Impact craters and evolution of planetary surfaces

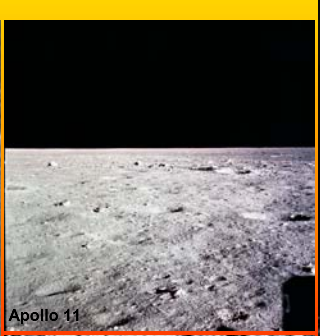
Impact craters and evolution of planetary surfaces

Introduction

Impact craters = a fundamental process in the evolution of planetary surfaces.
The lunar regolith

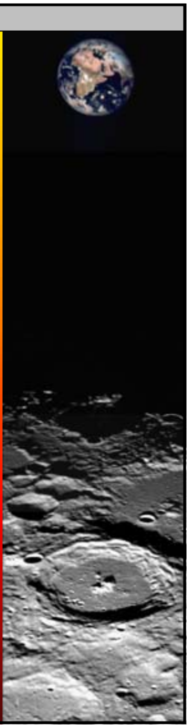
Obs. Sap, Toulouse

Clementine



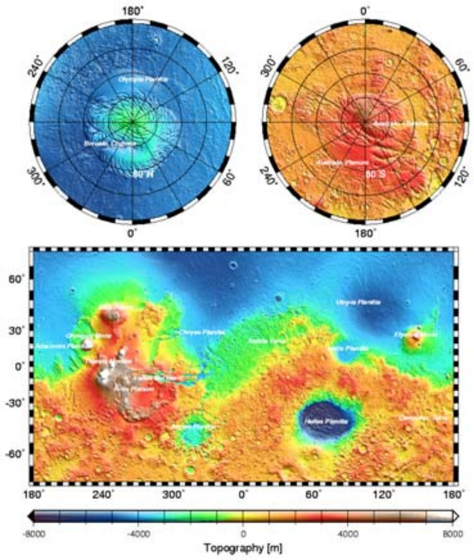
Apollo 11

Apollo 11



Introduction

Impact craters = a fundamental process in the evolution of planetary surfaces.
Mercury and Mars

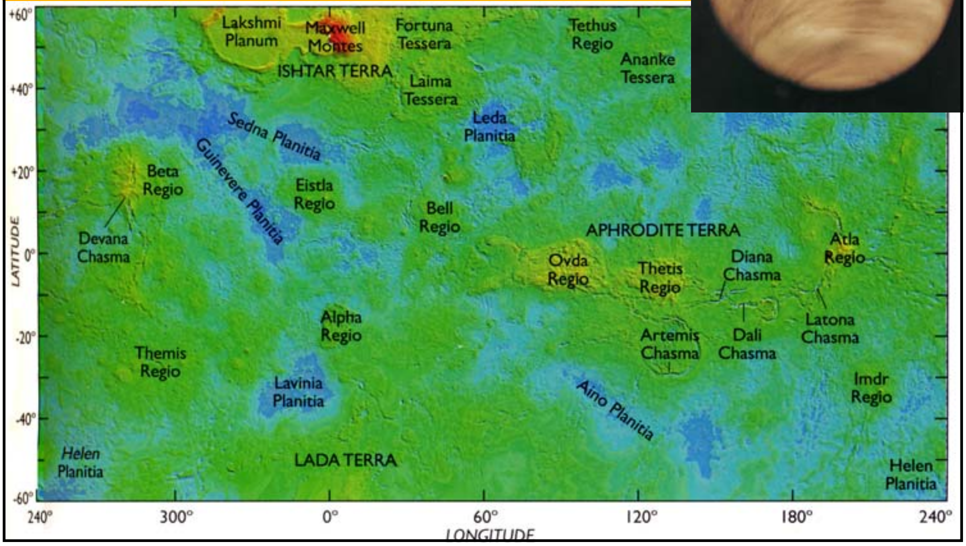


Bassin Caloris, Mercure

Carte topographique de Mars (MOLA/NASA)

Introduction

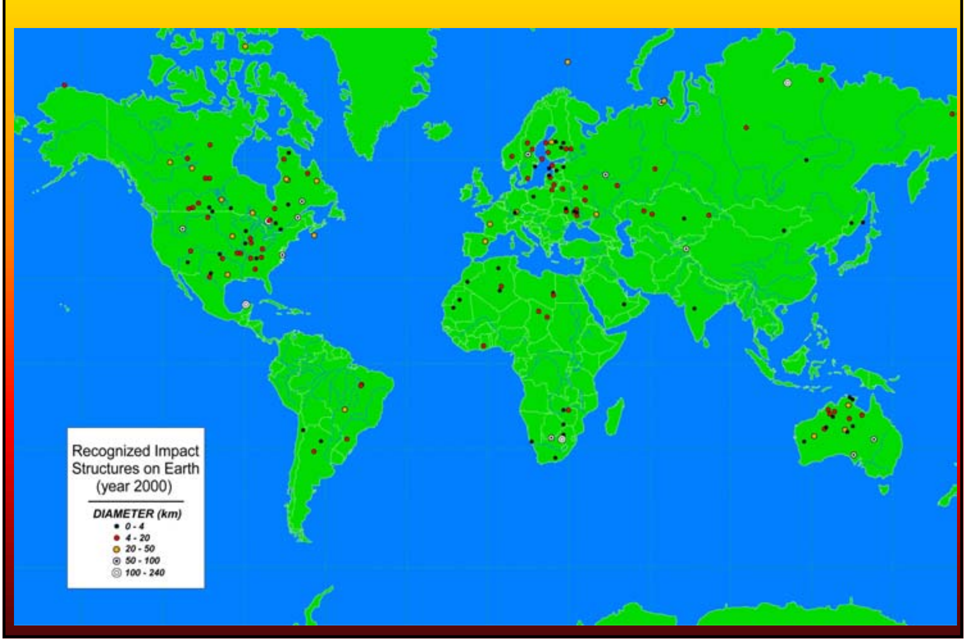
Impact craters = a fundamental process in the evolution of planetary surfaces.
Venus



Introduction

Impact craters = a fundamental process in the evolution of planetary surfaces.

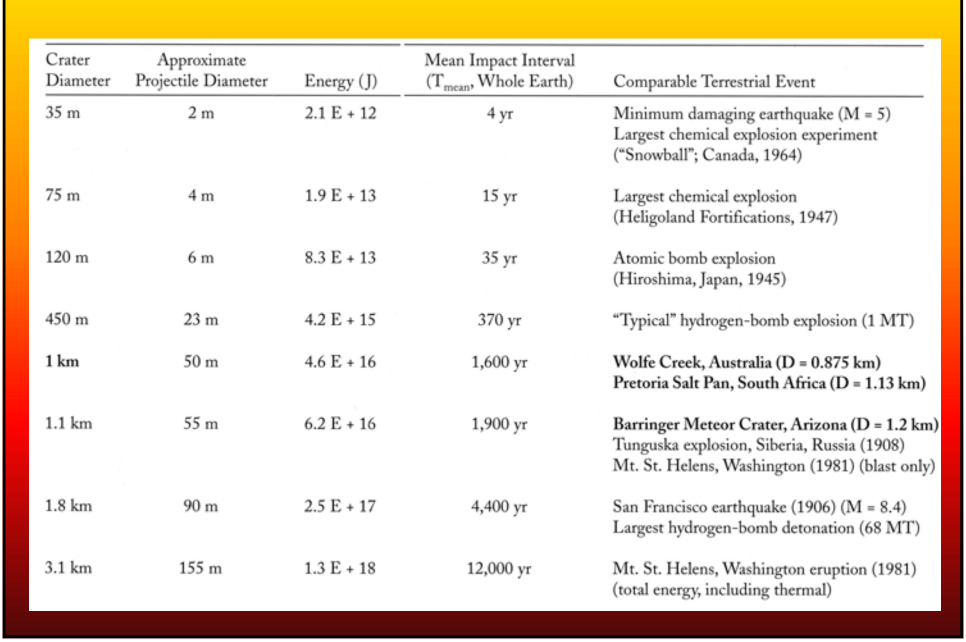
The terrestrial record



Introduction

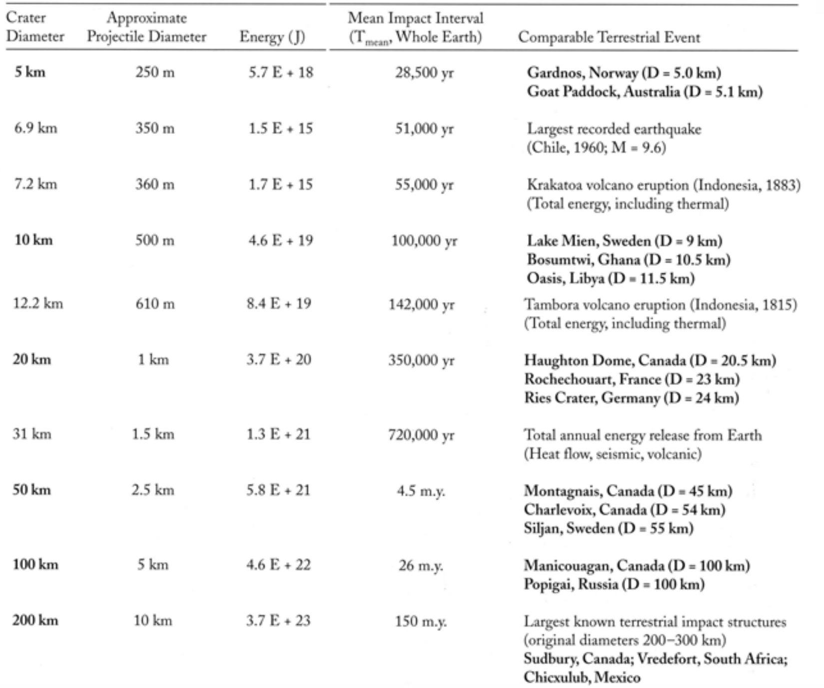
Impact craters = a fundamental process in the evolution of planetary surfaces.

