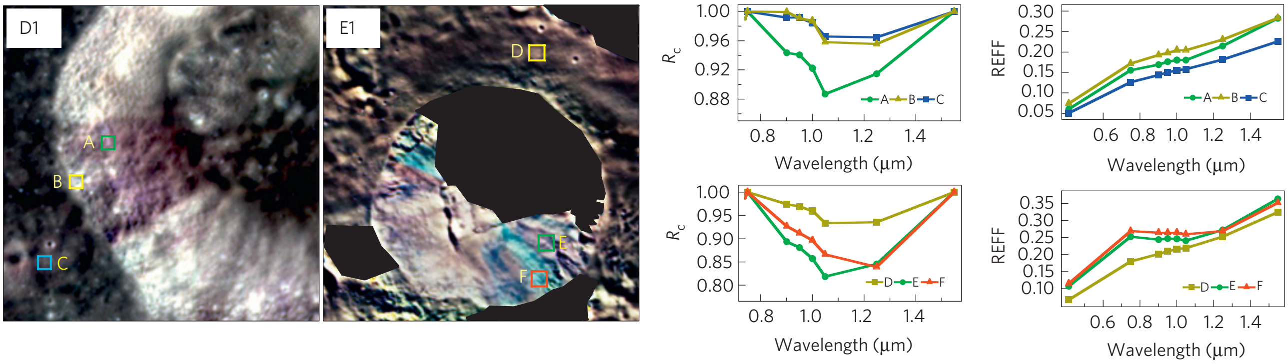

Figure 3 | Colour-composite image maps of olivine-rich sites D1 and E1 taken by the MI. (See ref. 14 for more detail on the MI images.) Blue, green and red are assigned to reflectances of 900, 1,050 and 1,250 nm, respectively. The continuum-removed reflectance spectra R_c and reflectance factor[9] (REFF) at the six locations marked A–F in the images are also plotted. The locations of A and E show olivine-rich spectra. All reflectance spectra are given as the average of a 500 m × 500 m area to remove spatial variation. Saturated data areas are masked (black filled areas).

(Schrödinger and Zeeman). They are located near the edge of the SPA, whereas there is no olivine-rich site in its central region. Although the number of olivine-rich sites was limited, the same distribution pattern was observed at other basins (Fig. 2d–i).

At each olivine-rich site, most of the olivine exposure was detected at several consecutive SP footprints. This indicates that the olivine-rich exposures extend over several footprint sizes spanning several kilometres. They are found on crater walls (for example, B2, D1 and E1) and on continuous ejecta (for example, A1 and F1). Figure 3 shows the MI images for sites D1 and E1, where the olivine-rich spectra appear in the landslide features on the crater wall. At site E1, there is also an area that has a clear plagioclase spectrum showing a strong 1.25 μm band on the crater wall (marked 'F'). On the other hand, spectral features for areas outside olivine (or plagioclase) exposures are too unclear to allow correct interpretation of their mineral compositions. This is because most of the lunar surface is covered with mixtures of various minerals. Space weathering also obscures spectral features. The olivine-rich exposures, however, are found in fresh areas such as landslide features on crater walls or recently formed craters (for example, F1).

Figure 1 does not includes the Olivine Hill, Langrenus, Keeler, Crookes and Tsiolkovsky craters, which were suggested as olivine-bearing areas by Clementine[5,6]. This is because the Clementine analysis was based on discrete spectral data with a limited wavelength coverage of $\lambda \leq 1$ μm, whereas the SP has continuous spectral data with $\lambda = 0.5$–1.6 μm (ref. 7). However, the Theophilus suggested by Clementine is identified as an olivine-rich site by the SP. Figure 2g shows that this crater is located in the concentric region around Nectaris.

In summary, olivine exposures on the Moon are limited to concentric regions around the impact basins that have thinner crusts. On a local scale, they are found mainly on small, fresh crater walls or continuous ejecta. What mechanism produced this distribution? We propose that basin formation is responsible for the observed distribution of the olivine exposures. Each basin formation could have blasted away the upper crust, excavating and redistributing deep-seated olivine-rich material to the rim. Whereas the central region of the basin would be covered with basaltic lava that erupted later in the cases of nearside basins and Moscoviense, the rim region would not. For the SPA the impact resulted in the production of a large amount of melted material, which puddled on the floor of the excavated cavity as a melt sheet. Local differentiation occurred in these melt layers, forming an orthopyroxene layer that overlies the olivine-rich layer[18]. Indeed, a recent SP survey[8] revealed the existence of an extensive layer of differentiated orthopyroxene in the central region of the SPA; the central peaks of the Finsen, Antoniadi, Bhabha and Lyman craters show clear orthopyroxene spectra. Thus, the deep-seated olivine-rich layers in the central region of the SPA would be hidden by the differentiated impact melt. Although olivine in the rim regions would have been covered with ejecta from the surroundings, later impacts could have excavated the olivine, exposing it to the surface. As a result, olivine-rich sites are observed only at fresh craters in the concentric regions around large basins.

Although most main thin-crust basins (for example, Moscoviense, Crisium, Humboldtianum) have olivine-rich sites, some basins (for example, Mare Smythii) do not. This may be due to the incomplete coverage of our survey. Some basins located in thin-crust regions may have olivine exposures in their concentric regions that the SP survey did not discover.

Where did the olivine-rich material originate? This is an important question for increasing our understanding of the structure and evolution of the Moon. Here we propose two possible scenarios. The first scenario is that the olivine-rich exposures originated in the upper lunar mantle. The basins with olivine-rich sites are located only in regions where the crust is relatively thin (Fig. 1). For example, if the general impact cratering theory[19] is applied to the mare Crisium (~1,000 km diameter), the depth of the excavation is >~ 100 km. The original crust thickness at Crisium could have been thinner than the maximum thickness of the current feldspathic crust, which is about 100 km (Fig. 1). Thus, basin formation impacts could plausibly have penetrated to the crust–mantle boundary.

The second scenario is that the olivine-rich exposure originates from the mafic-rich lower crust. In other words, the basin formations excavated the Mg-rich pluton intruding into the lunar lower crust[20–22]. Note that some of the olivine-rich sites are associated with plagioclase; the Schrödinger and Aristarchus craters were reported as the purest-anorthosite-bearing regions[14]. In addition, site E1 in the Schrödinger crater (Fig. 3) has areas that exhibit the 1.25 μm plagioclase absorption band adjacent to areas showing olivine-rich spectra. This may suggest that the basin formations excavated intrusions with spatially inhomogeneous plagioclase/olivine ratios in the lower crust, although there is the possibility that the excavation of the crust–mantle boundary resulted in mixtures of mantle olivine and anorthosite during the excavation process. If this scenario is true, the spatial distribution of olivine exposures (Fig. 1) gives important insights into constraints on early lunar basaltic magmatism and crustal growth after the crystallization of the LMO (refs 23,24).

Which of the above scenarios is more plausible? If the olivine-rich exposure originates from the upper mantle, the composition should be similar to dunite rather than troctolite in the lower lunar crust. To confirm whether this is the case, we examined the spectral data for some of the olivine-rich sites using radiative transfer modelling based on an intimate mixture model[4,8–10] (see Supplementary Information). Supplementary Fig. S4 shows that the