The Carbon Dichotomy of Mars Versus the Martian Moons: An Important Clue to Mars' History

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The Martian System Carbon Dichotomy

- Mars’ surface is one of the most carbon-depleted in the Solar System, but…
- Phobos and Deimos have carbon-rich surfaces to the point that they are some of the optically darkest (lowest albedo) objects in the Solar System
- All surfaces have received the same carbon infall flux and reside in very similar radiation environments
- This dichotomy is a product of the carbon fluxes and sinks of the martian system, and inquiry should inform us about Mars system history

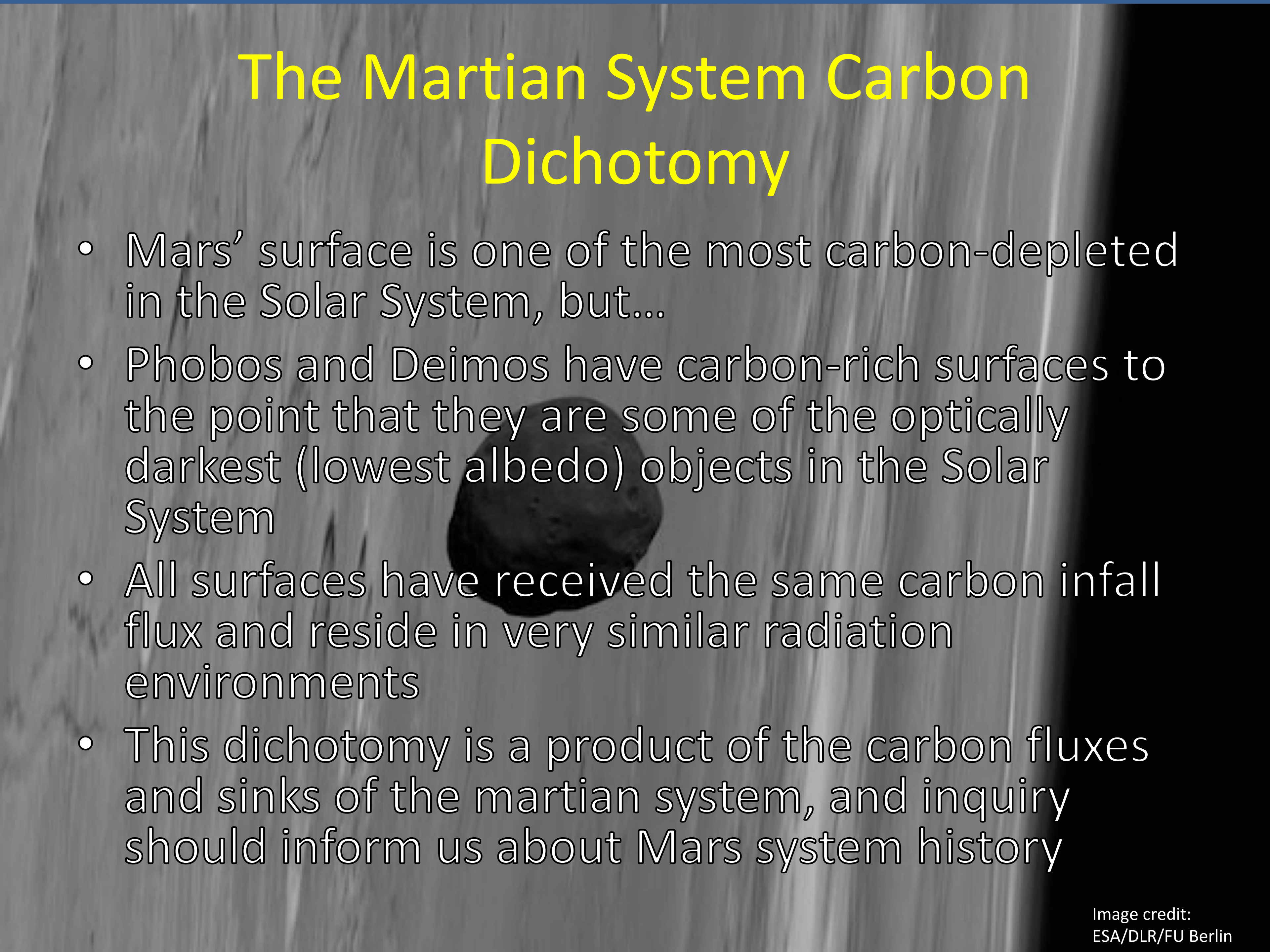


