M2

Cratères d’impacts et métamorphisme de choc

Première partie:

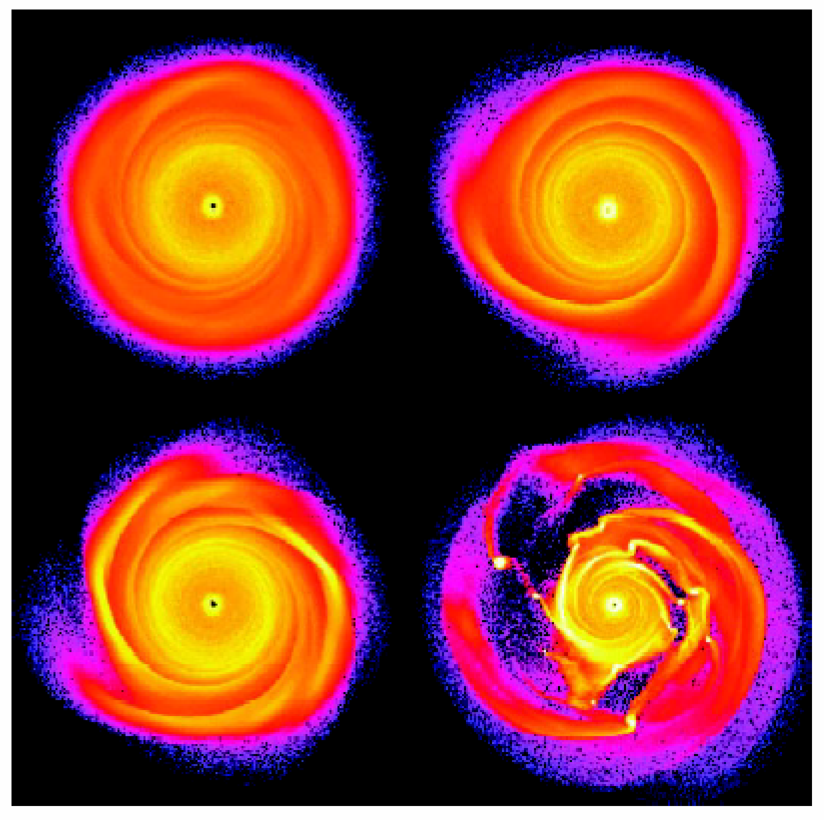
L’accrétion des planètes

La nébuleuse proto-solaire.

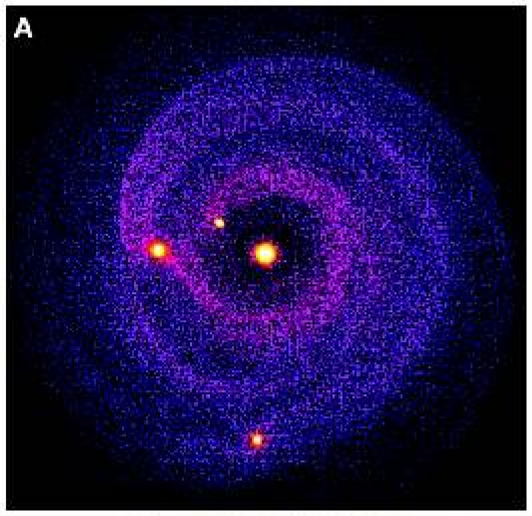
t~ -4.568 Ga

Les résolutions des télescopes actuels ne permettent pas d'observer dans le détail les mécanismes d'acrétion…

La formation des planètes



Mayers et al., 2002, *AJ*



Simulation.
On connaît la masse du SS
On connaît son moment d'inertie (+-)
On fait tourner le code

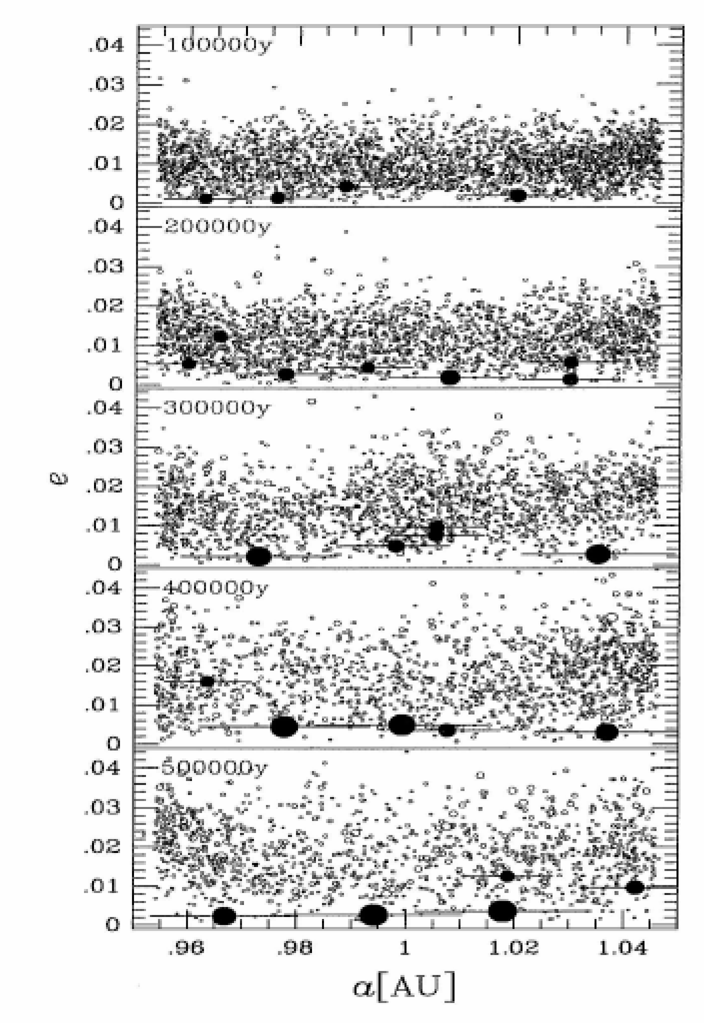
Des planètes aux planétésimaux

Mouvement et choc de particules en suspension dans un gaz

- collage par choc et sédimentation dans le plan équatorial du disque (environ 10^4 ans). Du micron au centimètre

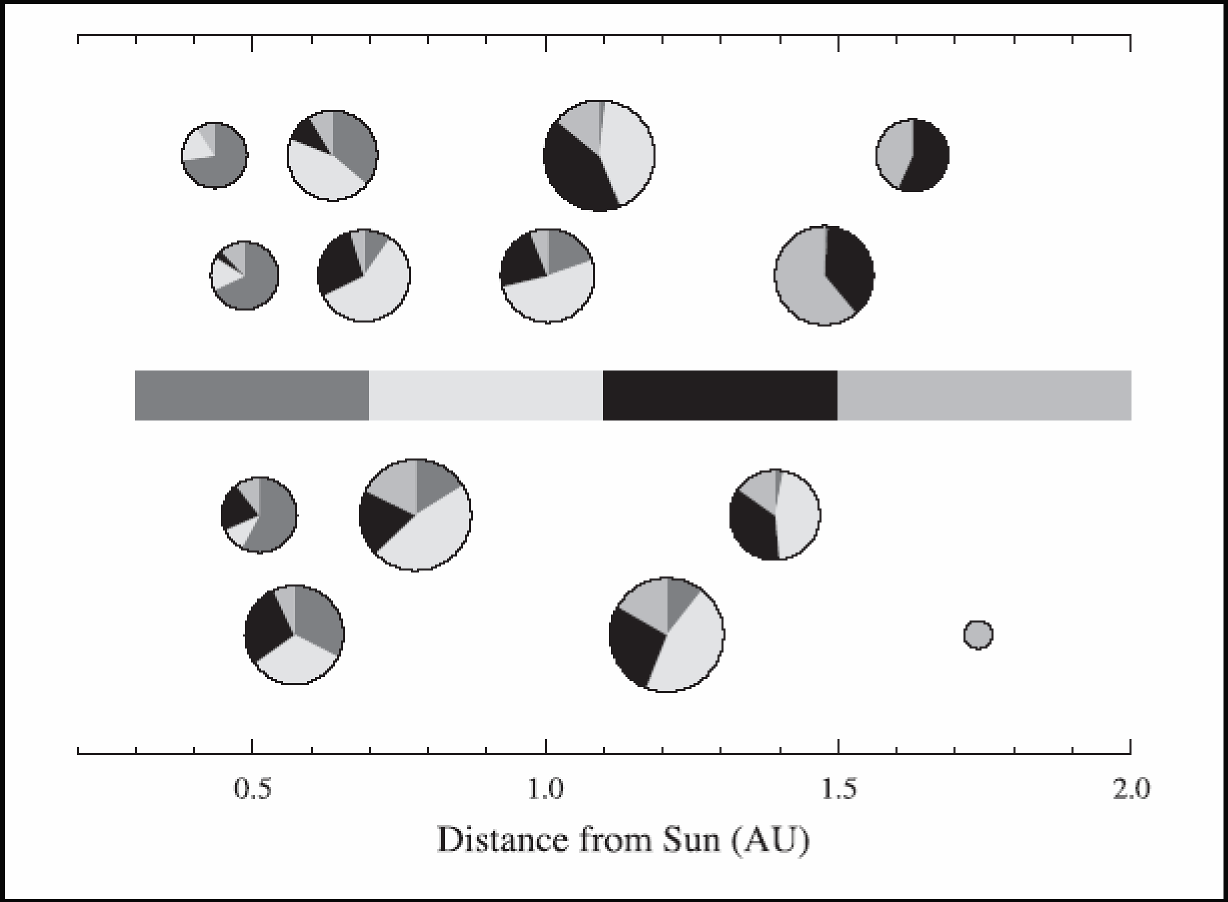
- du centimètre au kilomètre : dépend de la vitesse relative des grains et blocs

La formation des planètes internes



Kokubo et Ida., 2000, *Icarus*

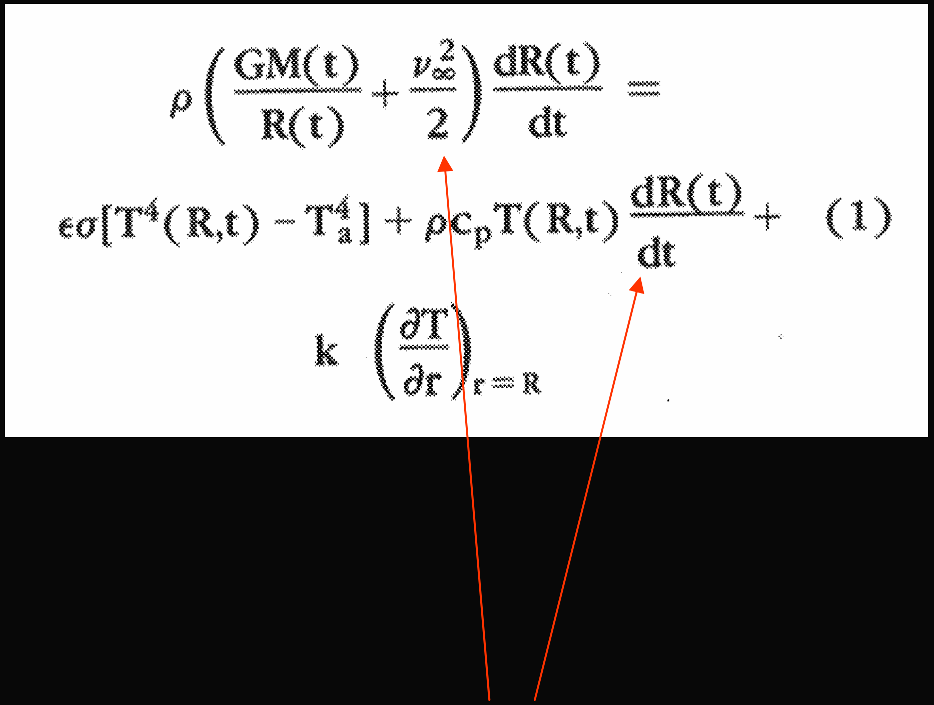
La formation des planètes: le mélange



Chambers (2004) *EPSL*

Impact et accrétion des planètes

Equation de conservation de l’énergie



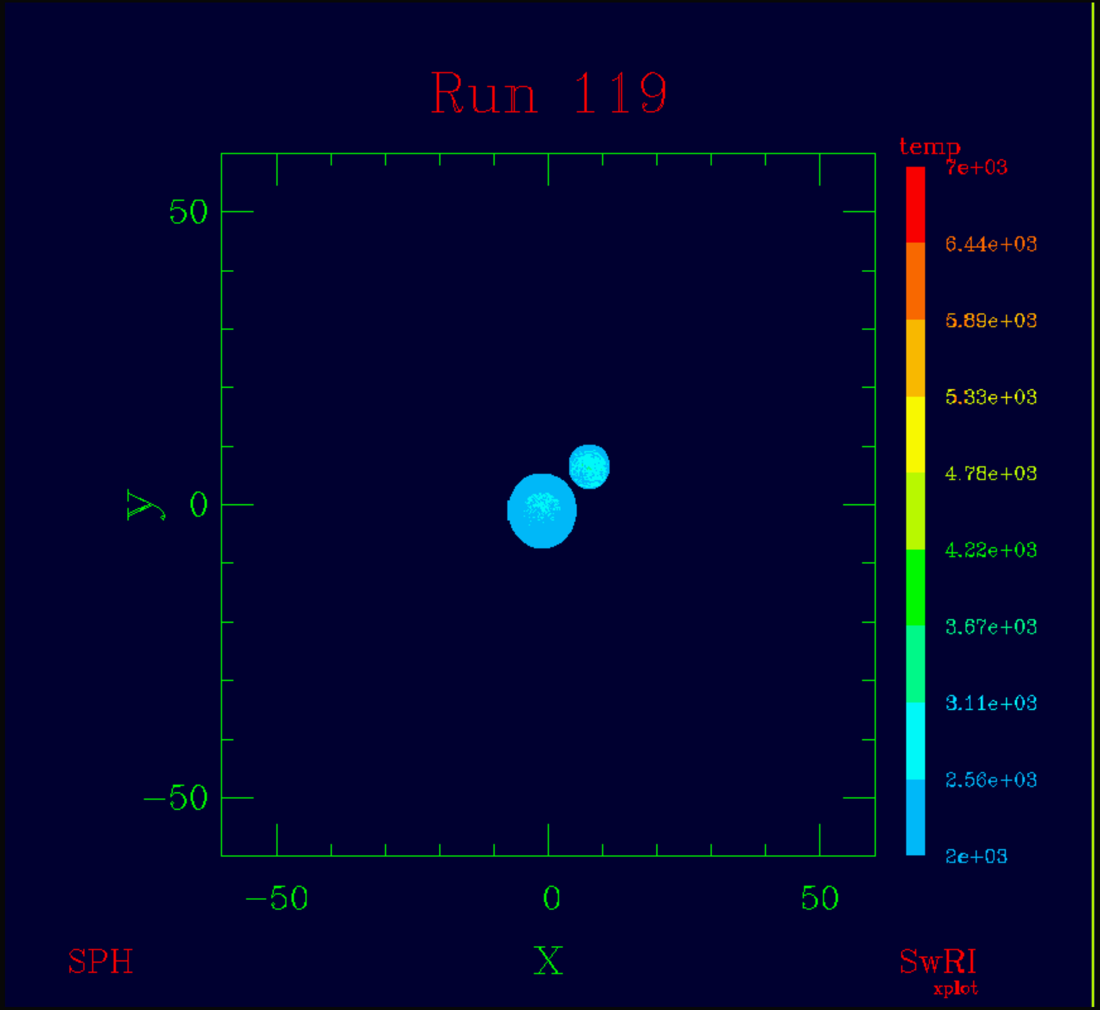
$$\rho\left(\frac{GM(t)}{R(t)}+\frac{v_\infty^2}{2}\right)\frac{dR(t)}{dt} =$$

$$\epsilon\sigma[T^4(R,t)-T_a^4]+\rho c_p T(R,t)\frac{dR(t)}{dt}+ \quad (1)$$

$$k\left(\frac{\partial T}{\partial r}\right)_{r=R}$$

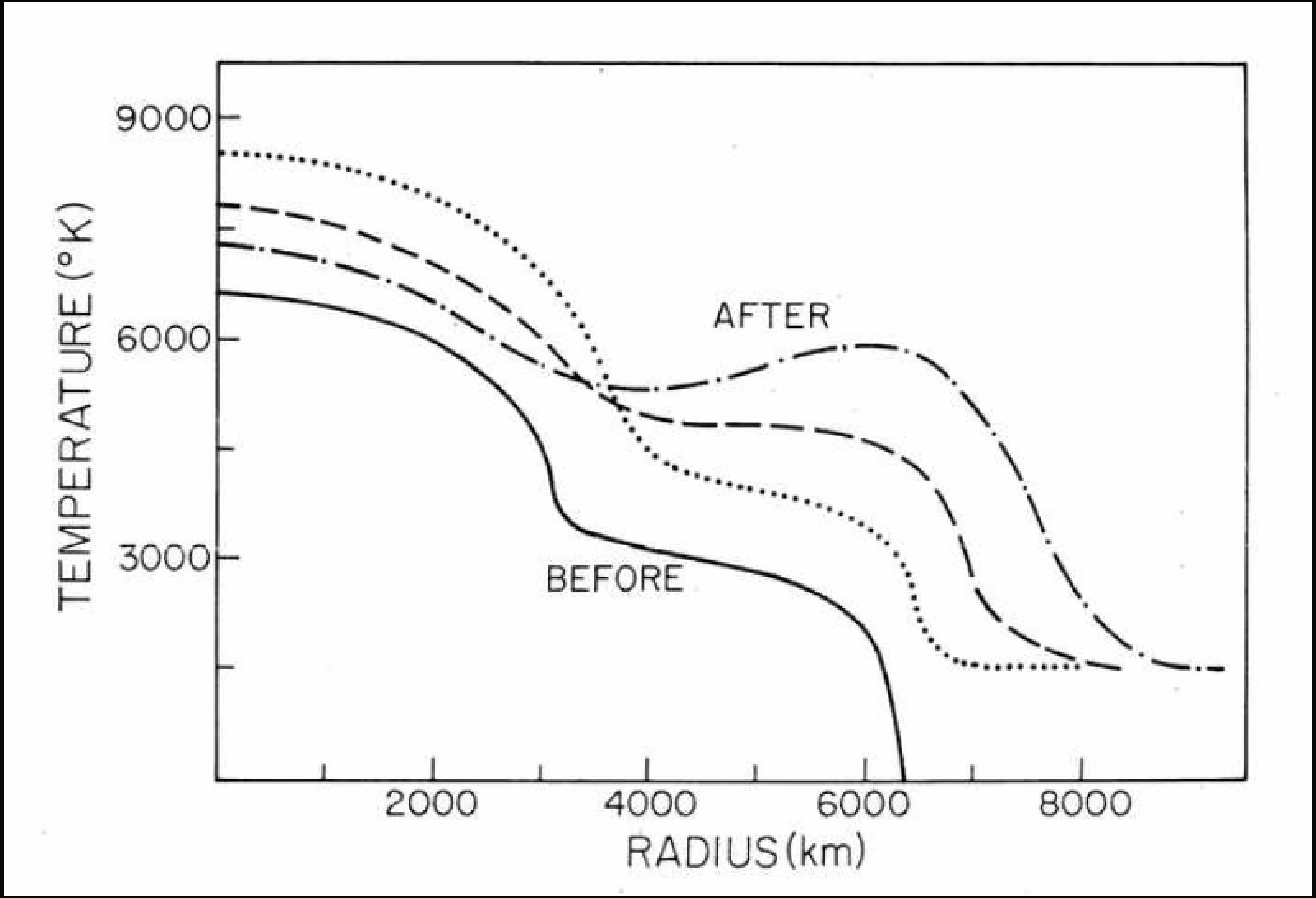
Le choc permet le transfert d’énergie.

La formation de la Lune



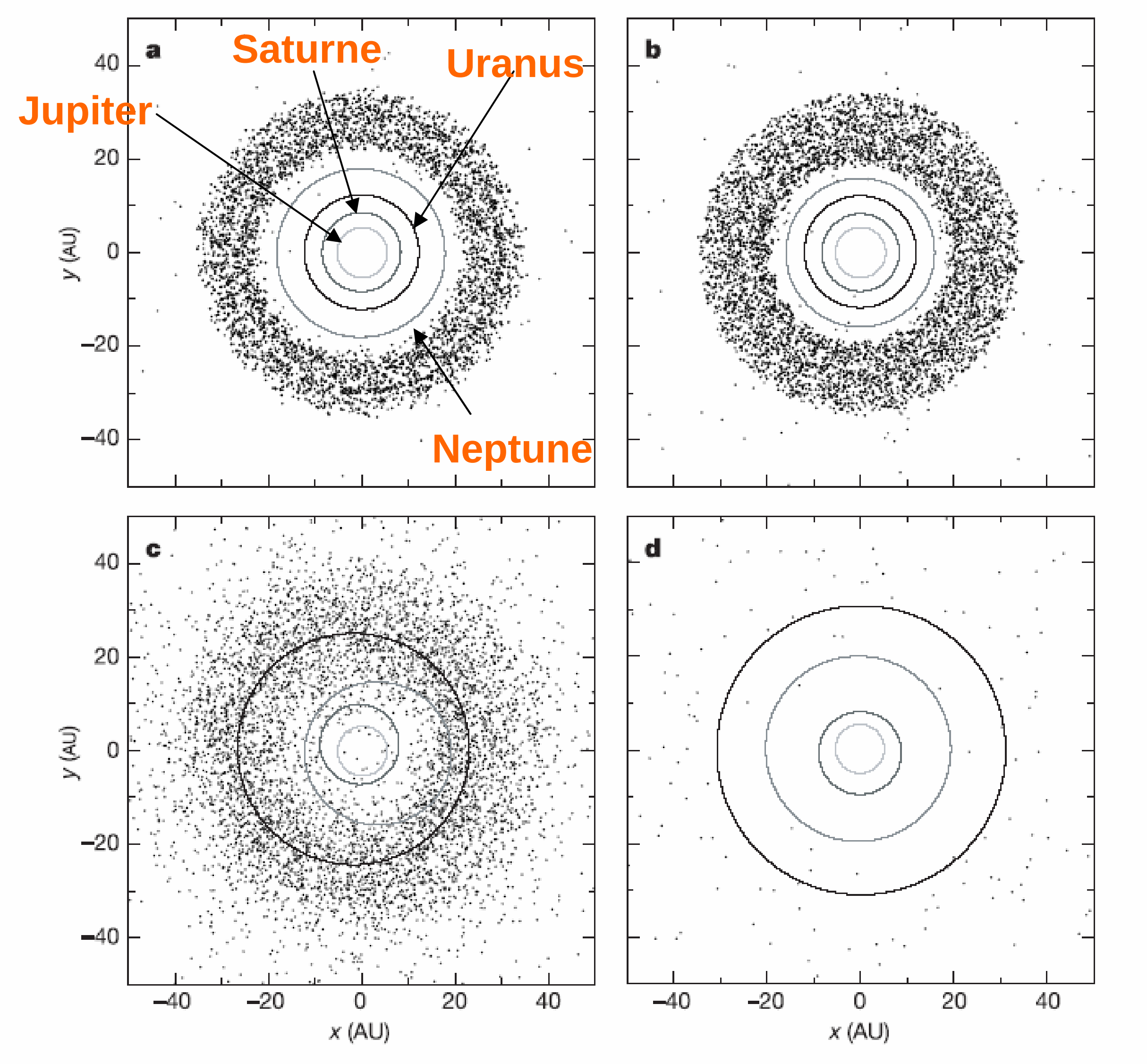
Canup (2004) *Icarus*

La formation de la Lune



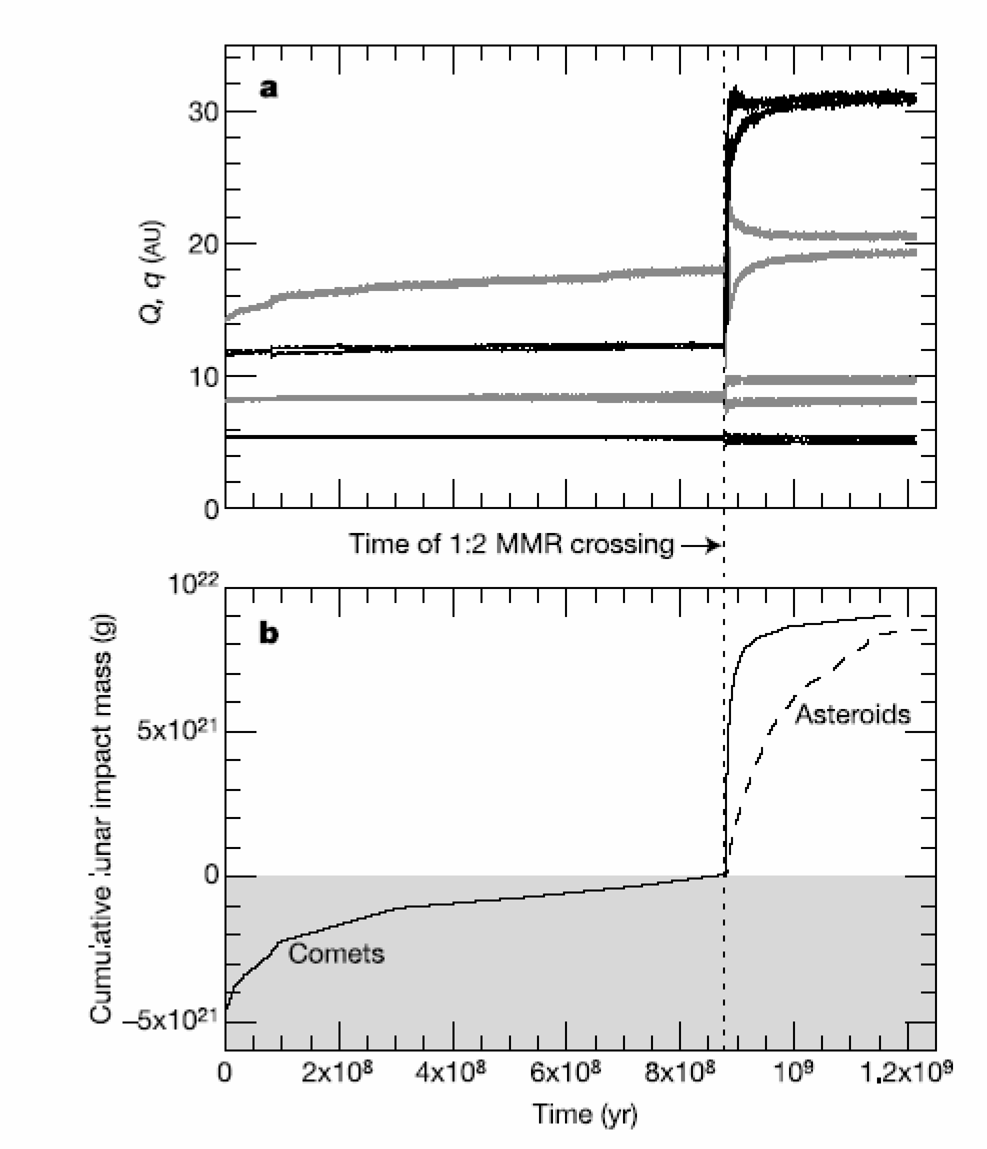
Stevenson (2004)

