Crater counting
and
Implications for the history of Mars

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Physics of Geological Processes

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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 an size-dependence

- Assume that cratering process is spatially and temporally random

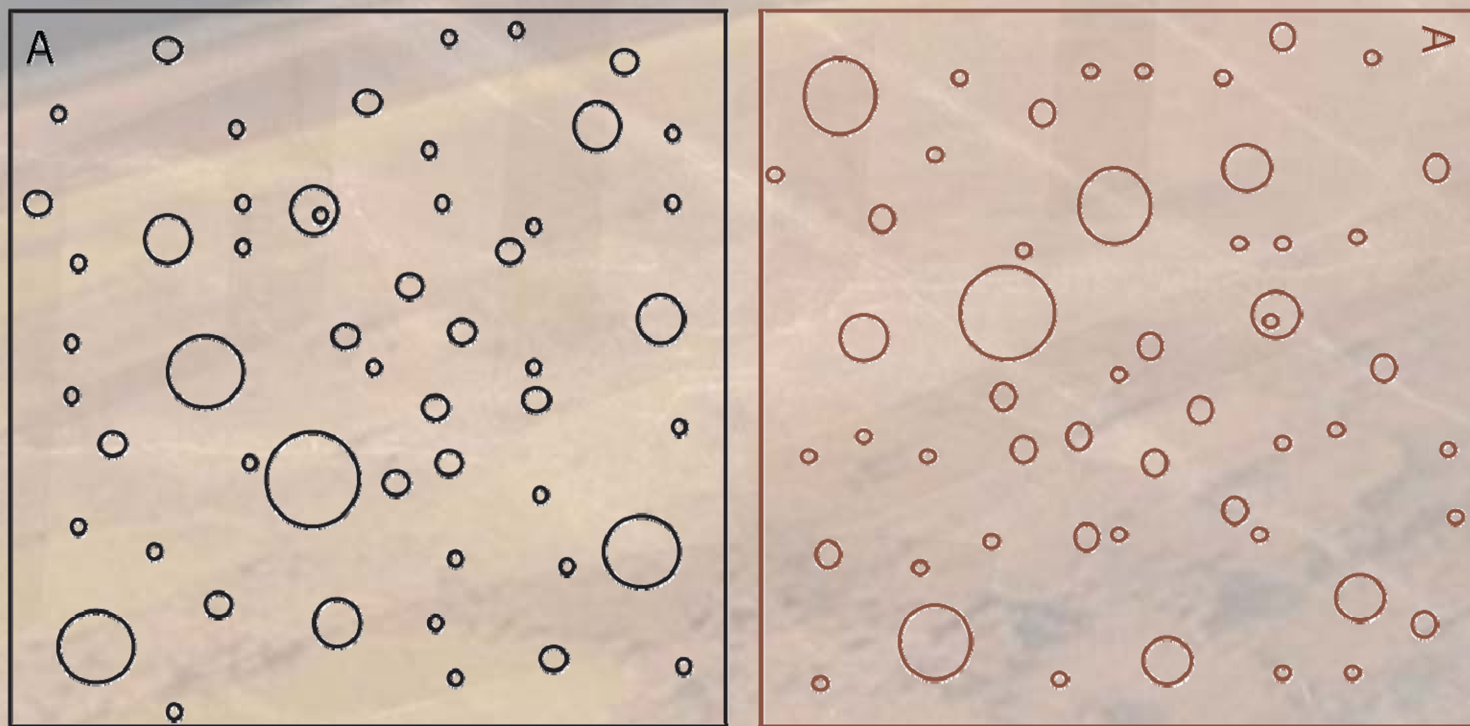
- Divide the surface into units based upon geologic criteria

- Calculate areal density of craters

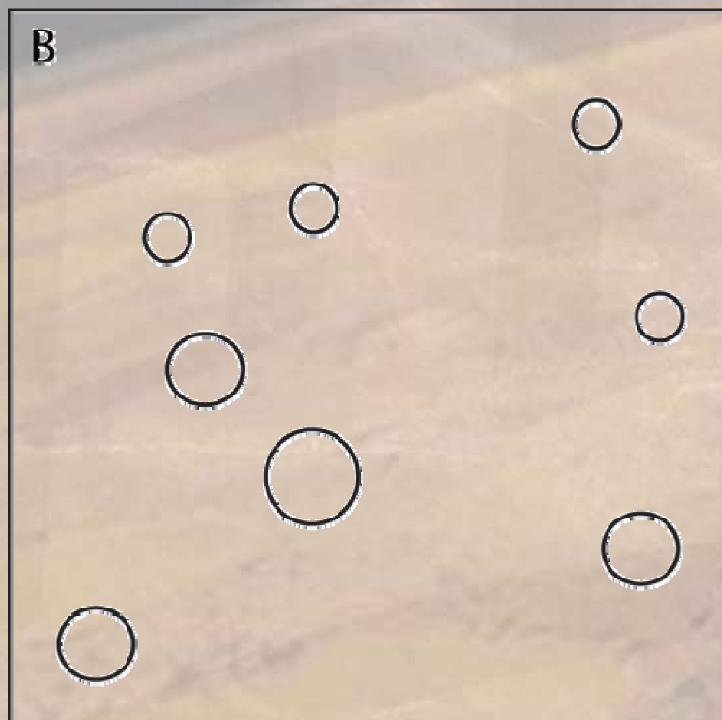
  Relative differences give relative ages

- Convert to absolute age

Cratering of Planetary Surfaces

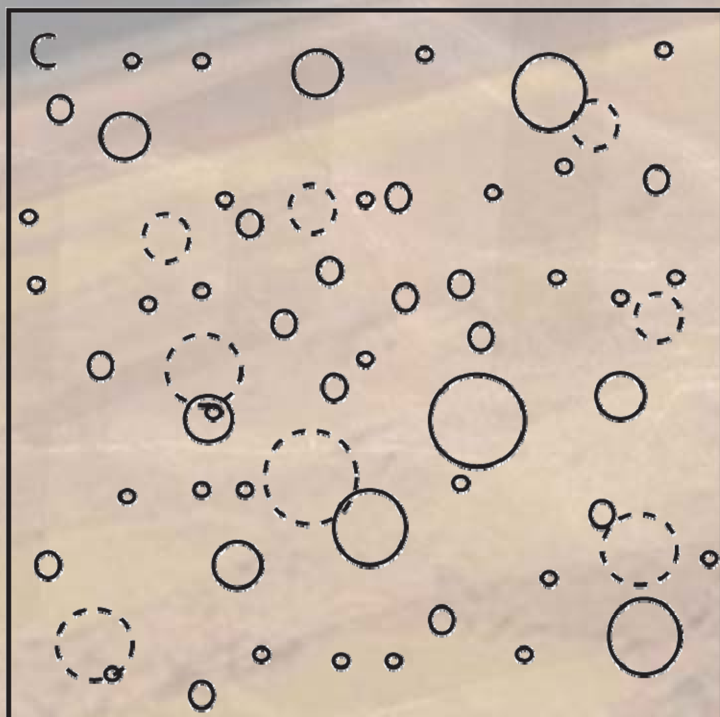


Resurfacing occurs …



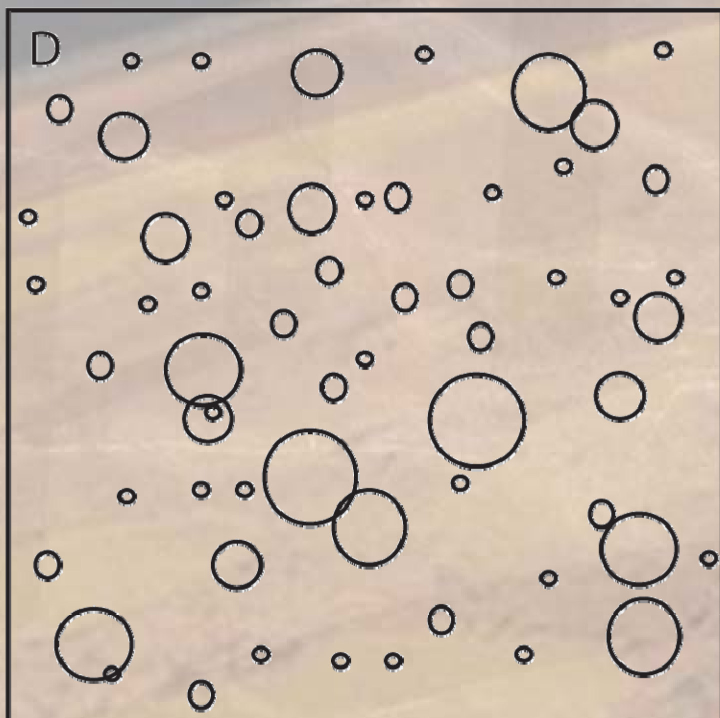
$$N_{\mathrm{cum}}(D,t) = \int_{D}^{\infty} \int_{0}^{t} g(D')\,dD' \cdot f(t')\,dt'$$

Partially Eroded Surfaces



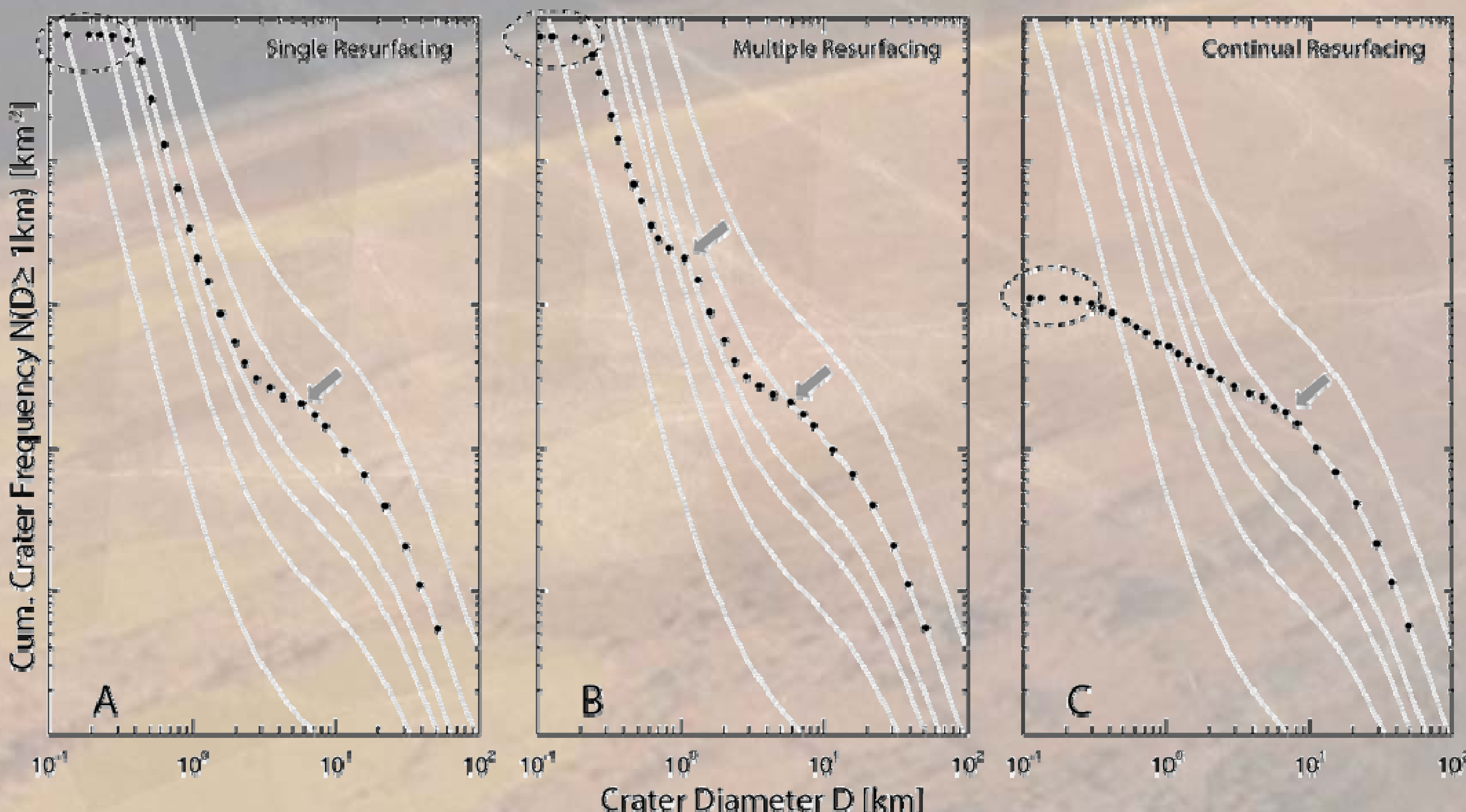
$$N_{eros} = \int_{D_{min}}^{D_{max}} g(D')\,dD' \cdot \int_{0}^{t_*} f(t')\,dt' + \int_{d_*}^{D_{max}} g(D')\,dD' \cdot \int_{t_*}^{t_{max}} f(t')\,dt',$$

Nature is not always cooperative



$$
\begin{aligned}
N_{eros} &= \int_{d_*}^{D_{max}} g(D')\,dD' \cdot \int_{0}^{t_{max}} f(t')\,dt' \\
&- \int_{d_*}^{D_{max}} g(D')\,dD' \cdot \int_{0}^{t_*} f(t')\,dt' \\
&+ \int_{D_{min}}^{D_{max}} g(D')\,dD' \cdot \int_{0}^{t_*} f(t')\,dt' \\
&= ((G(D_{max}) - G(D_*)) \cdot F(t_{max})) \\
&- ((G(D_{max}) - G(D_*)) \cdot F(t_*)) \\
&+ ((G(D_{max}) - G(D_{min})) \cdot F(t_*))
\end{aligned}
$$

Crater counting results



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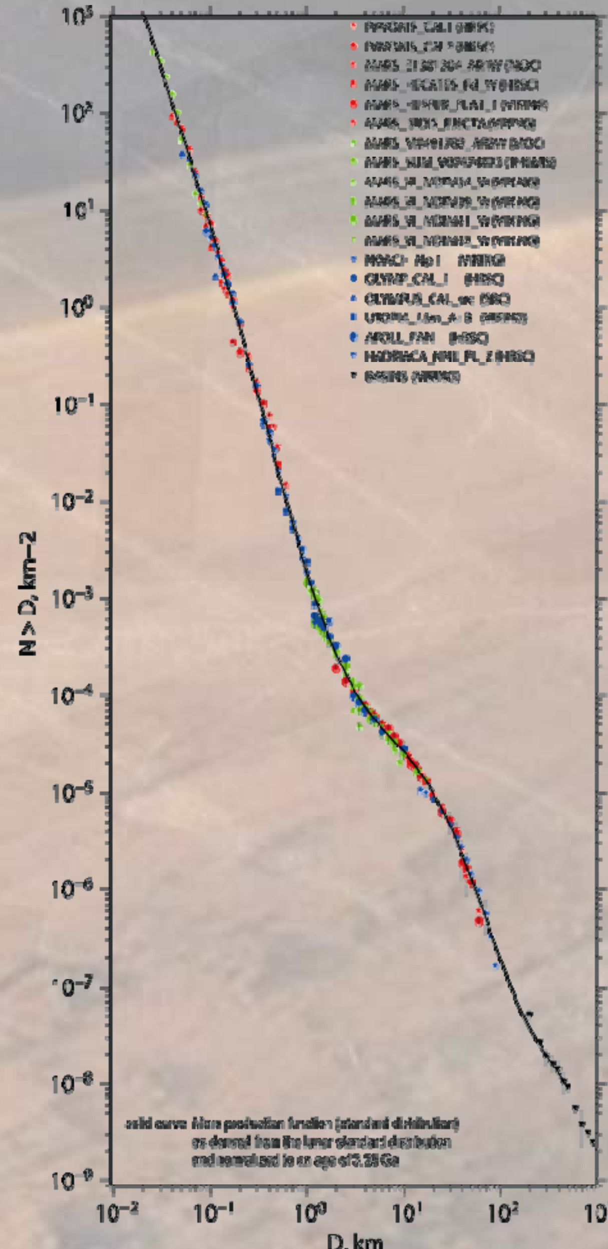
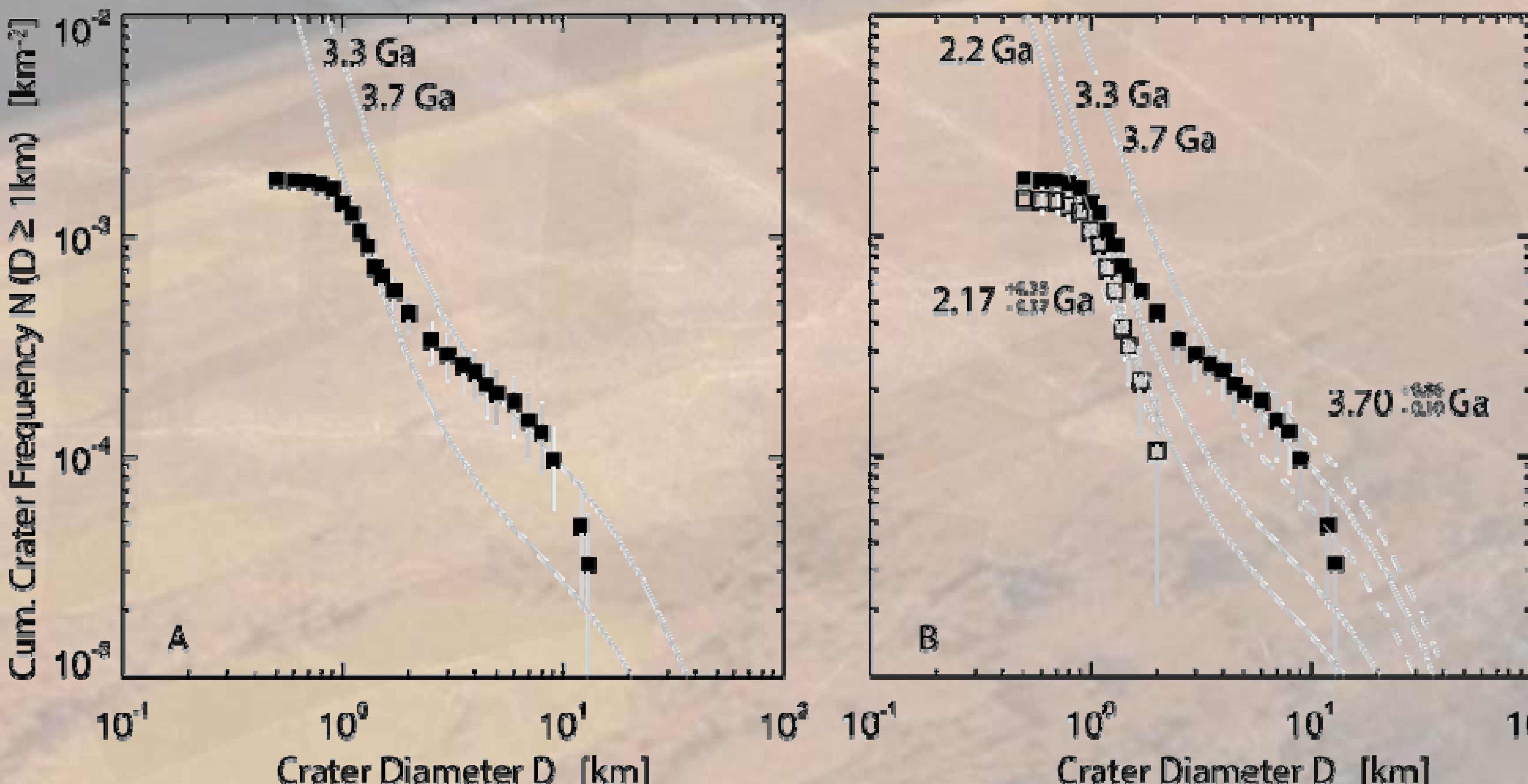
Erosion ages…

How do they appear in crater size frequency distributions?



An example



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(strength, volatile content)

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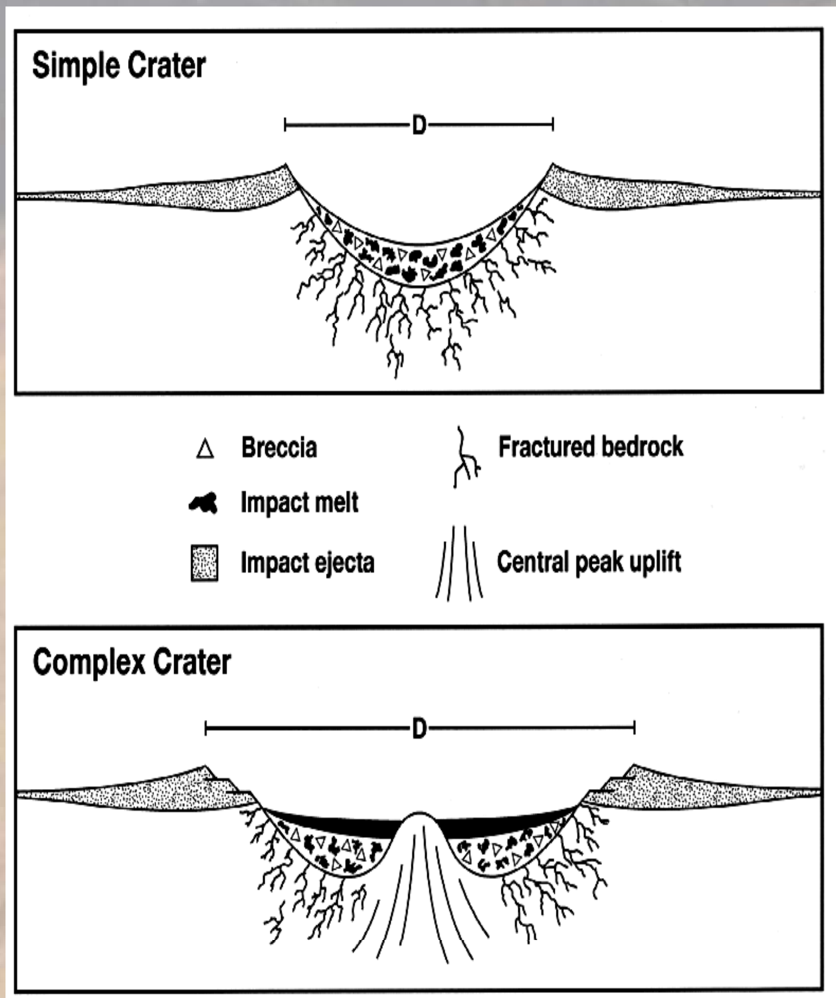
... and the planet

Lunar Crater Collection



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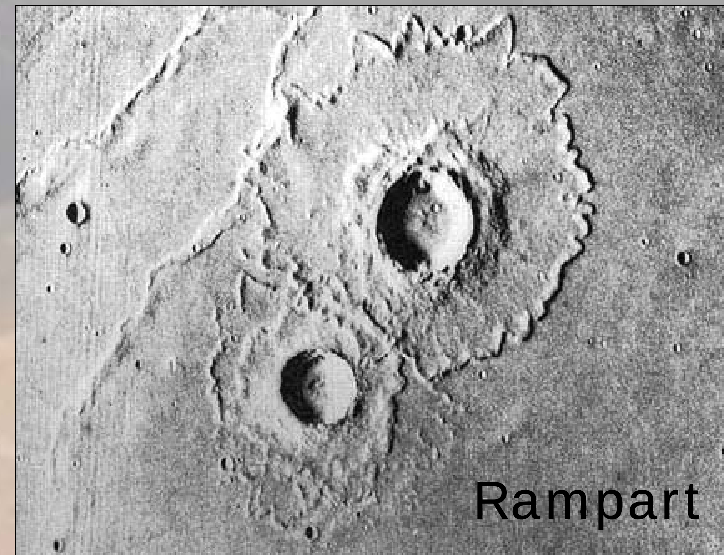
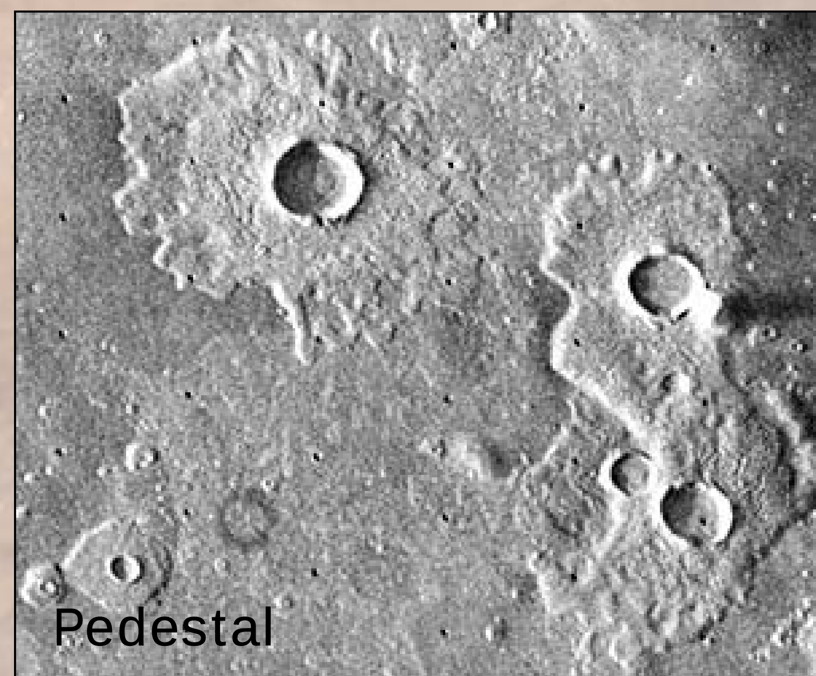
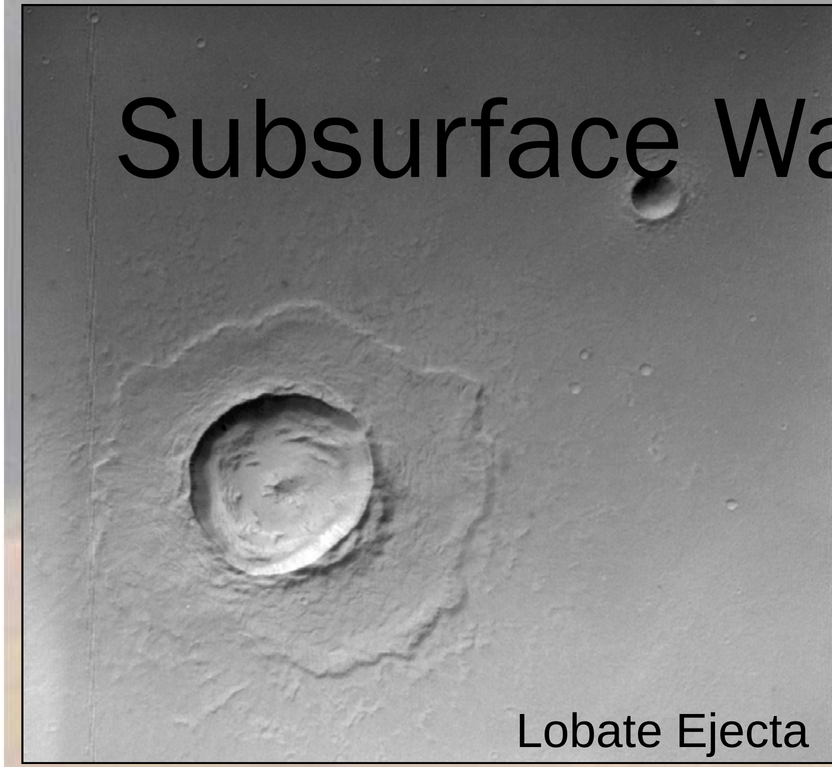
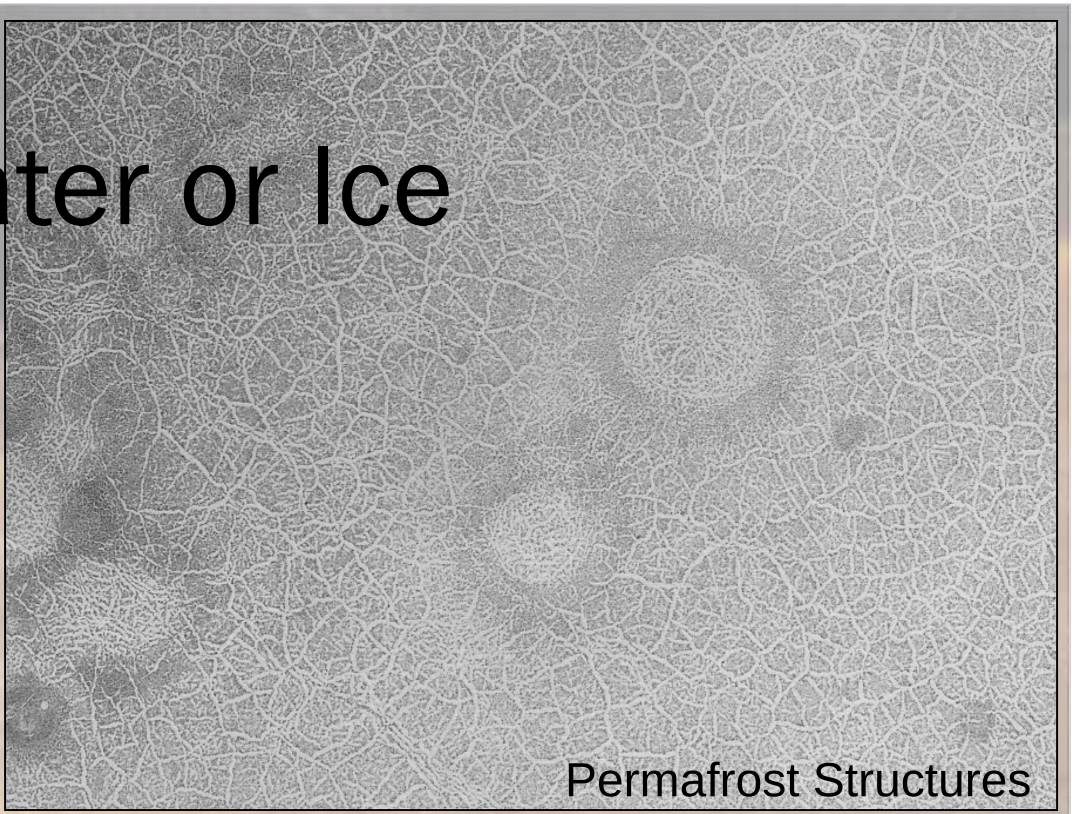
Martian Crater Collection

