floor, and as the scarp cuts the valley wall of North Massif, its trend cuts sharply to the west. The slope of North Massif approaches 20°, therefore if the scarp is the expression of a westwardly dipping reverse fault, the dip must exceed 20°. The problem, however, is that the morphology of wrinkle ridge systems is highly variable and permits a spectrum of tectonic styles to be involved. Within Serenitatis alone, there are complex systems of ridges (Fig. 1), some of which have distinct vertical offsets, while others do not (Fig. 2). Two models have been proposed to account for the vertical offsets: thrust faulting [25] and nearly vertical faulting [24]. There does not appear to be any correspondence between the vertical offset across a ridge element and its topographic relief. Furthermore, apparent offsets across some ridges are produced because the ridge is developed on a sloping mare surface; when the regional trend is removed, so is the offset in several cases. This suggests that wrinkle ridges include a variety of compressional tectonic structures, perhaps ranging from simple thrust faults to nearly vertical reverse faults to complex zones of buckling [22]. There does not, however, appear to be any indication of substantial overthrusting.

Nature and Timing of Tectonic Rille Formation: Concentrically oriented tectonic rilles deform the flanks of many of the large mare basins including Serenitatis. These structures have been attributed to the extensional deformation associated with mascon loading [1]. Golombek [25] proposed that these graben were produced through simple extension, that the bounding faults intersected at a depth of a few kilometers, and that the faulted layer corresponded to the "megaregolith." In that analysis, graben formation due to bending was dismissed because under the assumed conditions, the mare surface would slope away from the graben by up to 10°. However, Golombek apparently did not consider the effects of increasing the thickness of the faulted layer. Figure 3 shows the surface slope that would result from layer bending to produce the size of lunar rilles observed (50–150 m deep, 2–4 km wide; [25]). If the depth to the neutral surface were half the thickness of the elastic lithosphere (~100 km; [1]), then the slopes induced by bending would be ≤1°, in excellent agreement with measurements of the slopes on mare surfaces containing linear rilles [4]. This analysis indicates that graben around lunar basins can be accounted for solely by bending of the elastic lithosphere.

The stratigraphic relationships between tectonic rilles and the major volcanic units exposed in mare basins provide clues to the timing of basin deformation. It has long been recognized that rille formation ended prior to 3.4 Ga [26]. In addition, assessment of southeastern Serenitatis shows that the oldest volcanic unit (unit I; Plenius basalts equivalent; [3]) was emplaced prior to the onset of rille deformation. There are no cases where unit I clearly floods or embays any rilles nor is there any indication that rilles are truncated at the boundary between this unit and the highlands. In constrast, rilles that intersect the younger unit II surface are consistently truncated and embayed by these lavas. Elongate collapse features, indicative of buried rilles, are observed on unit II in the southeastern portion of the basin, but no such features are evident on exposed unit I surfaces. Consequently, it seems that rille formation in southeastern Serenitatis began after unit I emplacement and culminated before unit II.

Samples returned from Apollo 17 indicate that the unit I basalts were deposited over a range of ~150 Ma from ~3.84 Ga to ~3.69 [27]. Thus the post-unit-I onset of rille formation appears to signal a relatively slow response of the lithosphere to the increasing volcanic load in the Serenitatis Basin. The most likely explanation for this involves the isostatic state of the Serenitatis Basin during early mare emplacement. It is conceivable that appreciable quantities of the early volcanics would be required to offset the mass deficiency created during the impact basin formation. If this is the case, volcanic infilling of the southern portion of Mare Serenitatis did not reach superisostatic levels until the majority of unit I was emplaced.

