Advances in Lunar Basalt Classification Based on Remote Sensing Data: Postprint

Authors: Cai Tingni, Li Chunlai, Ren Xin, Liu Jianjun, Liu Bin, Liu Dawei, Xu Xuesen

Date: 2017-09-26T00:00:00+00:00

Abstract

Lunar basalt represents one of the significant categories of lunar rock formations, exposed across approximately 17% of the total lunar surface area and predominantly infilling large, flat basins on the lunar near side. Mare basalts are believed to originate from the remelting of lunar mantle cumulates produced by early magmatic differentiation, erupting onto the lunar surface under overpressure conditions; consequently, they are relatively young, less disturbed by major impact events, and preserve relatively complete geological information. The ages, distributions, and volumes of different basaltic geological units provide spatiotemporal records of lunar mantle melting processes, offering valuable insights into lunar mantle evolution, the internal compositional structure, and material composition of the Moon, thus holding significant research importance. This study introduces the exploration background of basalts, along with the structure, chemical composition, and spectral characteristics of their primary constituent minerals, focuses on the classification of basalts based on remote sensing detection data, and summarizes the existing limitations in current research findings.

Full Text

Progress in the Classification of Lunar Basalts Based on Remote Sensing Data

Authors: Cai Tingnian[12], Li Chunlai[12], Xu Xuesen[12], Liu Dawei[12], Liu Jianjun[1], Ren Xin[1], Liu Bin[1]
Affiliations:
1. National Astronomical Observatories, Chinese Academy of Sciences, Beijing
2. Key Laboratory of Lunar and Deep Space Exploration, National Astronomical Observatories, Chinese Academy of Sciences, Beijing
3. University of Chinese Academy of Sciences, Beijing

Abstract

Lunar basalts represent one of the most important rock types on the Moon, covering approximately 17% of the lunar surface and primarily filling large, flat basins on the lunar near side. These mare basalts are believed to originate from the remelting of early magma differentiation products that formed lunar mantle cumulates, which were subsequently extruded onto the surface under overpressure conditions. As relatively young geological units that have experienced minimal large-impact disturbance, they preserve relatively complete petrogenetic information. The temporal and spatial distribution of different basaltic geological units provides crucial records of mantle melting processes, offering valuable insights into lunar mantle evolution, internal compositional structure, and bulk composition. This paper reviews the background of basalt exploration and describes the structure, chemical composition, and spectral characteristics of their major constituent minerals, with particular emphasis on basalt classification schemes based on remote sensing data. Current research limitations and outstanding issues are also summarized.

Keywords: Lunar basalt; Remote sensing; Basalt classification

1. Introduction

The Moon represents humanity's primary target for deep space exploration, having been subjected to intensive investigation through numerous missions. The United States and former Soviet Union conducted extensive lunar exploration, including the Apollo program which successfully landed humans on the Moon six times between 1969 and 1972—a historic first for human exploration beyond Earth. Each mission returned substantial quantities of lunar data through orbital observations and sample collection. The return of 381.7 kg of lunar samples, combined with 0.321 kg from unmanned sample-return missions, dramatically expanded our understanding of lunar rock types, physical properties, and formation ages.

Lunar rocks are primarily classified into three categories: (1) Highland anorthosites, including granulites; (2) KREEP-rich rocks, comprising basalts, fractured plutonic rocks, and impact melts; and (3) Mare basalts. Compared to terrestrial basalts, lunar basalts exhibit higher titanium and iron contents but lower aluminum and magnesium contents, with significant variations in TiO (0.5–13 wt%) and Mg/(Mg+Fe) ratios (0.35–0.65). These compositional differences are evident in both sample analyses and remote sensing data, providing the basis for basalt classification schemes.

The major minerals in lunar basalts include plagioclase feldspar (predominantly anorthite), pyroxene, olivine, and ilmenite, with abundances varying among different basalt types. Isotopic dating reveals basalt ages ranging from 3.1 to 3.9 billion years, reflecting mantle heterogeneity. The mineralogical and chemical information preserved in basalts is crucial for understanding lunar evolution, though several key questions remain unresolved: (1) the relationship between later basin formation and basaltic infilling; (2) the origin of special basalt types; (3) the asymmetry between near-side and far-side mare basalt distribution; (4) the lack of petrogenetic indicators in compositional classification schemes; and (5) inconsistent interpretations of the same region using different datasets.