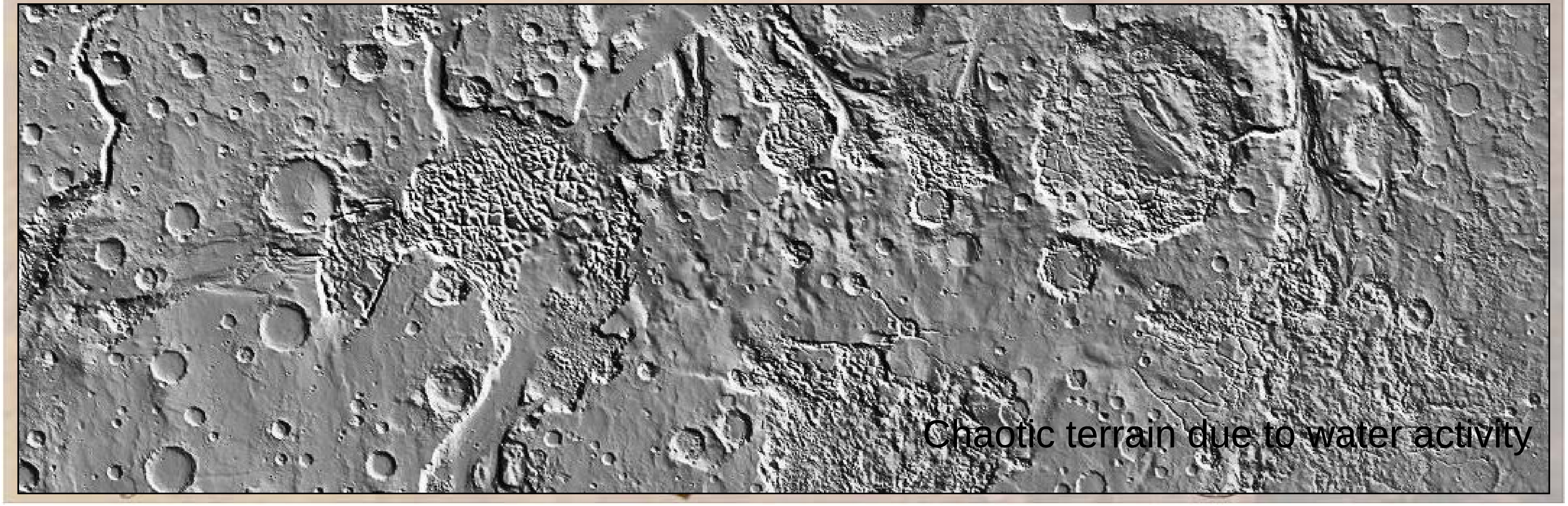




Subsurface Water or Ice







Characteristics of planets

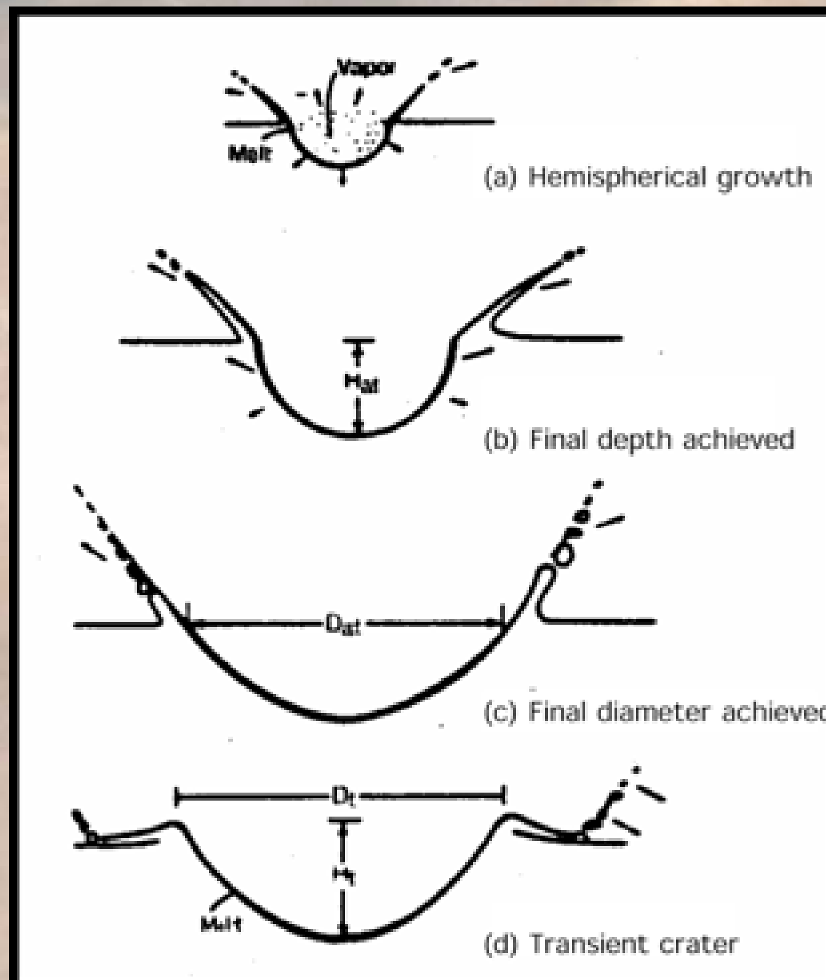
- Cratering on Mars (but also on Earth) is significantly affected by the presence of subsurface ice or water
- High volatility of H_2O modifies the crater formation process, resulting in more vapour production, higher ejection angles, fluidized ejecta blankets.
- Visible in the ejecta distribution (rampart 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



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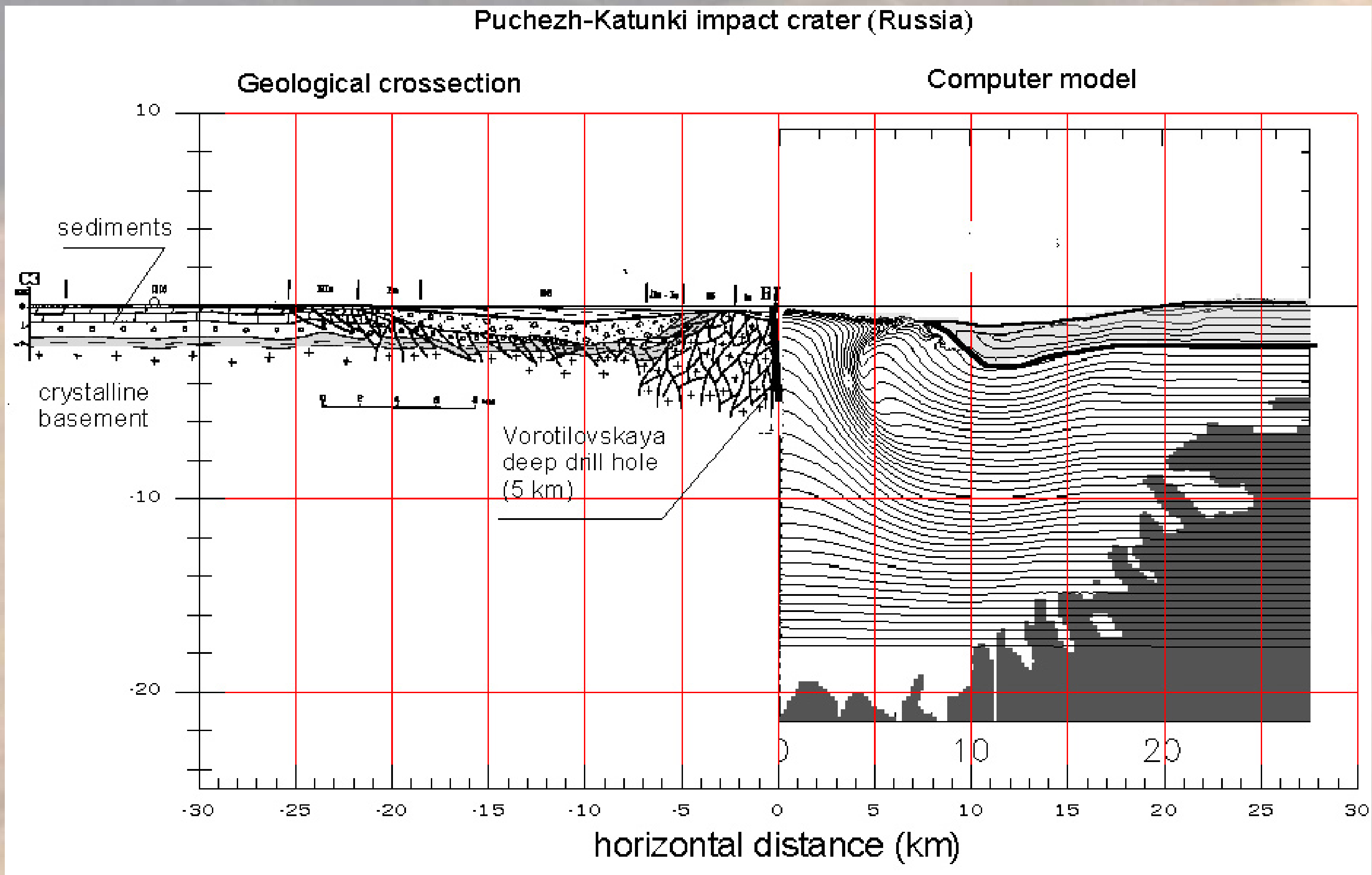
Hydrocode Simulation

- 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

Ivanov, 2005



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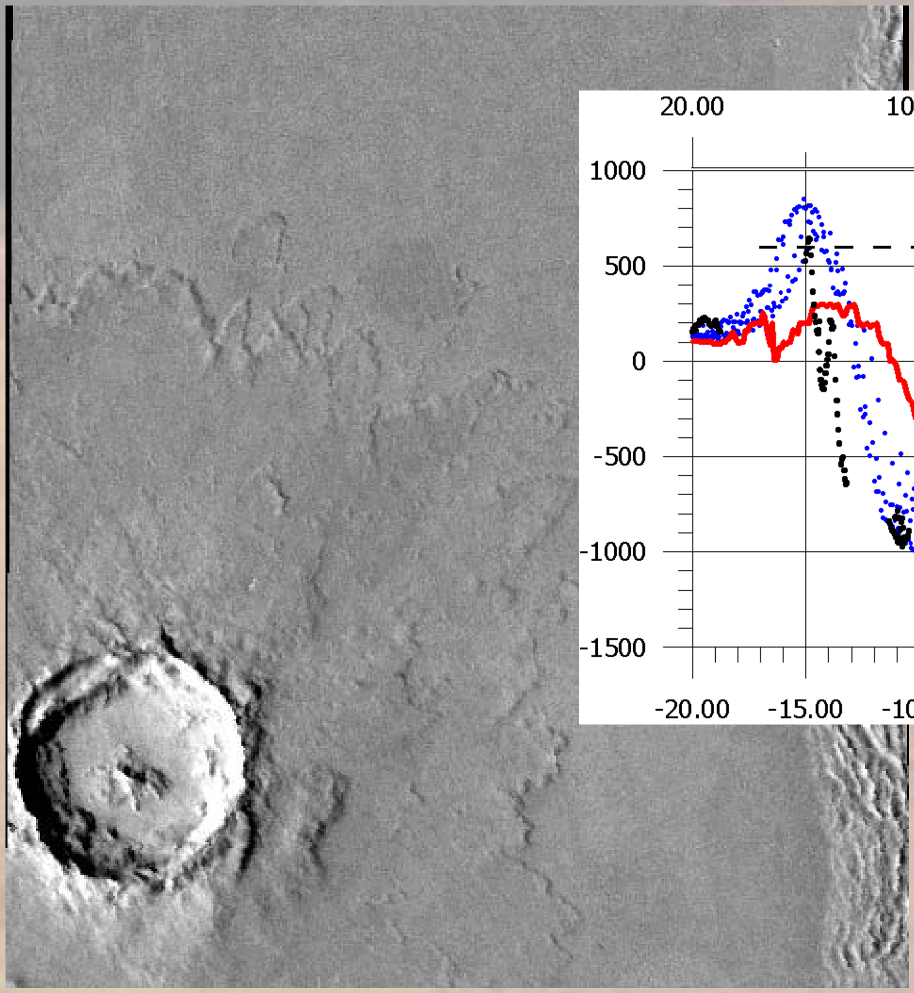
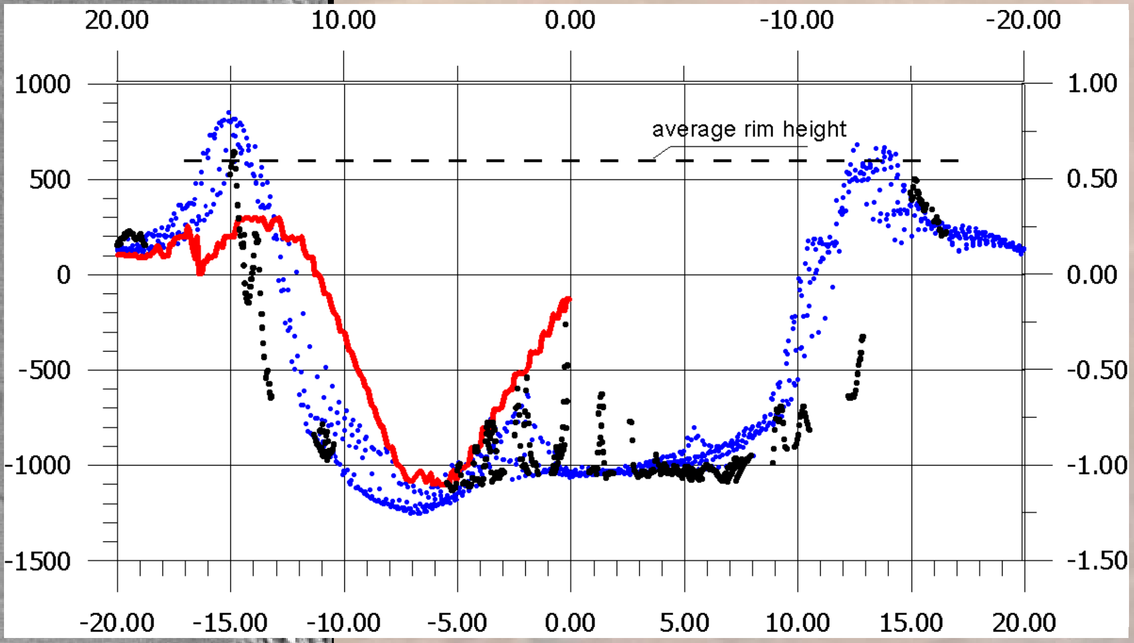
Fresh-looking 30-km crater

Werner et al., 2004





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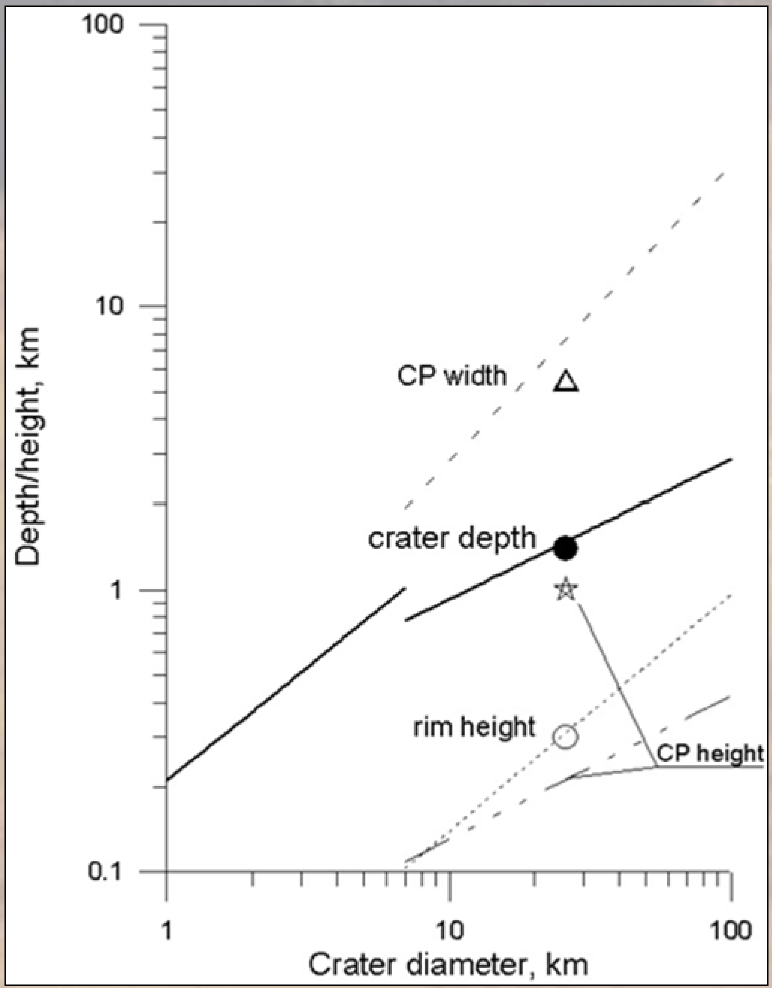
Model crater parameters vs. MOLA data

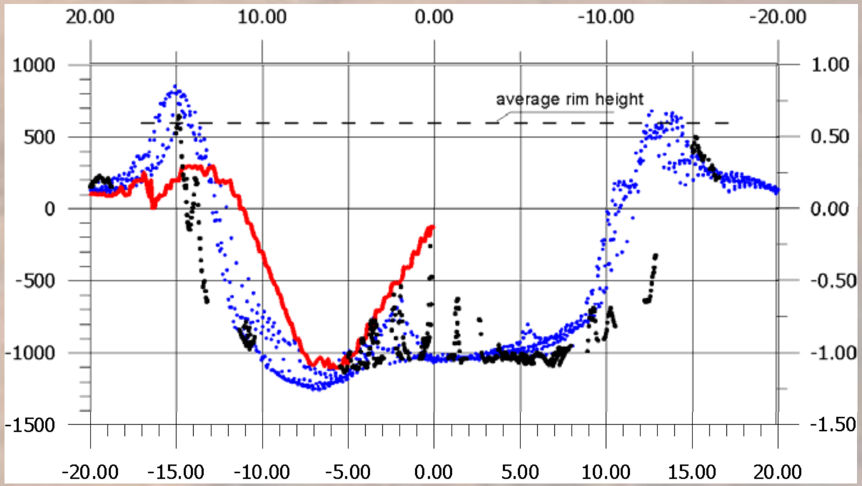
Werner et al., 2004



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.



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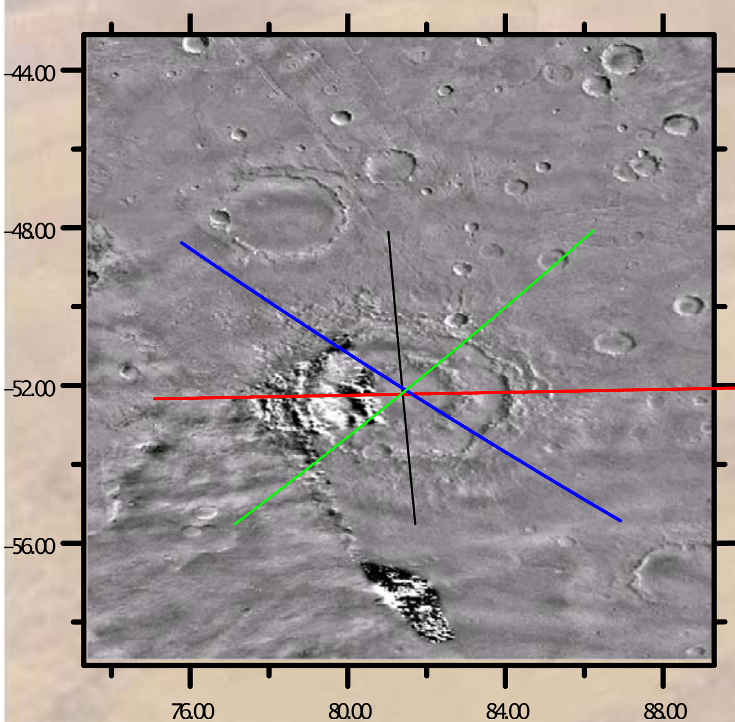
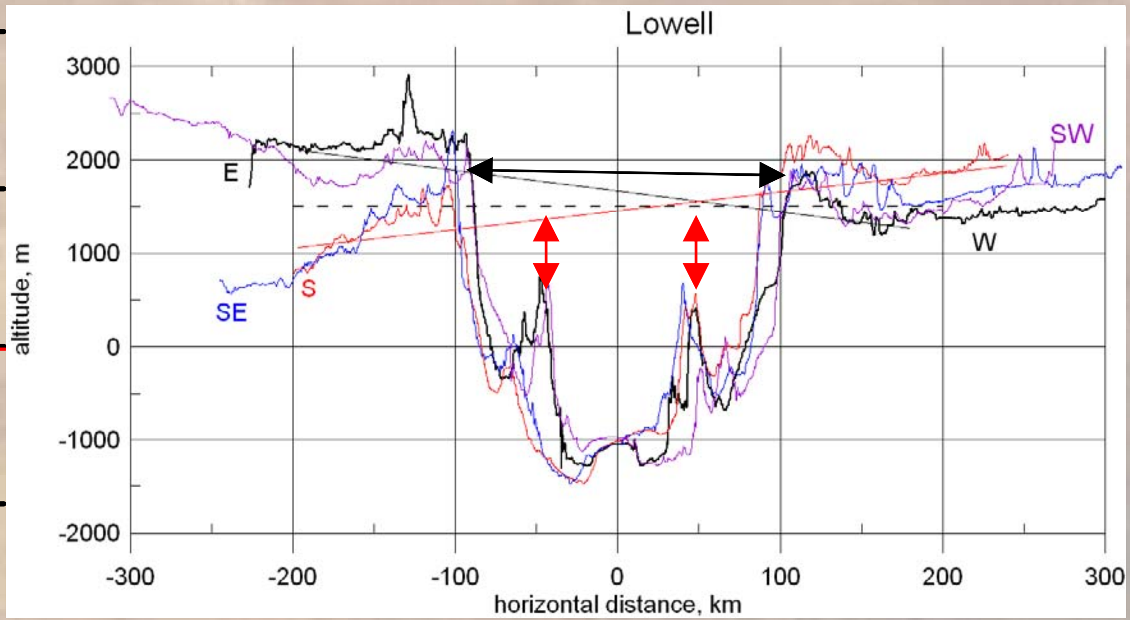
Lowell

Werner et al., 2004

Diameter ~ 220 km
Max depth (below surface) 2950m
Depth in trough ~2050m
Inner rim crest depth ~1000 m