References: [1] Solomon S. C. and Head J. W. (1979) *JGR, 84,* 1667–1682. [2] Bratt S. R. et al. (1985) *JGR, 90,* 3049–3064. [3] Howard K. A. et al. (1973) In *Apollo 17 Preliminary Science Report,* NASA SP-330, 29-1 to 29-35. [4] Sharpton V. L. and Head J. W. (1982) *JGR, 87,* 10983–10998. [5] Phillips R. J. et al. (1973) *Proc. LSC 4th,* 2821–2831. [6] Peeples W. J. et al. (1978) *JGR, 83,* 3459–3470. [7] Cooper M. R. et al. (1974) *Rev. Geophys. Space Phys., 12,* 291–308. [8] Lucchitta B. K. (1972) *U.S. Geol. Surv. Misc. Geol. Inv. Map I-800,* sheet 2. [9] Apollo Lunar Geology Investigation Team, U.S. Geological Survey (1972) *Astrogeology, 69,* 62 pp. [10] Wolfe E. W. et al. (1975) *Proc. LSC 6th,* 2463–2482. [11] Muehlberger W. R. et al. (1973) In *Apollo 17 Preliminary Science Report,* NASA SP-330, 6-1 to 6-91. [12] Wilhelms D. E. (1987) *U.S. Geol. Surv. Prof. Paper 1348,* 302 pp. [13] Head J. W. (1976) *Moon, 15,* 445–462. [14] Bailey N. G. and Ulrich G. E. (1975) *Apollo 17 Voice Transcript Pertaining to the Geology of the Landing Site,* USGS-GD-74-031, 361 pp. [15] Schmitt H. H. and Cernan E. A. (1973) In *Apollo 17 Preliminary Science Report,* NASA SP-330, 5-1 to 5-21. [16] Strom R. G. (1972) *Moon,* 187–215. [17] Young R. A. et al. (1973) In *Apollo 17 Preliminary Science Report,* NASA SP-330, 31-1 to 31-11. [18] Hodges C. A. (1973) In *Apollo 17 Preliminary Science Report,* NASA SP-330, 31-12 to 31-21. [19] Howard K. A. and Muehlberger W. R. (1973) In *Apollo 17 Preliminary Science Report,* NASA SP-330, 31-22 to 31-25. [20] Scott D. H. (1973) In *Apollo 17 Preliminary Science Report,* NASA SP-330, 31-25 to 31-29. [21] Bryan W. B. (1973) *Proc. LSC 4th,* 93–106. [22] Sharpton V. L. and Head J. W. (1987) *Proc. LPSC 18th,* 307–317. [23] Tjia H. D. (1970) *Geol. Soc. Am. Bull., 81,* 3095–3100. [24] Lucchitta B. K. (1976) *Proc. LSC 6th,* 2761–2782. [25] Plescia J. B. and Golombek M. P. (1986) *Geol. Soc. Am. Bull, 97,* 1289–1299. [25] Golombek M. P. (1979) *JGR, 84,* 4657–4666. [26] Lucchitta B. K. and Watkins J. A. (1978) *Proc. LPSC 9th,* 3459–3472. [27] Basaltic Volcanism Study Group (1981) *Basaltic Volcanism on the Terrestrial Planets,* Pergamon, 1286 pp.

N93-18812 3/6 p. 3

MELTING OF COGENETIC DEPLETED AND ENRICHED RESERVOIRS AND THE PRODUCTION OF HIGH-Ti MARE BASALTS.

Gregory A. Snyder[1], Lawrence A. Taylor[1], and Alex N. Halliday[2], [1]Department of Geological Sciences, University of Tennessee, Knoxville TN 37996, USA, [2]Department of Geological Sciences, University of Michigan, Ann Arbor MI 48109, USA.

Implicit in current understanding of the location of terrestrial enriched and depleted reservoirs is the notion that they are spatially separated. The depleted reservoir on Earth is situated in the upper mantle, and the complementary enriched reservoir is located in the crust. However, Earth reservoirs are continually being modified by recycling driven by mantle convection. The Moon is demonstrably different from Earth in that its evolution was arrested relatively early—effectively within 1.5 Ga of its formation [1]. It is possible that crystallized trapped liquids (from the late stages of a magma ocean) have been preserved as LILE-enriched portions of the lunar mantle. This would lead to depleted (cumulate) and enriched (magma ocean residual liquid) reservoirs in the lunar upper mantle. There is no evidence for significant recycling from the highland crust back into the mantle. Therefore, reservoirs created at the Moon's inception may have remained intact for over 4.0 Ga.

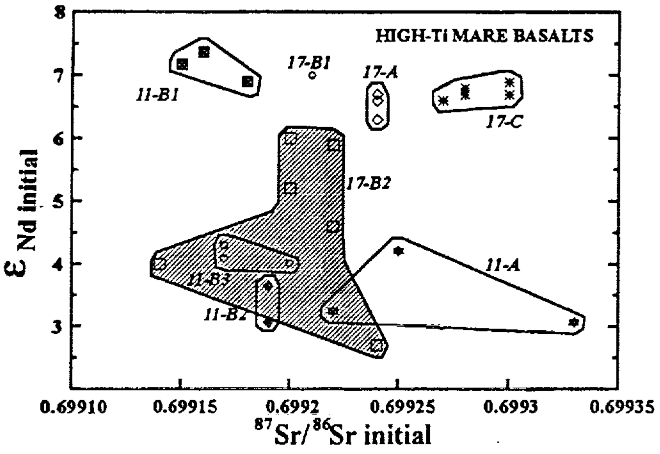

Fig. 1.

