Impact Craters: cradles of life, frustrators of life, or revealors of a wet subsurface?

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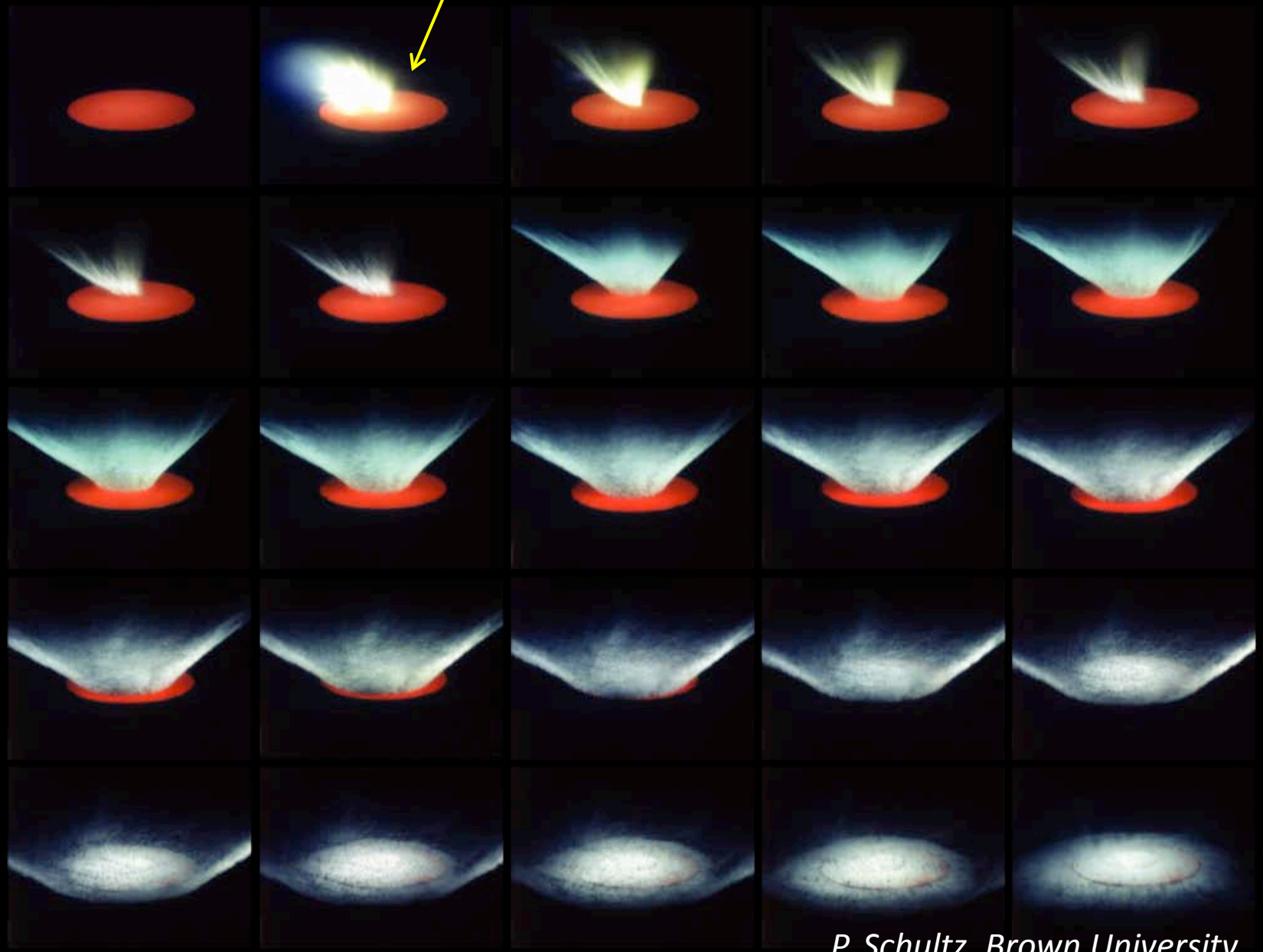
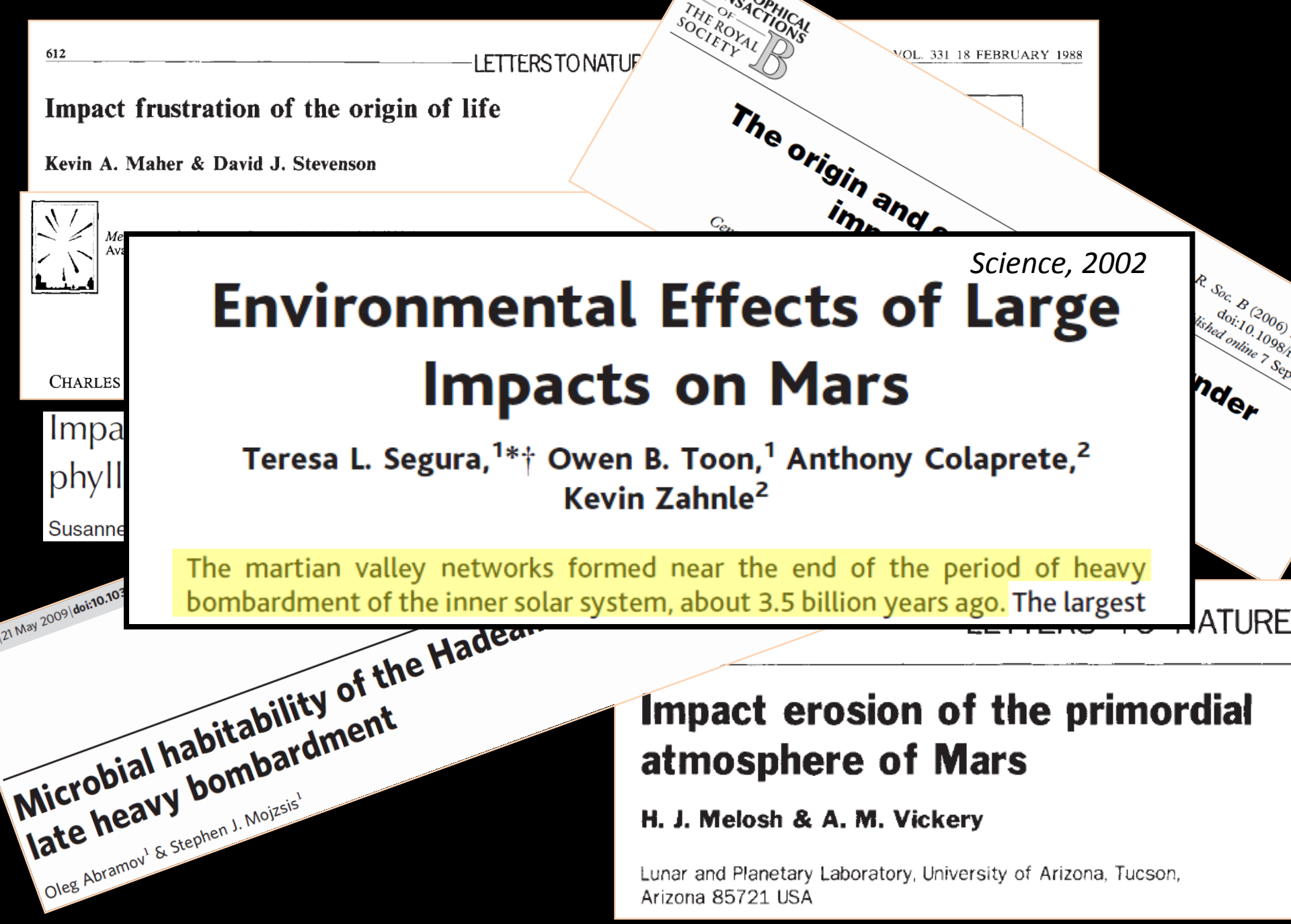
Institut d'Astrophysique Spatiale
(from Sept. 2011 @ Caltech; ehlmann@caltech.edu)

June 28, 2011

30 degrees, 1/8 inch Al - projectile into loose sand



P. Schultz, Brown University

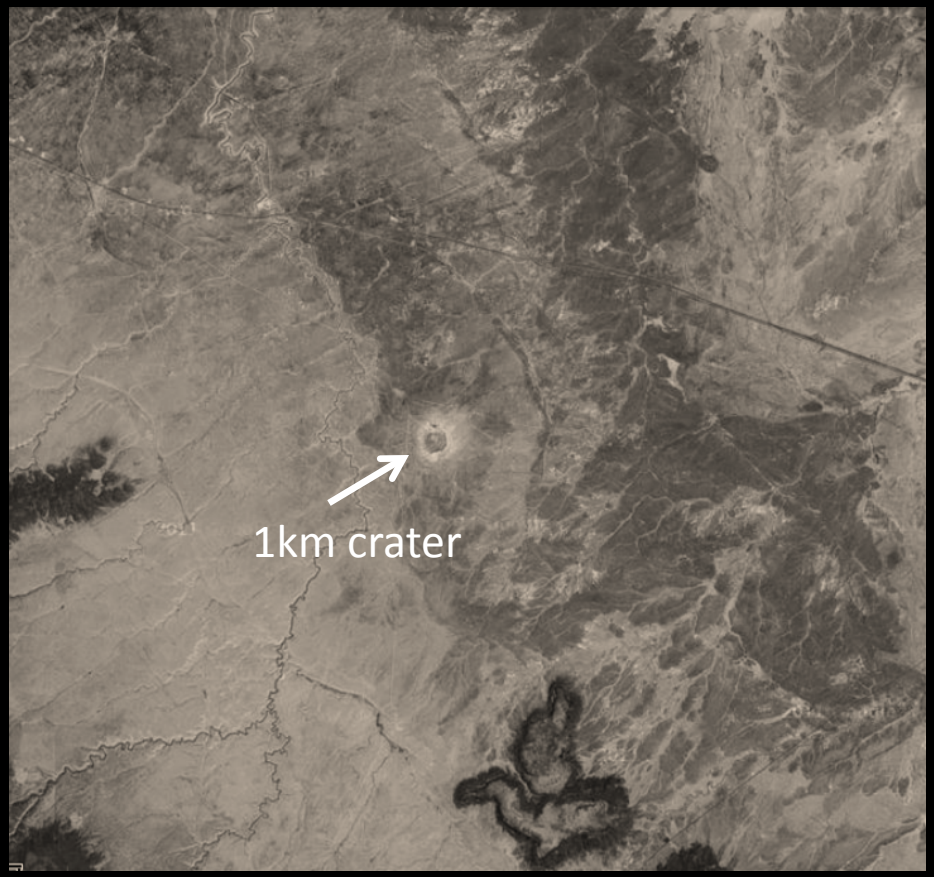

612
LETTERS TO NATUR
VOL. 331 18 FEBRUARY 1988
Impact frustration of the origin of life
Kevin A. Maher & David J. Stevenson
CHARLES
The origin and
Science, 2002
Environmental Effects of Large Impacts on Mars
Teresa L. Segura,1*† Owen B. Toon,1 Anthony Colaprete,2 Kevin Zahnle2
The martian valley networks formed near the end of the period of heavy bombardment of the inner solar system, about 3.5 billion years ago. The largest
21 May 2009 | doi:10.103
Microbial habitability of the Hadea
late heavy bombardment
Oleg Abramov1 & Stephen J. Mojzsis1
NATURE
Impact erosion of the primordial atmosphere of Mars
H. J. Melosh & A. M. Vickery
Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721 USA

=

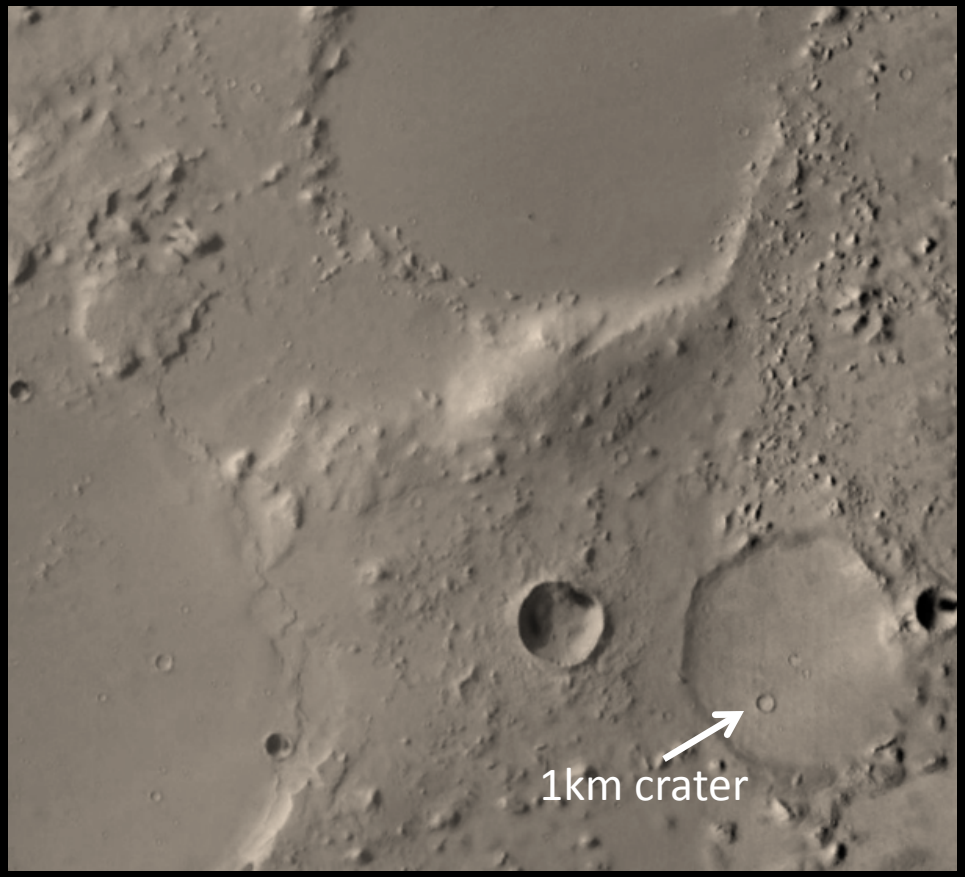
?

Craters serve (only?) as excavators to reveal what lies beneath

On Mars, cratering has an enormous role in shaping the landscape

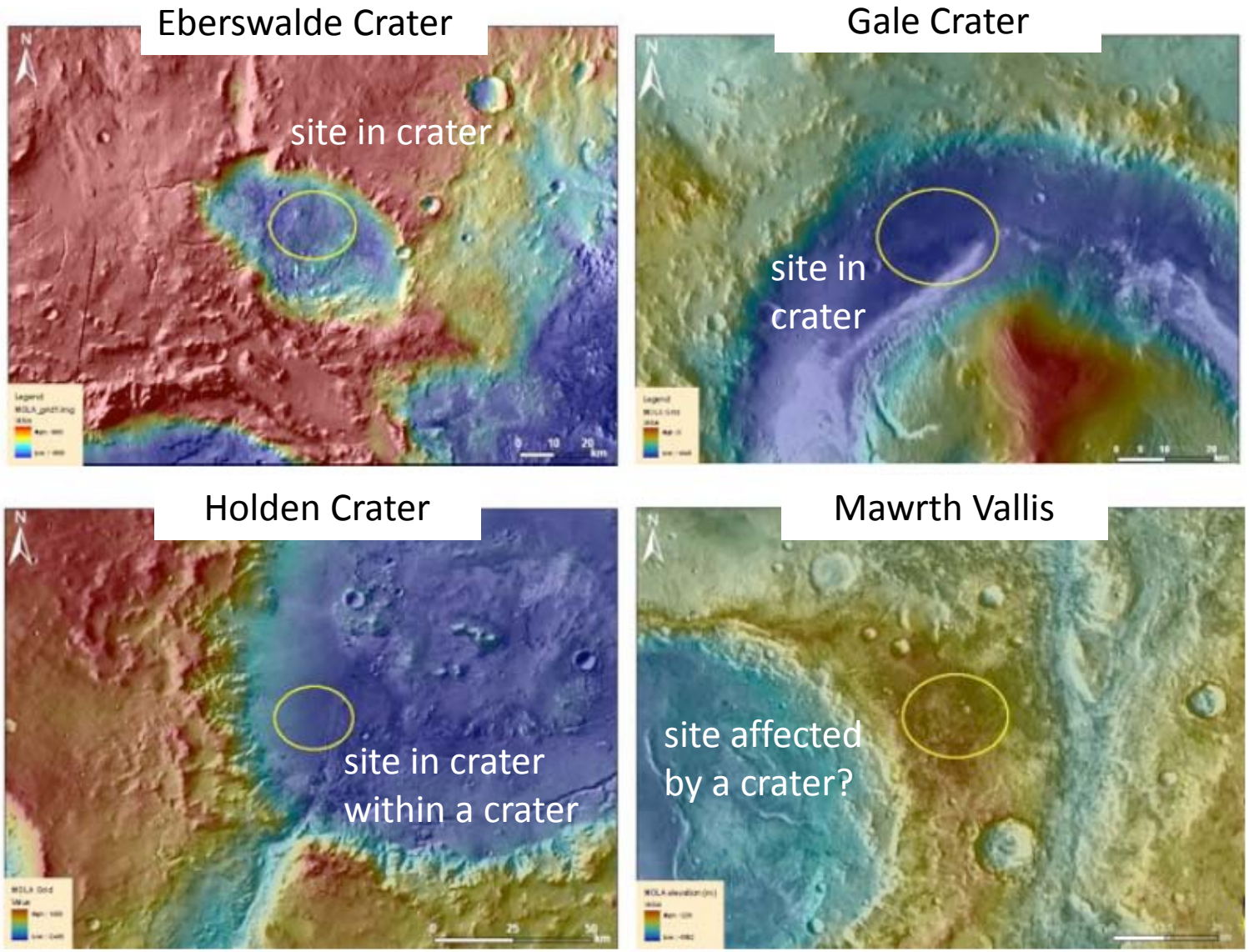


EARTH, Meteor Crater, Arizona



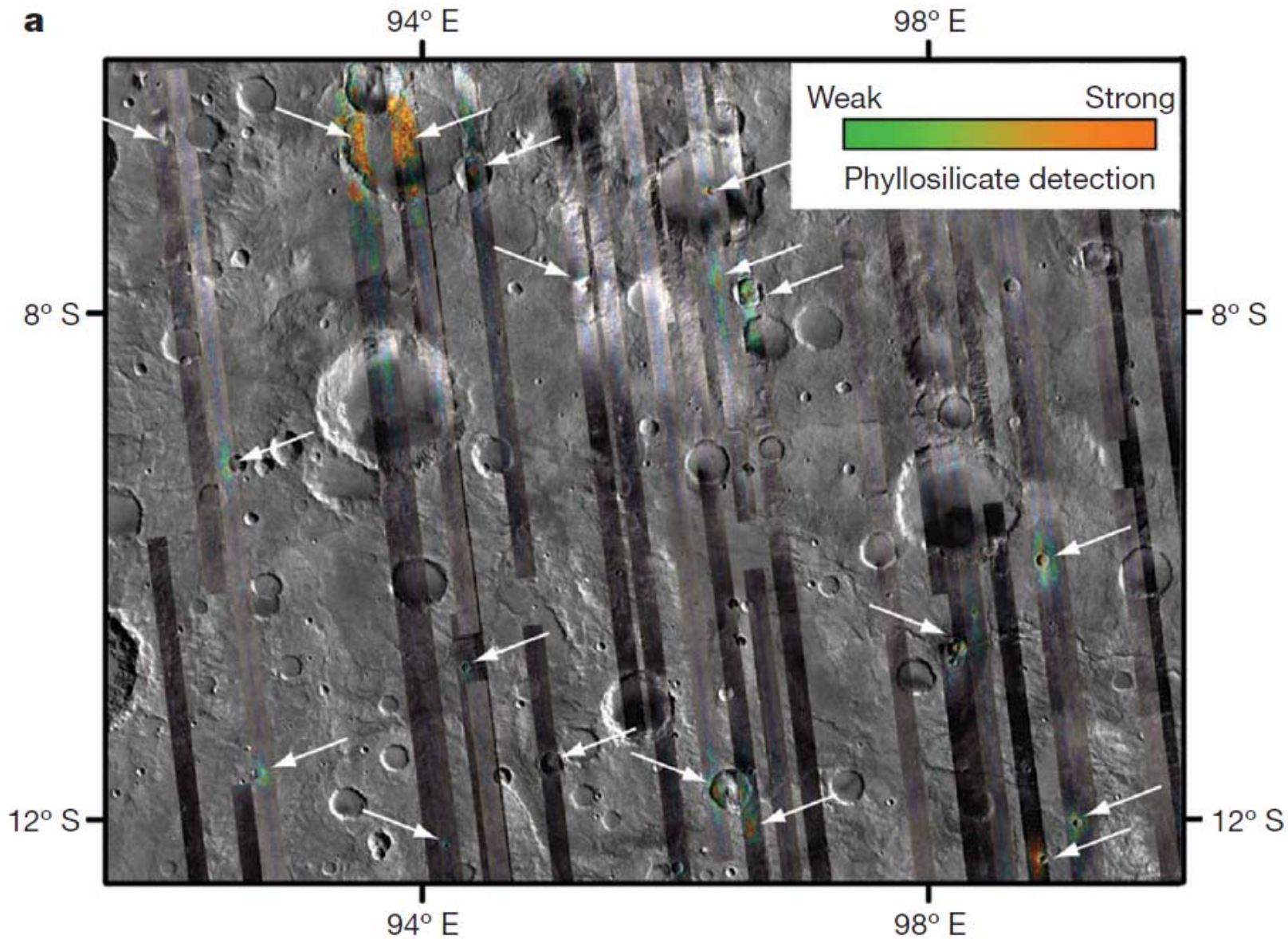
Mars, NE Syrtis Major lava plains

Understanding Effects of Cratering: Important for MSL landing site selection



Golombek et al., 2011, LPSC

1000s of exposures of hydrated minerals are associated with craters



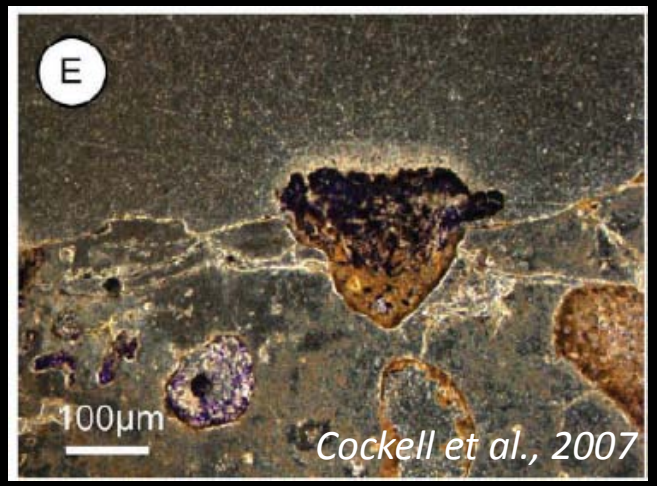
Craters and Life?

