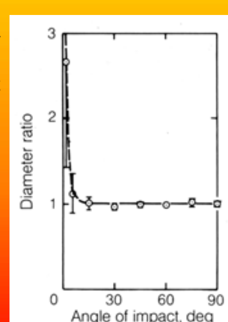
Impact craters and evolution of planetary surfaces

1) Impact craters = circular features

Impact crater ellipticity as a function of the impact angle, Melosh, 1989.



Density probability law as a function of the impact angle **P(θ) ~ sin(2θ)**

Only few elliptical craters

Elliptical impact crater due to oblique impact (Ceraunius Tholus Volcano)

All circular features seen in remote sensing data of planetary surfaces are not impact craters !!!

4.1 Morphologic and geometric evidences

Where are impact craters ?

What are the other circular features ?

4.1 Morphologic and geometric evidences

2) Depth – diameters relationships and other geometric characteristics

TABLE 8.1 *Lunar crater morphometry*

Parameter	Dependence on Rim-to-Rim Diameter (*D, km*)	Diameter Range (*km*)	Source
Crater Depth	$H = 0.196\ D^{1.01}$	<11	*
	$H = 1.044\ D^{0.301}$	11–400	*
Crater Floor Dia.	$D_f = 0.19\ D^{1.25}$	20–140	*
Central Peak Dia.	$D_{cp} = 0.22\ D$	20–140	†
Peak Ring Dia.	$D_{pr} = 0.50\ D$	140–450	‡
Central Peak Height	$h_{cp} = 0.0006\ D^{1.97}$	15–80	**
	$h_{cp} \simeq 3$	80–200	**
Rim Height	$h_R = 0.036\ D^{1.014}$	<21	*
	$h_R = 0.236\ D^{0.399}$	21–400	*
Terrace Zone Width	$W_T = 0.92\ D^{0.67}$	15–350	††
Widest Terrace Width	$w = 0.09\ D^{0.87}$	20–200	‡‡

*Pike (1977)
†Pike (1985)
‡Wood and Head (1976)
**Hale and Grieve (1982)
††Based on data from Pike (1976)
‡‡Pearce and Melosh (1986)

Compilation des analyses morphométriques des cratères lunaires, Melosh, 1989

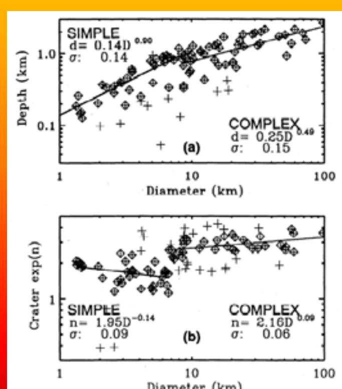


Figure 2. (a): Depth (d) versus diameter (D) for the 98 least degraded martian impact craters. Crater dimensions are measured from the topographic rim crest. The "+" symbols represent craters that fall outside the one-sigma confidence band. (b): Crater cavity cross-sectional geometry parameters from a power-function fit to the cavity. Cavity shape exponent (n) can be thought of in terms of the best fitting polynomial that approximates the crater cavity, so that n=2 is a paraboloid etc.

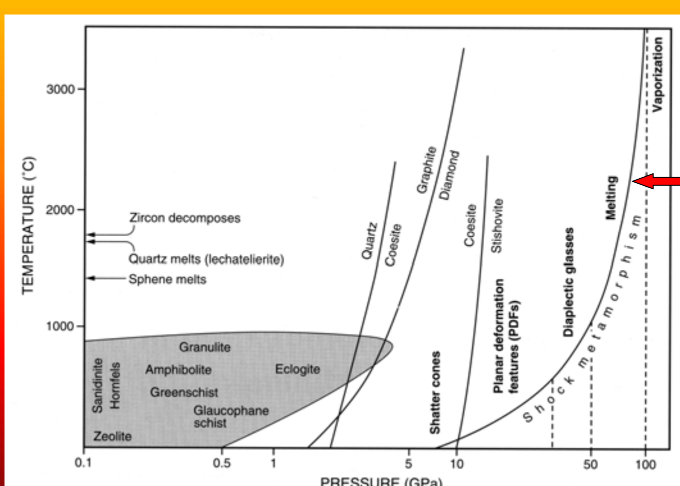
Garvin et. Al, 1998

3) Usually…random distribution of impact craters

No alignments (in comparison to volcanic structures)

