Martian Geochronology from Meteorites and Crater Counts

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Acknowledgments:
C.-Y. Shih, D. Bogard, J. Park
Introduction and Overview

- Current status of Martian meteorite (MM) ages
  - Methods, examples, and factors
  - No “old” shergottites
- Comparisons to cratering chronologies
  - Hartmann/Neukum
    - S. Werner’s 2005 Ph. D. thesis
  - Stöffler-Ryder derived curve
    - Implications for meteorite source regions
- Possibilities for calibrating the cratering curve
- Possibilities for dating secondary mineralization
  - Example: Nakhlite iddingsite.
    - VERY preliminary Rb-Sr studies of sulfates
- Some analytical requirements for *in situ* age dating
  - Mostly for Rb-Sr, Sm-Nd
Martian and Lunar Meteorite Ages and Cratering Chronology

Time before Present (Ga)

N(1) (km\(^{-2}\))

Lunar Meteorites

Martian Meteorites

Neukum et al. (2001) Moon

Lunar data

(Stoeffler & Ryder, 2001)

Mars = 1.55 x Lunar data

Werner (2005)

AAa2n

~AEC2

Werner (2005)

FH\(^2\) boundaries

% Surface Area

EN ~1%

MN/LN ~19%

H ~21%

EA ~9%

MA ~5%

LA ~2%
Werner (2005), Fig. 14.3. Geologic map from Tanaka et al. (2005) with numbered units for crater size-frequency distribution measurements by Werner.
Evolutionary History of Mars

Adapted from S. Werner (Thesis, 2005)
Adapted from Ph. D. Thesis of S. Werner (2005; Fig. 15.13)
Cum. Crater Frequency (km$^{-2}$) at D=1km

From S. Werner (Thesis, 2005, Fig. 14.11)
Impact Chronology of Mars

Nyquist (2005) : Revised Martian Crater Curve
(= Stoeffler & Ryder (2001) Lunar x 1.55)

Martian Meteorites (solid symbols)
- NDDS melts unsampled

Time before Present (Ga)

Surface Area (Vol. %)

EN
LN/MN
Hesperian

A
Hartmann & Neukum (this paper)
Stratigraphy:
Crater frequency data from Tanaka (1986)
Percentage of Exposed Volcanics on Modern Mars in Each Epoch

Time before Present (Ga)

Surface Area %

Noachian  Hesperian  Amazonian

Hartmann/Ivanov

Neukum/Ivanov

N  H  A

0  5  10  15  20  25  30
Basaltic Shergottite - NWA 1460

$^{147}\text{Sm}/^{144}\text{Nd}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$

- **interior**
- **fines**

- $T = 350 \pm 16$ Ma
- $\delta^\text{Nd} = +10.6 \pm 0.5$

Insert data points and labels:
- $\text{Leach}$
- $\text{WR2}$
- $\text{WR2(l)}$
- $\text{Plag2(r)}$
- $\text{Opq(r)}$
- $\text{Plag(r)}$
- $\text{Px1(r)}$
- $\text{Px2(r)}$
- $\text{Px2a(r)}$

- $\delta^\text{Nd}$ values:
  - $-0.8$
  - $-0.4$
  - $0.0$
  - $0.4$
  - $0.8$

- Time intervals:
  - $-16$ Ma
  - $+16$ Ma

Insert notes:
- $T = 350 \pm 16$ Ma
- $\delta^\text{Nd} = +10.6 \pm 0.5$
Basaltic Shergottite - NWA 1460

NWA 1460 - Plag
6-98% $^{39}$Ar

Age = 334±19 Ma
$^{40}$Ar/$^{36}$Ar$_{Tr}$=434±97
$^{36}$Ar/$^{37}$Ar=0.000456

Age = 353±16 Ma
$^{40}$Ar/$^{36}$Ar$_{Tr}$=372±98
$^{36}$Ar/$^{37}$Ar=0.000589
Zagami FG-Plag

Isochron plot of $^{40}\text{Ar}/^{36}\text{Ar}$ vs $^{39}\text{Ar}/^{36}\text{Ar}$

Isochron Age

= ? 300 Myr

$^{40}\text{Ar}_{xs}$ is distributed through the lattice

Bogard & Park (2008)
Slide courtesy of J. Park

Larger $^{40}\text{Ar}_{xs}$ (at intermediate temp extractions 23-54% of $^{39}\text{Ar}$ )

“hump”:

$^{40}\text{Ar}/^{36}\text{Ar}$= ? 1000 (could be Martian atm in a shock produced phase)
Excess 40Ar in Zagami Mineral Separates

Values calculated by subtracting from measured 40Ar, the amount of 40Ar* in situ, assuming Zagami formation age of 170 Myr.

