The secondary impact spike on Phobos from Stickney Crater ejecta

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Phobos Overview

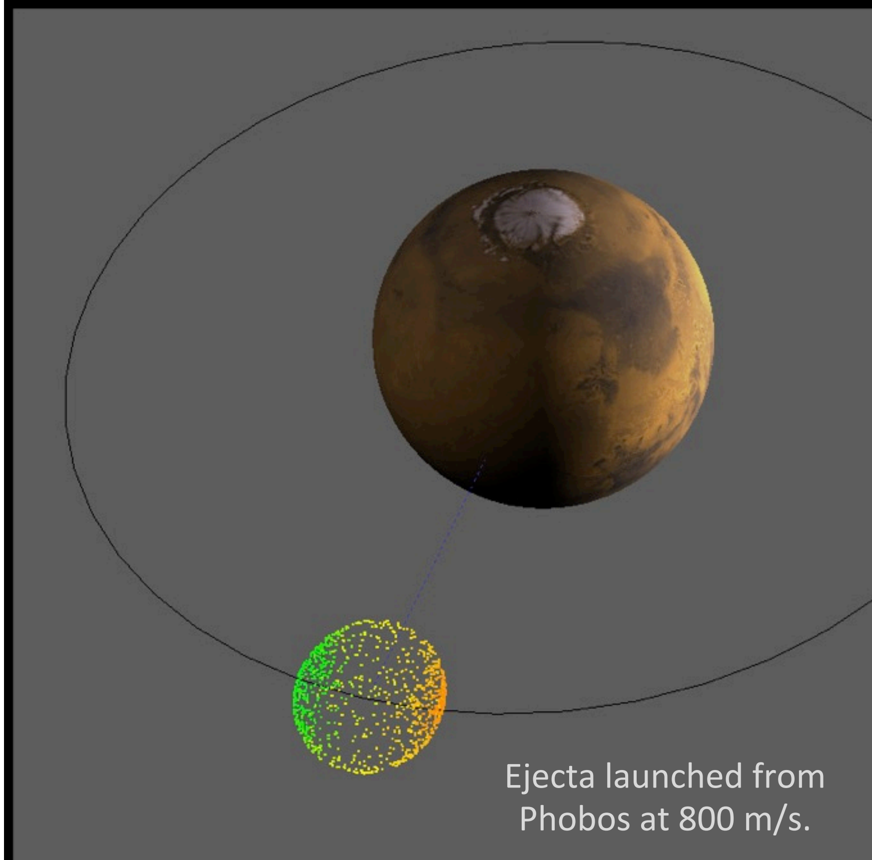
Notable Features

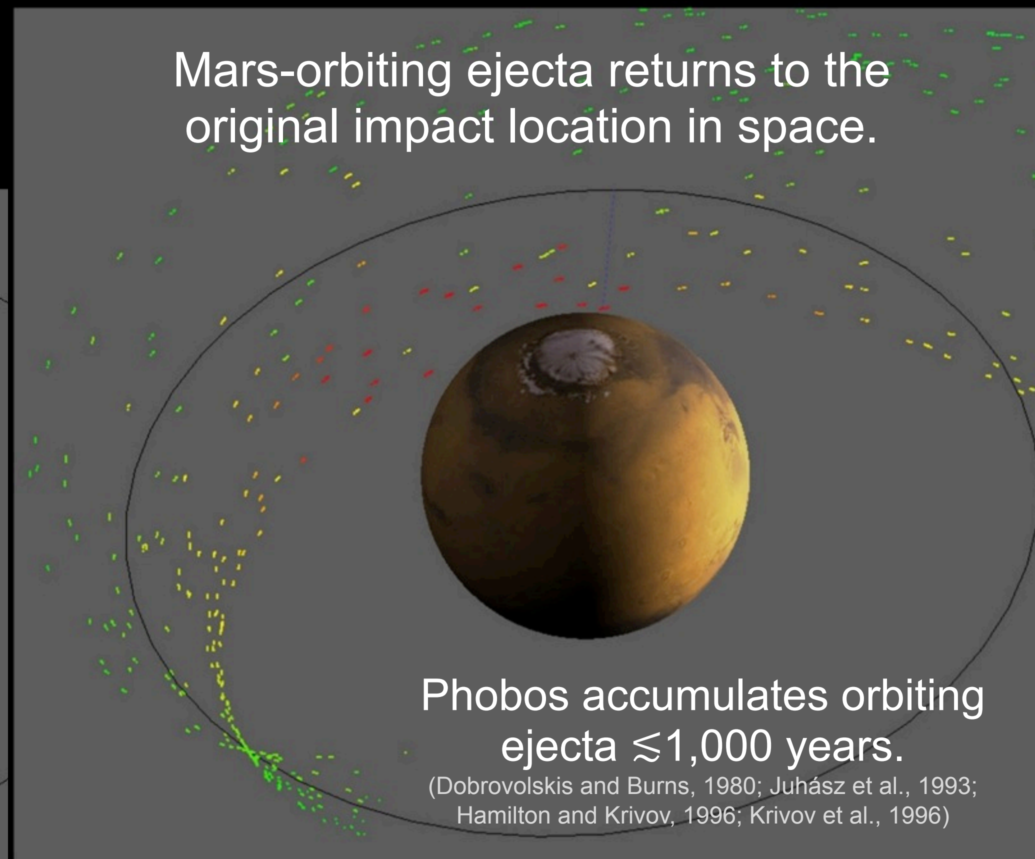
- **Average radius:** *11.07 km.*
- **Density:** *1.86 kg/m³*
- **Stickney Crater:** *~9 km dia.*
- **Synchronous rotation.** *Tidally locked similar to Earth's Moon.*
- **Orbital decay:** *Accelerating.*
- **Orbital altitude above Mars:** *5,838 – 6,121 km.*
- Grooves cover ~80% of Phobos.
- **"Red" and "Blue" units.**
- Albedo 0.07, *Heavily space-weathered.*

ESA

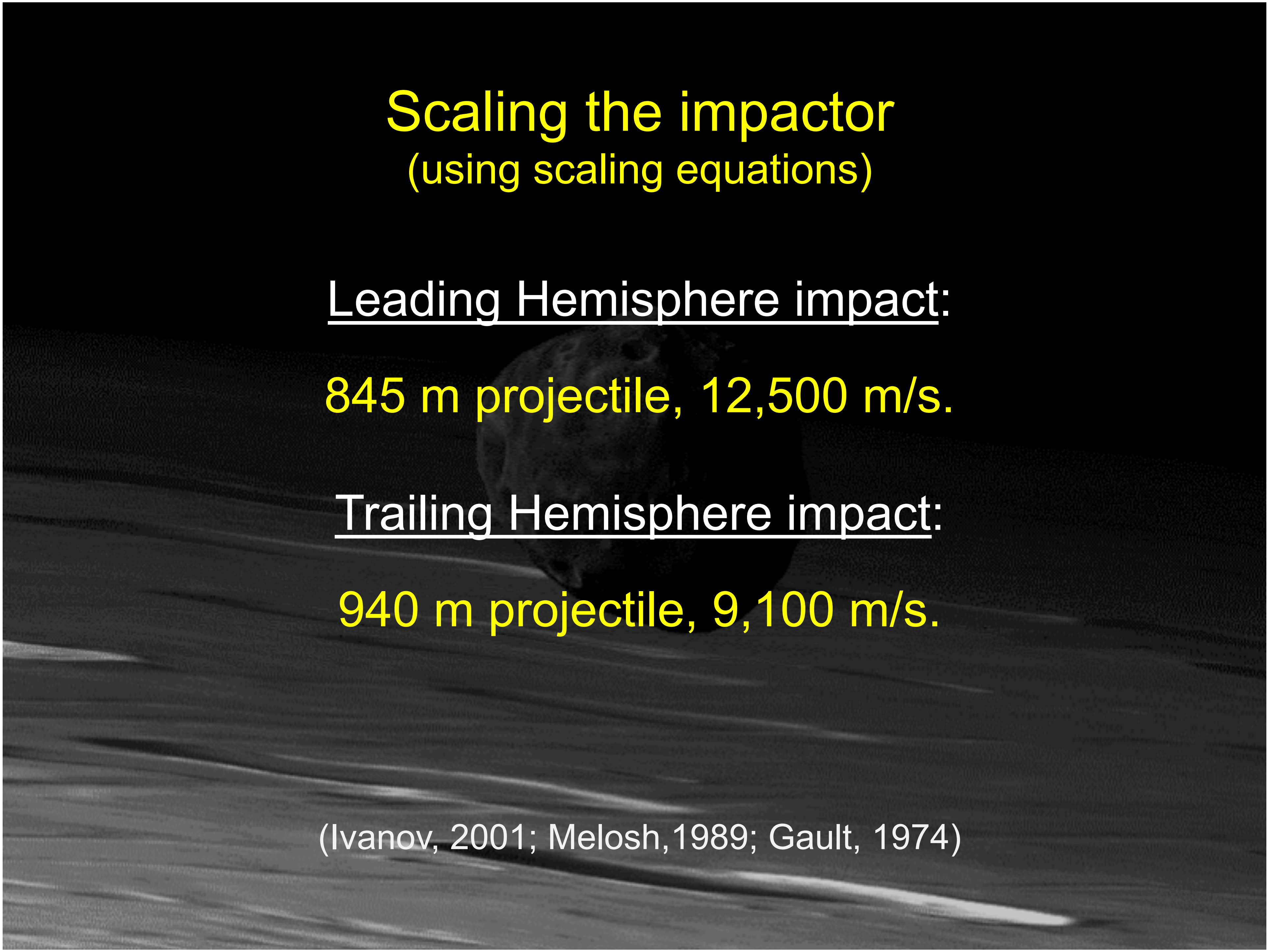
The majority of Phobos ejecta orbits Mars before returning to Phobos.

Up to 95% of ejecta that exits Phobos is trapped in orbits around Mars.
(Ramsley and Head, 2013)

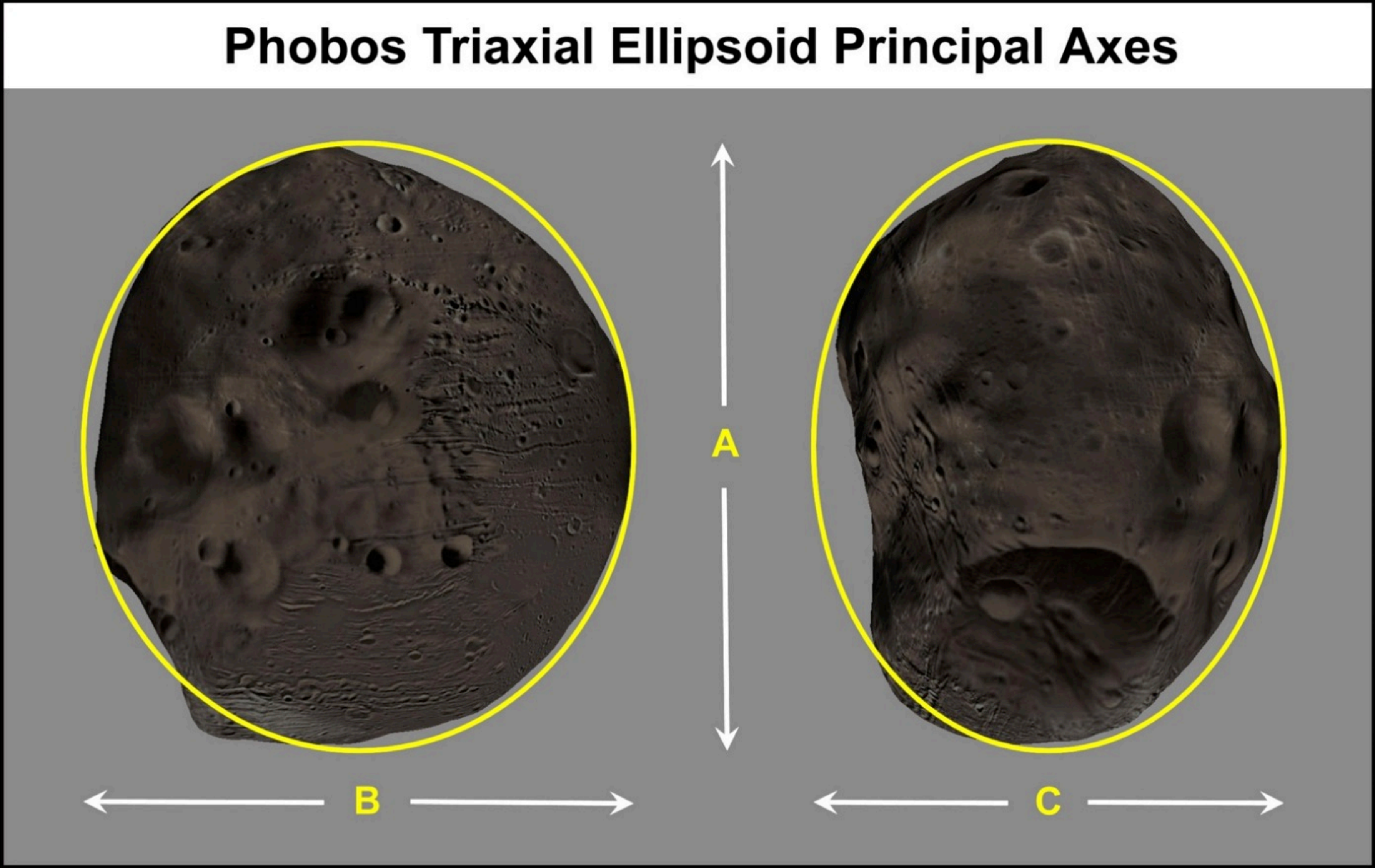




Due to the tidal locking of Phobos, all secondary impacts from craters on Phobos take place on the ***opposite*** hemisphere.


