**0- Numerical modeling (Finite differences)**

**1- TP1 : estimate thermal profile lithosphere**

**2- Strain and Stress**

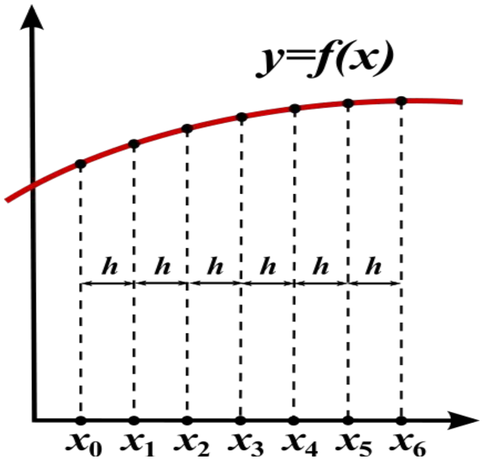
**3- A- Elasticity**

**4- B- Rupture, strength...**

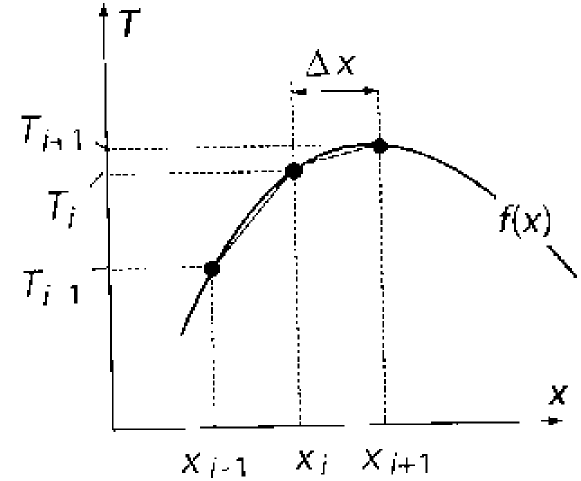
**5- Fracturing structures on Earth, Mars, and on some moons of Saturn and Jupiter.**

Aknowledgements : Francis Nimmo, Pierre Thomas, Gregor Gobalek

# Finite Differences, with the diffusion equation

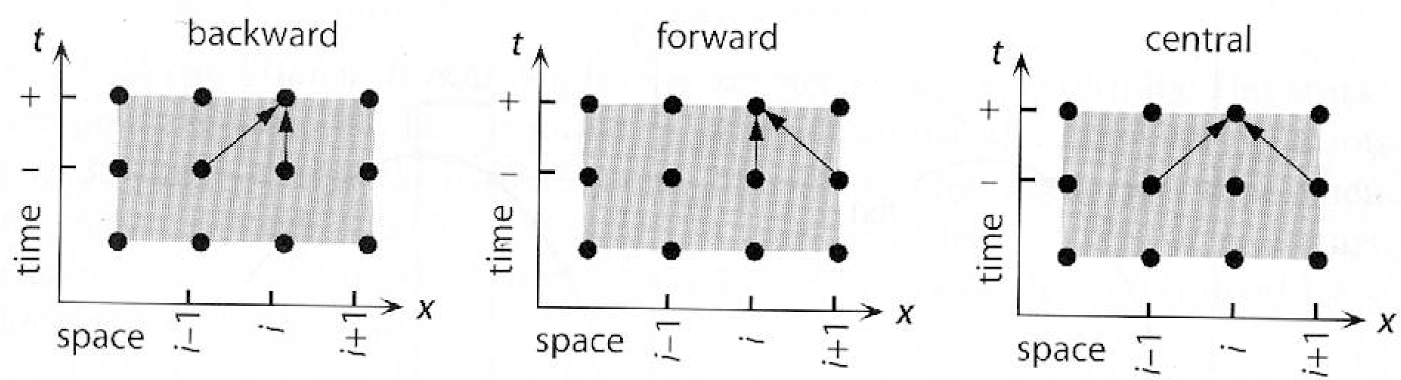



$$\frac{dT}{dt} = \kappa \frac{d^2T}{dx^2}$$




**b** finite difference approximation

We resolve the equation of heat diffusion, in 1D.
we need to discretize space (x), time (t) and temperature T.




Progade differenciation: $\frac{dT}{dx} \approx \frac{T_{i+1} - T_i}{x_{i+1} - x_i} = \frac{T_{i+1} - T_i}{\Delta x}$.

Retrogade differenciation: $\frac{dT}{dx} \approx \frac{T_i - T_{i-1}}{\Delta x}$, Central: $\frac{dT}{dx} \approx \frac{T_{i+1} - T_{i-1}}{2\Delta x}$.

$$\frac{dT}{dt} = \kappa \frac{d^2T}{dx^2}$$

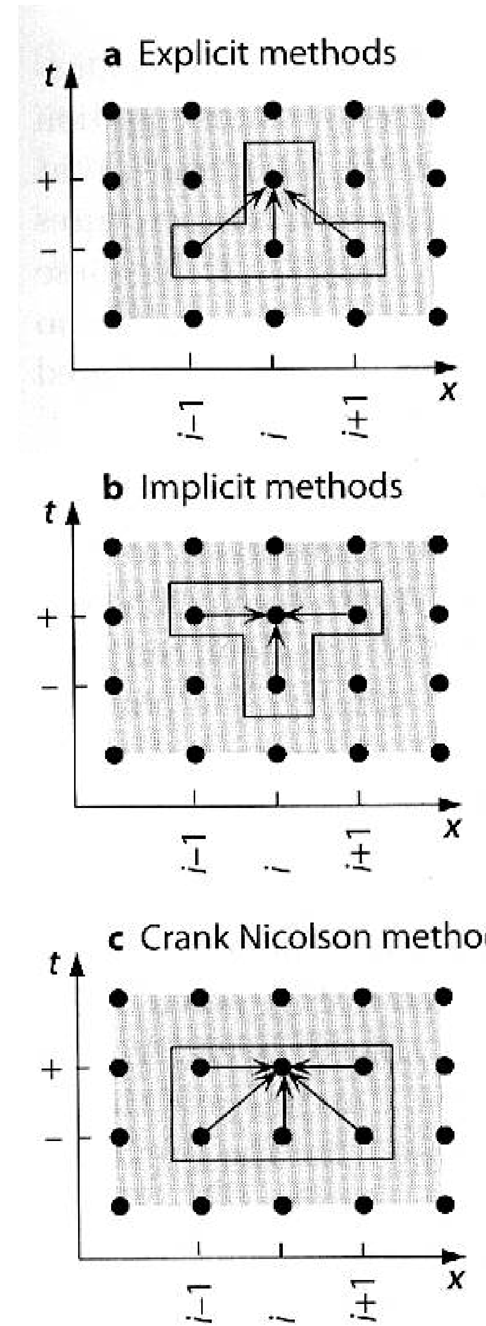
Second order derivative: $$\frac{d^2T}{dx^2} = \frac{d\left(\frac{dT}{dx}\right)}{dx} = \frac{\frac{T_{i+1}-T_i}{\Delta x} - \frac{T_i - T_{i-1}}{\Delta x}}{\Delta x} = \frac{T_{i+1} - 2T_i + T_{i-1}}{\Delta x^2}$$

Explicit method: $$T_i^+ = \left(1 - 2\kappa \frac{\Delta t}{\Delta x^2}\right) . T_i^- + \left(\kappa \frac{\Delta t}{\Delta x^2}\right) . \left(T_{i+1}^- + T_{i-1}^-\right)$$

Implicit method : $$T_i^+ = \frac{T_i^- + \kappa \frac{\Delta t}{\Delta x^2}\left(T_{i+1}^+ + T_{i-1}^+\right)}{1 + 2\kappa \frac{\Delta t}{\Delta x^2}}$$

Mixte method: ( well known as Crank-Nicolson )

$$\frac{T_i^+ - T_i^-}{\Delta x} = \frac{\kappa}{2}\left(\frac{T_{i+1}^+ - 2T_i^+ + T_{i-1}^+}{\Delta x^2} + \frac{T_{i+1}^- - 2T_i^- + T_{i-1}^-}{\Delta x^2}\right).$$



# Stability criteria for a finite difference method to work

$$T_i^{t+1} - T_i^{t} = k.\Delta t/\Delta x^2 \, (T_{i+1}^{t} - 2\, T_i^{t} + T_{i-1}^{t})$$

$$T_i^{t+1} = T_i^{t}(1 - 2.k.\Delta t/\Delta x^2) + 2k.\Delta t/\Delta x^2 \, (T_{i+1}^{t} + T_{i-1}^{t})/2$$

If $2kDT/dx^2 = DD = 0$ => $T_i^{t+1} = T_i^{t}$ , nothing changes.

If $DD = ½$ => $T_i^{t+1} = (T_{i+1}^{t} + T_{i-1}^{t})/2$ : new T is the mean.

If DD is between 0 and ½ => all good, but may take time to compute.

If $DD > ½$ => $T_i^{t+1} > (T_{i+1}^{t} + T_{i-1}^{t})/2$ , instability (divergence).

**Stability Condition for the numerical scheme: $\Delta t \leq \Delta x^2 / (4.k)$**

# Implementation with Matlab :

We write a script to calculate the thermal state of an oceanic lithosphere as it is created at an oceanic ridge (mantle arrives at the surface at 1300°C), with the surface condition To=0°C. Thermal diffusion is given $\kappa = 10^{-6} m^2/s$.

Prepocessing :
- Spatial discretisation 1D, 0 -100 km : resolution...
- Time discretisation 0 -200 Ma : numerical time-step...

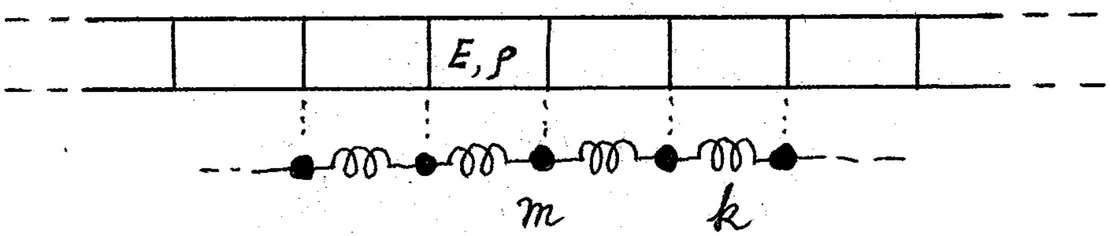
Processing : Resolve the equation step by step with a finite difference method.

Post-processing :Visualizet he geothermal gradient with time (per 5 Ma for instance)

* At which age is the temperature equal to 500°C at 20 km depth ?

* What is the critical time step, given a resolution of 1 km ?

An elastic bar may be discretized as a series of masses related by springs of rigidity k. Which system of equations allows to deduce the stresses and displacements of these masses ?



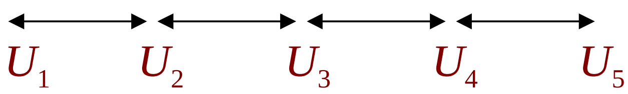

$$\begin{cases} \frac{\partial \sigma}{\partial x} = \rho . g \\ \varepsilon = \frac{\partial u}{\partial x} \\ \sigma = E . \varepsilon \end{cases}$$

$$\Rightarrow \quad \frac{\partial^2 u}{\partial x^2} = \frac{\rho . g}{E}$$

## 1- Analytical solution:

$$\begin{cases} \sigma = \rho g x \\ u = \rho g x^2 / 2E \end{cases}$$

## 2- finite difference solution:




$$\begin{cases} \sigma_{i+1} = \sigma_i + (x_{i+1} - x_i) . \rho . g \\ \frac{\partial^2 U_i}{\partial x^2} = \frac{U_{i+1} - 2U_i + U_{i-1}}{(x_{i+1} - x_{i-1})^2} = \frac{\rho g}{E} \end{cases}$$

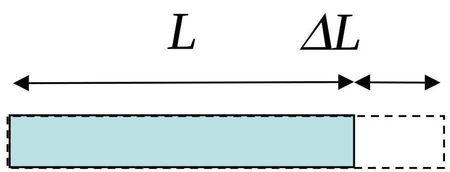
# Stress and Strain

- Are fundamental macroscopic quantities describing deformation
- Stress is the applied force per unit area which is causing the deformation (units $Nm^{-2}$=Pa)
- Strain is the relative length change in response to the applied stress (dimensionless)

- In general, compressional stresses and strains will be taken as *positive*, extension as *negative* (geologists may use the opposite convention!)

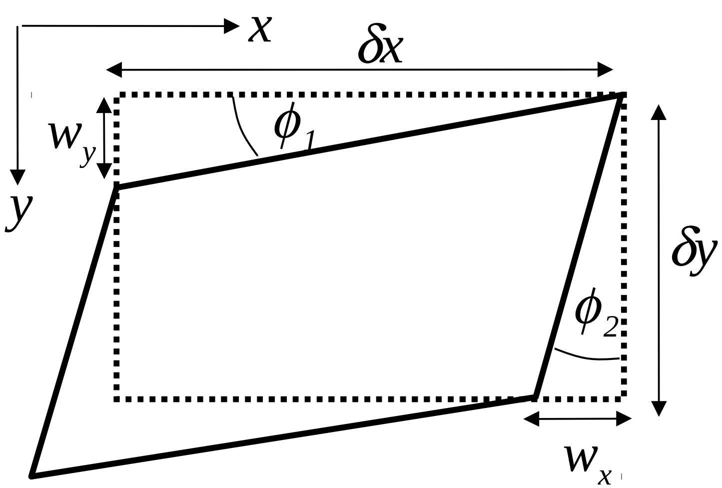
# Strain ($\varepsilon$)

- Normal strain $\varepsilon = \Delta L / L$ (dimensionless)




In three dimensions $\Delta$, the fractional change in volume, $=\Delta V/V = \varepsilon_x + \varepsilon_y + \varepsilon_z$

- Shear strain $\varepsilon_{xy}$ involves *rotations* (also dimensionless)

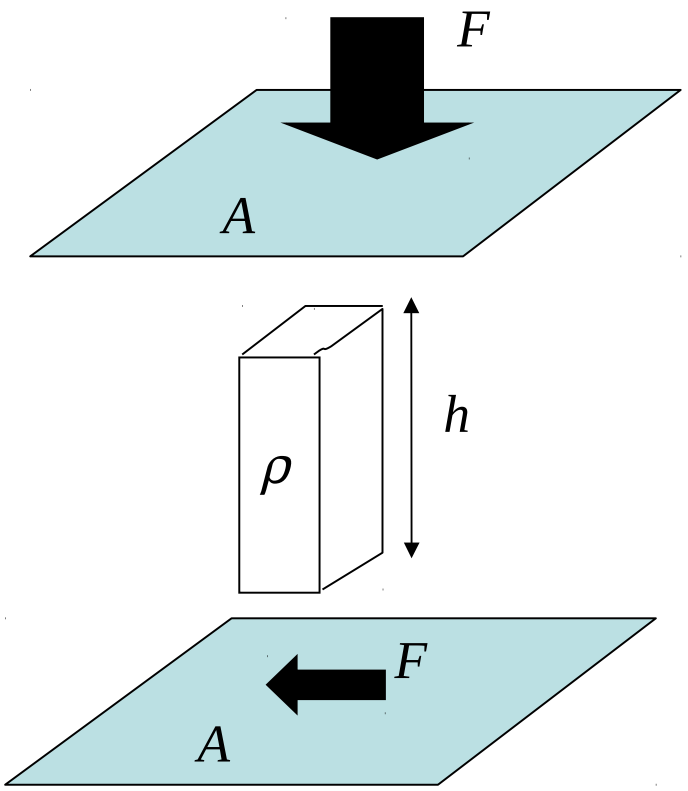



$$\varepsilon_{xy} = -\frac{1}{2}(\varphi_1 + \varphi_2)$$
$$= \frac{1}{2}\left(\frac{\partial w_y}{\partial x} + \frac{\partial w_x}{\partial y}\right)$$

Note that $\varepsilon_{xy} = \varepsilon_{yx}$

- Amount of solid body rotation ω is $\frac{1}{2}\left(\frac{\partial w_y}{\partial x} - \frac{\partial w_x}{\partial y}\right)$
- If ω=0 then there is no rotation – pure shear

# Stress ($\sigma$)




- Normal stress: $\sigma = F / A$

(stress perpendicular to plane)

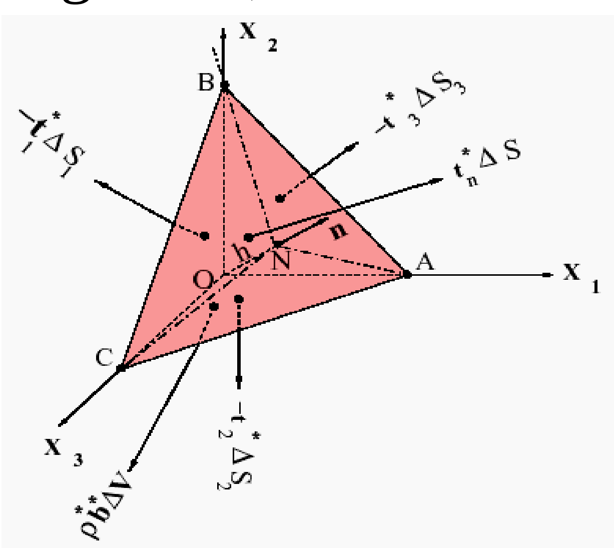
Example: mass of overburden per unit area = $\rho h$,

so pressure (stress) = $\rho g h$

- Shear stress: $\sigma = F / A$

(stress parallel to plane)

- In general,stress distribution involves both normal and shear stresses



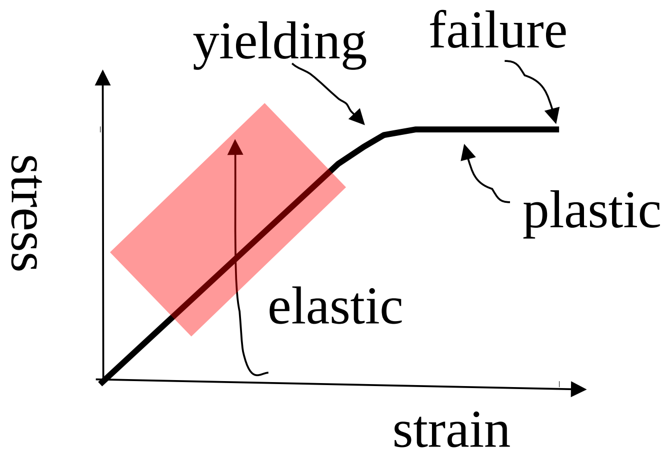

therefore the need of tensors.

The Cauchy stress tensor:

$$t_n = t_1 . n_1 + t_2 . n_2 + t_3 . n_3 = t_i . n_i$$

$$T_i . n_i = \sigma_{ji} . n_j = \sigma_{ij} . n_j$$ is a symetric tensor

# A- Elasticity

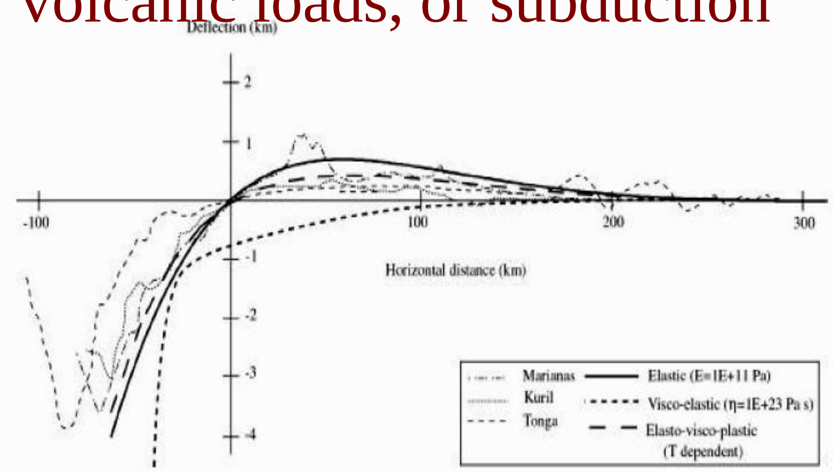



- In the elastic regime, stress is proportional to strain (Hooke's law):

$$\varepsilon = \frac{\sigma}{E}$$

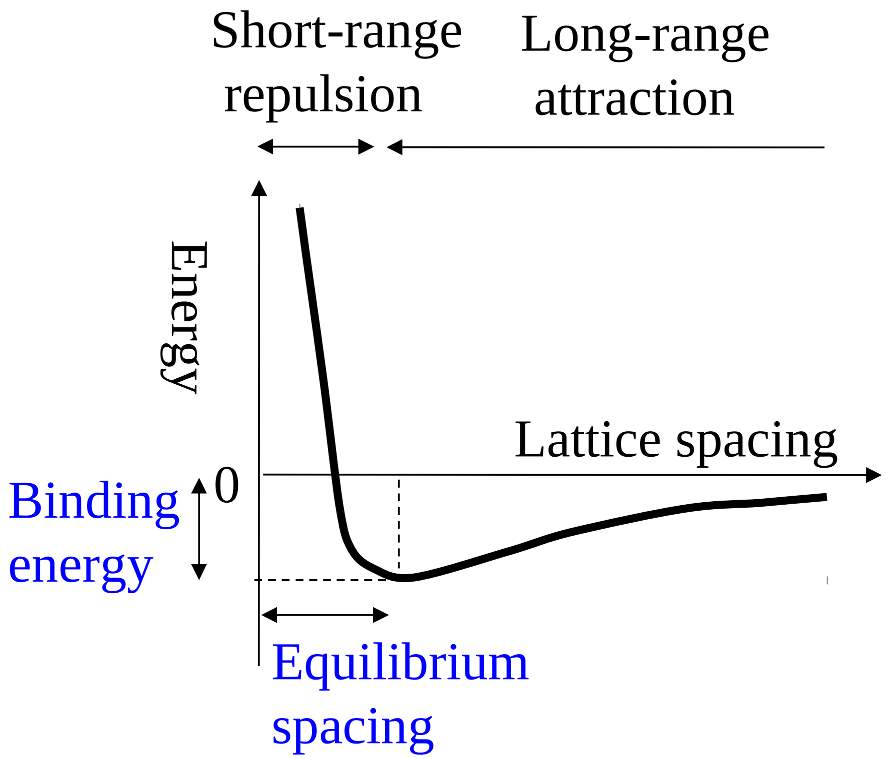
- The constant of proportionality *E* is Young's modulus

Useful to study flexural response of meteoritic impacts, volcanic loads, or subduction




- Young's modulus tells us how resistant to deformation a particular material is (how much strain for a given stress)
- Typical values of Young's modulus are $10^{11}$ Pa (for rock) and $10^{10}$ Pa (for ice)

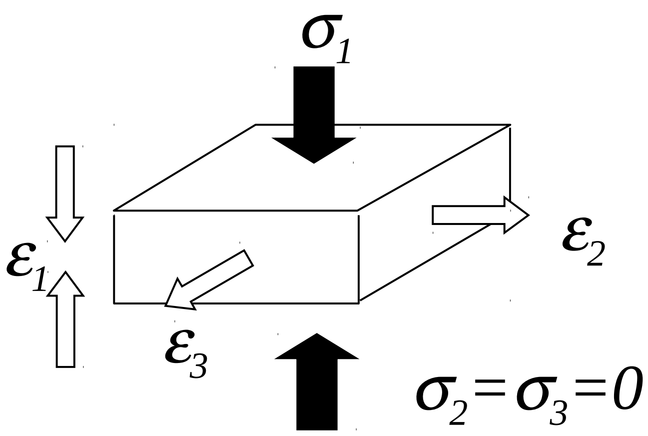
# Atomic Description




- *Equilibrium lattice spacing* is at energy minimum (at zero temperature)
- *Binding energy* is amount required to increase lattice spacing to infinity
- To increase or decrease the lattice spacing from the equilibrium requires work

- So deforming (straining) a solid requires work to be done, in other words we have to apply a stress
- Macro-scale properties of a solid are determined by its atomic properties.

