both vesicle pipes and massive interiors. Co, Cr, and Ni are relatively depleted in the vesicle pipe samples; those samples are somewhat deficient in phenocrysts, with which those elements are associated. Sc, Eu, Sr, FeO, and Na2O are enriched in vesicle pipes, but less so than the more incompatible elements, owing to their partial incorporation into the crystallized portion. The FeO concentration of mobile residual liquid is some 1.5 - 2.5 times that of the starting liquid, based on a mass balance and assumptions of 70% and 90% crystallization. These concentrations are similar to those for Skaergaard liquid at similar stages (9,10).
3.) Strongly incompatible LREE, Hf, Ba, Rb, Zr, and Nb are depleted in the bottom portions of the flows. HREE, Ni, Co, Cr, Sc, FeO, and Na₂O have the same concentrations in bottom portions as in massive interiors. The REE are fractionated. Mesostasis and phenocryst contents are very similar to those of the massive interiors. Portions of the strongly incompatible elements thus migrated out of the flow bottoms but were not accompanied by any significant percentage of the original mass of material in the flow bottoms. In complement, these same elements are enriched in the flow tops, without noticeable migration of the other elements. Apparently, a highly fluid, probably gaseous, phase comprising not more than 2% of the starting material has migrated upward through the flows, removing these elements from the bottoms displacing them within the interiors, and depositing them in the uppermost, relatively oxidized flow tops.

The nature of this highly fluid phase is unknown. Possibly it is a gas that evolved prior to, during, or throughout crystallization, carrying away strongly incompatible elements preferentially. Selective removal of a portion of the REE group during metasomatism has been documented (11). Possibly, this phase corresponds to the latest stages of solidification of the liquid portion, and the differentiation of REE results from extensive fractional crystallization. If so, a D value ≥ 0.9 for Yb and ≤ 0.2 for La is required during solidification of the 20% residual liquid if the LREE are to be carried away by < 2% of the original bottom mass.

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