



École des Ponts
ParisTech

Mesure des vitesses S et P pour une mission martienne

Philippe Lognonné

De Philippe Lognonné
Sujet: Mesures des vitesses S et P pour une mission martienne
Pour delage@cermes.enpc.fr <delage@cermes.enpc.fr>

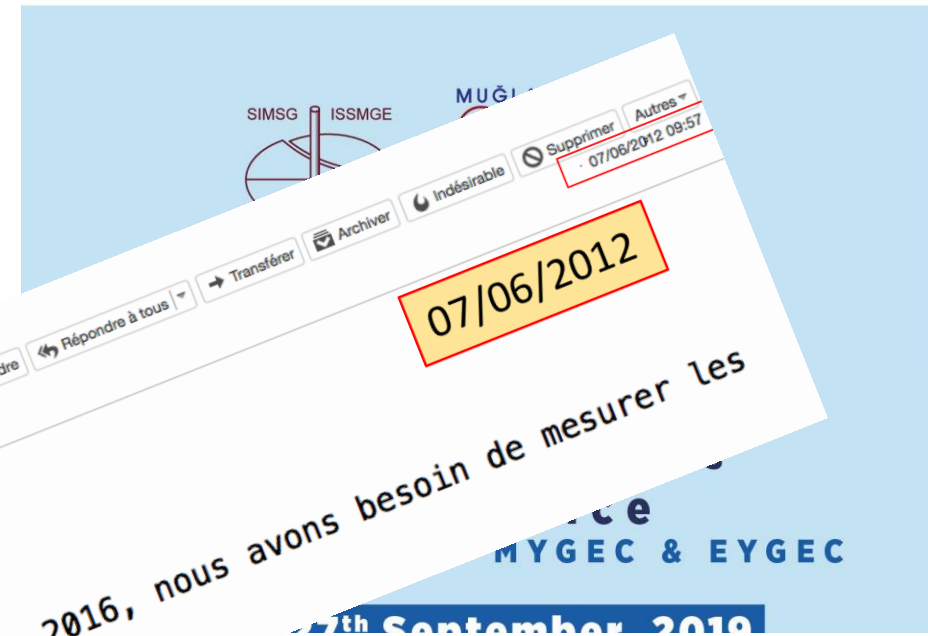
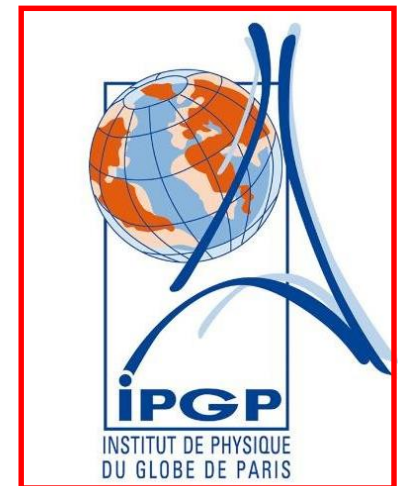
Cher collègue,

Je vous contacte suite à un conseil de Mme Zamora.
1 E Dans le cadre d'un projet géophysique visant à déployer un sismomètre sur Mars en 2016, nous avons besoin de mesurer les vitesses sismiques d'analogues martiens.

2 Je vitesses sismiques d'analogues martiens. A. Demaied¹, P. Lognonné³, B. Banerdt²

3 Institut de Physique du Globe de Paris, France

from InSight



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Research Interests:

- Planetary seismology (Mars and Moon interior structure, impact processes, Apollo data re-processing)



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The Mechanics of Martian soils Insights from InSight

Pierre Delage¹,

with M. Golombek², F. Karakostas³, A. Demaid¹, P. Lognonné³, B. Banerdt²

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² Jet Propulsion Laboratory, NASA – Caltech, Pasadena, Ca, USA

³ Institut de Physique du Globe de Paris, France



InSight ... into the early evolution of terrestrial planets.

Home

INTRODUCTION

- Understanding the processes that shaped rocky planets more than four billions years ago
- Determine the tectonic activity and the impact flux at the Mars surface

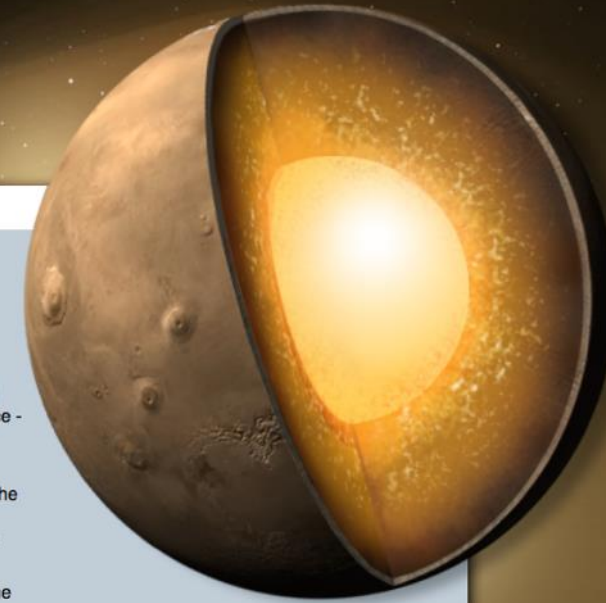
Mars

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formation, as well as measuring the planet's "vital signs": Its "pulse" (seismology), "temperature" (heat flow probe), and "reflexes" (precision tracking).

InSight seeks to answer one of science's most fundamental questions: How did the terrestrial planets form?



- NASA Call for proposal, June 2010
- 12th mission of the Discovery Programme (cost < 450 M\$)
 - 28 proposals received
 - August 2012 : **InSight wins!**
 - Launch postponed 2016 – 2018 (+ 150 M\$)
 - Launched Atlas V1 (160 M\$), 5 May 2018
 - **Successful landing** on Mars, 28 November 2018

et by examining features like canyons, volcanoes, rocks
its building blocks - which can only be found by looking

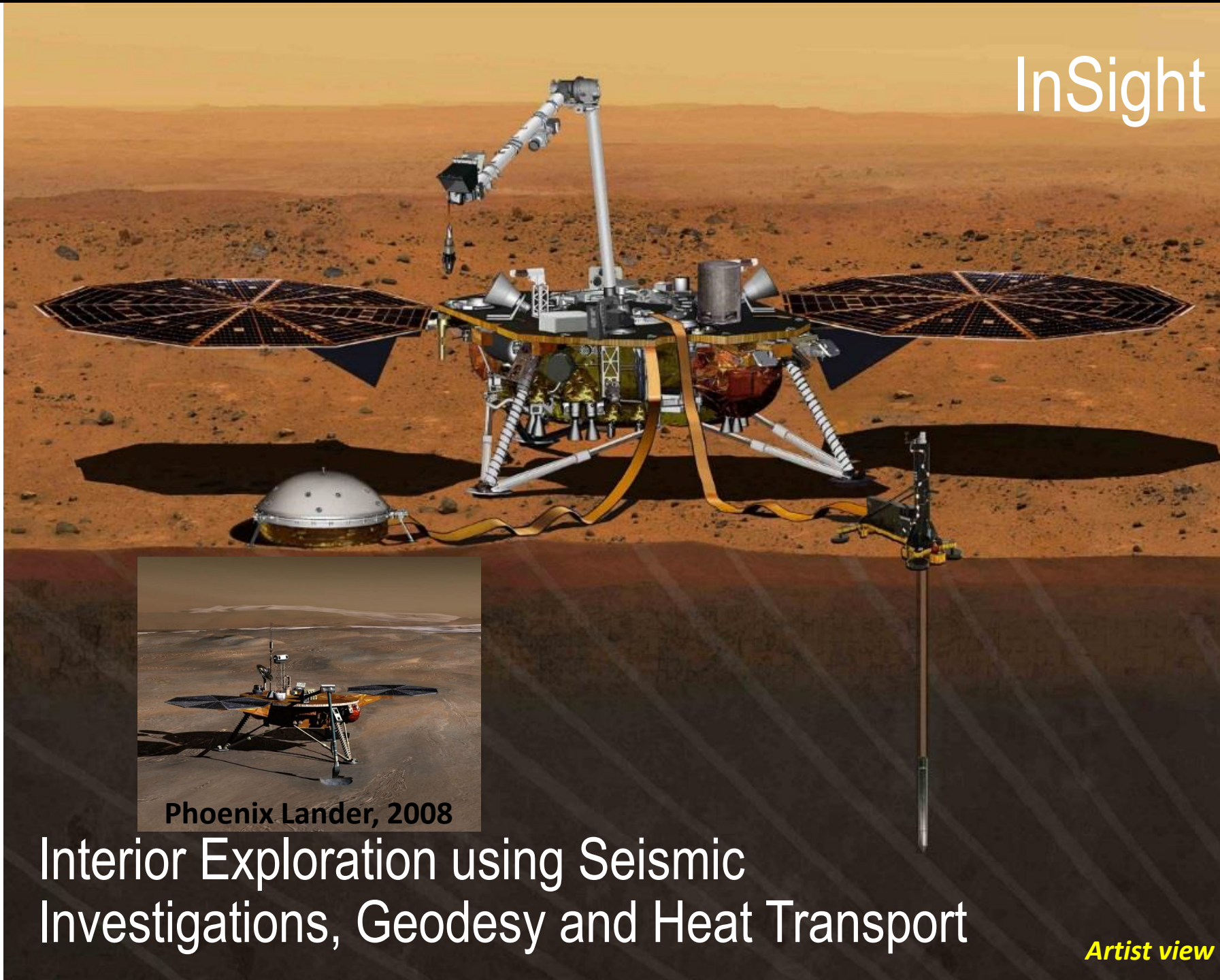


DR. BRUCE BANERDT
PRINCIPAL INVESTIGATOR





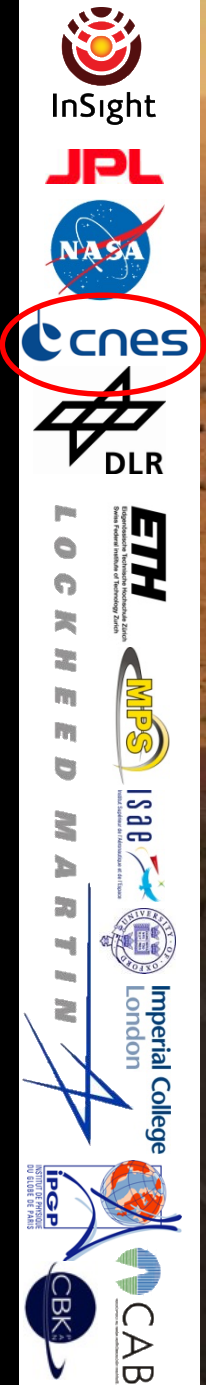
InSight



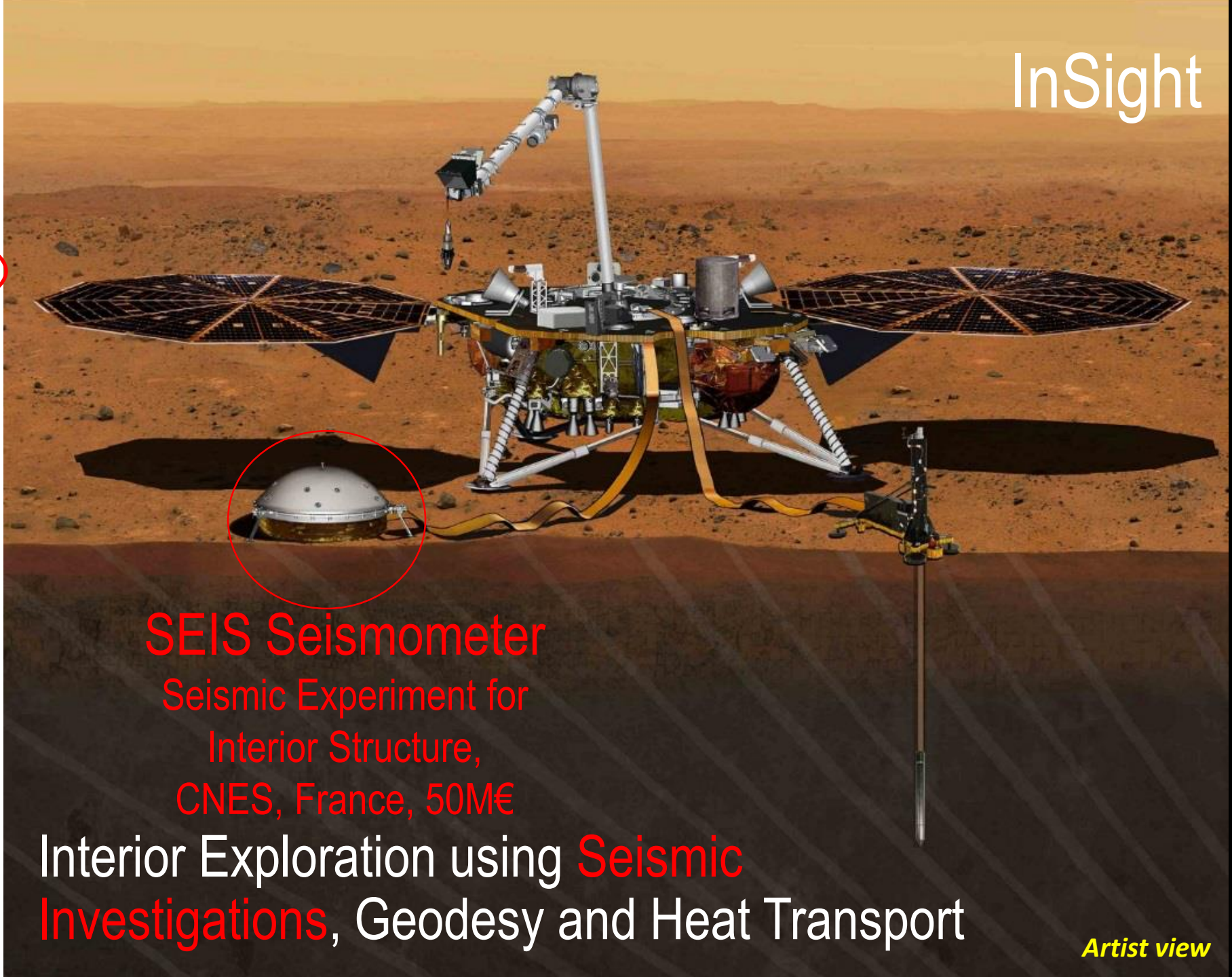
Phoenix Lander, 2008

Interior Exploration using Seismic Investigations, Geodesy and Heat Transport

Artist view



InSight

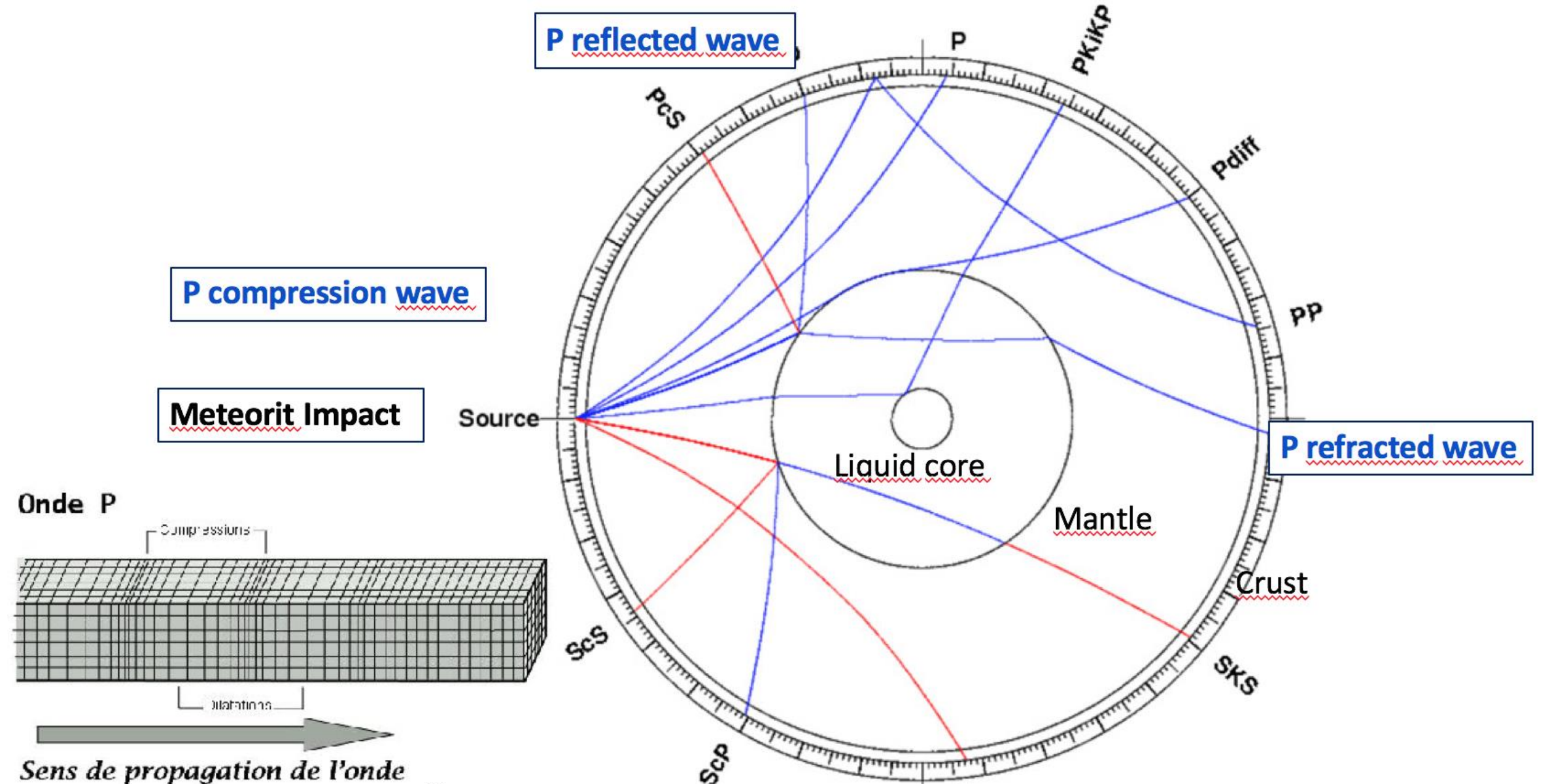


SEIS Seismometer

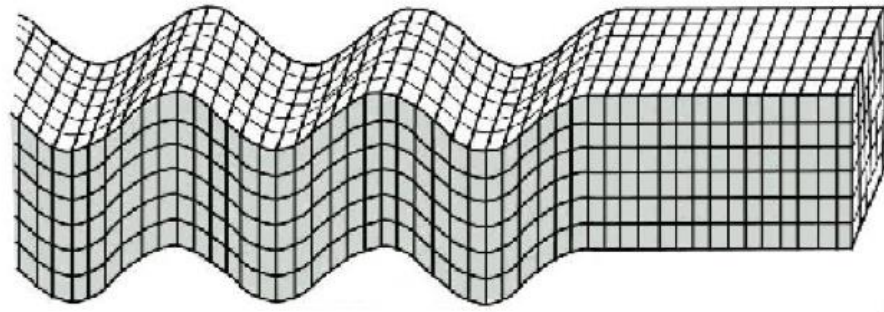
Seismic Experiment for
Interior Structure,
CNES, France, 50M€

Interior Exploration using **Seismic
Investigations**, Geodesy and Heat Transport

Artist view



Onde S



Sens de propagation de l'onde

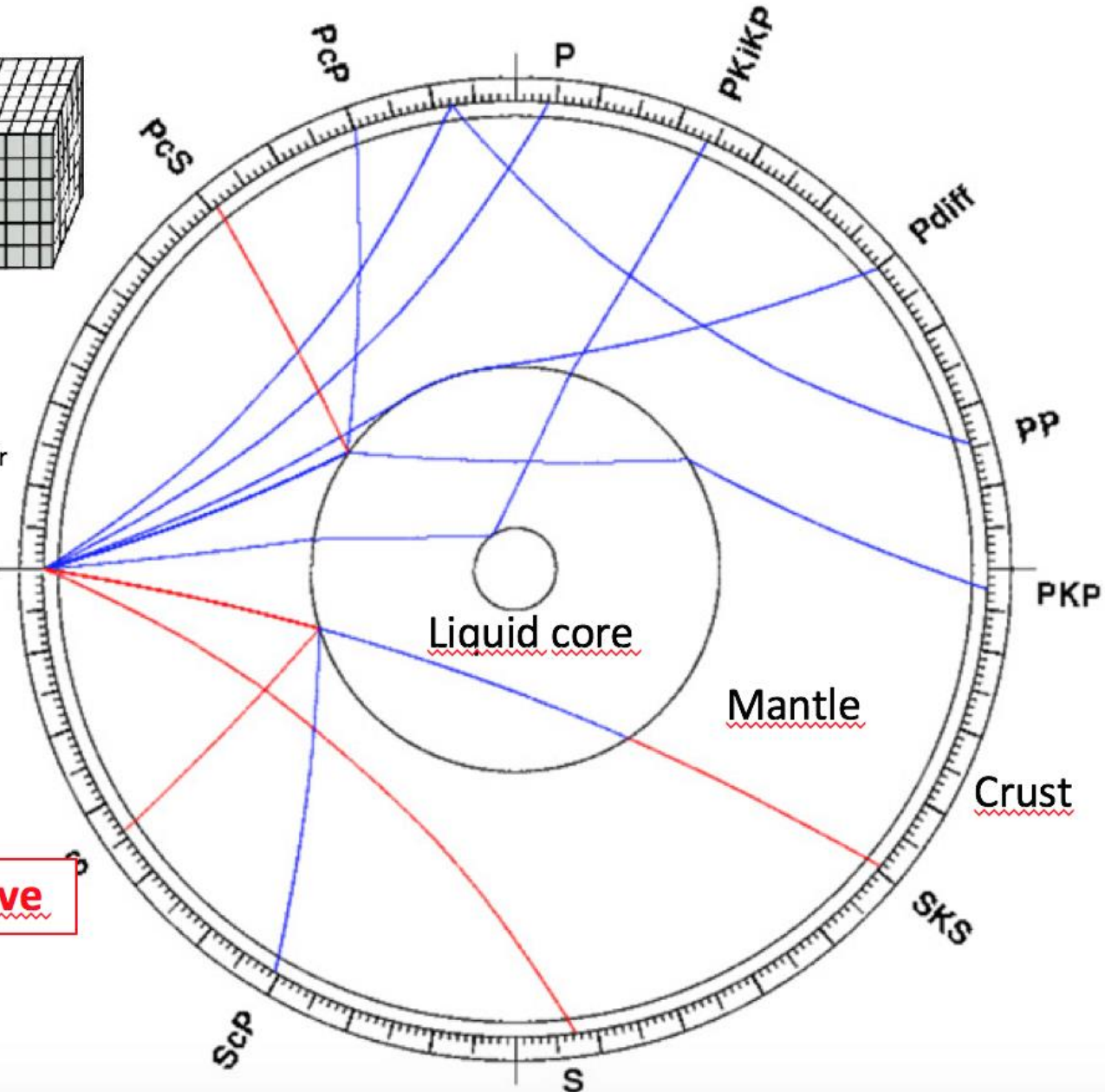
<http://nte-serveur.univ-lyon1.fr>

Meteorit Impact

Source

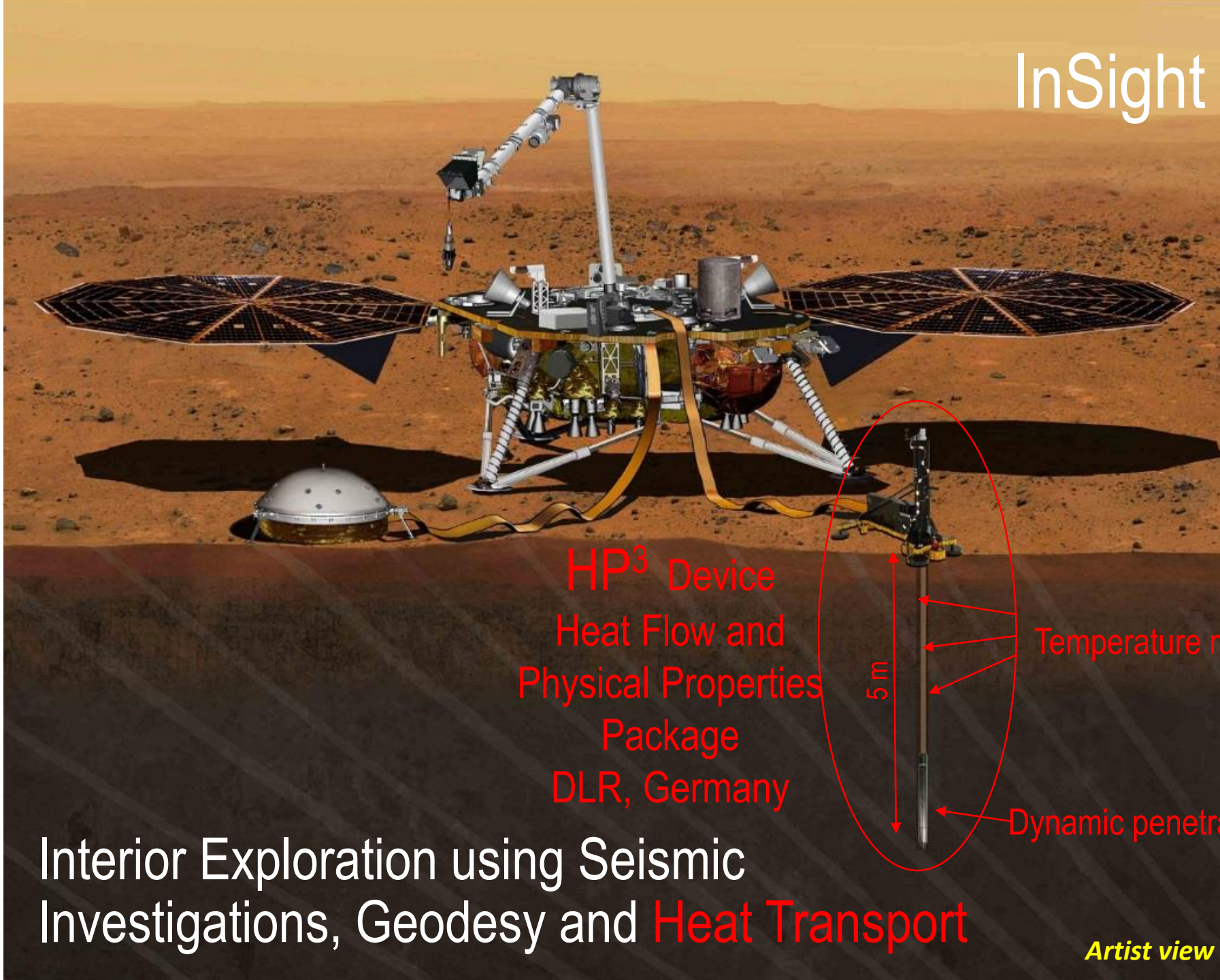
Shear wave S

Reflected S shear wave





InSight



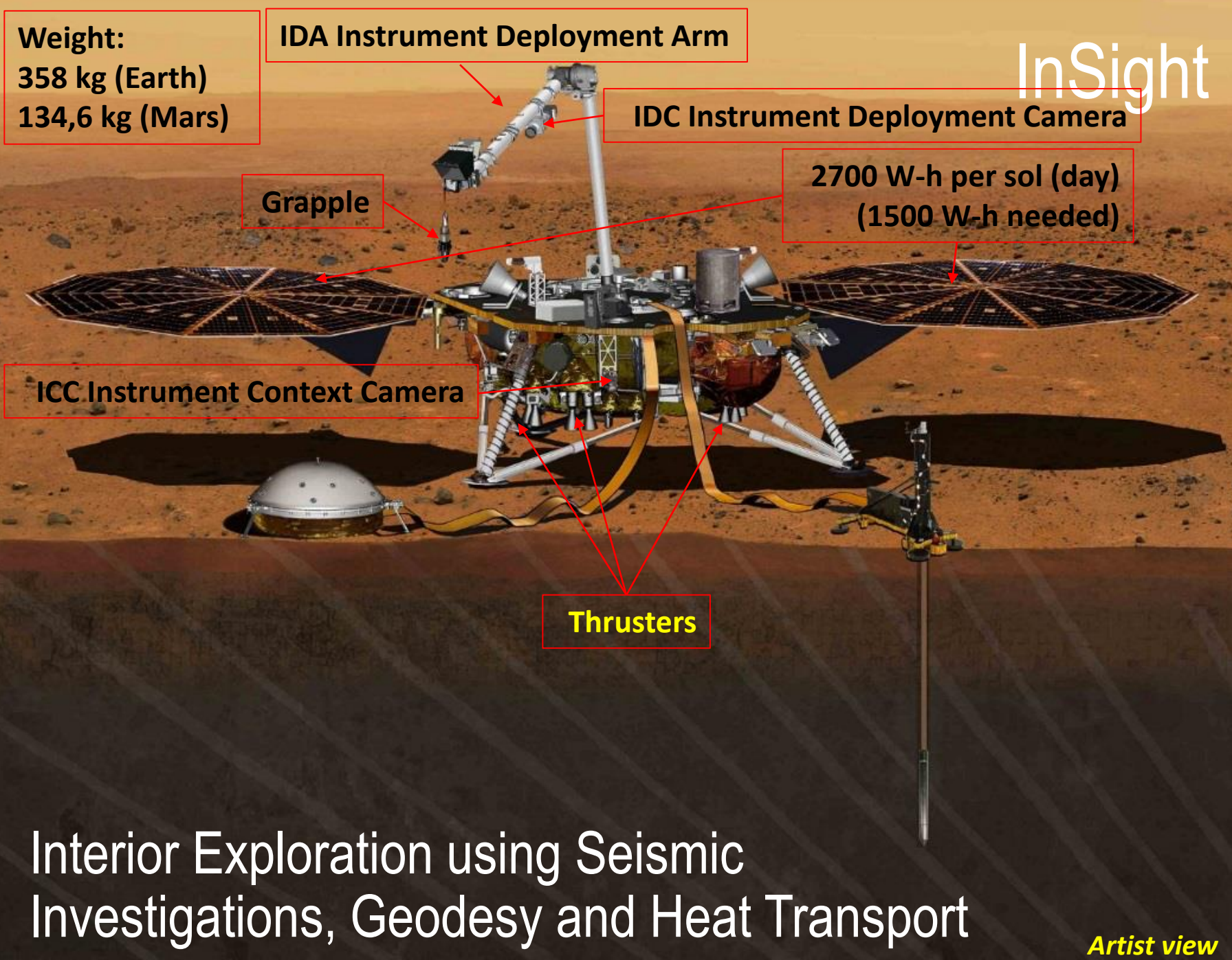
HP³ Device
Heat Flow and
Physical Properties
Package
DLR, Germany

Temperature measurements

Dynamic penetration

Interior Exploration using Seismic
Investigations, Geodesy and **Heat Transport**

Artist view



Weight:
358 kg (Earth)
134,6 kg (Mars)

IDA Instrument Deployment Arm

IDC Instrument Deployment Camera

Grapple

2700 W-h per sol (day)
(1500 W-h needed)

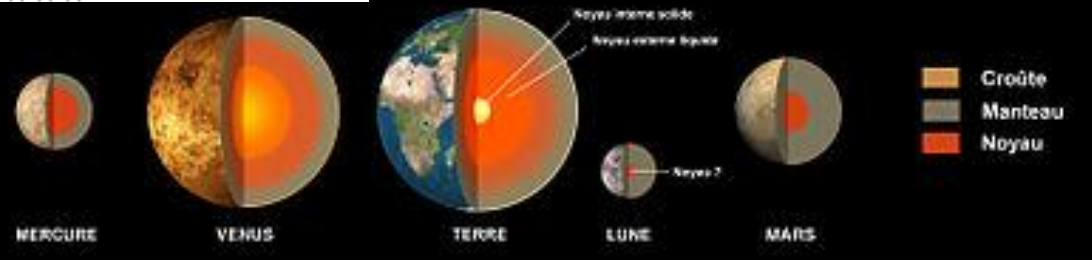
ICC Instrument Context Camera

Thrusters

InSight

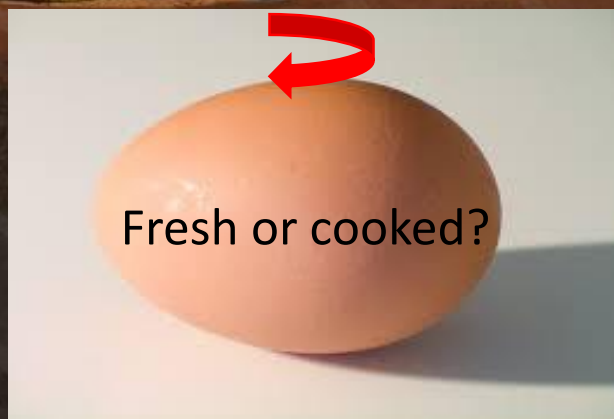
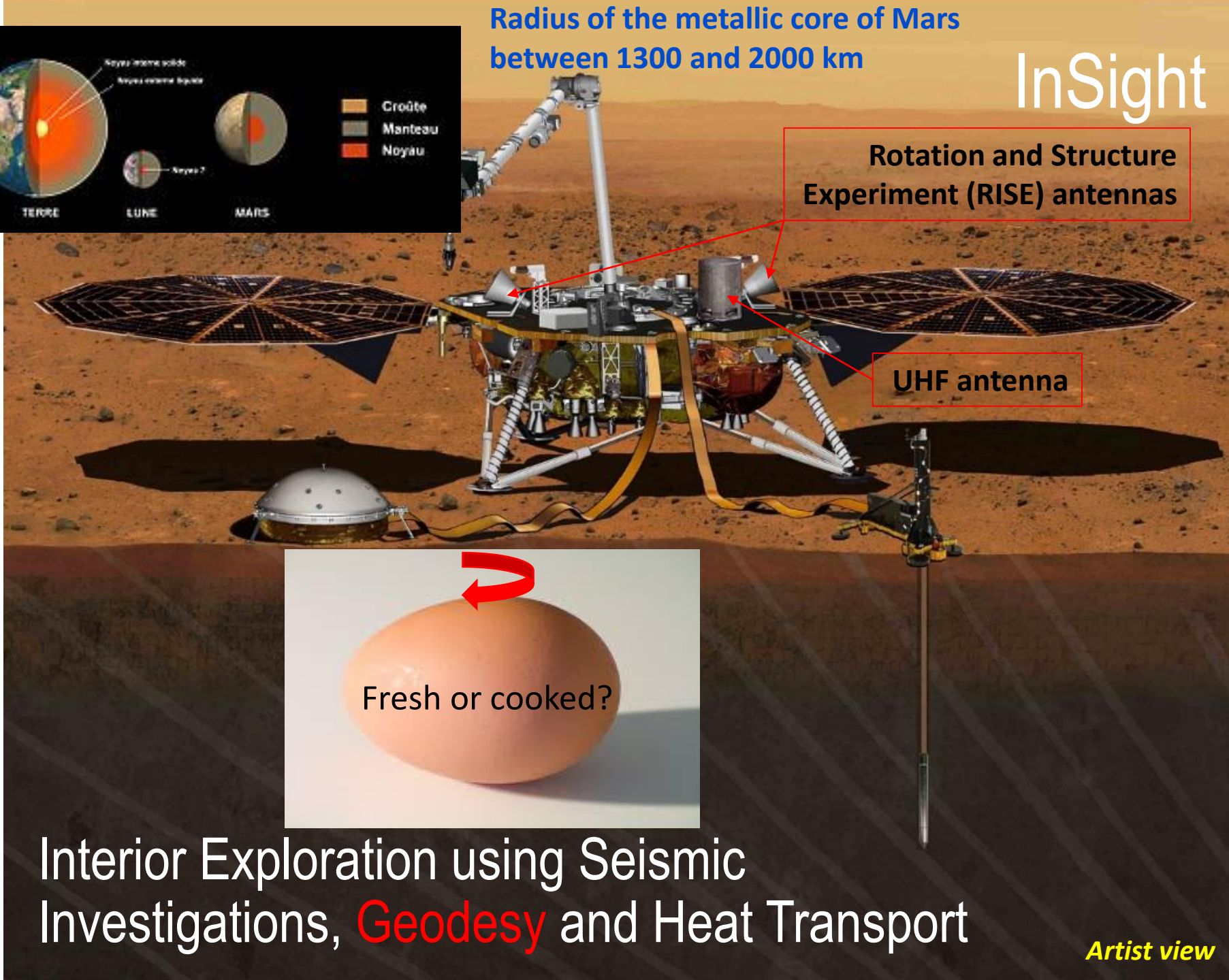
**Interior Exploration using Seismic
Investigations, Geodesy and Heat Transport**

Artist view



Radius of the metallic core of Mars
between 1300 and 2000 km

InSight



Interior Exploration using Seismic
Investigations, **Geodesy** and Heat Transport