# Uniaxial Stress




- Unconfined materials will expand perpendicular to the applied stress
- Amount of expansion is given by Poisson's ratio $\nu$

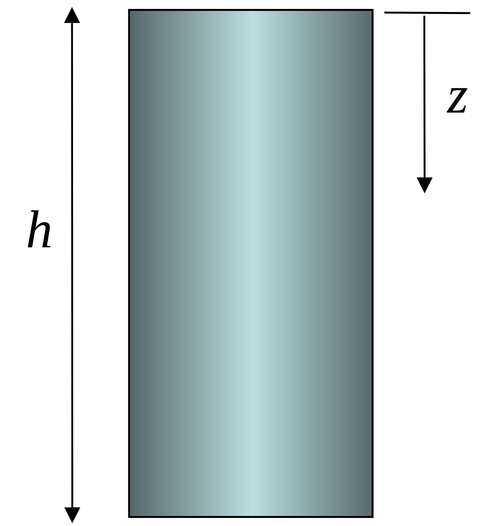
$$\varepsilon_1 = \frac{\sigma_1}{E}$$
$$\varepsilon_2 = -\nu \frac{\sigma_1}{E}$$
$$\varepsilon_3 = -\nu \frac{\sigma_1}{E}$$

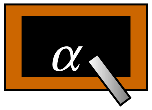
- A material with $\nu$=1/2 is *incompressible*.
- Geological materials generally have $\nu$ =1/4 to 1/3

| Material | $E$ (MPa) | $\nu$ |
|---|---|---|
| A316 Stainless Steel | 196,000 | 0.3 |
| A5 Aluminum | 68,000 | 0.33 |
| Bronze | 61,000 | 0.34 |
| Plexiglass | 2,900 | 0.4 |
| Rubber | 2 | $\rightarrow$0.5 |
| Concrete | 60,000 | 0.2 |
| Granite | 60,000 | 0.27 |

# Example

- Consider a column that is laterally unconstrained i.e. in a *uniaxial* stress state
- Vertical stress $\sigma = \rho\, g\, z$
- Strain $\varepsilon(z) = \rho\, g\, z\, /\, E$
- To get the total shortening, we integrate:



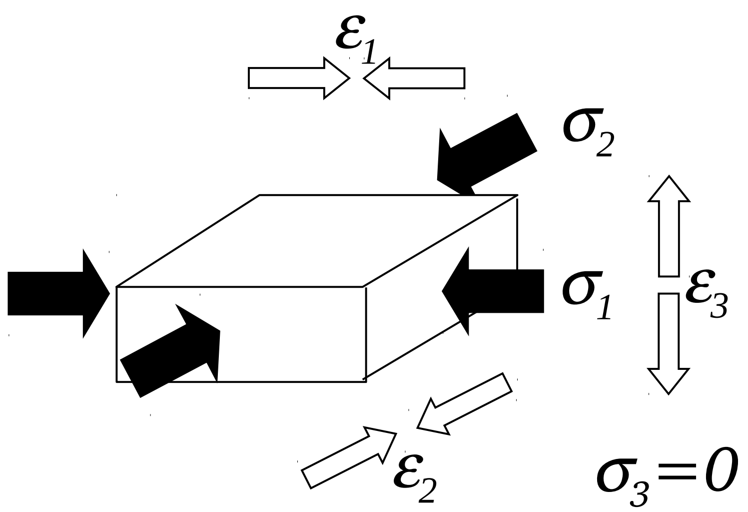



$$\delta h = \int_0^h \varepsilon dz = \frac{\rho g h^2}{2E}$$

E.g. Devil’s Tower (Wyoming)
$h$=380m, $\delta h$=2cm

# Plane Stress

- If we have two perpendicular stresses, we get plane stress,
- Results can be obtained by adding two uniaxial stresses,
- We use this when we consider flexure...



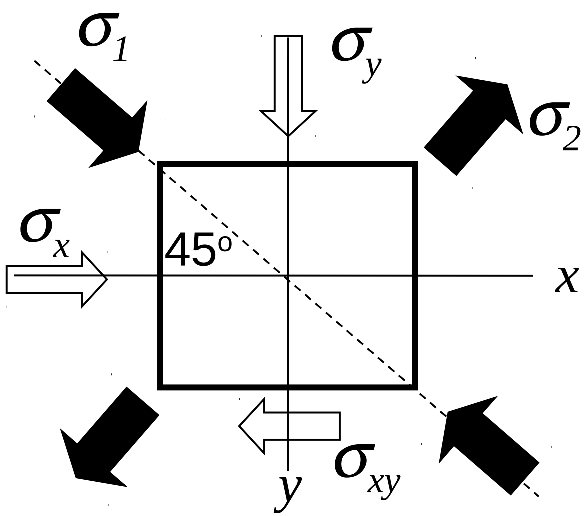

$$\varepsilon_1 = \frac{1}{E}(\sigma_1 - \nu\sigma_2)$$

$$\varepsilon_2 = \frac{1}{E}(\sigma_2 - \nu\sigma_1)$$

$$\varepsilon_3 = -\frac{\nu}{E}(\sigma_1 + \sigma_2)$$

# Pure Shear and Shear Modulus

- Pure shear is a special case of plane stress in which $\sigma_1$=-$\sigma_2$ and the stresses normal to the object are zero.




- The shear stresses $\sigma_{xy} = \sigma_1 = -\sigma_2$
- Froma previous slide we have $\varepsilon_1=(1+v)\sigma_1/E=(1+v)\sigma_{xy}/E$
- In this case, $\varepsilon_1=\varepsilon_{xy}$ so $\sigma_{xy}=E\varepsilon_{xy}/(1+v)$
- We can also write this as $\sigma_{xy} = 2G\ \varepsilon_{xy}$ where $G$ is the shear modulus and is controlled by $E$ and $v$:

$$G=\frac{E}{2(1+v)}$$

# Bulk Modulus

- *Isotropic* stress state $\sigma_1=\sigma_2=\sigma_3=P$ where $P$ is the pressure
- If the stresses are isotropic, so are the strains $\varepsilon_1=\varepsilon_2=\varepsilon_3$
- The dilatation $\Delta=\varepsilon_1+\varepsilon_2+\varepsilon_3$ , gives the fractional change in volume, so here $\Delta=3\varepsilon_1$
- From before we have

$$\varepsilon_1=\frac{1}{E}\sigma_1-\frac{\nu}{E}\sigma_2-\frac{\nu}{E}\sigma_3=\frac{1}{E}(1-2\nu)P$$

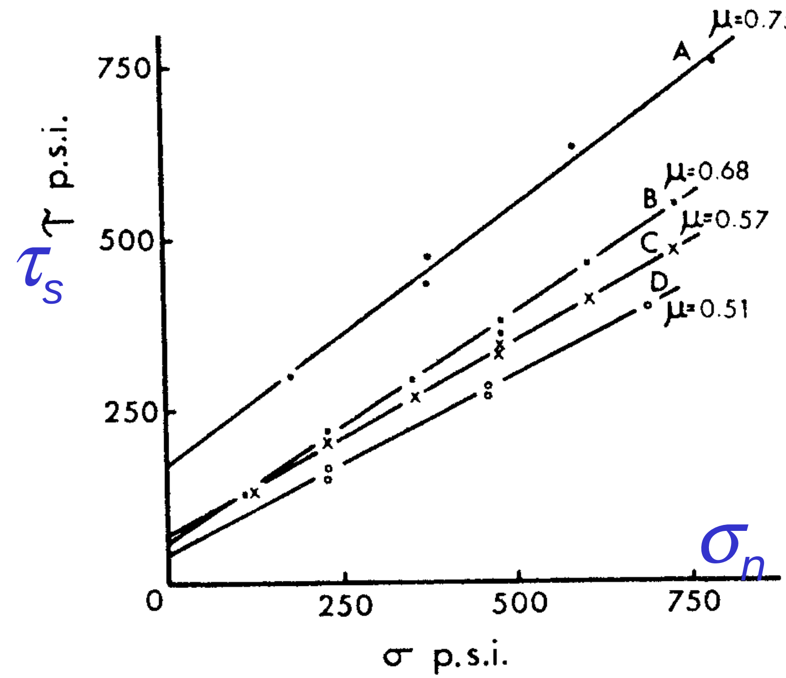
- So we can write $P=\frac{E}{3(1-2\nu)}\Delta=K\Delta$

- Here $K$ is the bulk modulus which tells us how much pressure is required to cause a given volume change and which depends on $E$ and $\nu$

- The definition of $K$ is $-\frac{dV}{V}=\frac{d\rho}{\rho}=\frac{dP}{K}$

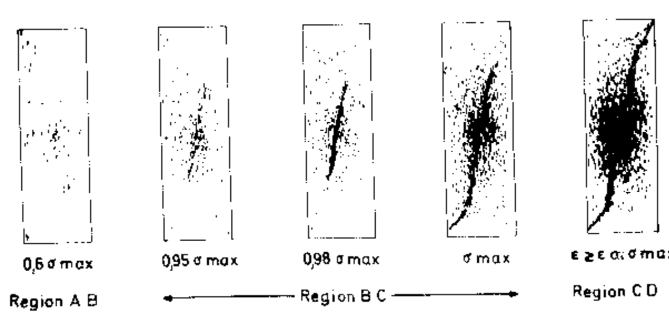
# B- PLASTICITY : Failure, rupture, strength

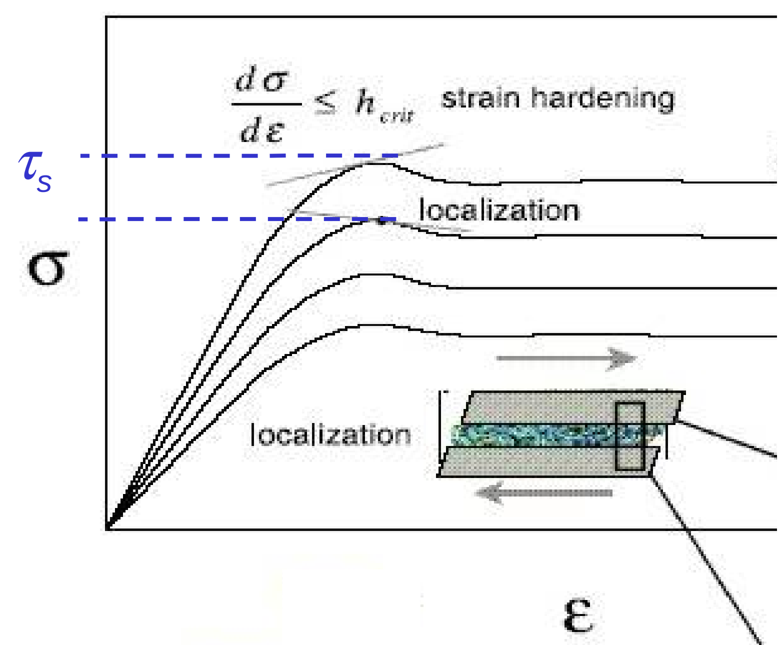
Several constitutive laws describe the yield strength, or yield surface : Von Mises (pressure independent), Drucker-Praeger, or Coulomb.




Most commonly used is Coulomb :

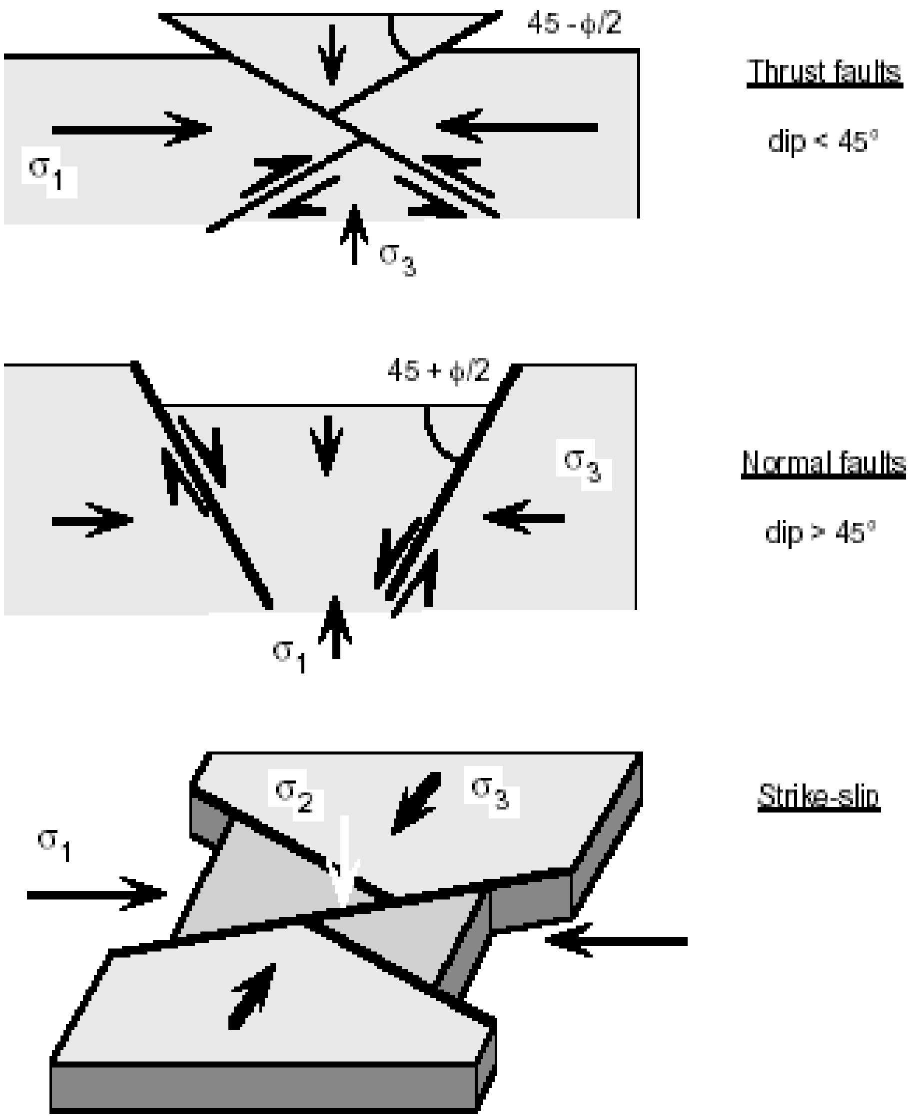
$\tau_s = S_o - \mu \ \sigma_{n,} \quad \mu = \ \tan\phi$



# Faults orientation on Earth (ANDERSON's theory, 1919)

The surface of the Earth is free of stress (contact with the Atmosphere). Since the orientation of the principal stresses correspond to directions of ZERO tangential stress, they must be parallel and perpendicular to the earth surface. With a criteriion of failure that considers the friction angle of 30° of most rocks, one can predict the orientation of faults.





This theory results from the Coulomb failure property of rocks.

# Slip-lines predicted by perfect plasticity (von Mises) and experiments

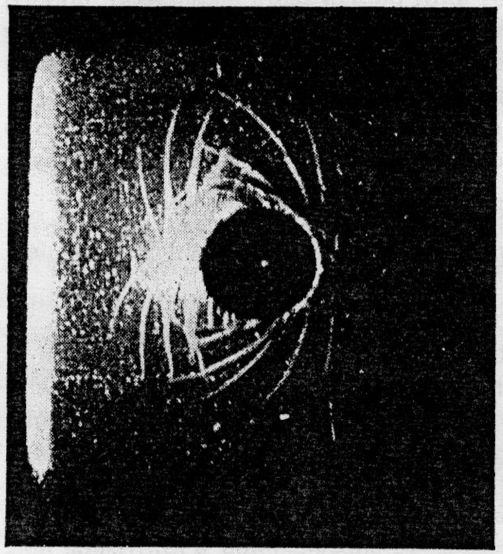


FIG. 37-12. Slip lines on surface of a steel block produced by forcing a cylindrical punch into it.

tends to cause, at least in th
surface layer, a plastic flow of
symmetry having the radii a
circles as the directions of pri
stress.[1] These slip lines ha
envelope.

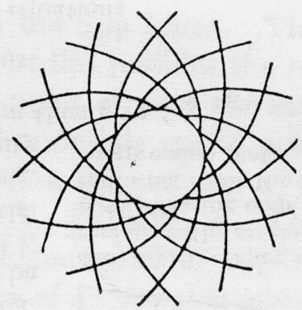
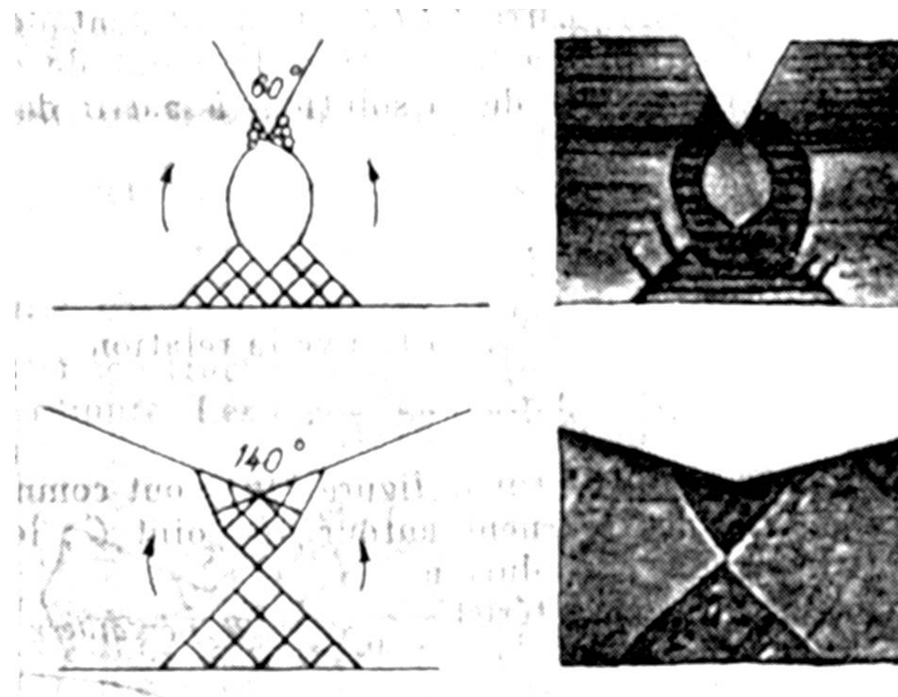
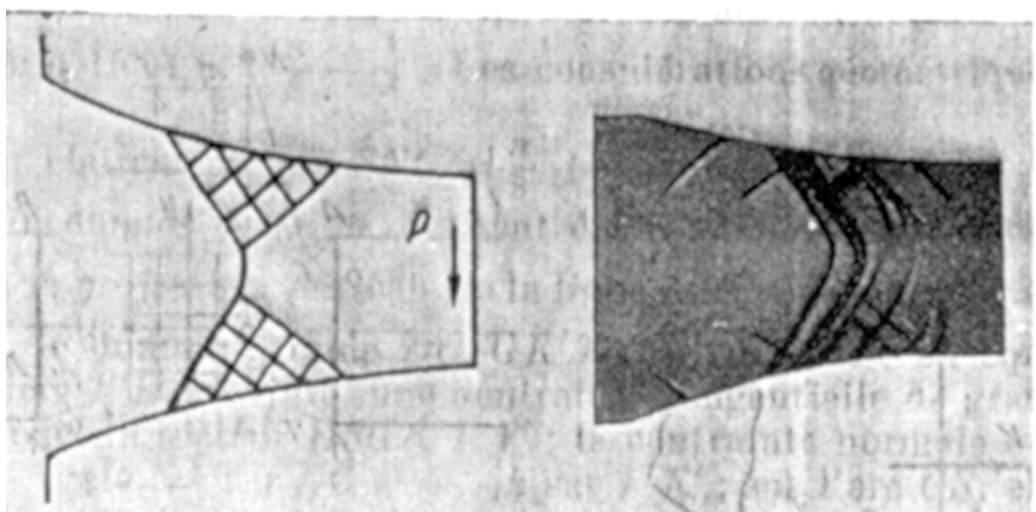


FIG. 37-13. Slip lines consist of system of orthogonal logarithmic spirals.