The terrestrial record



Crater Diameter	Approximate Projectile Diameter	Energy (J)	Mean Impact Interval (T_{mean}, Whole Earth)	Comparable Terrestrial Event
35 m	2 m	2.1 E + 12	4 yr	Minimum damaging earthquake (M = 5) Largest chemical explosion experiment ("Snowball"; Canada, 1964)
75 m	4 m	1.9 E + 13	15 yr	Largest chemical explosion (Heligoland Fortifications, 1947)
120 m	6 m	8.3 E + 13	35 yr	Atomic bomb explosion (Hiroshima, Japan, 1945)
450 m	23 m	4.2 E + 15	370 yr	"Typical" hydrogen-bomb explosion (1 MT)
1 km	50 m	4.6 E + 16	1,600 yr	**Wolfe Creek, Australia (D = 0.875 km)** **Pretoria Salt Pan, South Africa (D = 1.13 km)**
1.1 km	55 m	6.2 E + 16	1,900 yr	**Barringer Meteor Crater, Arizona (D = 1.2 km)** Tunguska explosion, Siberia, Russia (1908) Mt. St. Helens, Washington (1981) (blast only)
1.8 km	90 m	2.5 E + 17	4,400 yr	San Francisco earthquake (1906) (M = 8.4) Largest hydrogen-bomb detonation (68 MT)
3.1 km	155 m	1.3 E + 18	12,000 yr	Mt. St. Helens, Washington eruption (1981) (total energy, including thermal)

Introduction



Crater Diameter	Approximate Projectile Diameter	Energy (J)	Mean Impact Interval (T_{mean}, Whole Earth)	Comparable Terrestrial Event
5 km	250 m	5.7 E + 18	28,500 yr	**Gardnos, Norway (D = 5.0 km)** **Goat Paddock, Australia (D = 5.1 km)**
6.9 km	350 m	1.5 E + 15	51,000 yr	Largest recorded earthquake (Chile, 1960; M = 9.6)
7.2 km	360 m	1.7 E + 15	55,000 yr	Krakatoa volcano eruption (Indonesia, 1883) (Total energy, including thermal)
10 km	500 m	4.6 E + 19	100,000 yr	**Lake Mien, Sweden (D = 9 km)** **Bosumtwi, Ghana (D = 10.5 km)** **Oasis, Libya (D = 11.5 km)**
12.2 km	610 m	8.4 E + 19	142,000 yr	Tambora volcano eruption (Indonesia, 1815) (Total energy, including thermal)
20 km	1 km	3.7 E + 20	350,000 yr	**Haughton Dome, Canada (D = 20.5 km)** **Rochechouart, France (D = 23 km)** **Ries Crater, Germany (D = 24 km)**
31 km	1.5 km	1.3 E + 21	720,000 yr	Total annual energy release from Earth (Heat flow, seismic, volcanic)
50 km	2.5 km	5.8 E + 21	4.5 m.y.	**Montagnais, Canada (D = 45 km)** **Charlevoix, Canada (D = 54 km)** **Siljan, Sweden (D = 55 km)**
100 km	5 km	4.6 E + 22	26 m.y.	**Manicouagan, Canada (D = 100 km)** **Popigai, Russia (D = 100 km)**
200 km	10 km	3.7 E + 23	150 m.y.	Largest known terrestrial impact structures (original diameters 200–300 km) **Sudbury, Canada; Vredefort, South Africa;** **Chicxulub, Mexico**

Introduction

The study of terrestrial impact structure and the search for new impact structures: which objectives ?

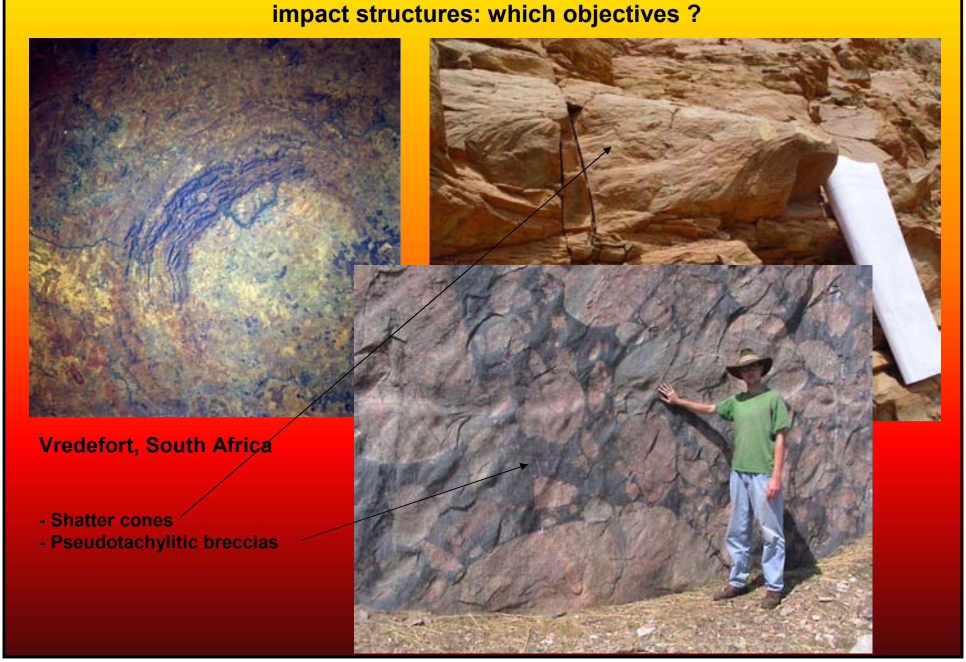
-Constrain the cratering history (impact flux) on Earth and for the solar system

-A contribution to the understanding of physical processes occuring during the formation of the solar system (planetary growth and accretation, thermal state of proto-planets, Moon formation…)

-Impact craters = natural laboratories for the understanding of physical processes occurring during the propagation of strong shock waves in geological media.

Give more evidences to the fact that impact cratering is a geological process as import as other geological processes usually taught in Earth sciences classes !

The study of terrestrial impact structure and the search for new impact structures: which objectives ?



Vredefort, South Africa

- **Shatter cones**
- **Pseudotachylitic breccias**

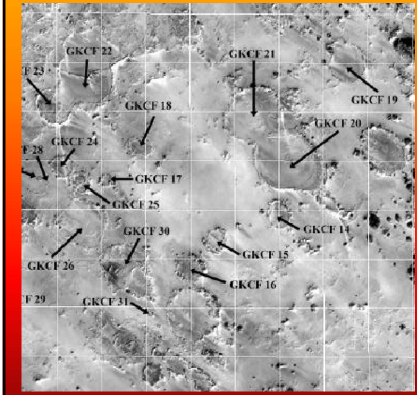
The study of terrestrial impact structure and the search for new impact structures: which objectives ?

Gilf-Kebir Plateau, Egypte.

Introduction

The study of terrestrial impact structure and the search for new impact structures: which objectives ?

Spot – 4 / CNES.



Introduction

The study of terrestrial impact structure and the search for new impact structures: which objectives ?

Shatter cones ou structures éoliennes ?

P.Paillou

2.1 Elastic waves and shock wave propagation in solids.

1. <u>Introduction</u>
2. Elastic waves in solids and shock waves
   - 2.1 Propagation of elastic waves
   - 2.2 Hugoniot equations
   - 2.3 Shock wave propagation and thermodynamics of impact
3. Formation and evolution of an impact crater
   - 3.1 Contact and compression
   - 3.2 Excavation flow and ejecta emplacement
   - 3.3 The case of large impact craters and basins
   - 3.4 Post-impact evolution of an impact crater (tectonism, erosion)
4. Criteria on the field
   - 4.1 Morphologic and geometric evidences
   - 4.2 Petrologic and mineralogic evidences
5. Impact craters as a tool for the sounding of the sub-surface of solid planets
6. Impact craters as a tool for the datation of planetary surfaces

---

2.1 Elastic waves and shock wave propagation in solids.

Elastic waves in solid. A brief review

Solid matter in opposition to fluids can resist to stress differences along different directions.

=> Two kind of waves : longitudinal and transverse

Wave equation for the longitudinal wave

$$\frac{\partial^2 u_L}{\partial t^2} = c_L^2 \frac{\partial^2 u_L}{\partial x^2}$$

Longitudinal wave speed :

$$c_L = \sqrt{\frac{K_0 + \frac{4}{3}\mu}{\rho_0}}$$

Wave equation for the transverse wave

$$\frac{\partial^2 u_{T_1,T_2}}{\partial t^2} = c_T^2 \frac{\partial^2 u_{T_1,T_2}}{\partial x^2}$$

Transverse wave speed :

$$c_T = \sqrt{\frac{\mu}{\mu_0}}$$

The longitudinal wave travels at a higher speed that the transverse wave

Plastic yielding and Hugoniot limit

Stress tensor of a longitudinal wave propagating along the x axis (in the frame of principal stresses):

$$\sigma = \begin{pmatrix} \sigma_L & 0 & 0 \\ 0 & \sigma_P & 0 \\ 0 & 0 & \sigma_P \end{pmatrix}$$

Although solids can resist almost arbitrarily large compressive stresses, their resistance to stress difference is limited. Beyond a yield stress, plastic flow begins and little subsequent increase inthe stress difference occurs (no fractures, but non-reversible deformation !)

Stress difference (longitudinal – transverse component) :

$$\tau = -\frac{\sigma_L - \sigma_P}{2}$$

Pressure in the solid :

$$P = -\frac{\sigma_L + 2\sigma_P}{3}$$

Maximum of the stress difference :

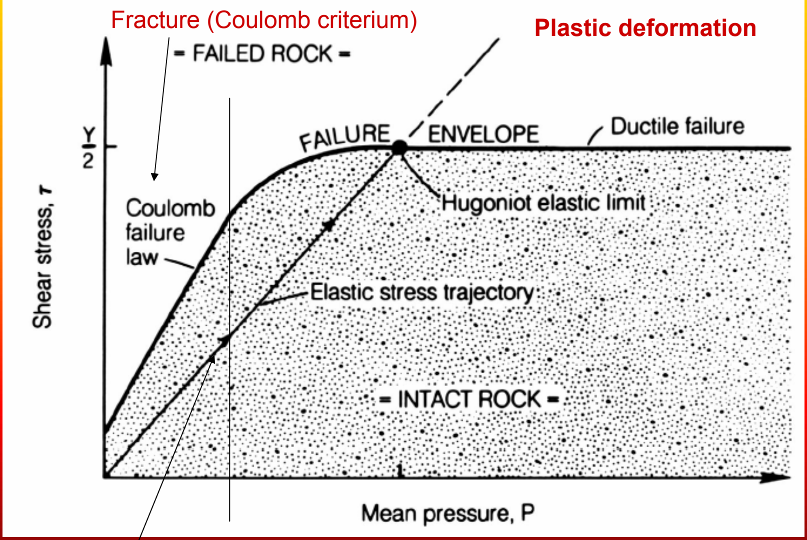
$$\tau_{max} = \frac{Y}{2}$$

Using linear elasticity equations

<u>Hugoniot elestac limit :</u>

$$\sigma_{HEL} = (\frac{1-\nu}{1-2\nu})Y$$

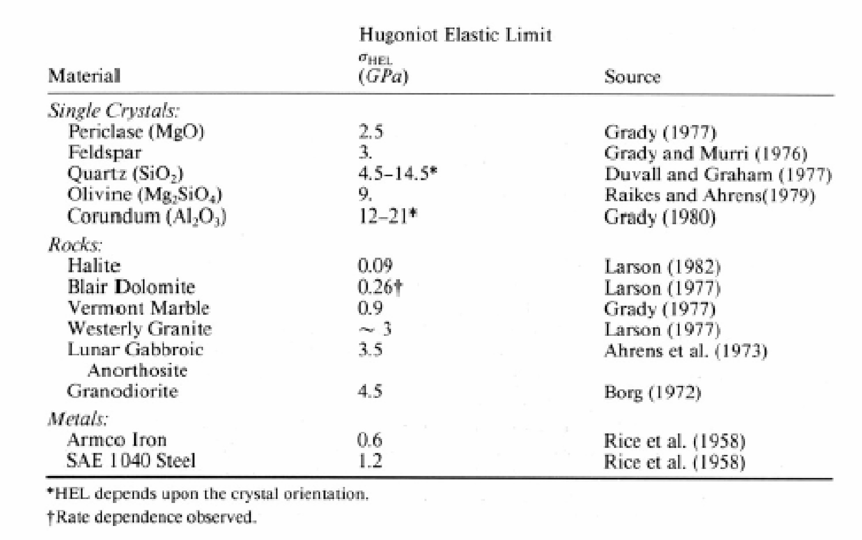
Plastic yielding and Hugoniot limit



Elastic deformation

2.1 Elastic waves and shock wave propagation in solids.

Plastic yielding and Hugoniot elastic limit
Hugoniot elastic limit for some minerals and rocks