Le bombardement cataclysmique



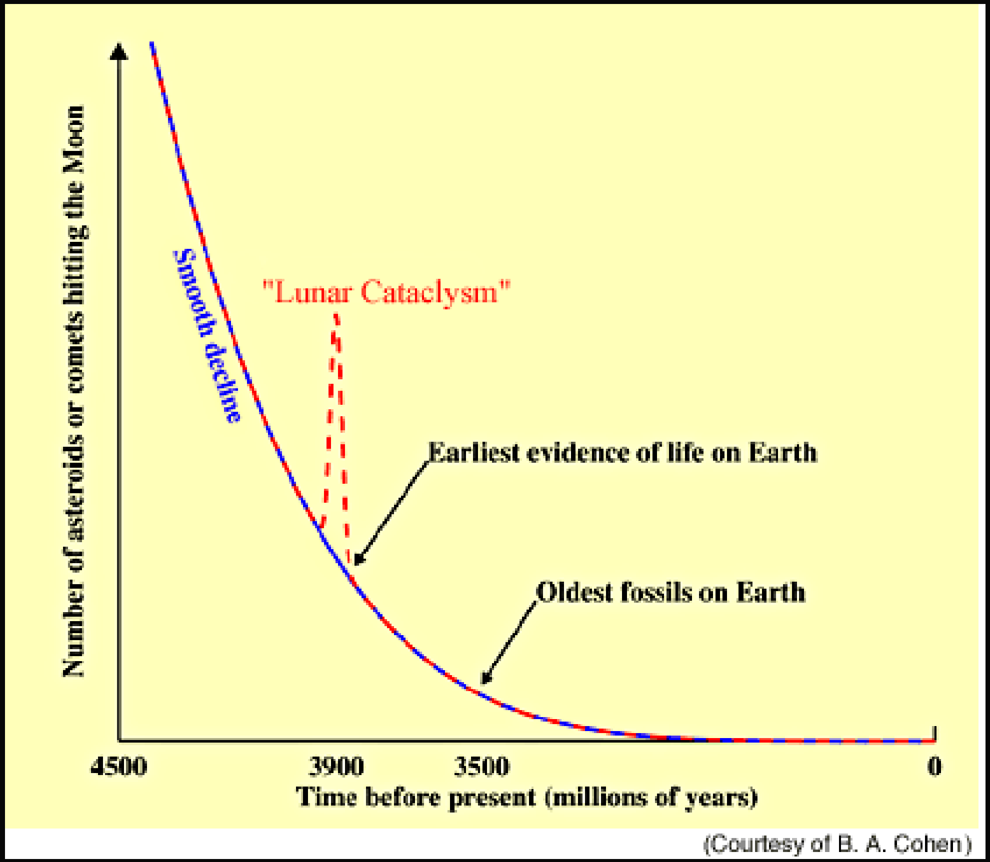
Gomes et al. (2005) *Nature*

Le bombardement cataclysmique



Gomes et al. (2005) *Nature*

Le bombardement cataclysmique de la Lune (et de la Terre)



(Courtesy of B. A. Cohen)

Le bombardement cataclysmique sur Terre. Le vernis tardif?

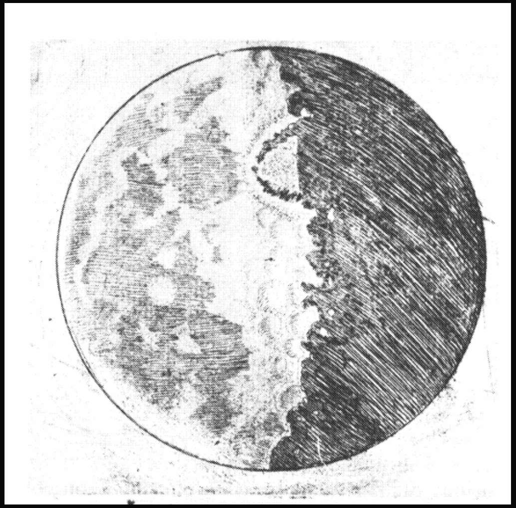
La concentration en éléments très sidérophiles du manteau terrestre (Os, Ir, Ru, Rh, Pd, Pt..), est trop élevée par comparaison au partage attendu métal/silicate lors de la formation du noyau terrestre.

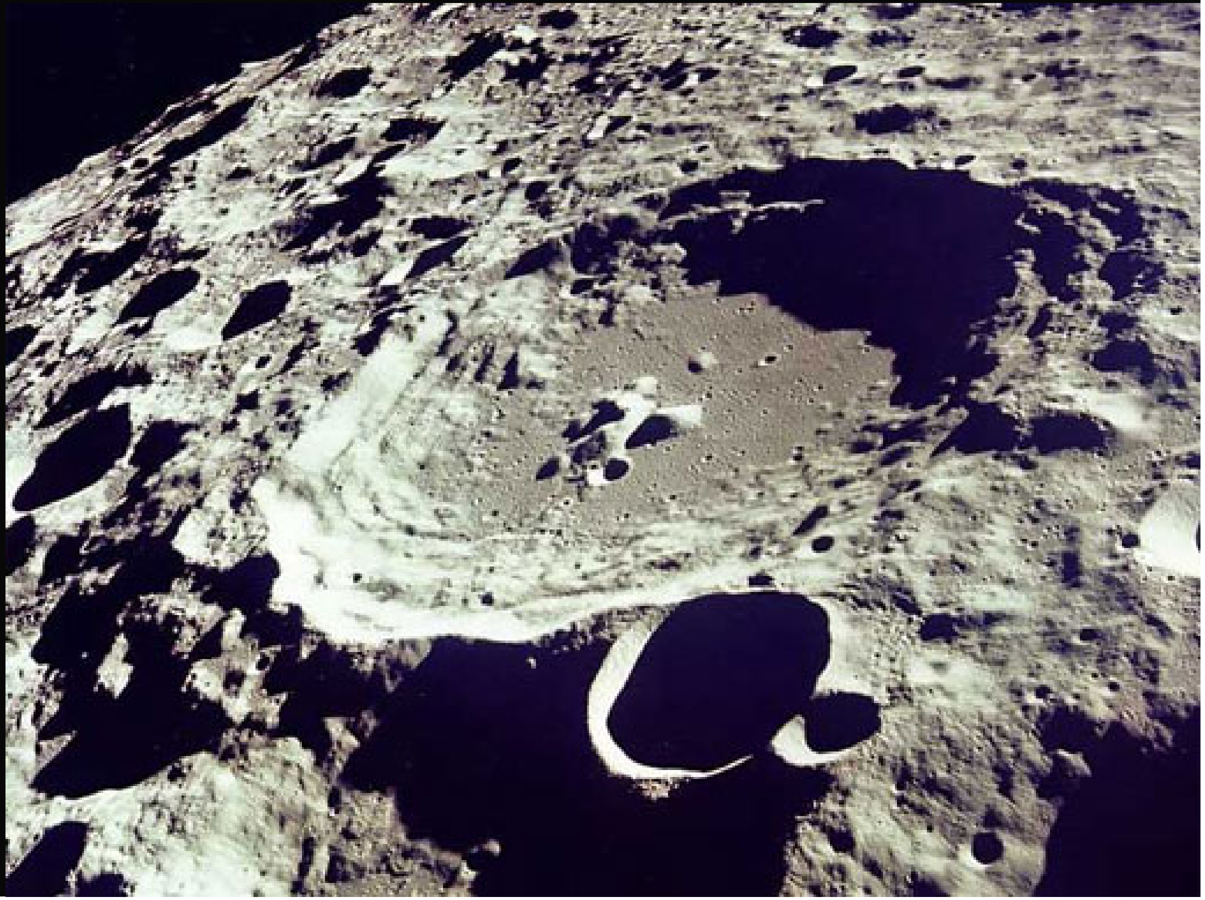
Ces éléments auraient été apportés par un bombardement tardif, après la formation du noyau terrestre. C’est le vernis tardif.

Deuxième partie:

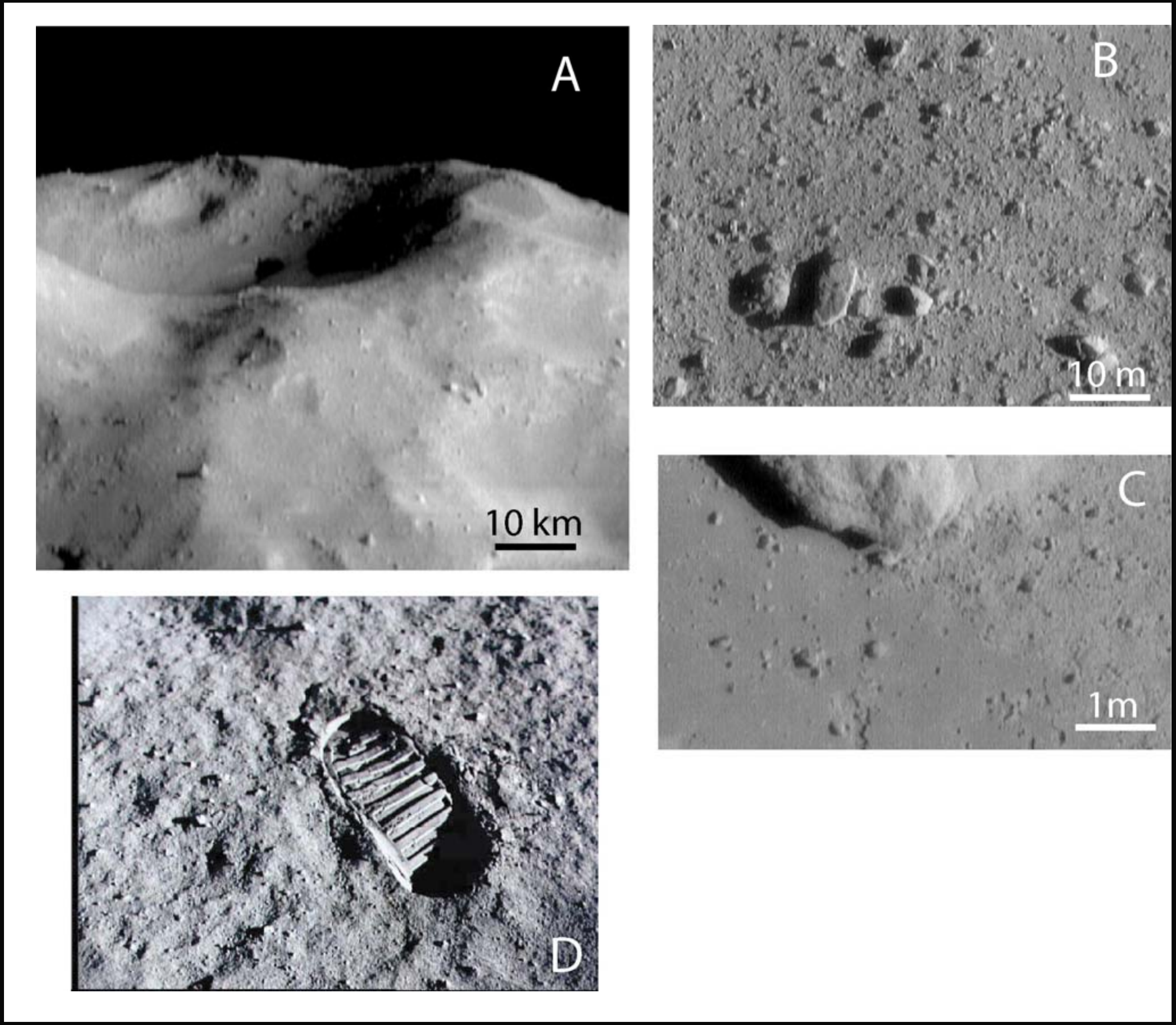
Les surfaces planétaires

La surface de la Lune

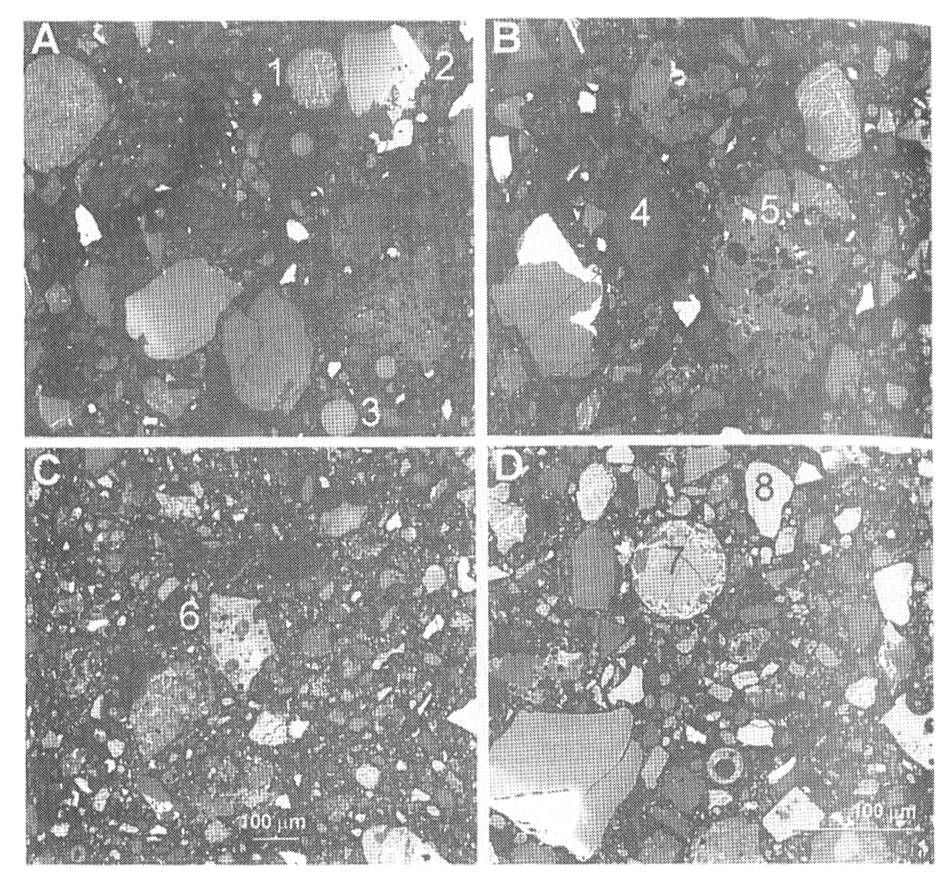


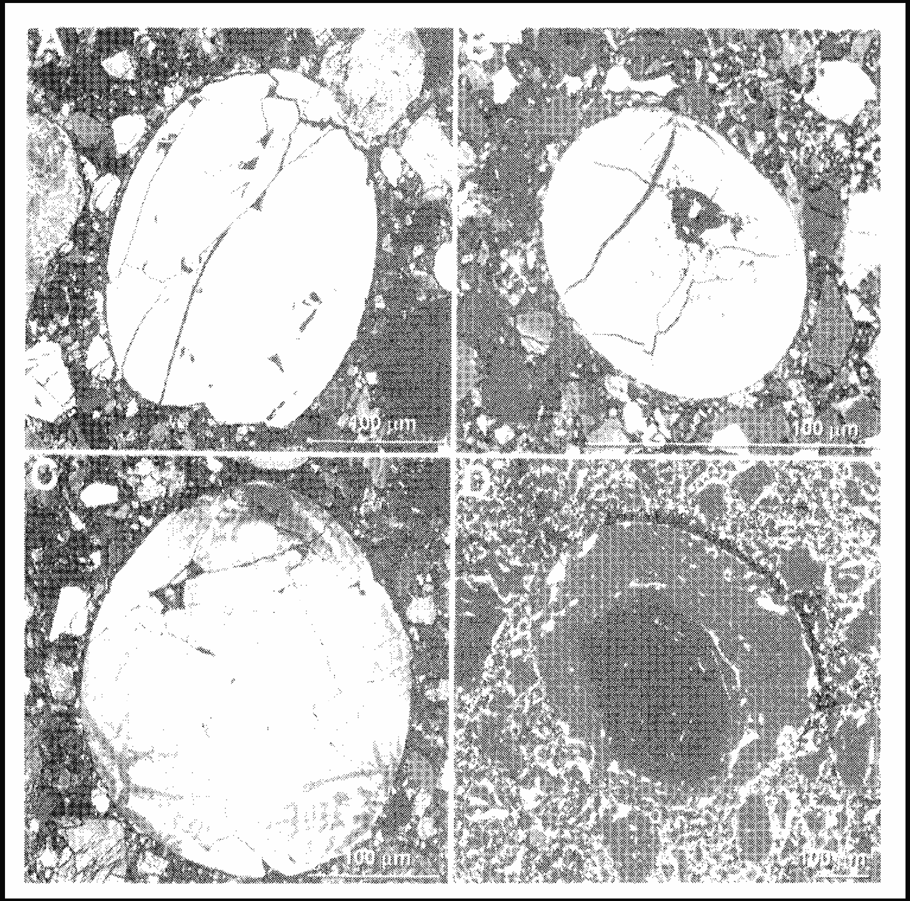


Le régolithe

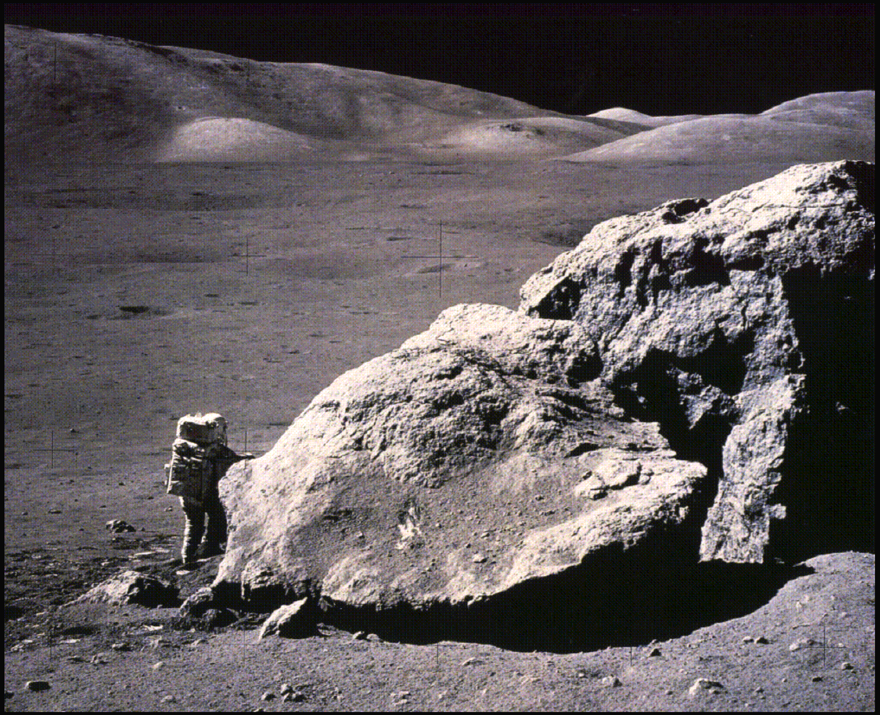


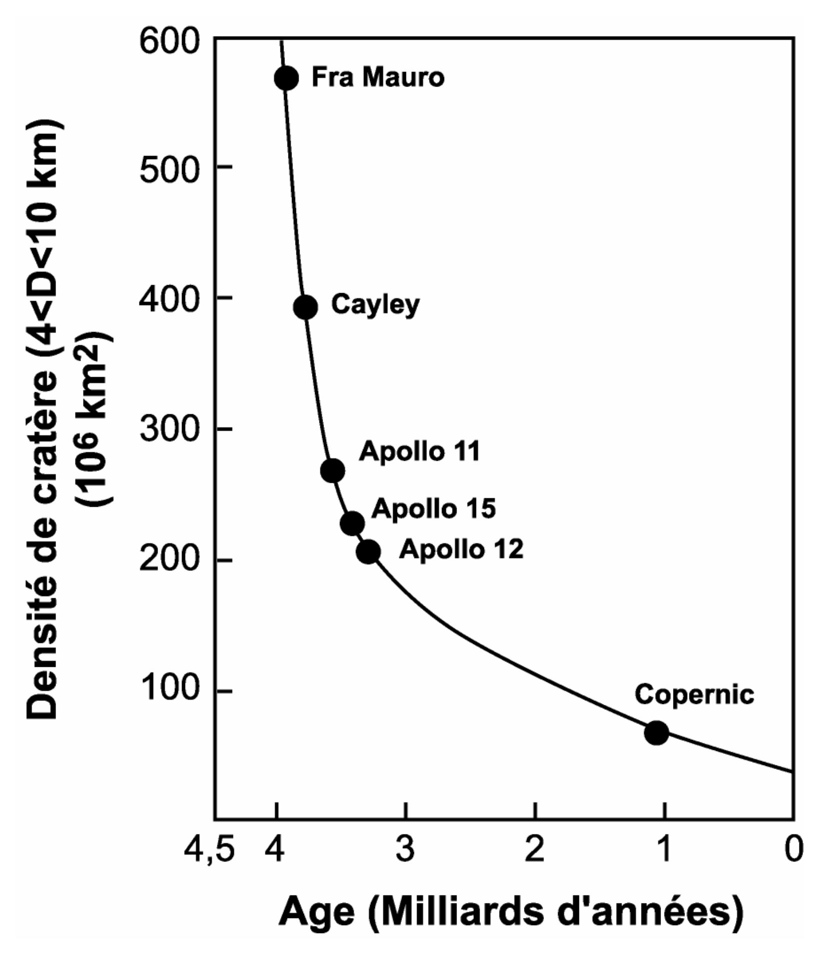
Le régolithe lunaire



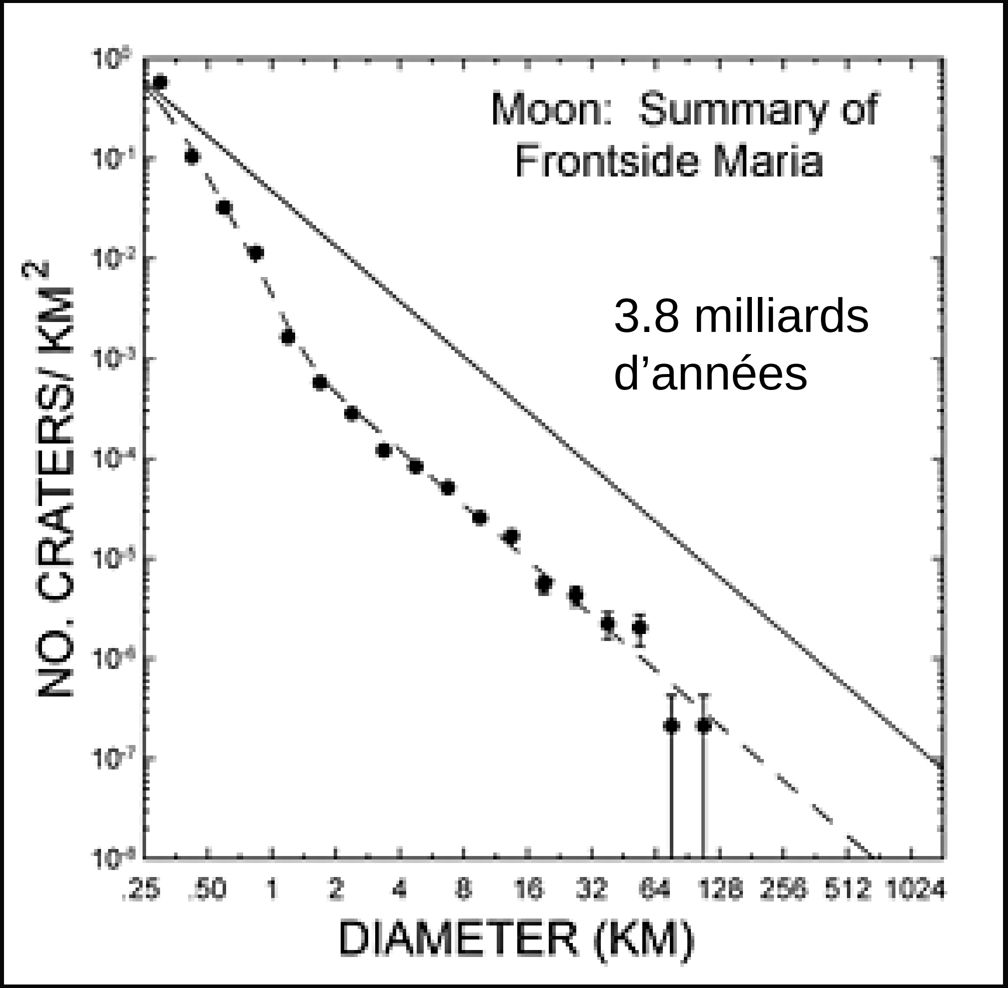


L’échelle chronostratigraphique lunaire.