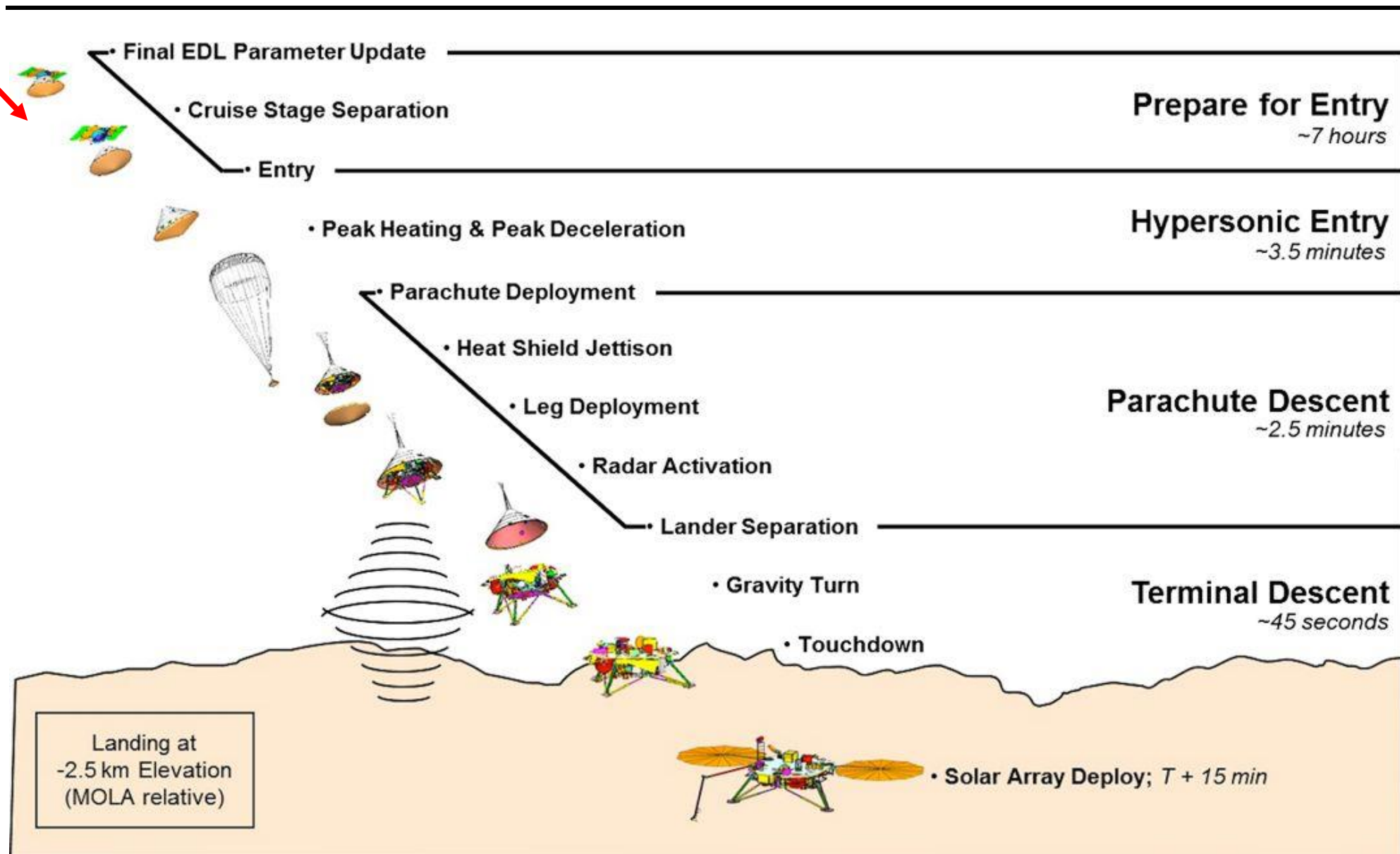
Artist view

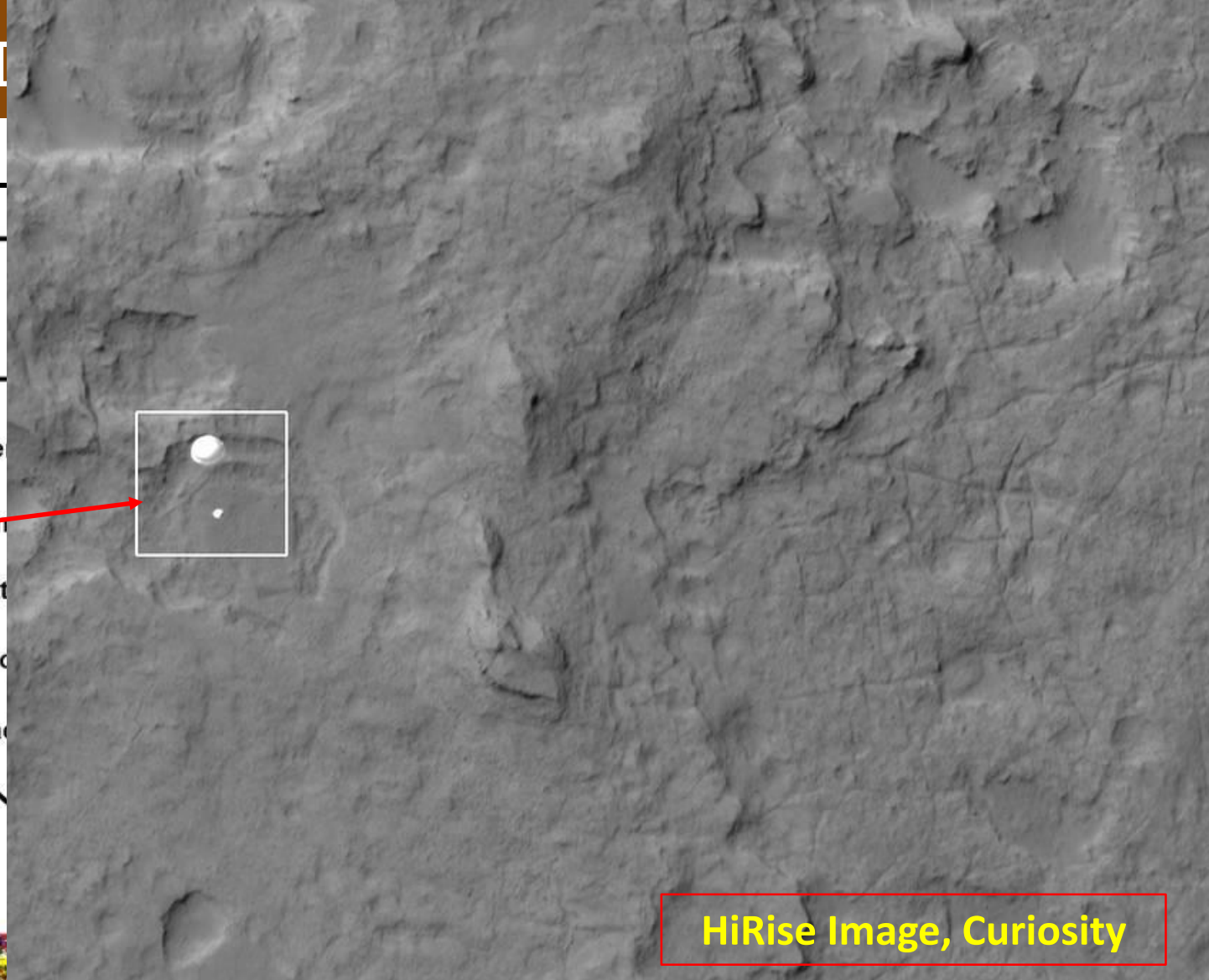
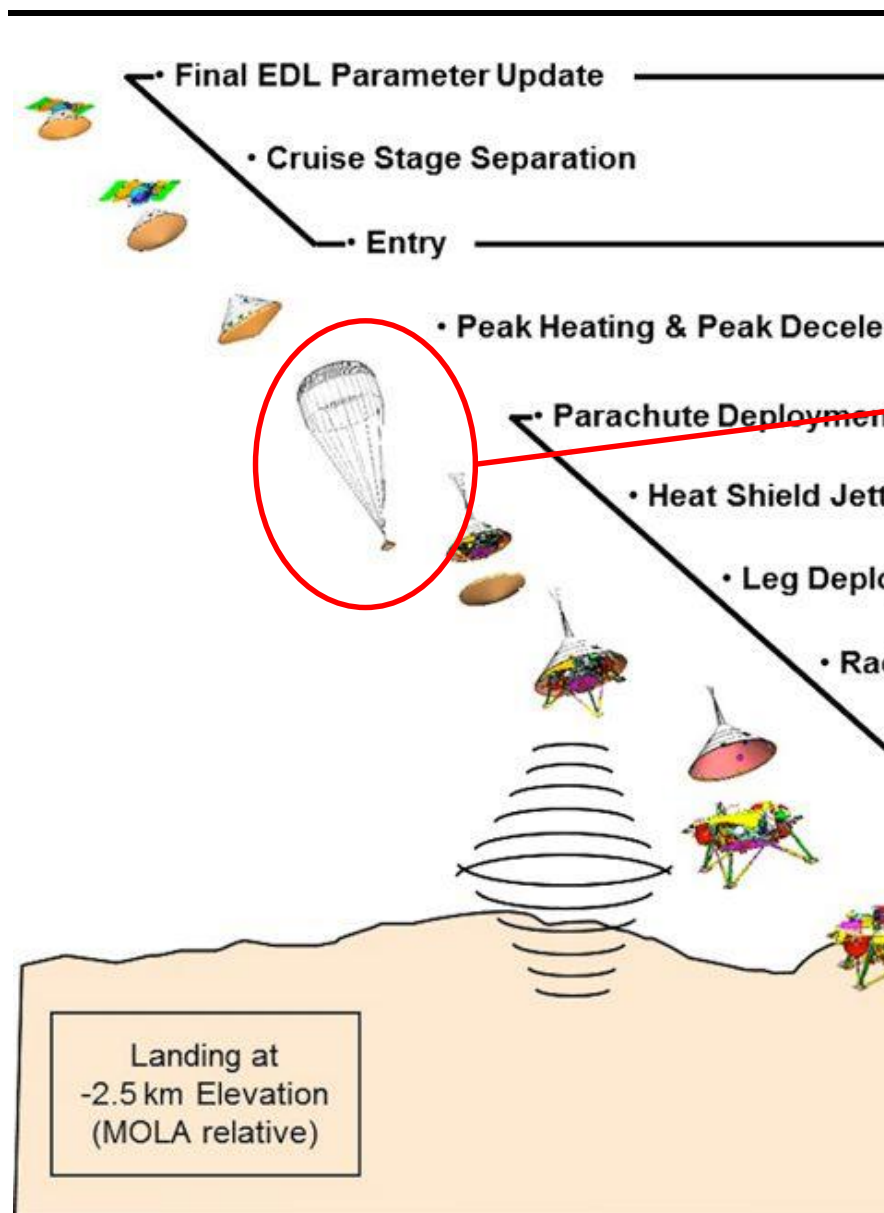
Launching on 5 May 2018, Vandenberg USAF Base, California



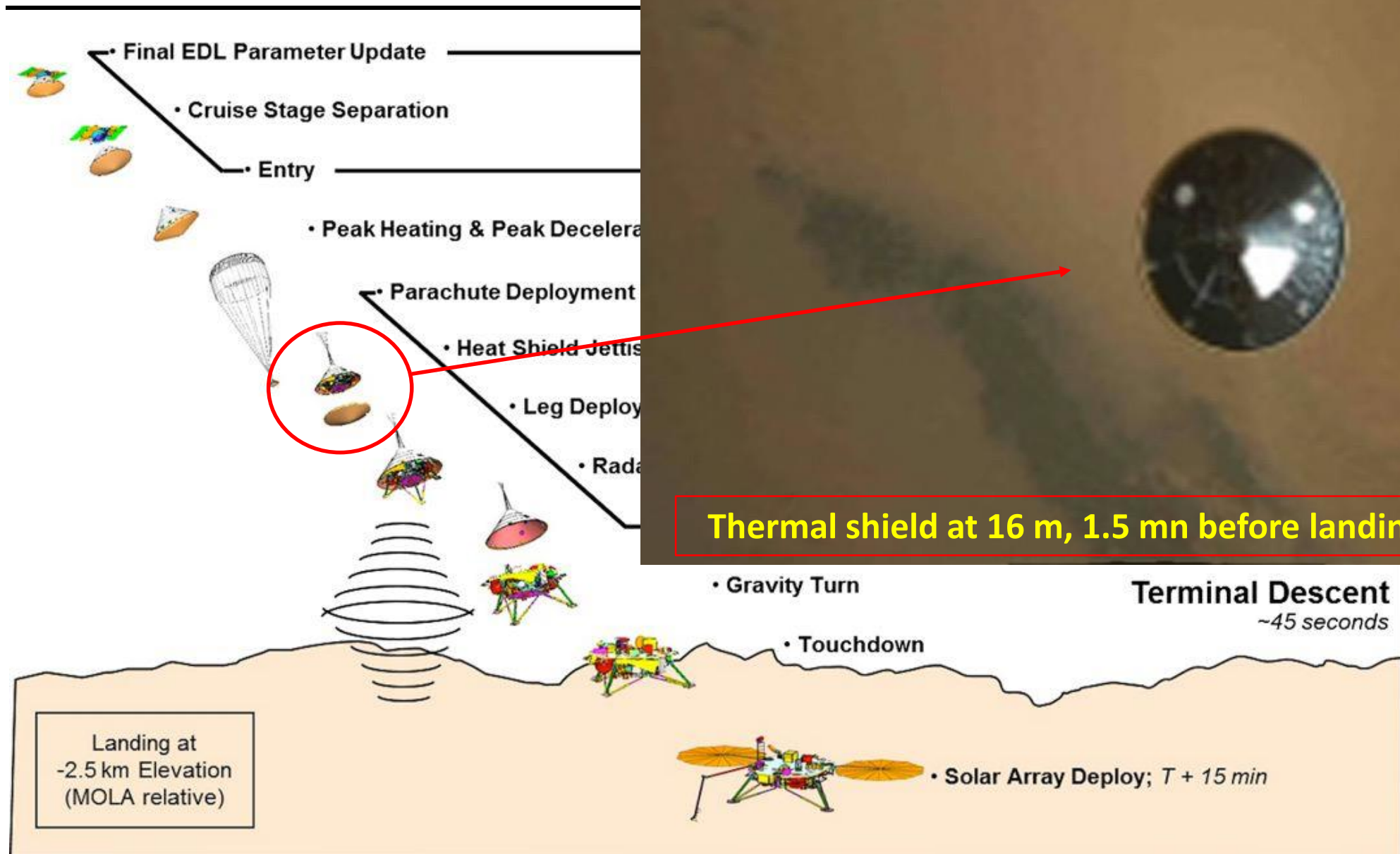
M. Golombek et al.

20 000 km/h
608 kg



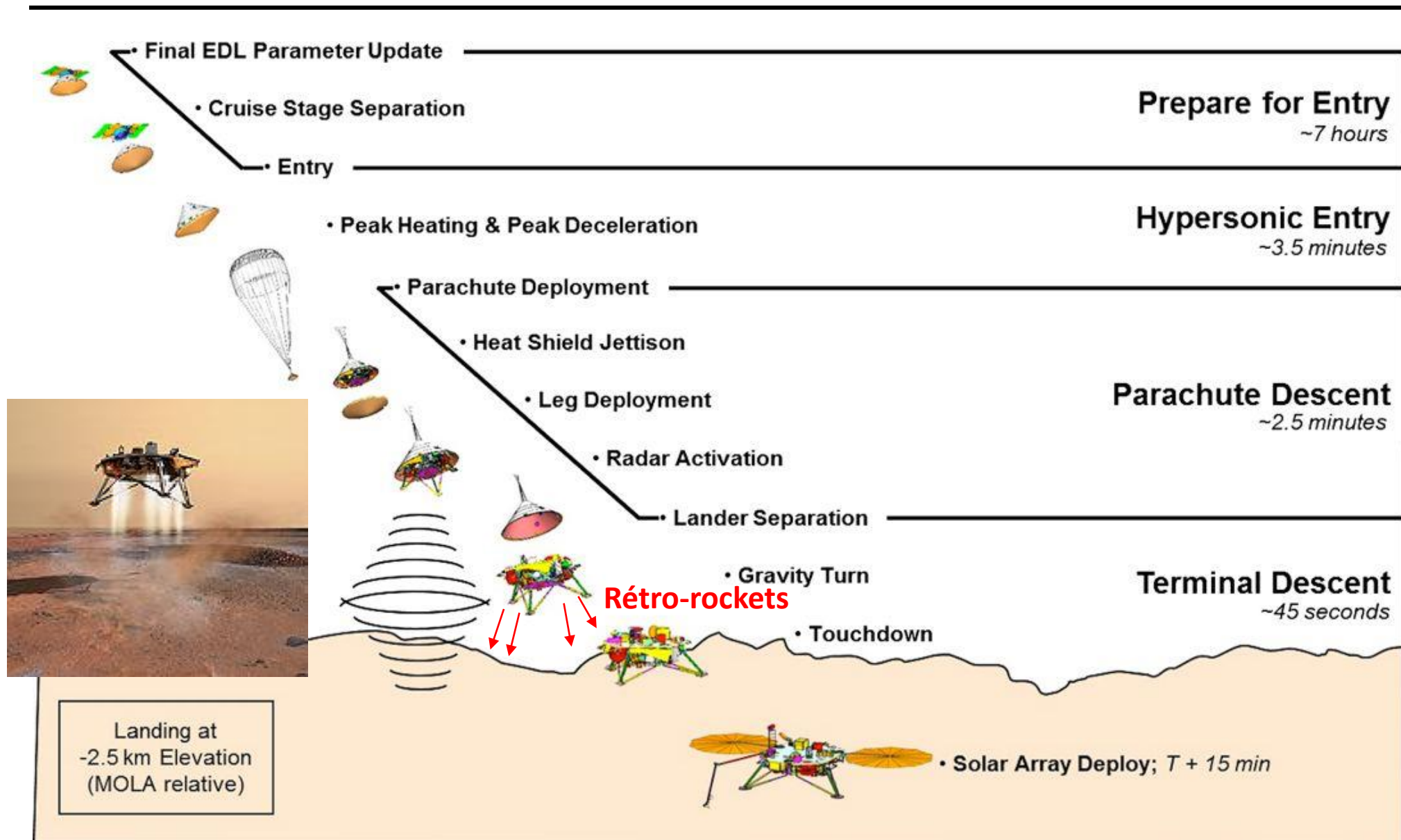


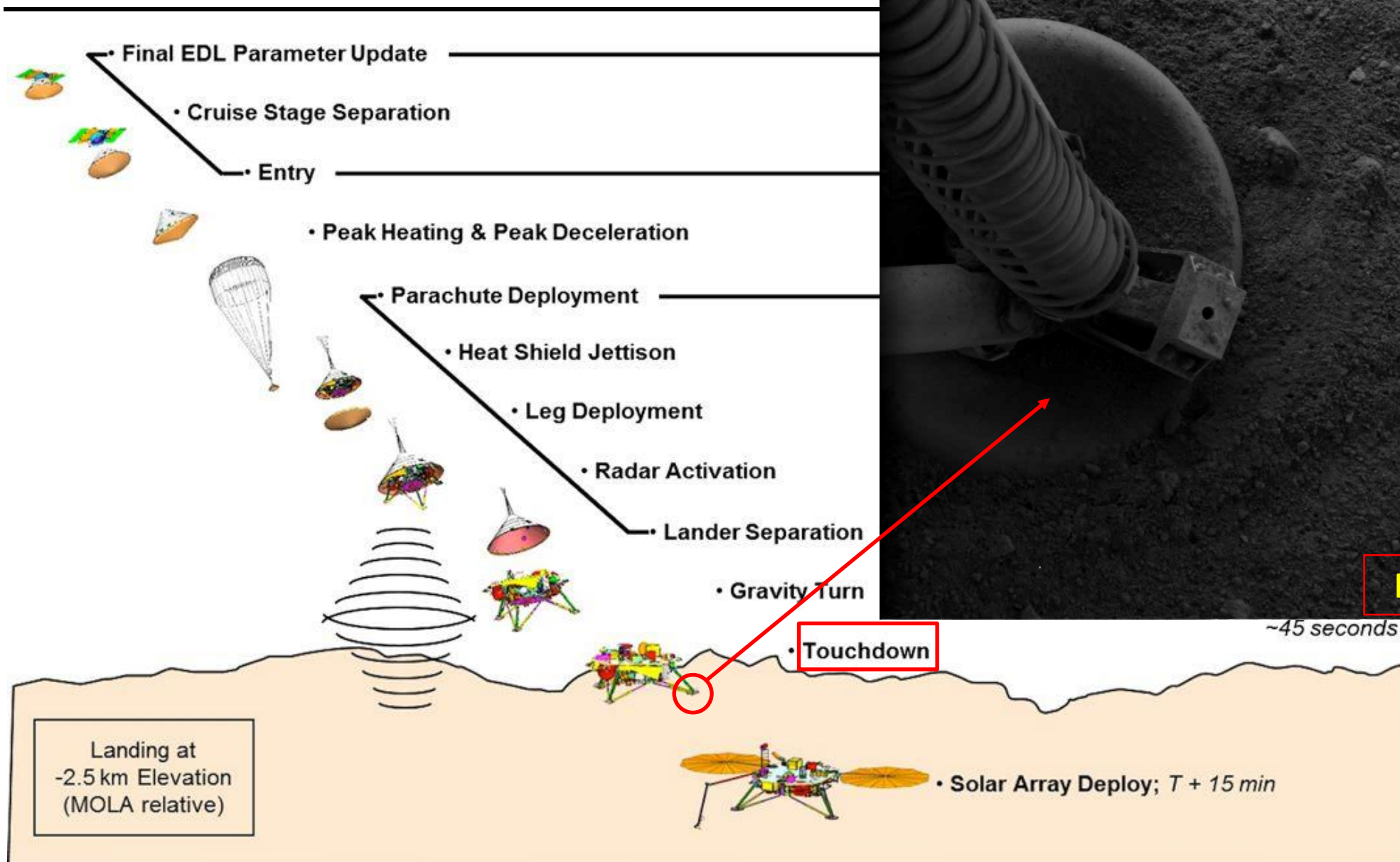
HiRISE Image, Curiosity



Thermal shield at 16 m, 1.5 mn before landing, Curiosity

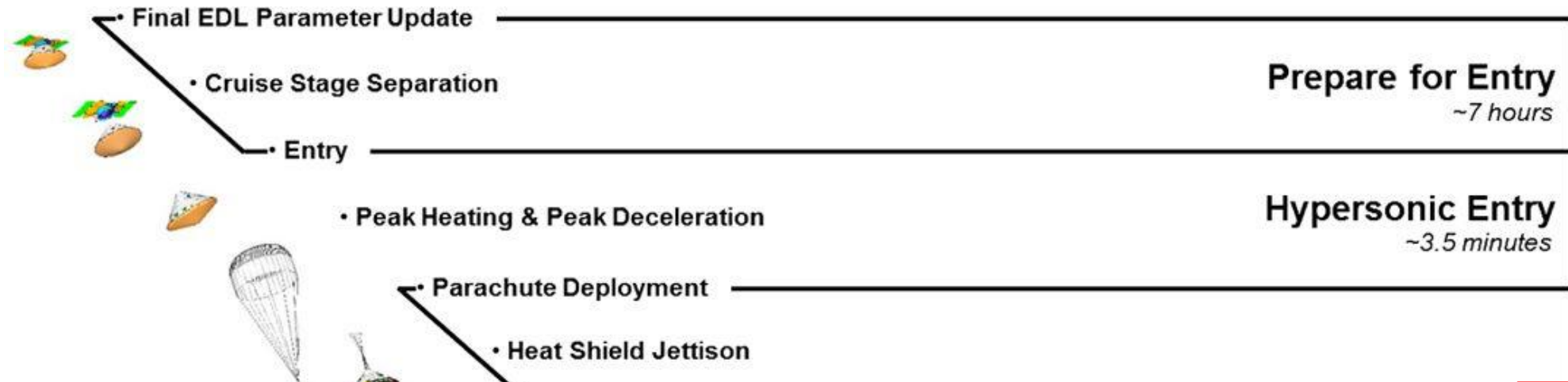
M. Golombek et al.



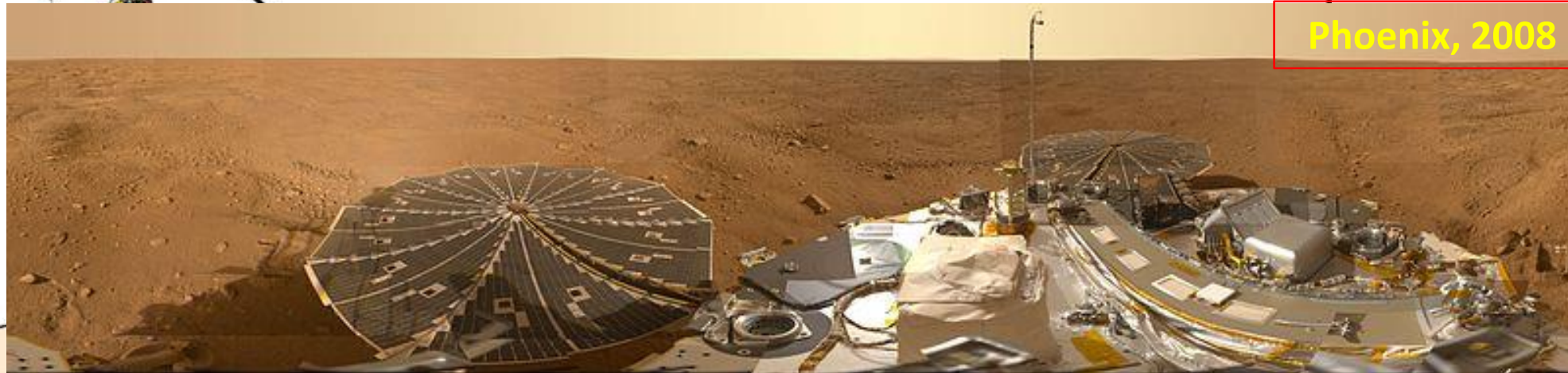


Phoenix, 2008

M. Golombek et al.



Phoenix, 2008



Landing at
-2.5 km Elevation
(MOLA relative)



• Solar Array Deploy; $T + 15 \text{ min}$

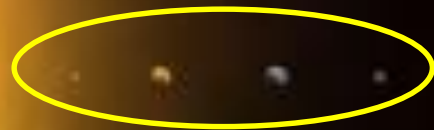
Mercure
Vénus
The Earth
Mars

Jupiter

Saturne

Uranus

Neptune



Rocky Planets

PLANÈTES



Vénus



The Earth



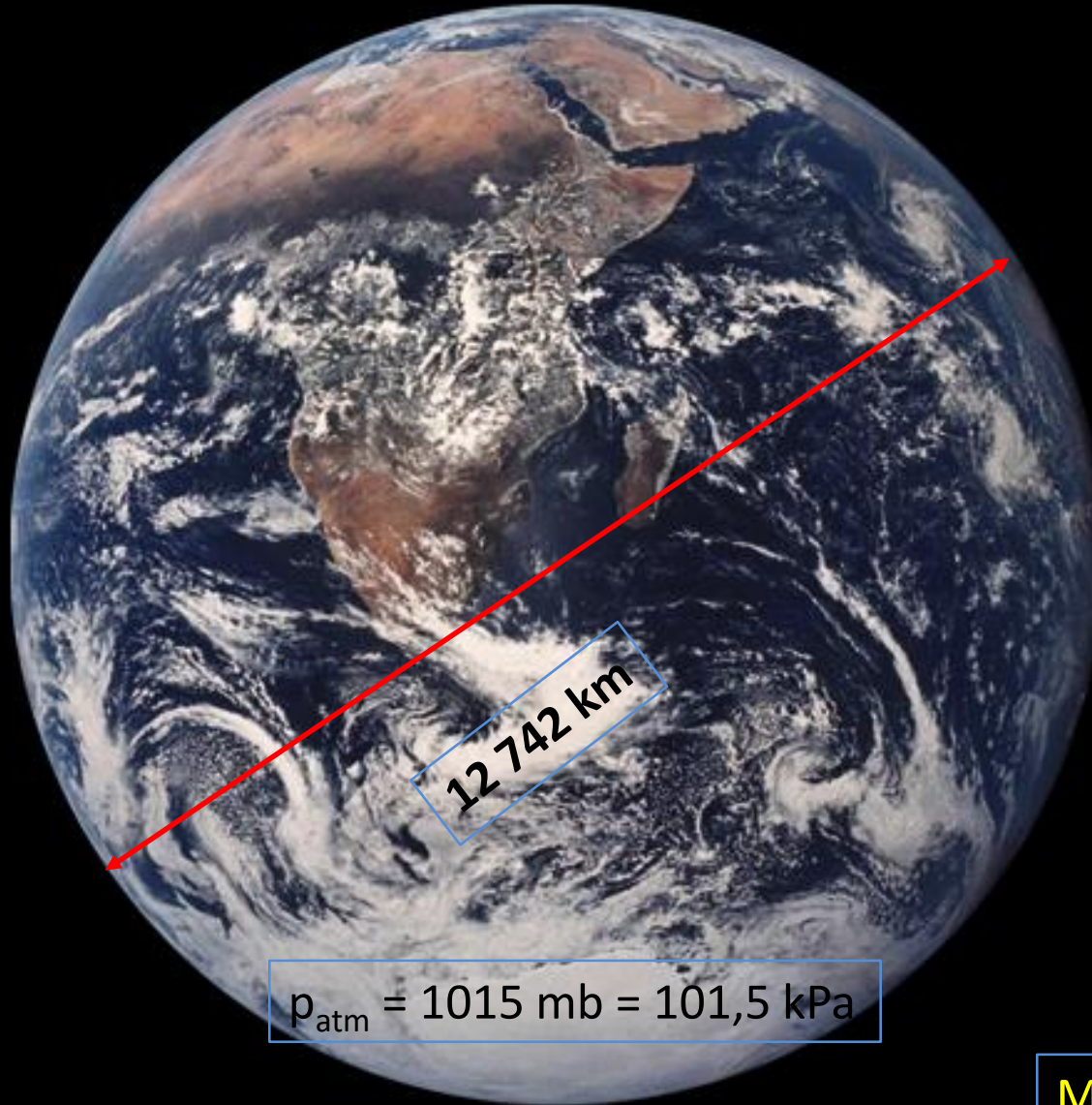
Mercure



Mars

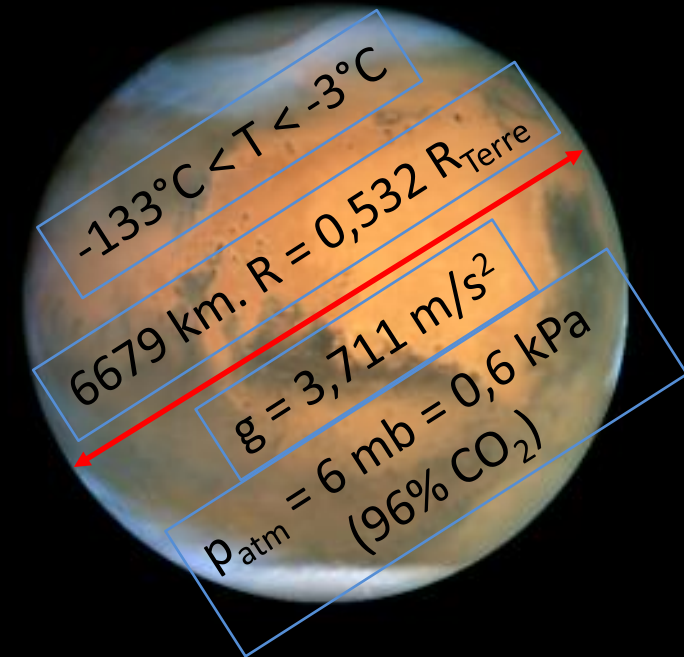


The Moon



12 742 km

$p_{\text{atm}} = 1015 \text{ mb} = 101,5 \text{ kPa}$



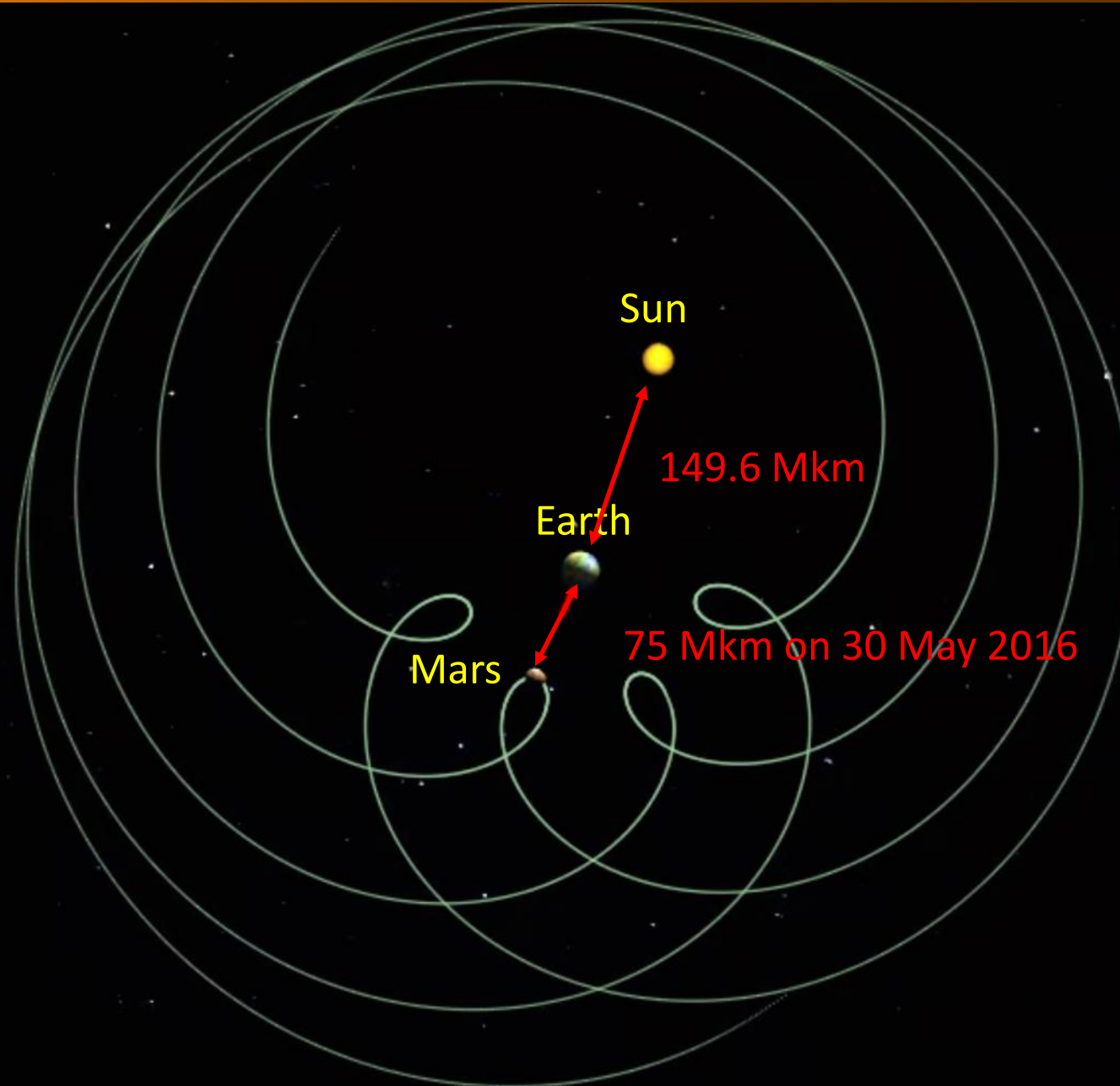
$-133^{\circ}\text{C} < T < -3^{\circ}\text{C}$