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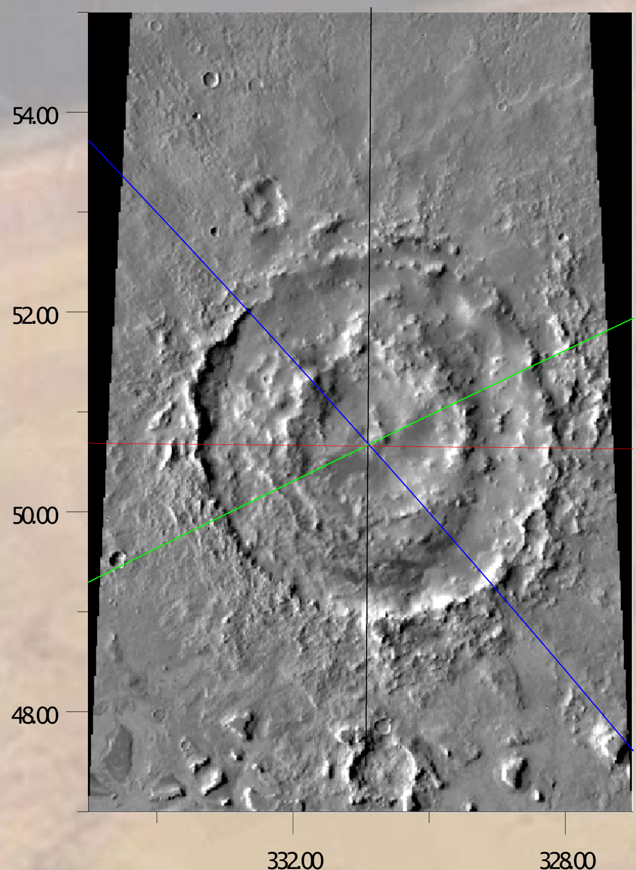
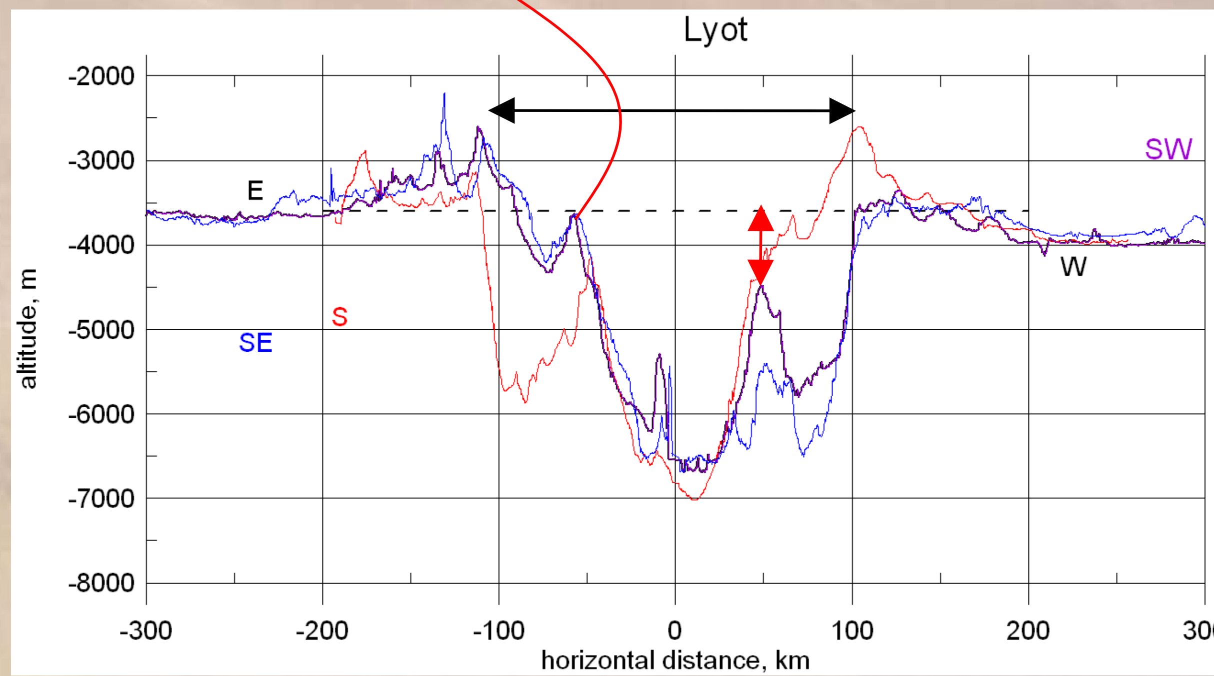
Lyot

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(!)





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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

	Crater diameter D, km	Max. apparent depth, $h_{a,max}$, m	Apparent depth of inner rim crest h_{irc}, m	Approximate pre-impact altitude, m	Visible state
Kepler	230	1200	800	+2300	partially filled
Lowell	240	3000	~1000	+1500	partially filled
Galle	230	2900	1500	-300	partially filled
Secchi	240	1900	1300	+2200	partially filled
Flaugergues	250	1100	>1100	+150	heavily filled
Lyot	*220*	*3400*	*~200*	*-3600*	*slightly filled*

Basin Morphology

Werner et al., 2004

... show that Martian crust in Northern lowlands differ from equatorial highlands (in Early Hesperian time)

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Clues for the evolution of the surface
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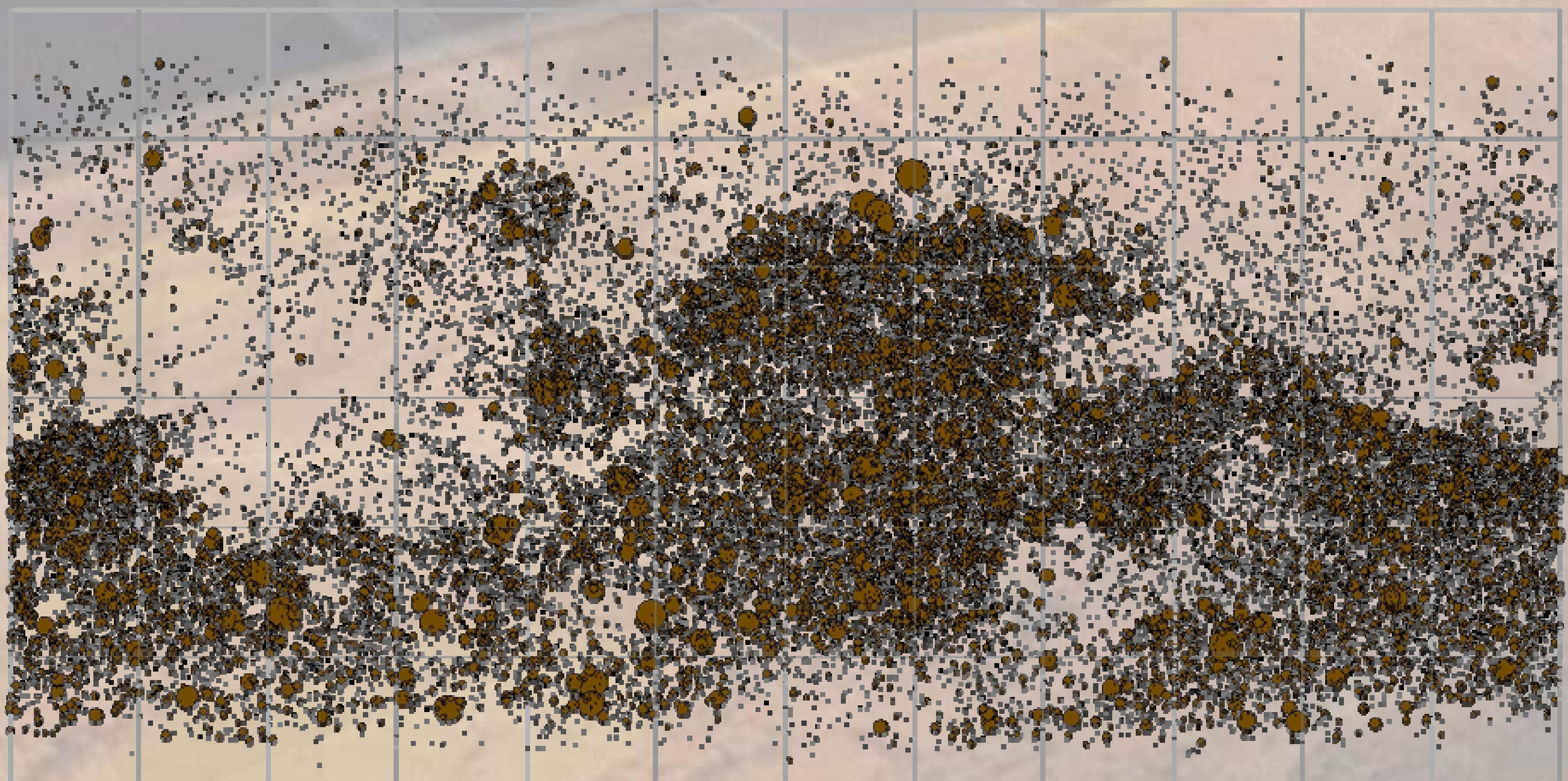
Crater Distribution on Mars



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

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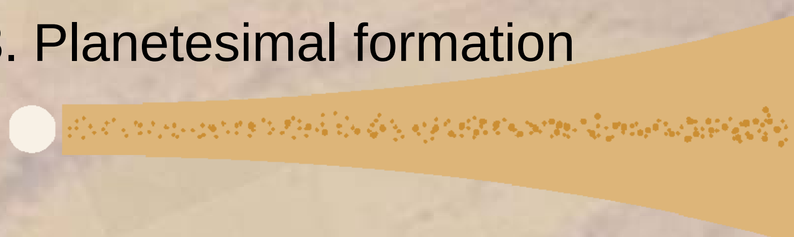
Planetary formation

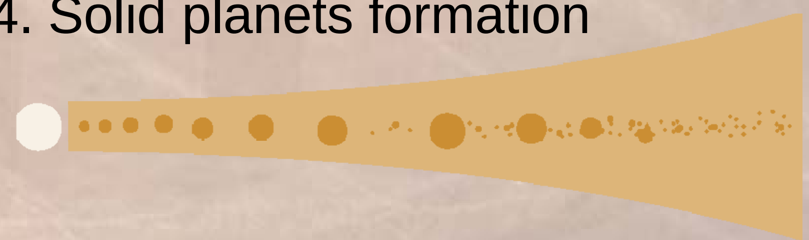
1. Disk formation

2. Dust sedimentation

3. Planetesimal formation



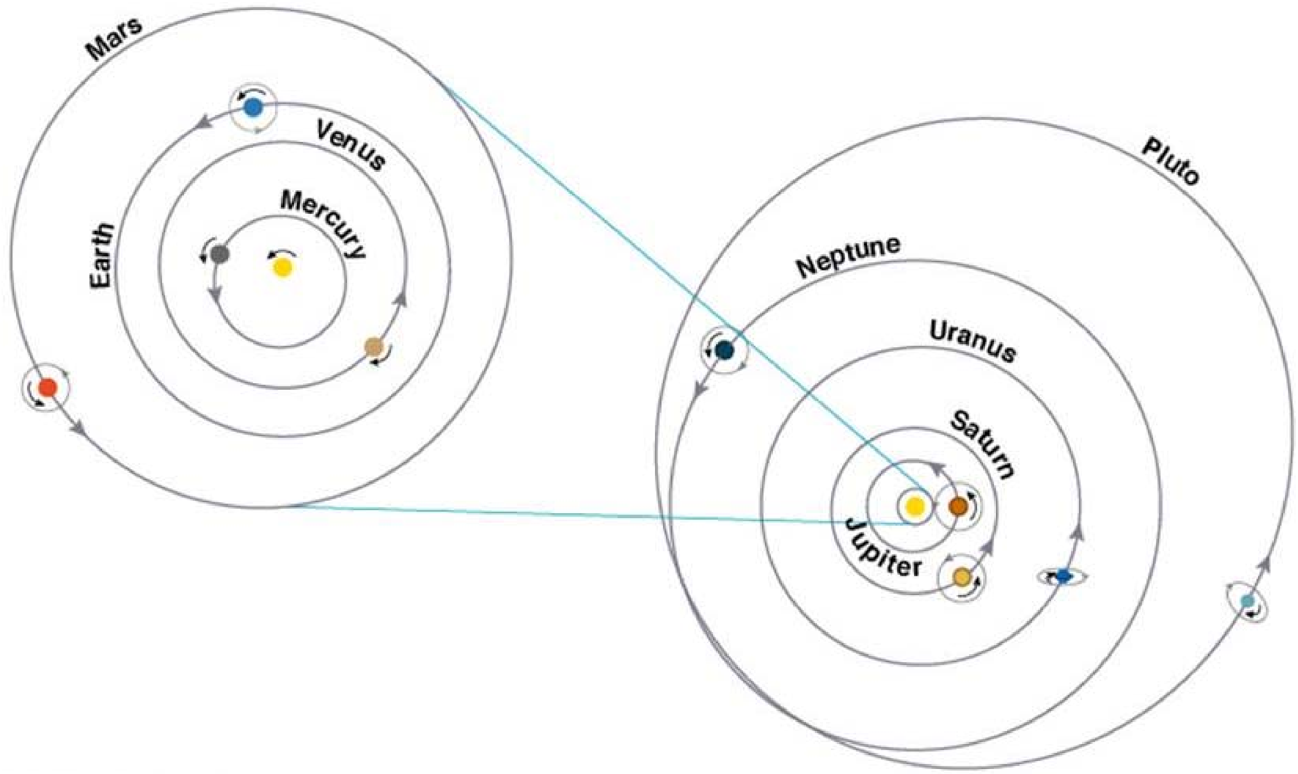
4. Solid planets formation

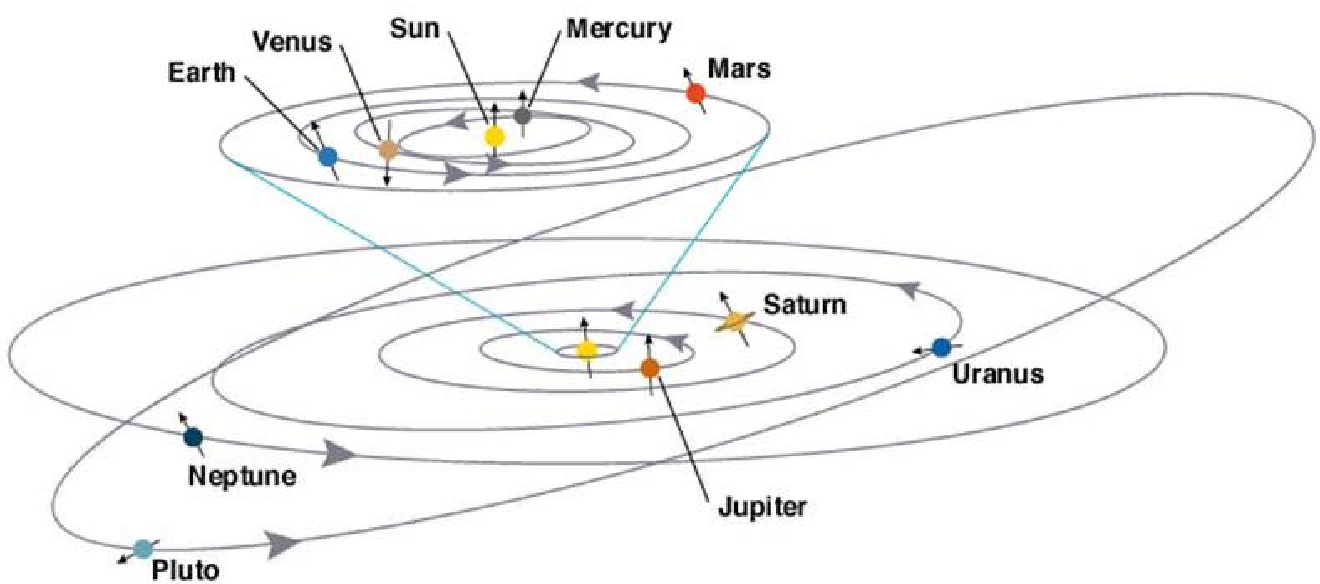


5. Gaseous planets formation

6. Disk dissipation

Orbit and Spin





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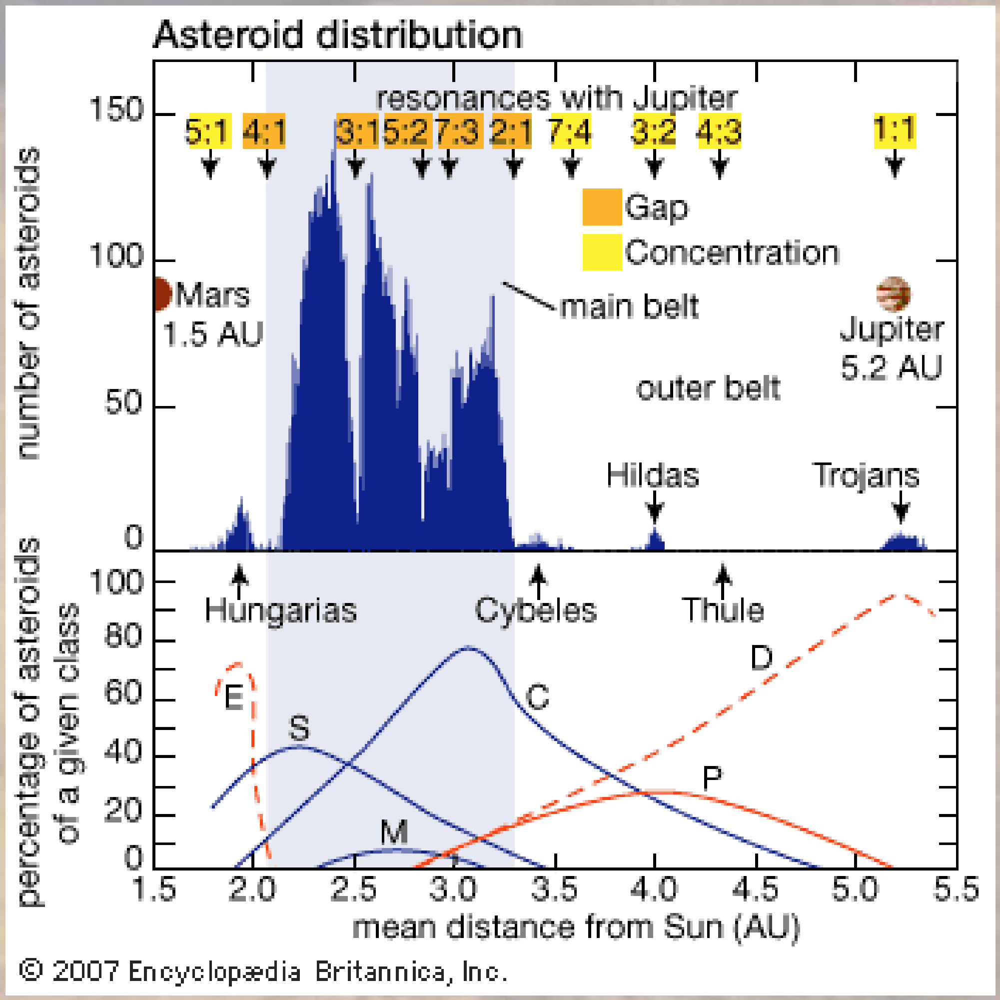
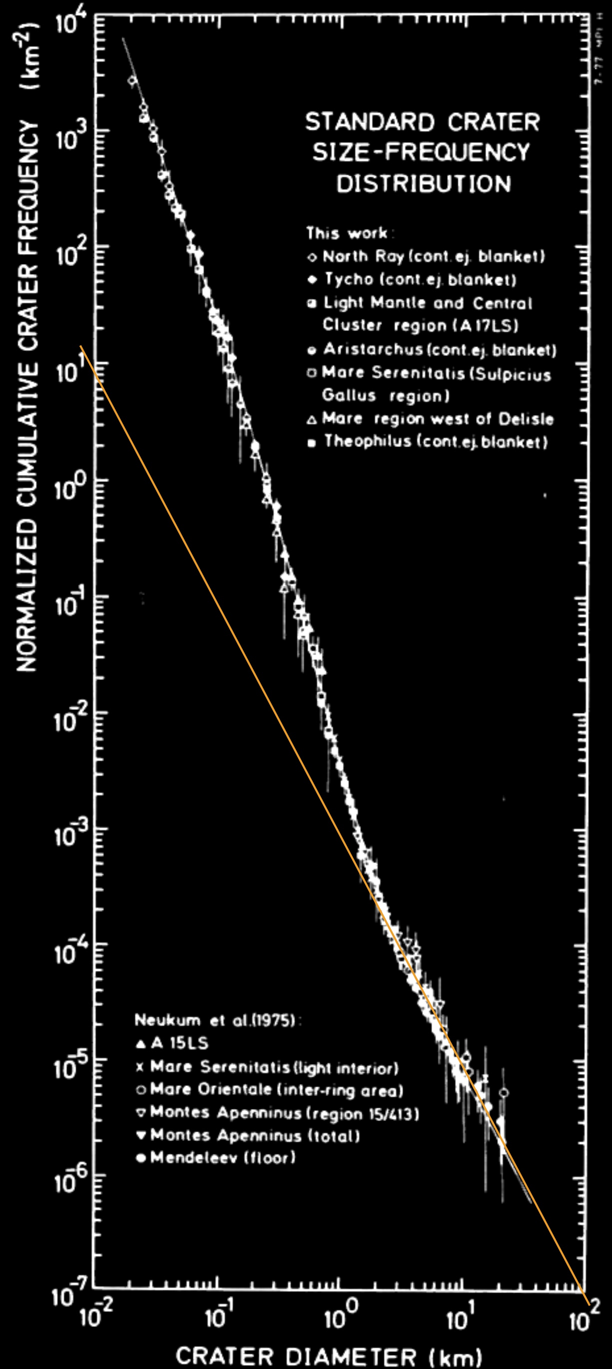
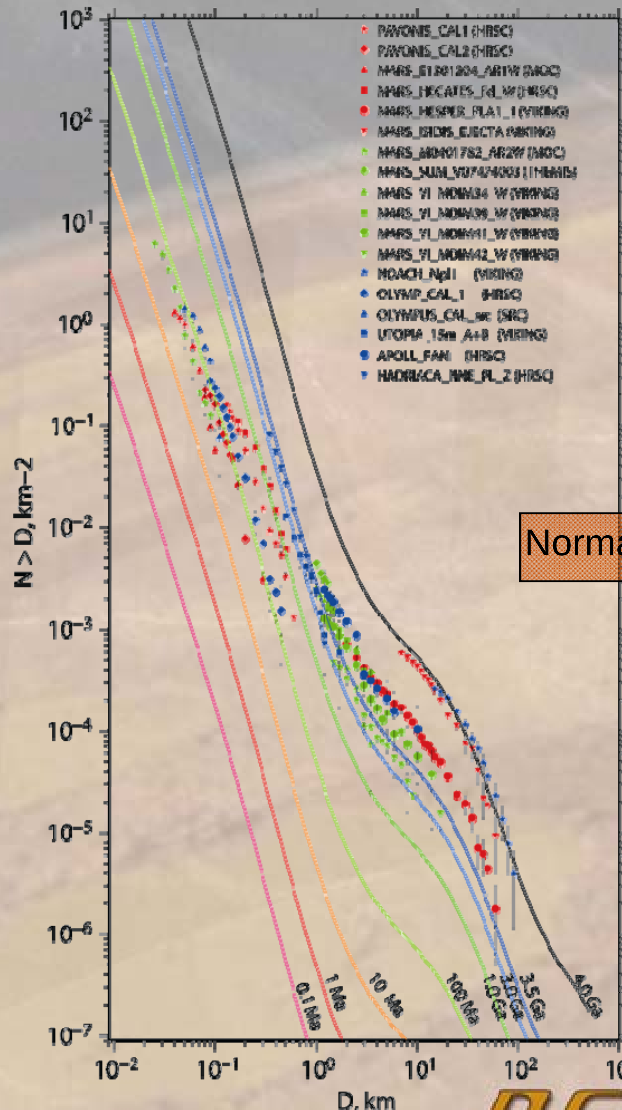
The Asteroid Belt



