Toward a Calibrated Geologic Time Scale: Stratigraphy and the Rock Record of Mars

John Grotzinger

with thanks to

A. Allwood
S. Bowring
B. Ehlmann
J. Griffes
L. Hinnov
K. Lewis
R. Milliken
J. Mustard
L. Roach
K. Tanaka

Mars Bedrock Stratigraphy: Major Questions

•What are the "ancient" cratered terrains composed of, and what does the coarse layering indicate? Impact breccia? Hydrothermal breccia? Volcanics? Sedimentary rocks?

•What are the vast, well- bedded terrains composed of? Eolian Sand and Dust? Subaqueously transported sediments? Lava? Pyroclastics?

•Is there a preserved record of temporal breakpoints in geologic processes or environmental conditions? Is there a global environmental history preserved that varies with time? (e.g. oxygenation of the Earth) Acidification of Mars?

•How old are these strata and when did the environmental break points occur?

•Are the hydrated minerals in these rocks closely related in time to the formation age of the rocks (e.g. magmatic crystallization, or sedimentation)? Or do they relate to much later alteration or diagenesis? (e.g. Could the phyllosilicates seen in "ancient, deeply exhumed" terrains be "younger and shallower" in origin? Could the hydrated sulfates be a more recent climatic phenomenon?

Principles, Important Concepts

Steno (1669): Laws of Superposition, original horizontality, lateral continuity

Smith (1770s): First applications of stratigraphy, first geologic map of England

Magnetostratigraphy (reversals, intensity)
Chemostratigraphy (isotopes, trace elements, mineral abundances)
Cyclostratigraphy (rhythmic changes in *rock* properties; *astronomically forced*)
~~Biostratigraphy~~

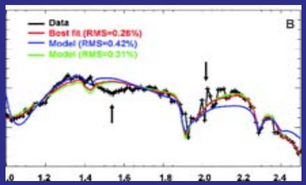
Chronostratigraphy: branch of stratigraphy that studies the absolute age of *rock* strata. Its ultimate aim is to arrange the sequence of formation and the duration of formation of all rocks within a geological region, and eventually, the entire geologic record of the *Earth*.

Any Geologic Timescale has two Components:

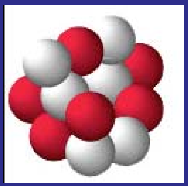
- Relative ordering of geologic events
- Absolute time constraints (radiometric age determinations)

