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Measuring the age of planetary surfaces using crater statistics

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27 January 2012 Last updated at 09:51 GMT

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Asteroid to make near-miss fly-by

An asteroid will pass by the Earth on Friday in something of a cosmic near-miss, making its closest approach at about 1600 GMT.

The asteroid is minuscule relative to the recently photographed asteroid Vesta

The asteroid, estimated to be about 11m (36ft) in diameter, was first detected on Wednesday.

At its closest, the space rock - named 2012 BX34 - will pass within about 60,000km of Earth - less than a fifth of the distance to the Moon.

Astronomers stress that there is no cause for concern.

"It's one of the closest approaches recorded," said Gareth Williams, associate director of the US-based Minor Planet Center.

"It makes it in to the top 20 closest approaches, but it's sufficiently far away... that there's absolutely no chance of it hitting us," he told the BBC.

The asteroid's path makes it the closest space-rock to pass by the Earth since object 2011 MD in June 2011.

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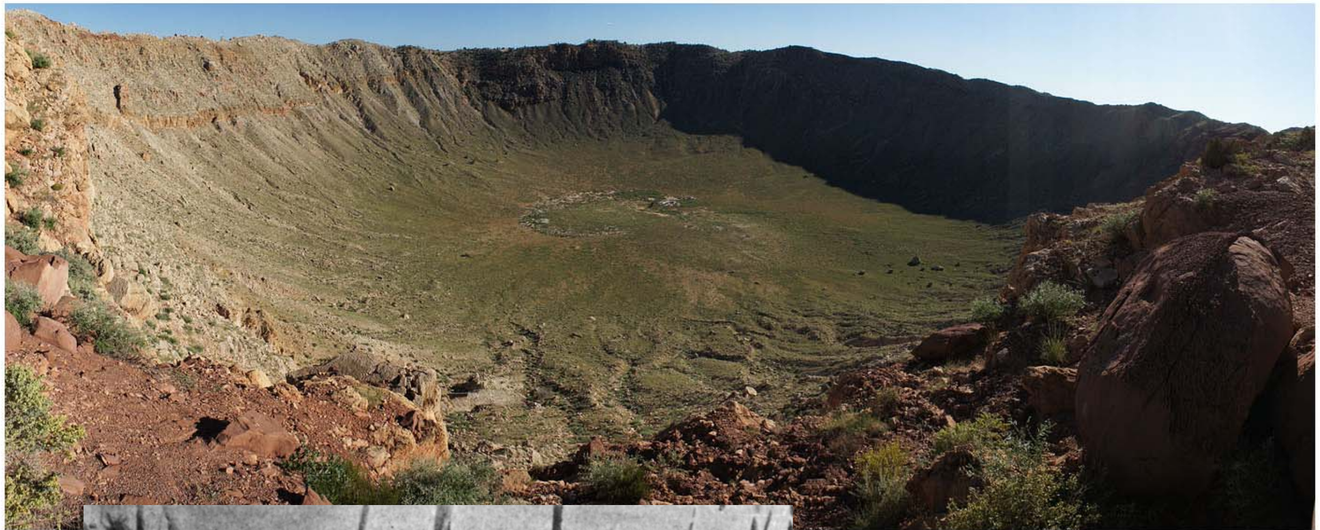
Giant asteroid passes near Earth

- 11 m impactor
- Flyby at 60,000 km
- Would have produced a crater of ~200 m diameter
- Roughly 10 Earth radii away... one in a hundred such events should hit the Earth

Berlin's central park - the Tiergarten

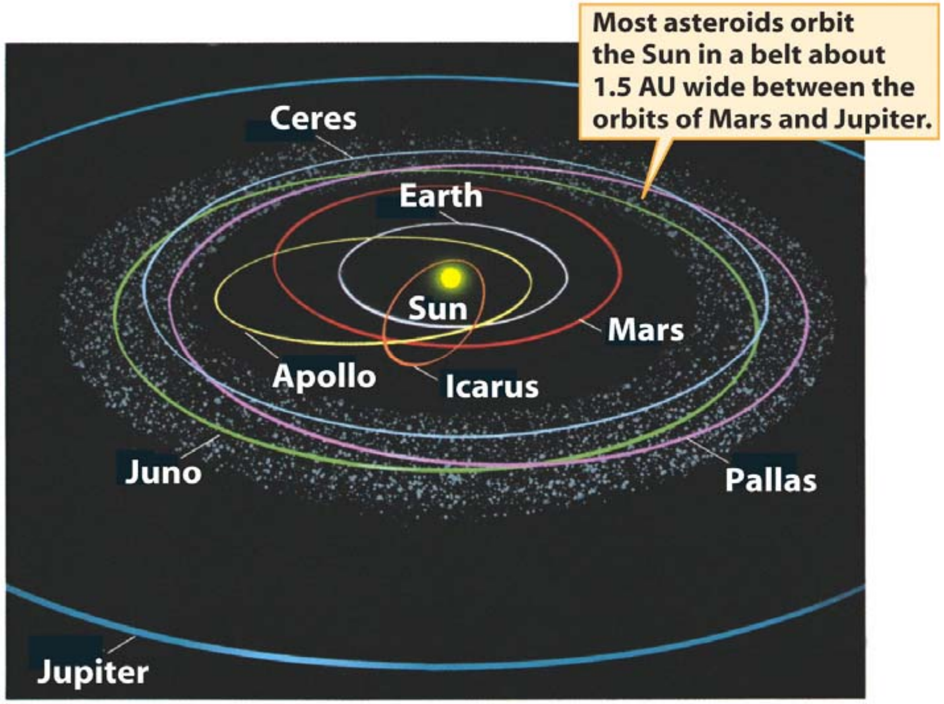
- One in a hundred such 'near miss' news items will be followed by one of these
- But probably not in Berlin
- ...impacts (or even news reports of near misses) can be used as a clock

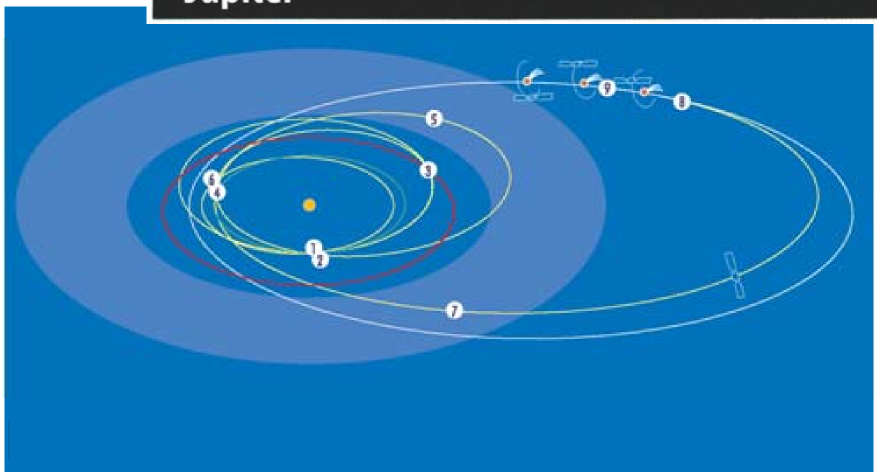


- Meteor Crater, Arizona, US
- 1200m across
- ~50m iron impactor
- Formed 50ka ago