Image credit: ESA/DLR/FU Berlin

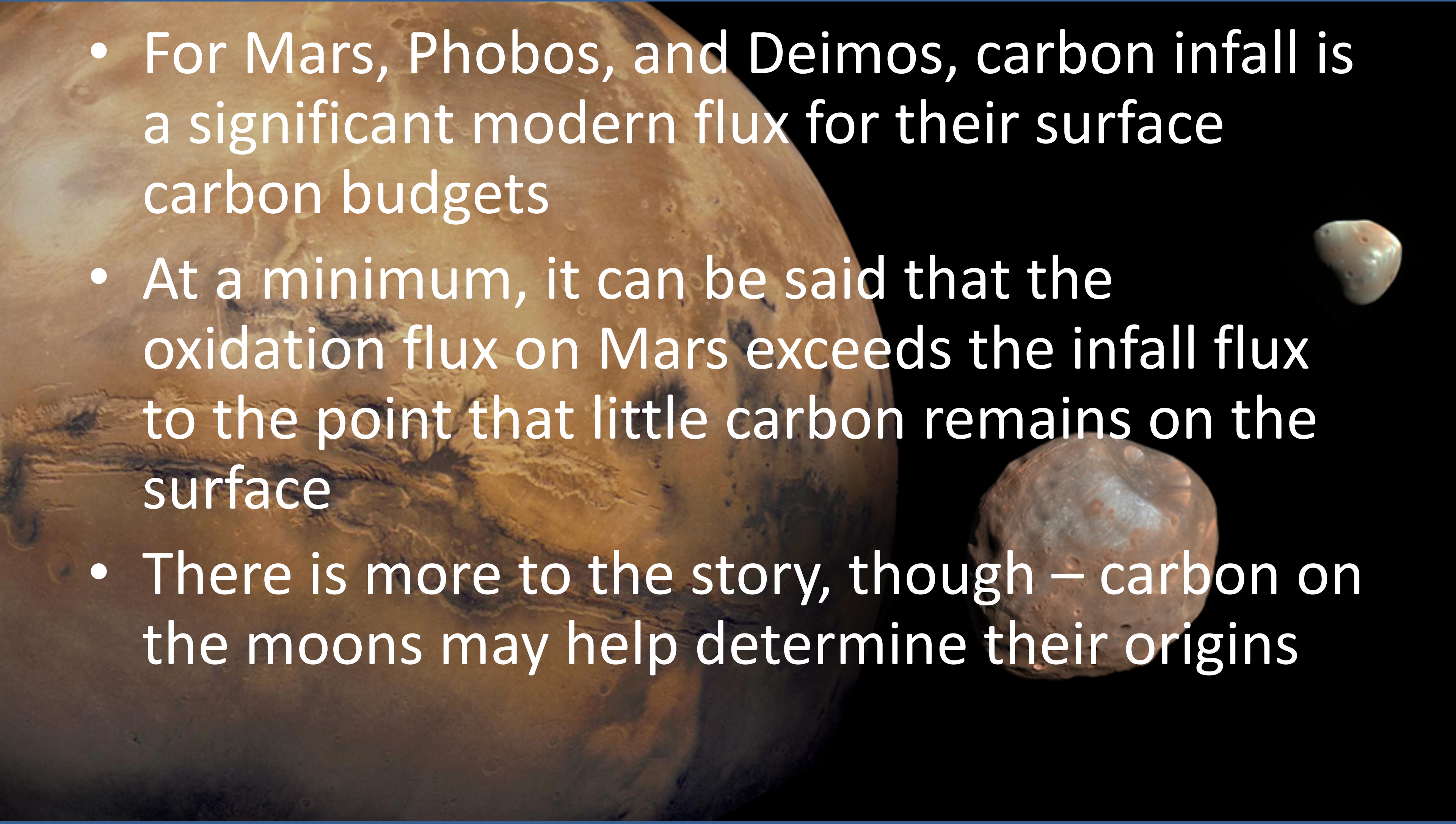
Carbon on Mars' Surface

- Mars' surface is strongly depleted in carbon
- Viking 1&2, MSL used ppb-sensitive instruments to determine that the abundance of light organic species ranges from BDL-low ppb
  - What they do find is heavily chlorinated and chemically degraded, to the point that ascertaining its origin is impossible
- Possible "refractory" carbon
  - "Refractory carbon" at ppm level (Eigenbrode et al 2014)
  - Mellitic acid (500 ppb to 500 ppm, Benner et al 1999)
  - Oxalate (110-320 ppm, or 150-700 ppm, or carbonate..., Applin et al 2015)
- In any event, total carbon is possibly as high as 100s of ppm at most