Correlatable rock property

Fossil



Mineral

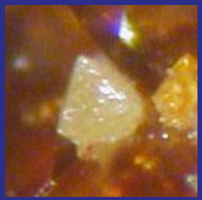


Isotope

+

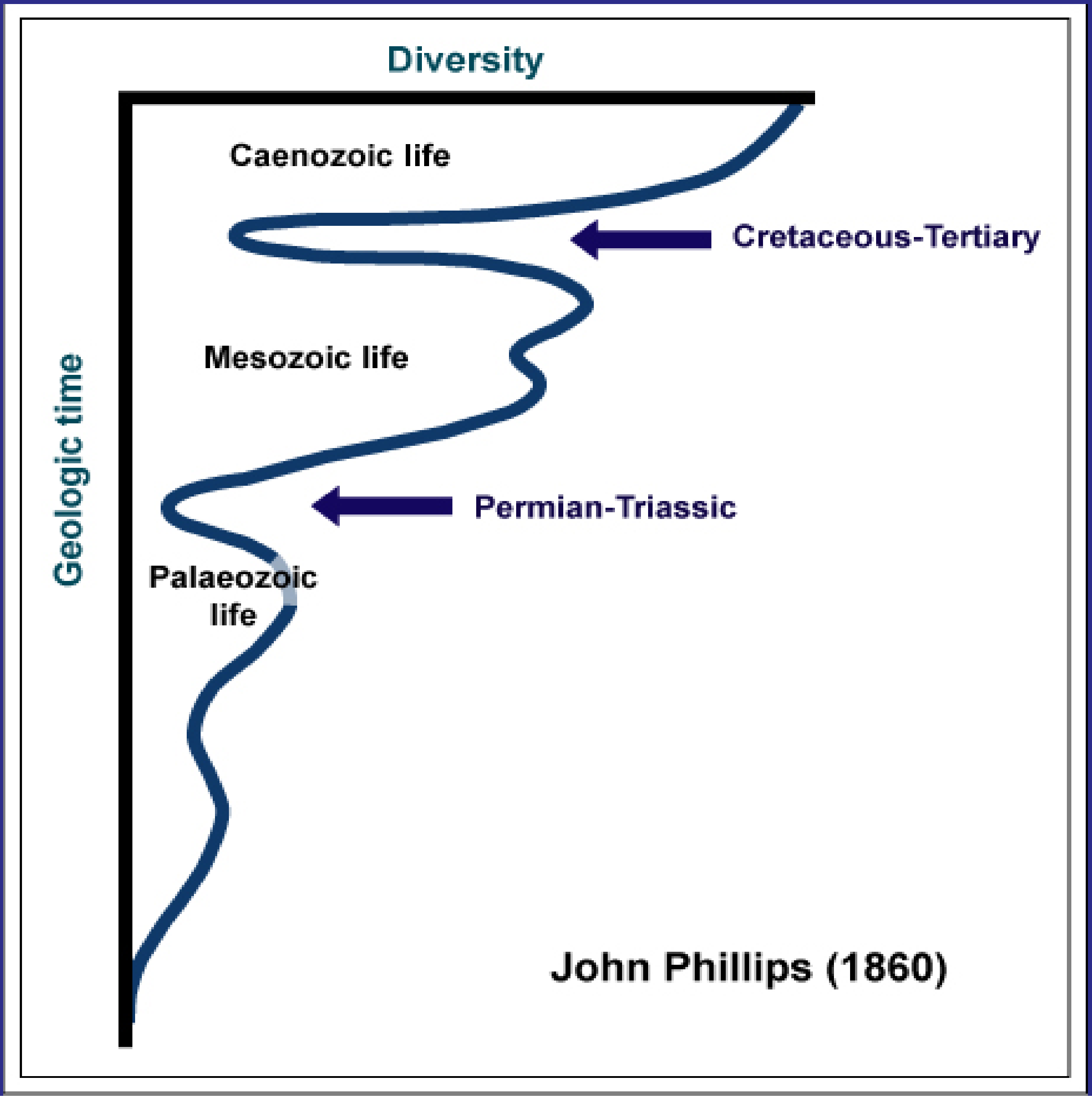