Tunguska event, 1908

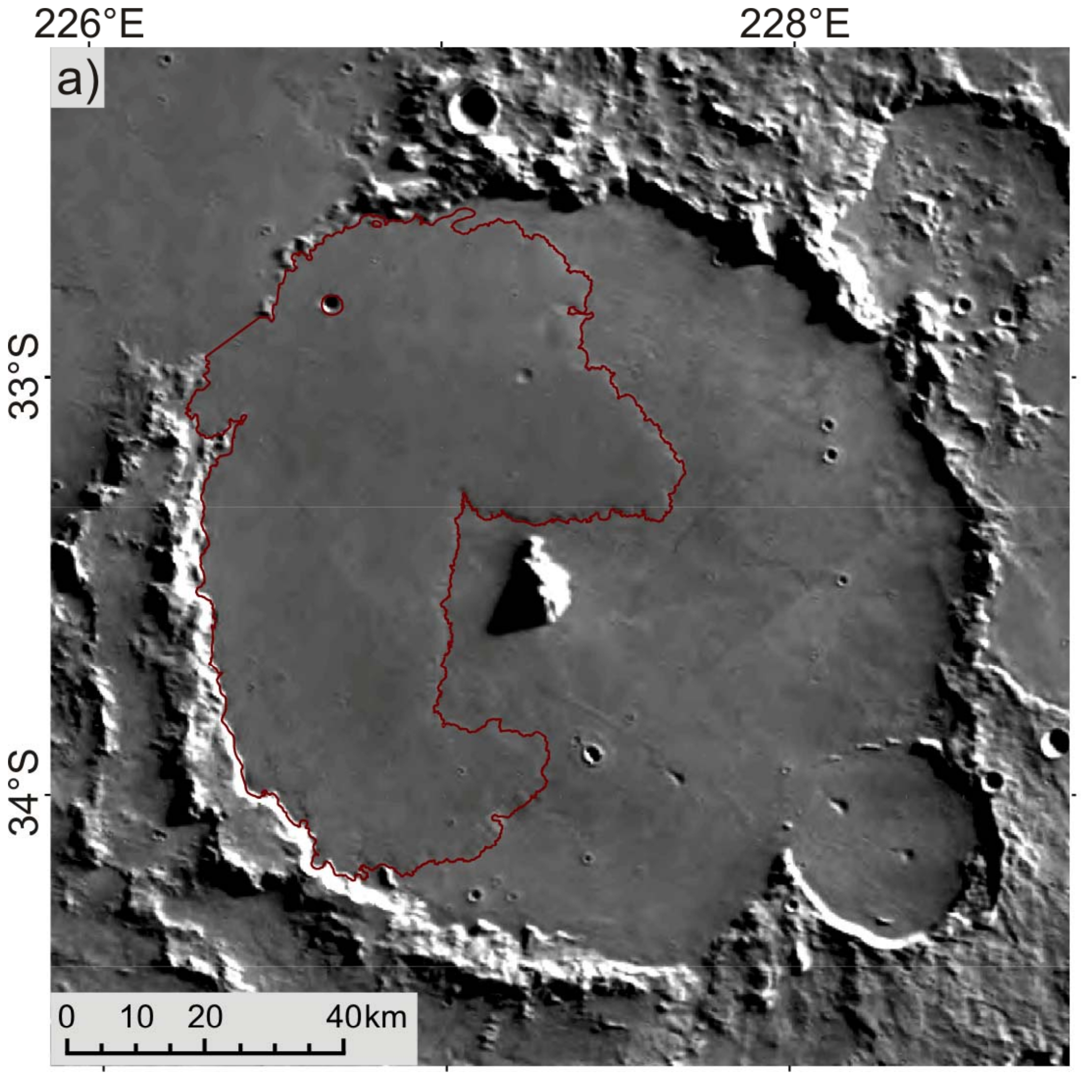
- No crater
- Impactor likely disrupted by atmosphere





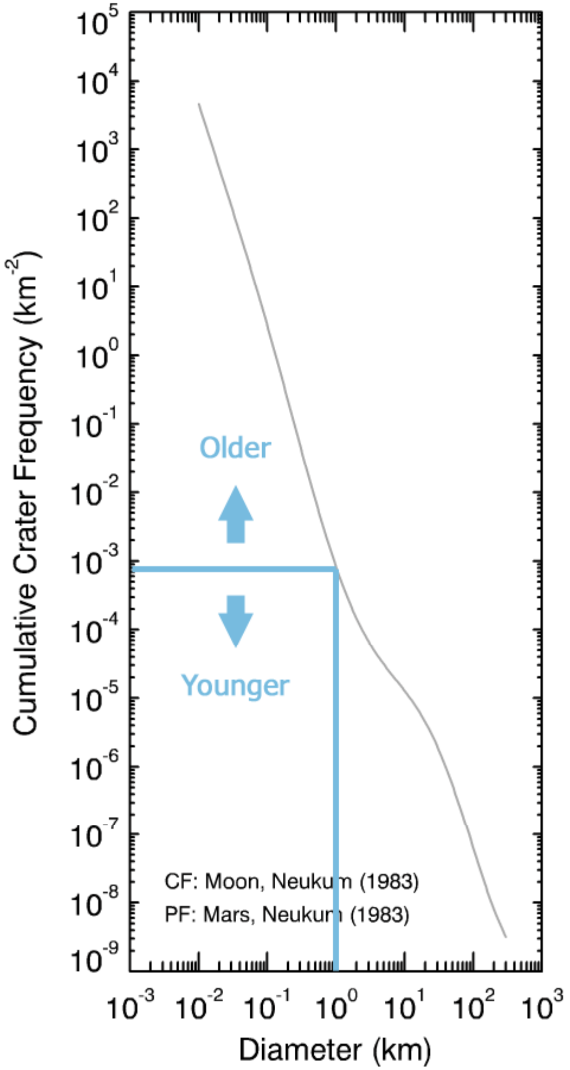
- Asteroids, comets, collisional debris
- Size distribution of asteroids appears consistent with observed crater populations
- Comet populations less known
  - Kuiper belt, Oort cloud
  - Capture to inner Solar System, but short-lived in solar vicinity
- Objects moved out of asteroid belt by planetary resonances and collisions

Crater counting



- Surface accumulates craters with time – this is a random process
- We try to understand characteristics of process to obtain *population—age* relationship
- Single geologic unit with homogeneous history
- Exclude areas: e.g. steep slopes, dunes, image defects, secondary crater clusters

Crater production function



- Differently sized craters form at different rates
- Production function (PF) – describes the *size—frequency* distribution of craters produced at the surface
  - i.e. how many craters of diameter D_2 can be expected for each one of size D_1.
- This is a *reverse-cumulative* frequency plot, showing

  log *N*(>*D*) vs. log *D*

  where $N(>D)$ is the number of craters larger than *D.*
- Directly related to the size-frequency distribution of impacting objects

How do we get the production function?

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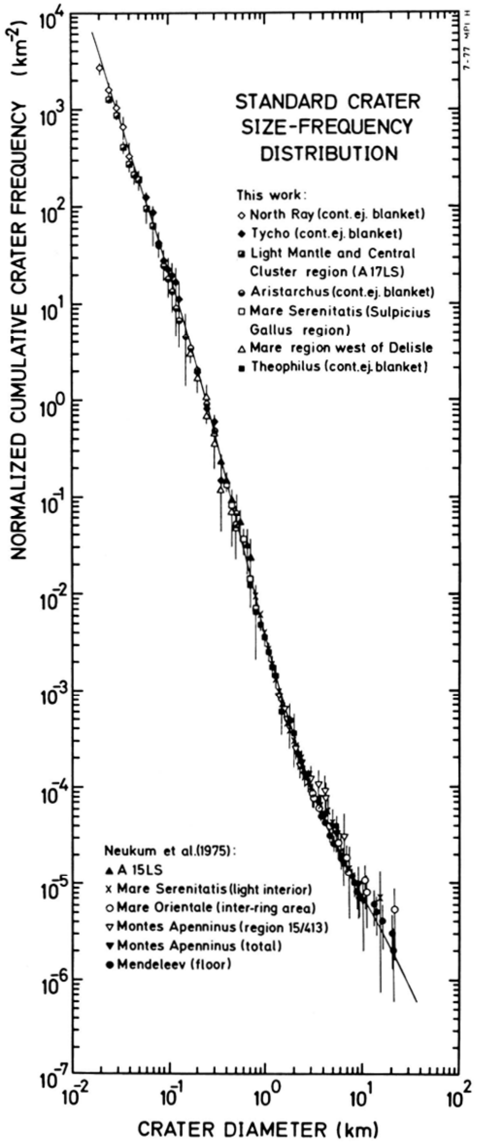
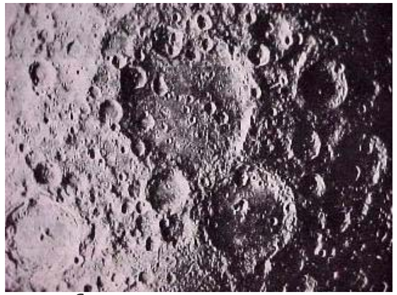


Normierte Produktionsverteilungen des Mondes mit Approximation durch ein Polynom 7ten Grades in logD (Abbildung: König, 1977).

- Unfortunately, no single unit shows the full range of crater diameters *'in production'* because of
  - saturation
  - erosion



- So, we make a series of crater counts on units with differing crater densities (i.e. of different ages)

- Then, make a piecewise normalization to match overlapping size ranges

- Finally, we make a polynomial approximation as our standard curve:

$$N_{cum} = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + \ldots$$

How do we get the production function?