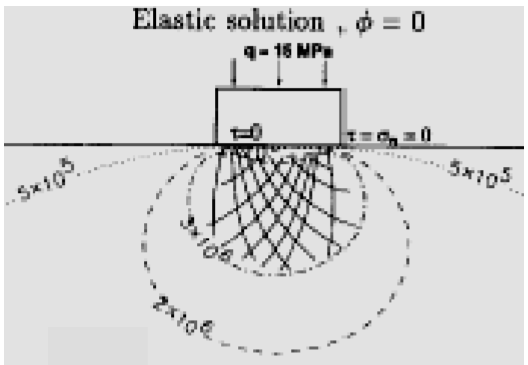


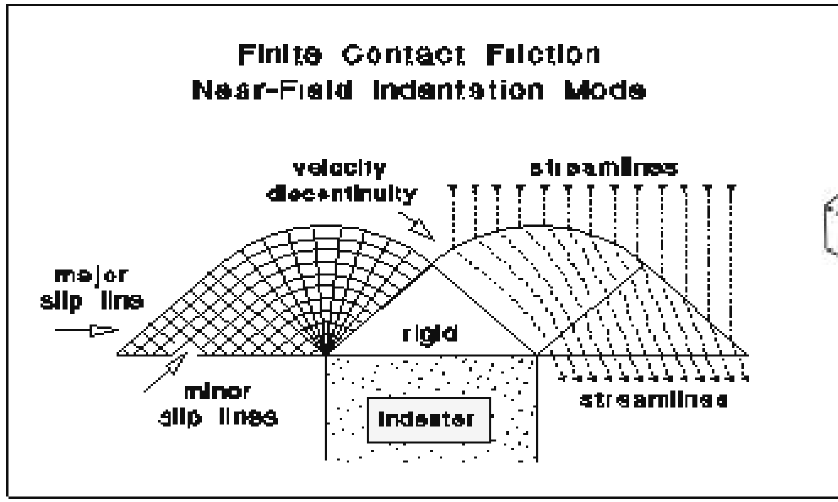

Nadai, 1960

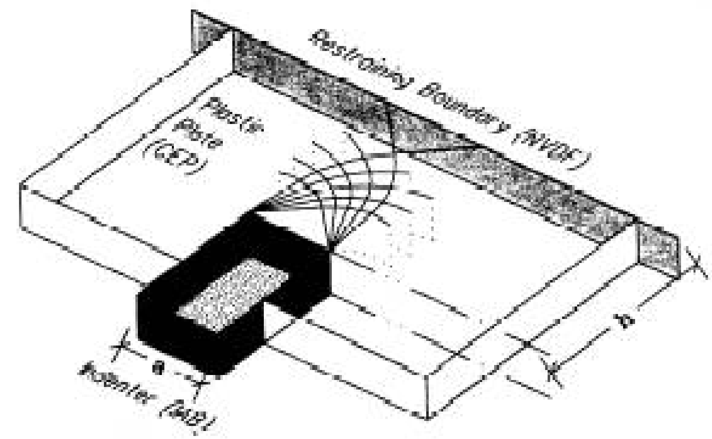
# Solutions for the problem of the INDENTOR

## Elasticity

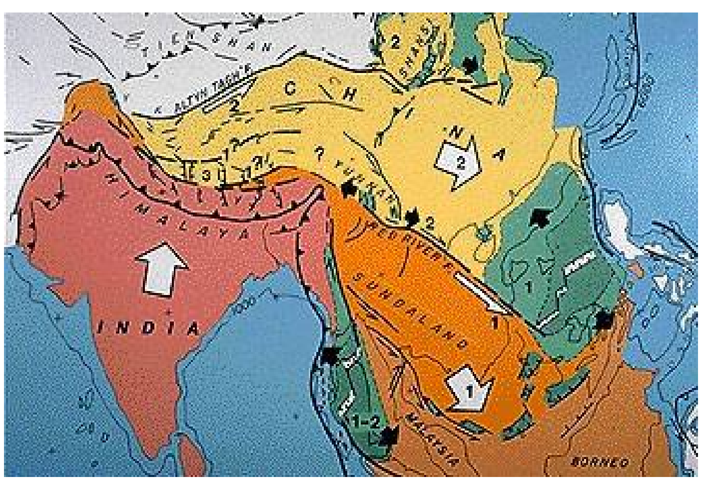



## Plasticity : slip along rigid blocs

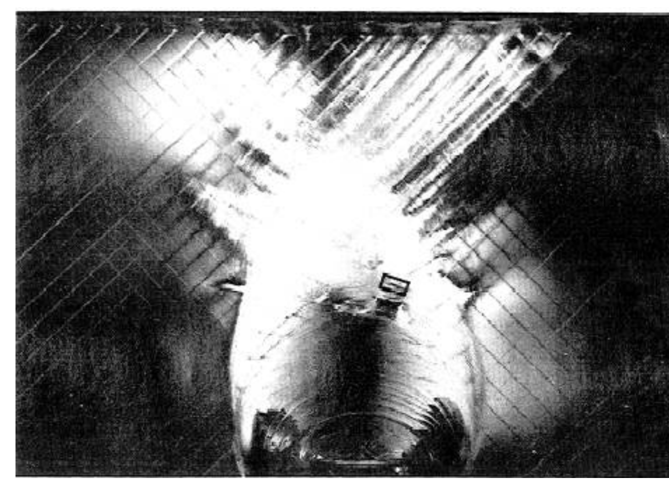


## Tectonic structure



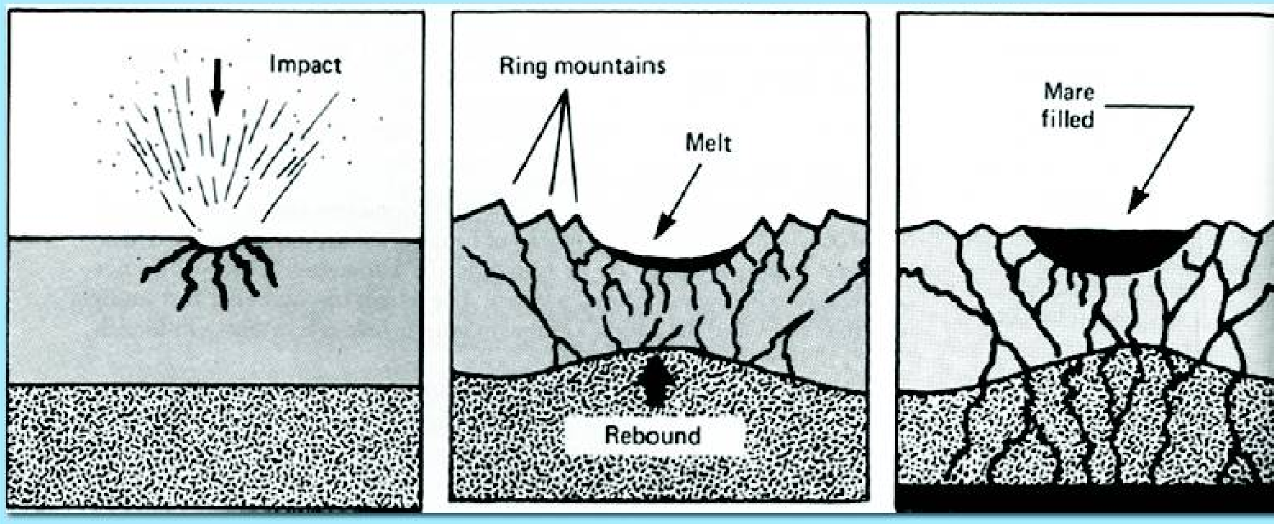

## Experiments



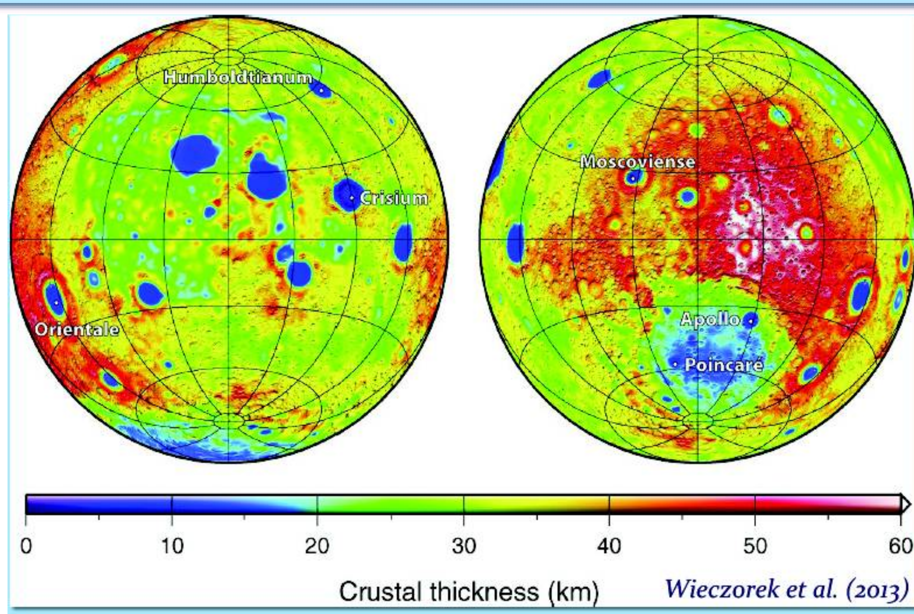
Tapponnier et al., 1976

# Elasto-plastic response of a meteoritic impact on the moon

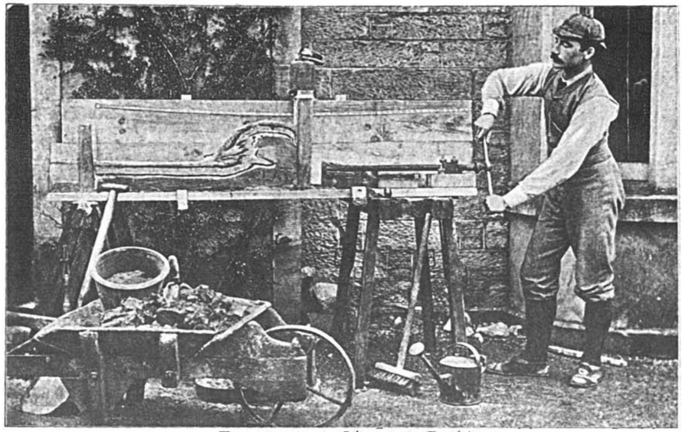
- Made of **basalt**
- Basalt is found on Earth and forms from solidification of lava flowing out of volcano
- Mare basalts formed by outpouring of lava into low-lying craters



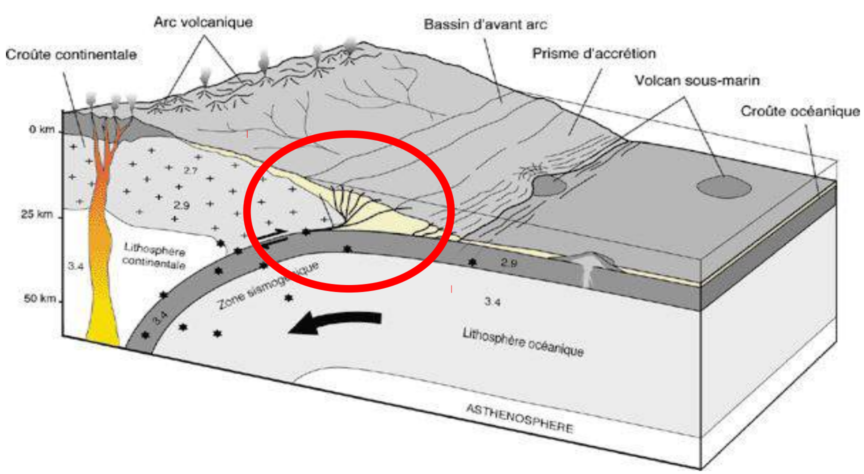

Lunar crustal thickness

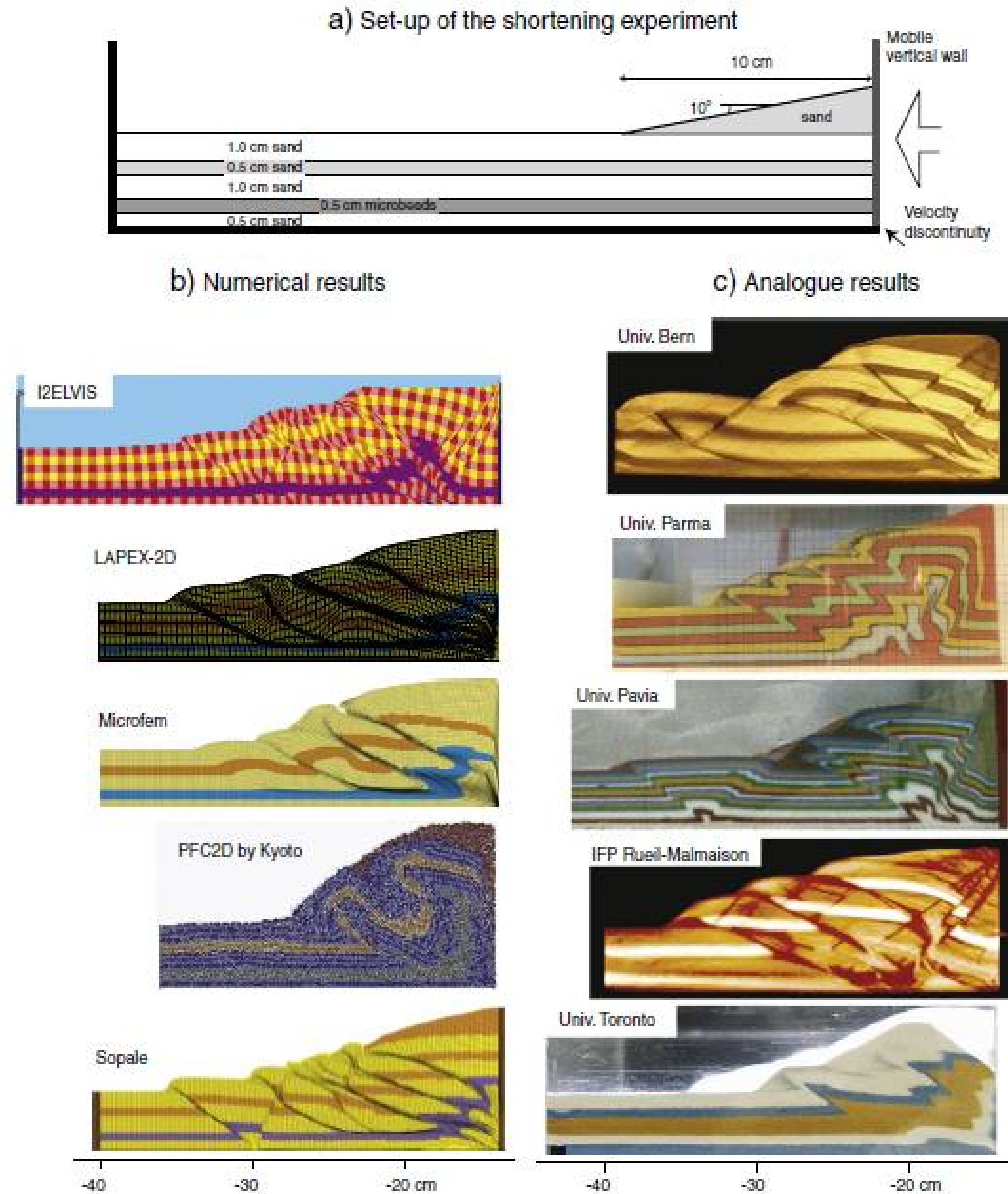


# Accretionary prisms and mountain slopes



*Experiments in Mountain Building*



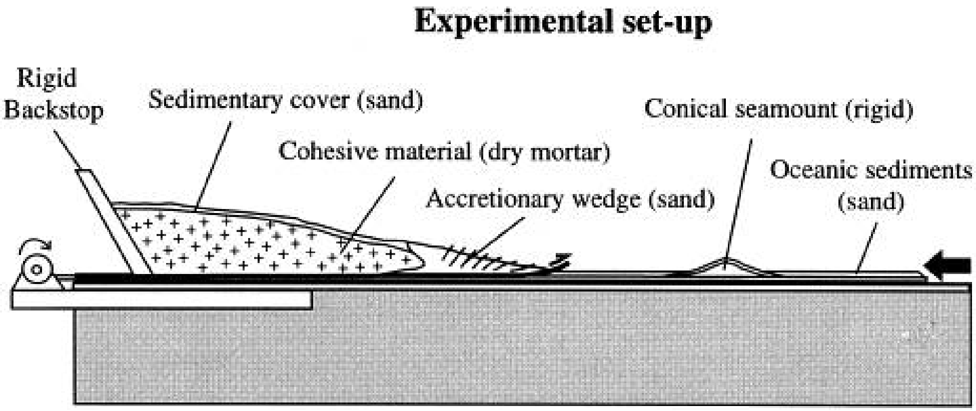

$$\alpha=\beta\left(\frac{1-\sin\varphi}{1+\sin\varphi}-1\right)+\mu_b.\frac{1-\sin\varphi}{1+\sin\varphi}$$

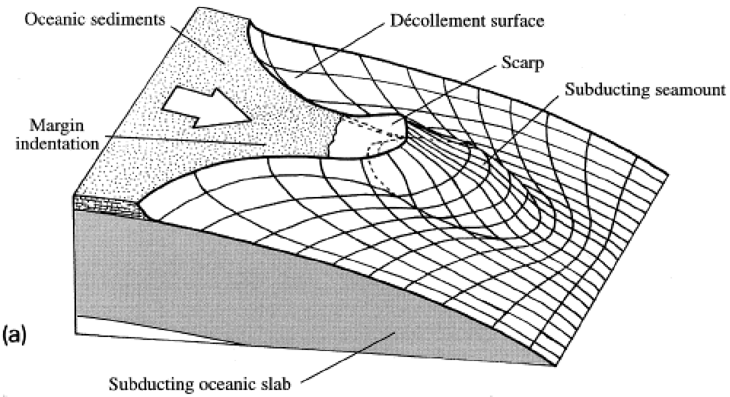
$\alpha,\beta$:surface and basal slopes

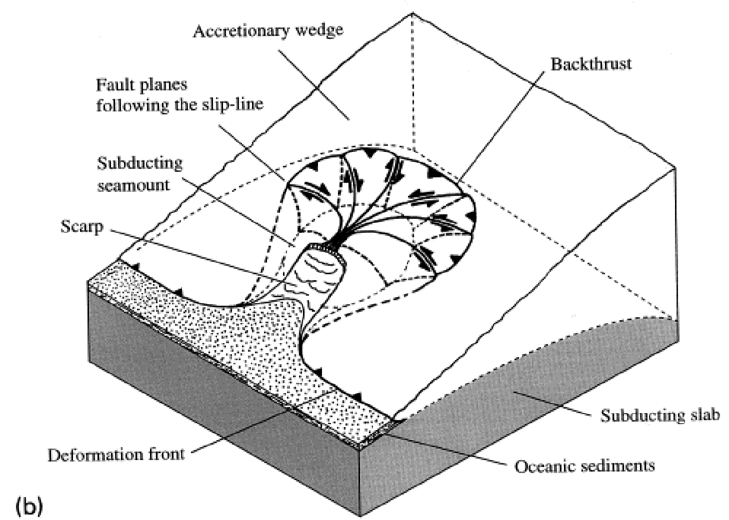
$\mu_b,\varphi$:basal friction, internal friction angle