<table>
<thead>
<tr>
<th>Phase</th>
<th>40Ar$_{xs}$</th>
<th>% total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG-Plag</td>
<td>15.7x 10^{-7} cm$^3$</td>
<td>32</td>
</tr>
<tr>
<td>FG-Plag*</td>
<td>23.4 (17.9)x 10^{-7} cm$^3$</td>
<td>54</td>
</tr>
<tr>
<td>CG-Px2</td>
<td>10.8x 10^{-7} cm$^3$</td>
<td>85</td>
</tr>
<tr>
<td>FG-Px 2</td>
<td>9.2x 10^{-7} cm$^3$</td>
<td>86</td>
</tr>
<tr>
<td>FG-Px 1</td>
<td>15.3x 10^{-7} cm$^3$</td>
<td>89</td>
</tr>
</tbody>
</table>

(*Second value for FG-Plag subtracts the trapped component with 40Ar/36Ar=1000.)

No significant difference between CG & FG, nor between Plag & Pyx

Bogard & Park (2008) suggest

40Ar$_{xs}$ = $\nabla$1-2x10^{-6} (in cm$^3$STP/g)

Similar 40Ar excesses are also observed in other shergottites (Bogard, Park & Garrison, 2008, submitted. Courtesy of J. Park)
For Nakhlites: Common Age; No Evidence of Significant Excess $^{40}$Ar

**Isochron Age** = $1325 \pm 18$ Myr

**$R^2$** = 0.9986

Nakhlites

<table>
<thead>
<tr>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIL03346</td>
</tr>
<tr>
<td>NWA-998</td>
</tr>
<tr>
<td>Y-000593</td>
</tr>
<tr>
<td>Nakhla</td>
</tr>
<tr>
<td>Gov. Valadares</td>
</tr>
<tr>
<td>Lafayette</td>
</tr>
<tr>
<td>Chassigny</td>
</tr>
</tbody>
</table>

For Nakhlites:

- Common Age
- No Evidence of Significant Excess

**Total $^{40}$Ar cm$^3$/g**

Courtesy D. Bogard
Common Age and 10-22 x10^{-7} cm^3/g Magma-Derived $^{40}$Ar

Shergottites

All 170 Myr Isochrons

<table>
<thead>
<tr>
<th>[K] ppm</th>
<th>0</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Total $^{40}$Ar, 10^{-7} cm^3/g</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
</tr>
</thead>
</table>

- Zagami
- Los Angeles
- NWA3171
- Shergotty
- NWA2975, 1068
- Y-00097, 793605
- EET79001

High-K Plag
Low-K Pyx
Mid-K WR

Courtesy of D. Bogard
Shergottites

Zagami Mask. leach (Bouvier et al. 2005)

95% conf. intervals

"4.0" Ga line

Assimilant range

MT

Zagami LA

Shergotty

(207 Pb/206 Pb) \text{i}

(204 Pb/206 Pb)
Shergottites

\[
\frac{^{204}Pb}{^{206}Pb} \quad \frac{^{87}Sr}{^{86}Sr}
\]


- Zagami
- Shergotty
- Bouvier et al

Assimilant range

95% conf. intervals

~0.064

~0.725
Figure 1 from Nimmo and Tanaka (2005)
Ann. Rev. Earth Planet. Sci., 33, 133-161
Surface ages from Hartmann et al. (1981)
Gusev Crater with Apollinaris Patera

