Crater counting and Implications for the history of Mars

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Why to study cratering?

Age determination

Key to sub-surface properties

Implication for the target (strength, volatile content)

Clues for the evolution of the surface ... and the planet
Craters to Surface Ages

- Assume the rate of impact crater formation is known
  The rate has a size-dependence
- Assume that cratering process is \textit{spatially and temporally random}
- Divide the surface into units based upon geologic criteria
- Calculate areal density of craters
  Relative differences give relative ages

- Convert to absolute age
Cratering of Planetary Surfaces
Resurfacing occurs ...

\[ N_{\text{cum}} (D, t) = \int_{D} \int_{0}^{t} g(D') \, dD' \cdot f(t') \, dt' \]
Partially Eroded Surfaces

\[ N_{eros} = \int_{D_{min}}^{D_{max}} g(D') dD' \cdot \int_{t_{0}}^{t_{e}} f(t') dt' \]

+ \int_{t_{e}}^{t_{max}} g(D') dD' \cdot \int_{t_{e}}^{t_{max}} f(t') dt'
Nature is not always cooperative
Crater counting results
Erosion ages...

How do they appear in crater size frequency distributions?
An example
Why to study cratering?

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(strength, volatile content)

Clues for the evolution of the surface
... and the planet
Lunar Crater Collection

Simple Crater

- Breccia
- Impact melt
- Impact ejecta
- Fractured bedrock
- Central peak uplift

Complex Crater
Martian Crater Collection

Rampart

Pedestal
Subsurface Water or Ice

Lobate Ejecta

Permafrost Structures

Chaotic terrain due to water activity
Characteristics of planets

- Cratering on Mars (but also on Earth) is significantly affected by the presence of subsurface ice or water.

- High volatility of H$_2$O modifies the crater formation process, resulting in more vapour production, higher ejection angles, fluidized ejecta blankets.

- Visible in the ejecta distribution (rampart crater) and crater floor morphology (pit crater).

- Strong erosion /overburden due to presence atmosphere and water/ice.

- Atmosphere is shielding the surface, similarly oceans on Earth, only large projectiles form craters.
Cratering Mechanics

Contact and Compression
Excavation
Modification
Hydrocode Simulation

- Numerical description of highly dynamical events (shock)
- Following principles of conservation of mass, momentum, and energy
- EOS (density/volume, temperature, pressure)
- Material properties (e.g., stress, strain)
Hydrocode Simulation

Puchezh-Katunki impact crater (Russia)

Geological cross section

Computer model

sediments

crystalline basement

Vorobiofskaya deep drill hole (5 km)

horizontal distance (km)
Fresh-looking 30-km crater

Werner et al., 2004
Model crater parameters vs. MOLA data

Werner et al., 2004

Observational data
(Garvin et al., 2003)

Good fit for crater depth, rim height and central mound width

Poor fit for central peak height: computed peak is too high.
Lowell
Werner et al., 2004

- Diameter ~ 220 km
- Max depth (below surface) 2950m
- Depth in trough ~2050m
- Inner rim crest depth ~1000 m
Lyot
Werner et al., 2004

Age 3.4 Ga
Diameter ~ 240 km
Max depth (below surface) 3000 m
Depth in trough ~2000 m
Inner rim crest depth 0-1500 m(!)
Basins larger D~200 km

Werner et al., 2004

6 basins are studied. All more than 3.5 Ga old.
It should reflect early Martian crust properties

<table>
<thead>
<tr>
<th></th>
<th>Crater diameter D, km</th>
<th>Max. apparent depth, $h_{a,max}$, m</th>
<th>Apparent depth of inner rim crest $h_{irc}$, m</th>
<th>Approximate pre-impact altitude, m</th>
<th>Visible state</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kepler</td>
<td>230</td>
<td>1200</td>
<td>800</td>
<td>+2300</td>
<td>partially filled</td>
</tr>
<tr>
<td>Lowell</td>
<td>240</td>
<td>3000</td>
<td>~1000</td>
<td>+1500</td>
<td>partially filled</td>
</tr>
<tr>
<td>Galle</td>
<td>230</td>
<td>2900</td>
<td>1500</td>
<td>-300</td>
<td>partially filled</td>
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<tr>
<td>Secchi</td>
<td>240</td>
<td>1900</td>
<td>1300</td>
<td>+2200</td>
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<tr>
<td>Flaugergues</td>
<td>250</td>
<td>1100</td>
<td>&gt;1100</td>
<td>+150</td>
<td>heavily filled</td>
</tr>
<tr>
<td>Lyot</td>
<td>220</td>
<td>3400</td>
<td>~200</td>
<td>-3600</td>
<td>slightly filled</td>
</tr>
</tbody>
</table>
... show that Martian crust in Northern lowlands differ from equatorial highlands (in Early Hesperian time)
Why to study cratering?