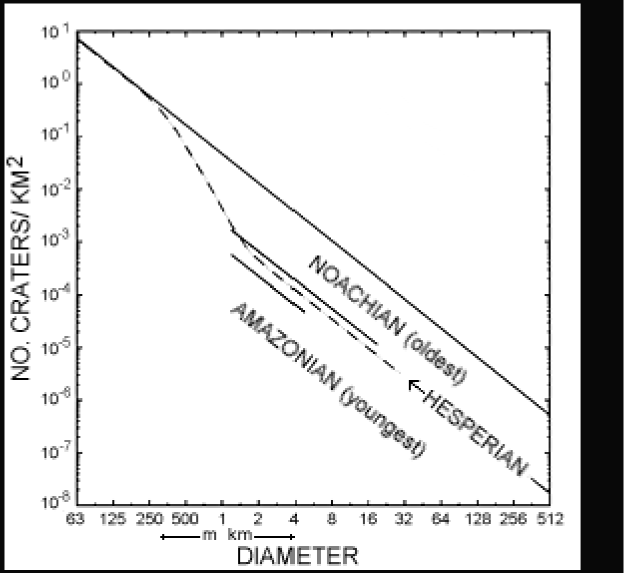


L’échelle chronostratigraphique lunaire.

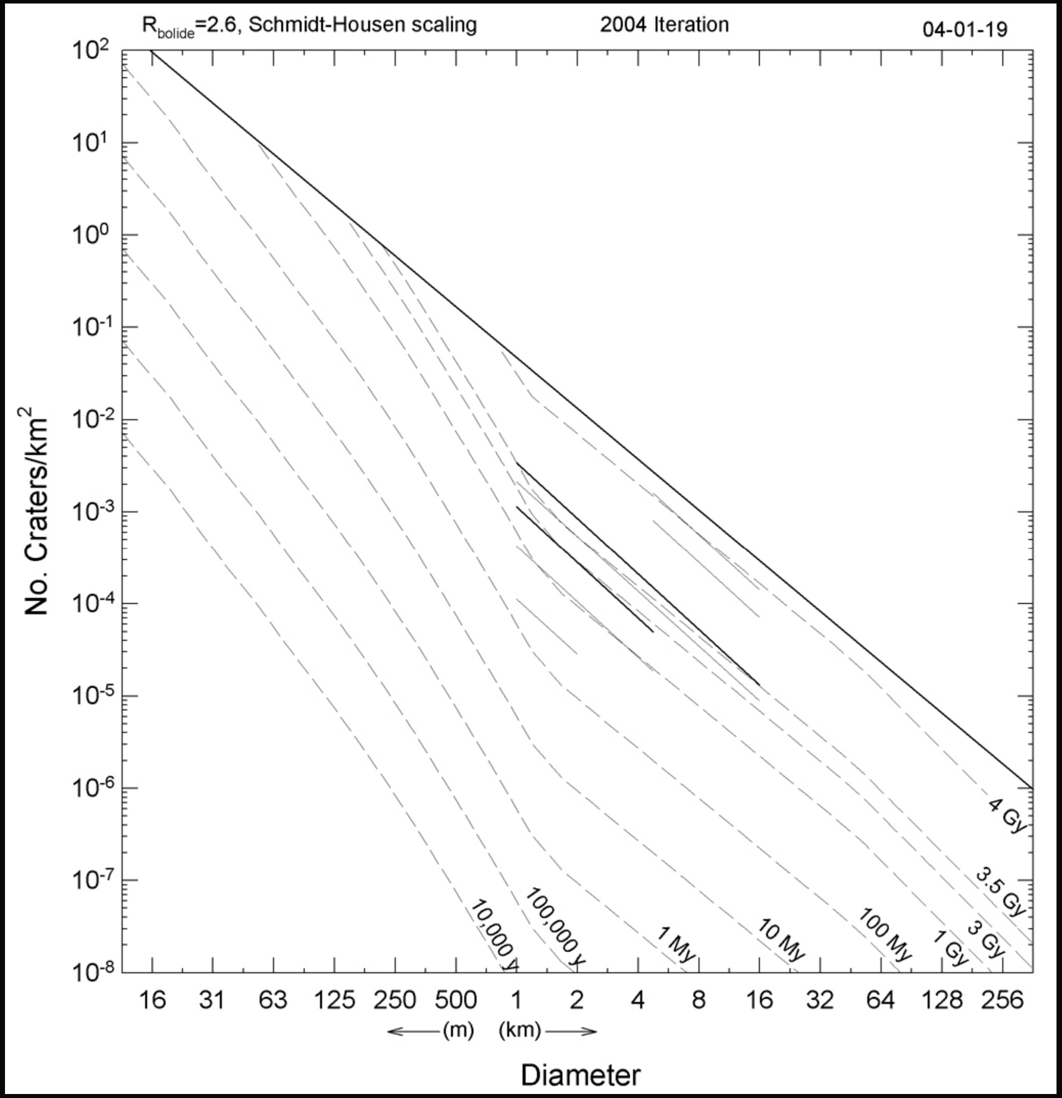


L’echelle chronostratigraphique lunaire est la référence permettant de dater les surfaces planètaires

L’échelle martienne

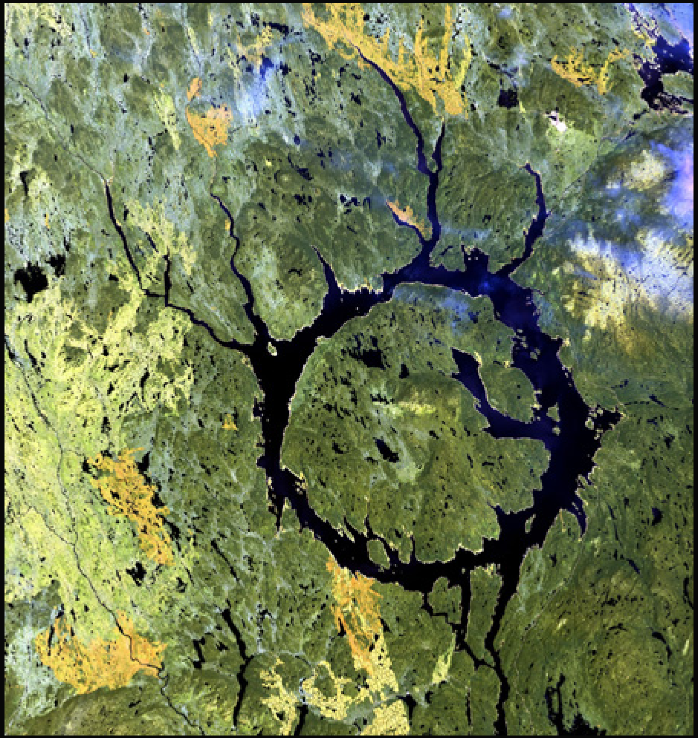


Correction de:
- la différence de gravité
- le flux d’astéroïdes/comètes

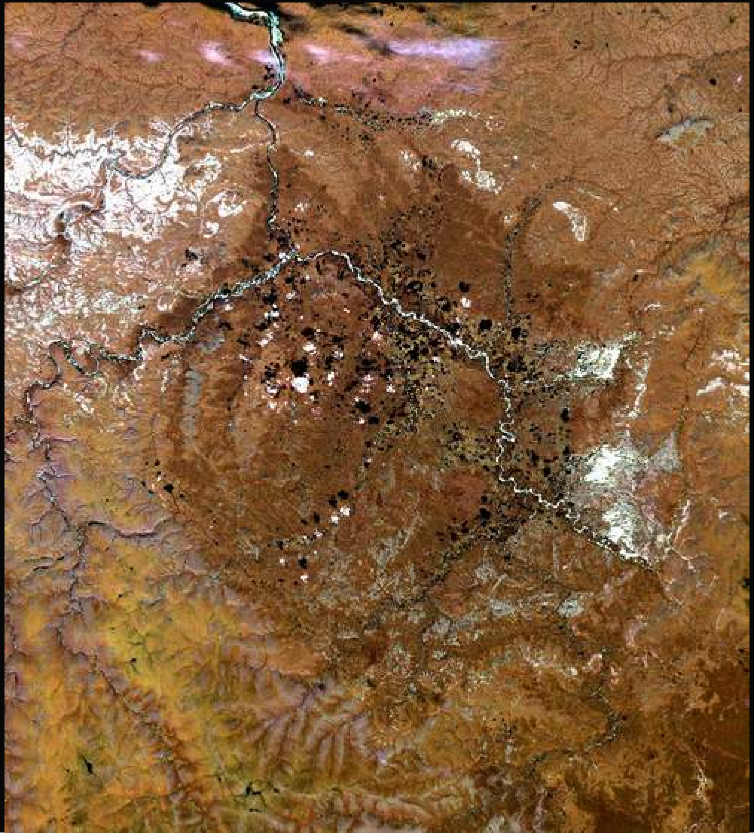


Echelle dérivée de l’echelle lunaire. Les âges ont une erreur d’un facteur 2.

Les cratères terrestres

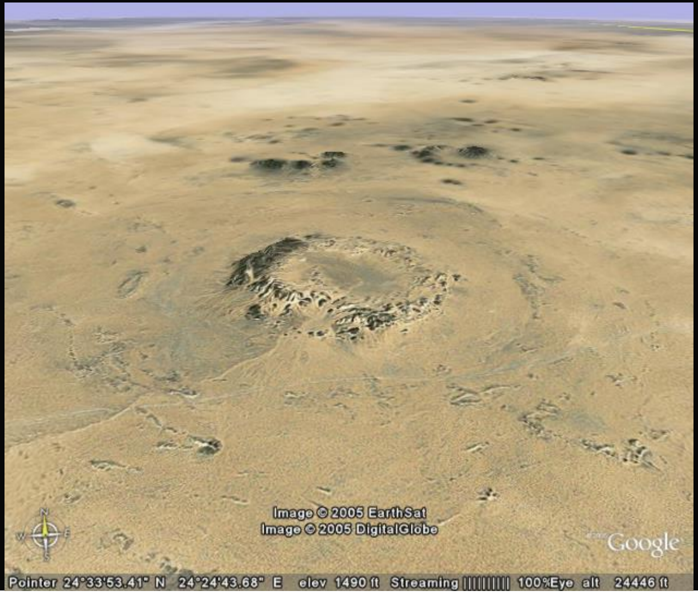


Popigai



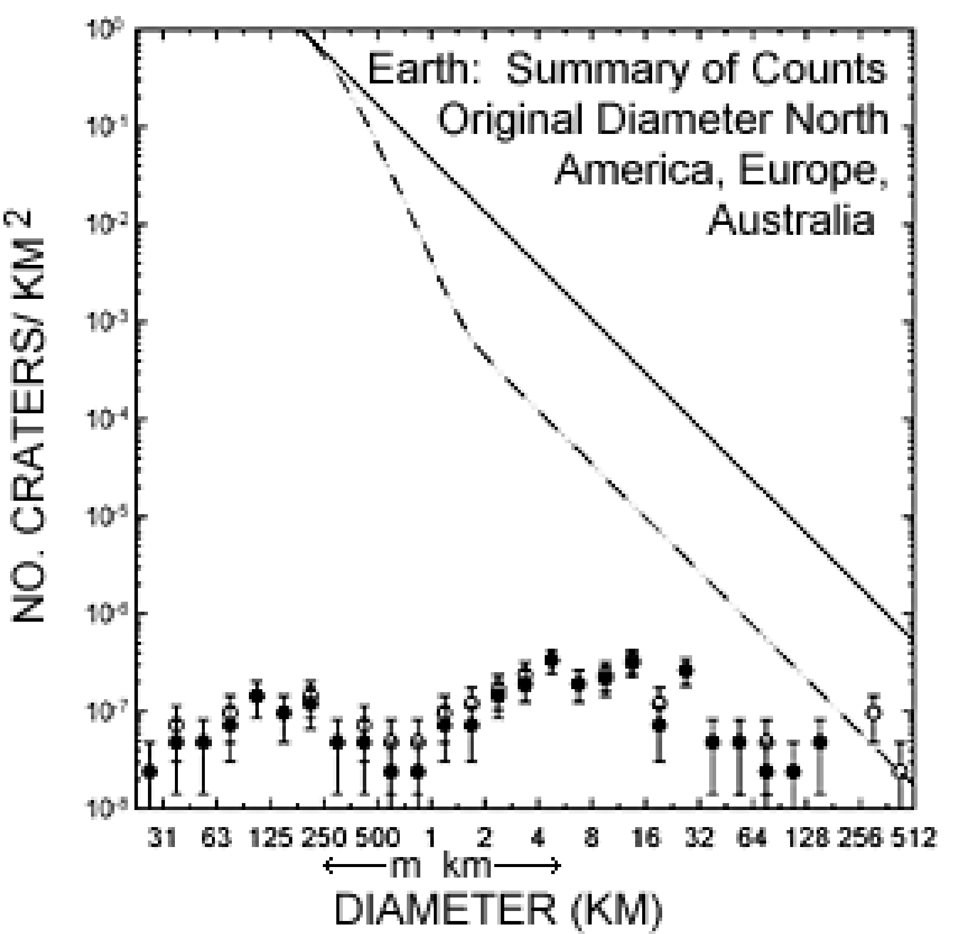
Manicouagan

Les cratères terrestres



Les cratères terrestres

Paillou et al. (2004) *CRAS*



Hartmann and Neukum (2001) *PSSR*

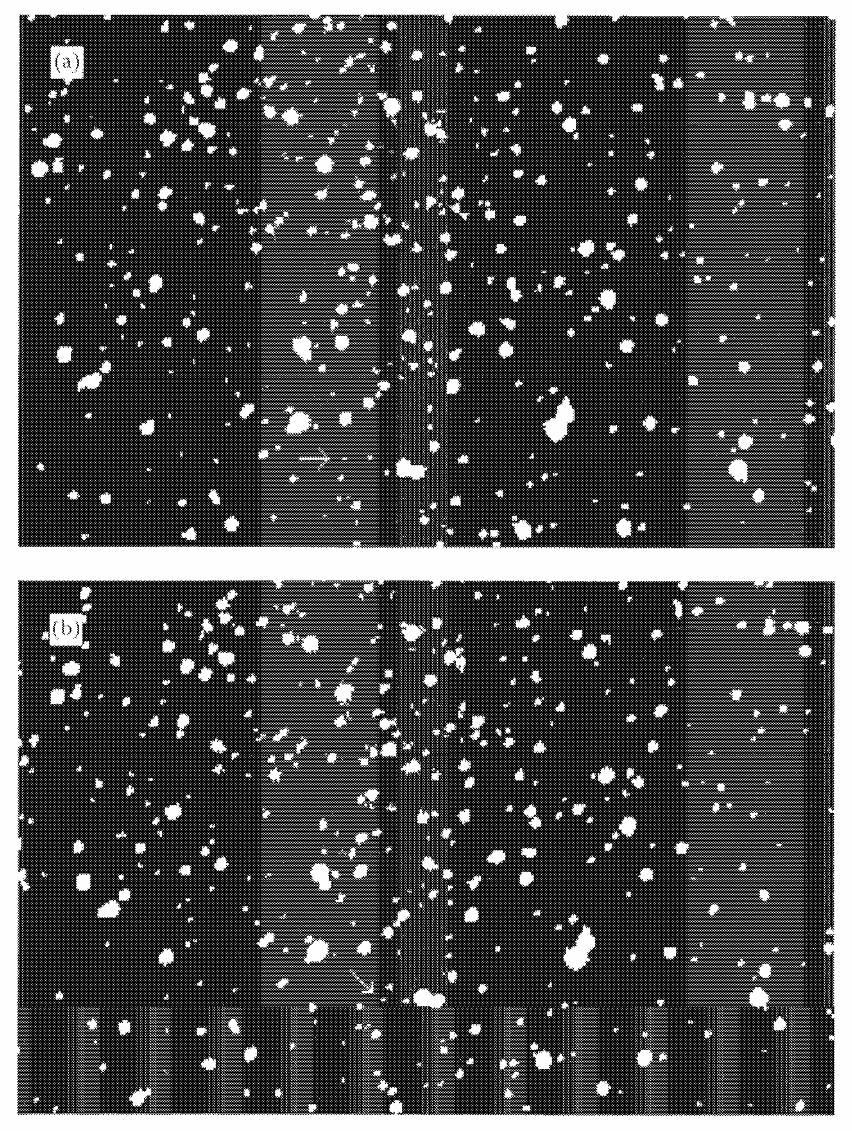
Les géocroiseurs

http://neo.jpl.nasa.gov/

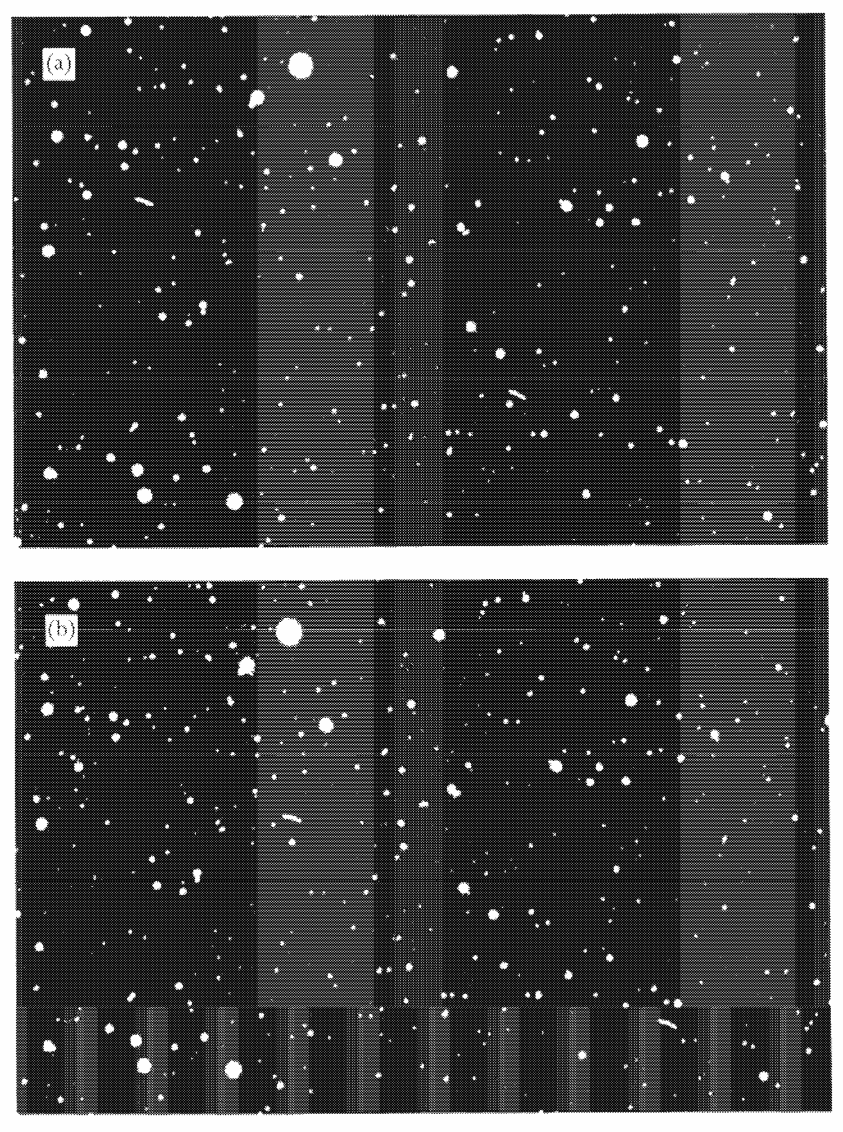
Object Name	Close Approach Date	Miss Distance (AU)	Miss Distance (LD)	Estimated Diameter*	Relative Velocity (km/s)
(2002 LW)	2004-Nov-30	0.0555	21.6	86 m - 190 m	6.31
(2004 VP)	2004-Dec-03	0.1088	42.3	77 m - 170 m	9.31
(2002 YP2)	2004-Dec-06	0.1415	55.1	420 m - 950 m	26.26
(2004 TD18)	2004-Dec-08	0.1414	55.0	95 m - 210 m	10.13
(2004 RZ164)	2004-Dec-08	0.0180	7.0	460 m - 1.0 km	11.89
(2004 LB)	2004-Dec-09	0.1191	46.4	120 m - 260 m	19.91
(2001 XW10)	2004-Dec-13	0.1842	71.7	400 m - 900 m	29.67
(2001 XX4)	2004-Dec-13	0.1547	60.2	100 m - 230 m	22.63
(2000 LB16)	2004-Dec-15	0.0868	33.8	530 m - 1.2 km	29.36
(2001 KO20)	2004-Dec-19	0.1486	57.8	270 m - 600 m	7.73
(2000 AE205)	2004-Dec-21	0.1173	45.7	70 m - 160 m	5.66
(2002 VX91)	2004-Dec-24	0.1895	73.7	40 m - 89 m	5.53
(2004 VW14)	2004-Dec-24	0.0127	4.9	320 m - 720 m	12.91
(2003 YN107)	2004-Dec-27	0.0459	17.9	15 m - 34 m	2.35
(2003 MS2)	2004-Dec-27	0.0953	37.1	150 m - 330 m	11.68
(2001 XR30)	2004-Dec-31	0.1941	75.6	180 m - 400 m	14.96
(2000 WP19)	2005-Jan-03	0.1550	60.3	91 m - 200 m	6.88
(2002 AA29)	2005-Jan-08	0.0874	34.0	41 m - 91 m	6.40
27002 (1998 DV9)	2005-Jan-11	0.0777	30.2	610 m - 1.4 km	8.65
(2002 RM129)	2005-Jan-21	0.1784	69.4	730 m - 1.6 km	13.19
(2002 PN)	2005-Jan-31	0.0814	31.7	29 m - 65 m	6.38
7350 (1993 VA)	2005-Feb-02	0.1427	55.5	920 m - 2.1 km	9.00
(2002 CC19)	2005-Feb-02	0.1833	71.3	870 m - 1.9 km	25.44
(2001 QC96)	2005-Feb-07	0.1159	45.1	240 m - 530 m	16.60
(2004 VJ1)	2005-Feb-07	0.1443	56.1	37 m - 83 m	3.38
(2001 DF47)	2005-Feb-10	0.1914	74.5	220 m - 490 m	18.31
(2000 YS134)	2005-Feb-14	0.0617	24.0	60 m - 130 m	7.08
(2004 EW)	2005-Feb-14	0.0586	22.8	200 m - 440 m	7.00
(2002 CC14)	2005-Feb-18	0.1511	58.8	31 m - 70 m	9.78
(2004 RF84)	2005-Feb-27	0.0603	23.5	680 m - 1.5 km	17.20

