Vieillissement thermique des matériaux à la surface des astéroïdes et des cométes

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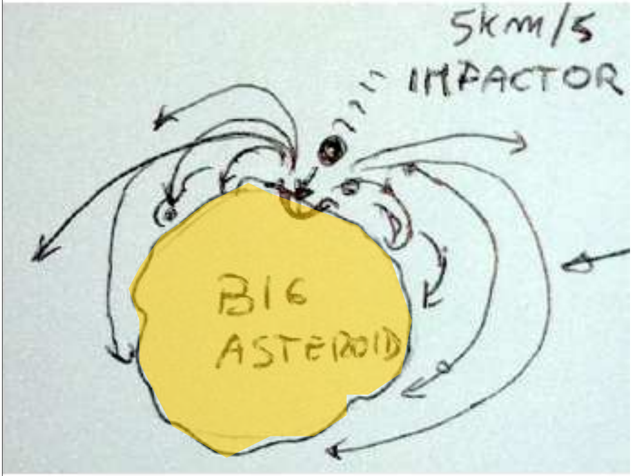
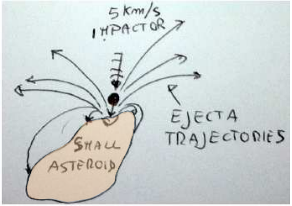
Asteroids are covered by regolith (this is the moon)

Classically it is thought that regolith is formed by impact debris

(and by the comminution of boulders by micrometeorite impacts)



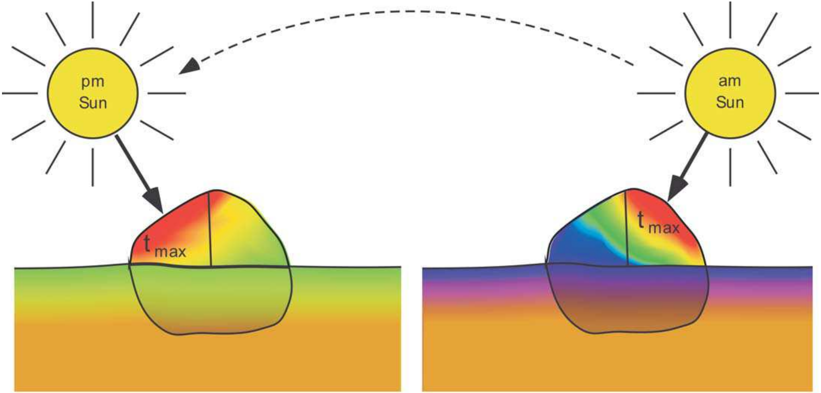


Ejecta exceed the gravitational escape velocity of small asteroids (km-sized and smaller)

Thermal fatigue cracking on asteroids ?

Day/night temperature variations causes differential expansions/contractions of rocks i.e. mechanical stress.

Cyclic stress → MATERIAL FATIGUE



from [McFadden et al., 2005]

Laboratory Experiments

Meteorite samples as asteroid analogues

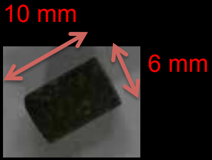

Murchison; CM2
Carbonaceous chondrite
(C-type asteroid)

Laboratory Experiments

Meteorite samples as asteroid analogues

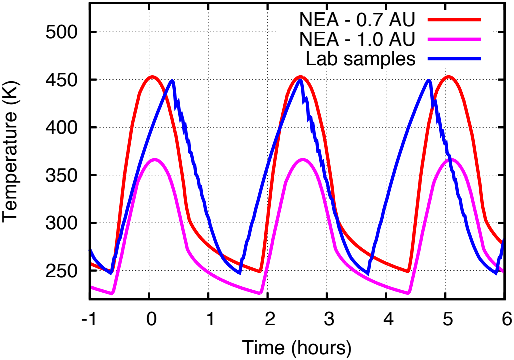
Sahara 97210;
LL3.2

Ordinary
chondrite
(S-type asteroid)



Laboratory temperature cycles of asteroid analogs

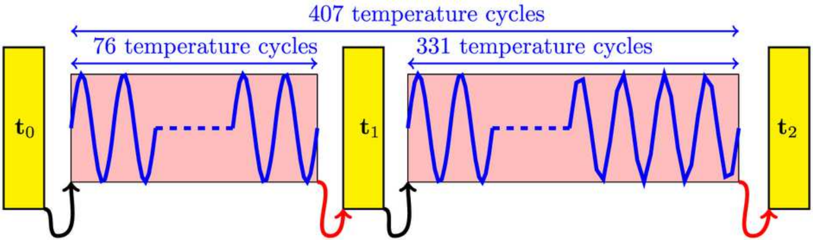
- We exposed meteorites temperature variations similar to those of the day/night cycle of NEAs
- We performed about 407 temperature cycles.
- Dynamical life of an NEA 1-10 My → $(0.5 - 30) \times 10^9$ cycles given a rotation period of 2.5-10 hours



For an albedo=0.2, P=2.5h, thermal inertia = 300 J $\mathrm{m^{-2}\,s^{-0.5}\,K^{-1}}$

Experiments by Guy Libourel (at GRPG Nancy)

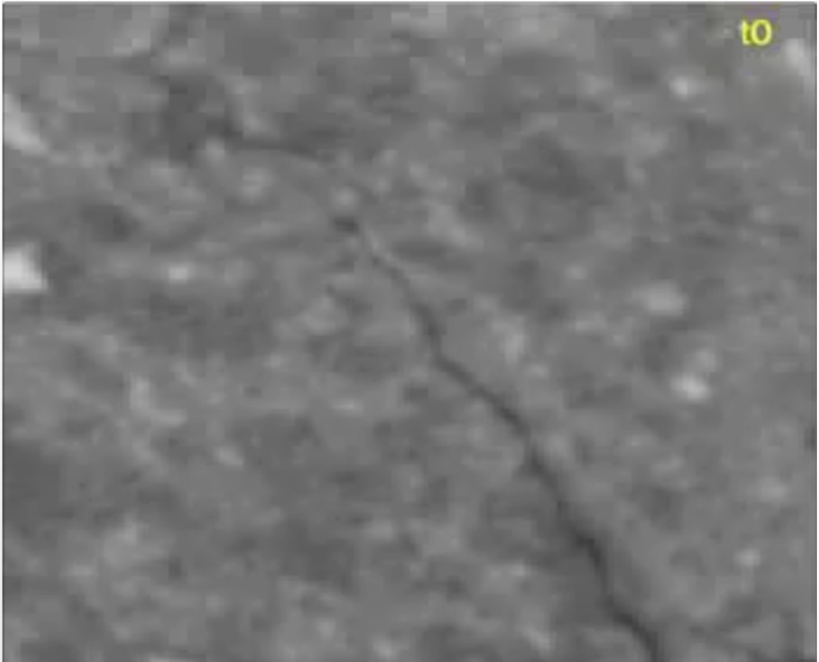
Protocol of the thermal fatigue laboratory experiments