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Implication for the target (strength, volatile content)

Clues for the evolution of the surface ... and the planet
Crater Distribution on Mars

Craters: 250 km > D > 5 km, after Barlow (2001)
Planetary formation

1. Disk formation
2. Dust sedimentation
3. Planetesimal formation
4. Solid planets formation
5. Gaseous planets formation
6. Disk dissipation
Orbit and Spin
The Asteroid Belt

Asteroid distribution

- Number of asteroids
- Percentage of asteroids of a given class

- Main belt
- Outer belt
- Mars 1.5 AU
- Jupiter 5.2 AU
- Resonances with Jupiter
- Gap
- Concentration
- Hildas
- Trojans

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Normalization

3.25 Ga Isochron
Impact Mechanics

Ivanov, 2001
Moon as a Reference System

lunar impact crater production function
single projectile source (asteroid belt)
Cratering on Mars

Neukum et al., 2001
Lunar Cratering Chronology
Cratering rate scaling

Ivanov, 2001
Transfer of the Lunar Cratering Chronology to Mars
Ivanov, 2001

Lunar Cratering Chronology

Martian Cratering Chronology

Model

(Adjustment of the relative cratering rates Moon/Mars, impact mechanics; assumption of the same time dependence)

\[ N(1\text{km}) = 5.44 \times 10^{-14} \exp(6.93t_A) - 1 + 8.38 \times 10^{-4}t_A \]

\[ N(1\text{km}) = 2.68 \times 10^{-14} \exp(6.93t_A) - 1 + 4.13 \times 10^{-4}t_A \]

\( N(1\text{km}) \): cumulative crater frequency for craters of diameter equal to and larger than 1km

\( t_A \): age of the measured surface in billion years (Ga)
Martian Chronology Model
Ivanov, 2001; Hartmann & Neukum 2001

Hartmann & Neukum (2001)

Stratigraphy:
Crater frequency data from Tanaka (1986)
with redefinition of the Lower Amazonian base
crater frequency (Hartmann & Neukum, 2001)

Age, Gyr
Different SFDs

Werner et al., in prep.

Cumulative SFD (Ivanov, 2001)
Cumulative SFD (this study: after Hartmann, 2005)
minus-two slope distribution
Series Boundaries

Werner et al., in prep.
Moon as a Reference System

radiometric ages of lunar samples, established lunar chronology

the idea of a marker horizon
which is reflected in the lunar data for the impact rate
(time derivative of the chronology function) in combination with the
c characteristics of the production function

a reliable Mars/moon impact rate ratio
Chronostratigraphy of Mars

Characteristics of the record of the heavy bombardment on Moon and Mars in comparison

Derivation of ages of the lunar and Martian crusts through determination of the basin ages:

How far do we look back?
Crater Distribution on Mars

Craters: D > 5 km, after Barlow (2001)
Martian Basins
Mapping & Dating Basins

Crater Retention Age $N(1) = 1.31E-02$
Crater Retention Age $N(10) = 1.07E-04$
Cratering model age : 3.84 Reons
Basin distribution in time

![Bar chart showing the distribution of ages in Ga for different basins. The chart includes data from Mars (this work), the Moon (Wilhelms, 1987), and the Moon (Wilhelms, 1987; Neukum, 1983), as well as the age of Nectaris. The x-axis represents ages in Ga, ranging from 3.4 to 4.3, and the y-axis represents frequency. The chart includes arrows indicating ages plus 10 Ga.]
Martian evolution

Accretion and differentiation

Crust formation

Strongest magnetized crust
Limit of crater count method

Crustal Dichotomy

Dynamo stops

Morphologic Dichotomy

ALH84001 - Carbonates

Argyre

Utopia

Acidalia

Lyot

Nakhlites

Shergottites

Meteorites

EN

MN

LN

EH

LA

MA

EA

LH

Cum. Crater Frequency (km$^{-2}$) at D=1km

0.02

0.01

0.001

0.0001

0.00001

0.000001

0.0000001

0.00000001

Cratering Model Age (Ga)