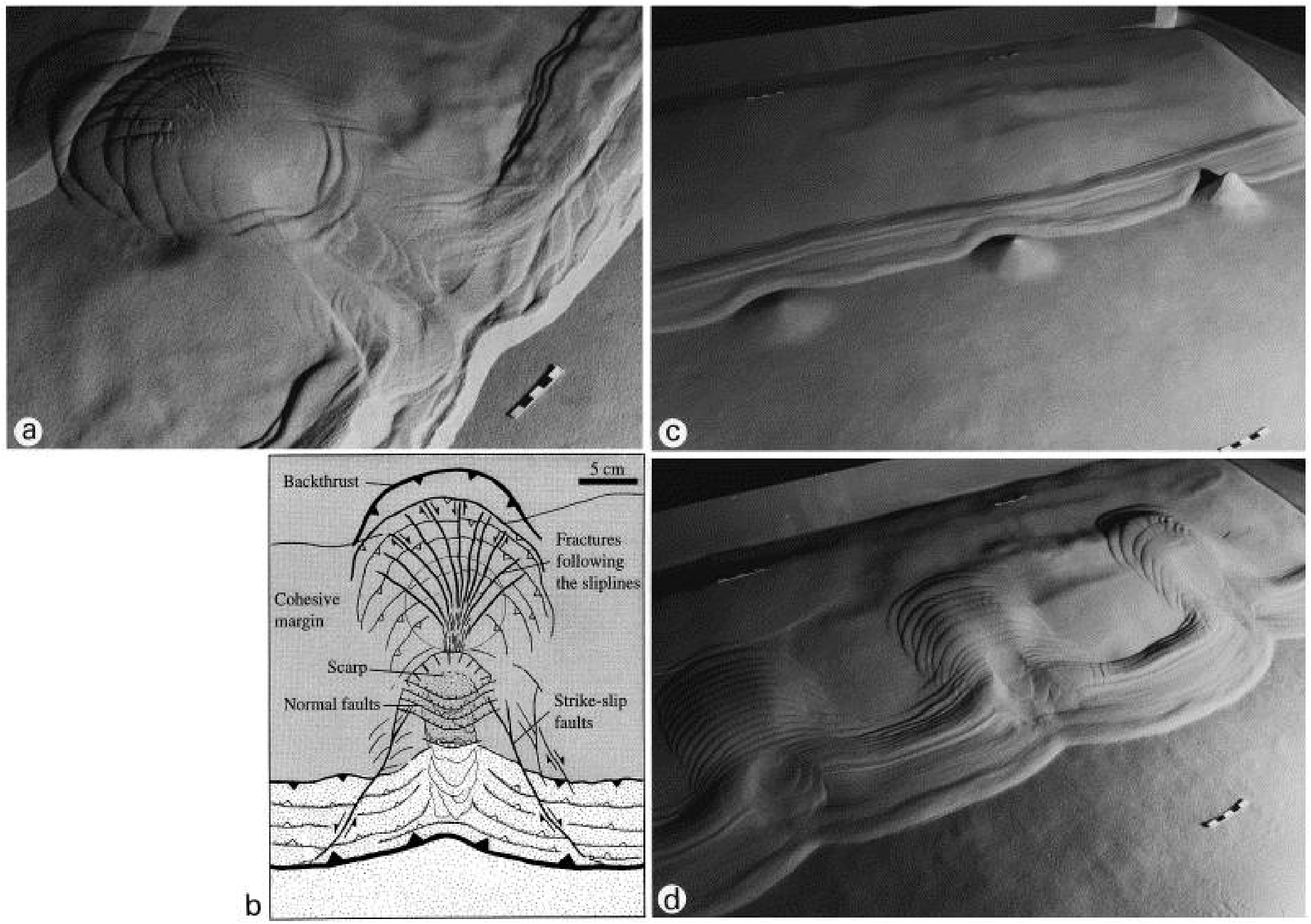
*Buiter et al., 2012*

# Subduction of seamounts



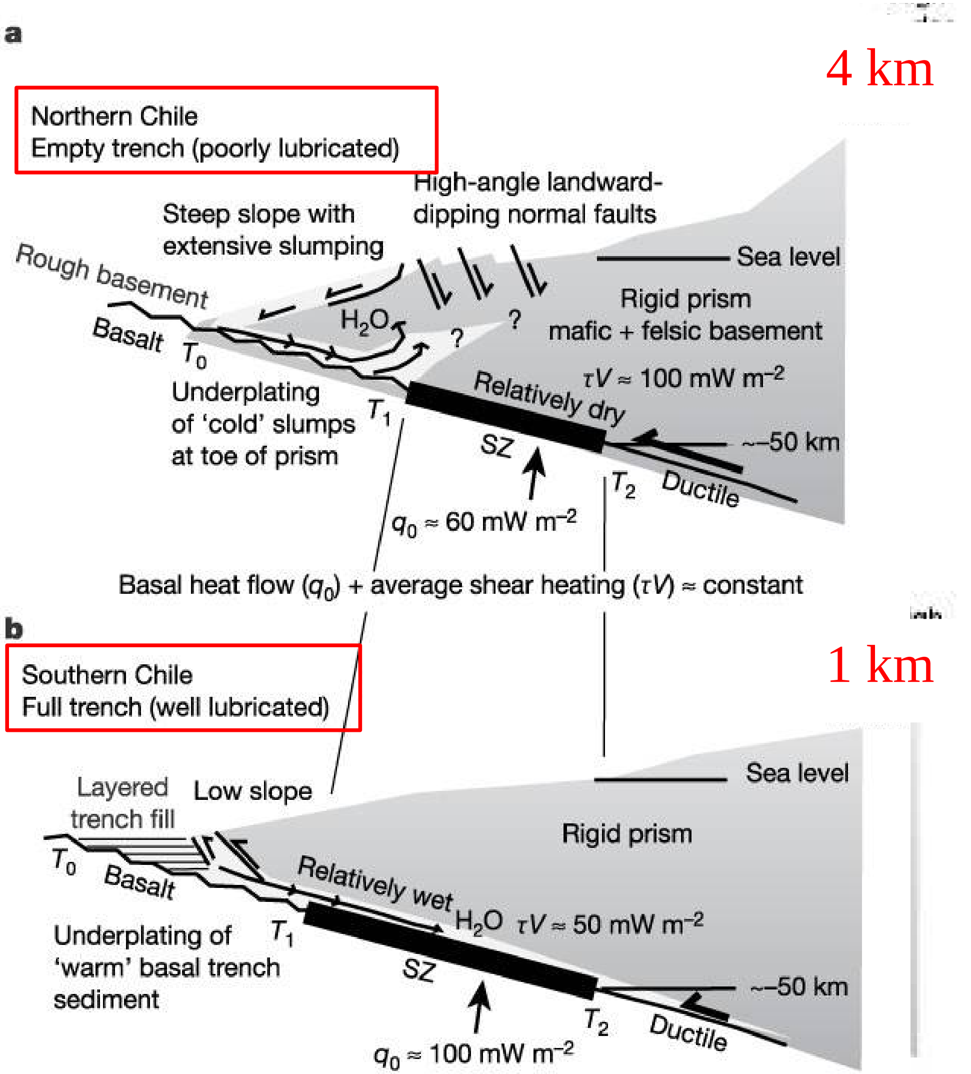



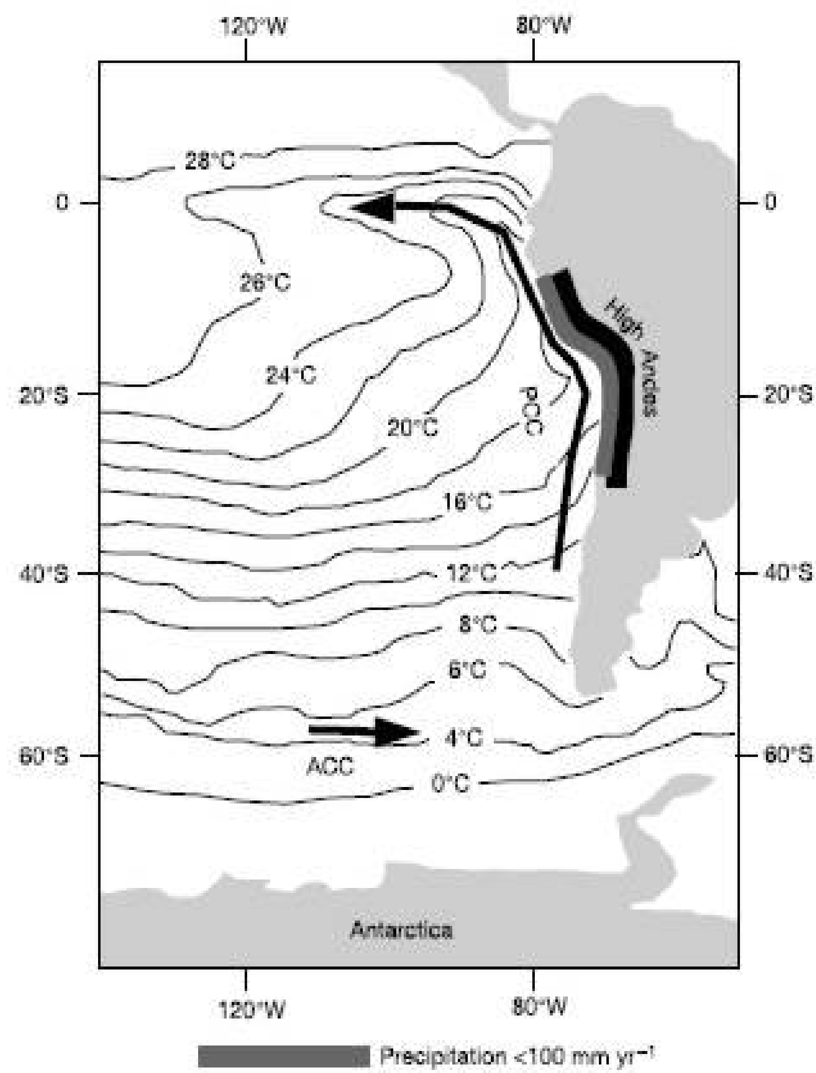




*Dominguez et al., 1998*

# Continental prism : role of climate on basal shear

$$\alpha = \beta \left( \frac{1-\sin\varphi}{1+\sin\varphi} - 1 \right) + \mu_b . \frac{1-\sin\varphi}{1+\sin\varphi}$$



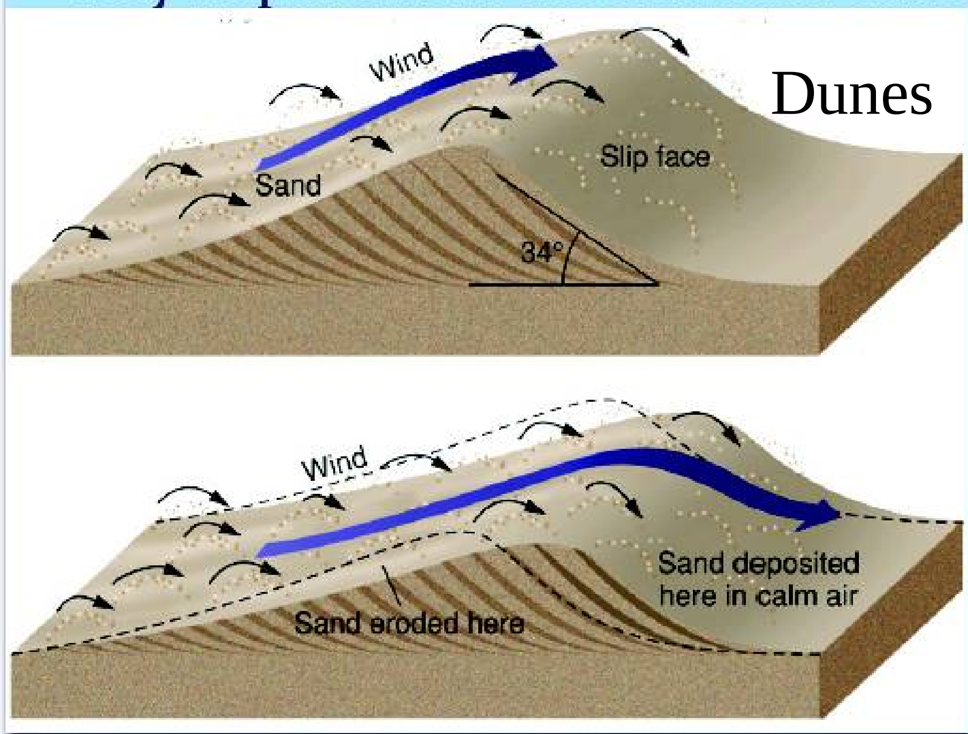

*Lamb et Davis, 2003*

# Climate and wind on planets: dunes

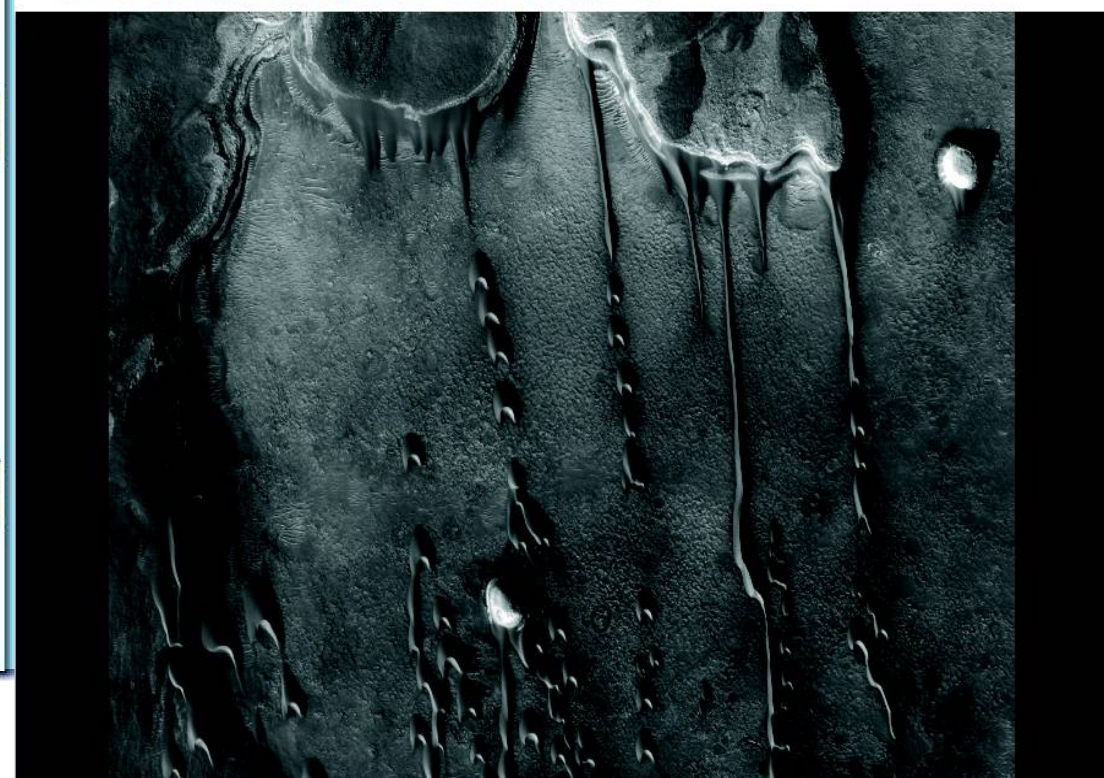
On Earth, wind can transport particles by:

- ... suspension (if particle size < 60 μm).
- ... saltation (60 < $d$ < 2000 mm).
- ... surface creep (larger particles).

Very important in deserts: sand dunes



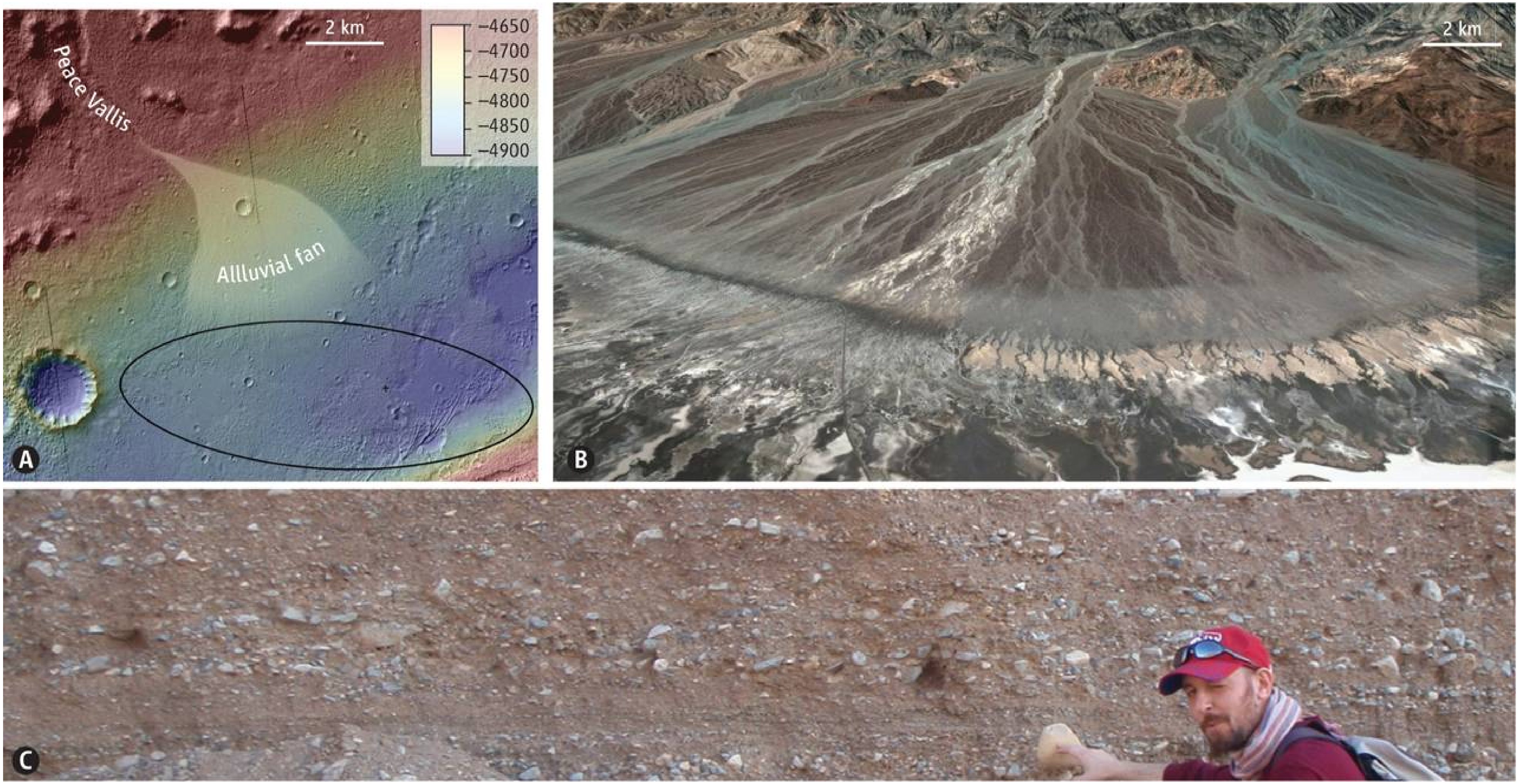

Barchan dunes on Mars



Wind also shapes surface on Mars.
Venus' surface is too dense to generate strong winds

# Climate and alluvial fans on planets

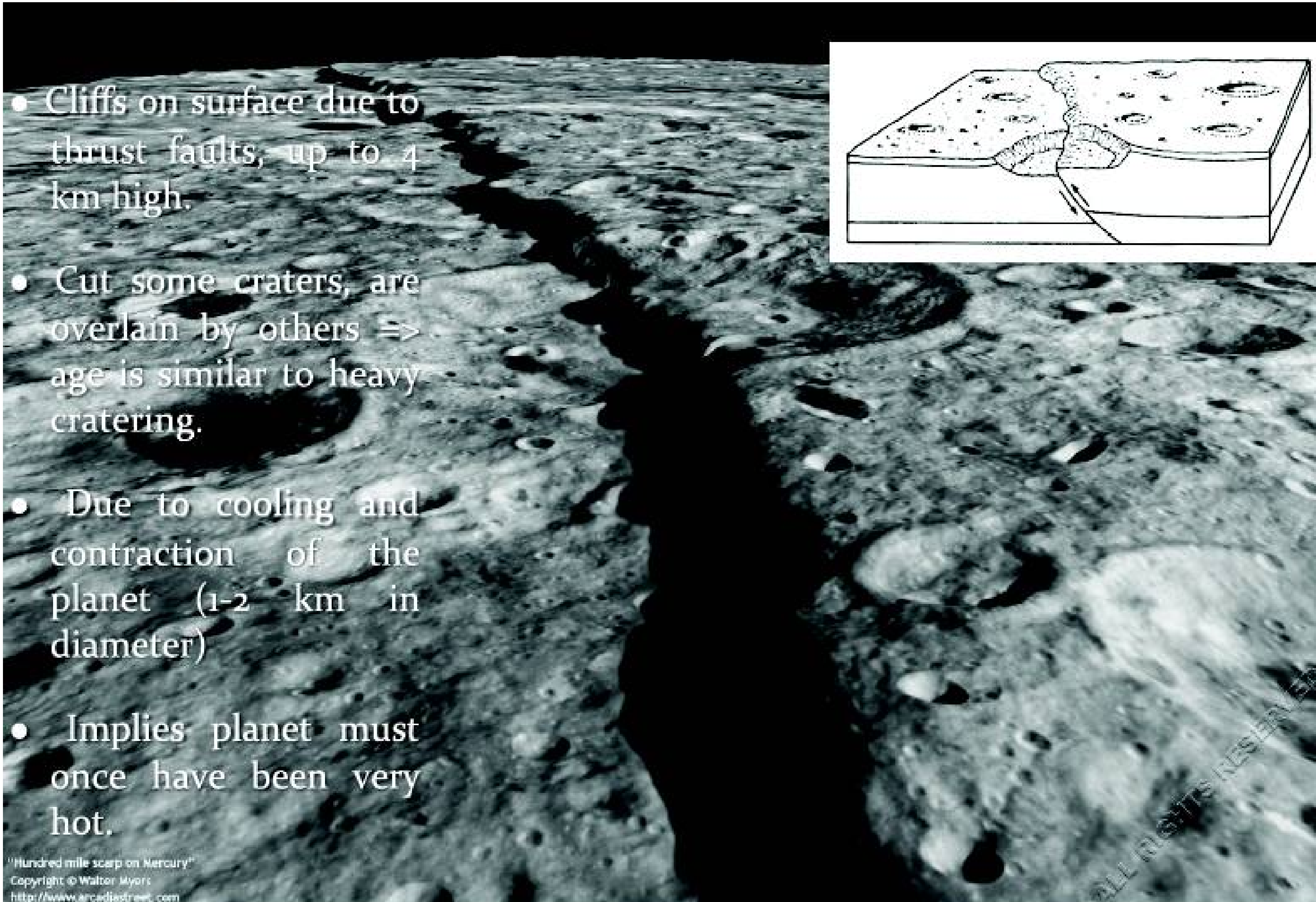
**Alluvial fans and associated deposits.(A) Topographic map draped on images showing the landing ellipse (oval) and landing site (cross) of Curiosity in Gale crater, Mars.**