6679 km. $R = 0,532 R_{\text{Terre}}$

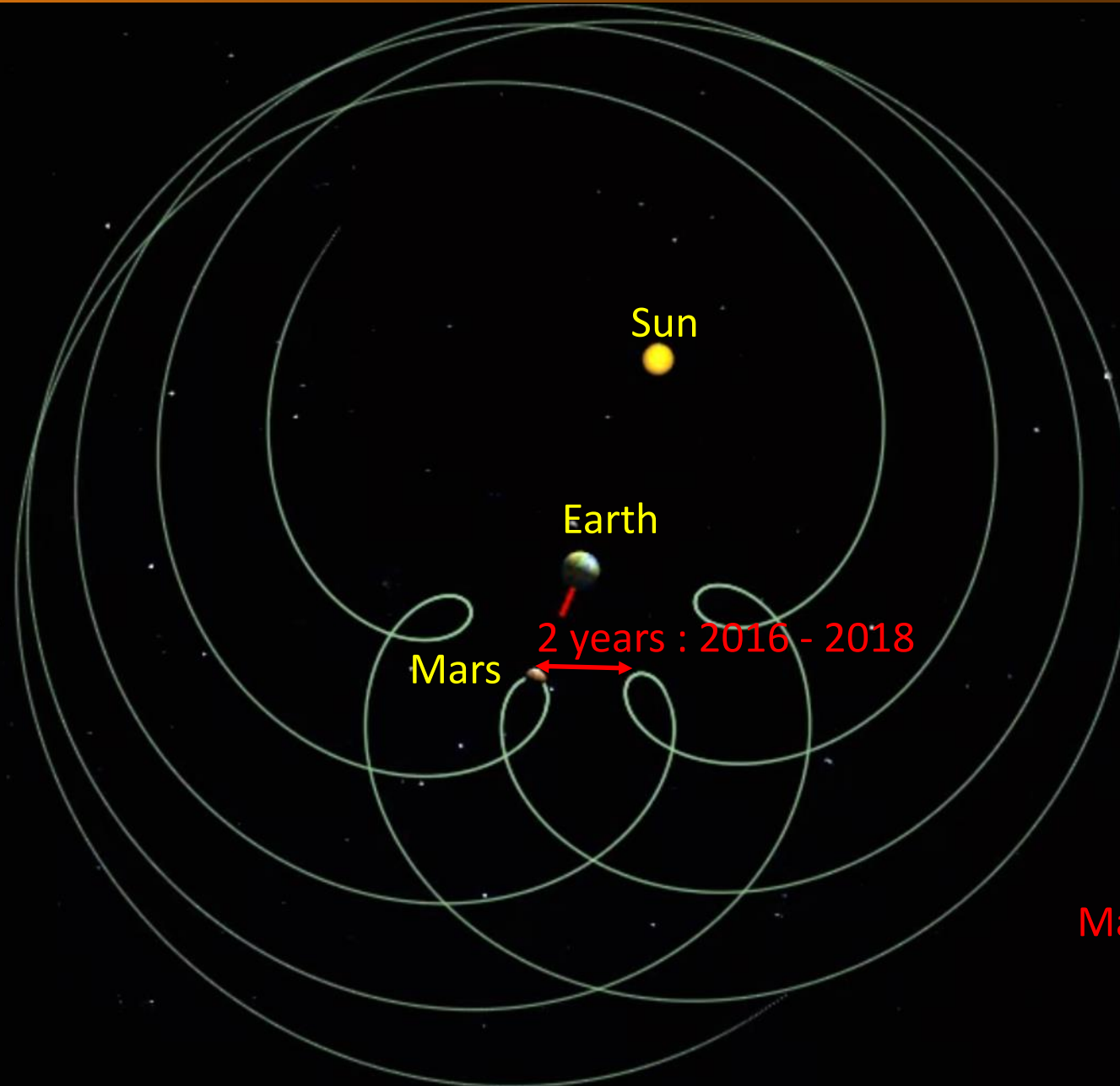
$g = 3,711 \text{ m/s}^2$

$p_{\text{atm}} = 6 \text{ mb} = 0,6 \text{ kPa}$
(96% CO_2)

Moon: 3774 km

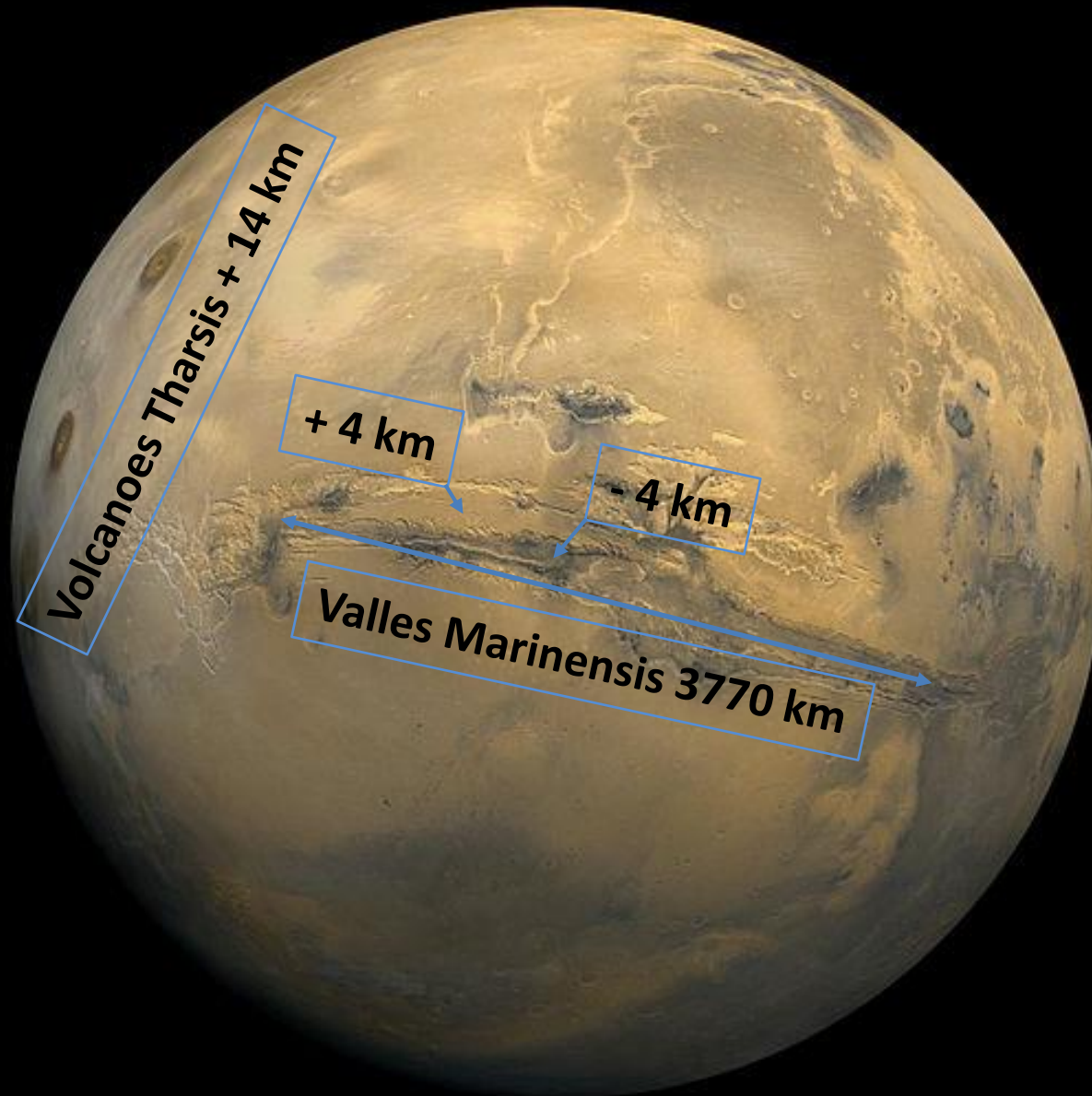


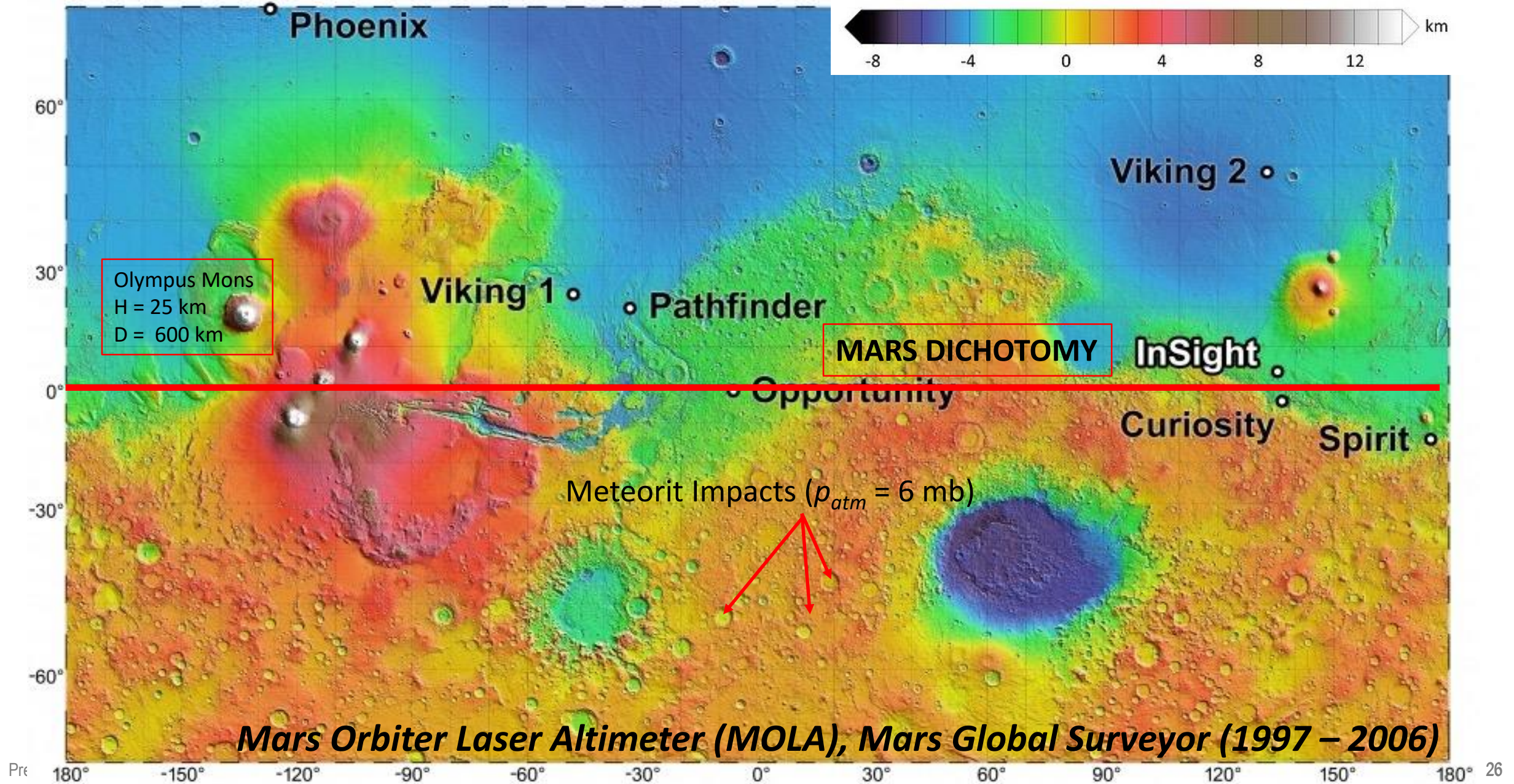
Earth – Moon 0.384 Mkm

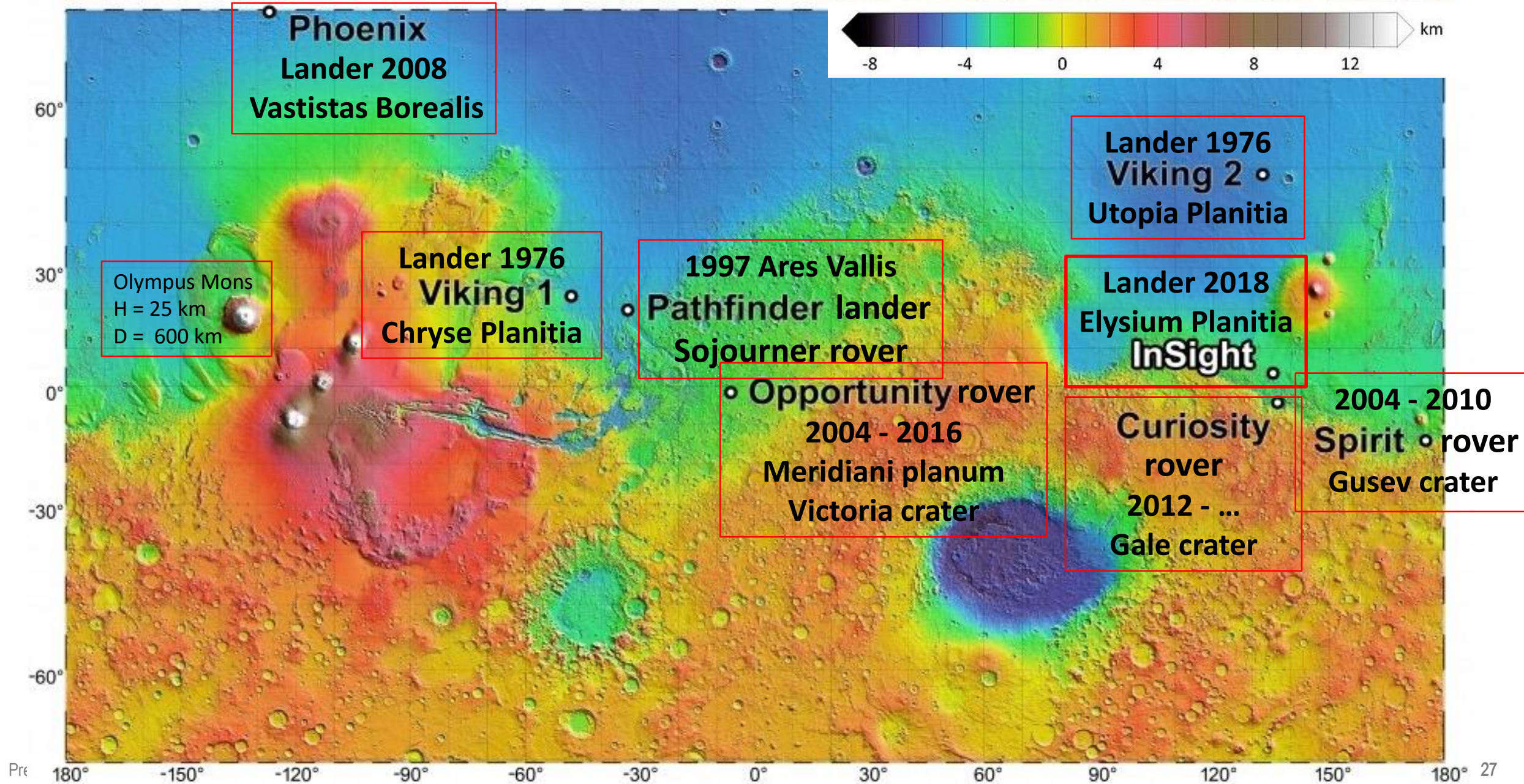


Martian year : 687 sols (days)





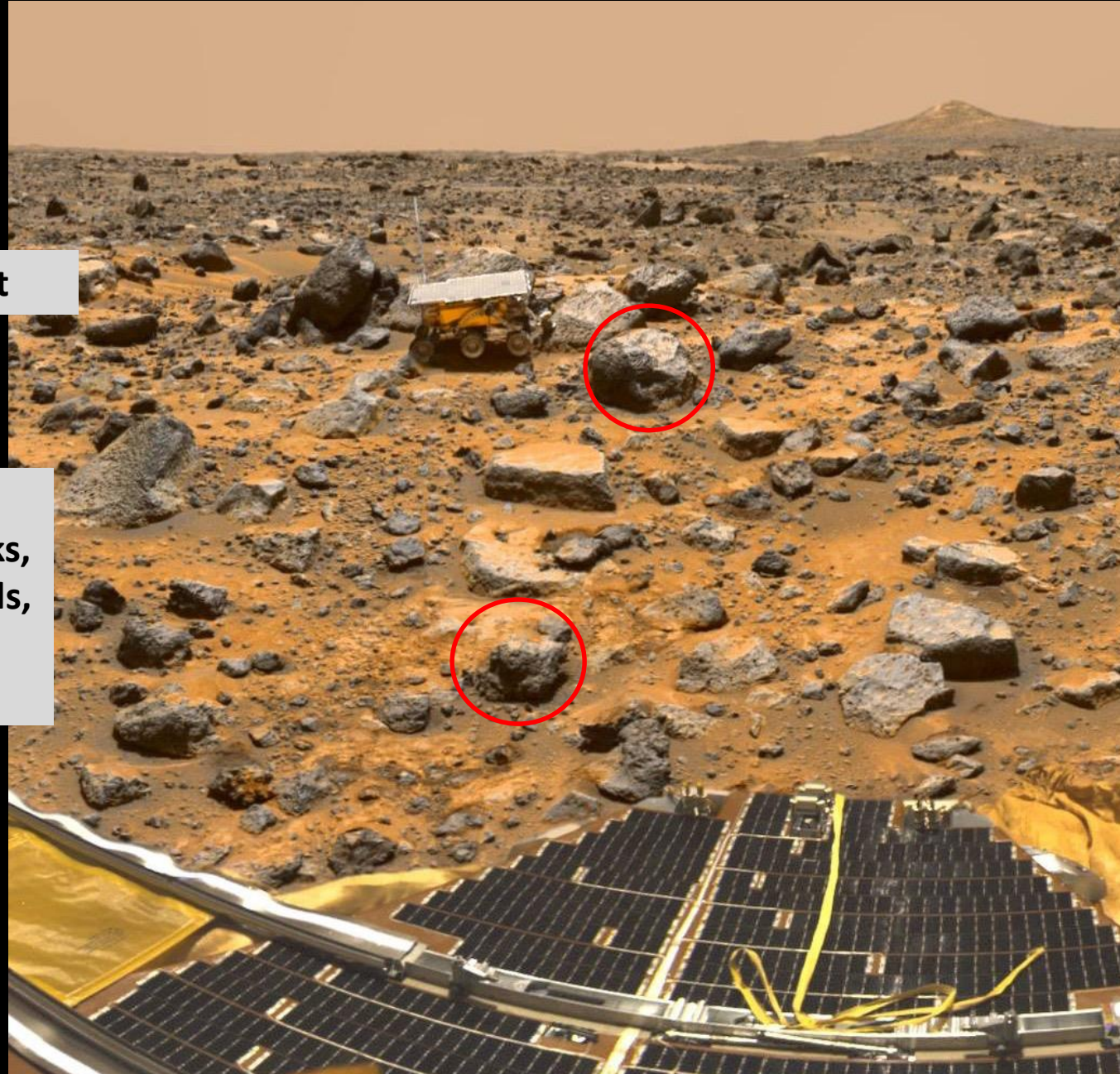




High rock density area

Warmer and wetter in the past

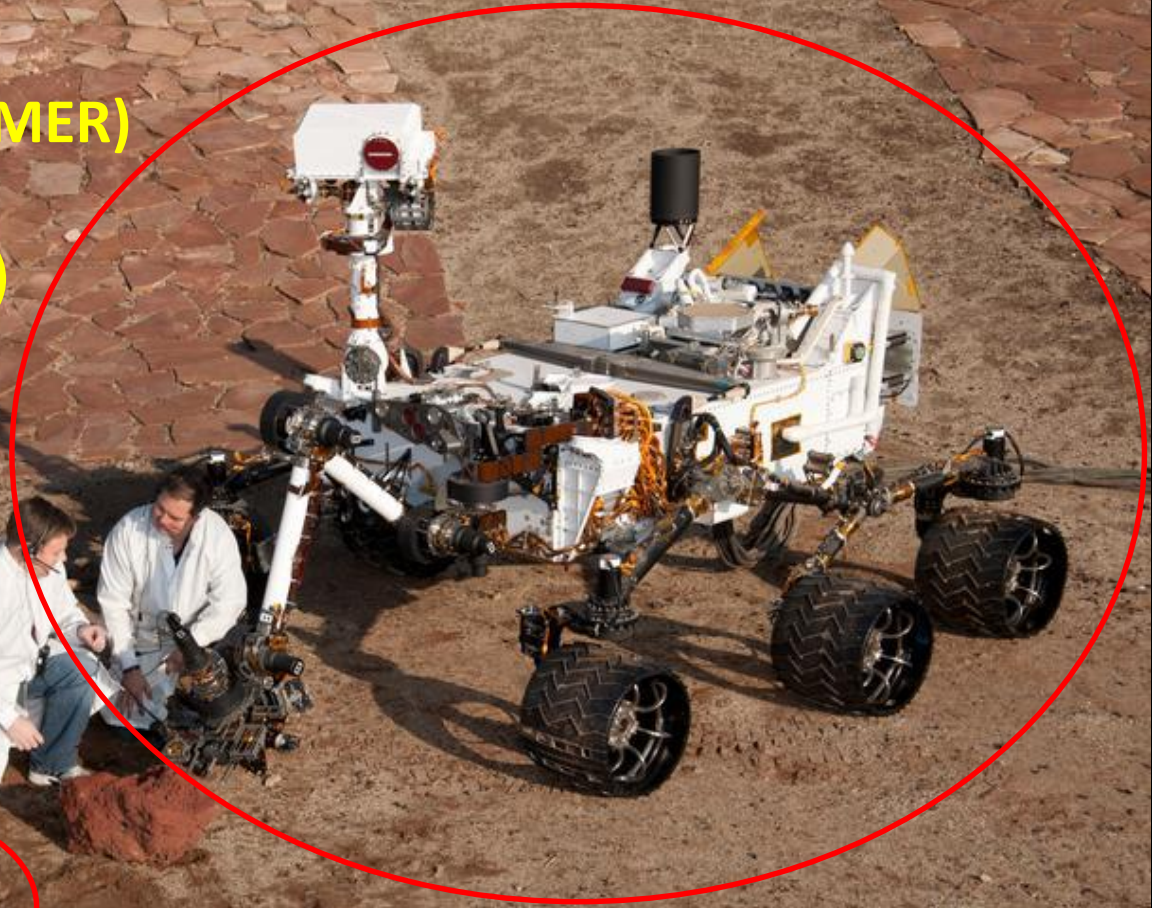
Flooding Plain, with some rounded or semi-rounded rocks, carried and deposited by floods, at the beginning of the planet evolution



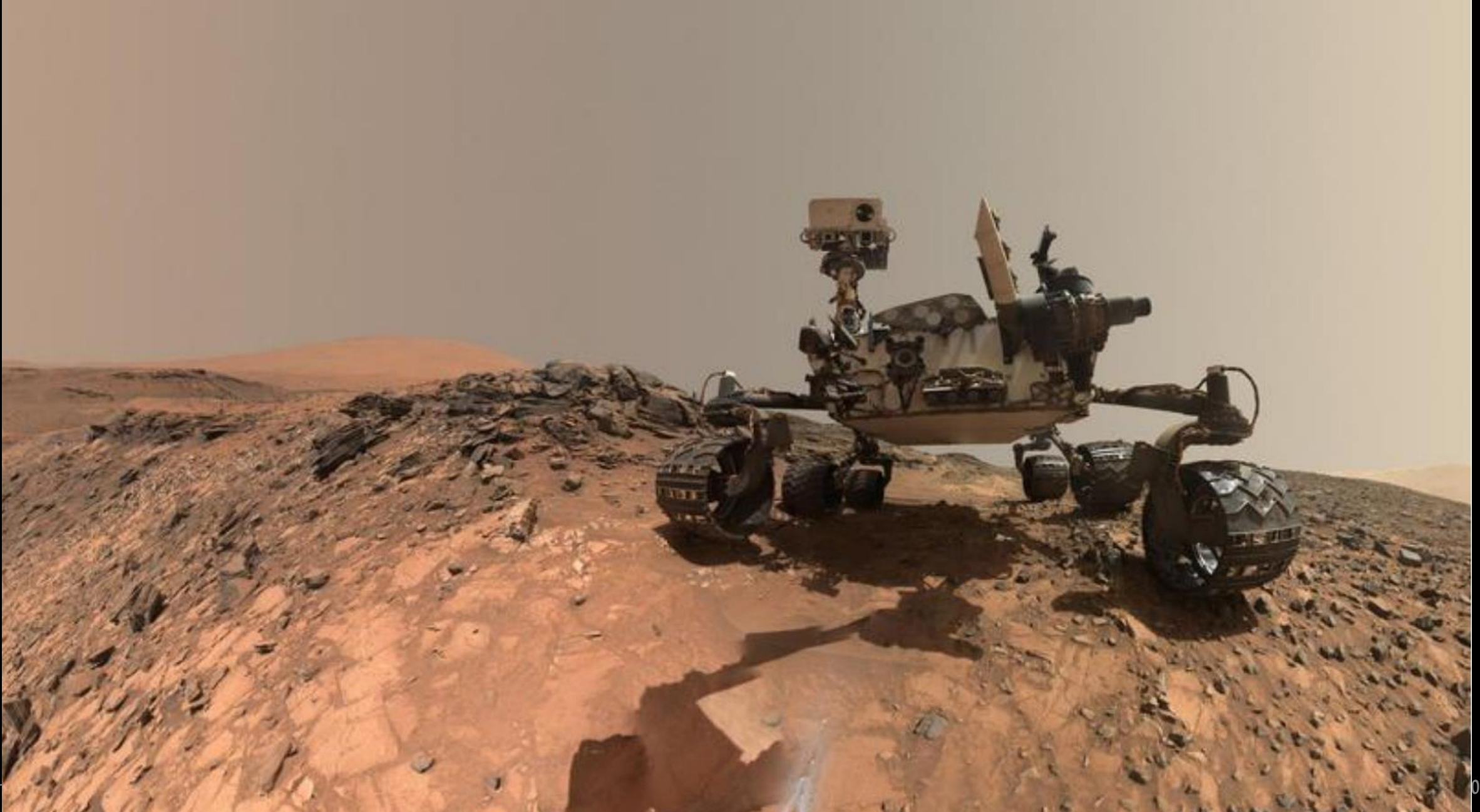
Mars Exploration Rovers (MER)
Spirit (2004 – 2011)
Opportunity (2004 – 2018)
174 kg

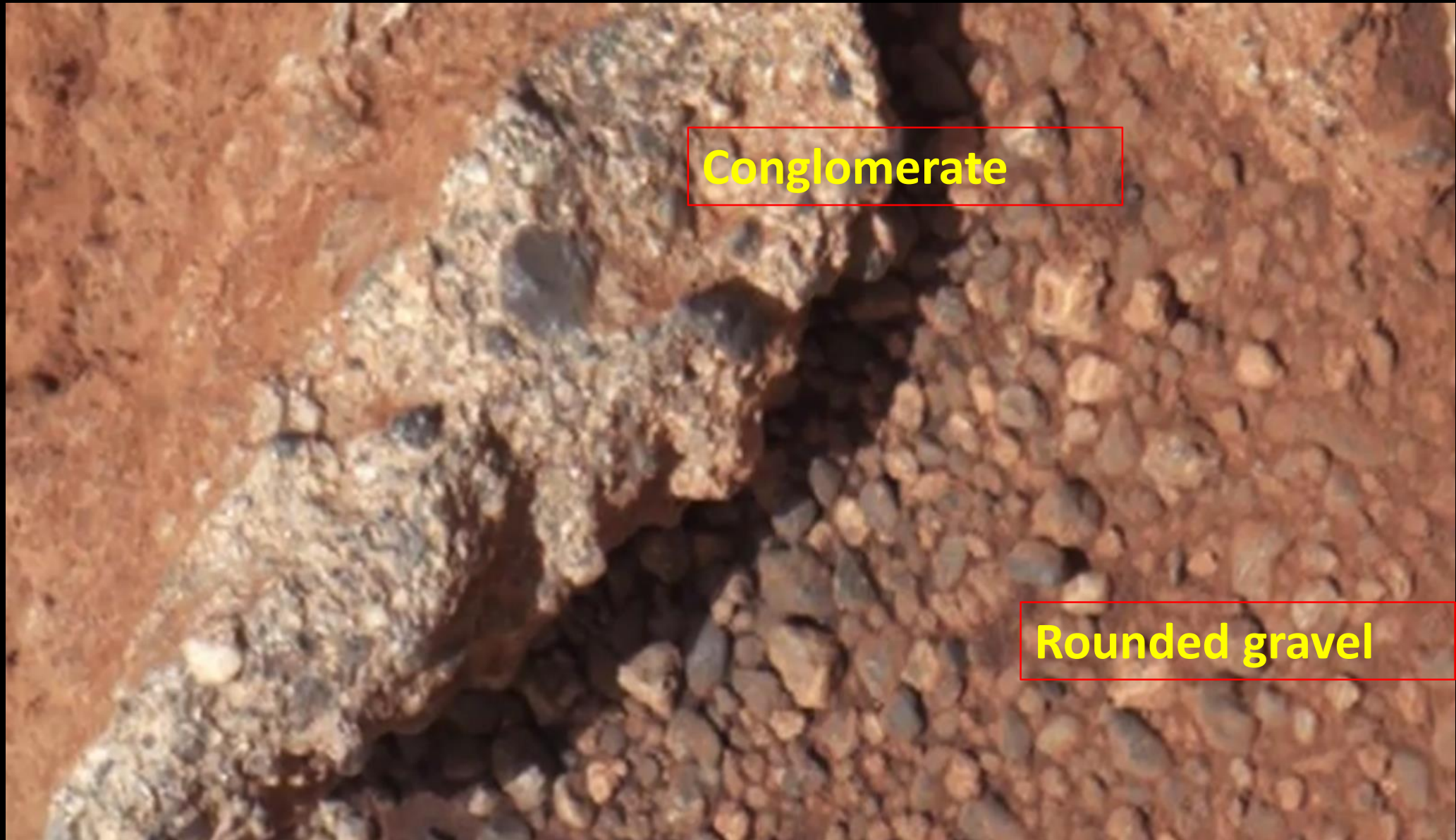


Sojourner, 1997
10 kg



Curiosity, 2012

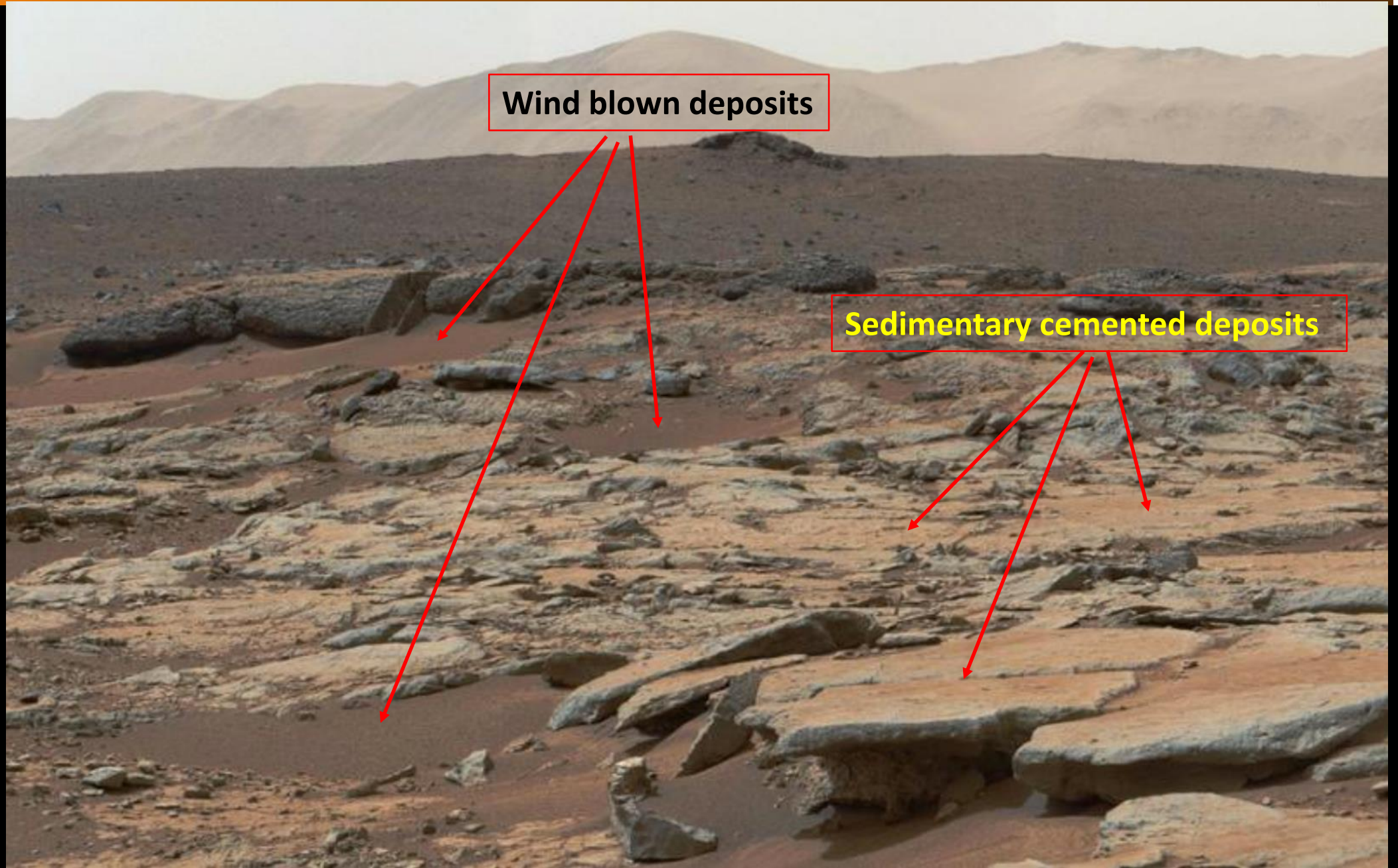


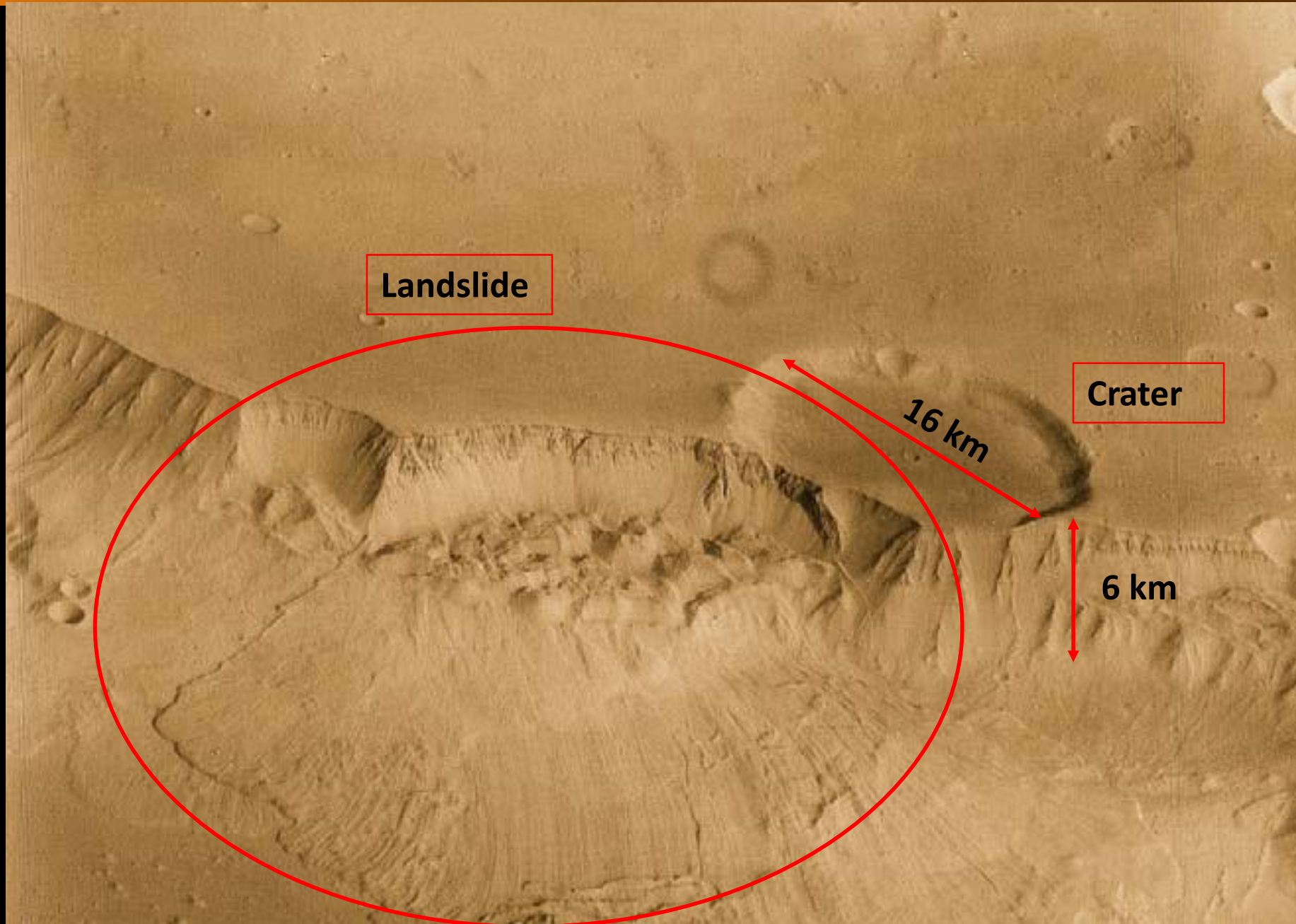


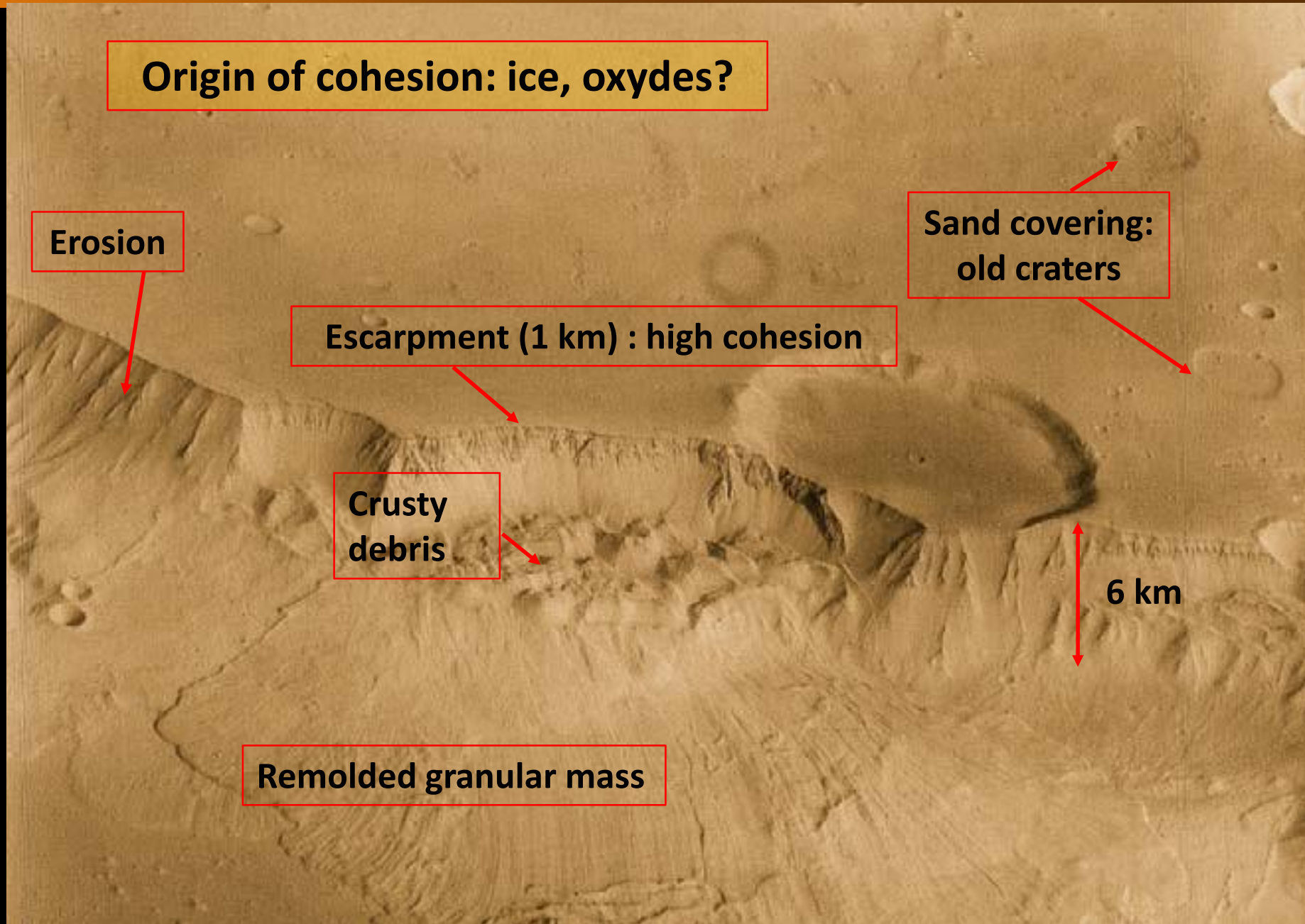
Conglomerate

Rounded gravel

Liquid water : higher temperatures in the past (3.5 billions years)