Carbon on Phobos and Deimos

- Surface carbon measured by reflectance spectrometry only (e.g. only the visible surface)
- Spectra are claimed to match C, D, or T type carbonaceous asteroids
- D type is close match to Tagish Lake meteorite, which contains 3.6±0.2 wt.% C (Brown et al 2000)
- Regardless of type, Phobos and Deimos are interpreted as carbon-rich to the multiple-wt.% level
- Ergo, the surfaces of Phobos and Deimos contain at least an order of magnitude more carbon than the martian surface as a conservative estimate

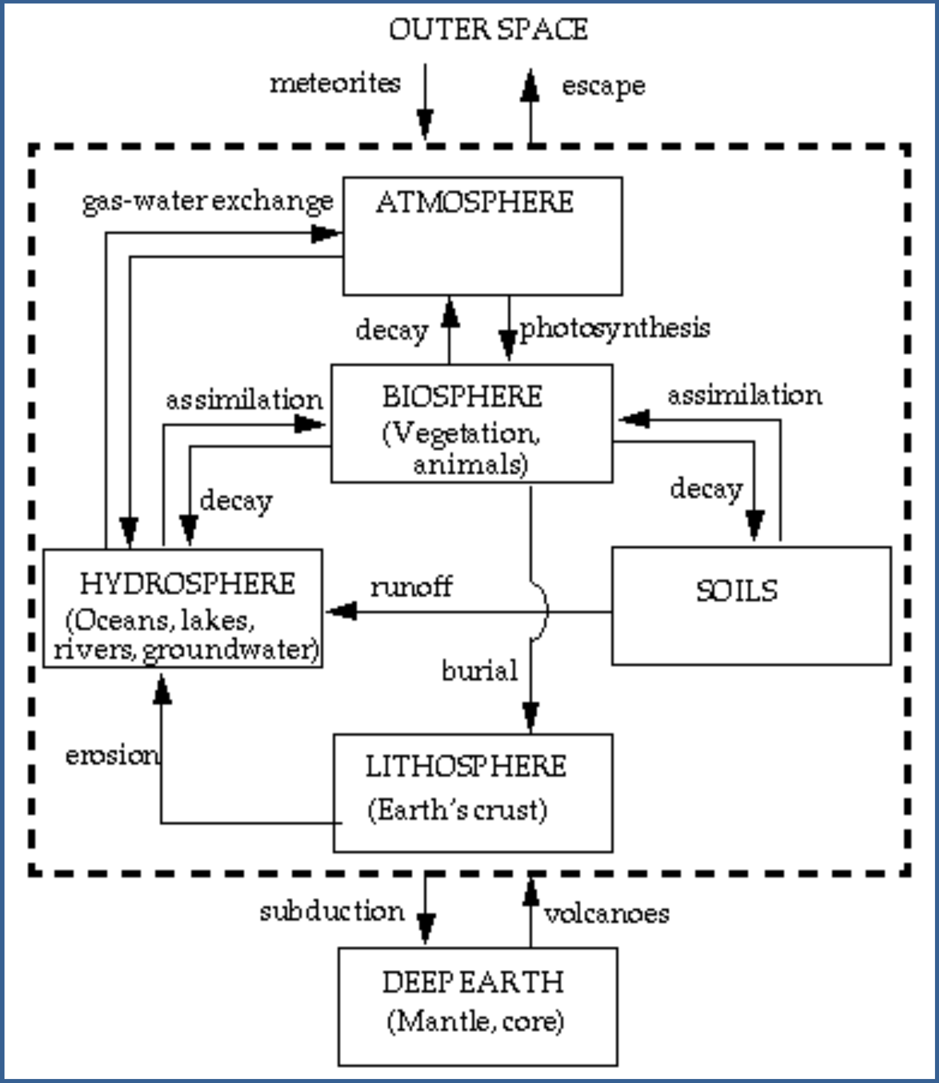
Carbon Has a Role to Play in Understanding the Mars System



