Annibale de Gasparis Workshop

Osservatorio Astronomico Capodimonte
7-8 Novembre 2019

ROSETTA INCONTRA STEINS & LUTETIA

Elena Martellato

Why asteroids?

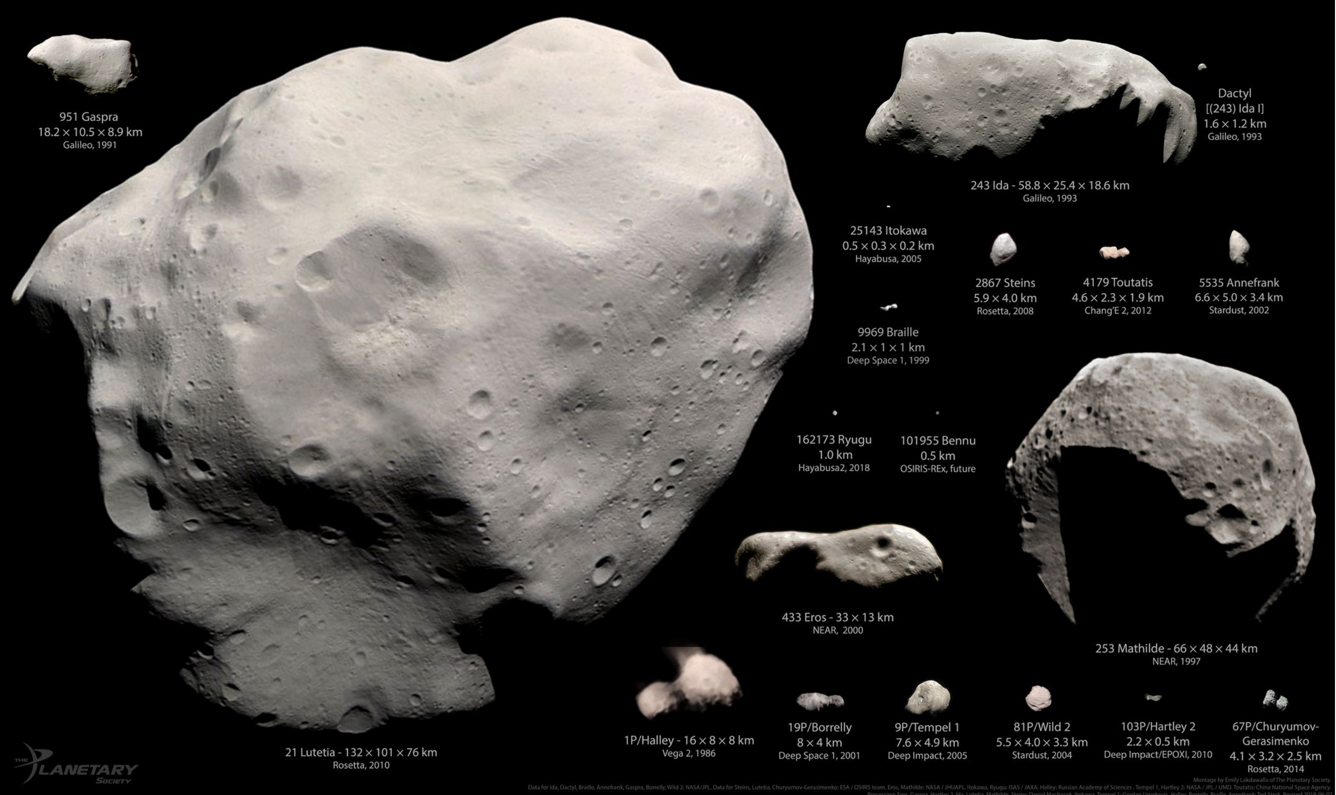
Observations 1

radar techniques can be used to image the asteroid, and allow to infer properties like rotational period, size, shape, albedo and composition of asteroids

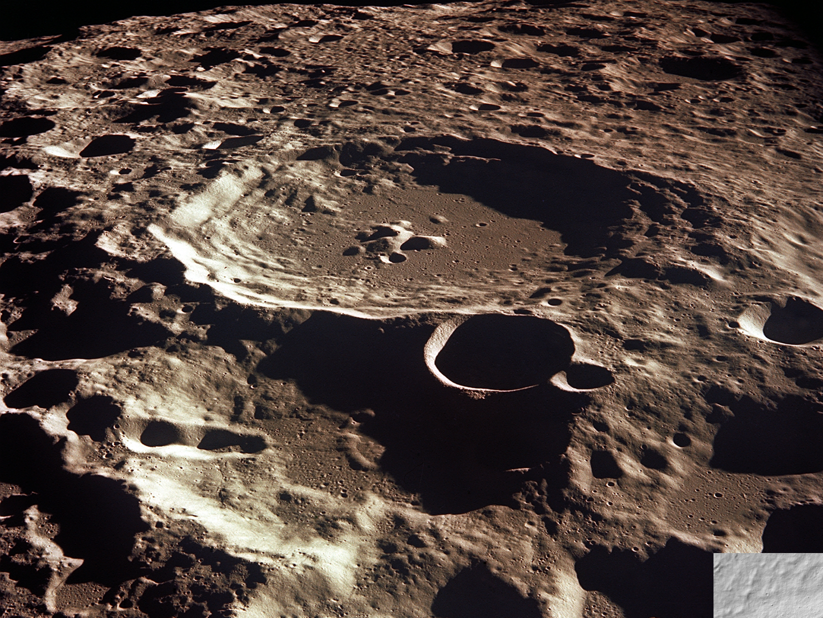
Radar Movie Highlights Asteroid 2006 DP14

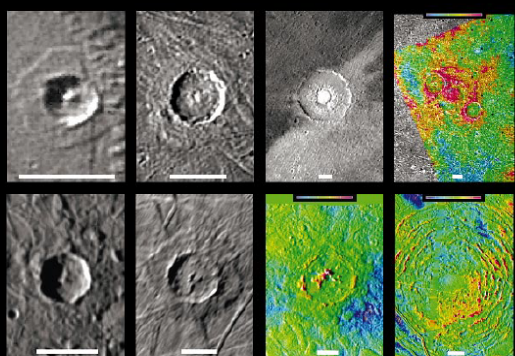
Observations 2

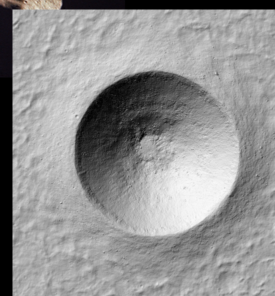
remote-sensing measurements made from spacecraft allow unprecedented high-resolution data of the surface processes

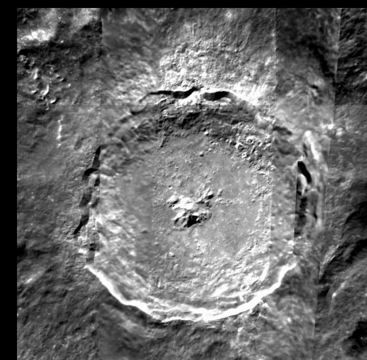


Impact Craters

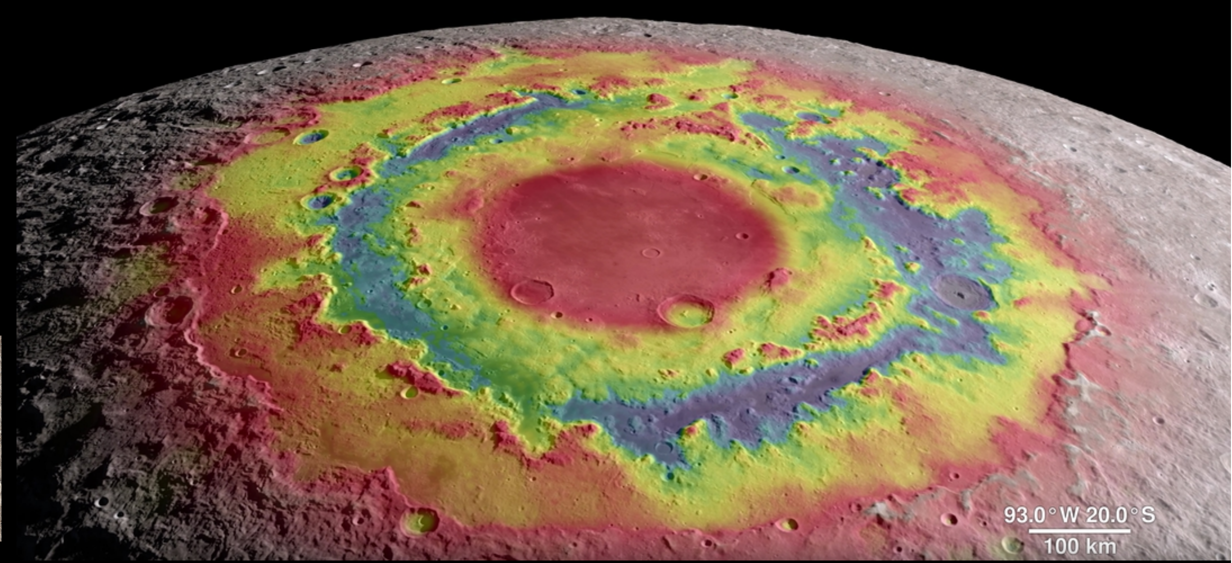


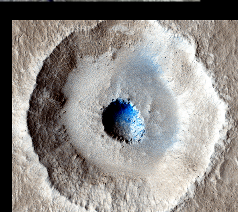






Orientale Basin
Gravity (*Science*, 28 Oct 2016, 438-441)