Scaling the impactor
(using scaling equations)
Leading Hemisphere impact:
845 m projectile, 12,500 m/s.
Trailing Hemisphere impact:
940 m projectile, 9,100 m/s.
(Ivanov, 2001; Melosh,1989; Gault, 1974)

What happens to the acceleration impulse?



Phobos may be approximated as a triaxial ellipsoid, Burns, 1977.
Phobos DTM data, Thomas (1997), 3DS model and texture mapping, Schrempp (2011).

The Tsiolkovsky rocket equation (or "ideal" rocket equation)

$$\Delta v = v_{exh} \ln\left(\frac{M_0}{M_1}\right)$$

The rocket's change in velocity is equal to the exhaust velocity times the natural log of the starting rocket mass (including fuel) divided by the ending rocket mass (minus the fuel).

"Rocket" = Phobos.

"Rocket exhaust" = The projectile and projectile velocity.

Crater formation process: an inefficient rocket engine

Source of acceleration impulse:
Crater excavation, flow and ejecta launch (mostly).
Resistance to compression (some).
Spallation (some). Vapor ejection (very little).

Inefficiencies:
Jetting (horizontal vector).
Heating, melting, vaporizing target and projectile rock.
Fracturing and shock metamorphosis of target rock.
Cone-shaped excavation flow angle.
Horizontal compression vector.

Conversion of impact energy to acceleration: **~60%** efficient.
Total acceleration impulse (near-present): **~1.1** m/s

De-spin of Phobos after the Stickney impact

$\tau_{despin} = \omega a^6 I Q / 3 G m_p^2 k_2 R_s^5$ (Gladman et al., 1996)

where:

- ω is the post-impact spin rate of Phobos (radians per second).
- a is the semimajor axis of the orbit of Phobos around Mars.
- $I = m_s(b^2 + c^2)/5$ is the rotational moment of inertia of Phobos.
- Q is the specific dissipation function of Phobos.
- G is the gravitational constant.
- m_p is the mass of Mars.
- k_2 is the tidal Love number of Phobos.
- R_s is the mean radius of Phobos.

De-spin time after the Stickney impact: **>14,000** years.

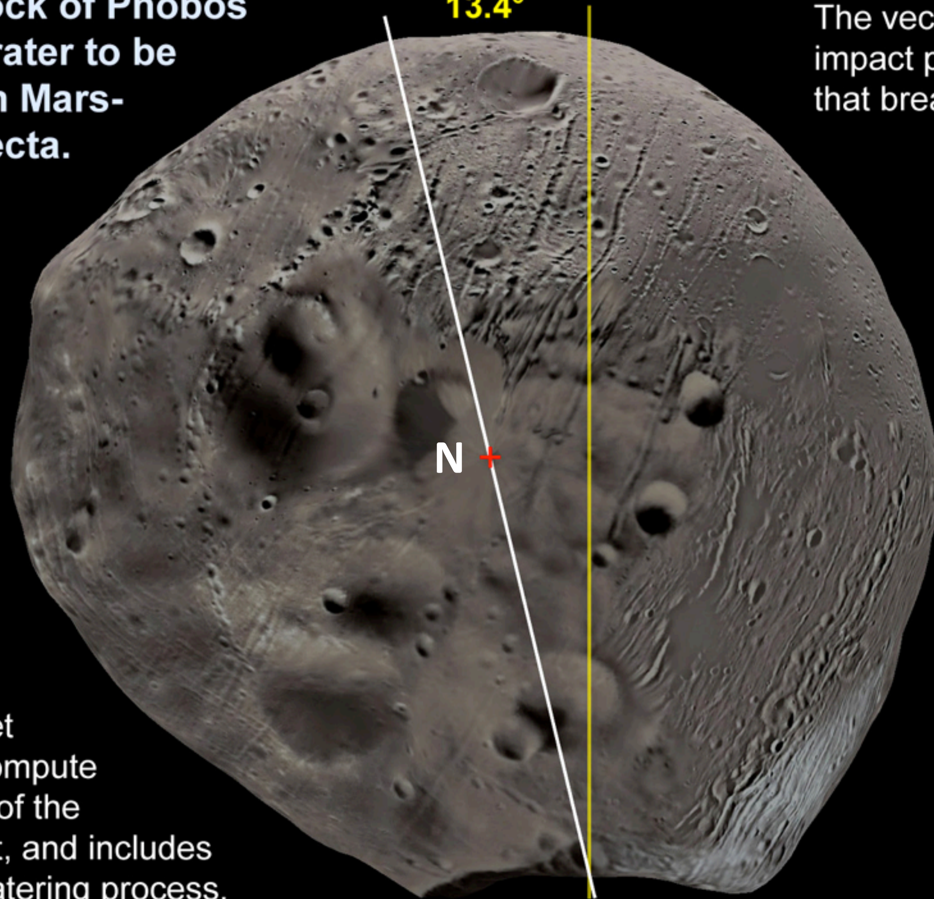
Does the Stickney impact break the tidal lock of Phobos?

(Yes)

The broken tidal lock of Phobos allows Stickney Crater to be exposed to its own Mars-orbiting impact ejecta.

Stickney is located on the equator of Phobos and offset from the spin axis of Phobos by 13.4°

The Tsiolkovsky "rocket equation" is used to compute the acceleration force of the Stickney Crater impact, and includes inefficiencies of the cratering process.



The vector offset of the Stickney impact produces angular momentum that breaks the tidal lock of Phobos.

Phobos initially rotates 6 times for every 5 orbits and continues to remain unlocked for at least 14,000 years.
(Burns, 1977; Gladman et al., 1996)

Present Day Sub-Mars

Does the Stickney impact break the tidal lock of Phobos?
and is the de-spin time >1,000 years? (Yes)

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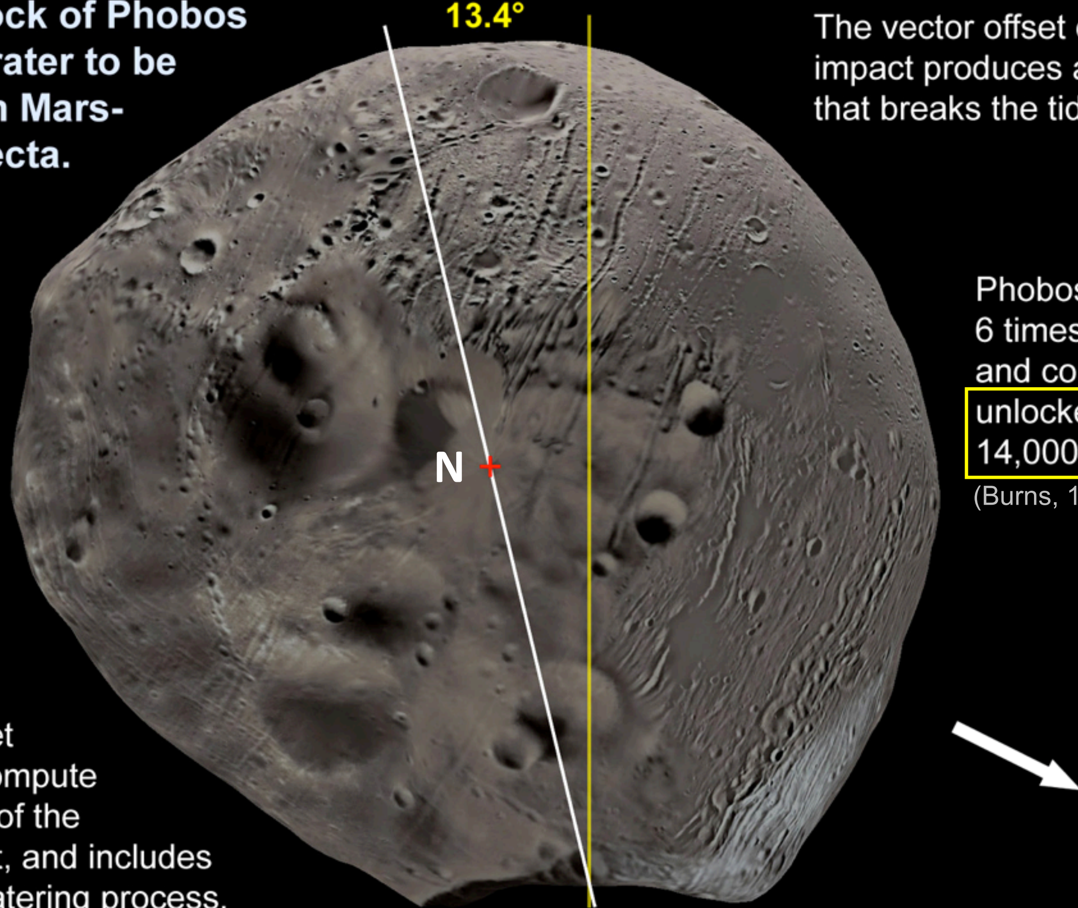

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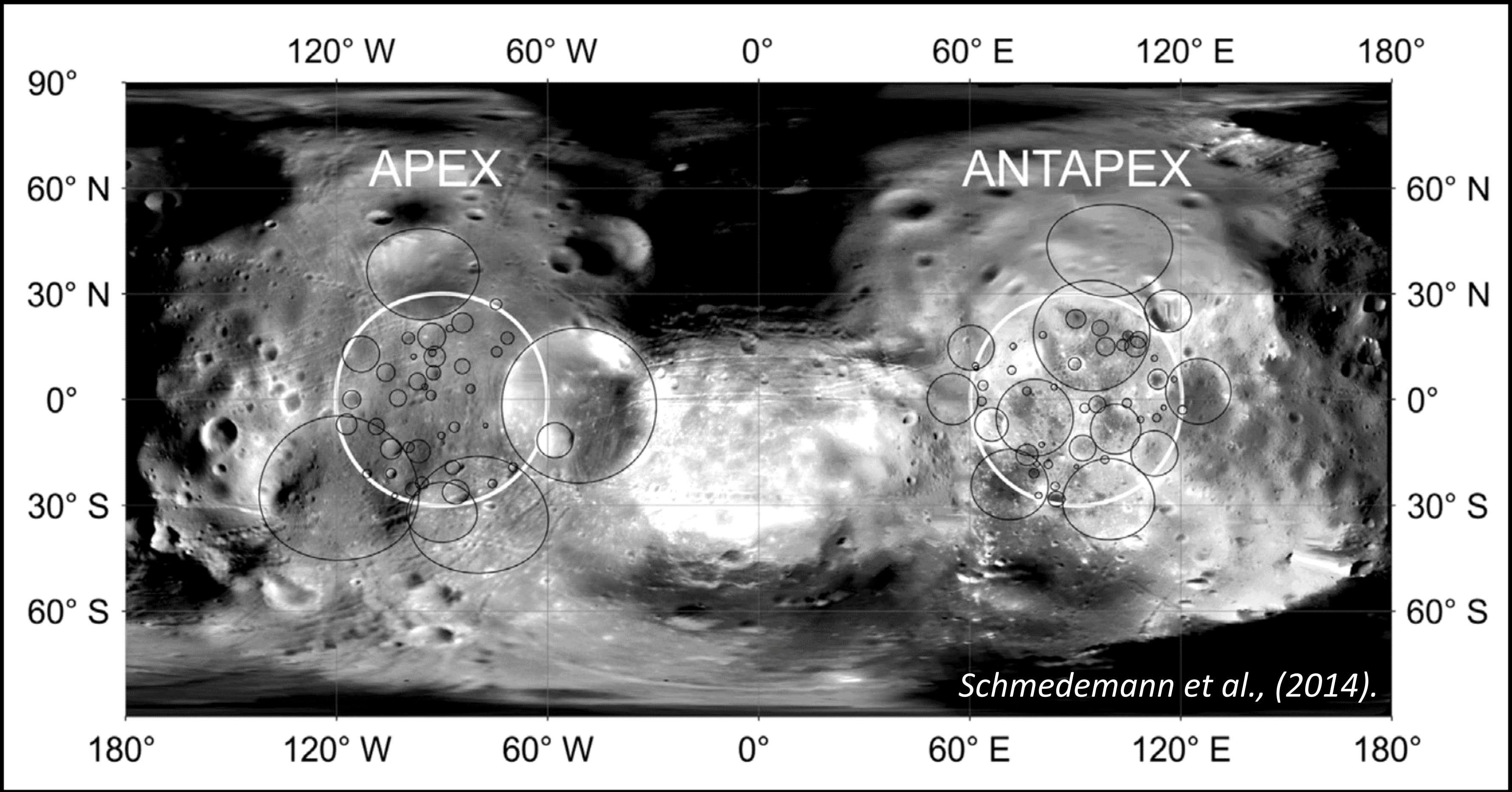
Present Day Sub-Mars