Geochronometer

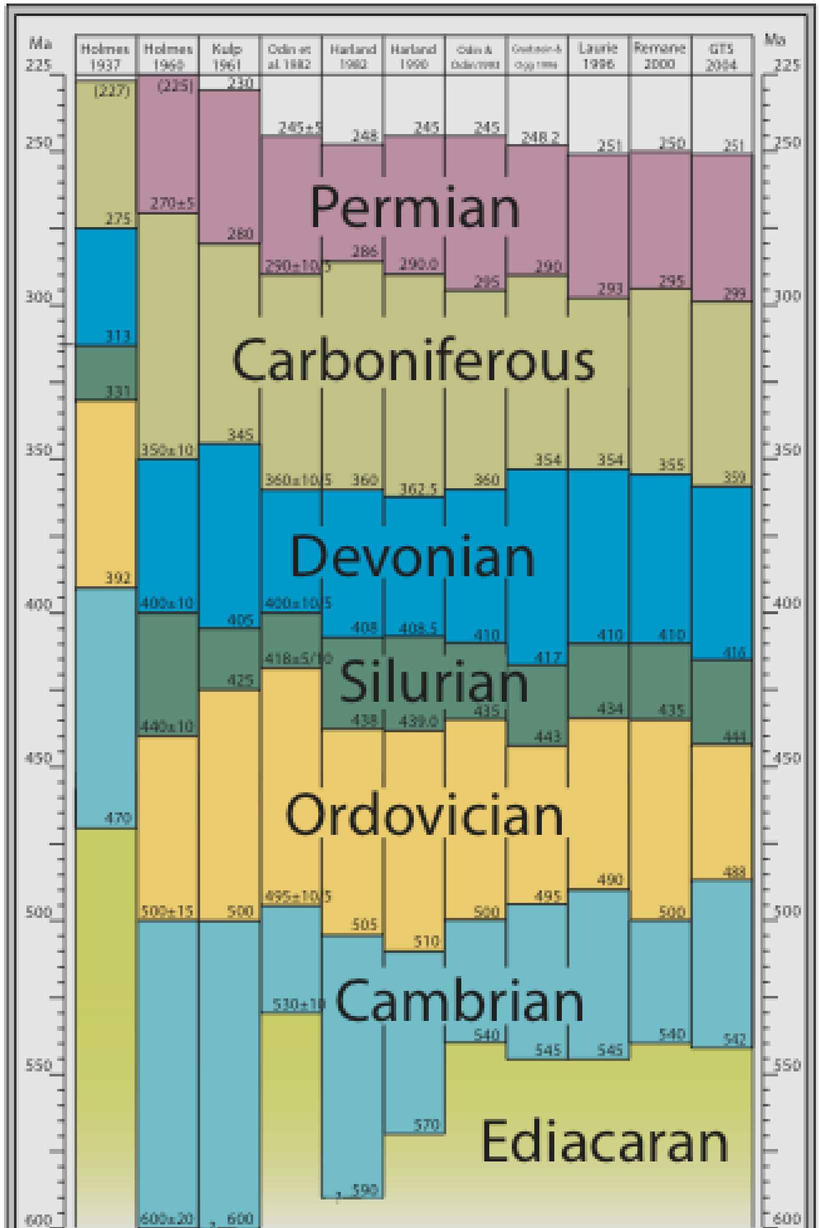
Zircon



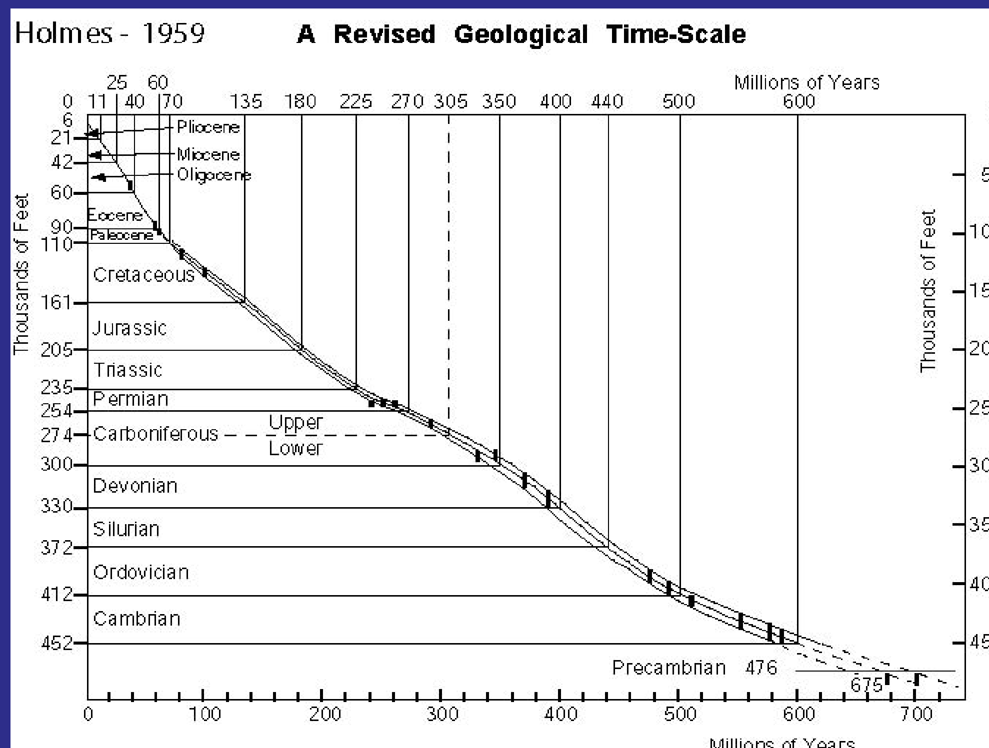
Jarosite?