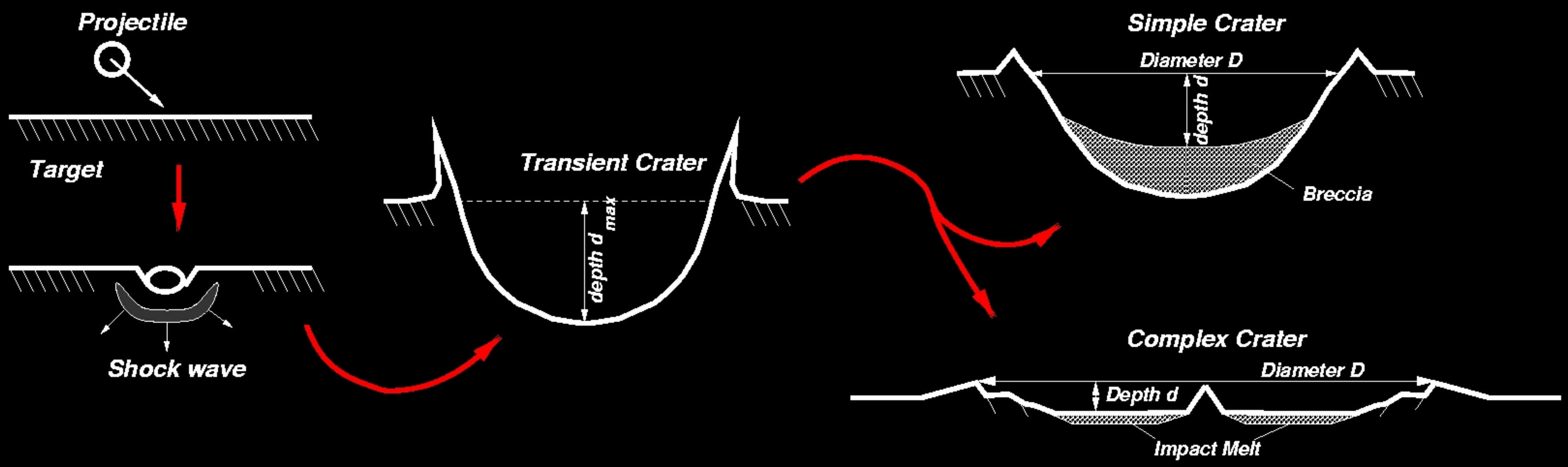


Impact Process: Meteor Crater example

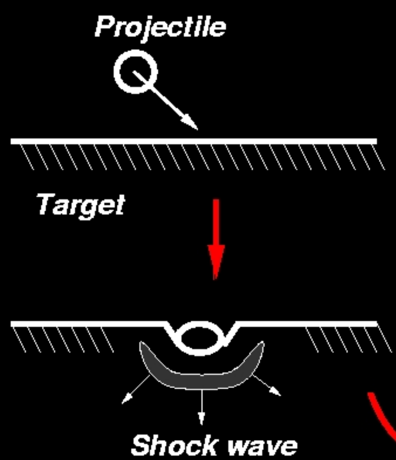
Meteor Crater, AZ
D=1.2 km

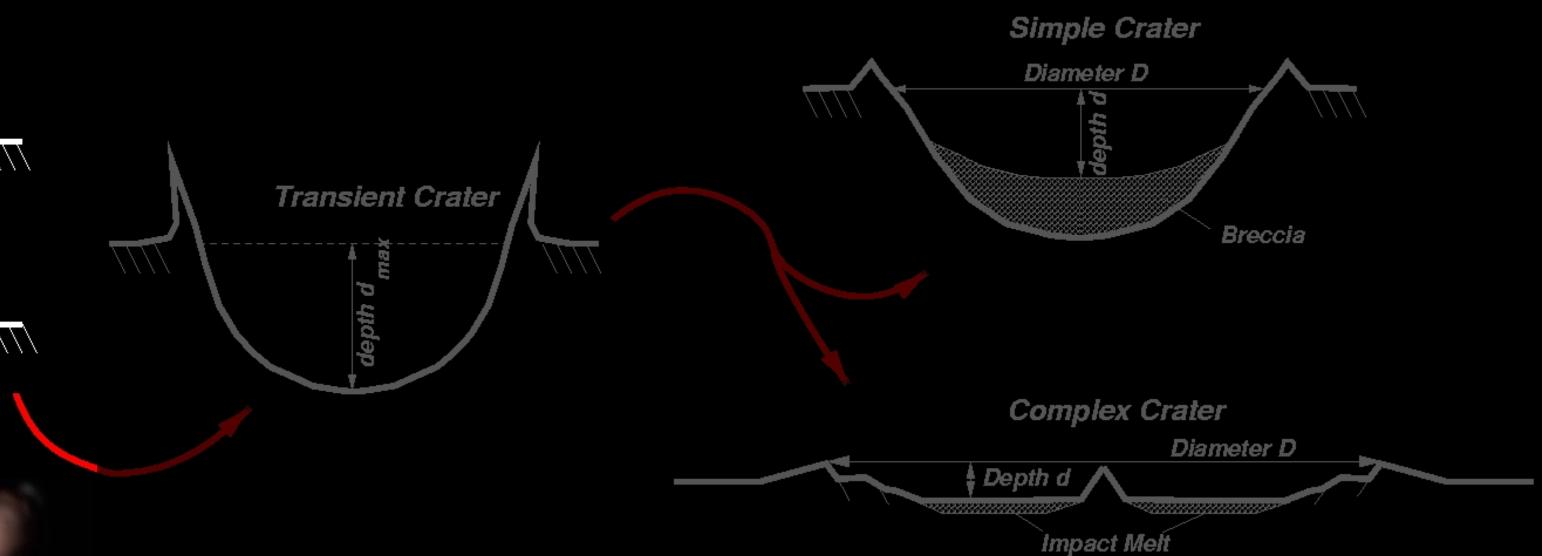
Credits: Barringer website

The Impact Process: general overview

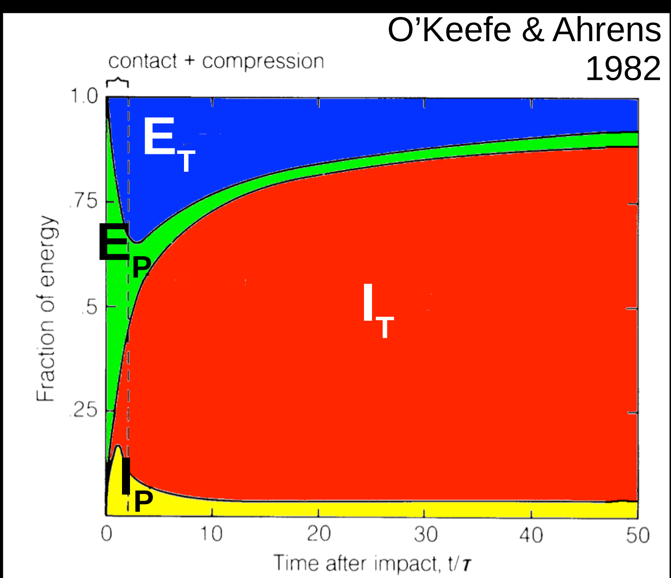


The Impact Process: contact & compression





Artwork courtesy of James Garry, Fastlight



E_T Kinetic Energy target

E_P Kinetic Energy projectile

I_T Internal Energy target

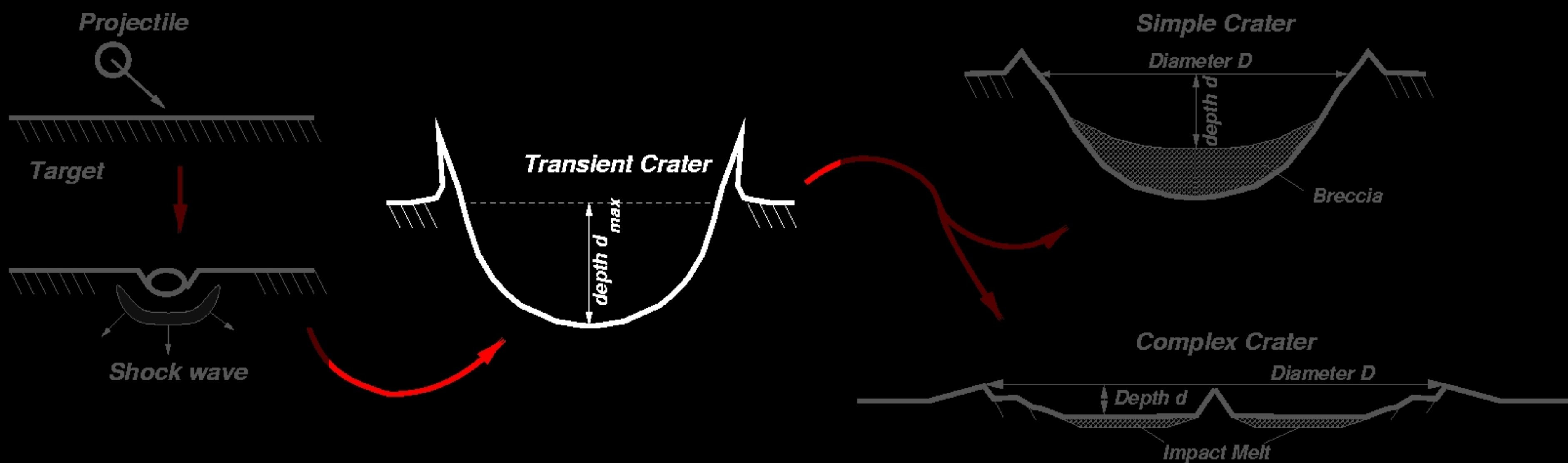
I_P Internal Energy projectile

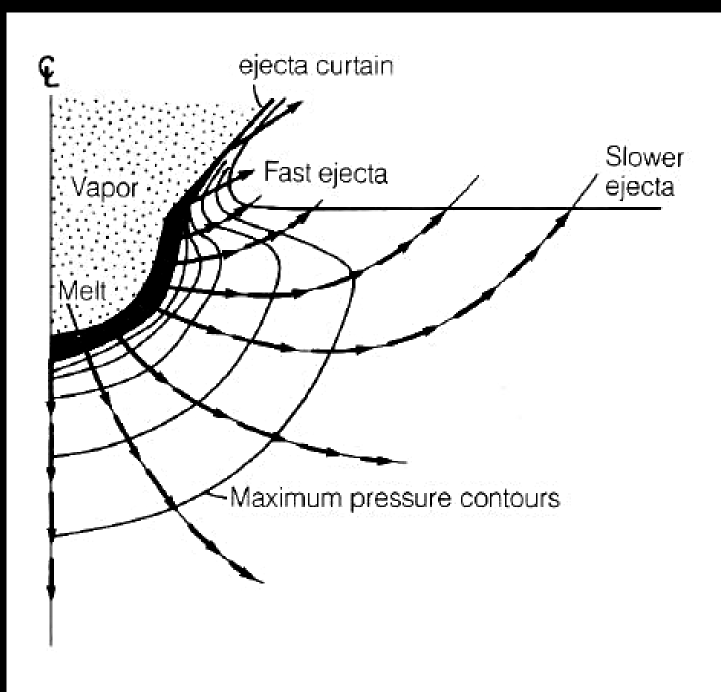
Partitioning of the kinetic energy

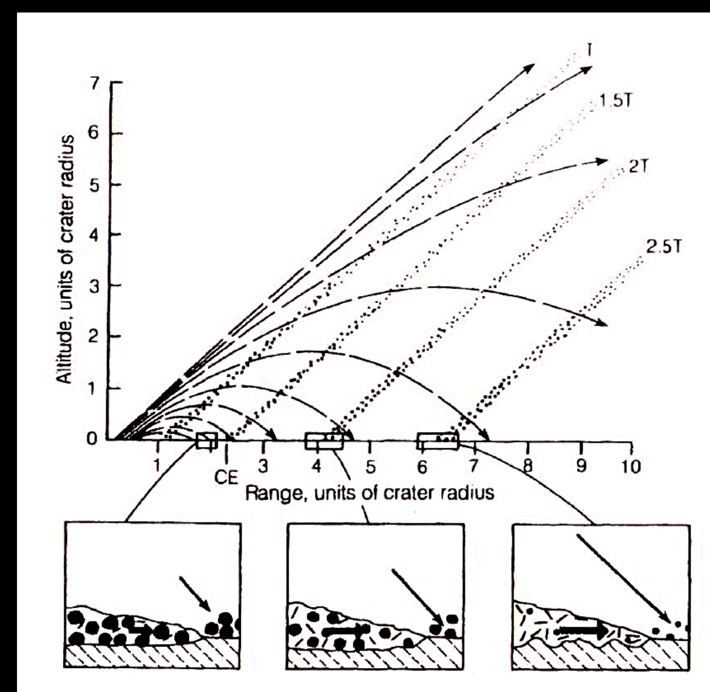
Vast majority of $\mathbf{E_P}$ is turned into internal energy of the target $\mathbf{I_T}$ by **SHOCK WAVES**

<u>Partitioning & distribution</u> of I_T
- material properties
- impact velocity and angle