Impact metamorphism

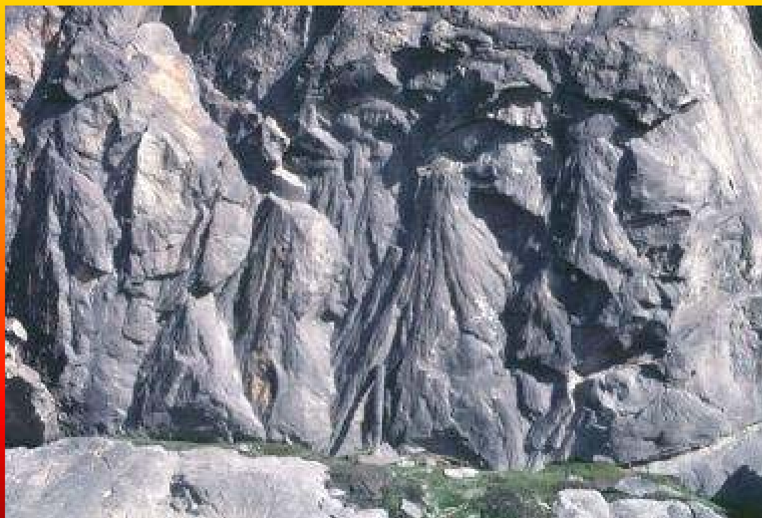
Pressure-Temperature diagram for the regional (« normal conditions) and impact metamorphism



Post-shock temperature for a granite

Metamorphism impact zone

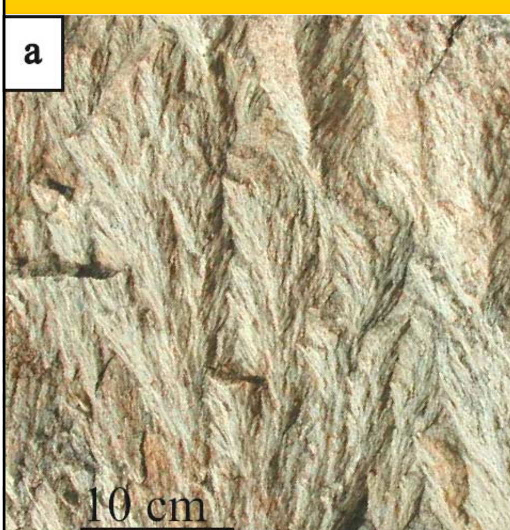
Impact metamorphism. Shatter cones



Sudbury, Ontario, Canada
Exceptionally, this structures can be as high as 12 meters high.
More common dimensions : Few centimeters to few tens of centimeters

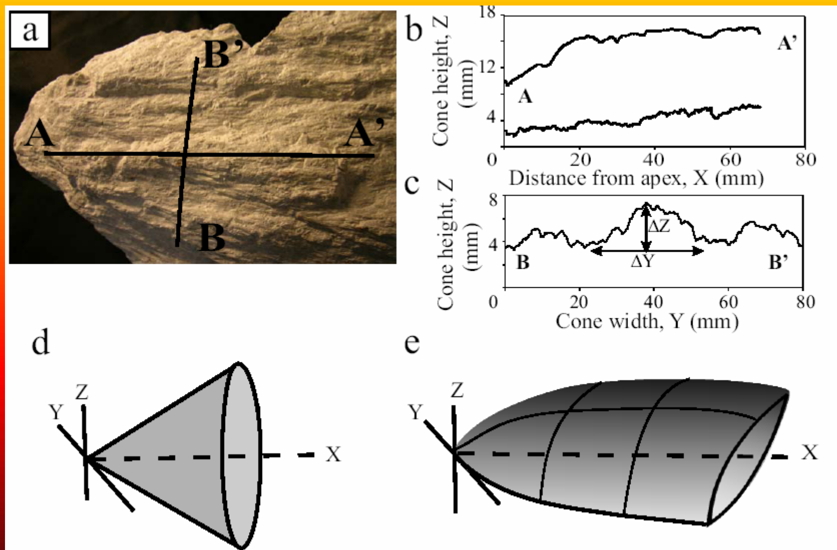
4.2 Petrologic and mineralogic evidences

Impact metamorphism. Shatter cones

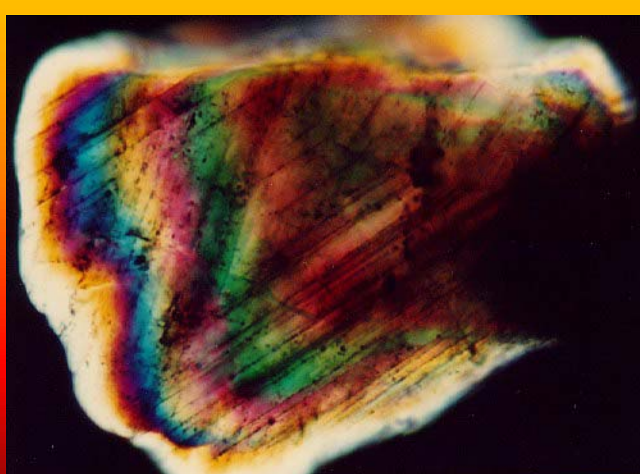


Impact metamorphism. Shatter cones

Shatter cones are not cones !!



