THE MOON'S UPPER MANTLE: MOSTLY OPX, NOT OLIVINE?. H. J. Melosh[1,2], J. Kendall[2], B. C. Johnson[2], T. Bowling[1], B. Horgan[1], P. G. Lucey[3] and G. J. Taylor[3], [1]EAPS Department, Purdue University, West Lafayette IN 47907 USA, [2]Physics Department, Purdue University, West Lafayette IN 47907 USA, [3]IGPP, University of Hawaii Manoa, Honolulu HI 96822 USA. (jmelosh@purdue.edu)

Introduction: The sparse occurance of olivine on the Moon's surface has been an enduring puzzle to impact modelers, whose simulations of the very largest basins on the Moon almost invariably result in the ejecton of large masses of lunar upper mantle material onto the surface. Small masses of olivine have indeed been detected [*1*], but their abundance is far smaller than impact scaling for large craters leads us to expect. This problem has become especially acute following the recent downward revision of the Moon's crustal thickness by GRAIL [*2*]. Stewart [*3*] has argued that, in the case of Orientale, better models of the rheology of partially melted rocks would limit the dispersal of upper mantle material to small ponds, but for the ca. 2500 km diameter South Pole Aitkin basin (SPA), it seems inevitable that lunar upper mantle material would be ejected onto the lunar surface. In this abstract we argue that the Moon's upper mantle is dominated by orthopyroxene (OPX) rather than olivine, a conclusion that is also consistent with recentseismic studies and petrologic studies of the Moon's upper mantle [*4*].

3-D SPA simulation: To test this idea, we simulate the impact event using the iSALE shock physics hydrocode [5,6,7]. Simulations were run with a variety of impactor sizes and impact angles [Table 1]. All simulations assumed an impact velocity of 15 km/s. Both the Moon and the impactor are assumed to be composed of dunite, with thermodynamic properties addressed using the ANEOS equation of state. A crust is not included in these models. Our model Moon assumes a near-surface thermal gradient of 10 K/km. All simulations were done in 3-D using a flat half space target. Lagrangian tracers were placed in the mesh at 5 km intervals to track the provenance of ejected material. Simulations are run out in time long enough for the transient crater, defined by a cavity of maximum volume, to completely form. Once this point is reached, ballistic trajectories are calculated for ejecta using tracer velocities. The trajectories determine where material will be emplaced outside of the final crater rim, assumed to be 2500 km in diameter and centered on the transient crater. Previous work suggests transient crater diameters of 800-1400 km: The larger estimates are based solely on crater scaling while the lower estimates come directly from two-dimensional hydrocode modeling [8]. Assuming a crustal thickness of 50 km [2], we expect that mantle material should be emplaced outside the final crater rim at transient crater diameters of ~800 km and greater [Table 1]. This suggests that the SPA-forming impact deposited a detectable amount of mantle material on the farside highlands of the moon.

D_{imp} (km)	Angle (^{o})	D_{trans} (km)	D_{ex} (km)
150	30	593	27.5
150	45	637	37.5
200	30	767	42.5
200	45	809	62.5
300	30	1049	77.5
300	45	1051	97.5

Table 1: Results of iSALE simulations of the SPA forming impact, showing the impact diameter (D_{imp}), impact angle, transient crater diameter (D_{trans}), and the maximum depth of excavation for material emplaced outside the final crater (D_{ex}). Note the maximum excavation depth will be larger than D_{ex} however we are interested in material ejected outside the final crater rim.

Multispectral identification of OPX in the highlands: Infrared remote sensing of the lunar surface has long noted that orthopyroxene is the most frequently detected mineral in the lunar highlands [9]. Recently, Lucey et al. [10] conducted a large scale spectral survey using the Kaguya Spectral Profiler of several thousand craters less than 1 km in diameter, and using a mixing model validated by analsysis of data from the Lunar Soils Characterization Consortium [11,12] found that this population of craters is overwhelmingly dominated by mafic assemblages with OPX as the main spectrally detectable mineral. Occurrences of lithologies common in central peaks (anorthosites, gabbros and troctolites) were present in fewer than 0.1% of the sample. Outside SPA the small crater population probably represents the mega-regolith and is composed of a mixture of crustal and mantle material excavated by large basins. If so, olivine was much less abundant than orthopyroxene in the mantle sources if excavation models are correct, and clinopyroxene is nearly absent.