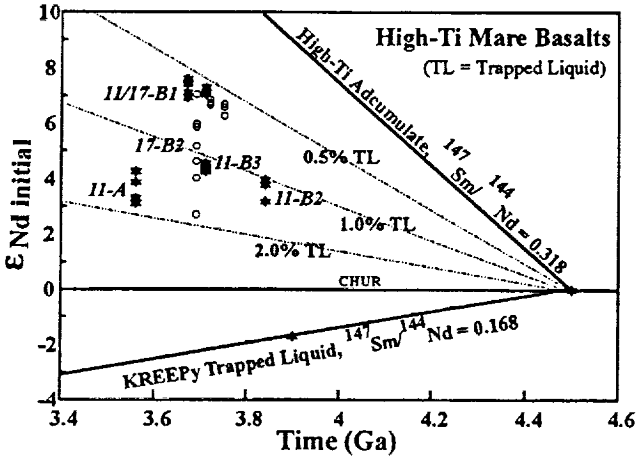

Fig. 3.

Radiogenic Isotopes in High-Ti Mare Basalts: Evidence of Heterogeneity? Data from all high-Ti basalts (Apollo 11 and Apollo 17 landing sites, as well as intermediate-Ti ilmenite basalts from Apollo 12) display a broad scatter in initial Nd and Sr isotopic composition as shown in Fig. 1 [2–5]. Basalts from Apollo 11 generally plot with less radiogenic Nd compared with those from Apollo 17. Although Apollo 11 group B1 basalts have ε_{Nd} values that are similar to Apollo 17 A, B1, and C basalts, these groups are distinct in Sr isotopic composition. These variations in initial Nd and Sr isotopic compositions have led previous workers to postulate that the basalts were derived from separate sources and have been used as evidence of heterogeneity in the lunar upper mantle [4]. Though this interpretation seems quite adequate, it is difficult to reconcile with the view that the lunar upper mantle was a simple system that crystallized early and has not been subject to later mixing and recycling processes. Furthermore, this interpretation, which includes myriad different sources, does not explain the homogeneity in mineralogy and major-element chemistry for these rocks.

Formation of Cogenetic Depleted and Enriched Reservoirs: It is generally believed that for less than the first 0.2 Ga of its history, the Moon differentiated into a small Fe-rich core, an olivine-rich lower mantle, and a differentiated magma ocean [6]. This outer magma ocean, or magmasphere, progressively crystallized to form the upper mantle of the Moon and, once plagioclase became a liquidus phase, its anorthositic crust. The crystallization of the magmasphere probably led to layering of the upper mantle and included phases, such as ilmenite, late in its differentiation. The residual liquid magmasphere became more evolved with time, leading to enrichment in the LILE. This LILE-enriched liquid could have been trapped in variable, yet small, proportions and effectively "metasomatized" the relatively LILE-depleted crystallizing mafic cumulate. In this way, adjacent regions or layers of the mantle could maintain mineralogic and major-element homogeneity while exhibiting heterogeneities in their trace elements.

The LILE-enriched, trapped liquid end member of the source is represented by residual liquid after 95% crystallization of the LMO (as per Snyder et al. [7]). The isotopic and trace-element composition of this KREEPy liquid component may be represented by KREEP basalt sample 15382 (Rb = 16 ppm, Sr = 195 ppm, $^{87}Sr/^{86}Sr(3.84\ Ga) = 0.70115$; Sm = 31 ppm, Nd = 112 ppm, $\varepsilon_{Nd}(3.84) = -3$; [8,9]). The cumulate portion of the source is modeled as a cpx-pigeonite-ilmenite-olivine perfect adcumulate (Rb = 0.01 ppm, Sr = 4.16 ppm,

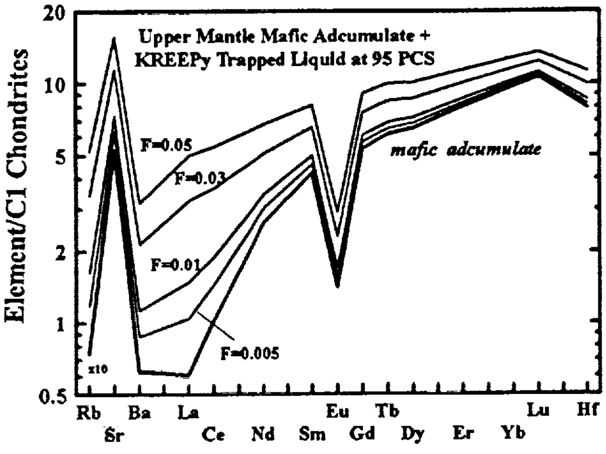

Fig. 2.