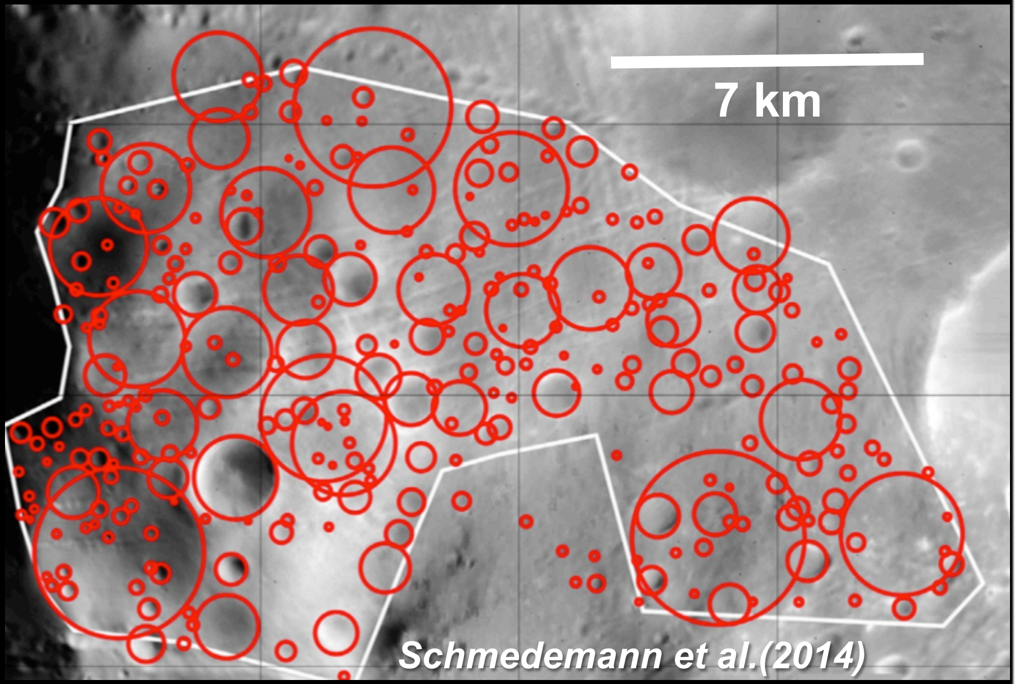
The SFD of *leading* and *trailing* hemisphere craters suggests that Phobos was previously locked 180° from its present-day orientation.



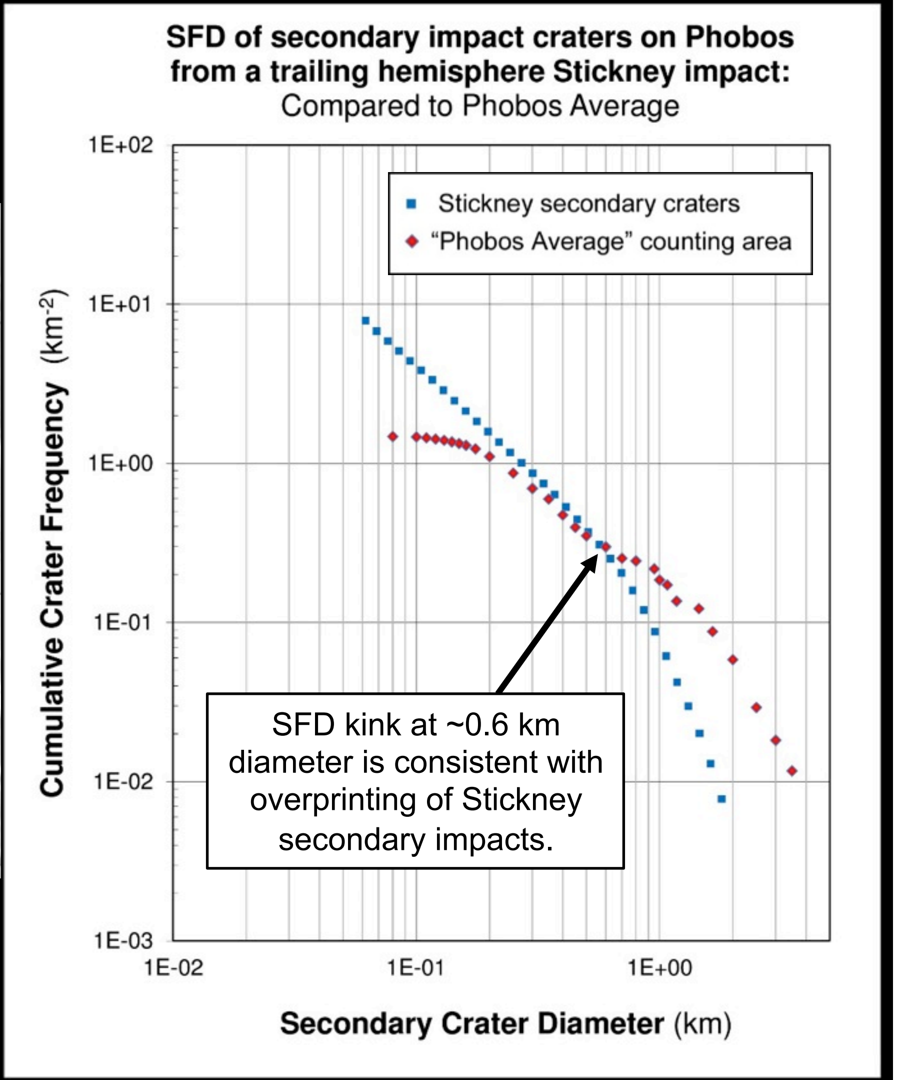
Due to its orbit around Mars, Phobos is exposed to a greater flux of background craters on its *leading* hemisphere. However, a greater SFD is observed on its *trailing* hemisphere.

The "Phobos average" SFD kink at ~0.6 km is consistent with an overprinting of Stickney secondary craters that superposes an older surface.

Stickney Crater ejecta volume is sufficient to account for all craters on Phobos < 0.6 km.
(Stickney Crater ejecta volume: ~39 km^3)

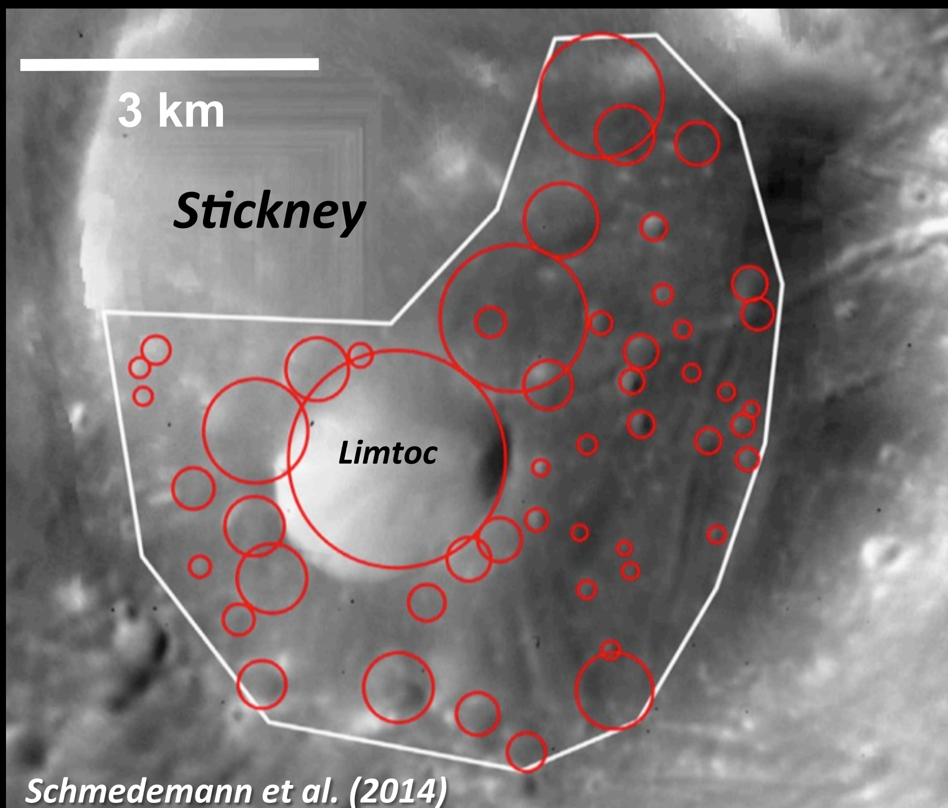


Phobos "average" crater counting area.

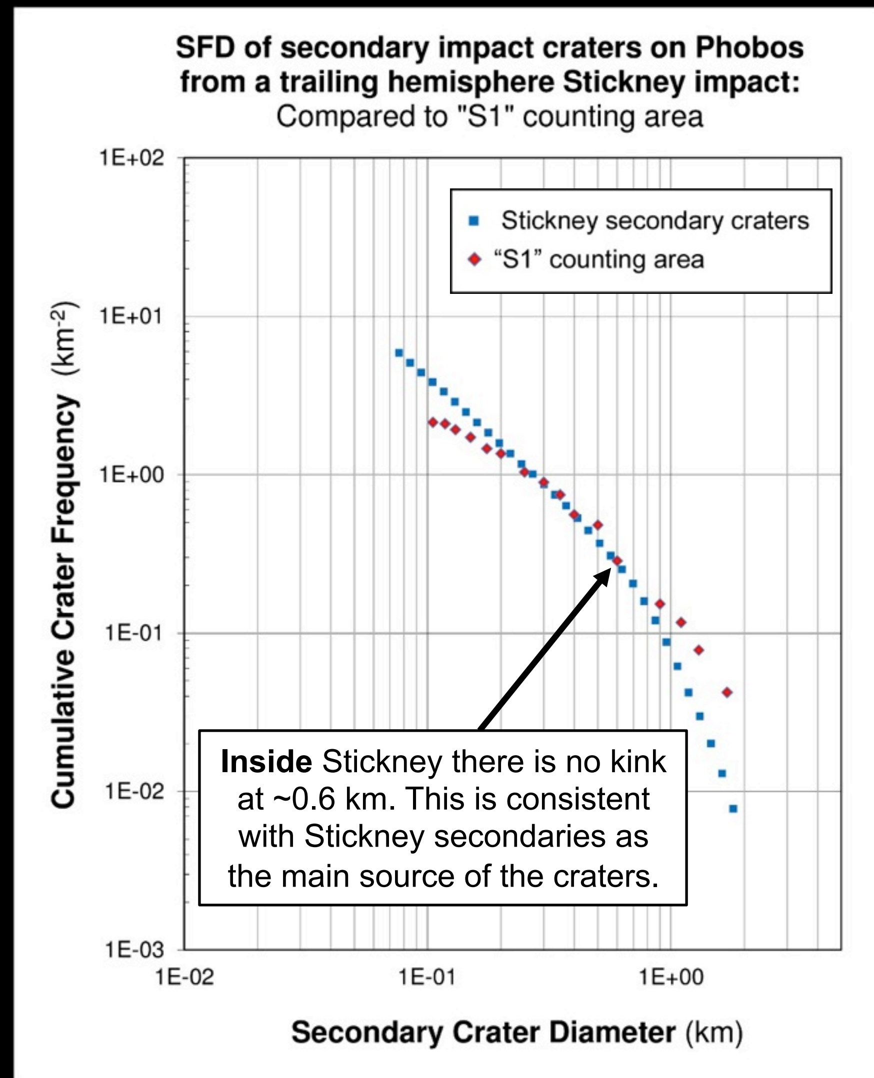


The craters inside Stickney are mostly Stickney secondaries.

Stickney Crater ejecta is sufficient to produce all craters inside Stickney as secondary impacts.
(Limtoc may be a primary impact)



Stickney Crater cannot be dated using crater-counting due to the overprinting of Stickney secondary impacts on Phobos.

