SIMILARITIES IN THE IGNEOUS DEVELOPMENT OF THE FELDSPATHIC CRUST OF EARTH AND MOON. Jeffrey L. Warner, NASA Johnson Space Center, Houston, TX 77058

Much attention has been directed to the differences between the feldspathic crusts of Earth and Moon. The lack of water, depletion in alkalies, and enrichment in refractories on Moon relative to Earth have been attributed to differences in the bulk chemical compositions of the two planets. The anhydrous and less evolved nature of Moon's crust relative to Earth's is cited to account for the lower abundance of Si in Moon's crust. It is an important observation that although the feldspathic crusts of the two planets are quite different in bulk composition and extent of fractionation, there are similarities in their igneous histories. Specifically, it has been established that each planet's crust has developed in an episodic manner, that each episode is represented by a pulse of igneous activity with a distinctive chemical composition, and that a directed sequence is defined by the various pulses. It is a curious and unexplained fact that although the lunar and terrestrial sequences of igneous compositions are different, the main pulse of potassium enrichment occurs late (is delayed) in each planet's development.

There are five major pulses of igneous crustal development on the Moon as outlined in Table 1. Most of the sequence is documented by isotopic dating (reviewed by Nyquist(1)). James(2) has established the temporal sequence between anorthosites and norites and troctolites based on geologic and petrologic data and arguments. Typical $\text{Al}_2\text{O}_3$ contents of each pulse are set out in the Table to illustrate that the pulses define a directed or progressive sequence in aluminum. $\text{K}_2\text{O}$ contents in wt.% are typically less than 0.03 for the anorthosite, norite, and troctolites, less than 0.1 for the Fe and Ti-rich mare basalts and the Fe-rich mare basalts, and over 0.5 for the Al-rich KREEP basalts. Potassium, rather than being progressive in a manner similar to aluminum, is sharply peaked in the mid portion of the sequence.

There is a well-known chemical distinction between the Archean and Proterozoic feldspathic crusts of Earth. For example, the Proterozoic is enriched relative to the Archean in $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio, $\text{TiO}_2$, $\text{La}/\text{Yb}$ ratio, $\text{LREE}/\text{HREE}$ ratio, and total REE(3,4). In addition, there does not appear to be a Eu anomaly in Archean rocks, but one is observed in Proterozoic rocks(4). Less well-known is that within the complexities of Archean shields there occurs a sequence of feldspathic, plutonic rock types. This sequence is chemically similar on each Archean shield, but the timing is different(5). The sequence typical of terrestrial Archean shield regions is illustrated in Figure 1. The earliest phase of feldspathic plutonic igneous activity is characteristically tonalite-trondhjemite. Differentiated granite-granodiorite is restricted to secondary and later phases of feldspathic plutonism. This sequence defines a trend from Na-rich, K- and REE-poor early Archean plutons to K- and REE-bearing plutons by the close of the Archean. Differences among the various Archean blocks on Earth are attributed to differences in underlying mantle(5). For example, the tonalite-trondhjemite terrain is dominated by tonalite in Southern Africa and the Superior province versus trondhjemite in Western Australia and the Western Greenland-Labrador regions. The first appearance of differentiated granite-granodiorite ranges from 3300 m.y. in the Swaziland craton of Southern Africa to 2600 m.y. in the Yilgarn block of Western Australia. Note that as in the formation of the lunar crust, potassium is delayed in the history of Earth's crustal development.

The spectrum of rock compositions in the lunar sequence is simple - each pulse is compositionally distinct from every other pulse(6). In contrast, for the terrestrial case the entire spectrum of rock compositions occurs in each pulse of the sequence. Pulses are defined in a statistical manner based on the
abundances of different rock compositions.