**Science 2013;340:1055-1056**

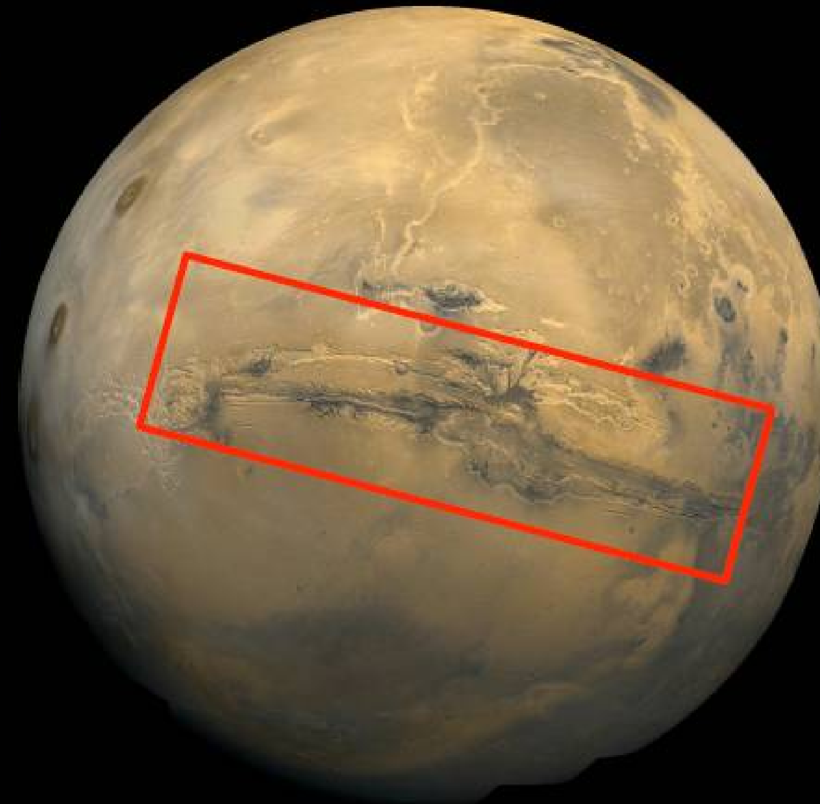
# Scarps

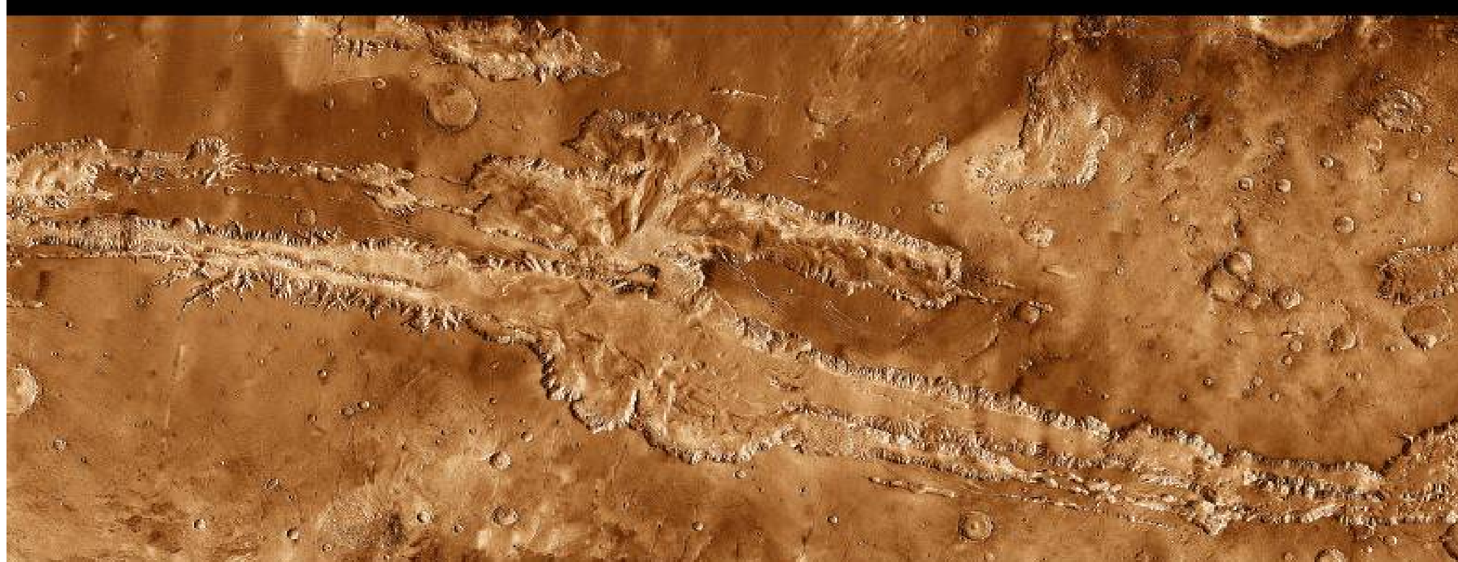
- Cliffs on surface due to thrust faults, up to 4 km high.
- Cut some craters, are overlain by others => age is similar to heavy cratering.
- Due to cooling and contraction of the planet (1-2 km in diameter)
- Implies planet must once have been very hot.



# Failure structures on MARS: Valles Marineris

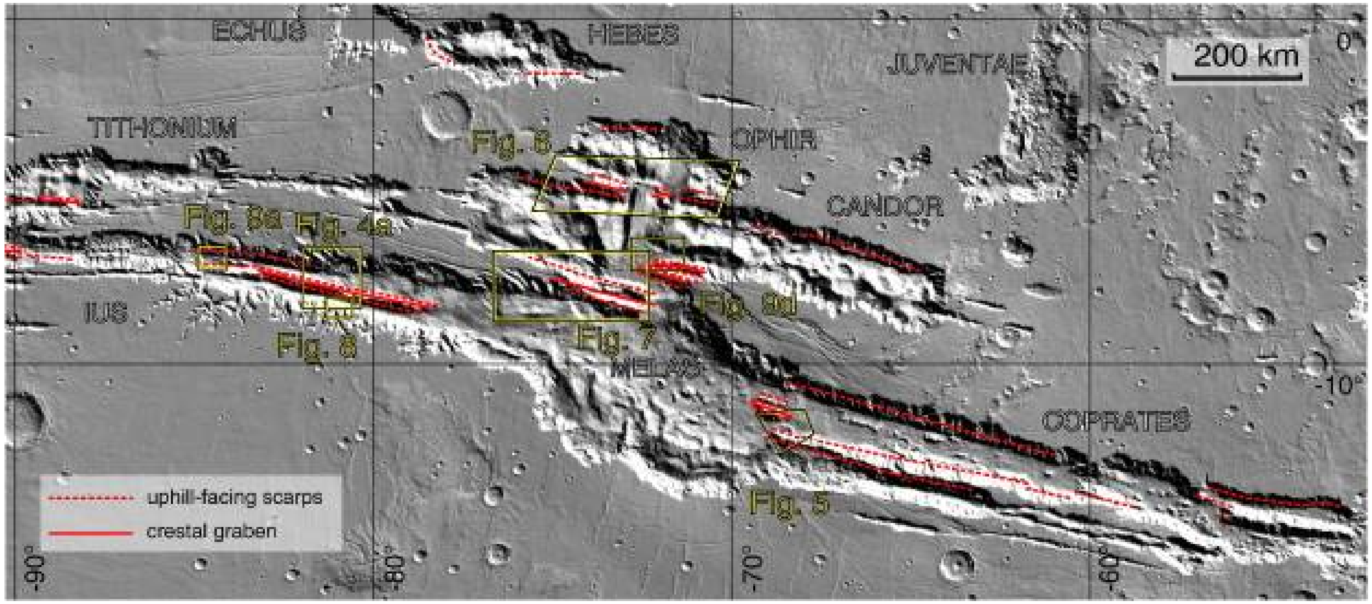
- Huge rift valley >4000 km long, up to 600 km wide, up to 7 km deep
- Caused by tectonics, not water
- Crustal expansion as Tharsis bulge formed

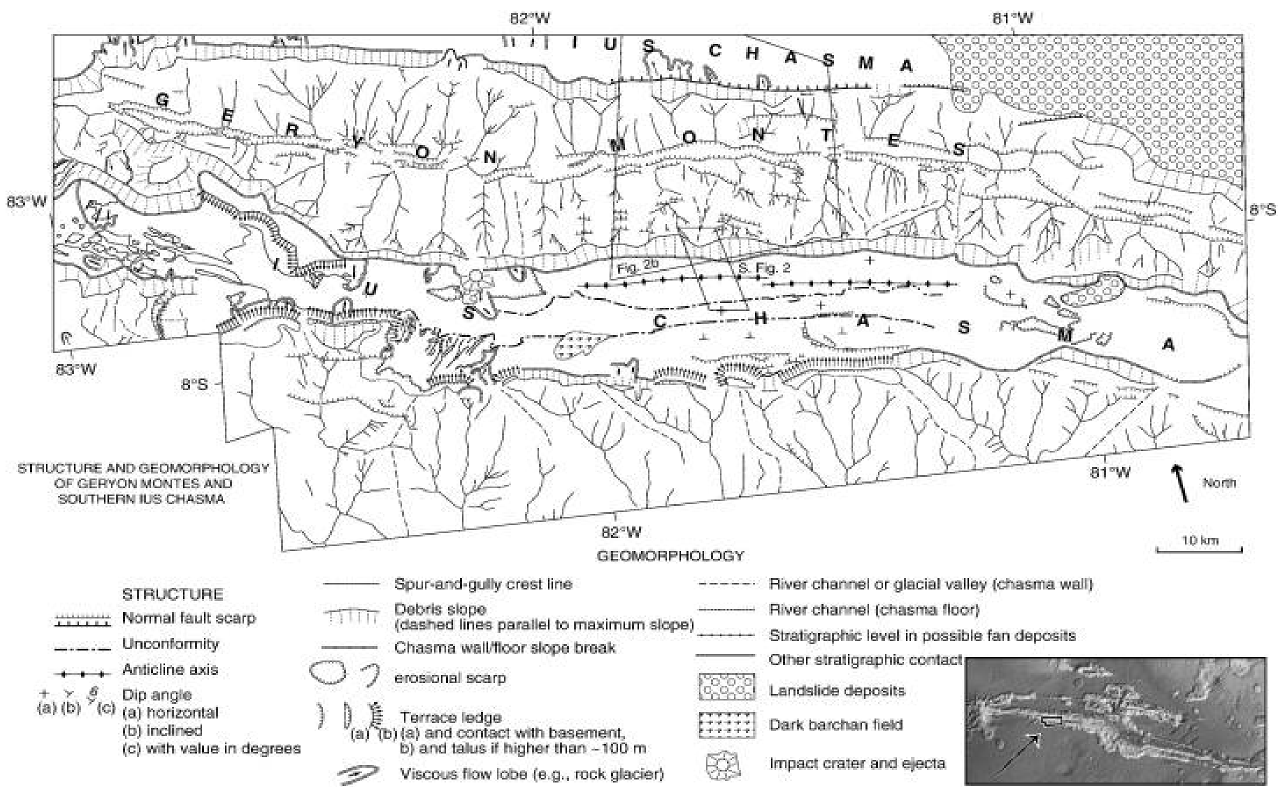




# *Equatorial glaciations on Mars revealed by gravitational collapse at Valles Marineris*

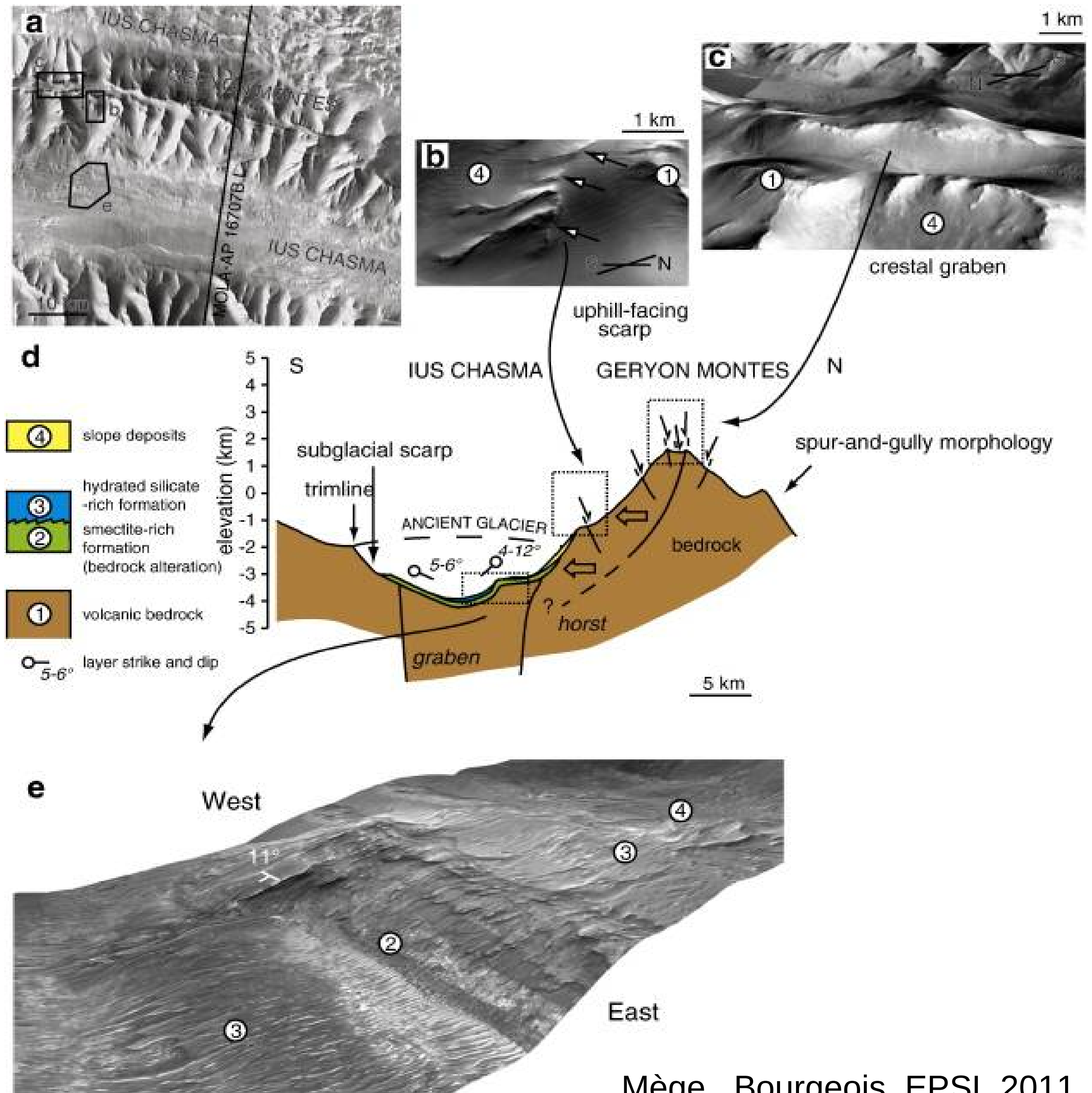
Mège , Bourgeois, EPSL 2011.



# Equatorial glaciations on Mars
# revealed by gravitational collapse of Valles Marineris wallslopes

Ius Chasma and geological cross section along MOLA topographic profile MOLA-AP 16707B.L.
Chasma floor deposits are identified following mineralogical interpretation.




Mège , Bourgeois, EPSL 2011.

# Sacking deformation on Earth and analogue features on Mars.

a, Crestal graben in the Austrian Alps. Glacial valleys and lakes on the ridge side.

b, Crestal graben at Geryon Montes (THEMIS day IR mosaic draped over HRSC digital elevation model).

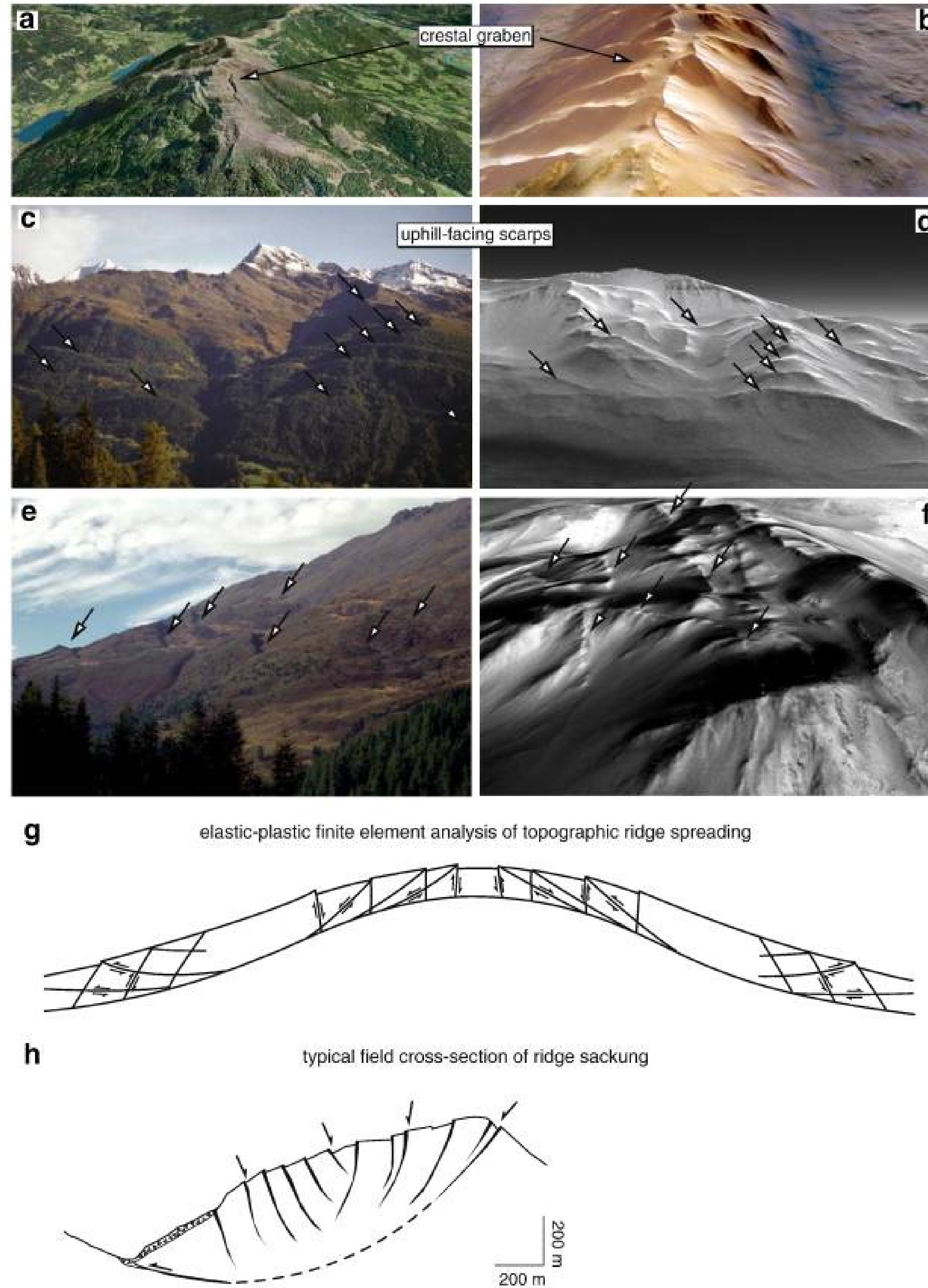
c, Uphill-facing fault scarps in Tyrol, Austria ( Reitner and Linner, 2009).

d-e, Uphill-facing scarps at the Melas–Candor chasma boundary.

f, Uphill facing fault scarps at the Candor–Ophir chasma boundary.

g, Plastic flow of gravitationally spreading ridge (Savage and Varnes, 1987).

h, Typical geometry of sacking features formed in the Tatra MountainTNormal faults (on the ridge) and thrust faults (in the valley). Dashed line: décollement.



# Modèles analogiques et numériques reproduisent bien ces structures
Ex : Bachmann, Bouissou, Chemenda, 2009

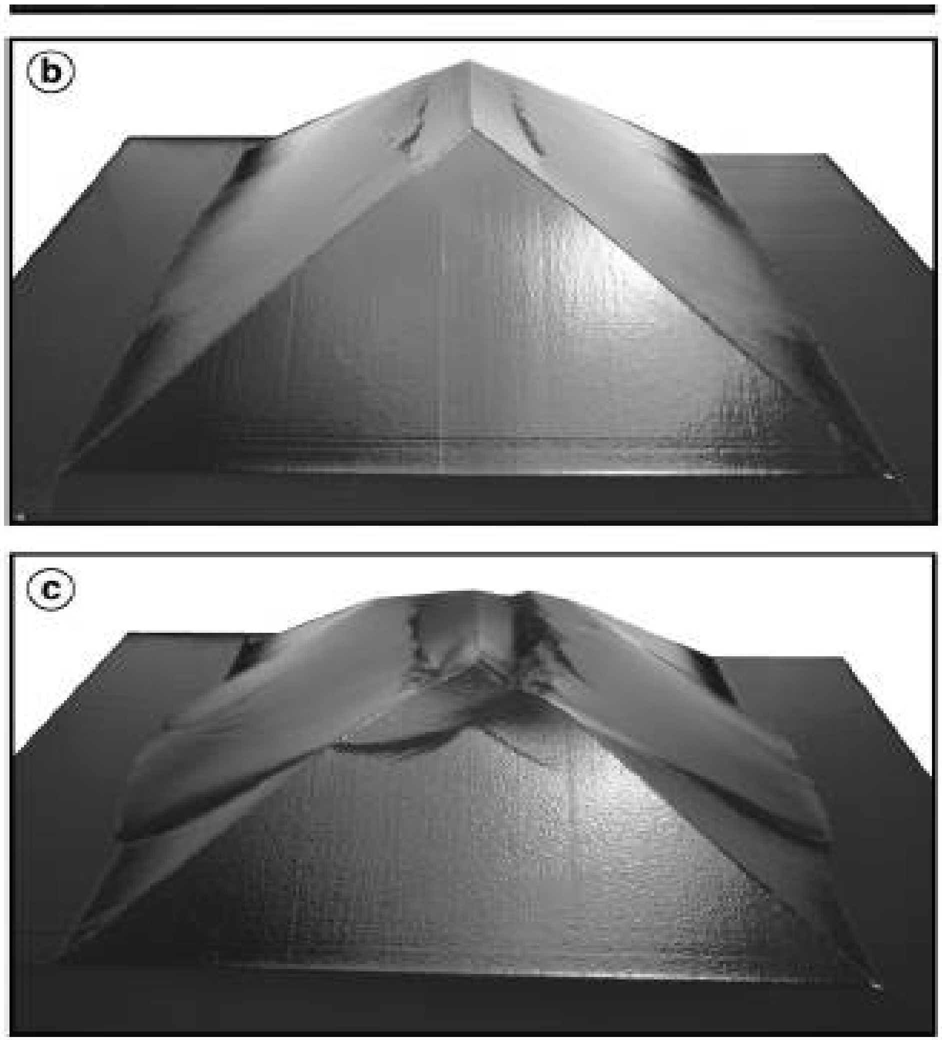



Fig. 5. Pictures presenting the failure of a model. (a) After 100 acceleration stages. (b) After 105 acceleration stages. (c) After 110 acceleration stages.