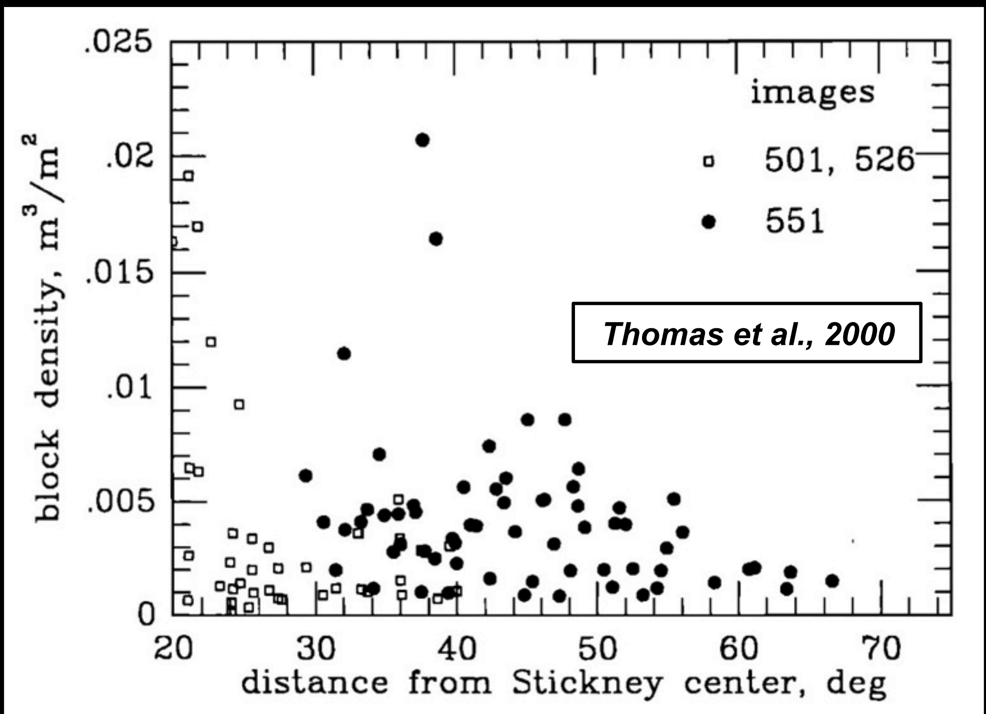


"S1" Stickney Crater counting area.
"2.8 – 4.2 Ga" Schmedemann et al. (2014)

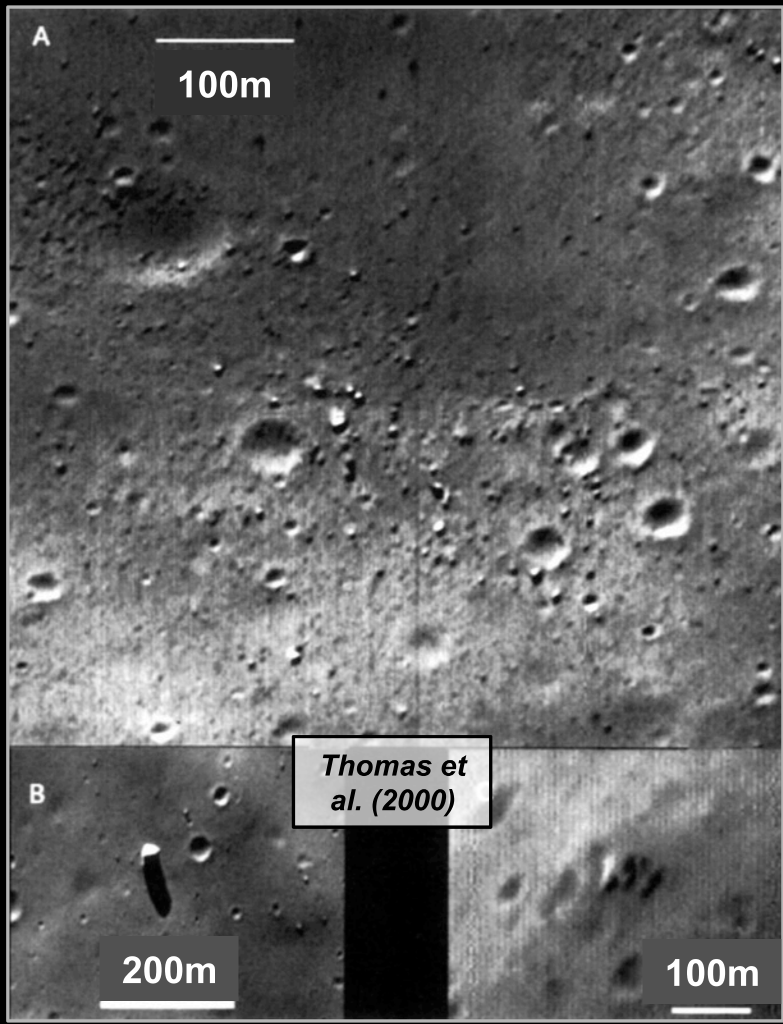
The present-day survival of Stickney Crater ejecta boulders sets an upper limit of ≲0.5 Ga for the age of the Stickney impact.

Boulders near Stickney Crater are Stickney ejecta blocks. *(Thomas et al.,2000)*

The maximum small boulder survival time at Phobos is ≲0.5 Ga. *(Basilevsky et al., 2015)*



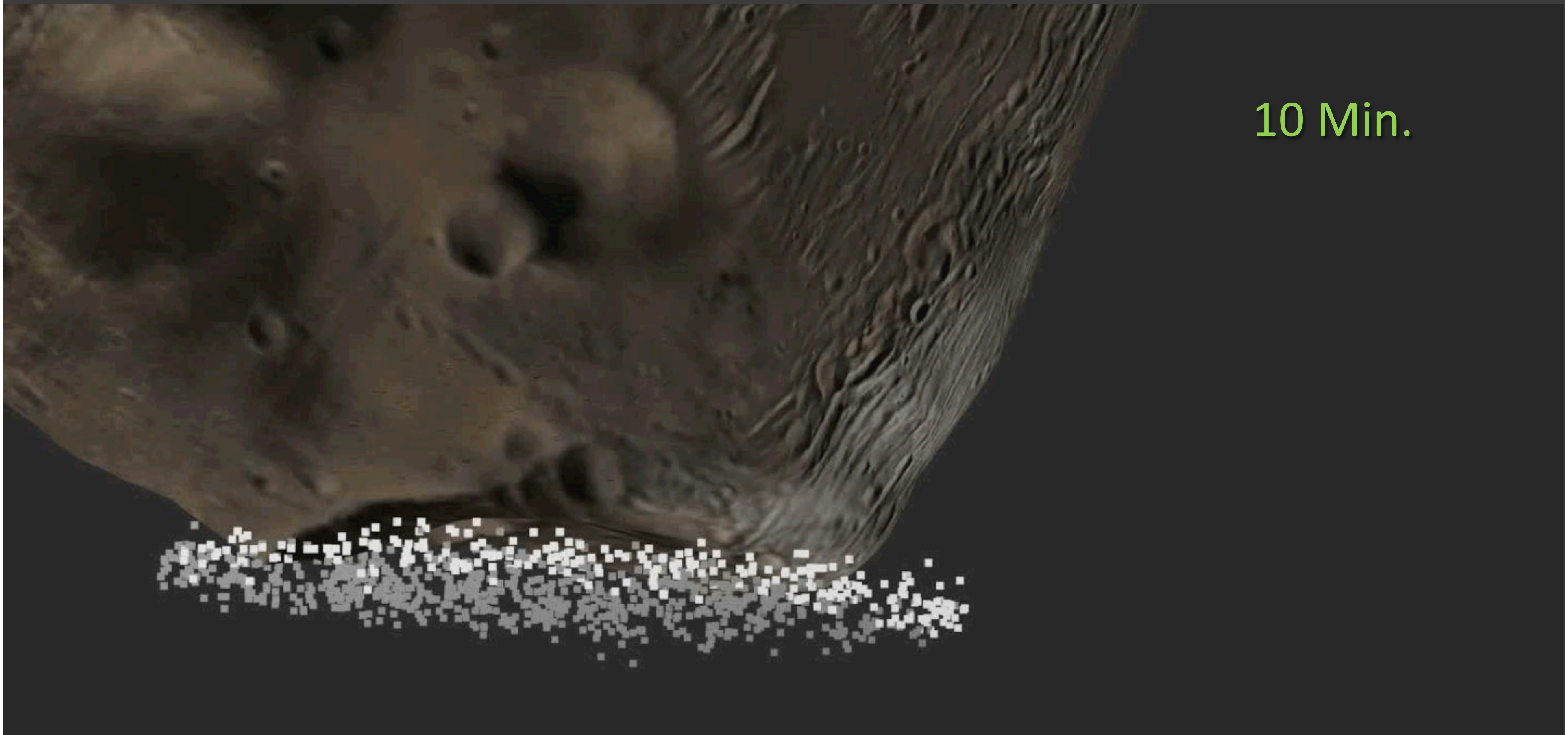
Stickney Crater ejecta boulder distribution.



Stickney Crater ejecta boulders.

The fate of low-velocity Stickney Crater ejecta.

Simulated ejecta exits from the rim of Stickney Crater at an initial radial velocity of 5-8 m/s.



Ejecta flight pattern is modified by:

Rotation of Phobos.
Orbit of Phobos.
Gravity of Phobos.
Gravity of Mars.

5 km

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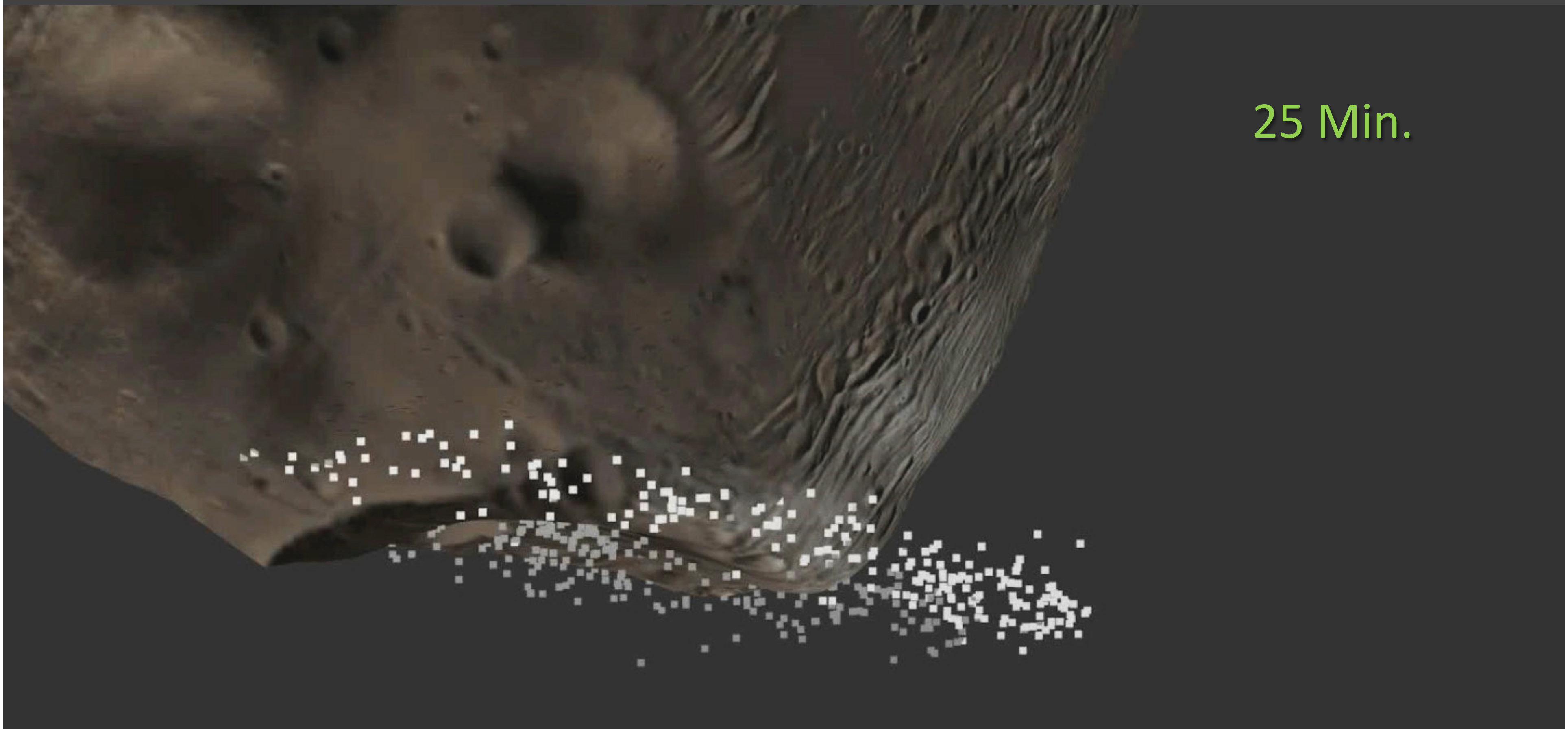