- For Mars, Phobos, and Deimos, carbon infall is a significant modern flux for their surface carbon budgets
- At a minimum, it can be said that the oxidation flux on Mars exceeds the infall flux to the point that little carbon remains on the surface
- There is more to the story, though – carbon on the moons may help determine their origins

Carbon Cycle for the Martian Surface

- Taking a carbon-cycling approach to identify important fluxes and sinks for present-day carbon on Mars, Phobos, and Deimos
- Very mature approach for Earth, adaptable for Mars' surface



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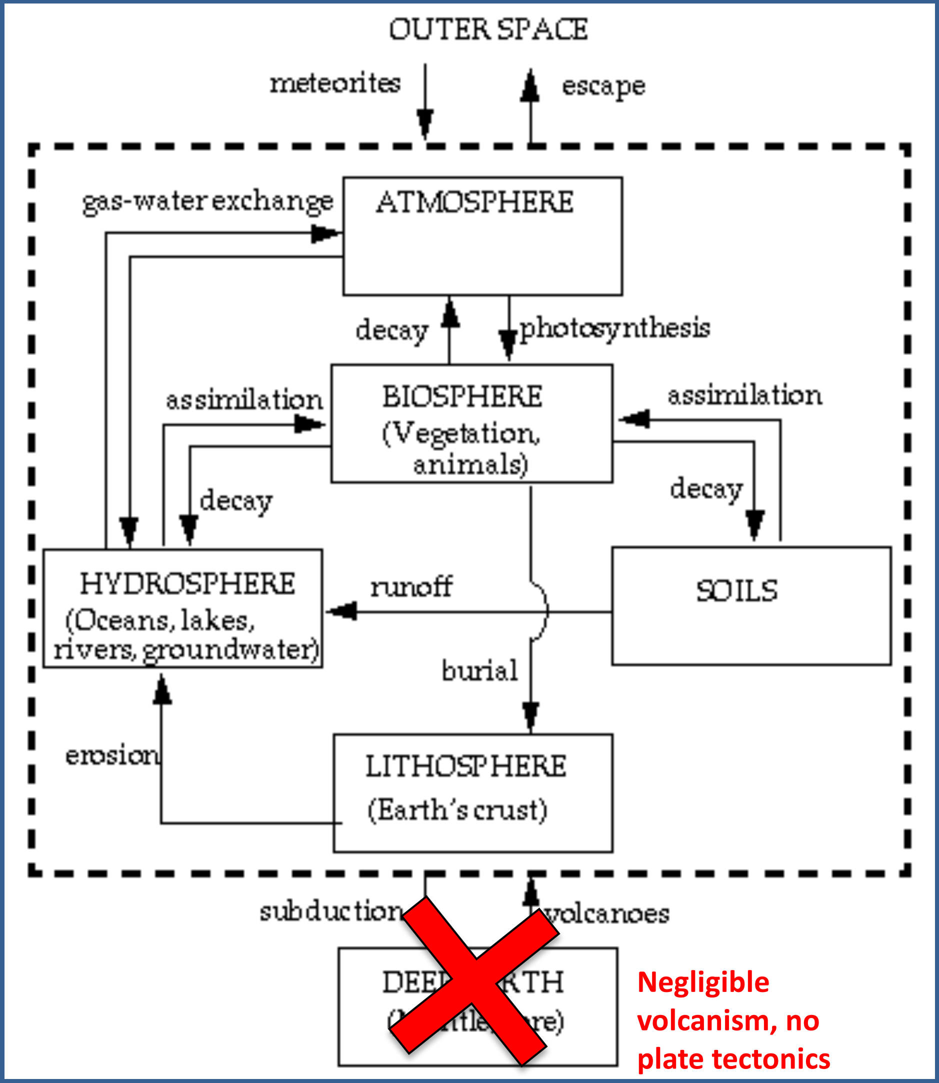