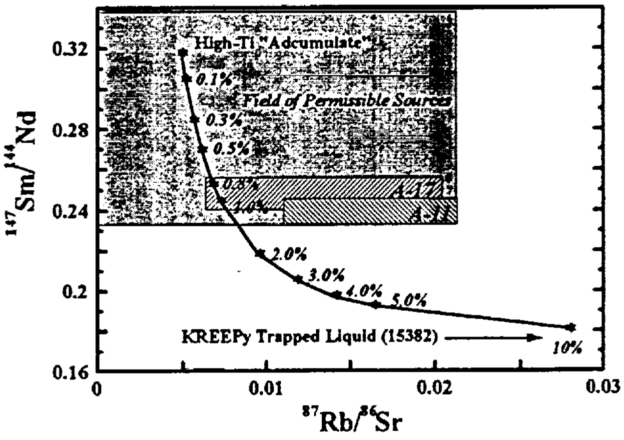

Fig. 4.

Sm = 0.631 ppm, Nd = 1.2 ppm, again as per [7]; Figs. 2 and 3) that has an extremely elevated ε_{Nd} (+8 at 3.84 Ga) and the lowest Sr initial ratio (0.69910) at 3.84 Ga. However, it is not likely that these two components remained distinct over a period of 500 Ma, when the interior of the Moon was still hot [10]. Recrystallization of the cumulate-trapped liquid pile could have occurred, yielding a source that was heterogeneous in trace elements on the scale of meters. Due to the low Sm/Nd ratio of the trapped liquid relative to the cumulate, those portions of the mantle that contained a larger proportion of this component would evolve with more enriched isotopic signatures.

Melting of the Source to Achieve High-Ti Mare Basalts: After an extended period of evolution (e.g., >0.5 Ga), earliest melting of the trapped liquid-cumulate pair would probably affect regions that were relatively enriched in the LILE (containing heat-producing elements U, Th, and K). Therefore, those regions that trapped the largest proportion of residual LMO liquid would melt first. Melts of these regions would exhibit relatively enriched isotopic signatures. Later melting would tap regions with less trapped liquid and would yield more isotopically depleted melts. Obviously, the degrees of enrichment and depletion of the melts are highly dependent upon the proportion of trapped liquid and the extent of melting of the cumulate + trapped-liquid pile. However, the trapped-liquid component is LILE-enriched (generally by at least an order of magnitude over the mafic cumulate) and would have originally consisted of low-temperature melting phases that would readily remelt. Therefore, even a small proportion (e.g., 1%) in the cumulate pile will greatly affect the isotopic signature of initial derived melts. However, because of its small proportion, the trapped liquid would have a lesser effect (inversely proportional to the degree of melting) on the major-element composition of the melt.

The low $^{147}Sm/^{144}Nd$ of this KREEPy trapped liquid, in concert with the relatively high abundances of Sm and Nd, obviates a large proportion of trapped liquid in the source (Fig. 2). This is illustrated in Fig. 2, where small proportions ($\leq 5\%$) of trapped liquid have been added to a model high-Ti adcumulate. This addition of trapped liquid has the effect of lowering the Sm/Nd ratio, yet increasing the abundances of Sm and Nd, thereby leading to a viable cumulate source region. Again, only 2–3% of trapped liquid is required in the source for modal melting, and less if the trapped liquid is an early melting component (if the source was not recrystallized).

This can be further appreciated by looking at the parent/daughter ratios of the high-Ti basalts (Fig. 4, diagonally hatched areas). Simple two-component mixing of a high-Ti "adcumulate" source with varying percentages of KREEPy trapped liquid (where sample 15382 represents the KREEPy liquid) yields a curve of chemical mixtures. The compositions of the high-Ti basalts from both Apollo 11 and Apollo 17 lie along this curve. Any source that contains residual mafic minerals, such as pigeonite, clinopyroxene, and olivine, would be more depleted (lower in $^{87}Rb/^{86}Sr$ and higher in $^{147}Sm/^{144}Nd$) than the basalts from which it was generated. Therefore, the field of permissible sources (shaded) indicates <1.5% trapped liquid. Although this trapped KREEPy liquid is minor in volume, it controls the radiogenic isotope signature of the derived melt.