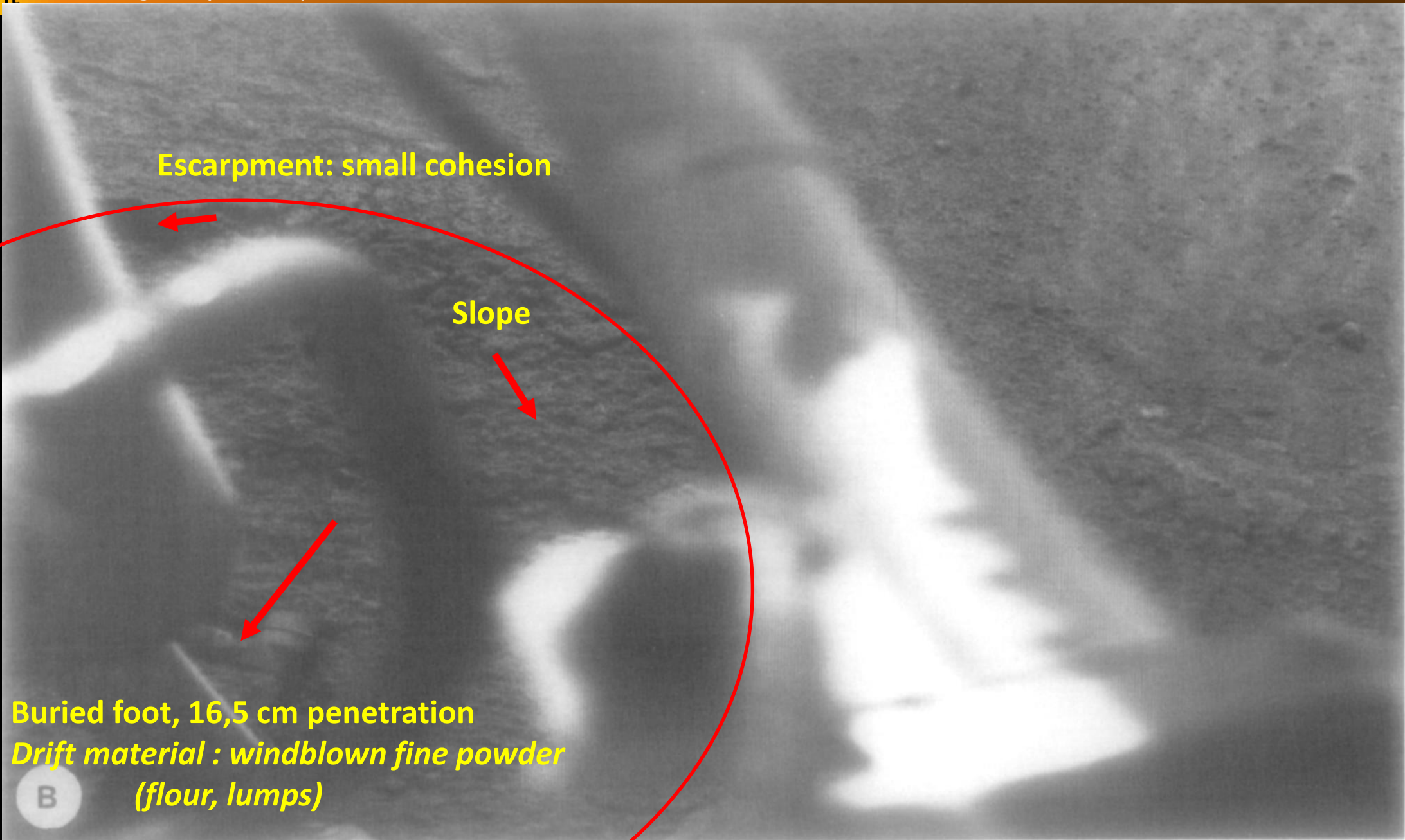


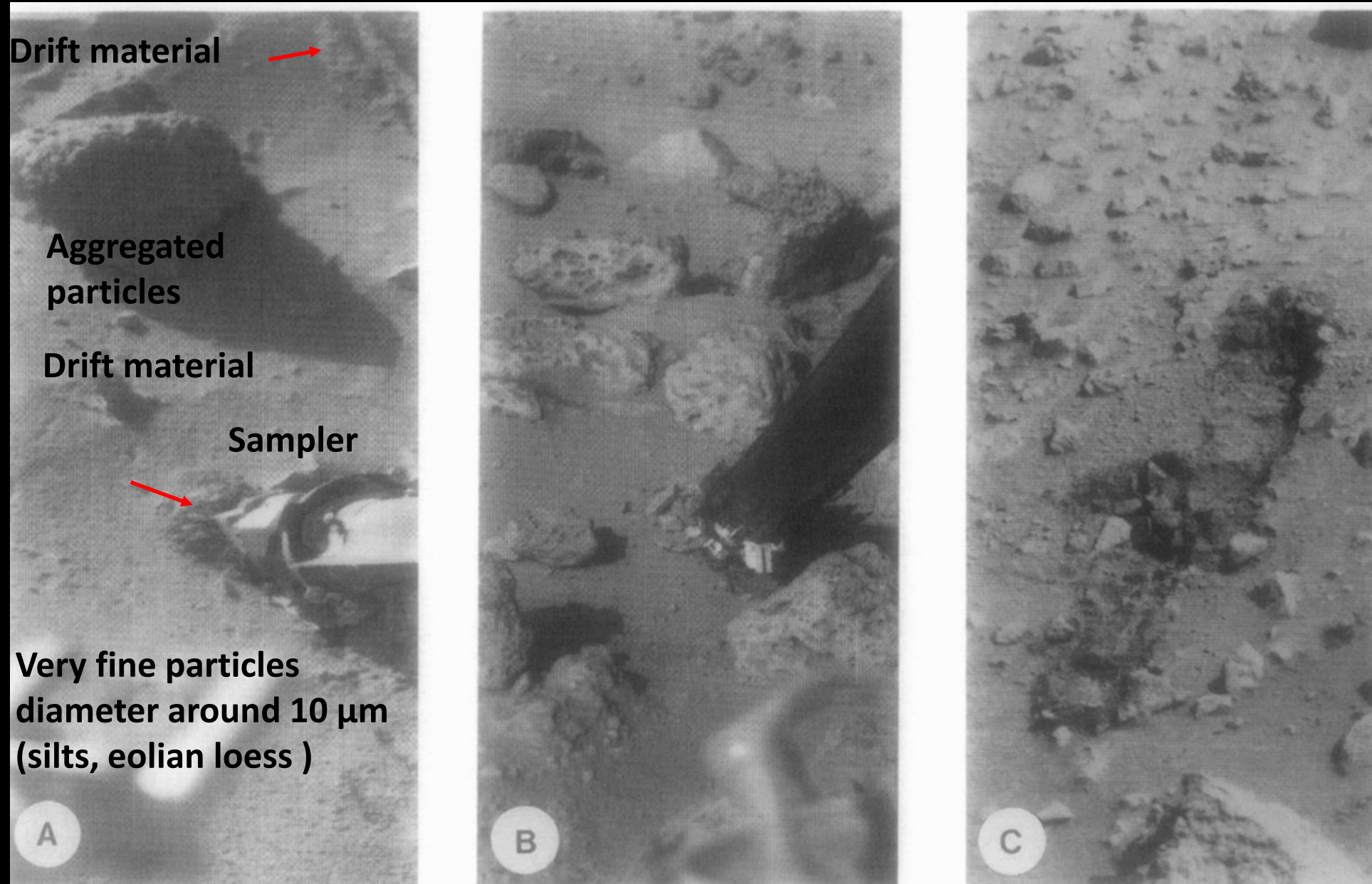


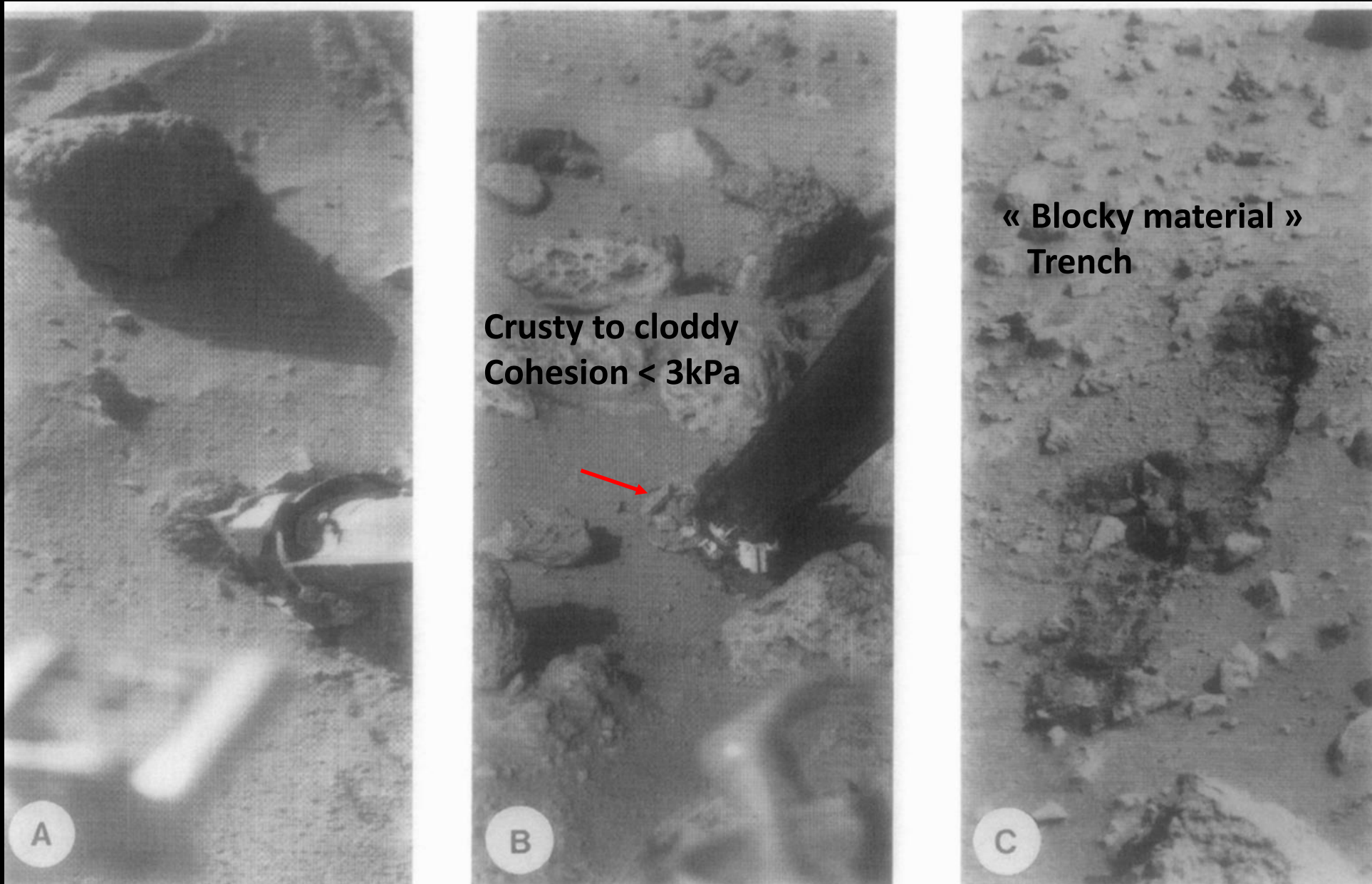




modes are comparable to the dielectric constants and thermal inertias for drift and crusty to cloddy material, respectively. Dielectric constants and thermal inertias for blocky material are larger but consistent with values in the northern plains. Our interpretations are compatible with an aeolian origin for drift and similar materials elsewhere on Mars. The postulate that moderate dielectric constants and thermal inertias larger than 3 or 4×10^{-3} are produced by cementation of soil-like materials is partly consistent with the data. The average dielectric constant and thermal inertia and their correlation with one another suggest that most of the surface of Mars should present few difficulties to future surface exploration, but some surfaces may present difficulties for spacecraft that are not suitably designed. © 1989 Academic Press, Inc.

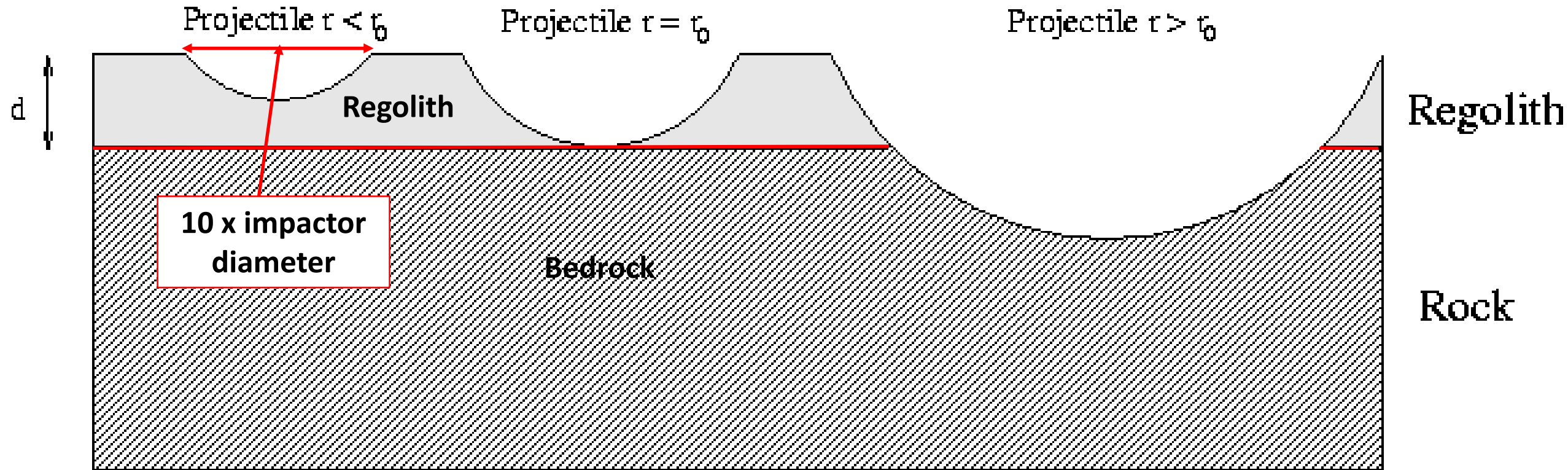






Meteorit at 30 km/s
vaporisation

Atmospheric pressure 6 mb (Moon 0 mb, Earth 1015 mb)



Meteorit at 30 km/s
vaporisation

Atmospheric pressure 6 mb

Projectile $r = r_0$

Projectile $r > r_0$

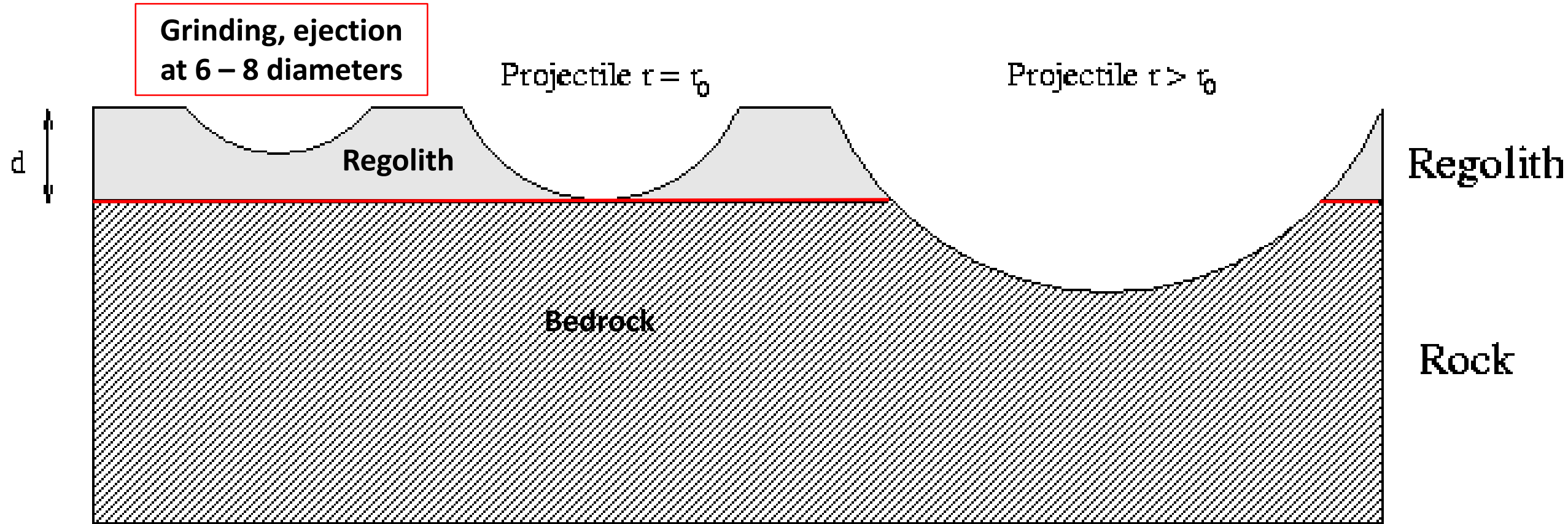
Regolith

1000 x impactor
volume

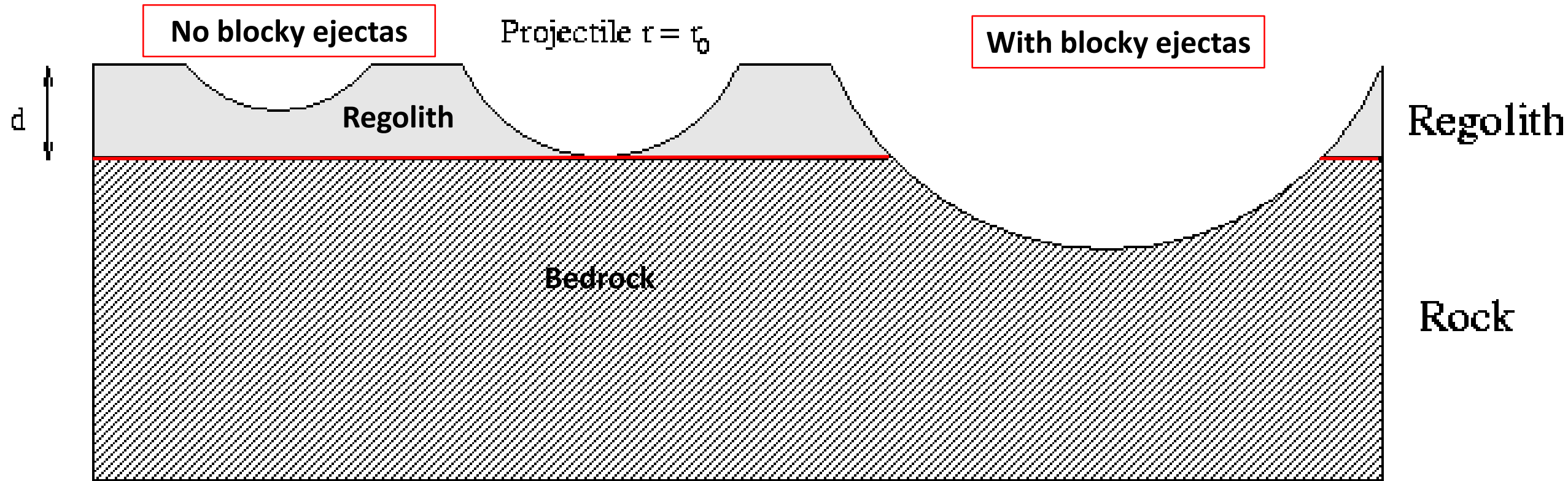
Regolith

Rock

Atmospheric pressure 6 mb



Atmospheric pressure 6 mb



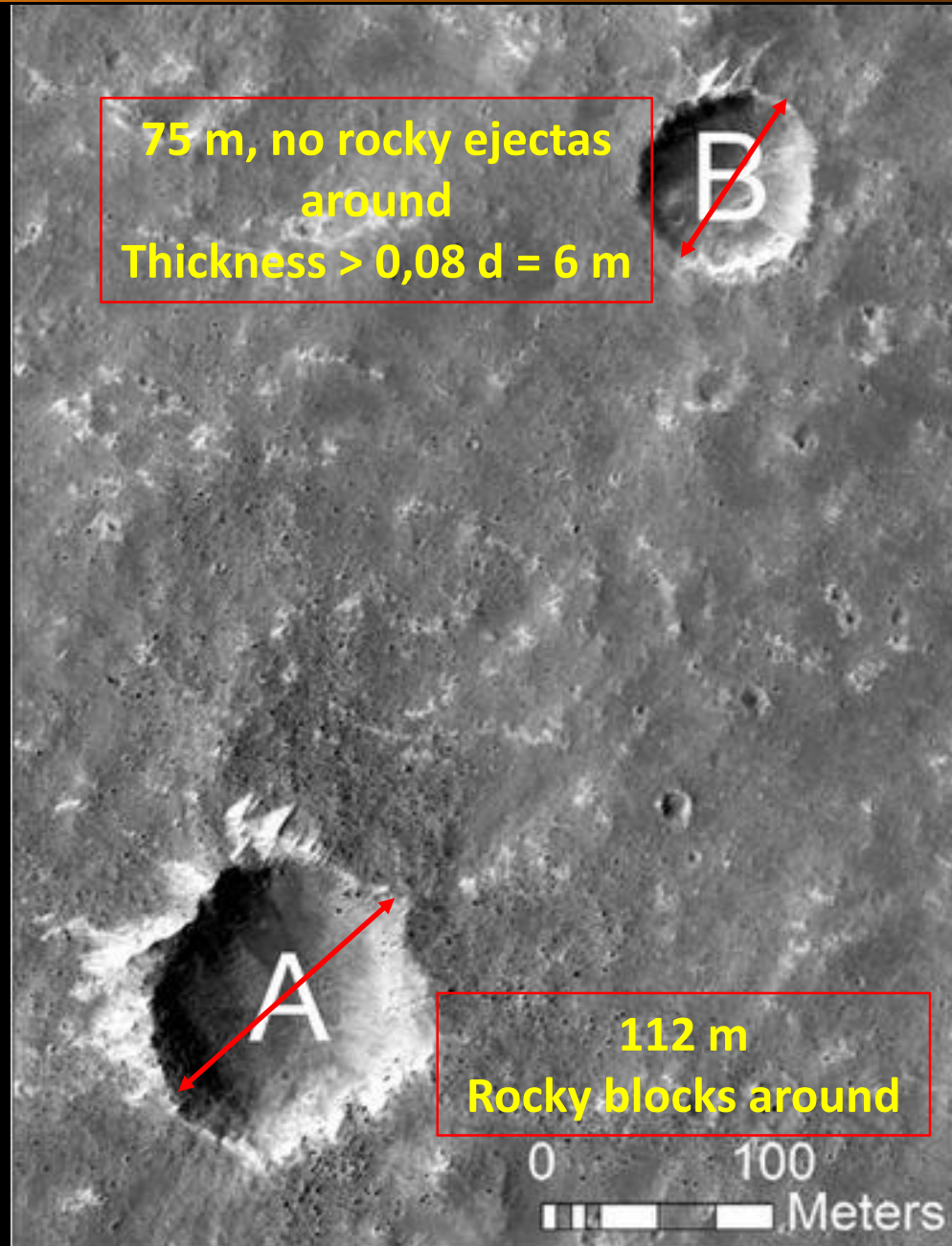
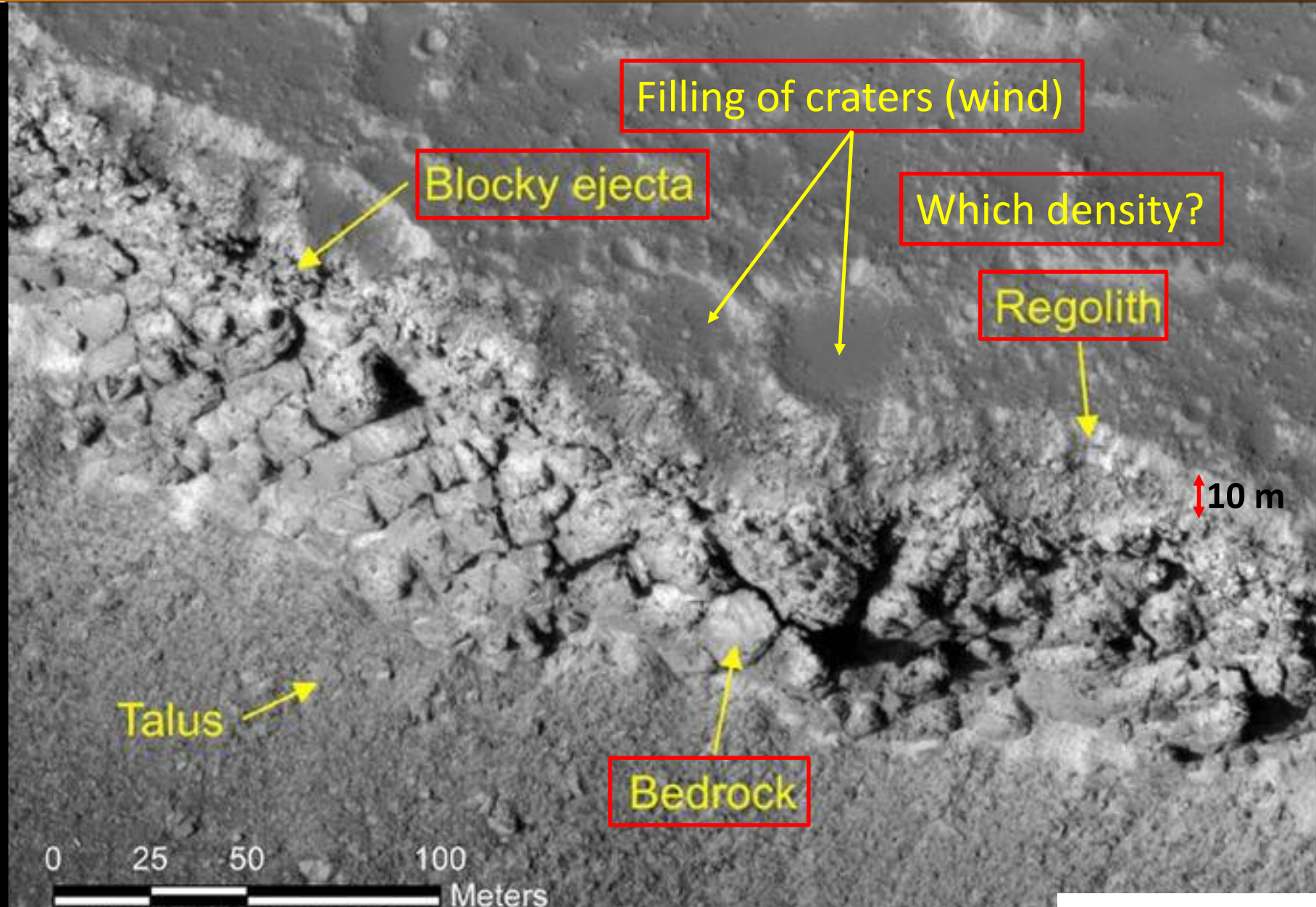
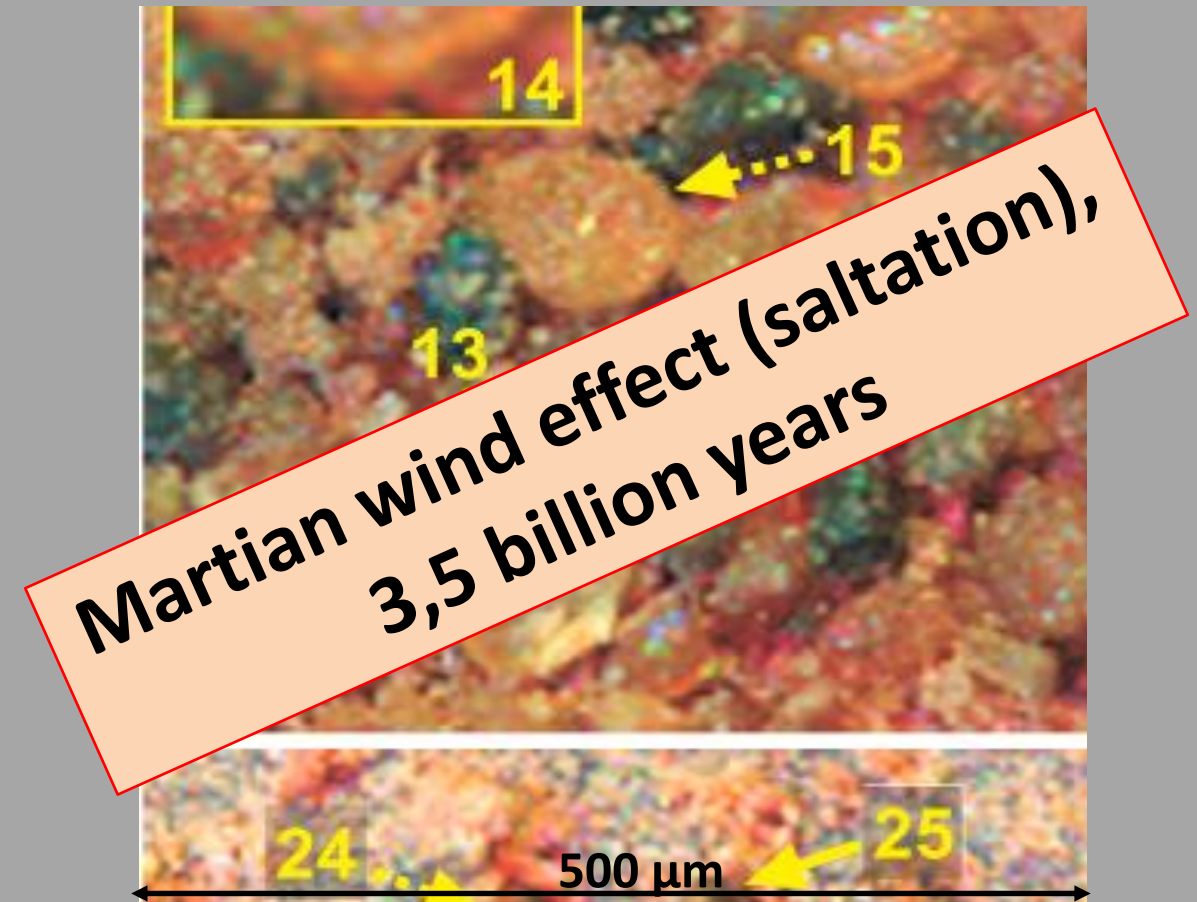
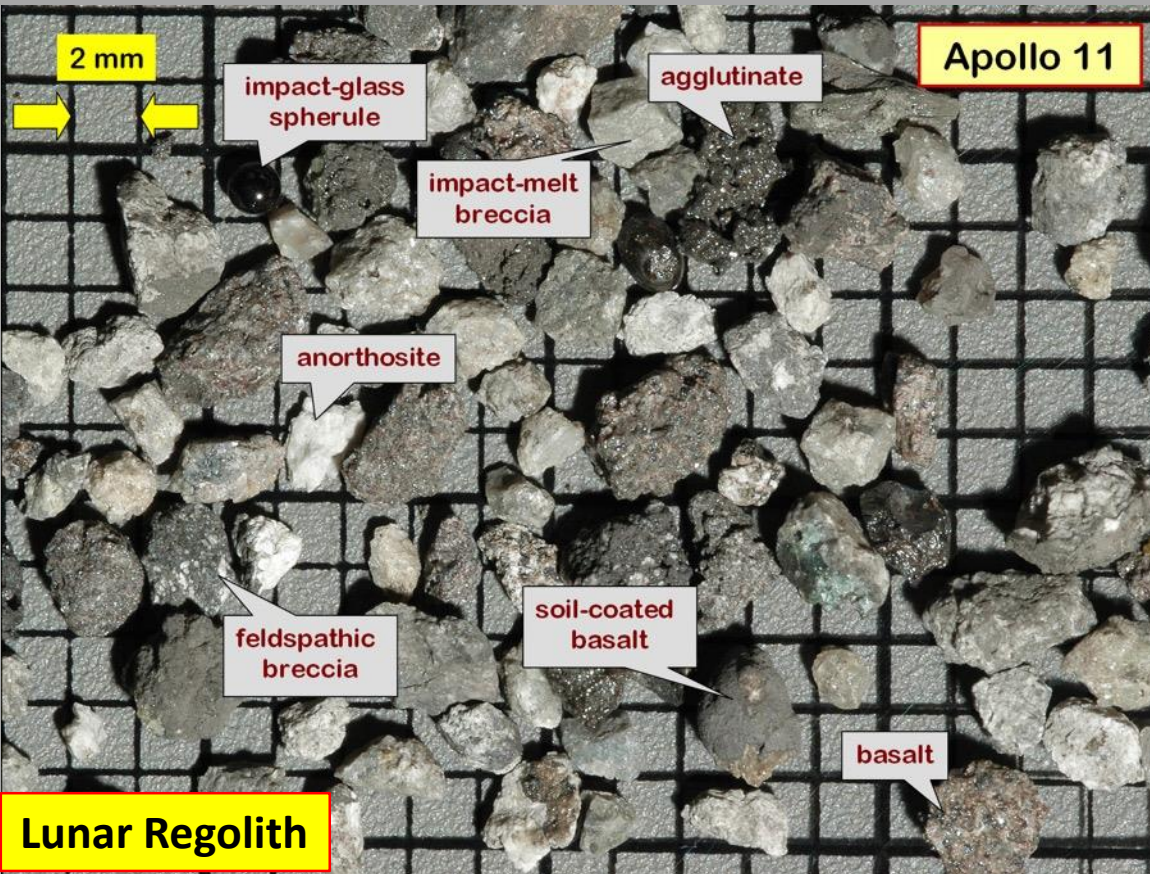


