Sources of Clasts in Terrestrial Impact Melts: Clues to the Origin of LKFM

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INTRODUCTION

Low-K Fra Mauro (LKFM) “basalt,” which is found exclusively as an impact melt rock, cannot be modeled geochemically from its clast population or from any combination of known pristine lunar rock types; there is a missing component enriched in both KREEP and transition metals (e.g., Ti and Sc). To clarify clast/melt relationships, we studied impact melt rocks from Mistastin Lake crater, Labrador, Canada, where there are only three target rocks: anorthosite, quartz monzonite, and granodiorite. Feldspar compositions in these rocks define distinct fields on the An-Ab-Or ternary diagram, allowing us to identify the source of each feldspar clast. Clasts in the Mistastin impact melts do not reflect the abundance of target rocks melted during the impact. The abundance of anorthosite in the clast population varies from 34% to 100%, compared to a relatively constant value of 65% calculated to be in the melt matrix. Therefore the clasts appear to be derived predominantly from material relatively far removed from the zone of impact melting. Melt-matrix composition is dictated strictly by the composition of the target materials within a small radius around and below the point of impact. This suggests that the LKFM composition was derived from a lower crustal source.

As informative as these studies were, the investigators did not analyze numerous mineral clasts and assign them to specific target rock types; they used the proportions of rock clasts only. Furthermore, previous studies have not assessed the compositional and/or relative spatial relation between melt composition and the nature of the included clast assemblage. This leaves a gap in our understanding of the complete petrogenesis of impact melt rocks and of relative movements of melted and clastic materials during crater formation. To understand the problem better, we decided to examine a terrestrial crater and determine quantitatively the proportions of target rocks present as clasts in the impact melt rocks.

We chose Mistastin Lake crater for study as it has only three target rocks, providing a good chance of determining the relative abundances of the target rocks within the clast population. The main goal was to see if we could use mineral compositions to determine rock compositions in and close to the target.

SAMPLES STUDIED

Mistastin Lake crater, Labrador, Canada (Fig. 1), is a 38-m.y.-old complex crater, about 28 km in diameter (Grieve, 1975). Much of the melt sheet around the crater is eroded away, though an 80-m-thick outcrop of it, called Discovery Hill, is found on the western side of Mistastin Lake. Virtually no melt is preserved on the central uplift (Grieve, 1975). Mistastin Lake crater has several virtues for our study. First, the target material consists of only three rock types: anorthosite, granodiorite, and...
quartz monzonite (also referred to as adamellite or mangerite; Carrie, 1971). This relatively simple geology allows us to determine readily the source lithology of each mineral clast. Second, almost all the mineral clasts are feldspars, hence have the same shock and thermal properties, so we avoid biases introduced by differential digestion of minerals by the superheated impact melt (Simonds et al., 1978). Third, the impact melt at Mistastin Lake crater outcrops in places equidistant from the crater’s center, so differences in clast populations are not due simply to variable distances from the point of impact. Finally, this crater is substantially eroded, so it is possible to sample rocks from the floor of the original crater. In many places, one can see the contact between the impact melt and the underlying breccia.

The melt matrix of the Mistastin Lake rocks is quite homogeneous, with an SiO₂ wt.% of 56.2±2 (1-σ standard deviation; Greie, 1975). This exceptional homogeneity is typical of terrestrial impact craters (Greie et al., 1977). Based on major element compositions, Greie (1975) modeled the proportions of target material that constitute the melt matrix as approximately 65% anorthosite and 35% granodiorite plus quartz monzonite. There is no evidence of missing components. We analyzed 8 samples of country rocks and 12 samples of melt rocks (one thin section each) from Mistastin Lake. They were sampled from the northern, western, and southern shores of the lake.

**METHODS OF ANALYSIS**

Electron microprobe analyses were carried out at 15 keV on a JEOL 733 superprobe. To decrease the probability of Na diffusional loss from the feldspars, we used a 10-μm-diameter beam. Maximum counting time was 20 sec. A 20 nA beam current was used for clast and country rock analyses, although a 2 nA beam current was used to reanalyze two rocks in which clasts gave consistently low wt.% totals. However, we noted no apparent improvement in totals with the 2 nA beam current. We also used 1-sec counts on an ARL microprobe using a 50-μm-beam diameter and 20 nA beam current to analyze a few of these problem clasts. Again, there was no significant improvement in the analyses. Analyses were corrected using the method of Bence and Albee (1968). Standards used for the eight-element feldspar analyses were an albite for Na and Si, synthetic anorthite for Ca and Al, benitoite for Ba, Marjalahi olivine for Fe and Mg, and adularia for K. We considered acceptable all analyses with wt.% totals between 98.5 and 101.5 and a stoichiometric error of 0.5% or less, i.e., for feldspars 4.975-5.025 (5 cations based on 8 oxygens).