Image and Age Ranges Courtesy of K. Tanaka

Young Elysium Volcanics ~100 Ma

Apollinaris Patera
3.7 to ~3.1 Ga

Gusev

~3.6 to ~1.8 Ga

~3.7 Ga

Gusev Crater with Apollinaris Patera
Image and Age RangesCourtesy of K. Tanaka
Nakhlite - MIL 03346

\[ T = 1.36 \pm 0.03 \text{ Ga} \]

\[ ?_{\text{Nd}} = +15.2 \pm 0.2 \]

\[ \frac{^{143}\text{Nd}}{^{144}\text{Nd}} \]

\[ \frac{^{147}\text{Sm}}{^{144}\text{Nd}} \]

\[
\begin{array}{cccc}
\text{Ol} & \text{Ol2} & \text{Ol1} & \text{Gl} \\
\text{Cpx2(l)} & \text{WR(l)} & \text{WR1} & \text{Cpx2(r)}
\end{array}
\]

\[
\begin{array}{cccc}
\text{Cpx1} & \text{Cpx3} & \text{WR1,2(r)} & \text{Cpx2(r)}
\end{array}
\]

\[
\begin{array}{cccc}
\text{T = 1.36 ± 0.03 Ga} & ?_{\text{Nd}} = +15.2 ± 0.2 & +30 \text{Ma} & -30 \text{Ma}
\end{array}
\]
\[ \frac{87\text{Rb}}{86\text{Sr}} \] vs. \[ \frac{87\text{Sr}}{86\text{Sr}} \] plot for Nakhlite - Lafayette.

- \( T = 1.26 \pm 0.07 \text{ Ga} \)
- \( I_{\text{Sr}} = 0.70260 \pm 0.00014 \)

Shih et al. (1998)
Kuebler et al. (2003) A study of olivine alteration to iddingsite using Raman spectroscopy. LPSC34.

“Iddingsite...a catch-all term to describe reddish alteration products of olivine...an Å-scale intergrowth of goethite and smectite (saponite)...

“Alteration conserves Fe (albeit oxidized), but requires addition of Al and H₂O and removal of Mg and Si.”

Kuebler et al. (2003), Fig. 2.
Orthopyroxenite ALH84001

Clark et al. (2005) Chemistry and mineralogy of outcrops at Meridiani Planum. EPSL 240, 73-94. Fig. 12 showing the modeled mineral components of outcrops at Endurance, Fram, and Eagle Craters from the APXS and MB instruments. Modeled total sulfate abundance is 35 % for $\text{SO}_3 = 20\%$. 
Outcrop sulfates at the Opportunity Site, Meridiani Planum (Mini-TES; Glotch et al. (2006) JGR 111, E12SO3)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>“Base Model”</th>
<th>Terr. Rb-Sr</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na-jarosite</td>
<td></td>
<td>Y</td>
<td>LNVJAR1-FP</td>
</tr>
<tr>
<td>NaFe$_3$(SO$_4$)$_2$(OH)$_6$</td>
<td>10% (5% ?)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-jarosite</td>
<td></td>
<td>Y</td>
<td>GCJAR1-FP</td>
</tr>
<tr>
<td>KFe$_3$(SO$_4$)$_2$(OH)$_6$</td>
<td>(5% ?)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kieserite</td>
<td></td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>MgSO$_4$·H$_2$O</td>
<td>20%</td>
<td></td>
<td>KIEDEI</td>
</tr>
<tr>
<td>Anhydrite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaSO$_4$</td>
<td>10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gypsum</td>
<td></td>
<td>Y</td>
<td>WD164A1</td>
</tr>
<tr>
<td>CaSO$_4$·2H$_2$O</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Terrestrial sulfate samples courtesy of R. Morris
Preliminary Rb-Sr Study of Terrestrial Sulfates

• K-Jarosite – KFe$_3$(OH)$_6$(SO$_4$)$_2$ (15 mg)
  – GCJAR1-FP (New Mexico)
  – Readily soluble in HF+HNO$_3$

• Na-Jarosite – NaFe$_3$(OH)$_6$(SO$_4$)$_2$ (16 mg)
  – LNVJAR1-FP (Nevada)
  – Readily soluble in HF+HNO$_3$

• Gypsum – CaSO$_4$·2H$_2$O (16 mg)
  – WD164A1 (Italy)
  – Insoluble in hot water, soluble in 1N HCl