Photo HiRise
Pixel 25 cm (!)
Mars Reconnaissance Orbiter
2006 -



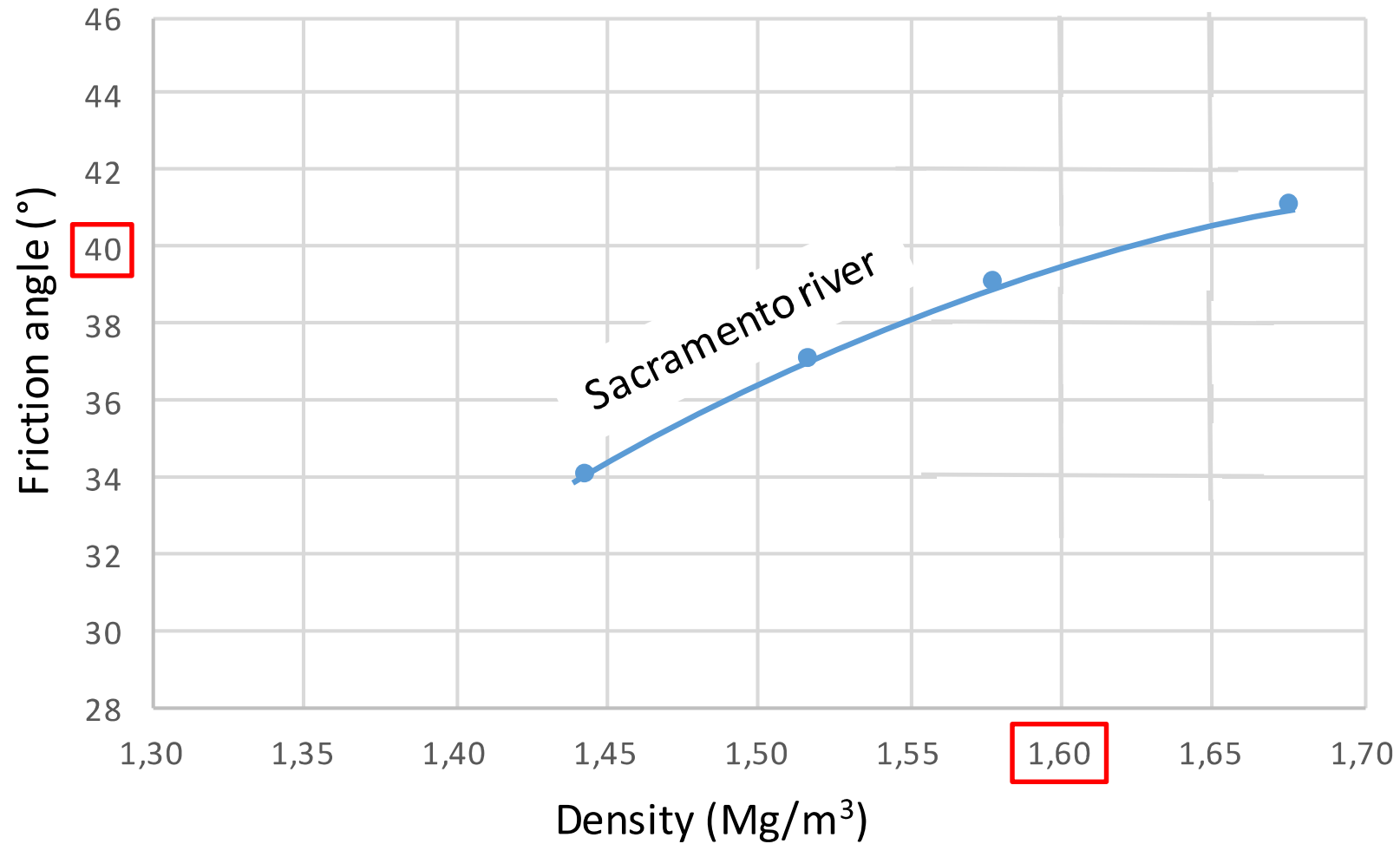


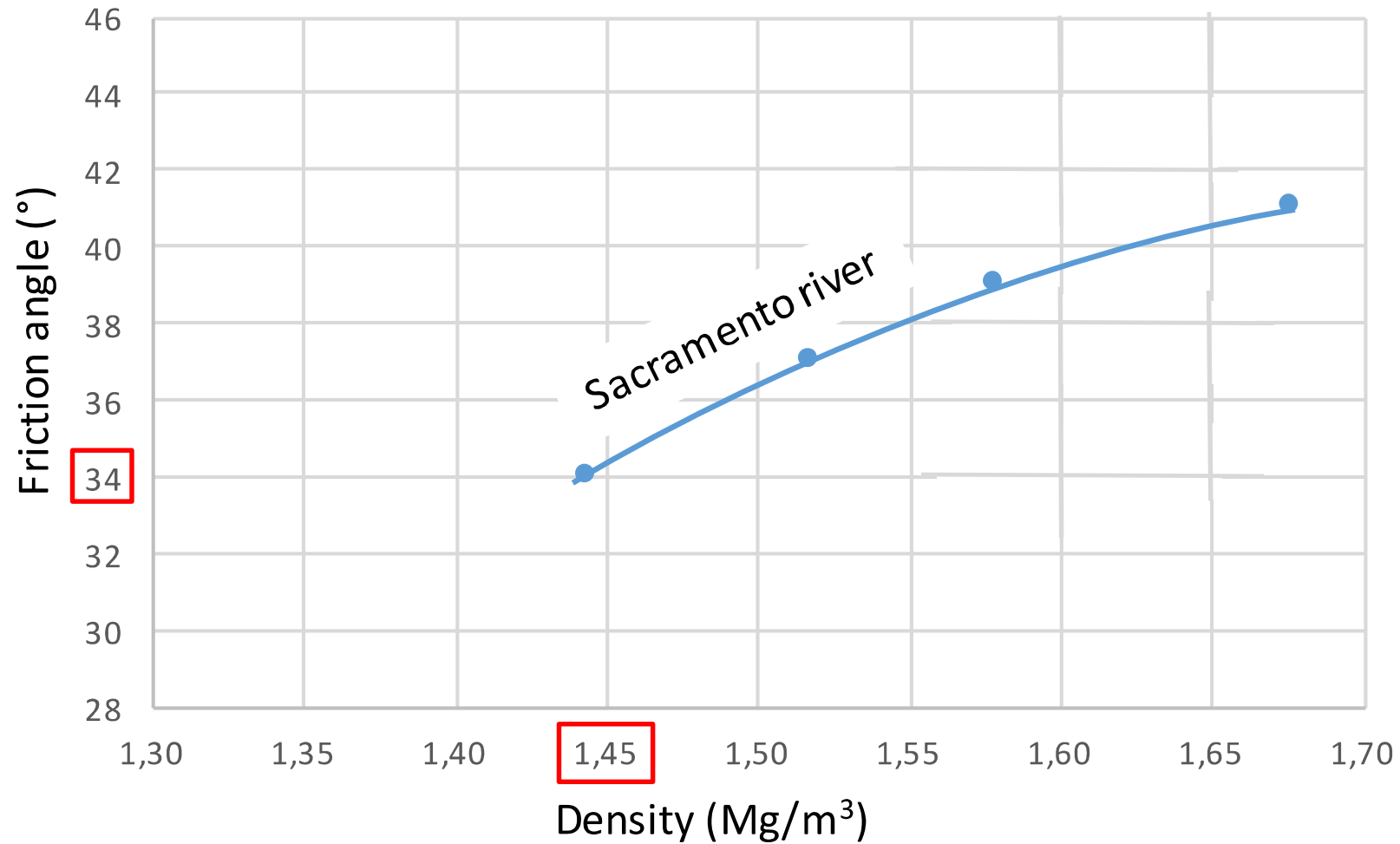
Optical Microscope, Phoenix landing site, Goetz et al. 2010)

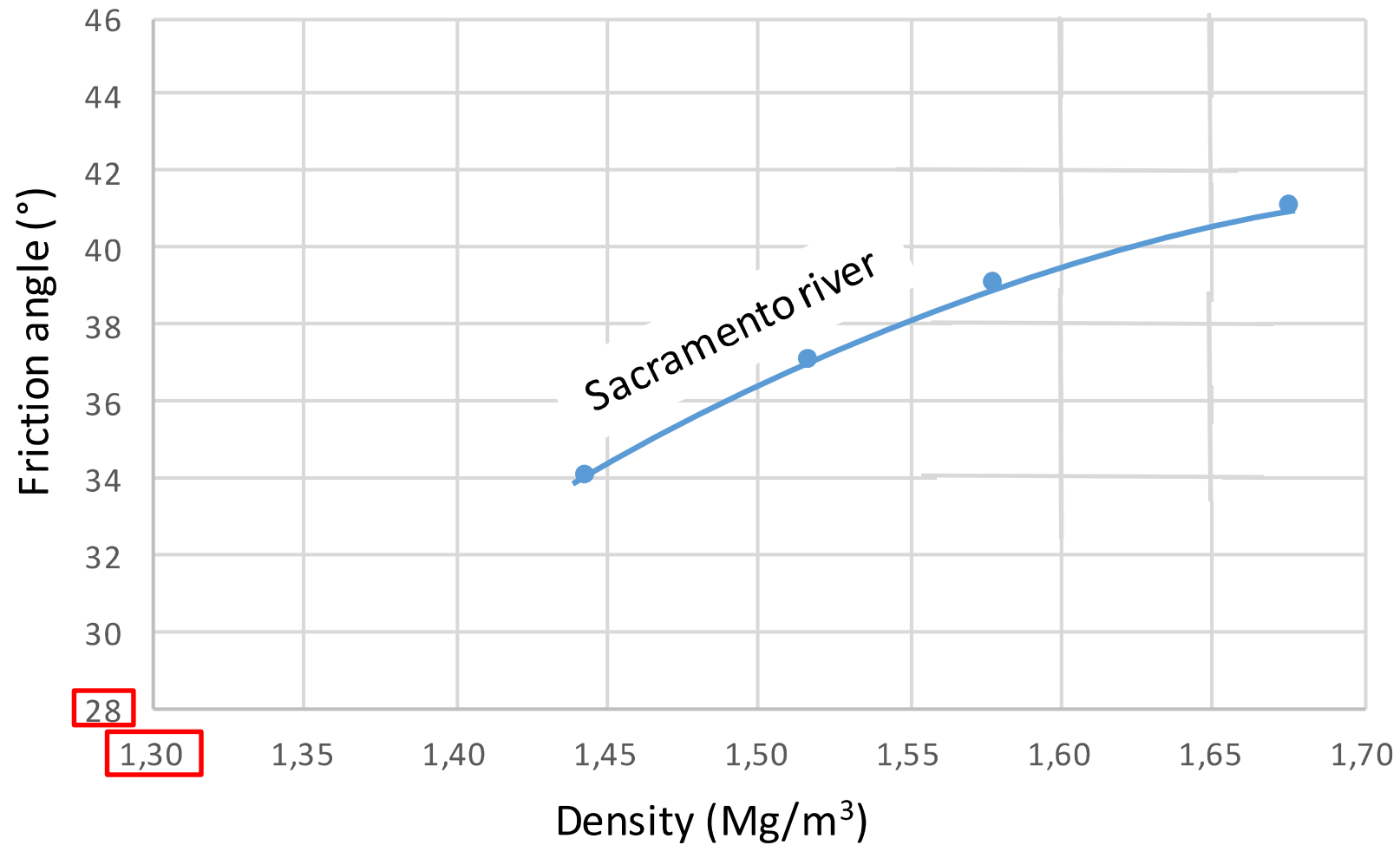
- Nature, size and shape of the particles
- Density
- Friction angle
- Cohesion
- Thermal Inertia

Various terrestrial sands ($\rho_s = 2700 \text{ kg/m}^3$, silica, calcareous)

Sand				ρ_{max}		ρ_{min}
Sand name	D_{60}	D_{10}	e_{min}	(Mg/m^3)	e_{max}	(Mg/m^3)
Brasted river	0.29	0.12	0.47	1,84	0.79	1,51
Mersey river	0.2	0.1	0.49	1,81	0.82	1,48
Monterey N°20	0.3	0.15	0.57	1,72	0.78	1,52
Monterey N°0	0.5	0.3	0.57	1,72	0.86	1,45
Ham river	0.25	0.16	0.59	1,70	0.92	1,41
Leighton Buzzard 14/25	0.85	0.65	0.49	1,81	0.79	1,51
Welland river	0.14	0.1	0.62	1,67	0.94	1,39
Chattahoochee river	0.47	0.21	0.61	1,68	1,10	1,29
Mol	0.21	0.14	0.56	1,73	0.89	1,43
Berlin	0.25	0.11	0.46	1,85	0.75	1,54
Guinea marine	0.41	0.16	0.52	1,78	0.9	1,42
Portland river	0.36	0.23	0.63	1,66	1,1	1,29
Glacial outwash sand	0.9	0.15	0.41	1,91	0.84	1,47
Karlshrue medium sand	0.38	0.2	0.54	1,75	0.82	1,48
Sacramento river	0.22	0.15	0.61	1,68	1,03	1,33
Ottawa sand	0.76	0.65	0.49	1,81	0.8	1,50







- Nature, size and shape of the particles
- Density
- Friction angle
- Cohesion
- **Thermal Inertia**

- Measured by THEMIS Orbiter
- Derived from the rate of change of the temperature surface (2 – 30 cm)
- $I = (k\rho c)^{1/2}$
 - k : thermal conductivity
 - ρ : bulk density at surface
 - c : specific heat

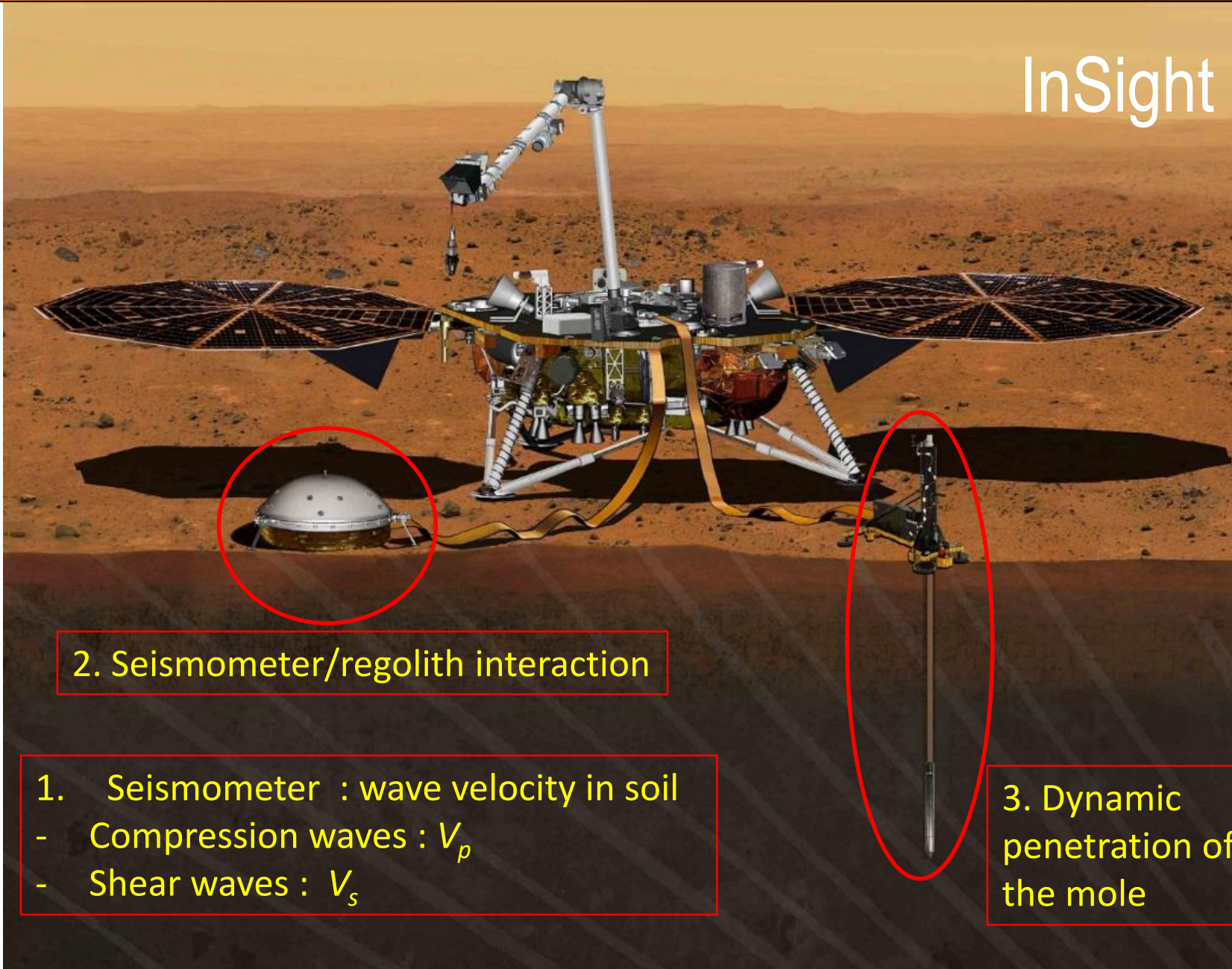
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 - c : specific heat
- Small grains : low inertia (larger specific surface)
- Large grains : high inertia (smaller specific surface)

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- Large grains : high inertia (smaller specific surface)
- **Cohesion** increases thermal inertia

Table 1 Characteristics of some Martian surface materials (Golombek et al. 2008, Chap. 20)

Surface material	Bulk density (Mg/m ³)	Grain size (mm)	Cohesion (kPa)	Friction angle (°)	Thermal inertia (J m ⁻² K ⁻¹ s ^{-1/2})
Drift	1–1.3	0.001–0.01	0–3	15–21	40–125
Sand	1.1–1.3	0.06–0.2	0–1	30	60–200
Crusty to cloddy sand	1.1–1.6	0.005–0.5	0–4	30–40	200–326
Blocky, indurated soil	1.2–2	0.05–3	3–11	25–33	368–410
Dense float rock, volcanic	2.6–2.8	2–2000	1000–10000	40–60	> 1200–2500
Clastic rock, Columbia Hills	2				620–1100
Sulfate rock, Meridiani	< 2				> 400–1100

Data derived from Moore et al. (1987, 1999), Moore and Jakosky (1989), Christensen and Moore (1992), Arvidson et al. (2004a, 2004b), Christensen et al. (2004a, 2004b), Herkenhoff et al. (2004a, 2004b), Fergason et al. (2006a) and Chap. 20 from Bell



InSight

2. Seismometer/regolith interaction

1. Seismometer : wave velocity in soil
 - Compression waves : V_p
 - Shear waves : V_s

3. Dynamic penetration of the mole

- **Regolith Reference Model** with the following parameters:
 - Emissivity, albedo (measured from orbiters)
 - Thermal inertia, thermal conductivity (from orbiters and lander)
 - Density, porosity, cohesion, internal friction angle
 - S and P wave velocities, attenuation factor Q
 - Elastic modulus, Poisson ratio
 - Pressure diffusivity

Mechanical parameters

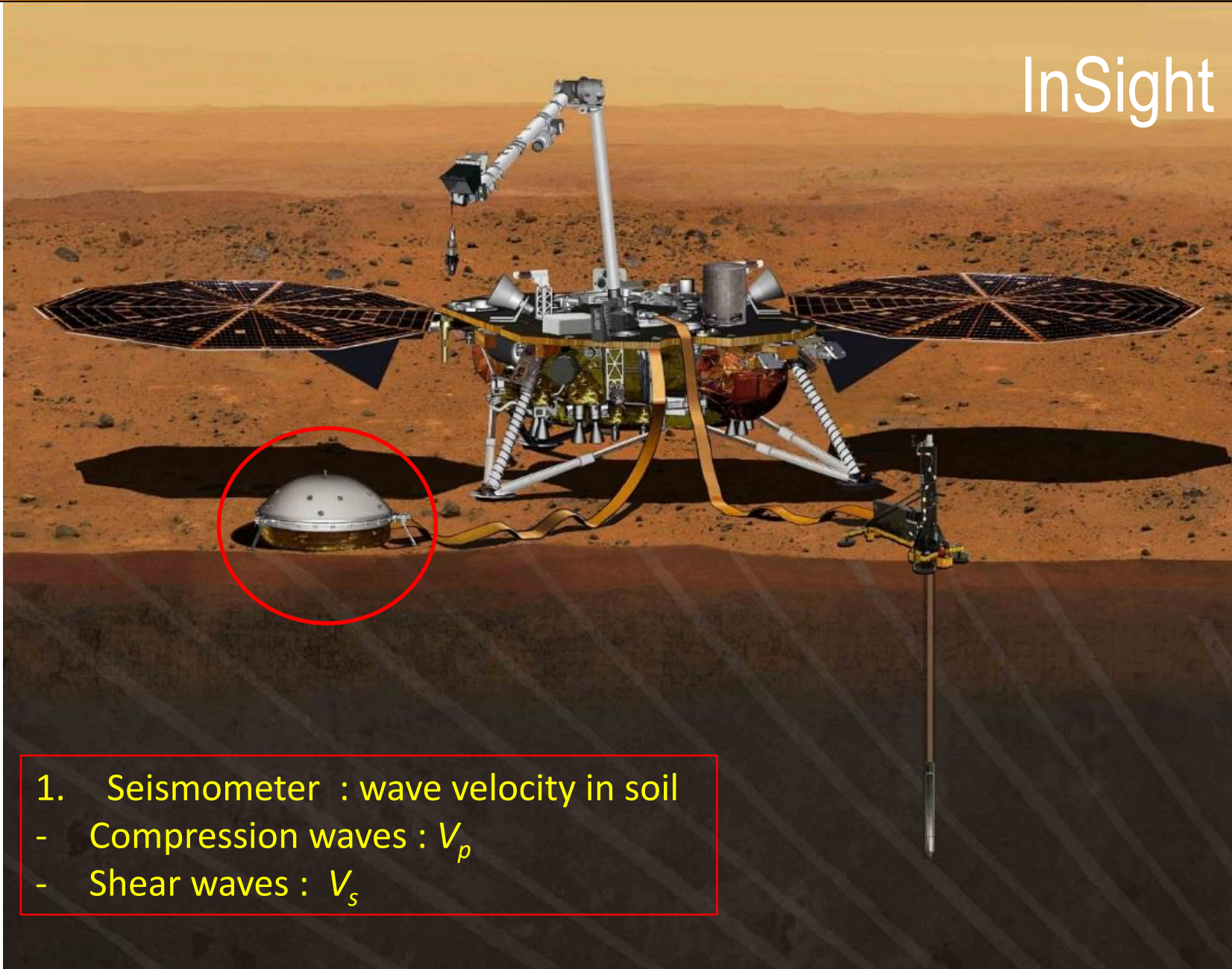
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Mechanical parameters

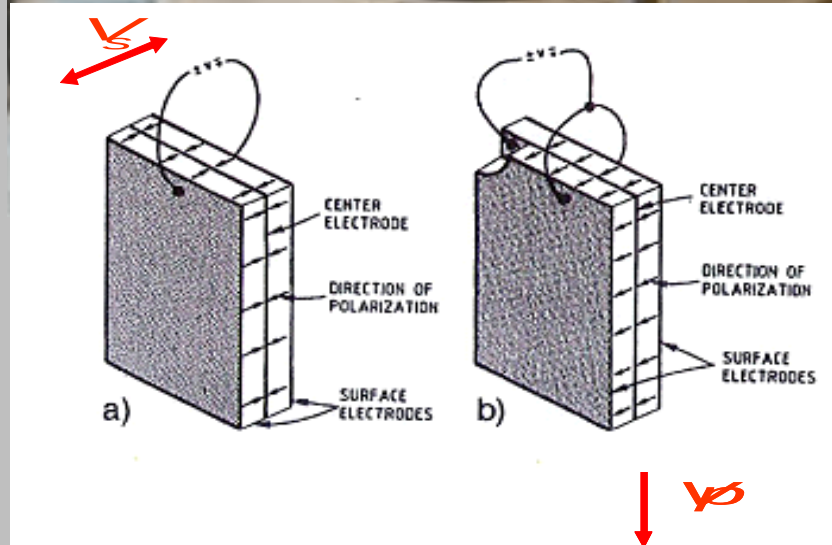
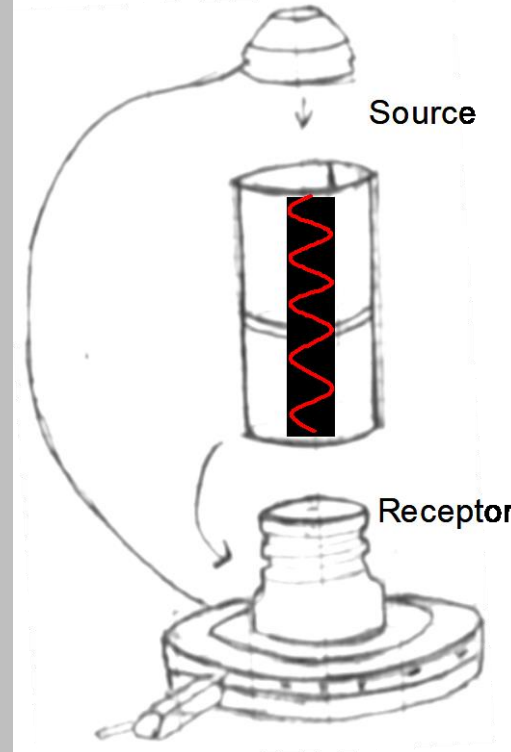
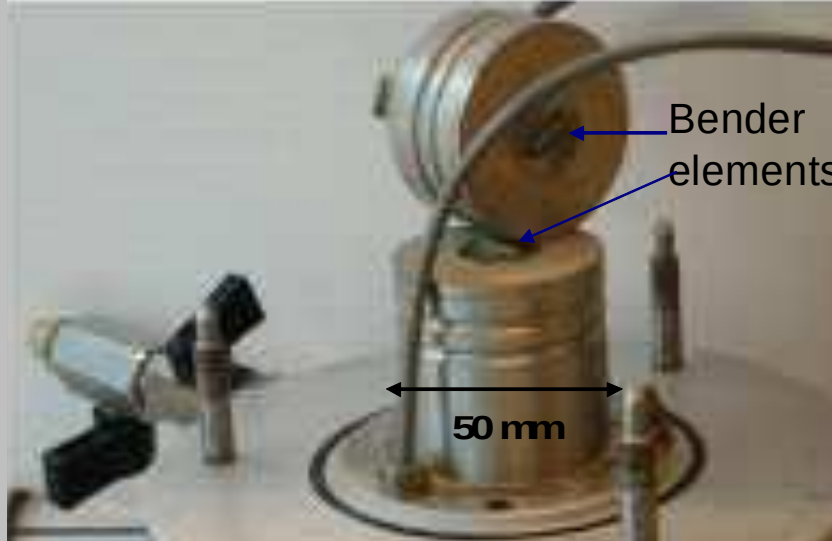
- Regolith Reference Model with the following parameters:
 - Emissivity, albedo (measured from orbiters)
 - Thermal inertia, thermal conductivity (from orbiters and lander)
 - Density, porosity, cohesion, internal friction angle
 - S and P wave velocities, attenuation factor Q
 - Elastic modulus, Poisson ratio
 - Pressure diffusivity

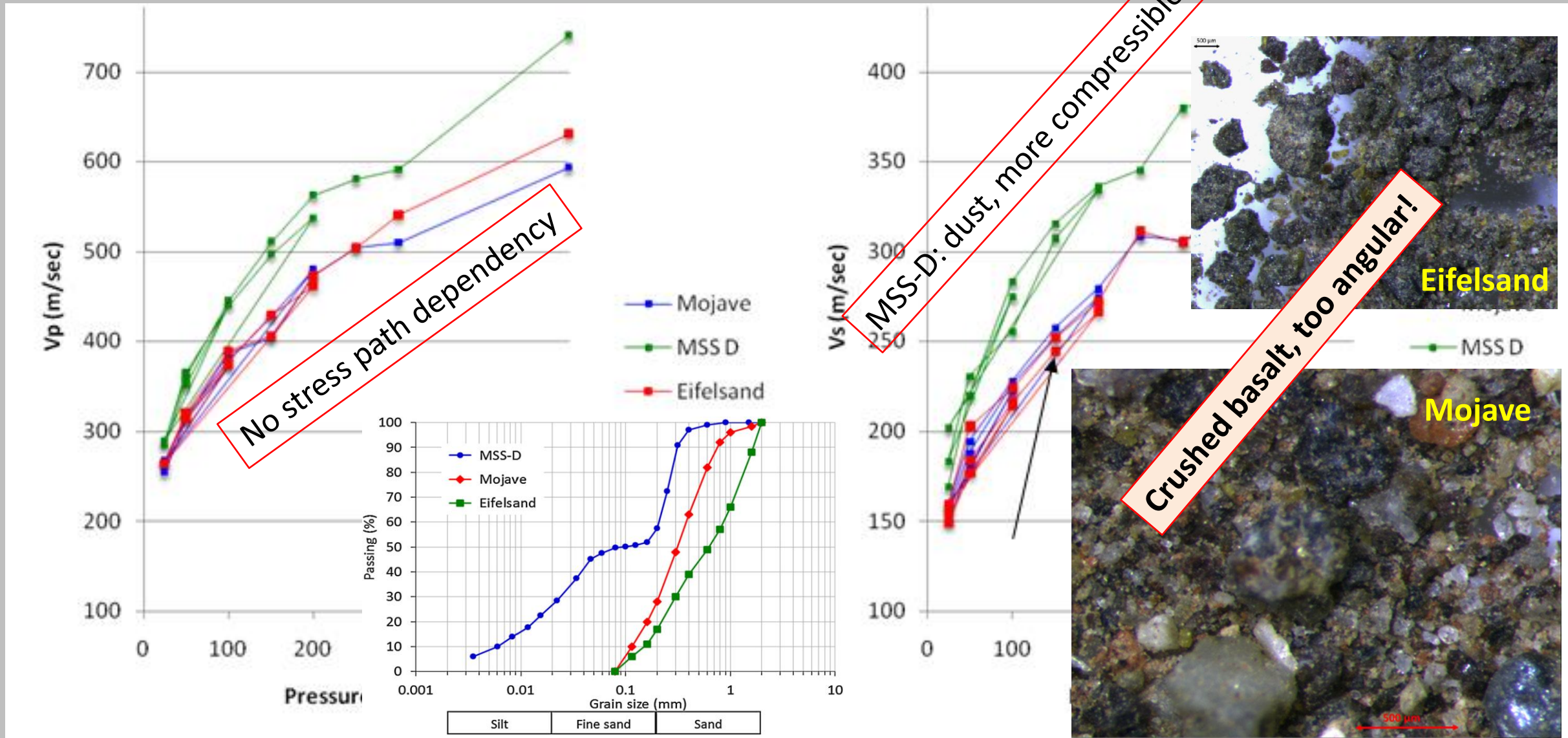
Mechanical parameters

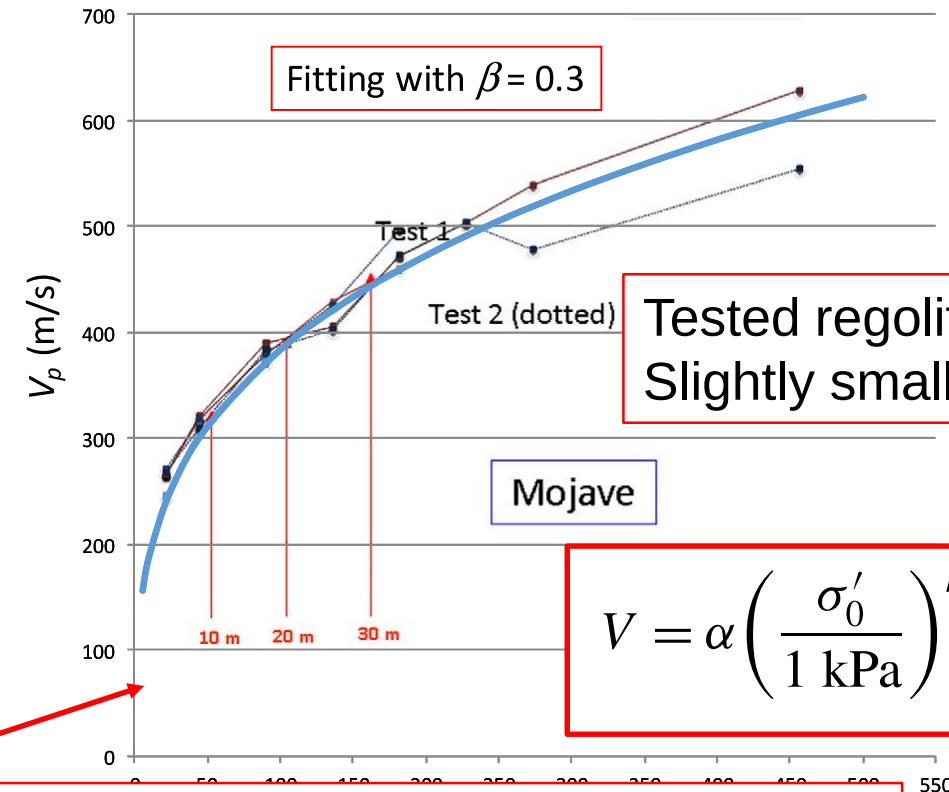
Stress
(reduced
gravity)



1. Seismometer : wave velocity in soil
 - Compression waves : V_p
 - Shear waves : V_s



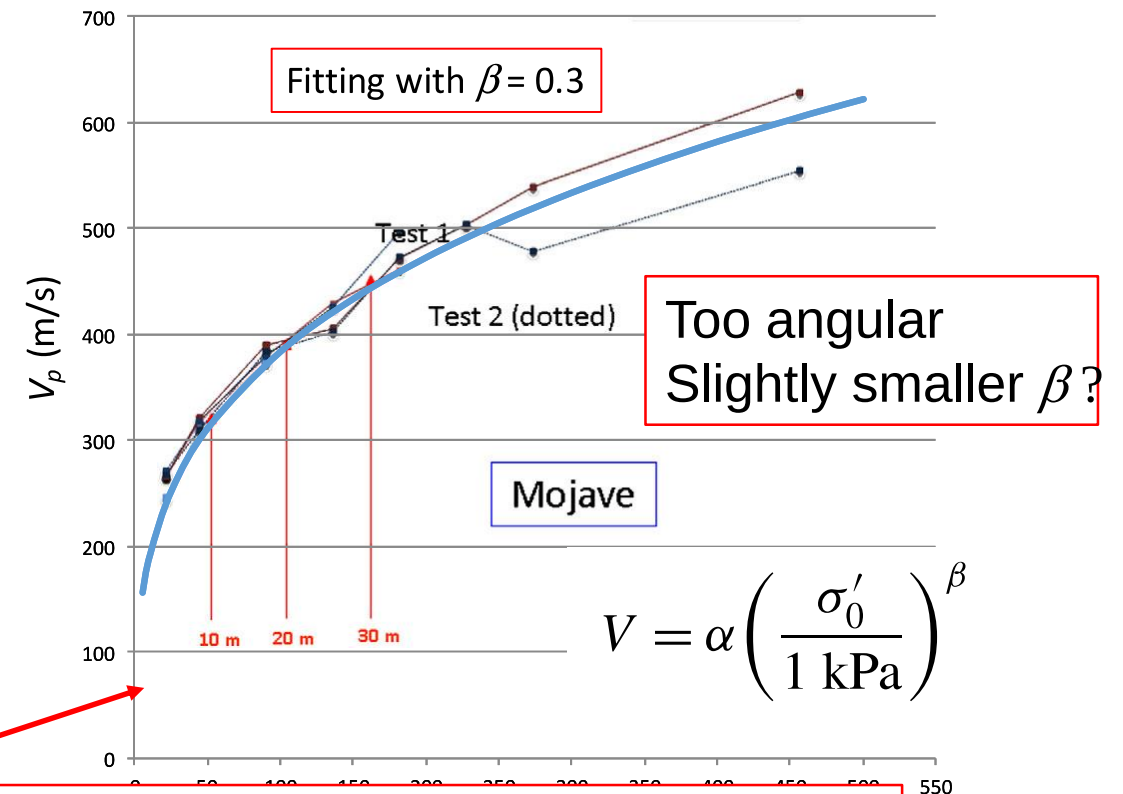
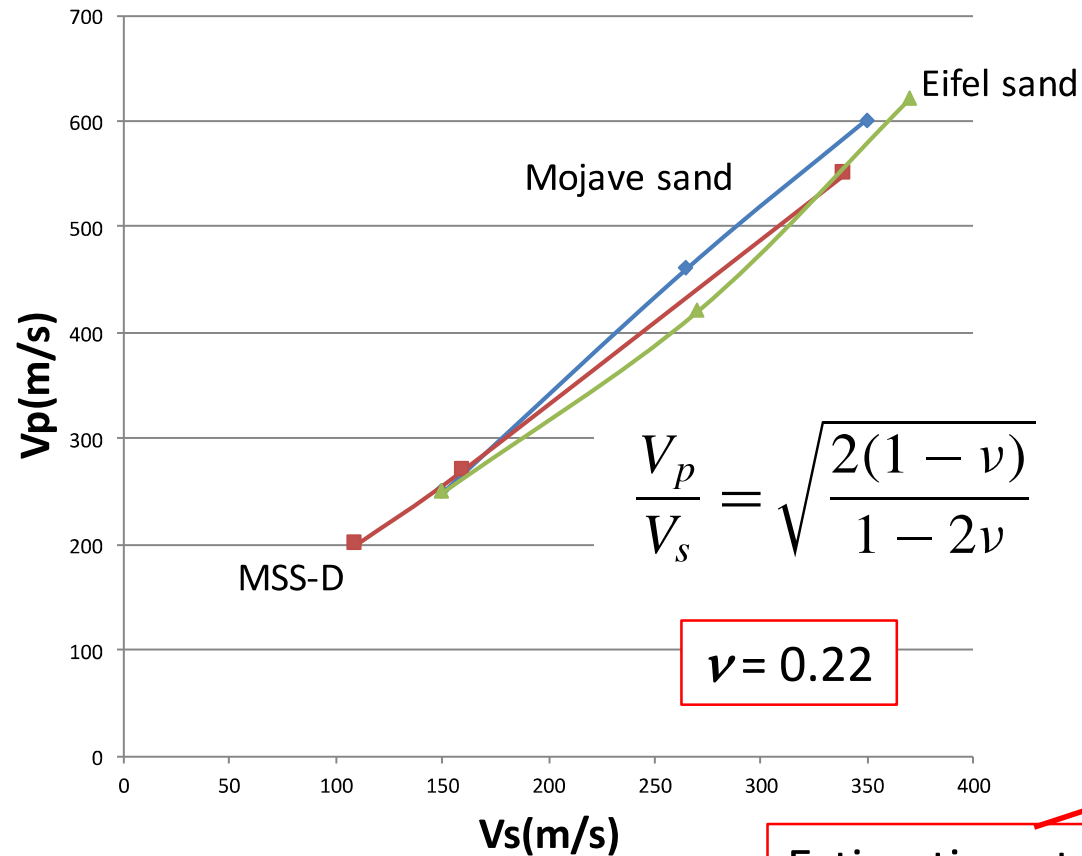