Impact metamorphism
Planar Deformation Features (PDFs)



Quartz grain with PDFs (Polarized-analyzed light)

4.2 Petrologic and mineralogic evidences

The formation of shatter cones by constructive interferences in shock waves

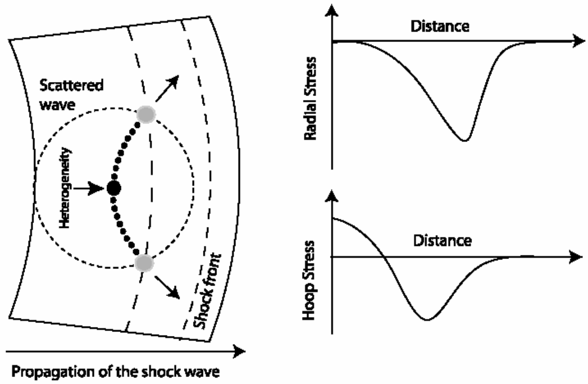


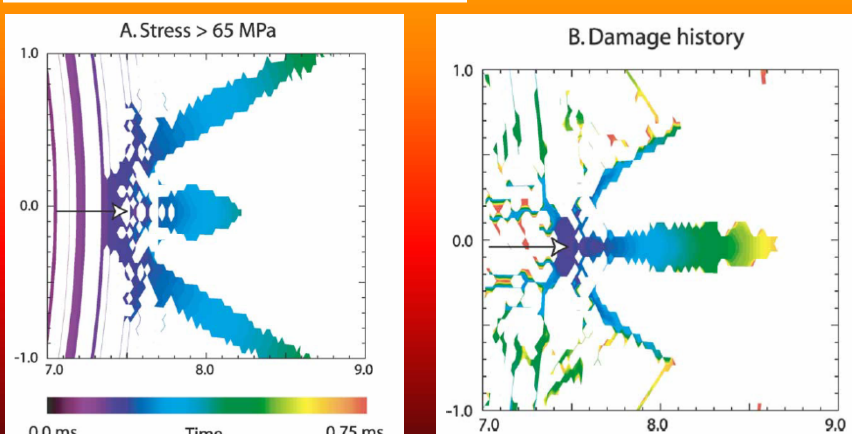
Fig. 2. Schematic representation of our model for the formation of shatter cones. Tensile fracture occurs at the intersection between the scattered tensile wave and the tensile hoop stresses in the main shock wave. When a critical value for the tensional stress is reached, the rock fractures in tension. The fractures accumulate on the surface of a conical region (indicated in the figure by filled circles and arrows).

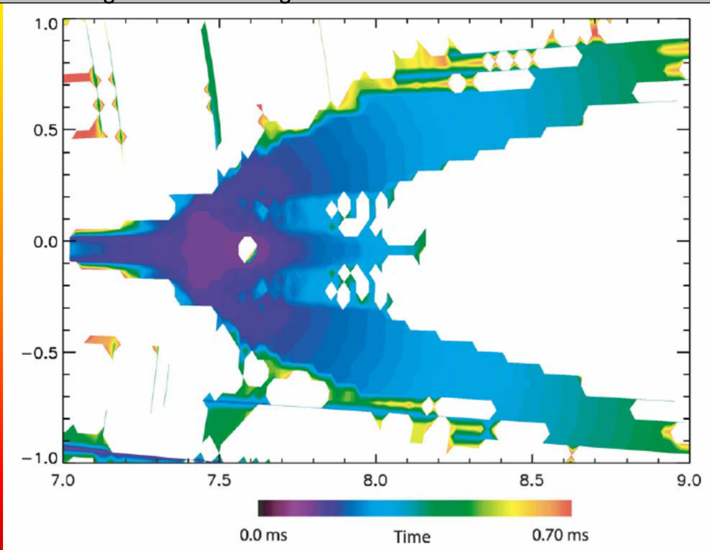
Baratoux and Melosh, 2003

4.2 Petrologic and mineralogic evidences

Table 2
Material parameters

	Material	Heterogeneity
Density (kg/m^3)	3000	3000
Bulk modulus (GPa)	50	5
Shear modulus (GPa)	30	3
Murnhagan exponent	4	4
Hugoniot elastic limit (GPa)	50	50





Parameters of the embedding material and of the heterogeneity (ice) [20,22]

	Density (kg/m³)	Bulk modulus (GPa)	Shear modulus (GPa)	Murnhagan exponent	c_g (m/s)	pweib (m)	cweib (m^{-3})
Embedding material	2980	60.1	36.7	5.5	1790	9.05	3.05×10^{40}
Heterogeneity	900	0.2	0.12	5.23	7500	8.7	3.2×10^{44}