Object Designation	Year Range	Potential Impacts	Impact Prob. (cum.)	$V_{infinity}$ (km/s)	H (mag)	Est. Diam. (km)	Torino Scale (max.)
2004 VD17	2036-2102	14	1.7e-05	18.22	18.8	0.590	1
1997 XR2	2101-2101	2	9.7e-05	7.17	20.8	0.230	1
2004 WG1	2008-2095	37	4.8e-08	13.24	17.4	1.148	0
1994 WR12	2054-2102	134	1.0e-04	9.84	22.4	0.110	0
1979 XB	2056-2101	3	3.3e-07	24.54	18.5	0.685	0
2000 SG344	2068-2101	68	1.8e-03	1.37	24.8	0.040	0
2000 QS7	2053-2053	2	1.3e-06	12.32	19.6	0.420	0
1998 HJ3	2100-2104	3	2.1e-07	24.09	18.4	0.694	0
1994 GK	2051-2071	7	6.1e-05	14.87	24.2	0.050	0
2000 SB45	2074-2101	83	1.5e-04	7.54	24.3	0.050	0
2001 CA21	2020-2073	4	1.7e-08	30.66	18.5	0.678	0
2002 RB182	2008-2099	64	3.2e-06	13.48	22.4	0.110	0
2002 TX55	2089-2096	3	2.4e-05	10.15	23.7	0.060	0
2001 BB16	2084-2100	4	5.4e-06	3.57	22.6	0.100	0
2002 VU17	2084-2099	5	1.9e-05	13.69	24.8	0.040	0
2000 TU28	2104-2104	1	2.3e-07	9.47	20.4	0.280	0
2002 MN	2070-2101	8	3.3e-06	10.40	23.3	0.070	0
2002 GJ8	2089-2089	1	1.2e-08	26.27	19.3	0.460	0
2001 FB90	2021-2091	3	7.7e-09	26.56	19.9	0.345	0
2004 VM24	2074-2098	18	2.9e-05	12.86	25.7	0.020	0
2004 PU42	2071-2103	18	7.7e-05	10.11	26.8	0.010	0
2001 GP2	2043-2099	32	1.0e-04	2.58	26.9	0.010	0

Identifier des géocroiseurs

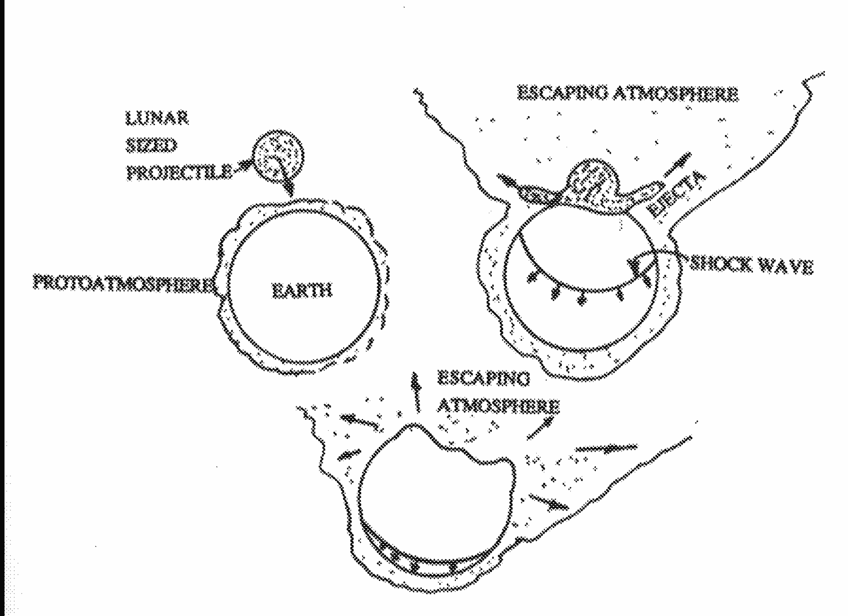


Pose = 75 min

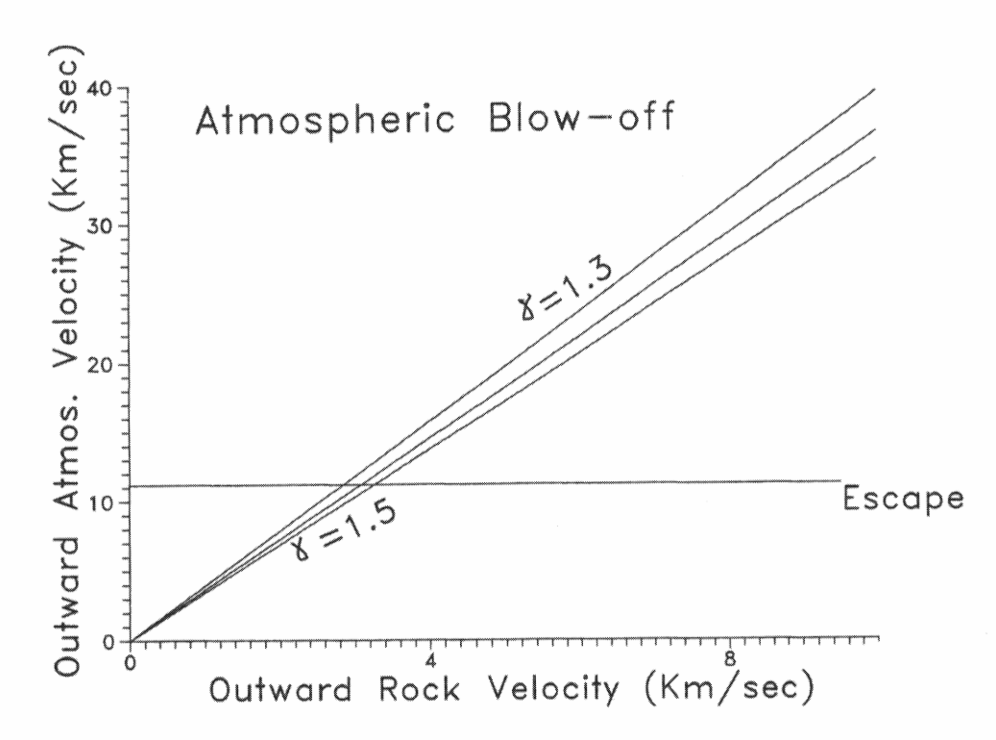


Pose = 3 heures

Impact sur l'atmosphère



$$u_{fs} = \{(\gamma + 1)^{1/2} + [(\gamma - 1)^2/(\gamma + 1)]^{1/2}\} (p_1 V_0/2)^{1/2} \quad (6)$$



Ahrens (1989)

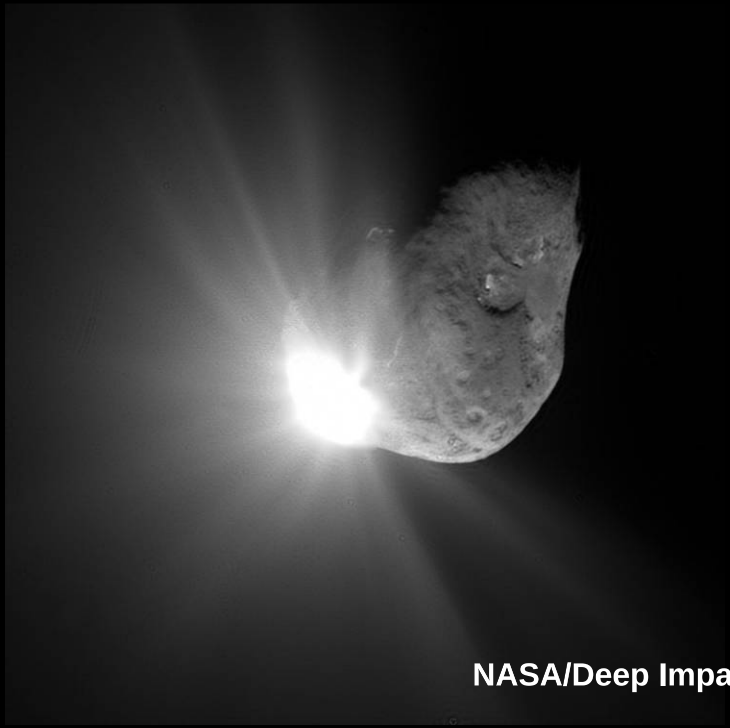
L’origine de l’eau dans le système solaire interne

Mars · February 1995 HST · WFPC2
PR95-17 · ST ScI OPO · March 21, 1995
P. James (U.Toledo), S. Lee (U.CO), NASA

D’ou vient cette eau?

Dégazage par le magmatisme.
Eau issue de l’acrétion initiale.

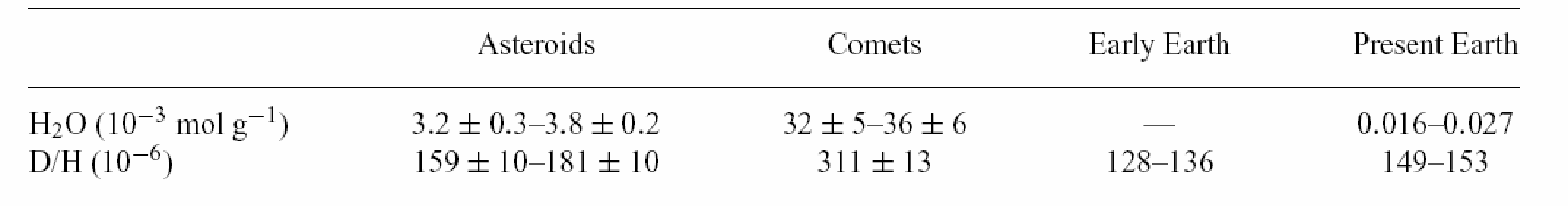
Impact d’astéroïde et de cométes



NASA/Deep Impact

Le D/H de l’eau terrestre

Avant Après

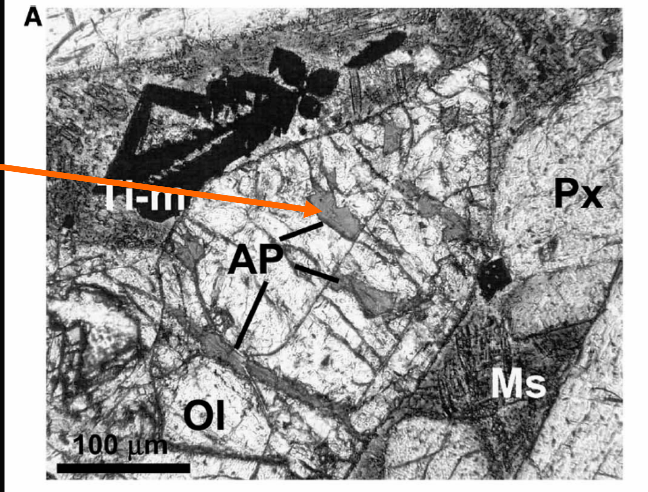


	Asteroids	Comets	Early Earth	Present Earth
H_2O (10^{-3} mol g^{-1})	3.2 ± 0.3–3.8 ± 0.2	32 ± 5–36 ± 6	—	0.016–0.027
D/H (10^{-6})	159 ± 10–181 ± 10	311 ± 13	128–136	149–153

Eau primitive 50-90%
Impact tardif d’astéroïde 10-50%
Impact tardif cométaire 0-10 %

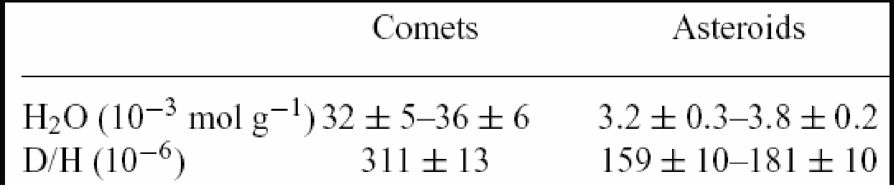
Le D/H martien

Atmosphère martienne: D/H = 234-780 ($x10^{-6}$)
Eau juvénile (meteorite) D/H = -129 ($x10^{-6}$)



Deux effets:

- bombardement tardif (jusqu'à 30 % d'apport cométaires).
- échappement préférentiel de H par rapport à D lors des impacts à la surface de Mars et de la photodissociation atmosphérique

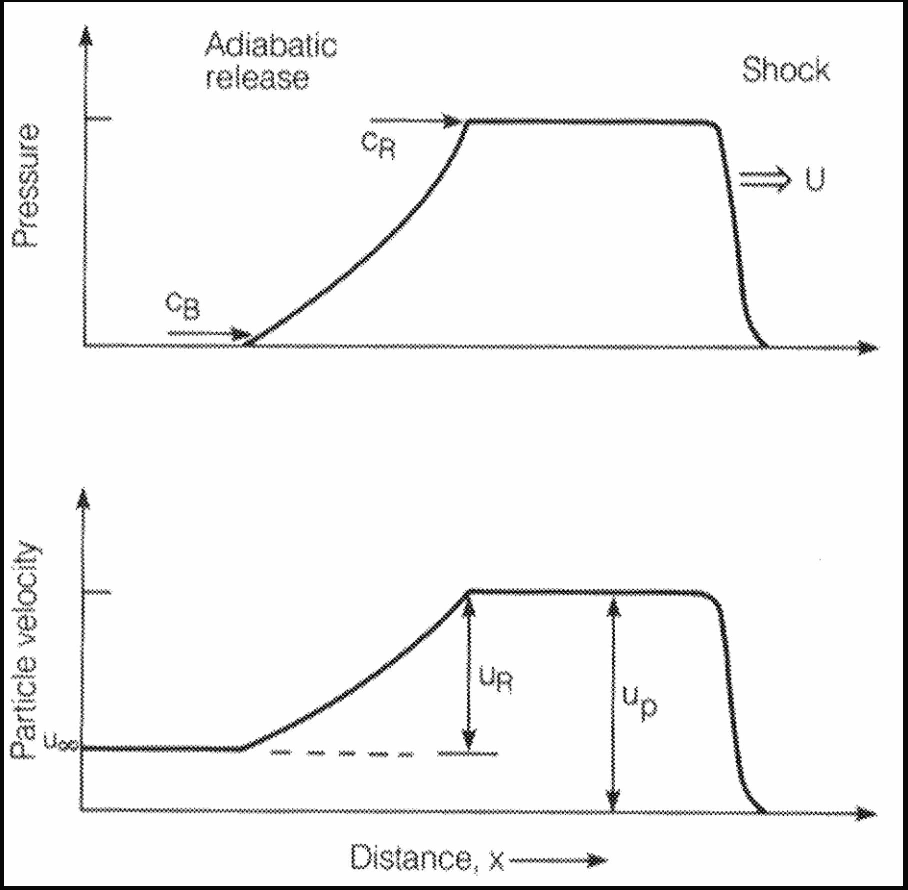


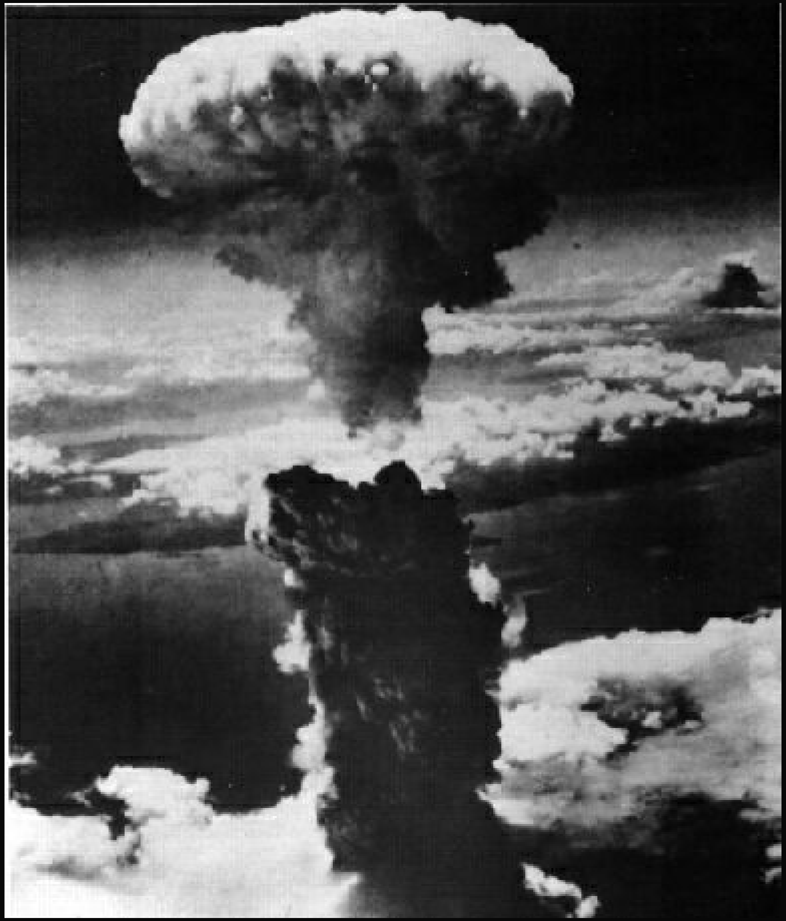
	Comets	Asteroids
H_2O (10^{-3} mol g^{-1})	32 ± 5–36 ± 6	3.2 ± 0.3–3.8 ± 0.2
D/H (10^{-6})	311 ± 13	159 ± 10–181 ± 10

Troisième partie:

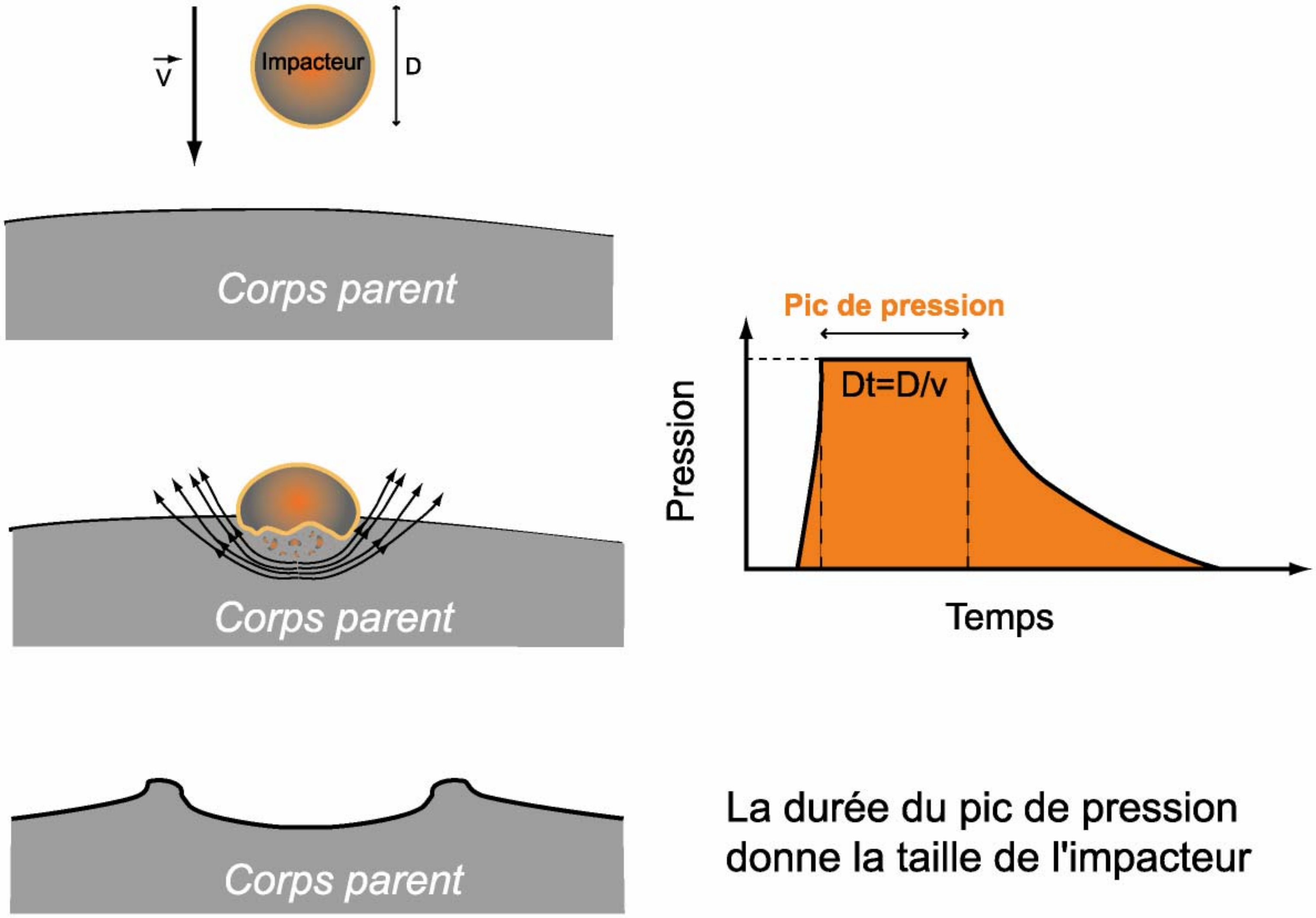
Physique du choc

L'onde de choc, théorie





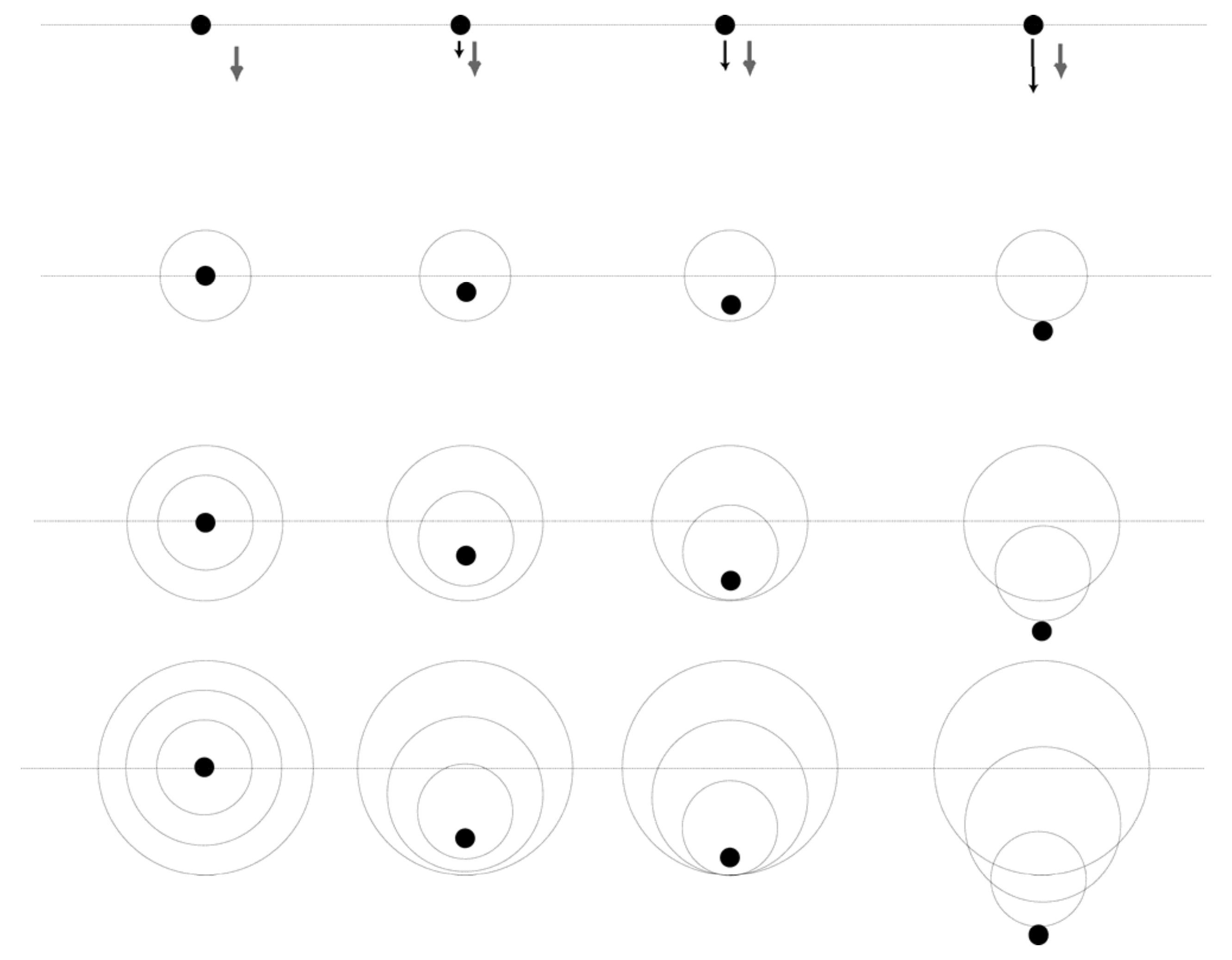
Le chemin P-t du choc.