Tested regoliths too angular
Slightly smaller $\beta = 0.28$?

$$V = \alpha \left(\frac{\sigma'_0}{1 \text{ kPa}} \right)^\beta$$

Estimation at surface: 85 – 100 m/s, but with $g = 9.81 \text{ m/s}^2$



Estimation at surface: 85 – 100 m/s, but with $g = 9.81 \text{ m/s}^2$

$$E = \rho V_p^2 * \left(\frac{3 - \frac{4}{l^2}}{l^2 - 1} \right)$$

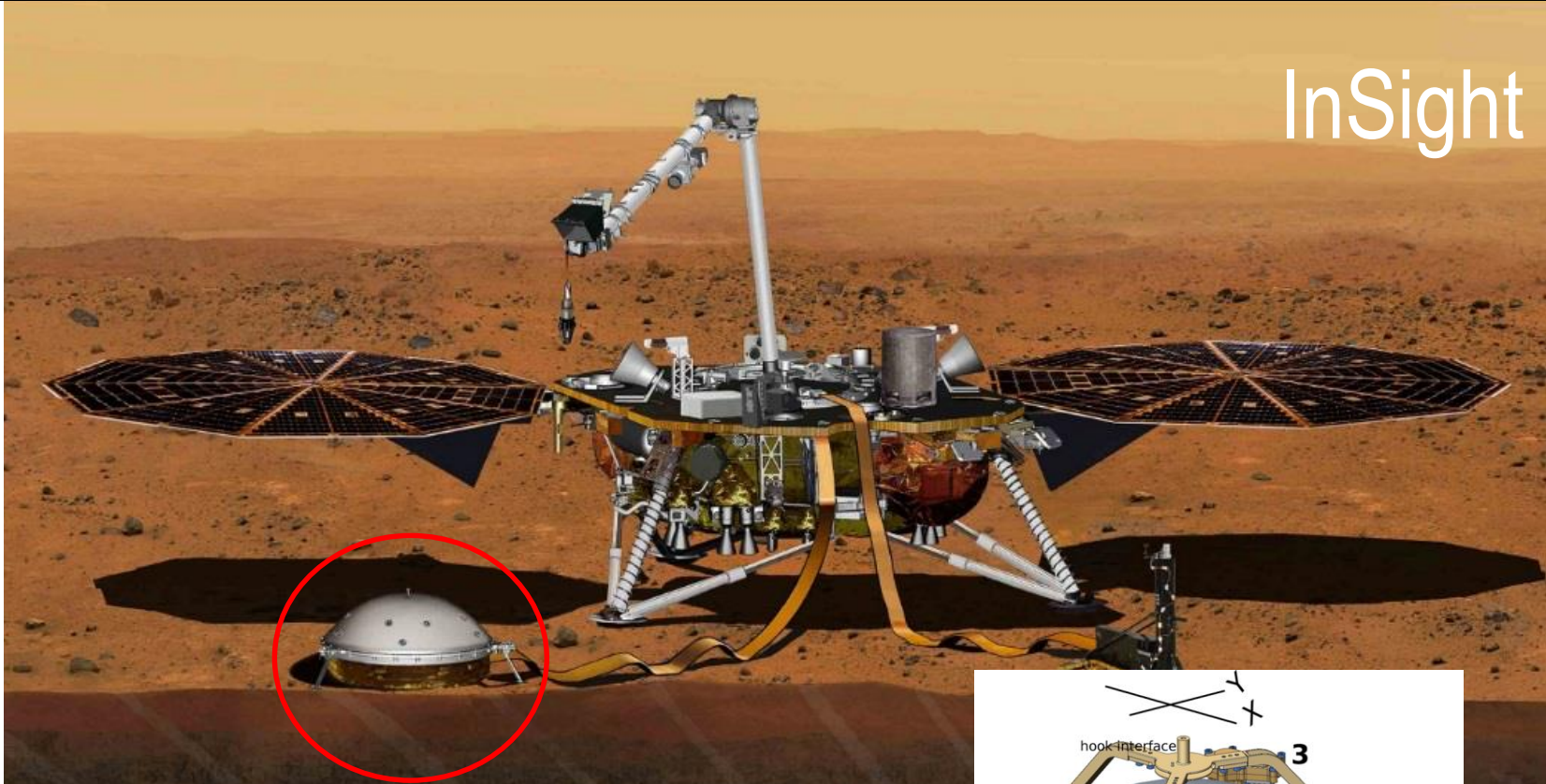
$E = 8 - 10 \text{ MPa}$ for $\rho = 1.3 \text{ Mg/m}^3$
and $V_p = 85 - 100 \text{ m/s}$

Space Sci Rev
DOI 10.1007/s11214-017-0339-7



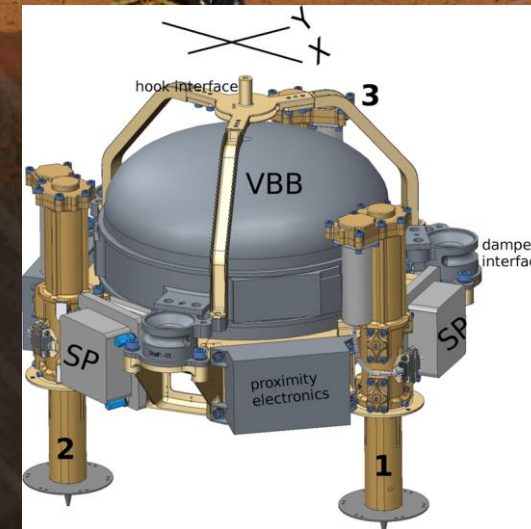
An Investigation of the Mechanical Properties of Some Martian Regolith Simulants with Respect to the Surface Properties at the InSight Mission Landing Site

Pierre Delage¹ · Foivos Karakostas² · Amine Dhemaied¹ · Malik Belmokhtar¹ · Philippe Lognonné² · Matt Golombek³ · Emmanuel De Laure¹ · Ken Hurst³ · Jean-Claude Dupla¹ · Sharon Keddar³ · Yu Jun Cui¹ · Bruce Banerdt³



InSight

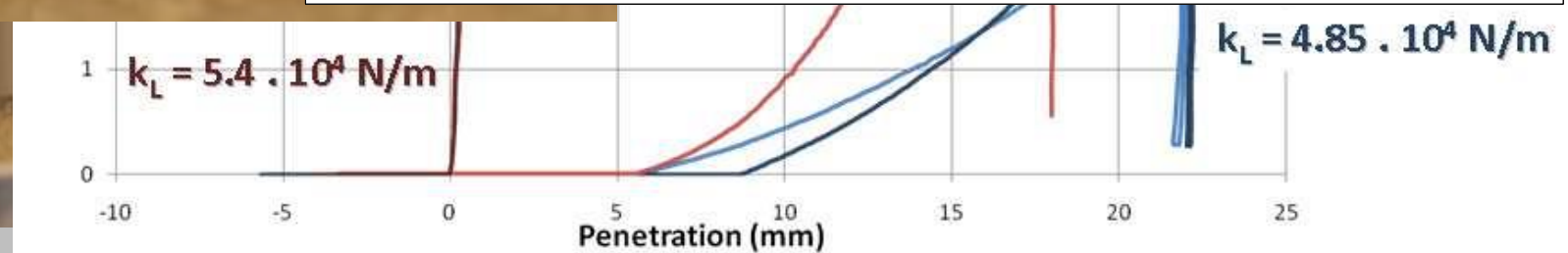
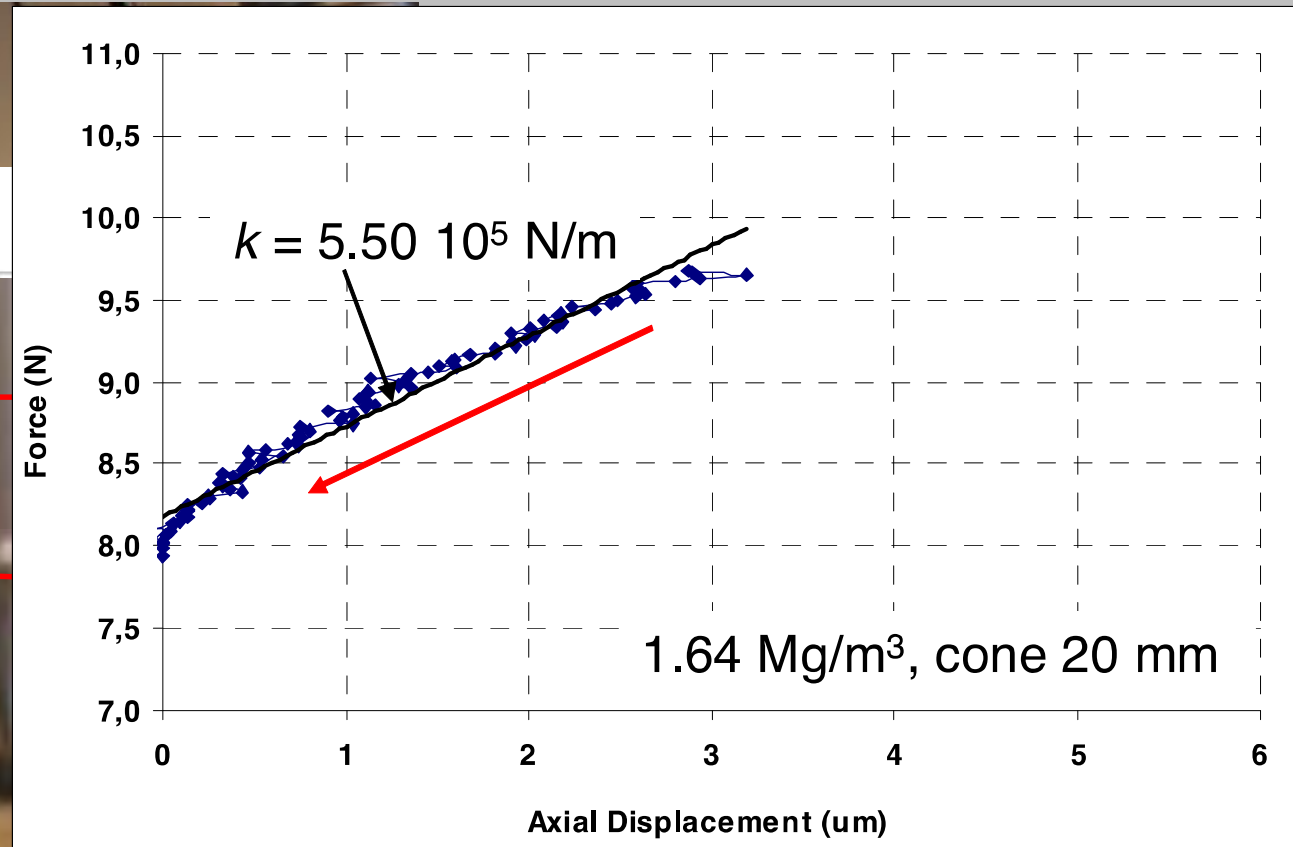
2. Seismometer/regolith interaction

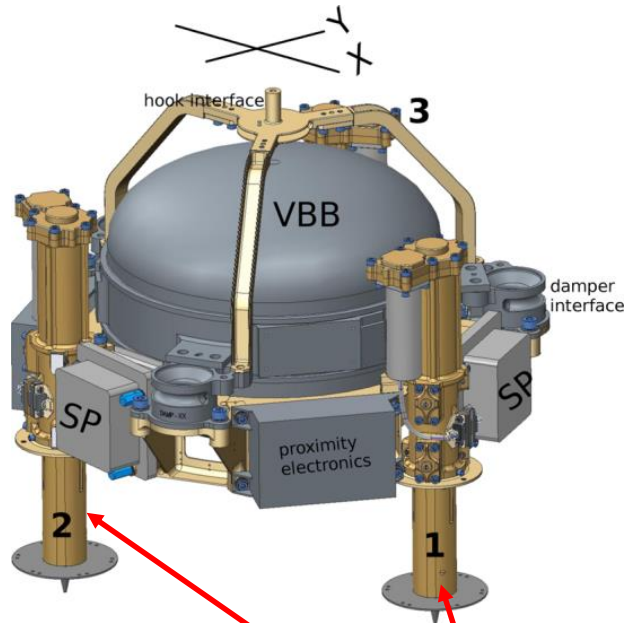


Final design of the SEIS foot



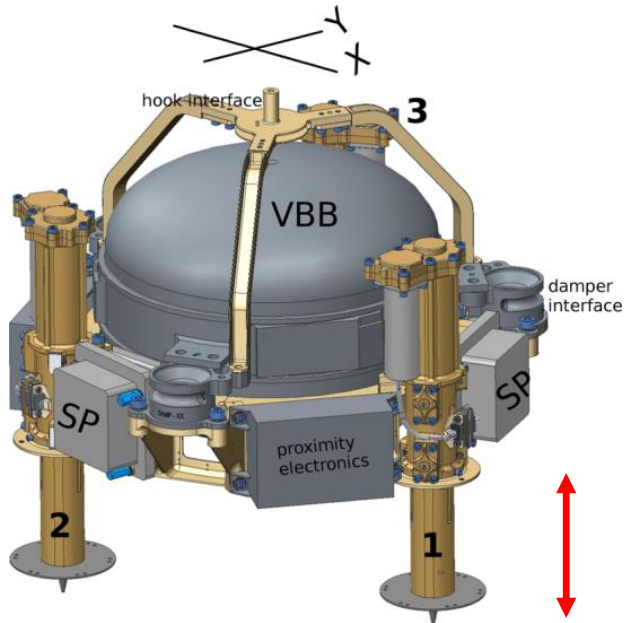
Mars Mojave Simulant (MMS)





Levelling system

- Axial elastic stiffness k_v^g (Boussinesq, Poul elastic circular plate of radius a



$$k_v^g = \frac{2E}{(1 - \nu^2)}$$

$$k_v^g = 0.55 \frac{E}{a}$$

$$E = 7,8 \text{ MPa}$$

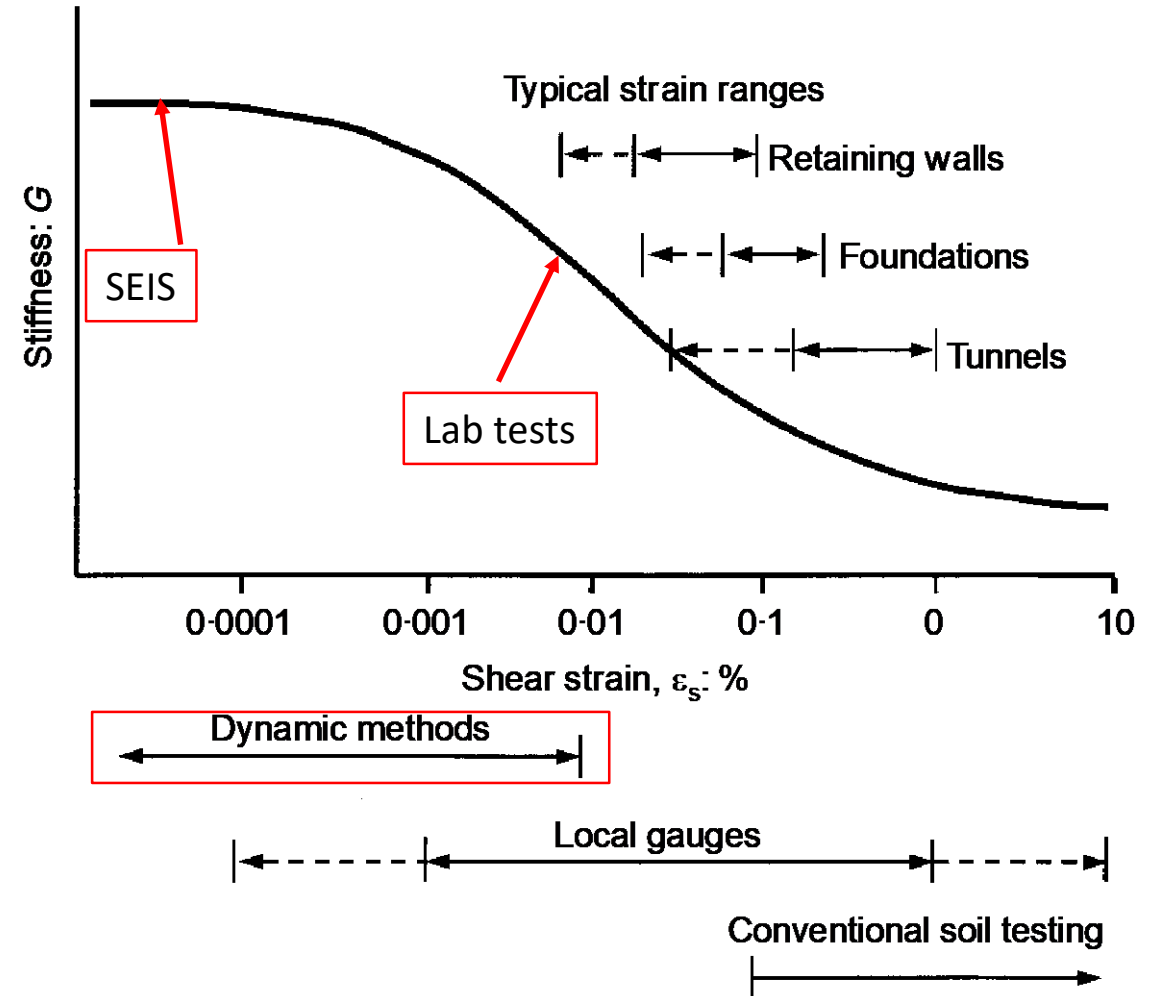
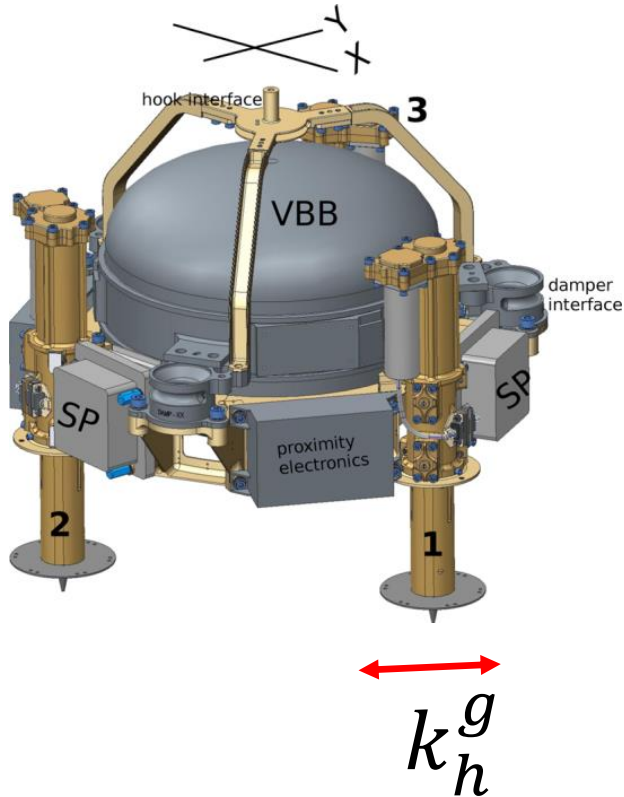


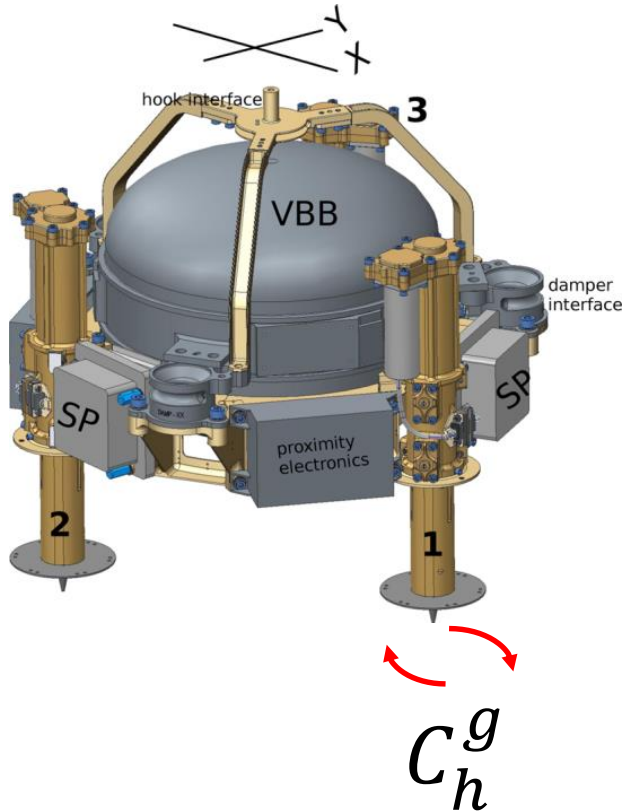
Fig. 1. Characteristic stiffness±strain behaviour of soil with typical strain ranges for laboratory tests and structures (after Atkinson & Sallfors, 1991 and Mair 1993)

- Lateral elastic stiffness k_h^g (Boussinesq, Poulos and Davis 1974), elastic circular plate of radius a



$$k_h^g = \frac{16(1 - \nu)Ea}{(7 - 8\nu)(1 + \nu)}$$

- Torque C_h^g (Boussinesq, Poulos and Davis 1974),
elastic circular plate of radius a



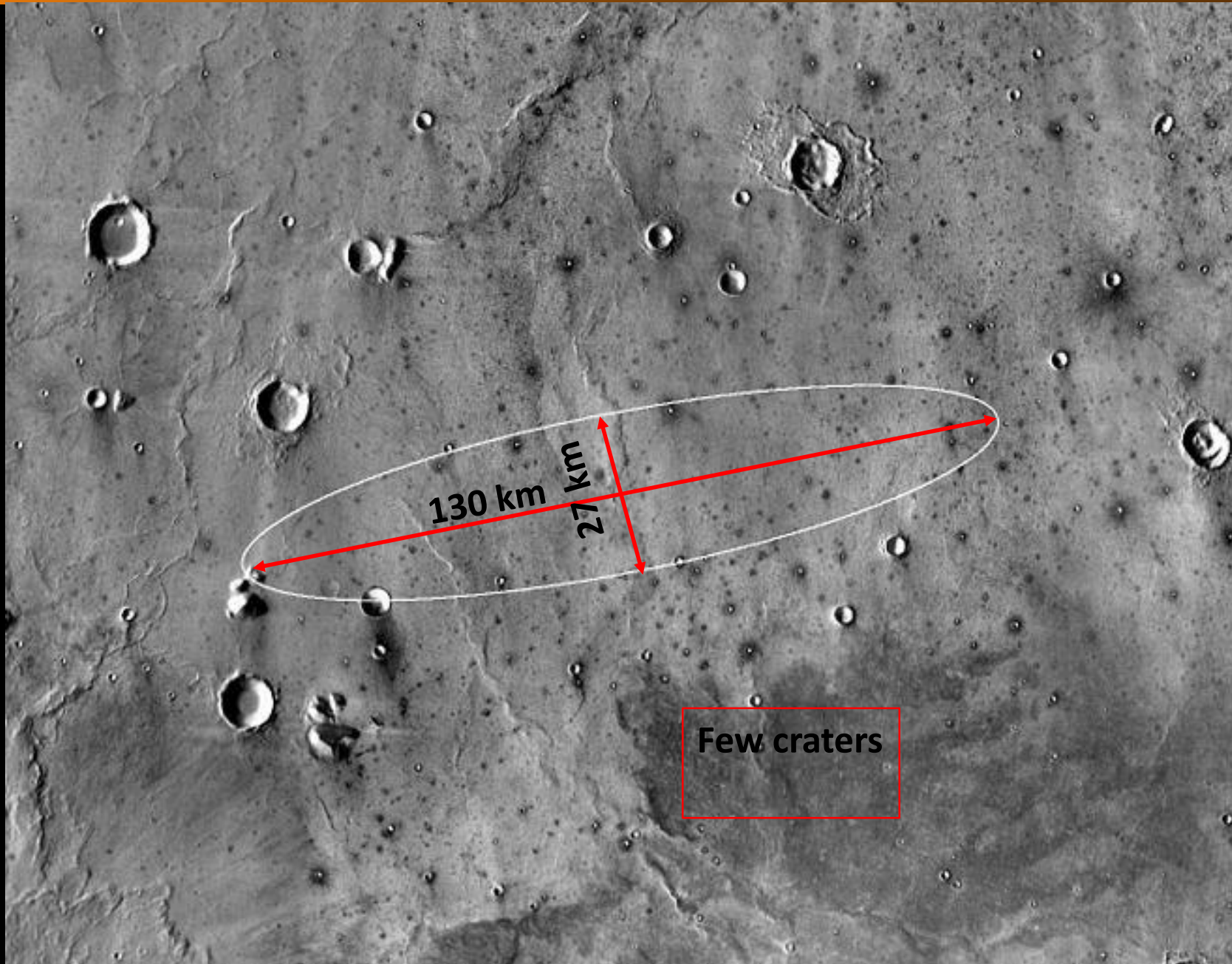
$$C_h^g = \frac{4Ea^3}{3(1 - \nu^2)}$$

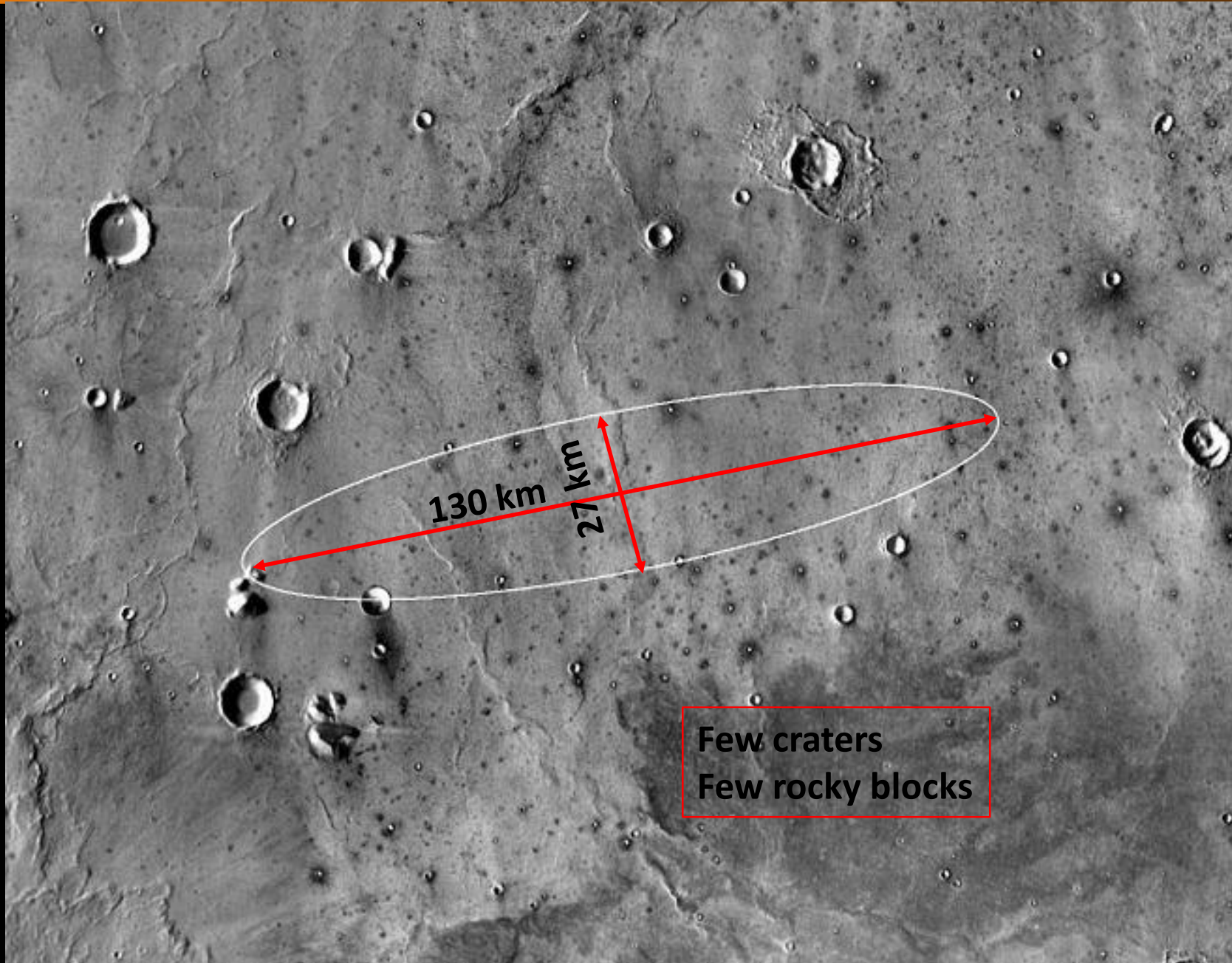
Space Sci Rev (2018) 214:119
<https://doi.org/10.1007/s11214-018-0555-9>



A Numerical Model of the SEIS Leveling System Transfer Matrix and Resonances: Application to SEIS Rotational Seismology and Dynamic Ground Interaction

**Lucile Fayon¹ · Brigitte Knapmeyer-Endrun² · Philippe Lognonné¹ ·
Marco Bierwirth³ · Aron Kramer³ · Pierre Delage⁴ · Foivos Karakostas¹ ·
Sharon Kedar⁵ · Naomi Murdoch⁶ · Raphael F. Garcia⁶ · Nicolas Verdier⁷ ·
Sylvain Tillier¹ · William T. Pike⁸ · Ken Hurst⁵ · Cédric Schmelzbach⁹ ·
William B. Banerdt⁵**





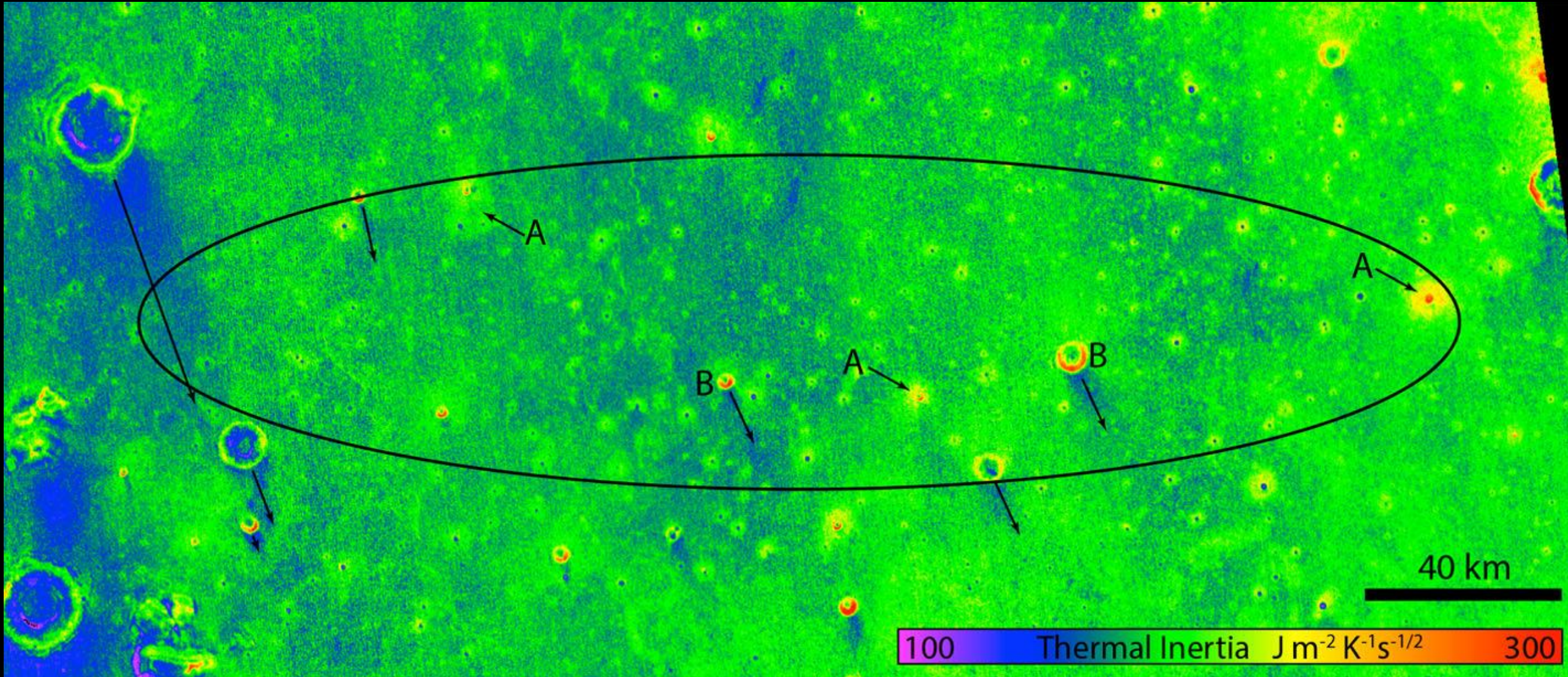
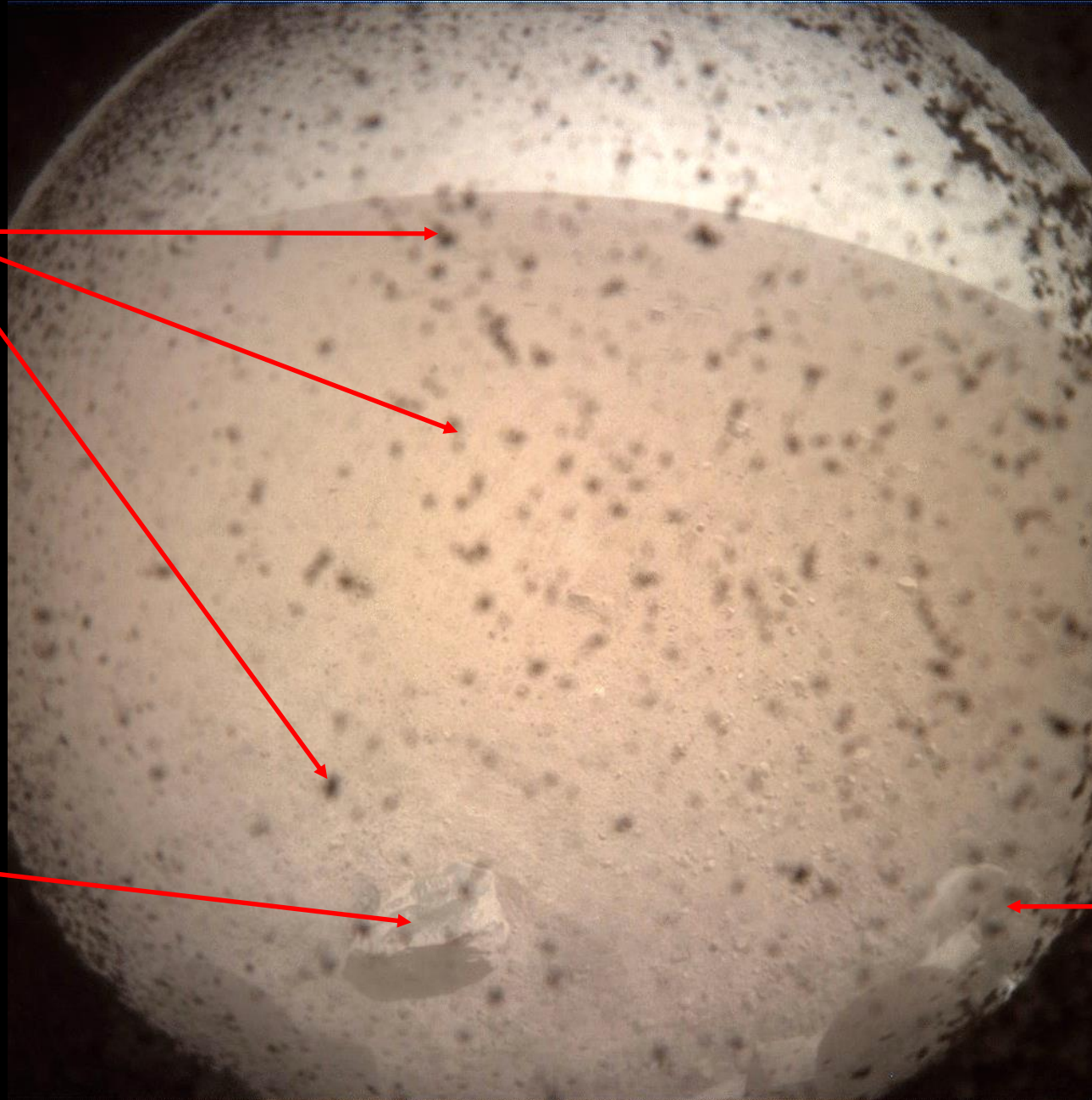


Table 1 Characteristics of some Martian surface materials (Golombek et al. 2008, Chap. 20)

Surface material	Bulk density (Mg/m ³)	Grain size (mm)	Cohesion (kPa)	Friction angle (°)	Thermal inertia (J m ⁻² K ⁻¹ s ^{-1/2})
Drift	1–1.3	0.001–0.01	0–3	15–21	40–125
Sand	1.1–1.3	0.170 micron	–1	30	180 J m ⁻² K ⁻¹ s ^{1/2}
Crusty to cloddy sand	1.1–1.6	0.005–0.5	0–4	30–40	200–326
Blocky, indurated soil	1.2–2	0.05–3	3–11	25–33	368–410
Dense float rock, volcanic	2.6–2.8	2–2000	1000–10000	40–60	> 1200–2500
Clastic rock, Columbia Hills	2				620–1100
Sulfate rock, Meridiani	< 2				> 400–1100

Data derived from Moore et al. (1987, 1999), Moore and Jakosky (1989), Christensen and Moore (1992), Arvidson et al. (2004a, 2004b), Christensen et al. (2004a, 2004b), Herkenhoff et al. (2004a, 2004b), Fergason et al. (2006a) and Chap. 20 from Bell.