4.2 Petrologic and mineralogic evidences

Parameters influencing the shatter cones occurences

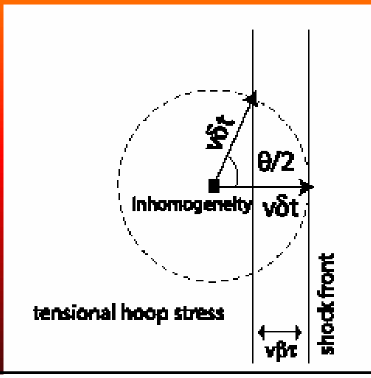
-Contrast of elastic properties

-Structure of the shock pulse

The rise time has to be very short (shorter than previously thought)

Influence of the rise time and the size of the heterogeneity

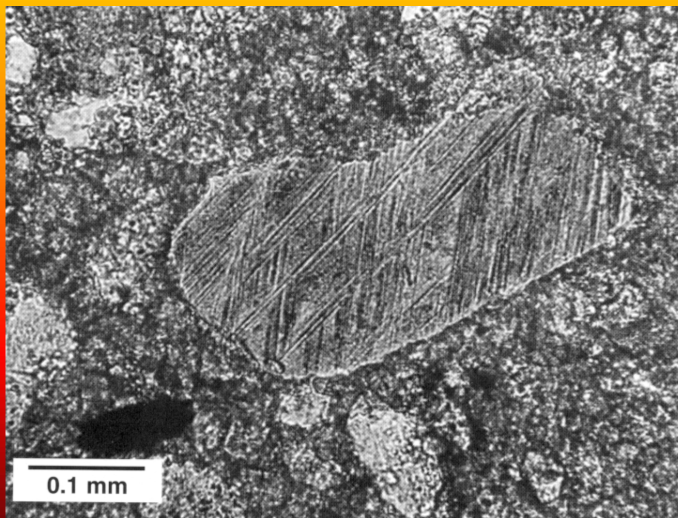
Size of the heterogeneity (m)	0.04	0.04	0.04	0.08	0.08	0.08	0.16	0.16	0.16	0.4	0.4	0.4	0.8	0.8	0.8	1.6	1.6	1.6
Rise time of the stress wave (ms)	0.01	0.02	0.04	0.01	0.02	0.04	0.01	0.02	0.04	0.01	0.02	0.04	0.01	0.02	0.04	0.01	0.02	0.04
β (decay time factor)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Time ratio[a]	1.37	2.73	5.47	0.68	1.37	2.73	0.34	0.68	1.37	1.37	2.73	5.47	0.68	1.37	2.73	0.34	0.68	1.37
Shatter cone	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes



Shape => Two expanding spheres
Apical angle varies with the shock pulse structure

$$\theta(t) = 2\arccos\left(1 - \frac{\beta\,\tau}{\delta t}\right)$$

Impact metamorphism
Planar Deformation Features (PDFs)



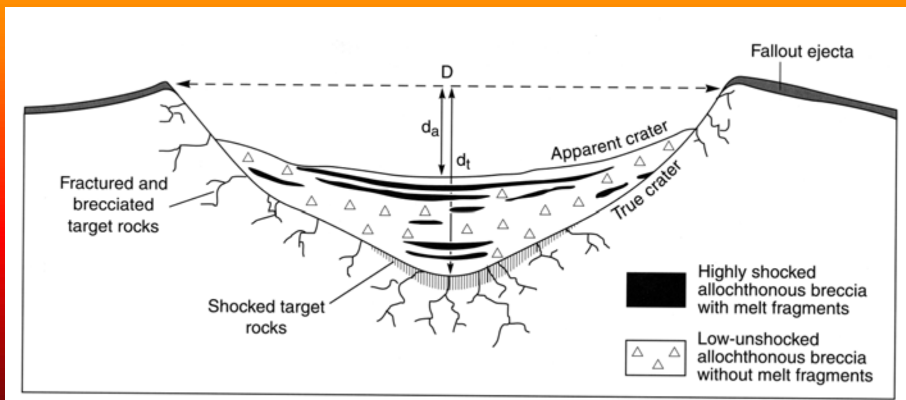
Impact metamorphism. Impact melt

Rochechouart impact melt (Glassy texture)

Impactites distribution in an impact structure

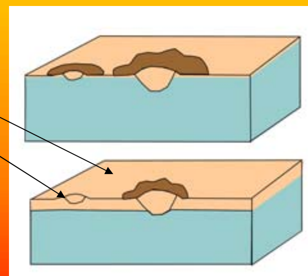
Impactite : shocked geological material : breccias, impact melt, elements characteristics of impact metamorphism

The Impactite distribution for a given structure depends on the conditions of formation (pressure as a function of the distance from the impact point. This distribution depends also on the post-impact movements/collapse.