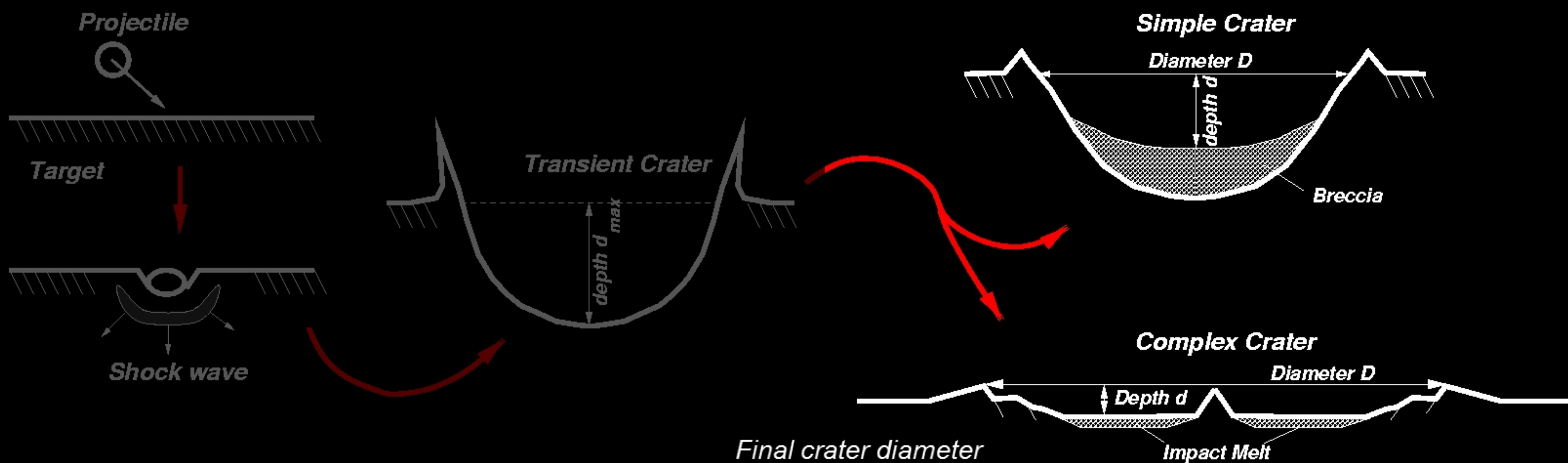
The Impact Process: excavation



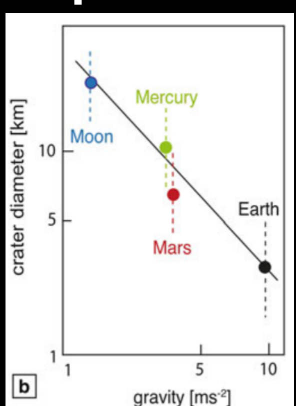


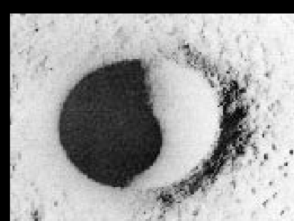


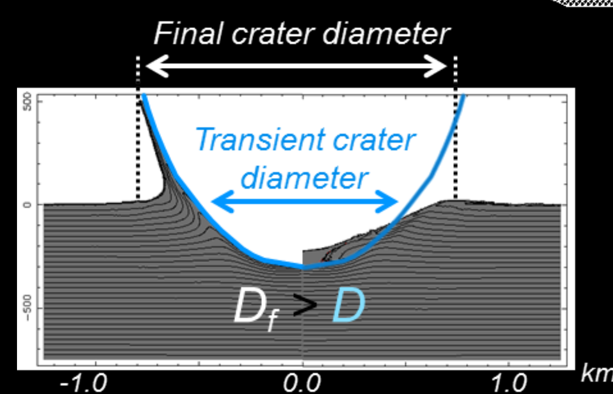
The Impact Process: collapse



Simple craters

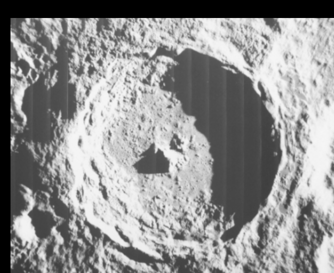


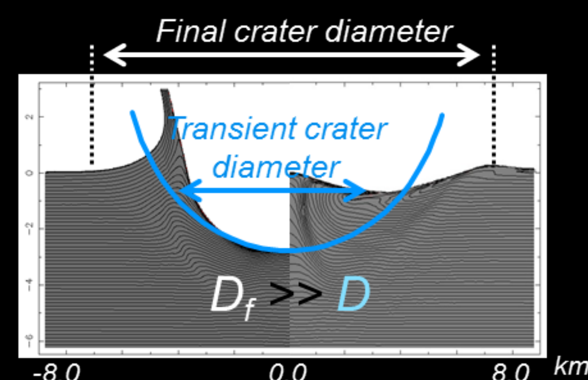




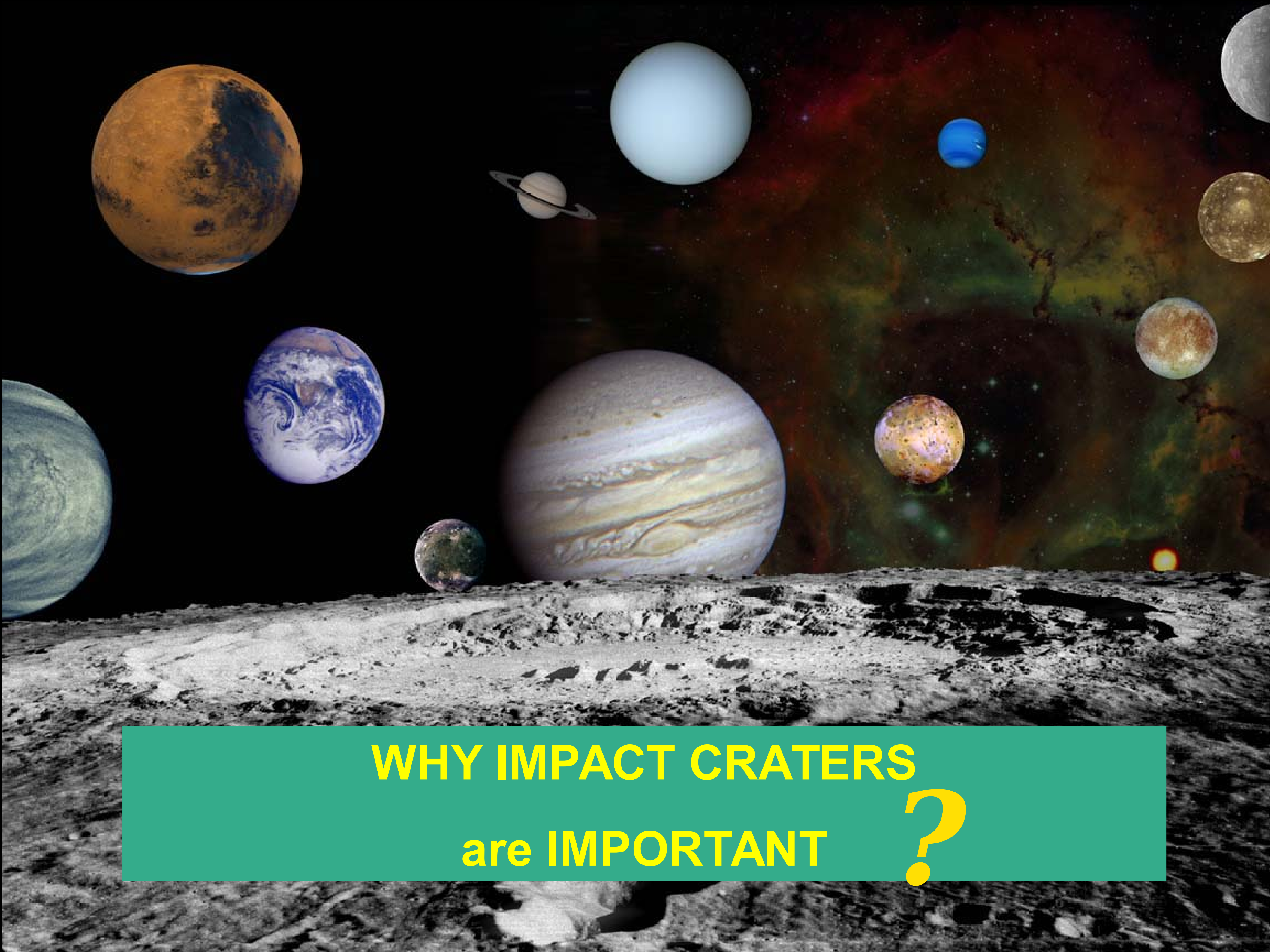
$$D_f = 1.25\, D$$

Complex craters



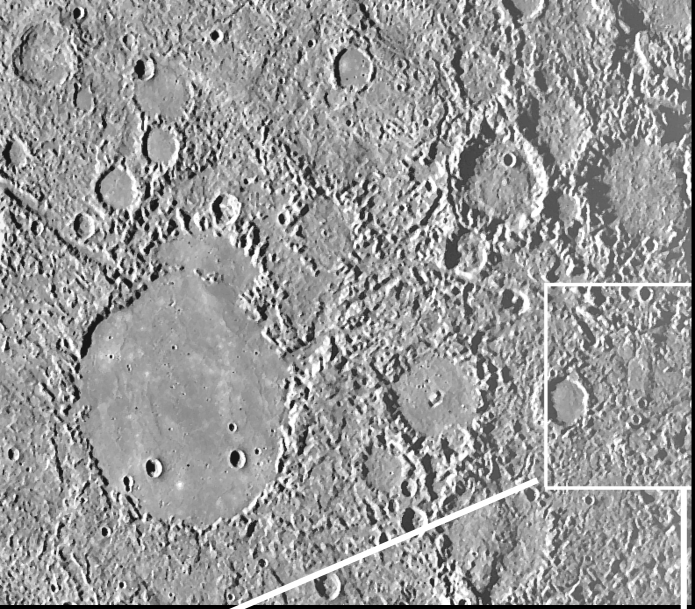


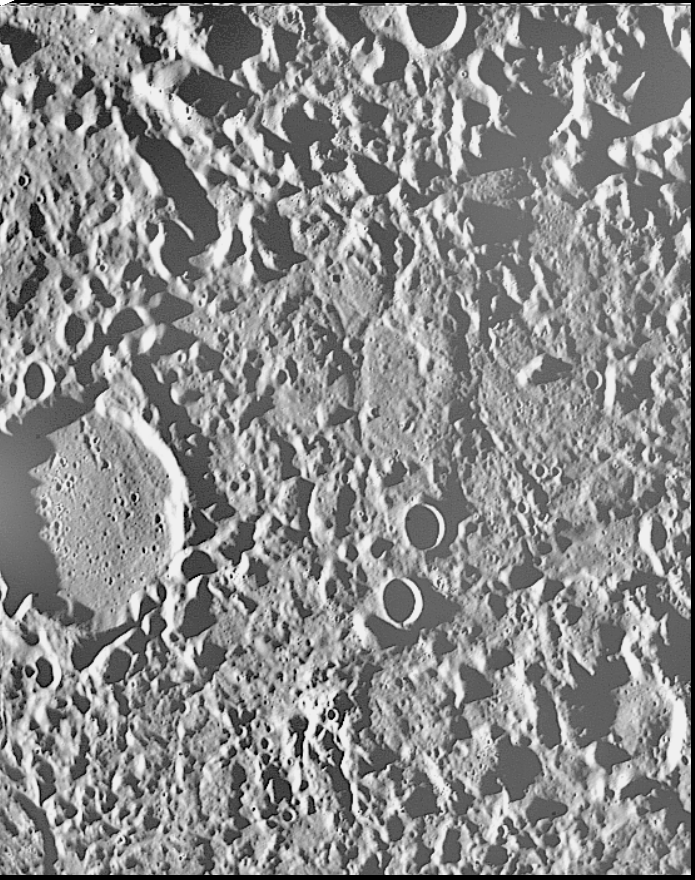
$$D_f = 1.17 \frac{D^{1.13}}{D_{s\text{-}c}^{\ 0.13}}$$


WHY IMPACT CRATERS
are IMPORTANT
?

Planet Formation

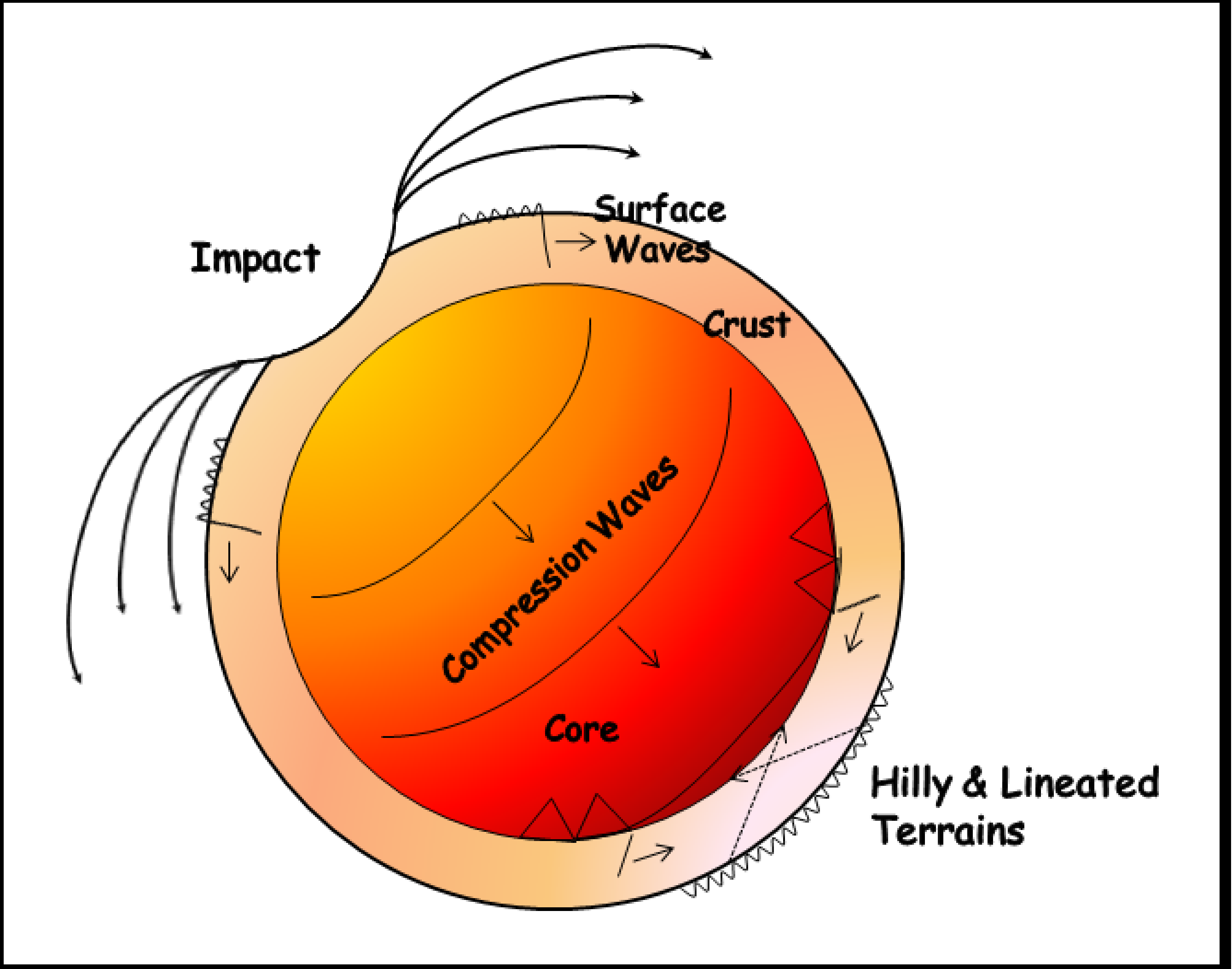
Image credit: NASA / JPL-Caltech



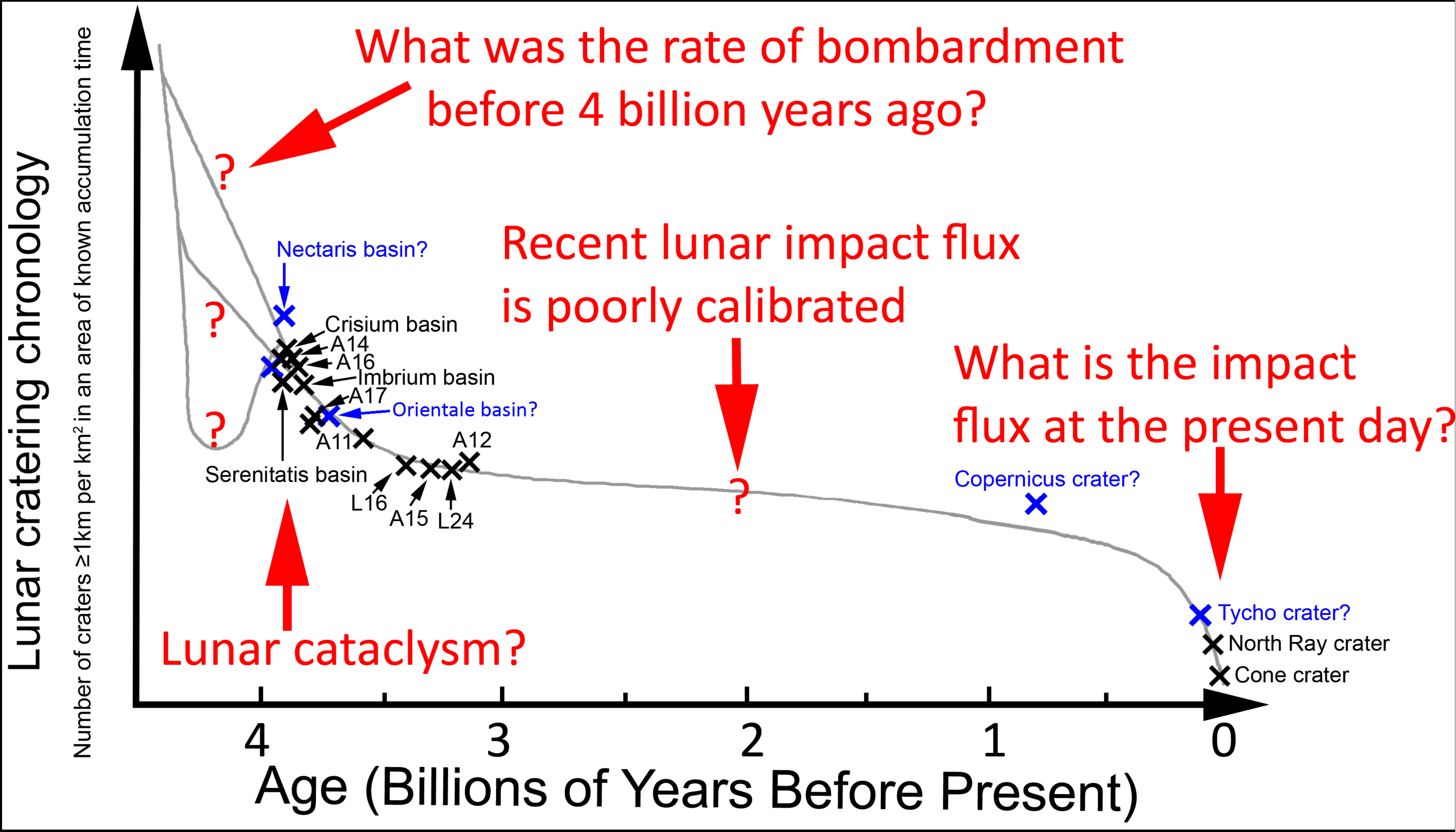


Planetary Geology

Modified after Strom & Sprague (2003)