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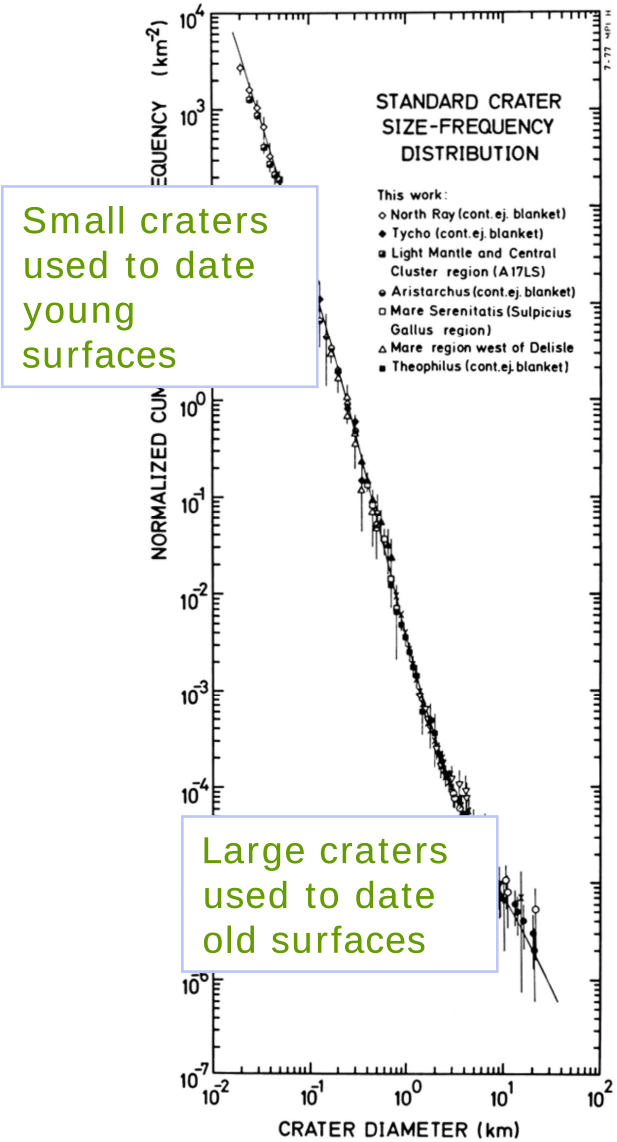

Normierte Produktionsverteilungen des Mondes mit Approximation durch ein Polynom 7ten Grades in logD (Abbildung: König, 1977).

- Some authors (e.g. Neukum, Hartmann) believe the crater populations are consistent with the PF having remained constant over the observable history of planetary surfaces.
- Others believe it has changed (e.g. Strom's two-population model)
- Crater populations do differ on ancient and young surfaces: is this due to different impacting populations, or differing retention periods for smaller and larger craters?
- What are the consequences for crater-dating?
  - the piecewise-constructed PF should be valid in either scenario
  - in the two-population case, the variation is included implicitly: the small diameter end represents the late population; the large diameter end represents the early population

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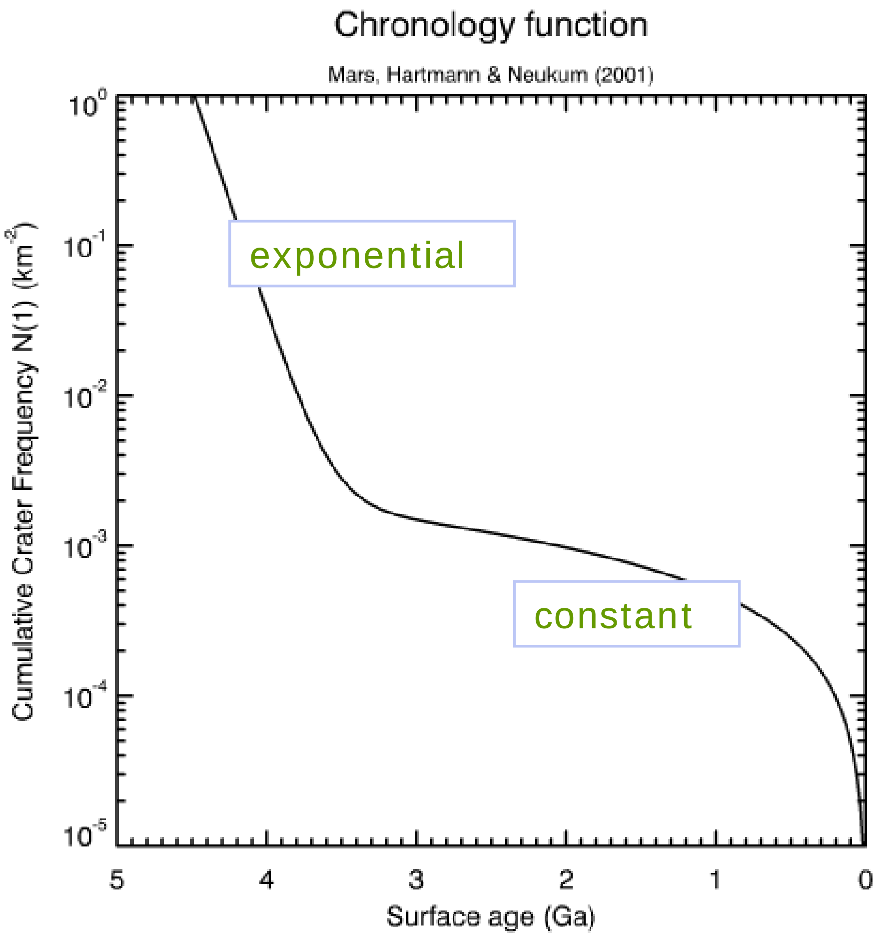
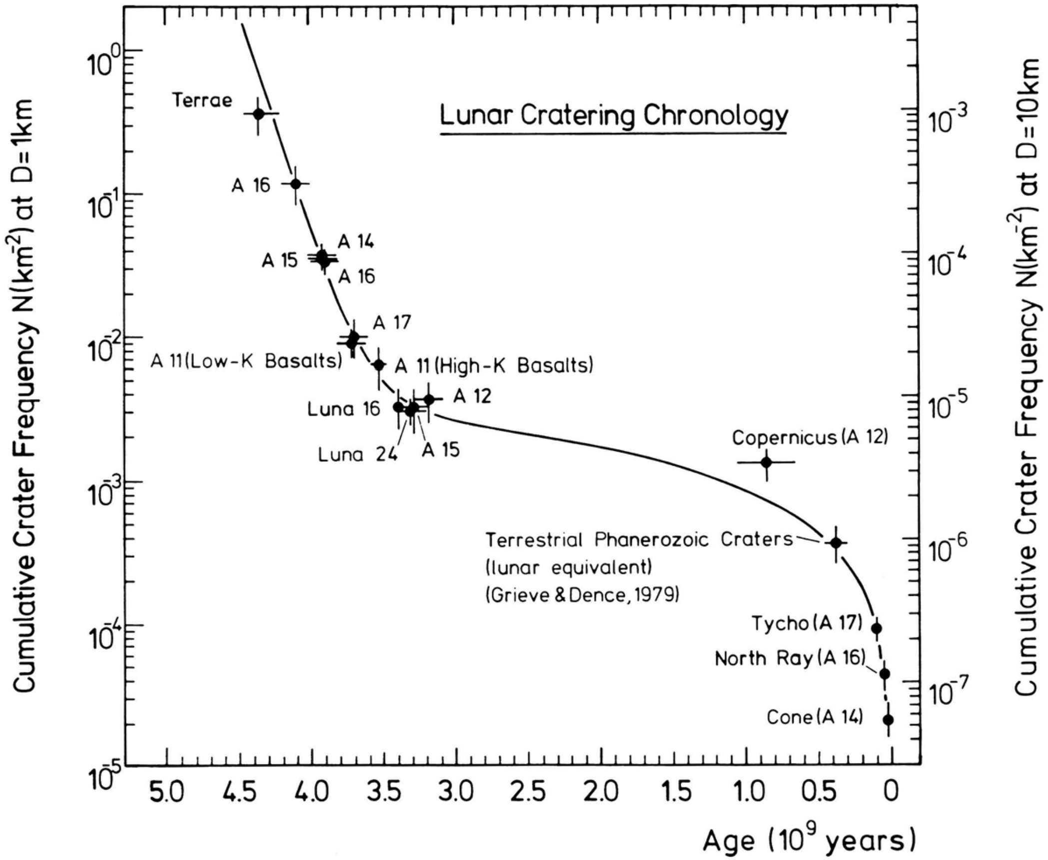


- Chronology function (CF) – describes the changing crater formation rate with time, for a reference crater size (1 km)
- The formation rate is constant back to 3 Ga, then exponentially increasing
- The rate for other diameters can be found by multiplying the 1 km by an appropriate constant obtained from the *production function*

