Moon 101: Lunar meteorites
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1) What are meteorites?
2) How do they get from Moon to Earth?
3) What is the JSC connection?
4) What have they contributed to lunar science?
I) What are meteorites? (rocks from space)

- enter Earth’s atmosphere and heat up – must be large enough to survive (meteor shower and fireballs)
- Glassy black fusion crust
- Commonly contain metal
- Detailed observations of fireballs can lead to information about orbit and source (asteroid belt)
1) What are meteorites? (rocks from space)

- Meteor-wrongs and meteorites

meteorite

Meteor-wrong (Earth rock)
1) What are meteorites? (rocks from space)

- Meteor-wrongs and meteorites
2) How do they get from Moon to Earth? Most meteorites are from the asteroid belt.
2) How do they get from Moon to Earth?

Most meteorites are from the asteroid belt, but there are important exceptions

- There were initially skeptics: how could samples from large gravity bodies like Mars or Moon be launched to Earth?

- Discovery of lunar meteorite from Antarctica in 1981 (recognized in 1982) changed thinking

- If it is possible to get pieces of Moon, then maybe also Mars (this is huge topic for another day)
How does one recognize a piece of Moon?

- Apollo collection was well characterized by 1982
- Brian Mason, Smithsonian curator: “some of the clasts resemble the anorthositic clasts described from lunar rocks”
- JSC curation staff: looks like a piece of the Moon
- Other key indicators:
  - Feldspar composition and other minerals
  - K-La correlation
  - O isotopes
How does one recognize a piece of Moon?

- Other key indicators:
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2) How do they get from Moon to Earth?

- Escape velocity for Moon is 2.4 Km/s, so ejecta have to attain this velocity to leave the Moon.

- Craters can be small – 450 m to a few km in diameter (Head, 2003).

From papers by Brett Gladman (1996, 1997) and colleagues
2) How do they get from Moon to Earth?

Exposure ages can be determined by studies of isotopes produced by cosmic ray interactions with rocks. Example: K, Ca and Ti are target elements for $^{36}\text{Cl}$, which when produced has a half life of 300 Ka.
3) What is the JSC connection? US Antarctic Meteorite Program 30 years = 17,000 meteorites
Conventional Wisdom (Circa 1976)

“The efficiency (0.1%) with which collectable falls (meteorites) finds its way to curators may seem surprisingly high, in view of the impossibility of recovery of falls from the oceans and the polar regions”.

1976-1978: joint NIPR - US

1976 – 11 meteorites - B. Cassidy, E. Olsen, K. Yanai
1977 – 300 meteorites - B. Cassidy, M. Funaki, B. Glass, K. Yanai
ANSMET since 1978

• From beginning of program, around 17,000 meteorite specimens have been collected from about 50 distinct icefields.

• 30 years of collection efforts have lead to a treasure trove of planetary materials.

• Samples are maintained and curated in controlled environment at NASA-JSC, available for study.

• Samples are from Moon, Mars, asteroids (Vesta), and other unknown bodies, and thus support many diverse fields of planetary science.
JSC involvement in ANSMET teams

John Annexstad
Everett Gibson
Robbie Score (2)
Mike Zolensky (2)
Faith Vilas
Jerry Wagstaff
Gary Lofgren
Rene Martinez (3)
David Mittlefehldt (4)
Nancy Chabot (5)
Kevin Righter
Bill Oefelein *
Carl Allen
Scott Messenger
Dean Eppler
Cady Coleman *
Stan Love *
Keiko Nakamura
Mary Sue Bell
Don Pettit *
Samples remain frozen from McMurdo to JSC
Transferred in isopods and stored in freezers
Collection is characterized and housed at JSC

**Newsletters**
Antarctic meteorite collection which has produced > 70 newsletters (twice a year) reporting 15,000 new samples for study (photos, basic descriptions, compositional data)

**Sample distribution**
Meteorite Working Group (MWG)

Sample requests are received, are peer/committee reviewed, and recommendations made to curators
Tools and materials
Stainless steel, aluminum, teflon, nylon
Notable samples

Martian meteorite EET 79001

Hornblende R chondrite

Howardite – Eucrite – Diogenite clan from 4 Vesta
Request statistics since 1978

As many requests as for Apollo samples
Lunar meteorites at JSC

- ALH 81005
- MAC 88104/105
- EET 87521/96008
- QUE 93069/94281
- QUE 94281
- MET 01210
- LAP 02205 (+pairs)
- PCA 02007
- MIL 05035
- GRA 06157
- LAR 06638
- MIL 07006
Sample was made available in 1989, requested 83 times, and subdivided ~ 250 pieces, allocated to close to 70 different scientists; still 600 / 662 g available for study
JSC Antarctic Meteorite Curation

QUE 93069

QUE 94269

reconstructed in March 2005, from information in datapacks, by K. Righter
Requests for lunar

# requests (cumulative)

- MAC88105
- LAP02205
- EET87521
- EET96008
- ALHA81005
- QUE93069
- QUE94269

Years:
- S83
- F84
- S86
- F87
- S89
- F90
- S92
- F93
- S95
- F96
- S99
- F00
- S02
- F03
- S05
- F06
- S08
~130 individual samples, ~63 with pairings, ~50 kg compared to 382 kg of Apollo samples

figure by R. Korotev
Key aspect of lunar meteorites is they represent a more representative sampling of the surface. Lunar Prospector GRS data compared to Apollo and Luna sites (5%).

from Korotev et al. (2003)
4) What have meteorites contributed to our understanding of the Moon?

- Helped to define the young age, and composition of fractionation of mare basalt volcanism

- Helped to define the age and composition of the feldspathic crust

- Terminal lunar cataclysm can be tested with more random samples of the Moon
Review of lunar rock types (from G. Lofgren lecture)

- Basalt (10072)
- Anorthosite (N1)
- Breccia (mixture)
Summary of major processes on early Moon

- Floated anorthosite layer
- Sub-crustal residual melt (KREEP-rich) layer
- Melting of sunken cumulates
- Primitive unmelted interior
- Mare basalts

300 km?
A) Age and composition of mare basalt volcanism

from Papike et al. (1998)
NWA 773 - olivine gabbro (oliv, pig, plag, aug, op)
regolith breccia – VLT basalt clasts and other basaltic lith.

from Fagan et al. (2002)
NWA 773 – youngest lunar rock yet dated

from Borg et al. (2004)
Lunar meteorite MIL 05035
One of oldest low Ti basalts known
A) Age and composition of mare basalt volcanism

• Age range for low Ti basalts increased from 2.6 to 3.9 Ga

• No high TiO$_2$ basalt yet recognized in meteorite collections
B) Feldspathic lunar meteorites contain magnesian feldspathic clasts (granulites, troctolites, and anorthosites) that are distinct from the Mg-suite and FAN rocks found in the Apollo and Luna samples. *Crust is not simply FAN*
Magnesian crust

- FLMs are more magnesian, on average, than the Apollo ferroan anorthosites.
- This indicates that the lunar highlands are a mixture of both ferroan and magnesian anorthosite, not just predominantly ferroan anorthosite, as suggested by the Apollo anorthosites.
C) Impacts and the "terminal lunar cataclysm"

- **Smooth decline**
- **"Lunar Cataclysm"**
- Earliest evidence of life on Earth
- Oldest fossils on Earth

(Courtesy of B. A. Cohen)
SaU169 – zircons from impact melts yield older ages

3.909 vs. 3.85 Ga

(From Gnos, E. et al. 2004. Science, v. 305, Fig. 3, p. 659.)
Impact melt clast ages $^{40}$Ar-$^{39}$Ar system

from Cohen et al. (2000)

Table 2. Individual impact events. An impact event was defined as an age recorded by two or more clasts in a single meteorite. The age of each event (1σ uncertainty values are in parentheses) was determined by fitting a normal distribution to the melt samples in the group.

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Event (Ga)</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAC 88105</td>
<td>3.35 (0.37)</td>
<td>5</td>
</tr>
<tr>
<td>MAC 88105</td>
<td>3.92 (0.14)</td>
<td>4</td>
</tr>
<tr>
<td>QUE 93069</td>
<td>3.00 (0.47)</td>
<td>3</td>
</tr>
<tr>
<td>QUE 93069</td>
<td>3.87 (0.23)</td>
<td>2</td>
</tr>
<tr>
<td>DaG 400</td>
<td>2.76 (0.38)</td>
<td>7</td>
</tr>
<tr>
<td>DaG 400</td>
<td>3.05 (0.13)</td>
<td>3</td>
</tr>
<tr>
<td>DaG 400</td>
<td>3.43 (0.10)</td>
<td>3</td>
</tr>
</tbody>
</table>

Ar ages of clasts from MAC 88105, QUE 93069 and DaG400 yield seven different impact events
Outstanding problems:
Have Apollo, Luna and meteorites provided enough samples to understand the Moon?

- Age of the Moon?
- Why are volatile elements depleted?
- What is the bulk composition of the Moon?: still large uncertainties in core-mantle-crust
- Late accretion events – how many?
  - Late veneer
  - Late Heavy Bombardment
  - Terrestrial atmospheric loss by late impact?

As more lunar meteorites are discovered, they will undoubtedly change our understanding of the Moon.
Want to know more?

- Washington University St. Louis
  Lunar Meteorite Webpage
  http://www.meteorites.wustl.edu/lunar/moon_meteorites.htm

- Lunar Meteorite Compendium
  NASA JSC Curation webpage
  http://curator.jsc.nasa.gov/antmet/lmc/index.cfm

- Planetary Science Research Discoveries (PSRD)
  http://www.psrd.hawaii.edu