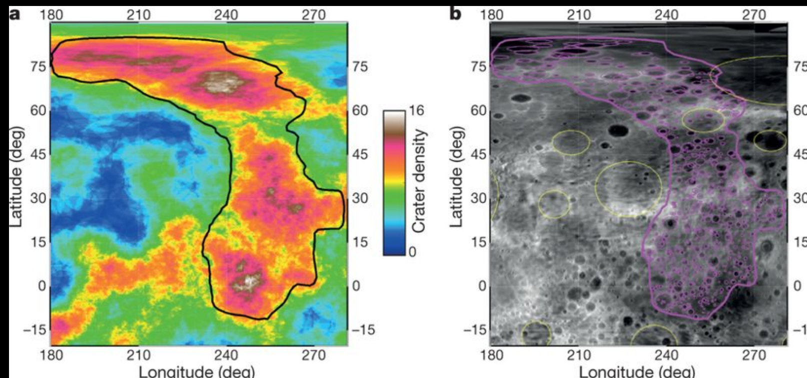
Impactor Flux Estimation



Credit Moon Zoo

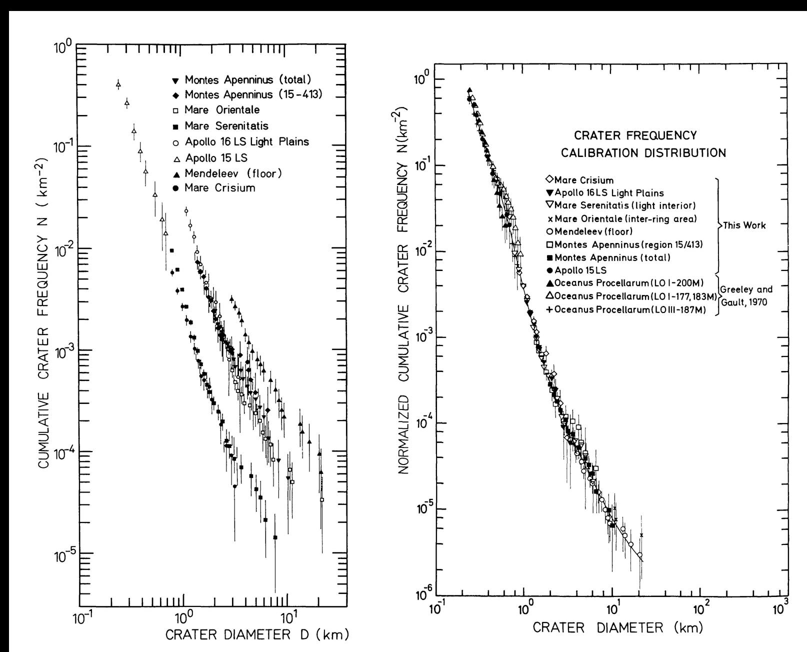
Planetary Age Determination

Relative Age

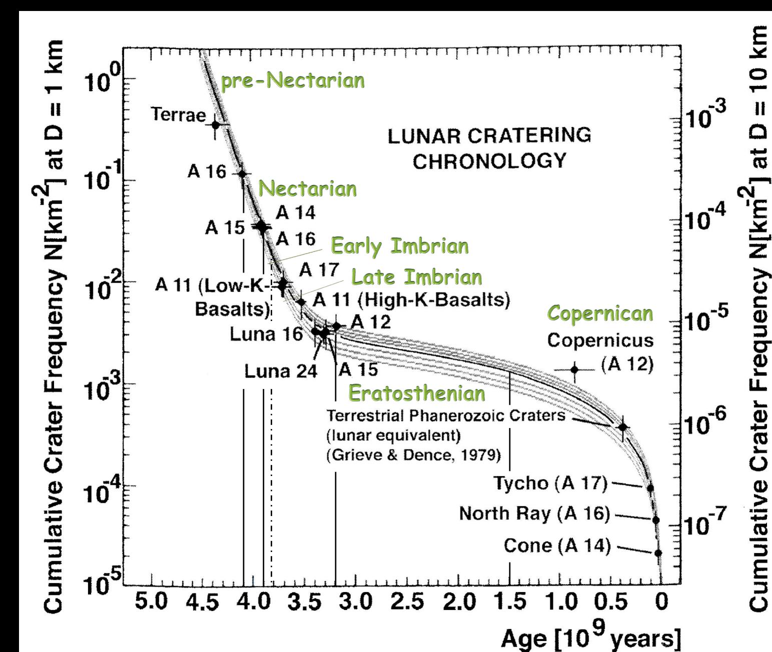


Marchi et al. (2013)

Absolute Age

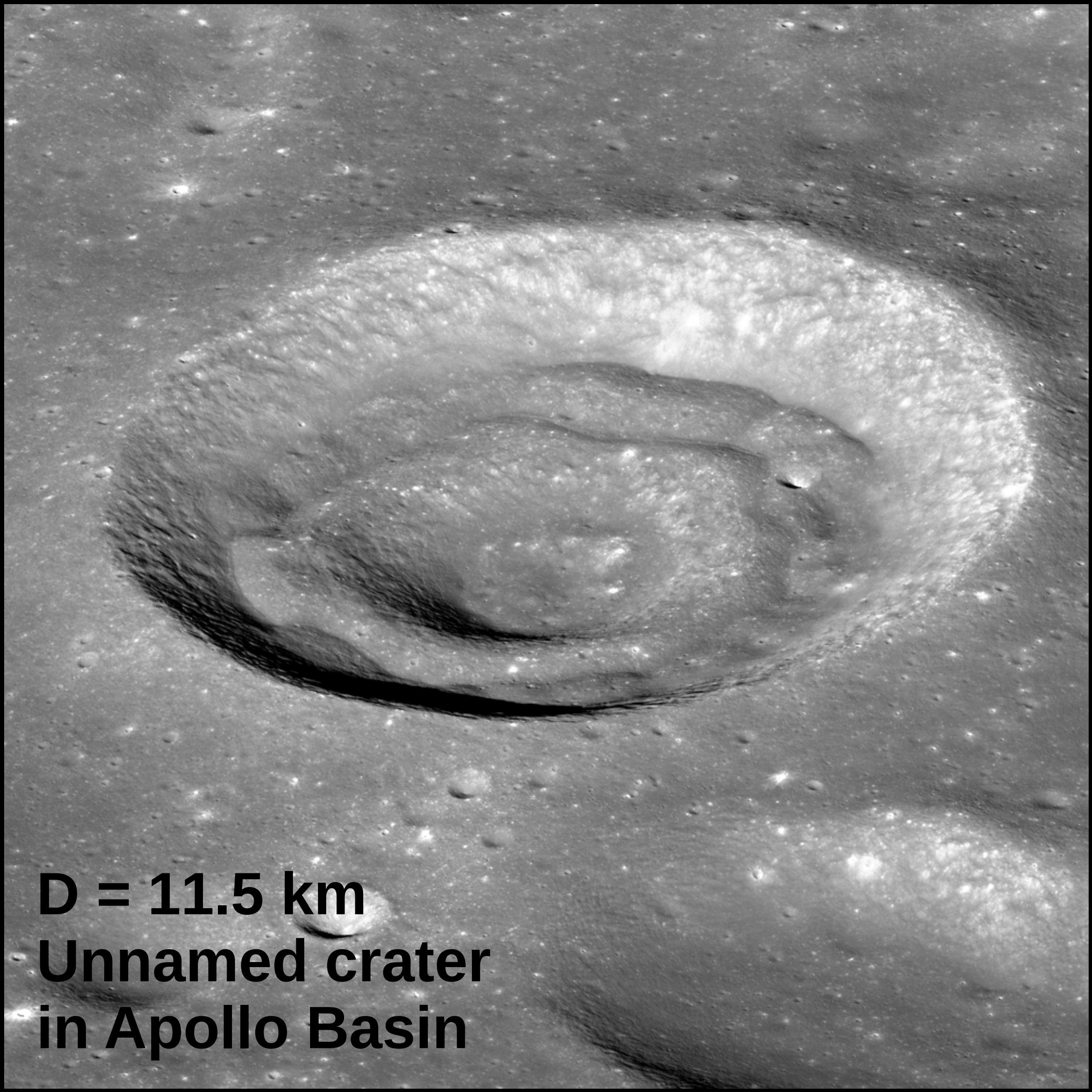


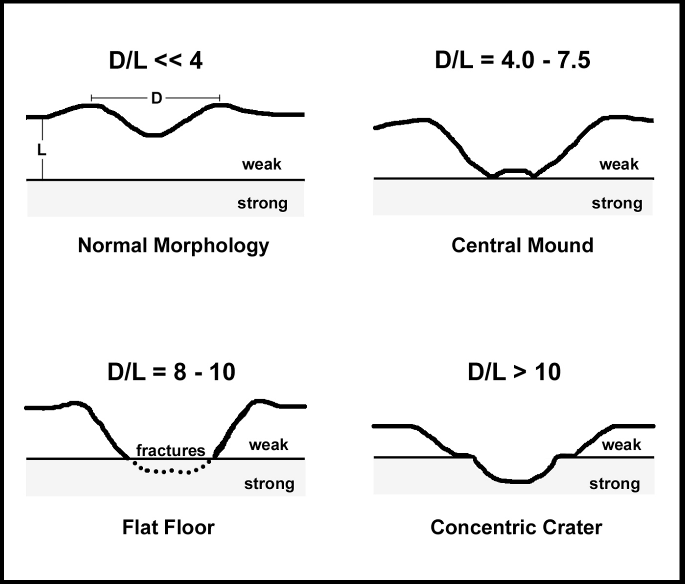
Neukum et al. (1975)



Modified after Hiesinger et al. (2000)

Surface Layering 1

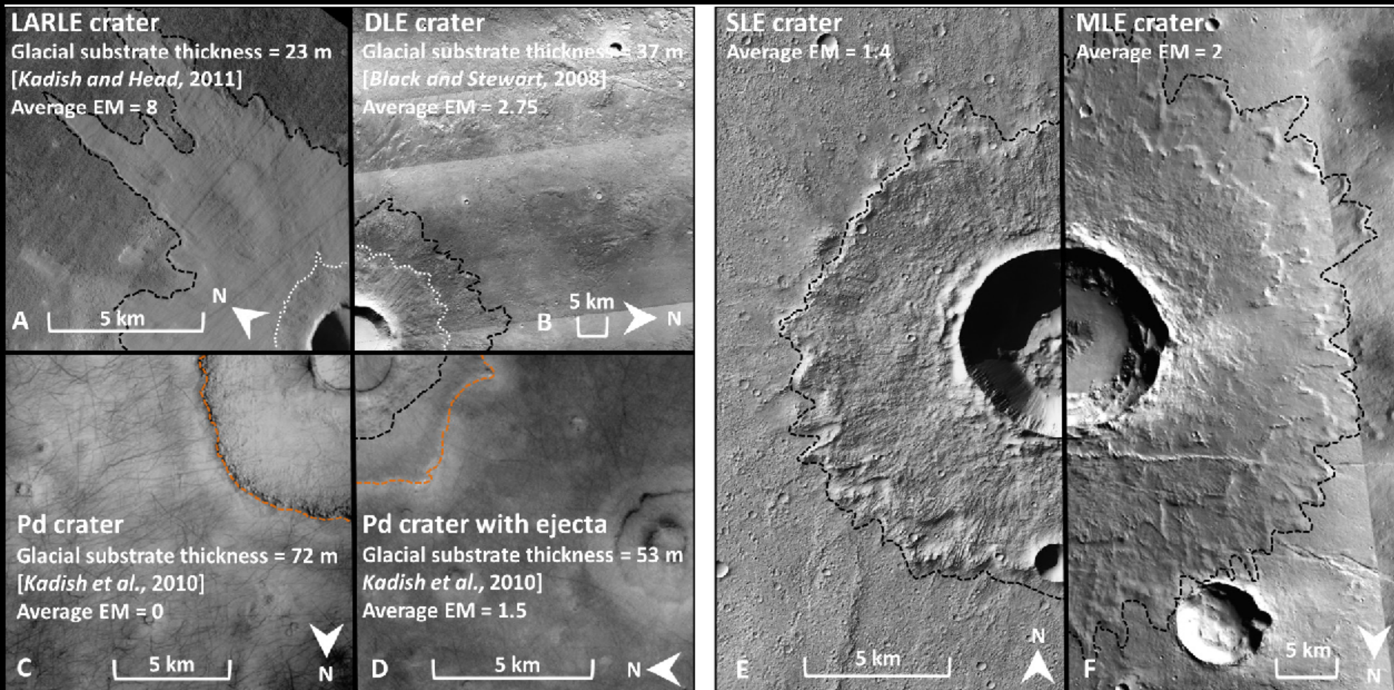




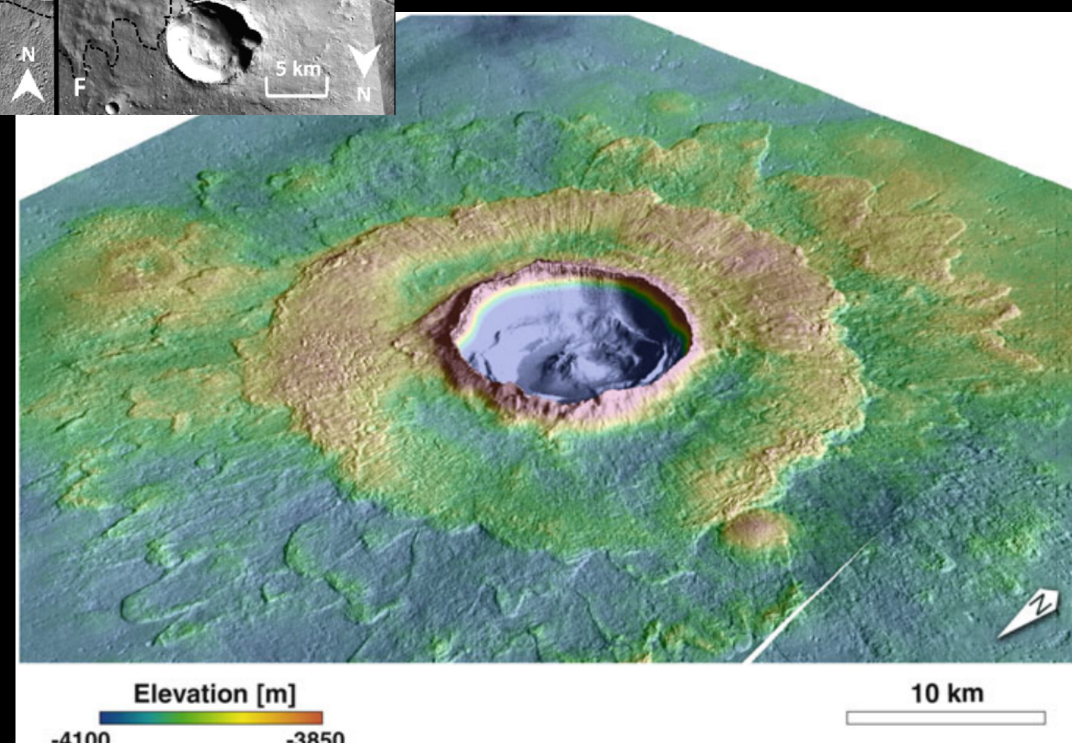
Quaide & Oberbeck (1968)