What happened on the landing site on 28 November 2019?



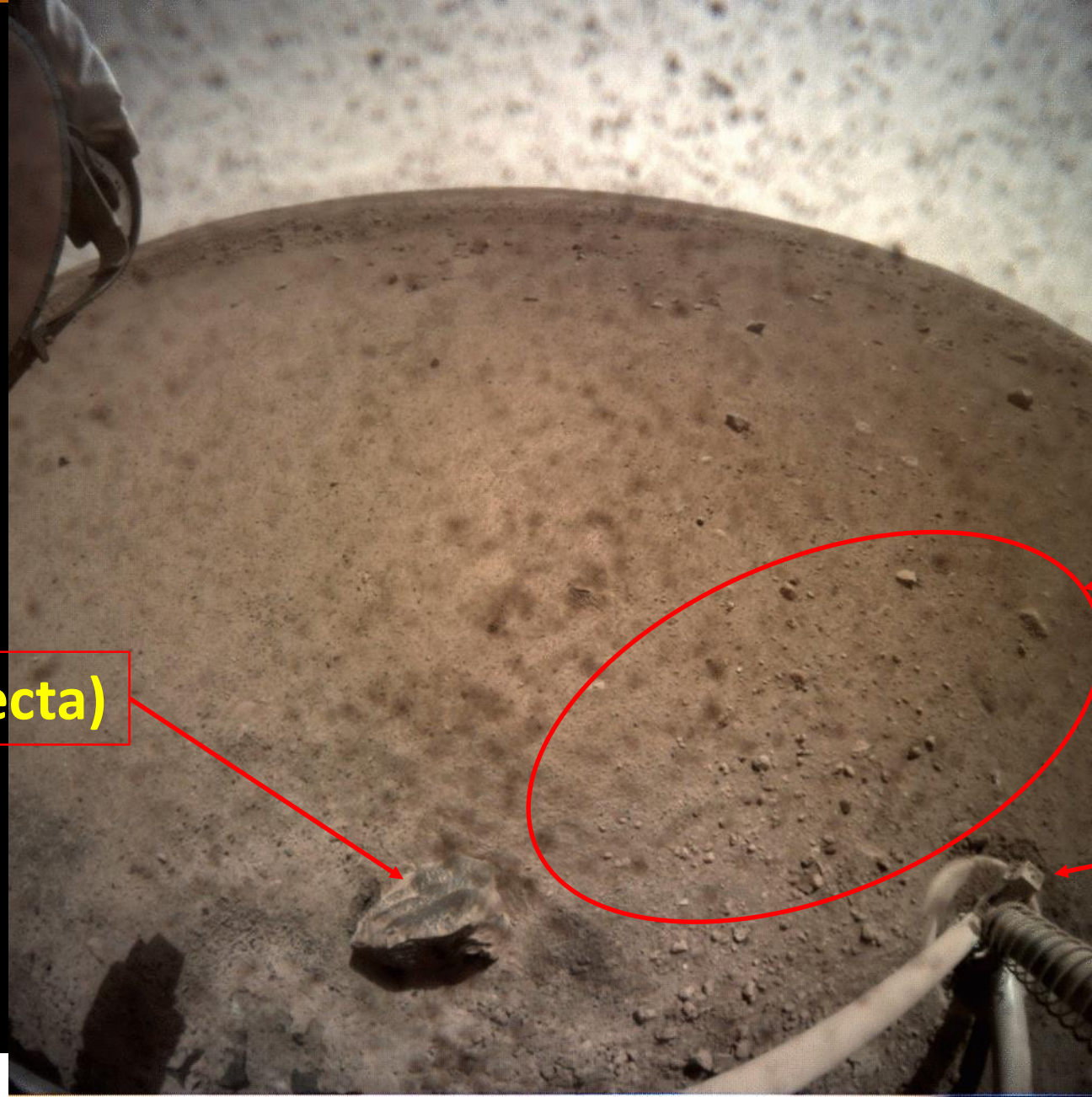
**Dust particles
on lens**

**1st Photo!
Instrument
Context Camera**

**Flat area
Few blocks
(good)**

Rock

Lander foot



Angular rock (ejecta)

Pebbles

Buried lander foot

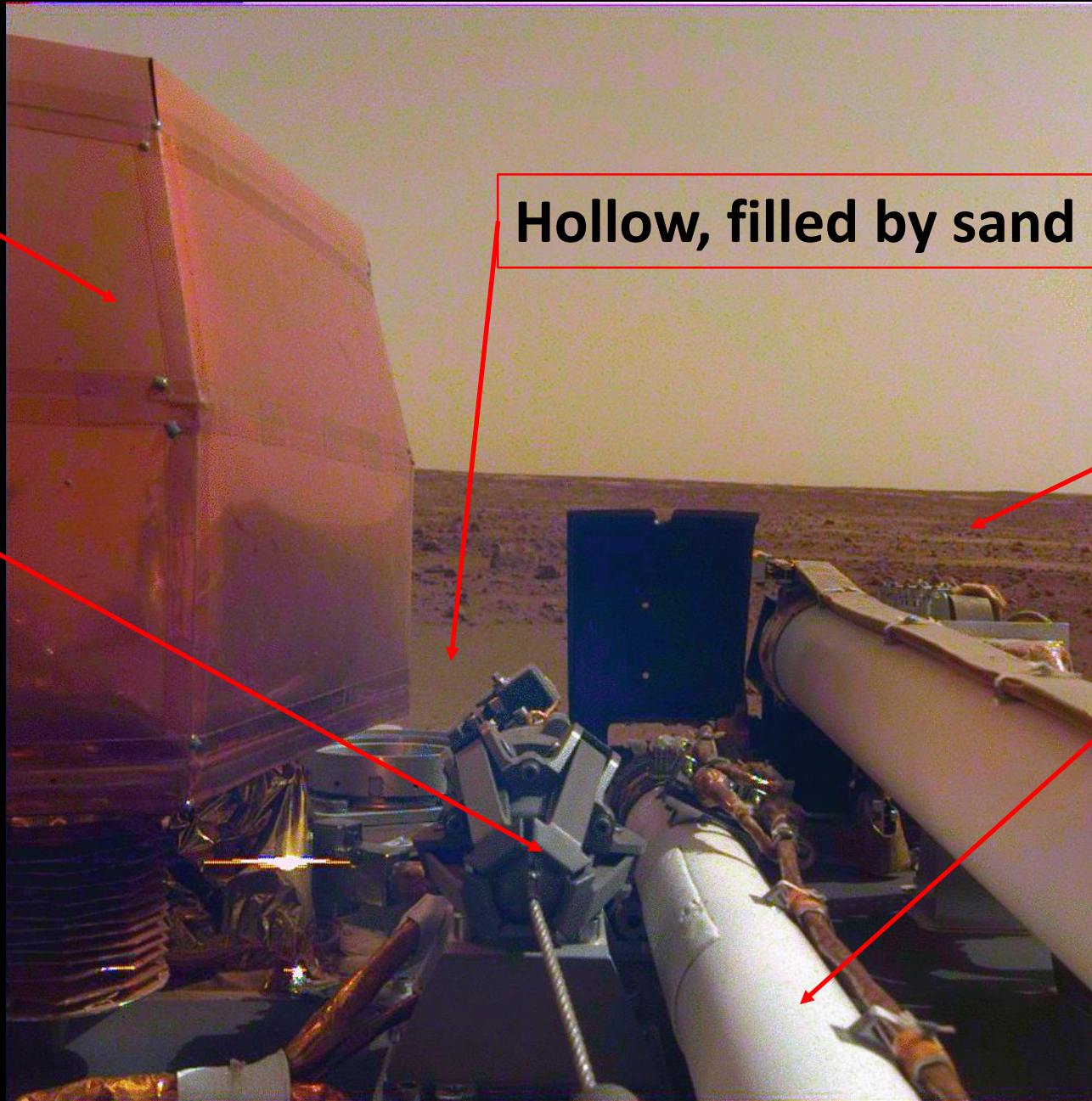
SEIS

Hollow, filled by sand

**Flat ground,
as expected,
few blocks**

IDA (Arm)

Grasping system







Heat shield



InSight Lander



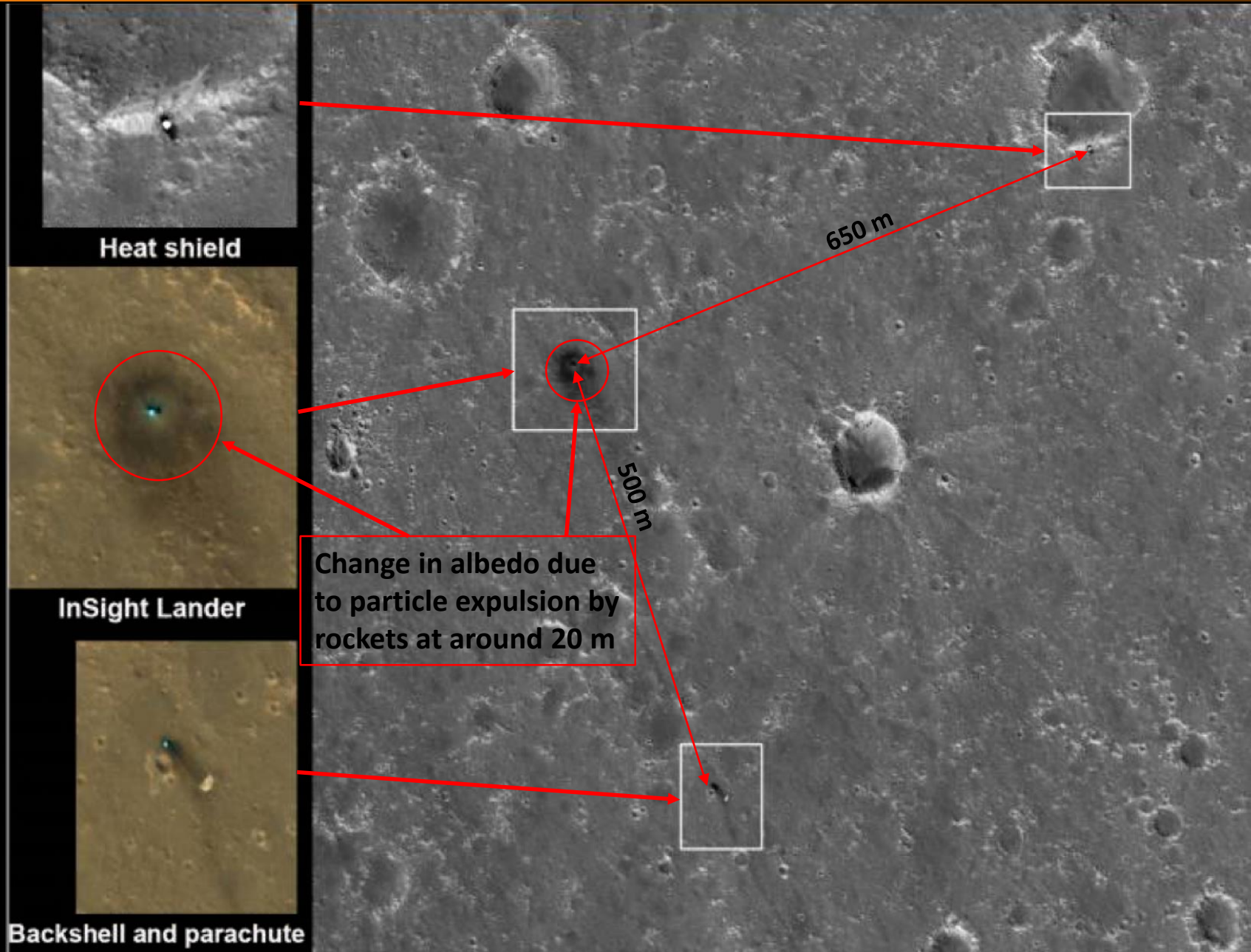
Heat shield



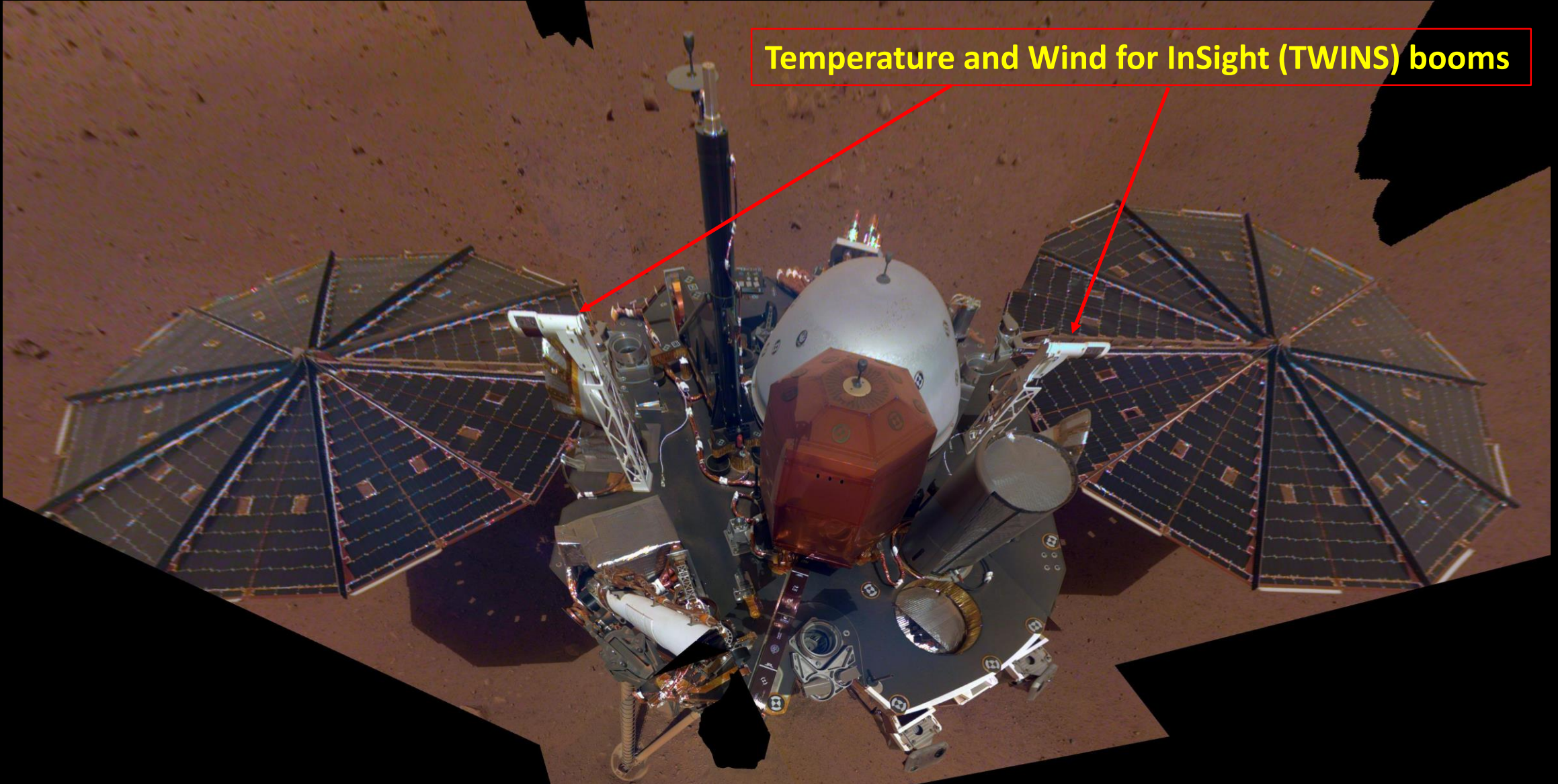
InSight Lander

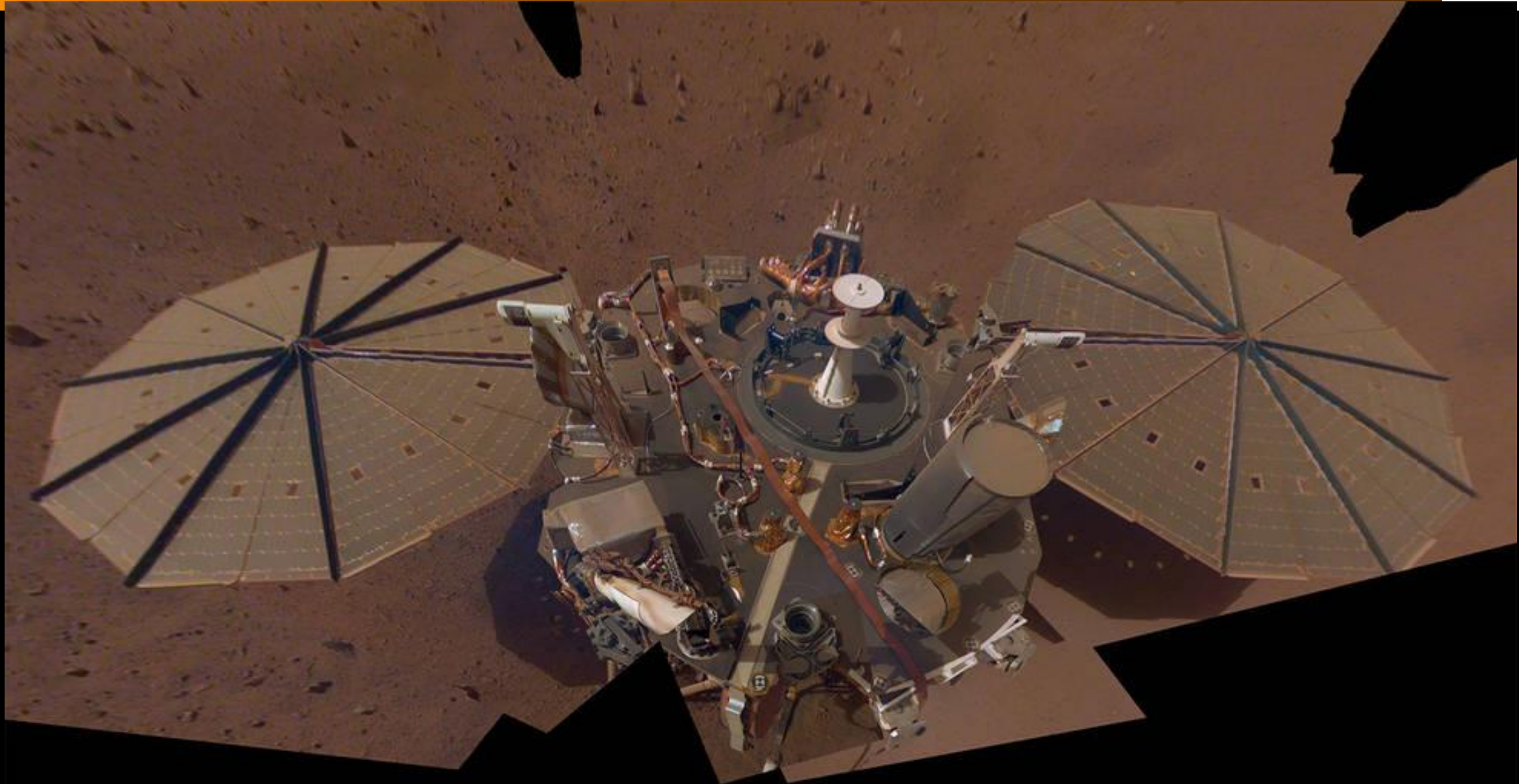


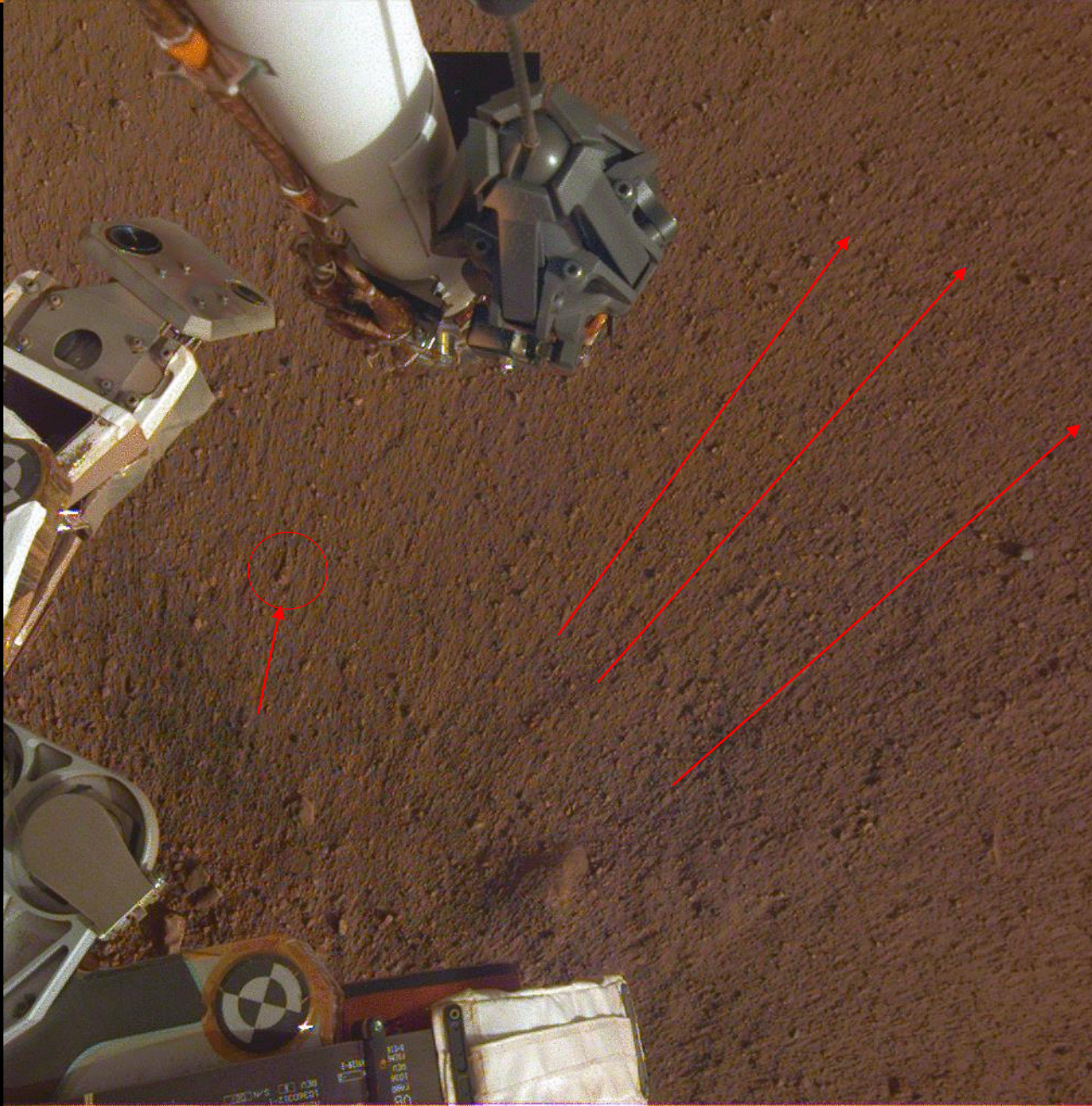
Backshell and parachute



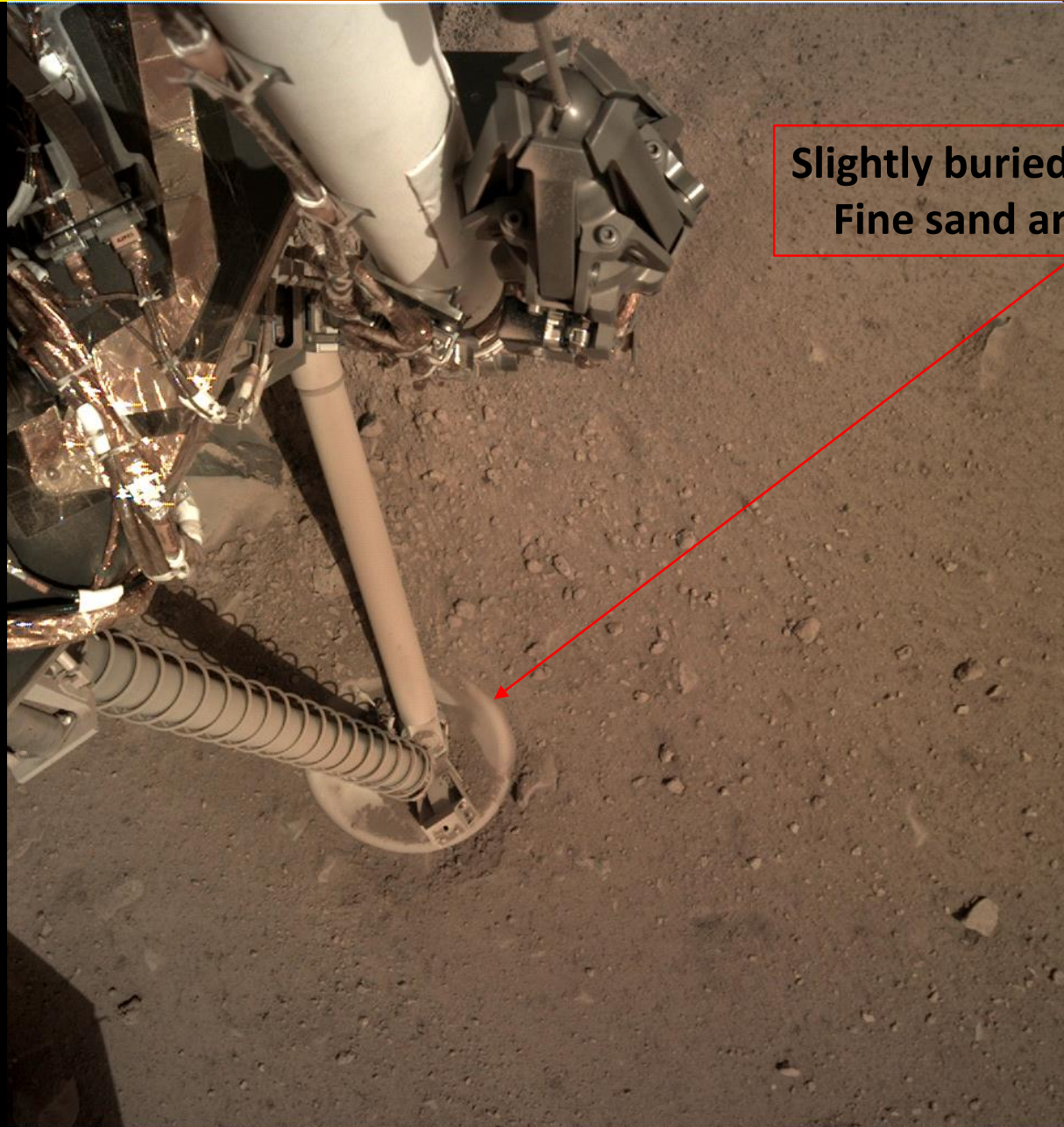
Temperature and Wind for InSight (TWINS) booms



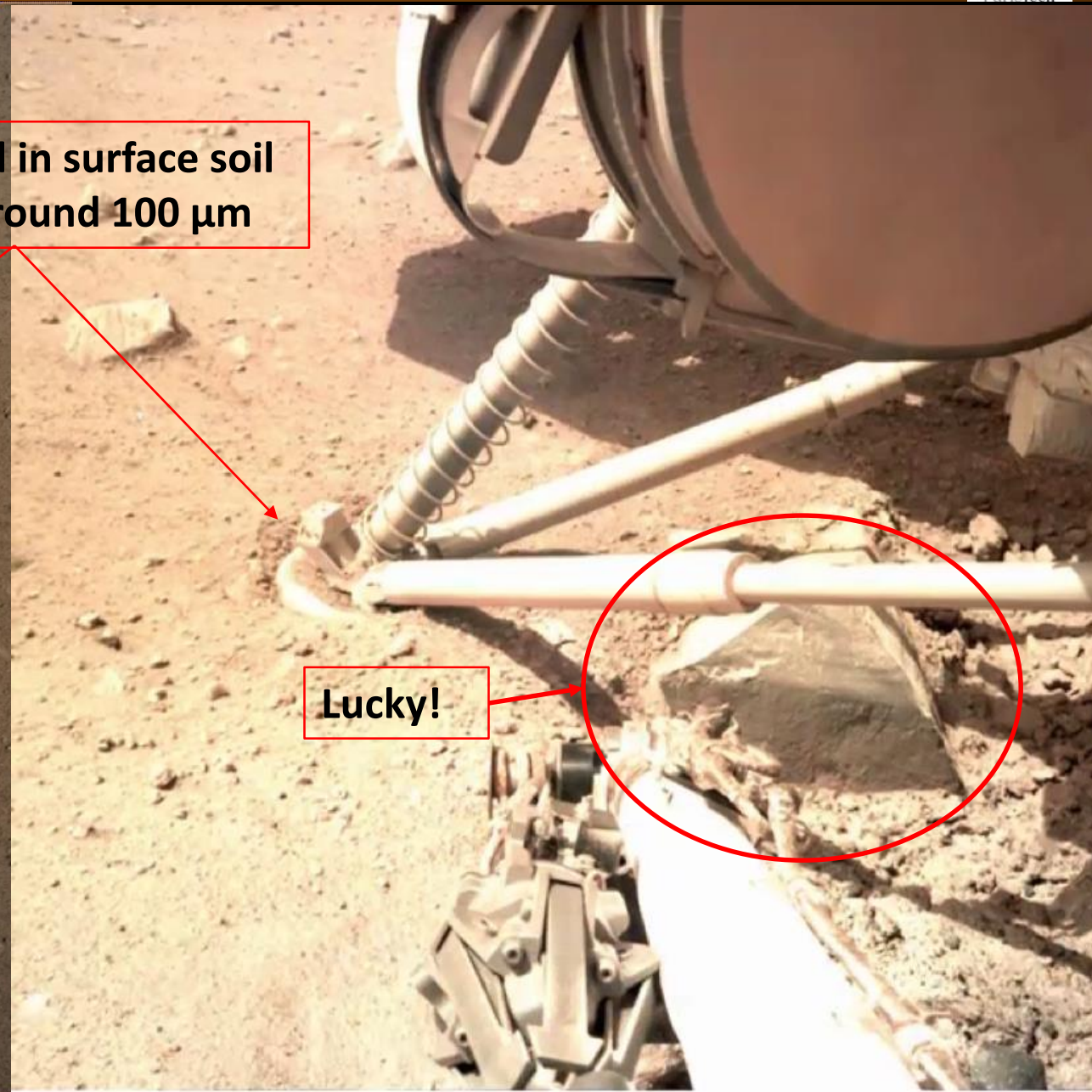




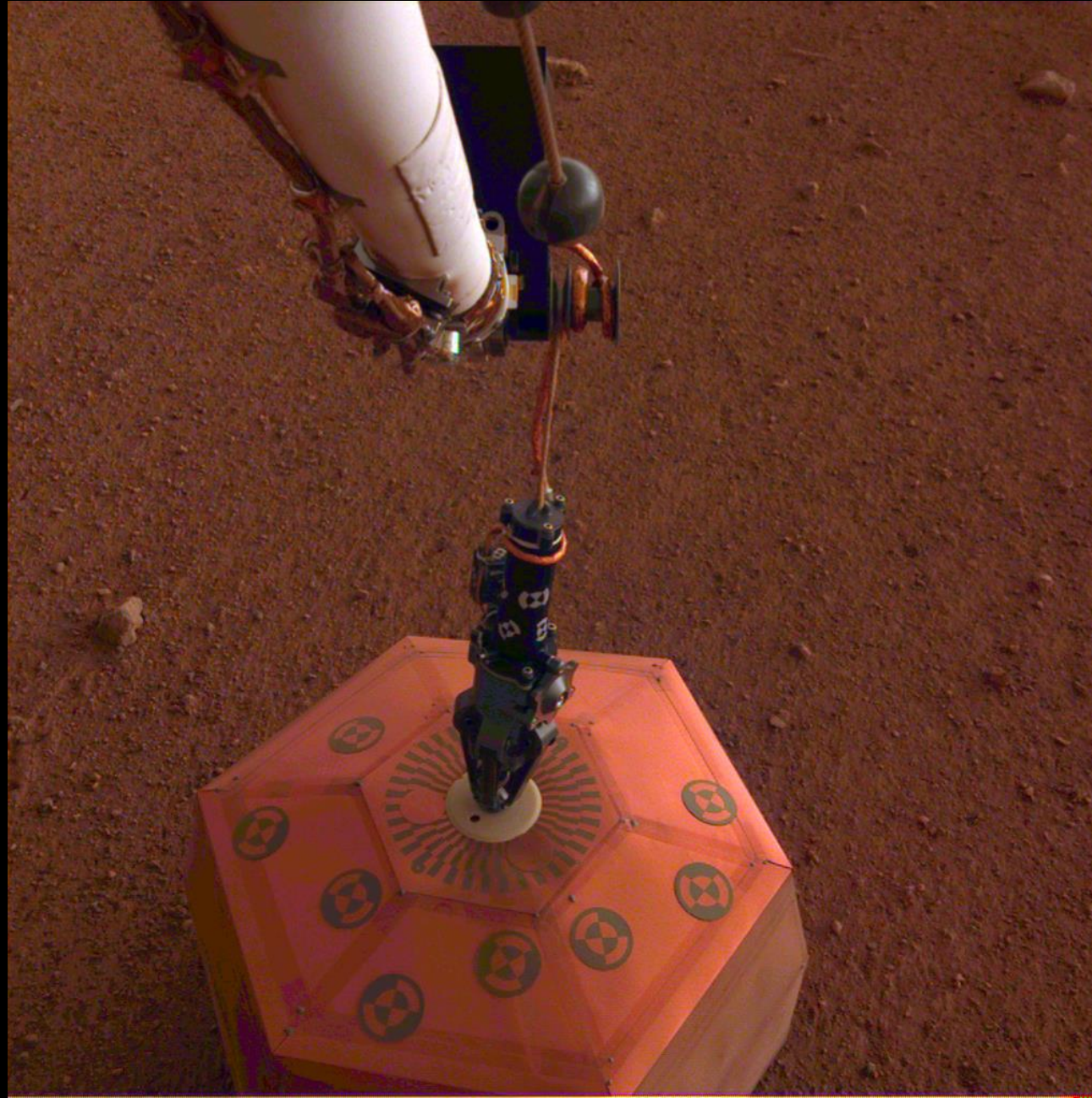
**Local confirmation by RAD
radiometer of Thermal Inertia:
170 - 180 TI units
Cohesionless fine grain sand 100 μm**