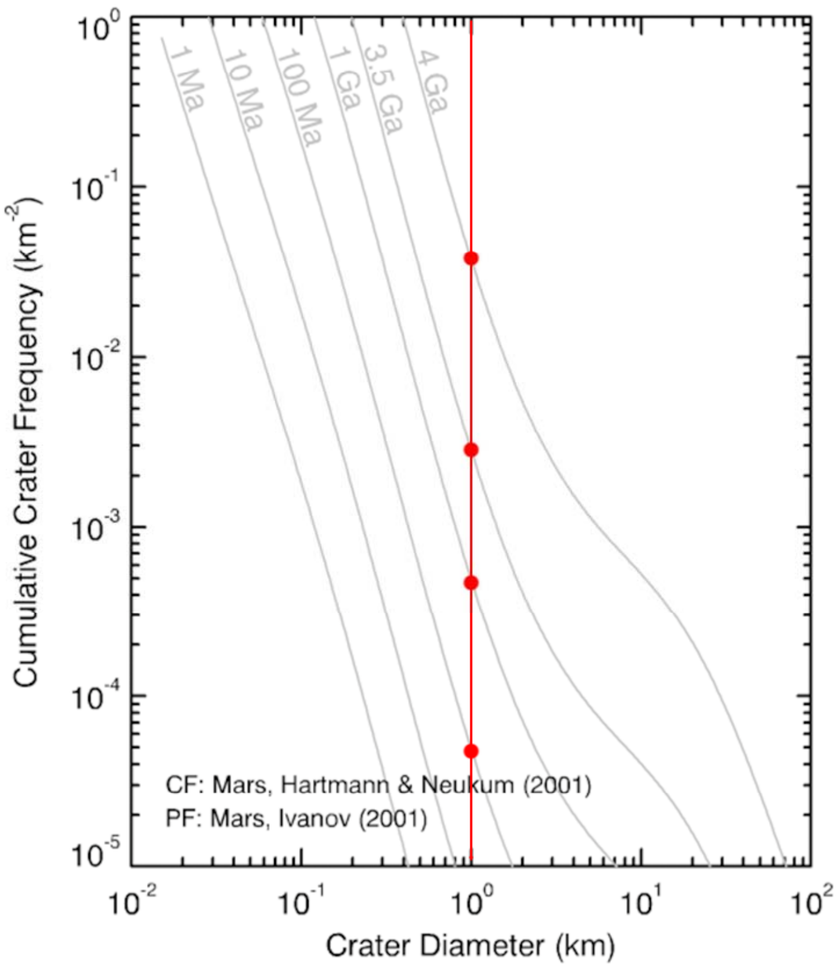


- Radiometric dating of returned lunar samples
- Relate samples to their source units, and measure their crater densities
- These are the calibration points for the *age—crater density* relationship
- We describe the relationship with the following empirical expression:

$$N_{cum}(1\,\mathrm{km}) = k_1(e^{k_2 t} - 1) + k_3 t$$

Where k_1, k_2, k_3 are constants

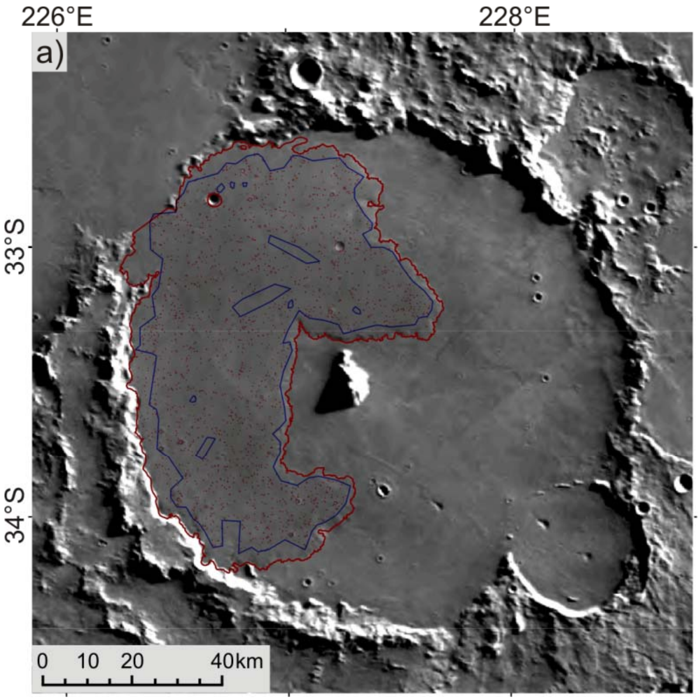
Isochron diagram



- The production and chronology functions together permit the construction of an *isochron diagram*
- This shows the expected crater densities for surfaces of different ages
- The red points are given by the chronology function for various ages
- The grey lines are the production function shifted up or down to intersect the points

Data preparation

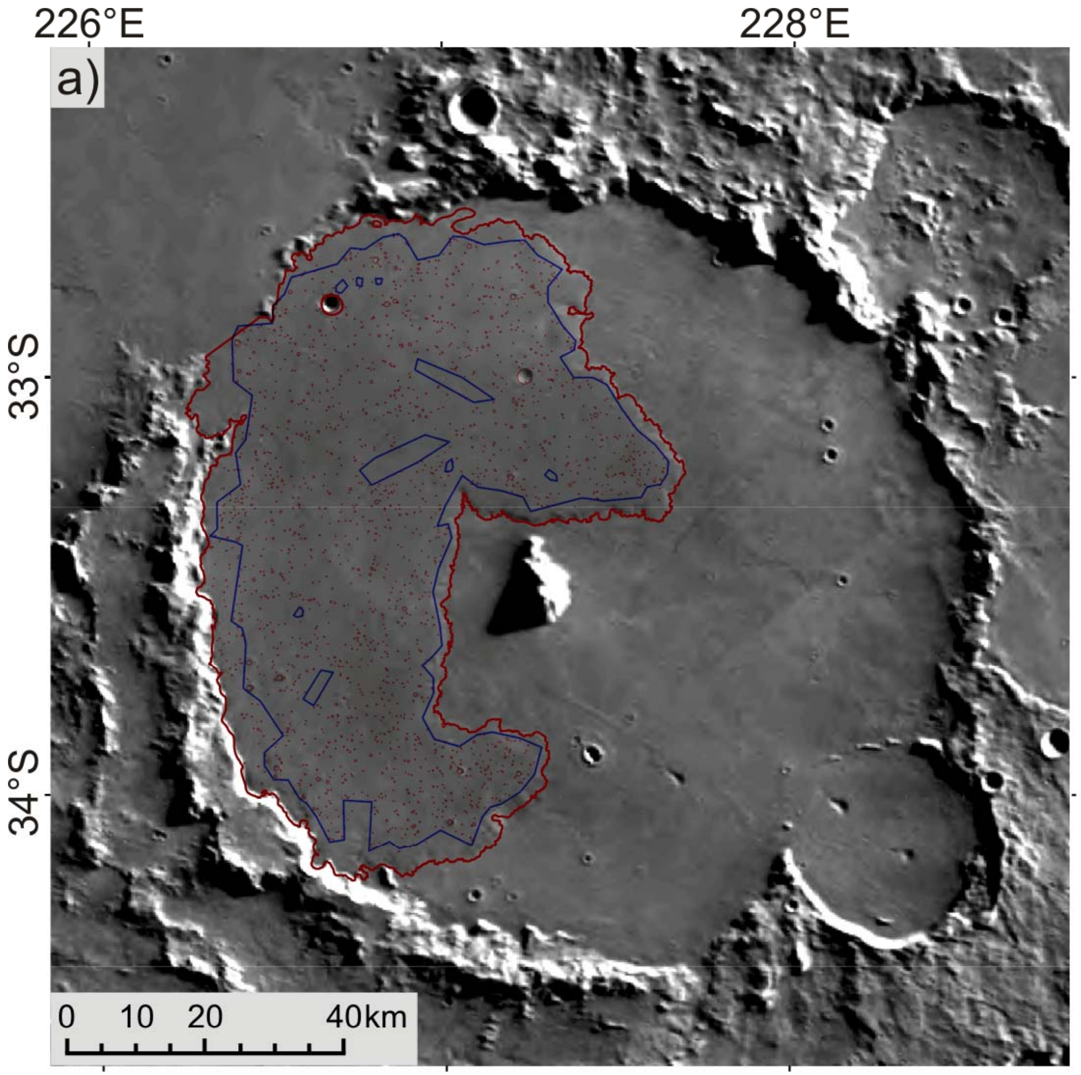
```
#Model .diam file for Craterstats
Area <km^2> = 3036.61
#diameter, km
0.511
0.166
0.095
0.100
0.261
0.208
0.208
0.103
0.112
0.170
0.100
0.130
0.219
0.172
0.202
0.117
0.154
0.130
0.098
...
```