Credits: LROC/NAC
NASA/GSFC/Arizona State
University

Surface Layering 2

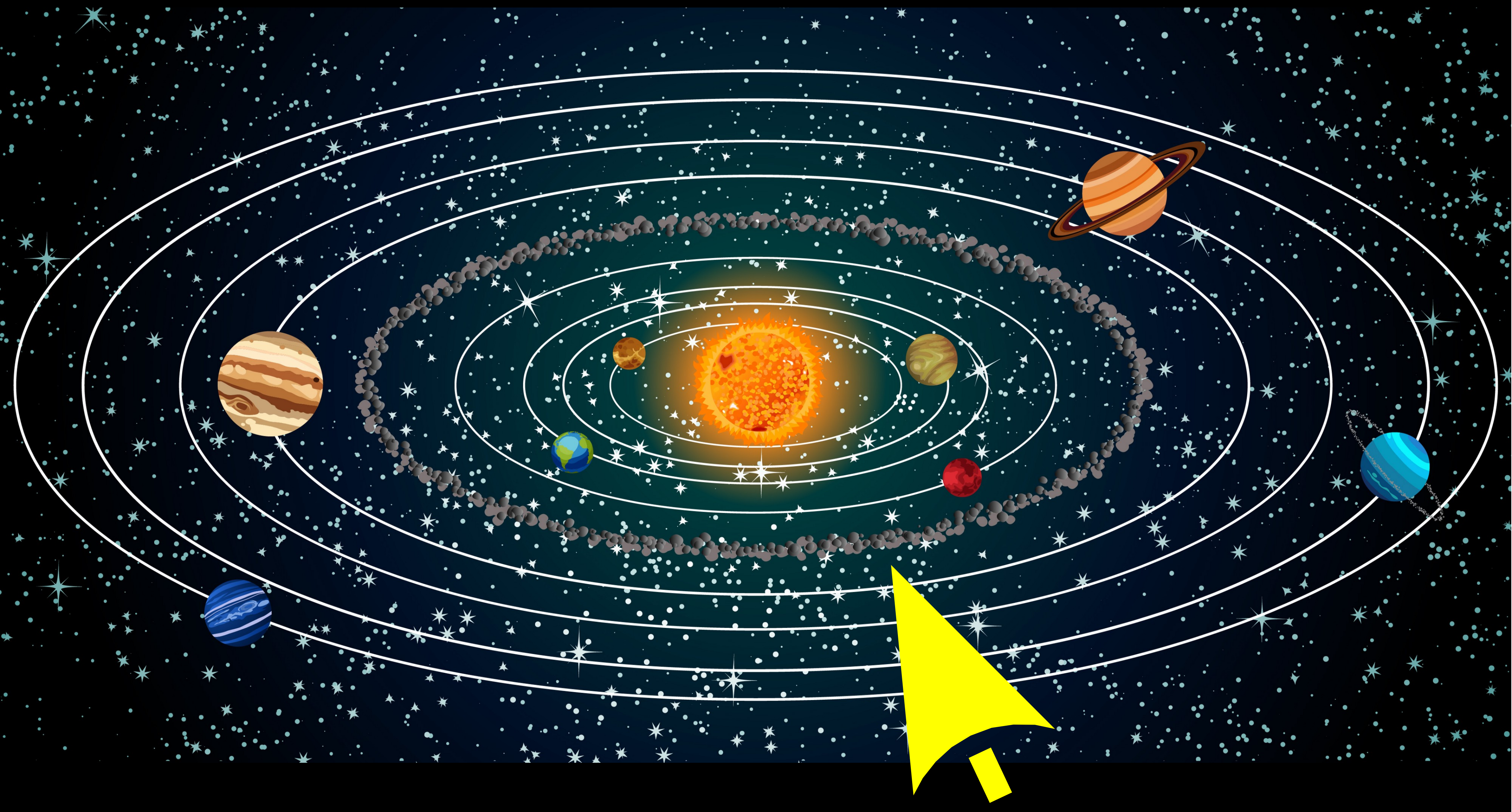


Kenkmann & Wulf (2018)



Weiss & Head (2014)

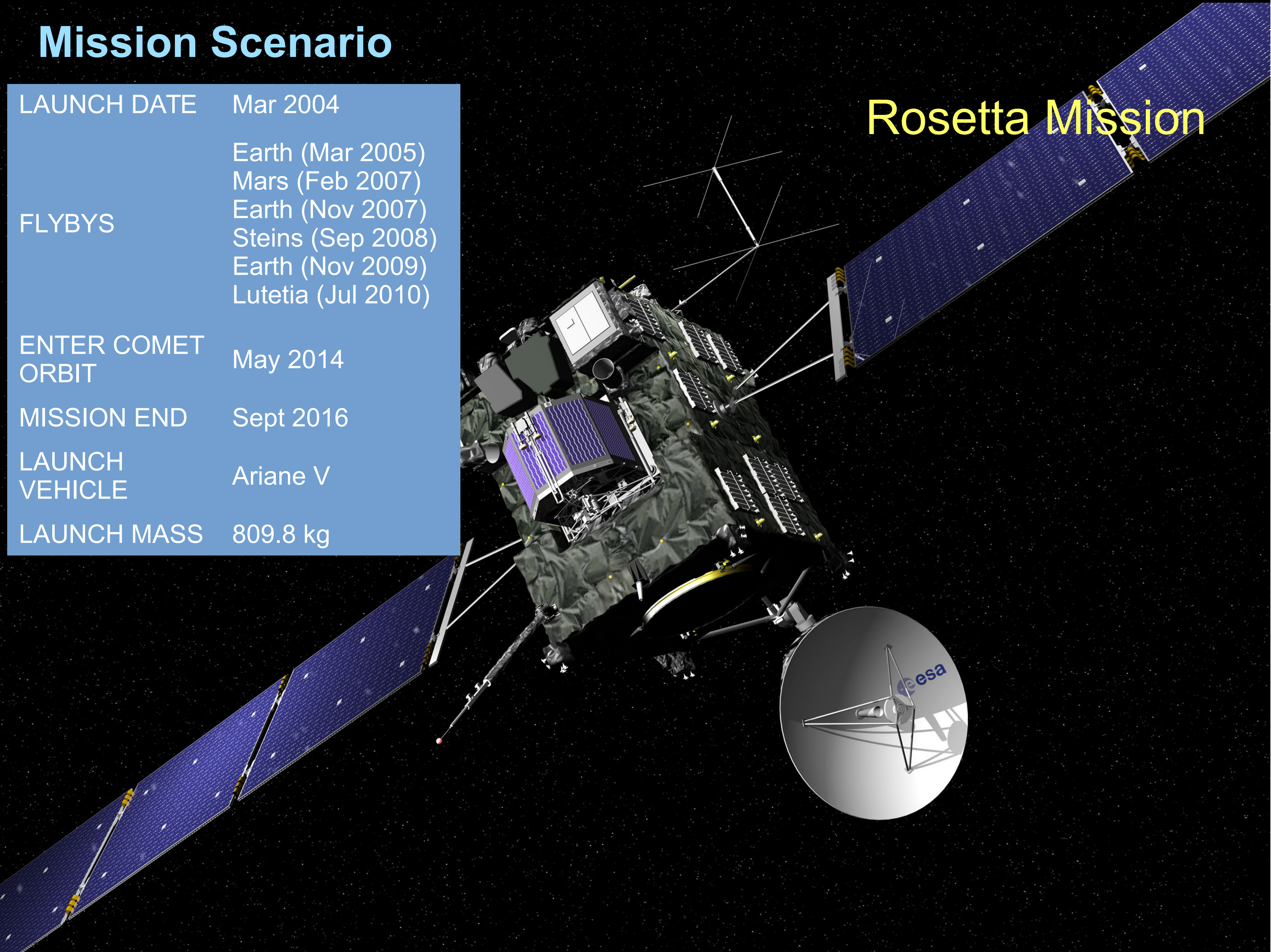
2 case studies



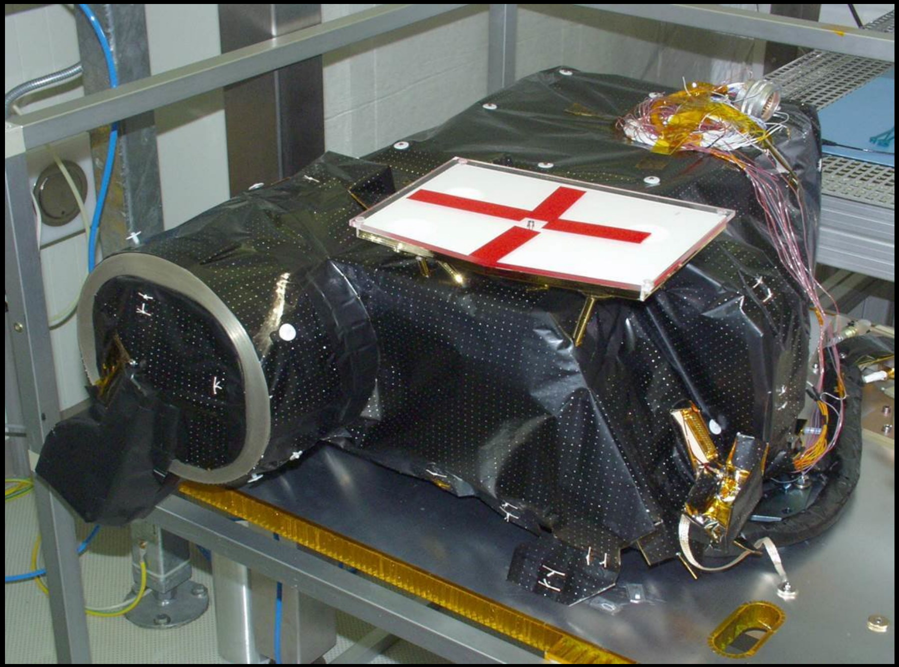
Mission Scenario

LAUNCH DATE	Mar 2004
FLYBYS	Earth (Mar 2005) Mars (Feb 2007) Earth (Nov 2007) Steins (Sep 2008) Earth (Nov 2009) Lutetia (Jul 2010)
ENTER COMET ORBIT	May 2014
MISSION END	Sept 2016
LAUNCH VEHICLE	Ariane V
LAUNCH MASS	809.8 kg

Rosetta Mission

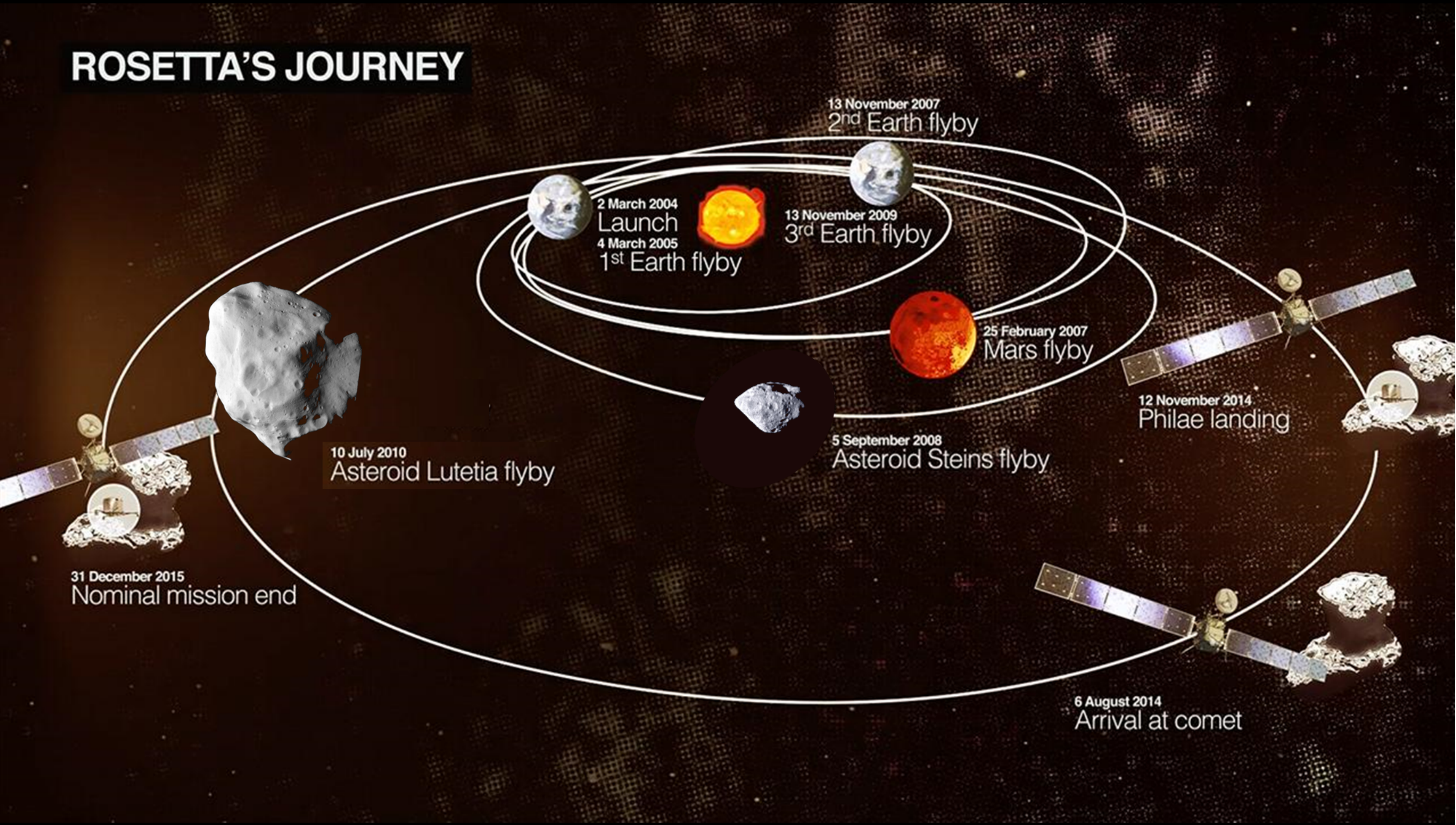


OSIRIS: Optical Spesctroscopic and Infrared Remote Sensing Imaging System



CREDITS: Max Plank

	NAC	WAC
OPTICAL DESIGN	3-mirror off-axis	2-mirror off-axis
DETECTOR TYPE	2k × 2k CCD	2k × 2k CCD
ANGULAR RESOLUTION (μrad px^{-1})	18.6	101
FOCAL LENGTH(mm)	717.4	140(sag)/ 131(tan)
MASS	13.2 kg	9.48 kg
FoV	1.20° × 2.22°	11.35° × 12.11°
WAVELENGTH RANGE	250-1000 nm	240-720 nm
No. of FILTERS	12	14
ESTIMATED DETECTION THRESHOLD (m_V)	21-22	18

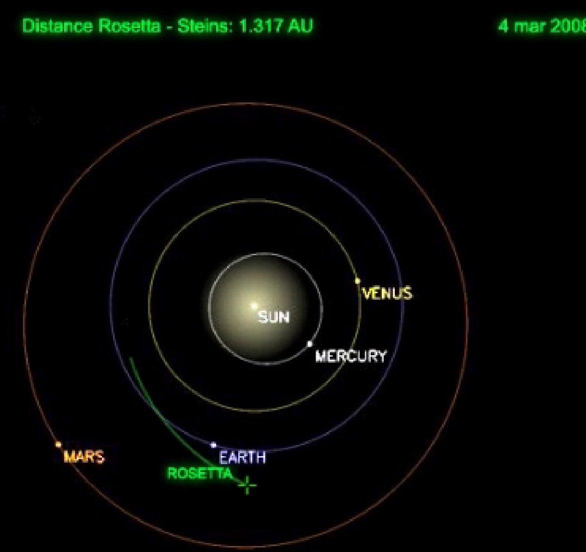


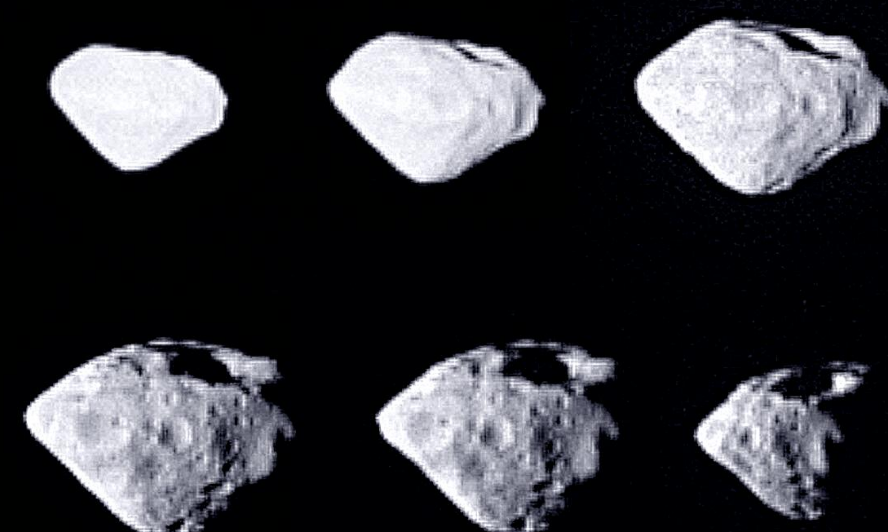
Modified from BBC

2867 Steins: 5th September 2008

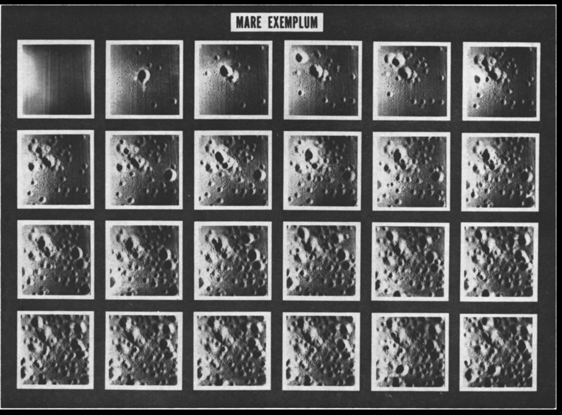
- D = 4.6 km
- E-type asteroid
- Characteristic feature: a 2-km crater
- Numerical models suggest Steins is either a monolithic, and then transformed in a rubble pile strucure as a result of the crater formation, allowing it to be reshaped in its current shape by the YORP spin-up thermal effect
- The chain may indicate partial drainage of loose surface material into a fracture within stronger, deeper material, possibly marking pre-existing physical inhomogeneities

