Composition of the first bulk melt sample from a volcanic region of Mars:
Queen Alexandra Range 94201

David A. KRING,¹* James D. GLEASON,² Timothy D. SWINDLE,¹ Kunihiko NISHIIZUMI,³ Marc W. CAFFEE,⁴ Dolores H. HILL,¹ A. J. Timothy JULL,⁵ and William V. BOYNTON¹

¹Lunar and Planetary Laboratory, University of Arizona, 1629 East University Boulevard, Tucson, Arizona 85721, USA
²Department of Geological Sciences, University of Michigan, 2534 C. C. Little Building, 425 East University Avenue, Ann Arbor, Michigan 48109, USA
³Space Sciences Laboratory, University of California, Berkeley, California 94720–7450, USA
⁴Purdue University, Department of Physics/PRIME Laboratory, 1396 Physics Building, West Lafayette, Indiana 47906–1396, USA
⁵NSF Arizona Accelerator Mass Spectrometer Facility, University of Arizona, Tucson, Arizona 85721, USA

*Corresponding author. E-mail: kring@lpl.arizona.edu

(Received 28 February 2003; revision accepted 08 May 2003)

Abstract–Antarctic meteorite Queen Alexandra Range (QUE) 94201 is a 12 g basaltic achondrite dominated by plagioclase (now maskelynite) and zoned low- and high-Ca pyroxene. Petrologic, geochemical, and isotopic analyses indicate that it is related to previously described basaltic and lherzolitic shergottites, which are a group of igneous meteorites that are believed to be from Mars. Unlike previous shergottites, however, QUE 94201 represents a bulk melt rather than a cumulate fraction, meaning it can be used to infer magmatic source regions and the compositions of other melts on Mars. This melt has much more Fe and P than basaltic melts produced on Earth and formed at a much lower oxygen fugacity. This has altered the crystallization sequence of the melt, removing olivine from the liquidus to produce a plagioclase and 2-pyroxene assemblage. If the high-phosphorus and low-oxygen fugacity conditions represented by QUE 94201 are common in magmatic regions of Mars, then olivine may be rare in martian basalts. No solar cosmic ray effects were seen in the concentrations of ¹⁰Be, ²⁶Al, and ³⁶Cl with depth in the meteorite, implying at least 3 cm of ablation during entry to Earth. Significant excesses of neutron capture noble gas isotopes (⁸⁰, ⁸²Kr and ¹²⁸, ¹³¹Xe) suggest that the QUE 94201 sample came from a depth >22 cm in a meteoroid of at least that radius. The meteorite also has very low ²¹Ne/²²Ne, which would often be interpreted to mean little ablation (contradicting above evidence) but, in this case, appears to reflect a very low abundance of Mg (the principal target element for Ne) in the meteorite, consistent with our bulk chemical analyses. The meteorite has a terrestrial ³⁶Cl age of 0.29 ± 0.05 Myr and a ¹⁰Be exposure age of 2.6 ± 0.5 Myr in a ⁴π geometry, implying an ejection age of 2.9 ± 0.5 Myr.

INTRODUCTION

Shergottites from Mars, like basalts on Earth, are important because they provide an opportunity to determine the evolution of the planet’s mantle, the relationships between crust and mantle, and the role of crustal assimilation in the petrogenetic processes that produce surface lavas. Attempts to use these and other martian igneous rocks, however, have been frustrated because they are cumulate rocks rather than bulk melt samples. To overcome this problem, estimates of bulk melt compositions have been made by trying to identify and subtract the compositions of suspected cumulate minerals (Stolper and McSween 1979; Smith and Hervig 1979; Treiman 1986; McSween et al. 1988; McCoy et al. 1992), by analyzing trapped melt inclusions (Johnson et al. 1991; Harvey and McSween 1992; Harvey et al. 1993; Treiman 1993), by interpreting phase equilibria constraints (Longhi and Pan 1989), and by using minor element compositions in pyroxene with equilibrium partition coefficients (Treiman and Sutton 1992). However, these attempts have produced often controversial and contradictory results.

Martian meteorite Queen Alexandra Range (QUE) 94201 provides a new opportunity to address this issue. The 12 g specimen is the first martian meteorite found in the Queen Alexandra Range area, which is located approximately 800 km south of McMurdo Station and on the west side of the...
Transantarctic Mountains, separating that part of the continent from the Ross Ice Shelf. It is one of 6 martian meteorites found in Antarctica and one of approximately 28 found globally, thus far. It is a basaltic shergottite (like Shergotty, Zagami, and Elephant Moraine [EET] 79001) rather than a lherzolitic shergottite, nakhlite, chassignite, or orthopyroxenite similar to Allan Hills (ALH) 84001.

In a preliminary report (Kring et al. 1996a), we presented mineralogic, textural, and geochemical evidence indicating QUE 94201 crystallized in a closed system and is the first basalt sample from Mars that represents a bulk melt composition. McSween and Eisenhour (1996) and McSween et al. (1996), drawing on analogies between QUE 94201 and lunar basalts, independently came to the same conclusion. In this contribution, we outline in more detail the evidence indicating that QUE 94201 is a bulk melt. We provide neutron activation analyses of the meteorite so that the composition of the melt can be used for future petrogenetic evaluations of the source region and other melts that may exist on Mars.

We are also interested in how the meteorite was delivered to Earth and have, thus, used noble gases and cosmogenic nuclides. Exposure histories, ejection conditions from the hypothesized martian parent body, and genetic relationships between SNC meteorites can be determined from nuclides produced by galactic cosmic rays (GCR) and solar cosmic rays (SCR) (see Nyquist et al. [2001] for a review). Cosmogenic nuclides produced by SCR reside in the uppermost few centimeters of material, and their presence in meteorites indicates the degree to which a meteorite has been ablated. Previous work shows ablation is less than 1 to 2 cm in at least 3 shergottites: ALH 77005, Shergotty, and EET 79001 (Bhandari et al. 1986; Nishiizumi et al. 1986a; Nishiizumi et al. 1986b; Garrison et al. 1995). This suggests that the atmospheric velocity and/or entry angle of these shergottites is much lower than the velocity and/or entry angle of ordinary chondrites. We measured all 5 noble gases, plus the cosmogenic radionuclides \(^{10}\text{Be},^{26}\text{Al},^{36}\text{Cl},\) and \(^{14}\text{C},\) to determine the exposure history of QUE 94201, its ejection age from Mars, and its ablation in the atmosphere.