5. Impact craters. Sounding the sub-surface of solid planets.

Lobate ejecta = indicator of the sub-surface ice ?



Depth of permafrost roof ?

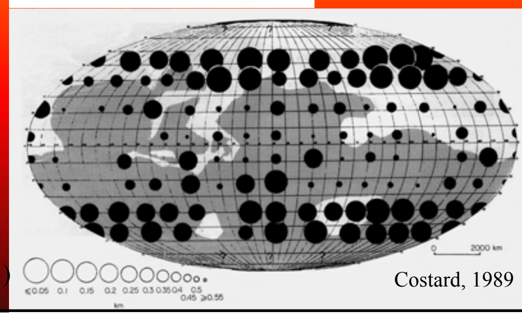
Equatorial regions:

500 m - 1 km deep

High latitudes:

30 m - 300 m

(very important = at the time of impact !)



Costard, 1989

5. Impact craters. Sounding the sub-surface of solid planets.

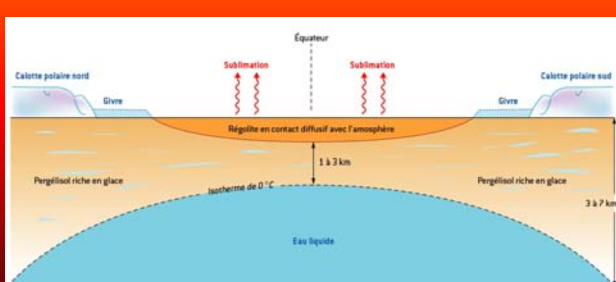
Lobate ejecta = indicator of the sub-surface ice ?

Theoretical distribution of the permafrost is consistent with the lobate ejecta distribution.

A low pressure (6 mbar), ice is not stable at the surface because of the low partial pressure of water vapor.

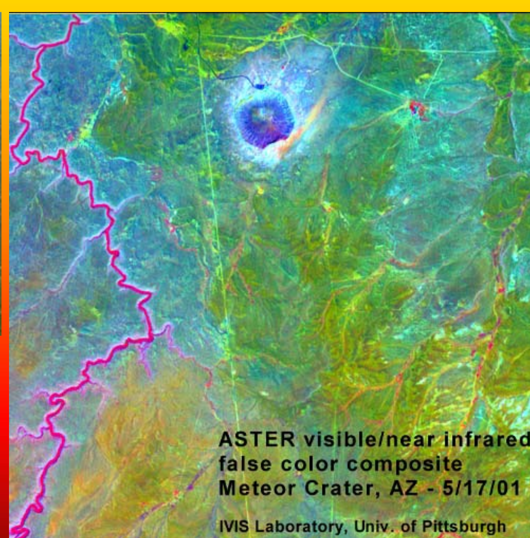
A higher latitudes (> 40°-50°), the annually-averaged temperature is colder and well below the triple point of water, ice is stable in the near surface.

At depth: the thermal gradient controls the ice thickness
and below…this is liquid water !
Average thermal gradient:
0° isotherm : 1 to 3 km deep at the equator / 3 to 7 km deep in the polar regions



From Costard, 2000

Meteor crater = a laboratory for the remote sensing studies of ejecta on Mars



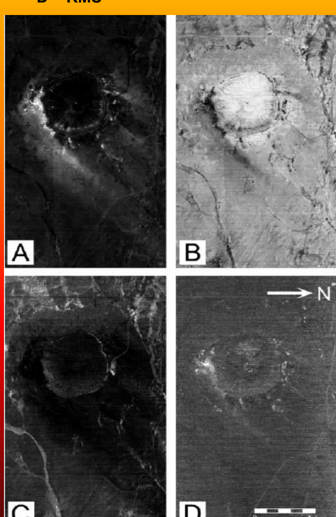
Objectives :

- Detect and map ejecta and excavated material

- Determine the state of degradation of ejecta

Meteor crater = a laboratory for the remote sensing studies of ejecta on Mars

A = Coconino sandstone
B = Kaibab permian formation
C = Triassic Moenkopi formation
D = RMS