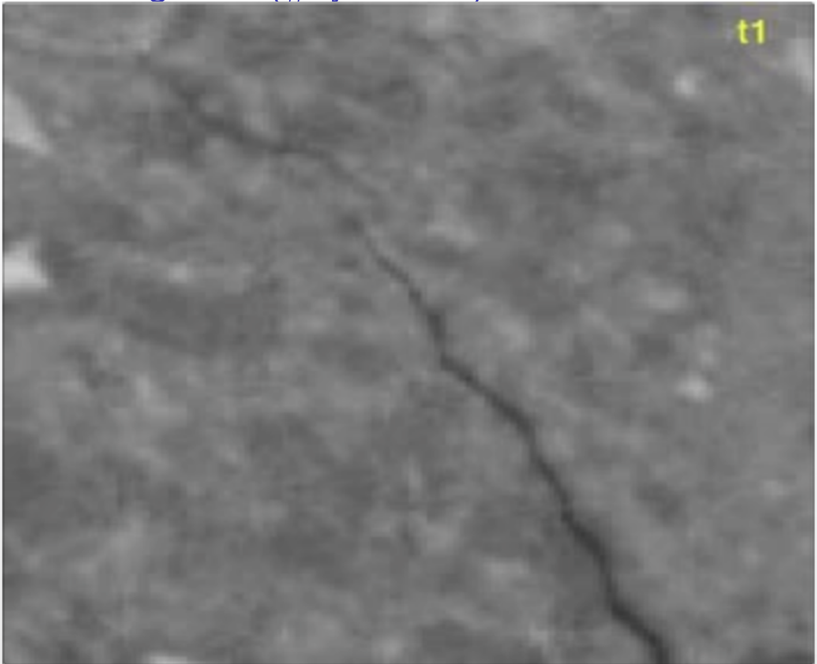
- 🟥 meteorites in the climatic chamber for temperature cycling.
- 🟨 meteorites in the computer tomographic (CT) scanner for crack imaging.
- → meteorites transported from the CT scanner to the climatic chamber.
- → meteorites transported from the climatic chamber to the CT scanner.

this and following slides from [Delbo et al., 2014]

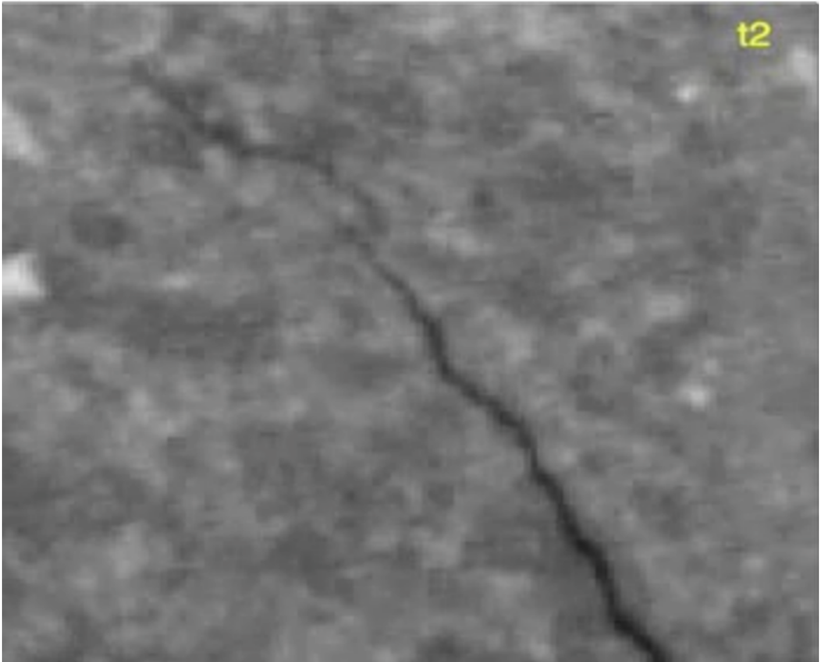
Visual crack growth (#cycles=0)



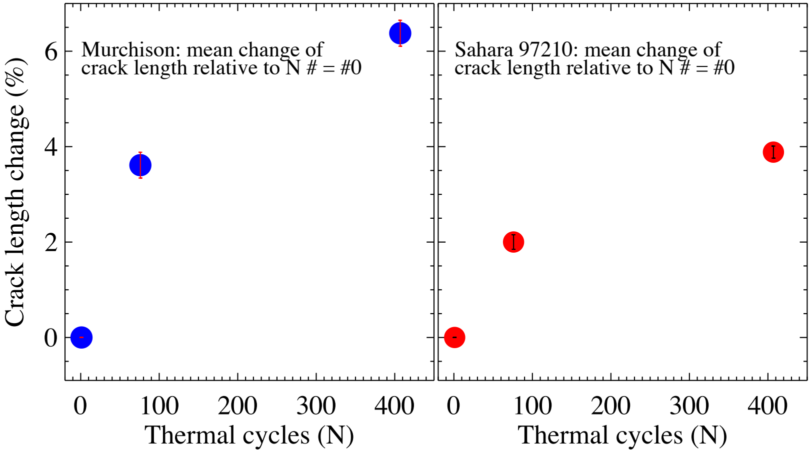
Visual crack growth (#cycles=76)



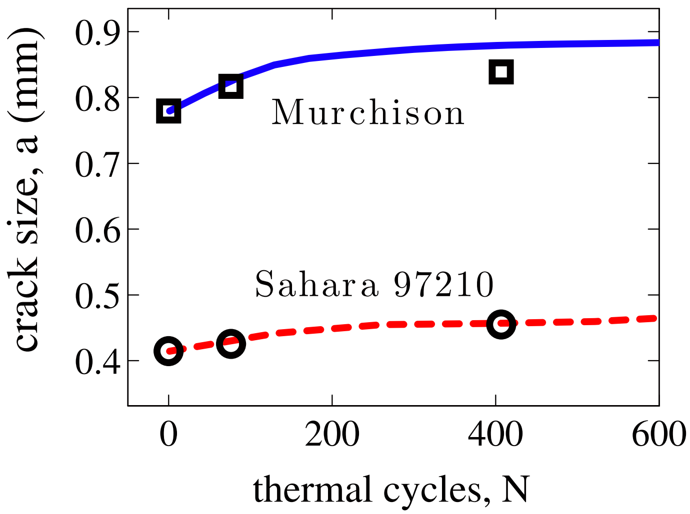
Visual crack growth (#cycles=407)



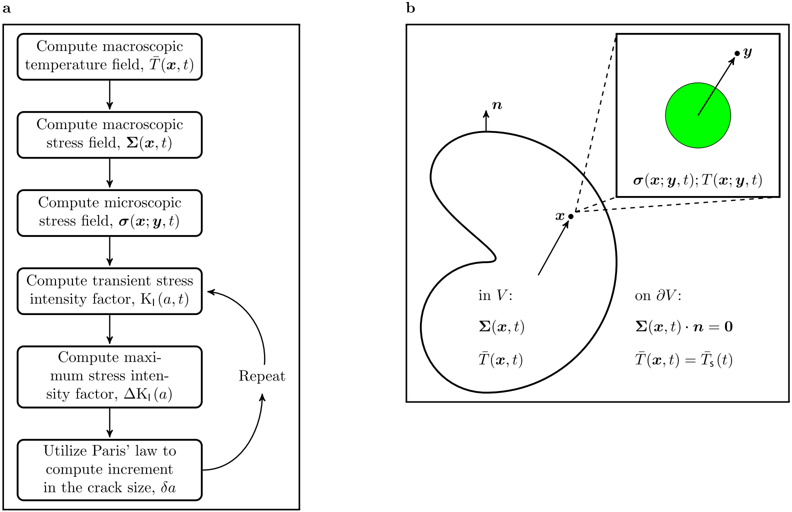
Average crack growth in Murchison and Sahara 97210