**METHODS**

**Electron-Induced X-ray Microscopy**

Electron microprobe analyses were made of split QUE 94201,7 (i.e., split 7 produced at the Johnson Space Center’s Antarctic meteorite facility) thin section using a Cameca SX-50 instrument with 4 wavelength-dispersive spectrometers, a 15 kV accelerating voltage, a 20 nA beam current, and a 1 \(\mu m\) diameter beam. Silicates and oxides were analyzed together, while sulfides were analyzed separately using different sets of standards. Additional details about standards, calibration, and analytical procedures are reported elsewhere (Kring et al. 1996b).

**Neutron Activation Analyses**

Bulk chemical analyses were made of split QUE 94201,16 using instrumental neutron activation techniques. The total sample mass was 254.58 mg. We further split the sample into 3 chips of 47.40, 81.32, and 125.87 mg to have a measure of sample heterogeneity. The samples were initially irradiated in the University of Arizona’s TRIGA reactor for 60 sec at 10 kW \((2.1 \times 10^{12} \text{neutrons/cm}^2/\text{sec})\) for a total fluence of \(-1.3 \times 10^{14} \text{n/cm}^2\) (“rabbit” conditions). Gamma-ray spectra were collected immediately after the samples were removed from the reactor to determine the concentrations of elements whose neutron-produced radioisotopes are short-lived (Na, Mg, Al, Ti, V, and Mn). The samples were then reirradiated in the University of Arizona’s TRIGA reactor for 3 hr at \(0.7 \times 10^{12} \text{neutrons/cm}^2/\text{sec}\) for an additional fluence of \(-1.3 \times 10^{14} \text{n/cm}^2\). The samples were then returned to the Lunar and Planetary Laboratory, where gamma-ray spectra were collected for 31 days. Counting was done using 2 detectors, including a fast-timing anticoincidence Compton suppression spectrometer, which gives an improved signal-to-noise ratio over standard Ge detector systems. Synthetic and natural rock standards were irradiated together with QUE 94201 for all experiments to determine absolute abundances of elements. These included the Allende meteorite (Jarosewich et al. 1987; Conard 1976; Takahashi et al. 1978; Kallemeyn and Wasson 1981; Ngo and Lipschutz 1980), Columbia River basalt (CRB; Gladney et al. 1983), and flyash (Korotev 1987; National Bureau of Standards 1979; Gladney et al. 1984).

**Noble Gas Analyses**

A 23.68 mg fragment of QUE 94201 was removed from the same bulk sample (split .16) used for neutron activation analyses. All 5 noble gases in this fragment were analyzed in a VG5400 in the University of Arizona noble gas mass spectrometry laboratory, using procedures previously described (Swindle et al. 1995). Gases were extracted in 4 steps, at 400°C, 800°C, 1400°C, and 1650°C. A split of the extracted gas was used to analyze Ar, while Kr and Xe were cryogenically separated. Then, liquid N\(_2\) was used to cool 2 cold fingers containing activated charcoal to trap as much of the Ar as possible while analyzing a split of the remaining gas for He and then a split for Ne. Finally, the remaining light gases were pumped away and the cryogenically separated Kr and Xe were released and analyzed simultaneously. The mass spectrometer filament burned out while analyzing the last step, after only He and Ar had been analyzed. That step had contained little He or Ar, so we suspect it also would have contained little Ne. Quite possibly, a larger fraction of the Kr and Xe, which tend to be more retentive, were lost. However, none of the conclusions we reach below hinge on the total amounts of Kr or Xe.
Cosmogenic Radionuclide Analyses

We measured the concentrations of cosmogenic radionuclides $^{10}$Be (half-life = 1.5 Myr), $^{26}$Al (0.705 Myr), $^{36}$Cl (0.301 Myr), and $^{14}$C (5,730 yr) by accelerator mass spectrometry (AMS). To investigate SCR effects in QUE 94201, we measured $^{10}$Be, $^{26}$Al, and $^{36}$Cl in 4 sub-samples with different shielding depths. Three sub-samples, at a depth of 0–1 mm (30.74 mg), 1–3 mm (51.66 mg), and 3–5 mm (25.76 mg) from the surface fusion crust were separated from QUE 94201,27. An interior sample, QUE 94201,13 (64.31 mg), was chipped 4–8 mm from the recovered surface. The distance between QUE 94201,13 and QUE 94201,27 is <10 mm. An interior sample, QUE 94201,16, (a complementary portion of the same split used for neutron activation analyses) was used for $^{14}$C measurement. After dissolving the powdered meteorite, Be, Al, and Cl were chemically separated and purified for AMS measurements (Nishizumi et al. 1986b). AMS measurements were performed at the Lawrence Livermore National Laboratory (Davis et al. 1990) for all nuclides except $^{14}$C, which was performed at the Arizona AMS facility.

RESULTS

Petrology

Our sample of this meteorite is greenish black (5G 2/1; Rock-Color Chart Committee 1991) and has a medium-grained (1–5 mm) texture dominated by plagioclase and pyroxene (Fig. 1). Plagioclase in QUE 94201 is normally zoned from An$_{68}$ to An$_{57}$ and contains magmatic melt inclusions (as opposed to shock-melted pockets) that partially crystallized after being trapped. The plagioclase sometimes occurs in parallel ranks with pyroxene between the limbs, which we infer to be parts of single parallel-growth skeletal crystals. The orientations of different parallel-growth crystals are diverse, however, and not indicative of a coherent crystal fabric in the rock. While not evident in thin section, we observed a spherulitic growth of plagioclase or a radiating intergrowth of plagioclase and pyroxene in our bulk chip; crystals up to 0.5 mm wide and 5 mm long occur in this bundle.

Pyroxene is adjacent to and sometimes enclosed by plagioclase. It occurs as euhedral prisms and equant cross-sections but is also anhedral in pockets adjacent to plagioclase laths. It is sometimes twinned, and extensive zonal growth of the pyroxene has produced a texture that is transitional to consertal. The pyroxene consists of both pigeonite and augite (Fig. 2). Pigeonite has normal Mg-Fe-Ca igneous zoning and forms a continuous compositional range from Wo$_{0.35}$En$_{0.69}$Fs$_{0.45}$ to an unusually Fe-rich Wo$_{0.16}$En$_{0.83}$Fs$_{0.31}$. In contrast, augite compositions are bimodal and average about Wo$_{0.40}$En$_{0.58}$Fs$_{0.58}$ and, again, an unusually Fe-rich Wo$_{0.40}$En$_{0.54}$Fs$_{0.58}$. Detailed mapping of this zoning has been reported by McKay et al. (1996) and Mikouchi et al. (1998).