Material	Hugoniot Elastic Limit σ_{HEL} (GPa)	Source
Single Crystals:		
Periclase (MgO)	2.5	Grady (1977)
Feldspar	3.	Grady and Murri (1976)
Quartz (SiO_2)	4.5–14.5*	Duvall and Graham (1977)
Olivine (Mg_2SiO_4)	9.	Raikes and Ahrens(1979)
Corundum (Al_2O_3)	12–21*	Grady (1980)
Rocks:		
Halite	0.09	Larson (1982)
Blair Dolomite	0.26†	Larson (1977)
Vermont Marble	0.9	Grady (1977)
Westerly Granite	~ 3	Larson (1977)
Lunar Gabbroic Anorthosite	3.5	Ahrens et al. (1973)
Granodiorite	4.5	Borg (1972)
Metals:		
Armco Iron	0.6	Rice et al. (1958)
SAE 1040 Steel	1.2	Rice et al. (1958)

*HEL depends upon the crystal orientation.

†Rate dependence observed.

2.2 Hugoniot equations.

1. <u>Introduction</u>

2. Elastic waves in solids and shock waves
   - 2.1 Propagation of elastic waves
   - 2.2 Hugoniot equations
   - 2.3 Shock wave propagation and thermodynamics of impact

3. Formation and evolution of an impact crater
   - 3.1 Contact and compression
   - 3.2 Excavation flow and ejecta emplacement
   - 3.3 The case of large impact craters and basins
   - 3.4 Post-impact evolution of an impact crater (tectonism, erosion)

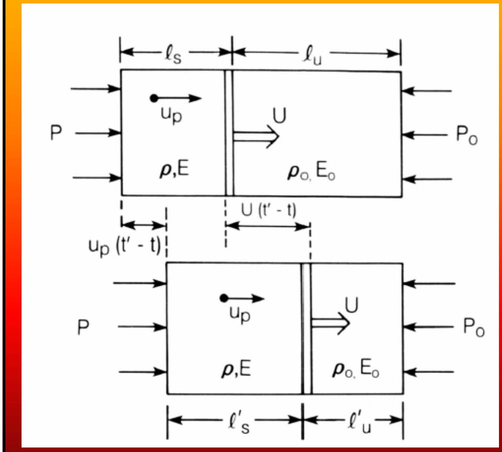
4. Criteria on the field
   - 4.1 Morphologic and geometric evidences
   - 4.2 Petrologic and mineralogic evidences

5. Impact craters as a tool for the sounding of the sub-surface of solid planets

6. Impact craters as a tool for the datation of planetary surfaces

2.2 Hugoniot equations.

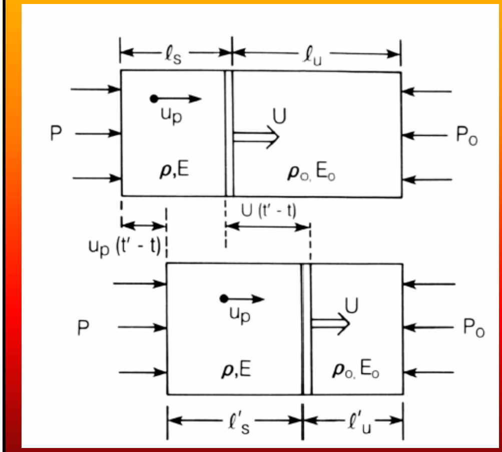
Shock = discontinuity



P_0: Pressure before the shock
P: Pressure after the shock
u_p: particle velocity after the shock
ρ_0: density of the material before the shock
ρ: density of the material after the shock
E_0: Specific energy before the shock
E: Specific energy after the shock
U: Shock wave propagation.

2.2 Hugoniot equations.

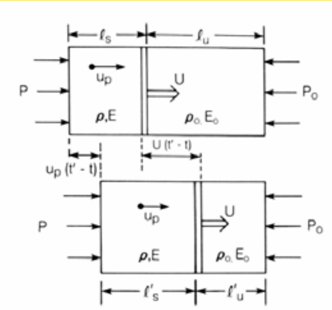
Shock = discontinuity



- Mass conservation
- Momentum conservation
- Energy conservation

$$\begin{cases} \rho(U-u_p) = \rho_0 u \\ P - P_0 = \rho_0 u_p U \\ E - E_0 = (P+P_0)(V_0 - V) \end{cases}$$

2.2 Hugoniot equations.



Mass conservation

-l$_s$: length of the shocked region at the time t
-l$_u$: length of the non-shocked region
-l'$_s$: length of the shocked region at the time t + dt
-l'$_u$: length of the non-shocked region at the time t + dt

$$\begin{cases} l'_u = l_u - U(t'-t) \\ l'_s = l_s + U(t'-t) - u_p(t'-t) \end{cases}$$

$$m = l_u A\rho_0 + l_s A\rho$$

$$m' = l'_u A\rho_0 + l'_s A\rho$$

$$m' = \rho_0 l_u A - \rho_0 U(t'-t)A + \rho l_s A + \rho U(t'-t)A - \rho u_p(t'-t)A$$

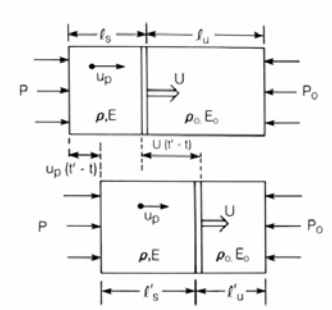
Mass conservation

$$\rho_0 l_u - \rho_0 U(t'-t) + \rho l_s + \rho U(t'-t) - \rho u_p(t'-t) = l_u\rho_0 + l_s\rho$$

First Hugoniot equation

$$\rho U - \rho_0 U - \rho u_p = 0 \quad \rightarrow \quad \boxed{\rho(u_p - U) = \rho_0 U}$$

2.2 Hugoniot equations.



Momentum conservation

-l$_s$: length of the shocked region at the time t
-l$_u$: length of the non-shocked region
-l'$_s$: length of the shocked region at the time t + dt
-l'$_u$: length of the non-shocked region at the time t + dt

The momentum variation during the time dt is equal to the pressure forces:

$$(P - P_0) * A * (t'-t) = \rho l'_s u_p A - \rho l_s u_p A$$

Use of **l'$_s$** and **l'$_u$** expressions:

$$(P - P_0)(t'-t) = \rho u_p(U(t'-t) - u_p(t'-t))$$

$$\Rightarrow \quad P - P_0 = \rho u_p(U - u_p)$$

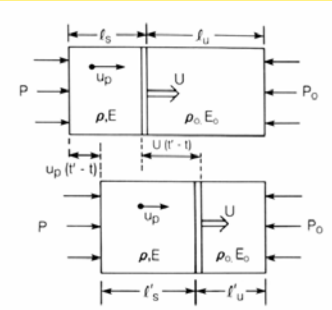
Using the first Hugoniot equation:

$$\rho(U - u_p) = \rho_0 U$$

Second Hugoniot equation:

$$\boxed{P - P_0 = \rho_0 * U * u_p}$$

2.2 Hugoniot equations.



Energy conservation

-l_s: length of the shocked region at the time t
-l_u: length of the non-shocked region
-l'_s: length of the shocked region at the time t + dt
-l'_u: length of the non-shocked region at the time t + dt

The energy variation during the time dt is equal to the work of pressure forces:

$$PAu_p(t'-t) = E_{totale}(t') - E_{totale}(t)$$

Energy = internal energy
+ kinetic energy
At the time t:

$$E_{total}\ (t) = \rho_0 l_u E_0 A + \rho l_s E A + \frac{1}{2}\rho l_s u_p^2 A$$

At the time dt:

$$E_{total}\ (t') = \rho_0 l'_u E_0 A + \rho l'_s E A + \frac{1}{2}\rho l'_s u_p^2 A$$

2.2 Hugoniot equations.

$$\rho_0[l_u - U(t'-t)]E_0 \rho(l_s + U(t'-t) - u_p(t'-t)]E + \\ \frac{1}{2}\rho u_p^2(-U(t'-t) - u_p(t'-t)) - \rho_0 l_u E_0 - \rho l_s E - \frac{1}{2}\rho u_p^2 l_s = P u_p(t'-t)$$

After few simplifications:

$$-\rho_0 U E_0 + \rho E(U - u_p) + \frac{1}{2}\rho u_p^2 (U - u_p) = P u_p$$

Using the first Hugoniot equation:

$$-\rho_0 U E_0 + E\rho_0 U + \frac{1}{2}\rho_0 U u_p^2 = P u_p$$

$$\rho_0 U(E - E_0) + \frac{1}{2}\rho_0 u_p^2 U = P u_p$$

2.2 Hugoniot equations.

We want to eliminate U and u_p to have an expression as a function of ρ and P only:

$$\begin{cases} \rho(U - u_p) = \rho_0 U \\ P - P_0 = \rho_0 U u_p \end{cases}$$

$$u_p^2 = \frac{(P - P_0)(\rho - \rho_0)}{\rho * \rho_0}$$

Specific volume V = 1/ρ

$$u_p = \sqrt{(P - P)(V - V_0)}$$

$$U = \frac{P - P_0}{\rho_0 u_p} = V_0 * \sqrt{\frac{P - P_0}{V_0 - V}}$$

2.2 Hugoniot equations.

$$\rho_0 U(E - E_0) + \frac{1}{2}\rho_0 u_p^2 U = P u_p$$

$$\rho_0 V_0 \sqrt{\frac{P - P_0}{V_0 - V}}(E - E_0) + \frac{1}{2}\rho_0 (P - P_0)(V_0 - V) V_0 \sqrt{\frac{P - P_0}{V_0 - V}} = P\sqrt{(P - P_0)(V - V_0)}$$