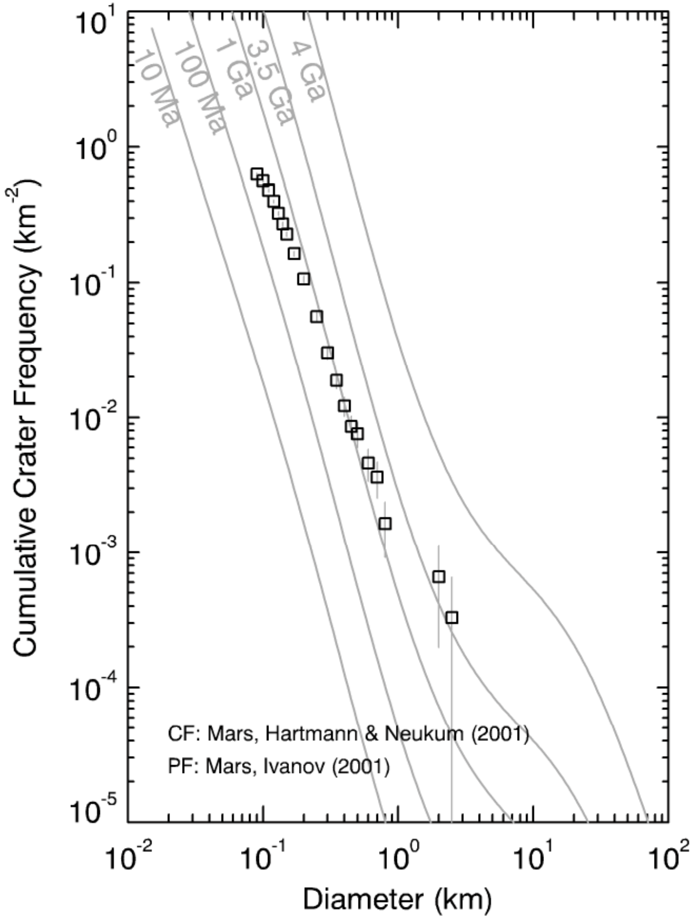


- Needed:
  - Unit's surface area
  - Crater diameters (~1900 in this case)
- Divide diameter measurements into appropriate *bins* (spaced on a logarithmic scale)
- Make a *reverse-cumulative* frequency plot, i.e.:

  plot **log *N*(>*D*) vs. log *D***,

  where $N(>D)$ is the number of craters larger than D per km^2

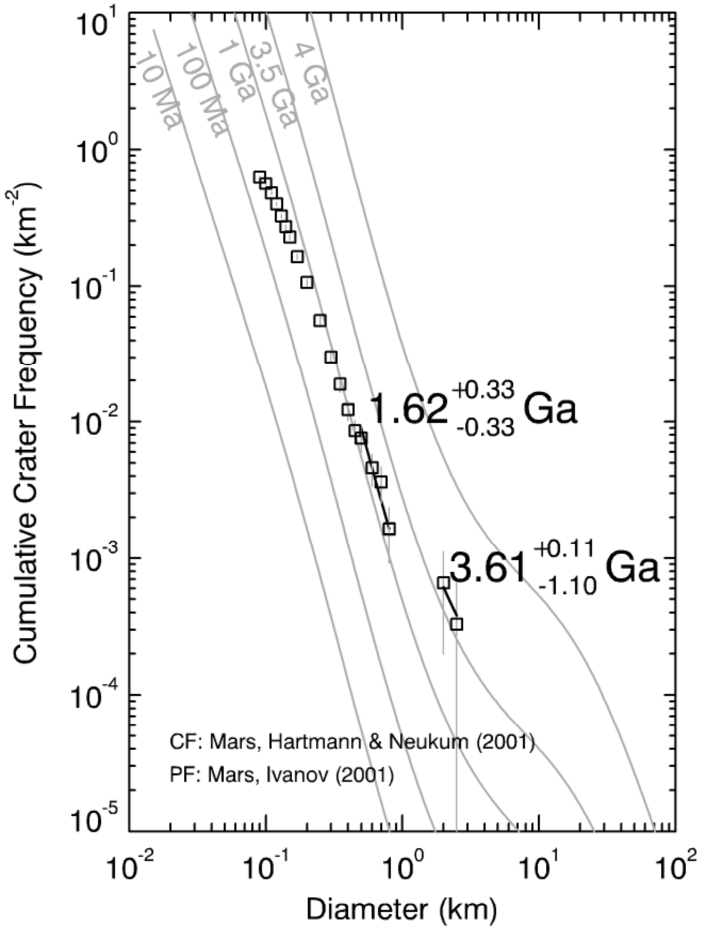

226°E
228°E
a)
33°S
34°S
0 10 20 40km


10 Ma
100 Ma
1 Ga
3.5 Ga
4 Ga
Cumulative Crater Frequency (km^{-2})
Diameter (km)
CF: Mars, Hartmann & Neukum (2001)
PF: Mars, Ivanov (2001)

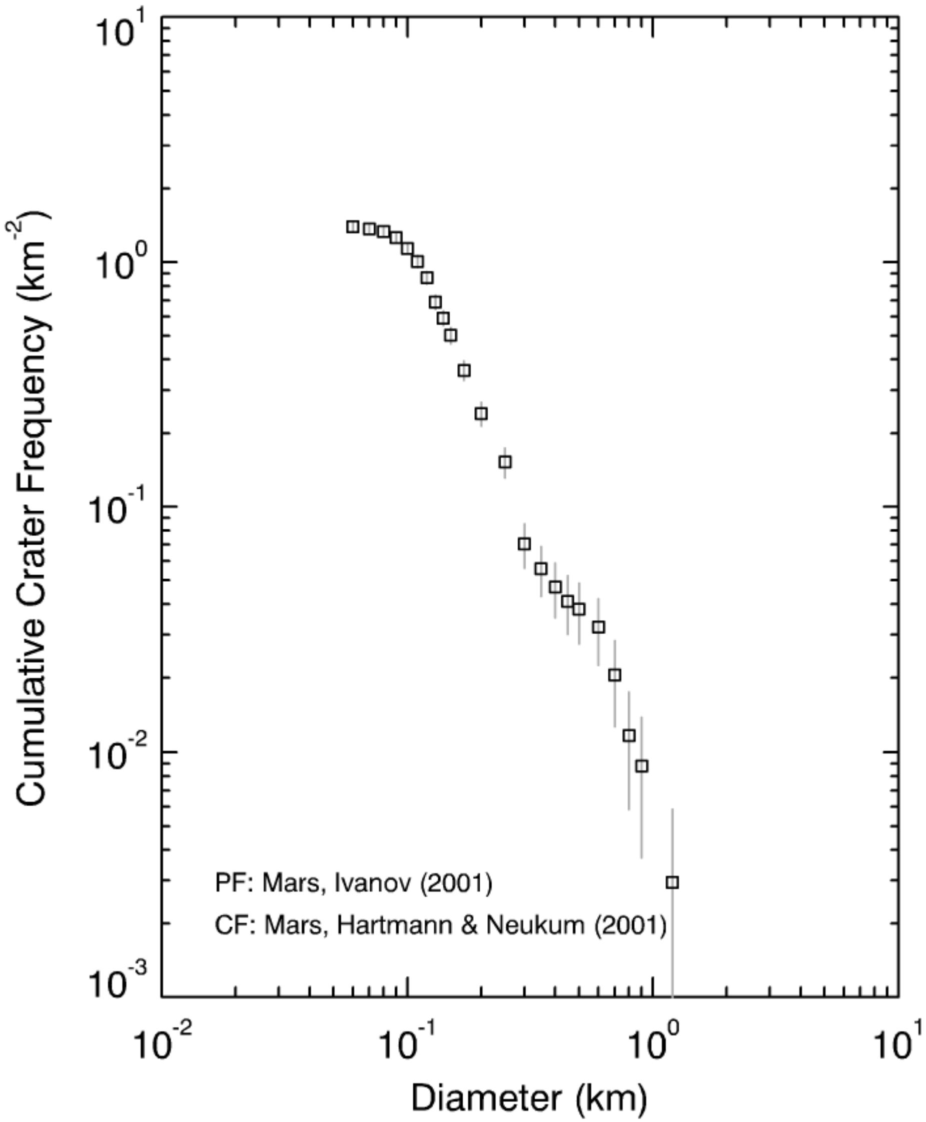
Cumulative PF fitting

- Select diameter range where points are consistent with PF, i.e. run parallel to it
- Shift the PF up or down for best fit
- Read off equivalent crater density at D=1 km
- Find age from chronology function