The minor phases in QUE 94201, particularly in regions where the last vestiges of melt were trapped, include whitlockite, ilmenite, ulvöspinel, olivine, a sulfide, and apatite (Table 1). The olivine is nearly pure fayalite (Fa$_{97}$ to Fa$_{99.7}$) and has a wt% FeO/MnO ratio of 47 that is characteristic of martian meteorites. Ilmenite has very little Fe$^{3+}$ and is uniformly Ilm$_{98-100}$Hm$_{2-0}$. The composition of ulvöspinel is more variable and involves several spinel group components. In terms of the ulvöspinel-magnetite solid solution, the grains have compositions that range from Usp$_{0.35}$Mt$_{0.65}$ to Usp$_{0.35}$Mt$_{0.55}$ but are dominated by Usp$_{0.50}$Mt$_{0.50}$. These oxide compositions are similar to those reported by McSween et al. (1996) and Herd et al. (2001), although, our
The whitlockite is very Fe<sup>2+</sup>-rich. For example, whitlockite in the lherzolitic shergottite Lewis Cliff (LEW) 88516 has 3.52 wt% MgO and only 0.81 wt% FeO (Gleason et al. 1997), while whitlockite in QUE 94201 has 0.61 wt% MgO and 6.10 wt% FeO (Table 1). This probably reflects the fact that the QUE 94201 melt is much more evolved than LEW 88516.

Abundant melt inclusions in plagioclase, pyroxene, and ilmenite, in addition to larger melt pockets interstitial to plagioclase, contain moderately siliceous to nearly pure silica glass. The glass in the melt inclusions contains 54 to 73 wt% SiO<sub>2</sub>. In larger interstitial areas, the SiO<sub>2</sub> in the glass ranges from 61–96 wt%, although, the glass composition is relatively homogeneous in any particular area of the thin section.

Plagioclase has been shocked-transformed to maskelynite and sometimes contains or is surrounded by impact melt (Fig. 3). The melt pockets are often quite large (up to 1 mm), contain schlieren (particularly of plagioclase-rich glass), and are brown and sometimes fely where they began to recrystallize. The melt pockets also contain rafts of unmelted plagioclase and pyroxene with resorbed margins and reaction coronas. The margins of pyroxene grains that are adjacent to these melt pockets are granulated. Elsewhere in the thin section, pyroxene exhibits mottled extinction, mosaicism, and contains multiple sets of planar deformation features. Shock transformation of plagioclase with an An<sub>57–68</sub> composition to maskelynite suggests a shock pressure of at least 28 GPa (Stöffler et al. 1986). Planar deformation features and mosaicism in pyroxene, although, not as well calibrated, suggest shock pressure of at least 25–30 GPa (Rubin et al. 1997). These shock pressures are comparable to those inferred for many other shergottites (Fritz et al. 2002) launched from Mars. Since the probability is low that such young basalts (~330 Myr in the case of QUE 94201; Borg et al. 1997) have been involved in 2 impact events, these shock pressures were probably experienced in the events that ejected the samples from Mars.

### Chemical Composition

The bulk chemical composition of split QUE 94201,16 is listed in Table 2. Element ratios that are characteristic of martian provenance, including Fe/Mn = 41, Fe/Sc = 3000, Al/Ga = 2330, and K/La = 1300, are similar to those measured in other shergottites, although, the K/La ratio is on the high end of the range (680–1300) among shergottites.

### Rare Earth Elements

The chondrite-normalized REE pattern in QUE 94201 is similar, although not identical, to those in other shergottites, particularly the basaltic shergottites. The abundances of HREE, however, are greater than in any other shergottite, with the possible exception of Los Angeles (Rubin et al. 2000). The fractionation of LREE from HREE is also greater in QUE 94201 than in any other shergottite (Fig. 4). The extreme depletion in LREE relative to HREE prompted us (Kring et al. 1996a) to suggest that QUE 94201 is more representative of a depleted mantle source than the other shergottites, an observation since confirmed by many studies (e.g., Borg et al. 1997; Blichert-Toft et al. 1999).

### Aluminum and Mg#

The abundance of Al is greater in QUE 94201 than in any other shergottite (Fig. 5), while the Mg# is lower in QUE
Fig. 3. Backscattered electron images of shock-metamorphosed components in QUE 94201: a) impact melt pocket within maskelynite; b) close-up view of melt pocket; c) larger interstitial impact-melted region; d) close-up view of melted region illustrating relict mineral clasts with resorbed margins in microcrystalline groundmass; and e) impact-melted margin of maskelynite. For comparison, magmatic melt inclusions within pyroxene are shown in (f).
Table 2. Chemical composition of QUE 94201.\(^a\)