- Heat and shock of impact are not conducive to life
- But, after the initial impact a number of effects may favor life
  - heat from impacts can melt ice
  - glassy materials make chemical nutrients more readily available
  - fractured surfaces available for colonization

Microbial tubule structures in glassy basalt, ~3.5Gyr

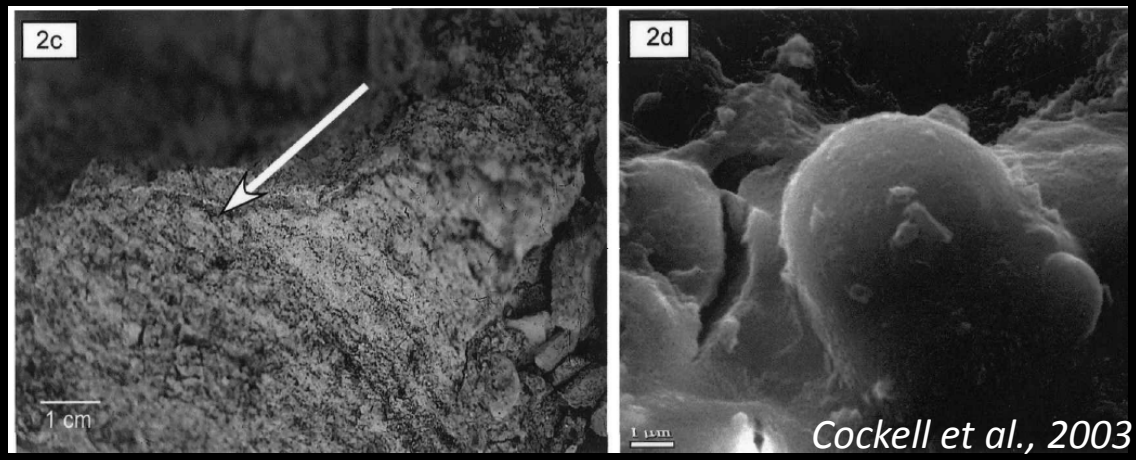
Banjerjee et al., 2006, EPSL

Lichen colonizing impact melt, Lockne crater



Cockell et al., 2007

Microbial colonization of shocked gneiss, Haughton crater

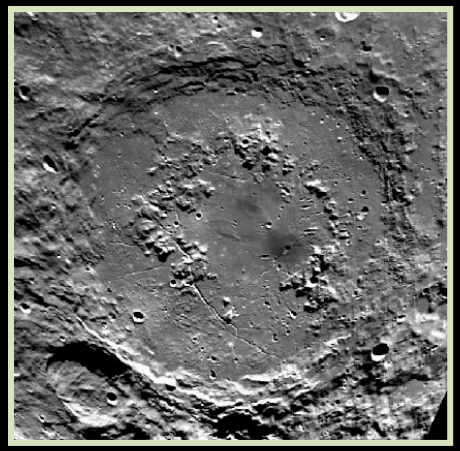
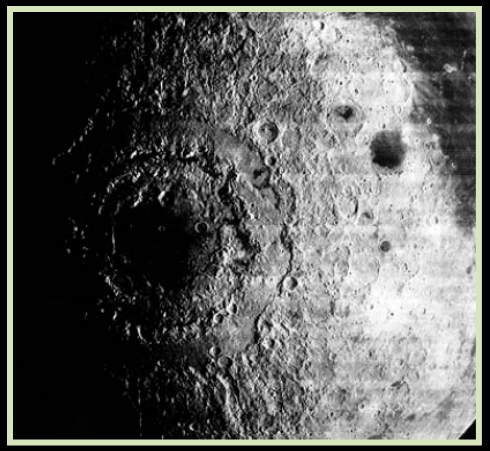


Cockell et al., 2003

Outline

I. How craters form and effects on geologic materials
II. Impact flux through time
III. Large-scale environmental implications of LHB
IV. Small-scale environmental implications of a single impact
V. Mars: what are the effects of craters?

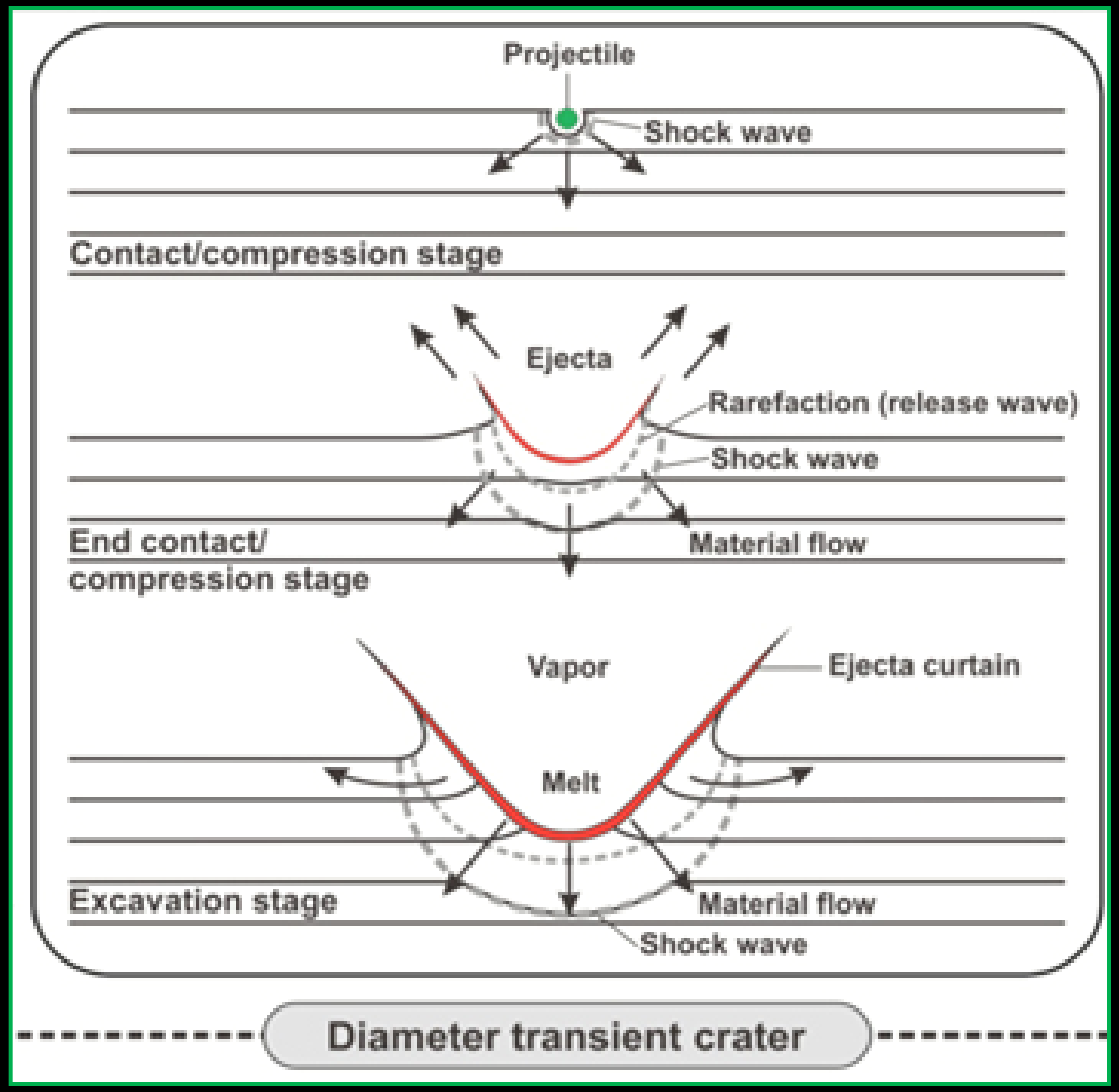
I. How craters form and effects on geologic materials

Simple (bowl)	Complex (central peak, slumping walls)	More Complex (Multiple rings, etc.)	Basin (Enormous!)
			
< Few km	Tens of km	Hundreds of km	> Hundreds km

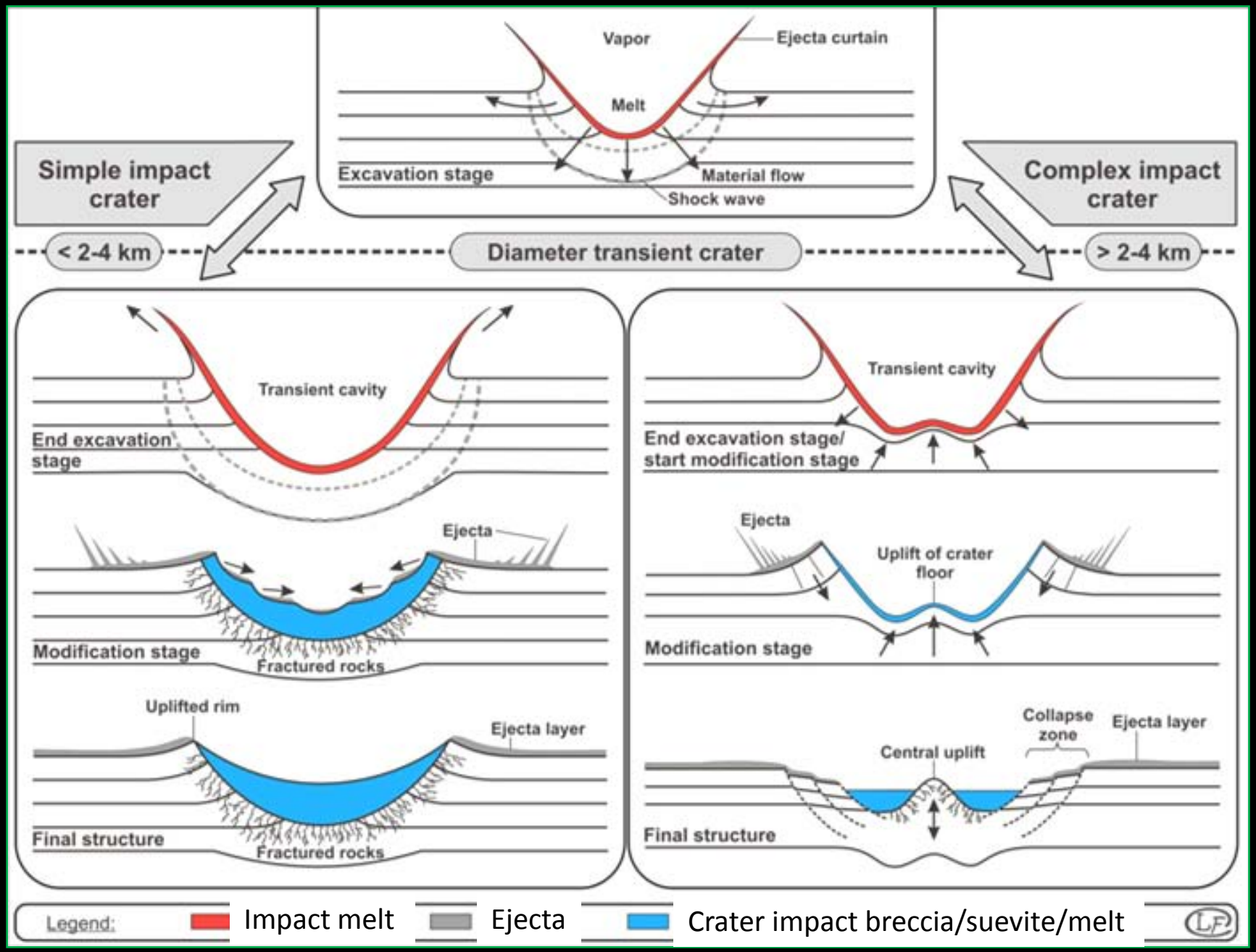
Size

Steps in Crater Formation

- Compression /Compaction
- Excavation
- Modification



French, 1998, Traces of Catastrophe



French, 1998, Traces of Catastrophe

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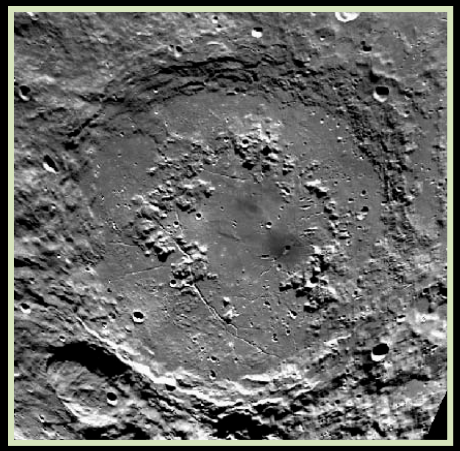
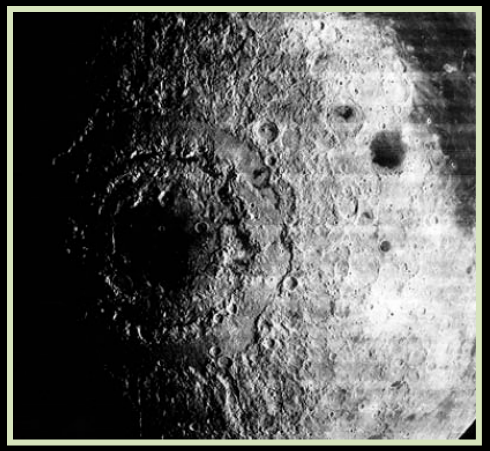
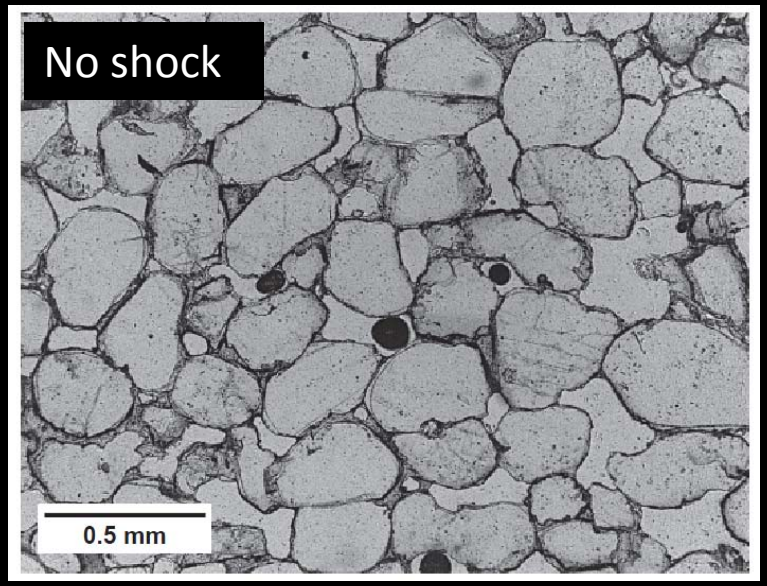
			
< Few km	Tens of km	Hundreds of km	> Hundreds km

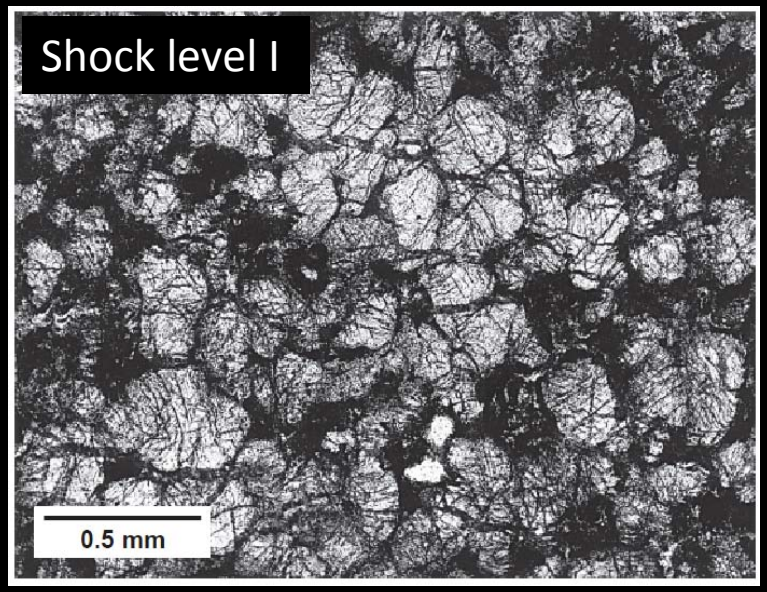
Size

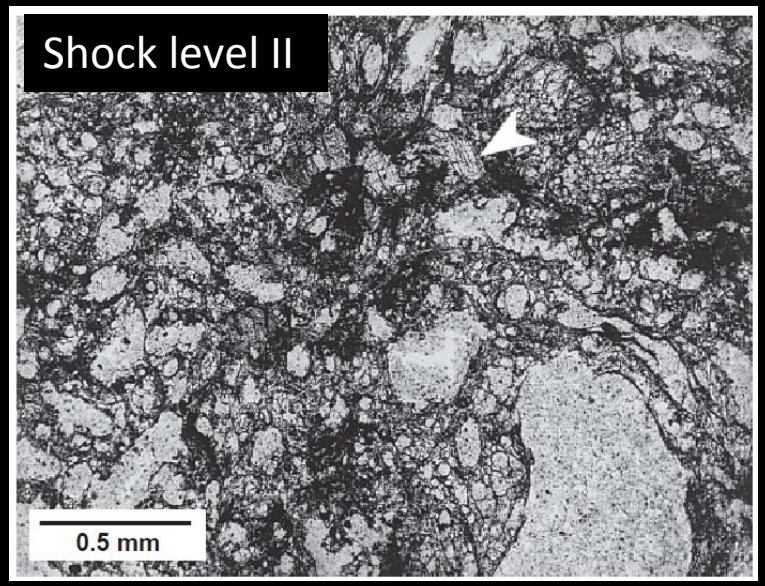
Efficiency

Compaction/ Compression stage

- Near-instantaneous shock of target materials
- Fracturing, melting, disrupting crystal structure of minerals
- Ex. Shocked quartz from Meteor Crater, Arizona





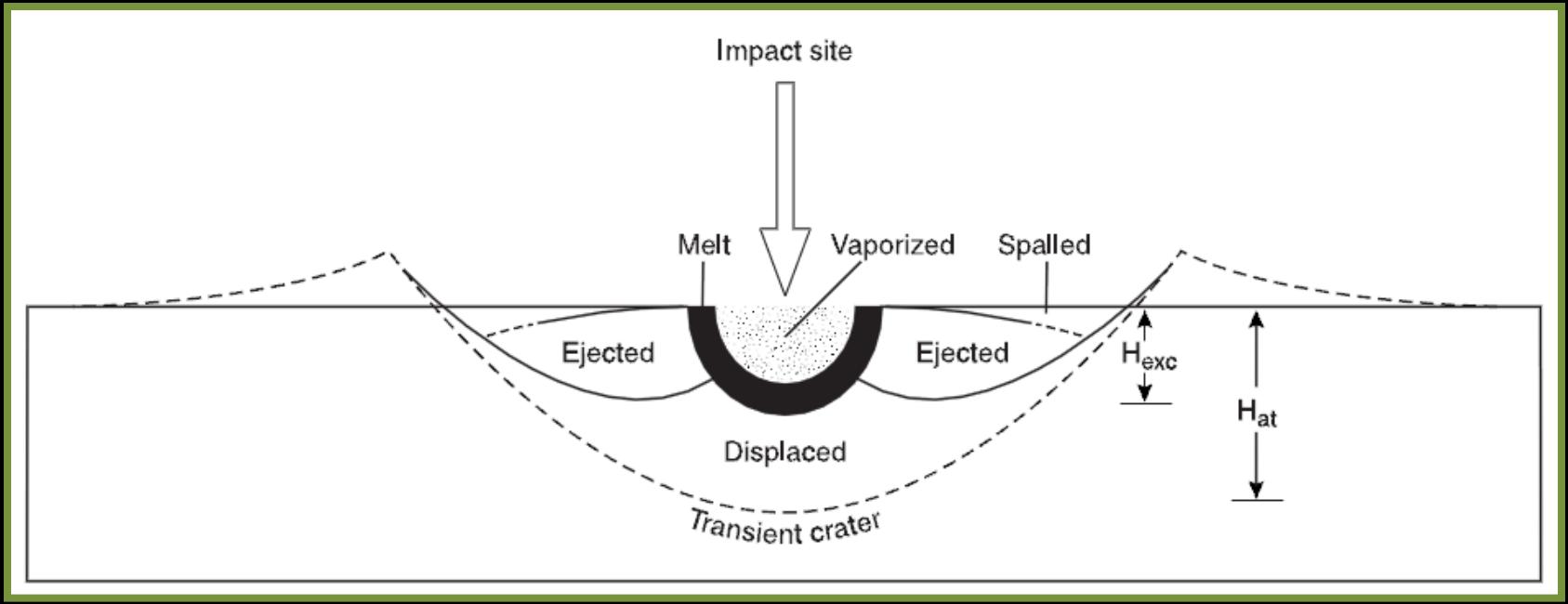


French, 1998, Traces of Catastrophe

Excavation stage

- Characterized by movement of material
- Rarefaction wave causes ejection of materials from the transient category
- Some materials within the crater transient cavity remain within and are disrupted

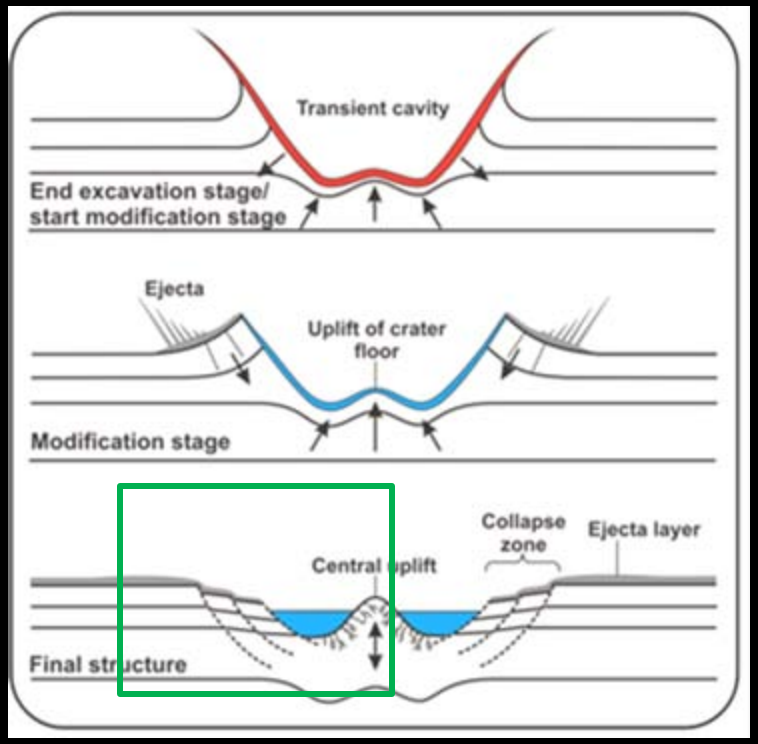
What is the fate of materials within the crater?