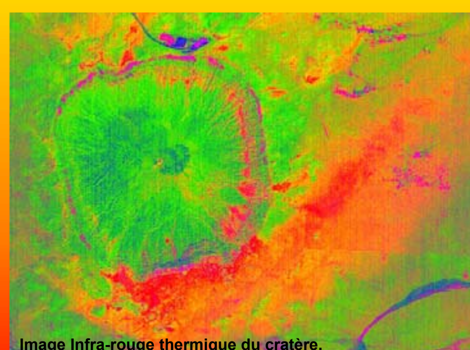
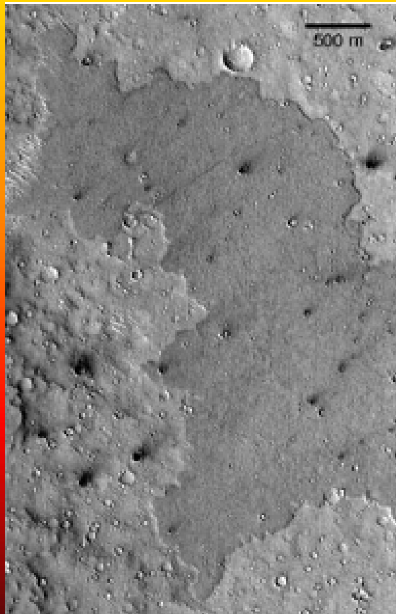


Image Infra-rouge thermique du cratère.

Figure 7. Color composite of the end-members derived from the line 3 data set, with the Coconino Ss. image in red, the Kaibab Fm. image in green, and the Moenkopi Fm. in blue. The Coconino Ss. dominated wind streak is easily discriminated up to 5 crater radii to the NE, appearing reddish-yellow where mixed with the Kaibab Fm. The crater floor consists primarily of Kaibab Fm. as does the surrounding region, where exposed by the erosion of the overlying Moenkopi Fm. To the NW of the visitor center parking lot the Moqui member of the Moenkopi Fm. has not been eroded and forms a low ridge that is highlighted in magenta. The quartz of the Moqui siltstone is more dominant and therefore shows as a mixture of blue and red (Moenkopi Fm. plus Coconino Ss.).

5. Impact craters. Datation of planetary surfaces



Recent lava flow (Elysium Planitia)

Hartmann, 2005

5. Impact craters. Datation of planetary surfaces

From the moon to Mars

- Sun distance (orbits) and ditance to the asteroids beld (asteroids density)
=> Impactor flow rate

- Surface gravity
=> Crater size for an asteroid/comet of a given size and given velocity

Hartmann, 2005

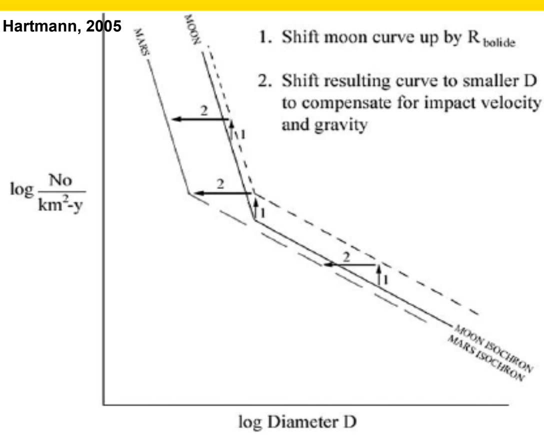
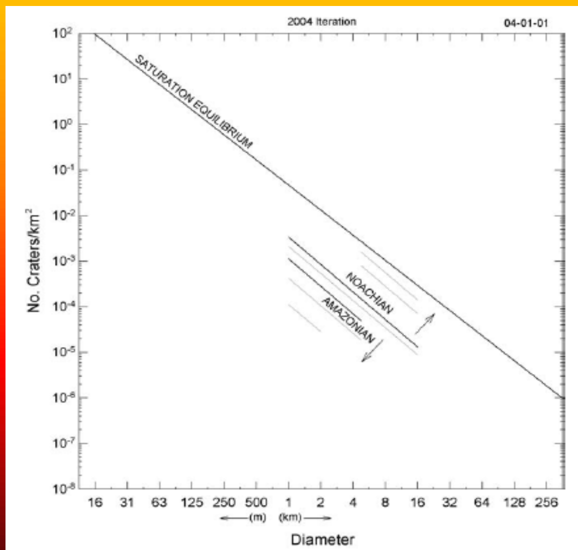


Fig. 3. Schematic diagram showing the conversion of the production function measured on lunar maria to martian conditions. The whole curve is shifted up by a fixed amount (1) to take into account the higher bolide impact rate on Mars. Then the curve is shifted left by a fixed amount (2), to take into account the smaller crater size formed by each bolide, due to lower impact velocity and higher gravity on Mars. The net result is that the shallow or "primary" branch has a different net apparent vertical shift, or change in crater production rate, than the steep or "secondary" branch.