<table>
<thead>
<tr>
<th></th>
<th>Split 1</th>
<th>Split 2</th>
<th>Split 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>47.40 mg</td>
<td>81.32 mg</td>
<td>125.87 mg</td>
<td>254.58 mg</td>
</tr>
<tr>
<td>Na</td>
<td>15780</td>
<td>13800</td>
<td>13280</td>
<td>13910</td>
</tr>
<tr>
<td>Mg (%)</td>
<td>3.3</td>
<td>2.9</td>
<td>4.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Al (%)</td>
<td>8.03</td>
<td>6.20</td>
<td>5.79</td>
<td>6.34</td>
</tr>
<tr>
<td>K</td>
<td>430</td>
<td>510</td>
<td>640</td>
<td>560</td>
</tr>
<tr>
<td>Ca (%)</td>
<td>7.7</td>
<td>7.4</td>
<td>7.61</td>
<td>7.6</td>
</tr>
<tr>
<td>Sc</td>
<td>38.5</td>
<td>45.8</td>
<td>48.8</td>
<td>45.9</td>
</tr>
<tr>
<td>Ti</td>
<td>9600</td>
<td>10900</td>
<td>10000</td>
<td>10200</td>
</tr>
<tr>
<td>V</td>
<td>84</td>
<td>92</td>
<td>104</td>
<td>96</td>
</tr>
<tr>
<td>Cr</td>
<td>792</td>
<td>809</td>
<td>1054</td>
<td>927</td>
</tr>
<tr>
<td>Mn</td>
<td>2940</td>
<td>3430</td>
<td>3510</td>
<td>3380</td>
</tr>
<tr>
<td>Fe (%)</td>
<td>11.95</td>
<td>14.50</td>
<td>14.00</td>
<td>13.78</td>
</tr>
<tr>
<td>Co</td>
<td>20.22</td>
<td>23.1</td>
<td>24.2</td>
<td>23.1</td>
</tr>
<tr>
<td>Ni</td>
<td>150</td>
<td>120</td>
<td>&lt;80</td>
<td>&lt;106</td>
</tr>
<tr>
<td>Zn</td>
<td>65</td>
<td>82</td>
<td>84</td>
<td>80</td>
</tr>
<tr>
<td>Ga</td>
<td>27.6</td>
<td>30.5</td>
<td>25</td>
<td>27.2</td>
</tr>
<tr>
<td>Se</td>
<td>2.9</td>
<td>2.8</td>
<td>1.8</td>
<td>&lt;2.3</td>
</tr>
<tr>
<td>Br</td>
<td>0.52</td>
<td>0.37</td>
<td>0.49</td>
<td>0.46</td>
</tr>
<tr>
<td>Rb</td>
<td>&lt;13</td>
<td>–</td>
<td>8.4</td>
<td>8.4(^b)</td>
</tr>
<tr>
<td>Zr</td>
<td>118</td>
<td>159</td>
<td>107</td>
<td>126</td>
</tr>
<tr>
<td>Ru</td>
<td>2.7</td>
<td>3.1</td>
<td>&lt;1.6</td>
<td>&lt;2.3</td>
</tr>
<tr>
<td>La</td>
<td>0.35</td>
<td>0.45</td>
<td>0.46</td>
<td>0.44</td>
</tr>
<tr>
<td>Ce</td>
<td>&lt;1.8</td>
<td>1.62</td>
<td>1.19</td>
<td>1.36(^b)</td>
</tr>
<tr>
<td>Nd</td>
<td>&lt;5</td>
<td>3.8</td>
<td>3.1</td>
<td>3.4(^b)</td>
</tr>
<tr>
<td>Sm</td>
<td>1.747</td>
<td>2.53</td>
<td>2.436</td>
<td>2.34</td>
</tr>
<tr>
<td>Eu</td>
<td>1.086</td>
<td>1.208</td>
<td>1.144</td>
<td>1.154</td>
</tr>
<tr>
<td>Tb</td>
<td>0.76</td>
<td>1.034</td>
<td>1.026</td>
<td>0.979</td>
</tr>
<tr>
<td>Ho</td>
<td>0.95</td>
<td>1.35</td>
<td>1.23</td>
<td>1.22</td>
</tr>
<tr>
<td>Tm</td>
<td>0.45</td>
<td>0.58</td>
<td>0.51</td>
<td>0.52</td>
</tr>
<tr>
<td>Yb</td>
<td>2.70</td>
<td>3.77</td>
<td>3.50</td>
<td>3.44</td>
</tr>
<tr>
<td>Lu</td>
<td>0.383</td>
<td>0.556</td>
<td>0.496</td>
<td>0.494</td>
</tr>
<tr>
<td>Hf</td>
<td>2.76</td>
<td>3.90</td>
<td>2.61</td>
<td>3.05</td>
</tr>
<tr>
<td>W</td>
<td>&lt;1.1</td>
<td>&lt;0.8</td>
<td>0.54</td>
<td>0.54(^b)</td>
</tr>
<tr>
<td>Re</td>
<td>0.060</td>
<td>0.042</td>
<td>0.029</td>
<td>0.039</td>
</tr>
<tr>
<td>Ir</td>
<td>&lt;0.012</td>
<td>0.006</td>
<td>0.005</td>
<td>0.005(^b)</td>
</tr>
<tr>
<td>Au</td>
<td>&lt;0.007</td>
<td>0.005</td>
<td>&lt;0.004</td>
<td>–</td>
</tr>
</tbody>
</table>

\(^a\)Compositions were determined by INAA; the calculated average is weighted according to sample mass. Element concentrations are in ppm (by weight) unless otherwise indicated. The errors are 5% for Na, Al, Sc, V, Cr, Mn, Fe, Co, Sm, Eu, Yb, Lu, and Hf; 5–10% for Ca, Zn, Ga, La, Tb, and Ho; 10–20% for Ti and Se; 20–35% for Mg, K, Ni, Br, Rb, Zr, Ru, Ce, Nd, Ir, and Au.

\(^b\)Average value is based on only 1 or 2 splits.

94201 than in other shergottites: 30 versus 43 (EET 79001B), 46 (Shergotty), 51 (Yamato-793605), 52 (Zagami), 69 (LEW 88516), and 70 (ALH 77005). As discussed below, variation is seen among different bulk analyses of QUE 94201. Warren and Kallemeyn (1997) report an even lower Mg# of 20 for QUE 94201.

**Silicon and Phosphorus**

Neutron activation analyses are unable to measure Si and P. In most cases, when silicate rocks are analyzed, Si is determined by difference. The elements measured by neutron activation are added together and subtracted from 100%, making the assumption that no significant quantity of an element other than silicon exists. In the case of QUE 94201, however, large quantities of phosphate minerals (Fig. 1), 2.77 wt% P\(_2\)O\(_5\) in the fusion crust (Table 3) and 2.05 wt% in a fused bead analysis (Mittlefehldt and Lindstrom 1996), indicate that both Si and P must be responsible for the difference. If one assumes that the abundance of P\(_2\)O\(_5\) in the fusion crust reflects bulk P\(_2\)O\(_5\), then there is 46.9 wt% SiO\(_2\) in our INAA sample of QUE 94201. On the other hand, if one assumes that the fused bead analysis reflects bulk P\(_2\)O\(_5\), then there is 47.6 wt% SiO\(_2\) in our sample of QUE 94201. We note that the phosphate crystals are so large in QUE 94201 (Fig. 1) that getting a good bulk determination of P may be difficult in either the sample used for INAA or the sample used for fused bead analysis. Potential heterogeneities in the production of the fusion crust (and volatility) may also compromise the
determination of P in analyses of QUE 94201. The fusion crust analyses are enriched in FeO and depleted in Al_2O_3 and Na_2O relative to our INAA determination. The SiO_2 abundance is also depleted relative to the UCLA and JSC fused bead analyses. This suggests that the fusion crust is enriched in the pyroxene component of the rock and depleted in the plagioclase component. Consequently, while the composition of the fusion crust is similar to that of the bulk rock, it is not an accurate proxy for the bulk composition of QUE 94201.

Noble Gas Composition

Our preliminary results were reported by Swindle et al. (1996) and are expanded here (note that the results quoted in the abstract include only the gas released in the 800°C and 1400°C extractions because the first extraction is often dominated by terrestrial contamination). The results of analyses of He, Ne, Ar, Kr, and Xe are shown in Tables 4–6.

The 129Xe/132Xe ratio is as high as 1.26 ± 0.05 (in the 1400°C extraction), well above the terrestrial value of 0.98 and suggestive of a contribution from the martian atmosphere, typical of a shergottite (Swindle 2002). The amount of atmospheric Xe incorporated (~0.7 × 10^{-12} cm^3 STP/gram of atmosphere) is far smaller than that found in the shock-melt or melt-rich samples from other shergottites (e.g., 1.7 to 47 × 10^{-12} cm^3 STP/gram; Becker and Pepin 1993; Garrison and Bogard 1998). Our sample was not pure melt, of course, so determining whether a concentration in the melt even exists would require physical separation of the melt. However, atmospheric incorporation might be more difficult in a medium-grained rock like QUE 94201 than it is in finer-grained, more vesiculated samples. As is also typical of a shergottite (Bogard and Garrison 1999), the Ar data requires some contribution from martian trapped 36Ar, since the 38Ar/36Ar ratios are all much less than the values typical of spallation (~1.5), and since a crude K-Ar age calculated with no correction for any martian component would give an age of ~1700 Myr, much larger than the crystallization age of 327 ± 10 Myr (Nyquist et al. 2001).