Similar calculations to discern the proportion of KREEP in these basalts were performed by Hughes et al. [11] and Paces et al. [4]. Both groups concluded that small percentages (generally <1%) of a Rb-, Sr-, and REE-enriched component, with high Rb/Sr and low Sm/Nd ratios, are required to explain the compositions of parental magmas for the high-Ti basalts. However, both groups envisioned this component as distal to the cumulate source and added to the source prior to its fusion, but not cogenetic with its inception. Paces et al. [4] pointed out the problems inherent in such a scenario, but neither group explored the possibility of an ancient KREEPy reservoir that was spatially associated with the cumulate source—as trapped intercumulus liquid from the late stage of evolution of the LMO—since its inception over 4.4 Ga.

Summary: The interpretation of cogenetic depleted and enriched reservoirs in the Moon is the consequence of events unique to the Moon. First, the late-stage LREE- and Rb-enriched residual liquid from a crystallizing LMO was trapped in variable and small proportions in the depleted upper mantle cumulates. A lack of recycling in the lunar environment would allow these reservoirs to diverge along separate isotopic evolutionary paths. This portion of the mantle would remain undisturbed for ≥ 0.5 Ga, prior to being melted to form the oldest high-Ti mare basalts. The isotopic character of the melts would be controlled by the degree of melting, as the least radiogenic reservoir would be melted first, i.e., that portion of the cumulate containing the greatest proportion of trapped liquid would melt first. The range in Sr and Nd isotopic ratios seen in basalts from Mare Tranquillitatis (Apollo 11) is due to melting of a clinopyroxene-pigeonite-ilmenite-olivine cumulate layer with variable proportions of trapped intercumulus liquid. Types B2 and B3 basalts were melted from a portion of the cumulate layer with intermediate amounts of trapped KREEPy liquid. Type B1 basalts from both Apollo 11 and 17 are melted from a "near-perfect" adcumulate portion of this layer. Apollo 12 ilmenite basalts represent the final known melting of this cumulate source, after it had been nearly exhausted of its ilmenite and trapped-liquid components. Type A basalts were probably extruded from a vent or vents near the Apollo 17 landing site [12] and could, therefore, represent melting of a similar source, albeit with the added complexity of neoKREEP assimilation.

References: [1] Nyquist L. E. and Shih C.-Y. (1992) *GCA, 56,* 2213–2234. [2] Papanastassiou D. A. et al. (1977) *Proc. LSC 8th,* 1639–1672. [3] Unruh D. M. et al. (1984) *Proc. LPSC 14th,* in *JGR, 89,* B459–B477. [4] Paces J. B. et al. (1991) *GCA, 55,* 2025–2043. [5] Snyder G. A. et al. (1993) *EPSL,* submitted. [6] Agee C. B. and Longhi J., eds. (1992) *LPI Tech. Rpt. 92-03,* 79 pp. [7] Snyder G. A. et al. (1992) *GCA, 56,* in press. [8] Nyquist L. E. (1977) *Phys. Chem. Earth, 10,* 103–142. [9] Lugmair G. W. and Marti K. (1978) *EPSL, 39,* 349–357. [10] Warren P. H. et al. (1991) *JGR, 96,* 5909–5923. [11] Hughes S. S. et al. (1989) *Proc. LPSC 19th,* 175–188. [12] Jerde E. A. et al. (1992) *EPSL,* submitted.

N93-18813 7 p- 3

BASALTIC IMPACT MELTS IN THE APOLLO COLLECTIONS: HOW MANY IMPACTS AND WHICH EVENTS ARE RECORDED?

Paul D. Spudis, Lunar and Planetary Institute, Houston TX 77058, USA.

Many of the rocks in the Apollo collections from the lunar highlands are impact melt breccias of basaltic bulk composition [1–3]. They are known by a variety of names, including "low-K Fra Mauro basalt" [1], "VHA basalt" [2], and "basaltic impact melts" [3]. These rocks have been studied to understand the compositional nature of the lunar crust [1,4], to decipher the processes of large body impact [4], and to comprehend the record of impact bombardment of the Moon [5].

Study of terrestrial craters has led to a model for impact melt generation (e.g., [6]) whereby diverse target lithologies are totally, not partially, melted during impact. The impact melt makes up a few percent of the total volume of crater material; superheated silicate liquids of the impact melt have extremely low viscosities and mix intimately. This mixing thoroughly homogenizes the melt chemically during the excavation of the crater. Colder, unmelted debris is