Thermo-mechanical model

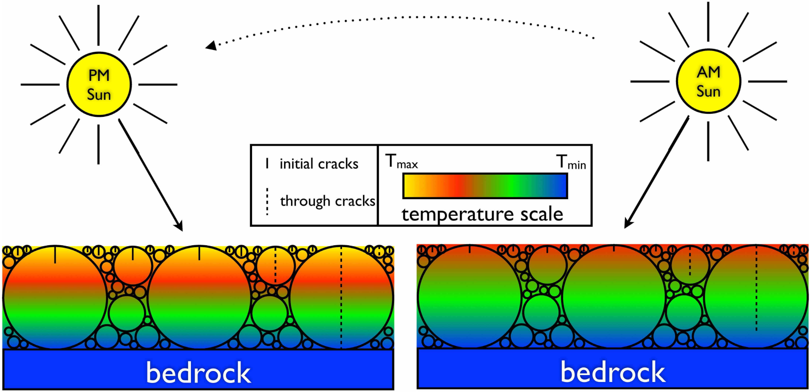


Comparison of theoretical and measured crack growth

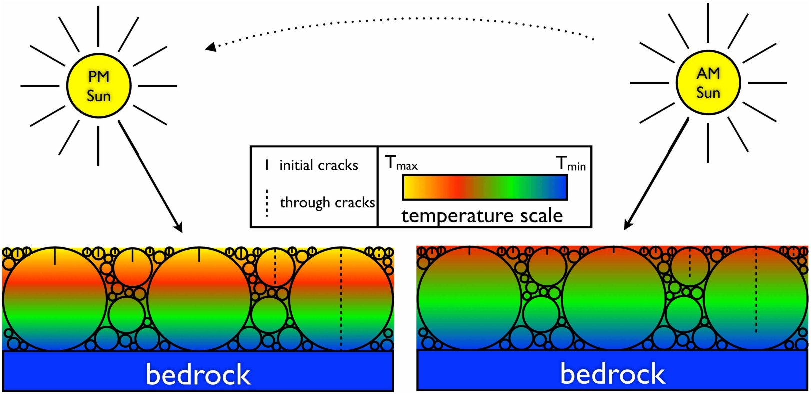


Extended Data Figure 6 | Schematics of our micromechanical model. **a**, Flow chart; **b**, schematic of the two-scale representation (Methods). ∂V is the surface of a body of volume V. A microscopic spherical inclusion, centred at the macroscopic point x is embedded in an infinite, effectively homogenized matrix. A general microscopic material point is located at a distance y measured from the centre of its nearest spherical inclusion located at x. The spherical inclusions of radius r_c are located at the vertices of a cubic lattice with lattice parameter 2ℓ.

Thermo-mechanical model application to asteroids



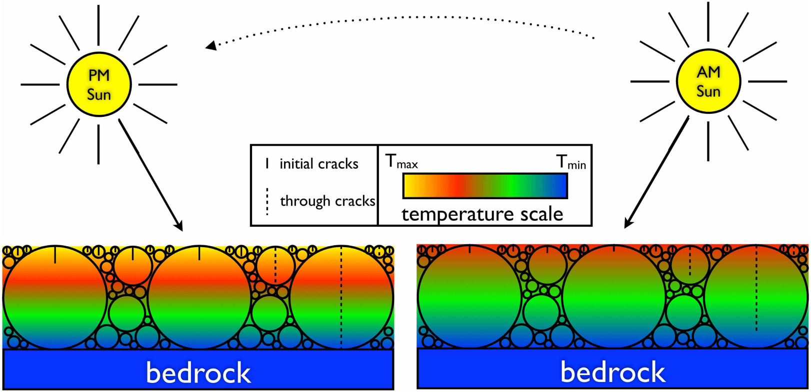
Thermo-mechanical model application to asteroids



Energy balance at the surface: $(1-A)S_{\odot}r^{-2}\mu = \epsilon\sigma T^4 - \kappa\frac{\partial T}{\partial z}$

Heat conduction in the subsurface: $\rho C\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\kappa\frac{\partial T}{\partial z}$

Thermo-mechanical model application to asteroids



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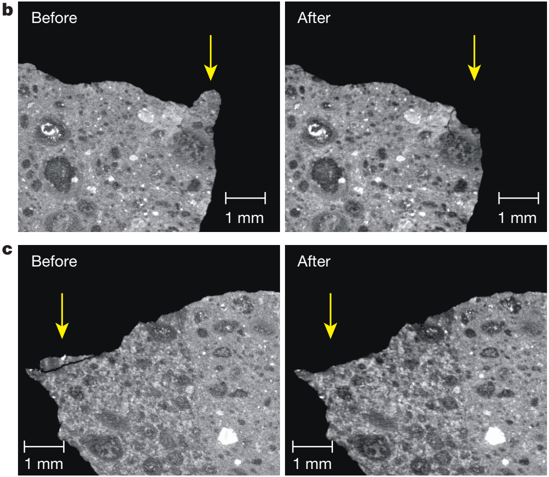
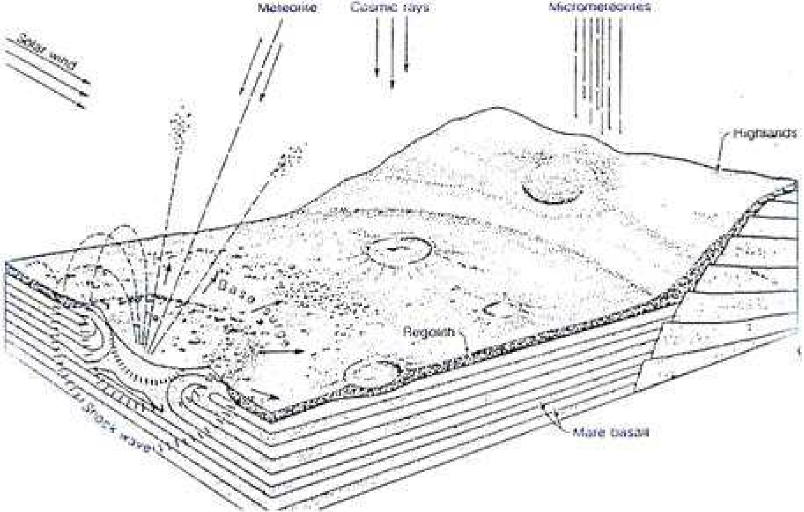
Time to breakdown is between 10^3-10^6 years in near-Earth space. and 10^5–10^9 years in the Main Asteroid Belt. Time to breakdown strongly depends on composition and size [Delbo et al., 2014].

Regolith formation from Murchison in the laboratory



Tomographic slices of regions of the same sample of Murchison before and after temperature cycling. The arrows indicate fragments that broke off from Murchison. From [Delbo et al., 2014].