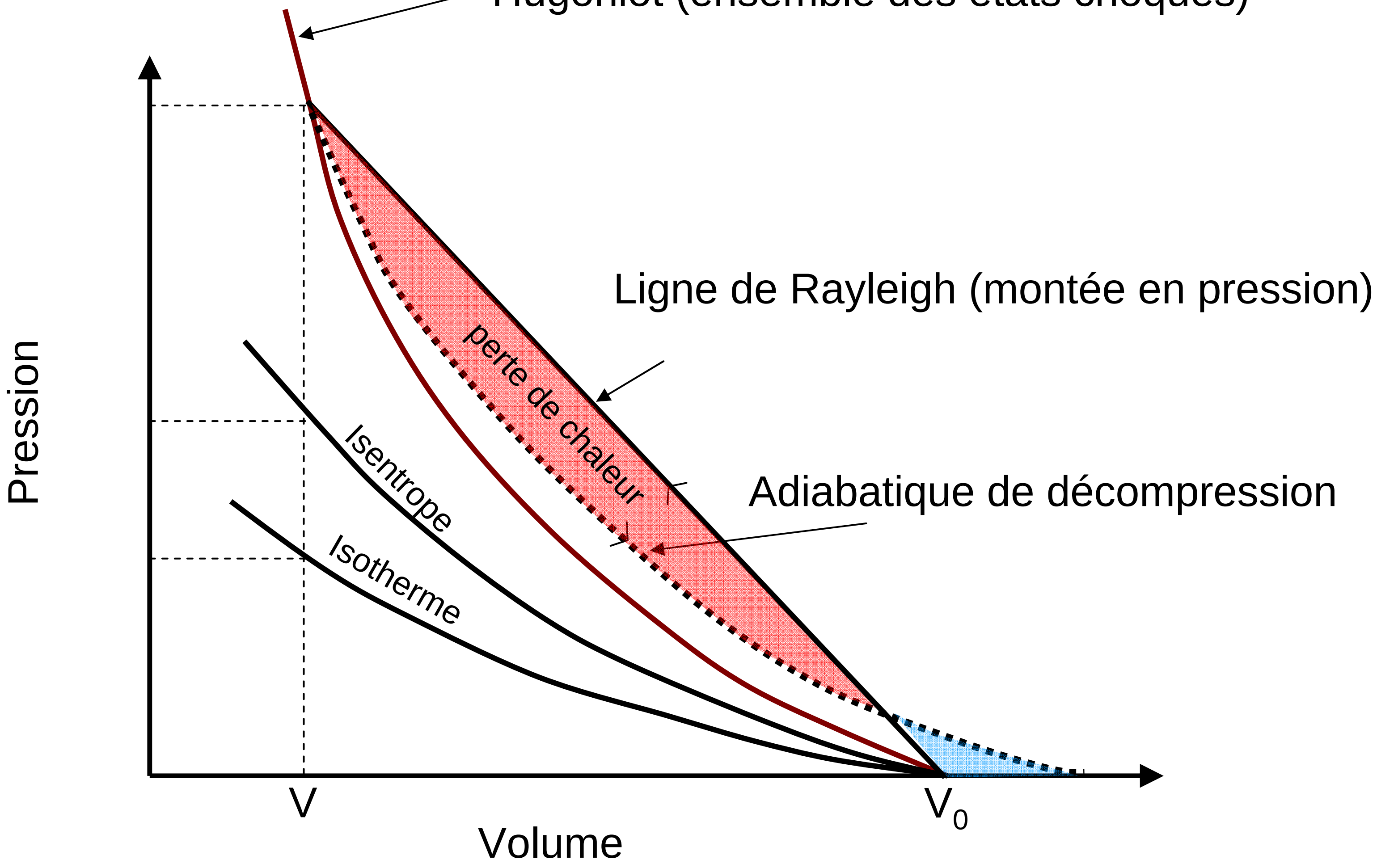
La durée du pic de pression
donne la taille de l'impacteur

Une onde solitaire.

Une onde supersonique.

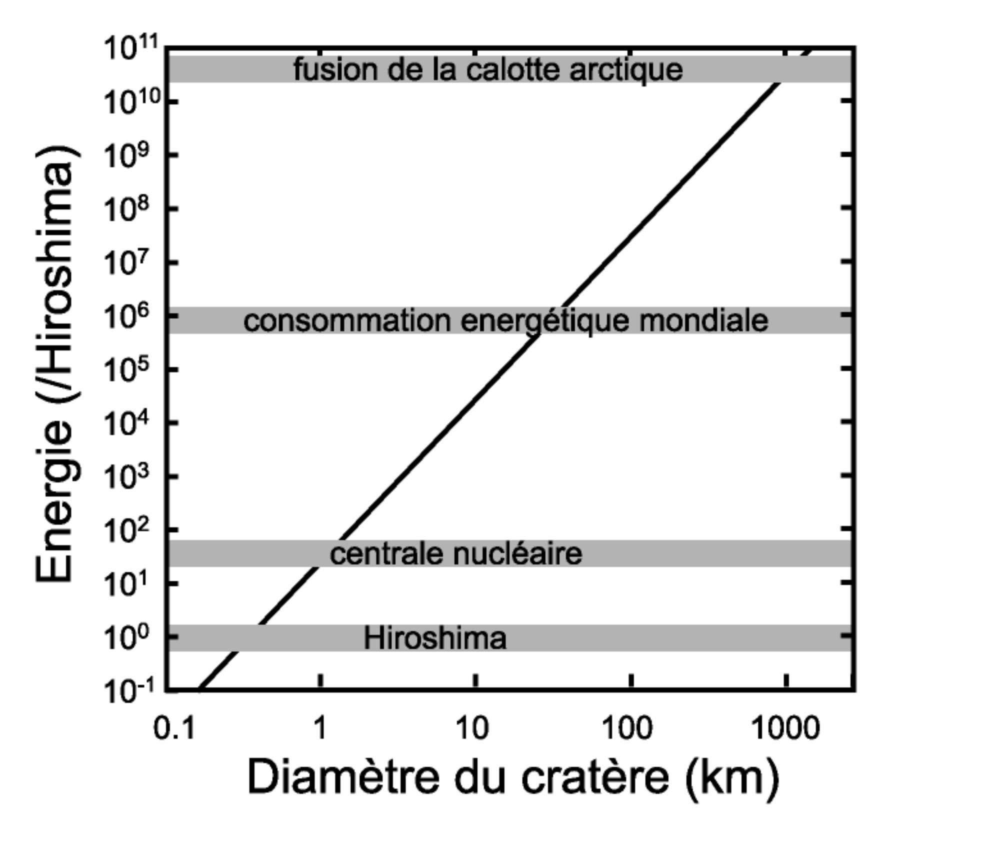


L’onde de choc, théorie

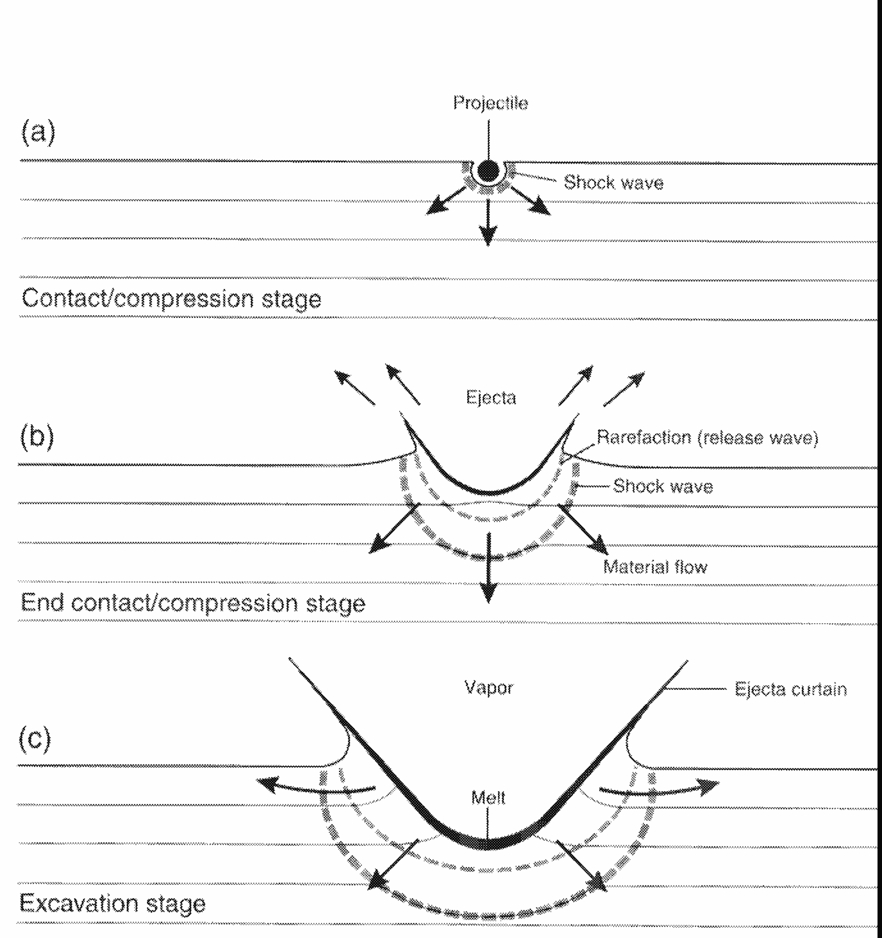


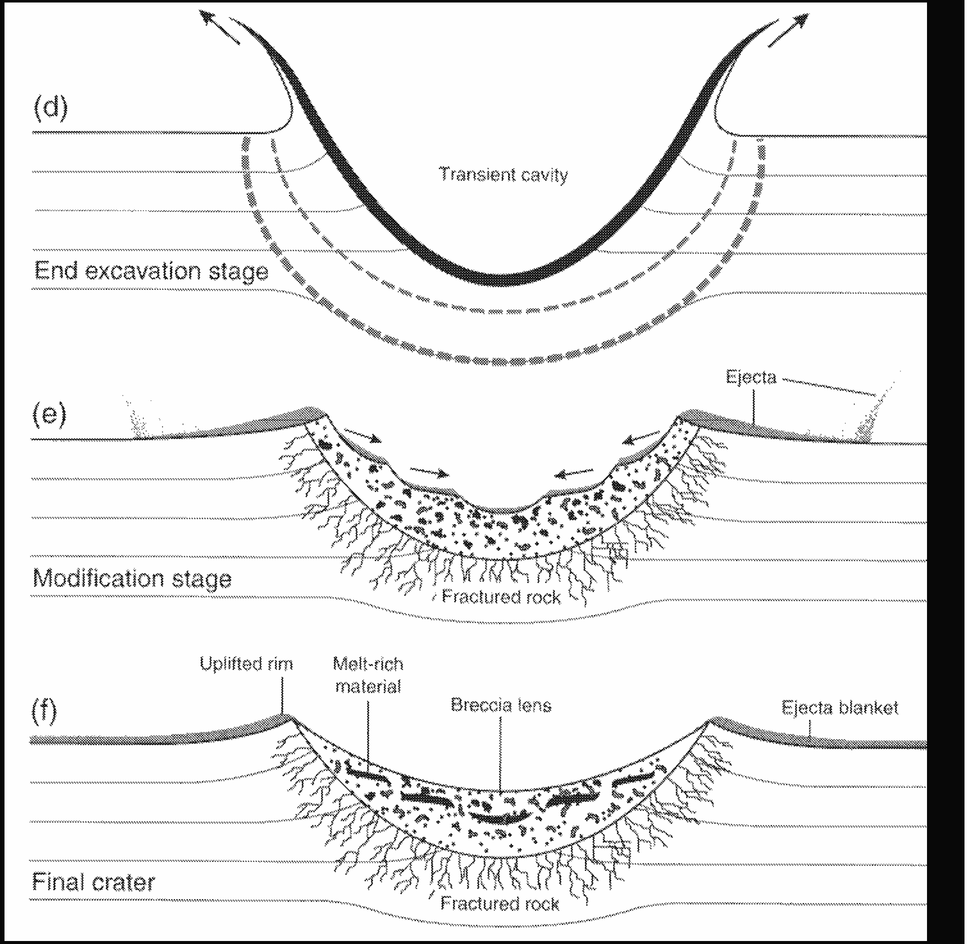
L’onde de choc dissipe de l’énergie

Les énergies mises en jeu



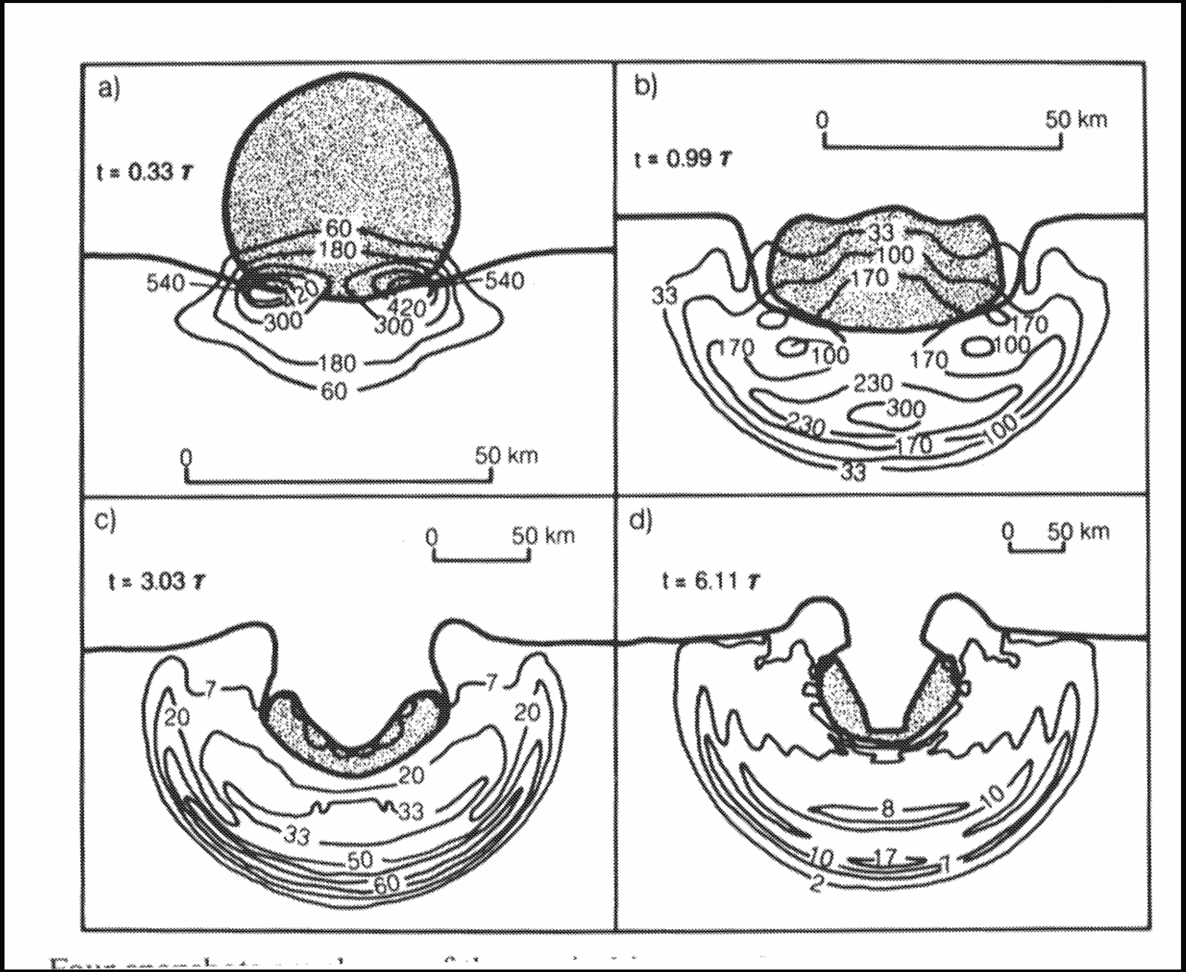
Etapes de formation d’un cratère





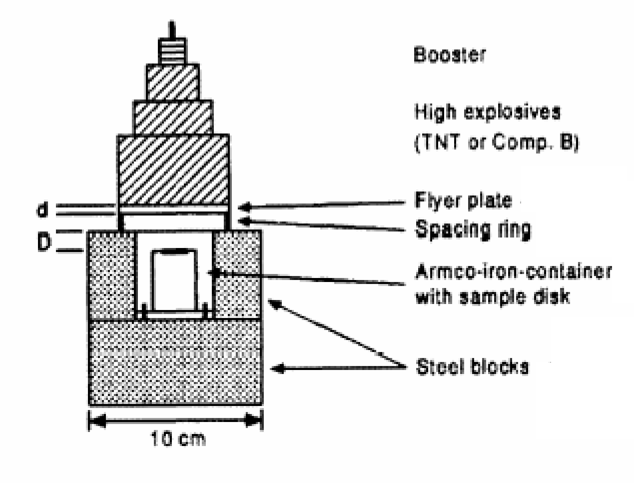
Durée ~ 100 s

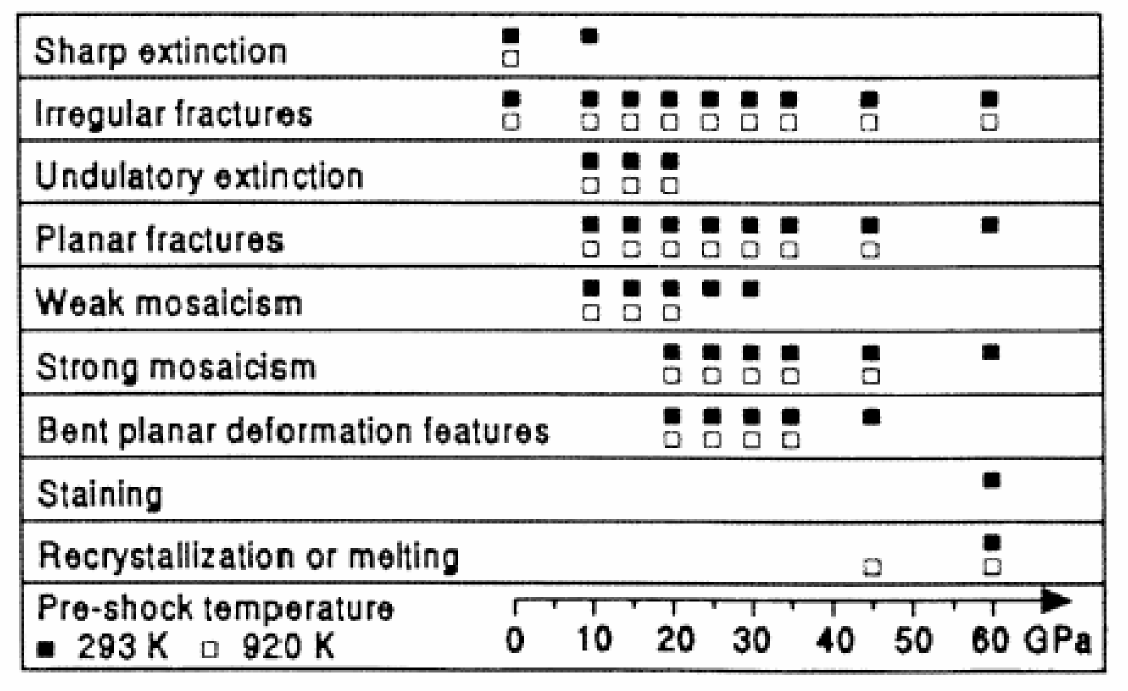
Modèles numériques, pression de choc



Melosh (1989)

Expériences de choc



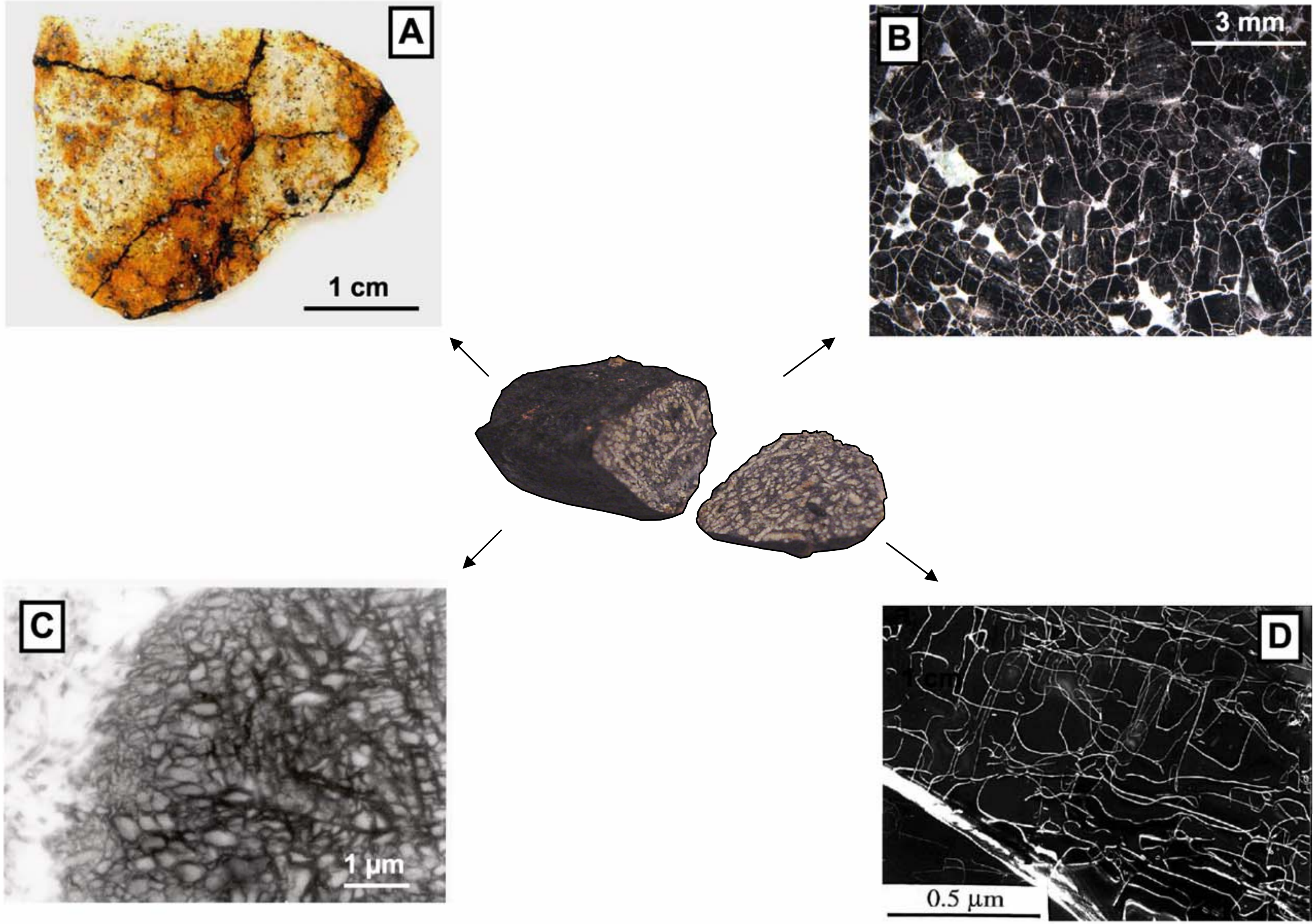


Schmitt et al., 2000

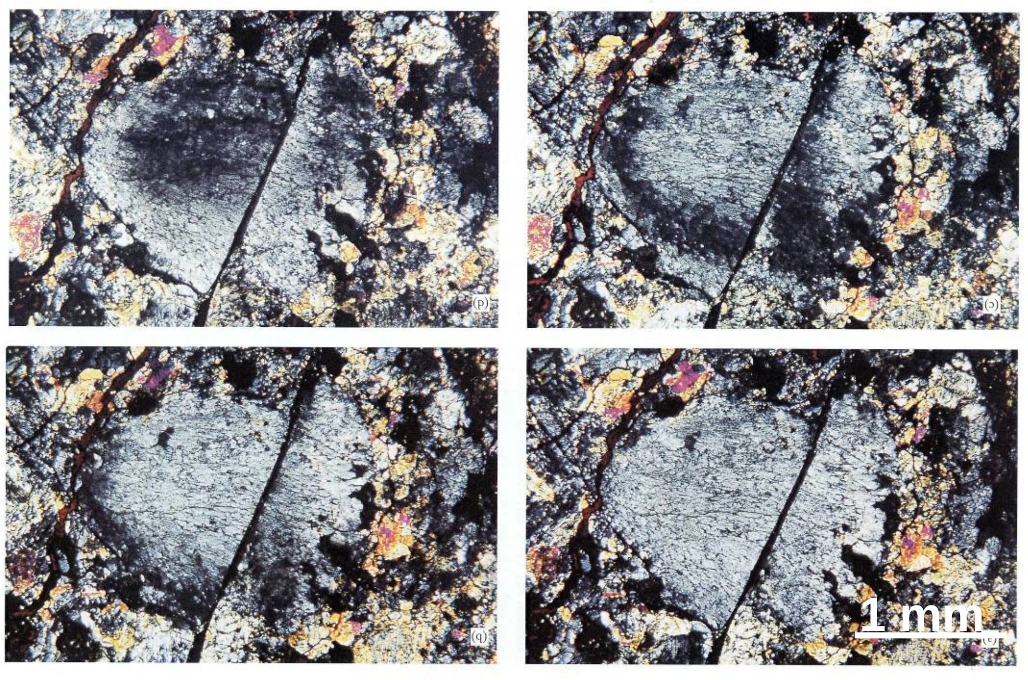
Expériences de choc

Caltech shock gun

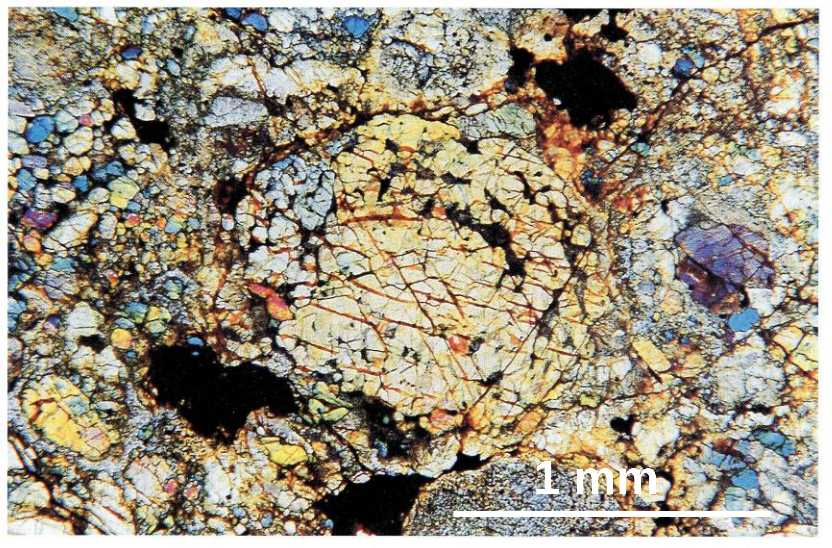
Les preuves du choc



Métamorphisme de choc (pratique)