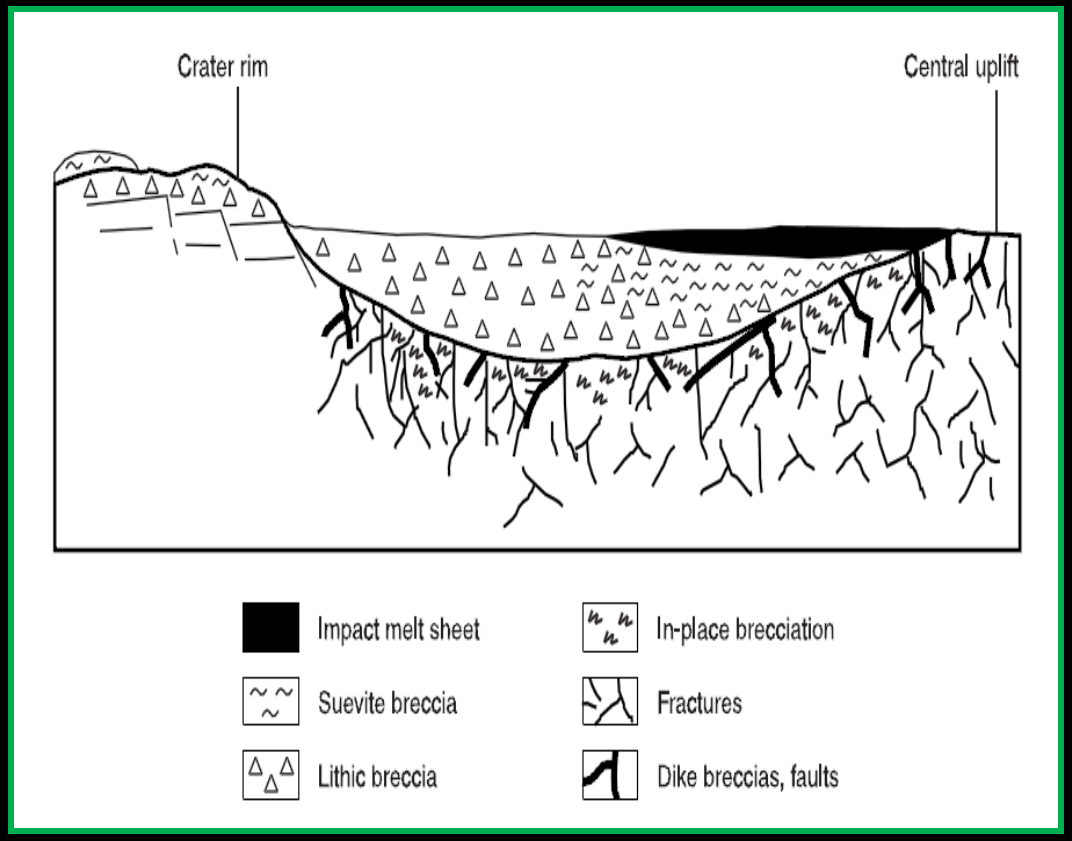


French, 1998, Traces of Catastrophe

Modification stage

- This stage is mostly complete by a few minutes after impact but can last up to years
- Crater assumes its final shape: transient crater collapse





French, 1998, Traces of Catastrophe

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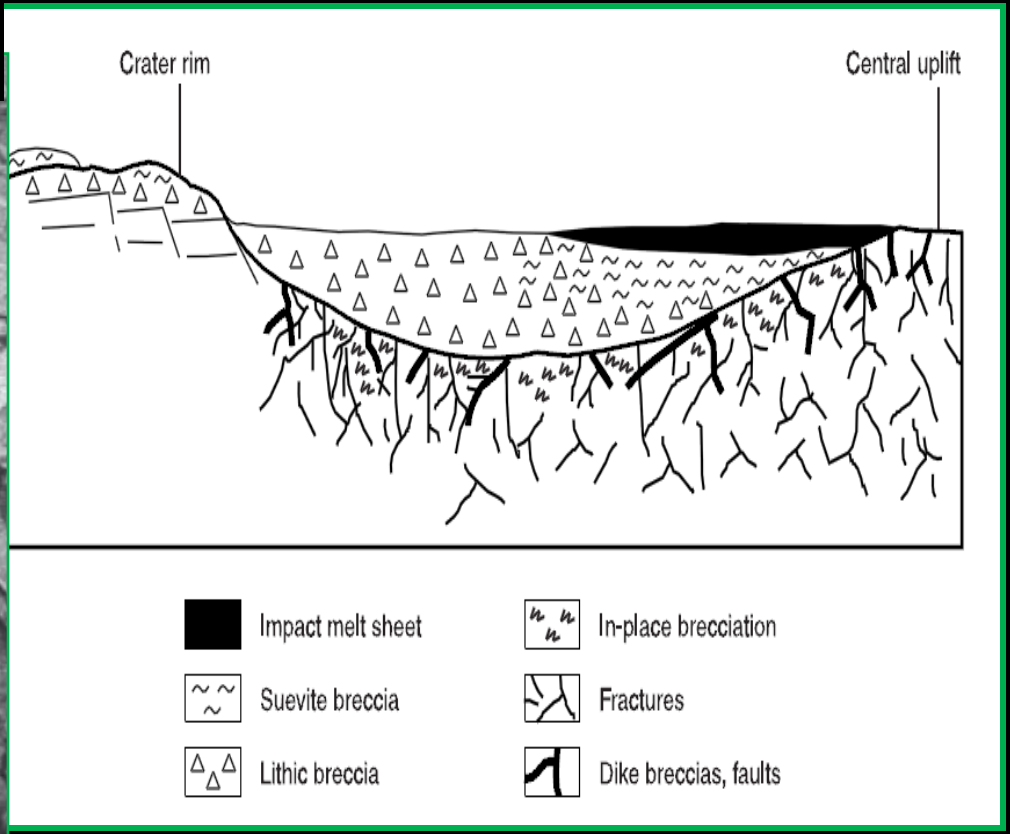
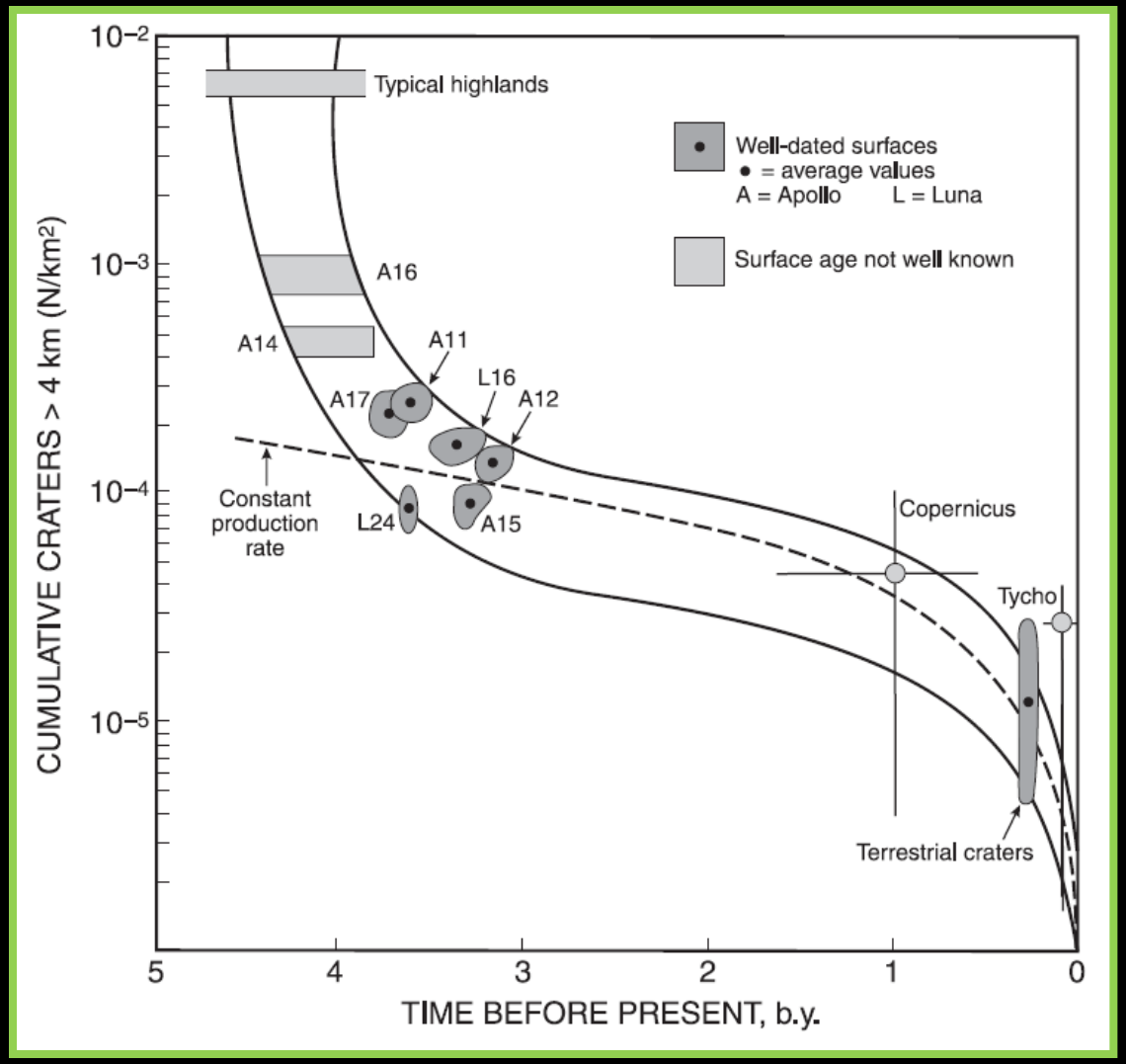
Breccia, Sudbury Impact, Canada
(D~250km)



French, 1998, Traces of Catastrophe

II. Impact flux through time

A record from the Moon



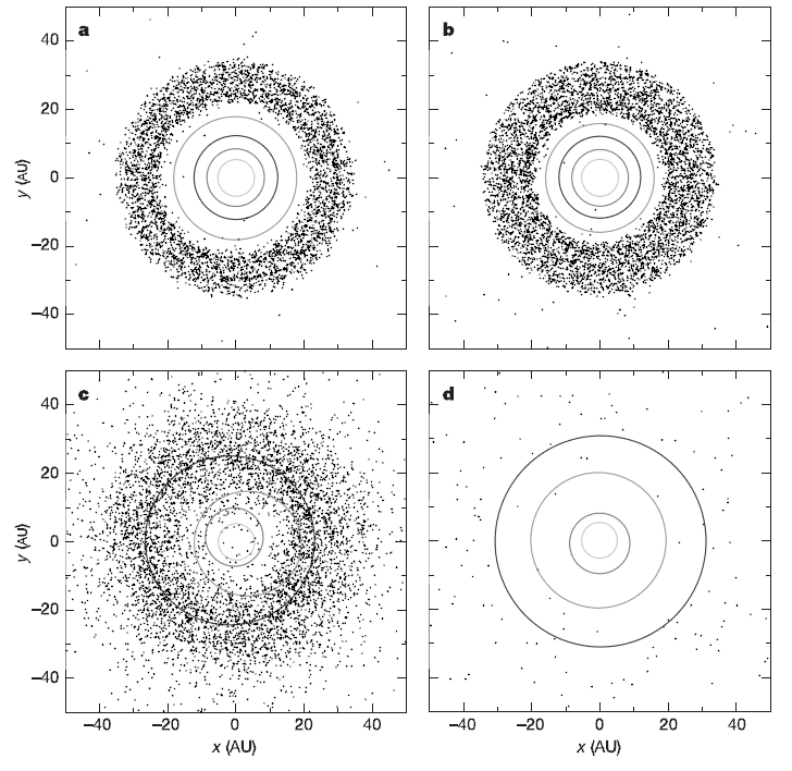
French, 1998, Traces of Catastrophe

- Impact craters can be mapped on the moon globally and relative timing studied
- Apollo samples permit dating of materials
- Appears to be a change in the flux rate just before 3.5 Gyr

Late Heavy Bombardment

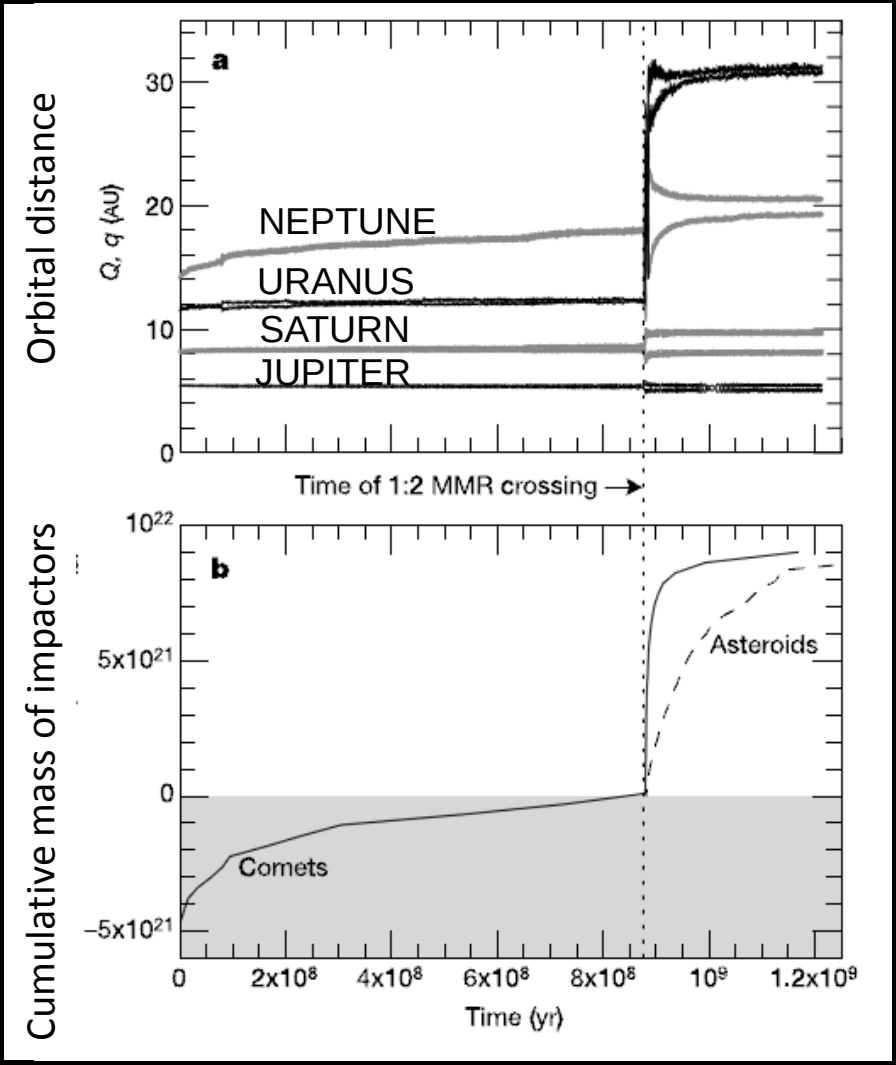
- Migration of the giant planets, in particular Jupiter and Saturn causes gravitational perturbation of smaller bodies
- Bombardment of the inner solar system
- Impact flux changes dramatically early in solar system history

<show movie>



Gomes et al., 2005, Nature

Changes in the Impactor Flux

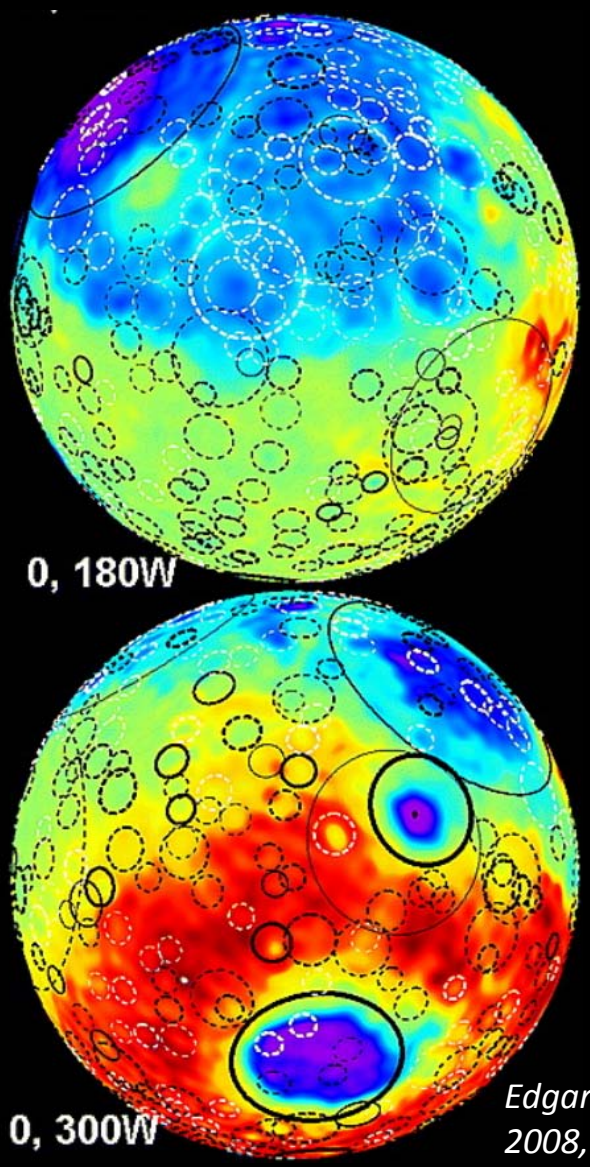


Changes in planetary position

Changes in impact flux

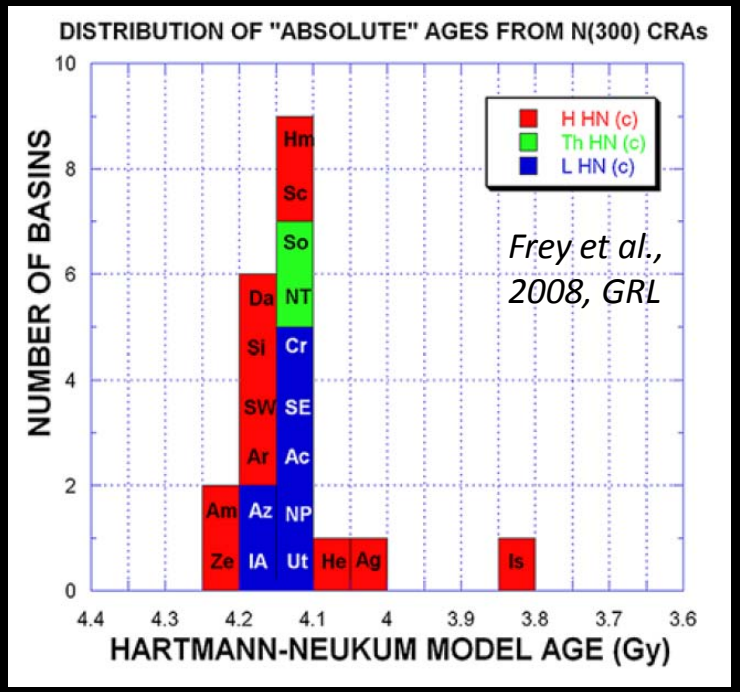
Gomes et al., 2005, Nature

Evidence of the LHB on Mars?



Edgar et al., 2008, GRL

- Buried quasi-circular depressions are visible over all of Mars using gravity and topography data
- These are believed to be early impact basins, subseuqently overprinted
- Clustering of ages: LHB?
- Implication: early crust of Mars was heavily churned



Frey et al., 2008, GRL

III. Large-scale environmental implications of LHB

Note: Not well-understood!

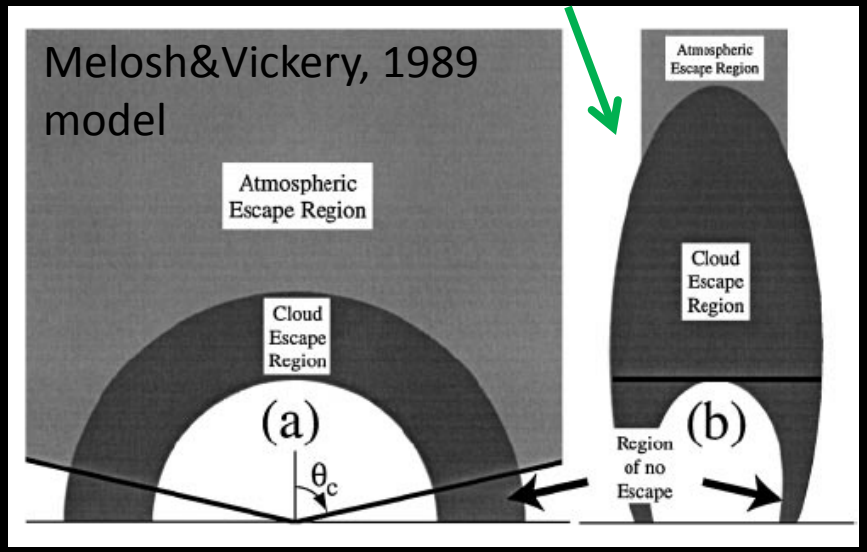
Massive Atmospheric Loss?

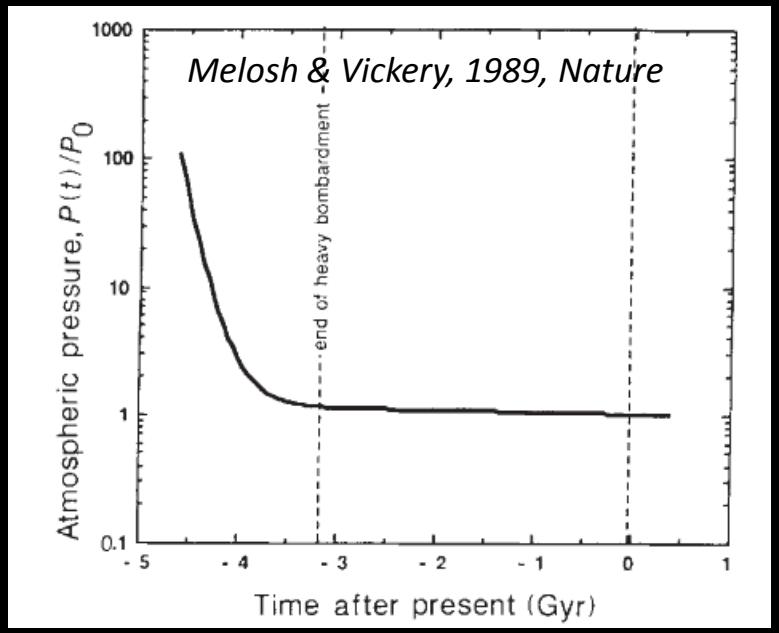
- >3km impactors remove all atmosphere above the tangent plane?

- → Mars could lose 99% of atmosphere by end of heavy bombardment?

- BUT later hydrocode modeling suggestions the region affected may be far smaller

Newman et al., 1999, Icarus



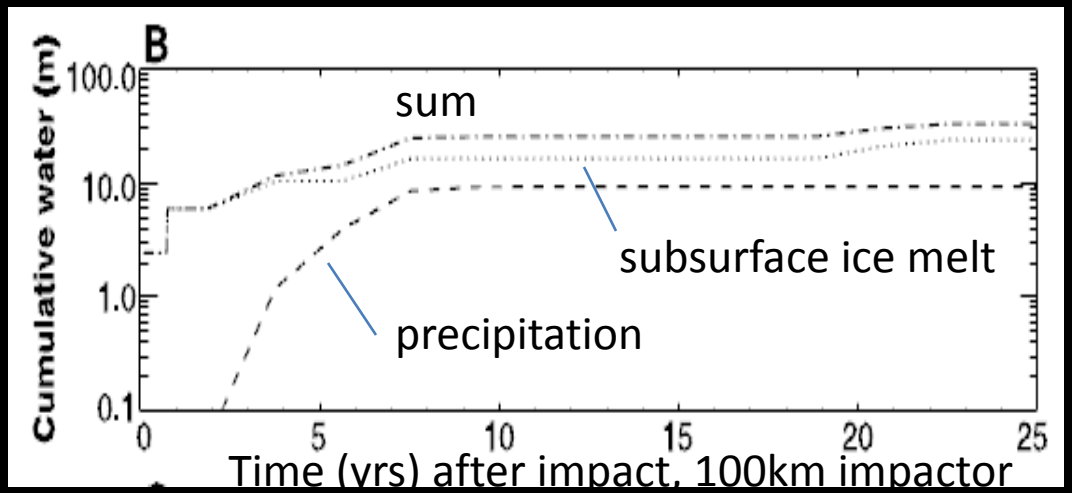


- *Shuvalov, 2009, Met. Plan. Sci.* shows oblique impacts are even less efficient at removal

Massive Liberation of Water?

• Impacts will also deliver water and volatiles to the surface since they have at least a few percent water

• *Segura et al., 2002, Science* propose
  1) delivery of volatiles in impactors
  2) vaporization of ice in the subsurface (20%)
  3) release of water from the polar cap



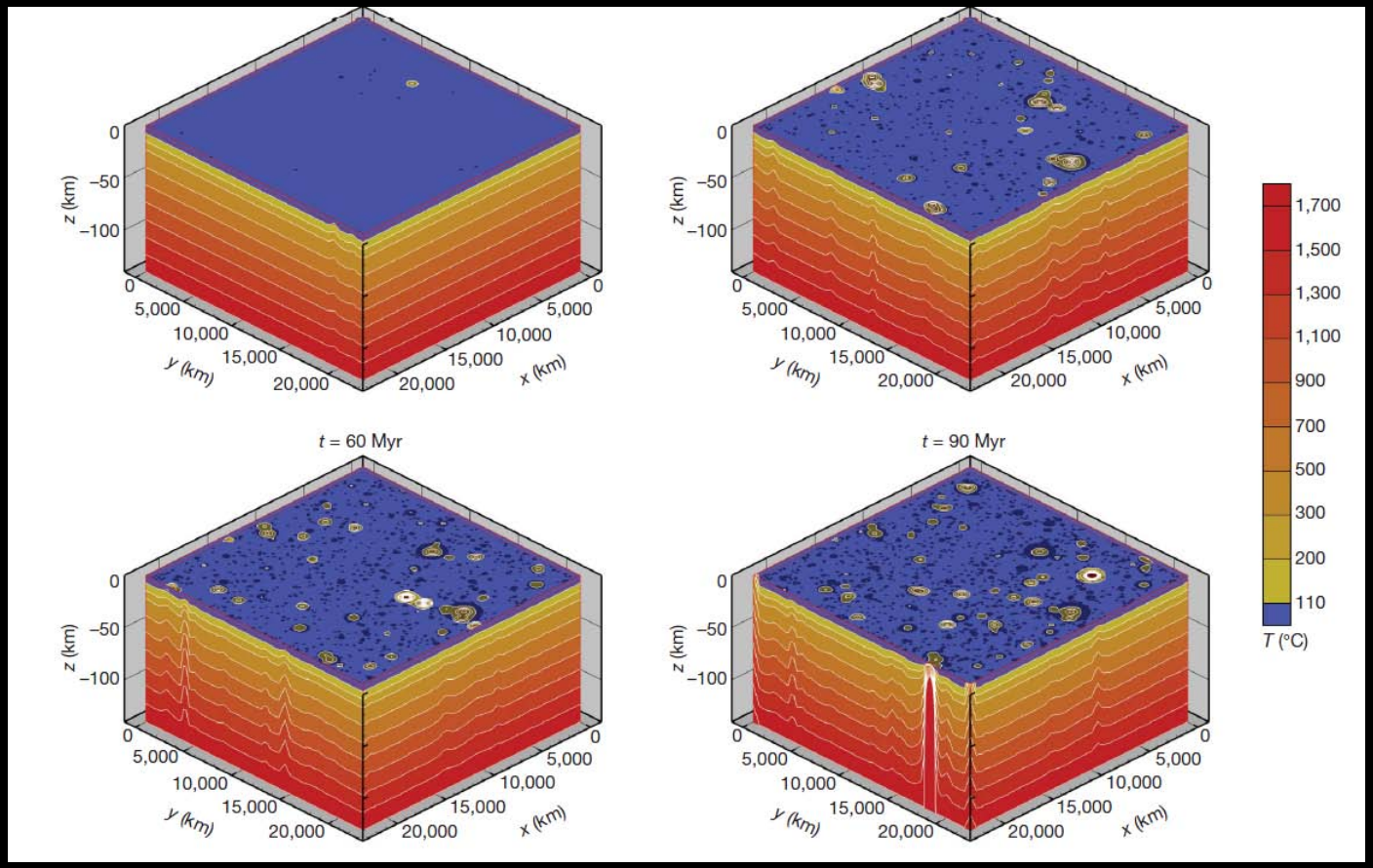
• They model a massive change in climate from these impact-driven processes → lots of rain on early Mars

• BUT, estimates of impactor size are rather large (less than 77 of this size or greater modeled in the asteroid belt at the time of the LHB). Also, (2) and (3) may be somewhat overestimated. Still no consensus…

Thermal Sterilization of the surface?

