
Introduction: Sample 65903,16-7 is a 16.7 mg rock fragment identified among the 2–4 mm size fraction of Apollo 16 rake sample 65900. In composition the particle resembles the KREEP-bearing impact melt breccias of group 1M [1]. It differs from such breccias, and known lunar samples in general, in several important ways. It contains abnormally high concentrations of alkali and siderophile elements (Table 1), the mafic silicates have unusually low Fe/Mg and Fe/Mn ratios, and there are no phosphates but an abundance of phosphides. In contrast to these indicators of stark reduction, the particle contains secondary carbonate and iron oxyhydroxide in veins and surface deposits. Here, we report on the petrology and geochemistry of the particle as a whole, with an emphasis on the unusual geochemistry and redox history. The reduction of Fe and P, but not Mn, constrains the $f_O_2$ of the sample during reduction to a maximum of $~10^{12.5}$. The carbonate and iron oxyhydroxide are described elsewhere [2].

Methods: The chemical analysis reported here (Table 1) was done by instrumental neutron activation analysis (INAA) of the entire rock fragment [3]. Mineral identification and compositions were determined using reflected light microscopy and a JEOL 733 electron microprobe on a polished thick section made from ~1/3 of the neutron-irradiated particle.

Petrography: The sample is a slightly vesicular impact melt breccia composed of anorthite clasts, forsteritic olivine grains, and opaque phases surrounded by a very fine-grained matrix (<30 µm) of plagioclase, augite, and glass (Fig. 1a-c). The matrix has a mode of 60% plagioclase, 24% augite, 16% glass.

The chemical analysis reported here (Tabela 1) was done by instrumental neutron activation analysis (INAA) of the entire rock fragment [3]. Mineral identification and compositions were determined using reflected light microscopy and a JEOL 733 electron microprobe on a polished thick section made from ~1/3 of the neutron-irradiated particle.

Petrography: The sample is a slightly vesicular impact melt breccia composed of anorthite clasts, forsteritic olivine grains, and opaque phases surrounded by a very fine-grained matrix (<30 µm) of plagioclase, augite, and glass (Fig. 1a-c). The matrix has a mode of 60% plagioclase, 24% augite, 16% glass.

The plagioclase clasts range in size from 0.02–0.5 mm, are of typical lunar highlands composition ($A_{95.2}A_{8.3}O_{8.01}$; Fig. 2a), are rounded, and are rimmed by more sodic plagioclase ($A_{91}A_{8.2}O_{8.5}$), which is slightly less sodic than the matrix plagioclase. One rounded clast (~0.1 mm) of low-Ca pyroxene ($E_{95}W_{0.5}F_{5.5}$; Fig. 2b) is also observed. The olivine ($F_{91}$; Fig. 2c) typically forms elongated grains (up to 0.5 mm), with matrix plagioclase commonly found as inclusions. The matrix consists of randomly oriented $A_{87}A_{8.3}O_{8.5}$ plagioclase laths, magnesian augite ($E_{95}W_{0.5}F_{5.5}$), and a glass with approximately ternary (but relatively mafic) feldspar composition. The opaque grains (up to ~0.1 mm) are intergrowths of schreibersite [(Fe,Ni)$_3$P] and Fe,Ni metal grains, with minor amounts of associated troilite (FeS) grains. Modally, opaque grains are ~4% of the sample. The schreibersite:Fe,Ni metal ratio for the bulk sample is abnormally high (~2:1), although the ratio varies among individual metal grains. Calcic siderite [(Fe$_{0.8}$Mg$_{0.2}$Mn$_{0.05}$Ca$_{0.14}$)CO$_3$] commonly rimmed by goethite ($\alpha$-FeOOH) occurs in the sample as grains on the surface of the particle and filling in veins and vesicles within the particle [2].

Geochemistry: The major-element composition of the bulk particle was determined by modal recombination and mixing-model analysis using average mineral compositions (Table 2). The resulting bulk chemistry closely matches the INAA values, with the exception of Na and K which are underestimated by a factor of 1.2 and 3.3 respectively. Overall, the particle is exceptionally magnesian, with a bulk Mg’ of 83, and silicate Mg’ of 92 (Mg’ = molar Mg/[Fe + Mg]*100).