5. Impact craters. Datation of planetary surfaces

Saturated surfaces



5. Impact craters. Datation of planetary surfaces

Derivation of martian isochrons

1 Diameter (m, km)	2 Lunar mare counts (No craters/km²)	3 Lunar mare WKH power laws (No craters/km²)	4 $N_{Mars\ 3.5\ Gy}$ (from WKH power laws)	5 $N_{Mars\ 3.5\ Gy}$ (using Neukum steep branch)	6 Popova corr. factor for Mars atm. losses	7 $N_{Mars\ 3.5\ Gy}$ (final 2004 iteration)	8 $N_{Mars\ 3.0\ Gy}$ (final 2004 iteration)	9 $N_{Mars\ 1.0\ Gy}$ (final 2004 iteration)
3.90			3.47 (6)	2.44 (5)[b]	0.095	2.31 (4)[b]	1.24 (4)[b]	4.04 (3)[b]
5.52			9.22 (5)	8.33 (4)[b]	0.16	1.33 (4)[b]	7.14 (3)[b]	2.33 (3)[b]
7.81			2.45 (5)	2.84 (4)[b]	0.23	6.53 (3)[b]	3.50 (3)[b]	1.14 (3)[b]
11.0	[7.33 ± 0.29 (1)][a]	7.37 (4)	6.53 (4)	9.70 (3)[b]	0.27	2.62 (3)[b]	1.41 (3)[b]	4.58 (2)[b]
15.6	[2.42 ± 0.12 (1)][a]	1.99 (4)	1.74 (4)	3.30 (3)[b]	0.33	1.09 (3)[b]	5.85 (2)[b]	1.91 (2)[b]
22.1	[1.57 ± 0.10 (1)][a]	5.29 (3)	4.61 (3)	1.12 (3)	0.34	3.81 (2)	2.04 (2)	6.66 (1)
31.2	[5.82 ± 0.48 (0)][a]	1.41 (3)	1.23 (3)	3.80 (2)	0.36	1.37 (1)	7.35 (1)	2.40 (1)
44.2	[3.13 ± 0.35 (0)][a]	3.75 (2)	3.29 (2)	1.35 (2)	0.40	5.40 (1)	2.90 (1)	9.44 (0)
62.5	[1.87 ± 0.27 (0)][a]	1.02 (2)	8.86 (1)	4.20 (1)	0.45	1.89 (1)	1.01 (1)	3.30 (0)
88.3	[1.84 ± 0.17 (0)][a]	2.67 (1)	2.33 (1)	1.39 (1)	0.50	6.95 (0)	3.73 (0)	1.22 (0)
125	[1.06 ± 0.13 (0)][a]	7.02 (0)	6.16 (0)	4.54 (0)	0.55	2.50 (0)	1.34 (0)	4.37 (−1)
176	[8.08 ± 0.55 (−1)][a]	1.89 (0)	1.64 (0)	1.40 (0)	0.60	8.40 (0)	4.51 (−1)	1.47 (−1)
250	[5.79 ± 0.52 (−1)]	5.03 (−1)	4.37 (−1)	4.08 (−1)	0.66	2.69 (−1)	1.44 (−1)	4.70 (−2)
353	1.04 ± 0.06 (−1)	1.34 (−1)	1.16 (−1)	1.13 (−1)	0.70	7.91 (−2)	4.24 (−2)	1.38 (−2)
500	3.23 ± 0.14 (−2)	3.54 (−2)	3.09 (−2)	3.06 (−2)	0.75	2.30 (−2)	1.23 (−2)	4.02 (−3)
707	1.14 ± 0.05 (−2)	9.45 (−3)	8.23 (−3)	8.36 (−3)	0.79	6.60 (−3)	3.54 (−3)	1.15 (−3)
1	1.64 ± 0.09 (−3)	2.52 (−3)	2.19 (−3)	2.19 (−3)	0.83	1.76 (−3)	9.44 (−4)	3.08 (−4)
1.41	5.74 ± 0.46 (−4)	6.72 (−4)	7.32 (−4)	7.32 (−4)	1.00	7.32 (−4)	3.93 (−4)	1.28 (−4)
2.83	2.82 ± 0.25 (−4)	2.53 (−4)	3.92 (−4)	3.92 (−4)	1.00	3.92 (−4)	2.10 (−4)	6.85 (−5)
4	1.21 ± 0.11 (−4)	1.36 (−4)	2.10 (−4)	2.10 (−4)	1.00	2.10 (−4)	1.13 (−4)	3.67 (−5)
5.66	8.31 ± 0.37 (−5)	7.26 (−5)	1.13 (−4)	1.13 (−4)	1.00	1.13 (−4)	6.06 (−5)	1.98 (−5)
8	5.10 ± 0.29 (−5)	3.90 (−5)	6.05 (−5)	6.05 (−5)	1.00	6.05 (−5)	3.25 (−5)	1.06 (−5)
11.3	2.56 ± 0.21 (−5)	2.08 (−5)	3.24 (−5)	3.24 (−5)	1.00	3.24 (−5)	1.74 (−5)	5.68 (−6)
16	1.67 ± 0.18 (−5)	1.12 (−5)	1.74 (−5)	1.74 (−5)	1.00	1.74 (−5)	9.33 (−6)	3.04 (−6)
22.6	5.51 ± 1.06 (−6)	5.98 (−6)	9.29 (−6)	9.29 (−6)	1.00	9.29 (−6)	4.98 (−6)	1.62 (−6)
32	4.29 ± 0.94 (−6)	3.21 (−6)	4.98 (−6)	4.98 (−6)	1.00	4.98 (−6)	2.67 (−6)	8.71 (−7)
45.3	2.24 ± 0.68 (−6)	1.72 (−6)	2.67 (−6)	2.67 (−6)	1.00	2.67 (−6)	1.43 (−6)	4.67 (−7)
64	2.04 ± 0.72 (−6)	9.22 (−7)	1.37 (−6)	1.37 (−6)	1.00	1.37 (−6)	7.35 (−7)	2.40 (−7)
90.5	2.14 ± 2.14 (−7)	4.61 (−7)	6.38 (−7)	6.38 (−7)	1.00	6.38 (−7)	3.42 (−7)	1.12 (−7)
128	2.14 ± 2.14 (−7)	2.15 (−7)	2.98 (−7)	2.98 (−7)	1.00	2.98 (−7)	1.60 (−7)	5.21 (−8)
181		1.00 (−7)	1.39 (−7)	1.39 (−7)	1.00	1.39 (−7)	7.46 (−8)	2.43 (−8)
256		4.69 (−8)	6.48 (−8)	6.48 (−8)	1.00	6.48 (−8)	3.48 (−8)	1.13 (−8)
362		2.18 (−8)	3.02 (−8)	3.02 (−8)	1.00	3.02 (−8)	1.62 (−8)	5.28 (−9)
512		1.02 (−8)	1.41 (−8)	1.41 (−8)	1.00	1.41 (−8)	7.56 (−9)	2.47 (−9)
723			6.58 (−9)	6.58 (−9)	1.00	6.58 (−9)	3.53 (−9)	1.15 (−9)
1024			3.07 (−9)	3.07 (−9)		3.07 (−9)	1.65 (−9)	5.37 (−10)

