

mafic minerals present in basalts [e.g., *Crown and Pieters, 1987*] and lose absorption features near $1\ \mu\text{m}$ when shocked, such that the mineral has proven difficult to detect even in most highland regions. Fe-rich lunar glasses also contain broad absorptions extending beyond $1\ \mu\text{m}$; however, these absorptions are more symmetrical than the composite absorption observed within olivine. Fe-rich glasses produced by rapid cooling of basalts could contribute to broad absorptions observed in the weak spectral features associated with the western high-Ti soils [*Pieters et al., 1980*]. However, FeO-rich glasses are less likely to produce a strong and distinctly olivine-like signature in fresh craters excavating and mixing materials from depth, as observed in the M^3 data of area 2.

[37] Olivine is less absorbing than pyroxenes and is thus likely to be masked by pyroxene absorptions, unless the olivine is present in relatively large abundance [*Singer, 1981; Pieters et al., 1980; Mustard and Pieters, 1987*]. The presence of the distinct olivine shape within spectra from area 2 suggests that either the olivine is very abundant relative to pyroxene (olivine/pyroxene > 1) or factors such as grain size and mineral associations within these basalts allow light to reflect more easily from the olivine-rich component. Since darkening components such as ilmenite may be associated with the pyroxene component or matrix of a basalt, independently of crystals of olivine, these basalts may have a lower olivine/pyroxene ratio than would be inferred by a linear interpretation of the strength of the olivine features observed in the M^3 data.

[38] The high-Ti basalts sampled in area 3 lie west of Aristarchus and appear as a light red hue in the M^3 IBD mosaic in Figure 2. The distribution of these basalts in both Procellarum and Mare Imbrium, as well as comparisons to mare age estimates, indicates that they generally predate the spectral unit sampled at area 2. These mare soils also have relatively weak $2\ \mu\text{m}$ absorptions compared with older, surrounding low-Ti basalts, but the differences in band strength are less extreme than observed for the basalts sampled in area 2. The spectral properties of fresh mare craters sampled from area 3 (Figure 4), also display a broad, long-wavelength $1\ \mu\text{m}$ band and weaker $2\ \mu\text{m}$ absorptions consistent with the presence of some olivine. The spectral properties of the ferrous bands within the area 3 basalts appear intermediate between those of the pyroxene-rich, low-Ti basalts and the youngest high-Ti basalts. Area 3 high-Ti basalts are, therefore, interpreted to have at least some olivine present, but a lower average olivine/pyroxene ratio than the basalts sampled in area 2. Alternatively, differences in grain size and associations between olivine and the opaques (e.g., chromite, ilmenite) within these basalts could also result in the observed spectral differences from area 2 with similar olivine contents. Exposure to greater amounts of vertical mixing with the underlying and pyroxene-rich low-Ti basalts could also result in lower inferred olivine contents than the stratigraphically younger high-Ti basalts. However, the global data sampled at area 3 have a similar spectrally blue slope like area 2 and do not display an increase in albedo or reddening that would be expected from such mixing of mare materials.

[39] The targeted M^3 data near Lichtenberg crater provides an opportunity to examine the shape of the $1\ \mu\text{m}$

feature within the youngest high-Ti basalts in greater detail. Unlike the global mode spectra presented in Figure 4, these data were thermally corrected using the approach of *Clark et al. [2011]*, which should provide improvements in the shape of the data near $2\ \mu\text{m}$, relative to the uncorrected data. These basalts are spectrally contiguous with area 2 in the global IBD parameter mosaic, but as described previously, are interpreted to be very thin in the region near Lichtenberg. The comparison in Figure 6 attempts to isolate some of the most olivine-rich basalts associated with craters in the high-Ti unit for comparison to the older, low-Ti and pyroxene-rich basalts to the west. It is again noted that the calibrations of the targeted data used for this study are very preliminary and a local smoothing of the data based on the EFFORT method was necessary to make these preliminary comparisons using the targeted data. The phase angles of the data themselves were quite high ($\sim 60^\circ$), also making comparisons of samplings of crater materials complicated by shadowed and illuminated slopes. The resulting spectra for both the high- and low-Ti units, however, are consistent with craters sampled in the lower spatial and spectral resolution global data. In particular, the low-Ti basalts in this region have spectral properties that are consistent with laboratory and telescopic measurements of typical pyroxene-rich lunar basalts. The crater materials sampled from the high-Ti unit have spectral properties that are consistent with a high abundance of olivine. Due to the limited locations of fresh crater ejecta that could be sampled in this small region of targeted data, it is not possible to determine how typical these olivine rich materials are within other craters sampling this spectral unit.

[40] Previous studies of Lunar Prospector and Clementine data have characterized the late stage western, high-Ti basalts as among the most FeO-rich basalts on the Moon [*Lawrence et al., 2002; Staid and Pieters, 2001*]. Determining whether the olivine compositions of these basalts are also relatively FeO-rich is relevant to the evolution and source regions of these basalts. The shape and position of the $1\ \mu\text{m}$ composite absorption for olivine are known to vary systematically from MgO- to FeO-rich compositions due to the position of Fe^{2+} in the crystal structure [*Burns, 1993; Sunshine and Pieters, 1998*]. The systematic changes in olivine band positions and shape with composition are well documented, and detailed modeling of olivine has been demonstrated in the laboratory and in remote sensing data [*Burns, 1993; Sunshine and Pieters, 1998; Sunshine et al., 2007*]. Qualitative comparisons of the spectra in Figure 6 to laboratory spectra of MgO-rich and FeO-rich (fosterite and fayalite) olivines indicate that the late stage, high-Ti basalts may be relatively FeO-rich. In particular, the longer-wavelength M2 absorption appears comparatively strong in these basalts relative to their central M2 absorption, producing an overall $1\ \mu\text{m}$ band shape and long-wavelength edge more similar to the FeO-rich than MgO-rich end-members measured in laboratory studies [*Sunshine and Pieters, 1998*]. However, the modeling of absorption band positions in lunar basalts containing both olivine and pyroxene is a complex problem and beyond the current scope of this paper. Furthermore, grain size can also affect the shape of olivine spectra and complicate the identification of MgO-rich versus FeO-rich olivines [e.g., *Lucey, 1998*]. As a result, no conclusions about