Exploring the Moon’s surface for remnants of the lunar mantle. Dunite xenoliths in mare basalts. A crustal or mantle origin? Charles K. Shearer1, Paul V. Burger1, Aaron S. Bell1, Yunbin Guan2 and Clive R. Neal1.
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Introduction: While many terrestrial-style geologic processes (e.g. plate tectonics) are not active on the Moon to bring mantle material to the surface, there are geologic regions of the lunar surface that may provide access to samples from the mantle. The lunar mantle may have been mechanically transported to the surface during large basin-forming events [e.g. 1-6]. In addition, the close proximity of the mantle to the surface, resulting from crustal thinning due to these events, may enable xenolith transport by mare magmas that subsequently flooded these basins [7,8]. It is puzzling that with large impact basins producing a thin crust [1-4] and presumably excavating mantle [2-6,9], deep crustal mineral assemblages are rare and mantle assemblages have not been unambiguously identified in the lunar sample collection. To assess the potential presence of deep crustal and mantle material on or near the lunar surface, we are evaluating a series of possible occurrences of these assemblages in the lunar sample collection. Here, we report on the initial results from this survey: the petrogenesis of dunite xenoliths in Apollo 17 basalts. Deep crustal or mantle lithologies in the sample collection? Only a few returned lunar samples are suspected to originate from either the deep crust or upper mantle. Spinel troctolites are inferred to have crystallized at depths of 15-25 km, whereas chromite-augite-orthopyroxene smplecities in troctolites and dunites suggest crystallization depths of 45-50 km [e.g.10-12]. These estimated depths approach the base of the crust as implied by the interpretation of GRAIL data and provide fundamental evidence for the potential for mantle rocks to be transported to the lunar surface [e.g. 2,3,8]. There are several examples from other petrologic studies that identified monomineralic Mg-rich olivine or unusual pyroxenes, the origins of which remain enigmatic. Studies by [13-15] dissected Lunar 24 samples collected at Mare Crisium and identified mineralogical components that could represent the high-Mg component referred to by [2-5]. Spudis et al. [16] and Ryder et al. [17] identified individual olivine grains in impact generated poikilitic melt breccias that they speculated could be either from Mg-suite lithologies or a component of the lunar mantle. Beatty and Albee [18] reported on a pyroxenite xenolith in the Apollo 11 high-Ti basalts and suggested that the pyroxene composition reflected a very high-pressure mineral assemblage of possible mantle origin. Dunite clasts occur in Apollo 17 breccias. It was initially speculated that these dunites represent a lithology from the lunar mantle [19] but they are now considered to be Mg-suite lithologies, formed through olivine accumulation in either near-surface [20] or deep-crustal [12] environments. The 74275 high-Ti mare basalt contains dunite “xenoliths” [21-23]. The 74275 basalt was collected adjacent to gas-driven, pyroclastic deposits represented by the Apollo 17 orange volcanic glass. The origin of these dunite xenoliths is particularly fascinating in light of continued speculation that peridotitic xenoliths from mantle or mid-crustal magma chambers may be associated with basaltic magmas erupted in a variety of lunar geologic settings such as maar-style volcanoes, rims of small craters, and massifs on the rims of large craters [e.g. 7,8].

Analytical Approach: Thin sections of high-Ti mare basalt 74275(96,97), and Mg-suite dunite 72415,55 were initially examined and documented using backscattered electron imaging (BSE) on the JEOL JXA-8200 Superprobe electron microprobe (EMP) in the Institute of Meteoritics at the University of New Mexico (UNM). Wavelength Dispersive X-ray maps were collected for Cr, Ca, Mn, P and Ti, while energy dispersive (EDS) maps were collected for Mg and Fe. Maps were collected using a 15 kV accelerating voltage, a 500 nA beam current and a dwell time of 800 ms/pixel. Quantitative analyses were conducted as traverses, from core to rim of dunite xenoliths, olivine megacrysts, and olivine micro-phenocrysts using the EMP. The point analyses were collected at an accelerating voltage of 15 kV, a beam current of 20 nA, and a spot size varying from 1-3 µm. Trace elements (Al, Ti, V, Co, Ni, Y) in the olivine from the dunite xenoliths were analyzed by secondary ion mass spectrometry (SIMS) by combining data derived from the Cameca NanoSIMS-50L at California Institute of Technology with data produced on the Cameca ims 4f at UNM. Results: The dunite xenoliths are anhedral in shape and are generally greater than 800 µm in diameter. The interior of the dunitic inclusions are fairly homogeneous with regards to Mg# ((Mg/Mg+Fe) x 100), which range from 82 to 83, and then decrease to 68 over the 10-30 µm-wide outer rim (Fig. 1). Titanium and phosphorus X-ray maps of the inclusion illustrate that these slow diffusing elements preserve primary cumulate zoning textures (Fig. 1).
These textures consist of many individual olivine grains, approximately 150 to 200 µm in diameter, with low Ti, Al, and P cores. This zoning is also correlated with zoning of both compatible and incompatible trace elements (Fig. 2) in the individual olivine grains that comprise the xenoliths.

**Figure 1.** BSE image and high-beam current x-ray maps of dunite xenolith. Area outlined in BSE image is the mapped area. Note various low-Ti and P cores within individual olivine grains.

**Figure 2.** Combined EMP and SIMS analyses of a traverse shown in Figure 1.

**Discussion:** Lunar basalt 74275 contains a complex population of olivine that consists of microphenocrysts, megacrysts, and dunite xenoliths. Reconstruction of melt compositions and liquid lines of descent (LLD) indicates that the microphenocrysts and megacrysts crystallized from a single high-Ti mare basalt magma under different conditions. The dunite xenoliths do not represent deep crustal or shallow mantle lithologies. They are texturally and chemically distinct from other dunites identified from the Apollo 17 site. More likely, they represent olivine cumulates that crystallized from a low-Ti mare basalt at intermediate to shallow crustal levels. As indicated by numerous calculated chemical characteristics, the parental basalt to the dunite xenolith lithology was more primitive than the low-Ti basalts thus far returned from the Moon. In addition, this parental magma, or its more evolved daughter magmas, was not collected on the surface of the Taurus-Littrow Valley by the Apollo 17 mission. The dunite lithology was exposed to several episodes of reequilibration. During the last episode of reequilibration (represented by the rim on the xenolith), the dunite cumulate was sampled by the 74275 magma and transported over a period of 30-70 days to the lunar surface.

There are several possible reasons for the ambiguity between the sample collection and remotely sensed observations and interpretations. The simplest explanation is that the sample collections (Apollo and Luna programs, lunar meteorites) do not adequately represent terrains that contain excavated mantle [1-6, 9]. Alternatively, the upper lunar mantle is considerably different than is currently envisioned and therefore has not been recognized in the sample collection. For example, [9] suggested that the upper mantle is dominated by orthopyroxene rather than olivine. There are interpretive issues tied to the remote sensing data on which many of these conclusions are based. Both olivine and orthopyroxene on the lunar surface could be derived from crustal rather than mantle sources. Finally, one must consider the possibility that large impacts that form basins on the Moon do not necessarily penetrate the crust and excavate the mantle. In an analysis of ejecta deposits associated with the Orientale Basin (∼1000 km in diameter), Spudis and Martin [24] concluded that only the upper crust was excavated. However, other basins such as South Pole-Aitken and Imbrium, clearly excavate more mafic, varied, and deeper crustal-mantle regions [9, 24] that may have transported mantle material to the lunar surface. Further exploration of these basins with a continued reassessment of samples in hand and future targeted sample return may help resolve this dilemma.