- Impacts may heat the atmosphere and subsurface beyond the limits of life…or not…

Heating of the Hadean Earth by LHB impacts

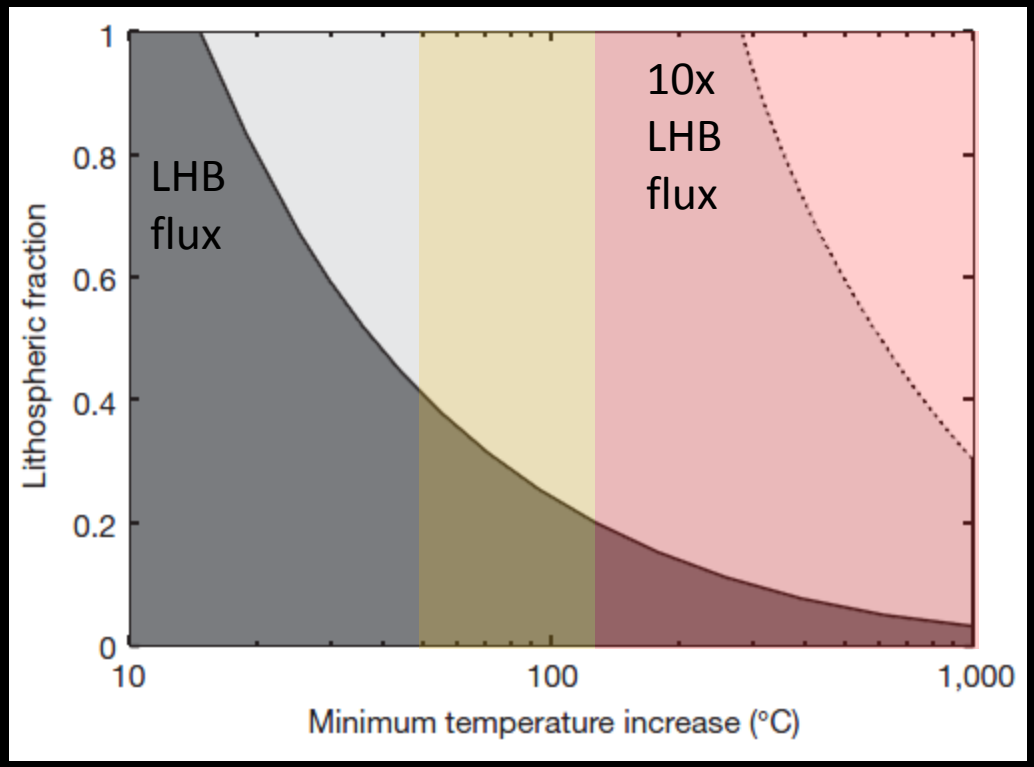


Abramov & Mojzsis, 2009, Nature

No Thermal Sterilization of the surface

- Modeling shows that for Earth (surface is initially warmer than Mars), no sterilization
- 5-10 C heating of the whole surface; T>35 C for only 40%

Heating of the Hadean Earth by LHB impacts



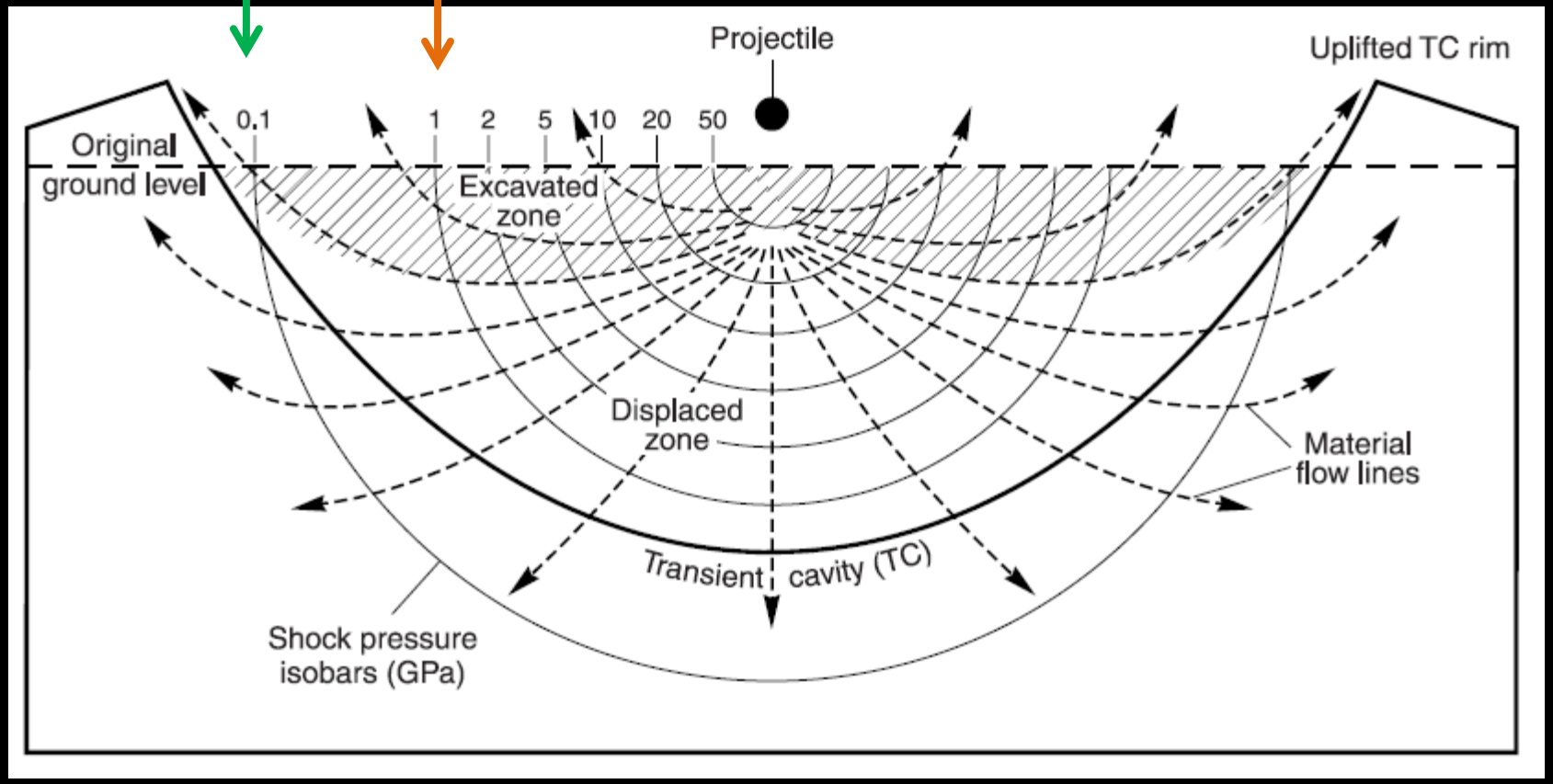
Abramov & Mojzsis, 2009, Nature

IV. Small-scale environmental implications of a single impact

Shock of Target Materials

- Would this destroy clays? Need for lab experiments, understanding of scaling relationships

1kbar: No 10kbar: Maybe



French, 1998, Traces of Catastrophe

Modification of Target Materials

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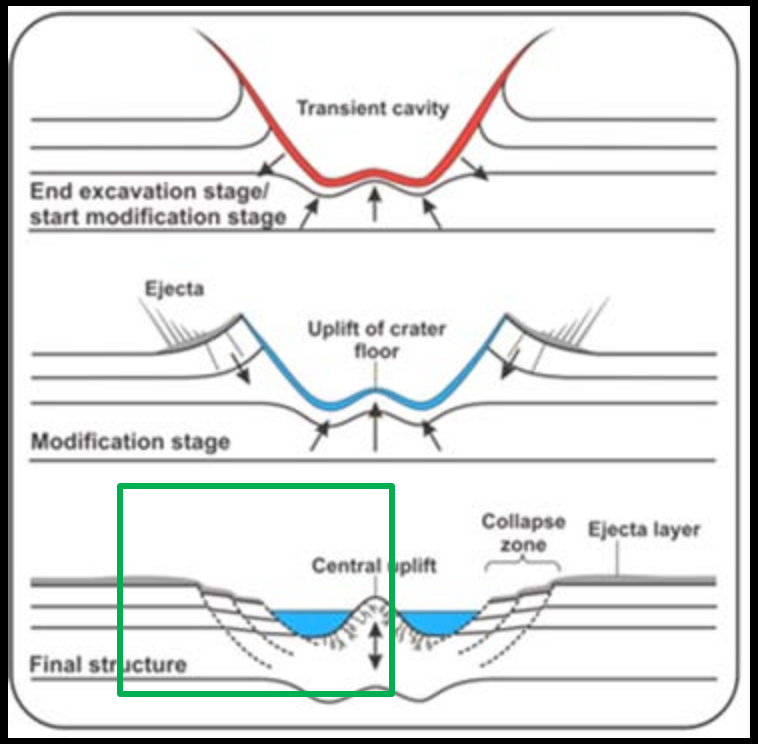
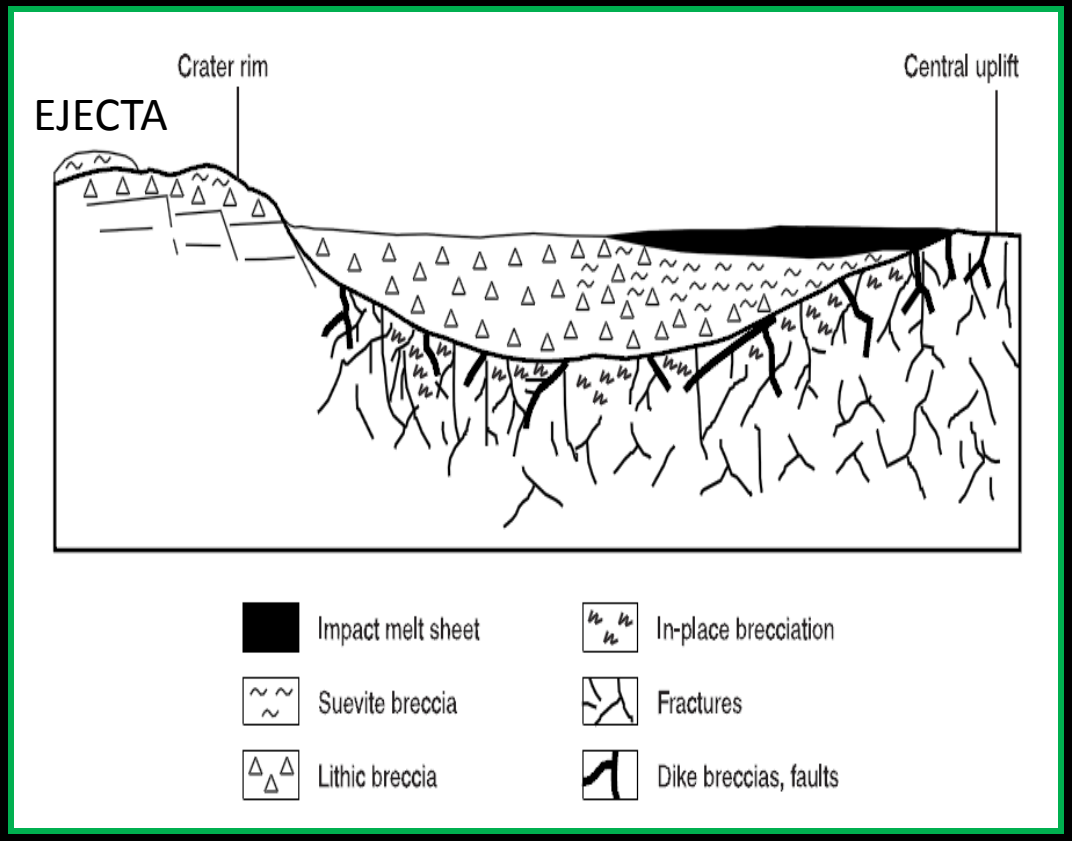




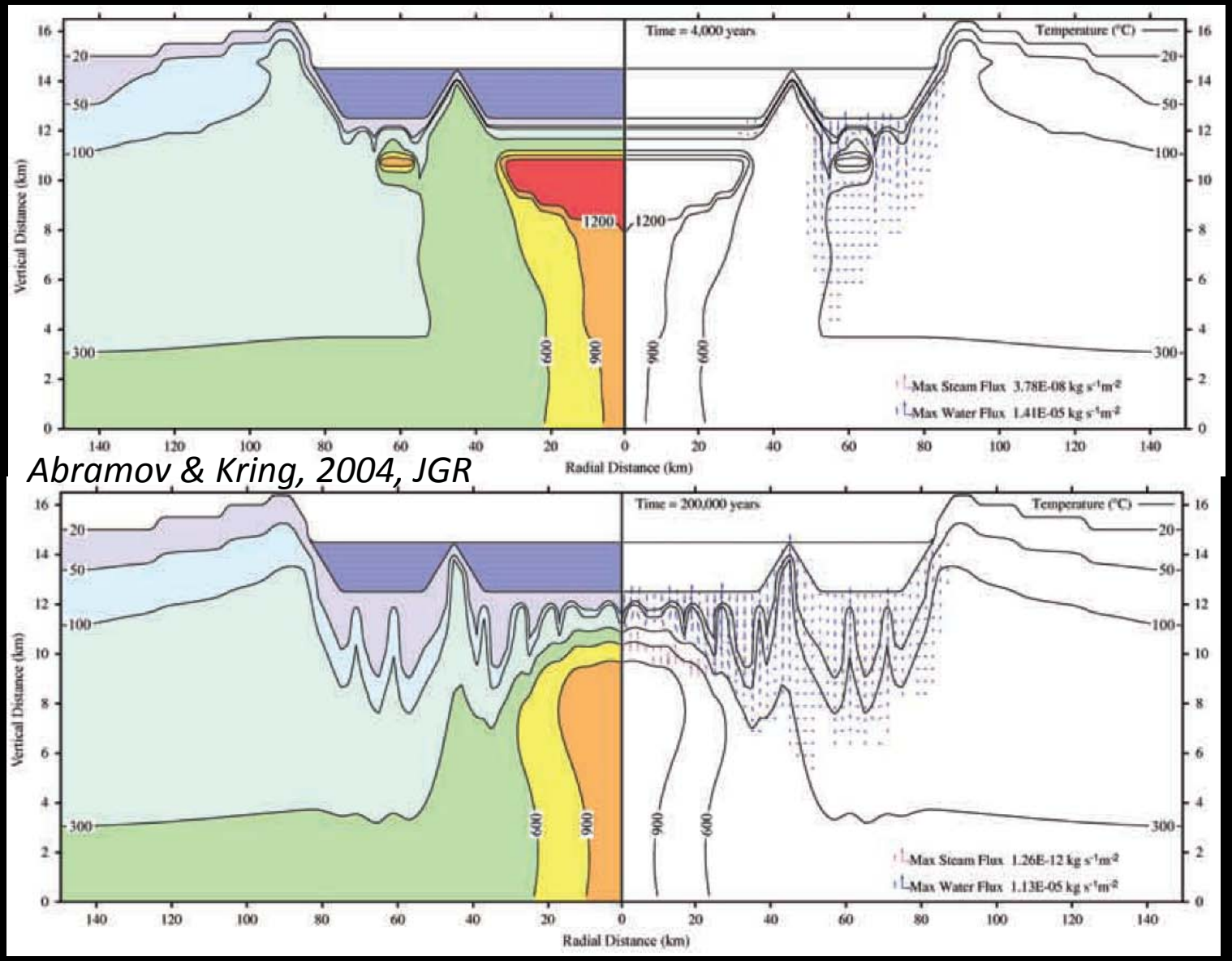
French, 1998, Traces of Catastrophe

Impact-Induced Hydrothermal Systems

Sudbury crater D~100km

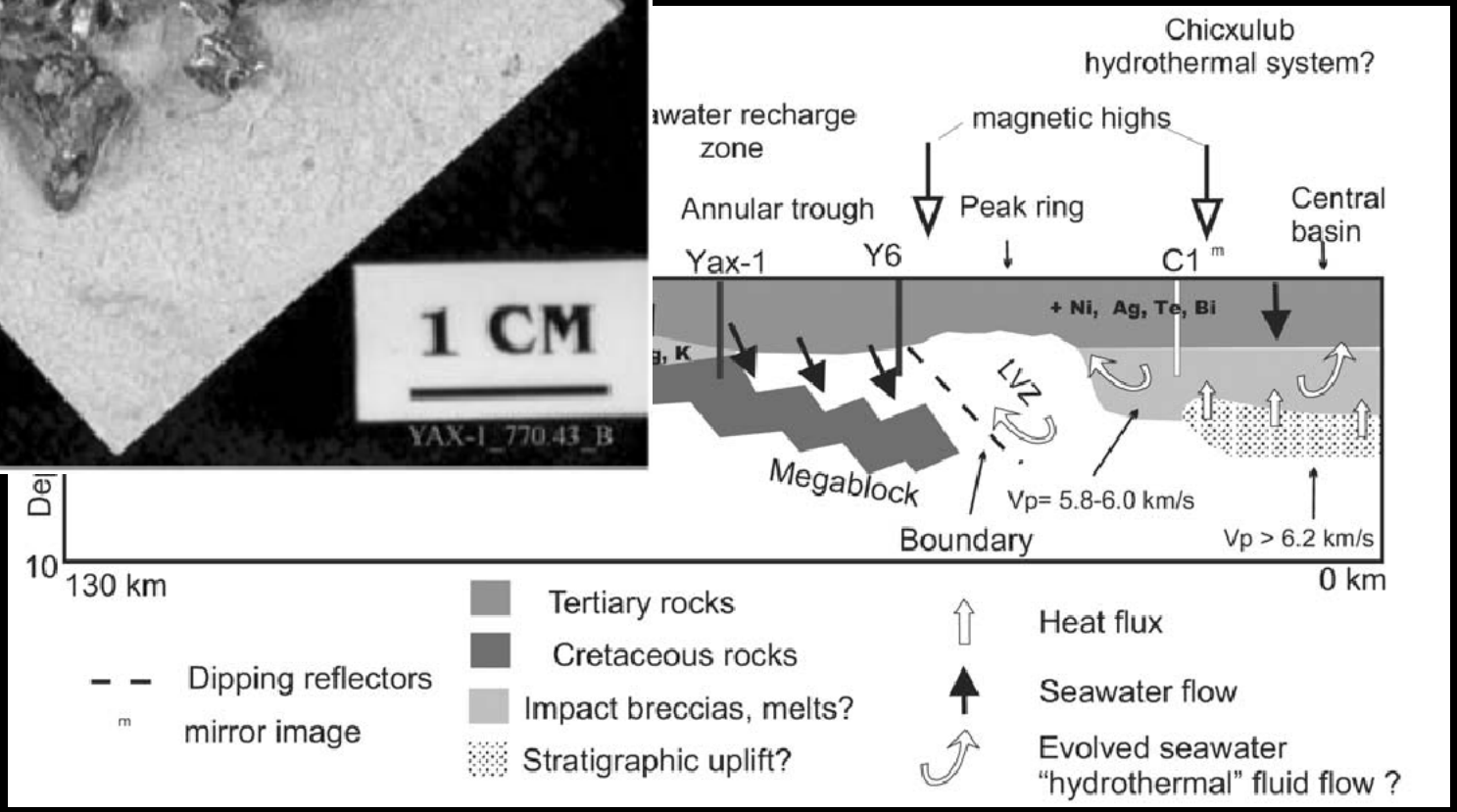
Time for persistence of hydrothermal system scales with size

System restricted to the crater interior



Abramov & Kring, 2004, JGR

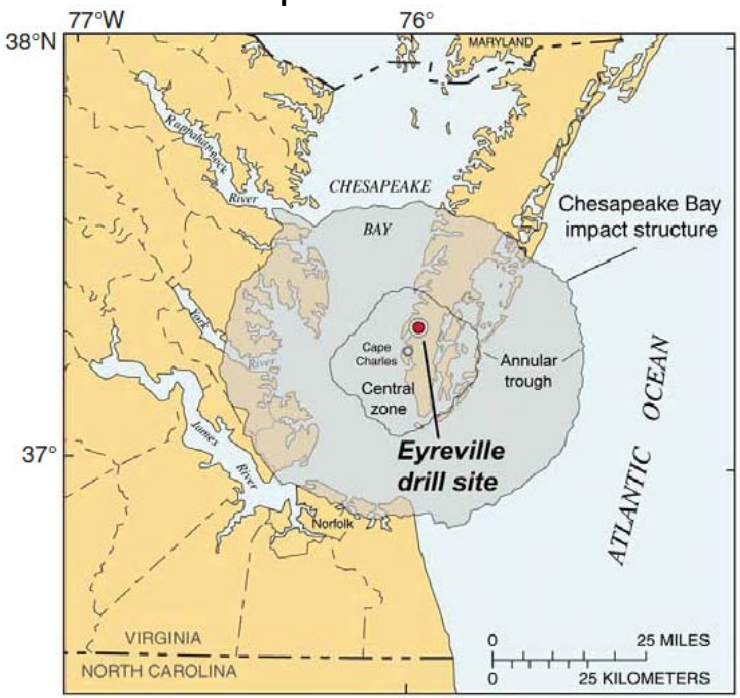
Evidence from Craters on Earth

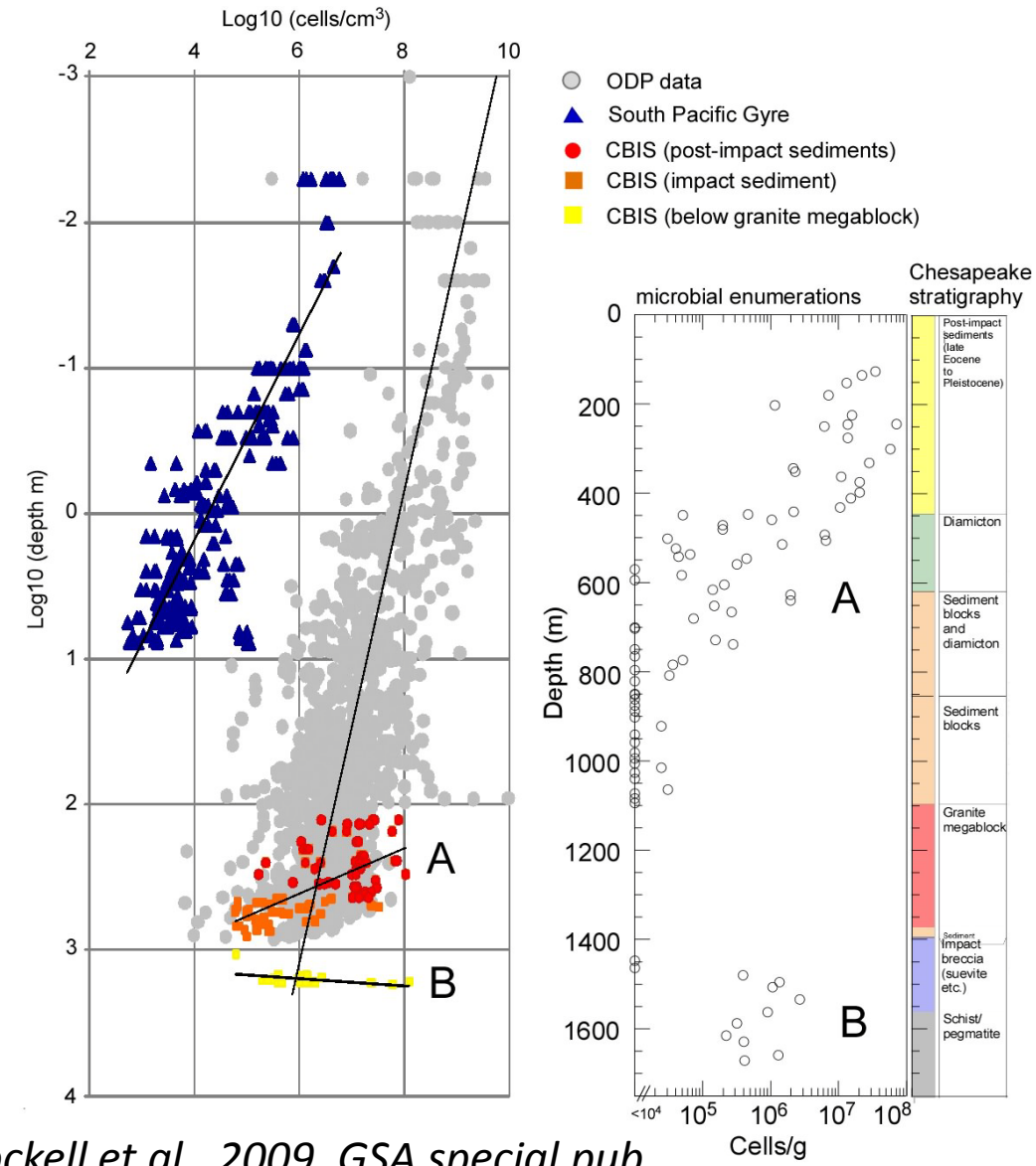


Ames et al., 2004, Met. Plan. Sci.