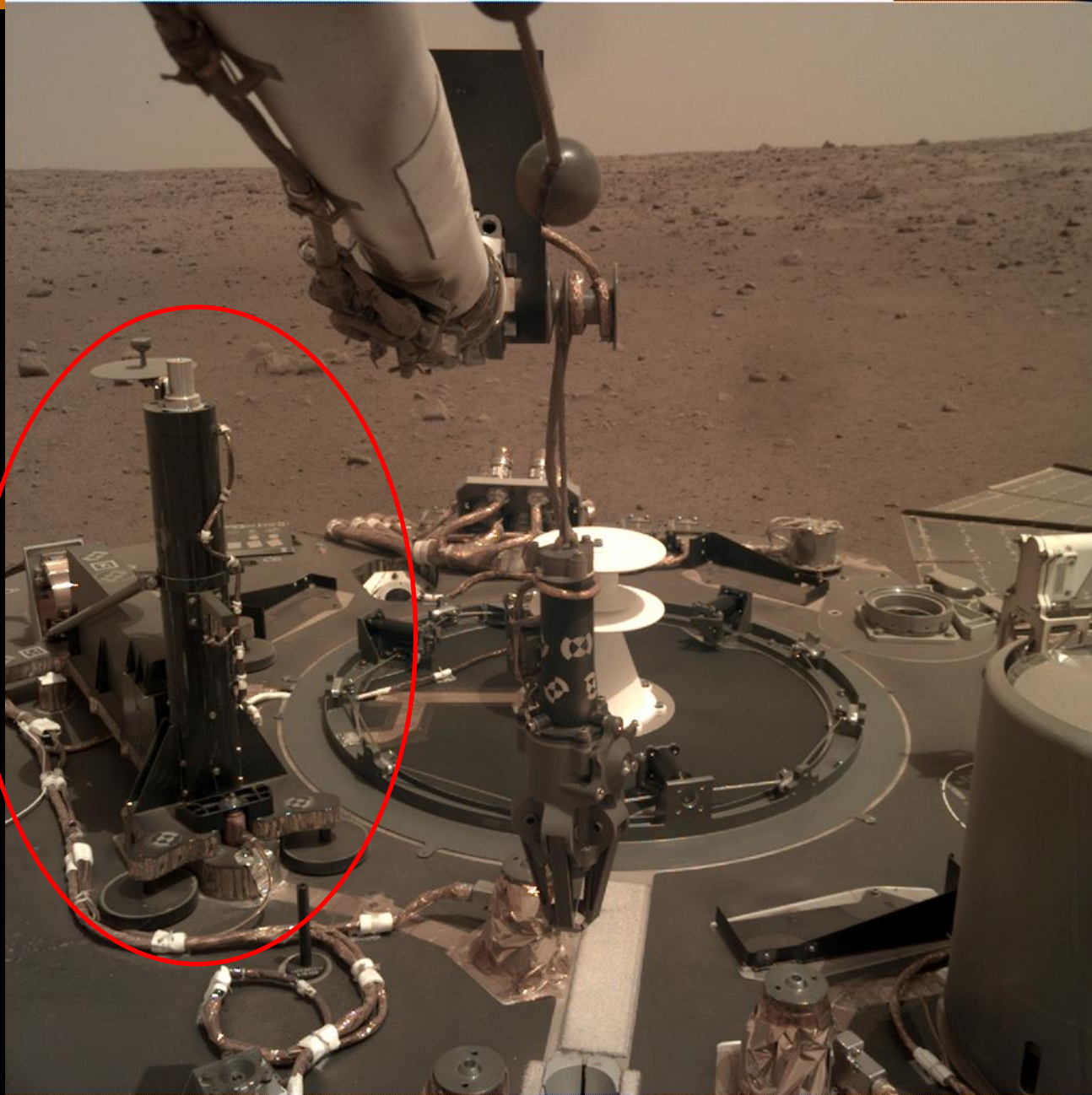


Slightly buried in surface soil
Fine sand around 100 μm

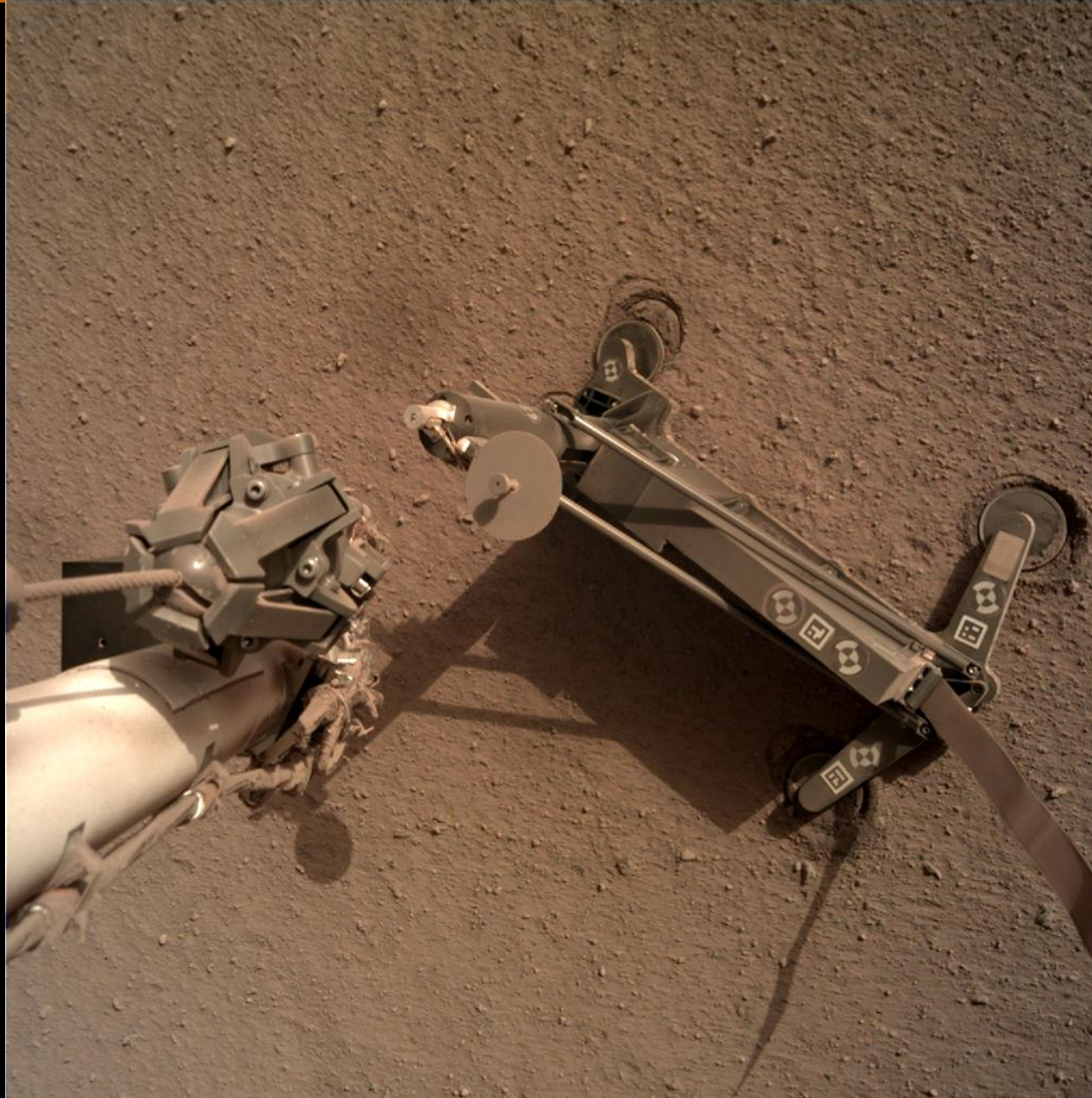


Lucky!





HP³





The image shows a close-up of a rover's mechanical arm and wheels on a sandy surface. The arm is metallic and has several circular components, including a large disc. The wheels are also visible, with some showing signs of wear. The ground is covered in fine, reddish-brown sand. Two red arrows point from a text box to specific areas on the ground: one points to a small, dark, circular mark, and the other points to a larger, more irregular mark. The text box contains the following text:

**Fine sandy surface particles
100 μm : TI 170 - 180**

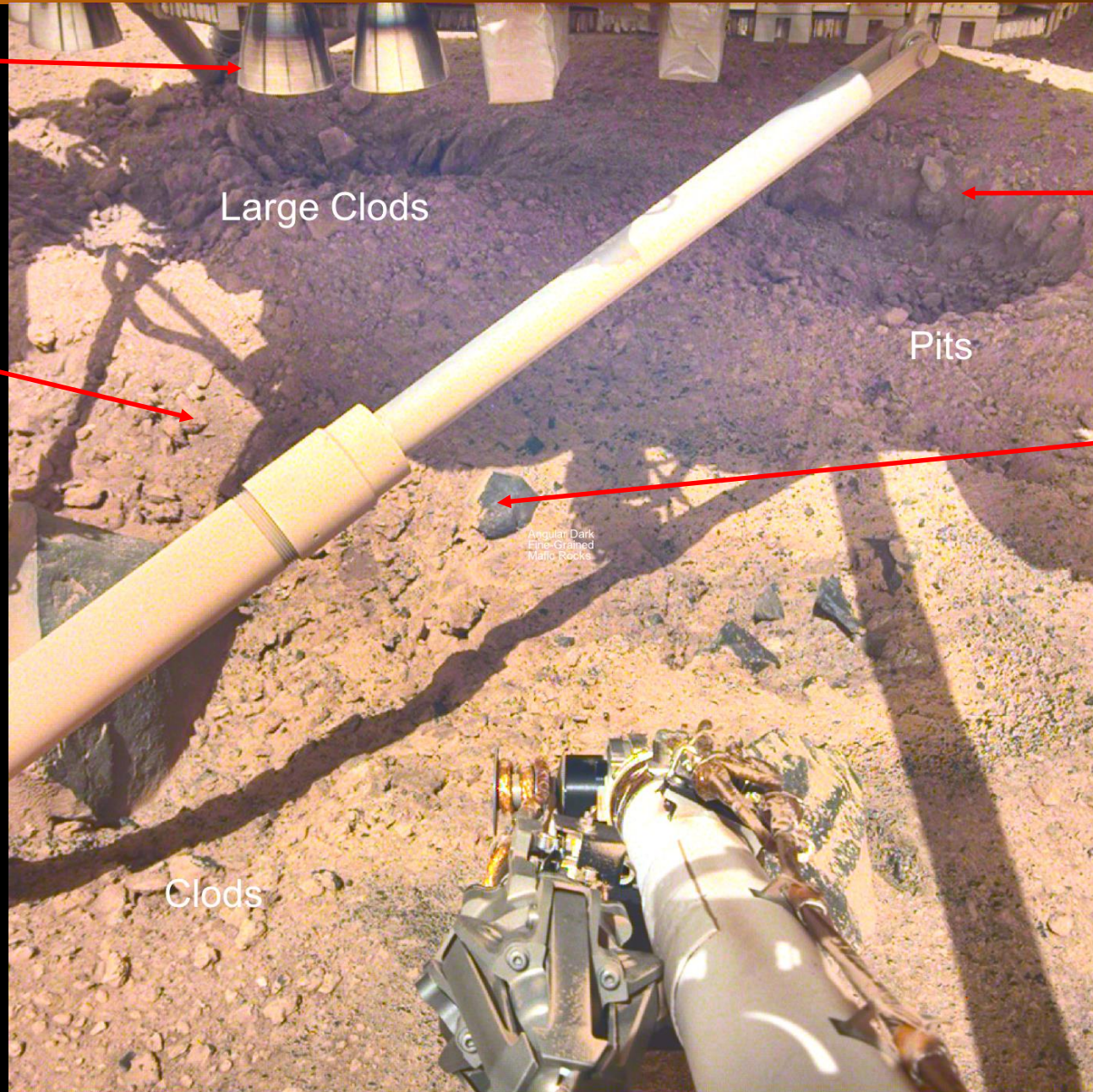


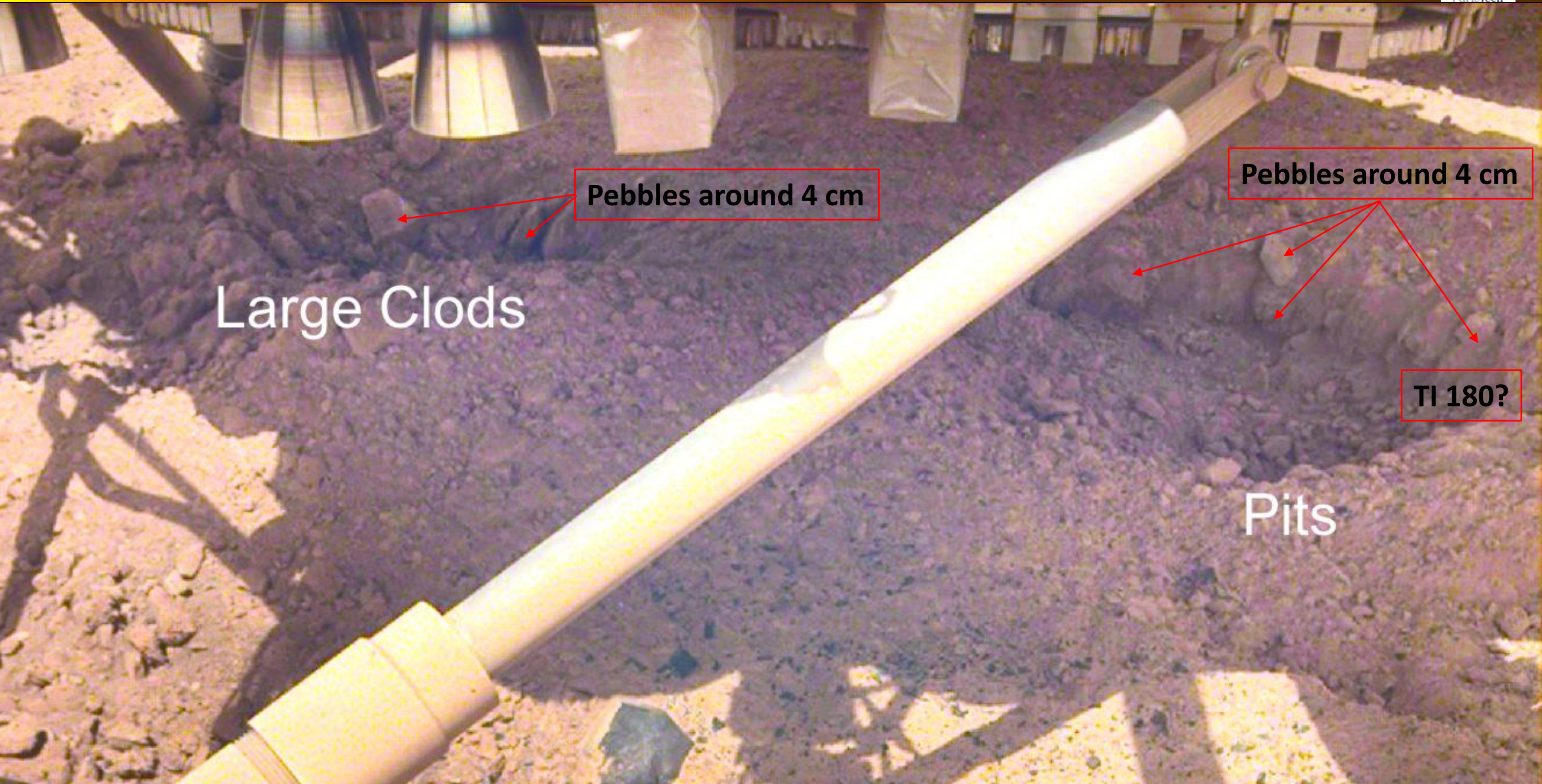
Rockets exhaust

Clods?

Cohesion?

**Angular pebbles
(basalt type)**





Pebbles around 4 cm

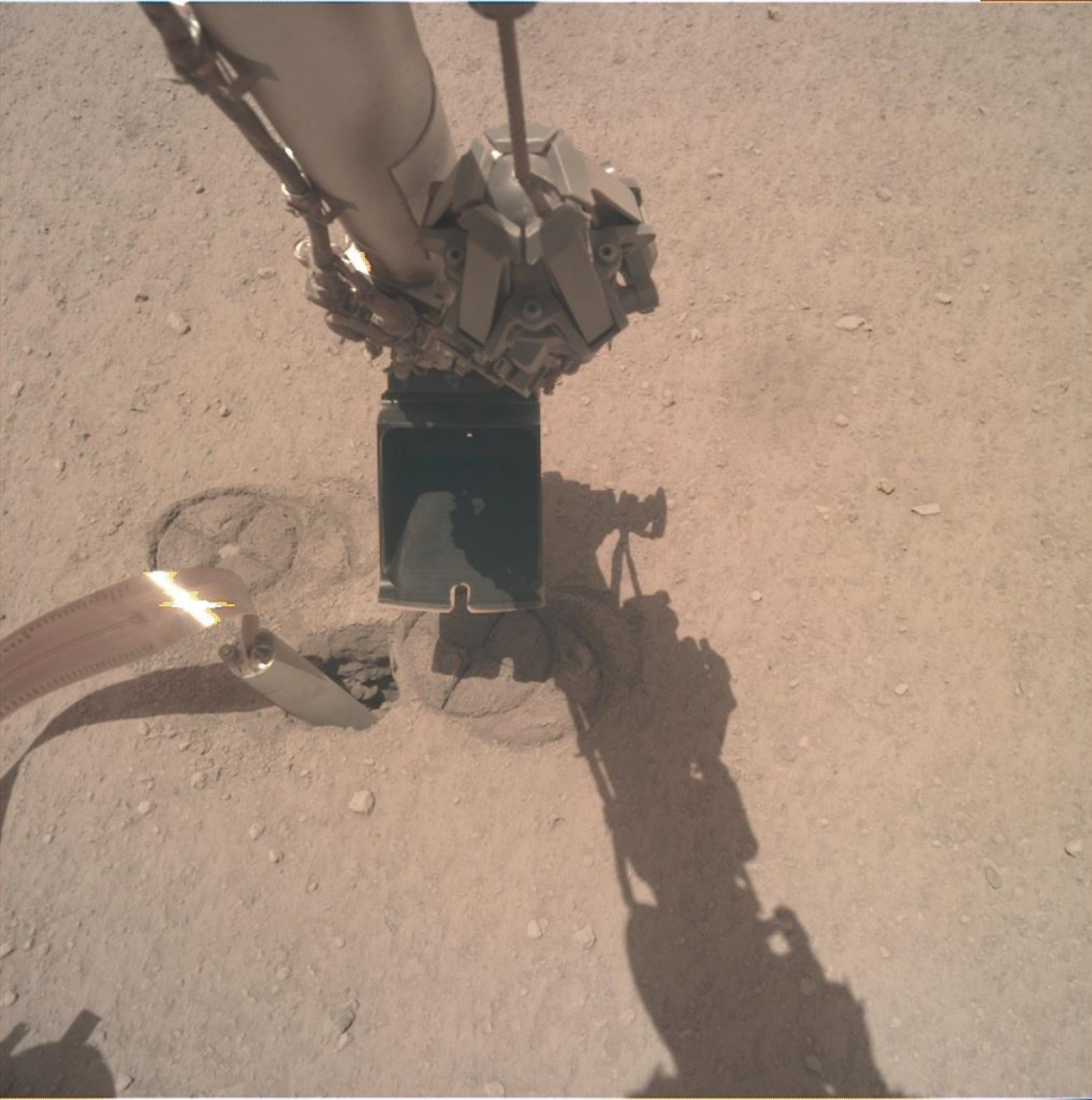
Large Clods

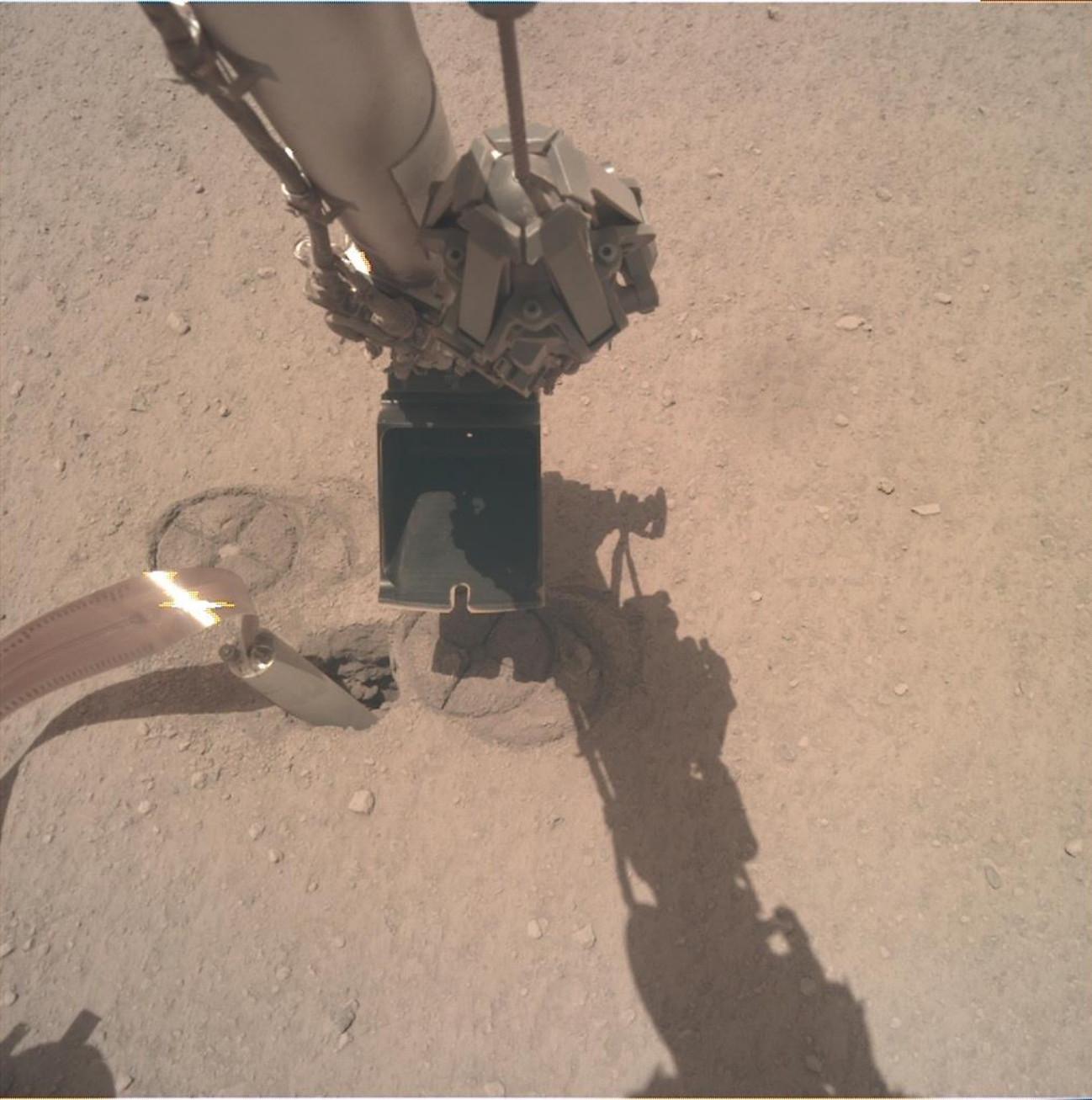
Pebbles around 4 cm

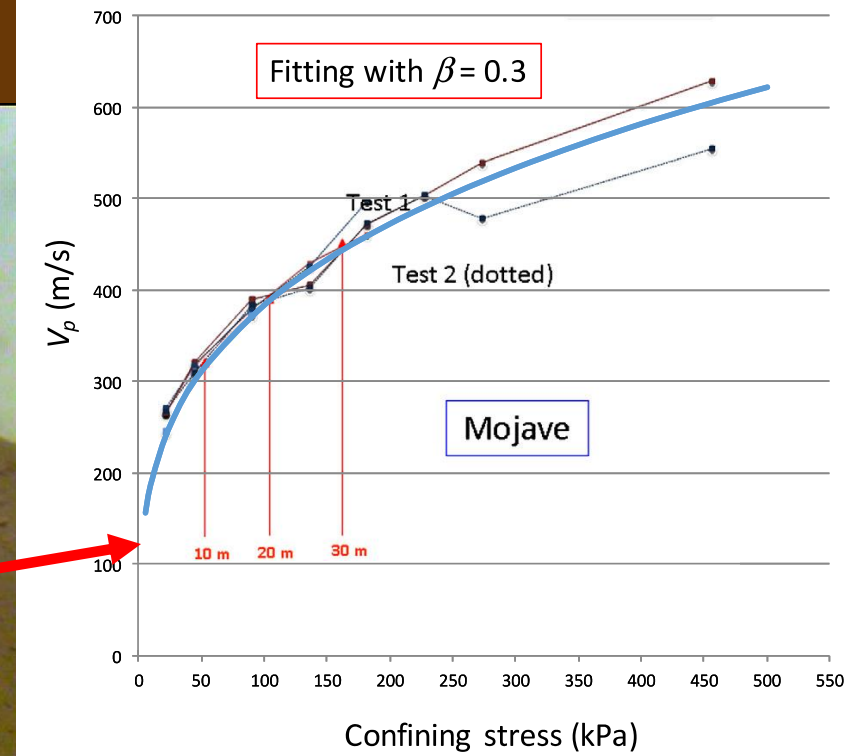
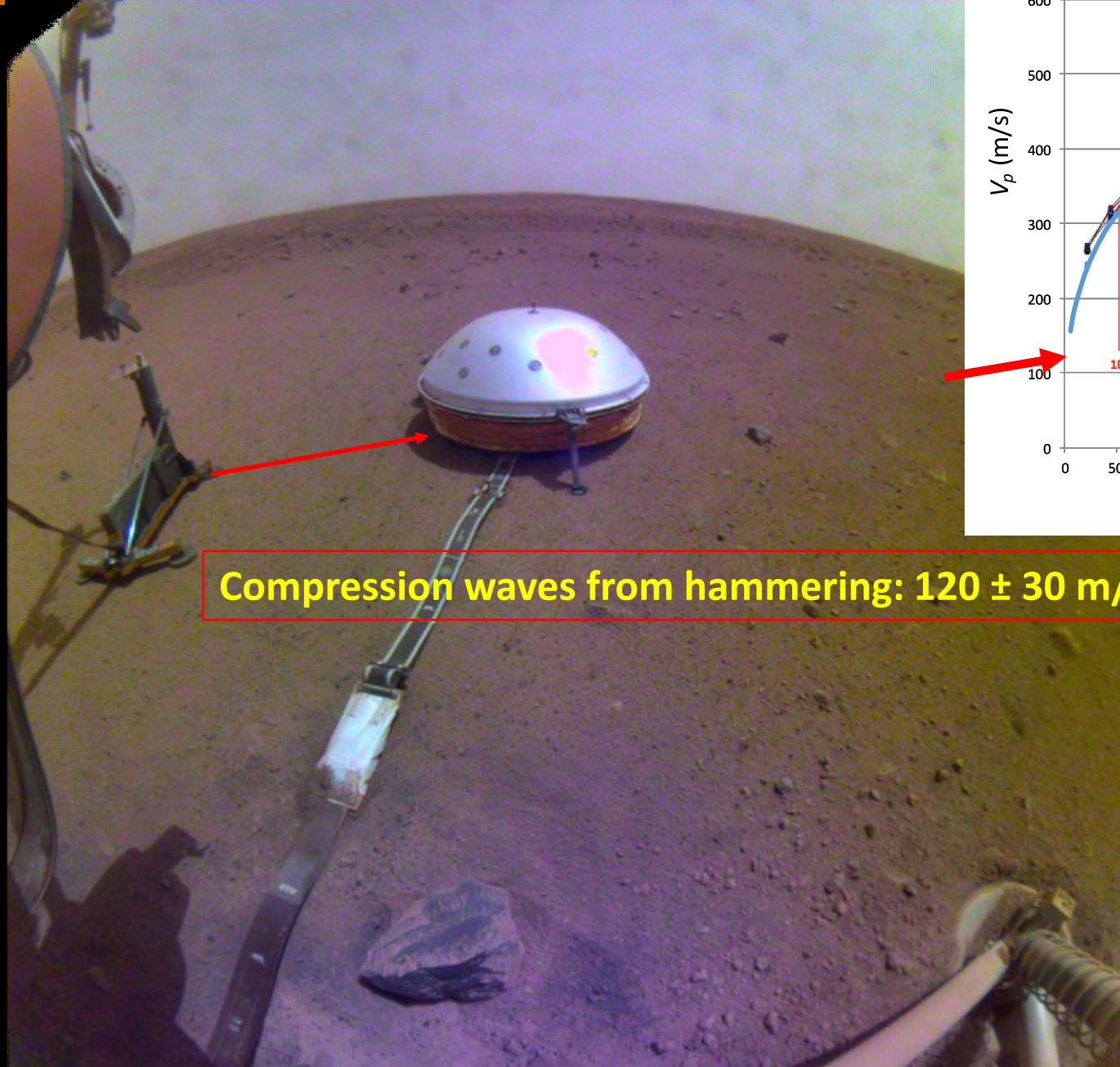
TI 180?

Pits

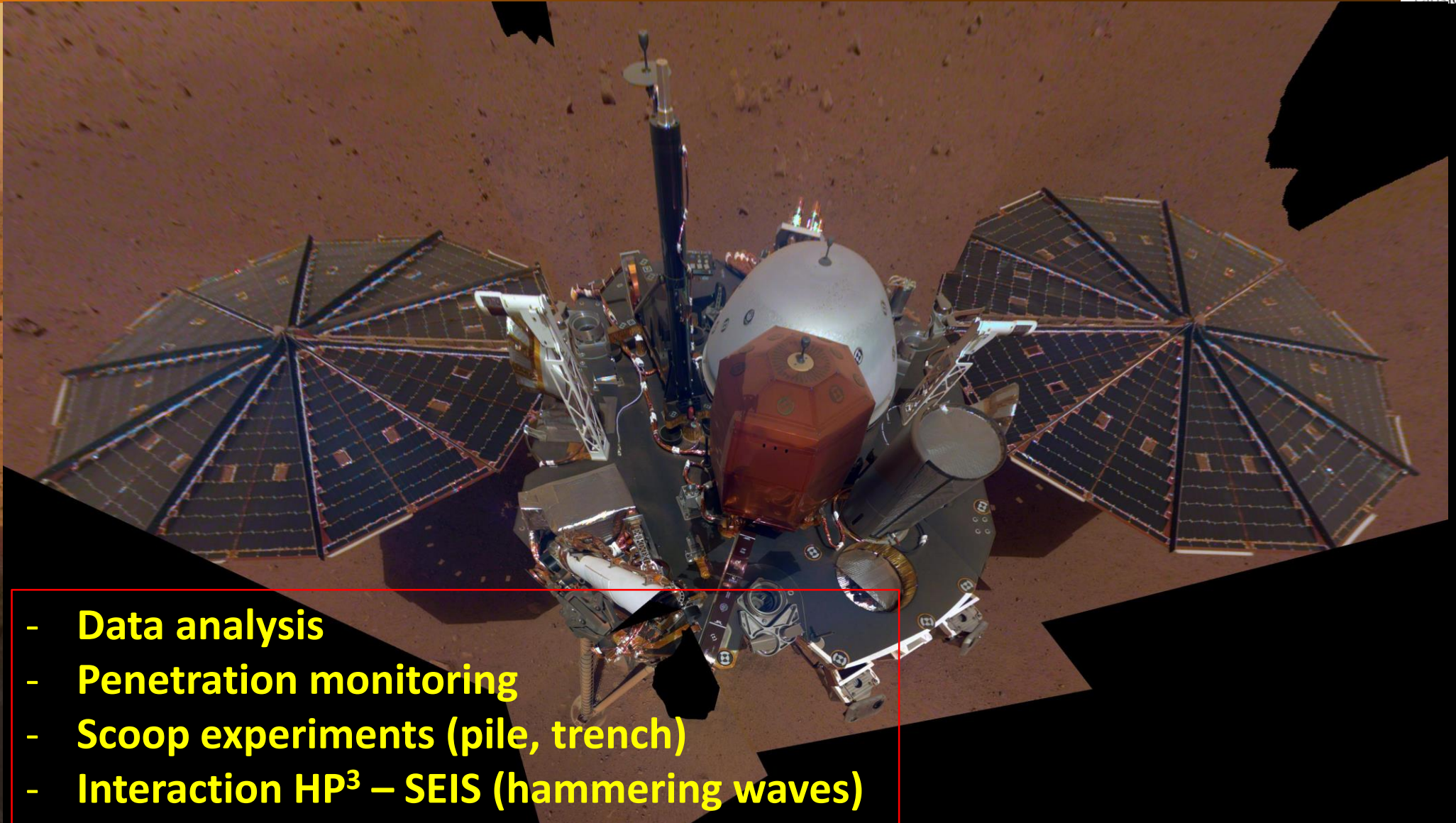
What about the mole penetration?





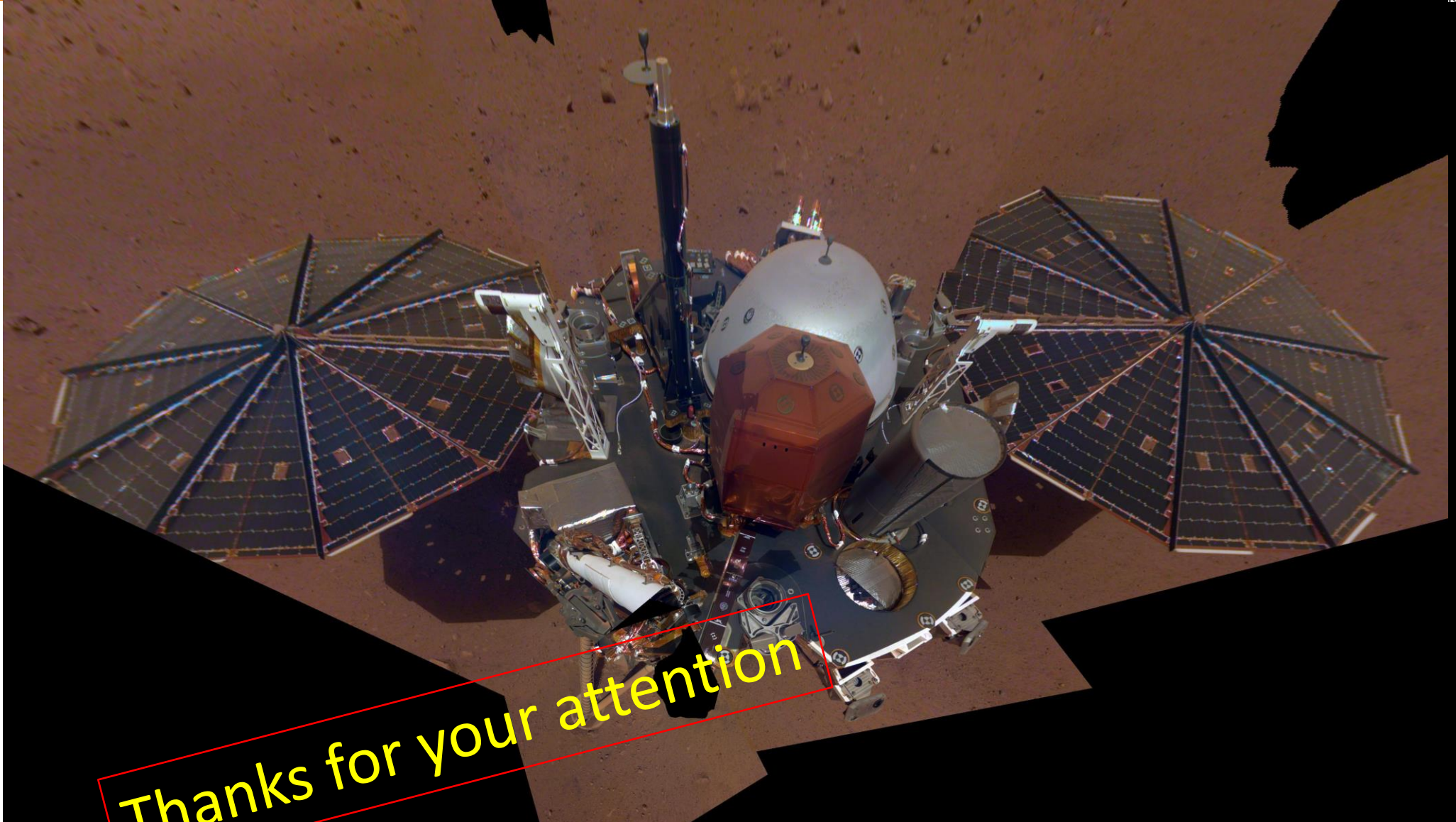


Compression waves from hammering: 120 ± 30 m/s



- Data analysis
- Penetration monitoring
- Scoop experiments (pile, trench)
- Interaction HP³ – SEIS (hammering waves)
- SEIS tilting experiment
- ...





Thanks for your attention