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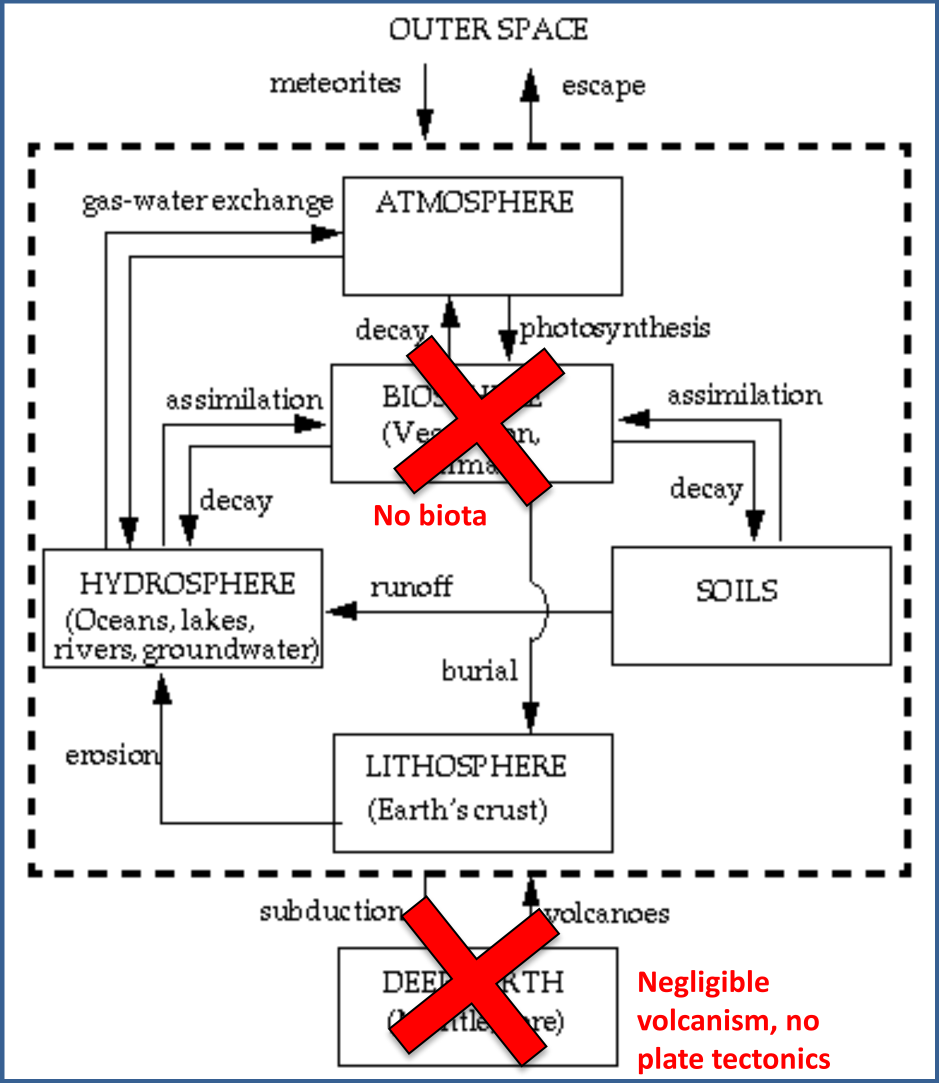