2. Major Minerals in Lunar Basalts

2.1 Plagioclase Feldspar Plagioclase, a framework silicate with the general formula (Ca,Na)Al Si O , forms a complete solid solution series between albite and anorthite endmembers. Lunar plagioclase is notably depleted in the albite component, reflecting the Moon’ s alkali-poor nature. In visible and near-infrared regions, pure plagioclase lacks strong spectral features, but trace amounts of iron (FeO ~0.1 wt%) can produce a diagnostic broad absorption near 1250 nm. This feature, while often weak and susceptible to masking by olivine and pyroxene spectra, becomes detectable when plagioclase exceeds 60–80% of the mixture volume. Shock metamorphism significantly affects plagioclase spectra, with moderate pressures causing internal structural changes and high pressures converting crystalline plagioclase to glass, thereby altering the 1250 nm absorption characteristic.

2.2 Pyroxene Pyroxene represents the most spectrally variable lunar mineral, with complex chemistry expressed as XY[T O], where X and Y cations occupy distinct crystallographic sites. The mineral exhibits two characteristic absorption bands near 1000 nm and 2000 nm, arising from electronic transitions of Fe^2 ions in the crystal structure. The precise positions of these bands shift systematically with Fe^2 and Ca^2 content, providing a powerful tool for compositional discrimination. Low-calcium pyroxenes display shorter wavelength absorption features compared to high-calcium varieties, enabling remote distinction of pyroxene subtypes.

2.3 Olivine Olivine, with formula (Mg,Fe) SiO , forms a complete solid solution series from fayalite to forsterite. It typically occurs in large impact basins and their margins, offering insights into deep-seated materials. Olivine spectra show a broad absorption feature between 850–1250 nm, with three overlapping peaks centered near 850 nm, 1050 nm, and 1250 nm. The band positions and widths correlate with Mg-number (Fo#), allowing compositional estimation through spectral deconvolution.

2.4 Ilmenite Ilmenite (FeTiO) is an opaque accessory mineral whose spectral signature is dominated by its high Fe and Ti content, significantly affecting the overall reflectance properties of basalts.

---

3. Classification of Lunar Basalts Based on Remote Sensing Data

3.1 Ground-Based Telescopic Spectral Classification Early classification efforts utilized ground-based telescopic observations of the lunar near side. Researchers identified distinct spectral differences between bright highlands and dark maria, attributing these variations primarily to mineralogical differences. The 1 m and 2 m bands proved particularly diagnostic, with the former related to mafic minerals and the latter to pyroxene.

Pieters (1978) established a classification scheme using four measurable spectral parameters: UV/VIS ratio, 1 m band depth, 2 m band depth, and band center position. This system categorized mare basalts into multiple types designated by letter combinations (e.g., hDSA, MS2) representing parameter values. For example, high-titanium basalts like those at Apollo 11 and 17 sites showed UV/VIS 1.05 and 1 m band depths 9.5%, while low-titanium basalts exhibited lower values.

3.2 Chemical Composition-Based Classification Laboratory analyses of returned samples enabled chemical classification, primarily using TiO content. Basalts are divided into: very low-Ti (<3 wt%), low-Ti (3-6 wt%), medium-Ti (6-9 wt%), and high-Ti (>9 wt%) varieties. Secondary classification employs mineralogical parameters such as Al O content and modal mineralogy. Table 3 illustrates this approach, showing how different Apollo and Luna mission basalts cluster into distinct compositional groups based on pyroxene, plagioclase, olivine, and opaque mineral abundances.

3.3 Remote Sensing Data-Driven Classification Modern classification leverages data from orbital missions including Clementine, Lunar Prospector, Kaguya/SELENE, Chang' e-1/2, and Chandrayaan-1. These missions provide multispectral and hyperspectral data covering UV to infrared wavelengths with increasing spatial and spectral resolution.

Multispectral Approaches: The Clementine mission's UV/VIS ratio method proved effective for TiO mapping. The UV/VIS ratio (e.g., 415/750 nm) correlates inversely with Ti content, as titanium suppresses UV reflectance. Color-ratio composites using bands such as 750/415 nm, 750/950 nm, and 541/750 nm enhance lithological variations and minimize illumination effects.

Hyperspectral Approaches: The Moon Mineralogy Mapper (M^3) on Chandrayaan-1 provides high-resolution hyperspectral data enabling detailed mineral mapping. Researchers have used integrated band depths at 950 nm, 1050 nm, 1250 nm, 1900 nm, and 2300 nm to distinguish pyroxene compositions and olivine abundances. For example, false-color composites highlighting 1000 nm and 2000 nm band depths reveal regional variations in low-Ca pyroxene, high-Ca pyroxene, and olivine, facilitating division of mare basalt units.