• Kieserite – MgSO$_4$·H$_2$O (26 mg)
  – KIEDEI (Germany)
  – Insoluble in room temperature H$_2$O (15 min)
  – Soluble in hot H$_2$O (1 hr)
Hypothetical Sr-Isotopic Evolution in Ancient Sulfates with Terrestrial-Sample Rb/Sr ratios

Gypsum (WD164A1)

Na-Jarosite (LNVJAR1)

Kieserite (KIEDE1)

K-Jarosite (GCJAR1)

Ancient alteration $T=4.56$ Ga
Mauna Kea Basaltic Tephra & Jarosite

- Altered tephra
- Jarosite
- Fresh tephra

Sm (ppm) vs Nd (ppm) plot.
Mauna Kea Basaltic Tephra & Jarosite

Basalt age
T(Ar-Ar) = 400 ± 26 Ka
(Sharp et al. 1996)

Maximum Jarosite Age
T = ~400 Ka; ?Nd = +6.5

Tephra-Jarosite errorchron
T = 230 ± 140 Ma

Fresh tephra

Altered tephra

Jarosite

\[
\frac{^{143}\text{Nd}}{^{144}\text{Nd}} \quad \text{vs.} \quad \frac{^{147}\text{Sm}}{^{144}\text{Nd}}
\]
Mauna Kea Basaltic Tephra & Jarosite

- Maximum Jarosite Age: $T=\sim400$ Ka; $I(Sr)=0.703451$

- Tephra alteration errorchron: $T=5.1\pm1.8$ Ma

- Basalt age: $T(Ar-Ar)=400\pm26$ Ka (Sharp et al. 1996)
Basaltic Shergottite - NWA 1460

Bulk Rock Acid-leaching Experiment

$^{147}\text{Sm}/^{144}\text{Nd}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$

- **Interior**
- **Fines**

$T = 354 \pm 22$ Ma

$\delta_{\text{Nd}} = +10.5 \pm 0.5$

Acid-leachates

Acid-residues

$147\text{Sm}/^{144}\text{Nd}$

$\delta_{\text{Nd}}$

+22 Ma

-22 Ma
Basaltic Shergottite - NWA 1460

Bulk Rock Acid-leaching Experiment

- interior
- fines

**T(Min.)** = 336 ± 15 Ma
**I(Sr)** = 0.708968 ± 30

**T(WR)** = 170 ± 36 Ma
**I(Sr)** = 0.709329 ± 61

Basaltic Shergottite - NWA 1460

Bulk Rock Acid-leaching Experiment
Martian Meteorites

Orthopyroxenite
T=~4.56 Ga

Shergottites
T=~165 Ma

Nakhlites
T=~1.3 Ga

Depleted shergottites
T=327-575 Ma

Olivine-shergottites
T= ~165 Ma

87Rb/86Sr, 87Sr/86Sr errors:
±10%
±5%
±1‰
Martian Meteorites

- Orthopyroxenite
  - $T = \sim 4.56 \text{ Ga}$

- Nakhliites
  - $T = \sim 1.3 \text{ Ga}$

- Shergottites
  - $T = \sim 165 \text{ Ma}$
  - Olivine-shergottites
    - $T = \sim 165 \text{ Ma}$

- Depleted shergottites
  - $T = 327-575 \text{ Ma}$

- $^{147}\text{Sm}/^{144}\text{Nd}$
  - Errors
    - $\pm 1\%$
    - $\pm 1\%$
    - $\pm 1\%$
    - $\pm 10\%$
    - $\pm 5\%$
Summary and Conclusions

- Large inherent uncertainty in cratering chronologies
  - Date an Early-Mid Amazonian (~1-3 Ga) surface to calibrate.
  - Gusev-like site probably OK
  - Absolute dating of the Hesperian/Noachian also desirable.
  - Better for “life”, “late heavy bombardment” issues.
  - Meridiani-like site may be OK

- Dating aqueous activity/secondary minerals/life habitats
  - Hard, even for laboratory-based geochronology.
  - Isochron methods (esp. Rb-Sr) look promising
  - Ar-Ar techniques also should be investigated.
  - Micro-beam techniques available for a returned sample.
  - SIMS: shergottite phosphates, baddeleyite; nakhlite phos.