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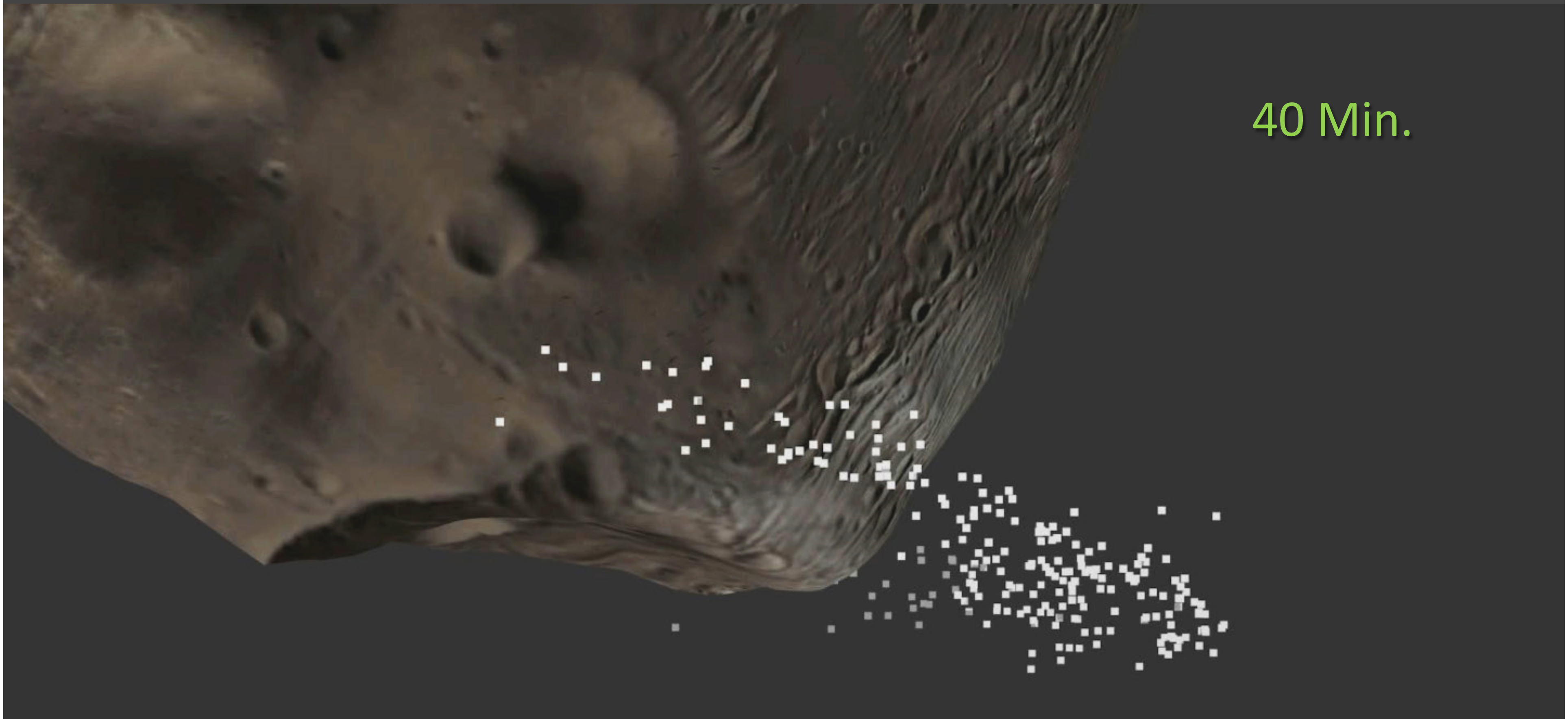

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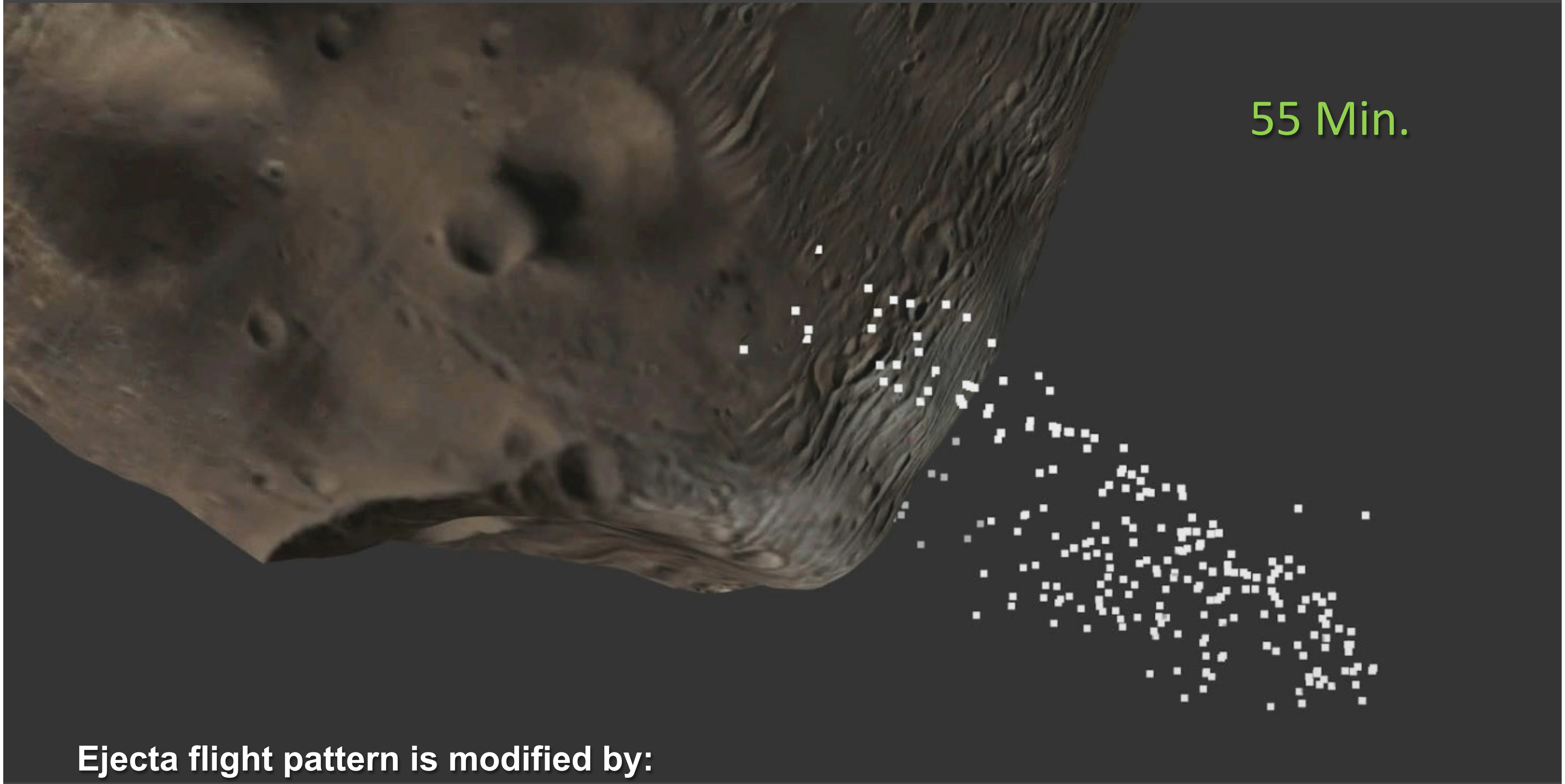

Ejecta flight pattern is modified by:

Rotation of Phobos.
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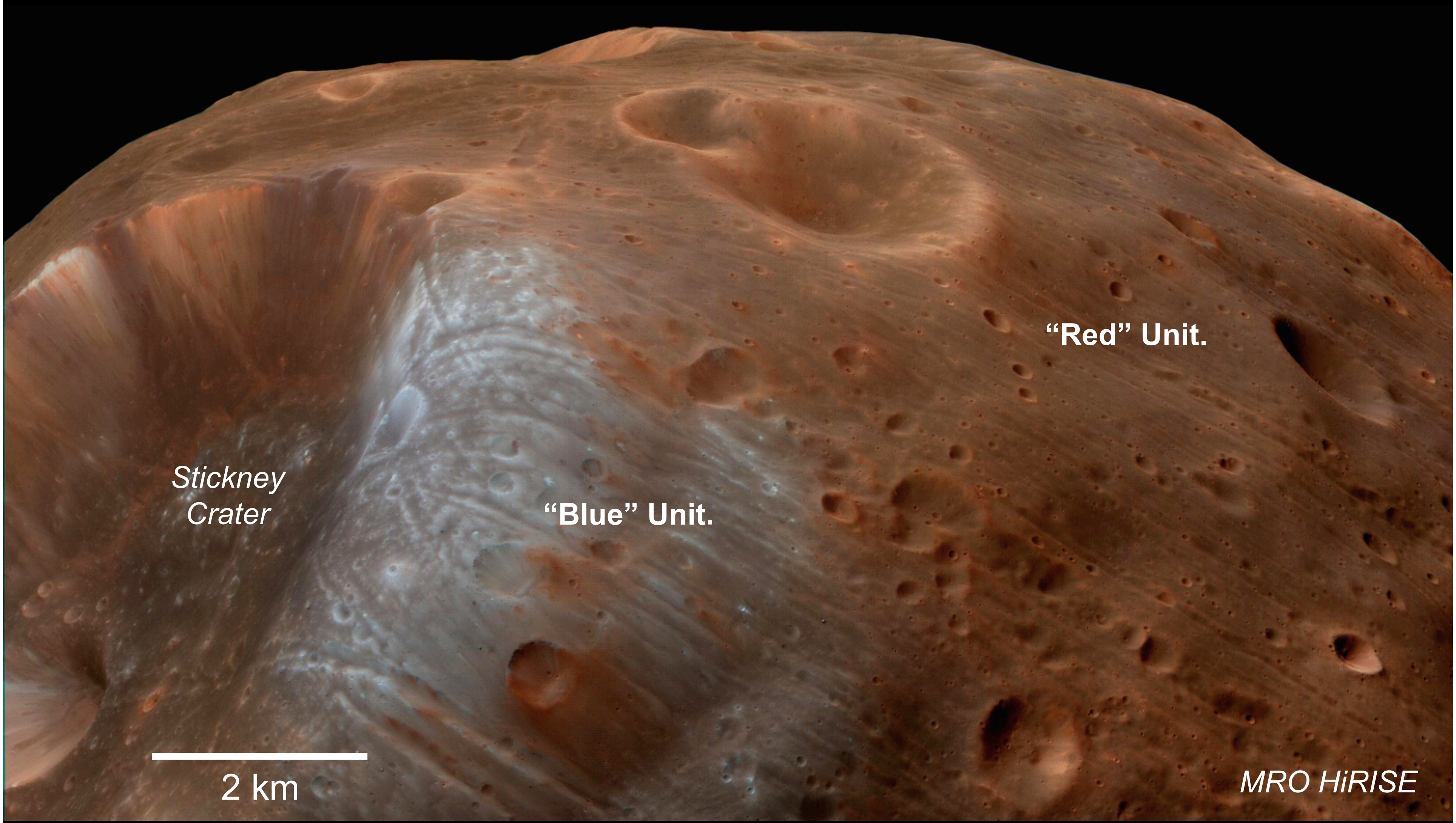
Gravity of Phobos.
Gravity of Mars.

5 km

The distribution of the "blue" unit is consistent with the preferential eastward flow of low-velocity Stickney ejecta.



Phobos colors are enhanced.

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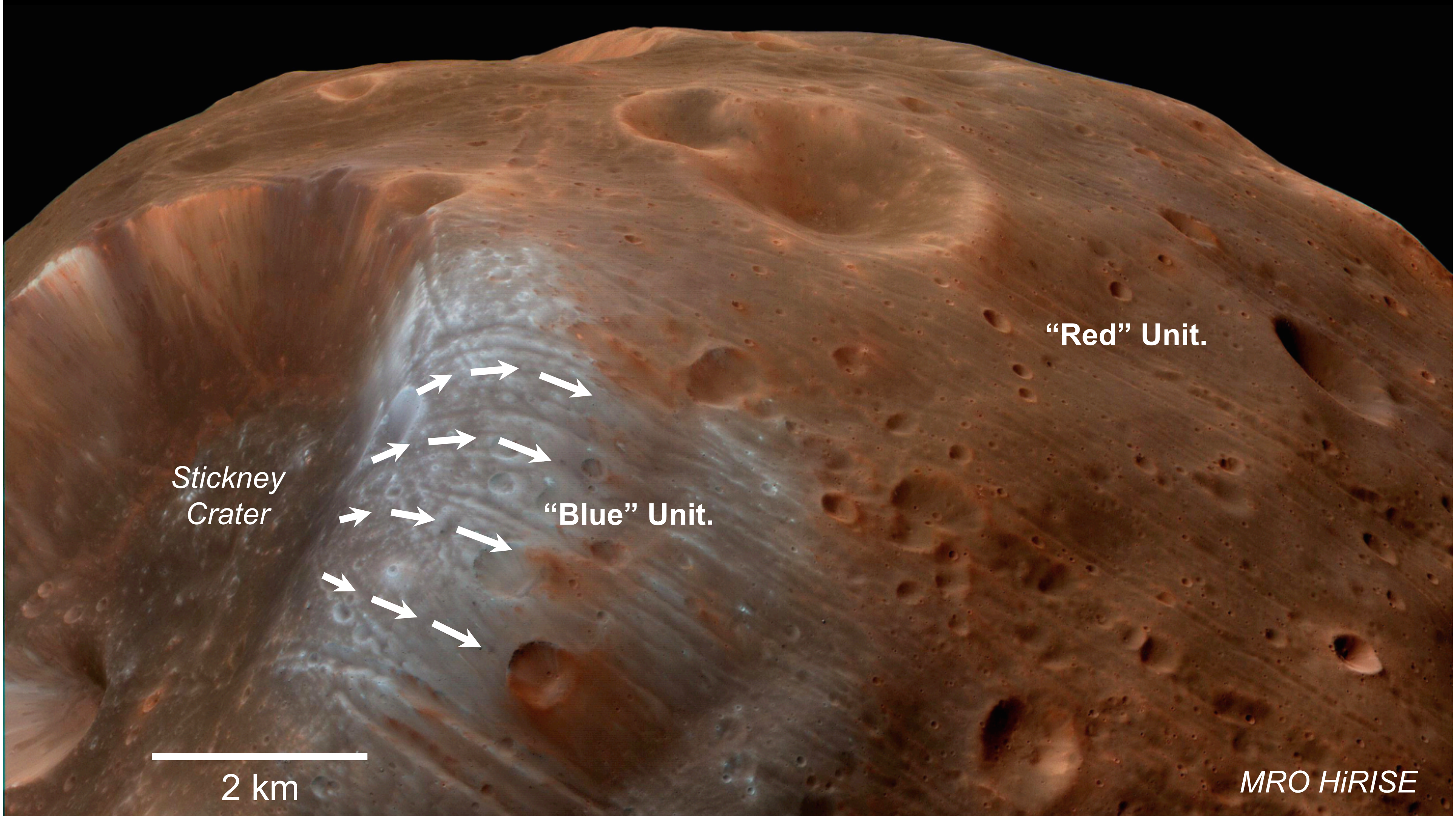

Phobos colors are enhanced.