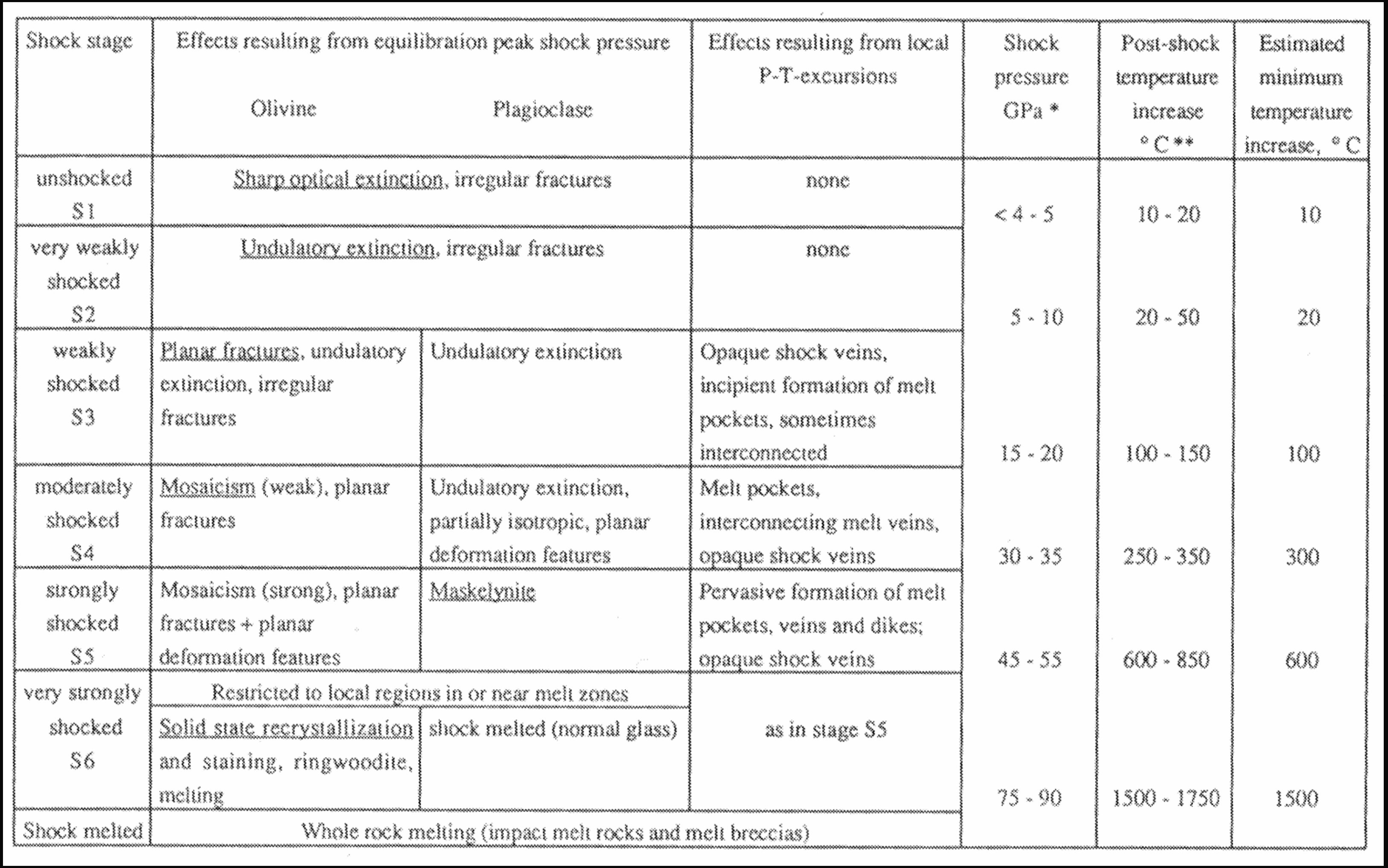


Extinctions ondulatoires



Fractures dans une olivine choquée

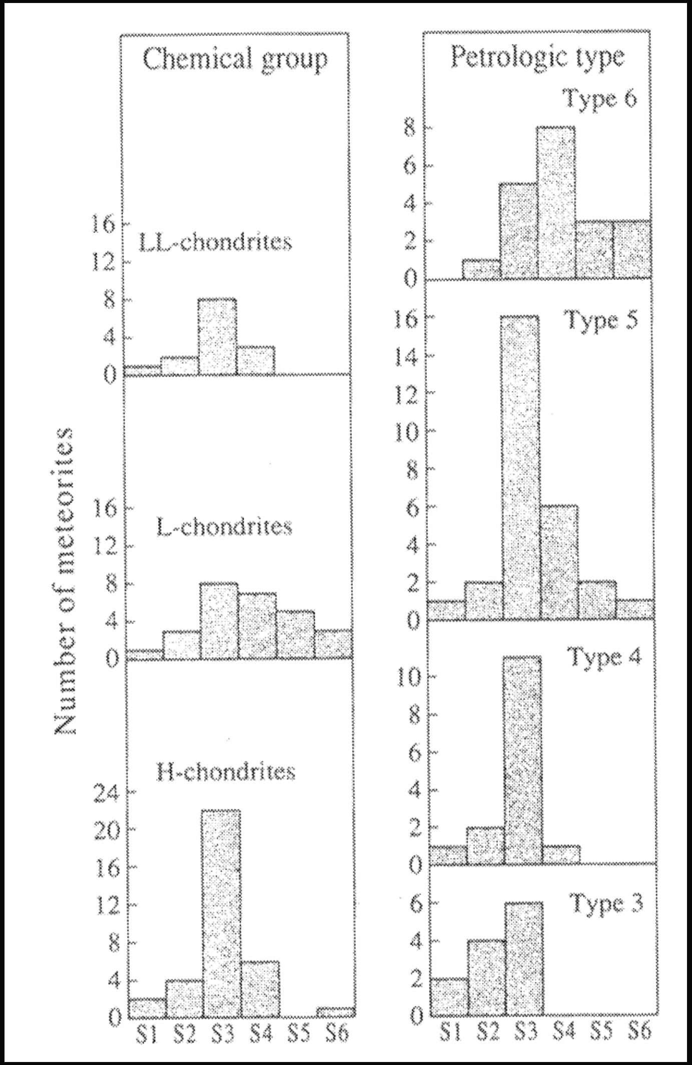
Métamorphisme de choc des météorites, classification



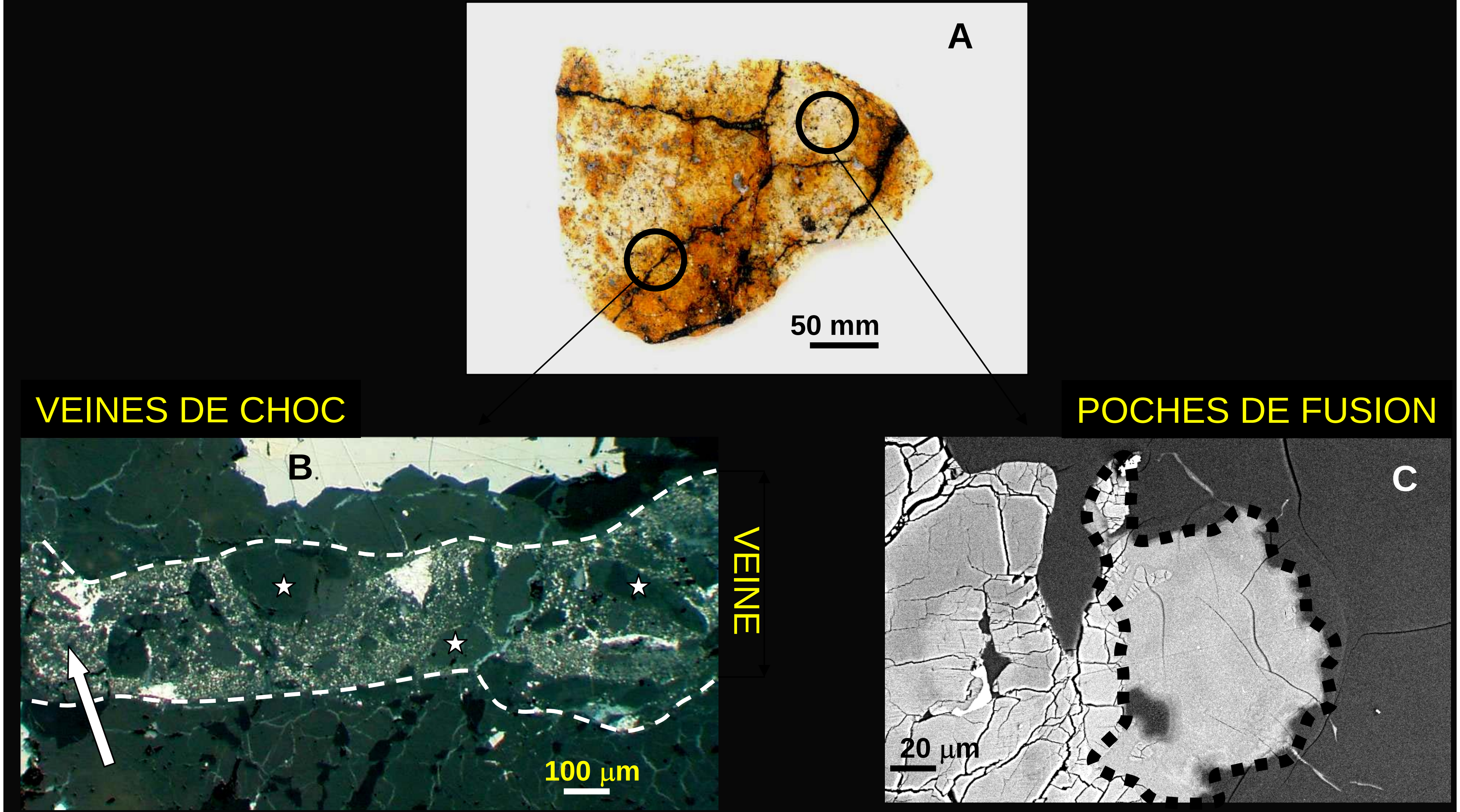
Shock stage	Effects resulting from equilibration peak shock pressure		Effects resulting from local P-T-excursions	Shock pressure GPa *	Post-shock temperature increase °C **	Estimated minimum temperature increase, °C
	Olivine	Plagioclase				
unshocked S1	Sharp optical extinction, irregular fractures		none	< 4 - 5	10 - 20	10
very weakly shocked S2	Undulatory extinction, irregular fractures		none	5 - 10	20 - 50	20
weakly shocked S3	Planar fractures, undulatory extinction, irregular fractures	Undulatory extinction	Opaque shock veins, incipient formation of melt pockets, sometimes interconnected	15 - 20	100 - 150	100
moderately shocked S4	Mosaicism (weak), planar fractures	Undulatory extinction, partially isotropic, planar deformation features	Melt pockets, interconnecting melt veins, opaque shock veins	30 - 35	250 - 350	300
strongly shocked S5	Mosaicism (strong), planar fractures + planar deformation features	Maskelynite	Pervasive formation of melt pockets, veins and dikes; opaque shock veins	45 - 55	600 - 850	600
very strongly shocked S6	Restricted to local regions in or near melt zones Solid state recrystallization and staining, ringwoodite, melting	shock melted (normal glass)	as in stage S5	75 - 90	1500 - 1750	1500
Shock melted	Whole rock melting (impact melt rocks and melt breccias)					

Intensité du choc suivant le type pétrologique

Reflets de l’accrétion primordiale?
Effet de la porosité?

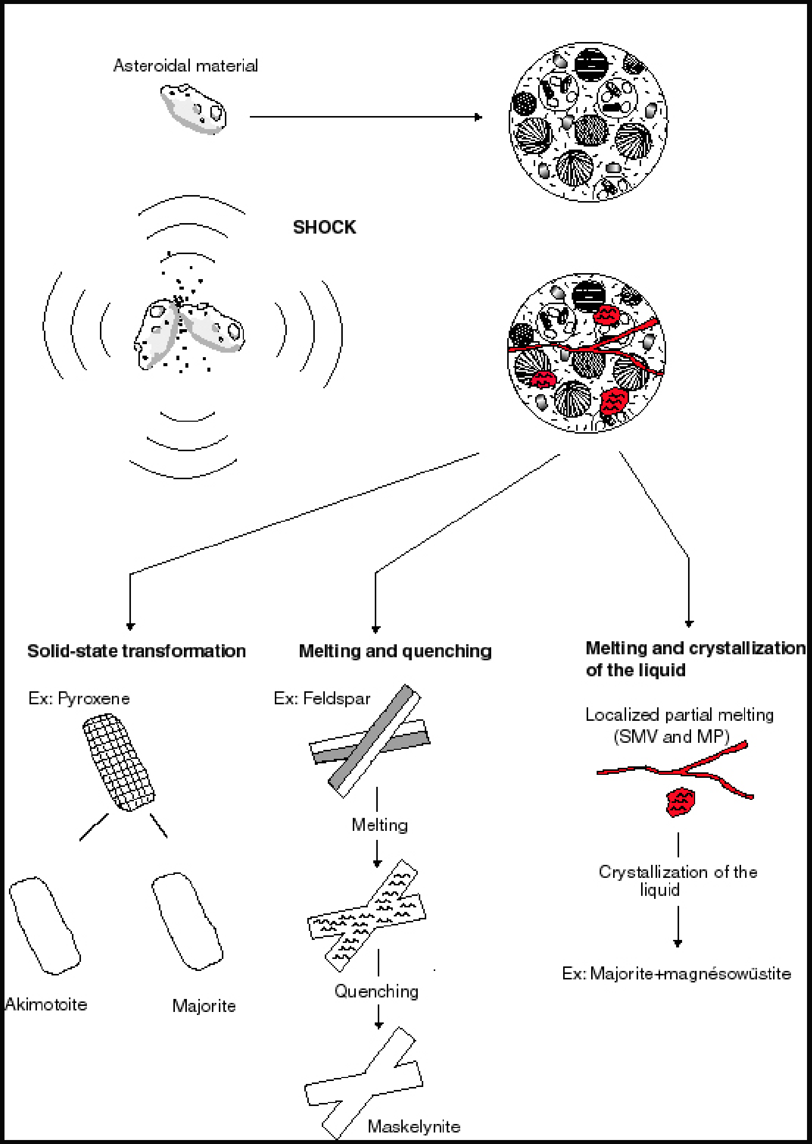


Fusion lors du choc



Transformations minéralogiques → déterminer P_{max} et T_{max}

Transitions de phases dans les météorites choquées



Transitions de phases dans les météorites choquées

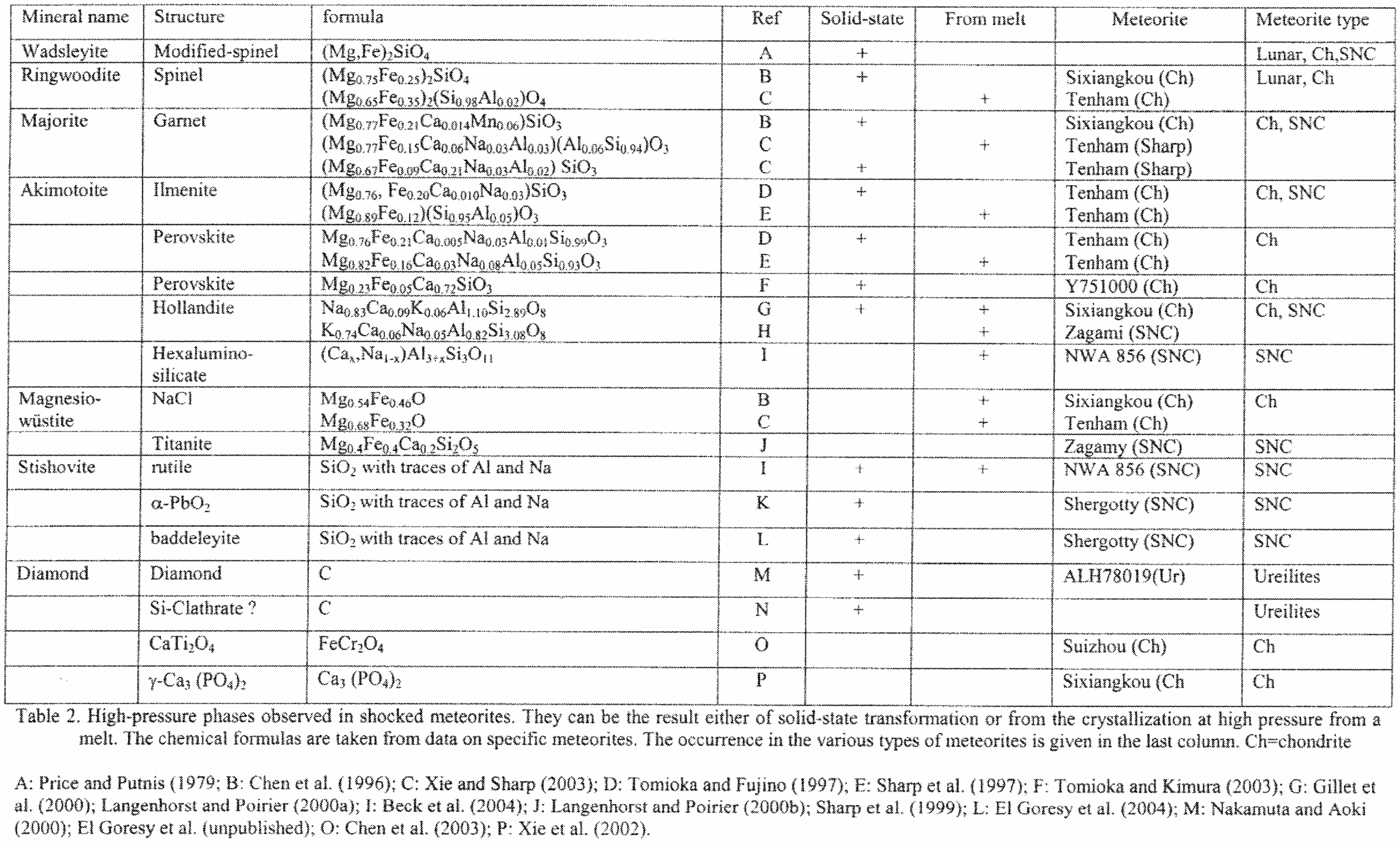
Tous les ferro-magnésiens supposés présents dans l'intérieur de la Terre ont été observés dans les météorites…

- Wadsleyite and Ringwoodite (Binns, 1970)
- Majorite (Smith and Mason, 1970)

- Akimotoïte (Sharp *et al*., 1997)
- Perovskite (Tomioka and Fujino, 1997)