- In Situ Dating
  - Hard to impossible by traditional methods
  - Best bet: redundant methods
    - K-Ar with gas source mass spectrometer
    - Automated chemistry lab for simple leaching, etc., with solids source mass spec (TIMS)
### Outcrop sulfates at the Opportunity Site, Meridiani Planum

(Mini-TES; Glotch et al. (2006) JGR 111, E12SO3)

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Terrestrial sulfate samples courtesy of R. Morris
Figure 13.1: The volcanic provinces of Mars are indicated in yellow. Known central vent constructs are displayed in red. The individual volcanoes are assigned in separate maps. The topographic dichotomy is shown in blue for the lowland parts and green for the highland parts. Large impact structures are shown in white. The background topography is given as a MOLA shaded-relief map.
Mauna Kea Basaltic Tephra and Jarosite
(Two End-member Mixing Model)

For Sr:
Jarosite=~75% Marine aerosol + ~25% Tephra

Sr (ppm)

87Sr/86Sr

Marine aerosol (contaminant)

% of Marine aerosol in Tephra

Jarosite (~75% aerosol)

Fresh Tephra
Mauna Kea Basaltic Tephra and Jarosite
(Two End-member Mixing Model)

For Nd:
Jarosite = ~50% Marine aerosol + ~50% Tephra

Aerosol (contaminant)

Jarosite (~50% aerosol)

Fresh Tephra

% of Aerosol in Tephra

Nd (ppm)

143Nd/144Nd

0 10 20 30 40 50 60 70

0.5110 0.5112 0.5114 0.5116 0.5118 0.5120 0.5122 0.5124
Nakhlite - Y000593

"Iddingsite"
\[ T=650\pm80 \text{ Ma} \]

\[ \frac{87\text{Rb}}{86\text{Sr}} \]
\[ \frac{87\text{Sr}}{86\text{Sr}} \]

\[ \text{Ol}(r) \]
\[ \text{Ol}(l) \]
\[ \text{Ol(residues)} \]
\[ \text{T}=614\pm29 \text{ Ma} \]

\[ \text{Cpx2}(r) \]
\[ \text{Cpx}(r) \]
\[ \text{Cpx2}(l) \]
\[ \text{Cpx}(l) \]
\[ \text{WR}(r) \]
\[ \text{WR}(l) \]
\[ \text{WR1} \]
\[ \text{NM}(r) \]
\[ \text{NM}(l) \]

\[ \text{T}=1.30\pm0.02 \text{ Ga} \]
\[ I(\text{Sr})=0.702525\pm27 \]

Misawa et al. (2005) Antarct. Met. Res., Fig. 3
Lunar Mare Basalt Meteorite - Kalahari 009

\[ T = 4.30 \pm 0.05 \text{ Ga} \]
\[ ?_{\text{Nd, CHUR}} = +0.83 \pm 0.47 \]
\[ ?_{\text{Nd, HEDR}} = -0.04 \pm 0.47 \]
Crystallization and Ejection Ages of Martian Meteorites

Compared to Martian Epochs with Hartmann/Neukum (2001) Ages

Lyon Hypothesis

H/N

EA

Nakhlites & Chassigny

DaG, Y98

Dho

NWA 1195

480/1460, QUE

Local Stratigraphy?

LA

EET

BU

PE

A77, LEW, Y79

Zag, She, LA, 856

1068

Basaltic shergottites

Lherzolitic shergottites

Dunite (Chassigny)

Clinopyroxenites (Nakhlites)

Orthopyroxenite

Compared to Martian Epochs with Hartmann/Neukum (2001) Ages

Lyon Hypothesis

H/N

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Basaltic shergottites

Lherzolitic shergottites

Dunite (Chassigny)

Clinopyroxenites (Nakhlites)

Orthopyroxenite
Hypothetical Sr-Isotopic Evolution in Sulfates with Terrestrial-Sample Rb/Sr ratios

- Basalt crystallization
  - T = 180 Ma
- Recent alteration
  - T = 10 ± 1.4 Ma

- Gypsum
- Na-Jarosite
- Kieserite
- K-Jarosite