Hartmann, 2005

How to proceed for crater counting ?

-Selection of one geological unit (of the same age !)
=> morphological/spectral arguments

- Use data sets with different resolution
  Warning: large craters can give you the age of a substratum while small ones will give you the age of a more recent mantling !

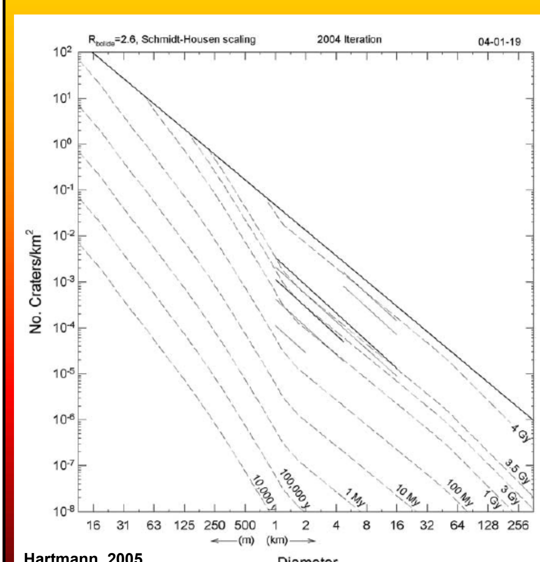
- Fit your result with the isochron theoretical curves (least squares methods). Use the data uncertainty in the fit (the uncertainty on crater count is equal to the square root of the number of craters/divided by the surface).

- Eliminate small craters from the fit (erosion, degradation processes, pb of image resolution)

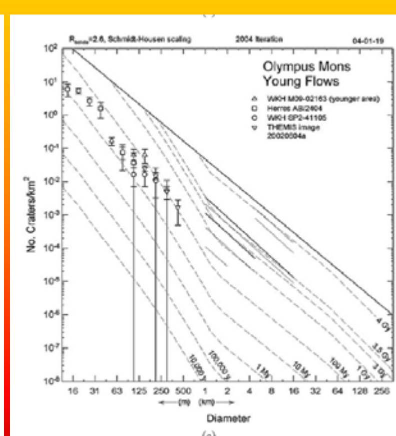
=> Age with an estimation of the formal uncertainty (this uncertainty does not take in account the uncertainty on the model –impactor flux-)

5. Impact craters. Datation of planetary surfaces

Martian isochron…last update



Hartmann, 2005



Example of crater counting and datation over recent Olympus Mons flow, Hartmann and Neukum, 2005.