Geologic Time Scale: Circa 1860

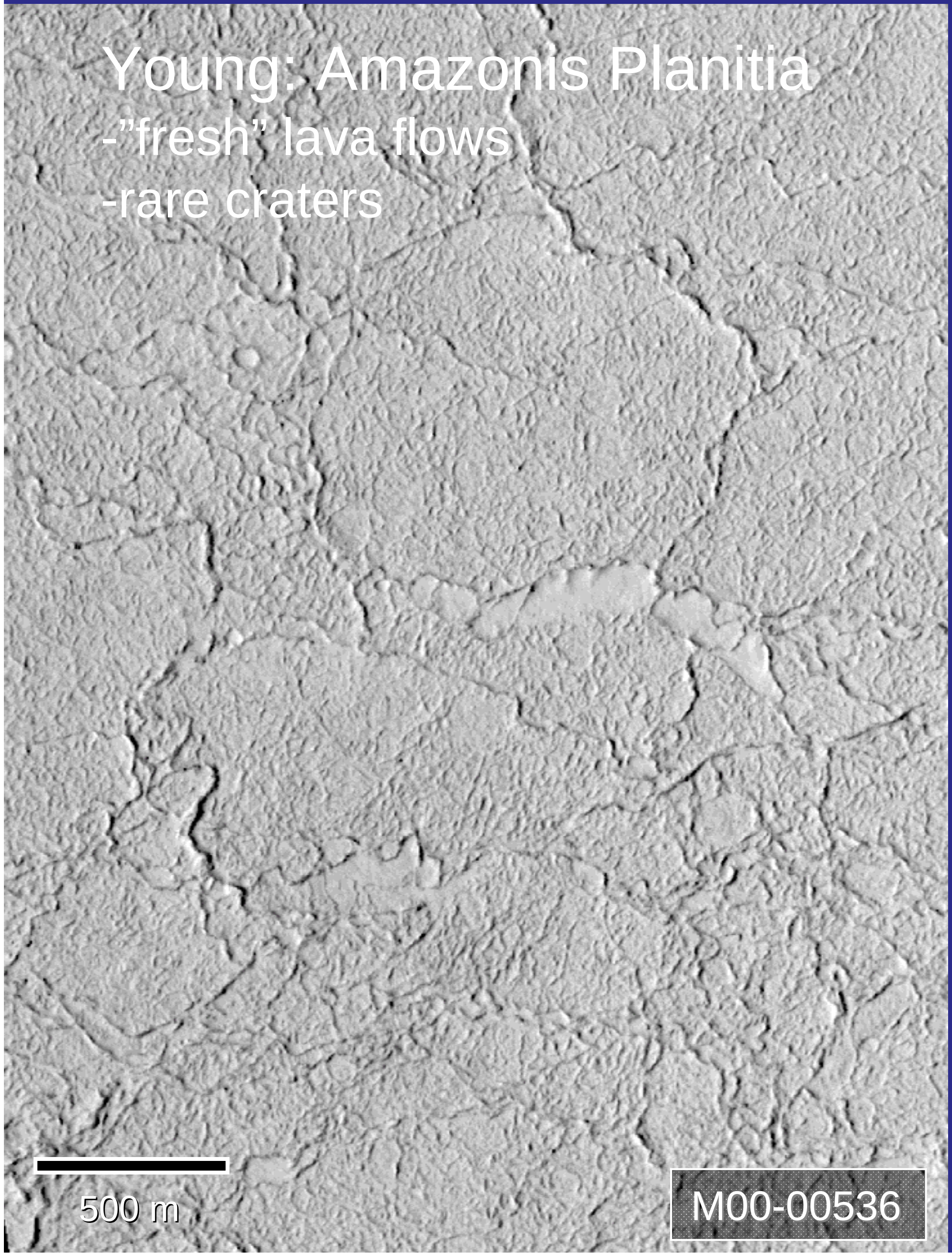


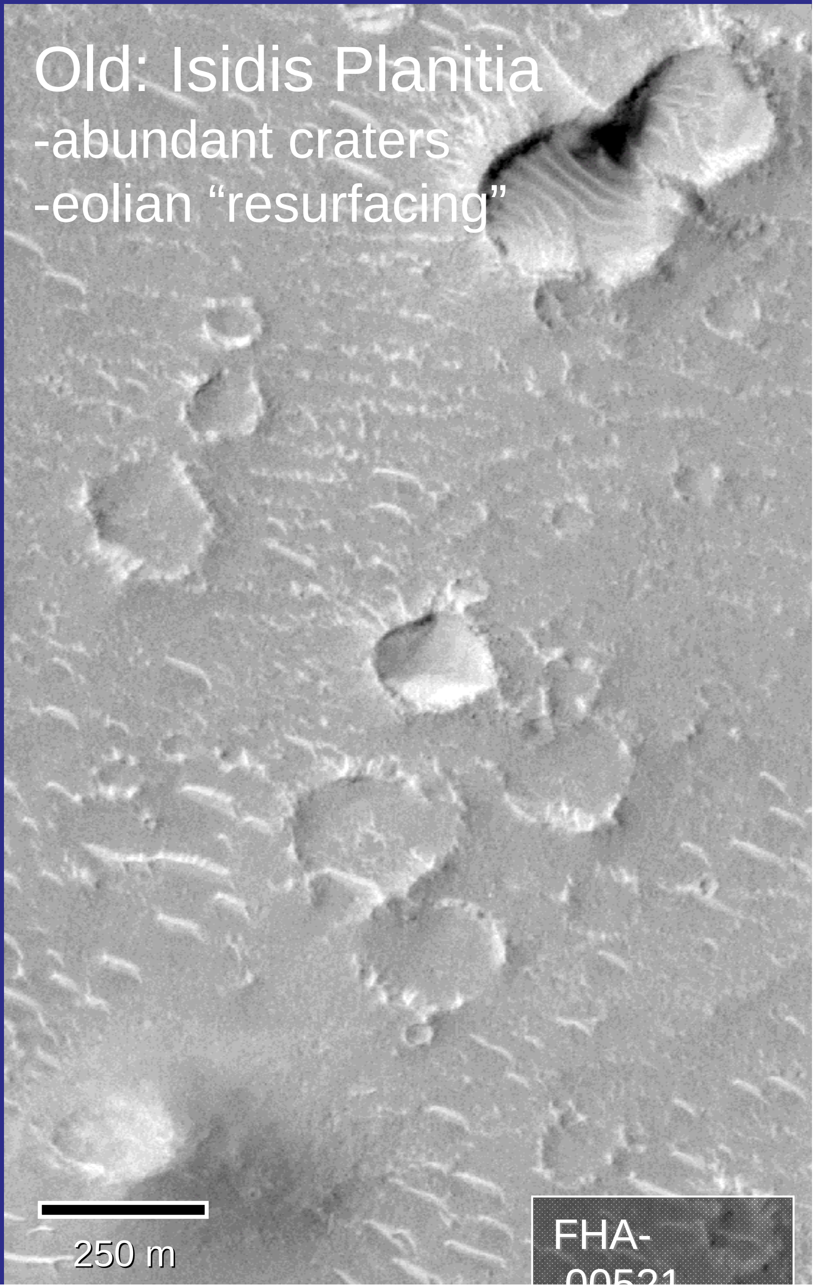


Evolving Geological Timescales (1937 to 2004) illustrating the continuous calibration of geological time. Adapted from GTS 2004, courtesy of G. and J. Ogg.