After few simplications…

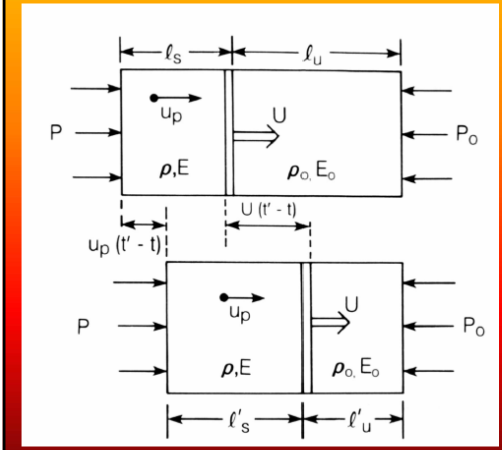
$$E - E_0 + \frac{1}{2}(P - P_0)(V_0 - V) = P(V_0 - V)$$

Third equation of Hugoniot

$$\boxed{E - E_0 = \frac{1}{2}(P + P_0)(V_0 - V)}$$

2.2 Hugoniot equations.

Shock = discontinuity

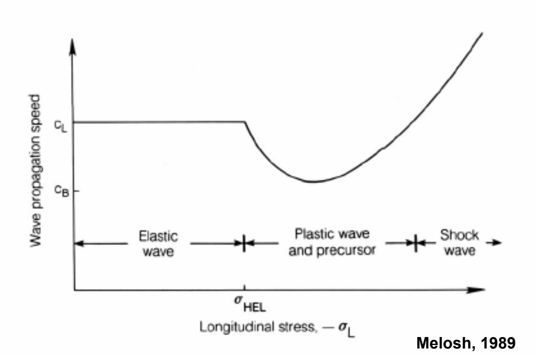


- Mass conservation
- Momentum conservation
- Energy conservation

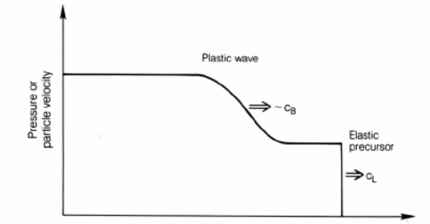
$$\begin{cases} \rho(U - u_p) = \rho_0 u \\ P - P_0 = \rho_0 u_p U \\ E - E_0 = (P + P_0)(V_0 - V) \end{cases}$$

2.2 Hugoniot equations.

Structure of the elastic wave, plastic wave and shock wave



Melosh, 1989



Melosh, 1989

Three regimes :

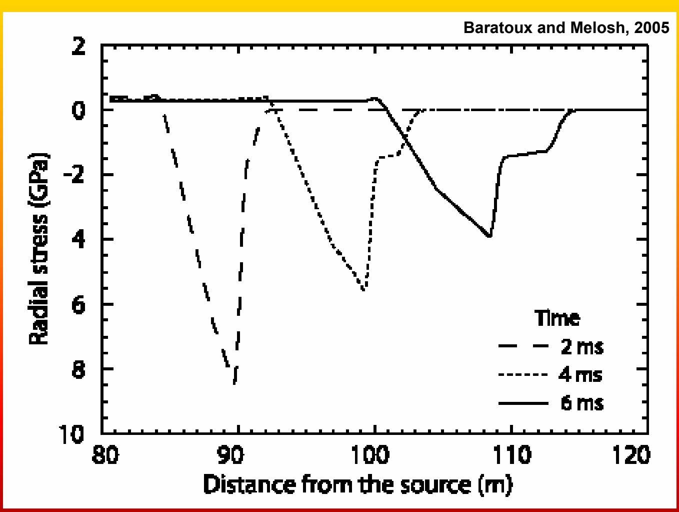
- Low pressure (Kpa)
Elastic waves propagating at the speed C_L

-Medium pressure < Gpa
Plastic wave propagating at a velocity slower than the elastic wave + Elastic precursor.

- High pressure >> GPa
Shock wave propagating at a velocity higher than the low pressure elastic wave

2.2 Hugoniot equations.

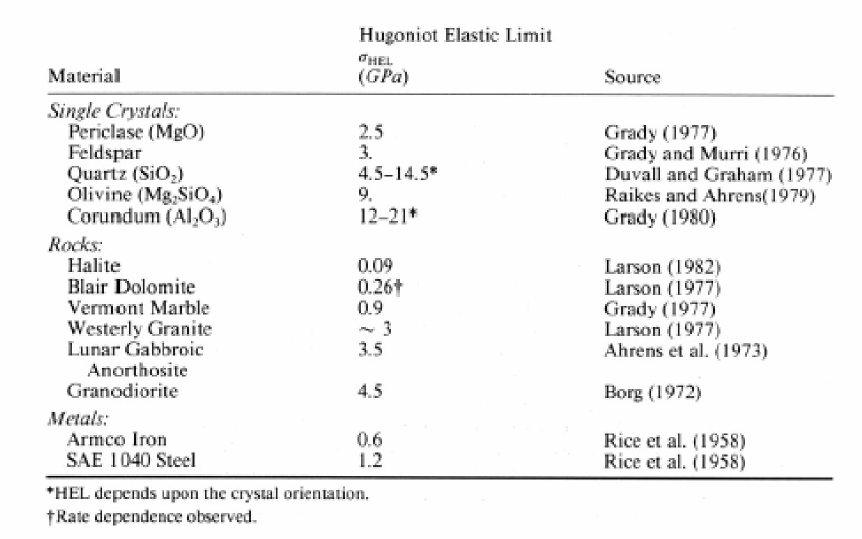
Structure of the elastic wave, plastic wave and shock wave


Baratoux and Melosh, 2005

Shock wave propagation in spherical geometry

2.1 Elastic waves and shock wave propagation in solids.

Plastic yielding and Hugoniot elastic limit
Hugoniot elastic limit for some minerals and rocks



Material	Hugoniot Elastic Limit σ_{HEL} (*GPa*)	Source
Single Crystals:		
Periclase (MgO)	2.5	Grady (1977)
Feldspar	3.	Grady and Murri (1976)
Quartz (SiO_2)	4.5–14.5*	Duvall and Graham (1977)
Olivine (Mg_2SiO_4)	9.	Raikes and Ahrens(1979)
Corundum (Al_2O_3)	12–21*	Grady (1980)
Rocks:		
Halite	0.09	Larson (1982)
Blair Dolomite	0.26†	Larson (1977)
Vermont Marble	0.9	Grady (1977)
Westerly Granite	~ 3	Larson (1977)
Lunar Gabbroic Anorthosite	3.5	Ahrens et al. (1973)
Granodiorite	4.5	Borg (1972)
Metals:		
Armco Iron	0.6	Rice et al. (1958)
SAE 1040 Steel	1.2	Rice et al. (1958)

*HEL depends upon the crystal orientation.

†Rate dependence observed.

2.3 Shock wave propagation and thermodynamics of impact

1. **Introduction**
2. **Elastic waves in solids and shock waves**
   - **2.1 Propagation of elastic waves**
   - **2.2 Hugoniot equations**
   - **2.3 Shock wave propagation and thermodynamics of impact**
3. **Formation and evolution of an impact crater**
   - **3.1 Contact and compression**
   - **3.2 Excavation flow and ejecta emplacement**
   - **3.3 The case of large impact craters and basins**
   - **3.4 Post-impact evolution of an impact crater (tectonism, erosion)**
4. **Criteria on the field**
   - **4.1 Morphologic and geometric evidences**
   - **4.2 Petrologic and mineralogic evidences**
5. **Impact craters as a tool for the sounding of the sub-surface of solid planets**
6. **Impact craters as a tool for the datation of planetary surfaces**

2.3 Shock wave propagation and thermodynamics of impact

NASA AMES, vertical gun range.

Experimental methods

Measurement of the shock wave velocity (U) and of the particle velocity (u_p)

$$\rho = \frac{\rho_0 u_p}{U - u_p}$$

First Hugoniot equation

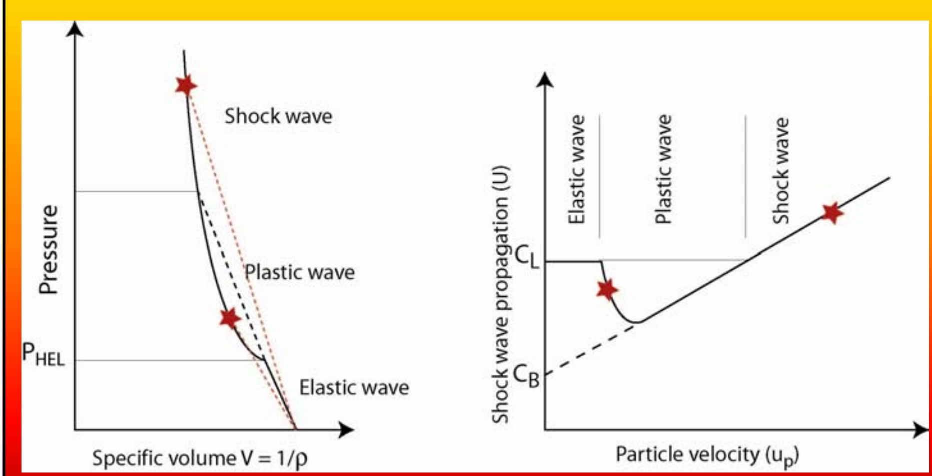
$$P = P + \rho_0 u_p U$$

Second Hugoniot equation

Third Hugoniot equation

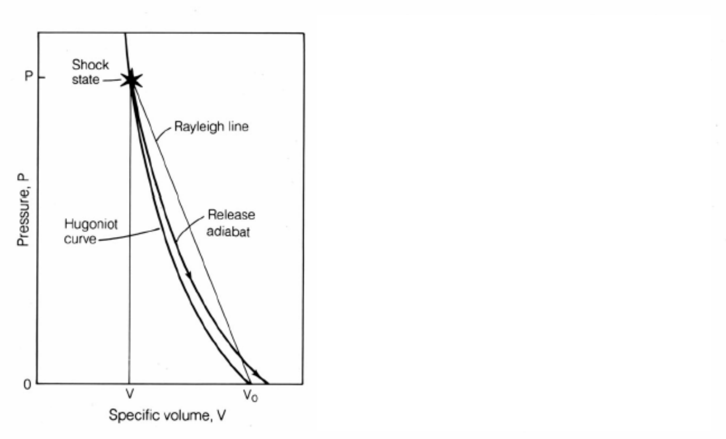
$$E = E_0 + (P + P_0)(V_0 - V)$$

2.3 Shock wave propagation and thermodynamics of impact



Shock : A discontinuity in the physical state (It is different from a thermodynamic path)