Jutzi et al. (2010)
Keller et al. (2010)





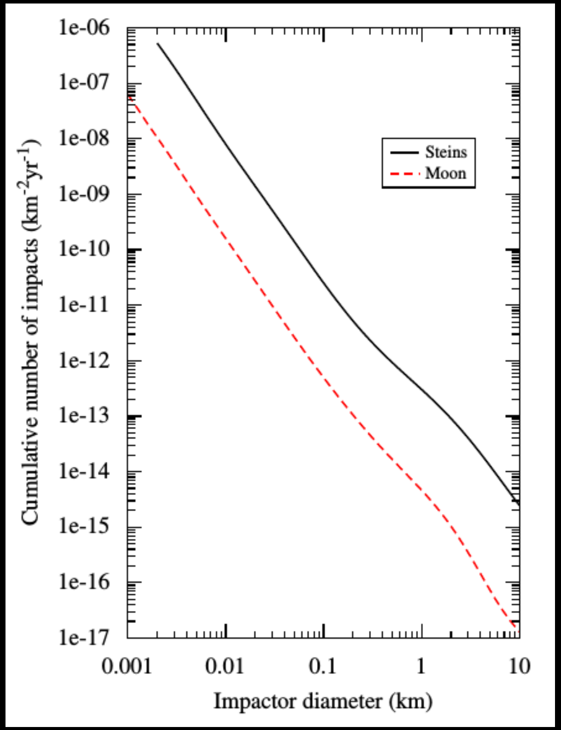
Courtesy of ESA 2008 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA, No. SEM27ZO4KKF



From Gault (1970)

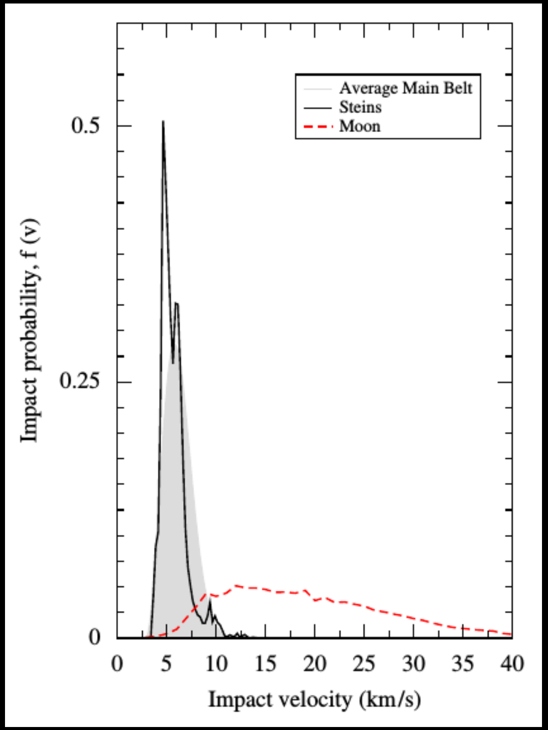
AGE: Crater-counting based Chronology

MBA size-distribution



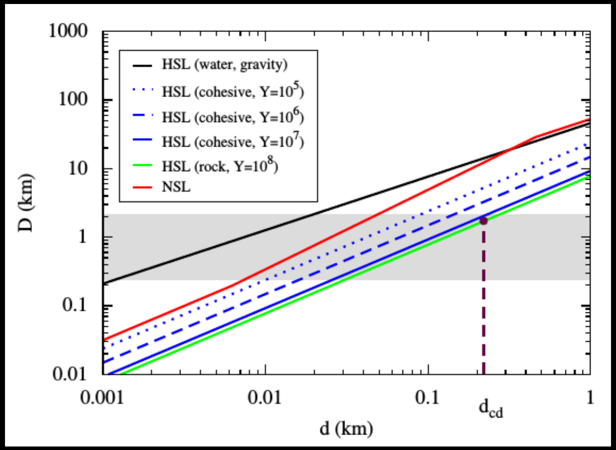
×

intrinsic probability of collision with Steins



+

scaling laws



Marchi et al. (2011)

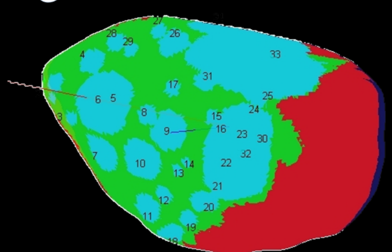
A

define region of interest by selecting the normal faces in relation to the direction of both the light and the spacecraft

B

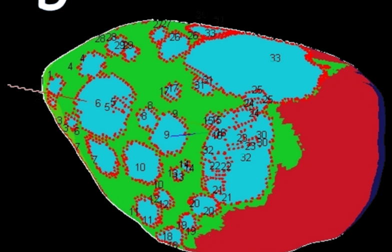
define their terminator by using the projected images

C



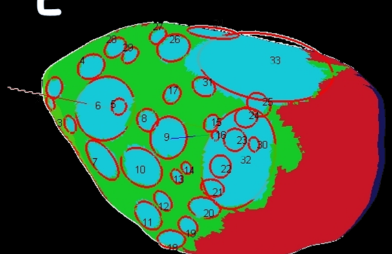
define 3D craters by projecting the ArcGIS masks

D



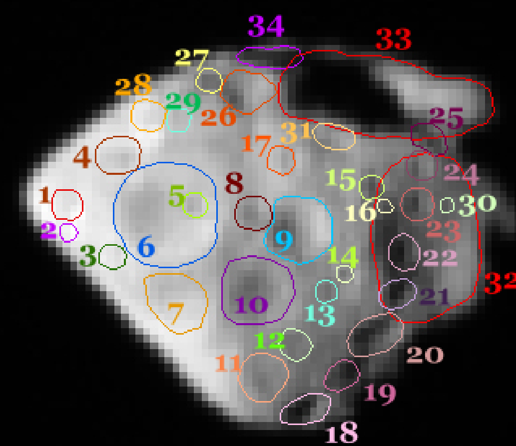
detect border vertices

E



elliptical fit (LMS) and mean diameter estimation

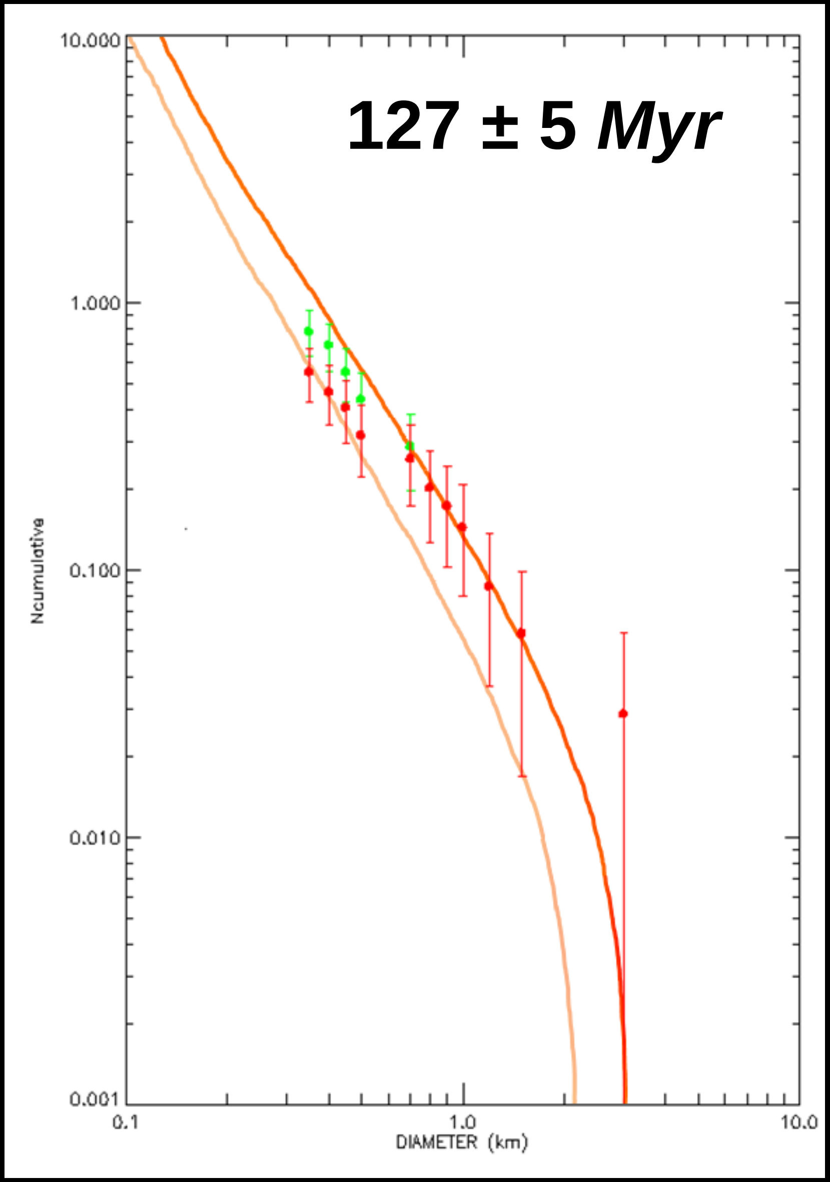
Crater Statistics



UT = 18:38:02.520. The area is 34.5254 *km²*, computed removing the shaded areas near the terminator seen by OSIRIS, since no crater is detected on them

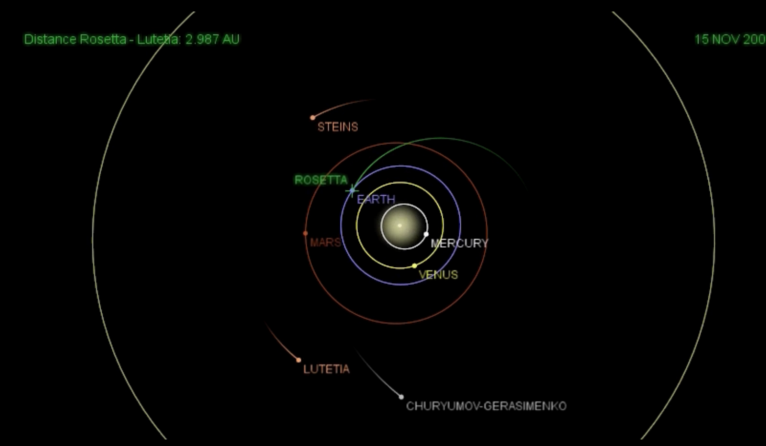
Age Determination

No	Type	2D SHAPE Mean Diameter (km)	Semi major axis (km)	3D SHAPE Semi minor axis (km)	Mean Diameter (km)
1	PRIMARY	0.22	0.22	0.18	0.40
2	?	0.53	0.13	0.14	0.27
3	PRIMARY	0.62	0.23	0.16	0.40
4	PRIMARY	0.94	0.30	0.26	0.56
5	PRIMARY	0.33	0.16	0.15	0.30
6	DEGRADED	1.20	0.65	0.59	1.24
7	ELLIPTIC	0.48	0.56	0.39	0.96
8	PRIMARY	0.29	0.24	0.20	0.44
9	DEGRADED	0.80	0.41	0.38	0.79
10	DEGRADED	0.78	0.59	0.41	1.01
11	PRIMARY	0.75	0.49	0.28	0.77
12	PRIMARY	0.72	0.31	0.19	0.50
13	PRIMARY	0.41	0.20	0.13	0.33
14	PRIMARY	0.34	0.13	0.11	0.25
15	PRIMARY	0.38	0.18	0.15	0.34
16	PRIMARY	0.80	0.10	0.08	0.17
17	PRIMARY	0.33	0.21	0.17	0.38
18	CHAIN	0.65	0.37	0.19	0.55
19	CHAIN	0.70	0.33	0.19	0.52
20	CHAIN	0.86	0.49	0.28	0.78
21	CHAIN	0.41	0.27	0.21	0.48
22	CHAIN	0.56	0.22	0.19	0.40
23	CHAIN	0.43	0.21	0.20	0.41
24	CHAIN	0.41	0.24	0.19	0.42
25	CHAIN	0.85	0.30	0.23	0.53
26	PRIMARY	0.52	0.50	0.30	0.80
27	PRIMARY	0.54	0.31	0.15	0.46
28	PRIMARY	0.27	0.27	0.20	0.47
29	PRIMARY	0.75	0.21	0.15	0.36
30	PRIMARY	0.40	0.11	0.13	0.24
31	ELLIPTIC	0.97	0.30	0.18	0.48
32	?	1.76	0.97	0.66	1.64
33	?	2.19	2.16	1.10	3.26
34	?	0.78	0.72	0.30	1.02



21 Lutetia: 10th July 2010

- D = 100 km
- composition: carbonaceous or enstantite chondirite
- density = 3.4 g/cm^3
- 5 major units
- heavily cratered
- surface covered by regolith