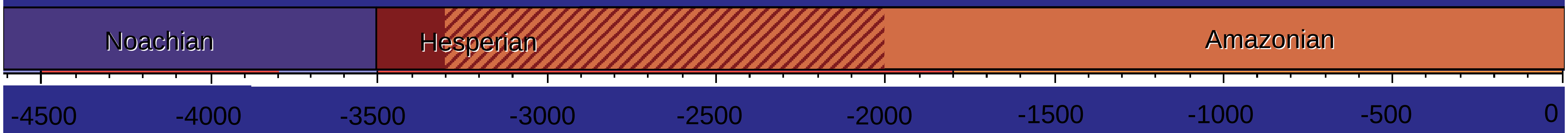
Mars Time Scale, Surfaces and Ages Hartmann and Neukum, 2002



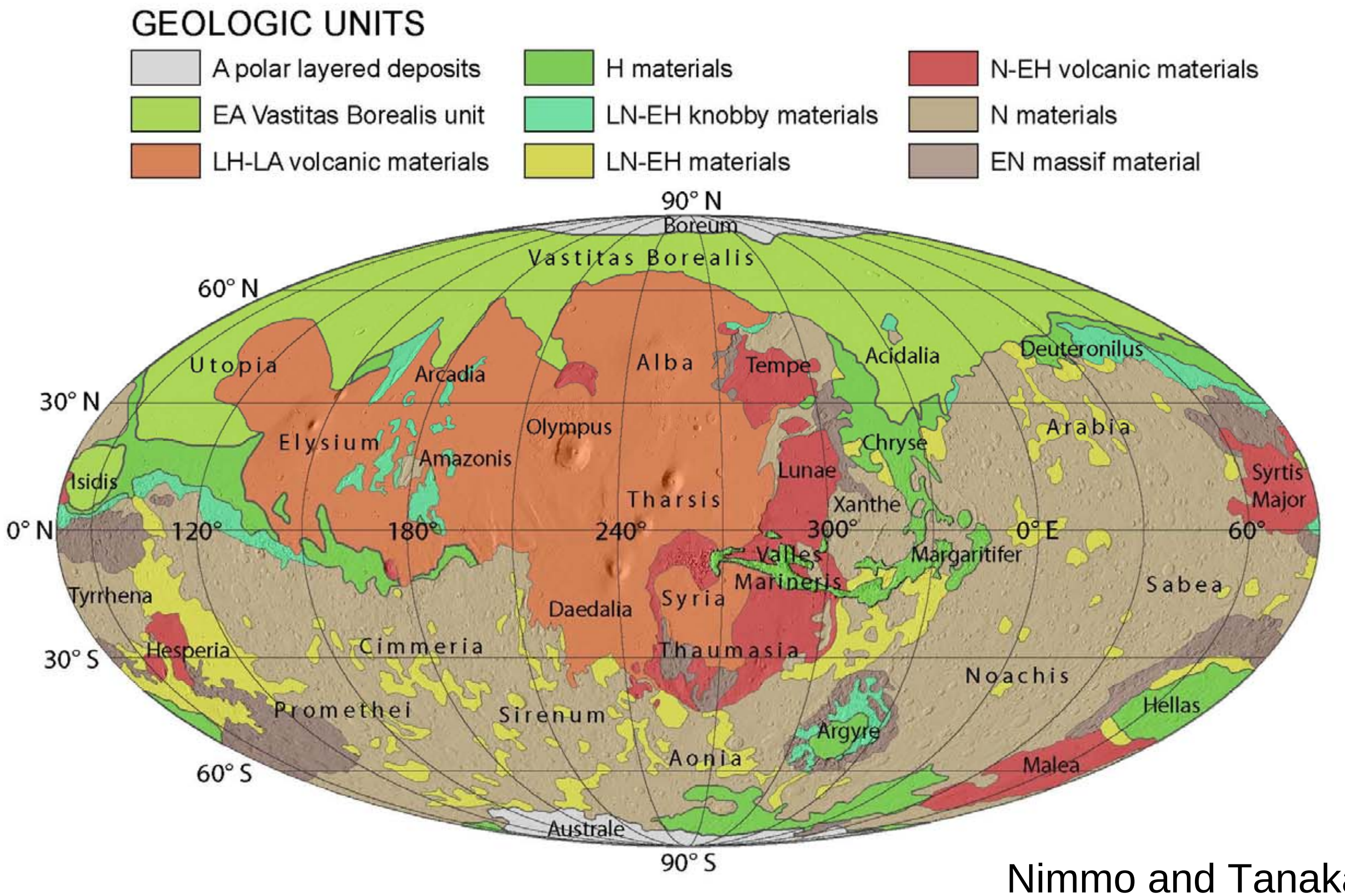


Status of Mars Chronstratigraphy

Time scale based on relative ages of geomorphic surfaces calibrated by crater density distributions, *with adjustments for resurfacing processes*