2.3 Shock wave propagation and thermodynamics of impact



After the shock:
- **Non – reversible plastic deformation**
- **Density (or specific volume) change**
- **Residual velocity responsible for the excavation flow and ejecta emplacement**

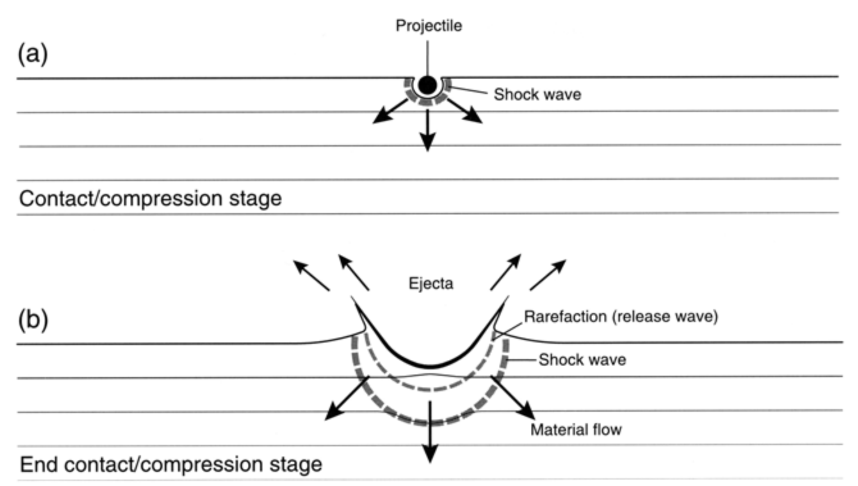
3.1 Contact and compression

1. Introduction
2. Elastic waves in solids and shock waves
    - 2.1 Propagation of elastic waves
    - 2.2 Hugoniot equations
    - 2.3 Shock wave propagation and thermodynamics of impact
3. Formation and evolution of an impact crater
    - 3.1 Contact and compression
    - 3.2 Excavation flow and ejecta emplacement
    - 3.3 The case of large impact craters and basins
    - 3.4 Post-impact evolution of an impact crater (tectonism, erosion)
4. Criteria on the field
    - 4.1 Morphologic and geometric evidences
    - 4.2 Petrologic and mineralogic evidences
5. Impact craters as a tool for the sounding of the sub-surface of solid planets
6. Impact craters as a tool for the datation of planetary surfaces

---

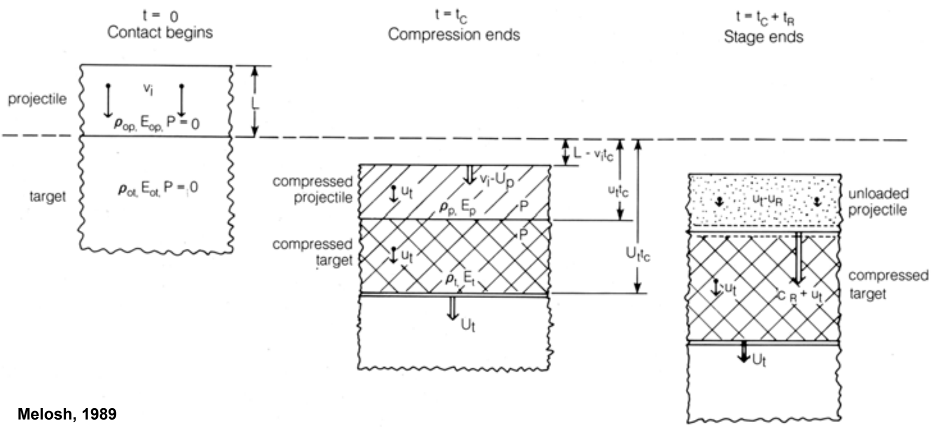
3.1 Contact and compression

Impact crater formation. Contact and compression stage



3.1 Contact and compression

A first estimation a pressure during the impact event
Plane impact approximation
=> shock pressure estimation during the contact phase

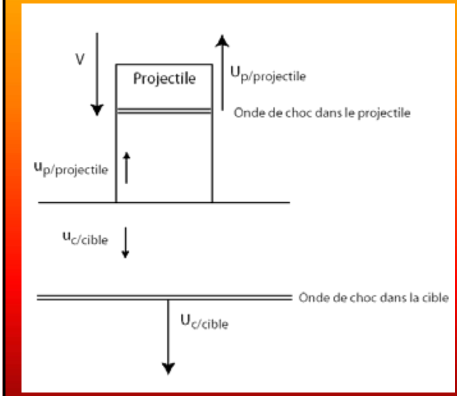


Melosh, 1989

3.1 Contact and compression

A first estimation a pressure during the impact event
Plane impact approximation

Projectile material (asteroid) = target material (planetary surface)



$$u_{c/cible} = \frac{V}{2}$$ Velocity continuity

$$P = \rho_0 u U$$ Second Hugoniot equation

$$U_t = C_t + S_T u_t$$ Experimental linear relation between the shock wave velocity and the particle velocity.

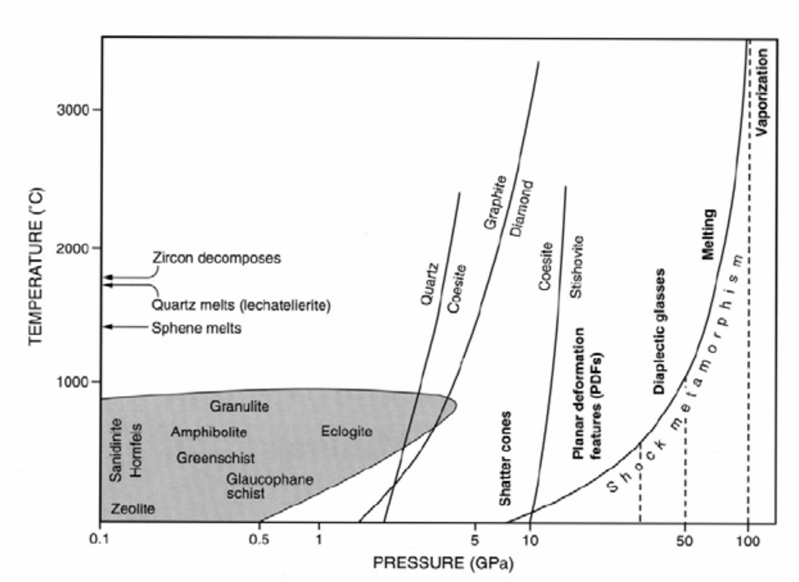
Hugoniot parameter for an anorthosite

- $\rho_0 = 3965\ kg/m^3$
- $C_t = 7.71\ km/s$
- $S_t = 1.05$

Projectile velocity = 10 km/s ⇨ 256 GPa

3.1 Contact and compression

A first estimation a pressure during the impact event
Plane impact approximation
=> shock pressure estimation during the contact phase

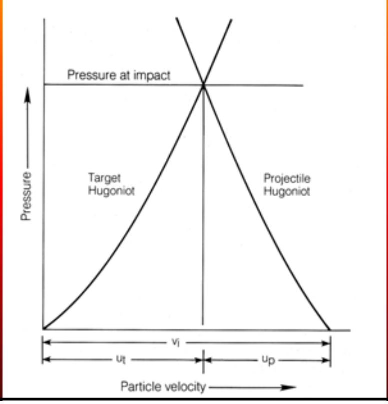


3.1 Contact and compression

A first estimation a pressure during the impact event
Plane impact approximation
=> shock pressure estimation during the contact phase

However the material of the projectile is often different from the material of the planetary surface:

- Comets (water ice) impact on a silicate surface
- Iron-rich meteorites impact on a silicate surface
- Rocky meteorite impact on an icy surface (Galiliean satellites)



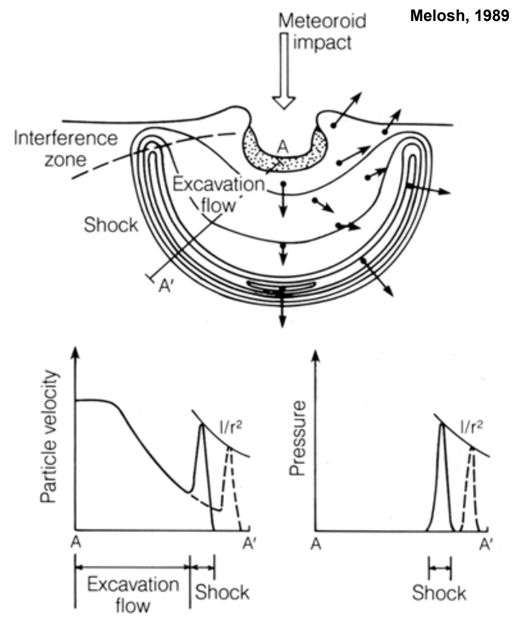
Graphic resolution of the pressure during the compression/contact phase.

Plane approximation is used for each material with the experimentally obtained Hugoniot parameters.