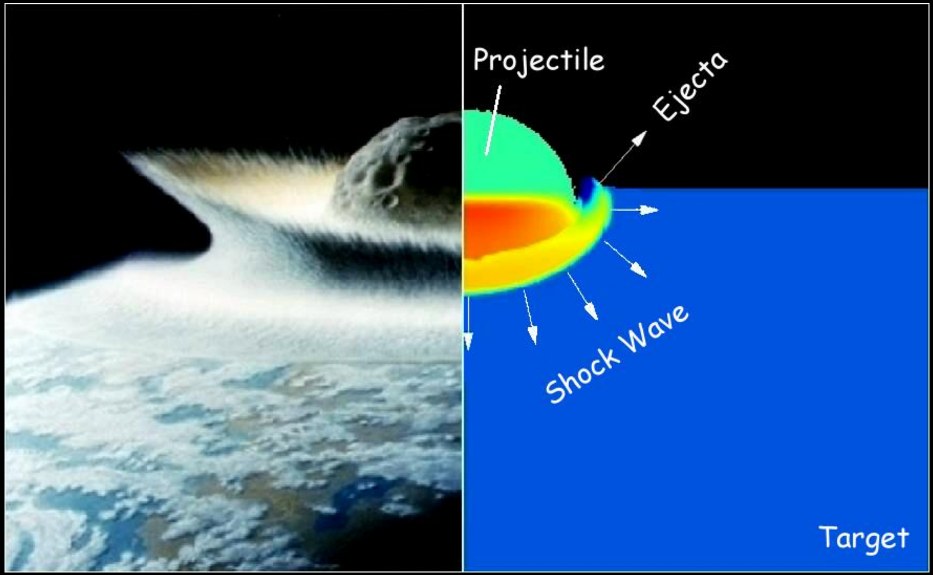
Sierks et al. (2011)

Courtesy of ESA 2010 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA, No. SEMSZCZOFBG

INTERNAL STRUCTURE: Numerical Modelling

Scientific Motivations

- determination of the projectile size
- hints on the asteroid composition and structure
- outline crater morphology
- boulders formation and ejection
- estimate of secondary formation
- fraction of escaping material



- Expand size scale from experimentally feasibile studies
- Study conditions beyond the reach of experiments (eg., velocity, size)
- Verify the physics of the process

Imperial College London

iSALE

MUSEUM FÜR NATURKUNDE BERLIN

impact - Simplified Arbitrary Lagrangian Eulerian

Conservation Laws:

Momentum $$\frac{Dv_i}{Dt} = f_i + \frac{1}{\rho}\frac{\partial \sigma_{ji}}{\partial x_j}$$

Mass $$\frac{D\rho}{Dt} + \rho\frac{\partial v_i}{\partial x_i} = 0$$

Energy $$\frac{DI}{Dt} = -\frac{p}{\rho}\frac{\partial v_i}{\partial x_i} + \frac{1}{\rho}\prod_{ij}\dot{\varepsilon}'_{ij}$$

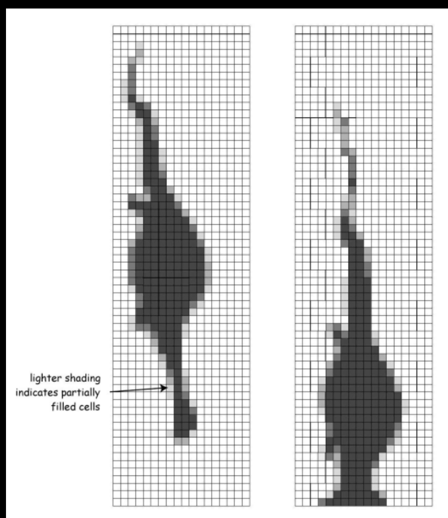
Contistitutive Material Models

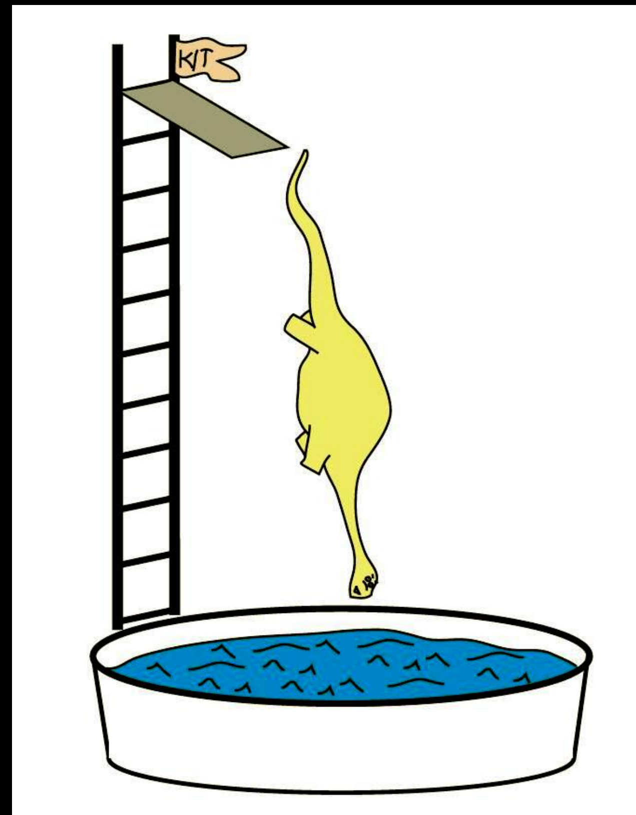
Equation of State $$p = p(\rho, I)$$

Strength Model $$\sigma_{ij} = g(\varepsilon_{ij}, \dot{\varepsilon}_{ij}, I, D)$$

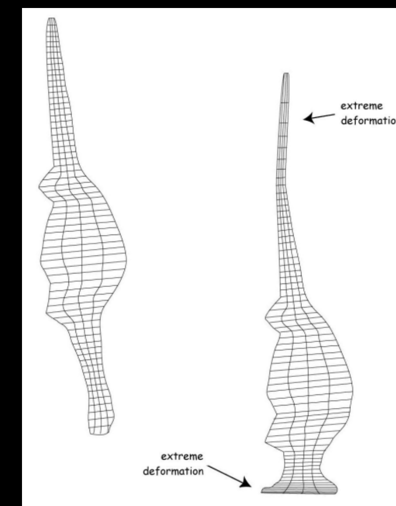
The implementation of the continuum dynamics occurs through
DISCRETIZATION

Eulerian





Lagrangian



material flows through a static mesh

- cell volume is constant
- cell mass changes with time

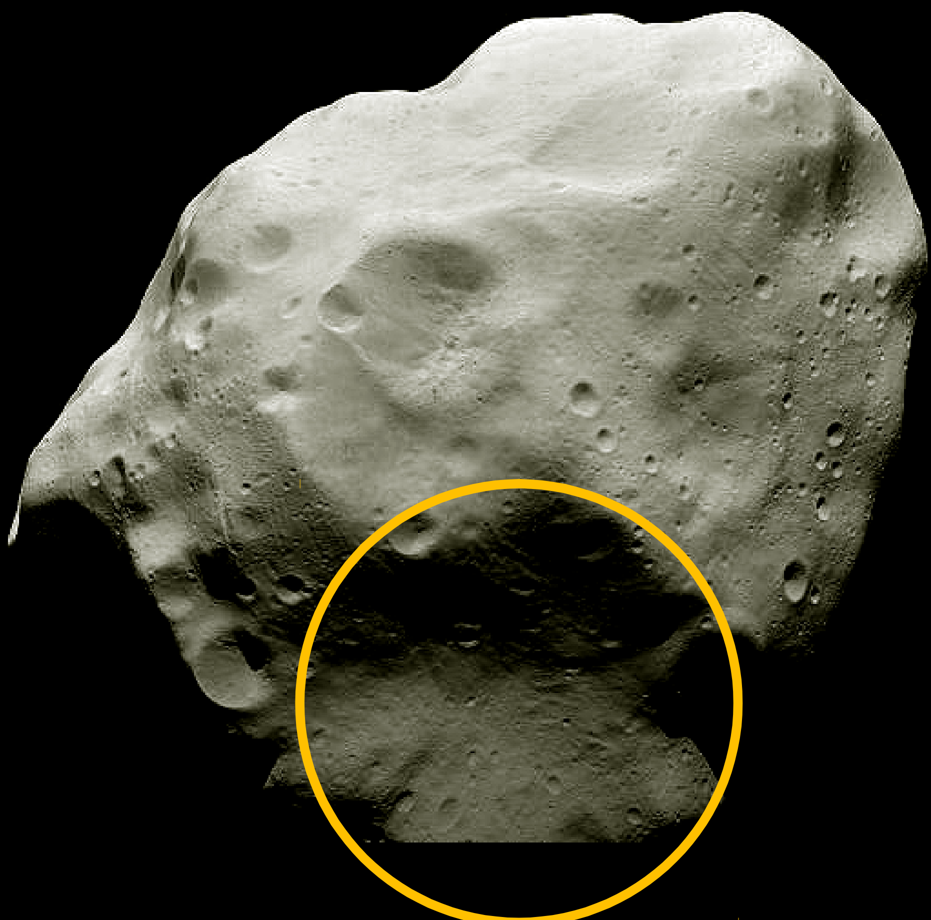
- time evolution limited only by total mesh size
- ✗ material interfaces are blurred

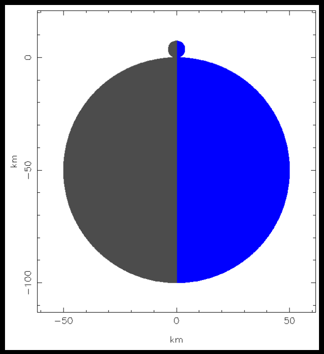
cells & mesh move with material

- cell volume changes
- cell mass is constant

- free surfaces and interfaces well defined
- ✗ mesh distorsion can end the simulation very early

MASSILIA, D=55 *km*





Impactor

Diameter : 7.5 km
Impact velocity : 4.3 km s^{-1}
Material : Dunite

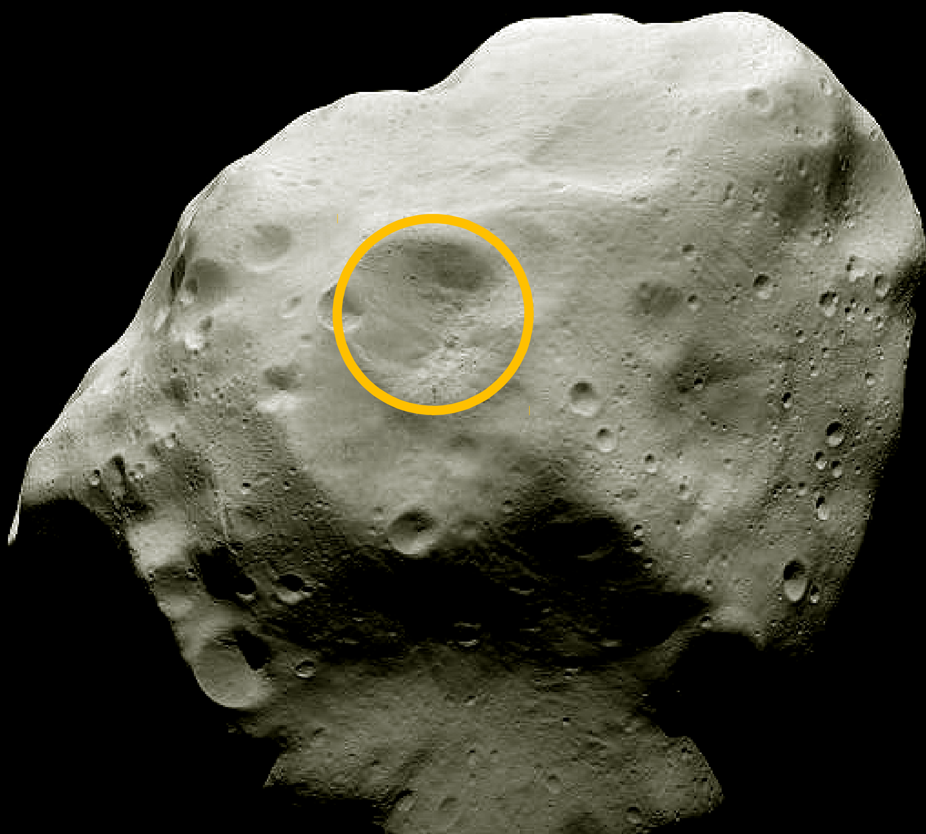
- porosity = 30%

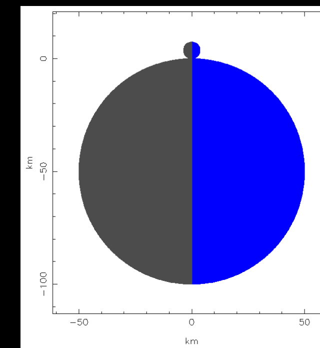
Target

Diameter : 100 km
Material : Dunite

- porosity = 0%

NPCC-d, D=21 *km*





Impactor

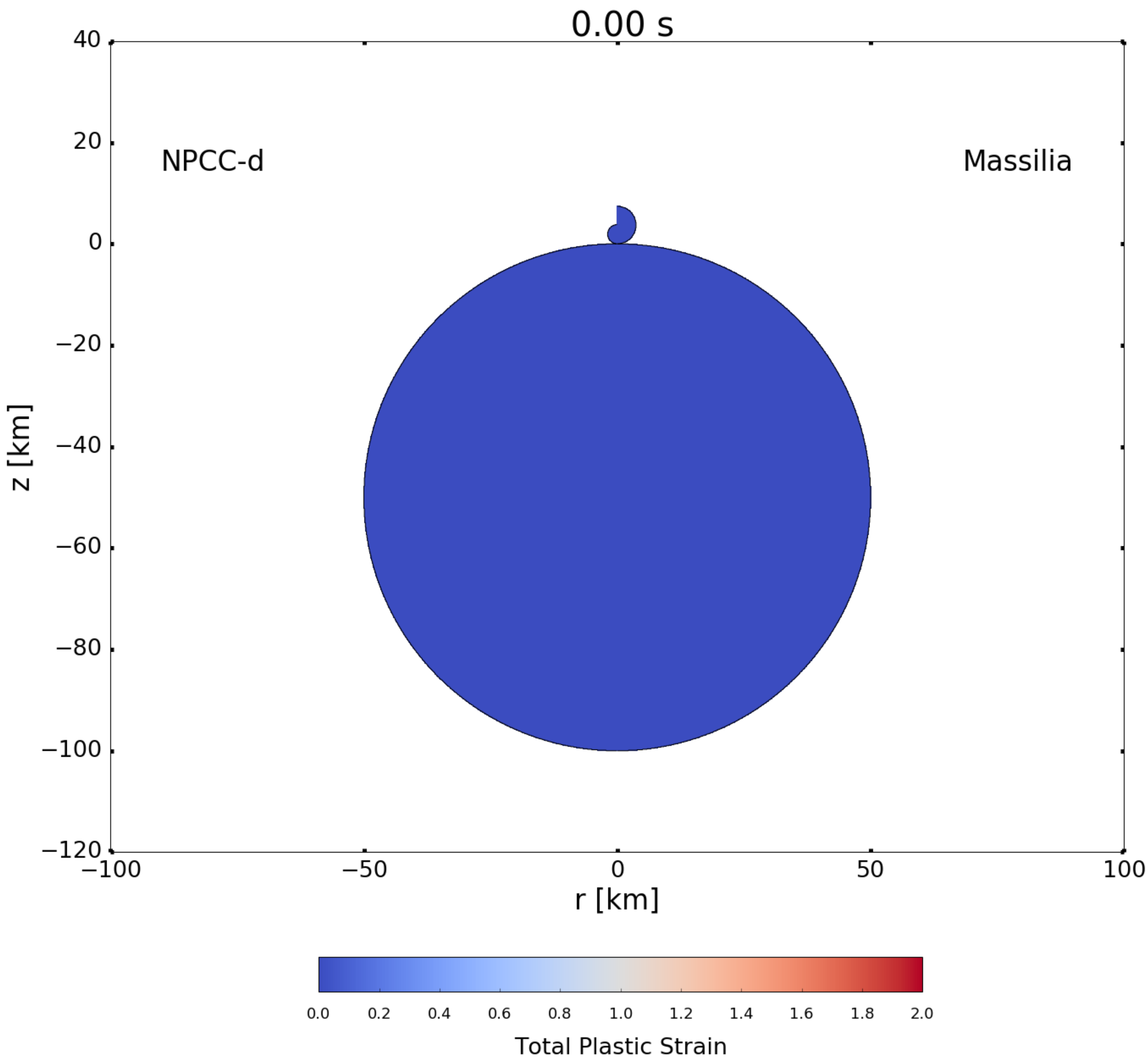
Diameter : 3.8 km
Impact velocity : 4.3 km s^{-1}
Material : Dunite