Our noble gas data are consistent with data for QUE 94201 reported by several other groups (Dreibus et al. 1996;
Eugster et al. 1997, 2002; Garrison and Bogard 1998; Mohapatra et al. 2002). The absolute amounts of cosmogenic Ne and Ar are higher than the average by roughly a factor of 2. We attribute this to sample heterogeneity (see the Sample Heterogeneity section), since our sample is only 24 mg, and note that Mohapatra et al. (2002) measured cosmogenic Ne and Ar totals less than the previous average by roughly the same amount (in a 39 mg sample) and also attributed the difference to sample heterogeneity. Also, note that, for 3He, where the main target element is O, the abundance of which varies little from sample to sample, our results are in good agreement with previous measurements.

Cosmogenic Nuclides

Our preliminary results were reported by Nishiizumi and Caffee (1996) and are expanded here. Table 7 shows the 14C, 10Be, 26Al, and 36Cl results in 4 sub-samples of QUE 94201. After blank and background corrections, the observed isotopic ratios are normalized to ICN 10Be, NBS 26Al, and NBS 36Cl standards diluted by Nishiizumi. The quoted errors represent ±1σ AMS measurement errors. Our measurements of 10Be and 26Al are similar to those of Schnabel et al. (2001). The 26Al concentrations in QUE 94201 scatter as the result of chemical heterogeneity between the 4 sub-samples. Aluminum and Si are major target elements for production of 26Al. The Al
concentrations in our samples range from 3.9 wt% to 5.3 wt%. By assuming the 26Al production rate from Al is 2.5 times higher than that from Si, the 26Al concentrations in QUE 94201 can be normalized to the 26Al activity in L chondrites (1.27 wt% Al and 18.7 wt% Si). The normalized 26Al activities in QUE 94201 are 34–36 dpm/(kg L chondrite). After correction for chemical composition, the 26Al concentrations in the 3 samples of QUE 94201, 27 with differing depths are nearly identical. Clearly, no evidence exists of increasing 26Al concentration toward the surface of the meteorite. Allan Hills 77005 and Shergotty (Nishiizumi et al. 1986a, b), by contrast, had high 26Al activities in samples taken at the surface. A reasonable interpretation is that no SCR effects occur at these sample depths, implying at least 3 cm ablation. The 36Cl concentrations were normalized to the measured concentrations of target elements, dpm/kg (8Ca + Fe), and are shown in the last column of Table 7. The depth profile of 36Cl concentrations also shows no evidence of SCR-produced effects. The normalized 36Cl concentrations in QUE 94201 are lower than those observed in other martian meteorites. For a 4π bombardment in transit to Earth from the parent body, the 36Cl saturation activity is 22 ± 3 dpm/kg (8Ca + Fe). The low 36Cl concentration in QUE 94201 is most likely the result of 36Cl decay during residence on the Earth. The terrestrial age obtained from 36Cl is 0.29 ± 0.05 Myr. The 14C content was very low, and given the small size of the sample measured for 14C, 96 mg after pretreatment, the observed value of 1.1 ± 0.7 dpm/kg is likely a limit measurement, which would constrain the terrestrial age to be >28 ka.

Assuming the terrestrial age, the 26Al activities at the time of fall are calculated to be 72–82 dpm/kg meteorite or 45–48 dpm/(kg L chondrite). The 10Be concentrations in the 4 sub-samples are nearly constant. After the terrestrial age correction, the 10Be activities are 13.6 ± 0.6 dpm/kg meteorite. The 10Be concentration in QUE 94201 at the time of fall is very similar to those in Shergotty (Nishizumi et al. 1986b) and Zagami (unpublished data). The 10Be production rate is estimated to be 17–22 atom/min • kg based on the 26Al concentration. The 10Be concentration indicates that QUE 94201 was exposed to cosmic rays from 2.6 ± 0.5 Myr in a 4π geometry. This is in good agreement with the preferred exposure age of 2.42 ± 0.20 Myr calculated by Nyquist et al. (2001), based on a compilation of noble gas and cosmogenic radionuclide data, including preliminary versions of the data presented here.

Since the 10Be exposure age is in good agreement with noble gas exposure ages, the QUE 94201 meteorite was exposed to cosmic rays in 4π irradiation conditions from the parent body to the Earth and the ejection depth was deeper than 3 m. The ejection age (sum of exposure age and terrestrial age) of QUE 94201 is 2.9 ± 0.5 Myr, based on the

---

**Table 5. Krypton in QUE 94201.**

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>10⁻¹² cm³ STP</th>
<th>⁸⁴Kr/⁸⁴Kr</th>
<th>⁷⁸Kr/⁸⁴Kr</th>
<th>⁸⁰Kr/⁸⁴Kr</th>
<th>⁸²Kr/⁸⁴Kr</th>
<th>⁸³Kr/⁸⁴Kr</th>
<th>⁸⁶Kr/⁸⁴Kr</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>14.8</td>
<td>0.017 (8)</td>
<td>0.054 (6)</td>
<td>0.208 (12)</td>
<td>0.209 (14)</td>
<td>0.334 (14)</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>2.6</td>
<td>-0.006 (40)</td>
<td>0.135 (37)</td>
<td>0.223 (48)</td>
<td>0.13 (7)</td>
<td>0.214 (38)</td>
<td></td>
</tr>
<tr>
<td>1400</td>
<td>3.4</td>
<td>0.008 (30)</td>
<td>0.151 (34)</td>
<td>0.265 (26)</td>
<td>0.208 (44)</td>
<td>0.275 (26)</td>
<td></td>
</tr>
<tr>
<td>Totalb</td>
<td>20.7</td>
<td>0.013 (9)</td>
<td>0.080 (10)</td>
<td>0.219 (11)</td>
<td>0.199 (15)</td>
<td>0.309 (13)</td>
<td></td>
</tr>
</tbody>
</table>

aValues in parentheses represent 1-sigma uncertainties in the last digits.
bThe 1650°C extraction was lost when the mass spectrometer filament burned out.