Recent studies have identified Mg-spinel-bearing lithologies in central peaks of impact craters, suggesting excavation of deep crustal materials. Theophilus crater and Aristarchus region analyses demonstrate the power of combining spectral parameters with topographic data to understand geological context and compositional diversity.

4. Limitations and Future Directions

Current classification schemes face several challenges: (1) Limited application of hyperspectral data for fine-scale regional mapping, which is crucial for landing site selection and in-situ exploration; (2) Uncertainty in spectral parameter selection and classification methods; (3) Insufficient integration of spectral data with elemental abundance data and other geophysical measurements; (4) Effects of space weathering and impact mixing that can modify original spectral signatures; and (5) Need for improved quantitative indicators beyond TiO content to enhance petrogenetic interpretation.

Future progress will benefit from: (1) Higher resolution spectral data from recent and upcoming missions; (2) Integration of multiple datasets (spectral, elemental, geophysical); (3) Development of advanced spectral unmixing algorithms; (4) Laboratory calibration using returned samples from Chang' e-5 and other missions; and (5) Combined use of orbital, in-situ, and sample data to establish more robust classification schemes.

References

1. Hartmann, K. W. (1986). Satellite-sized planetesimals and lunar origin. *Icarus*, 67, 504-515.
2. Head, J. W., et al. (1978). Regional stratigraphy and geological history of Mare Crisium. *Geochimica et Cosmochimica Acta*, 6(Suppl.), 43-74.
3. Vaniman, D. T., & French, B. M. (1991). Lunar sourcebook: A user' s guide to the moon. Cambridge University Press.
4. Snyder, G. A., Taylor, L. A., & Neal, C. R. (1992). A chemical model for generating the sources of mare basalts. *Geochimica et Cosmochimica Acta*, 56, 3809-3823.
5. Shearer, C. K., et al. (2006). New views of the moon. *Reviews in Mineralogy and Geochemistry*, 60, 221-364.
6. Burns, R. G. (1993). Mineralogical applications of crystal field theory. Cambridge University Press.
7. Bell, P. M., & Mao, H. K. (1972). Optical and chemical analysis of iron in Luna 20 plagioclase. *Geochimica et Cosmochimica Acta*, 3, 755-759.

8. Pieters, C. M. (1978). Mare basalt types on the front side of the moon. *Lunar and Planetary Science Conference*, 9, 2825-2849.
9. Adams, J. B., & Goullaud, L. H. (1978). Plagioclase feldspars: Visible and near infrared diffuse reflectance spectra. *Lunar and Planetary Science Conference*, 9, 2901-2909.
10. Staid, M. I., et al. (2011). The mineralogy of late stage lunar volcanism. *Journal of Geophysical Research*, 116, E00G10.
11. Pieters, C. M., et al. (2011). Mg-spinel lithology: A new rock type on the lunar farside. *Journal of Geophysical Research*, 116, E00G08.
12. Pieters, C. M. (1983). Strength of mineral absorption features in near-infrared reflected light. *Journal of Geophysical Research*, 88, 9534-9544.
13. Singer, R. B., & McCord, T. B. (1979). Mars surface composition from reflectance spectroscopy. *Journal of Geophysical Research*, 84, 8415-8426.
14. Clark, R. N., et al. (1993). A compositional study of the Aristarchus region. *Journal of Geophysical Research*, 98, 18861-18882.
15. Lucey, P. G., et al. (1998). Mapping the FeO and TiO content of the lunar surface. *Journal of Geophysical Research*, 103, 3679-3699.
16. Yamamoto, S., et al. (2010). Possible mantle origin of olivine around lunar impact basins. *Nature Geoscience*, 3, 533-536.
17. Isaacson, P. J., & Pieters, C. M. (2008). Detecting a broader lunar magnesian suite. *Lunar and Planetary Science Conference*, 39.
18. Isaacson, P. J., & Pieters, C. M. (2009). Deconvolution of lunar olivine reflectance spectra. *Icarus*, 204, 8-13.
19. Burns, R. G., & Huggins, F. E. (1972). Cation determinant curves for Mg-Fe-Mn olivines. *American Mineralogist*, 57, 967-985.
20. Hazen, R. M., & Bell, P. M. (1971). Effects of compositional variation on absorption spectra of lunar pyroxenes. *American Mineralogist*, 56, 625-629.
21. Adams, J. B. (1974). Visible and near-infrared diffuse reflectance spectra of pyroxenes. *Journal of Geophysical Research*, 79, 4829-4836.
22. Cloutis, E. A., & Gaffey, M. J. (1991). Pyroxene spectroscopy revisited. *Meteoritics*, 26, 235-253.
23. Dyar, M. D., et al. (2007). Effects of calcium content and crystal structure on pyroxene spectra. *Meteoritics & Planetary Science*, 42, 379-395.
24. Klima, R. L., et al. (2007). Spectroscopy of synthetic Mg-Fe pyroxenes. *Meteoritics & Planetary Science*, 42, 235-253.
25. McCord, T. B., et al. (1981). Moon: Near-infrared spectral reflectance. *Journal of Geophysical Research*, 86, 10883-10892.
26. Pieters, C. M., & Head, J. W. (1993). Crustal diversity of the Moon. *Journal of Geophysical Research*, 98, 17127-17148.
27. Blewett, D. T., et al. (1997). Lunar titanium content from UV-VIS measurements. *Journal of Geophysical Research*, 102, 16319-16325.
28. Fischer, E. M., & Pieters, C. M. (1994). Remote determination of exposure degree and iron concentration. *Journal of Geophysical Research*, 99, 2225-2234.
29. Lucey, P. G., et al. (1995). Abundance and distribution of iron on the