(shown without resurfacing correction)



Partial resurfacing



- Partial resurfacing occurs when some geological event erases a portion of the crater population
- Whatever the process, it is always the *smallest* craters which are lost (those below some threshold diameter, *D)*
- After the event, the population accumulates again, leaving a kink in the size-frequency plot
- Often better seen in a differential plot
- Note typical resolution roll-off

Partial resurfacing

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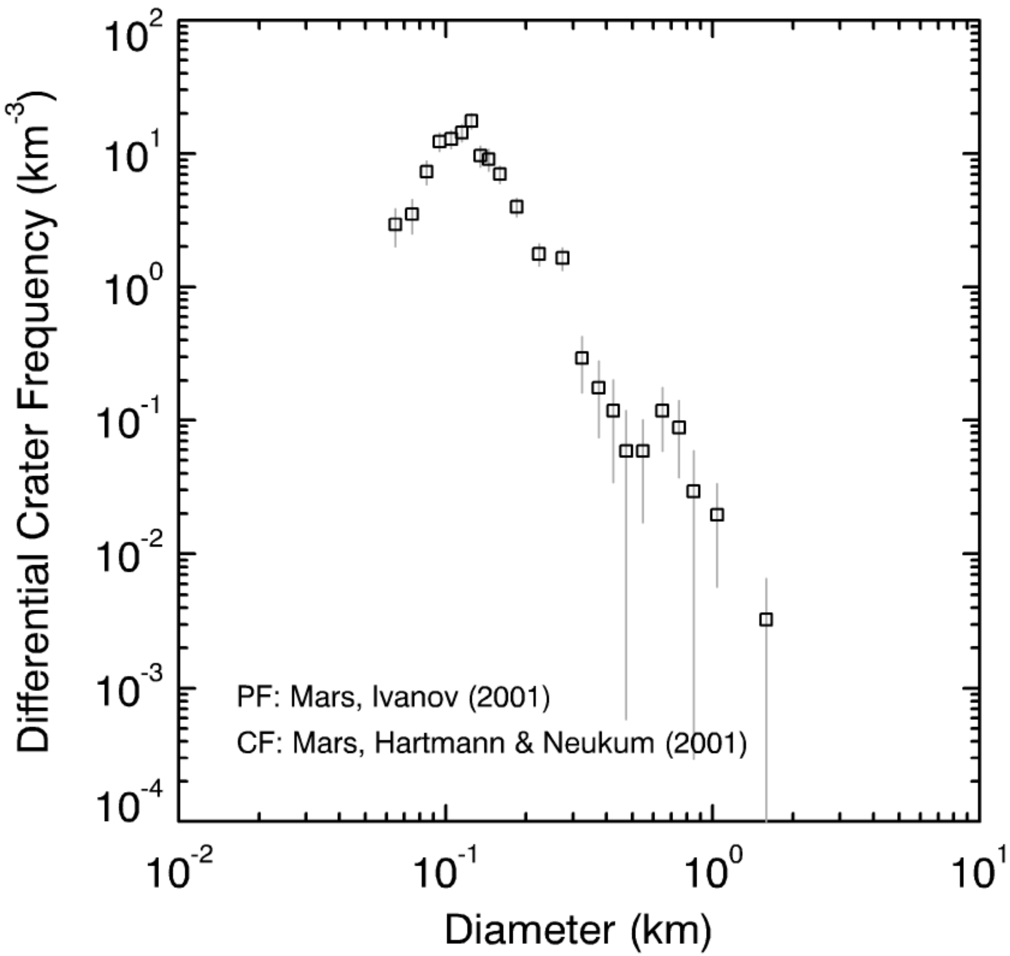

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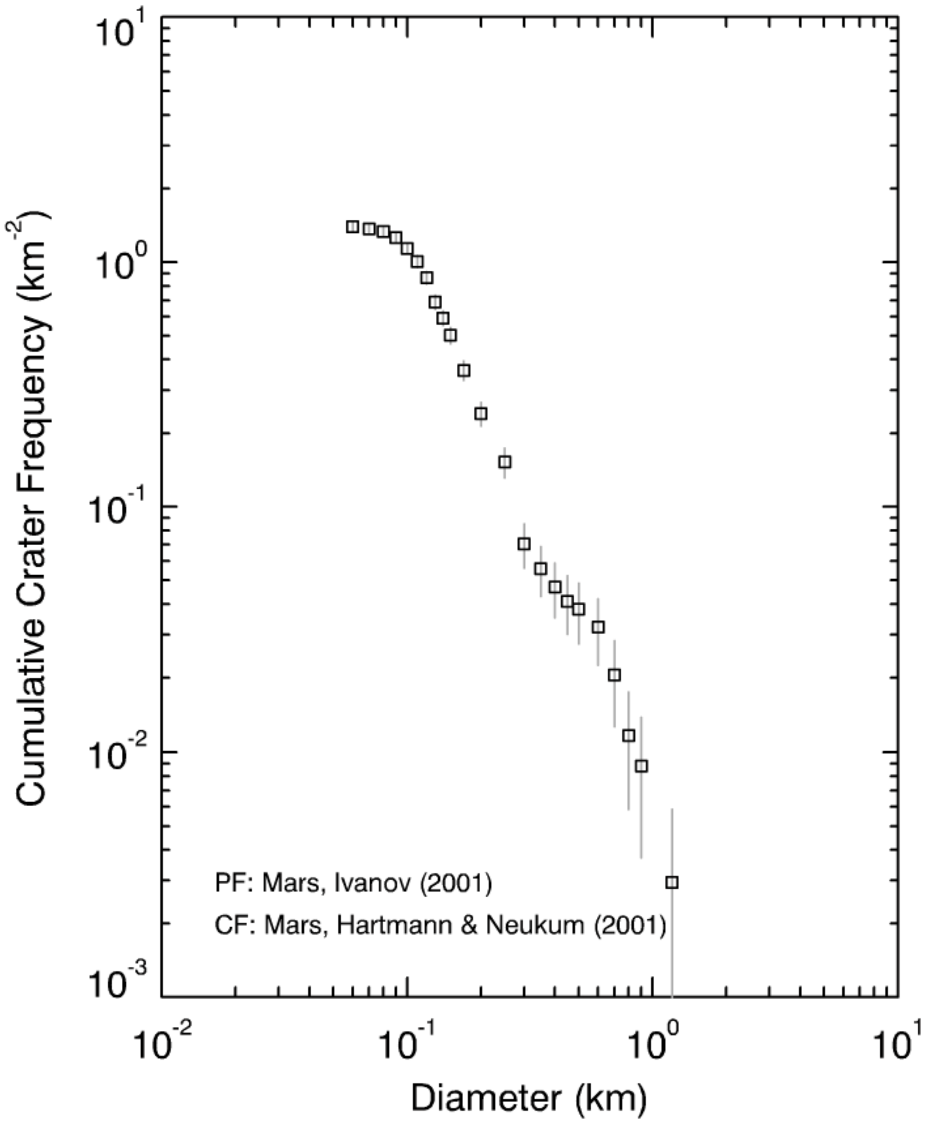
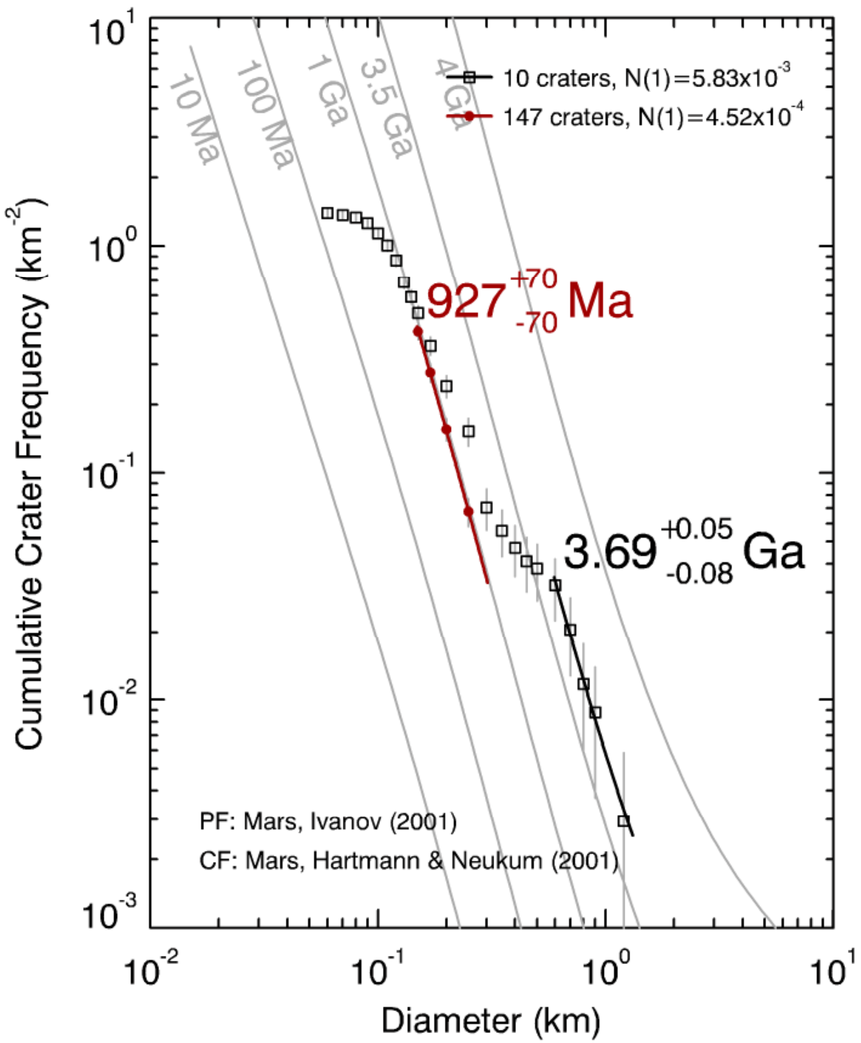
Partial resurfacing