0

1

2

3

4

5

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Physics of Geological Processes

EPOCHS

LOWLANDS

HIGHLANDS

Impact Basins

$10^{-5}$
The secondary-crater strewn field of Zunil
McEwen et al. (2005)

- 10-km crater in the youngest region of Mars, Cerberus Planitia
- Secondary craters in a radial distance of up to 1000 km
- Secondary craters exceeds the number of primaries at the smaller-size range enormously
- Steep branch due to secondaries
- Age determination impossible…

What is the *real* shape of the *primary* crater size-frequency distribution? and
Is *age determination* based on crater counts possible?
The secondary-crater strewn field of Zunil

Crater Size-Frequency Measurements

- Clustered dark haloed pits (Zunil secondaries) show a steeper distribution, $N \sim D^{-4}$
- Secondaries dominate at crater diameters below 100 m (primaries range between 500 m to 60 m)
- Misinterpretation of up to a factor of 2 in age
Secondary Cratering 1

CONs for a steep primary crater distribution

- Small-size range of the asteroid population not well known
- Secondary cratering observed (clusters, chains), which can reach large distances
- Secondaries exceed number of primaries
- Unrecognized *background secondary* craters could exist (Shoemaker (1965) TR, JPL)
- Unknown number of secondary crater contribution (variable steepness of the observed crater distribution)

❓ Is *age determination* possible using the crater frequencies below 1 km diameter?
Secondary Cratering 2

PROs for a steep primary crater distribution

- Near-Earth asteroids, fireballs hitting Earth’s atmosphere fit lunar CSFD (Werner et al., 2002; Ivanov, 2005)
- Measured on Gaspra, asteroid belt, the source region of inner solar system projectiles (Neukum & Ivanov, 1994)
- Show up in differently aged surface of different planets, and fit lunar CSFD
- Clusters, chains, and other features related to secondary (ejecta) cratering, are not considered in the counts
- ... cf. Hartmann (2005)
Distal fragments origin
Ivanov, 2006

1 km asteroid oblique impact

velocity, km/s
- 0.16 to 1.16
- 1.16 to 1.72
- 1.72 to 2.40
- 2.40 to 3.87
- 3.87 to 9.87

max. shock pressure, GPa
- 50 to 1000

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PHYSICS OF GEOLOGICAL PROCESSES

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Close and remote secondaries
Shoemaker, 1965

“reference curve” is a 
-4 slope approximation

“rollover” is seen just in 
original figures
Trial case for “rollover”: Weibull SFD

Ivanov, 2006

\[ V(>x) = V_0 \exp[-(x/x_0)^n] \]
\[ dV/dx = (V_0/x_0) (x/x_0)^{n-1} \exp[-(x/x_0)^n] \]
\[ R = x^3 (dN/dx) = dV/dx \]

Widely used to describe explosion fragmentation and mills efficiency

Arakawa, 99
Rim boulders, lunar crater
Bart & Melosh, 2005

defend −4 slope.

However, their careful boulder count in R-plot shows rollover at half of magnitude below max. size.

Fig. 8.13. R-plot for boulders counted by Bart and Melosh (2005) with power law (cumulative m=4), Weibull (8.31) and lognormal SFD fits. Bell-shaped SFD looks like a better proxy for data presentation in comparison with a power law fit. Left of the maximum observational data are going closer to the lognormal model. However, usual “undercounting” of small objects close to an image resolution image makes Weibull SFD equally perspective for future study.
Moon
Ivanov, 2006

R-plot shows rollover at \(~1/3 \ D_{2\text{max}}\)

Assumed production function is dramatically different

Basin secondaries – 1 to 1.5 km s\(^{-1}\): “remote” for smaller craters

Fig. 8. 14. R-plot for close secondary craters around lunar basins (Wilhelms et al. 1978) and craters (Block and Barlow 2005, Wilhelms et al. 1978) in comparison with the assumed production function exemplified with the NPF curve. Remote secondary craters are counted by Settle et al. (1979) for a small lunar crater with the diameter of 4.9 km at distances of 17 to 19 km corresponding to the ejecta velocity of 200±50 m s\(^{-1}\). Hartmann’s equilibrium is shown as dashed line for comparison. All curves for SFD of secondaries have a “bell-shaped” form. For comparison Neukum’s model isochrons (Neukum et al. 2001a) are shown for a set of surface ages.
Mars
Ivanov, 2006