Life Colonizing the Impact Megabreccia?

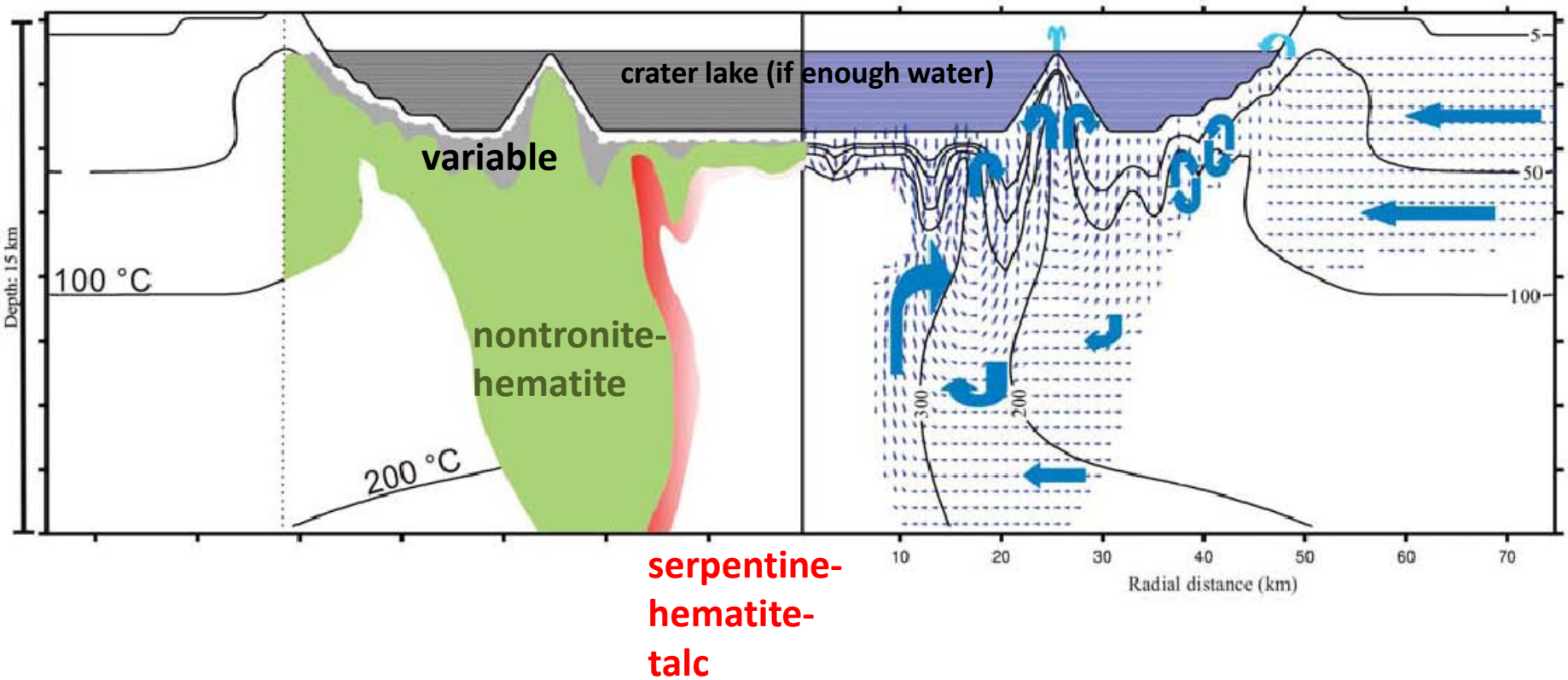
85-km diameter Chesapeake Bay Impact Structure





Cockell et al., 2009, GSA special pub.

Zones of Mineralization from Impact-Induced Hydrothermal Systems



Schwenzer et al., 2010, Geology

V. Craters on Mars: Effects?

1. What is the mineralogy of impact craters telling us?
2. Implications for environmental modification/ habitability?

Roles of Craters on Mars

- Basins
- Exposure of subsurface composition
- Creators/Destroyers of Habitable Environments?

Craters as Basins

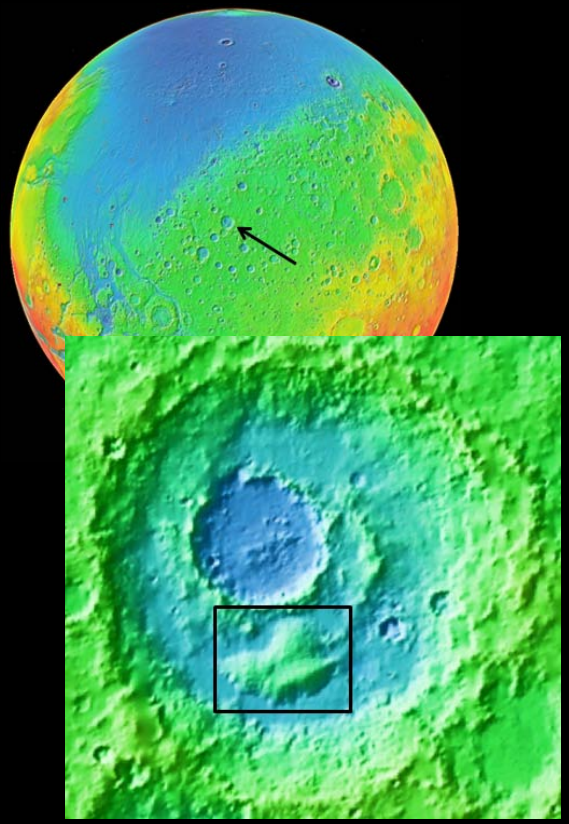
- Topographic lows collect material
- Repositories for a record of the past
- Hosts of crater lakes

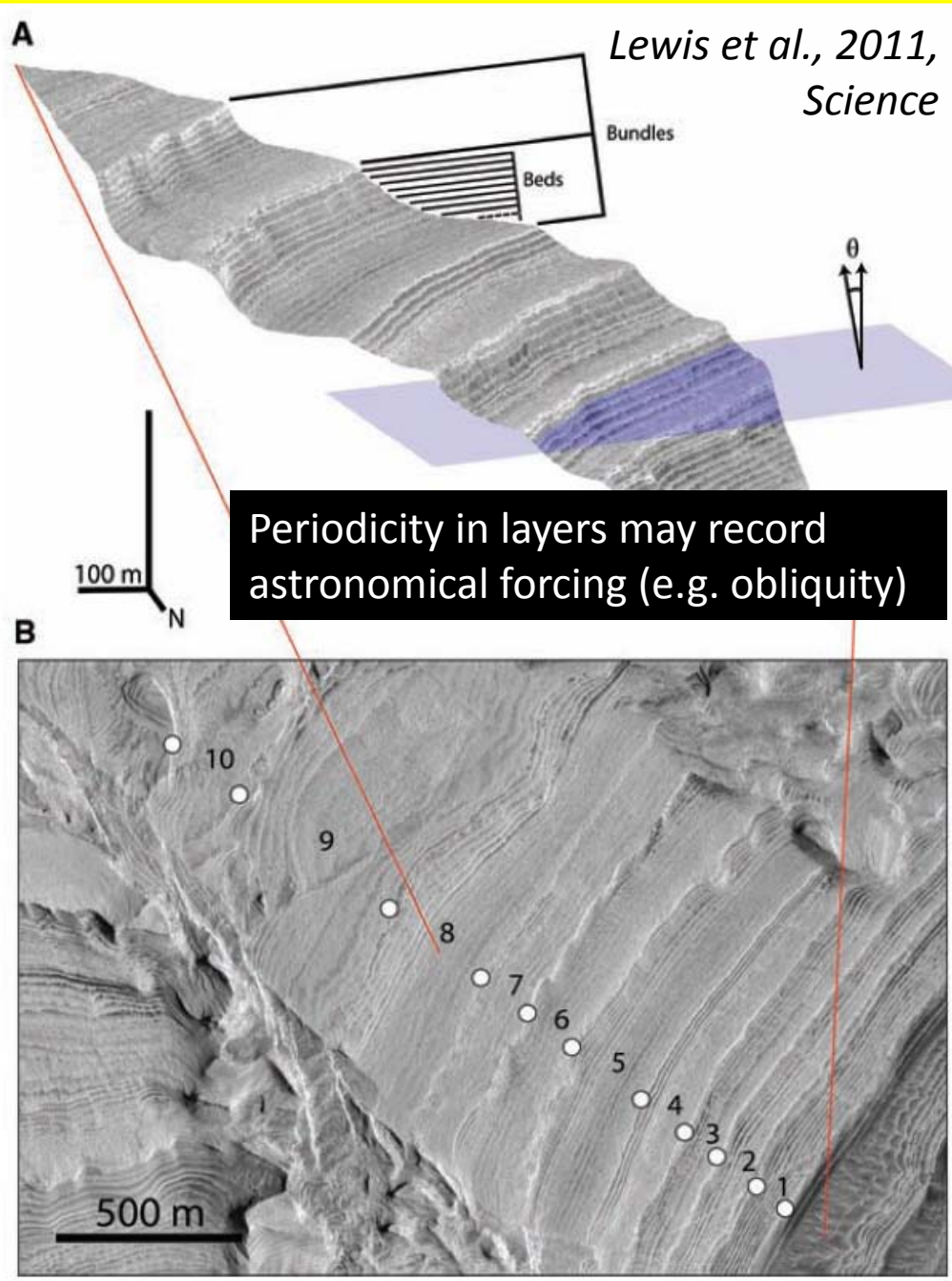
Dunes in Victoria Crater, Terra Meridiani

Pyroxene dunes from eroded mafic unit, Isidis Basin

Cr

- Topog
- Repos
- Hosts





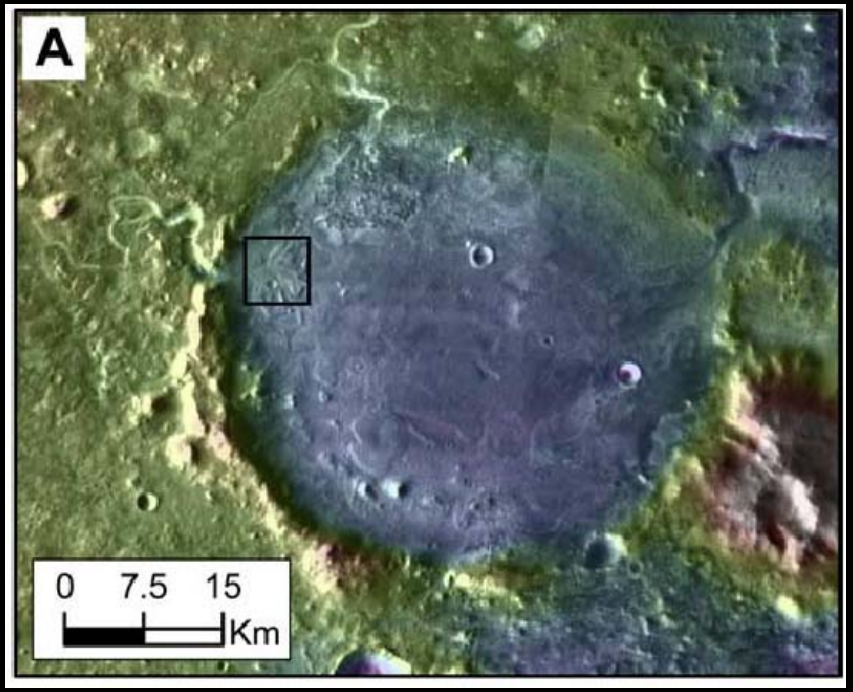
Lewis et al., 2011, Science

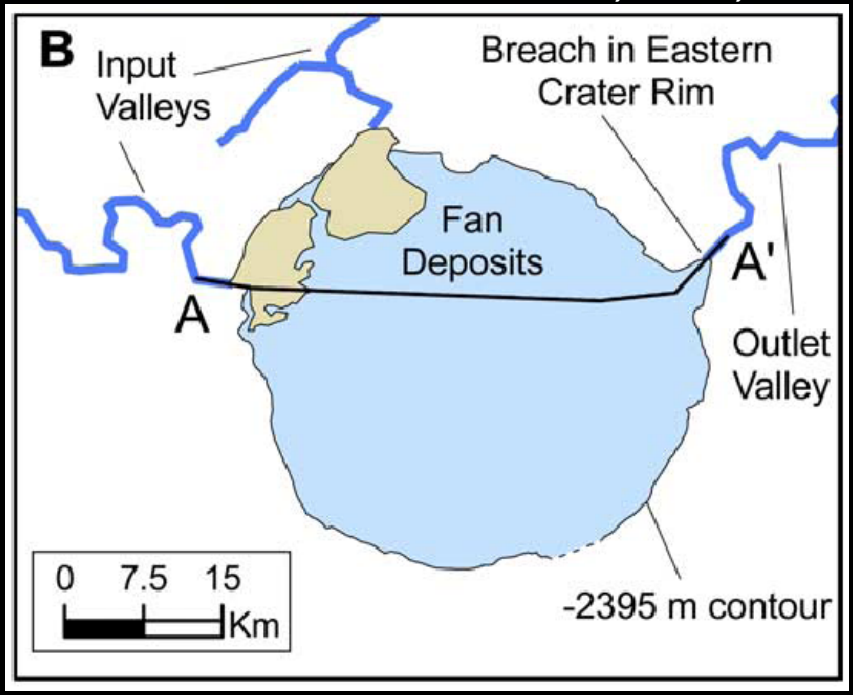
Periodicity in layers may record astronomical forcing (e.g. obliquity)

Craters as Basins

- Topographic lows collect material
- Repositories for a record of the past
- Hosts of crater lakes

Fassett & Head, 2005, GRL





Roles of Craters on Mars

- Basins
- Exposure of subsurface composition
- Creators/Destroyers of Habitable Environments?

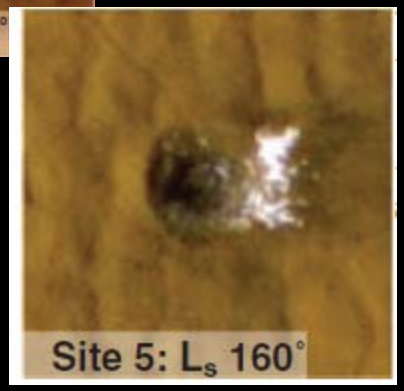
Roles of Craters on Mars

- Basins
- **Exposure of subsurface composition**
- **Creators/Destroyers of Habitable Environments?**

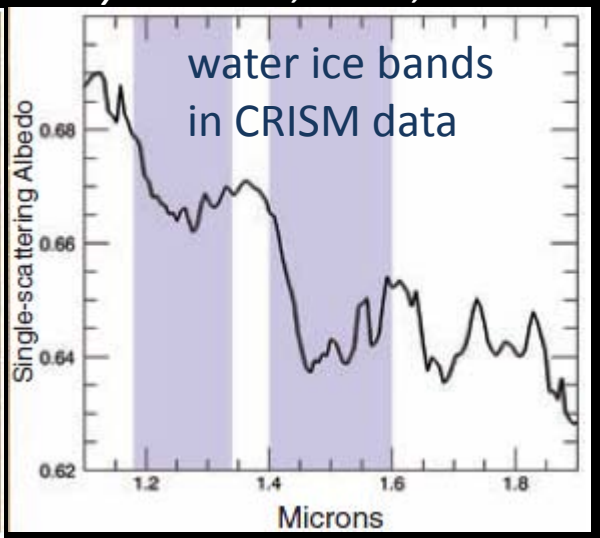
How to tell the difference?

Craters as Exposers of the Subsurface

- **Modern Processes on Mars, e.g. ice**
- Ancient Processes on Mars, e.g. igenous products, clays

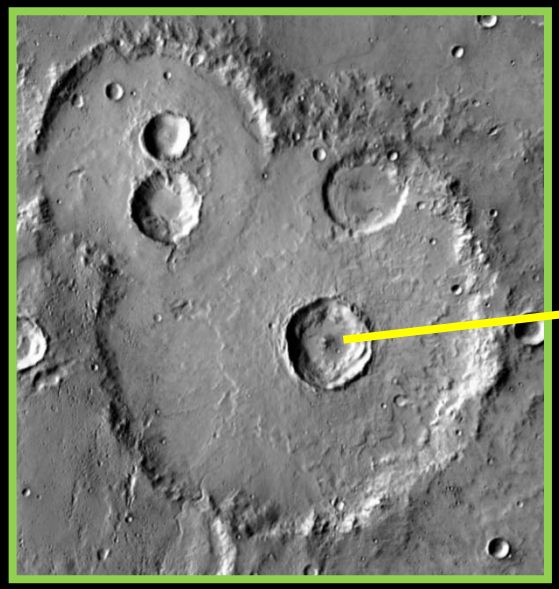


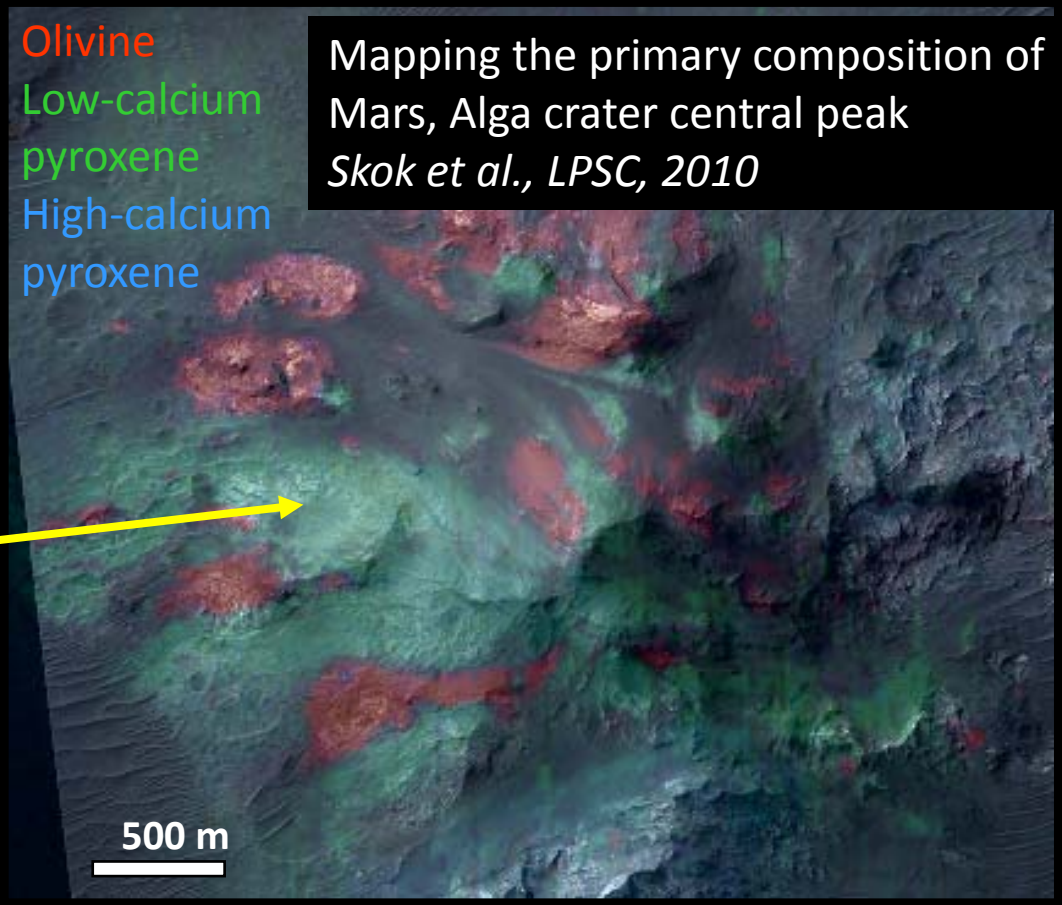
Byrne et al., 2009, Science



Craters as **Exposers of the Subsurface**

- Modern Processes on Mars, e.g. ice
- **Ancient Processes on Mars, e.g. igenous products**, clays





Mapping the primary composition of Mars, Alga crater central peak
Skok et al., LPSC, 2010

Mars craters with clays

timing/setting

- Do impact craters provide **information on subsurface stratigraphy**, i.e. a record of alteration events pre-dating the crater?
- Does cratering instead act as an **agent of alteration, causing alteration** post-dating the crater)?
  - (quasi-)instantaneous shock transformation
  - Impact-induced hydrothermal systems
  - Preferential weathering of shocked/glassy products

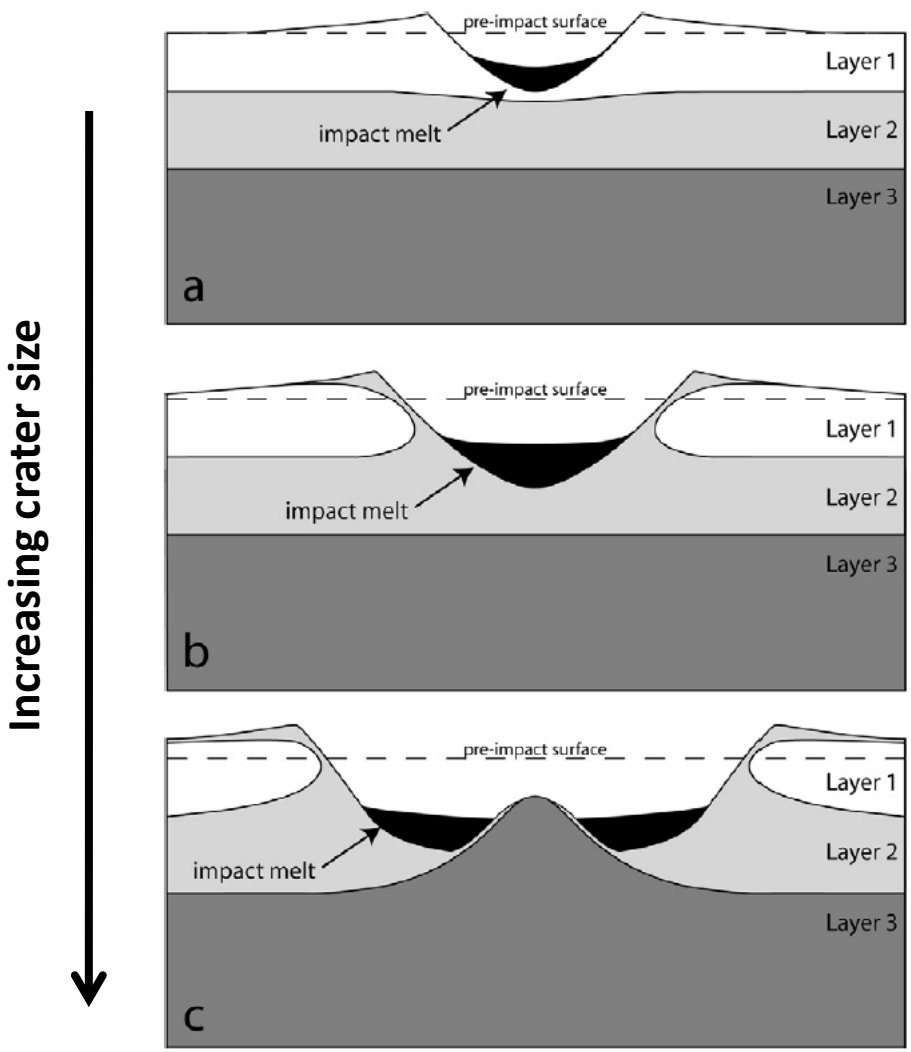
---

conditions

- What are the **physiochemical conditions indicated** by the minerals and mineral assemblages detected?