KREEP, the potassium-bearing Moon rock, is derived directly from a source in the lunar mantle that formed as a result of the primary lunar differentiation(7). The source in the mantle was KREEP-enriched (called urKREEP) and probably represents residual liquid from a lunar magma ocean(8). KREEP basalts introduced into the lunar crust at about 4000 m.y. were derived from urKREEP by partial melting. But why was KREEP retained in the mantle for so long? Thermal models show that it is barely possible to derive a KREEP partial melt from an urKREEP source as late as 3900 m.y.(9). But the thermal models suggest that KREEP should have been produced much earlier than it is observed: various models show urKREEP molten until 4300 or 4400 m.y. and 4100 m.y.(10). Did urKREEP residual liquid really have to crystallize before it could be remelted and introduced into the crust? Or is the current understanding of the origin of KREEP inadequate?

Granite-granodiorite, the potassium-bearing Earth rocks are derived by partial melting of tonalite-trondhjemite source regions in the lower crust(11). The tonalite-trondhjemite rocks are in turn the product of an assimilation or mixing process between basaltic magma and preexisting continental crust(11). Granites and granodiorites are 3-stage rocks in that they are derived from the mantle by a three step process: step one is partial melting of mantle to yield basaltic magma, step two is an interaction between the basaltic magma and continental crust to yield tonalite-trondhjemite (or andesite), and step three is partial melting of the step two to yield granite-granodiorite. It has been generally assumed that the enriched potassium in granite-granodiorite is a direct result of their three-stage derivation. In each stage potassium is preferentially concentrated in the melt, and total potassium is successively built-up by progressive enrichment.

The problem with the above terrestrial explanation for the delay of introduction of potassium into the continental crust is that the process took too long. Reference to Figure 1 shows that up to 850 m.y. elapsed between the oldest known tonalite-trondhjemite terrain and the oldest granite-granodiorite terrain in different shield regions. In the regime of modern tectonics, complete crustal cycling is accomplished in less than 100 m.y. Calculations of radioactive heat production indicate that in the Archean 2 to 4 times the energy was available for crustal processing, suggesting that crystal cycling should have been considerably faster in the Archean than it is under modern tectonics. So why is it that Archean crustal cycling was in fact slower?

The "standard" explanations to account for the temporal distribution of potassium rocks in the feldspathic crusts of Earth and Moon use characteristics that are unique to each planet. Perhaps the delay in potassium enhancement has a more fundamental cause than the processes outlined above, i.e., a single explanation that is applicable for both Earth and Moon. A potassium reservoir that was established within the planets very early in their history might have held potassium during the early stages of their crustal development. At some advanced stage the potassium reservoir might have been tapped by a major change in global tectonics. A potential reservoir that could hold potassium is a metallic core (as has been suggested on geochemical arguments by (12,13). This would be an addition indication that a metal core exists on the Moon. Several global thermo-mechanical phenomena may be responsible for the release of potassium from the core. One possibility is a change in the order of convection (i.e., change from a single convection system to multiple convection systems) within the core. This is similar to Runcorn's(14) suggestion that episodes of continental growth on Earth (at 2500 m.y., 1700 m.y., etc.) are triggered by a change in the order of mantle convection. Further examination of this and other possible mechanisms is warranted.
References:

### Table 1.

<table>
<thead>
<tr>
<th>AGE</th>
<th>ROCK TYPE</th>
<th>TYPICAL $\text{Al}_2\text{O}_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.55 b.y.</td>
<td>ANORTHOSTE</td>
<td>36 wt. %</td>
</tr>
<tr>
<td>4.55 b.y.</td>
<td>NORITNE &amp; TROCTOLITE</td>
<td>24 wt. %</td>
</tr>
<tr>
<td>4.0 b.y.</td>
<td>A1 RICH BASALT (KREEP)</td>
<td>17 wt. %</td>
</tr>
<tr>
<td>3.8 b.y.</td>
<td>Fe &amp; Ti RICH BASALT</td>
<td>10 wt. %</td>
</tr>
<tr>
<td>3.2 b.y.</td>
<td>Fe RICH BASALT</td>
<td>9 wt. %</td>
</tr>
</tbody>
</table>

### Figure 1.

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