**Table 6. Xenon in QUE 94201.**

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>10⁻¹² cm³ STP</th>
<th>¹³²Xe/¹³²Xe</th>
<th>¹²⁸Xe/¹³²Xe</th>
<th>¹²⁹Xe/¹³²Xe</th>
<th>¹³⁰Xe/¹³²Xe</th>
<th>¹³¹Xe/¹³²Xe</th>
<th>¹³⁴Xe/¹³²Xe</th>
<th>¹³⁶Xe/¹³²Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>4.7</td>
<td>0.014 (7)</td>
<td>0.074 (20)</td>
<td>0.941 (34)</td>
<td>0.172 (9)</td>
<td>0.776 (46)</td>
<td>0.420 (22)</td>
<td>0.320 (16)</td>
</tr>
<tr>
<td>800</td>
<td>2.4</td>
<td>0.003 (9)</td>
<td>0.086 (27)</td>
<td>0.953 (39)</td>
<td>0.149 (8)</td>
<td>0.92 (11)</td>
<td>0.352 (20)</td>
<td>0.288 (20)</td>
</tr>
<tr>
<td>1400</td>
<td>2.6</td>
<td>0.014 (13)</td>
<td>0.147 (30)</td>
<td>1.261 (61)</td>
<td>0.163 (17)</td>
<td>1.06 (8)</td>
<td>0.401 (26)</td>
<td>0.343 (24)</td>
</tr>
<tr>
<td>Totalb</td>
<td>9.7</td>
<td>0.0053 (51)</td>
<td>0.097 (14)</td>
<td>1.030 (26)</td>
<td>0.164 (7)</td>
<td>0.889 (41)</td>
<td>0.398 (14)</td>
<td>0.318 (11)</td>
</tr>
</tbody>
</table>

aValues in parentheses represent 1-sigma uncertainties in the last digits.
bThe 1650°C extraction was lost when the mass spectrometer filament burned out.

**Table 7. Cosmogenic radionuclide concentration (dpm/kg meteorite) in QUE 94201.**

<table>
<thead>
<tr>
<th>Depth from surface (mm)</th>
<th>¹⁴C</th>
<th>¹⁰Be</th>
<th>²⁶Al</th>
<th>³⁶Cl</th>
<th>³⁶Clα</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUE 94201,27</td>
<td>0–1</td>
<td>–</td>
<td>11.60 ± 0.32</td>
<td>54.4 ± 1.4</td>
<td>8.20 ± 0.14</td>
</tr>
<tr>
<td>QUE 94201,27</td>
<td>1–3</td>
<td>–</td>
<td>11.96 ± 0.26</td>
<td>60.1 ± 1.2</td>
<td>8.80 ± 0.19</td>
</tr>
<tr>
<td>QUE 94201,27</td>
<td>3–5</td>
<td>–</td>
<td>11.91 ± 0.45</td>
<td>61.4 ± 1.4</td>
<td>7.95 ± 0.14</td>
</tr>
<tr>
<td>QUE 94201,13</td>
<td>4–8</td>
<td>–</td>
<td>12.10 ± 0.22</td>
<td>55.7 ± 1.7</td>
<td>9.14 ± 0.18</td>
</tr>
<tr>
<td>QUE 94201,16</td>
<td>n.d.</td>
<td>1.1 ± 0.7</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

aValues in parentheses represent 1-sigma uncertainties in the last digits.
bThe 1650°C extraction was lost when the mass spectrometer filament burned out.

dpm/kg (8Ca + Fe).
DISCUSSION

Sample Heterogeneity

This meteorite is a medium-grained rock, making it difficult to obtain an accurate bulk chemical analysis with the sample mass available for destructive INAA. The sample mass used in this study was approximately 250 mg, which is appropriate for fine-grained igneous rocks but marginal for coarser rocks. Consequently, sample heterogeneity may have skewed the bulk composition reported in Table 2. Variations in measured abundances in our 47, 81, and 126 mg splits indicate that heterogeneity exists at the 10 to 100 mg level. We also compared our average bulk composition with those determined by INAA in other laboratories to evaluate whether heterogeneity exists at the 250 mg level (Table 3). To within error, our analysis and that of the Max-Planck group (Dreibus et al. 1996) agree. An analysis by a UCLA group (Warren and Kallemeyn 1997) is slightly more mafic. An average composition weighted on the basis of sample mass is computed for all laboratories and shown in the fifth column of Table 3. Because this average composition is based on nearly 740 mg of material (about 6% of the meteorite), it is the best bulk composition to use for petrogenetic studies and other types of experimental geochemical investigations. The fusion crust is composition to use for petrogenetic studies and other types of experimental geochemical investigations. The fusion crust is metallic and glassy, and a fraction of the melt was not lost after pyroxene began to crystallize. In contrast, similar agreement is completely lacking in other shergottites, with the possible exception of lithology B in EET 79001. Consequently, the bulk composition of QUE 94201 represents a bulk melt rather than a cumulate fraction.

The mineralogical evidence is similarly expressed in the chemistry of the rock. QUE 94201 is more aluminous than any other shergottite, all of which have compositions that are skewed from melt compositions by the presence of Al-poor cumulus phases. In addition, QUE 94201 has higher abundances of many other elements that are incompatible during the earliest stages of crystallization (Ti, P, and REE; Fig. 4). While QUE 94201 has more Al than any other shergottite, it still has less Al than terrestrial basalts. This relative deficiency suggests that the melt represented by QUE 94201, like other shergottites, was produced from a source region that was already depleted in garnet (Longhi et al. 1992).

Liquid Line of Descent

If QUE 94201 is a bulk melt, it can be used to investigate the petrogenetic evolution of magmas on Mars using liquidus phase diagrams. An initial attempt to do this is illustrated in Fig. 7, which shows the projection of the bulk composition of QUE 94201 onto an olivine-plagioclase-quartz ternary in the pseudobasaltic olivine-plagioclase-wollastonite-quartz system often used to investigate basaltic melts (Longhi 1991). As described above, QUE 94201 is dominated by plagioclase and pyroxene. Plagioclase is zoned from An87 to An68. Pigeonite is also continuously zoned, from Wo15En01Fs85 to Wo35En40Fs55. Augite compositions are bimodal, averaging Wo20En20Fs58 and Wo40En30Fs58. This is a coherent set of compositions that suggests closed system fractional crystallization. Consequently, one would expect the bulk composition of QUE 94201 to plot close to the pigeonite-augite-plagioclase boundary. Instead, the bulk composition plots in the olivine stability field, even though olivine does contrast to other shergottites, the rock contains an unusually large amount of accessory minerals, again suggesting that lower temperature melt fractions were not separated from the higher temperature crystallization products.