3.2 Excavation flow and ejecta emplacement

1. **Introduction**
2. **Elastic waves in solids and shock waves**
   - **2.1 Propagation of elastic waves**
   - **2.2 Hugoniot equations**
   - **2.3 Shock wave propagation and thermodynamics of impact**
3. **Formation and evolution of an impact crater**
   - **3.1 Contact and compression**
   - **3.2 Excavation flow and ejecta emplacement**
   - **3.3 The case of large impact craters and basins**
   - **3.4 Post-impact evolution of an impact crater (tectonism, erosion)**
4. **Criteria on the field**
   - **4.1 Morphologic and geometric evidences**
   - **4.2 Petrologic and mineralogic evidences**
5. **Impact craters as a tool for the sounding of the sub-surface of solid planets**
6. **Impact craters as a tool for the datation of planetary surfaces**

3.2 Excavation flow and ejecta emplacement



Melosh, 1989

Shock wave attenuation during its propagation

Excavation model. Analytical modeling
“Z-Model”

Impact crater ejecta are a mixture a material excavated from different depths

Kinematic model, approxmation: = Z-model (this model has been validated by both experimental explosions and numerical simulation of the excavation flow => First order approximation of the excavation flow, Croft, 1980, Austin, 1980 …)

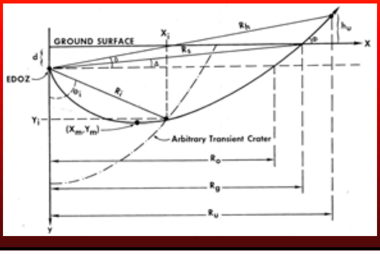
Strong point of this model => Analytical model easy to manipulate to predict the excavation flow and ejecta trajectory

<u>Three working hypothesis:</u>

(1) Incompressible material (correct because the excavation flow occur long after the shock front)

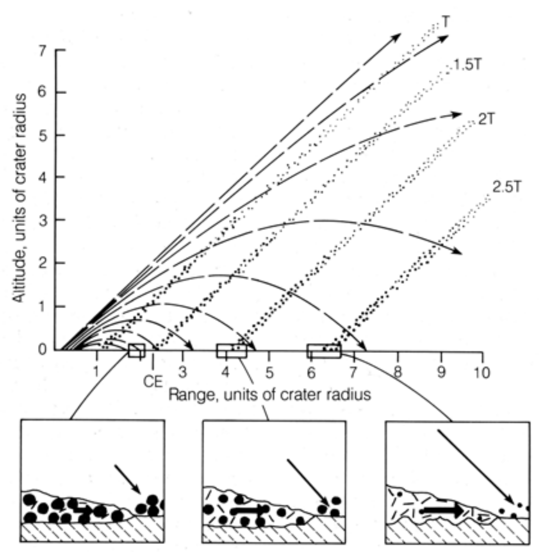
(2) Radial velocity is given by α/R^Z

(3) Particles follow independent trajectories



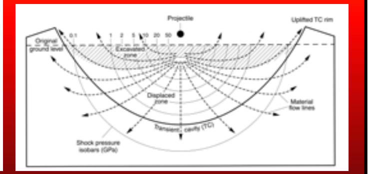
Z-model, geometrical description
Maxwell, 1973, 1977

Ballistic ejecta emplacement

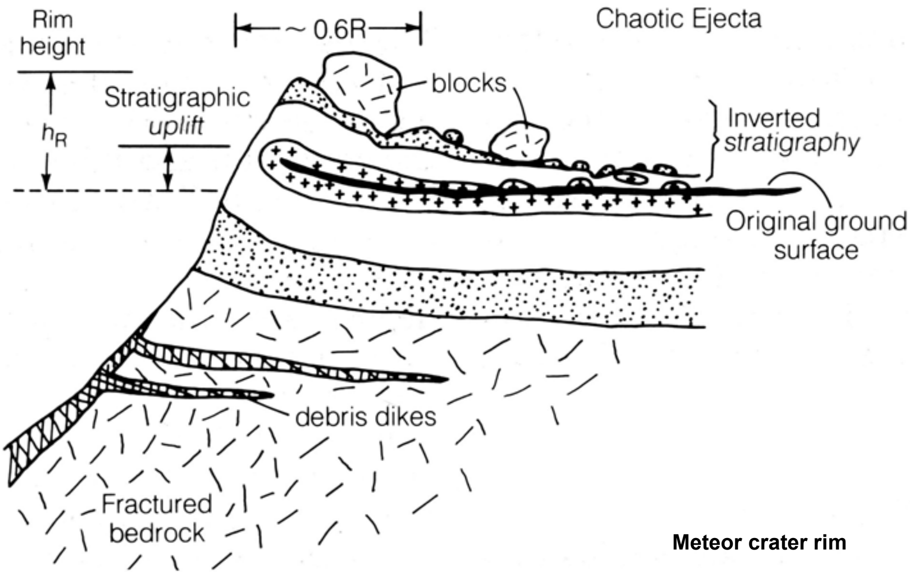


Formation of a curtain of ejecta

Ejecta falling at a given range contain a mixture of material excavated a different depths.



Ballistic ejecta emplacement

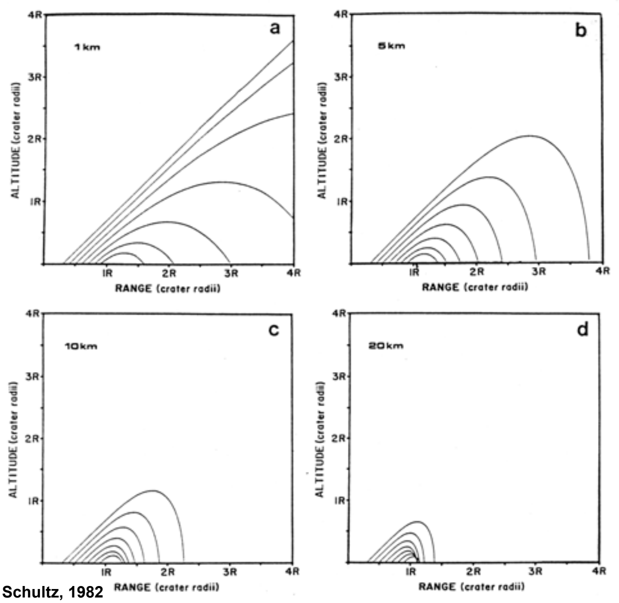


Meteor crater rim

Secondary craters

Euler crater (Moon)
+ Clusters of secondary impact from Copernic crater !

Ejecta emplacement – Interaction with the planetary atmosphere



Schultz, 1982

First effect of the atmosphere = Aerodynamic drag of ejecta fragments.

- Without the aerodynamic drag => Trajectories = parabolas
- The aerodynamic drag is more efficient for small particles

Simulation of ejecta trajectories for craters of different sizes under a martian atmosphere (particles diameter = 0.5 cm), Schultz, 1982.

Ejecta emplacement – Interaction with the planetary atmosphere

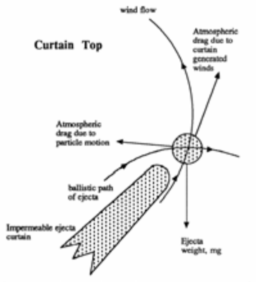
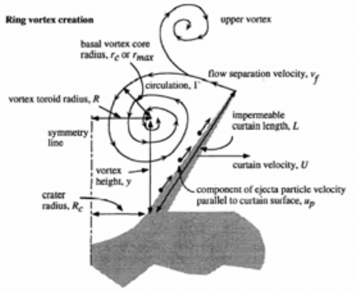
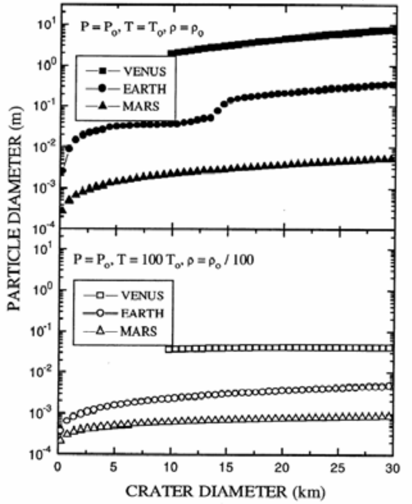


Figure 11. Sketch of forces affecting particles at the top of the ejecta curtain when the curtain becomes permeable. By balancing these forces, we can determine the maximum ejecta particle diameter that will be entrained by the curtain-generated winds (see text).



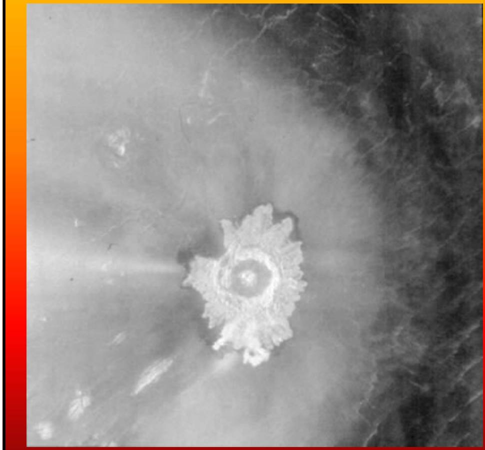
Particle sizes transported by impact winds, on Earth, Venus for the present conditions and for hot conditions.

Barnouin-Jha, 1996

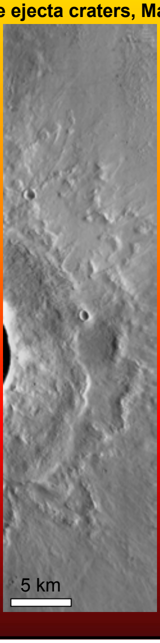


3.2 Excavation flow and ejecta emplacement

Lobate ejecta craters, Mars

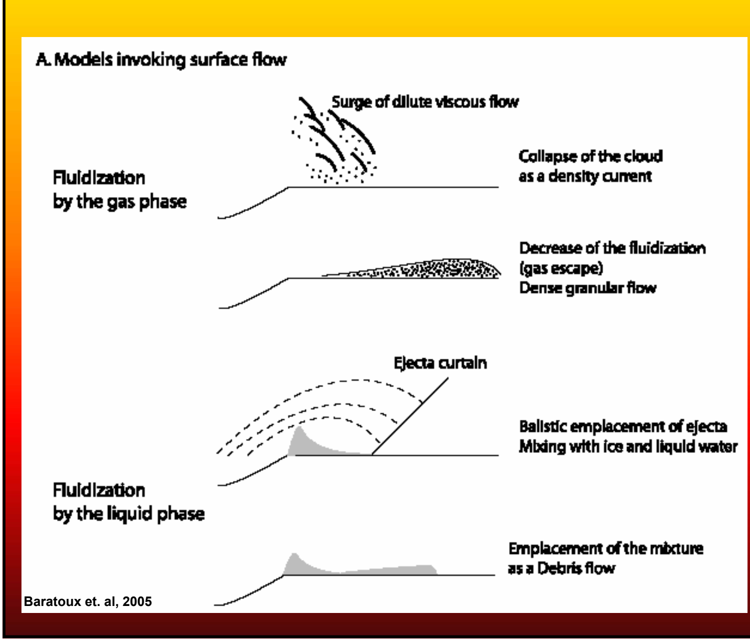


Adivar Crater (Venus), 27 km.