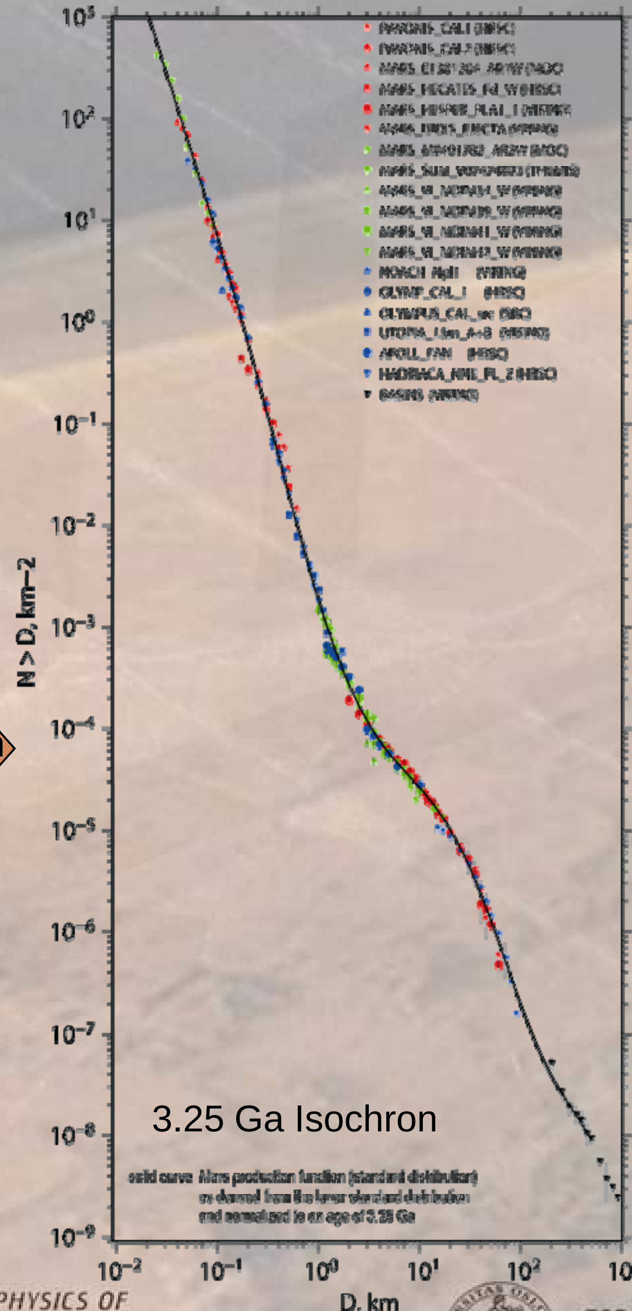


Neukum et al. 1975

Mars

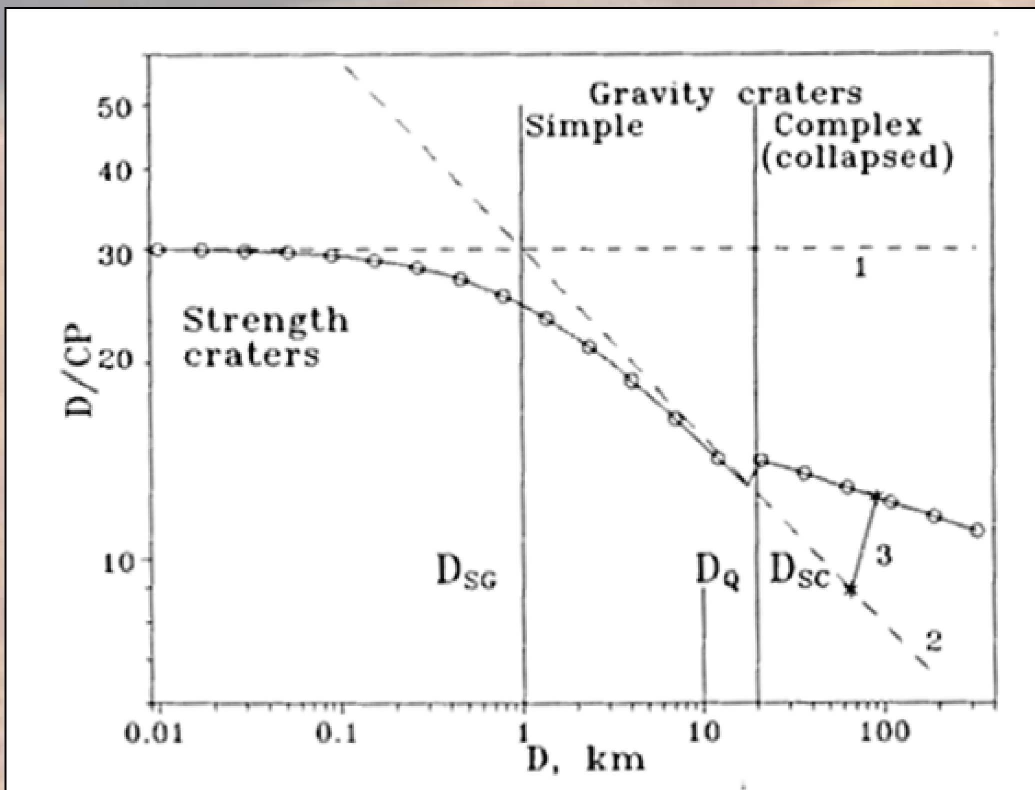


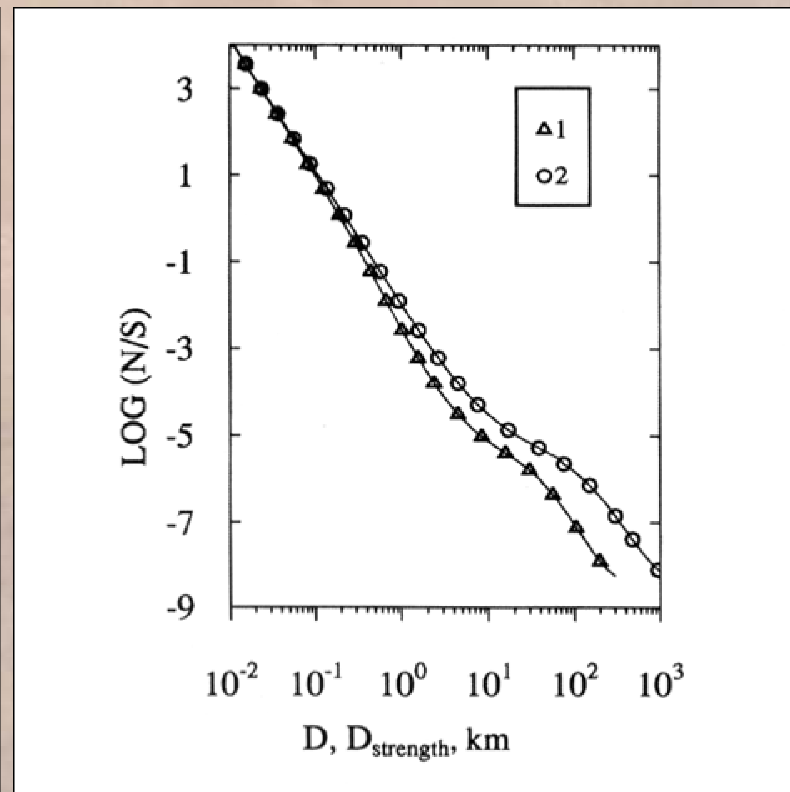
Normalization



Impact Mechanics

Ivanov, 2001





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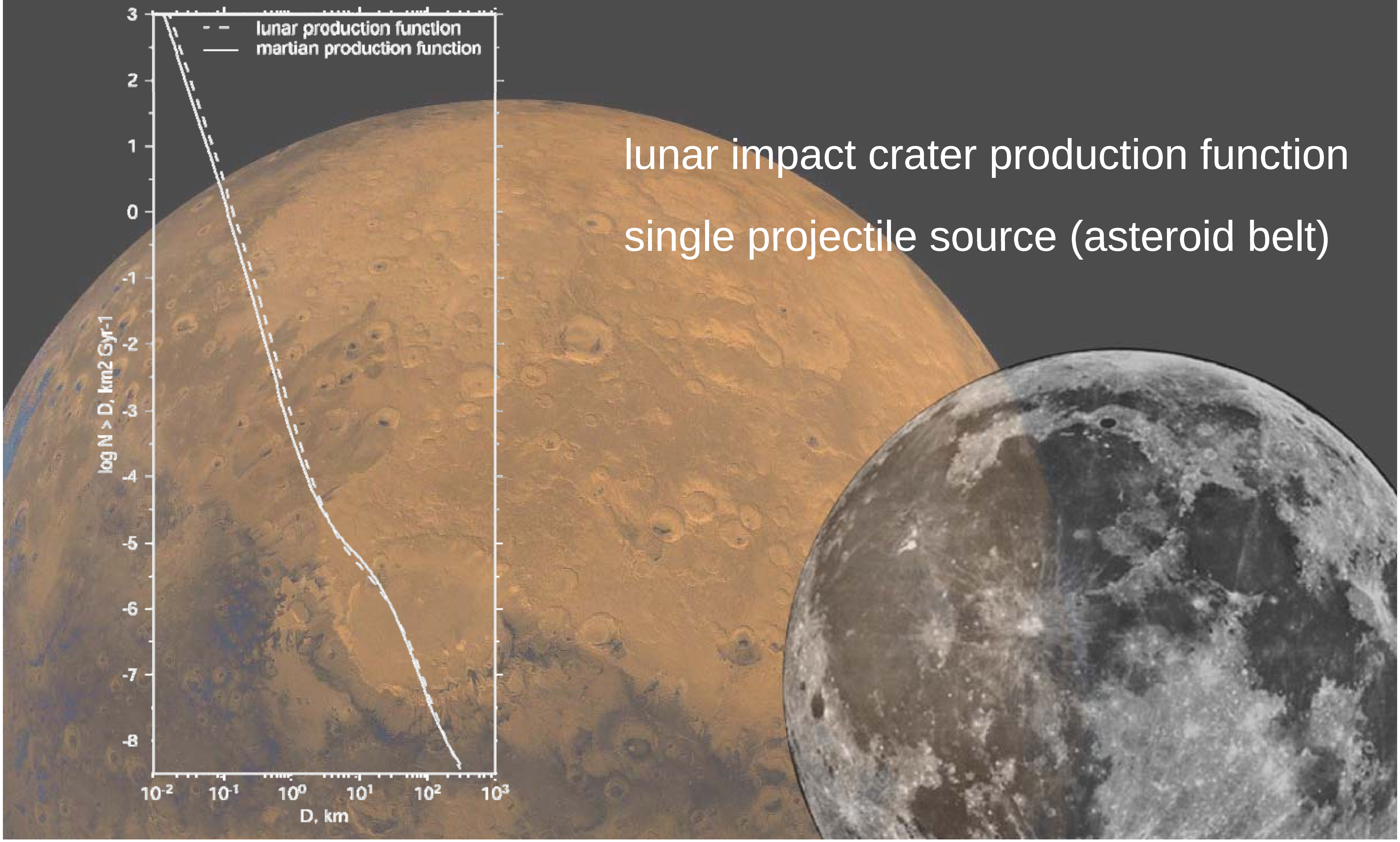
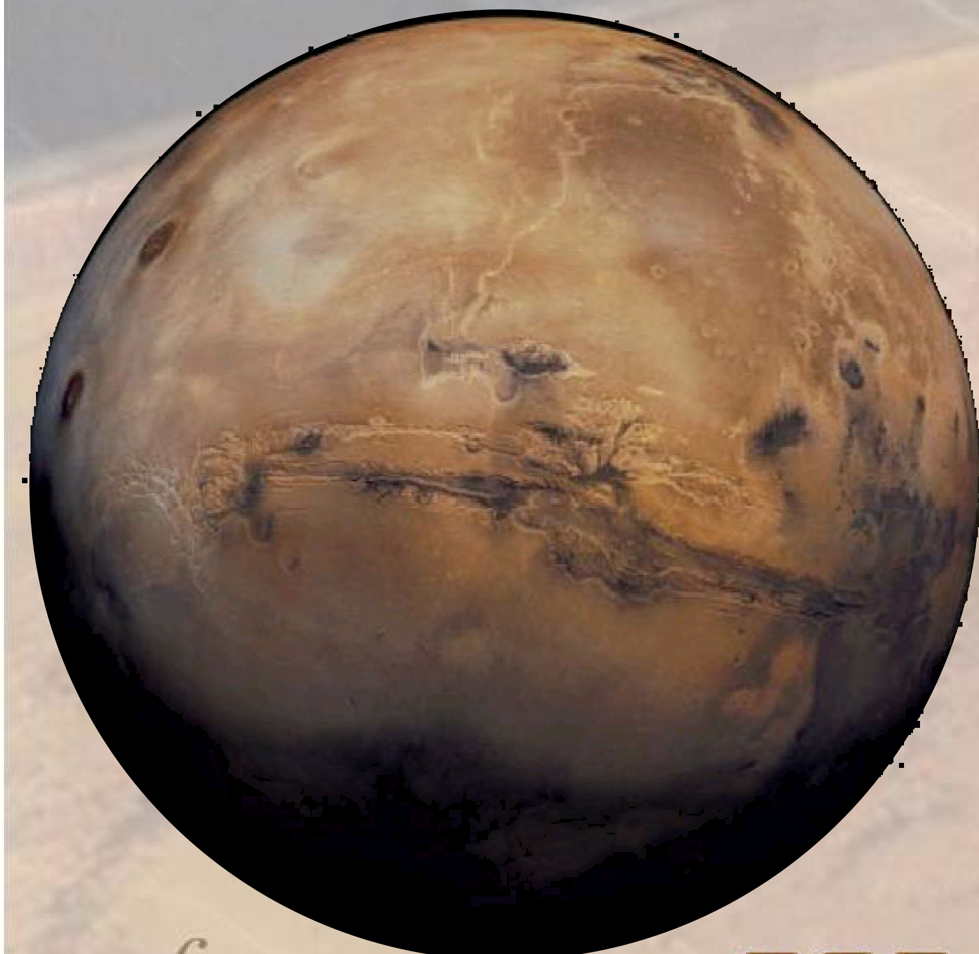
Moon as a Reference System

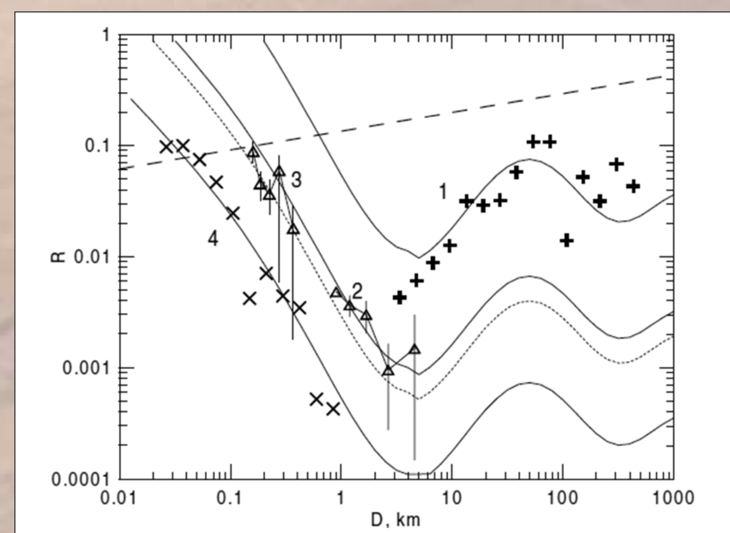


lunar impact crater production function

single projectile source (asteroid belt)

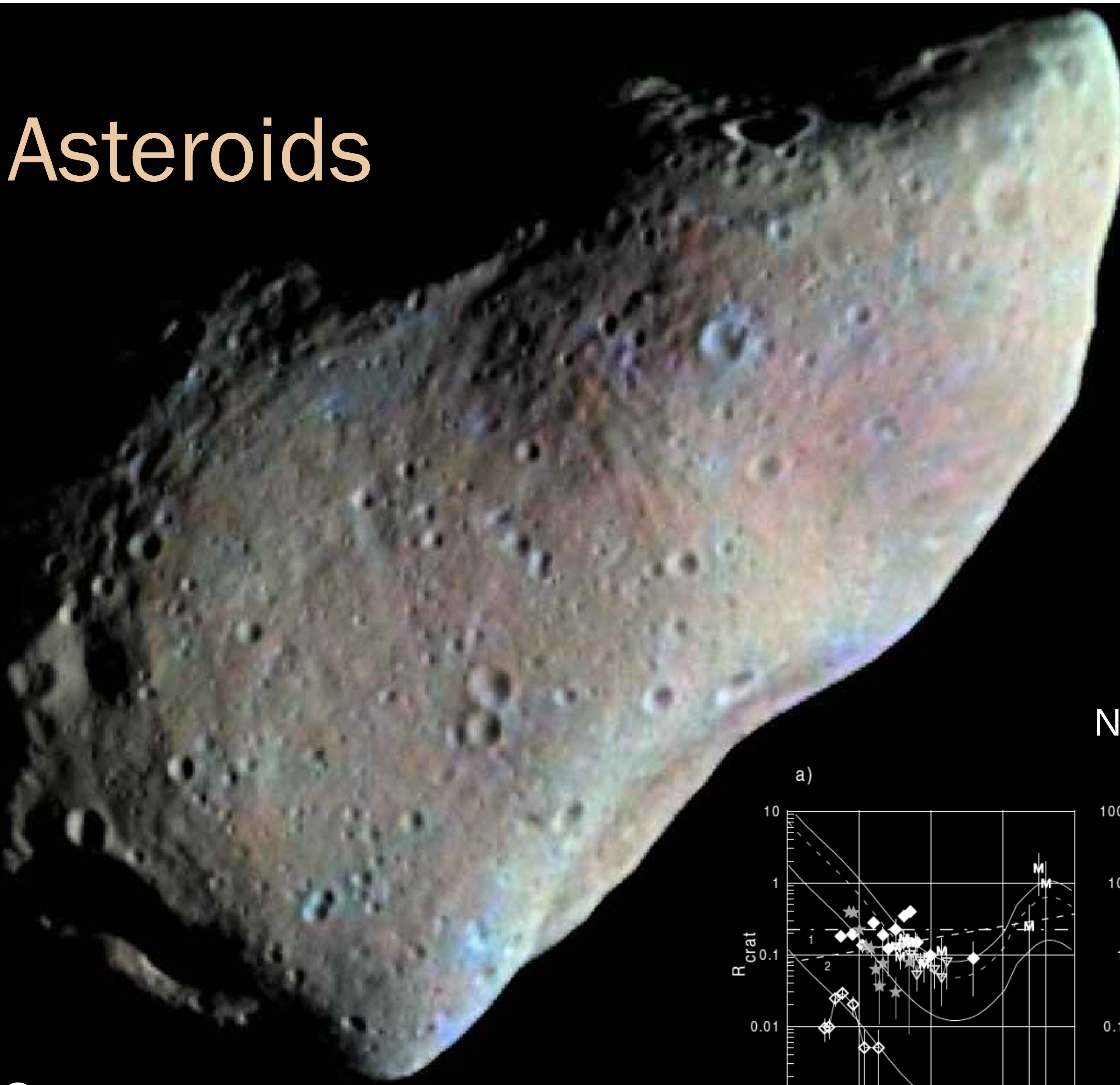
Cratering on Mars





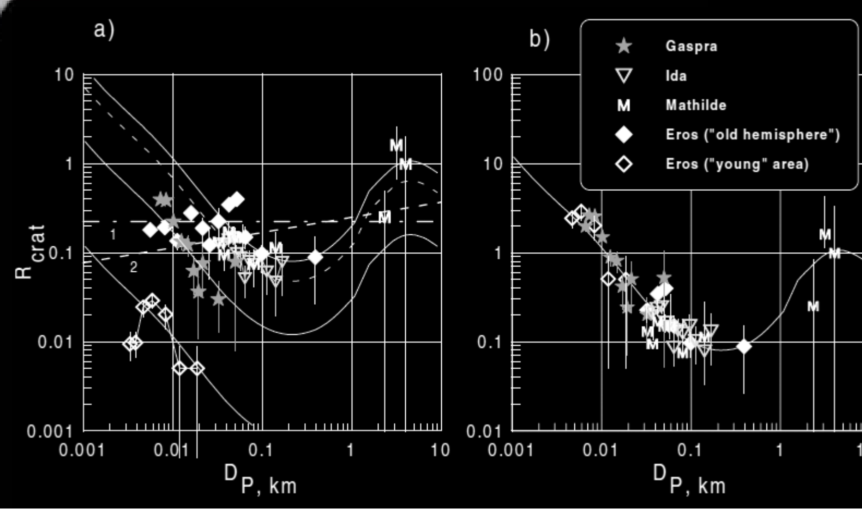
Neukum et al., 2001

Asteroids

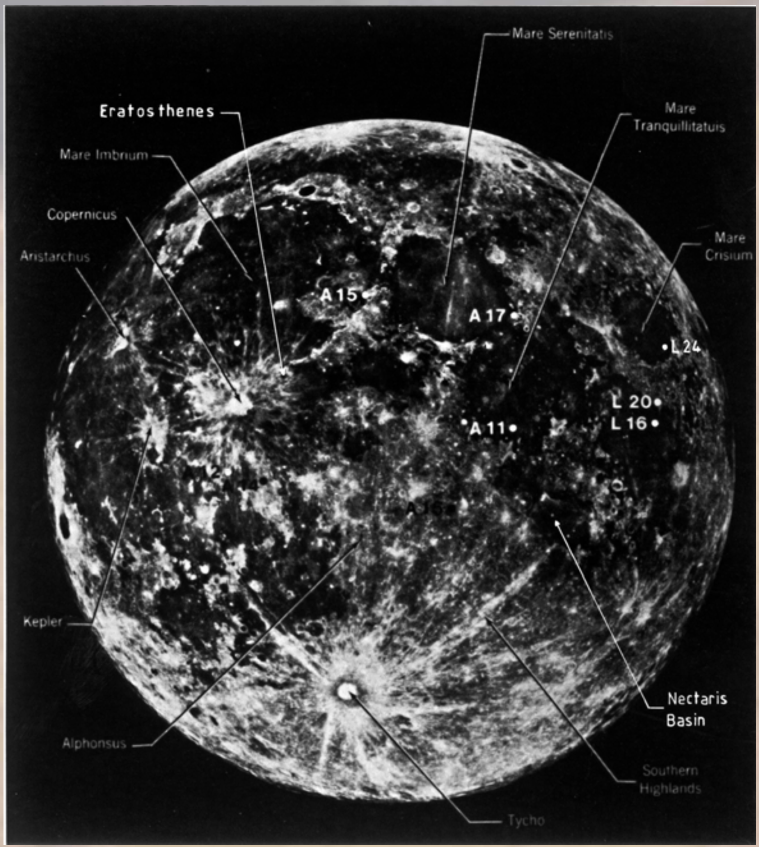


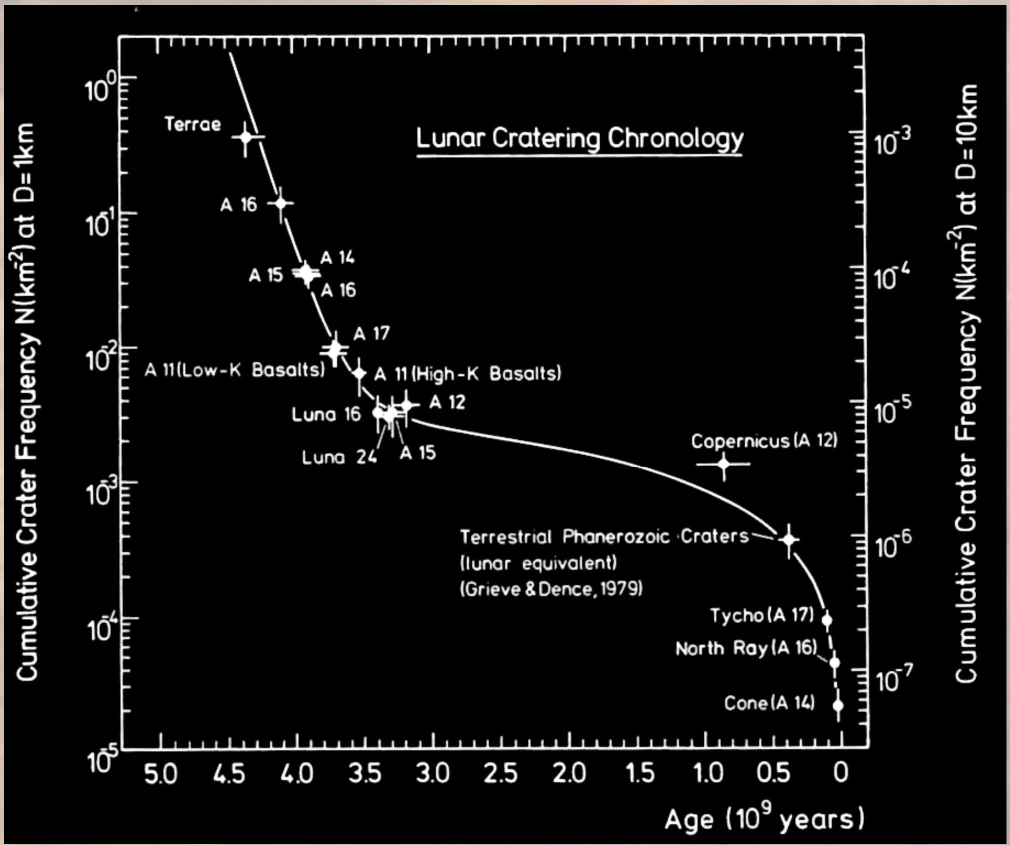
Gaspra

Neukum et al., 2001



Lunar Cratering Chronology





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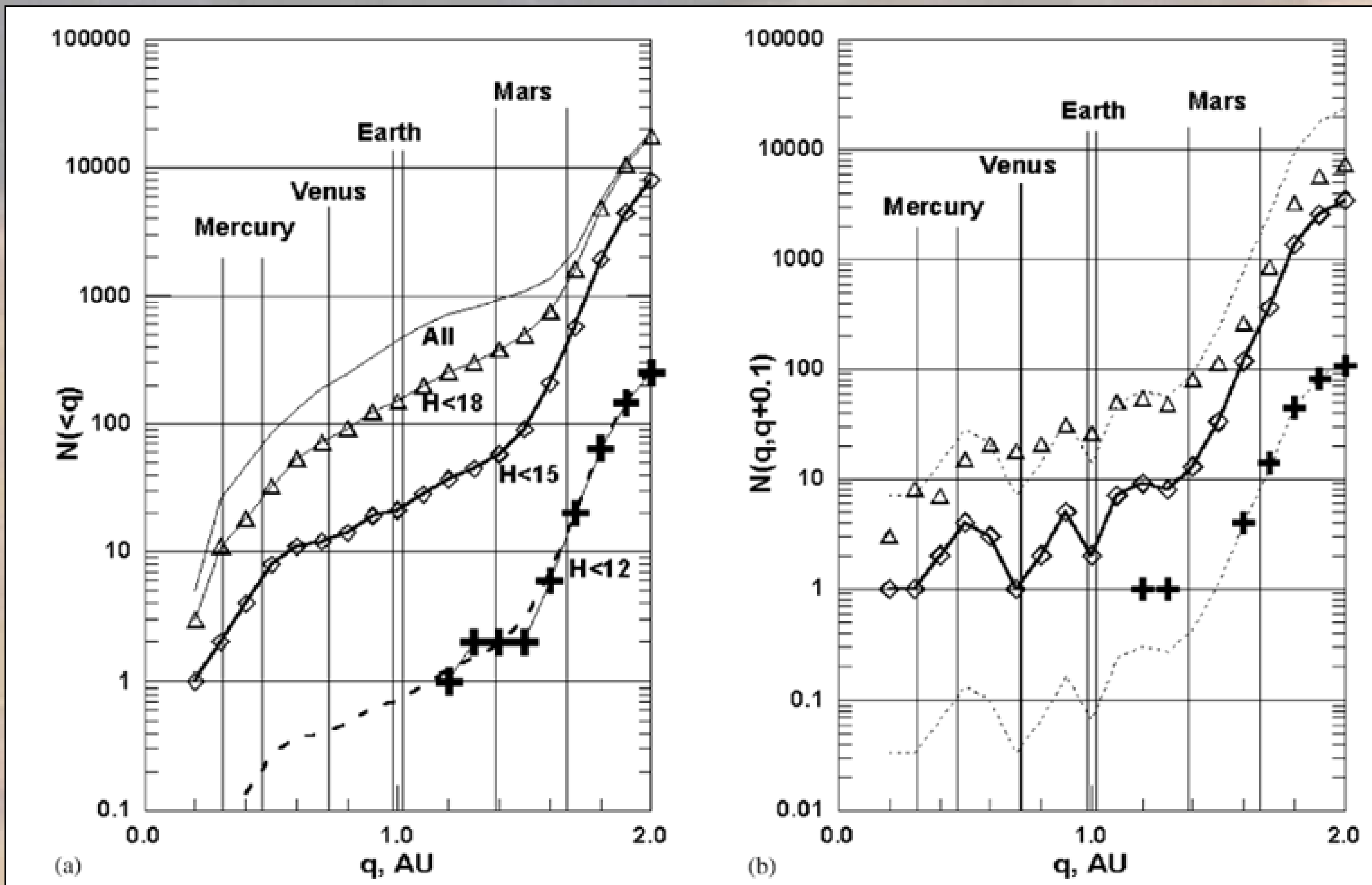
Cratering rate scaling