**RESULTS**

Optical microscopy revealed that the clast population in the melt rocks consists almost exclusively of quartz and feldspar mineral fragments; lithic fragments are rare. Less than 1% of the clasts are mafic (pyroxene, biotite, or amphibole), in contrast to 15-20% in anorthosite, 15-40% in quartz monzonite, and about 20% in granodiorite (this study). This is consistent with other studies (e.g., Simonds et al., 1978) where preferential loss of mafics has been ascribed to differential digestion of clasts by the superheated melt. As a result, we analyzed only feldspars in the impact melt rocks.

**Country Rock Analyses**

Feldspars in each of the types of country rock were analyzed to determine compositional variations within grains and from

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**Fig. 2.** Feldspar compositions in country rocks at Mistastin (x = quartz monzonite, + = anorthosite, Δ = granodiorite).
grain to grain. These data were then plotted on an An-Ab-Or ternary diagram to be used as the data base for comparison with feldspar compositions in melt rock clasts (Fig. 2). We found that the country rock analyses define three compositional regions: one of feldspars in anorthosite (Anor) and two of feldspars in granodiorite plus quartz monzonite (Gd-Qm). Unfortunately, we could not distinguish the granodiorite from the quartz monzonite feldspars using this endmember ternary plot. We plotted BaO vs. K2O in an unsuccessful attempt to distinguish between the two. As a result, we were forced to combine granodiorite and quartz monzonite in our study. Between the anorthosite and the plagioclase of the granodiorite and quartz monzonite regions there is a small but distinct gap from 38% to 41% anorthite in which no country rock feldspar compositions fall.

Clast Analyses

Mineral clasts in the melt rocks were distinguished from phenocrysts by optical microscopy on the basis of shape, presence or absence of zoning, and, occasionally, size. Phenocrysts are present in all melt rocks, and in most cases they are acicular, thus easily distinguished from the clasts (Fig. 3). In those melt rocks with a more coarsely grained melt matrix, however, the distinction between phenocrysts and clasts is not so easily made. Often the clasts have significant overgrowth from the melt, are fewer in number, and show greater effect from incorporation into the superheated melt (Fig. 4). In these cases, phenocrysts are of two types: smaller, acicular ones and relatively large, blocky ones, both showing a continuous zoning symmetrically outward from the core. It is also common to find that some of these large, blocky phenocrysts have small, unzoned cores onto which the new material has nucleated (Fig. 5). This type of phenocryst has been observed in the melt rocks of other terrestrial craters, and the unzoned cores are believed to be remnant clasts (e.g., Simonds et al., 1978; Phinney et al., 1978).

Fig. 3. Melt matrix of acicular plagioclase in melt rock LM 44-4B from Mistastin. Note clastic material at top and bottom. Plane transmitted light. Field of view: 0.5 mm.

Fig. 4. Typical effects of incorporation of plagioclase clasts into superheated melt in melt rock LM 52A from Mistastin. Large center clast is partially assimilated; lower right clast (near extinction) has plagioclase overgrowth. Crossed polars, transmitted light. Field of view: 1.0 mm.

Fig. 5. Large, blocky zoned plagioclase phenocryst (center) with unzoned remnant core (near extinction) in melt rock LM 7 from Mistastin. Crossed polars, transmitted light. Field of view: 1.0 mm.

Although we analyzed both apparently unaltered and visibly heat-altered clasts, we initially worked only with clasts that appeared to be unaltered (e.g., Fig. 6). Unaltered clasts in most of the melt rocks gave analyses within our acceptable error. In a few rocks (in particular LM 43A and LM 44-2A), however, clast analyses yielded good stoichiometry but low totals (below 90% in some cases). The sections had been carbon-coated properly, so poor conductivity was not the cause of the low totals. Assuming that Na was volatilized during analysis, we reanalyzed sections of LM 43A and LM 44-2A using only a 2 nA beam current, but there was no improvement of the analyses. One-second counts were then used on a few clasts of another section of LM 43A, but once again we observed no significant
Fig. 6. Unaltered plagioclase clasts in melt rock LM 41A from Mistastin. Plane transmitted light. Field of view: 1.0 mm.