OPX and olivine in highlands breccias: Lunar samples (Apollo, Luna, and meteorites) provide a complementary view of the highlands than that provided by remote sensing measurements. Two types of samples are particularly informative: granulitic breccias and feldspathic lunar meteorites (most of which are fragmental breccias). The granulitic breccias were metamorphosed in hot (1000-1100°C) impact melt sheets or ejecta of craters 50-200 km in diameter [13,14], so likely formed from upper crustal protoliths. They are rich in plagioclase (62 to 90%). Mafic silicates are mostly olivine and orthopyroxene, with molar Mg/(Mg+Fe) (Mg#) varying directly with the amount of olivine in the mafic component (Mg# = 0.0036 x percentage of olivine in mafic component + 0.59; R^2 = 076). This correlation suggests that the granulitic breccias are mixtures of ferroan anorthosites with a mafic component that varies in Mg# and olivine/orthopyroxene. This component could be derived from a series of crustal intrusions, but is equally likely to represent an assortment of mantle rocks. If the latter, the average granulite contains a mantle component consisting of half orthopyroxene and half olivine, substantially more pyroxene than indicated by remote sensing data of the near surface. Lunar meteorites also contain a mafic component that averages roughly half orthopyroxene and half olivine (normative abundance determined from bulk chemical analyses). The presence of olivine suggests that some regions of the olivine-rich mantle have been sampled, but are not abundant enough to be detected by Spectral Profiler spectra of small craters.

Hyperspectral follow-up: To verify these OPX detections with hyperspectral, longer-wavelength data, we selected a near-infrared observation from the Moon Mineralogy Mapper (M^3) reflectance dataset [15] covering a swath of the highlands between 172-175°E and -16-10°N. All the mafic components in this region are limited to small craters, and exhibit strong 1 and 2 µm iron bands consistent with pyroxene (Fig 1c). The location of the bands, however, is not consistent with pure OPX, as the 1 µm band centers are clustered between 0.95-1.0 µm. This could be an indication of the presence of olivine in this region, which would shift the 1 µm band away from a typical OPX value (~0.9-0.92 µm), and produce the broader, occasionally asymmetric bands we observe in the M^3 spectra. However, it is currently unclear why this region of the highlands appears to differ in mineralogy from the broader spectral survey conducted by Lucey *et al*. [10]. Further investigations of other M^3 observations in the highlands may help to understand this discrepancy.

Inferences for the lunar mantle We have shown that the SPA basin almost certainly excavated the lunar upper mantle and deposited large amounts of material on the farside highlands. If the Moon's upper mantle were dominantly composed of olivine, we should see the spectral signature over large parts of the lunar farside. Such a signature is not seen. However, we do see evidence of large additons of an orthopyroxene (OPX) component in the lunar highlands. From this evidence we infer that the Moon's upper mantle must have a large, perhaps dominant, component of OPX in addition to olivine. This inference is also consistent with recent suggestions that the upper mantle of asteroid 4 Vesta might also be dominated by OPX [16], as exhibited in the diogenite meteorite clan. It thus seems that, as has happened before in planetary science, we may have been misled by too-facile extrapolation from our own planet to other solar system bodies.

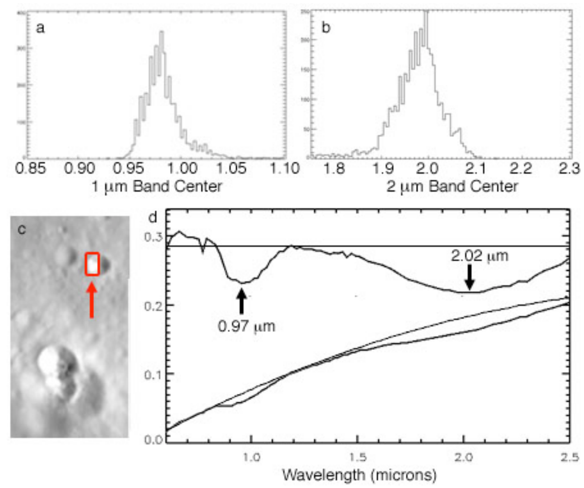

***Figure 1:** Deriving mineralogy of the highlands from M^3 observation M3G20090123T064545. (a) 1 and (b) 2 µm band centers of all spectra with band depths greater than 2%. While the 2 µm band centers are potentially consistent with OPX, the 1 µm band centers are at longer wavelengths than expected, possible suggesting an olivine contribution. (c) Location of sample spectrum shown in (d). Reflectance spectrum (bottom) with calculated continuum and continuum removed spectrum (top), both shifted for clarity*

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