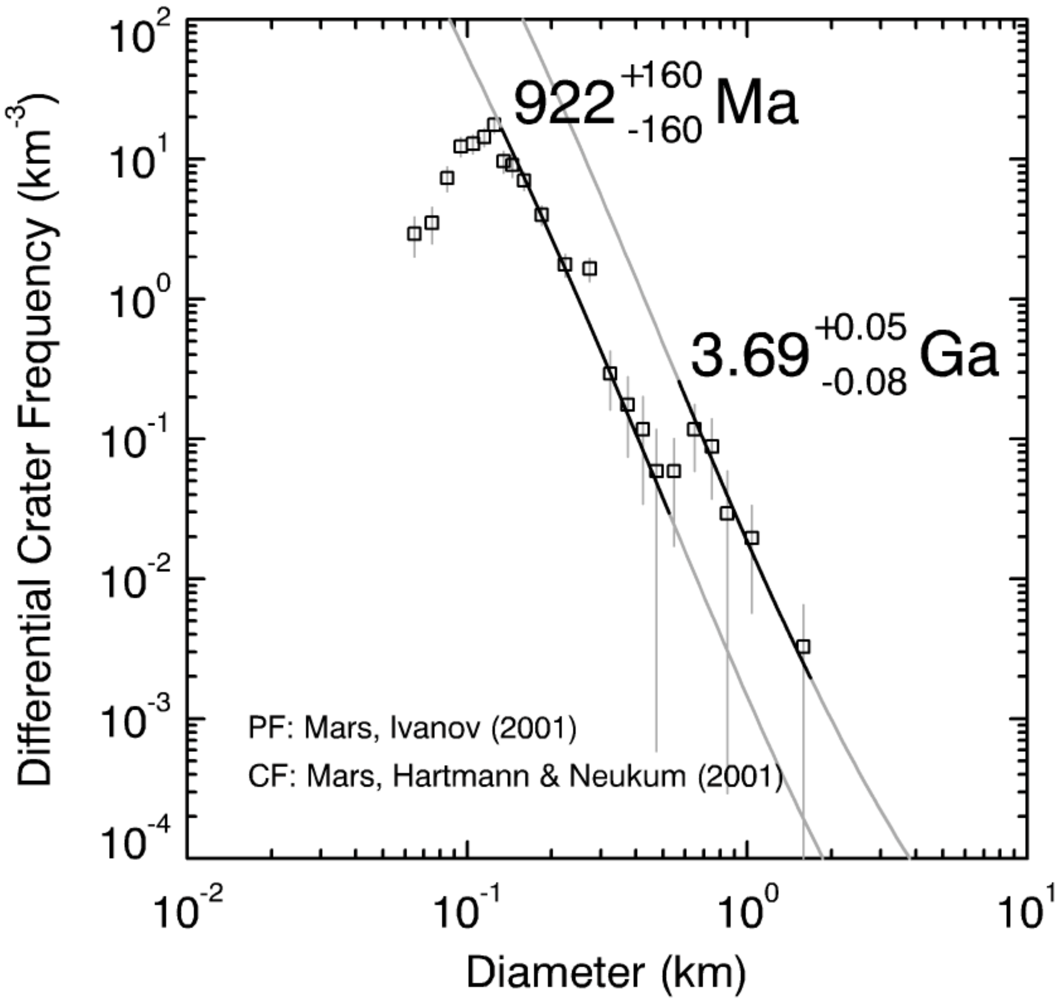
- In such a case, one can obtain two ages:
  - the original surface
  - the partial resurfacing event
- Sometimes, we observe more than one resurfacing event
- Other times, the resurfacing process can be of extended duration, so that there is a continuous range of ages present

Resurfacing correction



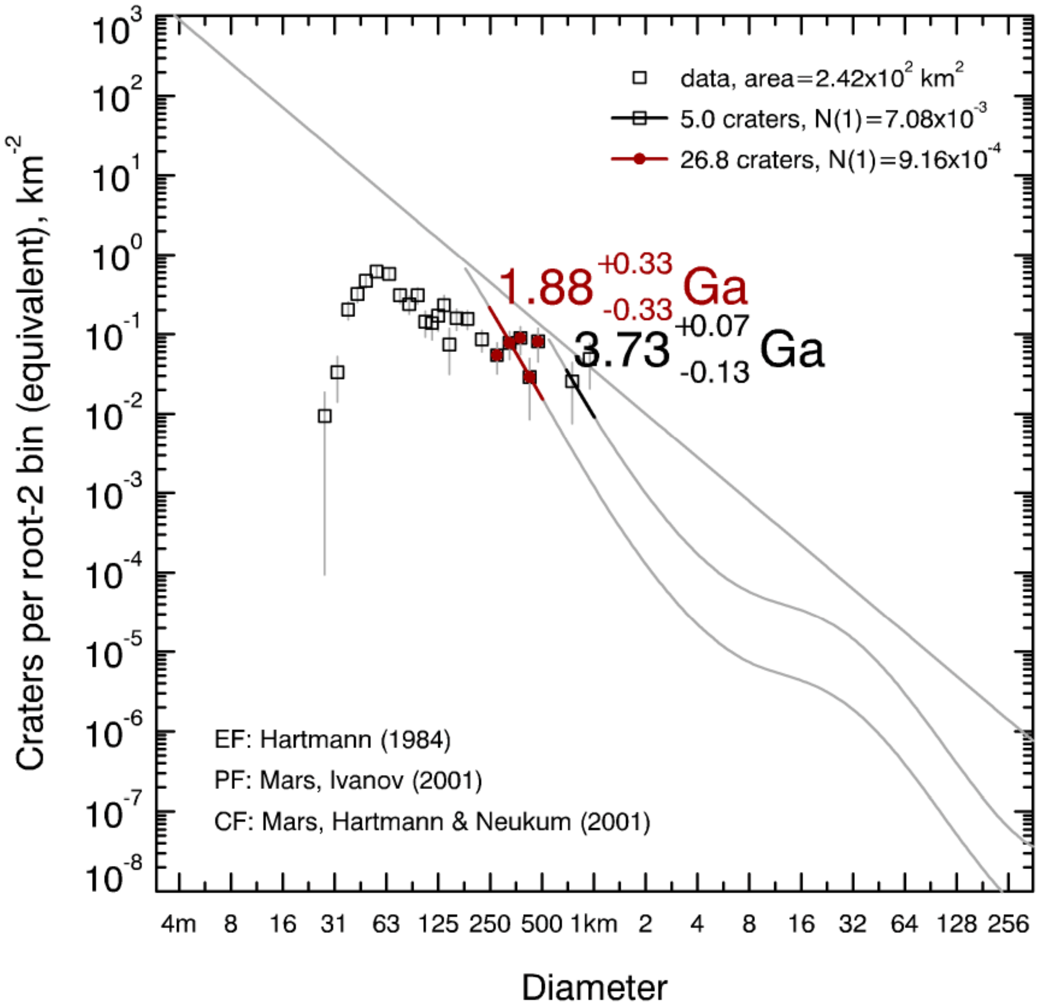
- On a cumulative plot, each point includes all the points to its right
- The younger, ‘partially resurfaced’ portion of the plot includes craters belonging to the older underlying surface
- These points therefore plot higher than they would for a unit which was fully resurfaced at the time of the resurfacing event
- Can correct for this by calculating the population beyond the resurfaced portion which would be consistent with the observed PF in the chosen range (Michael & Neukum, 2010)
  - Iterative calculation
  - Reduces the derived age by a small amount

