How well do we understand the geological field record on the Moon?

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The Role of Field Geology and Geophysics in the Return to the Moon
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The Geological Style of the Moon

Airless, waterless body
Crust made up of plutonic and volcanic rocks, modified by impact
Regolith is created by slow bombardment of micrometeorites
Bedrock on the Moon
  Mare bedrock widely exposed in crater walls, floors, linear features (e.g., rilles, graben)
  Highland bedrock unknown; may be at least partly in place within central peaks of complex craters

Key Questions:
Where does a given rock come from?
How do we sample appropriate targets to answer critical science questions?
The Apollo Sample Collection

Approx. 382 kg of rock and soil
Approx. 40% mare basalt and 60% highland rock (by mass)
Carefully devised field collection procedures resulted in more than 90% of the collection coming from documented locations (within 1 m) on Moon
Regolith

Formed by micrometeorite “rain”
Disaggregation and lithification
  Slow grinding of surface rocks in particles
  Bonding of particles by impact melt glass (agglutinates)
Thickness proportional to age
  Lunar erosion rate ~ 0.5-1 mm/ 20 Ma
  Mare lava regolith ~2-10 m thick
  Highland regolith > 15-20 m thick
Sense of mixing
  Predominantly vertical, but amounts of lateral mixing undetermined
Regolith mixing

Concentration of exotic debris is highly variable
More highlands in mare regolith than mare material in highlands regolith
Suggests that lateral mixing is not efficient
Most highland debris is local and comes from beneath relatively thin mare flows
Much less than 1% of material comes from distances greater than tens of km
Mare/Highland boundaries

Lateral transport on Moon appears to be relatively inefficient

Composition gradients at Apollo sites are abrupt and well-preserved

Sharp contacts preserved in remote-sensing data, showing that extensive lateral transport does not occur on the Moon

Clementine Fe concentration maps
How do you best sample the Moon?

Samples without context have limited value

Bulk planet properties, inventory of compositions

Context requires either geologic field work or a simple regional setting

Robotic missions tend to provide less context than human field study

cf. Luna 20 and Apollo 16
Apollo Mare Sampling

Apollo 11 – Mare Tranquillitatis
- Sampled uppermost flows of an old, “blue” mare region
- Landing avoided large, boulder-strewn crater
- Very high Ti mare basalts, of several types (ejecta)
  - 3.6-3.8 Ga

Apollo 12 – Oceanus Procellarum
- Sampled younger, “red” mare flows
- Concentrated on crater rims (more basalt than regolith breccia)
- Low-Ti basalts, younger than A11 - 3.1 Ga

Apollo 15 – Mare Imbrium
- Medium-age “reddish” mare flows
- Sinuous rille; mare bedrock exposed (rake sample collected instead!)
- Two, low-Ti mare basalts, pyroclastic green glass - 3.3 Ga; non-mare KREEP basalt -3.84 Ga

Apollo 17 – Mare Serenitatis
- Mare flows fill massif valley; regional dark mantle
- Very old, high Ti mare basalts, orange and black glass (3.7 Ga)
Apollo Highlands Sampling

Apollo 14 – Fra Mauro
Sent to sample Fra Mauro Fm (Imbrium ejecta)
Returned complex breccias; basaltic, KREEP-rich
Which samples are Imbrium basin primary ejecta?

Apollo 15 – Hadley-Apennines
Sample front (deep Imbrium rim material)
Anorthosite, KREEP basalts, mafic impact melts
Which samples represent Imbrium basin ejecta and melt?

Apollo 16 – Descartes
Sent to sample highland volcanic rocks
Anorthosites, feldspathic breccias, some mafic melts (VHA)
Basin-related? If so, which basins?

Apollo 17 – Taurus-Littrow
Sample rim massifs of Serenitatis basin
Mafic melt “sheet” (poiks); other melts (Imbrium?)
Mg-suite plutonics
Serenitatis basin? Any Imbrium basin material? If so, which samples?
Geological reconstructions
Apollo 12 v. Apollo 17

Although both cross sections have considerable uncertainties, they are greater at the highlands site.
A stratigraphic problem

15205 - a fragmental (regolith?) breccia
Contains clasts of A15 pyroxene basalt,
A15 KREEP basalt, and green pyroclastic glass
No A15 olivine basalt, highlands breccia
or plutonic rocks

Source crater is ~20-30 m below lip of Hadley Rille

Rille wall outcrop: lower layered unit (~25 m below rille edge) overlain by middle massive unit (4-20 m)
Types of Sample Exploration Targets

Reconnaissance
Geologically simple sites where a "grab sample" of rocks and regolith can address and solve scientific issues
Example: youngest mare lava flow, impact melt floor of fresh crater, regional pyroclastics

Field Study
Complex, multi-unit sites having a protracted evolution. Require human interaction, sampling, mapping, re-visiting field sites
Examples: basin ejecta blanket, Aristarchus plateau, crater central peaks

See Ryder et al., 1989, EOS, v. 70, n. 47, p. 1495; 1505-1520
How well do we understand the geological field record on the Moon?

Not very well

Context is reasonably clear for mare sites
  Outcrop recognized (and perhaps will be sampled next time)
  Evidence suggests that most samples are derived locally
  Thin lava flows over highlands substrate

Context at highland sites is largely guesswork
  Paucity of true outcrop
  Still don’t understand origin of massifs
  Pseudo-outcrop: boulders, central peaks

Remote sensing does not resolve context issues
  Virtually all remote data can be interpreted multiple ways

Understanding more thoroughly the geological style of the Moon must be a key objective of future exploration