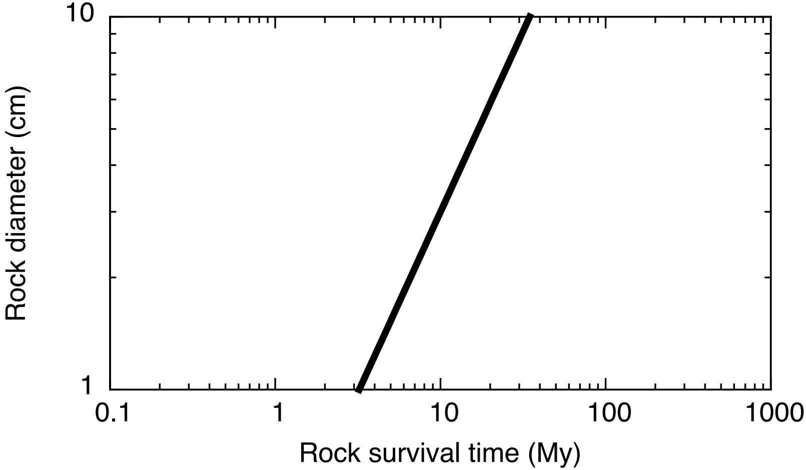
Regolith formation by impacts on the Moon

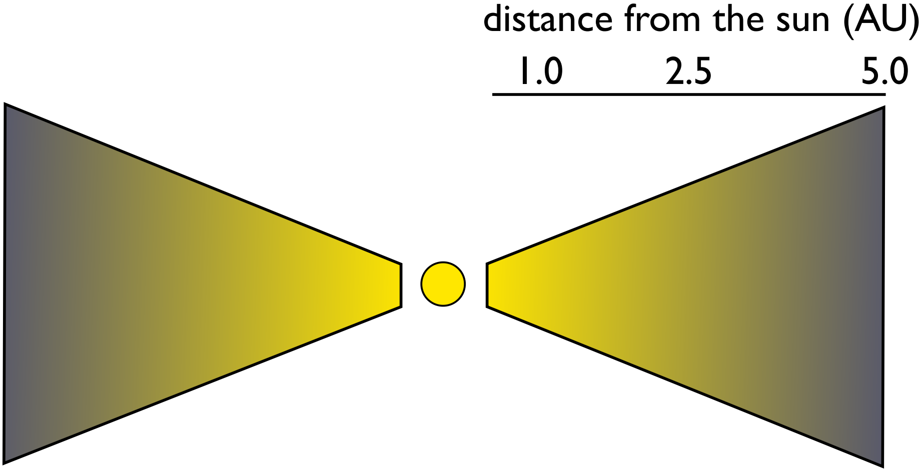


see [Hoerz et al., 1975, Hörz and Cintala, 1997].

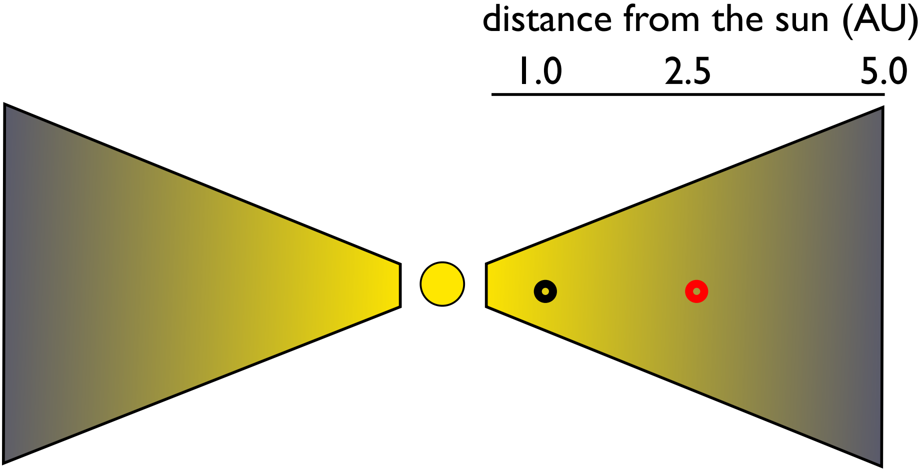
Efficiency of regolith production on the Moon by impacts

Monte Carlo simulation of surface residence time of Lunar rocks against meteoroid impacts
by [Hoerz et al., 1975, Hörz and Cintala, 1997]





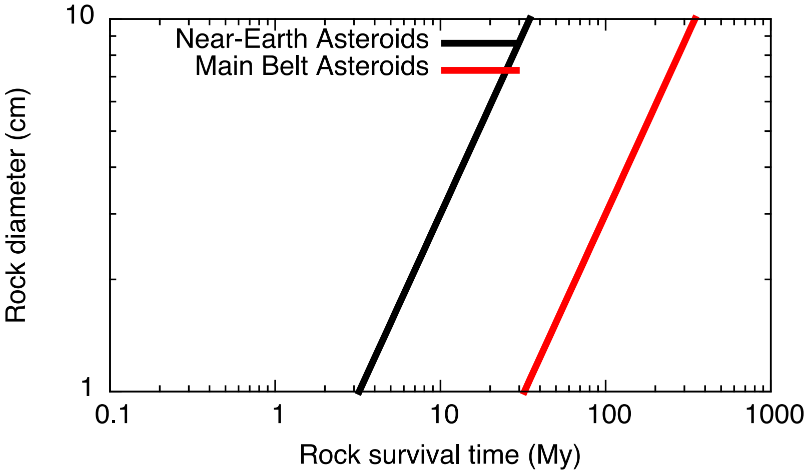
Dust particles spiral in, towards the sun, due to the PR drag. Orbital inclination is conserved. Higher particle density at 1AU than at 2.5 AU



Dust particles spiral in, towards the sun, due to the PR drag. Orbital inclination is conserved. Higher particle density at 1AU than at 2.5 AU

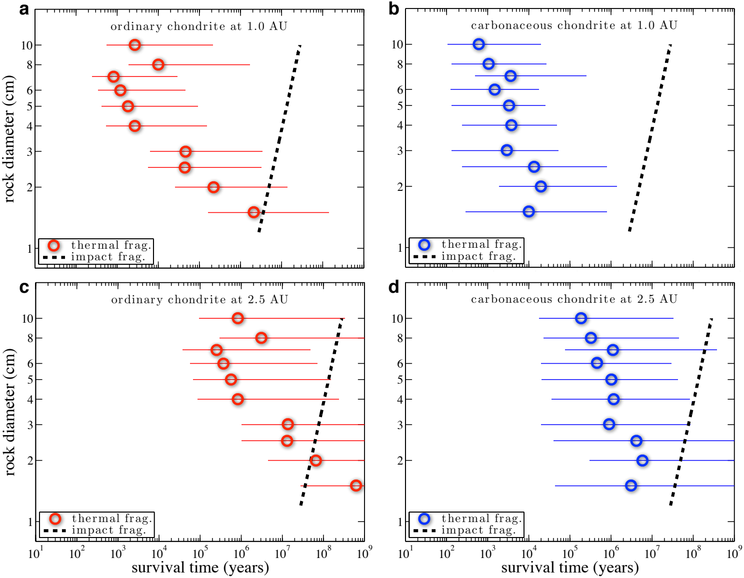
Efficiency of regolith production on Asteroids

Near-Earth Asteroids and
Main-Belt Asteroids by micro-meteoroid impacts



see [Delbo et al., 2014].

Time required to break rocks on asteroids by thermal fatigue



from [Delbo et al., 2014].

The doom of low-perihelion asteroids

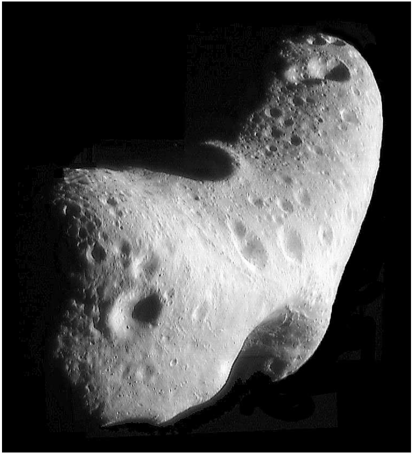
- at 0.3 AU the solar radiation pressure can remove grains with radii of the order of millimetres from the surface of an asteroid with a radius of 100 m [Jewitt, 2012]
- mm-sized grains these can be produced in $\lesssim 200$ yr.
- low-perihelion NEAs loose regolith at a rate of 5×10^{-5} m/yr
- implying that an object with a radius of 100 m would be completely eroded in about 2 Myr.
- We found observational evidence that asteroids are indeed destroyed as their orbits approach the sun [Granvik et al., 2016]

Asteroid regoliths: (4) Vesta

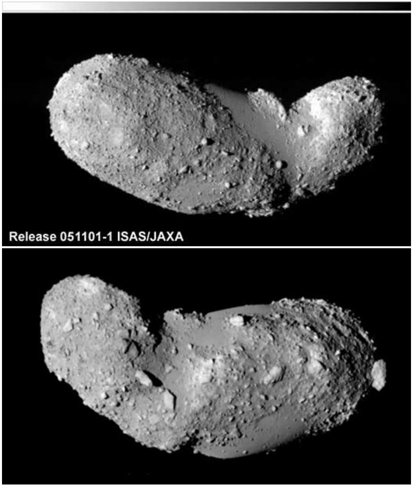
Asteroid regoliths: (433) Eros and (25143) Itokawa

Same spectral class. Same albedo. Different size.