3.2 Excavation flow and ejecta emplacement

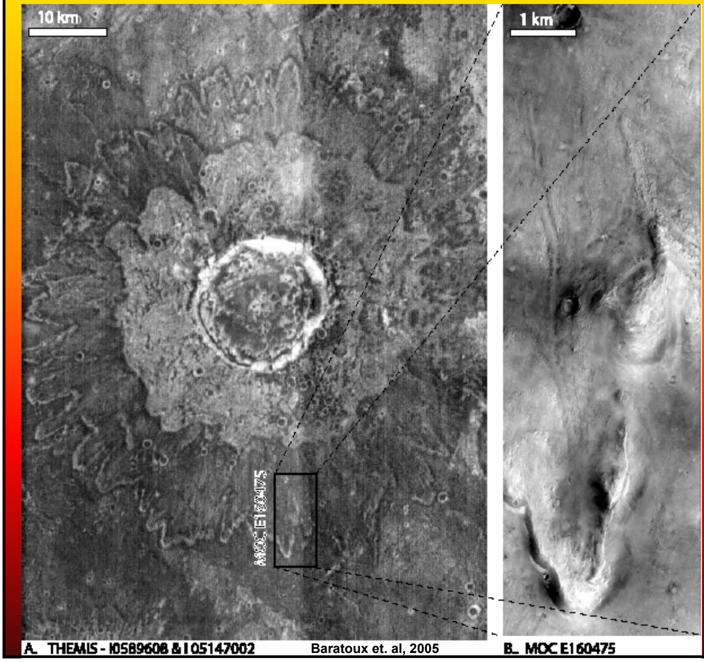
Fluidized ejecta on mars. Melting of sub-surface ice



Baratoux et. al, 2005

3.2 Excavation flow and ejecta emplacement

Fluidized ejecta on mars. Melting of sub-surface ice



Baratoux et. al, 2005

3.3 The case of large impact craters and basins

1. **Introduction**

2. **Elastic waves in solids and shock waves**
    - **2.1 Propagation of elastic waves**
    - **2.2 Hugoniot equations**
    - **2.3 Shock wave propagation and thermodynamics of impact**

3. **Formation and evolution of an impact crater**
    - **3.1 Contact and compression**
    - **3.2 Excavation flow and ejecta emplacement**
    - **3.3 The case of large impact craters and basins**
    - **3.4 Post-impact evolution of an impact crater (tectonism, erosion)**

4. **Criteria on the field**
    - **4.1 Morphologic and geometric evidences**
    - **4.2 Petrologic and mineralogic evidences**

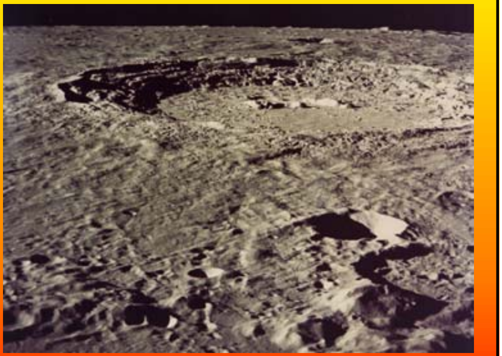
5. **Impact craters as a tool for the sounding of the sub-surface of solid planets**

6. **Impact craters as a tool for the datation of planetary surfaces**

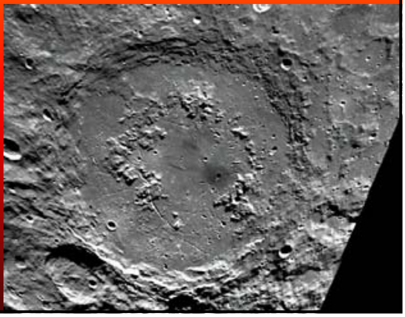
3.3 The case of large impact craters and basins

Euler, 27 km

Copernic, 93 km

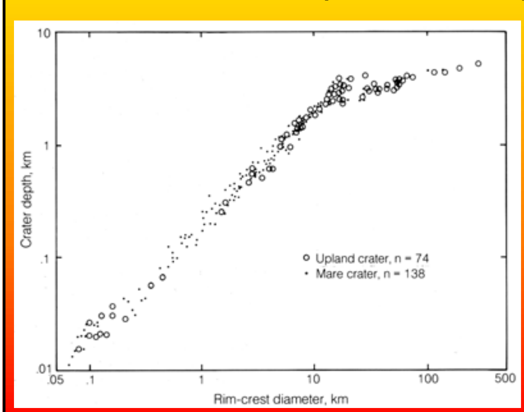


Schrodinger, 320 km



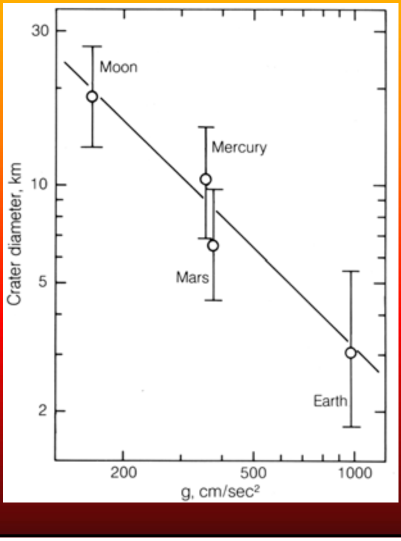
3.3 The case of large impact craters and basins

Simple craters – complex craters



Transition diameter simple crater – complex crater for the Moon

Transition diameter for simple crater – complex crater for solid planets

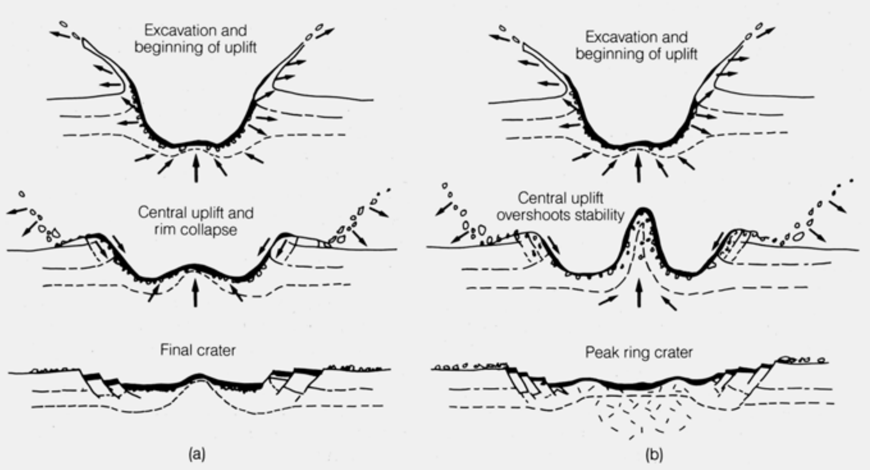


Simple craters – complex craters

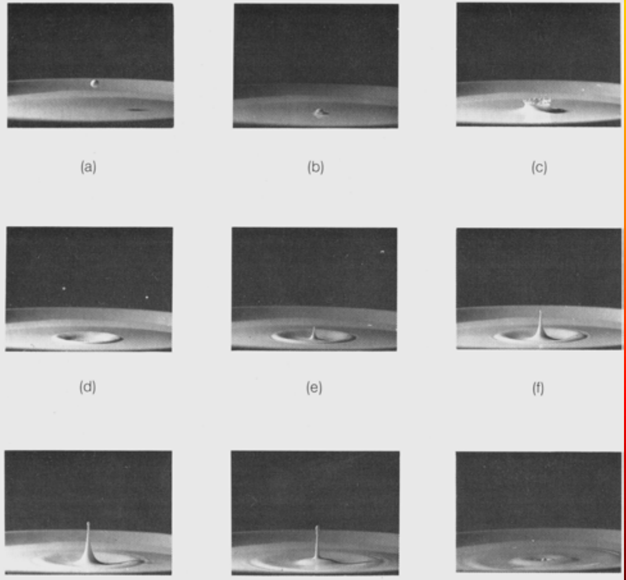
Stages of formation of a complex crater, Melosh, 1989.

Complex crater with a central peak

Complex crater with a central ring



Simple craters – complex craters



Hydrodynamical model for the formation of a complex crater

Analog of the formation of a central peak or a pink ring.

3.3 Post-impact evolution of an impact crater

1. **Introduction**

2. **Elastic waves in solids and shock waves**
   - **2.1 Propagation of elastic waves**
   - **2.2 Hugoniot equations**
   - **2.3 Shock wave propagation and thermodynamics of impact**

3. **Formation and evolution of an impact crater**
   - **3.1 Contact and compression**
   - **3.2 Excavation flow and ejecta emplacement**
   - **3.3 The case of large impact craters and basins**
   - ➡ **3.4 Post-impact evolution of an impact crater (tectonism, erosion)**

4. **Criteria on the field**
   - **4.1 Morphologic and geometric evidences**
   - **4.2 Petrologic and mineralogic evidences**

5. **Impact craters as a tool for the sounding of the sub-surface of solid planets**

6. **Impact craters as a tool for the datation of planetary surfaces**

3.3 Post-impact evolution of an impact crater

Erosion, volcanism, tectonism

On Earth, various geological processes strongly contribute to the alteration/erosion and finaly progressively erose of old impact structures.

1) Tectonics
   Crater deformation, buried craters, subduction of craters on oceanic floors.

2) Sedimentation
   Buried crater under sedimentary layers

3) Volcanism
   Buried craters under volcanic layers/edifices

4) Erosion
   Wind erosion, fluvial erosion or glacial erosion

3.3 Post-impact evolution of an impact crater

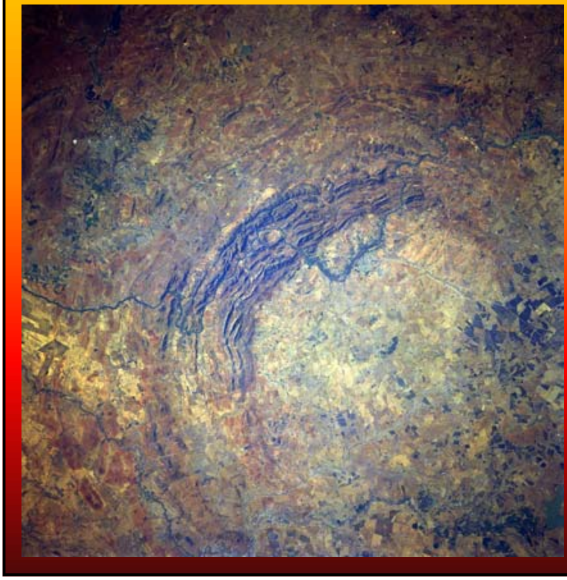
Erosion

Localization: *51°23'N, 68°42'W*
Diameter (initial): *~100 kilometers*
Age: *214 ± 1 million years*

Manicouagan

3.3 Post-impact evolution of an impact crater

Erosion



Vredefort

Localization *27°00'S, 27°30'E*
Diameter (estimation shock metamorphism): *~300 kilometers*
Age: *2023 ± 4 million years*

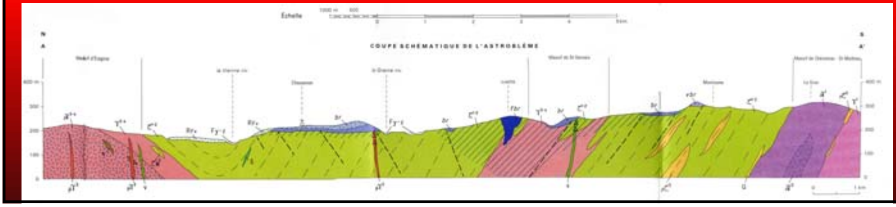
The oldest crater on Earth

3.3 Post-impact evolution of an impact crater

Erosion

Rochechouart

Contact between the fractured basement and the breccias in the crater floor.