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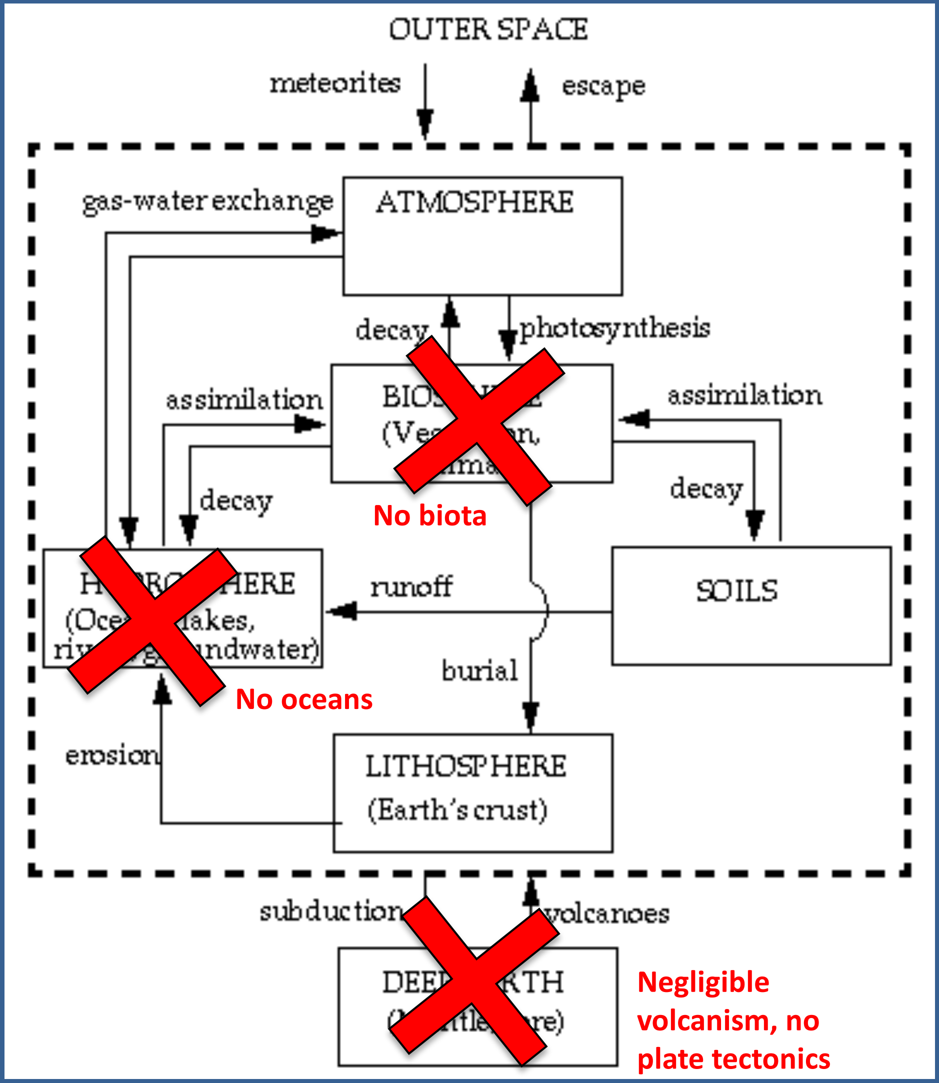

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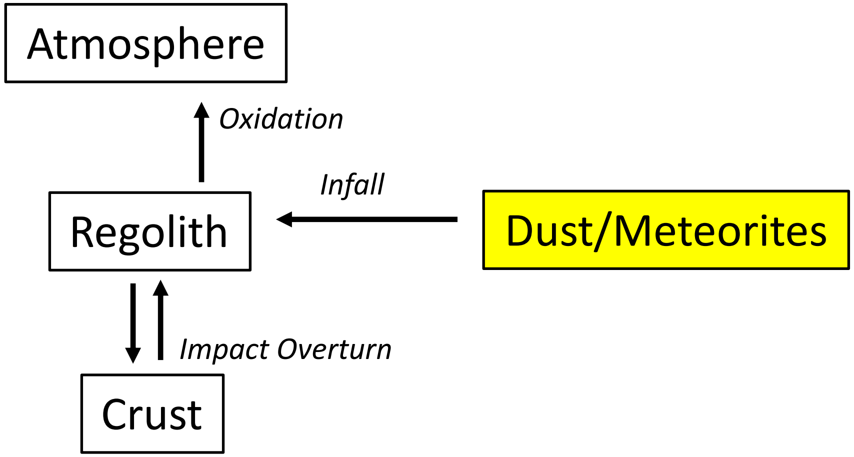
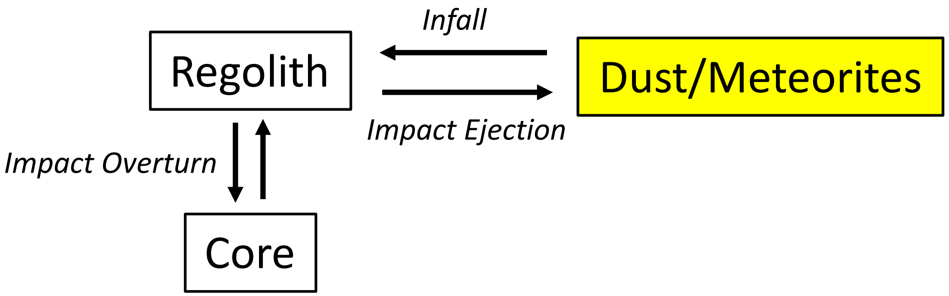