(433) Eros



(25143) Itokawa



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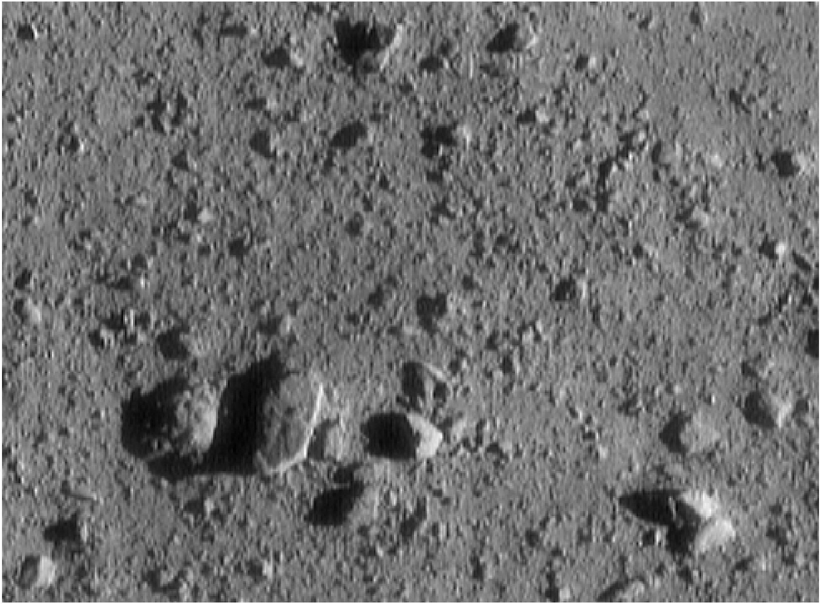
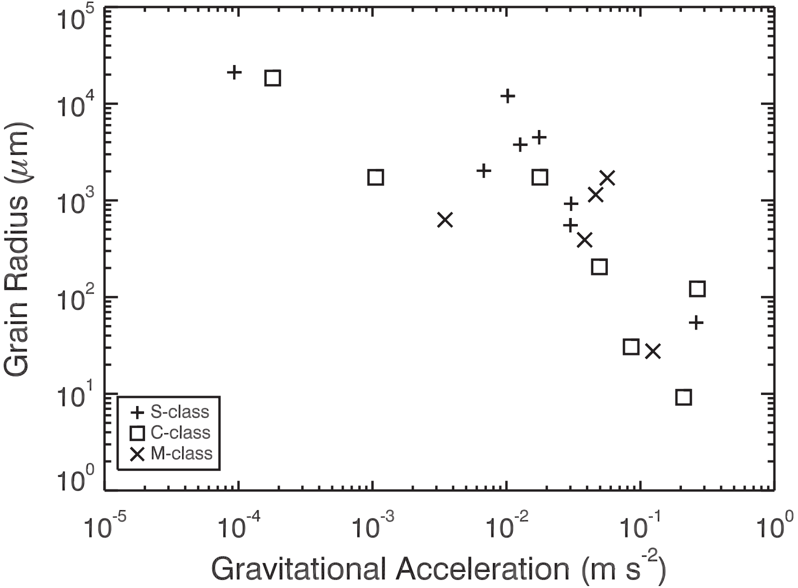
Asteroid regoliths: (433) Eros



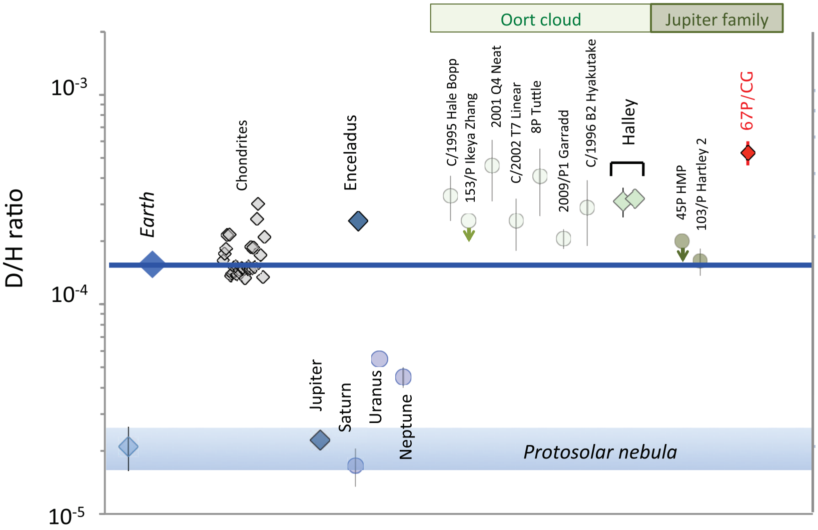
Asteroid regoliths: (25143) Itokawa

The size of the regolith depends on the size of the body



From [Gundlach and Blum, 2013].

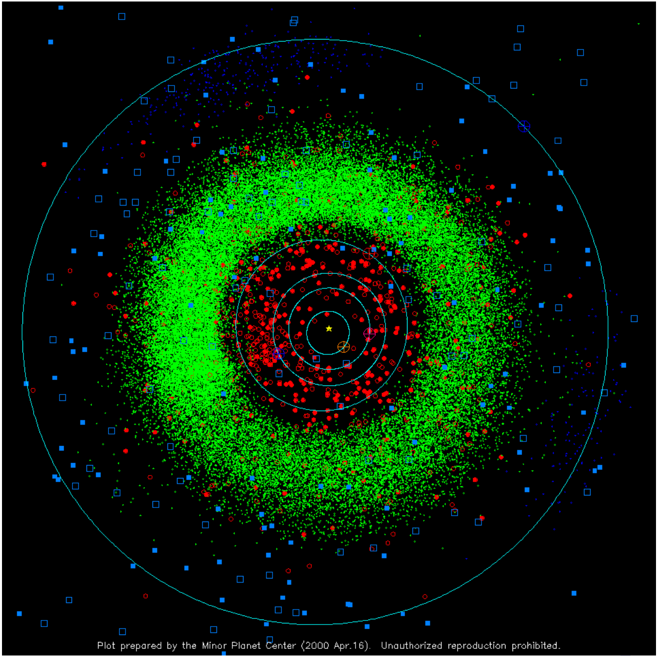
Asteroids, parents of chondrites, delivered water to Earth



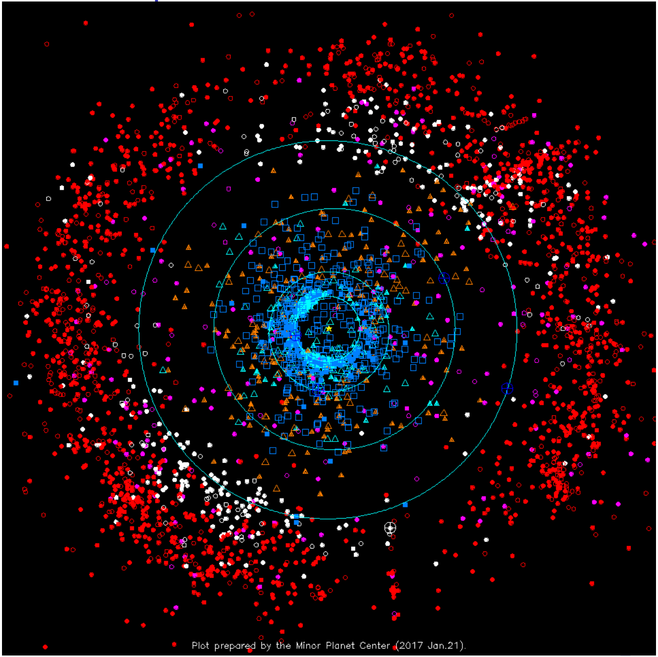
From [Altwegg et al., 2015].