Ivanov, 2001



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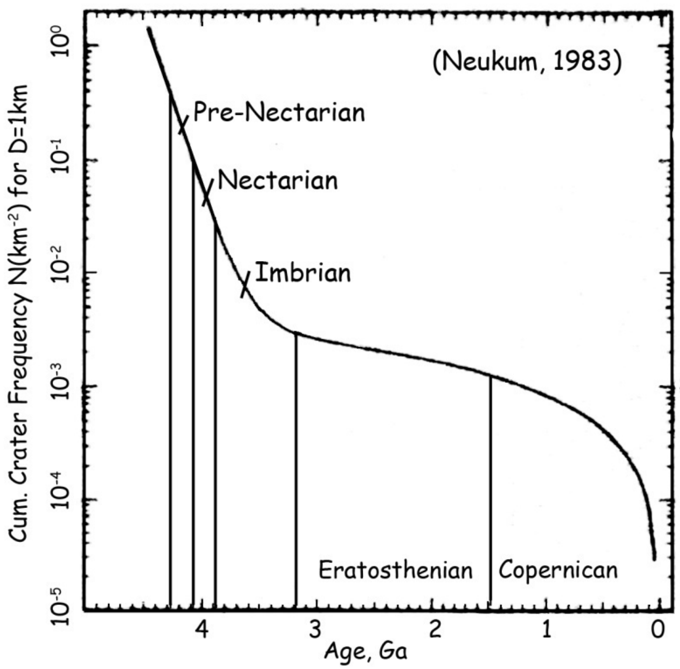
Transfer of the Lunar Cratering Chronology to Mars

Ivanov, 2001

Lunar Cratering Chronology

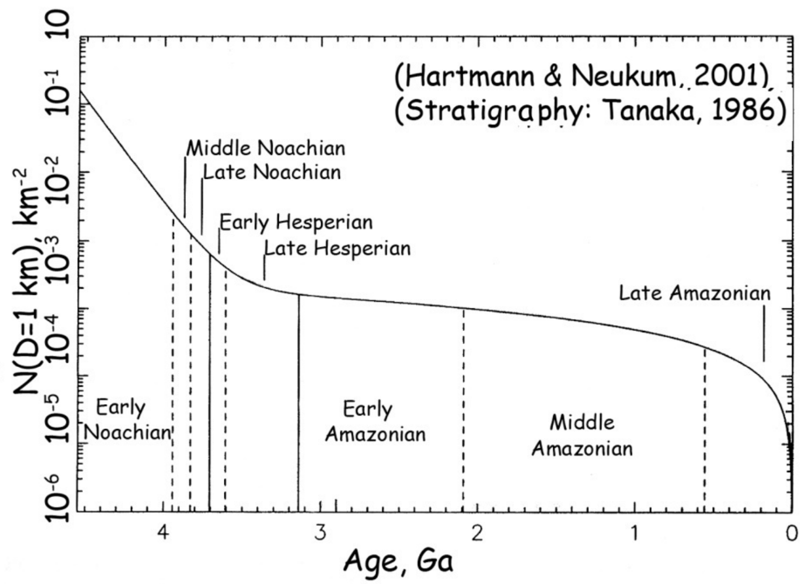


$N(1km) = 5.44\ 10^{-14}\ (\exp(6.93t_A)-1) + 8.38\ 10^{-4}t_A$

Model →

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

Martian Cratering Chronology



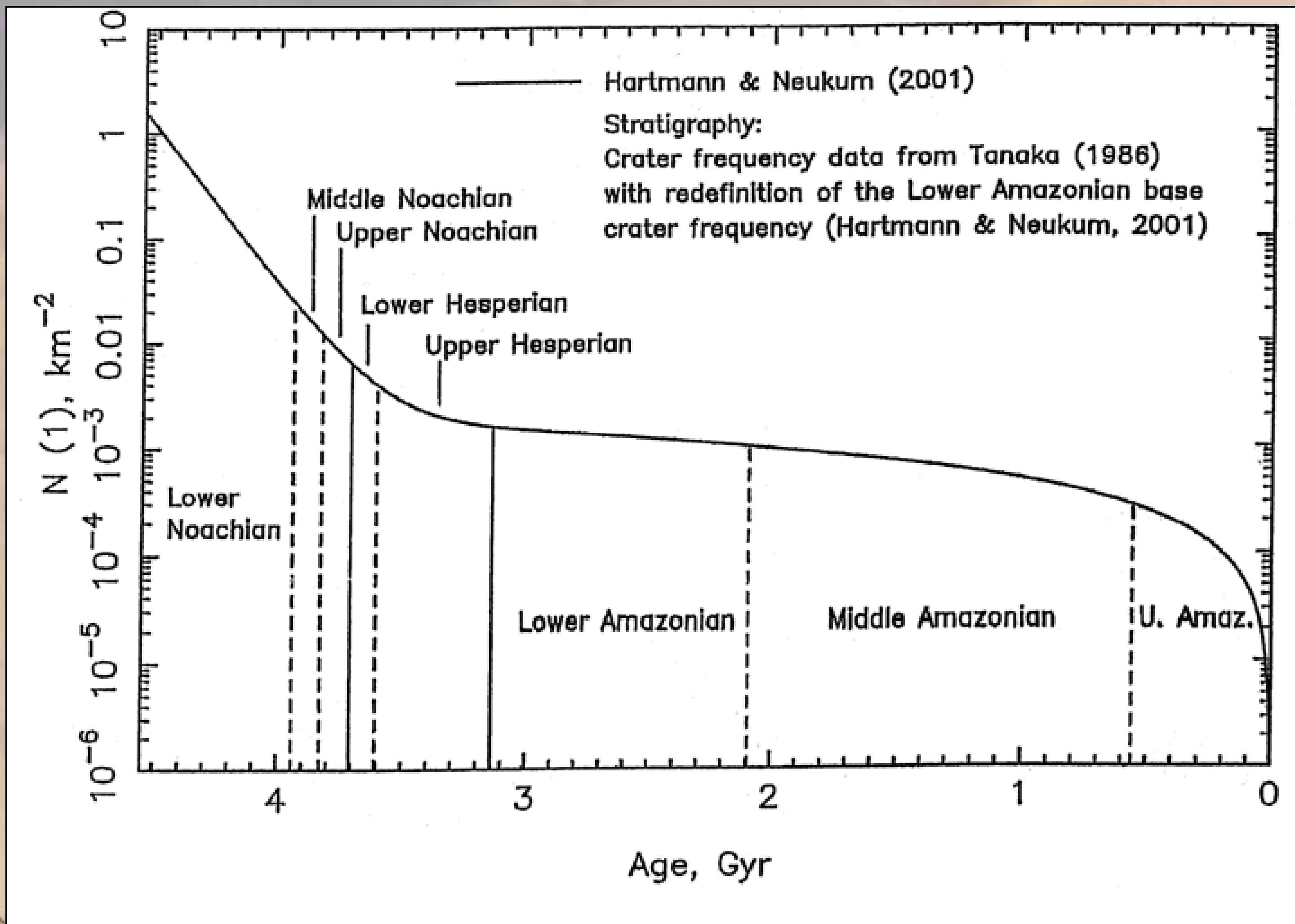
$N(1km) = 2.68\ 10^{-14}\ (\exp(6.93t_A)-1) + 4.1310^{-4}t_A$

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

t_A : age of the measured surface in billion years (Ga)

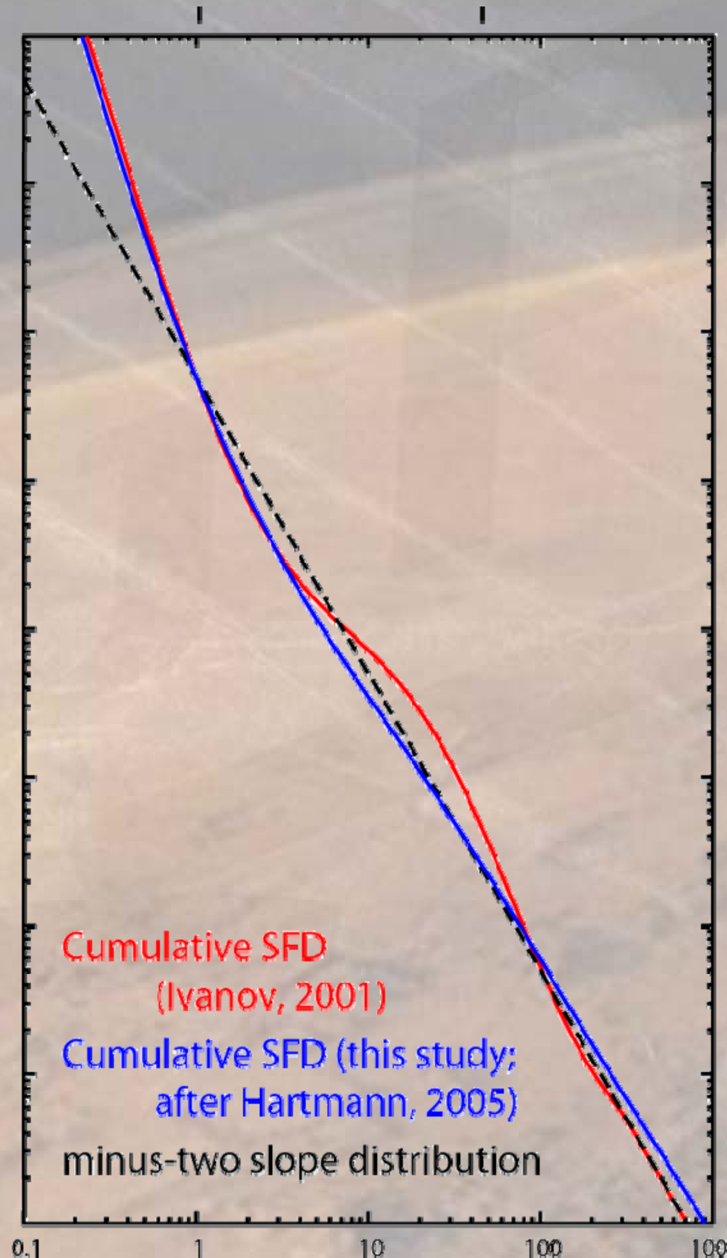
Martian Chronology Model

Ivanov, 2001; Hartmann & Neukum 2001



Different SFDs

Werner et al., in prep.



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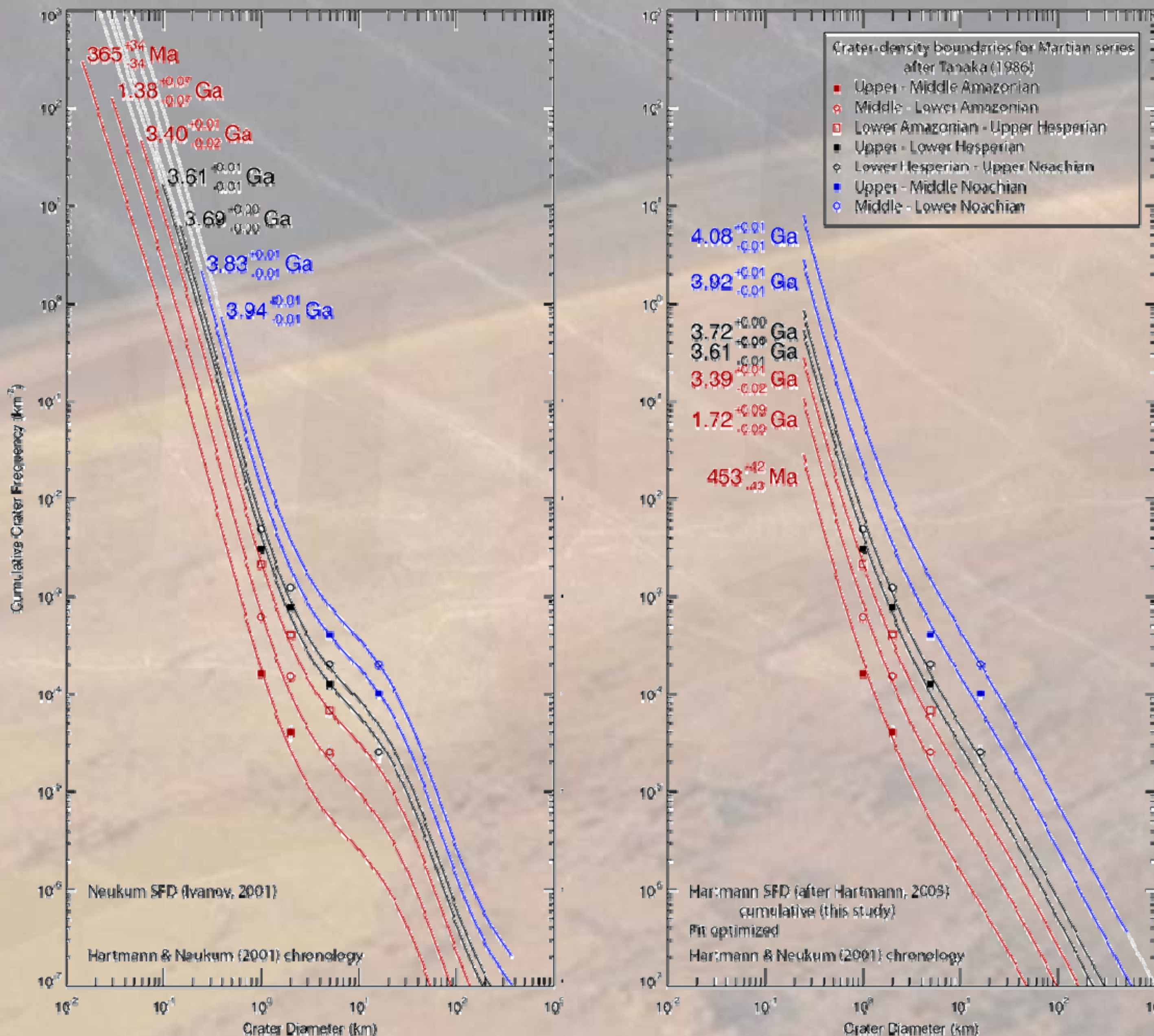
Series Boundaries



Werner et al., in prep.

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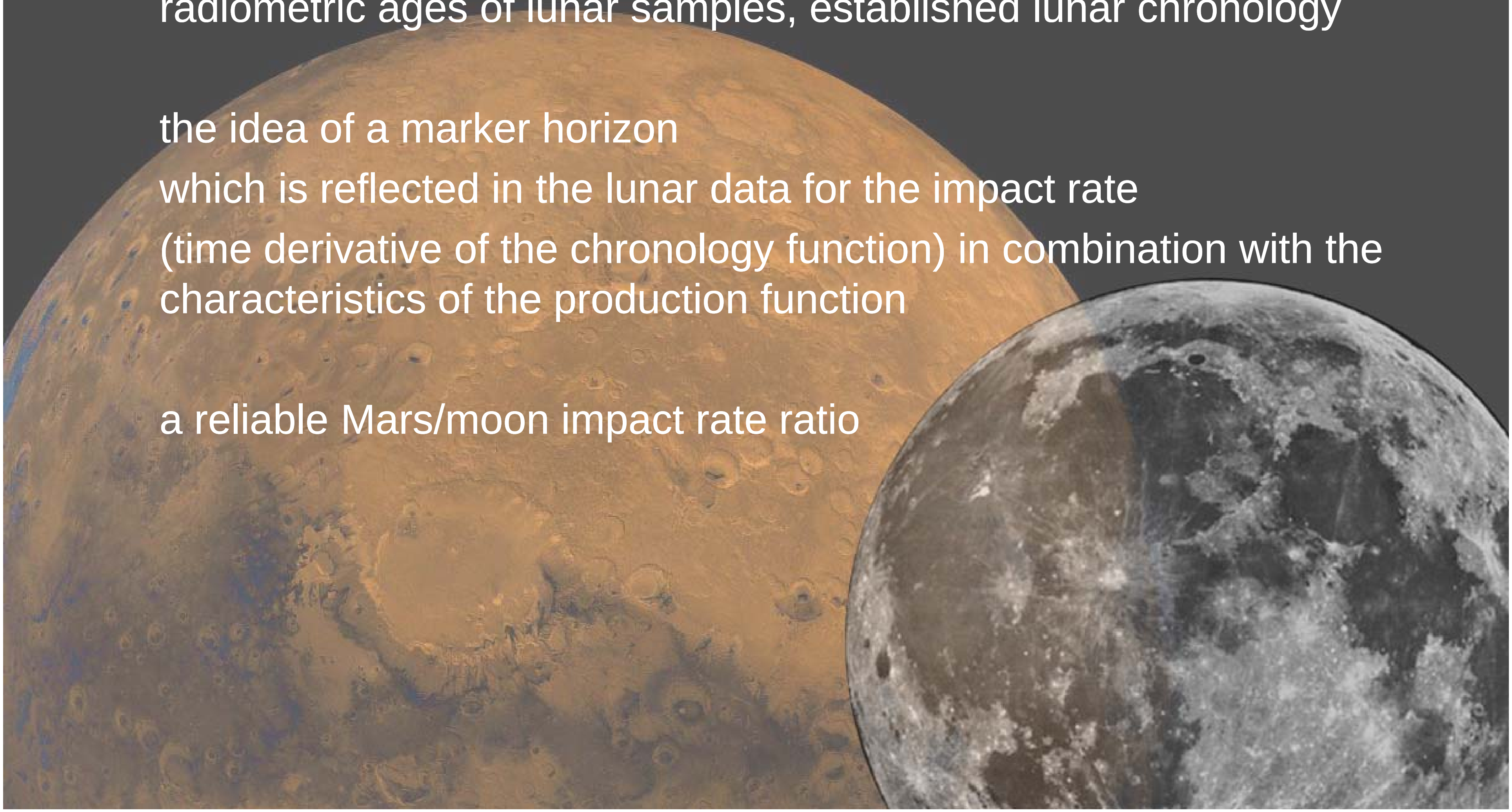
Moon as a Reference System

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 characteristics of the production function

a reliable Mars/moon impact rate ratio



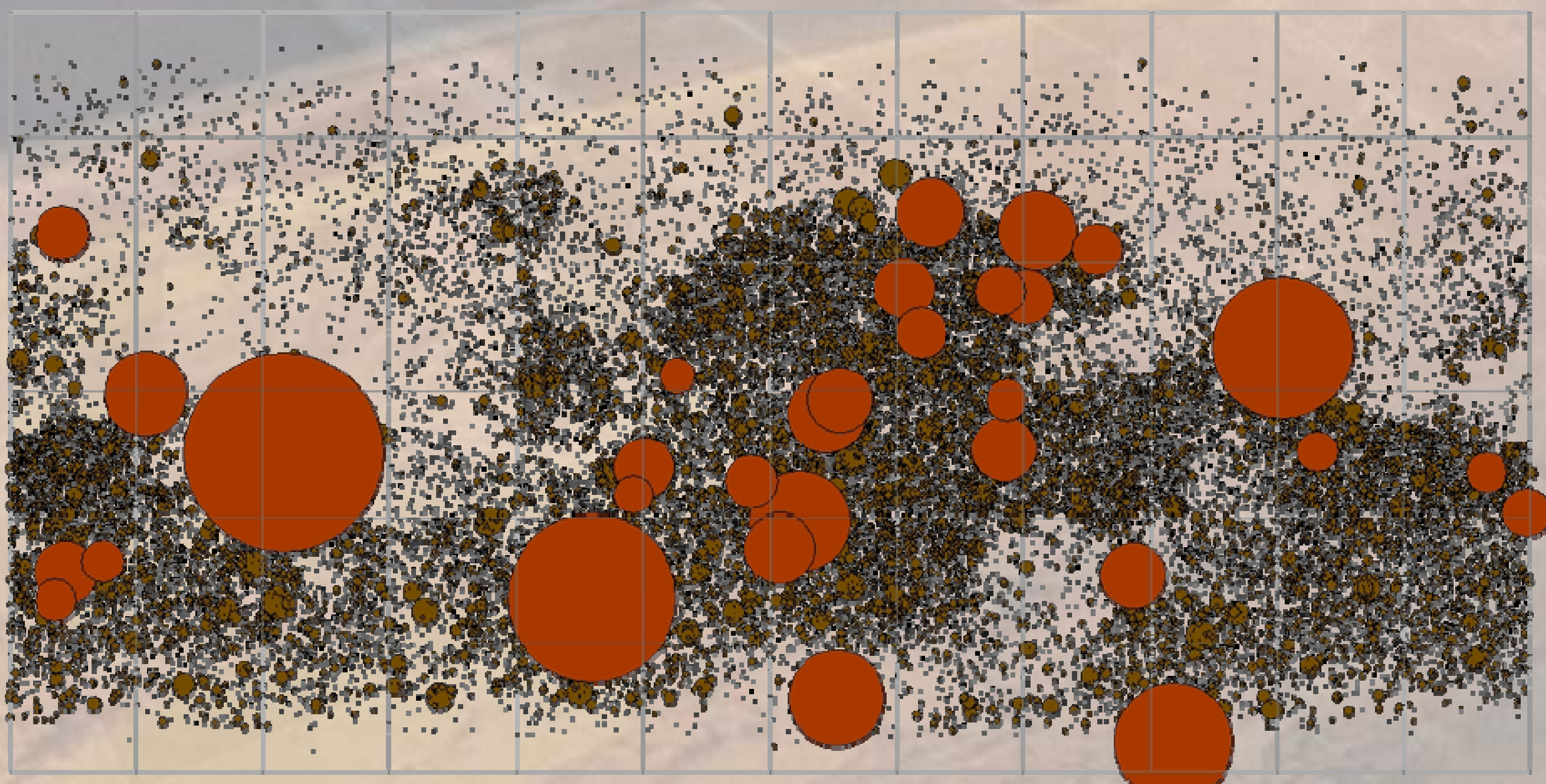
Chronostratigraphy of Mars

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)

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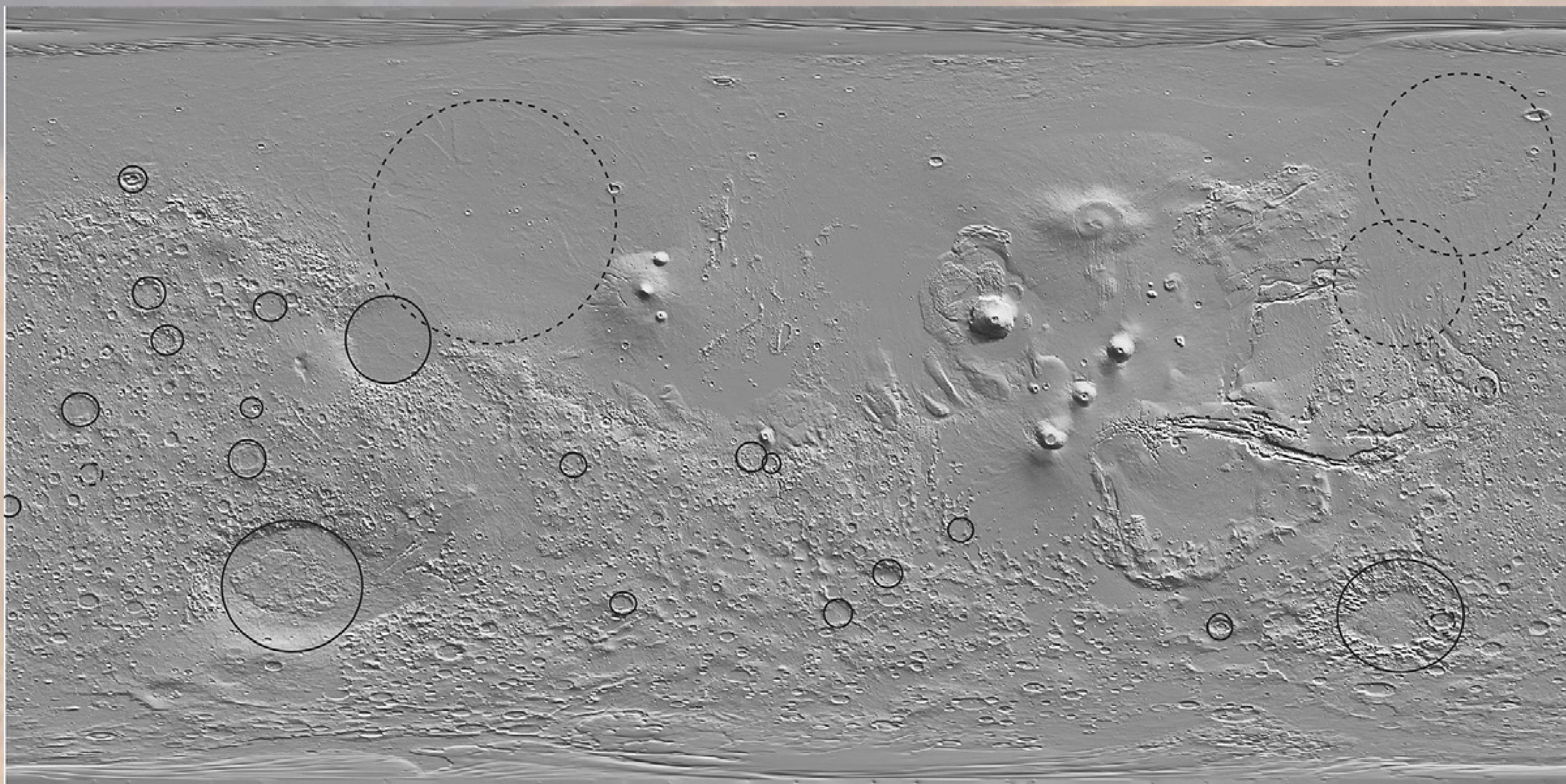
Martian Basins