- Mars' surface carbon cycle simplifies to interactions between the surface, atmosphere, and infall
- Impact overturn is a very slow process

Carbon Cycle for Phobos and Deimos

- Phobos and Deimos are similarly simple
- Impact ejection may be significant since gravity is low
- Similar to Mars' surface, but without oxidation to atmosphere



- *Unlike Earth, infall mass is a significant contributor to carbon surface budget*

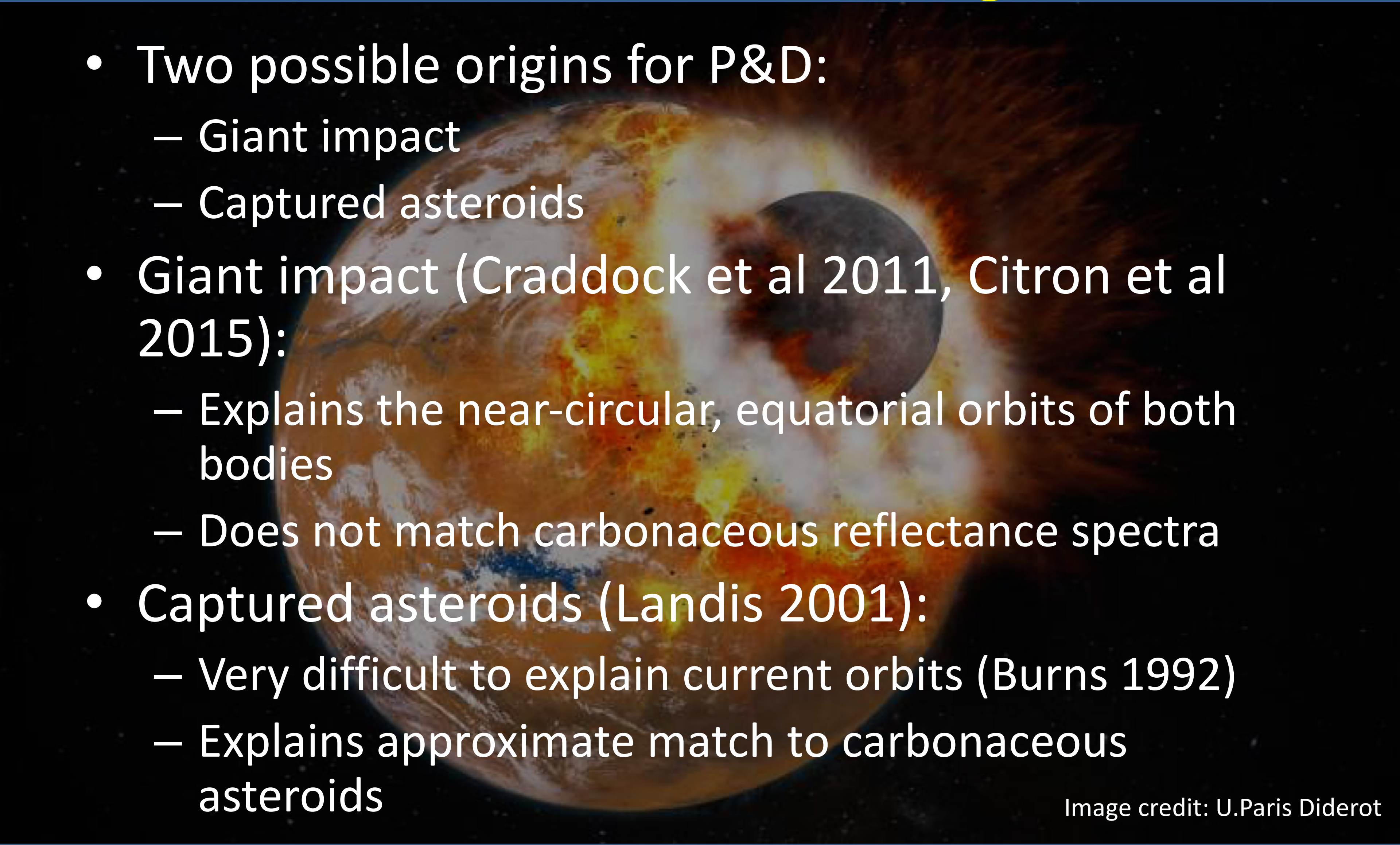
Interplanetary Dust Particle (IDP) Infall