Allende CV3 Carbonaceous Chondrite

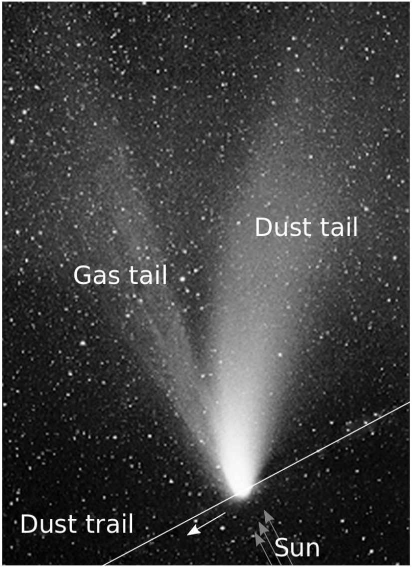
Asteroid distribution

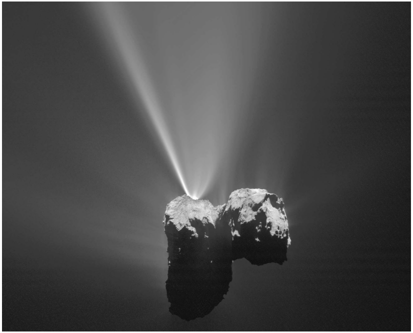


Other minor planets: Comets, Centaurs and TNOs

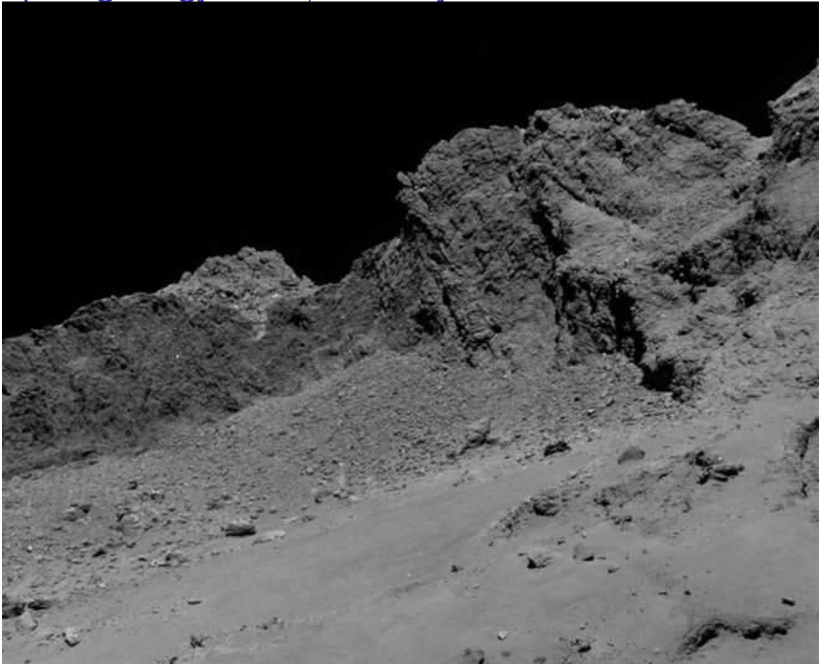


Comets and 67/P Churyumov–Gerasimenko

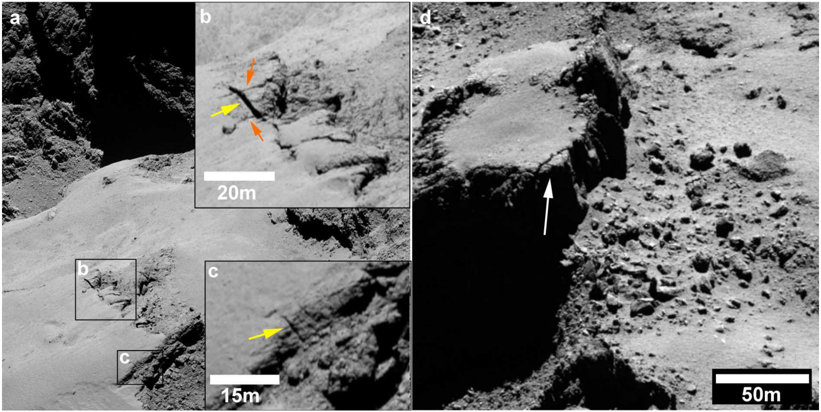




Complex geology of 67/P Churyumov–Gerasimenko

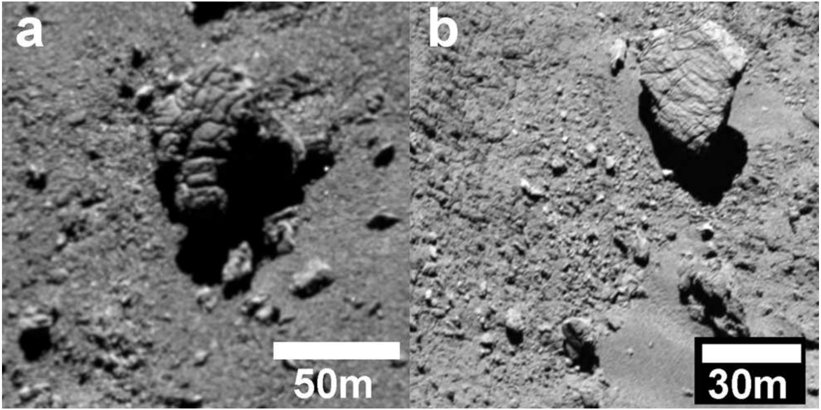


Fractures on 67/P Churyumov–Gerasimenko



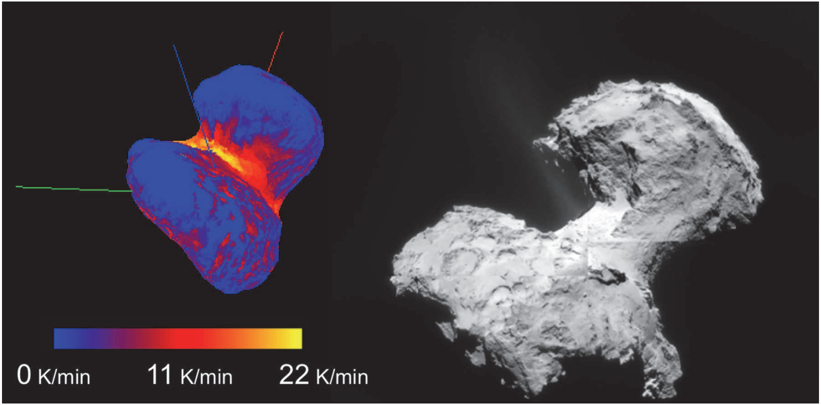
From [El Maarry et al., 2015]