Fig. 7. Plagioclase clast with checkerboard texture (from melt rock LM 38B from Mistastin). Plane transmitted light. Field of view: 1.0 mm.

Fig. 8. Feldspar compositions in melt rock LM 55A from Mistastin (o = good totals, x = poor totals).

Fig. 9. Feldspar compositions in melt rock LM 43A from Mistastin (o = good totals, x = poor totals).

Improvement of the analyses. This seems to imply that Na-loss is not the cause of these low totals, or at least is not an important factor. Loss of water that has diffused into the crystal lattice may be able to account for some of the problem, but certainly not up to 10 wt.%

Heat-altered clasts constitute most of the clast population in LM 59H [a "fine-medium-grained poikilitic melt with relatively few recognizable inclusions" (Grieve, 1975)], and they are also found in a few of the other rocks (e.g., LM 38B). For the most part, these heat-altered clasts have a checkerboard texture (Fig. 7). Analyses of checkerboard clasts also have low totals with acceptable stoichiometry. Additionally, there is some indication that analyses of these altered clasts give higher than true values of anorthite vs. albite component (based on a very few analyses of unaltered and altered areas of single clasts). Still, some analyses of altered clasts are albite-rich (i.e., of Gd-Qm source), so even if there is some skewing of data toward anorthite, it does not affect all of the data from altered clasts and they still provide data sufficient to discriminate their original source rocks. Consequently, we include analyses of altered-clasts in our data.

An area of each thin section was chosen in which to analyze clasts. For those samples in which clasts were few, we analyzed
TABLE 1. Abundances (vol.%) of target rocks in the clast populations of Mistastin Lake impact melt rocks.

<table>
<thead>
<tr>
<th>No.</th>
<th>Gd-Qm</th>
<th>Anor</th>
<th>Uncet</th>
<th>Modal Quartz</th>
</tr>
</thead>
<tbody>
<tr>
<td>38B</td>
<td>34</td>
<td>5.9</td>
<td>88.2</td>
<td>5.9</td>
</tr>
<tr>
<td>52A-69</td>
<td>49</td>
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<td>100.0</td>
<td>0.0</td>
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<tr>
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<td>57</td>
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<td>100.0</td>
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<td>90.6</td>
<td>0.0</td>
</tr>
<tr>
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<td>20</td>
<td>0.0</td>
<td>95.0</td>
<td>5.0</td>
</tr>
<tr>
<td>59H</td>
<td>7</td>
<td>57.1</td>
<td>42.9</td>
<td>0.0</td>
</tr>
<tr>
<td>43A</td>
<td>41</td>
<td>51.2</td>
<td>45.9</td>
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</tr>
<tr>
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<td>34.3</td>
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<tr>
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<td>45</td>
<td>13.3</td>
<td>86.7</td>
<td>0.0</td>
</tr>
</tbody>
</table>

1Number of clast analyses.
2Percent of granodiorite plus quartz monzonite components.
3Percent of anorthosite component.
4Undetermined source (either Gd-Qm or Anor).
5Volume percent of quartz in the clast population as determined by modal analysis.

Two important clast/melt relationships are revealed by the proportions of target rock in the clast populations. First, the proportions of target material in the clast populations (unlike the homogeneous melt matrix) vary considerably among the melt rocks. The proportions of anorthosite represented by the melt rock clasts range from 100% to 34%, whereas the proportions of target materials that constitute the melt matrix (determined by geochemical mass balance) remains unchanged at 65% anorthosite, 35% granodiorite plus quartz monzonite. Second, the relative proportions of target rocks in the clast populations vary with sample locations. From prior mapping of the Mistastin Lake crater area it is known that the breccias that directly underlie the sampled melt rocks are predominantly anorthositic to the north and northwest of the crater, with a decreasing anorthosite component to the southwest and south. We found that the proportions of anorthosite in the various melt rocks roughly correlate with sample location (Fig. 10). The one exception is LM 44-4B, located about 2 m above LM 44-2A, implying that a relatively significant vertical variation in clast populations also exists.