The distribution of ejecta from a superposed 800 m crater is consistent with the preferential flight of low-velocity ejecta in this region of Phobos.

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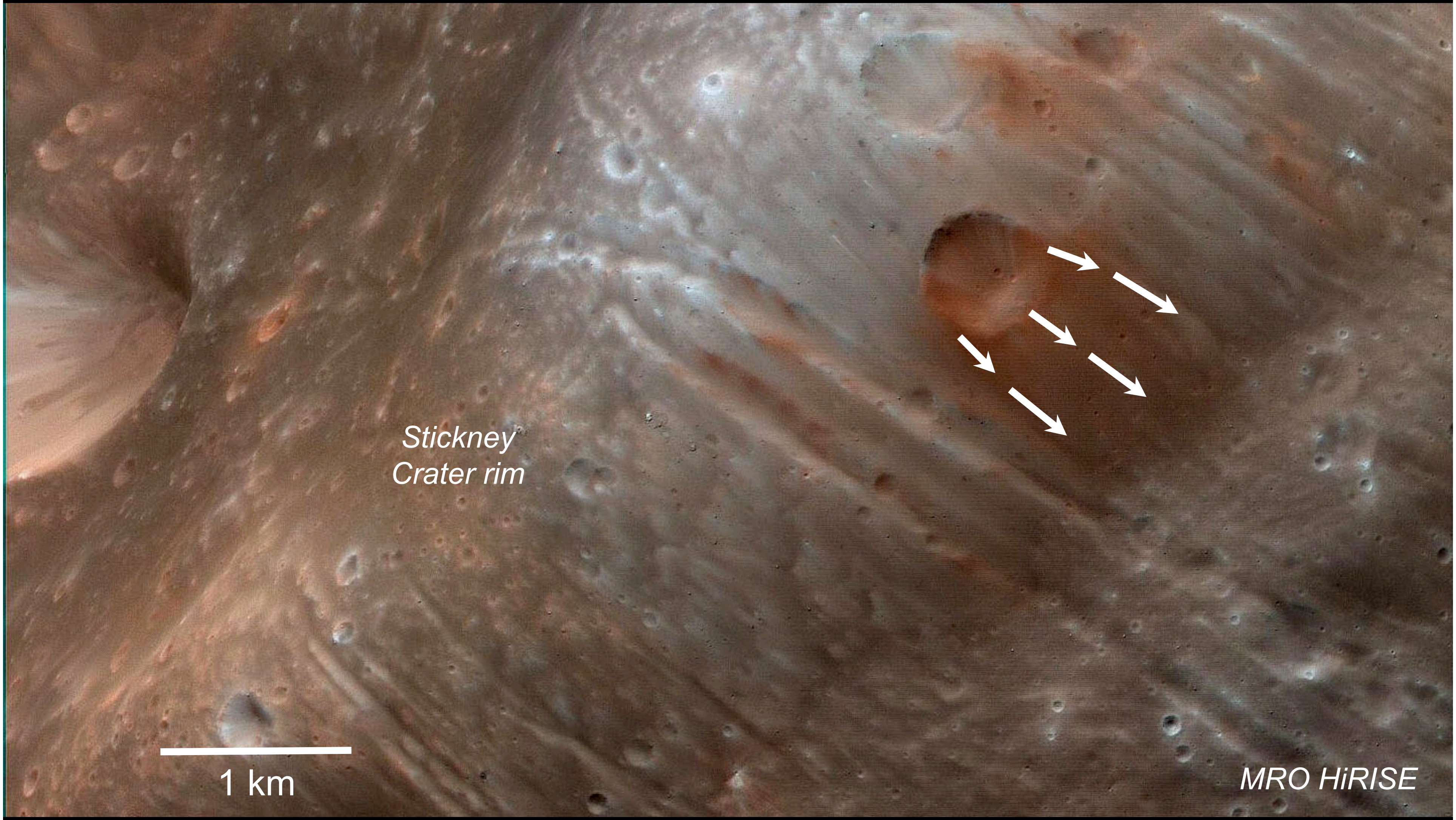

Phobos colors are enhanced.

Conclusions

1. Stickney Crater was fully exposed to its own secondary impacts. Phobos rotated faster than a tidal lock period during the entire time when Stickney ejecta was returning to Phobos.

2. Crater-counting is an invalid method to estimate an age for Stickney, due to the overprinting of Stickney secondary craters $\lesssim$0.6 km in diameter and a proportion up to 2 km.

3. Stickney Crater is $\lesssim$0.5 Ga in age, based on the survival time of Stickney ejecta boulders.

4. The preferentially eastward flight of low-velocity Stickney ejecta suggests that the “blue” unit may be excavated crater floor material from Stickney Crater.

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Conclusion (1/4)

Stickney Crater was fully exposed to its own secondary impacts. Phobos ejecta is typically trapped in Mars orbits. Phobos rotated faster than a tidal lock period during the entire time when Stickney ejecta was returning to Phobos.

Evidence:

1. Calculations demonstrate the Stickney impact produced a sufficient impulse to increase the rotation rate of Phobos.

2. Phobos appears to have been reoriented in phase by 180 degrees, which is consistent with a large equatorial impact on Phobos.

3. The overall SFD and the kink in the Phobos “average” counting area is consistent with secondary impacts from Stickney Crater.

4. The lack of a kink inside Stickney Crater is consistent with secondary impacts from Stickney.

Conclusion (2/4)

Crater-counting is an invalid method to estimate an age for Stickney, due to the overprinting of Stickney secondary craters < 0.6 km in diameter and a proportion up to 2 km.

Evidence:

1. Phobos rotated faster than its tidal lock for at least 14,000, whereas Stickney ejecta returned to Phobos in $\lesssim$ 1,000 years – thereby exposing the entire surface of Phobos to Stickney secondary impacts.

2. The SFD of craters of Phobos < 0.6 km and a proportion up to 2 km is consistent with the flux of secondary impacts from Stickney Crater.

3. All craters inside Stickney Crater are < 2 km in diameter and most are likely to be Stickney secondary impacts.

Conclusion (3/4)

Stickney Crater is $\lesssim$ 0.5 Ga in age, based on the survival time of Stickney ejecta boulders.

Evidence:

1. Thomas et al. (2000) observes boulders near Stickney Crater that are interpreted to be ejecta blocks from the Stickney impact.

2. Basilevsky et al. (2015) conclude that small boulders are destroyed on Phobos in $\lesssim$ 0.5 Ga.

Conclusion (4/4)

The preferentially eastward flight of low-velocity Stickney ejecta suggests that the “blue” unit may be excavated crater floor material from Stickney Crater.

Evidence:

1. Modeling suggests a strong preferential eastward flow of low-velocity ejecta (5 – 8 m/s).

2. Modeling also shows that westward exiting ejecta reenters the crater which suggest that excavated impact melt and breccia may be mobilized and distributed preferentially to the east.

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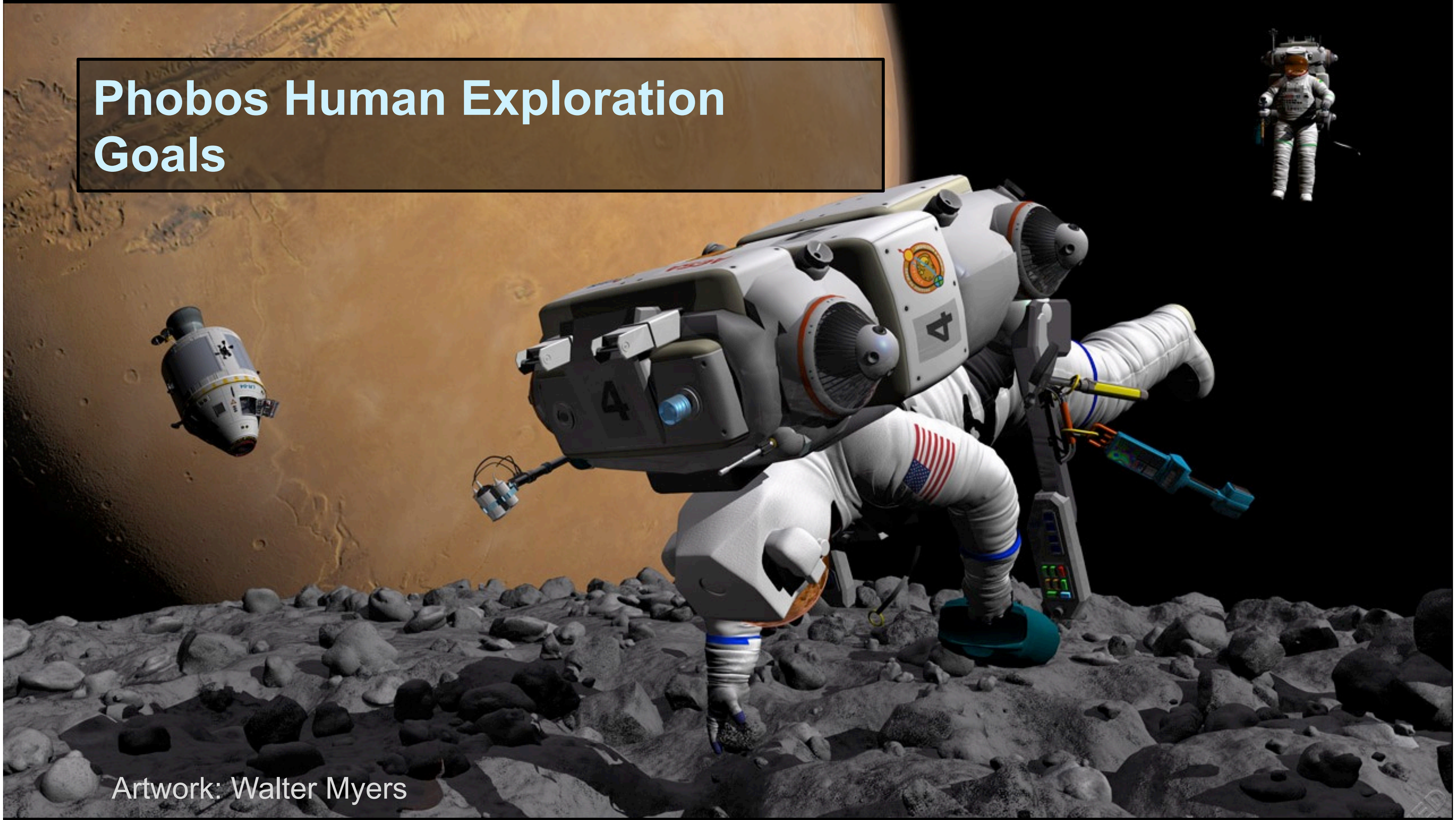
Phobos Human Exploration Goals



Artwork: Walter Myers

Science Questions

Origin of Phobos?

Giant impact on Mars.
Captured asteroid.
Co-accretion with Mars.

Origin of the grooves?

Stickney impact fracturing.
Stickney Crater boulder tracks.
Mars gravity tidal displacement.
Impact ejecta from Mars (crater chains).

Concentration of Mars ejecta on Phobos?
Interior structure, voids, or water ice at depth?
Origin of the “red” and “blue” units?
Age of Stickney Crater?

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Phobos Human Exploration Goals

Origin of Phobos: sample protected boulder surfaces.
Giant impact on Mars.
Captured asteroid.
Co-accretion with Mars.

Origin of the grooves: sample along grooves, ground penetrating radar.
Stickney impact fracturing.
Stickney Crater boulder tracks.
Mars gravity tidal displacement.
Impact ejecta from Mars (crater chains).

Concentration of Mars ejecta on Phobos: core sample of the upper regolith.
Interior structure, voids, or water ice at depth: radar, active seismic probing.
Origin of the “red” and “blue” units: core and regolith samples from each unit.
Age of Stickney Crater: sample proximal boulders.