➔ Critical for understanding the nature of Mars' crust, its evolution through time, and **implications for the creation and exposure of habitable environments**

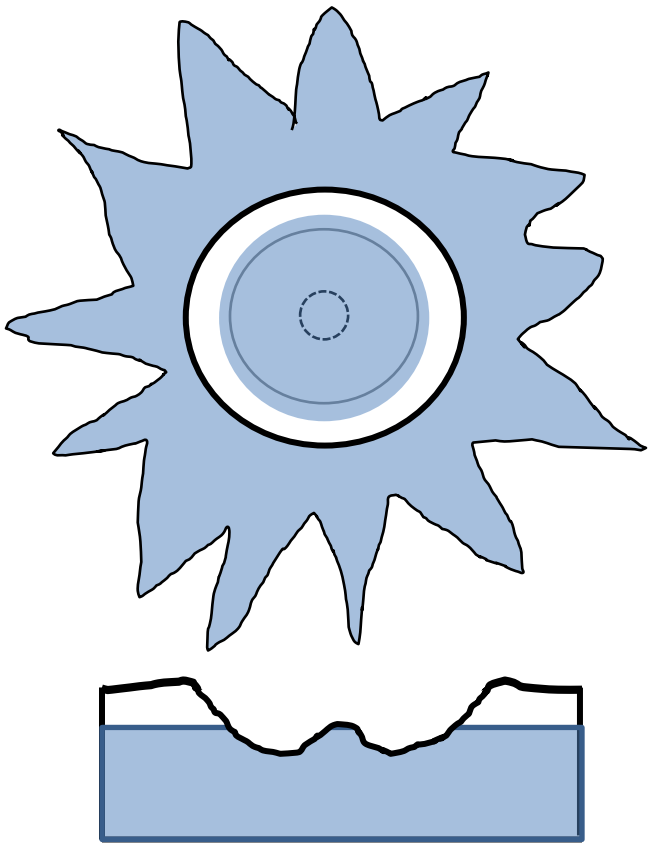
Craters as probes of Stratigraphy



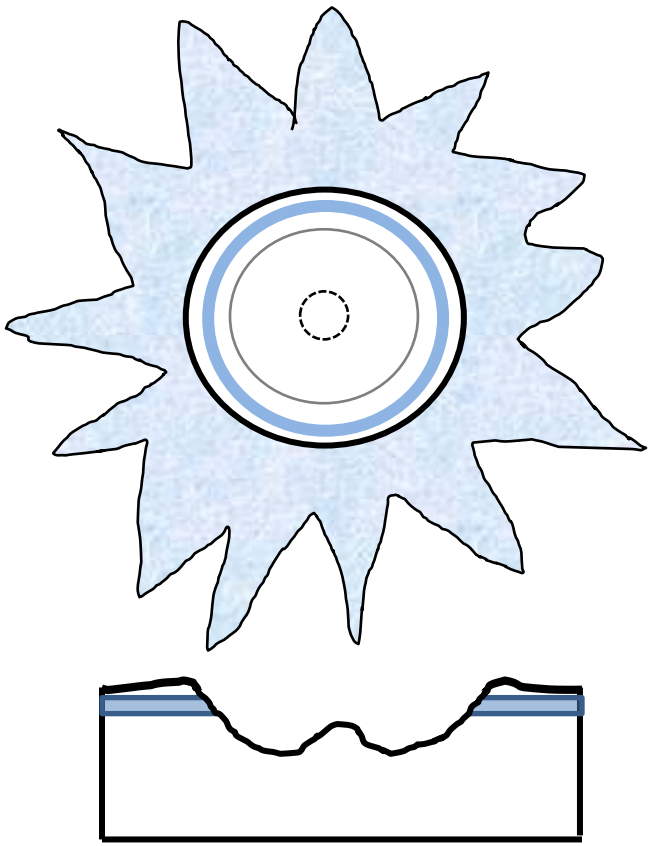
Ernst et al., 2010, Icarus

- Wall rock
  - stratigraphy is exposed
- Ejecta
  - diameter/depth/distance scaling relationship
- Central peak
  - diameter/depth scaling relationship

Sketch map of expected exposure pattern of hydrated minerals :
exposing pre-existing clays



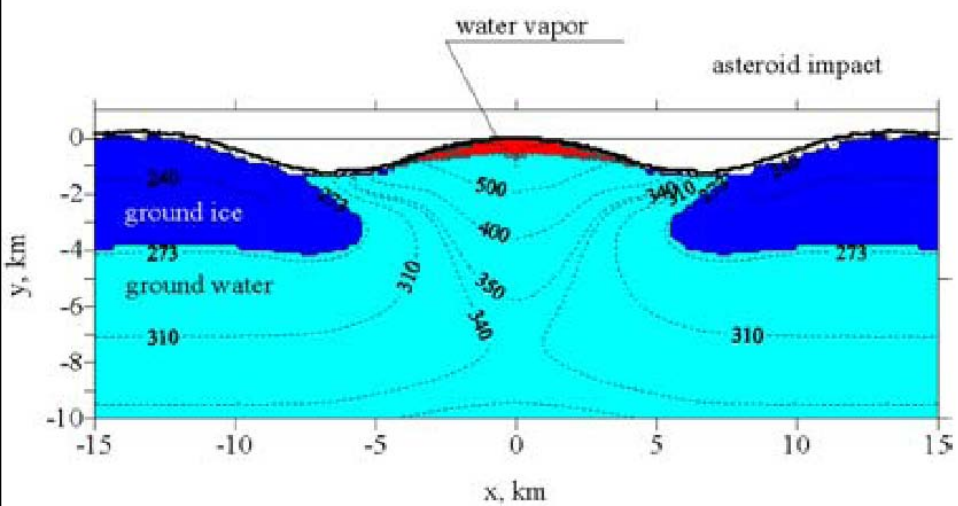
Thick stratigraphic layer
of hydrated silicates



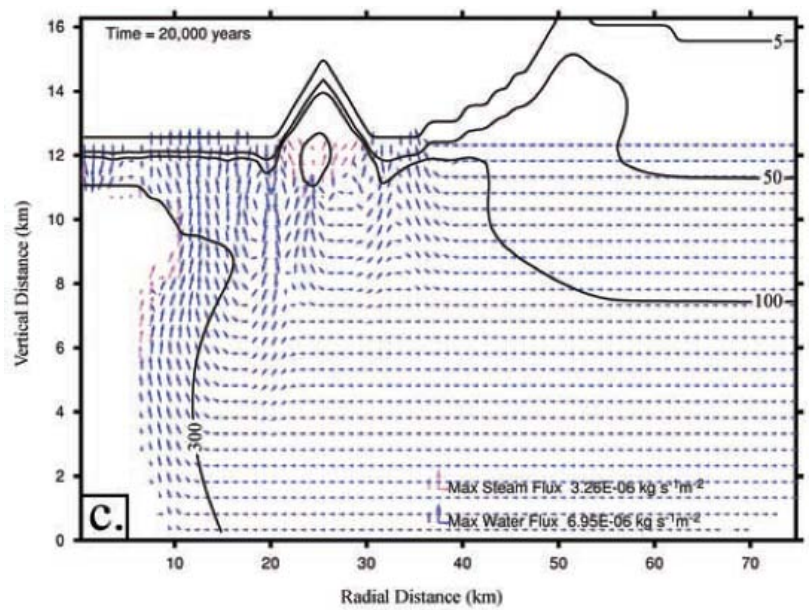
Thin stratigraphic layer of
hydrated silicates

Cratering as an agent of alteration

- Impact itself can induce mineralogic change, especially if water is present
  - shock transformation → damaged lattices, amorphous glass, (hydrated xll minerals?)
  - **impact-induced hydrothermalism → mineralization around conduits of fluid flow**
  - preferential weathering of shocked/glassy products

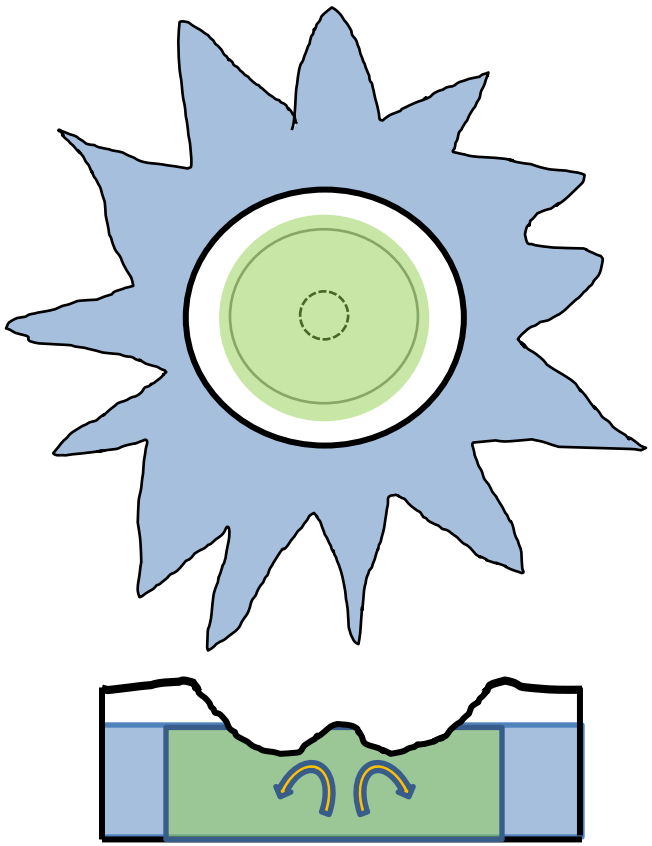


Pierazzo et al., GSA, 2005 (D=30 km)

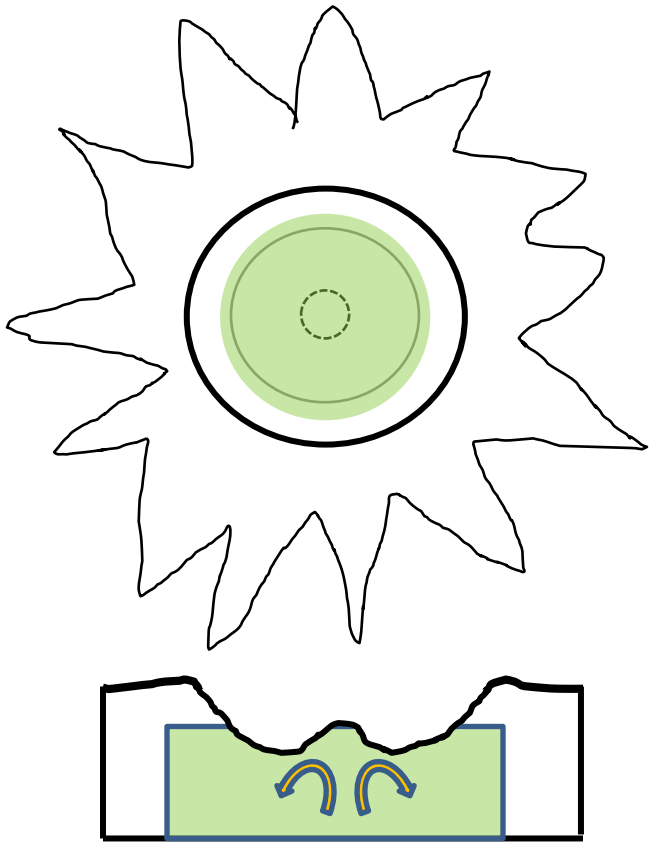


Abramov & Kring, JGR, 2005 (D=100 km)

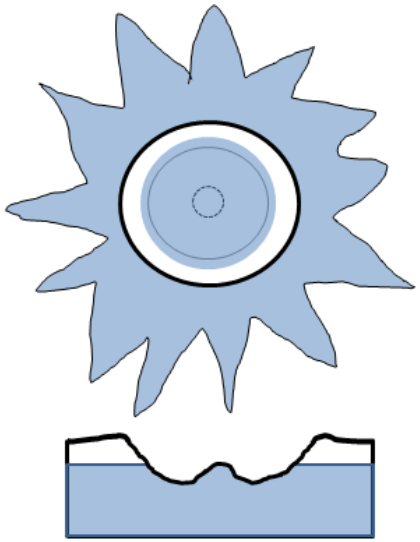
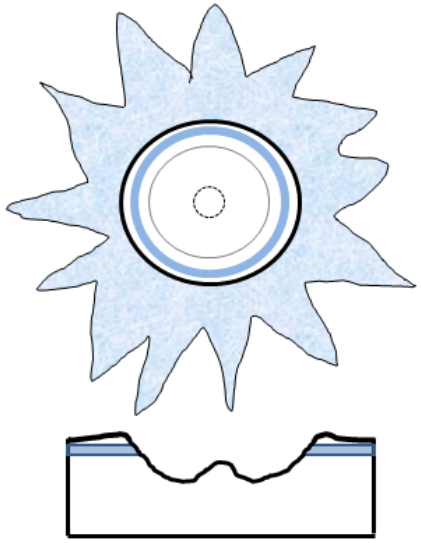
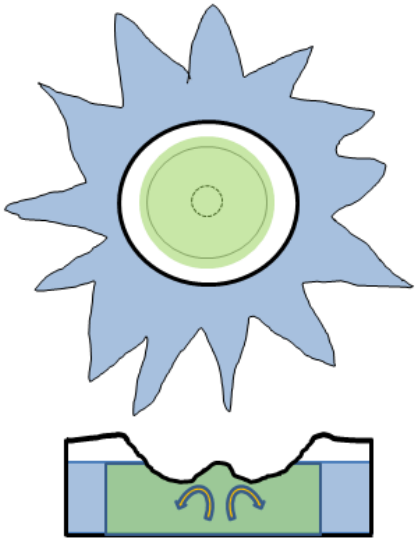
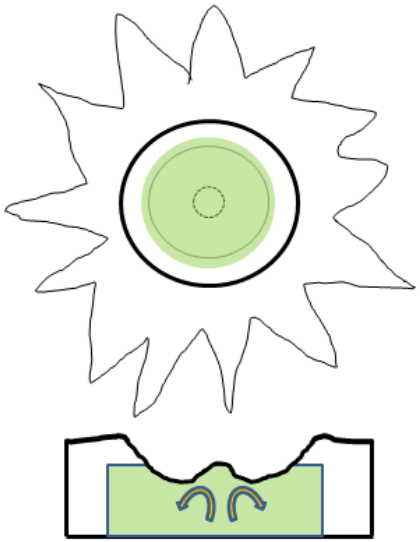
Sketch map of expected exposure pattern of hydrated minerals :
impact-induced hydrothermal system,
w/ and w/o pre-existing clays



Impact-induced
hydrothermal system
with pre-existing clays



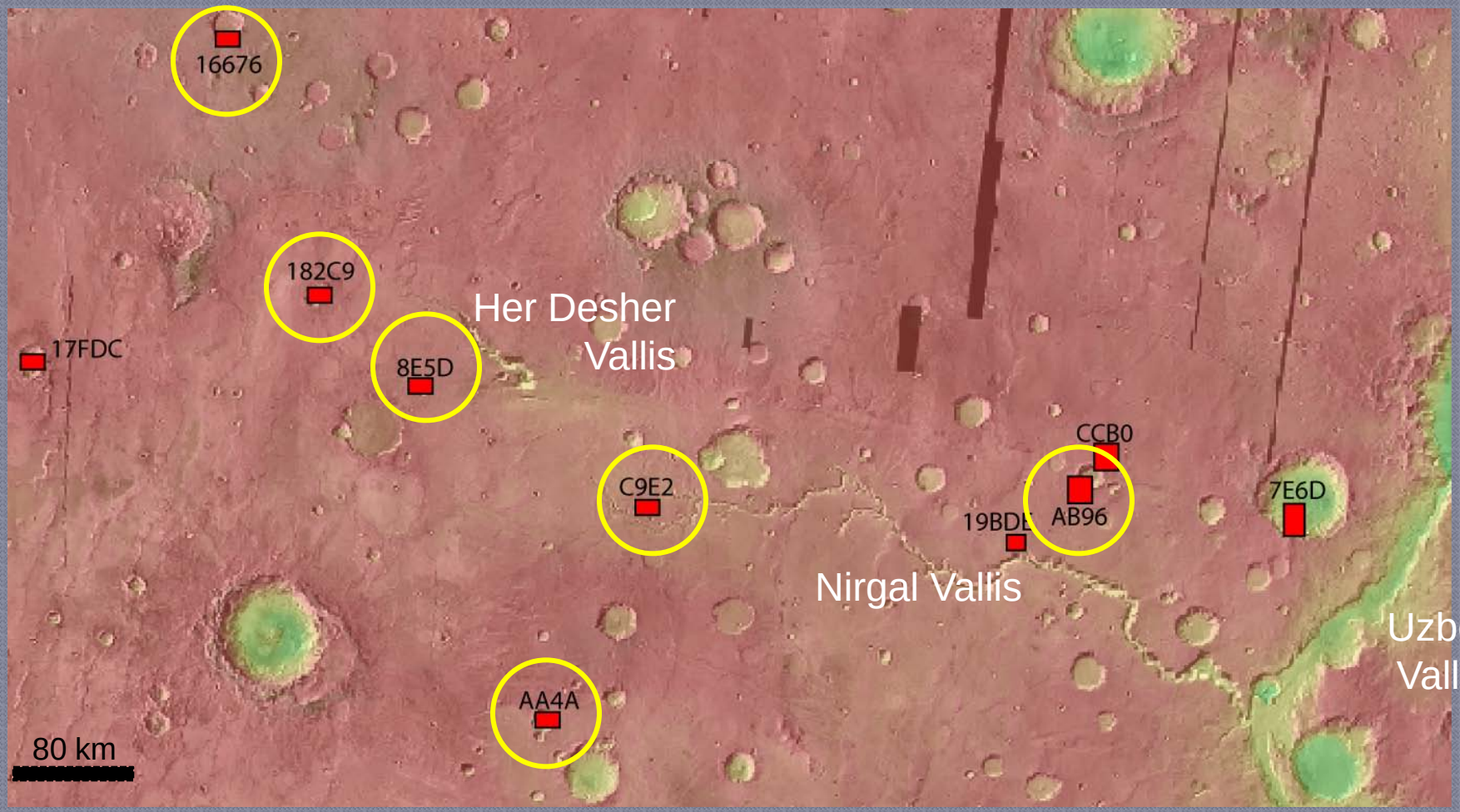
Impact-induced
hydrothermal system
with no pre-existing clays

	Pre-existing Thick Clay Layer	Thin or no pre-existing clay layer
No HT System		
HT system		