Incompatible trace-element (ITE) concentrations have KREEP-like interelement ratios, but absolute con-
concentrations about 1/3 those of high-K KREEP [4]. Nota-
ably, U is enriched by a factor of 1.4 in the bulk particle
relative to other ITE, and the particle has high concen-
trations of alkali elements (but not Ba), particularly Rb,
which is enriched by a factor of 5 when compared to average
group-1M IMB composition. To a first approxi-
mation the composition, the particle corresponds to a
mixture of 81% average group 1M IMB [1], 15% fer-
roan anorthosite [5], and 4% average 65903,16-7 metal
(Table 2). Because of its small size, the particle may be
an unrepresentative sample of a group 1M IMB; high
U/ITE ratios and high alkali element ratios have not
previously been reported in small subsamples of group
1M IMB, however [1].

Oxidation: The presence of siderite and goethite in-
dicates that the sample has been in contact with an ox-
idizing fluid after (and unrelated to) the earlier reducing
event. In sample 65903,16-7 alkali-rich feldspar cannot
account for all of the excess alkali elements observed.
Trace amounts of K-feldspar in the matrix might ac-
count for the excess K, Rb, and Cs, but that Ba is not similarly enriched. Other alkali rich com-
ponents on the Moon (e.g., felsite, granite) have distin-
cuous from the olivine and augite. Excess U could be
reduced to FeO and Pb (~0.2 wt % as PbO).

Reduction: Based on modal recombination, the
sample has approximately 0.5 wt % P expressed as
P2O5. Assuming that P behaves like the other ITE, then
the silicate portion of the sample should have a mini-
mum of 0.3 wt % P2O5 (~1/3 the P concentration in hi
K-KREEP). Over 98% of the P is concentrated in the
schreibersite, however. Furthermore, the polished sec-
tion contained only one ~4 μm whitlockite grain, sug-
A. Petrology and Geochemistry of 65903, 16-7: Zeigler et al.

Lunar Fe:Mn ratios for whole rock compositions are
commonly ~75 [6]. Although the Fe:Mn ratio of 65903,
16-7 is 64, the average Fe:Mn ratios in the mafic sili-
cates are these: 30 (olivine), 37 (low-Ca pyroxene), and
14 (augite). These values are considerably lower than
typical Fe:Mn ratios of lunar pyroxene and olivine,
which are 45-75 and 75-120, respectively [6]. These
differences are consistent with reduction of Fe2+ to Fe0
during the impact-melting event.

The low Fe:Mn ratios of the olivine and augite sug-
gest that Fe2+ was reduced to Fe0 without Mn2+ being
reduced to Mn0. The almost complete lack of phosphate
coupled with the abundance of phosphide suggests that
P2+ was extensively reduced to P0. The fO2 ranges asso-
ciated with reduction of Fe and P at 1150–1200°C are
~1011.5-12.8 and ~1012.5-13.6, respectively (the fO2 for
the reduction of Mn is ~1020 [7,8]). Because Fe2+ is not
completely reduced, the fO2 during crystallization was
probably not far below the level required for P reduc-
tion. The nearly constant Fe:Mn ratio in the olivine and
augite and the nearly complete lack of phosphate indi-
cates that the reduction occurred while the particle was
still molten from the impact event. Furthermore, rapid
cooling indicated by the fine-grained matrix, precludes
later reduction and diffusion of P and Fe.


Acknowledgements: This work was sponsored by NASA grant
NAG5-4172 (LAH). We would like to thank Jeff Gillis for his help
with the image analysis.

<table>
<thead>
<tr>
<th>(n)</th>
<th>Met</th>
<th>Shr</th>
<th>Plm</th>
<th>Aug</th>
<th>Gls</th>
<th>Mat</th>
<th>Oli</th>
<th>Plc</th>
<th>BC</th>
<th>INAA</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>5</td>
<td>10</td>
<td>14</td>
<td>8</td>
<td>NA</td>
<td>8</td>
<td>9</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Average mineral and bulk particle major element compositions. Met = Fe,Ni metal, Shr = Schreibersite, Plm = matrix plagio-
clave, Aug = augite, Gls = glass, Mat = combined matrix, Oli = oli-
vine, Plc = plagioclase clasts, BC = bulk composition, (n) = number
of analyses averaged, % = modal percentage. Fe:Mn = ratio of Fe:Mn,
n.a. = not analyzed, NA = not applicable, bdI = below detection limit.

Figure 2: Mineral compositions in 65903,16-7. (a) Portion of feld-
spar ternary. (b) Portion of pyroxene quadrilateral. (c) Olivine com-
positions. Each tick = 10 units.