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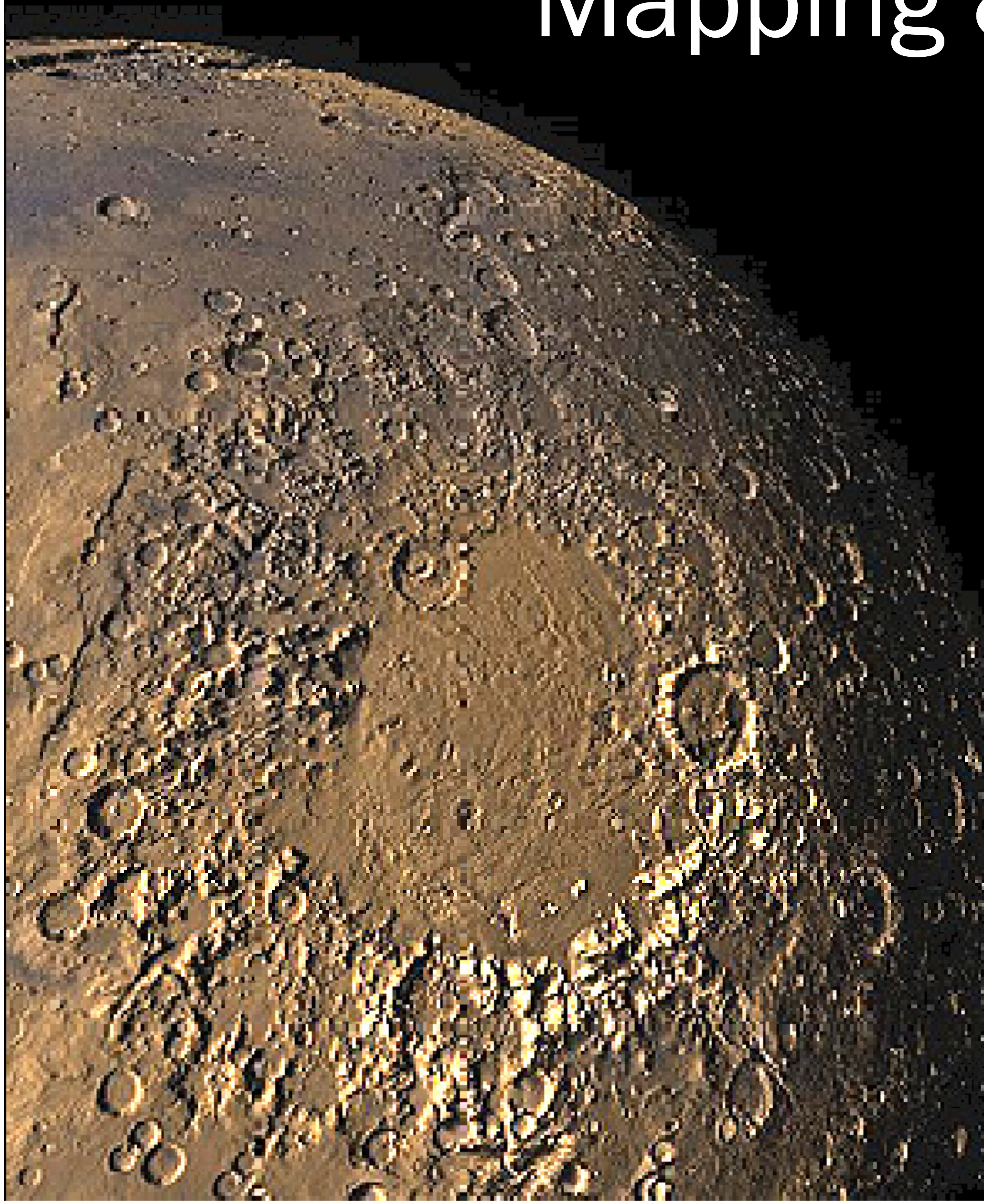
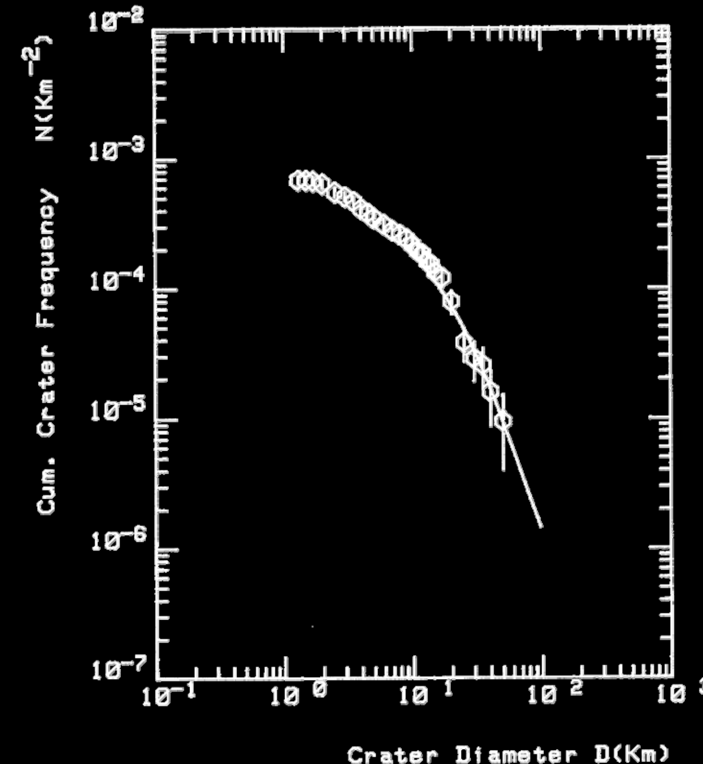
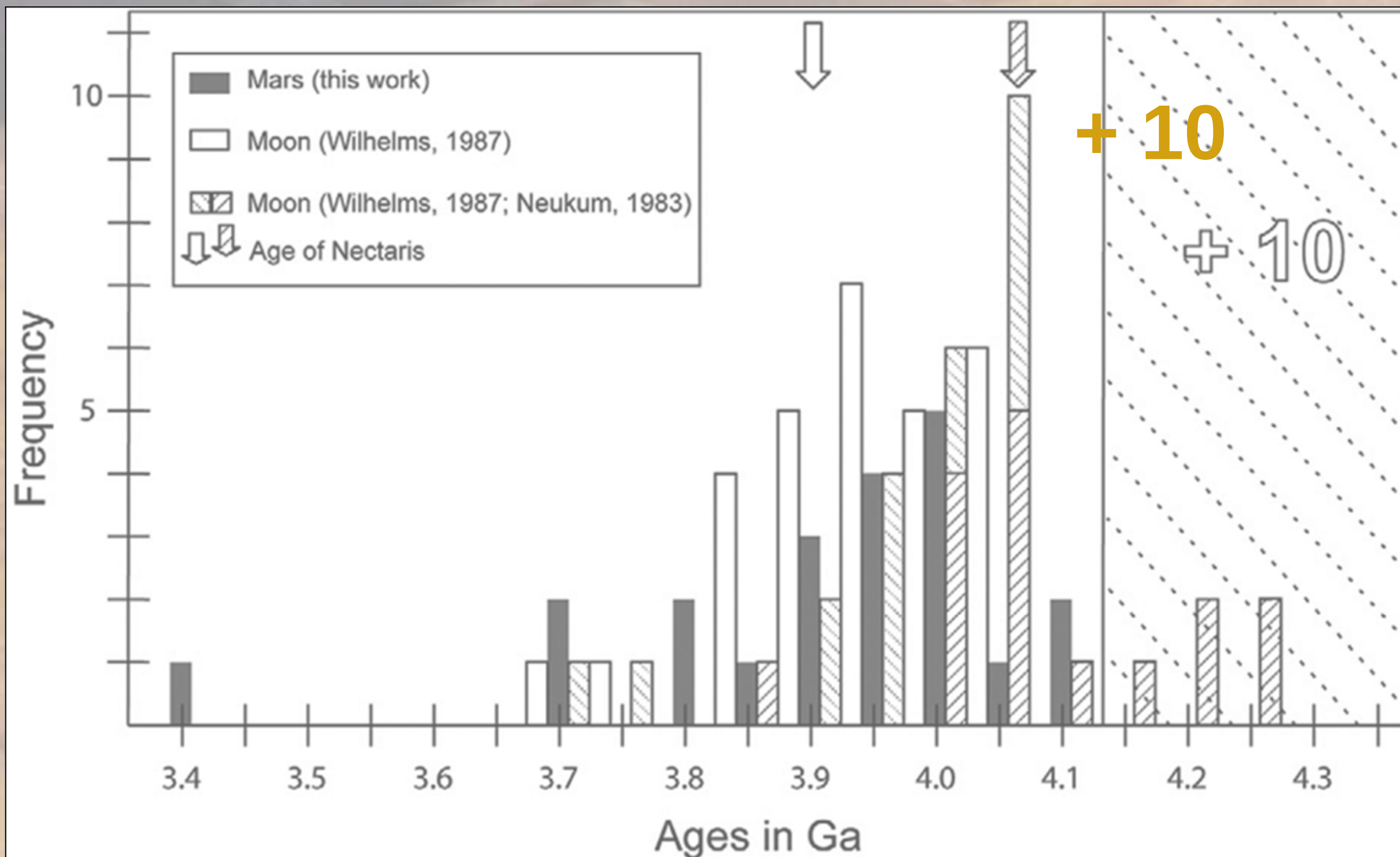
Mapping & Dating Basins





Crater Retention Age N(1) = 1.31E-02
Crater Retention Age N(10) = 1.87E-04
Cratering model age : 3.84 Aeons

Basin distribution in time



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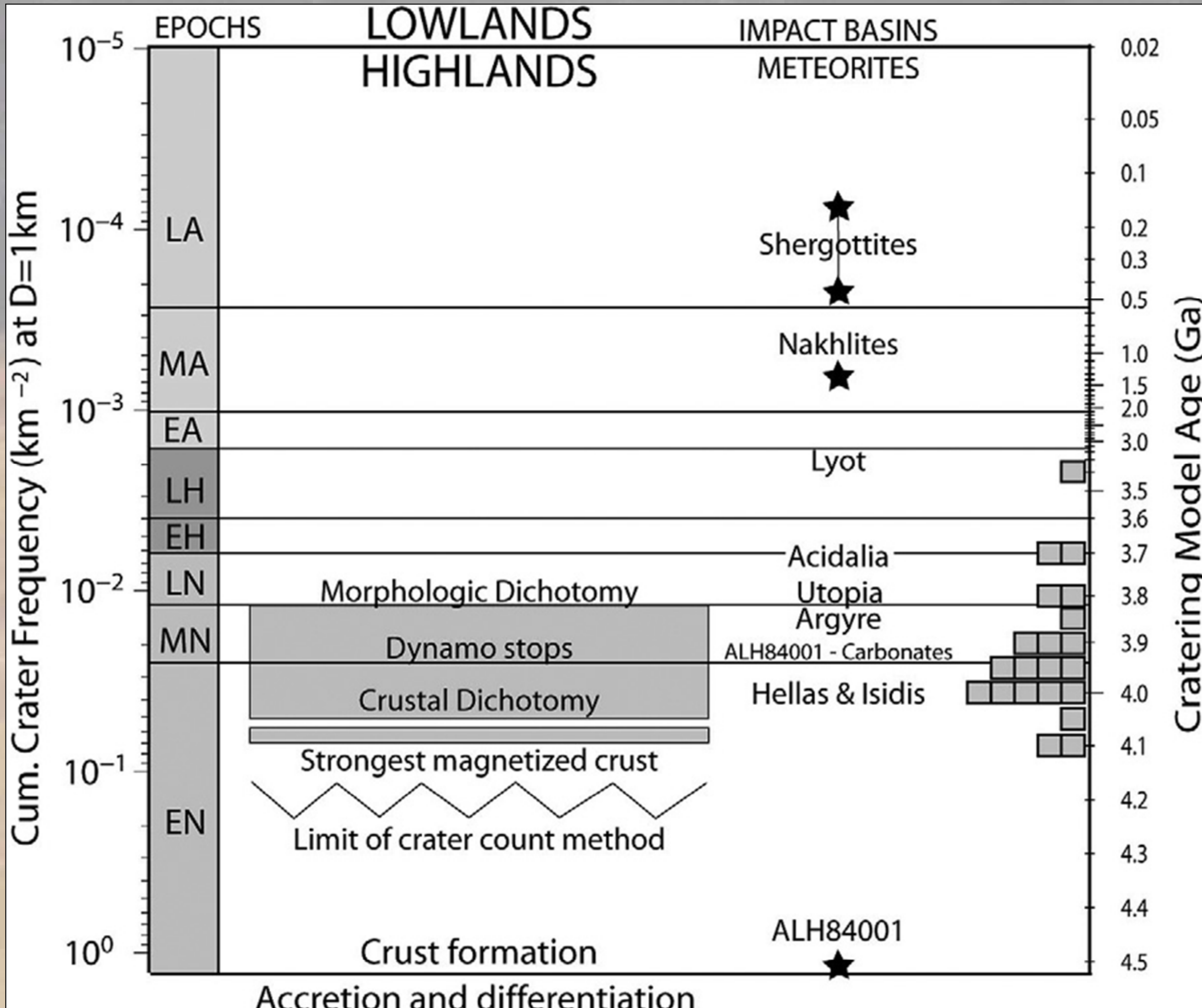
Martian evolution



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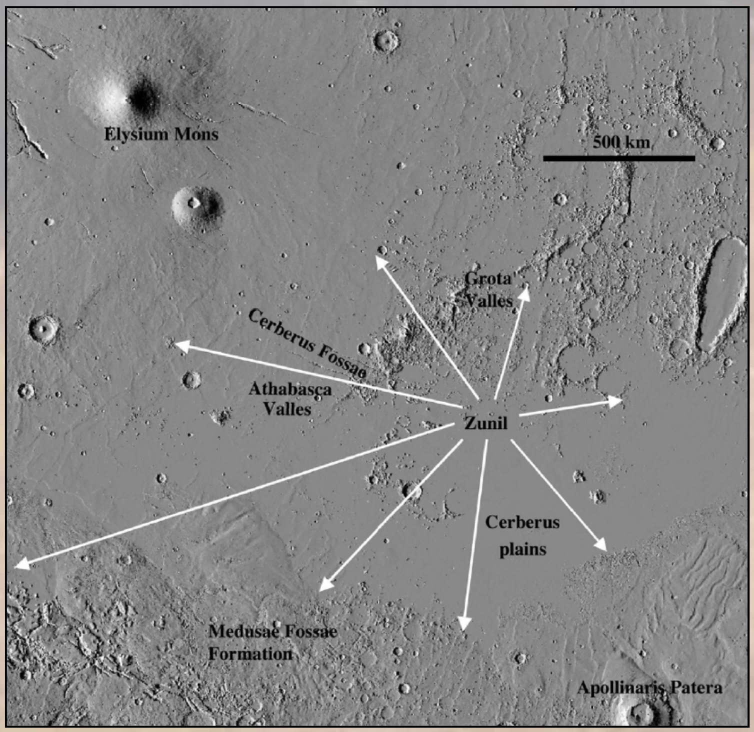
The secondary-crater strewn field of Zunil

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?

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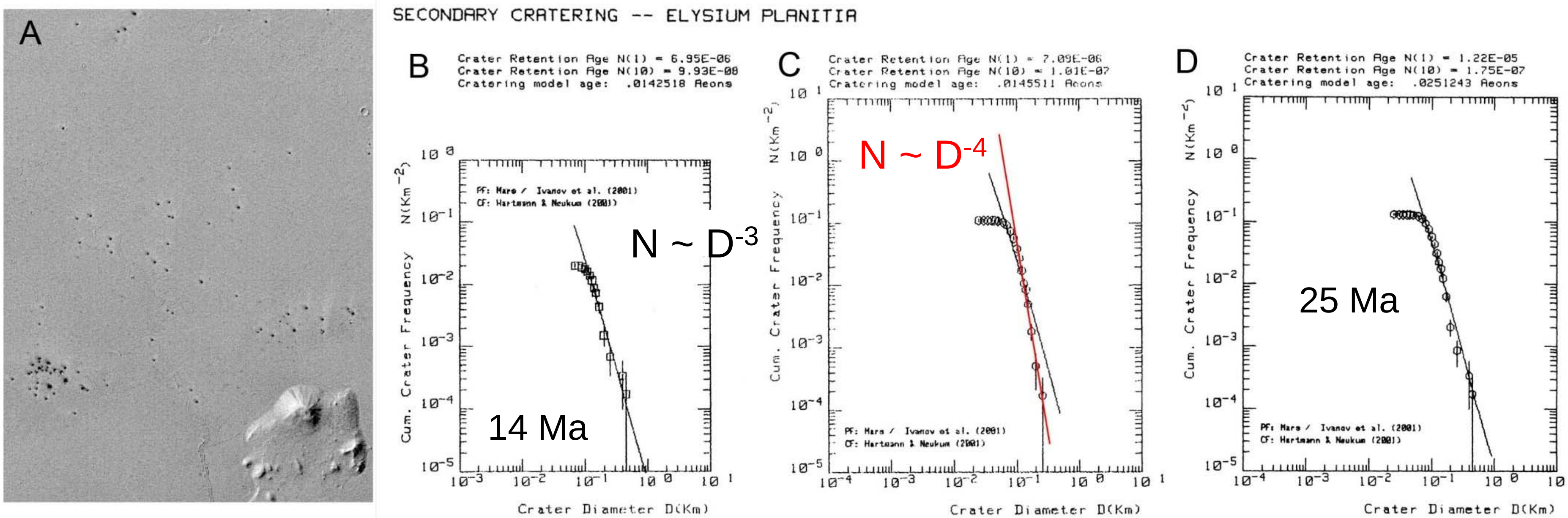
The secondary-crater strewn field of Zunil

Crater Size-Frequency Measurements



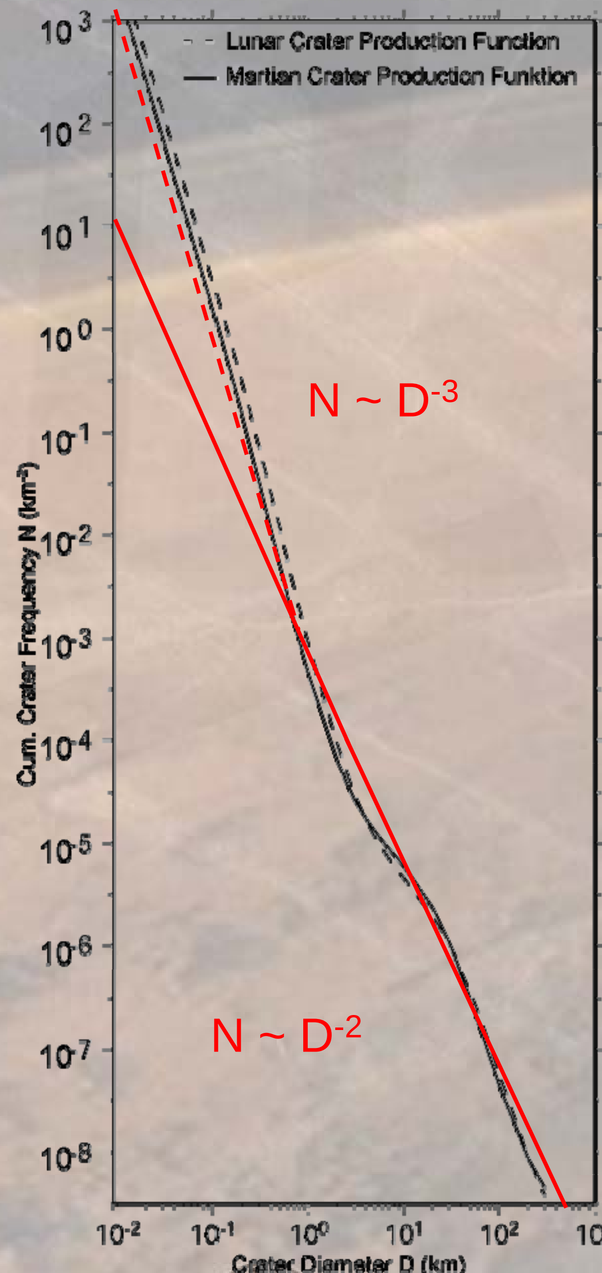
- Clustered dark haloed pits (Zunil secondaries) show a steeper distribution, $N \sim D^{-4}$
- Secondaries dominate at crater diameters below 100 m (primaries range between 500 m to 60 m)
- Misinterpretation of up to a factor of 2 in age

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?



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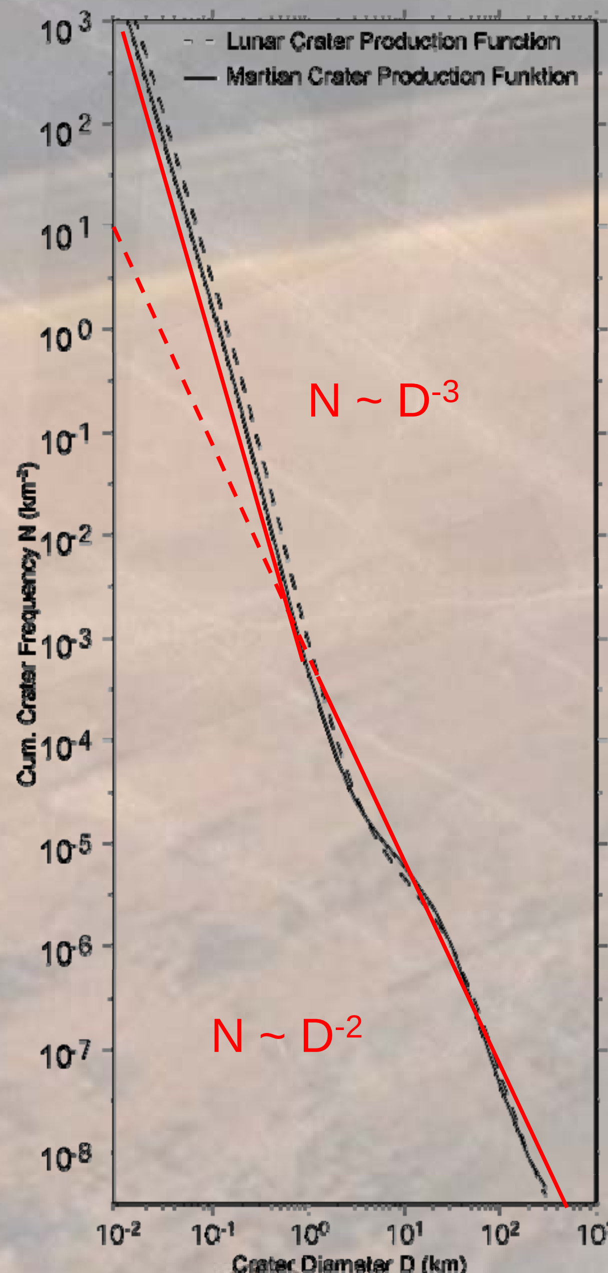
Secondary Cratering 2

PROs for a steep primary crater distribution

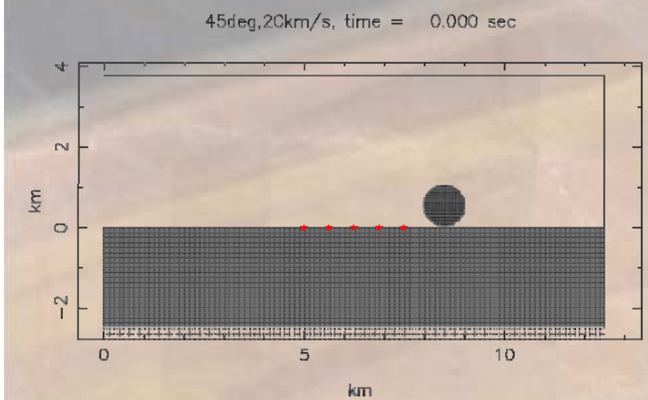
- Near-Earth asteroids, fireballs hitting Earth's atmosphere fit lunar CSFD (Werner et al., 2002; Ivanov, 2005)
- Measured on Gaspra, asteroid belt, the source region of inner solar system projectiles (Neukum & Ivanov, 1994)
- Show up in differently aged surface of different planets, and fit lunar CSFD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

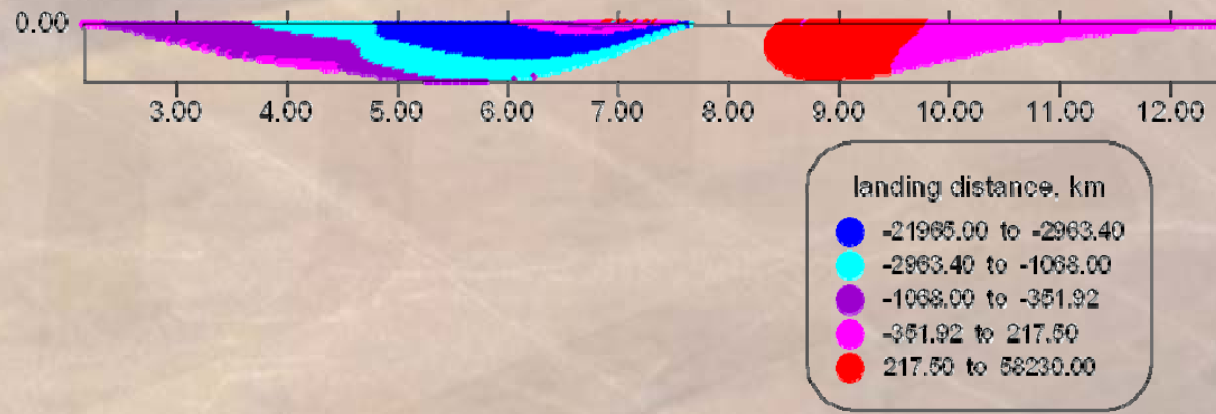


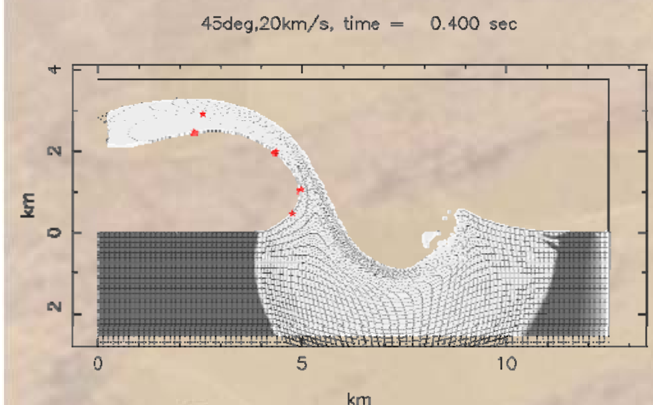
Distal fragments origin

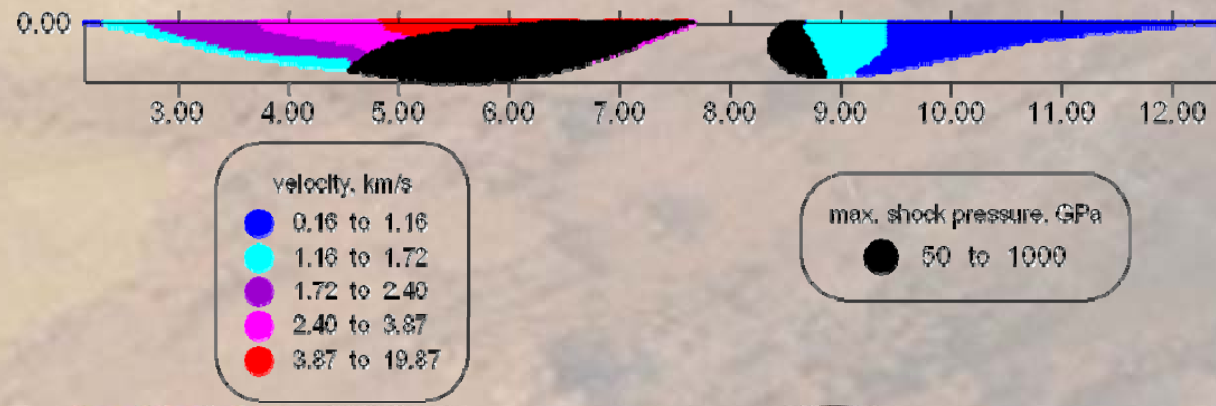
Ivanov, 2006

1 km asteroid oblique impact









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Close and remote secondaries

Shoemaker, 1965

“reference curve” is a
-4 slope approximation

“rollover” is seen just in original figures

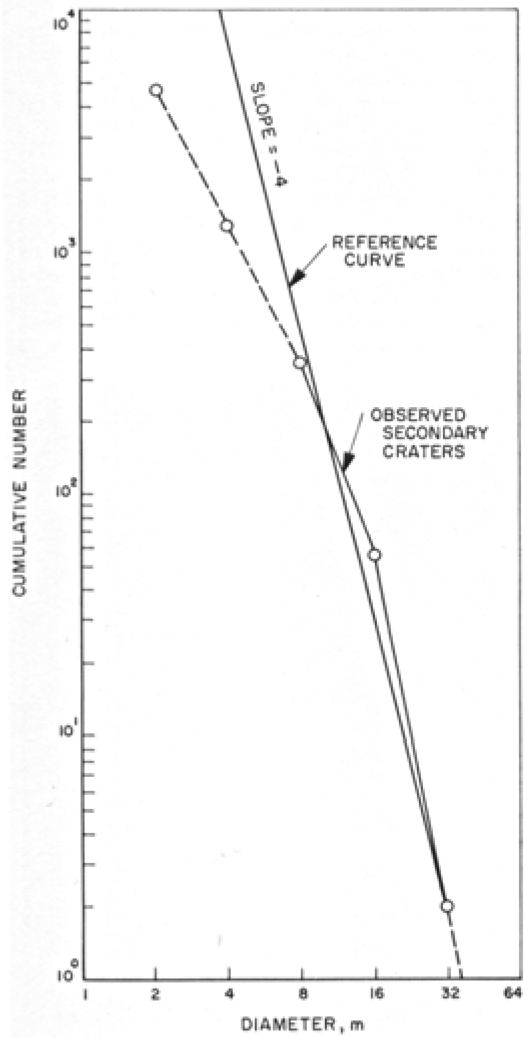


Fig. 45. Cumulative size–frequency distribution of Sedan secondary craters.

