representative spectra are more consistent with a dunite-dominant model than with troctolite. This is mainly because most of the spectral data for the olivine-rich sites in Supplementary Fig. S4 have lower absolute reflectance (<0.23 at $\lambda \sim 0.7\,\mu$m). In other words, it is difficult to fit the dark spectra of the olivine-rich exposures with bright components such as plagioclase (see Supplementary Information). Therefore, radiative transfer modelling supports the concept that materials in the olivine-rich sites originated in the upper mantle. We cannot, however, rule out the possibility that plagioclase is present in olivine exposures, but its diagnostic band was completely erased by shock[25]. Although further work is required to resolve the origin issue, we believe that at least some of the larger basin formations could have excavated the lunar upper mantle to produce the basin-related olivine. In this case, the distribution of olivine-rich sites gives us valuable new constraints for the Moon's evolution. In the mantle cumulate crystallization sequence[11,12], the lowermost layer would be Mg-rich olivine and the residual KREEP (potassium, rare-earth elements and phosphorus) layer would underlie the anorthositic lunar crust. Therefore, basin formation would have excavated not only the lunar mantle but also the KREEP layer as well. However, although neither Moscoviense nor Crisium, which have the thinnest crust on the Moon, shows a high thorium concentration[16], their formations excavated the Mg-rich olivine layer. A large-scale overturn of the mantle cumulate[26] may have occurred before the two basins were formed. Although further work is required to resolve this issue, the present data provide important modelling constraints for the evolution of the lunar crust and mantle.

Method

Data in the SP Level 2A (L2A) product processed by the SELENE Operation and Analysis Center at the Institute of Space and Astronautical Science were radiometrically calibrated. (Dark current removal, non-linearity correction and minor wavelength correction are included in the calibration procedures.) The L2A data were then further corrected using the reflectance spectra of the Apollo 16 landing site and the spectral reflectance of the Apollo 16 soil 62231 as measured in the laboratory[27]. We also corrected small gaps between data measured by different SP detectors resulting from differences in exposure time and sampling timing. As the radiometric calibration for wavelengths longer than 1.6 μm remains incomplete, we use only data at wavelengths shorter than 1.6 μm.

The SP obtained continuous spectral reflectance data for more than 68 million points during its mission period from November 2007 to June 2009. (The total SP coverage area is about 20% of the lunar surface at the equator.) We discovered olivine-rich points using the following procedure. First, we rejected the following data with low signal-to-noise ratios: (1) data in which the radiance at wavelength $\lambda = 0.5126\,\mu$m is less than $23.3\,\mathrm{W\,m^{-2}\,\mu m^{-1}\,sr^{-1}}$ and (2) data in which continuum-removed reflectance R_c (divided by a linear tangential continuum) does not show an absorption band minimum with $R_c < 0.95$ within the wavelength range from 0.7 to 1.6 μm. This is because such data cannot be used to examine whether the characteristic olivine bands exist at $\lambda = 0.85$, 1.05 and 1.25 μm. Second, we searched for the wavelengths at which R_c with $\lambda = 0.7$ and 1.6 μm are the first-, second- and third-lowest values, and selected the data in which these three wavelengths were within the range of $1.05 \pm 0.03\,\mu$m. Third, we rejected the jagged spectral data in which the difference in R_c between $\lambda = 1.04$ and 1.07 μm was larger than 0.02. After applying this algorithm, only 266 candidate spectra remained out of more than 68 million original spectra. Then, to remove spectra that had a clear plagioclase absorption band, we also rejected those for which the difference between the mean R_c over the wavelength range from 1.04 to 1.07 μm and the mean R_c over the wavelength range from 1.17 to 1.20 μm was less than 0.01. This left 245 observational points, which we designated olivine-rich points.

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Author contributions

Data analyses were conducted by S.Y., R.N., T. Matsunaga, Y.O. and M.O. The manuscript was produced by significant contributions from S.Y., R.N. and T. Matsunaga. T.H. contributed to the assessments of spectral features in the survey programme. Y.I. contributed to the production of the base maps of Figs 1 and 2 and discussion on the crust thickness. All of the authors, including T. Morota, N.H., J.H. and Y.Y., discussed and provided significant comments on the results and the manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to S.Y.