Fractures on 67/P Churyumov–Gerasimenko



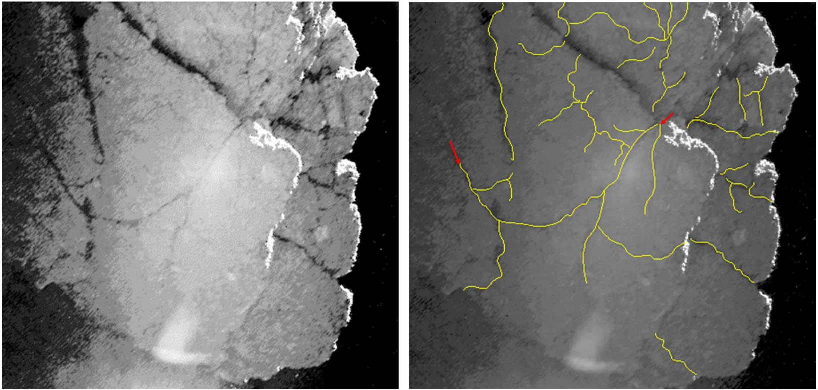
From [El Maarry et al., 2015]

Rapid temperature variation on 67/P C–G



Comparison between $(\Delta T/dt)_{max}$ map for epoch 2 and an image of 67P taken in 2014 September 2 (image credit ESA/Rosetta/Navcam/). From [Alí-Lagoa et al., 2015]

Small fracture on Philae landing Site on 67/P C–G

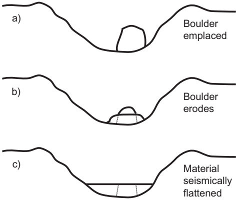


Close-up from CIVA no. 1 showing the fractured block. The left image was stretched to emphasize the fractures. The two reds arrow indicate the limit of the fracture having the maximum length (537.6 mm at 1 mm/pix resolution or 752.6 mm at 1.4 mm/pix resolution). From [Poulet et al., 2016].

Observations of thermal fatigue cracking on other bodies

by day/night temperature variations

Earth: dry deserts (McFadden et al. 2005, Keil, 2005);
From lab experiments, rocks crack if $\frac{dT}{dt} > 2^{\circ}$ C/min

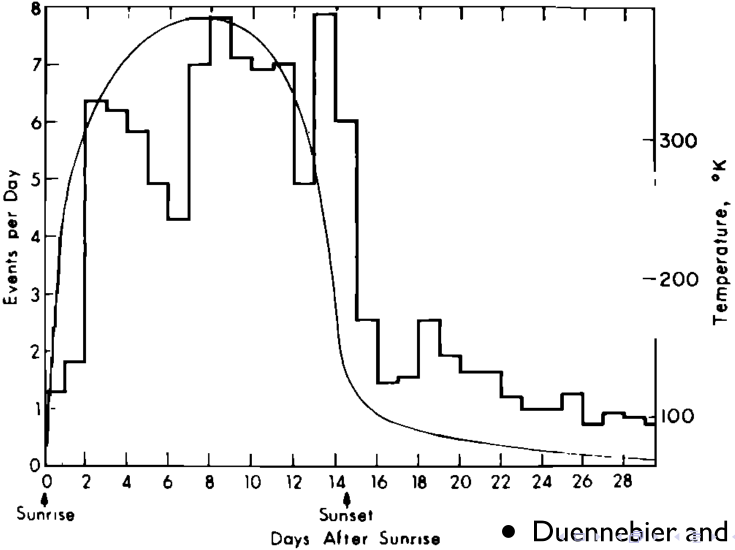


Boulder on (433) Eros erode on place and create characteristic deposits in ponds (Dombard et al. 2010)

An eroding boulder in a pond on Eros

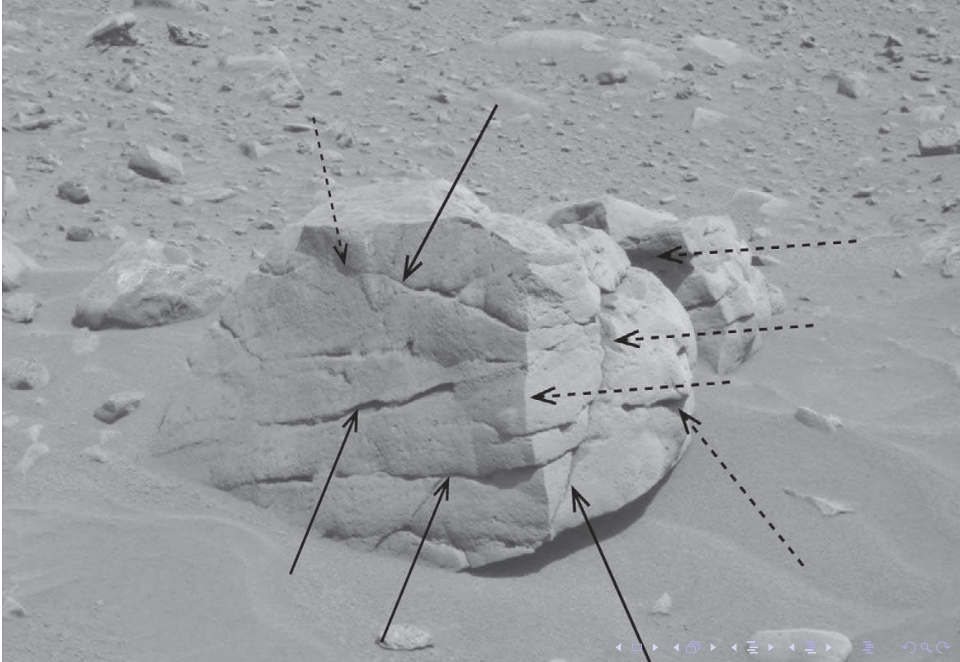
From [Dombard et al., 2010]