This can be illustrated quantitatively by comparing the compositions of pyroxene cores (the highest temperature and, thus, earliest crystalline phase) with the calculated pyroxene composition that would be in equilibrium with the bulk rock (i.e., when it was initially wholly molten). Figure 6 shows the molar Mg/(Mg + Fe) ratio across a zoned pyroxene crystal in QUE 94201. The calculated pyroxene composition that would be in equilibrium with a melt with the bulk composition of the meteorite is also shown. Because the core pyroxene composition is identical to the equilibrium composition, clearly, the pyroxene is not a cumulus mineral, and a fraction of the melt was not lost after pyroxene began to crystallize. In contrast, similar agreement is completely lacking in other shergottites, with the possible exception of lithology B in EET 79001. Consequently, the bulk composition of QUE 94201 represents a bulk melt rather than a cumulate fraction.

Petrogenesis

Typically, basaltic and lherzolitic shergottites contain cumulus olivine and/or pyroxene. Estimated abundances of cumulus phases range from 14 to 63% (Stolper and McSween 1979; McCoy et al. 1992). In contrast, no evidence exists of any xenocrysts or cumulus crystals in QUE 94201. Indeed, the mineral assemblage, mineral compositions, textures, and bulk composition of QUE 94201 indicate that it fractionally crystallized in a closed system.

QUE 94201 contains numerous melt inclusions and abundant interstitial melt pockets, suggesting that most interstitial melt was trapped in the rock rather than being removed during the crystallization process. Likewise, and in contrast to other shergottites, the rock contains an unusually large amount of accessory minerals, again suggesting that lower temperature melt fractions were not separated from the higher temperature crystallization products.
not appear to be an early crystallizing principal phase in QUE 94201. (The meteorite contains traces of fayalite, Fa$_{97-99.7}$, but this olivine was produced from the last vestiges of melt and is not relevant to the projected phase composition.) Consequently, while the phase diagram suggests that the rock contains olivine, it does not.

Several ways to resolve this conundrum are available. The chemical composition of QUE 94201 used in the projection could be in error. If the rock contained several more wt% of SiO$_2$, the composition would not plot in the olivine stability field. The data seem robust, however, having been replicated with multiple splits in the same laboratory and in different laboratories.

The conundrum can also be resolved if the meteorite is not representative of its parent lithology. While QUE 94201 appears to be in chemical equilibrium with olivine, it may have been physically separated from olivine. One should remember that QUE 94201 is a very tiny sample for a medium-grained rock, weighing only 12 g. Conceivably, QUE 94201 is not representative of the outcrop or near surface lithology from which it was excavated from Mars. In particular, it could potentially be the matrix of a porphyritic olivine basalt rather than a representative bulk sample of the basalt. This would account for olivine appearing to be part of the residuum in the phase space topology but not actually part of the meteorite. While other shergottites are plagued with too many crystals (xenocrysts and cumulate phases), QUE 94201 may be plagued with having too few (the missing olivine). Unfortunately, if this was the case, it would mean QUE 94201 is not representative of a true bulk melt, nor can a true bulk melt be calculated easily because the proportion of olivine in the bulk basalt from which it came is unknown. Furthermore, if olivine was physically separated from QUE 94201, the meteorite’s bulk composition will not lie on an equilibrium
liquid line of descent. Rather, it will lie on an open system crystal fractionation line that is controlled by the loss of olivine. Calling upon missing (invisible) olivine, however, is ad hoc and not a very satisfactory solution.

A third solution is implied by the work of Kushiro (1975) and Toplis et al. (1994). Kushiro (1975) examined the shift of the forsterite-enstatite cotectic in a dominantly MgO-SiO₂ system as other components were added. He found that P₂O₅ in the system causes a far greater shift in the cotectic than K₂O, Na₂O, TiO₂, CaO, FeO, Fe₂O₃, and Al₂O₃. Toplis et al. (1994) further explored this effect using basalt compositions and varying the amount of P₂O₅ and the oxygen fugacity of the system. They found that the addition of phosphorous to basaltic melts causes the disappearance of olivine at low oxygen fugacities. In the case of terrestrial basalt compositions, olivine would no longer be on the liquidus if the system had 2.5 wt% P₂O₅ and the oxygen fugacity was 2 log units below the quartz-fayalite-magnetite (QFM) buffer. The pseudoquaternary projection system represented in Fig. 7 takes into account variable melt compositions (including variable P₂O₅) and oxygen fugacities but, perhaps, not to the extreme values represented by QUE 94201. As noted above, abundant P₂O₅ exists in QUE 94201, which measurements indicate is between 2 and 3 wt%. Also, very little Fe₃⁺ exists in ilmenite (Ilm 98–QUE 94201, which measurements indicate is between 2 and

Experimental work by G. McKay (2002, personal communication) on a synthetic QUE 94201 composition at an oxygen fugacity 1 log unit above the IW buffer (~2.5 log units below the QFM buffer) suggests that this is the case because no olivine was seen in the crystallization sequence; only pyroxene and plagioclase were seen.

This implies that liquidus phase diagrams used to determine liquid lines of descent among relatively P-poor terrestrial basalts cannot be used for some types of martian basalt systems, including the system represented by QUE 94201. New liquidus equilibria will need to be generated for the high-phosphorus and low-oxygen fugacity conditions represented by QUE 94201 before the petrogenesis of this and related melts can be investigated fully.

Cosmic Ray Exposure

Two notable effects occur in our noble gas data (Tables 4–6) that we wish to point out. Both have been reported before, but they were used to reach contradictory conclusions.

First, the ²¹Ne/²²Ne ratio of 0.753 ± 0.020 is remarkably low among meteorites in general, though not among shergottites. Such a low ²¹Ne/²²Ne ratio can only be achieved by spallation from GCR under very low shielding conditions, from low-energy SCR, or from a very low-Mg target chemistry. Since SCR effects are confined to the outer few cm of a rock, both of the first 2 explanations require that many shergottites, including QUE 94201, were within a few cm of the surface of their parent objects in space and suffered very little ablation loss (Garrison and Bogard 1998; Garrison et al. 1995). Measurements of variations in cosmic ray production with depth or of very high ²⁶Al have apparently confirmed this for ALH 77005, Shergotty, and EET 79001 (Garrison et al. 1995). Nishiizumi et al. (1986a, b), but our cosmogenic radionuclide measurements of QUE 94201 show no variation with depth.

Our heavy noble gas data, on the other hand, show significant excesses at ⁸⁰Kr and ²¹²⁸Xe, which are all isotopes that can be produced by neutron capture. Based on ⁸⁰Kr excesses in QUE 94201 and several other martian meteorites, Eugster et al. (2002) suggested that these meteorites were all exposed near the center of parent objects >22 cm in radius, since such large objects are required to build up enough neutrons from the cosmic ray bombardment.