+ SiO2 polymorphs

Les minéraux de HP dans les météorites choquées

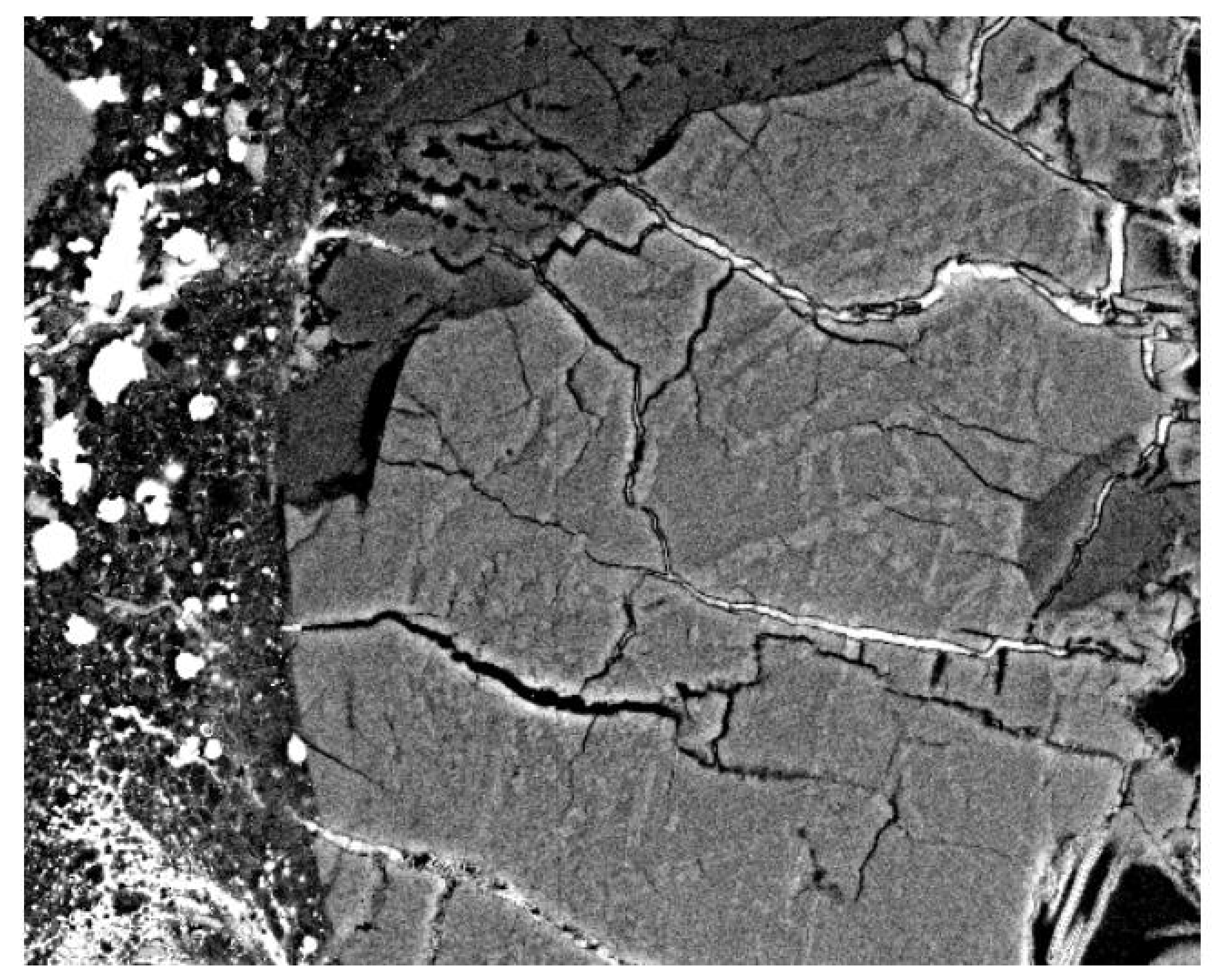


Mineral name	Structure	formula	Ref	Solid-state	From melt	Meteorite	Meteorite type
Wadsleyite	Modified-spinel	$(Mg,Fe)_2SiO_4$	A	+			Lunar, Ch,SNC
Ringwoodite	Spinel	$(Mg_{0.75}Fe_{0.25})_2SiO_4$ $(Mg_{0.65}Fe_{0.35})_2(Si_{0.98}Al_{0.02})O_4$	B C	+	 +	Sixiangkou (Ch) Tenham (Ch)	Lunar, Ch
Majorite	Garnet	$(Mg_{0.77}Fe_{0.21}Ca_{0.014}Mn_{0.06})SiO_3$ $(Mg_{0.77}Fe_{0.15}Ca_{0.06}Na_{0.03}Al_{0.03})(Al_{0.06}Si_{0.94})O_3$ $(Mg_{0.67}Fe_{0.09}Ca_{0.21}Na_{0.03}Al_{0.02})\ SiO_3$	B C C	+ +	 + 	Sixiangkou (Ch) Tenham (Sharp) Tenham (Sharp)	Ch, SNC
Akimotoite	Ilmenite	$(Mg_{0.76},\ Fe_{0.20}Ca_{0.010}Na_{0.03})SiO_3$ $(Mg_{0.89}Fe_{0.12})(Si_{0.95}Al_{0.05})O_3$	D E	+	 +	Tenham (Ch) Tenham (Ch)	Ch, SNC
	Perovskite	$Mg_{0.76}Fe_{0.21}Ca_{0.005}Na_{0.03}Al_{0.01}Si_{0.99}O_3$ $Mg_{0.82}Fe_{0.16}Ca_{0.03}Na_{0.08}Al_{0.05}Si_{0.93}O_3$	D E	+	 +	Tenham (Ch) Tenham (Ch)	Ch
	Perovskite	$Mg_{0.23}Fe_{0.05}Ca_{0.72}SiO_3$	F	+		Y751000 (Ch)	Ch
	Hollandite	$Na_{0.83}Ca_{0.09}K_{0.06}Al_{1.10}Si_{2.89}O_8$ $K_{0.74}Ca_{0.06}Na_{0.05}Al_{0.82}Si_{3.08}O_8$	G H	+	+ +	Sixiangkou (Ch) Zagami (SNC)	Ch, SNC
	Hexalumino-silicate	$(Ca_x,Na_{1-x})Al_{3+x}Si_3O_{11}$	I		+	NWA 856 (SNC)	SNC
Magnesio-wüstite	NaCl	$Mg_{0.54}Fe_{0.46}O$ $Mg_{0.68}Fe_{0.32}O$	B C		+ +	Sixiangkou (Ch) Tenham (Ch)	Ch
	Titanite	$Mg_{0.4}Fe_{0.4}Ca_{0.2}Si_2O_5$	J			Zagamy (SNC)	SNC
Stishovite	rutile	SiO_2 with traces of Al and Na	I	+	+	NWA 856 (SNC)	SNC
	α-PbO_2	SiO_2 with traces of Al and Na	K	+		Shergotty (SNC)	SNC
	baddeleyite	SiO_2 with traces of Al and Na	L	+		Shergotty (SNC)	SNC
Diamond	Diamond	C	M	+		ALH78019(Ur)	Ureilites
	Si-Clathrate ?	C	N	+			Ureilites
	$CaTi_2O_4$	$FeCr_2O_4$	O			Suizhou (Ch)	Ch
	γ-$Ca_3\ (PO_4)_2$	$Ca_3\ (PO_4)_2$	P			Sixiangkou (Ch	Ch

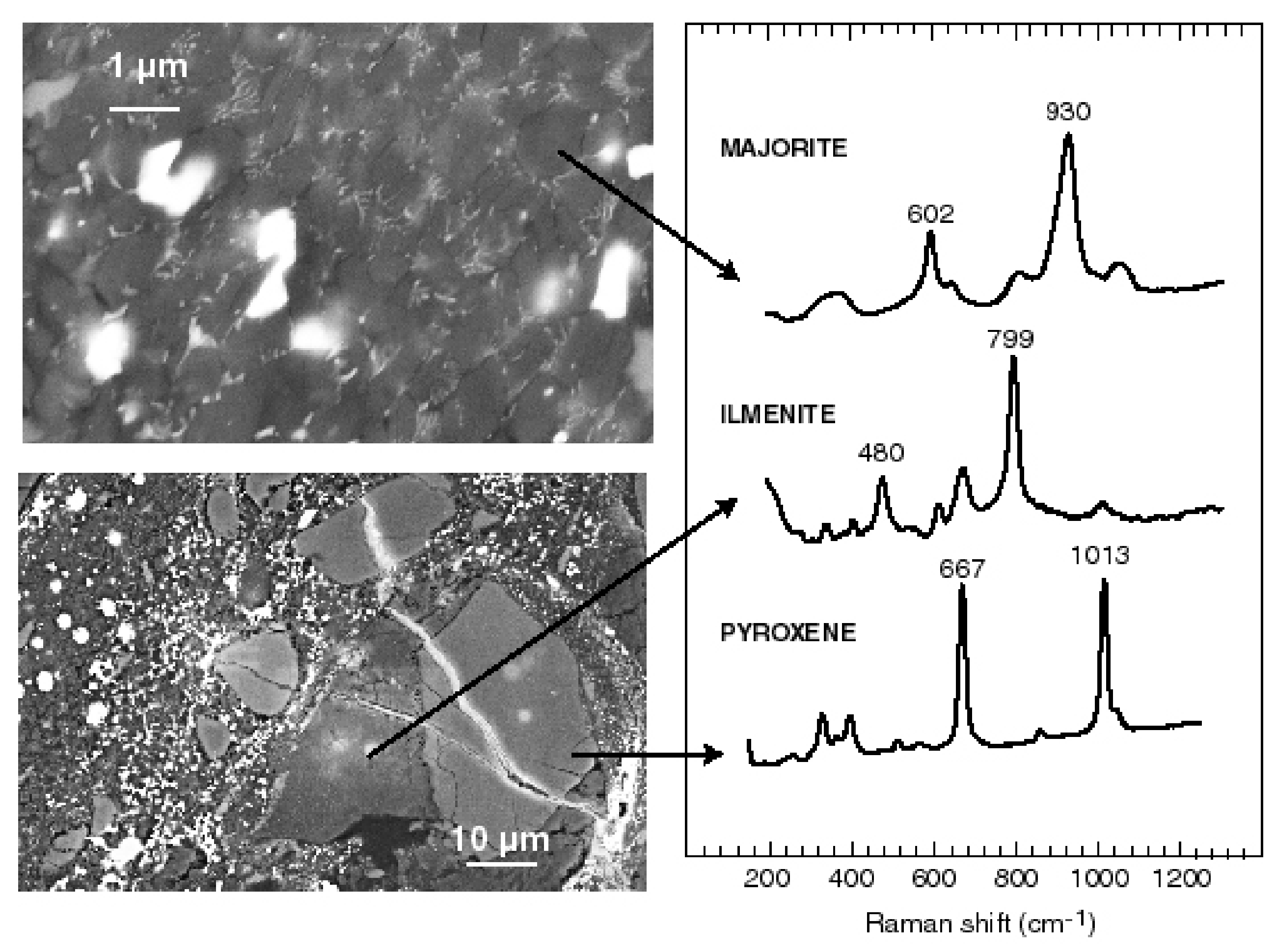
Table 2. High-pressure phases observed in shocked meteorites. They can be the result either of solid-state transformation or from the crystallization at high pressure from a melt. The chemical formulas are taken from data on specific meteorites. The occurrence in the various types of meteorites is given in the last column. Ch=chondrite

A: Price and Putnis (1979; B: Chen et al. (1996); C: Xie and Sharp (2003); D: Tomioka and Fujino (1997); E: Sharp et al. (1997); F: Tomioka and Kimura (2003); G: Gillet et al. (2000); Langenhorst and Poirier (2000a); I: Beck et al. (2004); J: Langenhorst and Poirier (2000b); Sharp et al. (1999); L: El Goresy et al. (2004); M: Nakamuta and Aoki (2000); El Goresy et al. (unpublished); O: Chen et al. (2003); P: Xie et al. (2002).

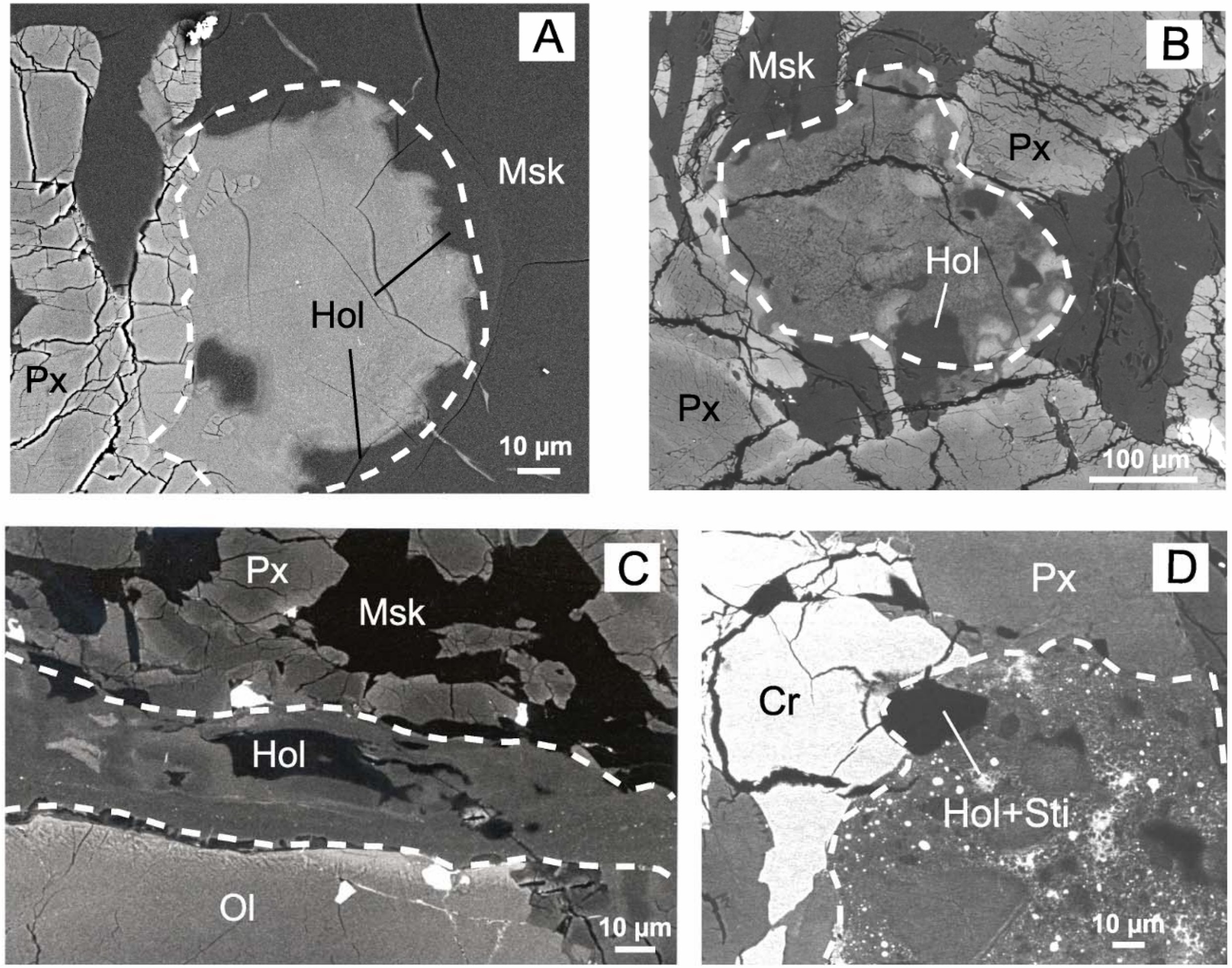
Un exemple de transformation solide / solide



Un exemple de cristallisation d’un liquide à très haute pression



Les feldspaths de type hollandite

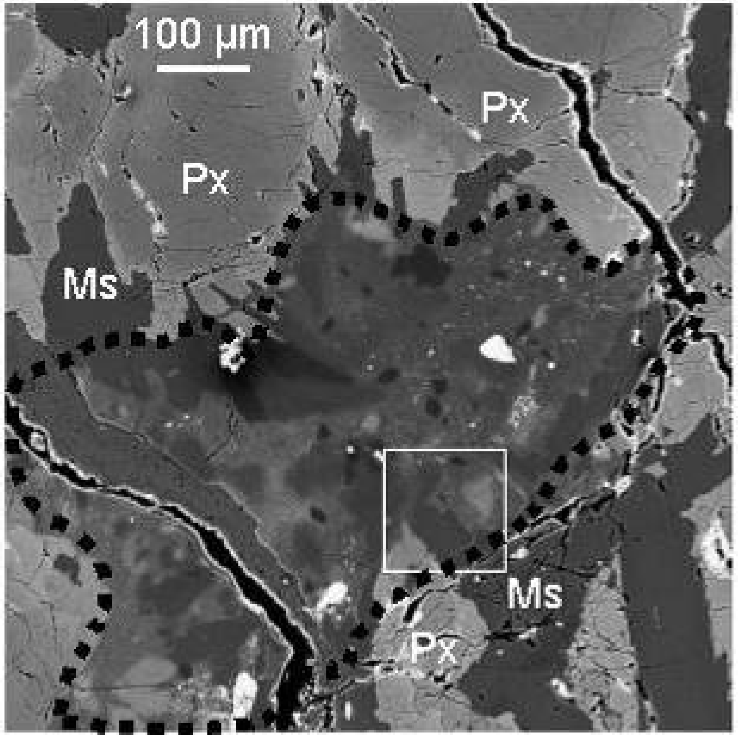


A, B, C
Ca-Na hollandites

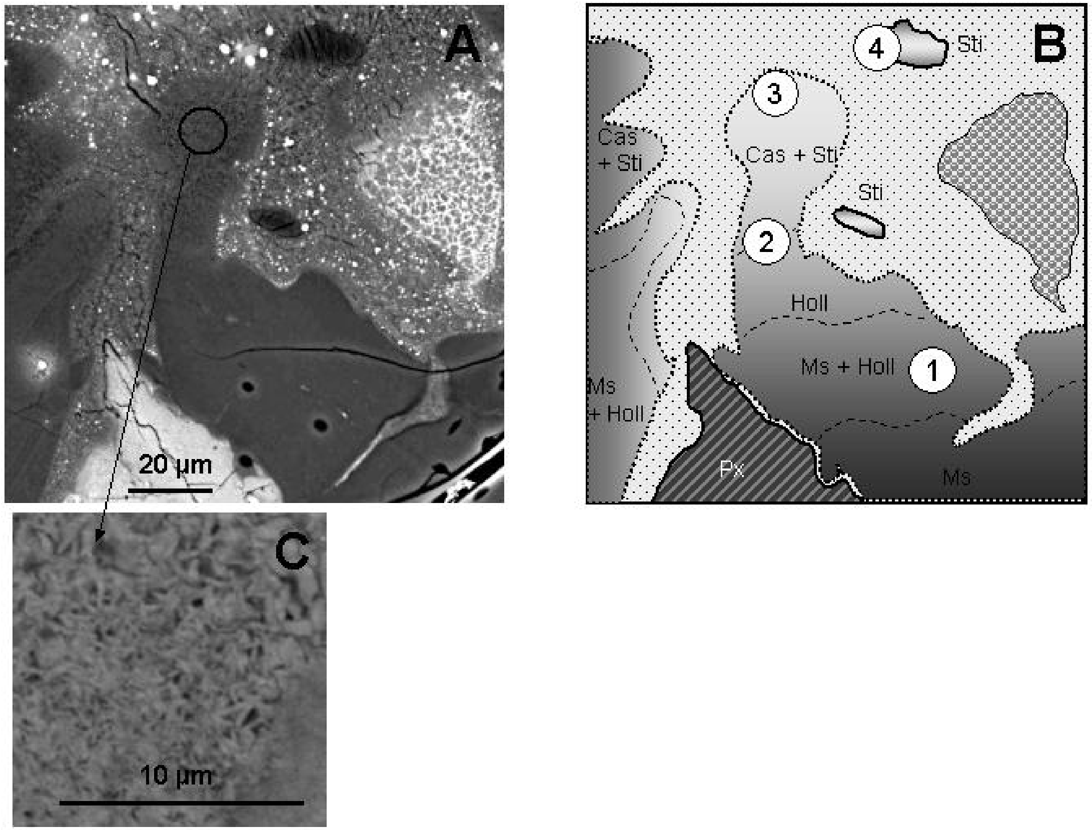
D
K - hollandites

Cristallisation depuis le liquide à très haute pression ou transformation directe du feldspath?

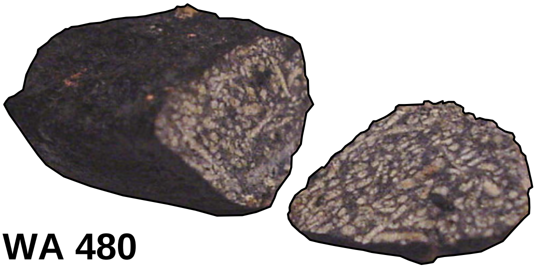
L’assemblage CAS + Sti



CAS= Calcium Aluminosilicate
$(Ca_xNa_{1-x})_4Al_{3+x}Si_{3-x}0_{11}$

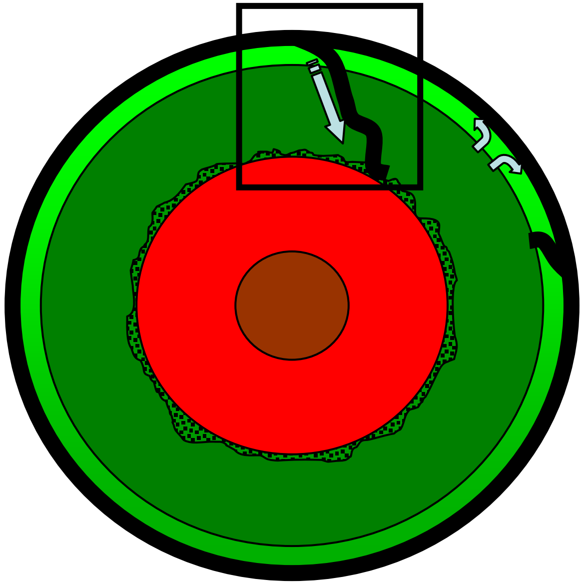


Détermination des conditions P-T du choc (i).

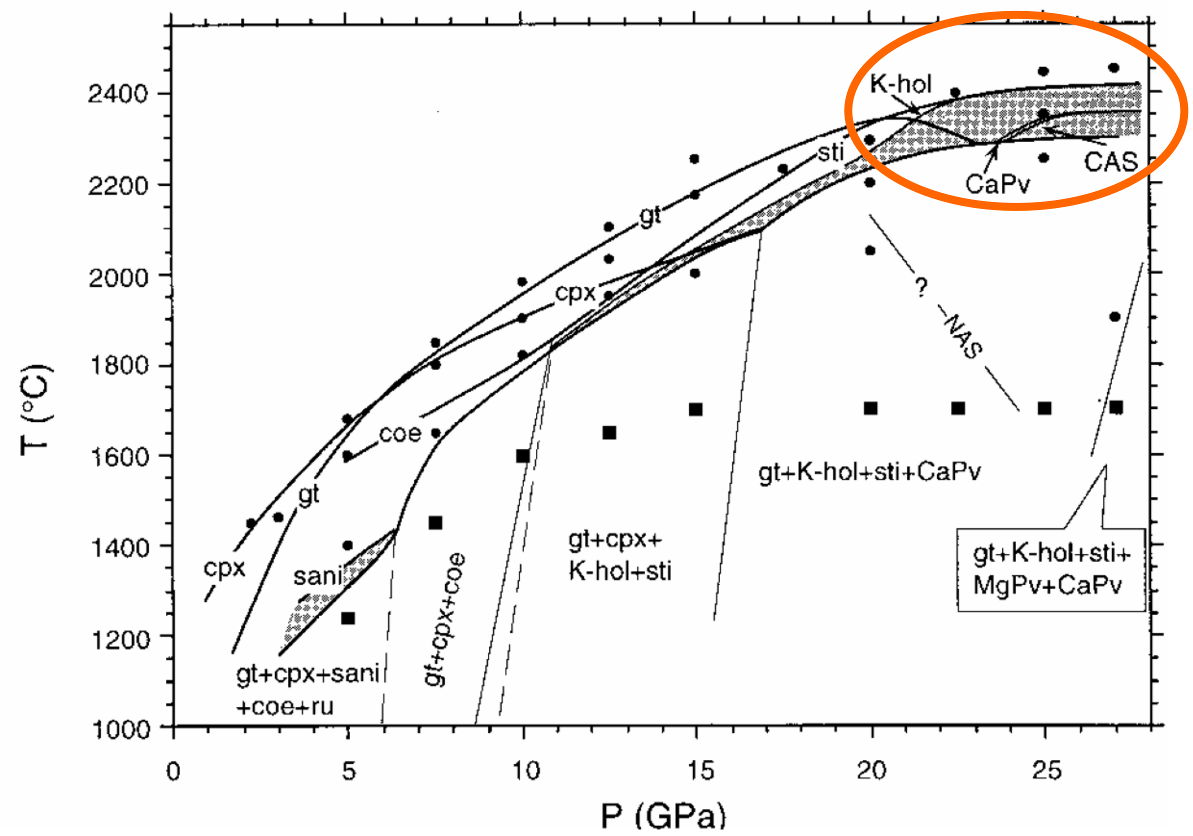


NWA 480
Météorite martienne

≈



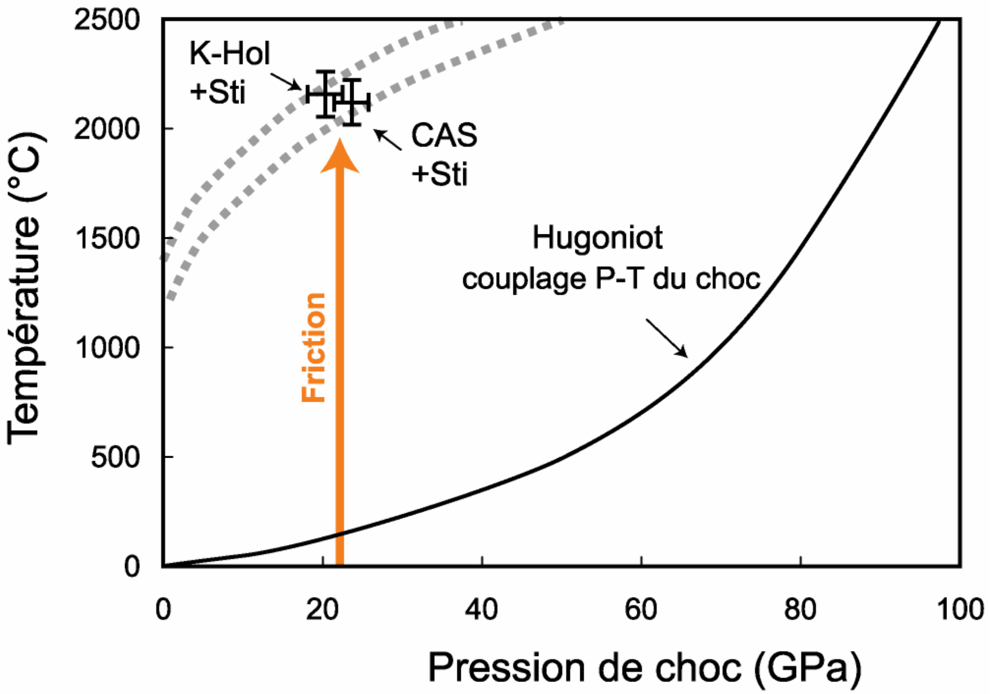
Conditions P-T des veines et poches de fusion



P > 23 GPa
T=2450 K +/- 50

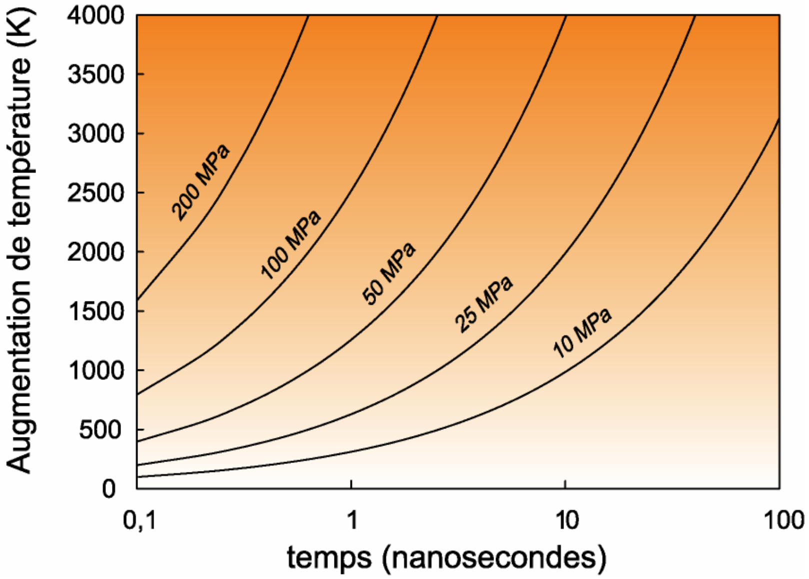
P > 25 GPa
T=2400 K +/- 100

Comment expliquer ces très hautes températures?