[redacted]

Groove Character

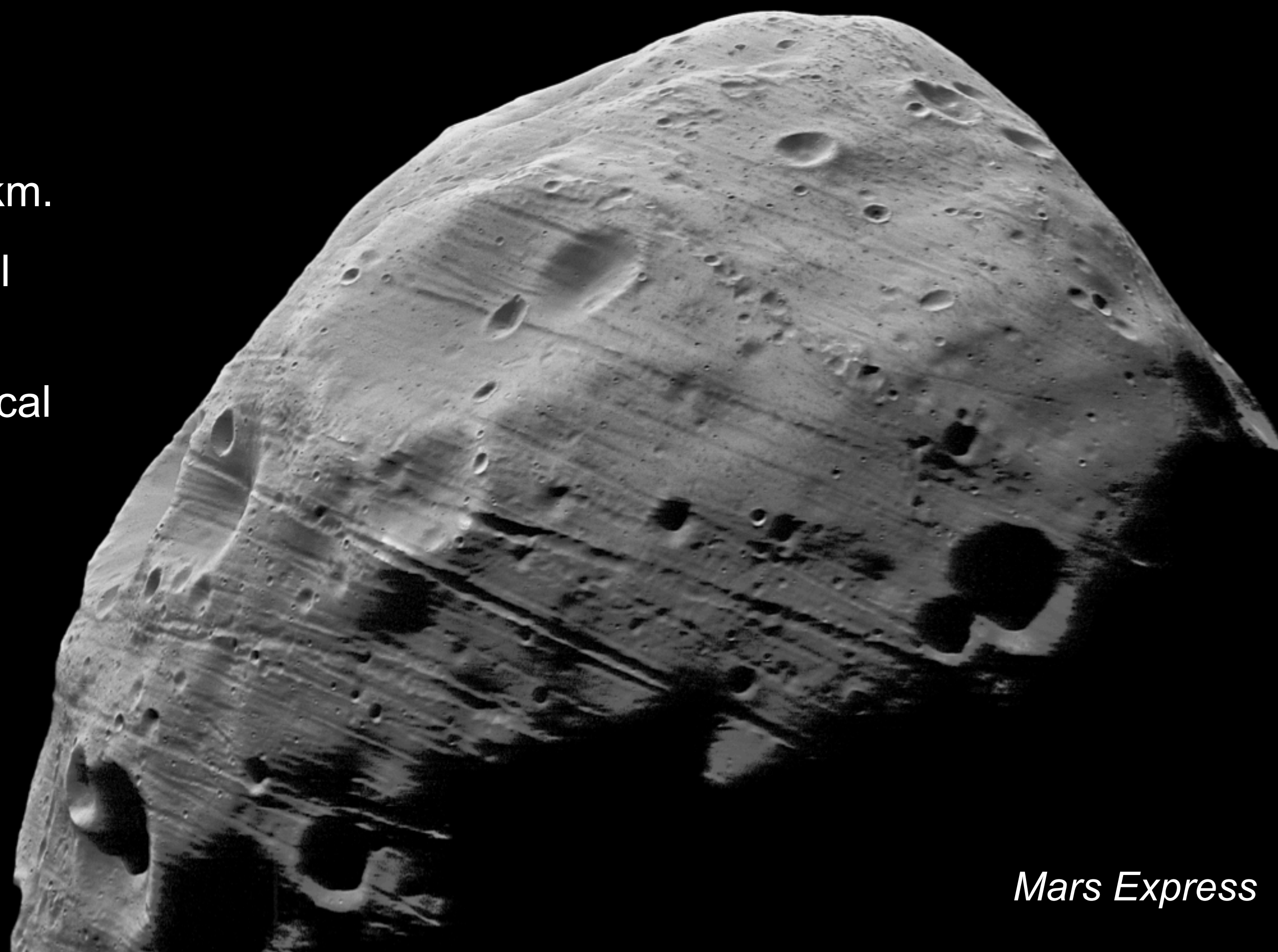
Widths: 80 – 400 m
Typically: ~150 m

Lengths: Typically 20 – 30 km.

Generally linear and parallel to adjacent grooves.

Linearity is unaffected by local terrain variations.

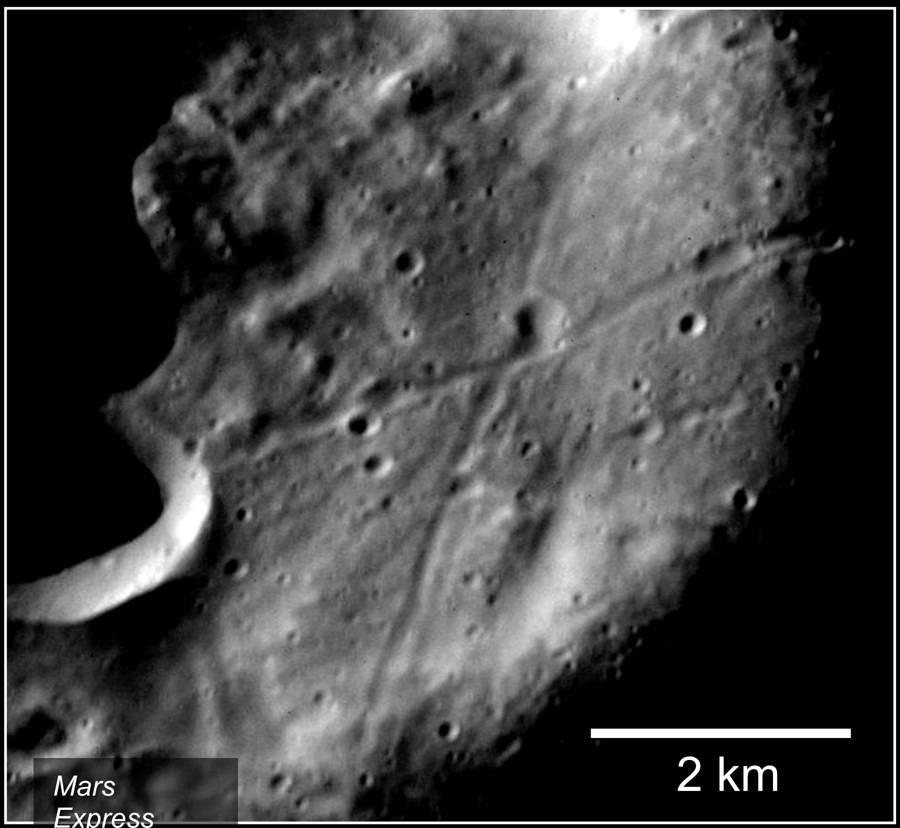
~1% are non-linear, solitary and irregularly pitted.

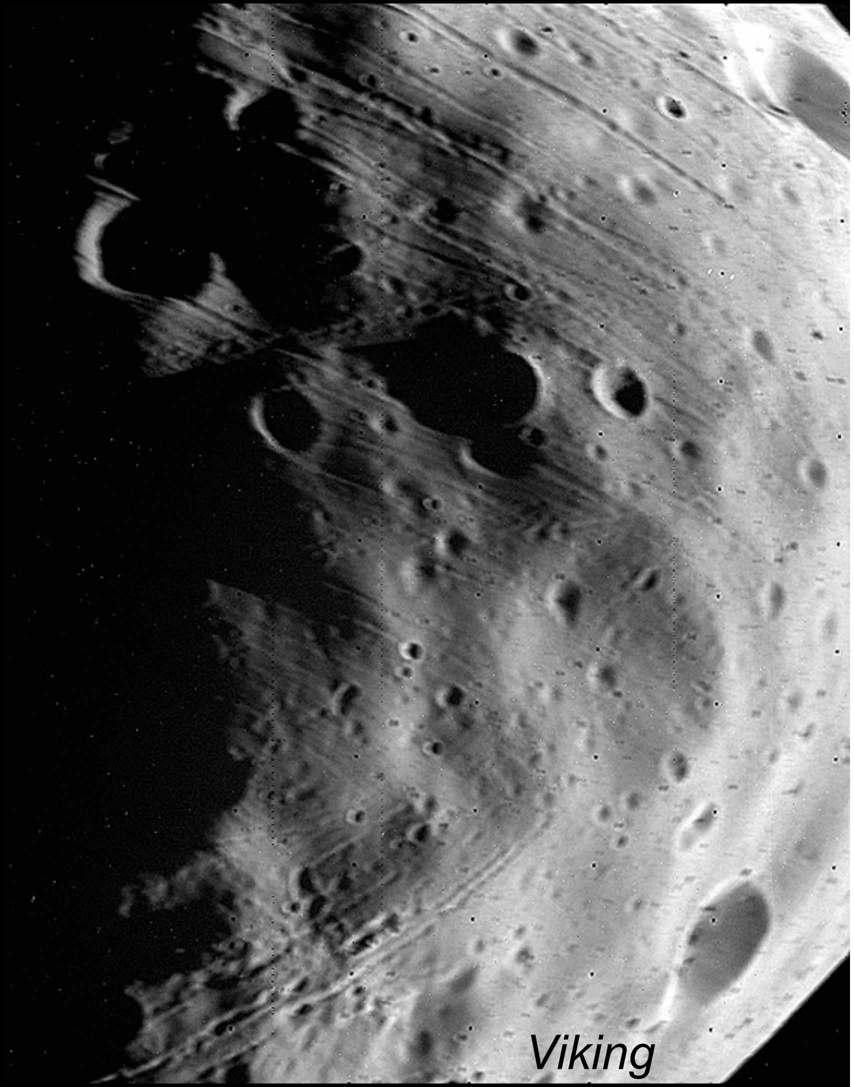


Mars Express

Groove Character

Some grooves crosscut other grooves.





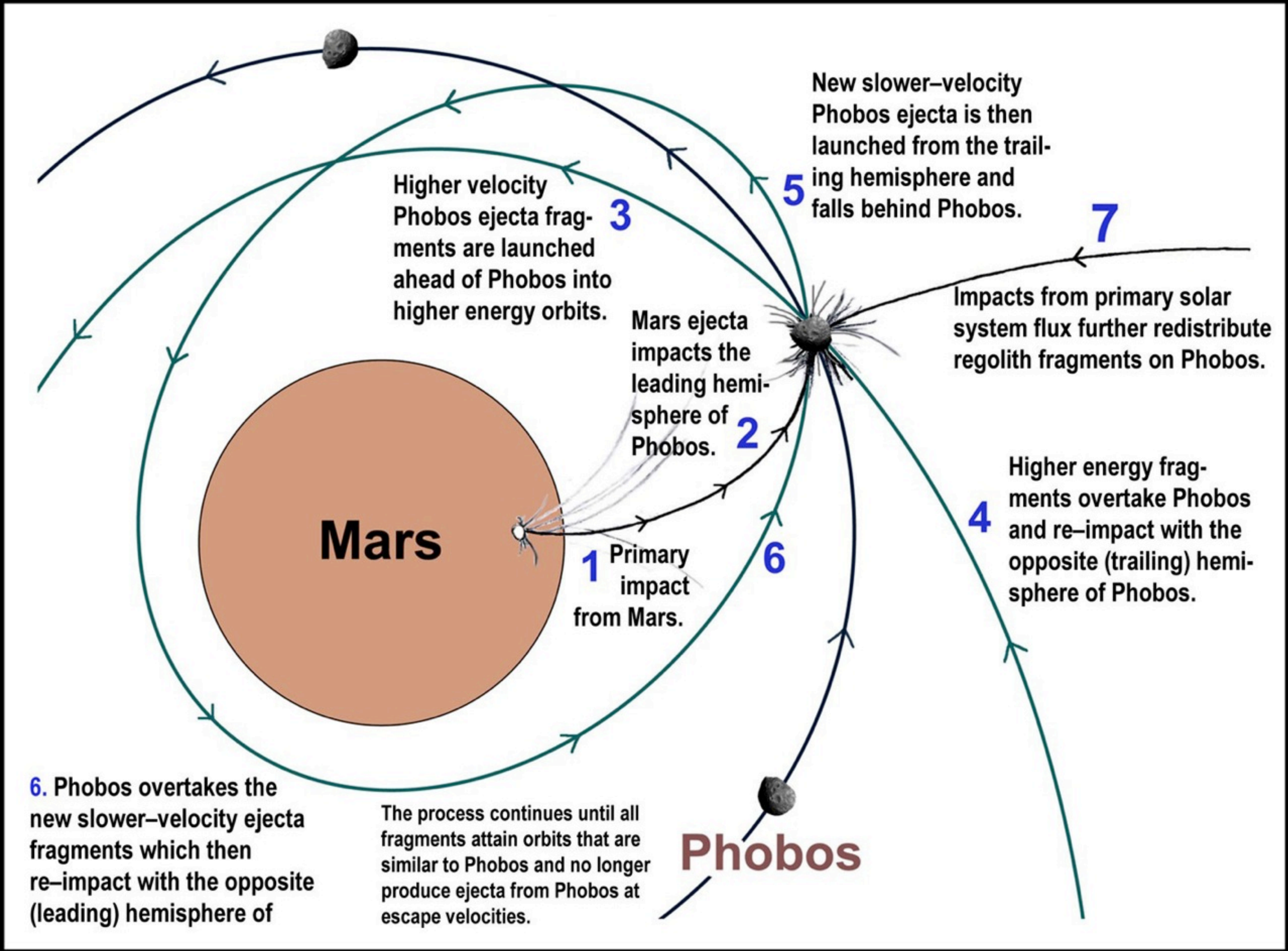
Groove Character

Grooves crosscut craters ≳ 2 km and are overprinted by craters ≲ 2 km in diameter.