HRSC, Zunil, v~ 1 km s^{-1}
Zunil’s “close” secondaries have “normal” size

Ivanov, 2006
Hypothetical Crater Distribution for an 1-Ga old Martian Surface

- flat primary distribution (N ~ D^{-2})
- largest possible secondary crater diameter is a factor of 0.05 of the largest primary
- unrecognized background secondaries are responsible for the smaller size range craters (steep distribution, N ~ D^{-3}, -3.5, -4)
- secondary crater distribution: N ~ D^{-4}
Hypothetical Crater Distribution for an 1-Ga old Martian Surface

- Flattening for craters smaller than $0.7 \ D_{\text{SEC}}^{\text{max}}$ is observed by König, 1977 ($N \sim D^{-2.5}$) on the Moon.

- Summed cumulative secondary crater distributions are most suitably represented by distributions between $N \sim D^{-3}$ and $N \sim D^{-3.5}$.

- Total hypothetically observed distribution is the sum of the primary and secondary crater distributions.
Hypothetic secondary crater contribution for two possible different slope indices (-3.0 and -3.5):

- Contribution generally below 10% or
- Contribution of more than 100%, which does not fit the observed distributions.

The shape of the distribution would vary with surface age...
Age dependence
Surface Age Dependence of...

- the contributing max. primary crater
- the contribution max. secondary crater
- crossover diameters, implying that the onset of the secondary crater branch moves to larger diameters for older surfaces...

... that is not observed!
Summation of secondary craters
created by ejecta from primaries

Melosh et al. 1992
The Evolutionary History of Mars
Crustal Thickness and Magnetic Anomaly Maps

Acuna et al. (2001)

Zuber et al. (2000)
Evolutionary History of Mars

- EPOCHS
  - LOWLANDS
    - Fluvial activity triggered by volcanism
    - Outflow deposition ended Outflow channel formation
    - Youngest possible Ocean Northern Lowland basement
  - IMPACT BASINS
    - Tharsis
    - Medusae Fossae Fm.
  - HIGHLANDS
    - Elysium
    - Elysium
    - Vents
    - Global Volcanism
    - Utopia
      - Argyre
        - ALH84001 - Carbonates
      - Hellas and Isidis
    - Shergottites
    - Nakhla
      - Shergottites
    - Episodic glacial activity outside the polar regions

- Cum. Crater Frequency (km^-2) at D=1km
  - LA
  - MA
  - EA
  - LH
  - EH
  - LN
  - MN
  - EN

- Cratering Model Age (Ga)
  - 4.5
  - 4.4
  - 4.3
  - 4.2
  - 4.1
  - 4.0
  - 3.9
  - 3.8
  - 3.7
  - 3.6
  - 3.5
  - 3.4
  - 3.3
  - 3.2
  - 3.1
  - 3.0
  - 2.9
  - 2.8
  - 2.7
  - 2.6
  - 2.5
  - 2.4
  - 2.3
  - 2.2
  - 2.1
  - 2.0
  - 1.9
  - 1.8
  - 1.7
  - 1.6
  - 1.5
  - 1.4
  - 1.3
  - 1.2
  - 1.1
  - 1.0
  - 0.9
  - 0.8
  - 0.7
  - 0.6
  - 0.5
  - 0.4
  - 0.3
  - 0.2
  - 0.1
  - 0.05
  - 0.02
  - 0.01
  - 0.005
  - 0.0005

- Crust formation
  - Limit of crater count method
  - Strongest magnetized crust
  - Crustal Dichotomy
  - Atmospheric escape
  - Dynamo stops
  - Valley Networks

- Accretion and differentiation
Implications of the Results

• time frame for thermo-dynamical evolution of Mars (e.g. magnetic field cessation, volcanic activity in time and space) which can form input to thermal evolution models for Mars (and planetary models in general)

• indications for timing of an Martian water cycle

• youngest activity: Volcanism, triggering ground ice melting (fluvial activity);
  episodic formation of ice-containing landforms over the last 500 Ma

• Comparative planetology: The Martian entire geological evolution is still recorded on its surface and give clues about how planets can evolve in comparison with other terrestrial bodies