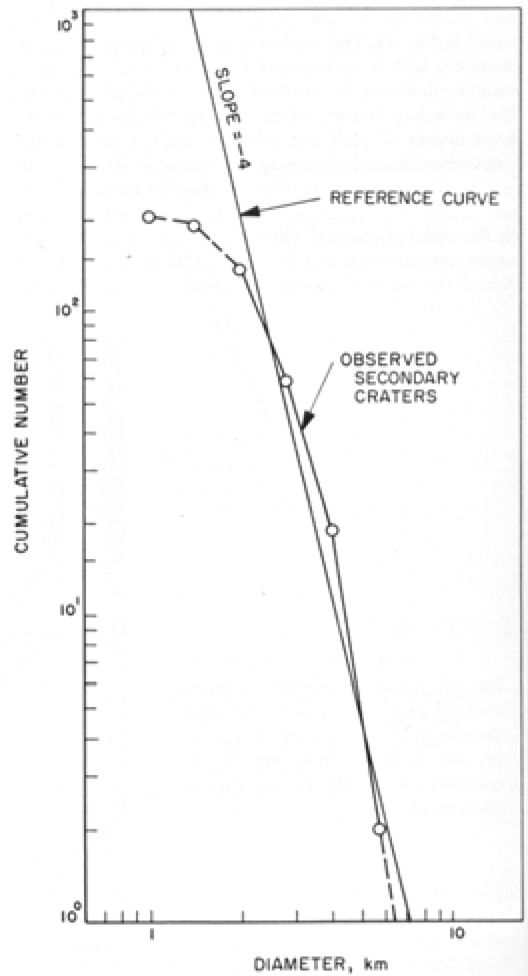


Fig. 46. Cumulative size–frequency distribution of Langrenus secondary craters.

Trial case for "rollover": Weibull SFD

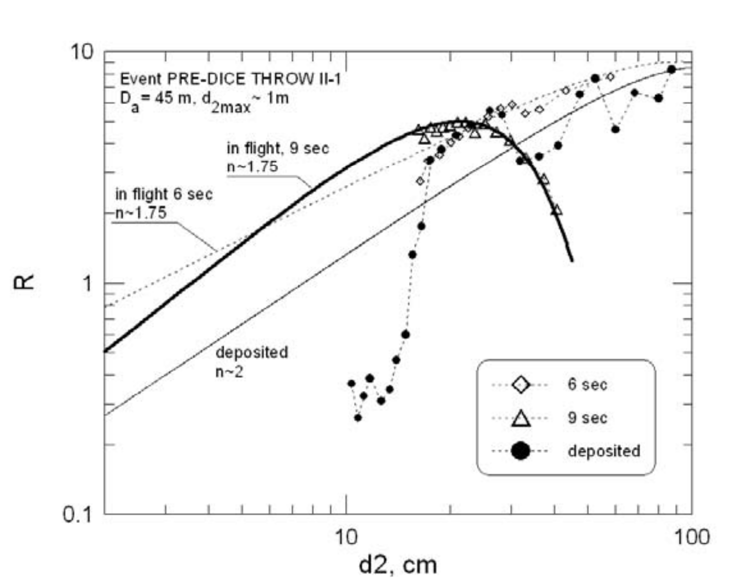
Ivanov, 2006

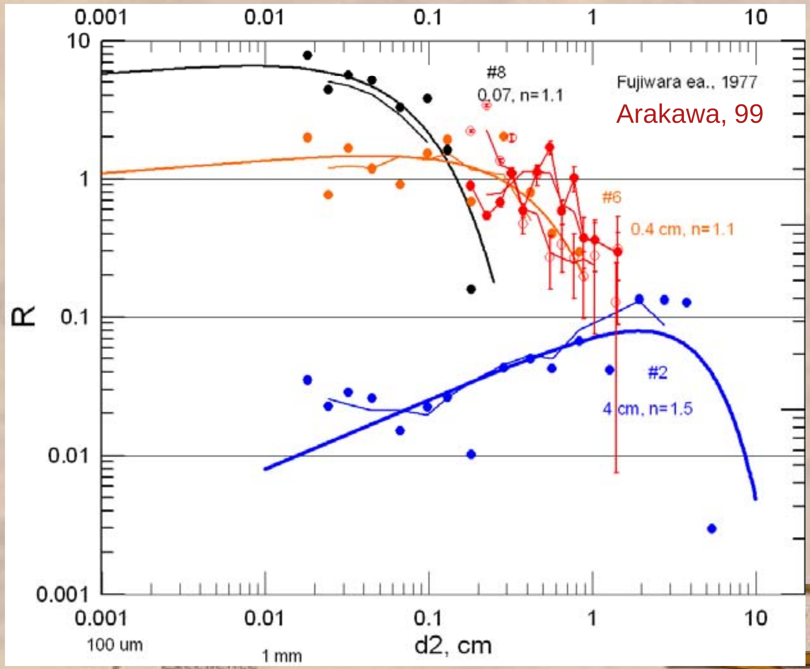
$V(>x) = V_0 \exp[-(x/x_0)^n]$

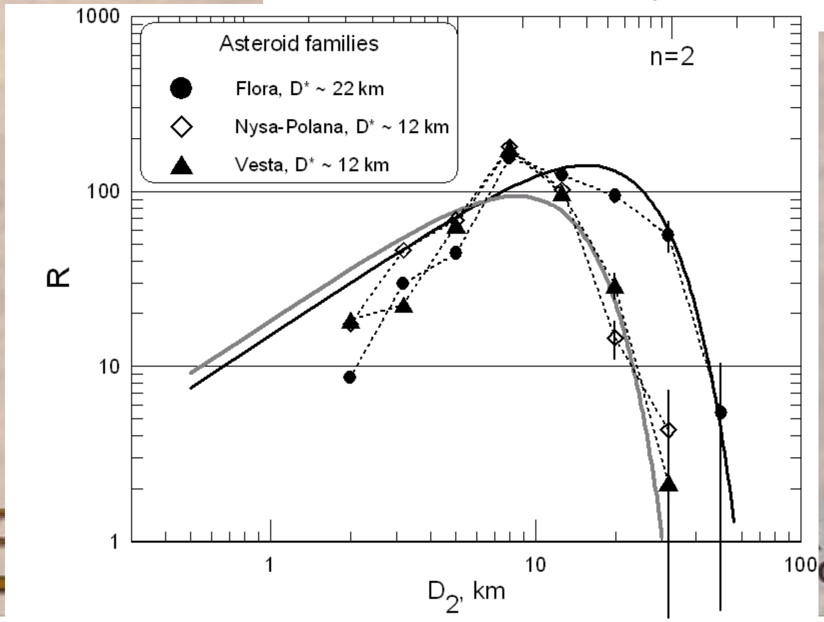
$dV/dx = (V_0/x_0)(x/x_0)^{n-1} \exp[-(x/x_0)^n]$

$R = x^3 * (dN/dx) = dV/dx$

Widely used to describe explosion fragmentation and mills efficiency







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

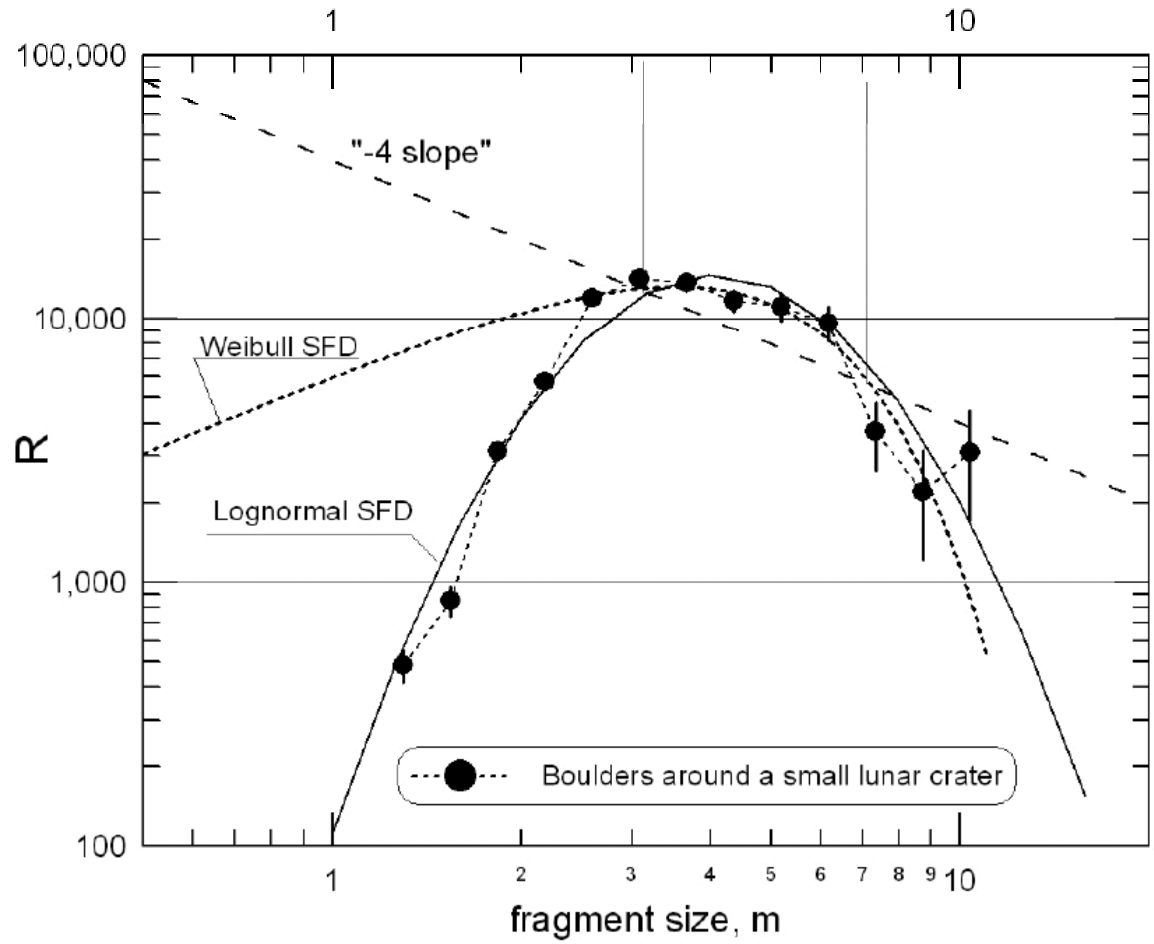


Fig. 8. 13. R-plot for boulders counted by Bart and Melosh (2005) with power law (cumulative m=4), Weibull (8. 31) and lognormal SFD fits. Bell-shaped SFD looks like a better proxy for data presentation in comparison with a power law fit. Left of the maximum observational data are going closer to the lognormal model. However, usual "undercounting" of small objects close to an image resolution image makes Weibull SFD equally perspective for future study.

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Moon

Ivanov, 2006

R-plot shows rollover at ~1/3 D_{2max}

Assumed production function is dramatically different

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

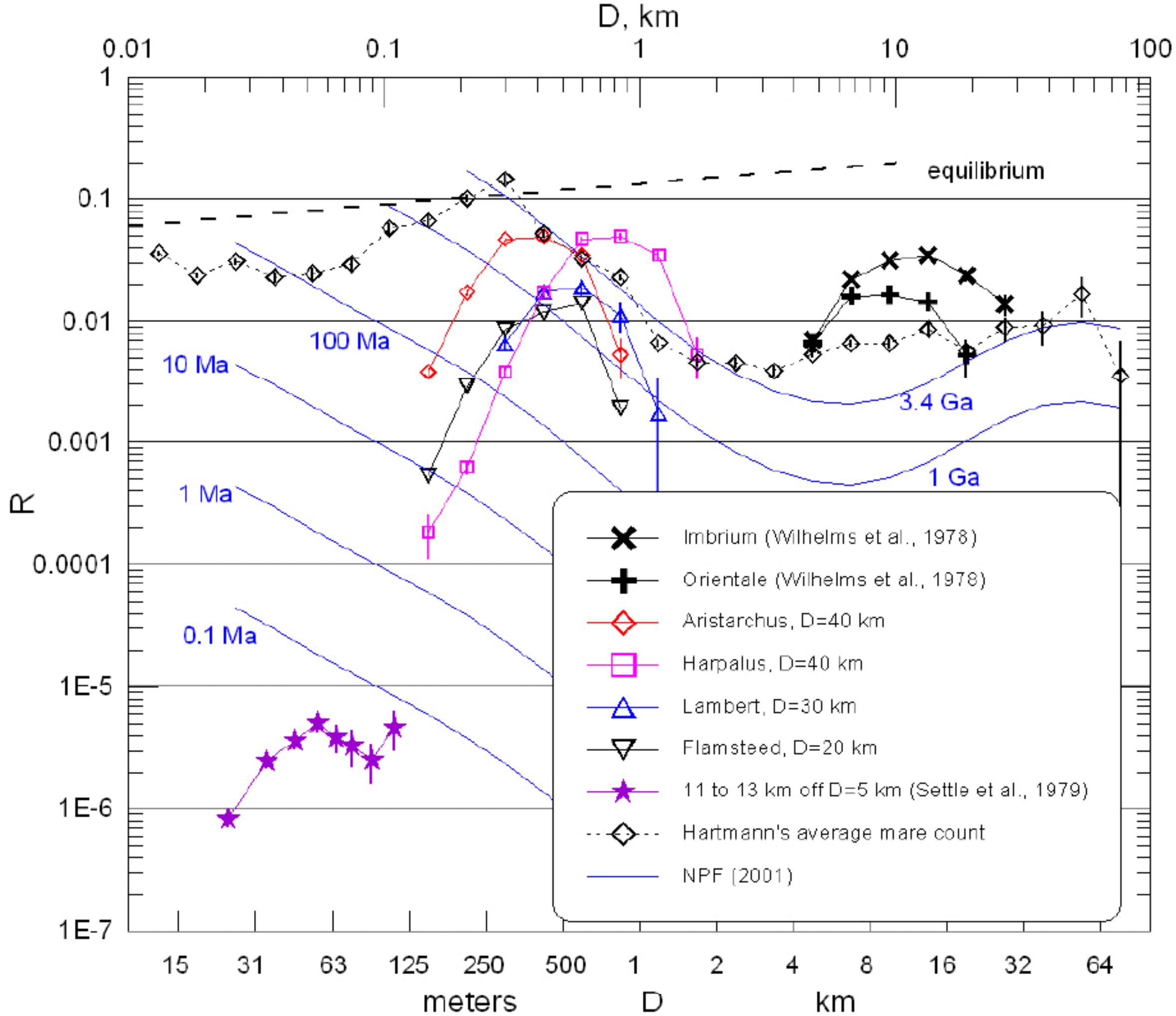

Fig. 8. 14. R-plot for close secondary craters around lunar basins (Wilhelms et al 1978) and craters (Block and Barlow 2005, Wilhelms et al 1978) in comparison with the assumed production function exampled with the NPF curve. Remote secondary craters are counted by Settle et al (1979) for a small lunar 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.

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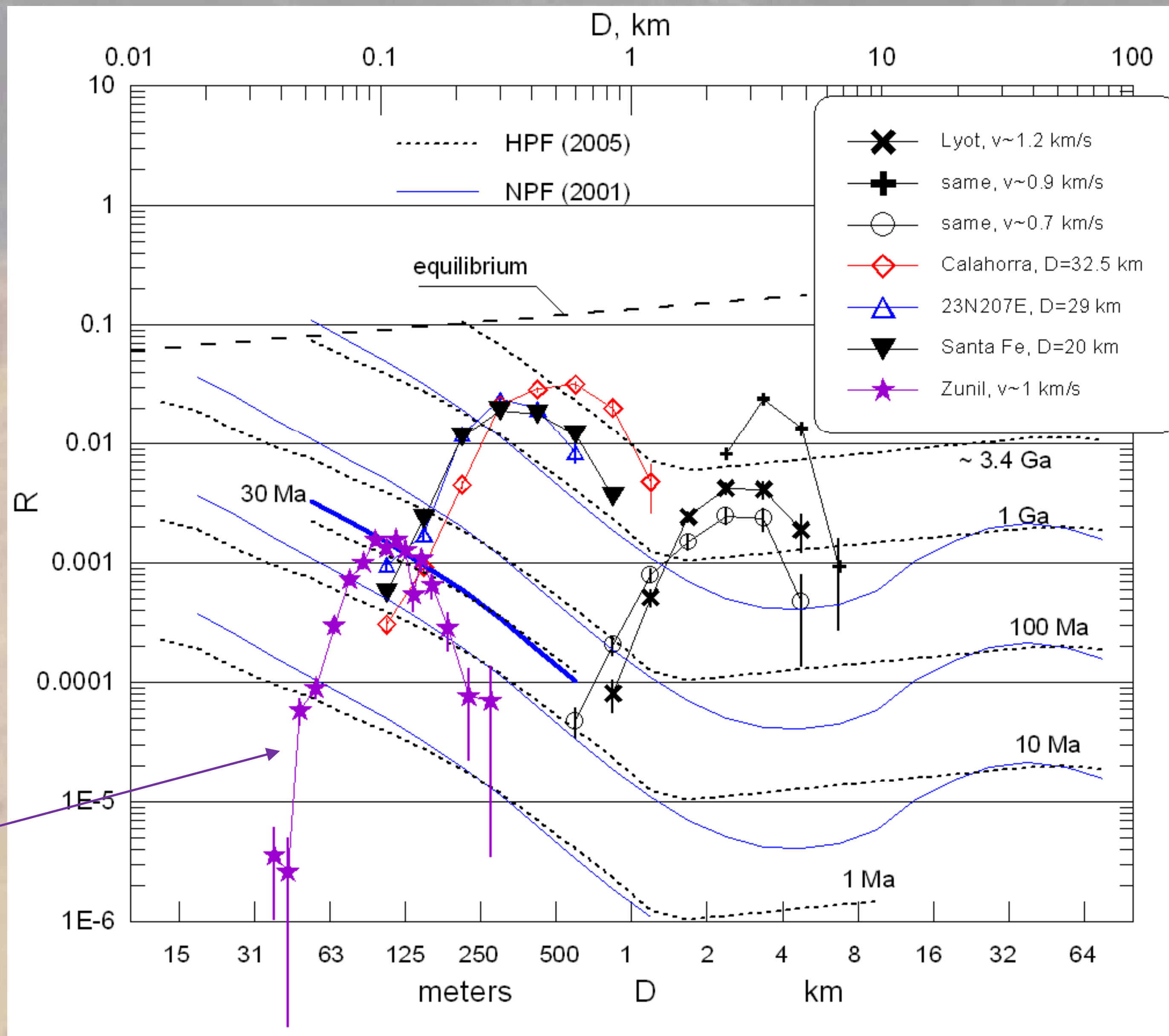
Mars

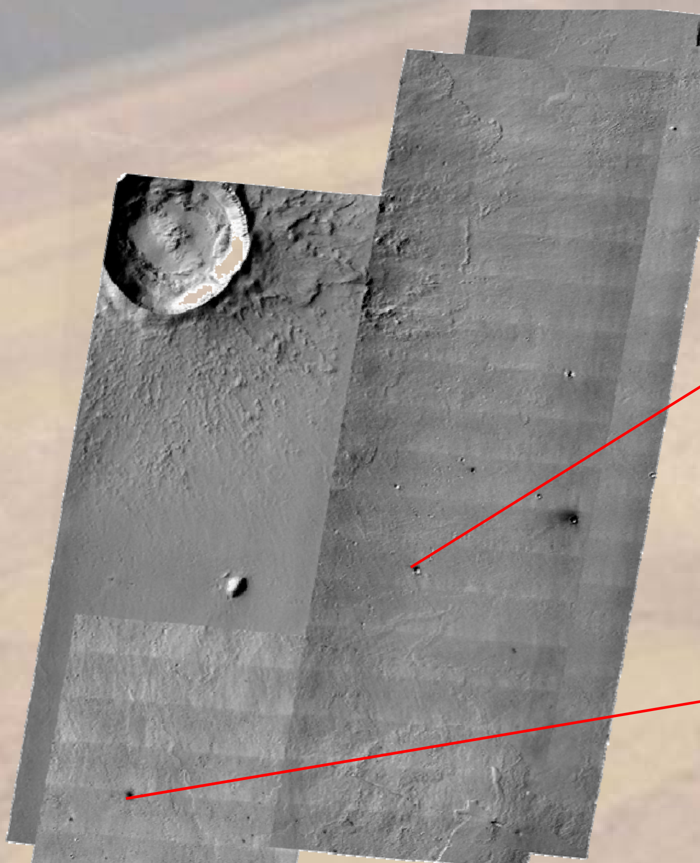
Ivanov, 2006

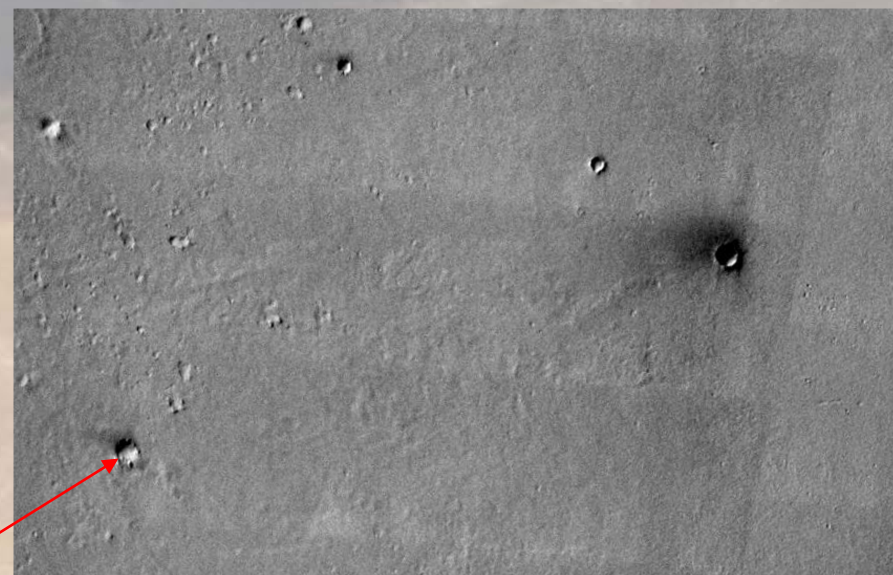


HRSC, Zunil, v~ 1 km s^{-1}

Zunil's "close" secondaries have "normal" size

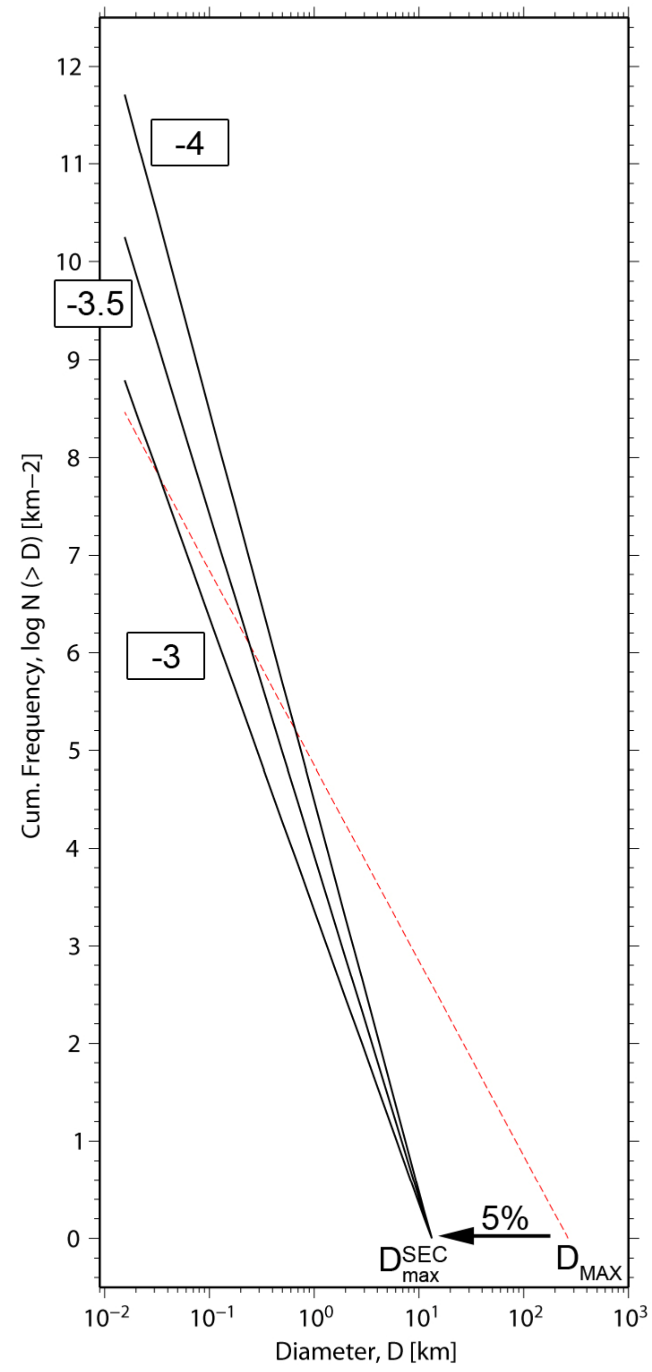
Ivanov, 2006





Hypothetical Crater Distribution for an 1-Ga old Martian Surface

- flat primary distribution ($N \sim D^{-2}$)
- 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, $N \sim D^{-3, -3.5, -4}$)
- secondary crater distribution: $N \sim D^{-4}$