The first evidence of fracturing of the model occurs after about a hundred acceleration steps for a 400 m s$^{-2}$ acceleration. First fractures appear on the upper part of the two large sides of the model (Fig. 5a), parallel to the summit crest. Fractures are then observed at the base of both mountain sides (Fig. 5b). At this stage, we can observe the

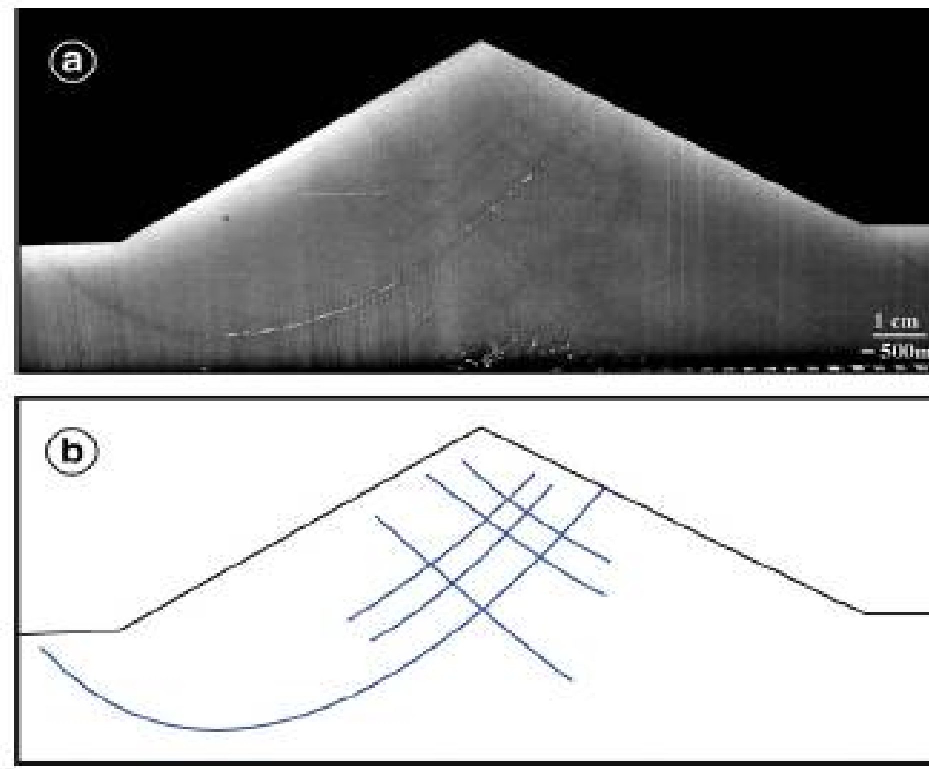



Fig. 6. Cross-section realized at an early stage of evolution (after 100 acceleration stages), in the middle of the model and perpendicular to the crest. (a) Picture of the section. (b) Sketch of the section.

# Fatigue and rupture on Asteroids

*Delbo, Libourel, Michel, Ganino, Verati, 2013*

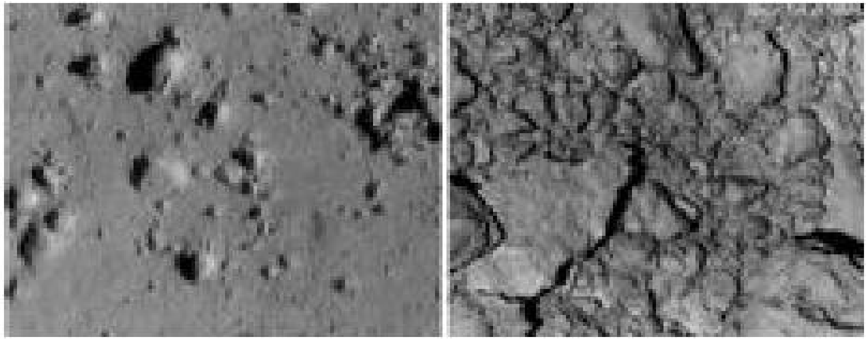


Figure 1: Regolith on NEAs from direct imaging. Left panel: the 30 km-size asteroid (433) Eros – the second largest NEA observed by the NASA NEAR Shoemaker mission [1]. Right panel: the 0.35 km-size Itokawa, visited by the JAXA Hayabusa spacecraft [3].

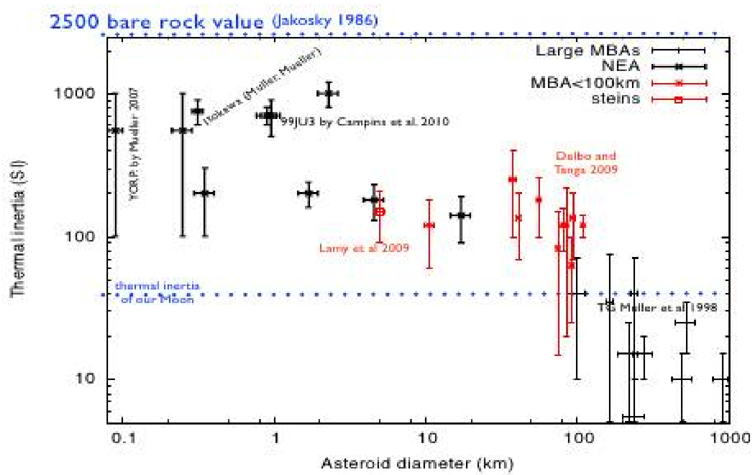



Figure 2: Thermal inertia values (Γ) vs. sizes of asteroids. The value of Γ is inversely proportional to the porosity of the material [9, 10]. A regolith-covered surface has a porosity larger than a bare, solid surface of the same material. Consequently, the presence of regolith decreases the value of the asteroid thermal inertia: the finer the regolith, the higher the porosity.

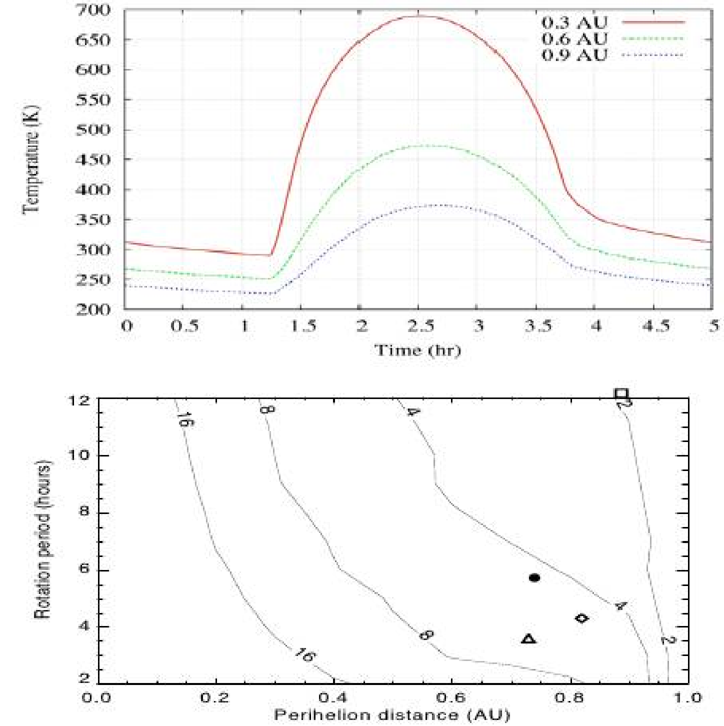



Figure 3: Top: Examples of day/night temperature curves on NEAs. The value of the thermal inertia Γ is 200 J $m^{-2}$ $s^{-0.5}$ $K^{-1}$. Bottom: contour plot of the maximum value of the temperature - time gradient $dT/dt$ (K/min) as a function of the rotation period and the

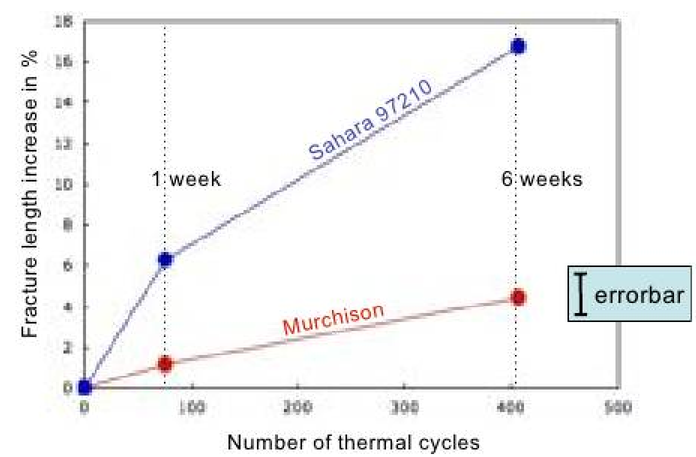
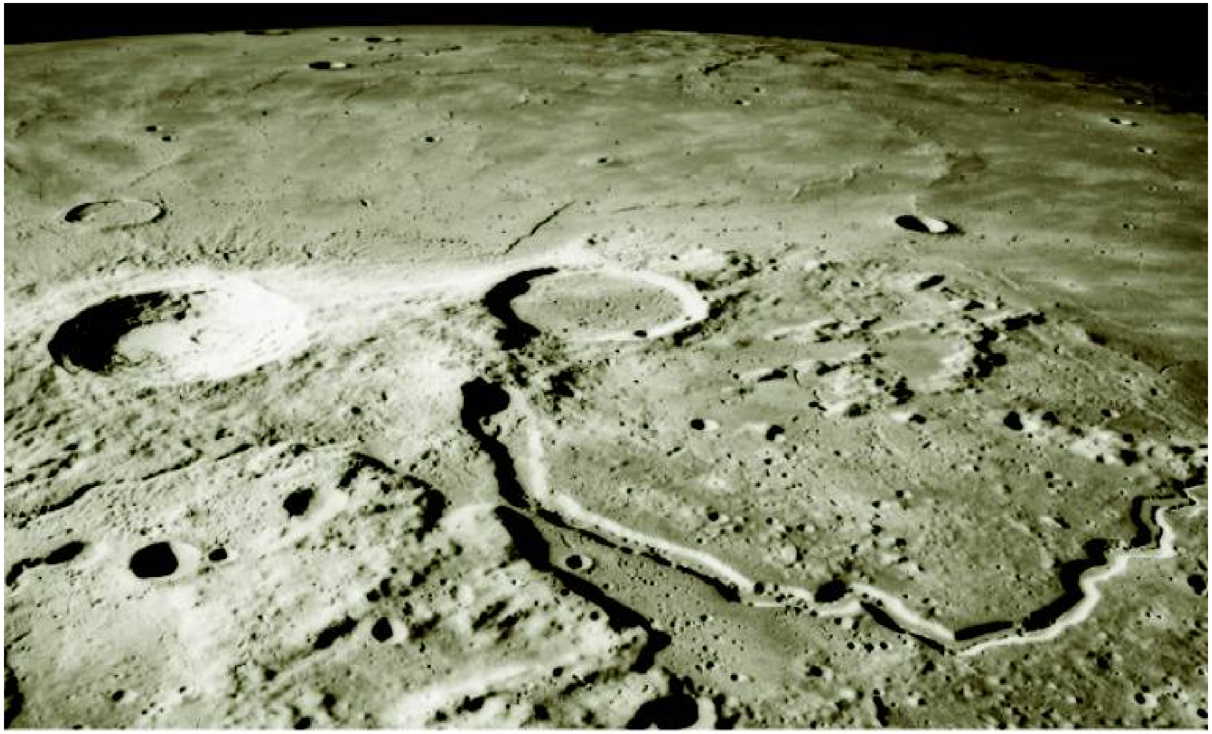


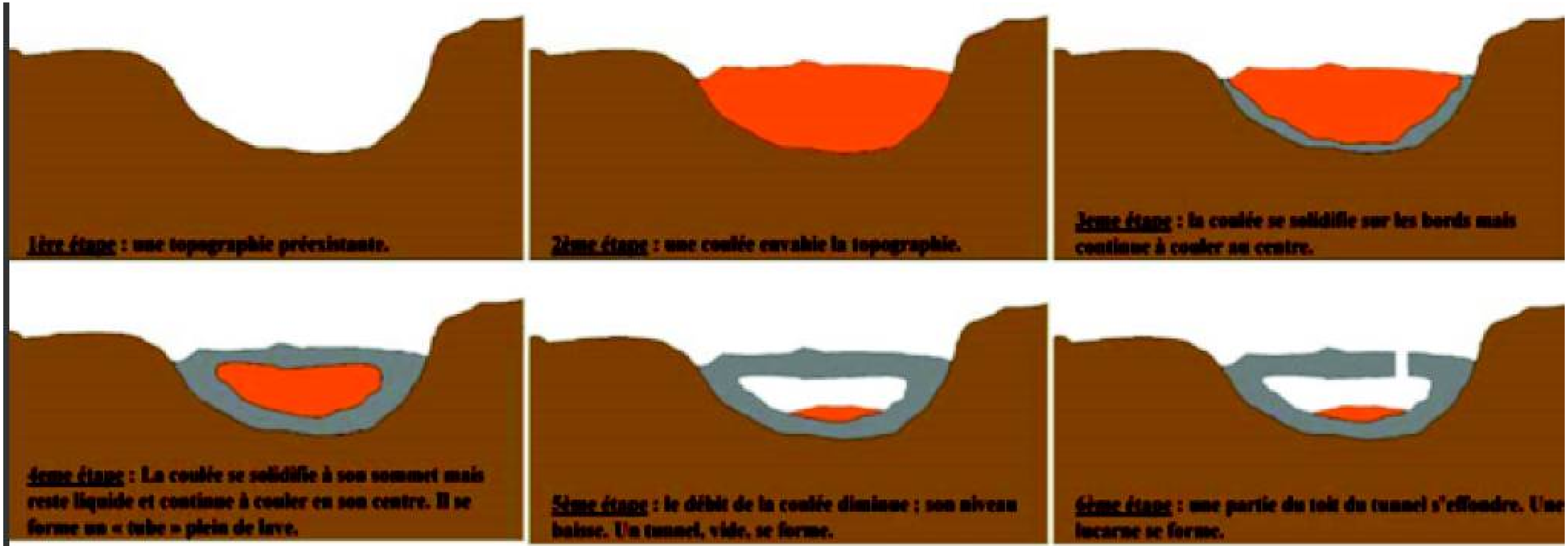

Figure 4: Increase in the average length of the cracks in the meteorites samples (see text) as a function of the number of thermal cycles.

# De drôles de traces sur la lune..



**Qu'est ce que c'est ? Des vallées ; mais il n'y a pas d'eau sur la Lune !**

# Une analogie terrestre (plateau de la Snake River, Idaho) : un tunnel de lave effondré



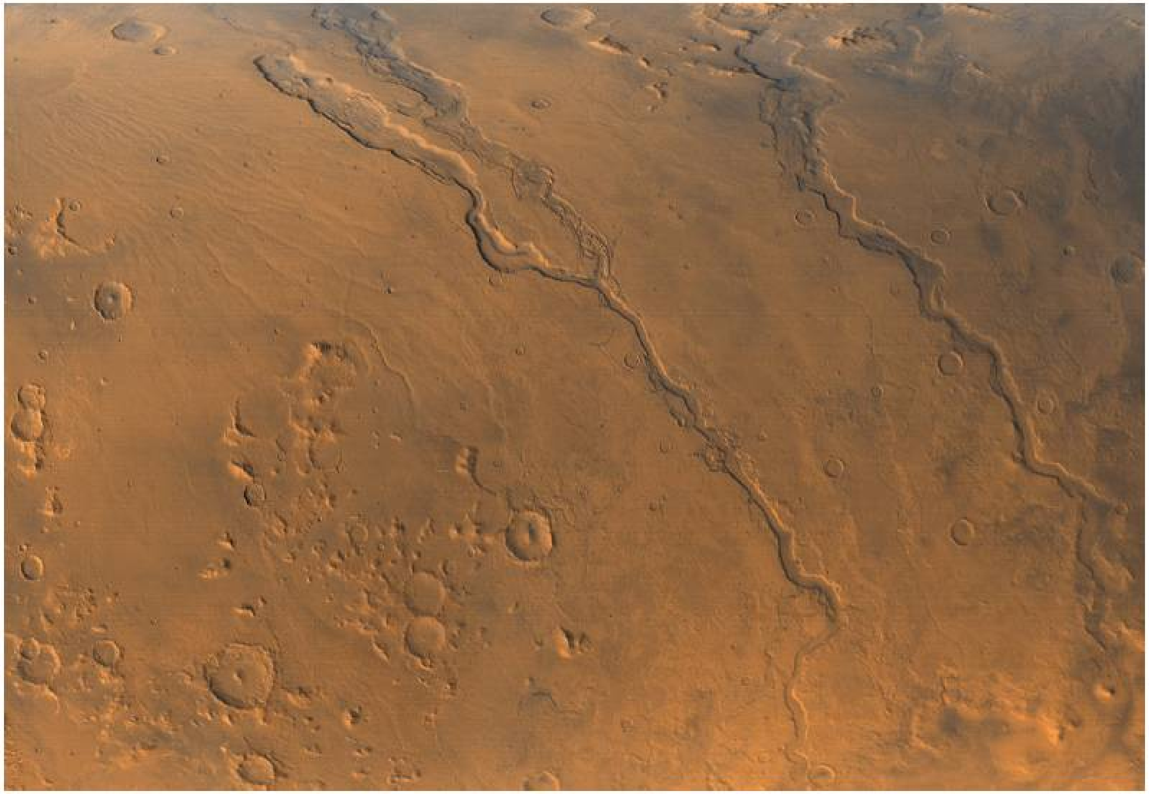


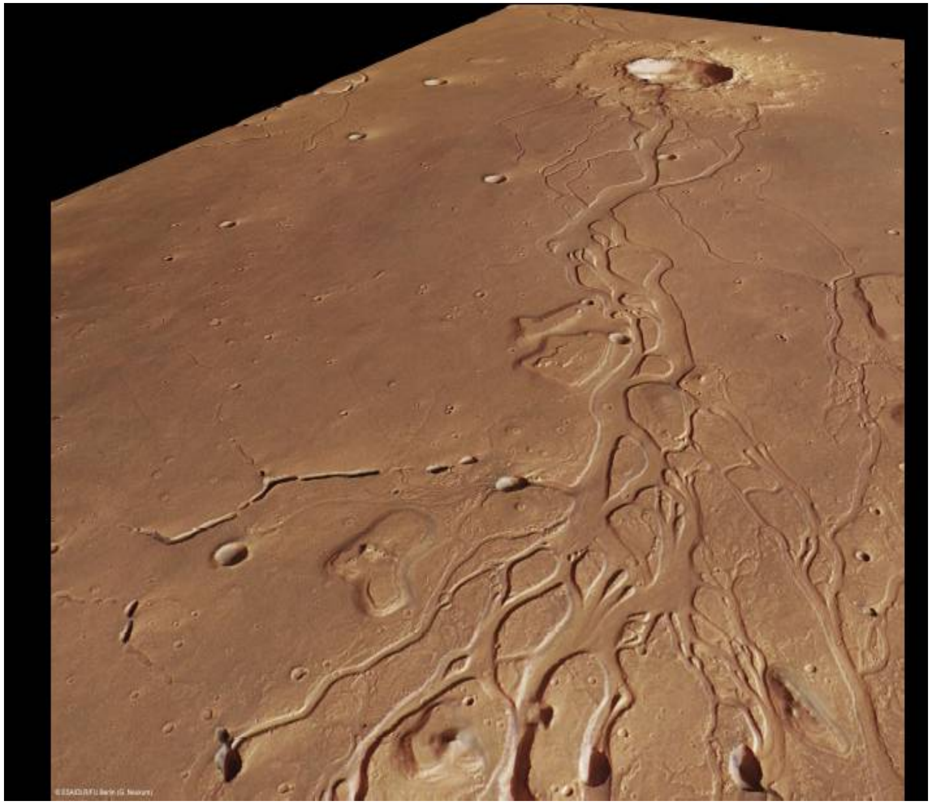
Sept étapes de la formation d'un tunnel de lave
et d'une lucarne

Schéma Pierre Thomas


**Si le tunnel s'effondre cela donne ces vallées.**

# Outflow channels





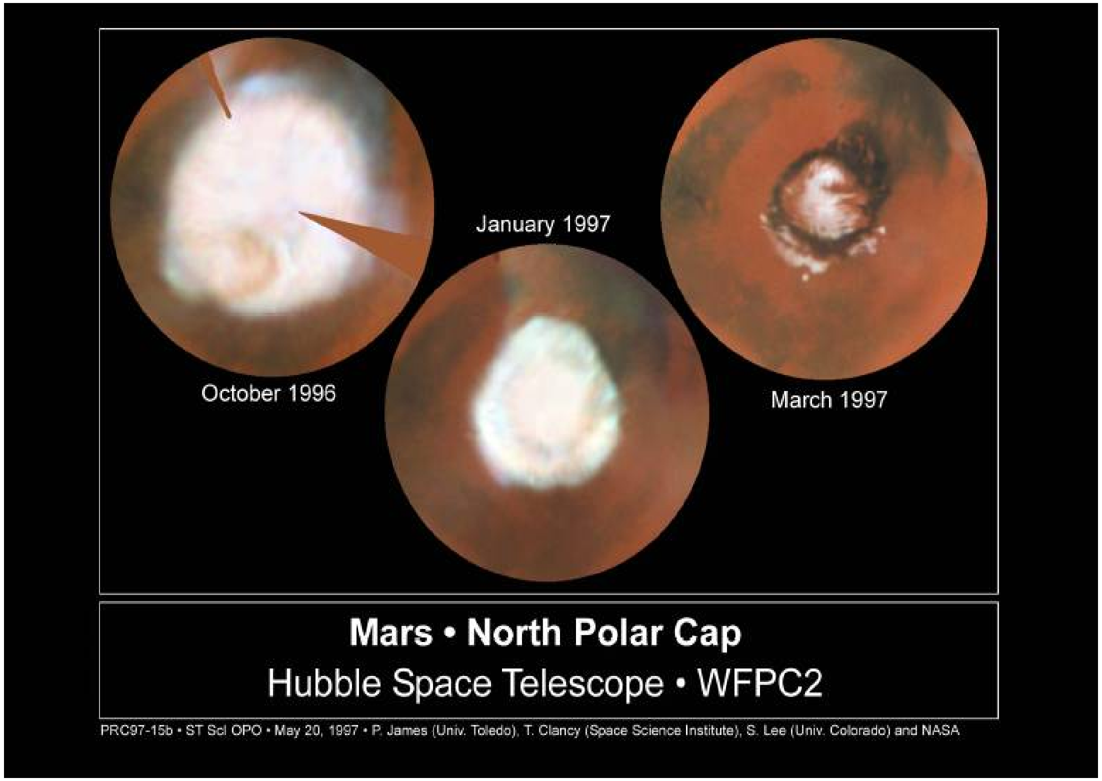
- Surface too cold for liquid water today but channels look as if they were made by water
- ***Outflow channels***: Flow from highlands to lowlands, due to catastrophic floods?
- ***Dendritic runoff channels***: More like Earth's river networks, due to more steady-state flow?