Le découplage P-T peut s’expliquer par la friction

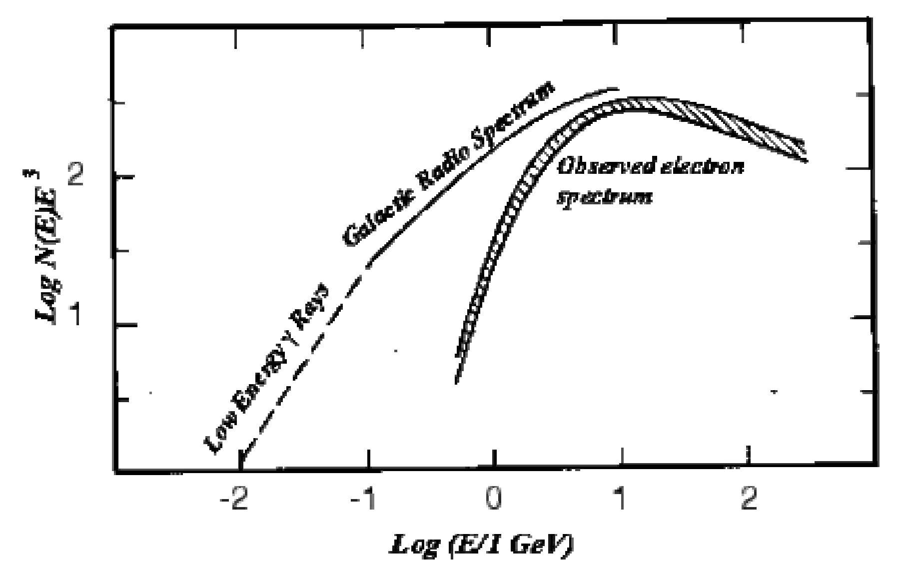
La friction génère instantanément, lors de l’arrivée de l’onde de choc, de très haute températures



Quatrième partie:

Dynamique des échanges de matériaux planétaires

Vent solaire, rayonnement cosmique galactique



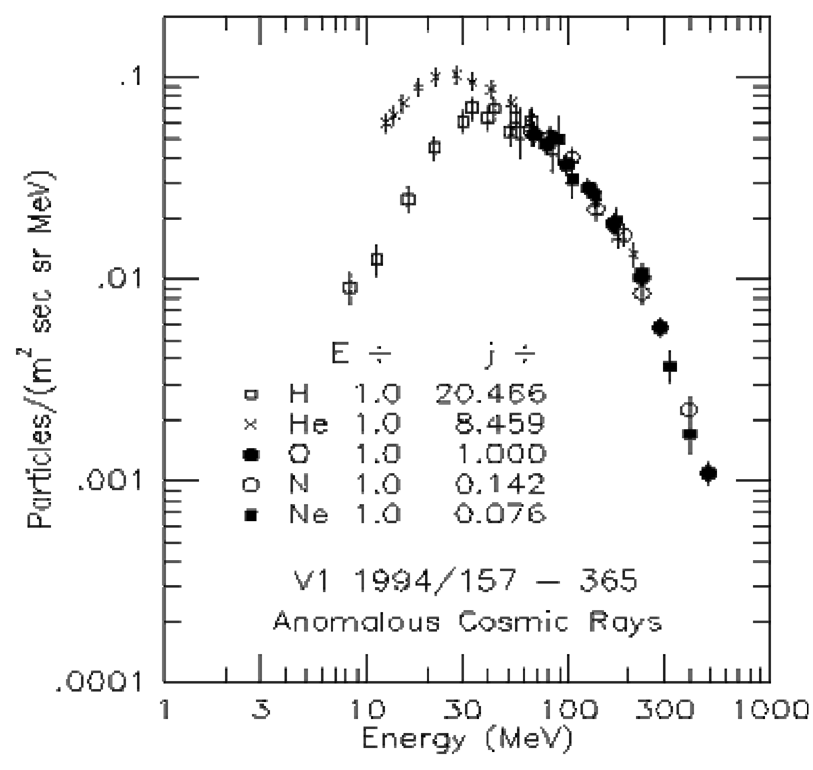
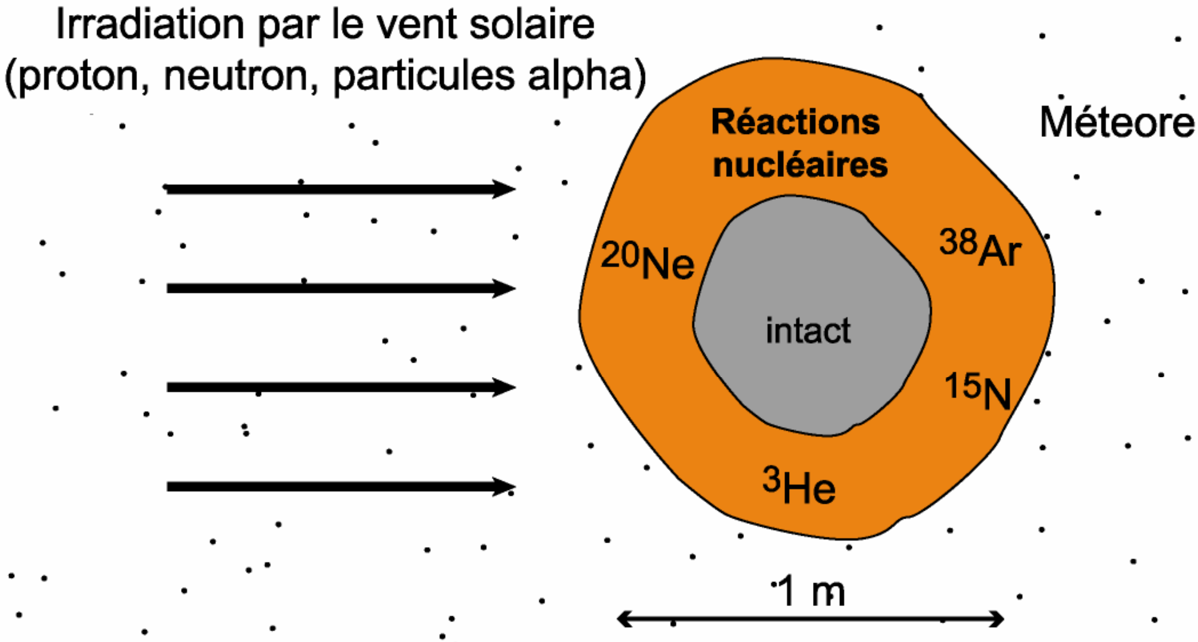


Figure 7

Très énergétique: des réactions nucléaires sont possibles.

Les âges d'exposition



+ rayonnement cosmique galactique

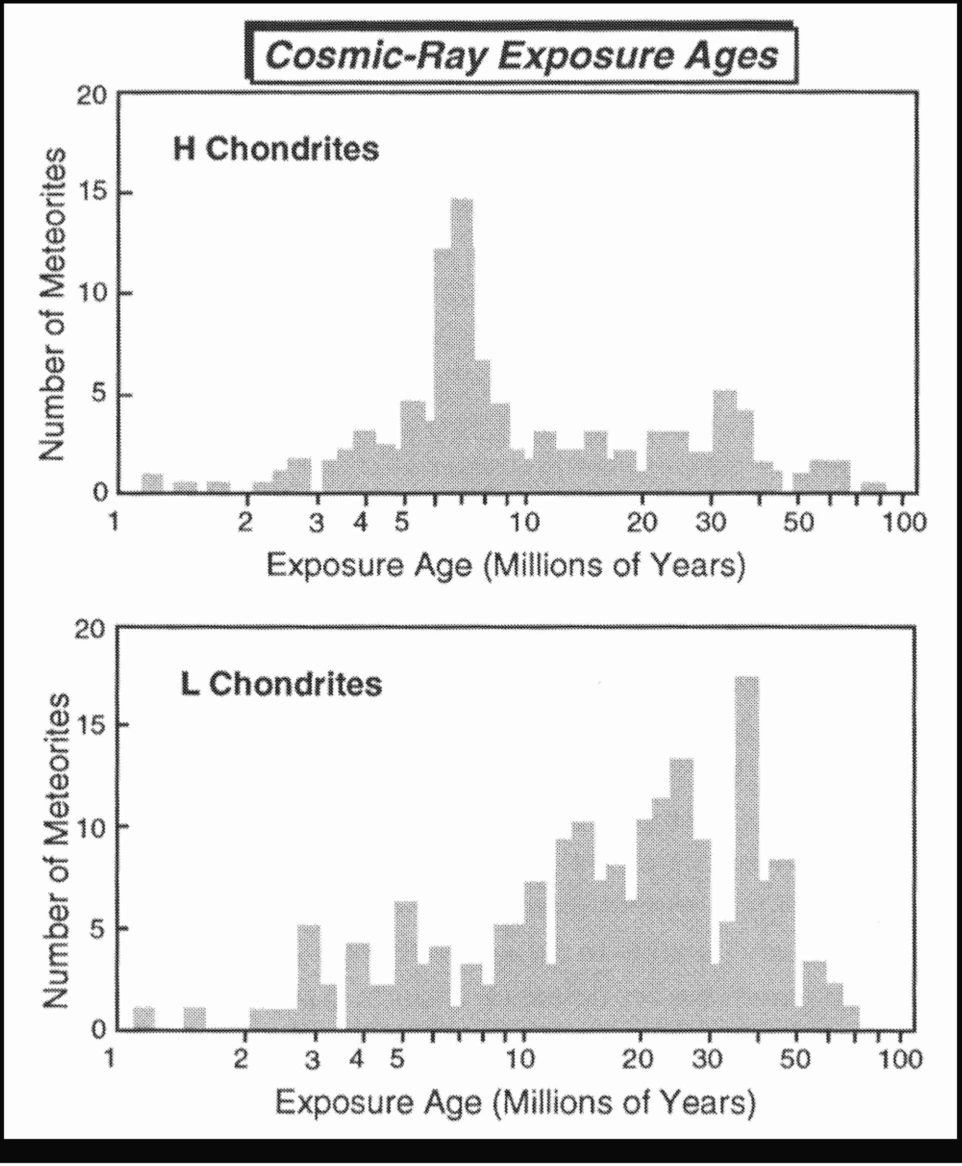
Les âges d’exposition

Plus une météorite sera restée longtemps dans l’espace plus elle contiendra d’isotopes cosmogéniques.
Les taux de production sont connus.
On peut donc déterminer la durée de l’irradiation.

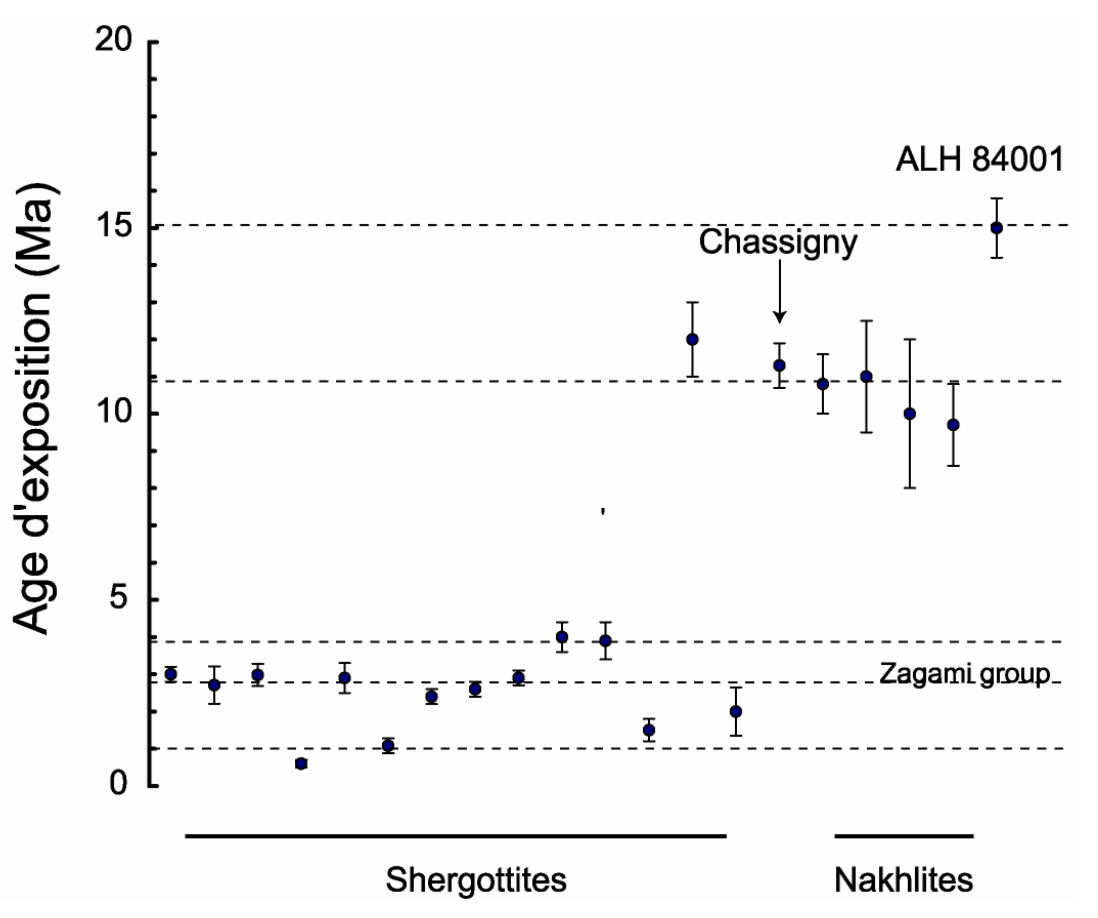
Ages d'expositions des chondrites

Chocs récent ou anciens?

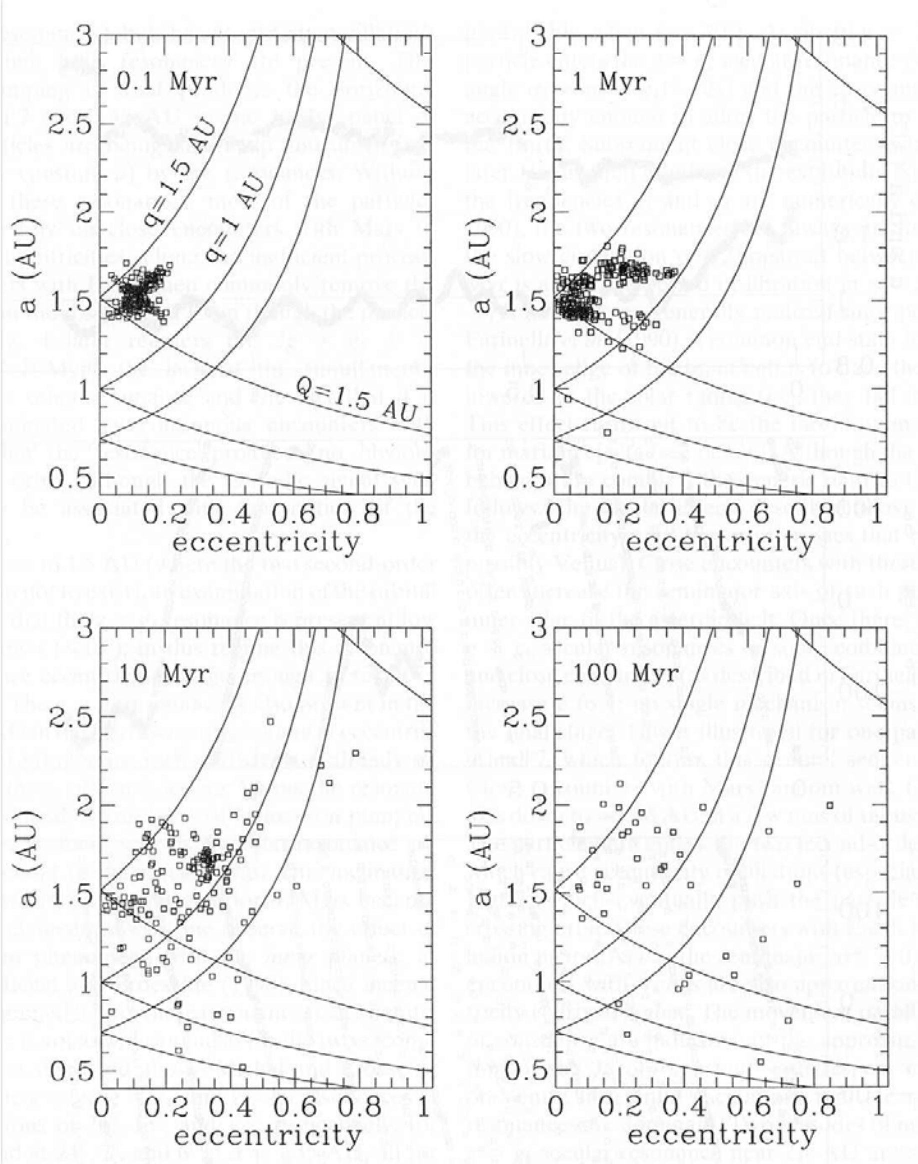
McSween (2002)



Ages d'expositions des météorites martiennes



Efficacité du transfert



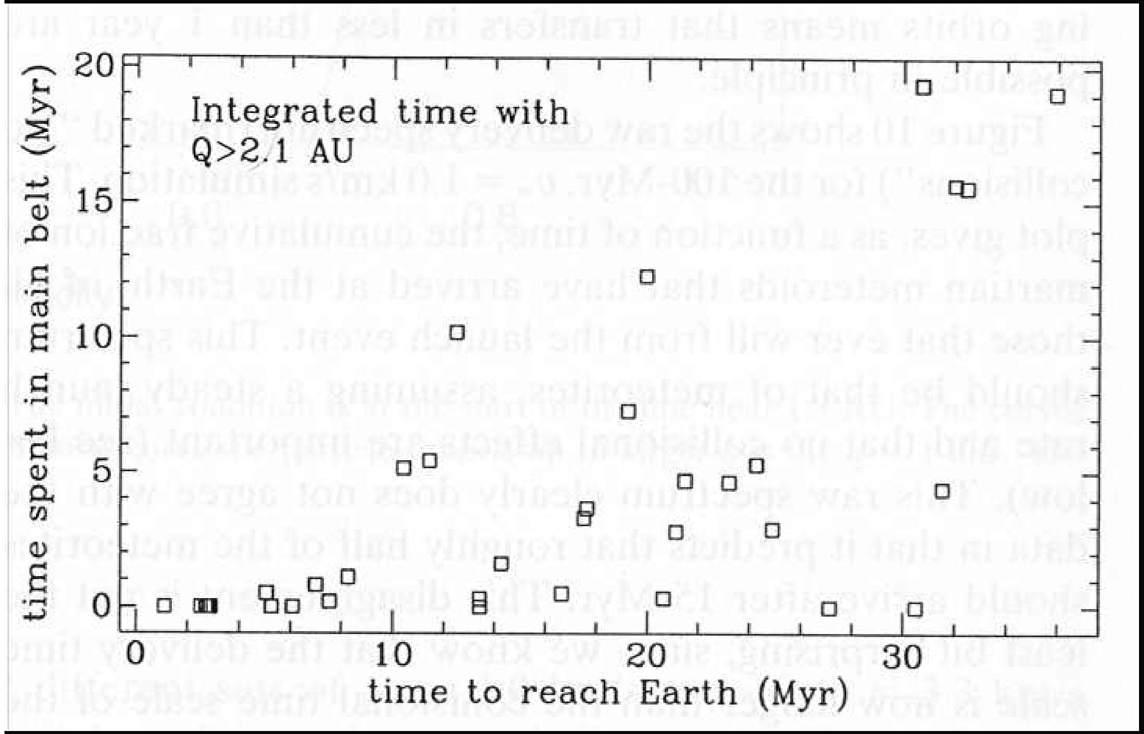
Demi grand-axe

Demi grand-axe

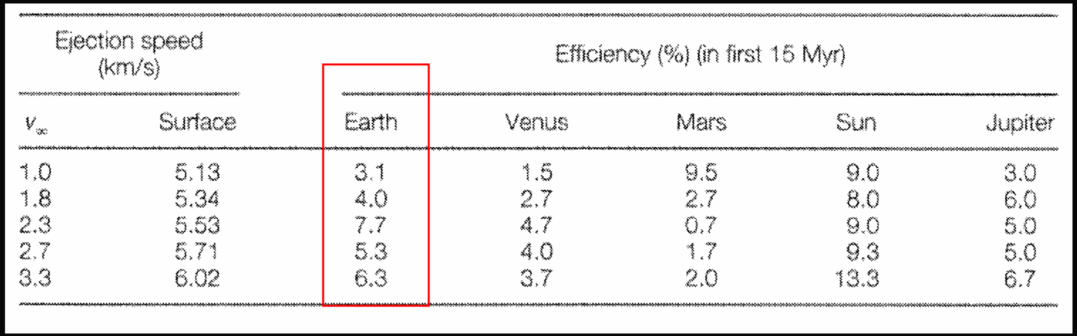
q=a(1-e)   perihelion (petit)
Q=(1+e)   aphelion (grand)

Gladman et al., 1996, 1997

Efficacité du transfert



Gladman et al., 1996, 1997



Ejection speed (km/s)		Efficiency (%) (in first 15 Myr)				
v_∞	Surface	Earth	Venus	Mars	Sun	Jupiter
1.0	5.13	3.1	1.5	9.5	9.0	3.0
1.8	5.34	4.0	2.7	2.7	8.0	6.0
2.3	5.53	7.7	4.7	0.7	9.0	5.0
2.7	5.71	5.3	4.0	1.7	9.3	5.0
3.3	6.02	6.3	3.7	2.0	13.3	6.7

Jumping life?

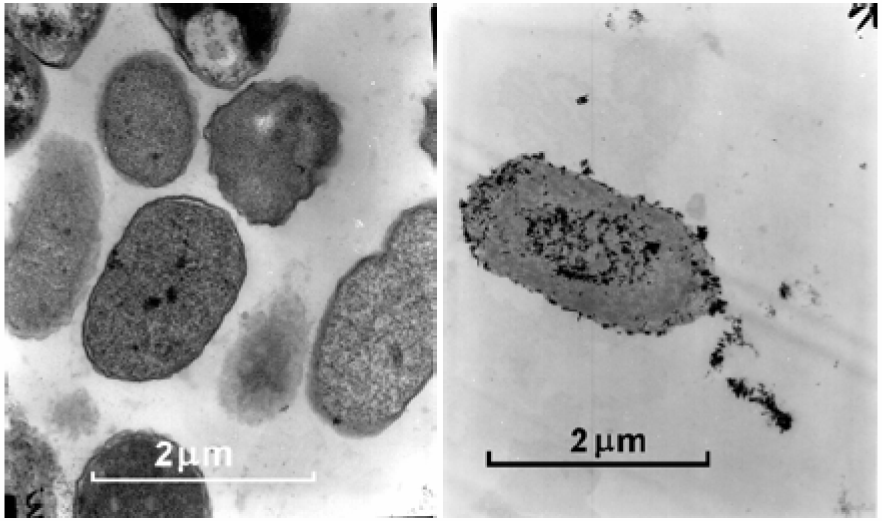


Figure 3: TEM images of unshocked (l) and shocked (r) E.coli cells from Shot 1173. Shocked cell shows irregularities in the cell wall.

Durée des chocs: TD