Moon. *Icarus*, 115, 475-488.

30. Blewett, D. T., et al. (1995). Clementine images of lunar sample-return stations. *Science*, 268, 1150-1153.
31. Giguere, T. A., et al. (2000). The titanium contents of lunar mare basalts. *Meteoritics & Planetary Science*, 35, 193-200.
32. Melendrez, D. E., et al. (1994). Remote sensing of potential lunar resources. *Journal of Geophysical Research*, 99, 5601-5619.
33. Charrette, M. P., et al. (1974). Application of remote spectral reflectance measurements. *Journal of Geophysical Research*, 79, 1605-1613.
34. Papike, J. J., et al. (1977). Mare basalts: Crystal chemistry, mineralogy. *Lunar Science Conference*, 8.
35. Matson, D. L., et al. (1977). A TiO abundance map for the northern maria. *Lunar Science Conference*, 8.
36. Hawke, B. R., et al. (1990). Remote sensing of potential lunar resources. *Journal of Geophysical Research*, 95, 475-540.
37. Bence, A. E., et al. (1980). Petrology of Apollo 12 basalts. *Lunar and Planetary Science Conference*, 11.
38. Burns, R. G. (1970). The polarized spectra of iron in silicates. *American Mineralogist*, 55, 1608-1632.
39. Holzwarth, R. D., & Hardy, R. W. F. (1973). Isolation of the Mo-Fe protein. *Biochemical and Biophysical Research Communications*, 50, 90-99.
40. Singer, R. B. (1981). Near-infrared spectral reflectance of lunar soils. *Journal of Geophysical Research*, 86, 10195-10200.
41. Wells, E. N., et al. (1972). Lunar soil composition. *Science*, 175, 977-979.
42. Johnson, J. R., et al. (1991). Lunar soil compositional properties. *Journal of Geophysical Research*, 96, 18861-18882.
43. Thiessen, F., et al. (2014). Compositional diversity at Theophilus crater. *Planetary and Space Science*, 101, 244-252.
44. Dhingra, D., et al. (2011). Compositional diversity at Aristarchus crater. *Journal of Geophysical Research*, 116, E00G08.
45. Mustard, J. F., et al. (2011). Compositional diversity and geological insights. *Journal of Geophysical Research*, 116, E00G12.
46. Staid, M. I., et al. (2011). Mapping lunar mare basalt units in Mare Imbrium. *Journal of Geophysical Research*, 116, E00G10.
47. Check, L. C., et al. (2013). The distribution and purity of anorthosite. *Journal of Geophysical Research*, 118, 1805-1820.
48. Pieters, C. M., et al. (1993). A sharper view of impact craters. *Science*, 259, 1844-1848.
49. Boardman, J. W., et al. (2011). Measuring moonlight. *Journal of Geophysical Research*, 116, E00G14.
50. Green, R. O., et al. (2011). The Moon Mineralogy Mapper (M^3). *Journal of Geophysical Research*, 116, E00G19.
51. Isaacson, P. J., et al. (2011). The lunar rock and mineral characterization consortium. *Journal of Geophysical Research*, 116, E00G11.
52. Klima, R. L., et al. (2011). New insights into lunar pyroxenes. *Journal of*

Geophysical Research, 116, E00G09.
53. Dyar, M. D., et al. (2011). Spectroscopy of synthetic Mg-Fe pyroxenes II. *Journal of Geophysical Research*, 116, E00G13.

Note: Figure translations are in progress. See original paper for figures.