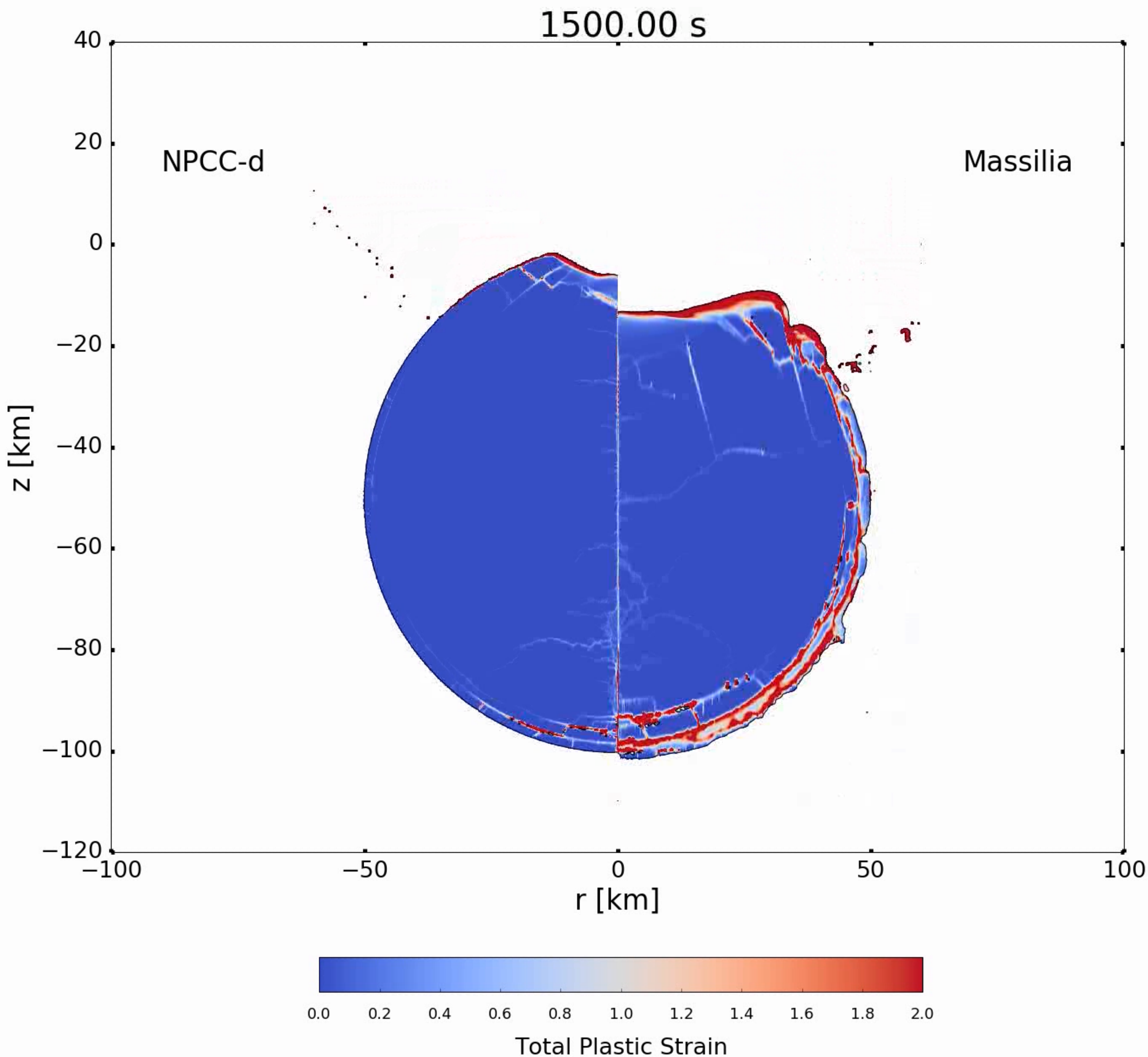
- porosity = 30%

Target

Diameter : 100 km
Material : Dunite

- porosity = 0%

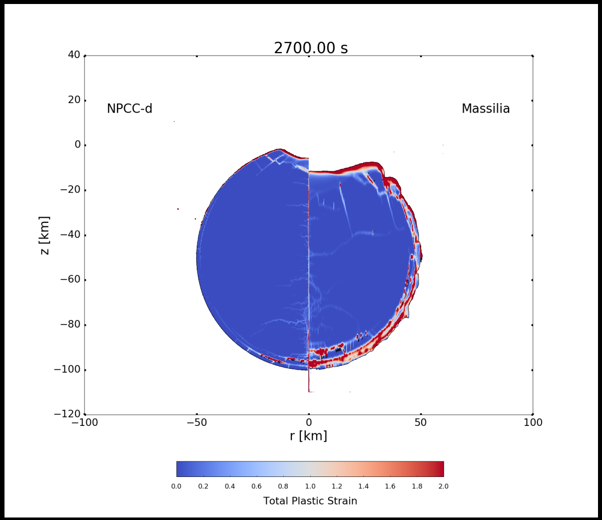

0.00 s
NPCC-d
Massilia
z [km]
r [km]
40
20
0
−20
−40
−60
−80
−100
−120
−100
−50
0
50
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Total Plastic Strain



1500.00 s
NPCC-d
Massilia
z [km]
r [km]
40
20
0
−20
−40
−60
−80
−100
−120
−100
−50
0
50
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Total Plastic Strain

NPCC-d

MASSILIA



- d/D = 0.15
- Collisional age = 2.1 Gyr

→ end of Late Heavy Bombardment: typical outcome of the present belt collisional evolution

- Lutetia is a *monolithic body,* and survived *intact* to the subsequent collisional evolution
- creation of a *layer of damaged material* at the surface following the propagation of the compression wave within the body
- poor of craters in the size range 5-8 km: damaged material influenced small craters and/or reset from the large impact
- Impact Frequency: 1/9 Gyr^{-1}

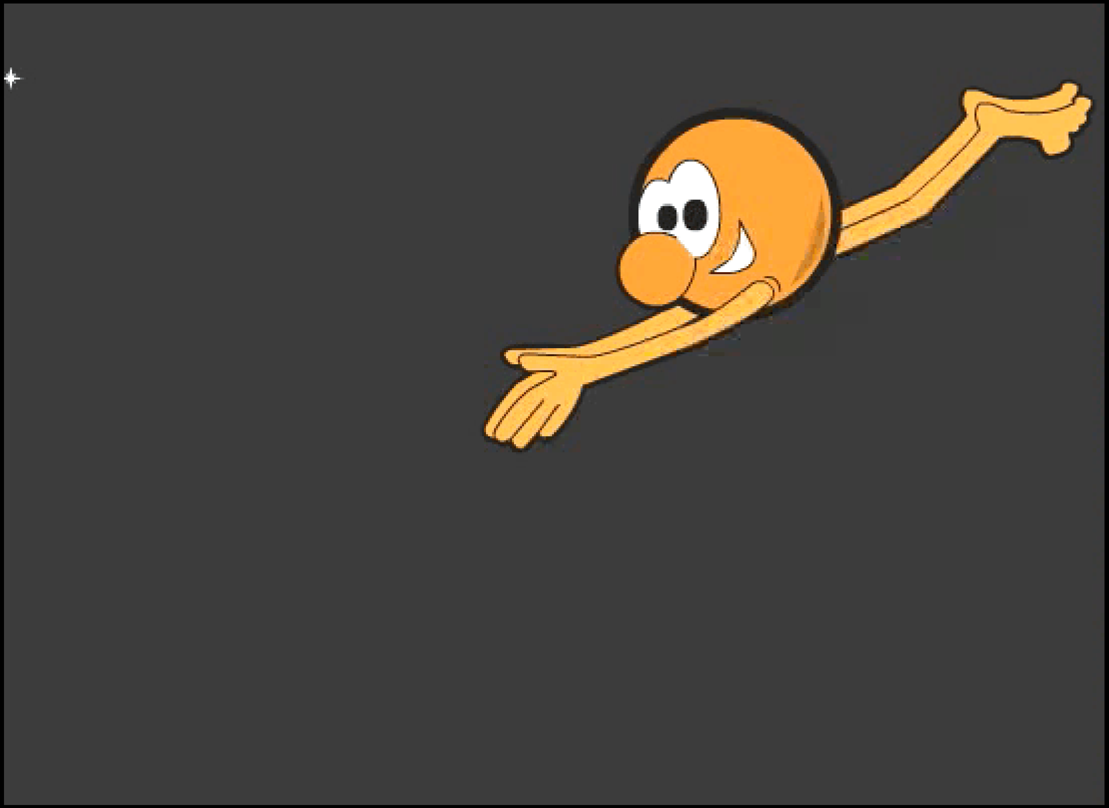
→ collisional event possibly occurred during the *Late Heavy Bombardment*

Take-Home Message

- ✓ Impact craters are the most widespread landform in the Solar System
    - ❑ impact cratering is a fundamental process that both form palanetary bodies and then shape their surface
- ✓ The impact process is subdivided into 3 stages:
    - ❑ contact & compression
    - ❑ excavation
    - ❑ modification

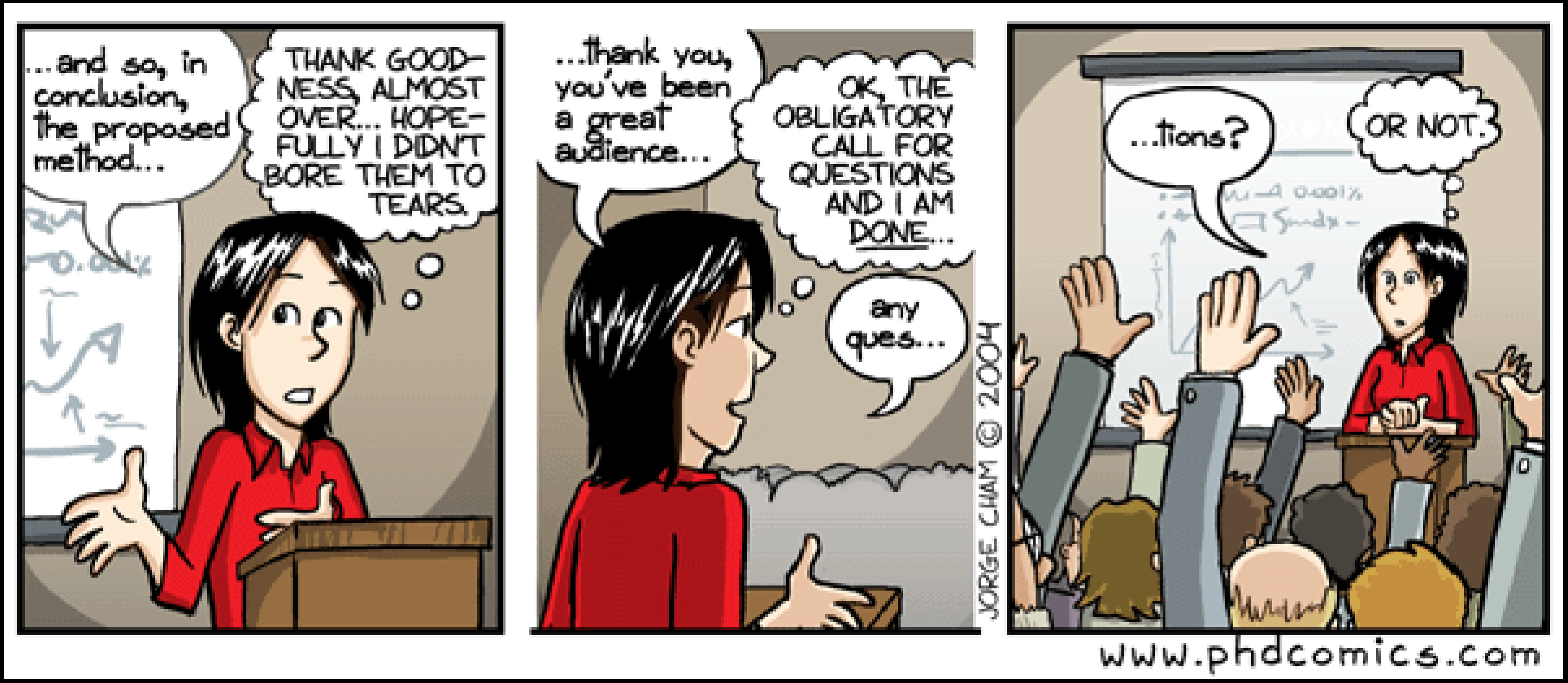
  each of these phases is governed by physical processes that cause different material flow fields
- ✓ Impact craters are tools to:
    - ❑ derive age of planetary body surfaces
    - ❑ probe planetary body interiors

Thank you !



We gratefully acknowledge the developers of iSALE-2D, including G. Collins, K. Wünnemann, D. Elbeshausen, B.A. Ivanov and J. Melosh, and Tom Davison for the development of pySALEPlot tool (www.iSALE-code.de).

Questions ?



...and so, in conclusion, the proposed method...
THANK GOODNESS, ALMOST OVER... HOPEFULLY I DIDN'T BORE THEM TO TEARS.
...thank you, you've been a great audience...
OK, THE OBLIGATORY CALL FOR QUESTIONS AND I AM DONE...
any ques...
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...tions?
OR NOT.
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