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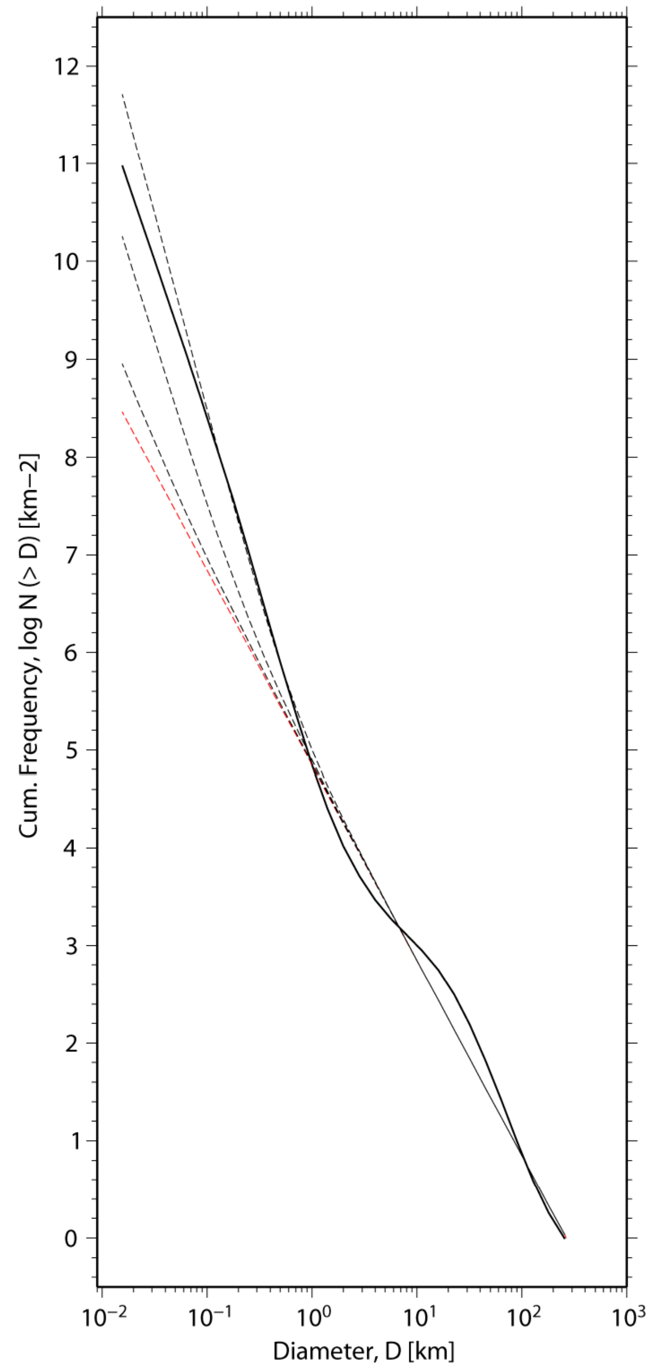
Hypothetical Crater Distribution for an 1-Ga old Martian Surface

- flattening for craters smaller than 0.7 D^{SEC}_{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



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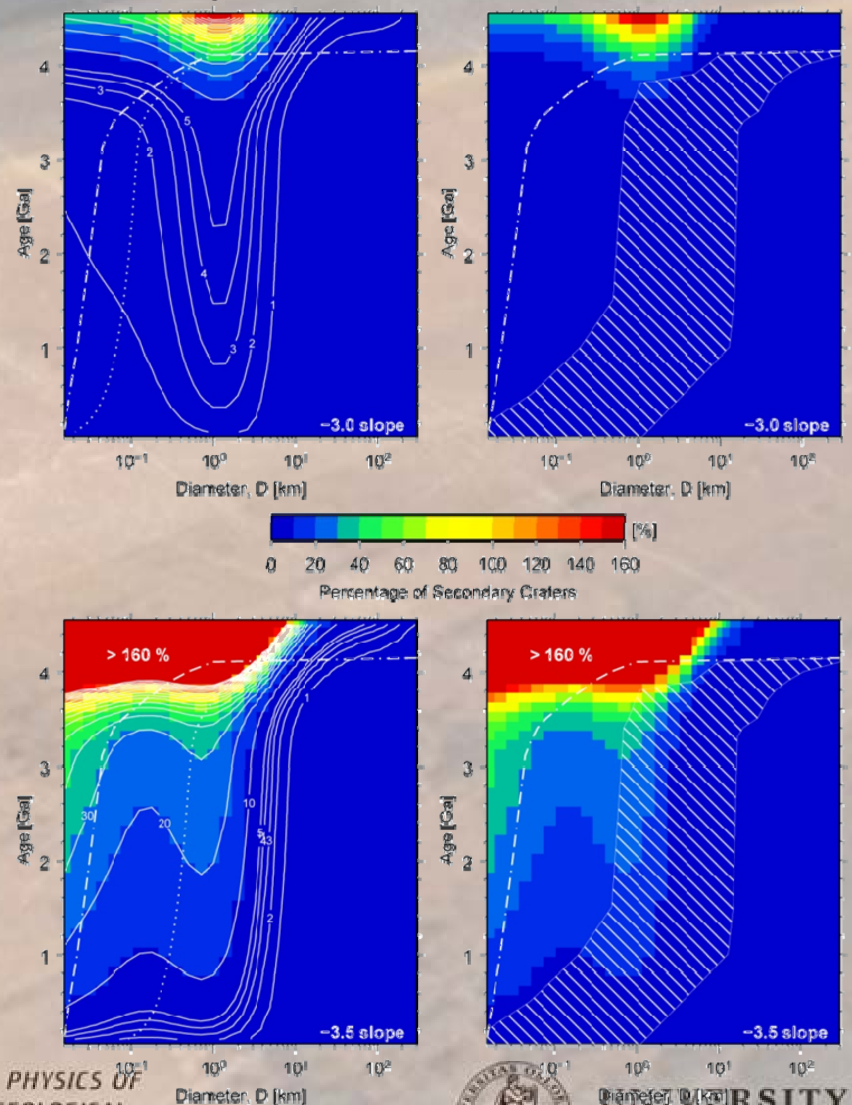
Percentage of Secondary Crater Contribution in an Observed Crater Size-Frequency Distribution



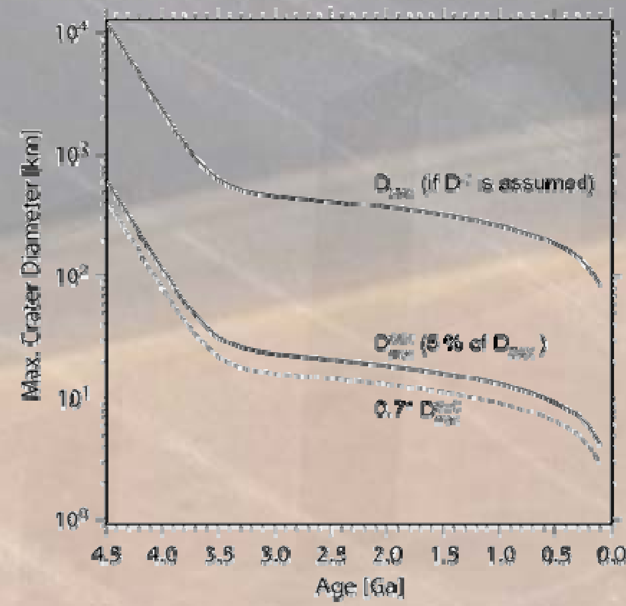
Hypothetic secondary crater contribution for two possible different slope indices (-3.0 and -3.5):

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

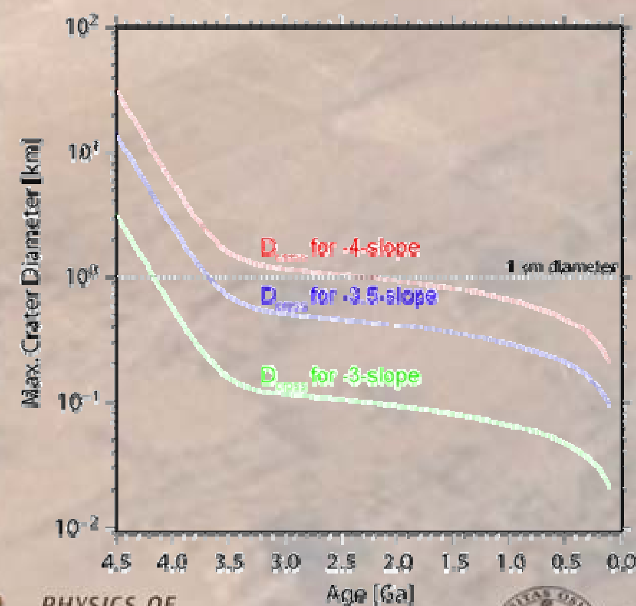
The shape of the distribution would vary with surface age…

Age dependence

Maximum Diameter – Age Relation



Crossover Diameter – Age Relation



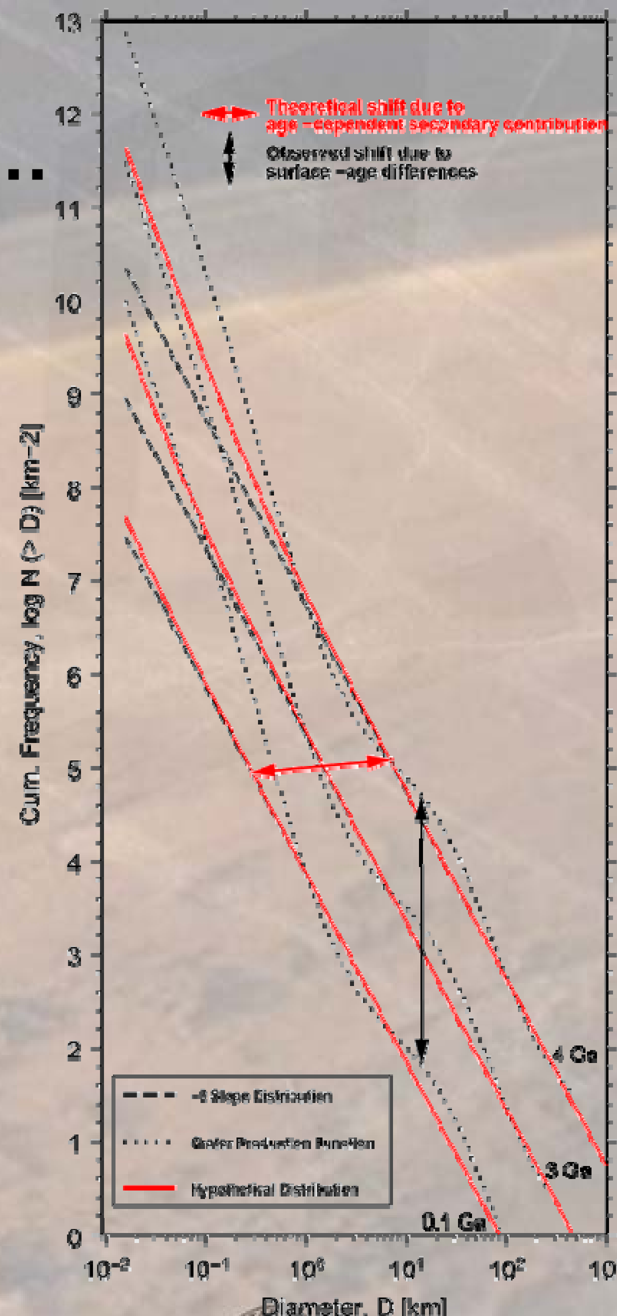
Surface Age Dependence of…

- 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…

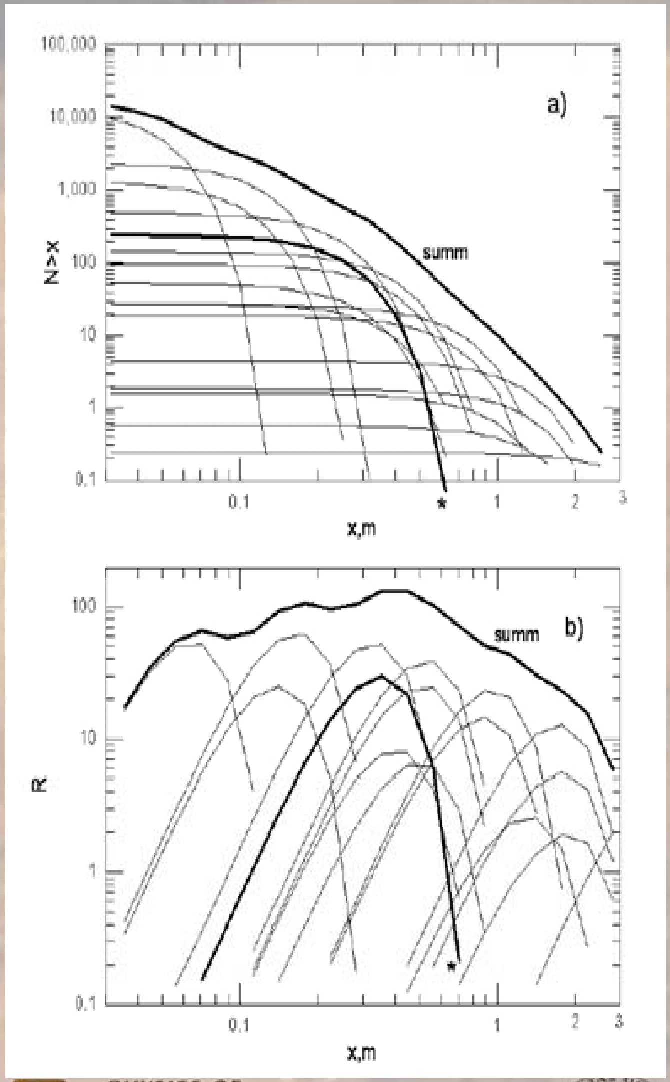
… that is not observed!



Summation of secondary craters

created by ejecta from primaries

Melosh et al. 1992



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The Evolutionary History of Mars

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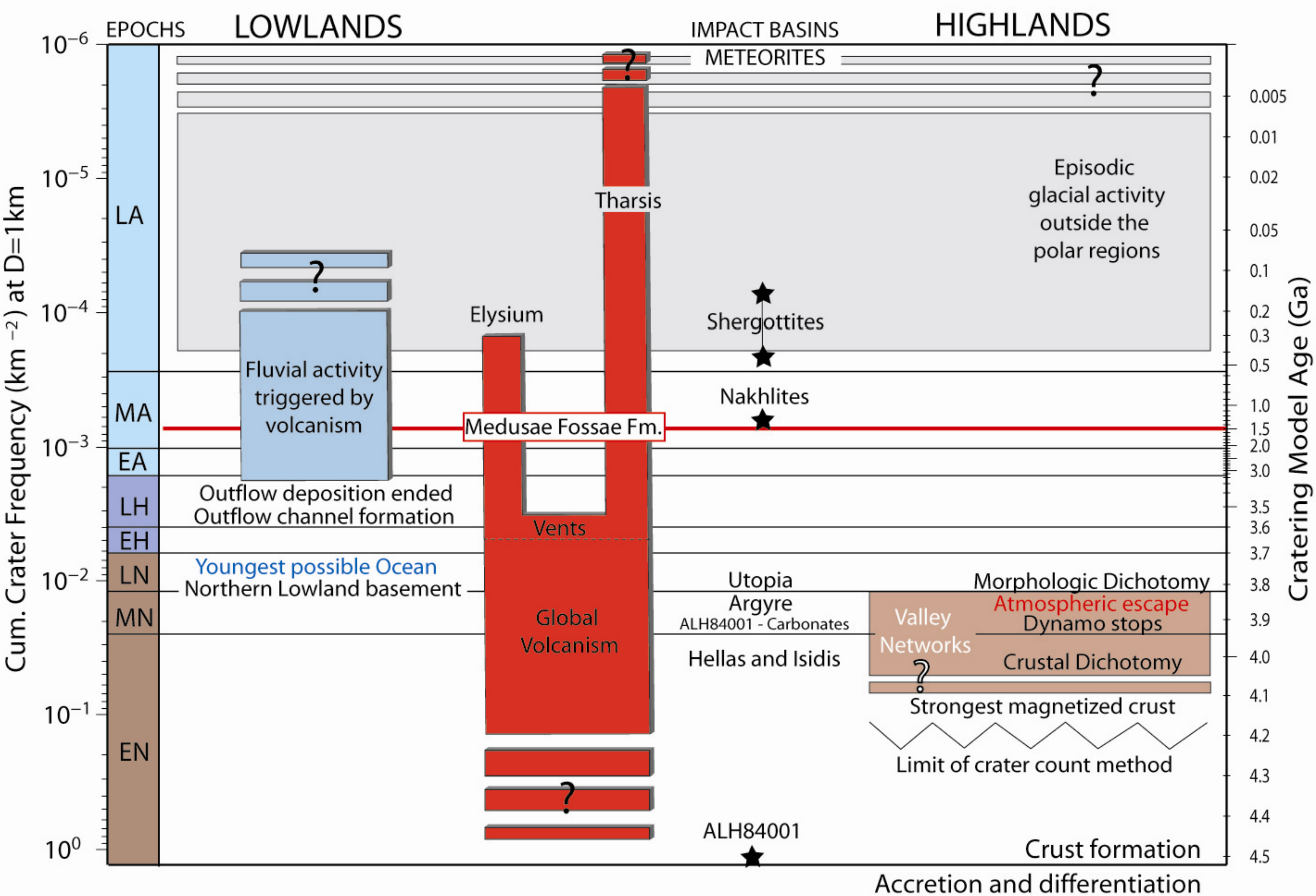
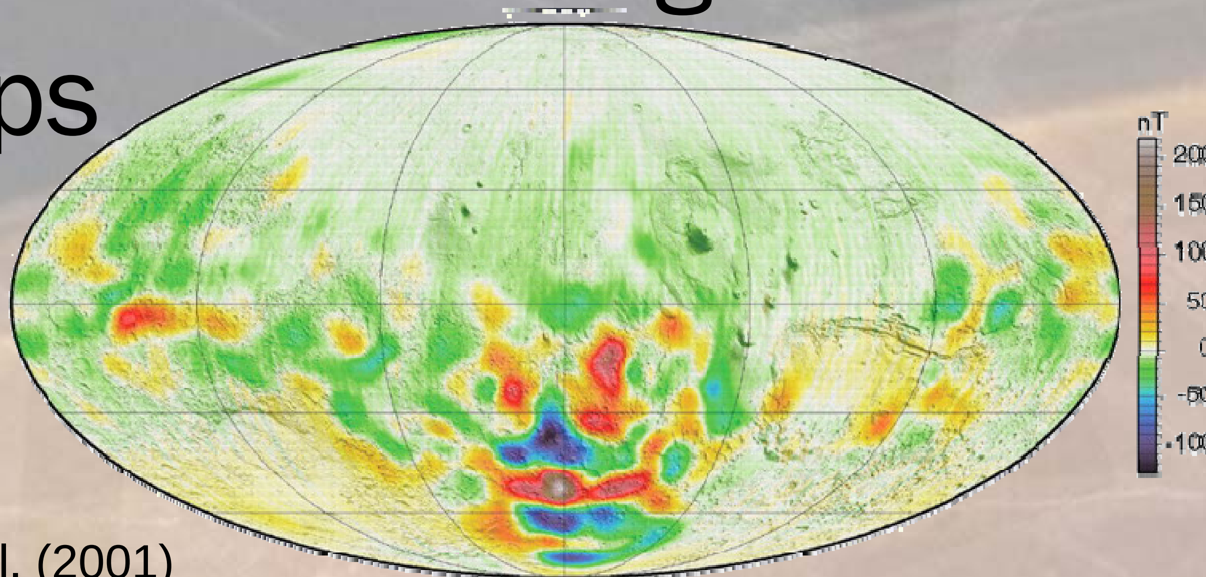
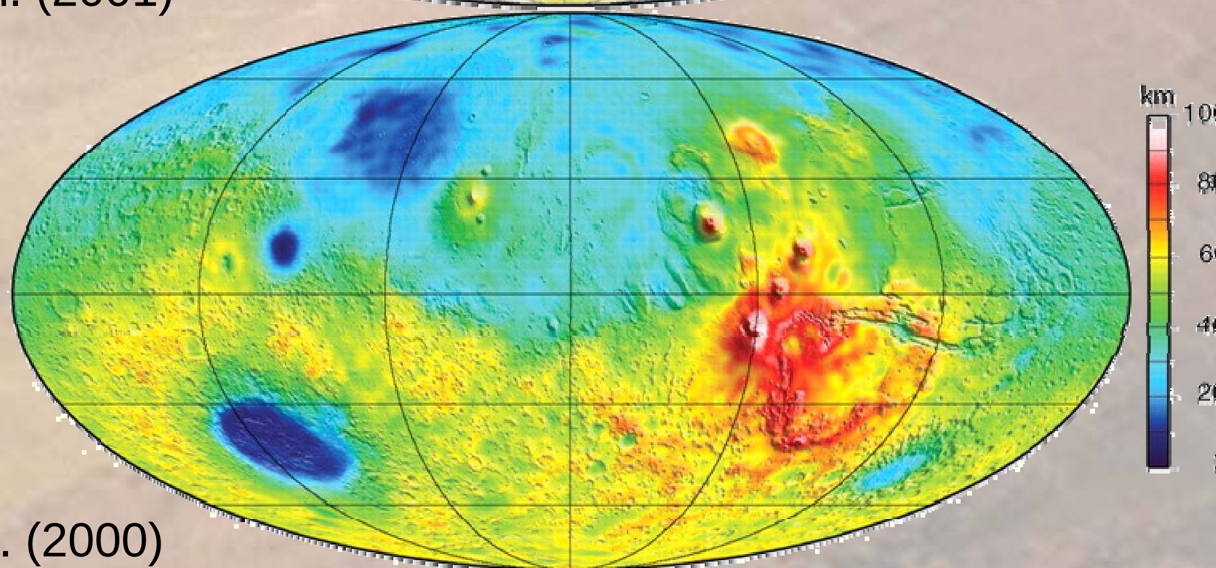
Evolutionary History of Mars



Crustal Thickness and Magnetic Anomaly Maps

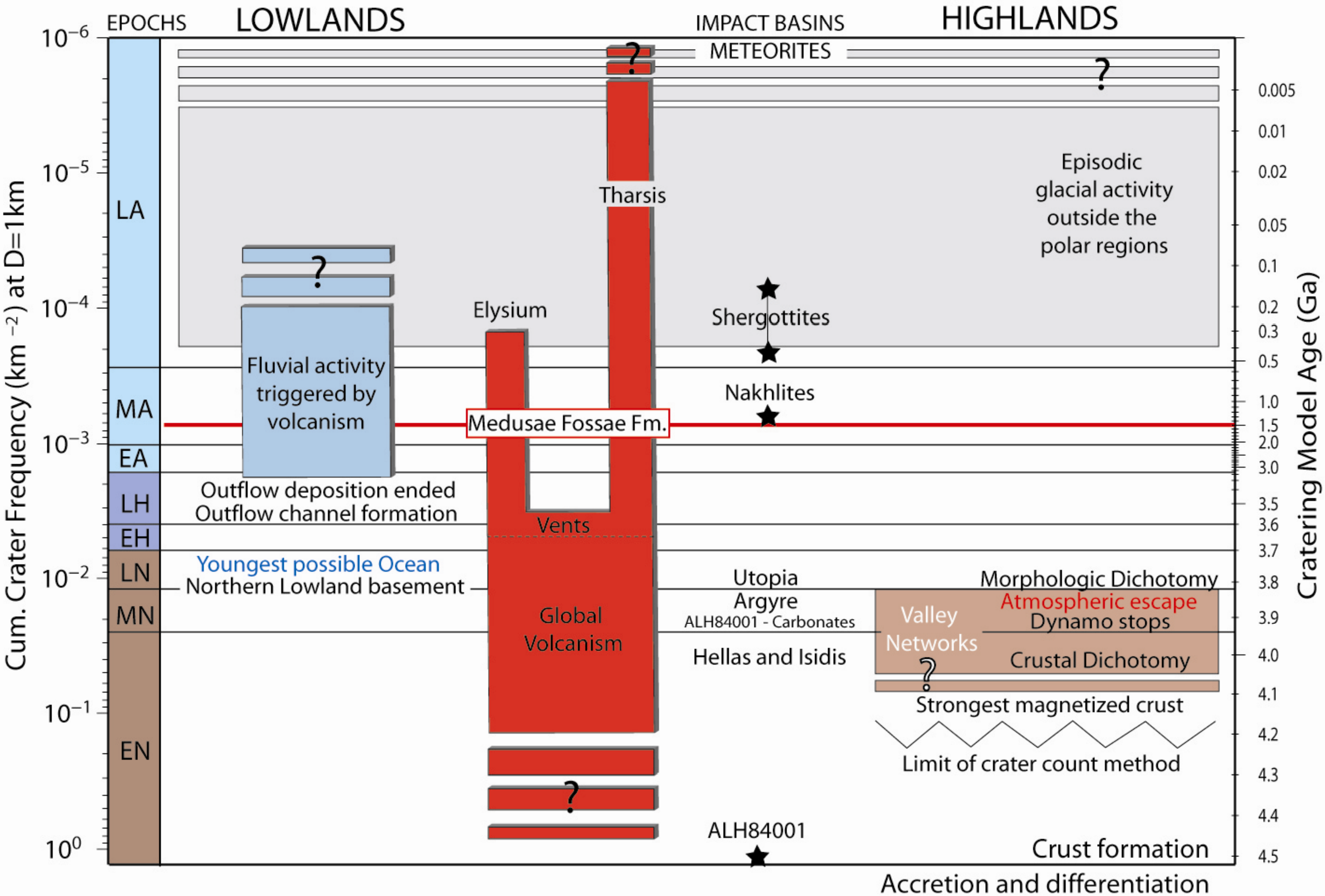


Acuna et al. (2001)



Zuber et al. (2000)

Evolutionary History of Mars



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