MRO HiRISE

Mars ejecta is uniformly distributed on Phobos

Mars ejecta on Phobos: ~250 ppm in the upper 1 m of regolith.

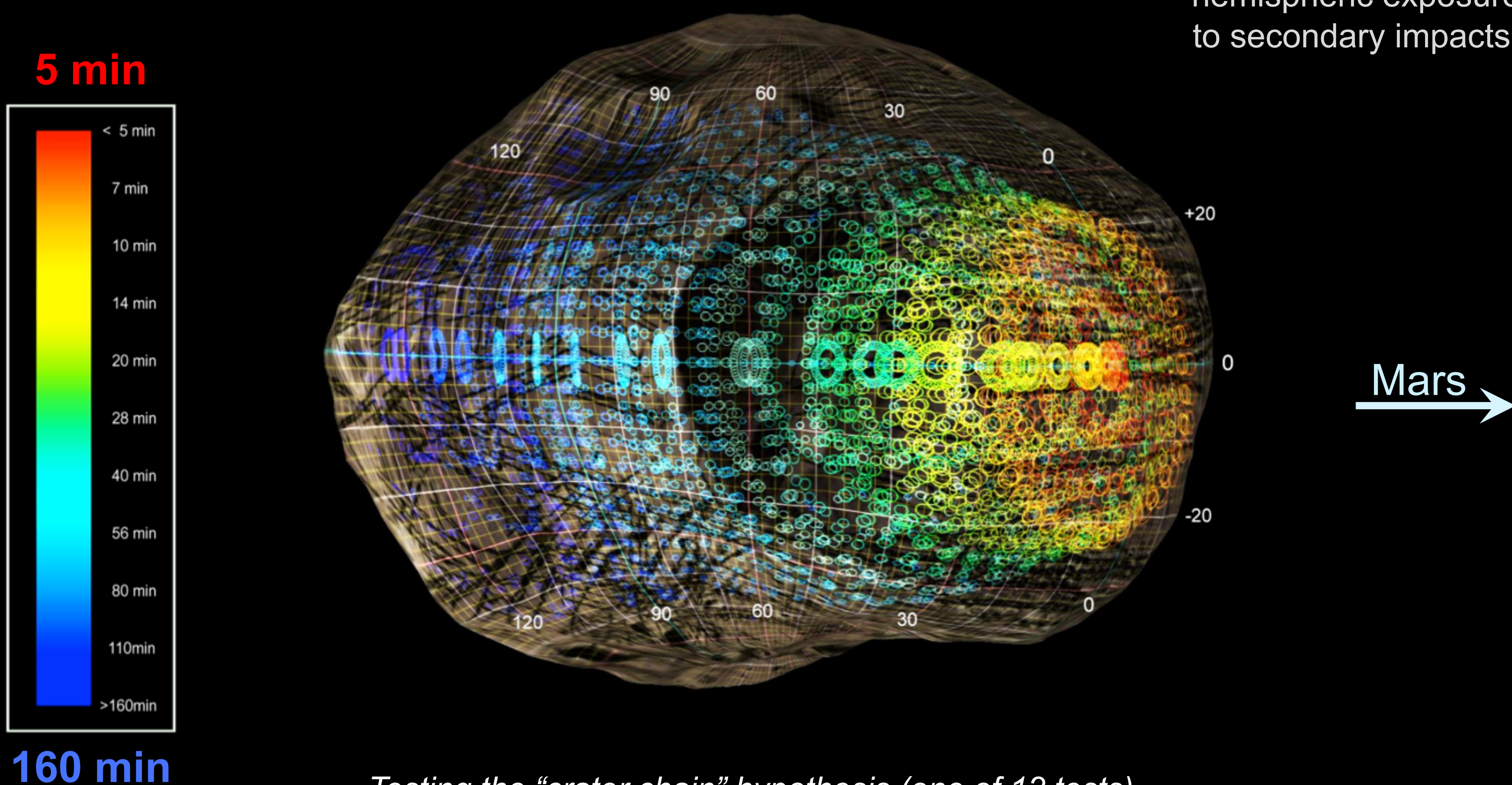


Phobos grooves as crater chains from impacts on Mars?

Murray et al. (1995 – 2014)

Colors represent flight times from Mars to Phobos.

Smallest circles represent centers of hemispheric exposure to secondary impacts.



Testing the "crater chain" hypothesis (one of 12 tests).

How stable is the pattern of ejecta during a flight from Mars to Phobos?

Test: Dispersion due to launch velocity variations of 0.1 to 8.0 mm/s.

25 minute flight. Each frame = one minute of flight.

Pit emplacement pattern errors at Phobos.
Launch velocity variations of 0.1 to 8.0 mm/s.

Ejecta Launch Velocity (m/s)

A. 4159.04346
B. 4159.05945
C. 4159.04746
D. 4159.05545
E. 4159.05046
F. 4159.05245
G. 4159.05136
H. 4159.05156

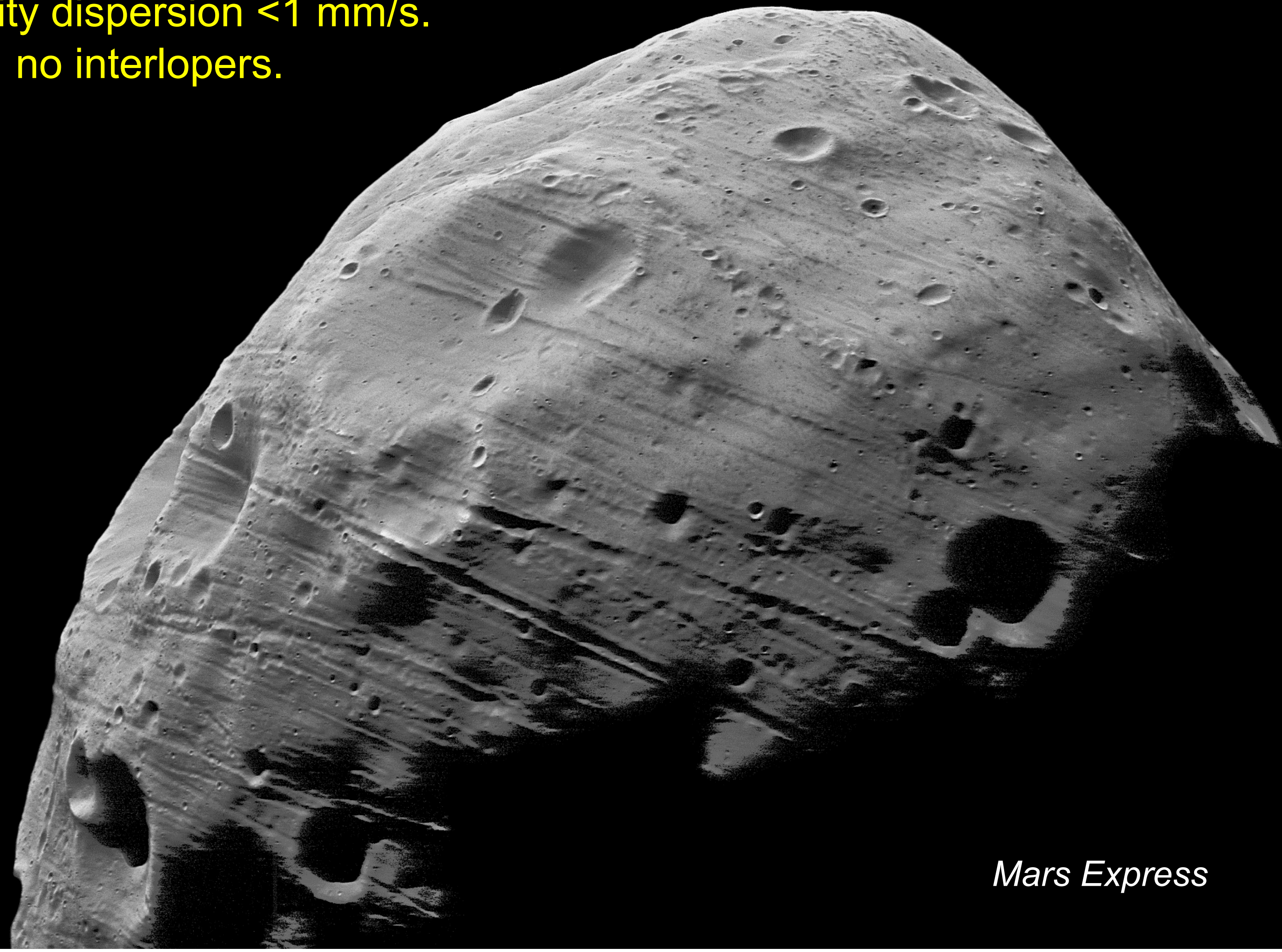
200 m

Reference Pattern
4159.05146 m/s

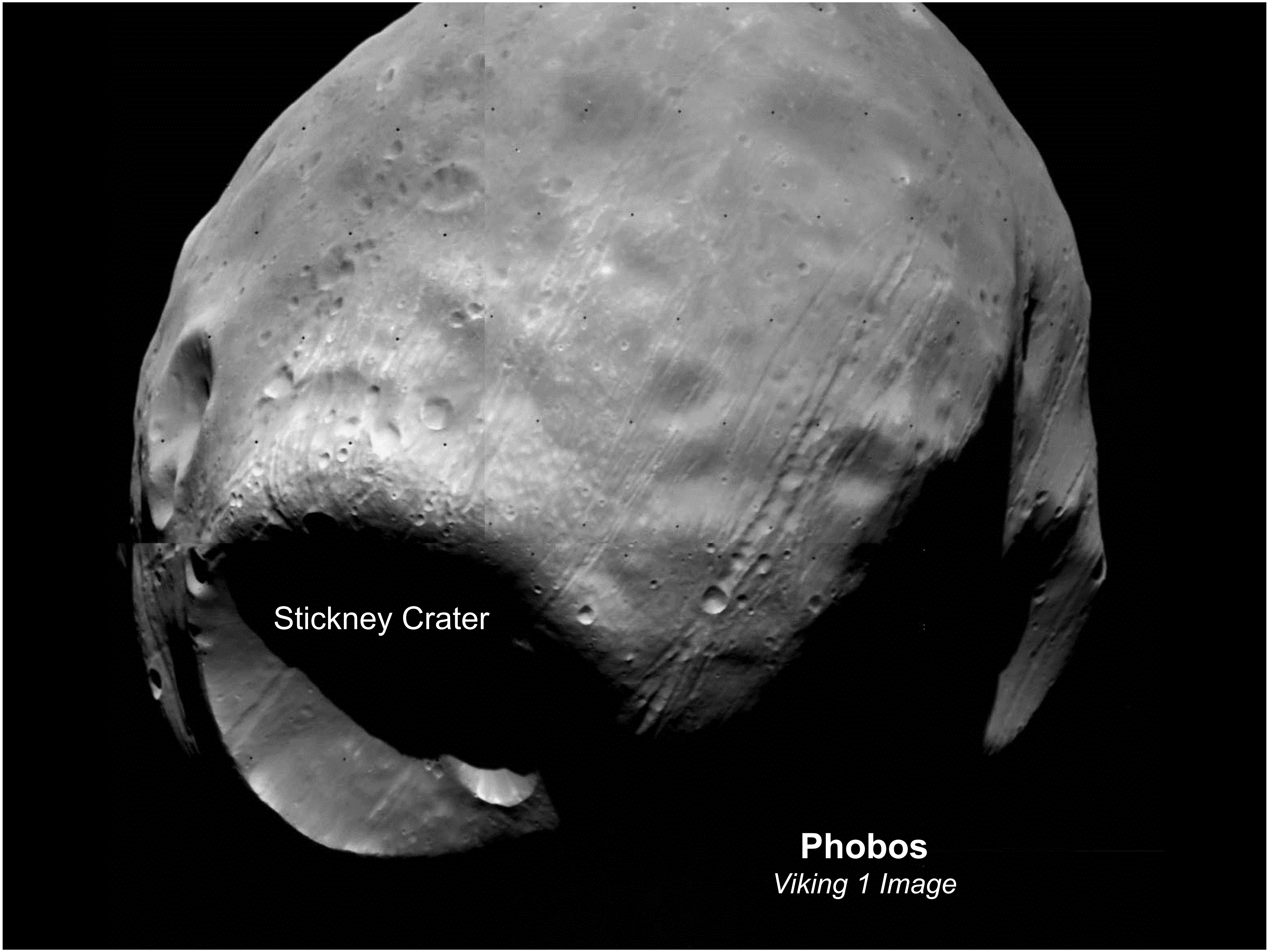
+/-1.0 mm/s ejecta block launch velocity deviation from a zero-dispersion pattern is sufficient to disrupt the linearity of groove pit emplacement.

Parallel grooves from impacts on Mars require:

1. Ejecta flight times of 10 – 160 minutes.
2. Tens of thousands of equal-mass projectiles.
3. Precisely-launched grid-patterns of ejecta.
4. Launch velocity dispersion <1 mm/s.
5. No odd sizes, no interlopers.



Mars Express


Stickney Crater
Phobos
Viking 1 Image