KREEP FISSION TRACK AGES FROM HADLEY DELTA

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The main purpose of the study reported here was to search further for KREEP fragments displaying large fission track excesses, fragments such as those collected at Hadley Delta Station 6 (1). The significance of large track excesses is 1) the great ages they imply, and 2) the new knowledge they impart about $^{244}$Pu in the early Solar System. Lunar soil 15433.1 was examined for this purpose. The second purpose of this study was to relate fission track chronology to $^{40}$Ar-$^{39}$Ar and $^{87}$Rb-$^{87}$Sr chronologies through the study of sample 15382.14 (2,3).

The identification of KREEP fragments having large track excesses implies that some or all of the KREEP was formed at 4.2-4.3 Gy or earlier, and that the age of some fraction of the KREEP was later reset by events surrounding the Imbrium impact or still later by mare volcanism. The results reported here suggest that some KREEP bodies were heated sufficiently to anneal fission tracks in plagioclase as late as 3.2 Gy.

Experimental methods closely followed the bordering phase method reported in (1). The advantage of the bordering phase method is that one examines the fission tracks in a neighboring phase which contains no fissioning material rather than examining the actinide-bearing phase itself. The bordering mineral examined in this study was plagioclase. Plagioclase, containing no radioactive material, is not metamict; well defined tracks were easily etched when polished interior surfaces of soil fragments were boiled in 6N NaOH for 6 hr. Track density gradients were observed at plagioclase borders by means of a scanning electron microscope. Borders displaying track gradients were opposite phases containing $U$, usually a phosphate phase. In one case (911-9) the bordering surface itself was examined rather than the gradient edge. Gradients were extrapolated to the border by means of an analytical model to determine the correct border track density, which is the quantity required for age calculations. Prior to the plagioclase etching, the $U$ concentration of the actinide-rich phases were determined by fission track activation using muscovite detectors, $U$-glass standards, and reactor thermal neutrons. The greatest challenge presented by these samples was the extremely minute scale of the areas containing significant track information, typically 10 to 30 $\mu$m. The small areas yielded fewer tracks, and therefore greater uncertainties in the ages.

The results are presented in Table I. Sub-sample numbers represent different soil fragments in the case of 15433.1, whereas both fragments of 15382.14 are from the parent rock. The Greek letter $\rho$ represents track density in units of $10^6$ tracks cm$^{-2}$. The subscripts of $\rho$ are I, reactor induced fission of $^{235}U$; $n$, lunar thermal-neutron induced fission of $^{235}U$; CR-Th, cosmic-ray induced fission of $^{232}$Th; CR-U, cosmic-ray induced fission of $U$; CR-Fe, iron-group cosmic-rays; $\sum \rho_n$, sum of induced fission; $o$, observed density; and $s$, spontaneous density. $U$ is $\mu$g/g uranium; $R$ is the ratio $\rho/\rho_i$; and $T$ is the calculated age in Gy. The cosmic-ray induced track densities were first computed on the basis of reported exposure ages to cosmic-rays and lunar thermal neutrons (2,4). However, the sum of these induced densities was greater than the observed border densities, making the assumption of such great exposures implausible. It was noted that the iron-group cosmic-ray...
track density in one fragment of soil 15433,1, viz. (971-3b), was 1.1x10<sup>6</sup> cm<sup>-2</sup>, which is very much lower than the CR-Fe density of 7x10<sup>8</sup> cm<sup>-2</sup> observed in fragment 15272,33 from Station 6 (1). This ratio of 1/700 was applied to the exposure ages for cosmic-ray protons and thermal neutrons to arrive at the values for induced fission in Table I. The application of this ratio may be justified, however tenuously, on the basis that the Spur Crater event excavated these fragments approximately 1 My ago. The ages reported in the last column, T, reflect this assumed exposure age and are therefore upper limits to the track retention ages.

The average track retention age of 15382,14 is 3.2±0.3 Gy, significantly lower than the 40Ar-39Ar release and 87Rb-87Sr ages reported elsewhere for this and other Spur Crater samples (2,3,5). This lower age for track retention may represent an episode of complete track erasure at about 3.2 Gy, which corresponds to the ages of some mare basalts collected near Hadley Rille. Temperatures exceeding 500 to 530°C are required to anneal fission tracks in bytownite in geologically significant times, 1 to 100 My. Alternatively, a later and lower temperature event may have shortened the tracks, resulting in lower track densities and lower calculated ages. This seems less likely than complete erasure at 3.2 Gy, since temperatures would have to be maintained in the interval 470 to 500°C for 10 My. Fragments from soil 15433,1 have track retention ages ranging from 3.2 to 4.0 Gy.

The fragments collected at Stations 6 and 7 originated in solid rock sources stretching from the base of Hadley Delta to its 3.5 km top. Variations in age and geological history are not unlikely considering such a vertical span. Rock units near the base may have been heated to 500°C during episodes of mare volcanism, while those units higher up the mountain were spared the thermal exposure. One fragment reported here has a track retention age of 4.0 Gy (932-4) and appears to have been spared the thermal excursion at 3.2 Gy. The fact that the track retention age of 15382,14 is measurably lower than the Ar-retention and Rb-Sr ages (2,3,5) points with all the more emphasis to the importance of the very high track retention age, 4.3 Gy, reported for KREEP fragment 15272,33 (1).

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<table>
<thead>
<tr>
<th>Sample</th>
<th>( R_{(a)} )</th>
<th>( U_{(b)} )</th>
<th>( \rho_{n} )</th>
<th>( \rho_{e-Tm} )</th>
<th>( \rho_{e-Pu} )</th>
<th>( \rho_{e-Pe} )</th>
<th>( R_{(c)} )</th>
<th>( T_{(d)} )</th>
</tr>
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<tbody>
<tr>
<td>15382,14</td>
<td>56±6</td>
<td>739</td>
<td>0.8</td>
<td>0.7</td>
<td>0.1</td>
<td>1.1</td>
<td>58.9</td>
<td>650±30</td>
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<td>(X5-2b)</td>
<td>59±6</td>
<td>383</td>
<td>0.4</td>
<td>0.3</td>
<td>0.1</td>
<td>1.1</td>
<td>30.8</td>
<td>384±30</td>
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<td>15433,1</td>
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<td>265</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
<td>1.1</td>
<td>21.7</td>
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<td>(911-9)</td>
<td>32±8</td>
<td>422</td>
<td>0.5</td>
<td>0.4</td>
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<td>1.1</td>
<td>34.0</td>
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<td>(971-3b)</td>
<td>6.8±2.0</td>
<td>90</td>
<td>0.1</td>
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<td>0.0</td>
<td>0.0</td>
<td>8.0</td>
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<td>(932-4)</td>
<td>2.4±1.8</td>
<td>90</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>4.0</td>
<td>40±18</td>
</tr>
</tbody>
</table>

(a) Track densities, \( \rho \), in units of \( 10^6 \) tracks \( \text{cm}^{-2} \).
(b) \( U \) in \( \text{g/g} \).
(c) \( R = \frac{(\rho_{e} - \rho_{n})}{\rho} \)
(d) \( T = \frac{T_{\text{exp}}}{T_{\text{rad}} + 1} \) in Gy, where \( c=0.05611 \) is a constant of the experiment, and \( T=1/\lambda_{3} \);
corrected for the presence of \( ^{244}\text{Pu} \) (assuming \( \text{Pu}/U \) \( (4.6 \text{ Gy}) = 0.02 \) when \( R>13 \).

REFERENCES: