TIMING OF LUNAR BASALTIC MAGMATISM: NEW INSIGHTS

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How do we know about lunar magmatism?

Landing sites

Meteorites
Basaltic magmatic activity on the Moon: Previous studies

<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>Group</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500</td>
<td>Group A</td>
<td>Apollo 11 (High-Ti)</td>
</tr>
<tr>
<td>3000</td>
<td>Group B1</td>
<td>Apollo 11 (High-Ti)</td>
</tr>
<tr>
<td>3500</td>
<td>Group B2</td>
<td>Apollo 14 (High-Al)</td>
</tr>
<tr>
<td>4000</td>
<td>Group A</td>
<td>Apollo 15 (KREEP)</td>
</tr>
<tr>
<td>4500</td>
<td>Group B</td>
<td>Apollo 15 (KREEP)</td>
</tr>
<tr>
<td>5000</td>
<td>Group C</td>
<td>Apollo 15 (KREEP)</td>
</tr>
<tr>
<td>6000</td>
<td></td>
<td>Luna 16 (Hi-Al)</td>
</tr>
</tbody>
</table>

Meteorites:
- KAL 009
- MIL 13317
- Y-793169
- A-881757
- MET 01210
- MIL 05035
- EET 96008
- Dhofar 287A (previous data)
- LAP 02205-LAP 02224 paired stones
- NWA 773 clan (previous data)
- NEA 003A
- NWA 4734 (previous data)
- NWA 032-NWA 479 paired stones

Analytical methods:
- O-C-Ar method
- Sm-Nd+Lu-Hf methods
- Rb-Sr method
- Pb-Pb isochron method
- Other U-Th-Pb methods

Main phase | Magmatic activity (remote sensing data)
Basaltic magmatic activity on the Moon: Previous studies

Continuous activity since 4400 Ma?
Main phase of activity: 3900-3200 Ma?
Basaltic magmatic activity on the Moon: Investigated samples

- NWA 4734: basalt (coarse-grained)
- Dhofar 287: basalt (coarse-grained)
- LAP 02224: basalt (coarse-grained)

- NWA 773 clan: 6 stones
  - NWA 2700: basalt (fine-grained)
  - NWA 2727: basalt (fine-grained)
  - NWA 773: gabbro
  - NWA 2977: gabbro
  - NWA 3170: gabbro
  - NWA 3333: gabbro

All basaltic rock types on the Moon are represented
Methodological approach

How to date lunar basaltic rocks?

• Classic radiometric techniques:
  – $^{40}\text{Ar} - ^{39}\text{Ar}$
  – Rb-Sr
  – Sm-Nd
  – U-Pb

Based on the radioactive decay of a element ($^{40}\text{K}$, $^{87}\text{Rb}$, $^{143}\text{Sm}$, $^{235}\text{U}$ and $^{238}\text{U}$) into a daughter element ($^{39}\text{Ar}$, $^{143}\text{Nd}$, $^{206}\text{Pb}$ and $^{207}\text{Pb}$)

• A novel approach:
  – In-situ Pb-Pb by SIMS
Methodological approach

How to date lunar basaltic rocks?

**Issues:**

- Few minerals suitable for dating (containing large quantities of parent element and no initial daughter element)

- Impossible to monitor the presence of terrestrial contamination (from sample prep., desert alteration)

- A novel approach:
  - In-situ Pb-Pb by SIMS
In-situ Pb-Pb dating by SIMS

Principle:

*Construction of $^{207}\text{Pb}/^{206}\text{Pb}$ vs $^{204}\text{Pb}/^{206}\text{Pb}$ isochrons from in-situ analyses of minerals containing Pb*

Advantages of SIMS Pb-Pb dating:

1) Analysis of Pb isotopes only
2) High spatial resolution
3) Monitoring terrestrial Pb contamination

CAMECA IMS1280 at NRM-Geovetenskap
$\frac{207\text{Pb}^*/206\text{Pb}^*}{204\text{Pb}^*/206\text{Pb}} = \frac{235\text{U}}{238\text{U}} \times \left( e^{\lambda_{235}t} - 1 / e^{\lambda_{238}t} - 1 \right)$

$\lambda$: decay constant
Spatial resolution:

Possibility of analysing small individual grains containing Pb

Analysis of phases formed during the late stage of crystallisation

- Phosphates
  (radiogenic + minor initial Pb bearing phase)
- Potassium feldspars
  (initial Pb bearing phase)
- Zr-oxides and -silicates
  (Baddeleyite, zircon, zirconolite: radiogenic Pb bearing phase)
Monitoring terrestrial Pb contamination

Data contaminated by terrestrial Pb tend to yield older dates

"Leftmost isochron"
Results I: coarse-grained basalts

Age = 2981 ± 12 Ma (95% confidence) on 18 points; MSWD = 0.60; Probability of fit = 0.89

Age = 3208 ± 22 Ma (95% confidence) on 33 points; MSWD = 1.4; Probability of fit = 0.077

Age = 2977 ± 13 Ma (95% confidence) on 42 points; MSWD = 1.2; Probability of fit = 0.18
Results II: gabbros (NWA 773 clan)

**NWA 3333**

- Age = $3038 \pm 20$ Ma (95% confidence)
- on 14 points; MSWD = 1.5;
- Probability of fit = 0.13

**NWA 2977**

- Age = $3085 \pm 9$ Ma (95% confidence)
- on 30 points; MSWD = 1.5;
- Probability of fit = 0.052

All data Terrestrial contamination filtered
Results III: fine-grained basalts (NWA 773 clan)

Age = 2871 ± 300 Ma (95% confidence)  
on 19 points; MSWD = 1.5;  
Probability of fit = 0.072

Age = 3081 ± 21 Ma (95% confidence)  
on 5 points; MSWD = 1.04;  
Probability of fit = 0.37
Summary of new ages

- **NWA4734**: 2981 ± 12 Ma
- **Dhofar 287**: 3208 ± 22 Ma
- **LAP 02224**: 2977 ± 13 Ma
- **NWA 773 clan**: 5 stones with reliable and precise ages
  - NWA 2727: 3081 ± 21 Ma
  - NWA 773: 3087 ± 7 Ma
  - NWA 2977: 3085 ± 9 Ma
  - NWA 3170: 3088 ± 11 Ma
  - NWA 3333: 3038 ± 20 Ma

  **Average age**: 3086 ± 5 Ma

  **Younger magmatic event**

  **2 magmatic events recorded in NWA 773 clan**
New age dataset

Data quality assessment required
(Based on methodological parameters)
Data filtering-Step 1: methodological criteria

- Dates with doubtful geological meaning: **Have to be discarded**
  - Unreliable methodology
    - Rocks suite isochrons
    - Whole-rock isochrons
    - Whole-rock K-Ar or Ar-Ar dating
      - Unpicked mineral or whole-rock fractions
    - No Ar degassing plateau developed (< 50% degassed Ar = disturbed patterns)
  - Statistically non-valid age calculation
    - Mean Square Weighted Deviation (MSWD) > 2; Probability of fit: P < 0.05
    - 2-points isochrons
  - Imprecise ages: Uncertainty > 3% (> 100 Myrs) = Too large to be meaningful

- "Age estimates": **Need careful data quality assessment**
  - Magmatic groundmass Ar-Ar plateau age
    - Hand-picked fractions only
  - Mini-plateau (50-70% degassed Ar)
    - Mineral fractions only
  - Whole-rock+ mineral Rb-Sr or Sm-Nd isochrons

Presence of impact melt and/or terrestrial alteration products

Analytical issues? Terrestrial contamination? Data reprocessing
Most of previously published U-Pb and Pb-Pb dates pass through the quality test.

Previous U-Pb and Pb-Pb data are older than new data.

Terrestrial Pb contamination?
Data filtering-Step 2:  
Tracing evidence of terrestrial contamination in U-Pb/Pb-Pb datasets

*Example from NWA 4734*

Previously published age:

3073 ± 15 Ma  
(weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age)

Isochron age calculation:

Model 1 Solution (±95%-conf.) on 22 points  
Age = 3056±18 Ma

MSWD = 4.6, Probability = 0.000
Data filtering-Step 2:
Tracing evidence of terrestrial contamination in U-Pb/Pb-Pb datasets

Example from NWA 4734

Comparison old data vs new data
Tracing evidence of terrestrial contamination in U-Pb/Pb-Pb datasets

Example from NWA 4734

Previous data filtered for terrestrial Pb contamination

New data

Wang et al., 2012

Identical ages

Age = 2981 ± 12 Ma (95% confidence)
on 18 points; MSWD = 0.60;
Probability of fit = 0.89

Recalculated age:
Model 1 Solution (±95%-conf.) on 7 points
Age = 2997±36 Ma
MSWD = 1.02, Probability = 0.40

Magmatic crystallisation isochron

Toward terrestrial Pb composition
Towards a new chronology of magmatic events on the Moon:

New filtered age dataset

Two magmatic phases: 3950-3575 Ma and 3375-3075 Ma
Pb initial ratios of lunar basalts

Low-Ti affinity

KREEP affinity

Progressive contribution of a KREEP-like component from 3400 Ma until 3100 Ma.
Summary

Geochronology:

- Two major magmatic phases on the Moon:
  - 3950-3575 Ma
  - 3375-3075 Ma

Isotope geochemistry:

- Progressive contribution of a KREEP-like component in the chemical characteristics of the low-Ti basalts from 3400 Ma until 3100 Ma