3.3 Post-impact evolution of an impact crater

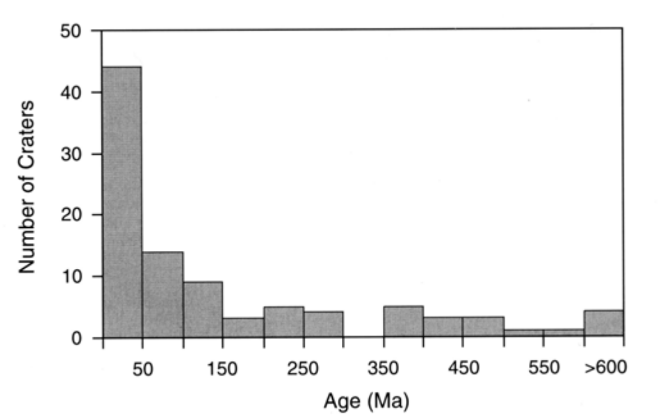
Erosion

« Remnants » of the crater in the Island morphology…
Crater mostly eroded and buried under sedimentary layers

Localization : Hiiuma Island Estonia
Diamèter : 4 km
Age : 450 millions years

Erosion of terrestrial impact craters

Progressive erase of old craters



Erosion of impact crater on other planetary surfaces

On Mars, all geological processes identified on Earth may contribute as well to the degradation of impact craters (except those related to plate tectonics):

1) Tectonism
   Crater deformation, buried crater (no subudction or mountain belt formation…)
2) Sedimentation
   Buried crater under martian sediments (northern hemisphere – ghost craters)
3) Volcanism
   Buried craters under volcanic layers and edifices
4) Erosion
   Wind erosion, fluvial erosion or glacial erosion as well

Erosion of impact crater on other planetary surfaces

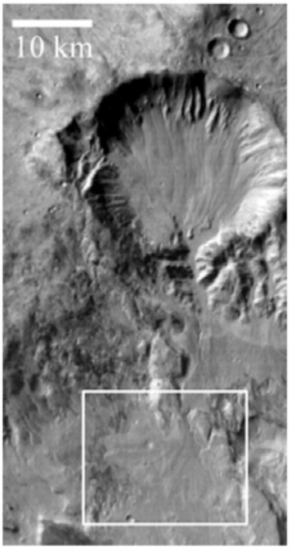


Figure 1. The fluvial modifications of a crater near Terby Crater. Notice the delta-like formation within the box. This figure is part of THEMIS-IR image I01571002.

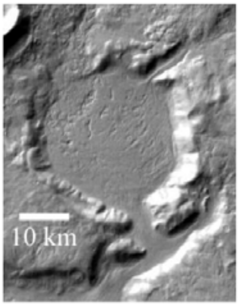
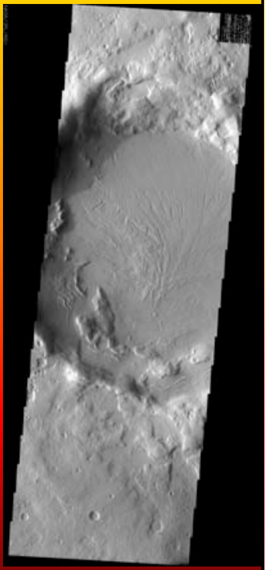
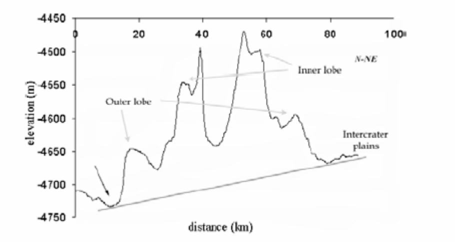


Figure 3. Crater with apparent "feeding" channel and substantially larger outflow channel from THEMIS-IR image I01982002.



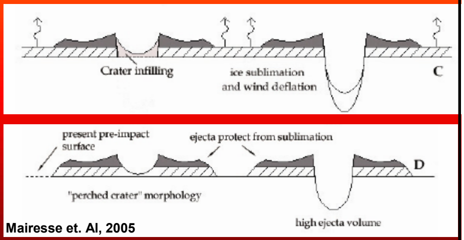
Remplissage des cratères

Perched craters and eolian deflation of the northern plains of Mars ?



3.3 Post-impact evolution of an impact crater

Perched craters and eolian deflation of the northern plains of Mars ?



Mairesse et. Al, 2005

3.3 Post-impact evolution of an impact crater

Erosion of impact crater on other planetary surfaces

Strom et al., 1994

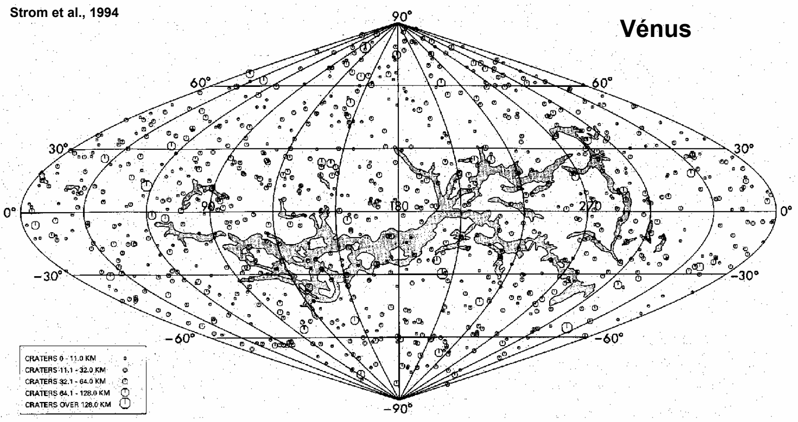


Figure 1a. Map in sinusoidal equal-area projection showing the sizes and distribution of the 932 impact craters on 98% of Venus' surface. Sizes of symbols are scaled to crater diameter bins but not to map. Shaded areas indicate fracture belts of concentrated extensions (modified from *Schaber* [1982] using Magellan data).

- Random distribution of the craters at the Venus surface
- Fresh crater, no-erosion even in the presence of the Venusian atmosphere.

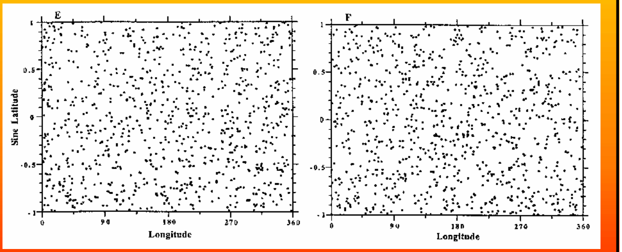
3.3 Post-impact evolution of an impact crater

Erosion of impact crater on other planetary surfaces

Less than 1000 impact craters for all the Venus surface !

⇒Estimated age between 300 et 700 millions years (impact-rate model-dependent)

Random distribution of impact craters => similar age for all the surface



Random distribution / Venus distribution

This situation is unique in the solar system at the planetary scale

Consequences for the dynamics and the thermal history of Venus :

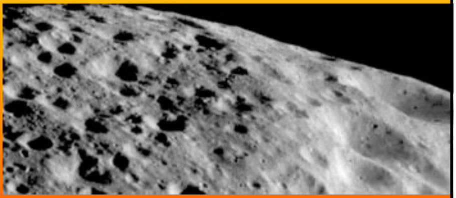
Global resurfacing of Venus 500 millions year ago, Catastrophic event, unit even, progressive event ?

3.3 Post-impact evolution of an impact crater

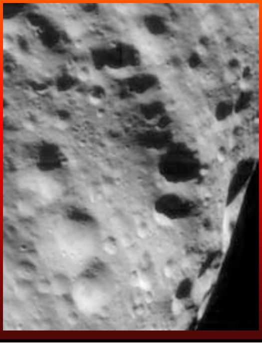
Impact crater erosion on the Moon, asteroids or Mercury (without atmosphere) ?

Moon, asteroids, Mercury => No winds, no surface, no water…=> Surface erosion ?

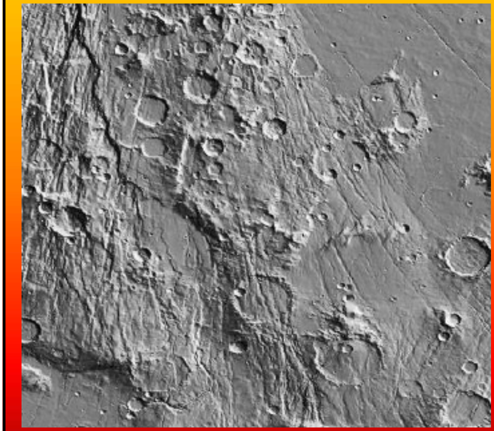
Erosion occurs due to impact cratering itself (small craters erode big ones !)



Eros surface images (NEAR)



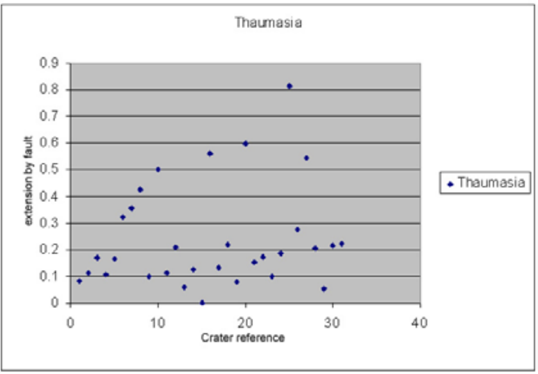
Tectonic deformation

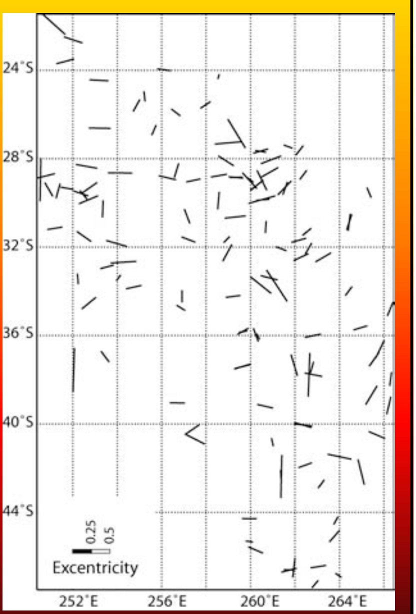


Thaumasia, Mars (Shaded relief à partir des données MOLA/NASA)

Exemple de cratère d'impact déformés par le mouvements de failles extensives (Thaumasia)

Tectonic deformation





Allemand et. Al, LPSC 2006