Differential fitting



- It’s possible to make a fit directly on a differential plot
- If using Neukum-style polynomial PF, requires differential form of polynomial (Michael & Neukum, 2010)
- Results agree with those obtained with cumulative fit for ‘ideal’ populations; may differ slightly in real data
  - cause: cumulative data points are not fully independent

Hartmann plot



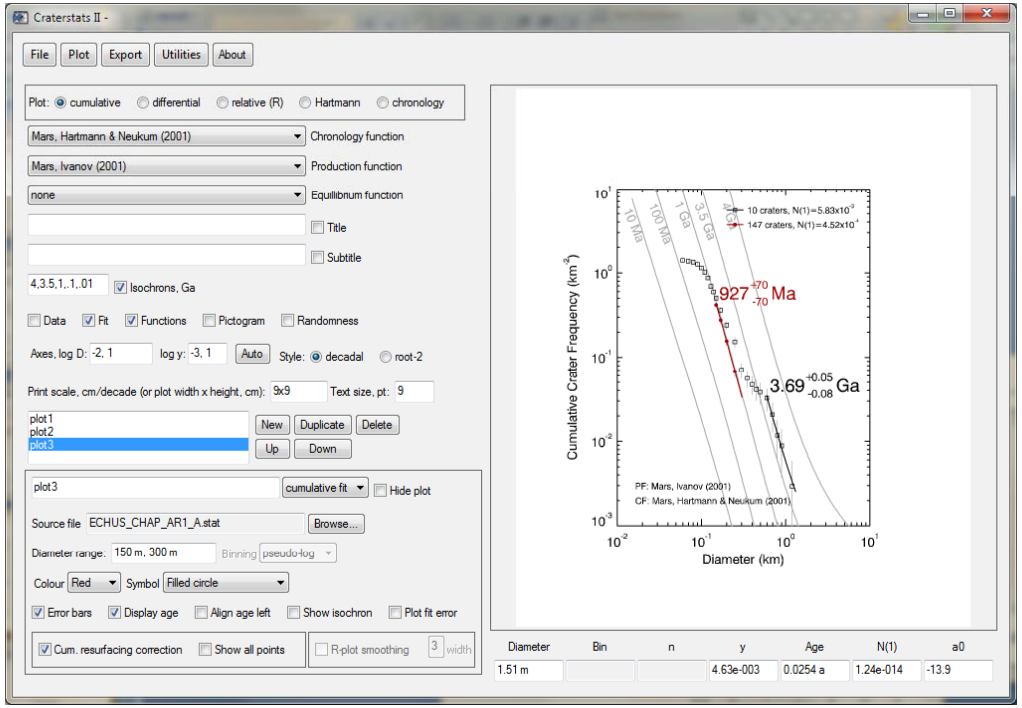
- A Hartmann plot is a special case of a differential plot
    - Craters per root-2 bin
    - Fixed axes
- Here, a differential fitting may be a more natural approach
- It is frequently useful to examine both views – cumulative and differential/Hartmann – when selecting a diameter range for fitting

Craterstats software

Craterstats is a software tool for analysing crater counts

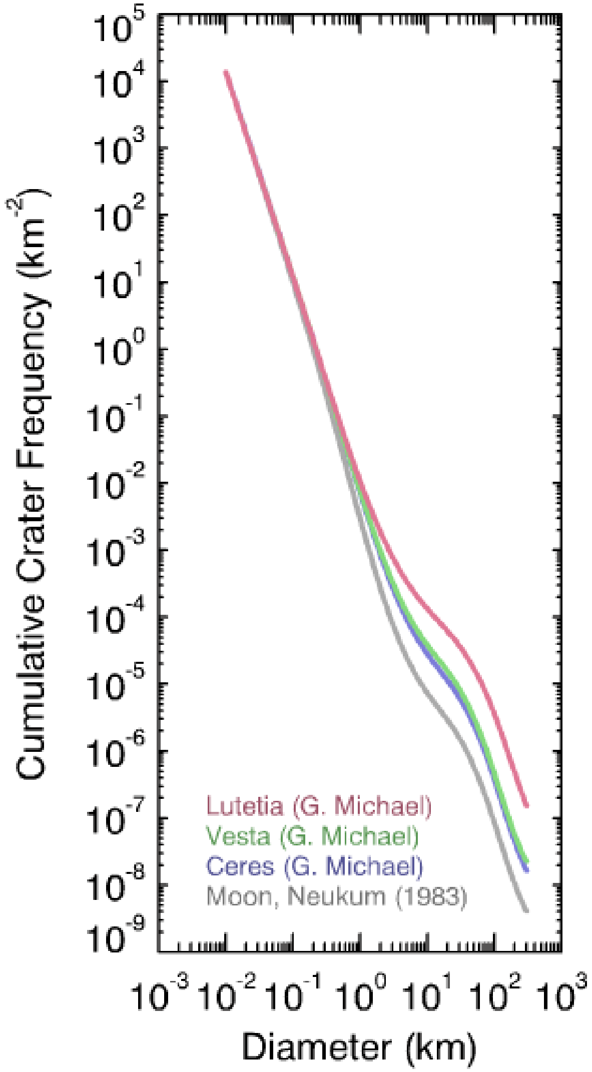
- Import, bin and plot crater counts
- Fit a production function
- Obtain an age from a chronology function

- Plot isochrons
- Apply resurfacing correction
- Export graphics



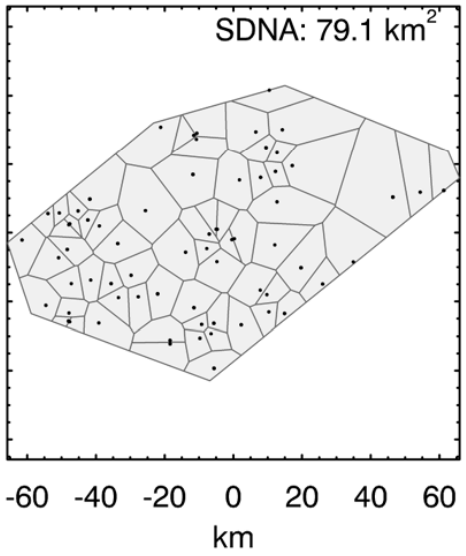
http://hrscview.fu-berlin.de/software.html

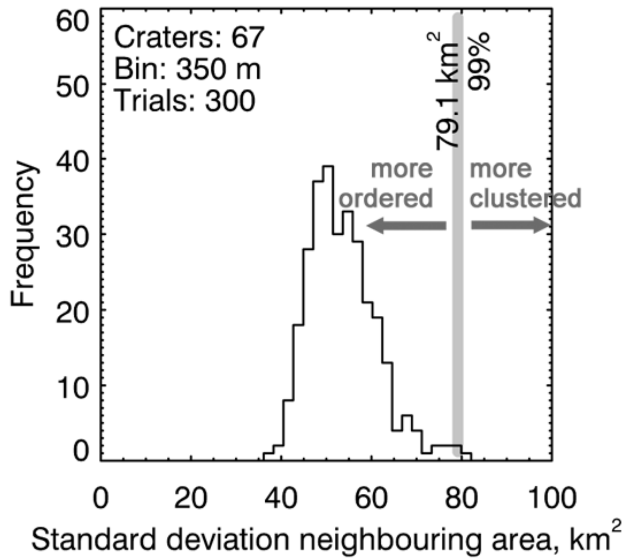
Recalibration to other Solar System bodies



- No samples from bodies other than the Moon
- Calibration made relative to the Moon, considering:
  - Asteroidal impactor flux
    - More/fewer craters per unit time
  - Impact velocity
    - Local heliocentric velocity
    - Body escape velocity
    - Greater/lesser impact energy for given impactor
  - Surface gravity
    - Easier/harder to excavate volume for given energy of impact
  - Surface strength
    - Easier/harder to excavate volume for given energy of impact

Clustering and randomness analysis





- Idea is to verify that the spatial distribution of the craters is random, as expected for a surface with *homogeneous history*

- Compare the actual spatial configuration with a series of computer-generated random distributions:
  - Clustered, or consistent with being random?

- Any type of clustering suggests either the presence of secondary craters (which are normally excluded), or a non-uniform counting area
  - inadequate for drawing conclusions about either age, or impacting population