In several cases, including QUE 94201, both low ²¹Ne/²²Ne and excess ⁸⁰Kr have been reported. Clearly, QUE 94201 cannot have been both at the surface and deep within the interior of its parent object, since the total recovered mass is a single 12 g stone. The fact that both of these effects have been reported by more than 1 laboratory makes the contradiction unlikely to be a measurement artifact. One way out of the dilemma would be if many of the shergottites, including QUE 94201, had been exposed near the surface of Mars at a depth sufficient to generate neutron capture products and then were ejected from Mars and exposed in space as small objects. However, measurements reported here and elsewhere (Schnabel et al. 2001) are all consistent with a single stage exposure for QUE 94201.

Garrison et al. (1995) suggested that shergottites might have been exposed to higher ratios of SCR to GCR than virtually any other meteorites (including the other martian meteorites) because their parent objects during the Earth-
Mars transit either see higher SCR fluxes or have lower entry velocities (hence lower ablation rates), or both. Either effect would be the result of the meteoroid orbit (staying closer to the sun in the first case or having a lower Earth encounter velocity in the second). We now know that both of these effects would be expected of the shergottites, even compared to other martian meteorites (which do not have low $^{21}\text{Ne}/^{22}\text{Ne}$ ratios), because of their orbital histories (Gladman 1996; Gladman et al. 1996). Shergottites have shorter exposure ages than other martian meteorites, and the early-arriving martian meteorites in numerical simulations tend to have orbits with smaller semi-major axes (staying closer to the sun) and lower Earth encounter velocities than either later martian meteorites in the simulations or the ordinary chondrites with well-determined orbits. However, even at the lowest encounter velocities, ablation models predict the loss of ~40% of a 22 cm radius meteorite (ReVelle 1979), which would be 3.5 cm, leaving very little, if any, material showing SCR effects.

The solution, at least for QUE 94201, appears to lie in its chemical composition, which is unusually Mg-poor for a meteorite and is even on the Mg-poor end of the Mg-poor shergottites. Sodium, Mg, Al, and Si are major target elements for the production of cosmogenic Ne isotopes. Among them, only Mg produces a $^{21}\text{Ne}/^{22}\text{Ne}$ ratio higher than 0.9 for normal shielding conditions because of the production reaction $^{24}\text{Mg}(n, \alpha)^{21}\text{Ne}$ (e.g., Hohenberg et al. 1978). The reaction is more effective at deeper shielding conditions due to the build up of low-energy secondary neutrons. The production rate ratios of $^{21}\text{Ne}/^{22}\text{Ne}$ in ordinary chondrites are ~0.87–0.94 (Masarik et al. 2001; Leya et al. 2001). The low Mg concentration in QUE 94201 (3–4%) compared to L chondrites (~15%) contributes to lower $^{21}\text{Ne}/^{22}\text{Ne}$ ratios than L chondrites at the same shielding condition. In addition to this effect, higher concentrations of Na and Al in QUE 94201 (Chemical Composition section) also contribute to a lower $^{21}\text{Ne}/^{22}\text{Ne}$ ratio. Furthermore, in contrast with ordinary chondrites, the $^{21}\text{Ne}/^{22}\text{Ne}$ ratios decrease with increasing shielding depth due to the lower Mg and higher Na and Al in QUE 94201. This effect is consistent with higher neutron fluence observed in the meteorite. (Since Mg is usually the principal target element for Ne, and Mg produces a $^{21}\text{Ne}/^{22}\text{Ne}$ ratio of 0.8 or higher for any shielding depth greater than 0.3 cm, extremely low shielding would be required to generate low $^{21}\text{Ne}/^{22}\text{Ne}$ ratios from a Mg-rich sample.) Although Garrison et al. (1995) considered the possibility of compositional effects, they concluded that this was an insufficient explanation for their data. For ALH 77005, which is rather Mg-rich, and for which they measured Ne isotopic variations with depth that would be predicted for SCR effects, they are almost certainly correct. However, we do not see the expected SCR variations in $^{26}\text{Al}$ with depth. Hence, this is likely a case of 2 fundamentally different effects producing the same result in Ne isotopic composition for ALH 77005 and QUE 94201. Other shergottites need to be considered on a case-by-case basis—a real contradiction remains for Shergotty, which appears to have both high, presumably SCR-derived, $^{26}\text{Al}$ (Nishizumi et al. 1986b) and neutron-capture $^{80}\text{Kr}$ (Eugster et al. 2002).

**CONCLUSIONS**

QUE 94201 represents the first bulk melt sample from a volcanic region of Mars. This basalt has much greater Fe and P than terrestrial basalts and is also relatively depleted in Al. The high abundance of phosphorus, in addition to crystallization at a very low oxygen fugacity, has also produced a distinctly different set of equilibrium phases. Olivine does not appear to be on the QUE 94201 liquidus but, rather, has been replaced by pyroxene and plagioclase. Experiments with similar high phosphorus compositions and low oxygen fugacity conditions are needed to produce liquidus diagrams that can be used to infer the petrogenesis of this and other martian melts.

Solar cosmic ray effects in several of the shergottites (ALH 77005, Shergotty, EET 79001) are interpreted to have been launched from within a few cm of their parent bodies in space and to have suffered very little ablation during entry, either because of a lower entry velocity or a lower entry angle compared to ordinary chondrites. In the case of QUE 94201, however, the lack of solar cosmic ray effects among $^{10}\text{Be}$, $^{26}\text{Al}$, and $^{36}\text{Cl}$ imply at least 3 cm of ablation during entry to Earth. In addition, significant excesses of neutron capture noble gas isotopes ($^{80},^{82}\text{Kr}$ and $^{128},^{131}\text{Xe}$) suggest that the QUE 94201 sample came from a depth $>22$ cm in a meteoroid of at least that radius. This conclusion at first seems to be contradicted by a very low $^{21}\text{Ne}/^{22}\text{Ne}$ ratio, but in this case appears to reflect a very low abundance of Mg (the principal target element for Ne) in the meteorite.

The meteorite came from a region that had magmatic, if not volcanic, activity as recently as ~330 Myr (Borg et al. 1997). Combined $^{36}\text{Cl}$ and $^{10}\text{Be}$ analyses suggest the meteorite was ejected from Mars at 2.9 ± 0.5 Myr, at which time it seems to have been affected by shock pressures in excess of 25 GPa. The meteorite collided with the Earth 2.6 ± 0.5 Myr later, falling to Antarctica at 0.29 ± 0.05 Myr.

**Acknowledgments—**We thank the 1994 ANSMET field team for collecting QUE 94201. We also thank the Meteorite Working Group and NASA's Antarctic meteorite curatorial facility at the Johnson Space Center for distributing samples, and we recognize the support NSF and the Smithsonian Institution provides the Antarctic meteorite recovery program. John Longhi very kindly helped us resolve issues involving the projection of the QUE 94201 composition onto liquidus diagrams. We thank Gordon McKay and others very much for their comments during a discussion of liquidus equilibria for QUE 94201 compositions at a workshop at the
REFERENCES