As the impact melt flows radially outward from the point of impact, it engulfs slower-moving clastic materials (Simonds, 1975; Pinney and Simonds, 1977). Precisely what clastic materials it includes depends on the nature of the clastic assemblage encountered during flow. Our data indicate that even though the impact process produces melt with uniform composition, the proportion of each target rock represented in the clast assemblage is related to the path the melt follows.

**DISCUSSION**

**Mistastin Lake Impact Melt**

We determined the proportions of anorthosite vs. granodiorite plus quartz monzonite represented by the clast populations of each melt rock (Table 1). For some of the melt rocks, one might question the indicated proportions because the number of analyses are low (for 59H in particular). While statistical uncertainties are definitely higher for those rocks with few analyses, note that point-counting of the percent of quartz in the clast populations of each rock (far right column) roughly correlates with the corresponding percent of granodiorite plus quartz monzonite that we determined from feldspar compositions.

In addition to the good analyses, we used those points with totals between 90.0 and 98.5 wt.% and good stoichiometry (4.975-5.025). In spite of this problem, we believe these low totals give good An-Ab-Or endmember proportions within reasonable error for two reasons: First, they plot within the country rock feldspar composition fields. Second, both points with acceptable totals and those with low totals give the same results in terms of representative lithologies (e.g., Figs. 8 and 9).

**Fig. 10.** Generalized map of Mistastin Lake, Labrador, with sample locations and percent anorthosite in the clast population in melt rocks (in black on pie diagrams) at each site. The abundance of anorthosite varies systematically around the crater and corresponds to the nature of underlying clastic breccias (see text for details).
and to its final emplacement, not to the rock types present at the zone where the melt is generated. In a heterogeneous target, therefore, the clast population of individual samples of the same melt sheet may be variable.

Implications for Lunar Impact Melts and LKF M

Our results on the study of clasts in the Mistastin Lake crater impact melt rocks can help us understand the origin of lunar LKF M melt rocks. Rocks of LKF M composition are exclusively impact melts and not pristine lunar igneous rocks. In contrast to the relative abundance of LKF M in the sample collections, the available orbital chemical data for the Moon show that the typical lunar surface compositions do not resemble LKF M, containing more aluminum and less KREEP, and that regions with compositions similar to LKF M are rare (Davis and Spudis, 1985, 1987). Moreover, as previously stated, the LKF M composition cannot be modeled as a mixture of known lunar rock types (Ryder and Bower, 1977; Ryder, 1979); there is always a missing component that is rich in KREEP and transition metals (e.g., Ti, Sc). This situation, of course, is opposite to that of terrestrial craters where the impact melts can generally be modeled geochemically as mixtures of their respective target rocks (e.g., Manicouagan melt sheet; Grieve and Floran, 1978).

These unusual attributes of LKF M have led to the development of a hypothesis for its origin that may be of great significance to understanding lunar crustal structure and petrological evolution. Ryder and Wood (1977) and Spudis (1984) proposed that LKF M impact melts were generated mostly by formation of impact basins. As such, these rocks provide information on both the compositions present within the lower lunar crust and, possibly, clues to the formation mechanics operating during basin formation (Spudis, 1984).

The data presented here from the Mistastin Lake crater melt sheet suggest that, while the clasts present in a melt sheet are derived from the target rocks, their proportions do not necessarily reflect the quantitative abundance of such rock types within the melt matrix. Moreover, the proportions of clast types that are preserved in these melt rocks appear to be related to the path the melt follows and the substrate onto which the melt was finally emplaced. For the Moon this suggests that melt rocks such as LKF M may incorporate most of their preserved clasts toward the latter stages of the cratering process. Thus if LKF M represents basin impact melt, the clast population in it informs us more about lithologies far removed from the zone of melting than it does about the bulk crustal composition. During basin-forming events, melt that moves laterally must also be traversing successively higher stratigraphic levels. Consequently, the melt matrix relates only to lower, not bulk, crustal levels.

An implication of this interpretation is that an unsampled rock type(s) exists within the lower lunar crust that substantially contributes to the LKF M melt matrix composition. Based on the general compositional features of LKF M, this unsampled rock type should possess a relatively high Mg/(Mg+Fe) ratio (greater than about 0.7), high concentration of transition metals (e.g., Ti > about 1.5 wt.%), and variable KREEP content.

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