I. A Regional Clay-Bearing Straigraphic Layer, Exposed

D. Buczkowski, K. Seelos, et al.

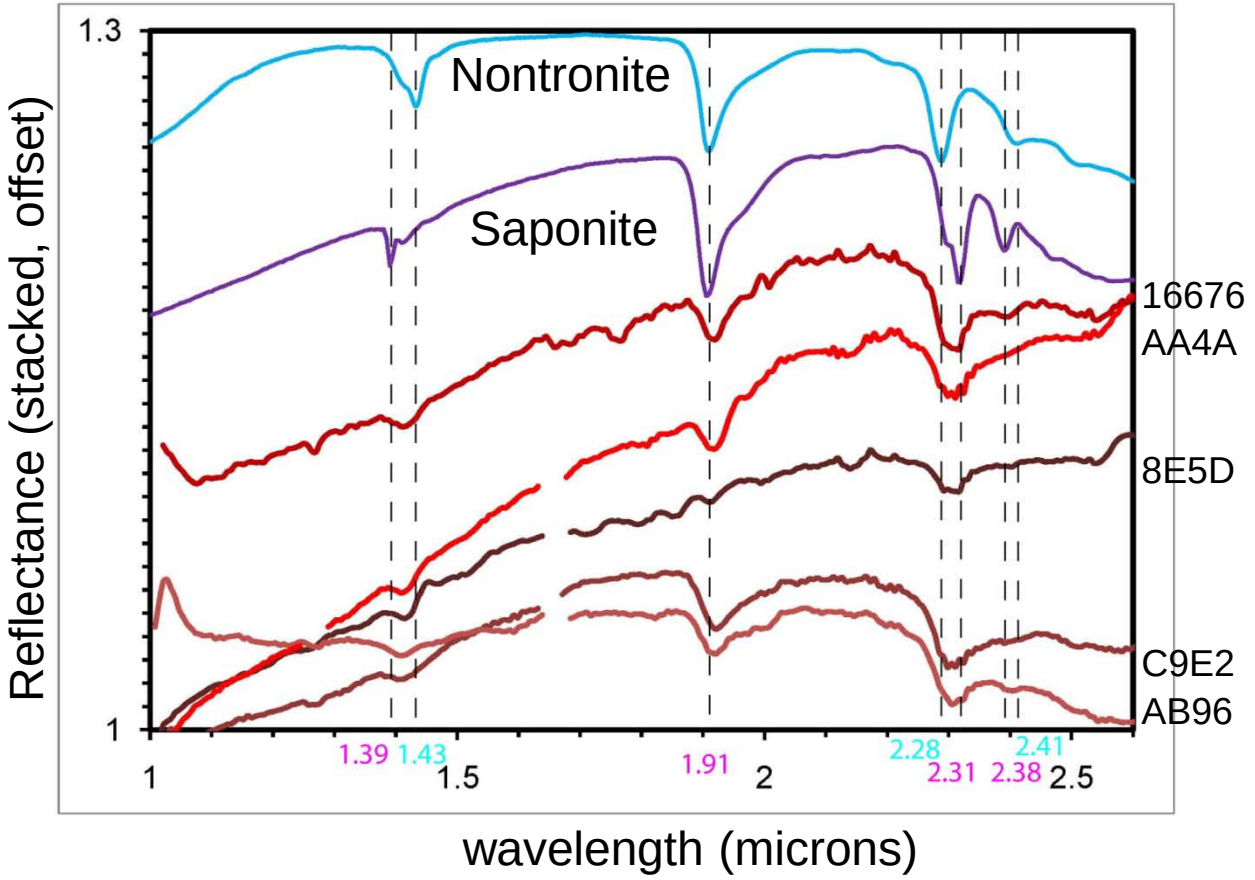
NW Noachis Crater Observations

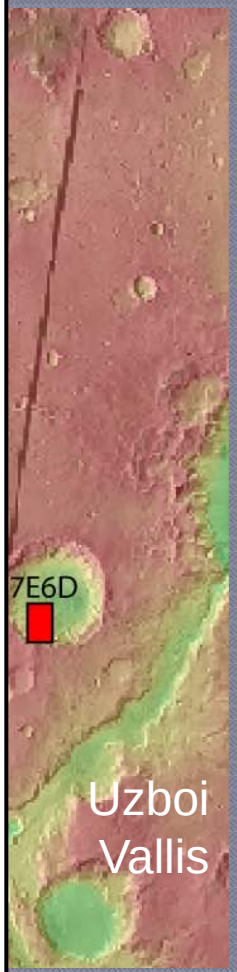


Buczkowski et al., LPSC, 2010

NW Noachis Crater Observations

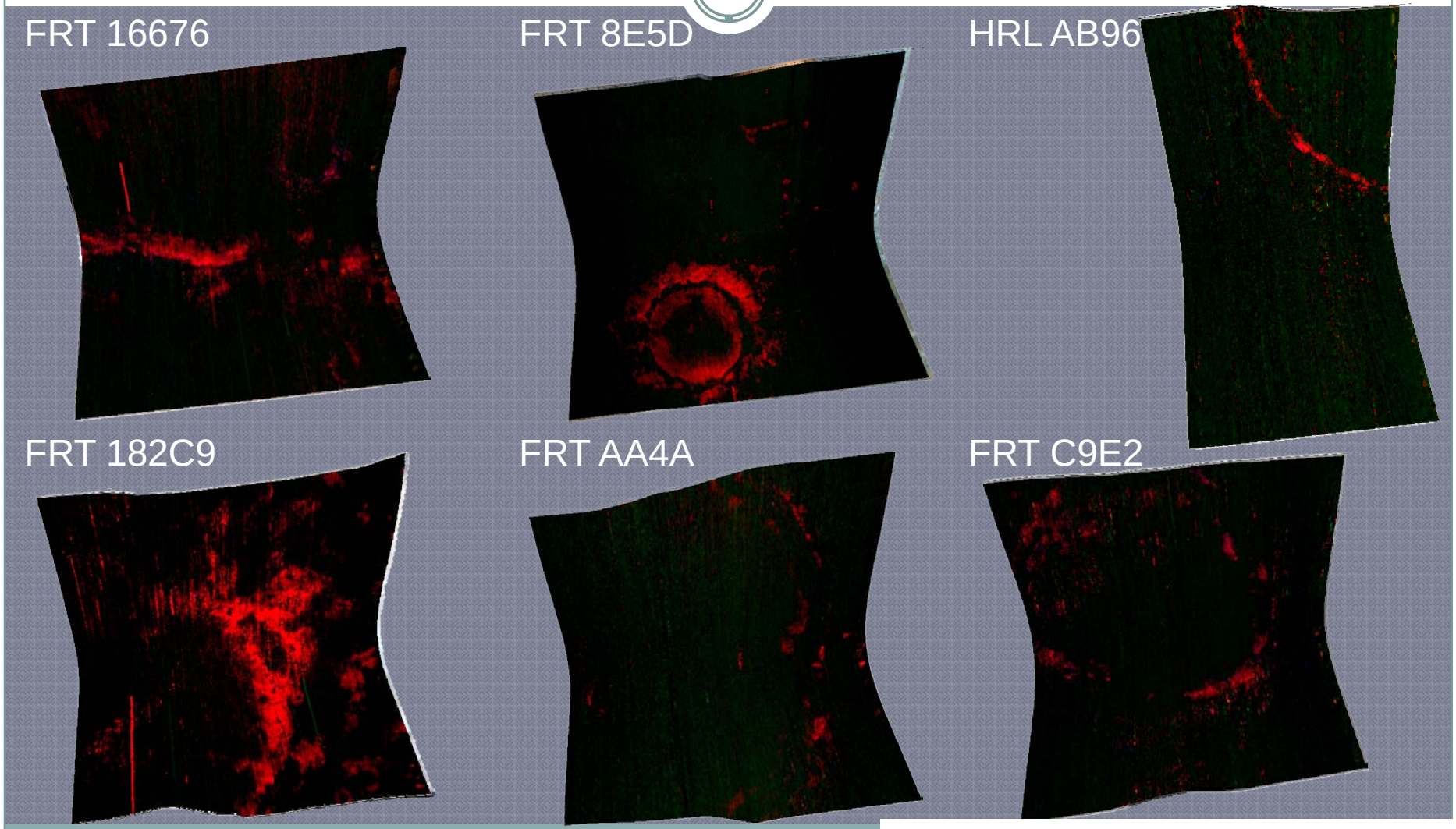
Crater Spectra:CRISM ratios (bottom), library spectra (top)





Buczkowski et al., LPSC, 2010

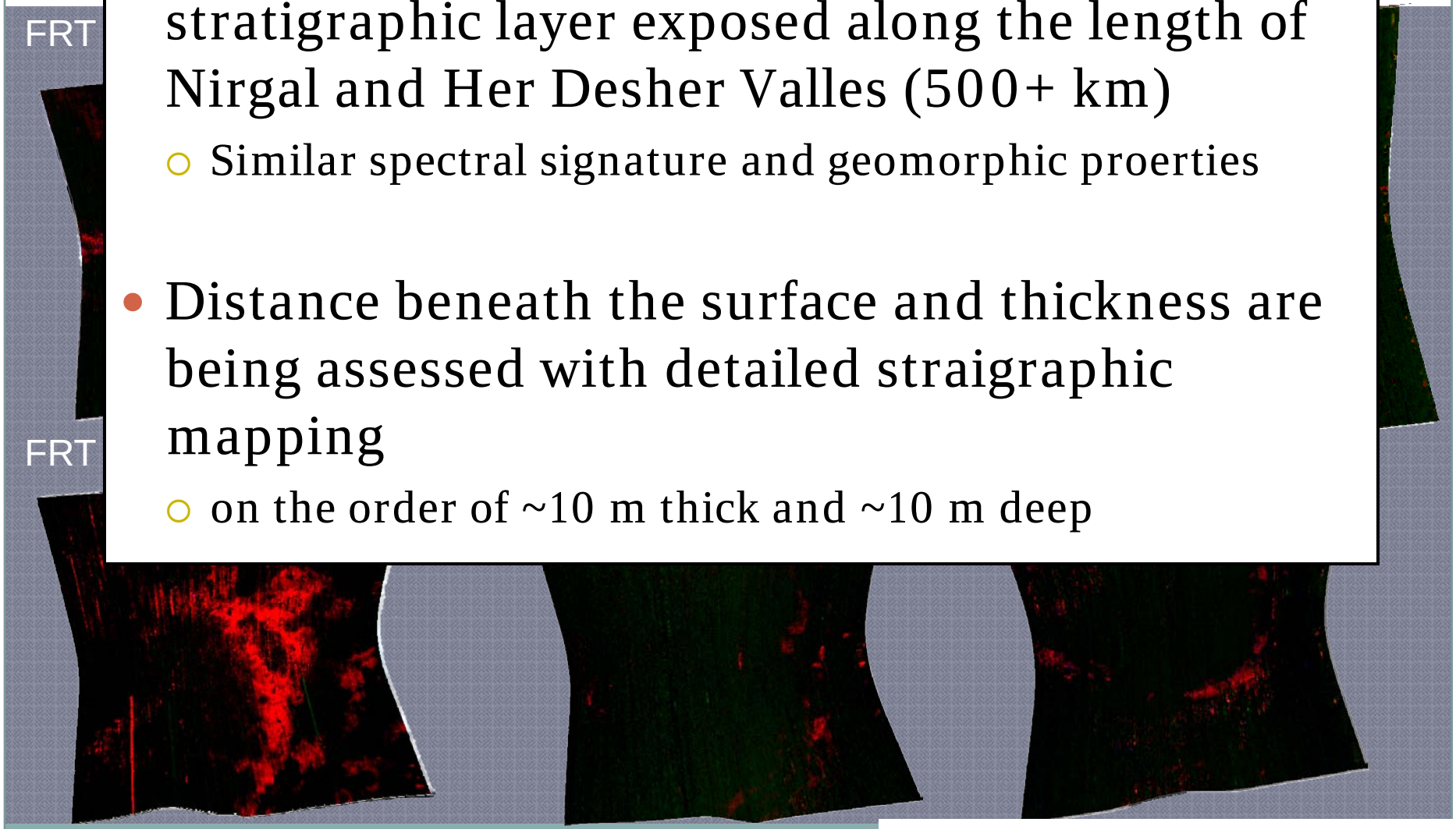
Nearby Craters



Buczkowski et al., LPSC, 2010

Nearby Craters

- Data are consistent with a clay-bearing stratigraphic layer exposed along the length of Nirgal and Her Desher Valles (500+ km)
  - Similar spectral signature and geomorphic proerties
- Distance beneath the surface and thickness are being assessed with detailed straigraphic mapping
  - on the order of ~10 m thick and ~10 m deep

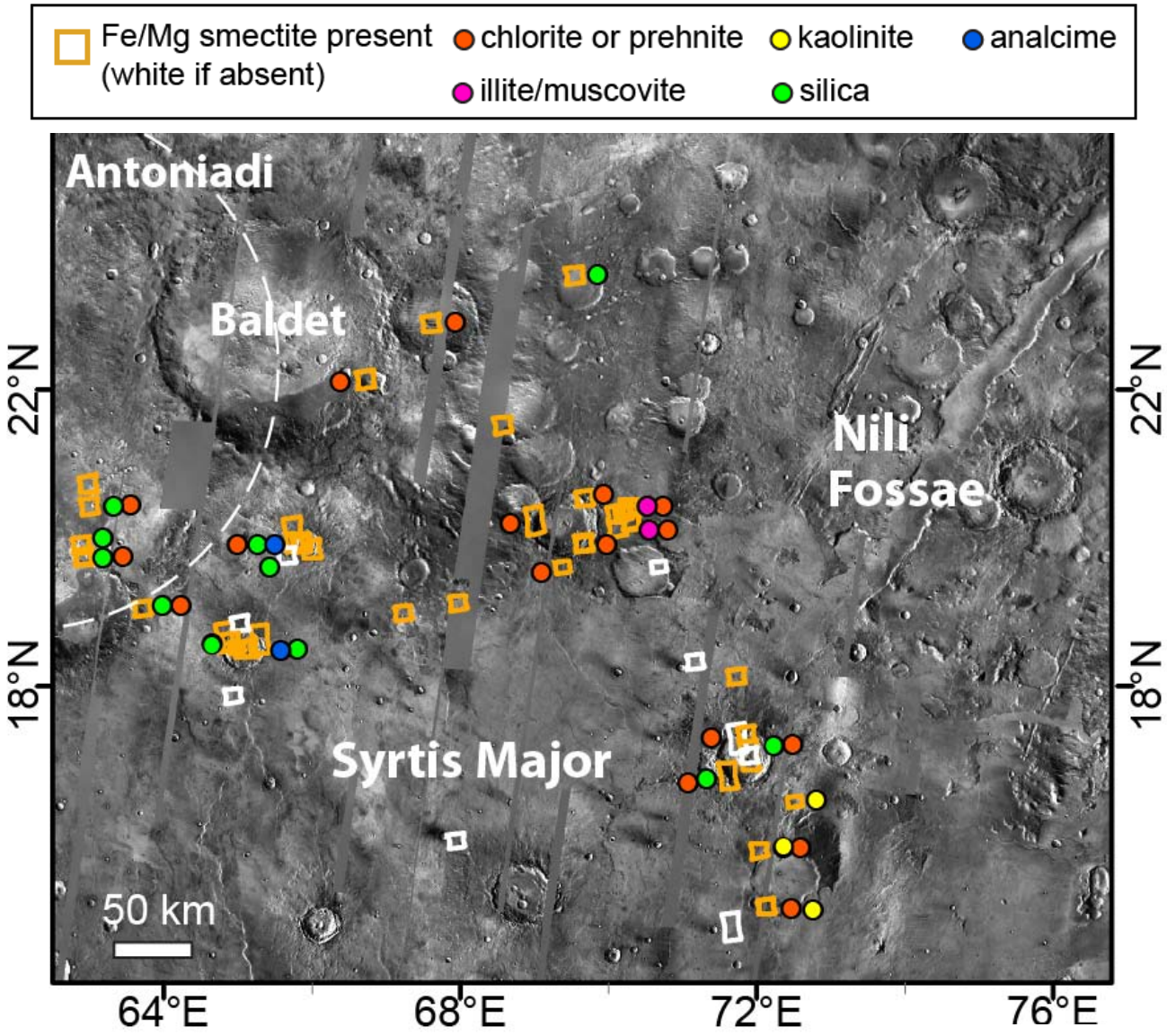


Buczkowski et al., LPSC, 2010

II. Probing the Martian Crust: Diverse Crater Mineral Assemblages and Higher Temperature Aqueous Alteration

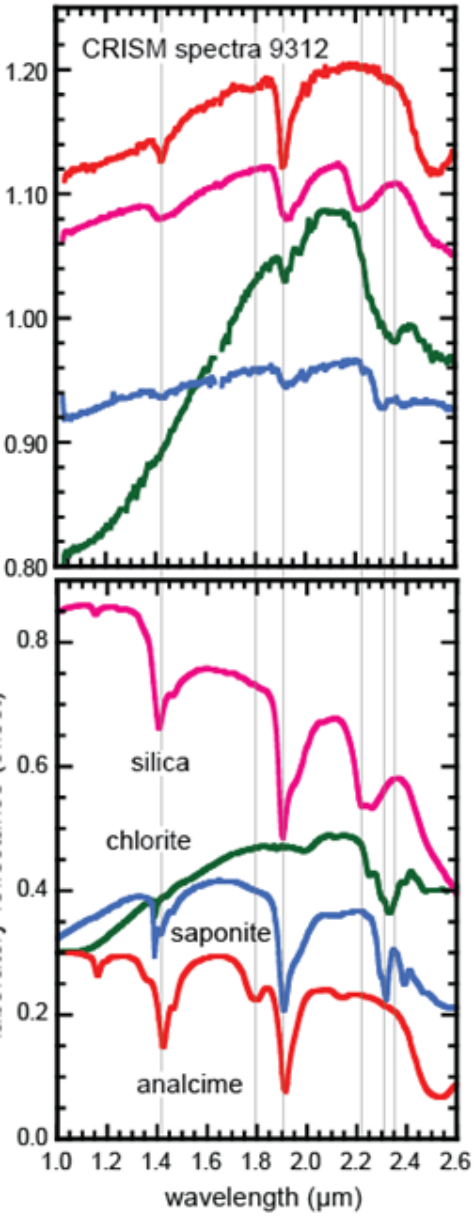
B. Ehlmann, J. Mustard, G. Swayze,
R. Clark, S. Murchie et al.

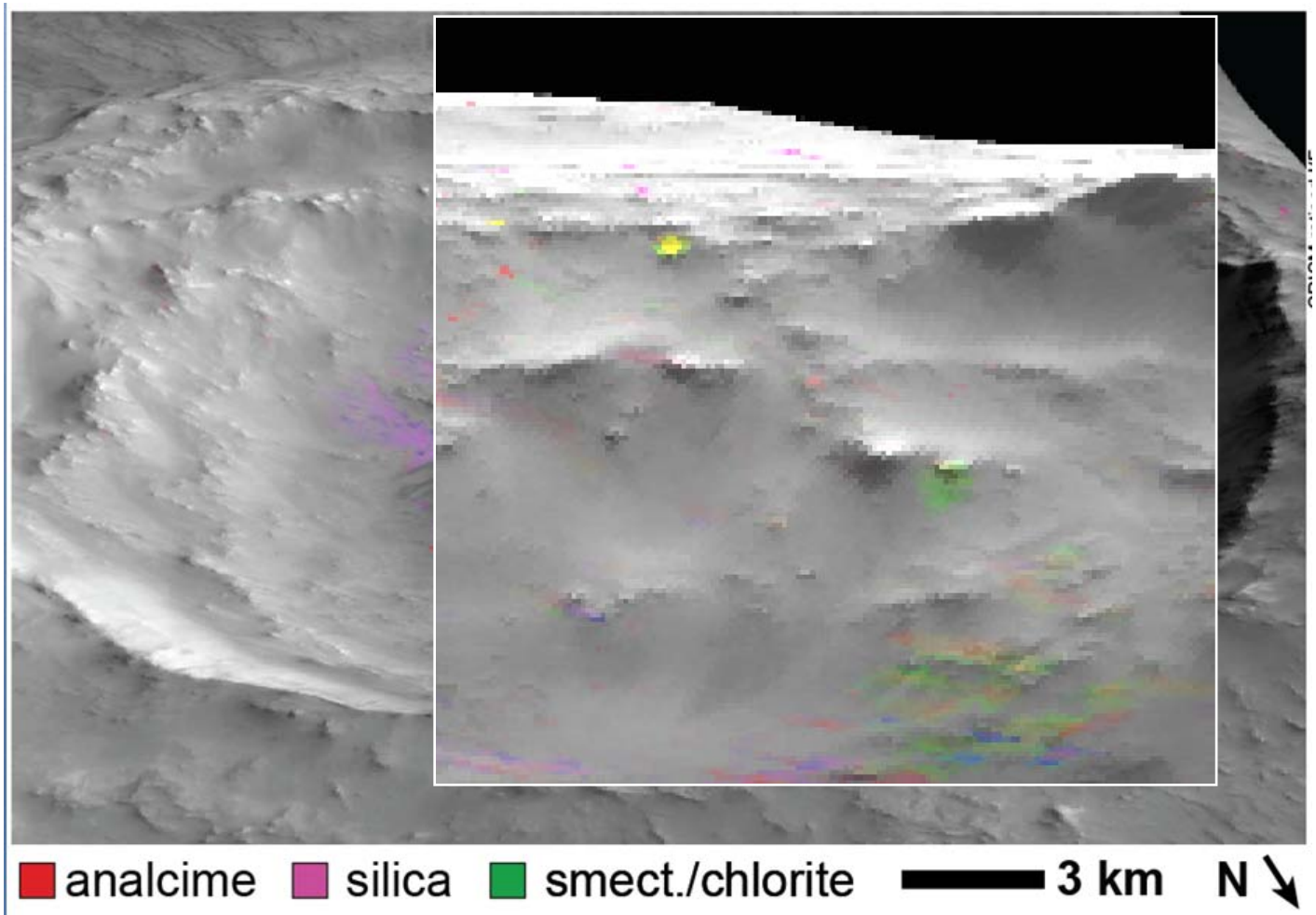
Mineralogic Diversity in NW Syrtis craters