# Polar ice caps

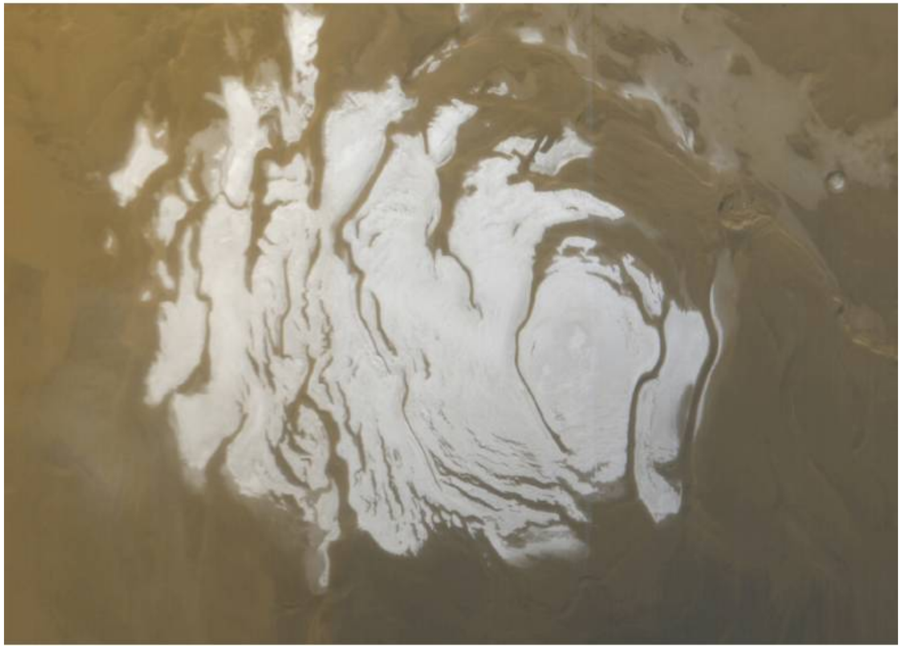
- Northern cap larger than Southern cap because of orbital eccentricity *(1100 km vs. 400 km diameter of permanent caps).*
- Grow and shrink seasonally.
- Seasonal caps made of $CO_2$ ice (freezes at 150 K).
- Also permanent caps made of water ice.

## Permanent northern ice cap

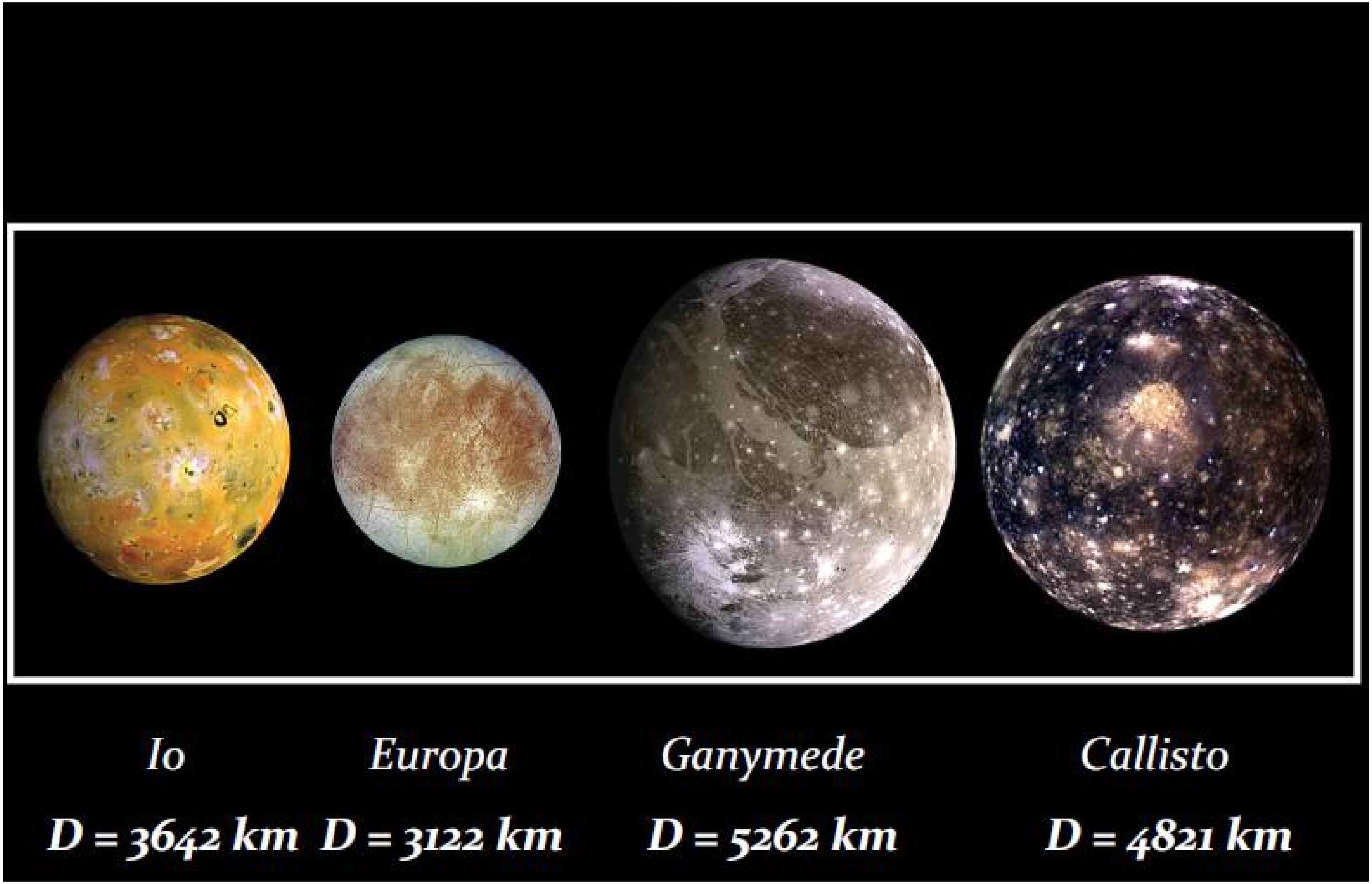
## Seasonal variations




## Permanent southern ice cap

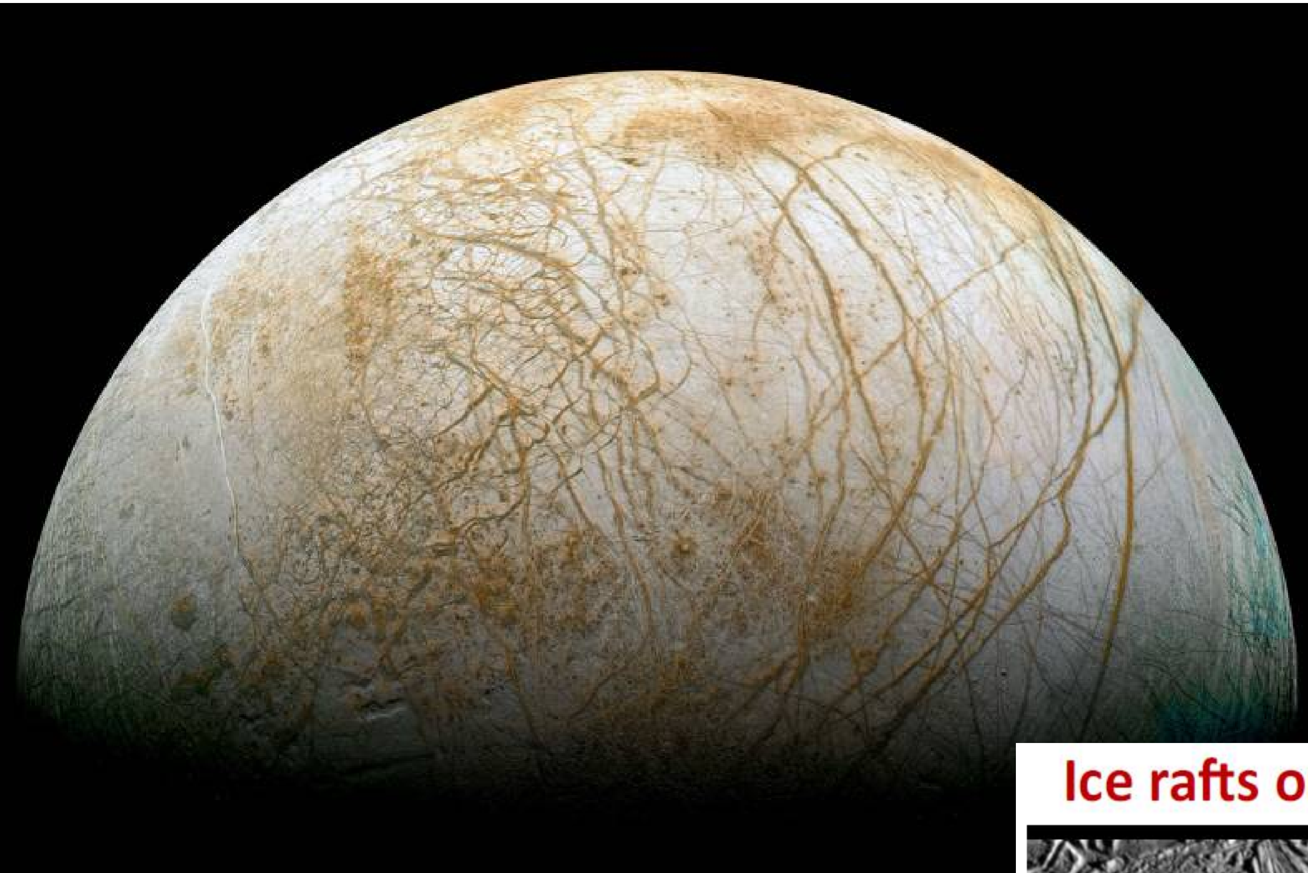


# Jupiter's Galilean moons

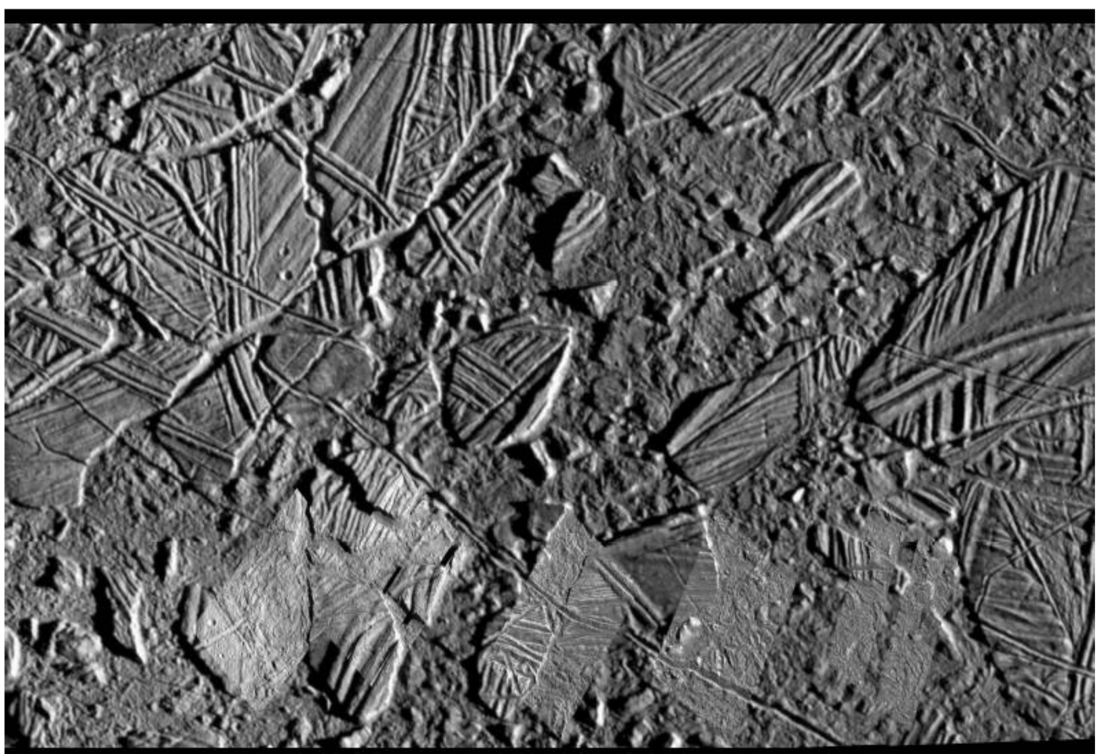



Présentent des structures de surface très hétéroclites

# Europa



## Ice rafts on Europa *(42x34 km)*

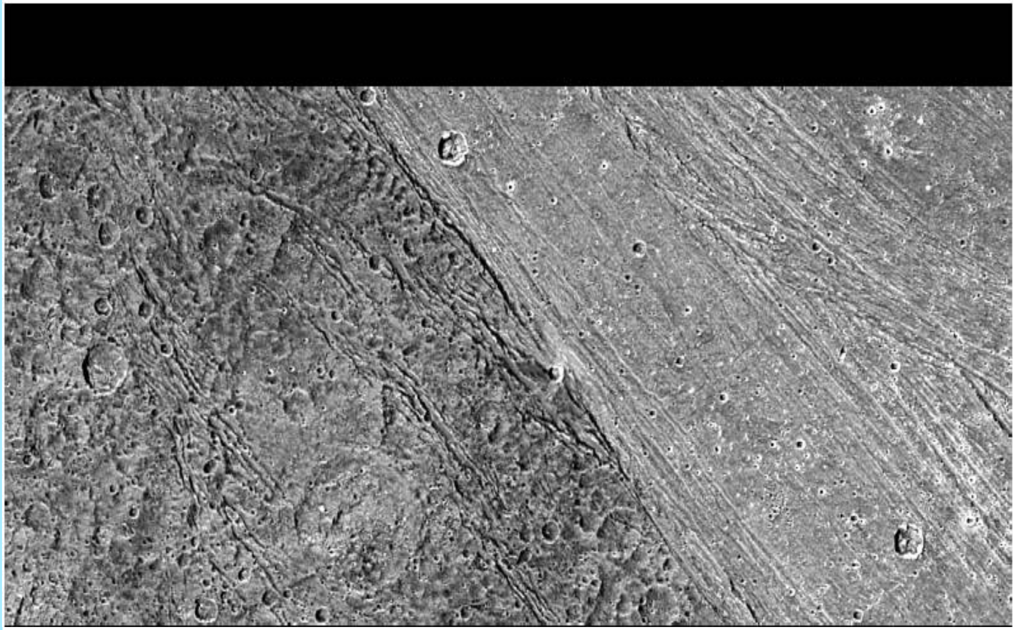


- Smooth, cracked icy surface.
- Young surface.
- Small topography (few 100 meters).
- Crust is broken by long (up to a few tens of km) broad cracks.
- Some cracks have symmetric ridge pattern: ice tectonics (with ice crust a few tens of km thick)

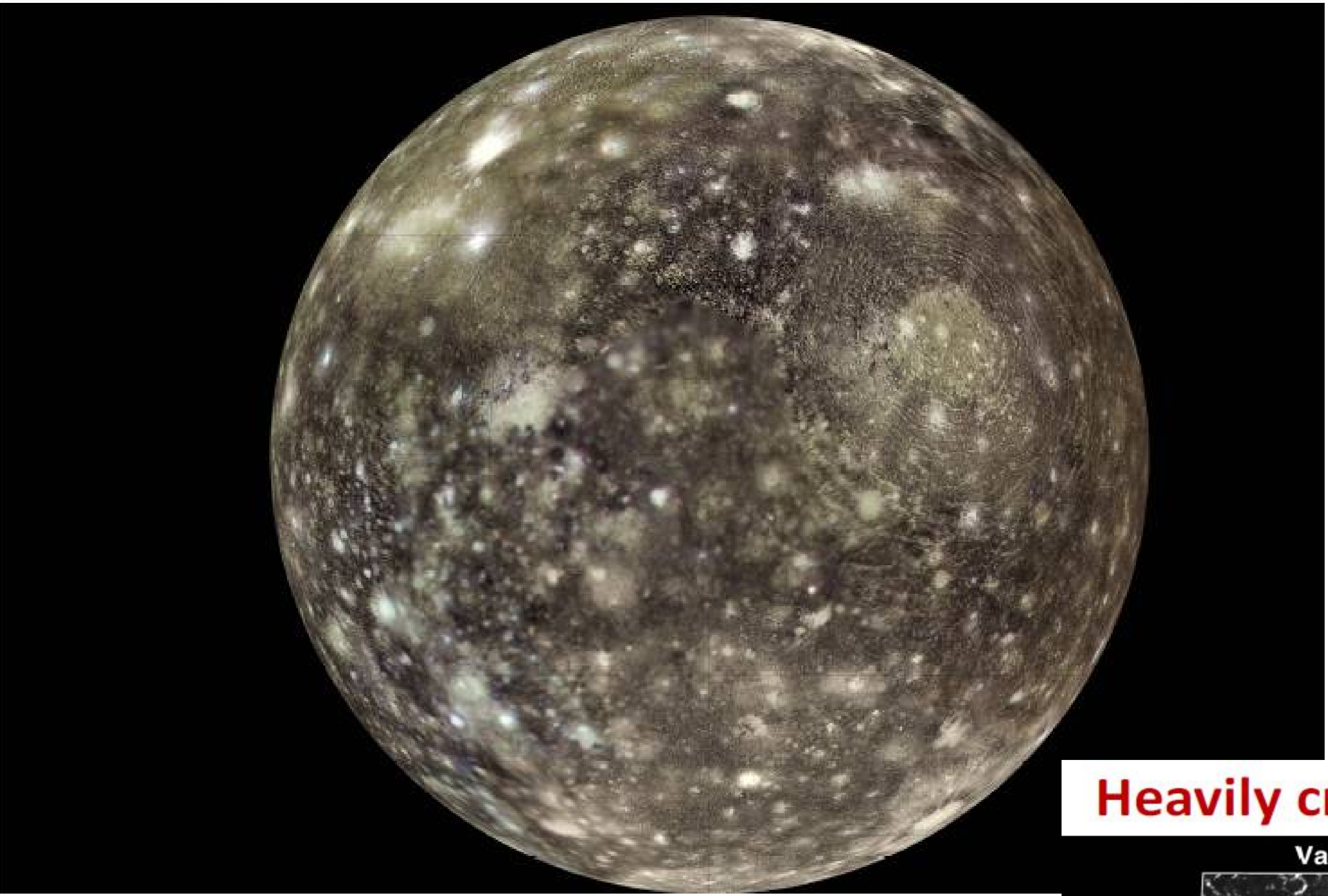
# Ganymede

- Largest moon in solar system (larger than Mercury).
- Varied surface: light and dark regions, blocks with relative motion, 'wrinkly' areas, intersecting mountain ridges.
- Brown color: from meteorites impacts
- Light grooved areas are younger than dark areas.
- Crater counting indicate that youngest terrains (light areas) are 3 Ga old.
- Ganymede might have experienced ***heating episodes*** during its early history *(expansion causing faulting and subsidence, followed by upwelling of new material)*.

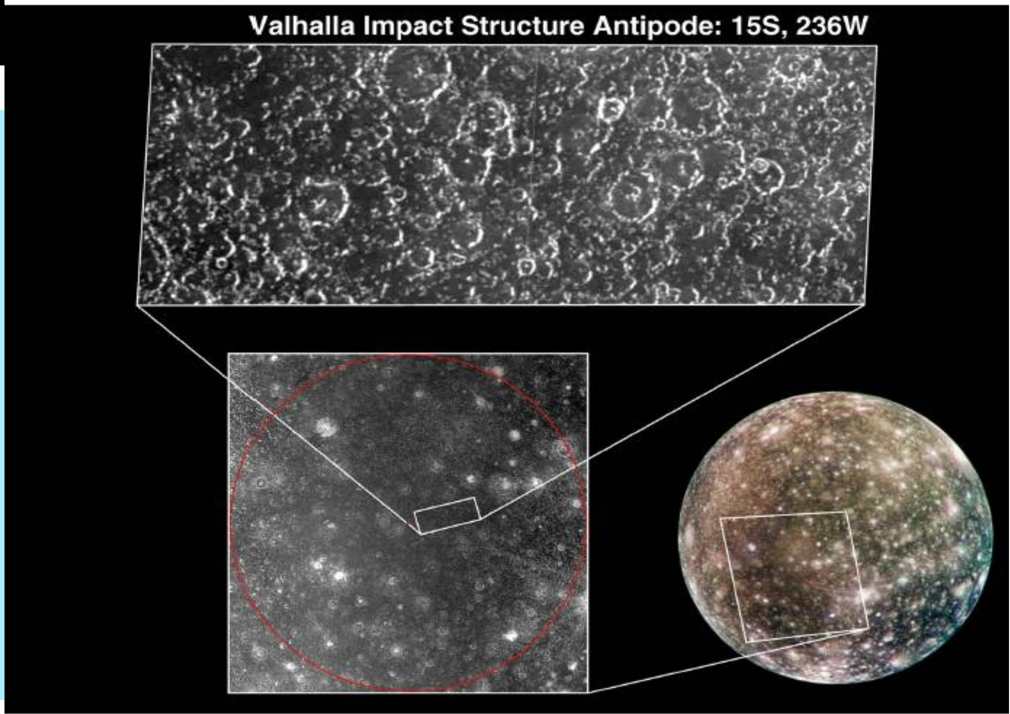
## Dark and light terrains



# Callisto



## Heavily cratered terrain




- Surface is heavily cratered but ...
- ... contains no mountains, volcanoes, or cracks.
- The most heavily cratered body in the solar system.
- Surface age about 4.5 Ga
- Craters flatter than on terrestrial planets, and large ones erased by ice flows.
- Huge impact, with central region ~300 km, and concentric rings up to ~1500 km.