Thermal Moonquakes



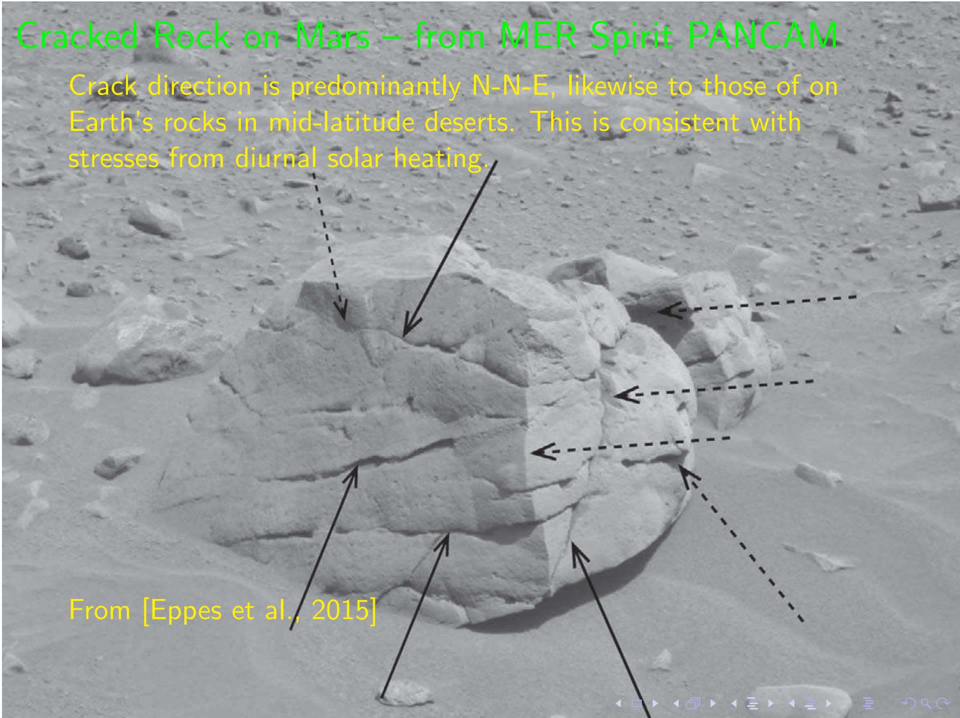
- Duennebier and Sutton, 1974

Cracked Rock on Mars – from MER Spirit PANCAM



Cracked Rock on Mars – from MER Spirit PANCAM

Crack direction is predominantly N-N-E, likewise to those of on Earth's rocks in mid-latitude deserts. This is consistent with stresses from diurnal solar heating.



From [Eppes et al., 2015]

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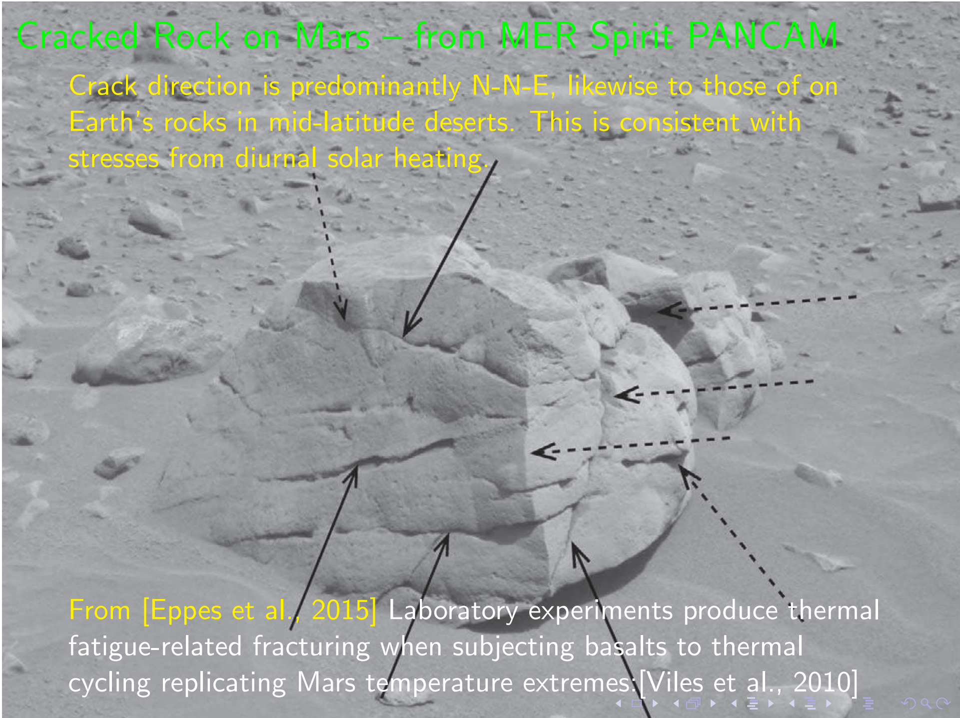
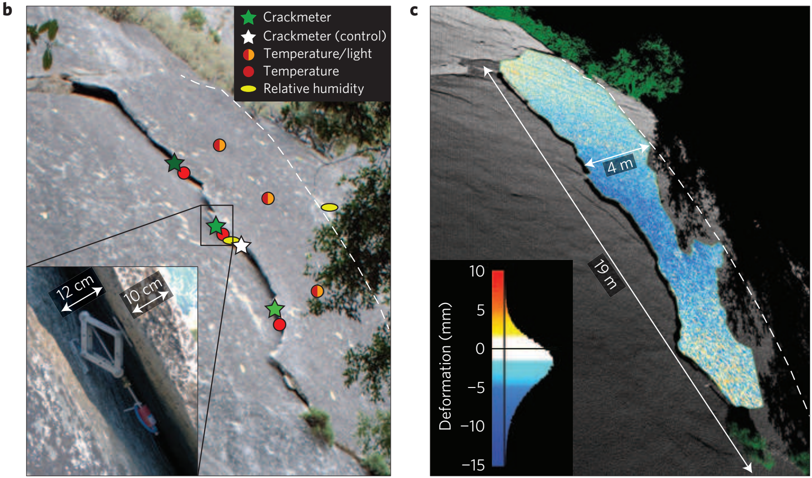


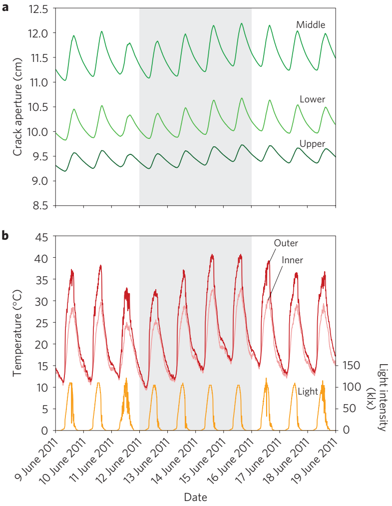
From [Eppes et al., 2015] Laboratory experiments produce thermal fatigue-related fracturing when subjecting basalts to thermal cycling replicating Mars temperature extremes:[Viles et al., 2010]

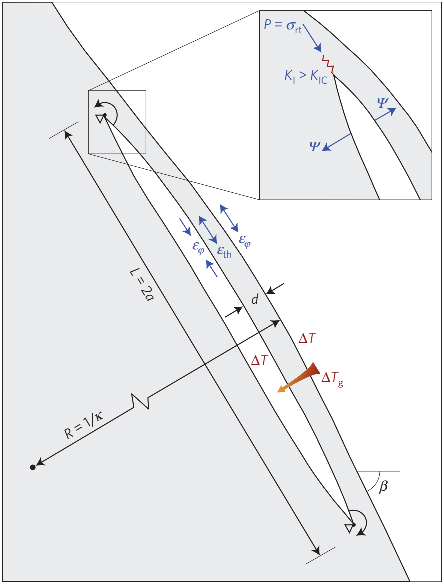
Rockfall triggering by cyclic thermal stressing of exfoliation fractures



From [Collins and Stock, 2016]

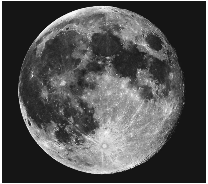
Rockfall triggering by cyclic thermal stressing of exfoliation fractures – From [Collins and Stock, 2016]





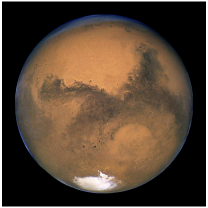
Conclusions

Moon



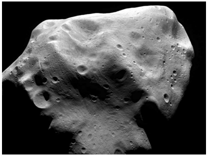
[Duennebier and Sutton, 1974,
Levi, 1973, Levi, 1976,
Molaro and Byrne, 2011,
Molaro et al., 2015]

Mars



[Viles et al., 2010,
Eppes et al., 2015]

Asteroids



[Delbo et al., 2014,
Dombard et al., 2010,
Molaro et al., 2015]

Comets

[Vincent et al., 2016,
El Maarry et al., 2015,
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