- Dominates modern martian surface carbon addition
- Phobos and Deimos, regardless of origin, differ from asteroids in one important way – they lie down in Mars' gravity well, therefore, *they receive Mars' infall flux*
- Using IDP flux for Mars of 0.71-2.96E^{6} kg/yr (Frantseva et al 2018) and a simple assumption based on surface area ratio, Phobos receives 8-32 kg/yr and Deimos 2-10 kg/yr

Here Comes the Math

- Assuming Phobos and Deimos have been in their present orbits for 4 Ga, this means:
  - Phobos accreted ~2m of IDPs and Deimos accreted ~3m of IDPs in 4Ga
  - With regolith gardening, time to accumulate 2% carbon on their surface (enough to dominate reflectance spectra) is 155-650 Ma for Phobos and 110-440 Ma for Deimos
    - 4-16% of Phobos' age and 3-11% of Deimos' – implies that Stickney crater is young!
  - Assumes IDP density of 1.6 g/cc and 10% C, Moon-like gardening rate
- Meteoritic infall requires more sophisticated treatment; mass ejection becomes important
- Radar measurements indicate Phobos and Deimos have some of the lowest radar albedos, and therefore the finest-grained regolith, of any bodies in the Solar System (Busch et al 2007, described as "powdery", only 1.47 g/cc)

Phobos/Deimos Origins



- Two possible origins for P&D:
  - Giant impact
  - Captured asteroids
- Giant impact (Craddock et al 2011, Citron et al 2015):
  - Explains the near-circular, equatorial orbits of both bodies
  - Does not match carbonaceous reflectance spectra
- Captured asteroids (Landis 2001):
  - Very difficult to explain current orbits (Burns 1992)
  - Explains approximate match to carbonaceous asteroids

Image credit: U.Paris Diderot

Third Option: Giant Impact Followed by Carbon Infall

- Formation by giant impact would explain current orbits
- IDP infall may explain carbonaceous reflectance spectra (Fries et al 2017)
- Matches recent findings of Phobos as a “rubble pile, barely holding together, with a powdery regolith” (Hurford et al 2015)
- If so, Phobos and Deimos have IDP-rich carbonaceous exterior with Mars-origin, rubble-pile interior
  - No ice!
  - Poor mechanical toughness

Implications/Summary

- Dichotomy itself:
  - Carbon is not accumulating on the martian surface. Mars' oxidative loss to atmosphere is faster than 0.71-2.96E^6 kg/yr IDP infall rate. Carbon on the surface should be *young* (Frantseva et al 2018).
- Origins of Phobos and Deimos:
  - If P&D are captured, carbon infall is irrelevant and they are carbonaceous asteroids
  - If P&D formed from giant impact, carbon addition is necessary to explain their current spectra
  - If infall explains reflectance spectra, then the surface composition does not match the interior, Stickney is young, and there is no ice on the moons
- JAXA MMX sample return mission should resolve the origins issue

Thank You!

Image credit: Celestia

Carbon Paucity on Mars

- Mars, Phobos, and Deimos receive the same carbonaceous infall
- An oft-quoted reason for the paucity of carbon on Mars is degradation of carbon species via UV + GCR radiolysis
- Phobos and Deimos reside in a very similar radiation environment, but without atmospheric shielding
- Two observations:

1. Radiolysis *per se* is not sufficient to denude Mars' surface of carbon, otherwise Phobos and Deimos would be equally carbon deficient
   – Oxychlorine species probably play a oxidative role that is poorly understood
2. Loss rate of carbon at the martian surface is greater than the carbon infall rate

The Photolytic Degradation and Oxidation of Organic Compounds Under Simulated Martian Conditions

J. Oró and G. Holzer

The effect of ionizing radiation on the preservation of amino acids on Mars

Gerhard Kminek *, Jeffrey L. Bada

The effects of Martian near surface conditions on the photochemistry of amino acids

Inge Loes ten Kate[a, b], James R.C. Garry[a], Zan Peeters[a], Bernard Foing[c], Pascale Ehrenfreund[a]

Amino acid photostability on the Martian surface

Inge Loes TEN KATE[1, 2*], James R. C. GARRY[2], Zan PEETERS[2], Richard QUINN[2, 3], Bernard FOING[4], and Pascale EHRENFREUND[2]