# Les structures particulières des lunes de Saturne

- **62 known moons** (by March 2013).
- **1 large moon**: Titan (5150 km diameter), has atmosphere!
- **4 medium-sized** ($D$ = 1000-1500 km): Tethys, Dione, Rhea, Iapetus
- **3 small moons**: Mimas ($D$ = 392 km), Enceladus ($D$ = 500 km), Hyperion (360×280×225).
- **Many smaller objects and moons** (10-200 km), including:
  - Phoebe (230×220×210 km).
  - 3 companion satellites at Trojan points of other moons: Helene (Dione), Calypso and Telesto (Tethys), all 30-35 km
  - 2 embedded moons: Pan & Atlas
  - 2 shepherd moons: Prometheus & Pandora
  - 2 other tiny moons: Janus and Epimetheus
  - etc.

**Discovered by Herschel in 1789** *(except Hyperion)*.

**1. Mimas ($R$ = 392 km, $\rho$ = 1400 kg/m$^3$)**

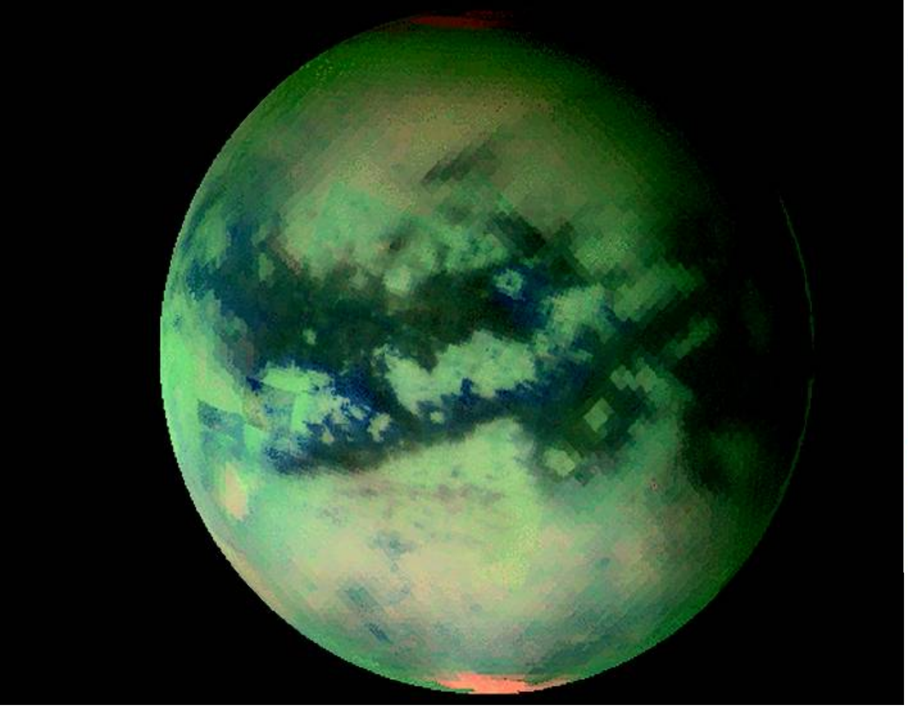
- Heavily cratered
- 1 very large crater with , called Hershel.

**2. Enceladus ($R$ = 500 km, $\rho$ = 1610 kg/m$^3$)**

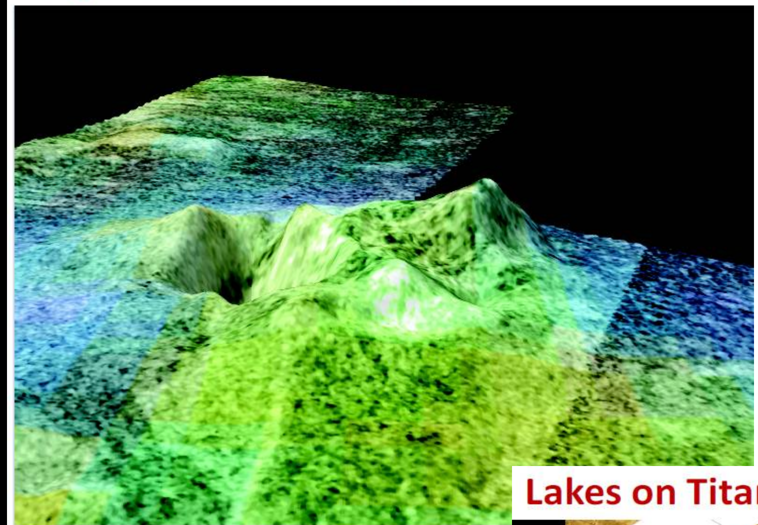
- Very bright (albedo ~1).
- Young surface.
- Geysers erupting from tiger stripes in south pole region

**3. Hyperion (360×266×205 km, $\rho$ = 544 kg/m$^3$)**

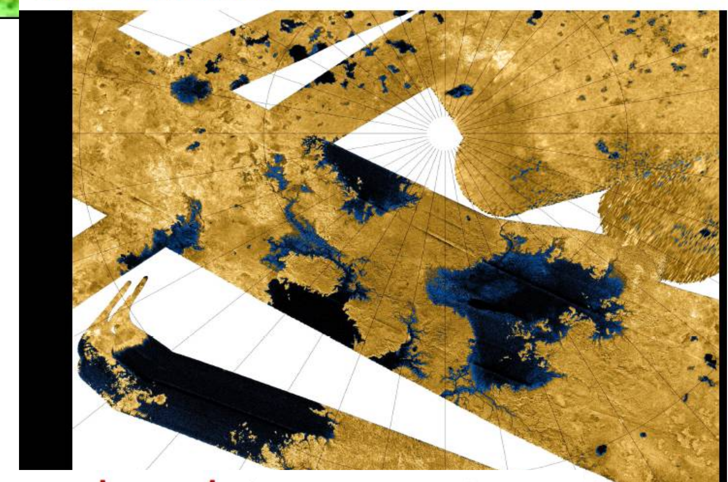
- Irregular shape.
- Low density, indicates largely composed of water, high porosity.
- Many deep, sharp-edge craters filled with dark material.



**Cryovolcano Sotra Facula?**

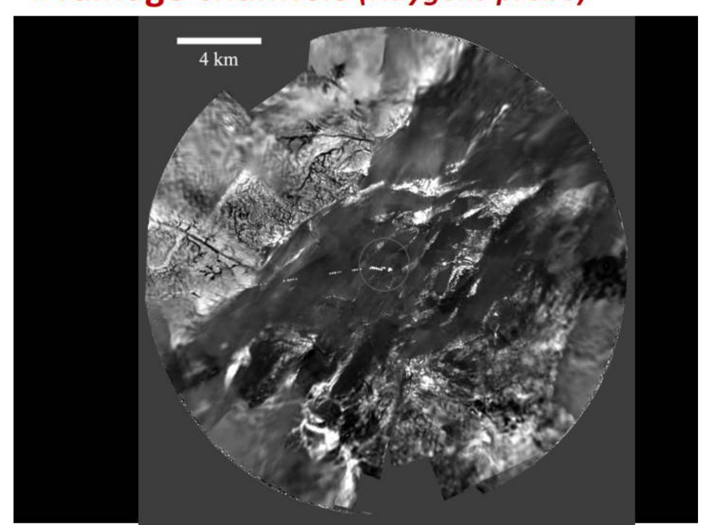


**Lakes on Titan**



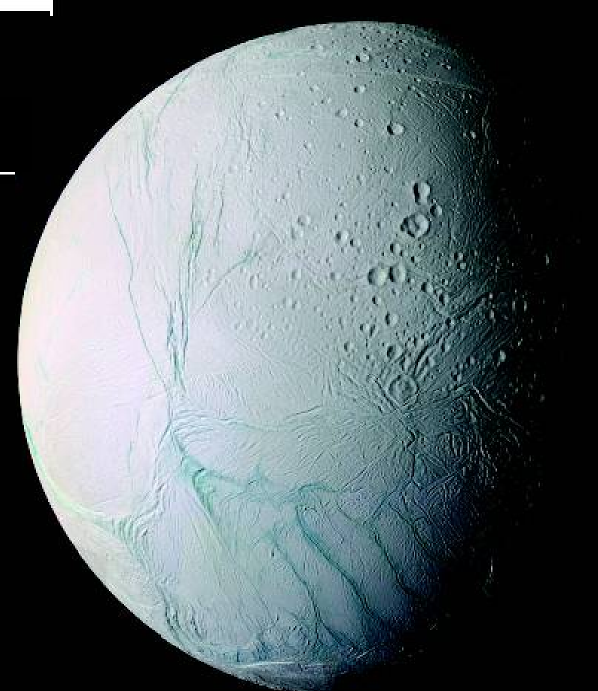
- Discovered by Huygens (1655)
- Diameter = 5150 km & density = 1900 kg/m$^3$, similar to Ganymede/Callisto
- The only moon to have a substantial atmosphere, P~150 kPa
  - Nitrogen (98.4%) with 1.6% methane
  - Covered by orange smog, caused by photochemical reactions with N and methane
  - Has methane clouds & rain
- $T_{surf}$ = 94 K: Methane and ethane are stable under liquid and gas.
- Surface exhibits
  - Lakes of ethane or methane
  - dunes
  - Water-ice "rocks" + hydrocarbon deposits
  - Mountains

**Drainage channels** *(Huygens probe)*

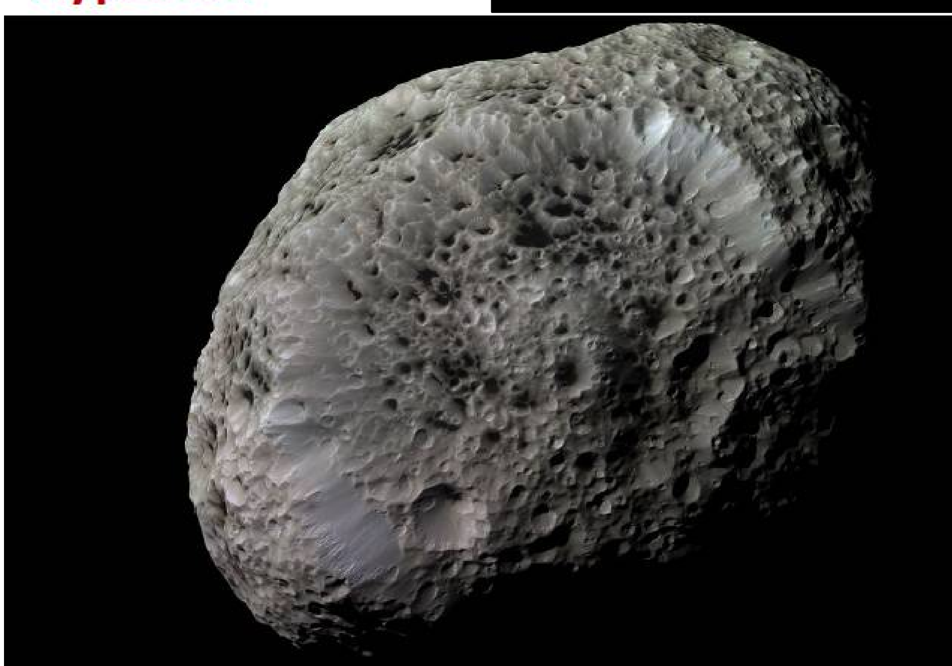


**Mimas**

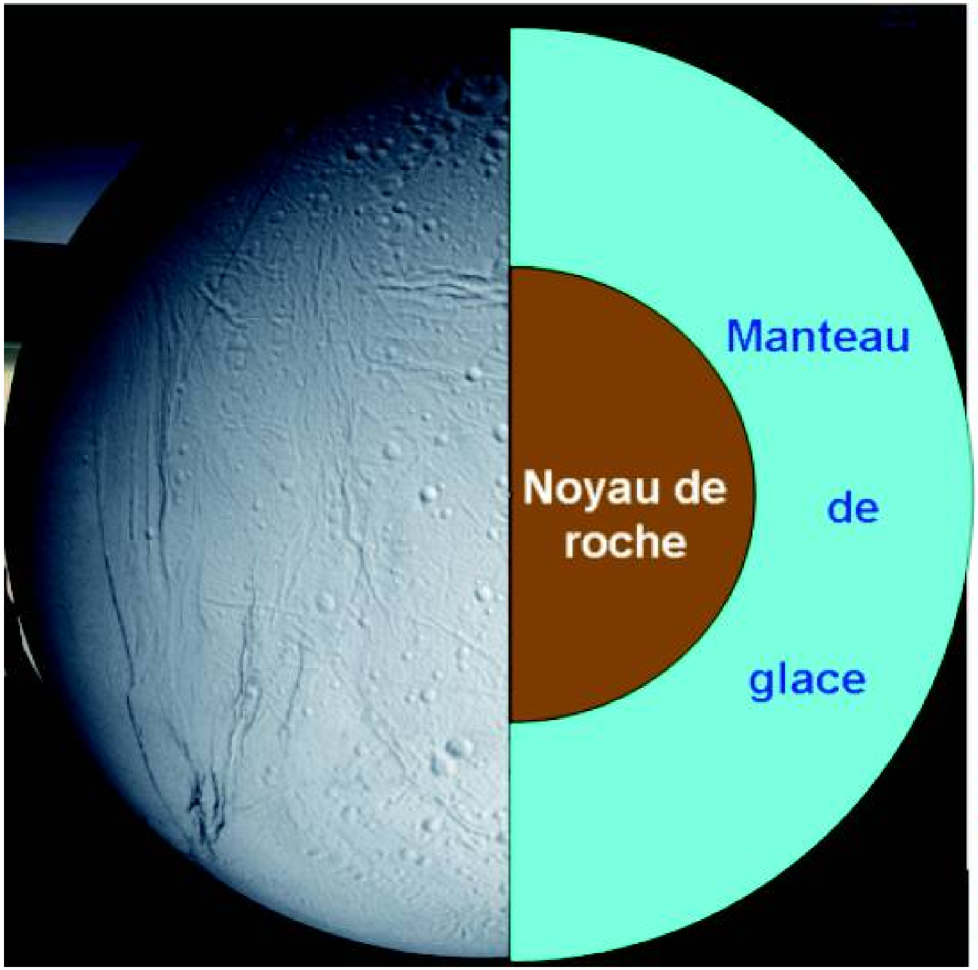
**Enceladus**

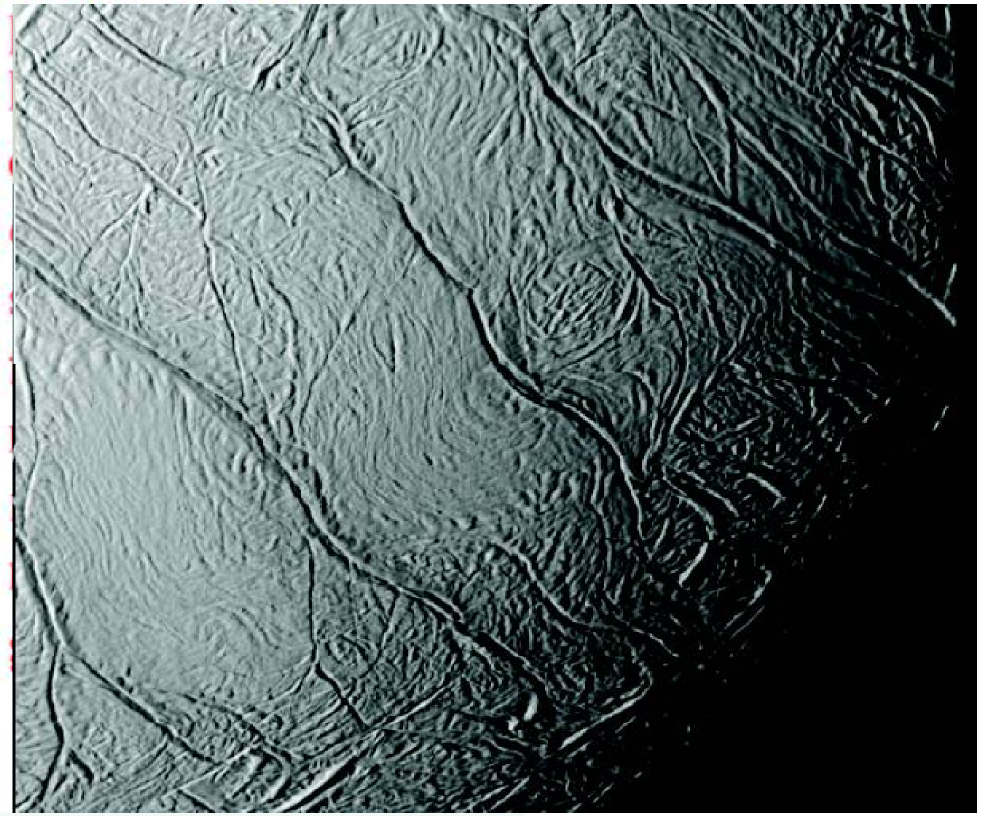


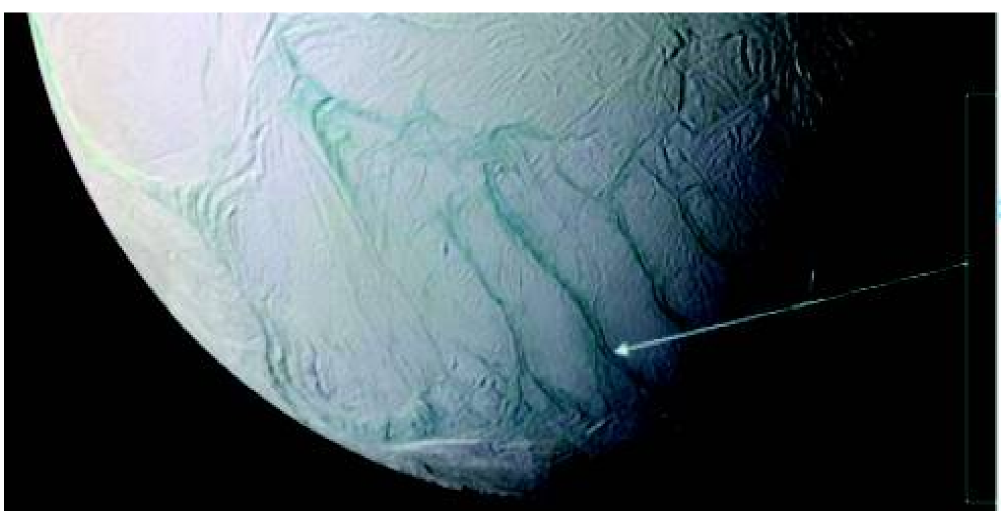
**Hyperion**



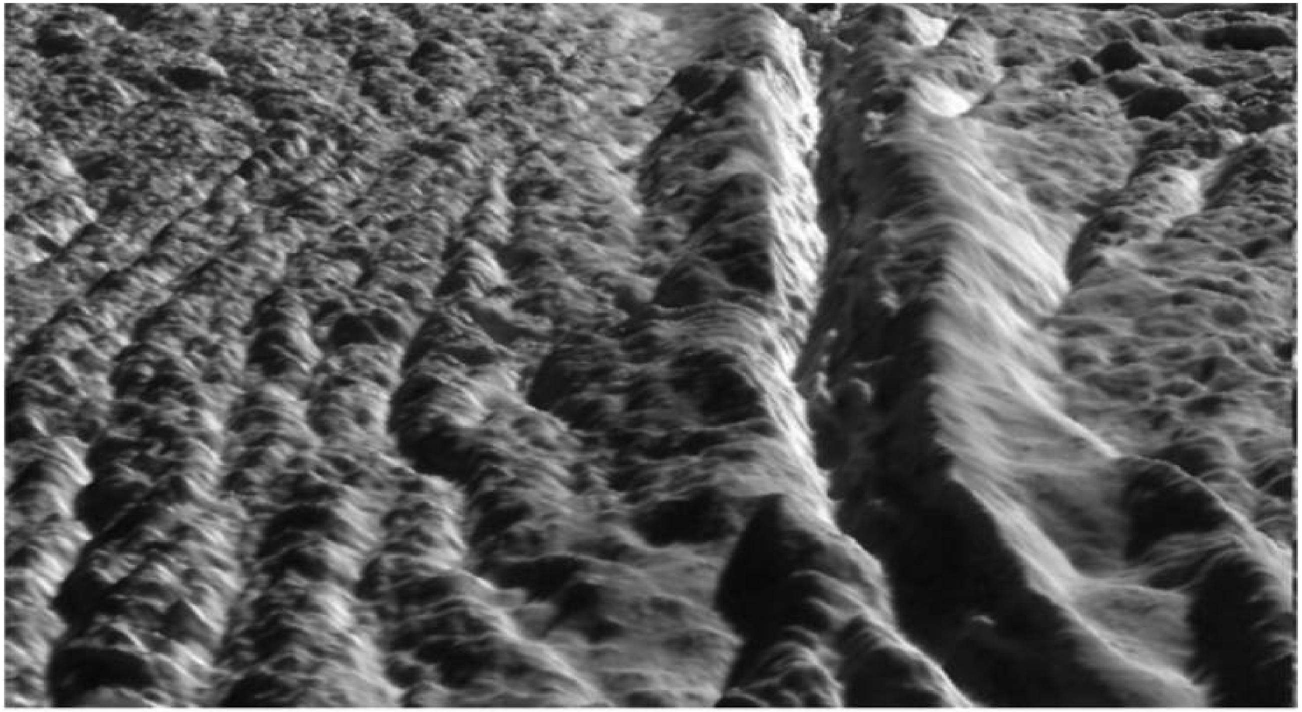
Encelade (D=502 km), est faite pour moitié de roche et moitié de glace.





Le Pôle Sud, région avec moins de cratères et encore plus « tourmentée » que le reste, avec des « rayures de tigre »



La rayure de tigre Damas, ressemble au relief volcanique des rides océaniques.
Mais: volcans d'eau!
Un tel volcanisme dans un petit corps froid, est possible grâce à l aprésence d'ammoniaque et de sel dans la glace. Cela abaisse le seuil de fusion, ajouté aux déformations et variations de chaleur causés par la présence proche de Saturne.

Et par ces espèces de fissures, il sort de la vapeur d'eau ! Des volcans d'eau !