Ehlmann et al., JGR, 2009

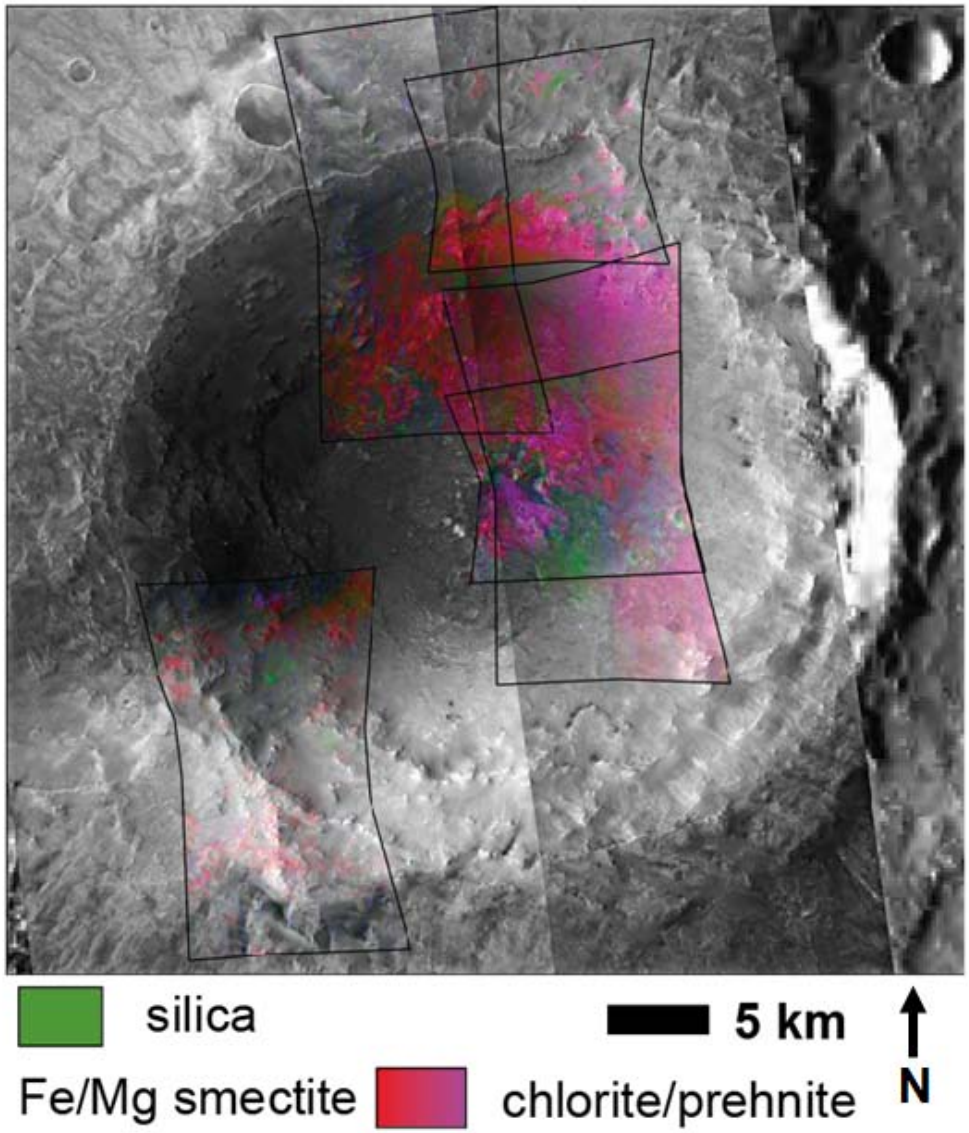
Analcime-Silica-Chlorite-Fe/Mg smectite

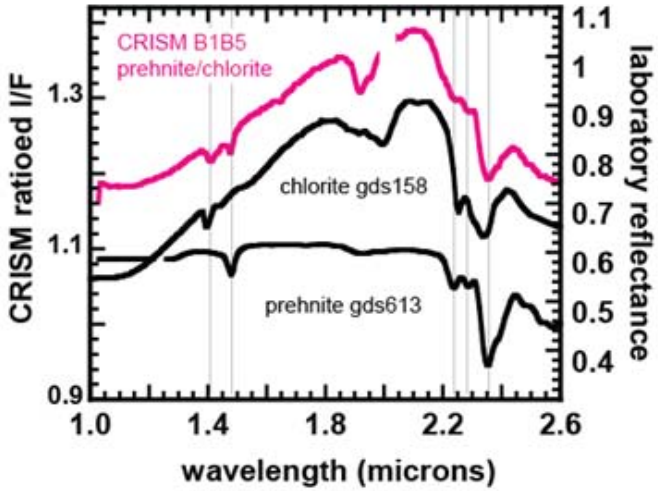


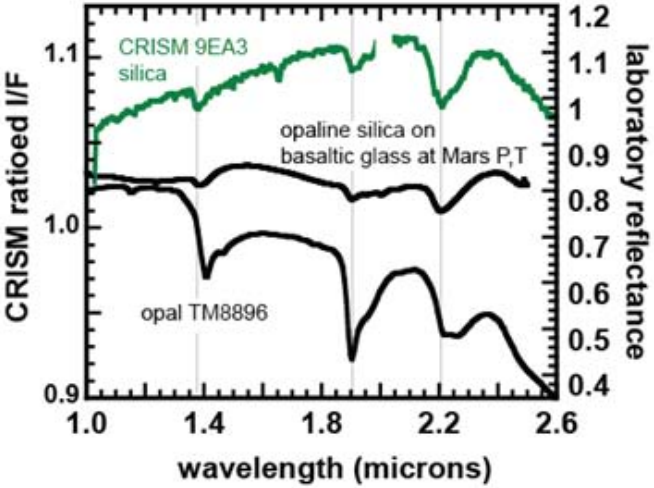


Ehlmann et al., JGR, 2009; CCM, in review

Prehnite-Chlorite-silica-Fe/Mg smectite

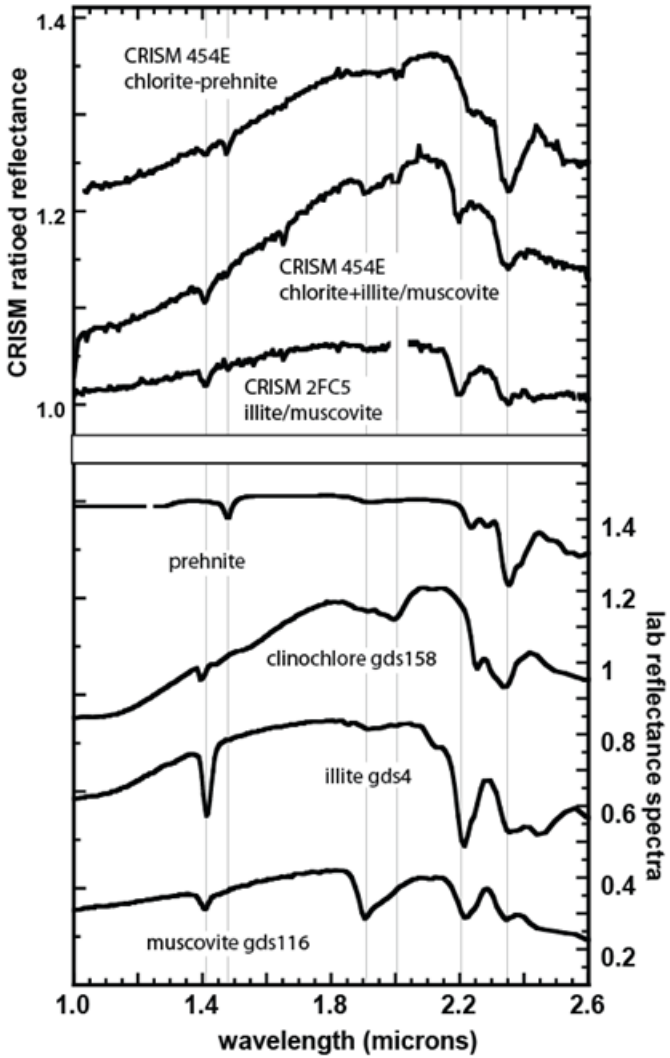


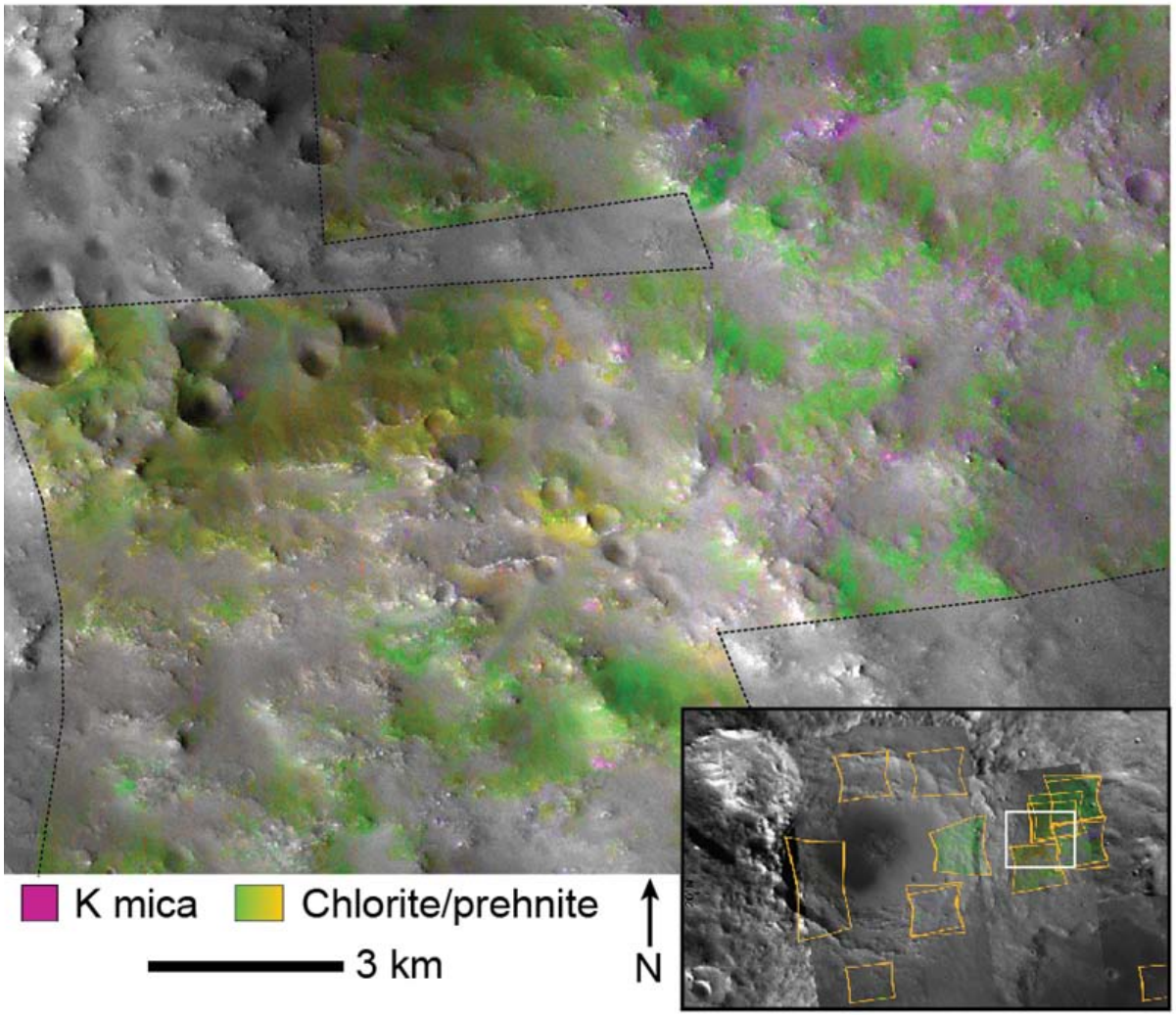




Ehlmann et al., JGR, 2009; CCM, in review

Chlorite-Prehnite-Illite/Muscovite in ejecta

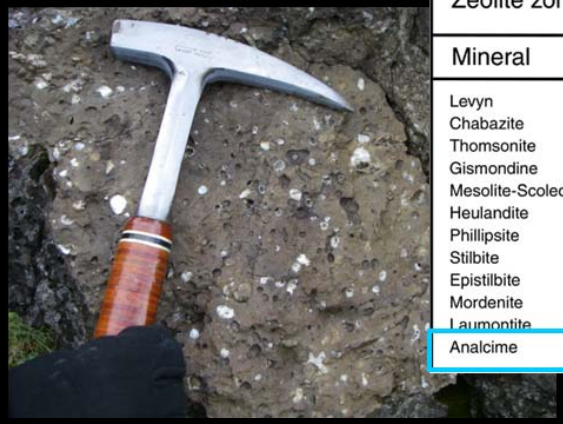


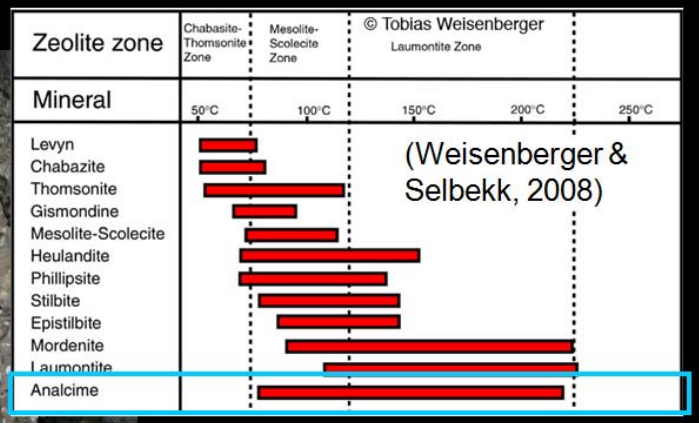


Ehlmann et al., JGR, 2009; CCM, in review

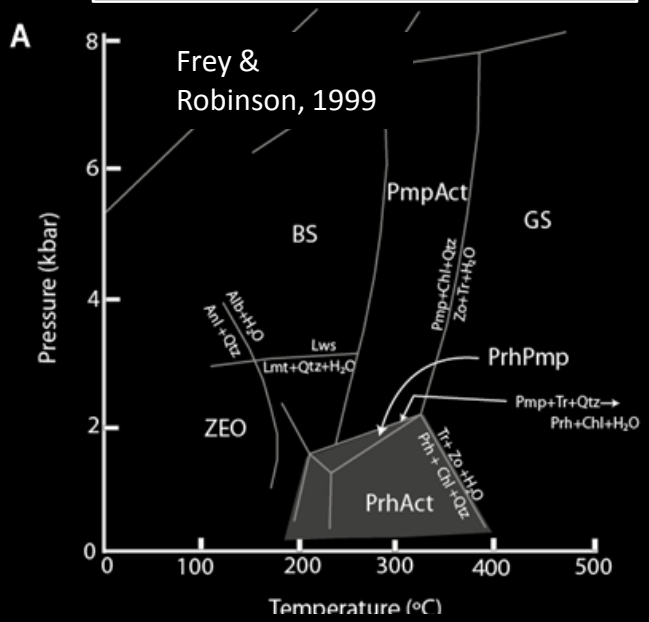
Mineral Indicators

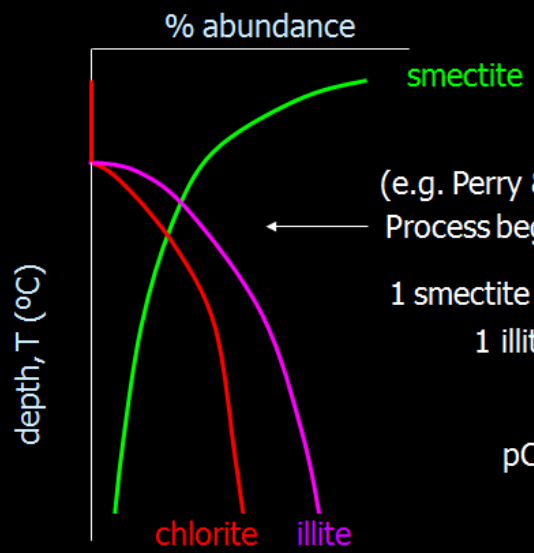
ANALCIME: 50-250ºC





PREHNITE: 200-400ºC





ILLITE/MUSCOVITE: >50ºC

(e.g. Perry & Hower, 1970)

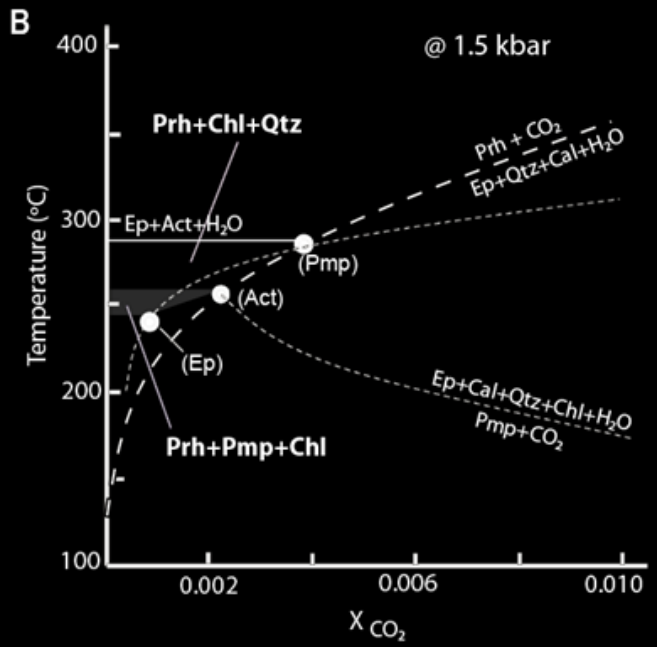
Process begins **T ~ 50-80ºC**

1 smectite + K^+ →

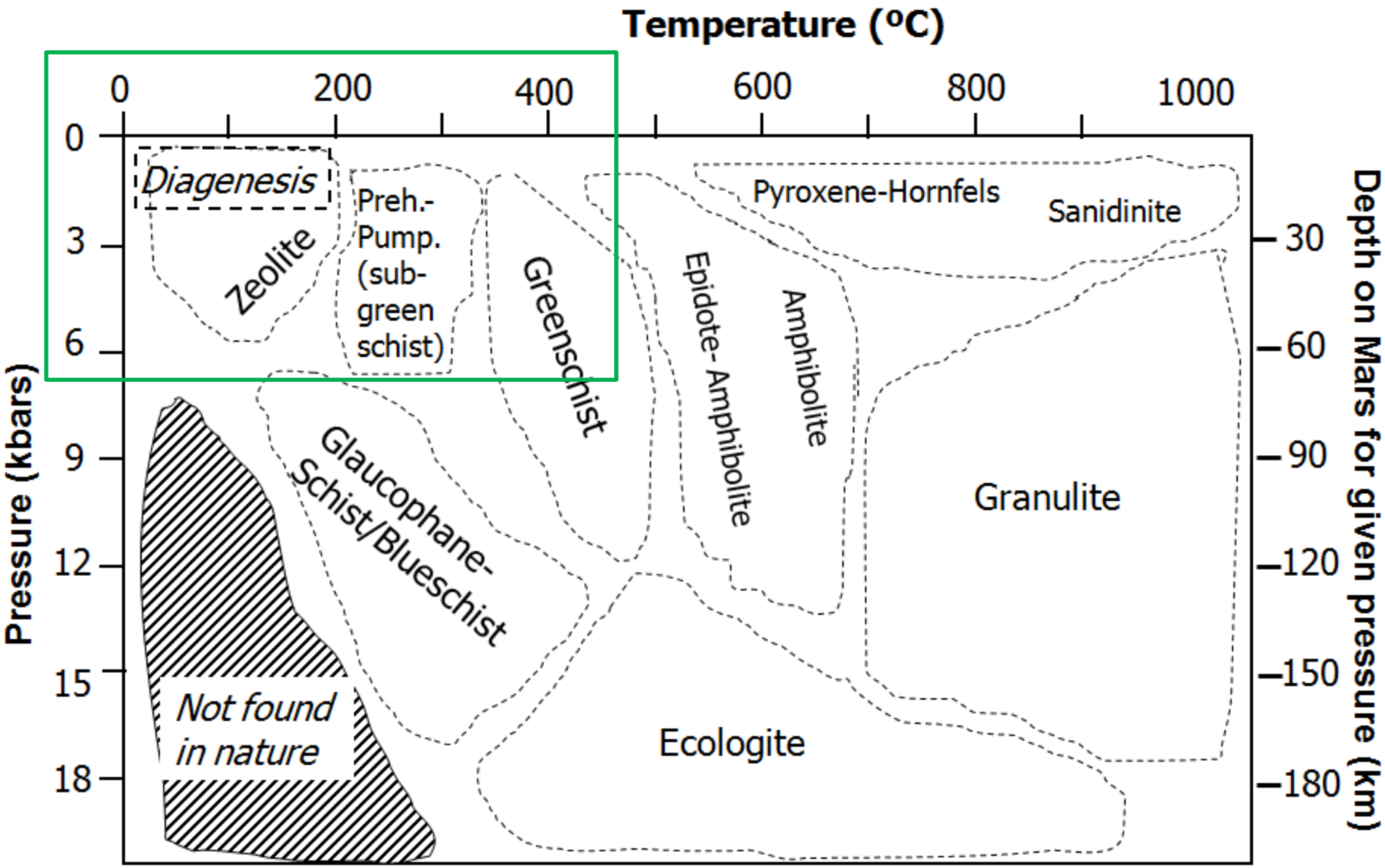
1 illite + Na^+ + Ca^{2+} + Si^{4+} + Fe^{2+} + Mg^{2+} + H_2O

pCO_2 — high → carbonates (Ca, Mg, Fe)

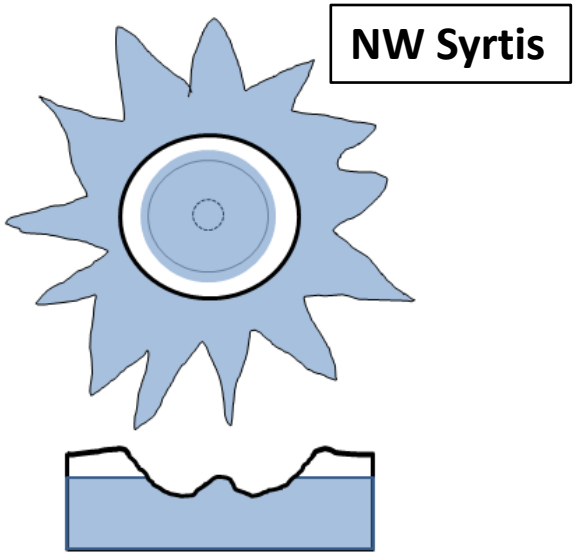
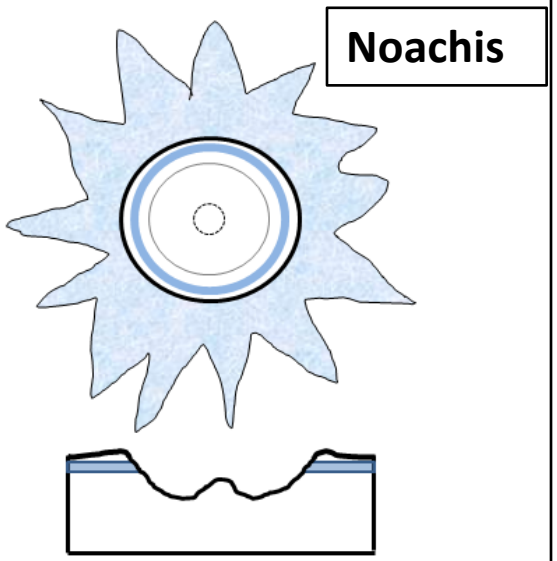
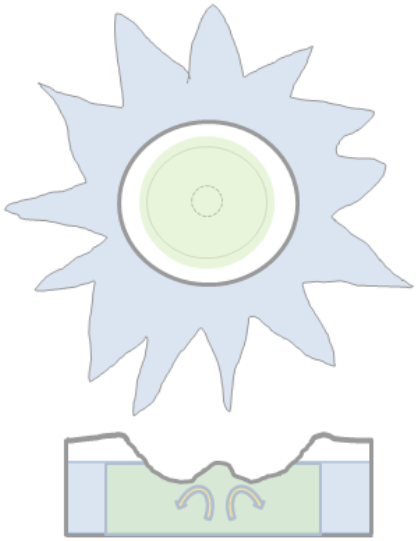
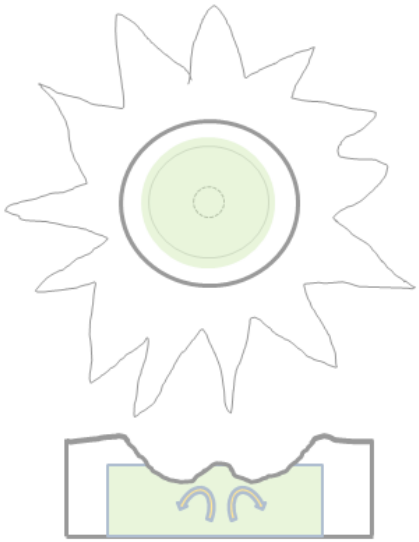
pCO_2 — low → Fe-rich chlorites



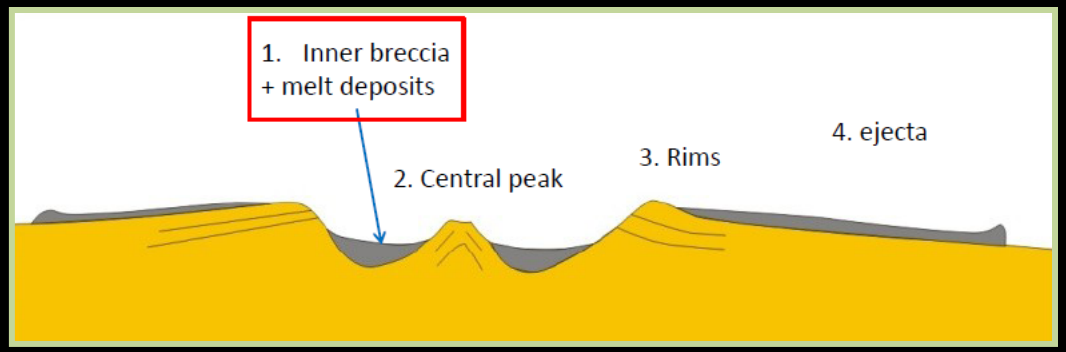
for discussion, see Ehlmann et al., JGR, 2009; CCM, in review



Ehlmann et al., Clays & Clay Minerals, accepted

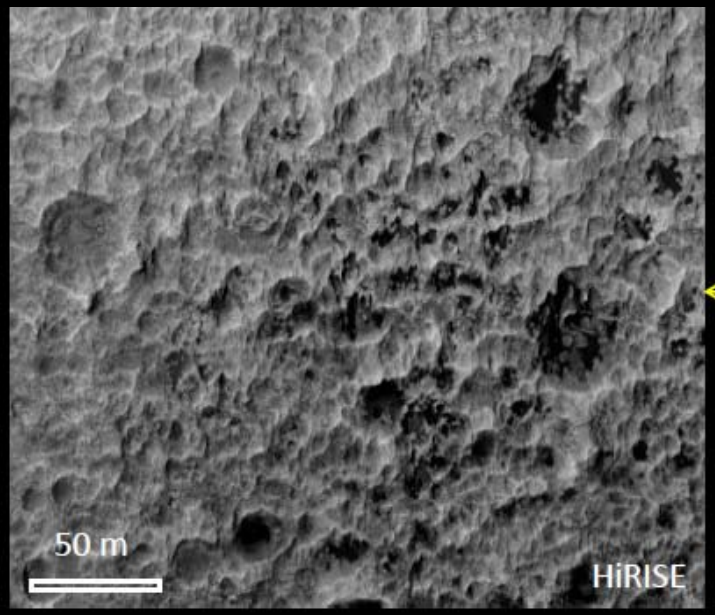
	Pre-existing Thick Clay Layer	Thin or no pre-existing clay layer
No HT System		
HT system		

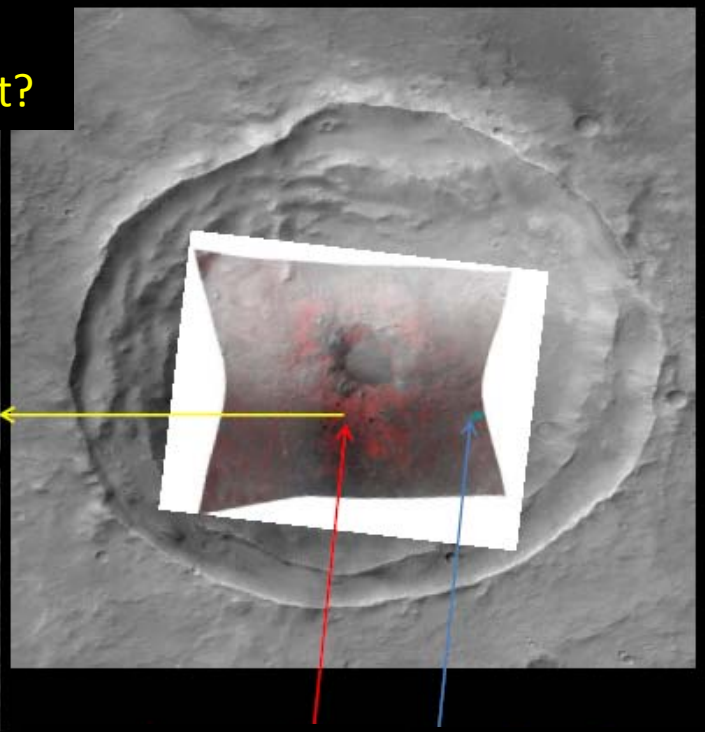
But…new evidence for aqueous alteration caused by cratering?



Mangold et al., April 2011, OMEGA Team Meeting

Pitted texture typical of suevite or melt.
Interaction of water/ice with warm impact melt?





Fe/Mg smectites Opaline silica

Conclusions & Outstanding Questions

- Impacts did not sterilize the Earth or Mars
  - How did they affect the climate?
- Impact-induced hydrothermal systems existed on Earth
  - Did they exist on Mars?
  - How can we identify them remotely?
- Potential for craters to create environments suitable for life
  - Could they be colonized on Mars?
  - Are biosignatures preserved through time?
  - Should we send a mission to investigate this? How?