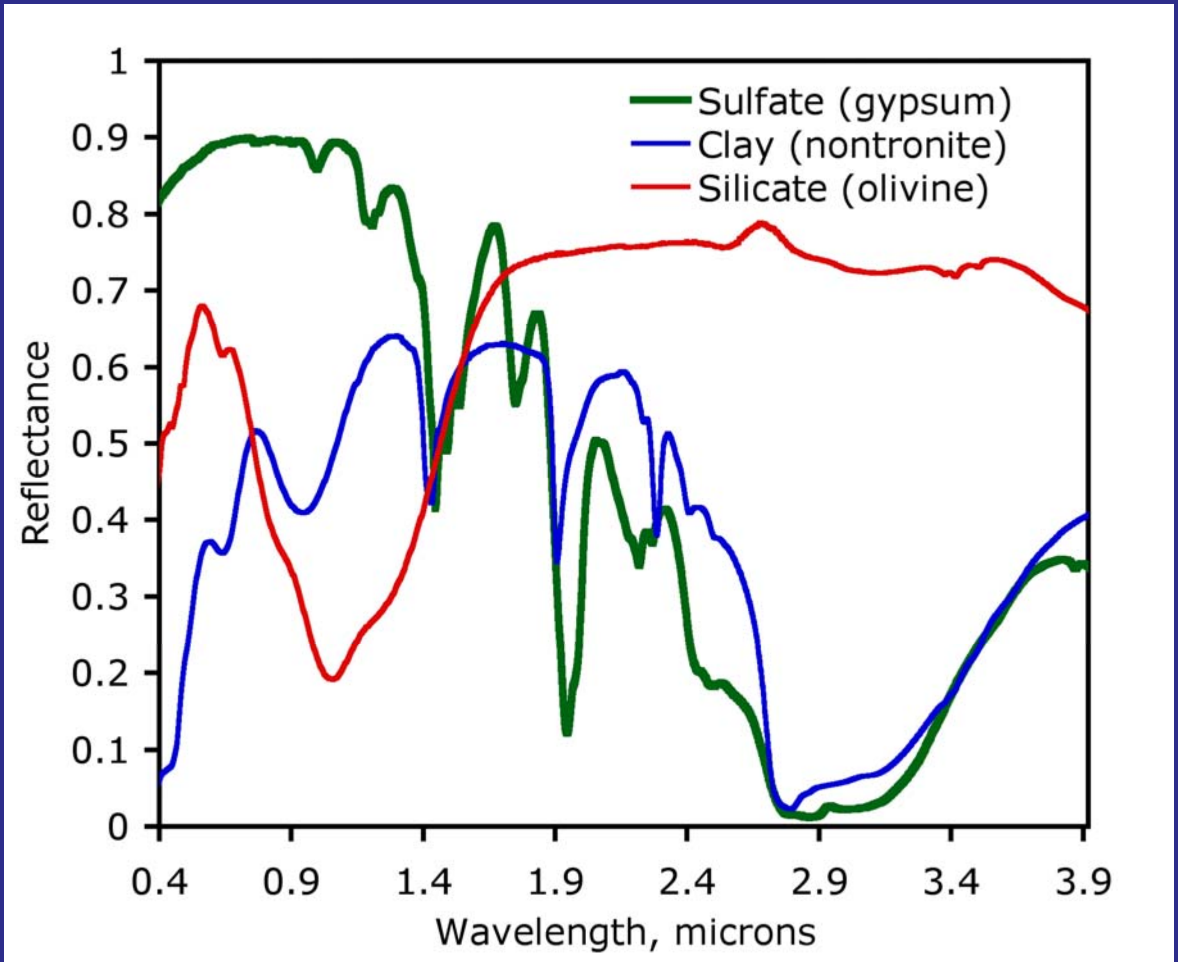
Generalized Mars Geology



Nimmo and Tanaka, 2005

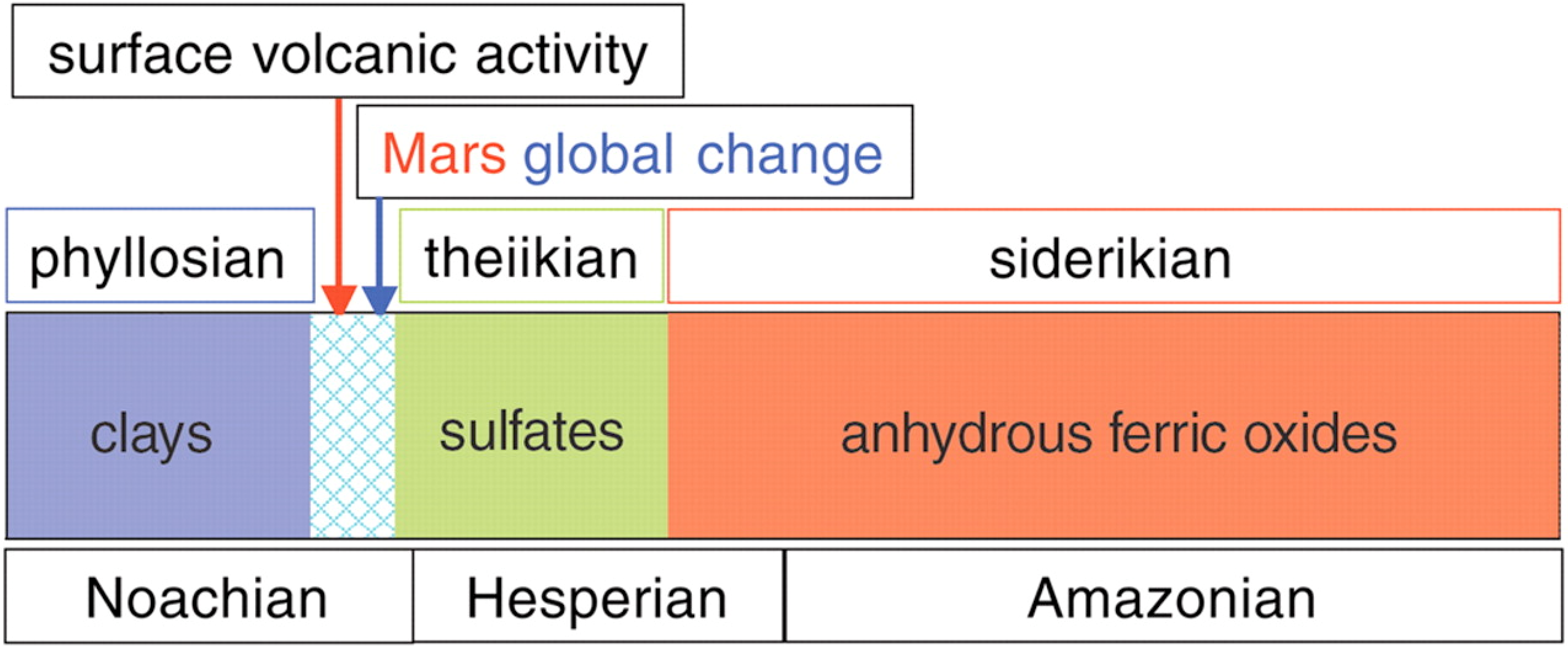
Status of Mars Chronstratigraphy

•Recent VNIR hyperspectral (OMEGA, CRISM) mapping suggests hydrated mineral distributions may relate to relative geologic age as determined via crater density distributions



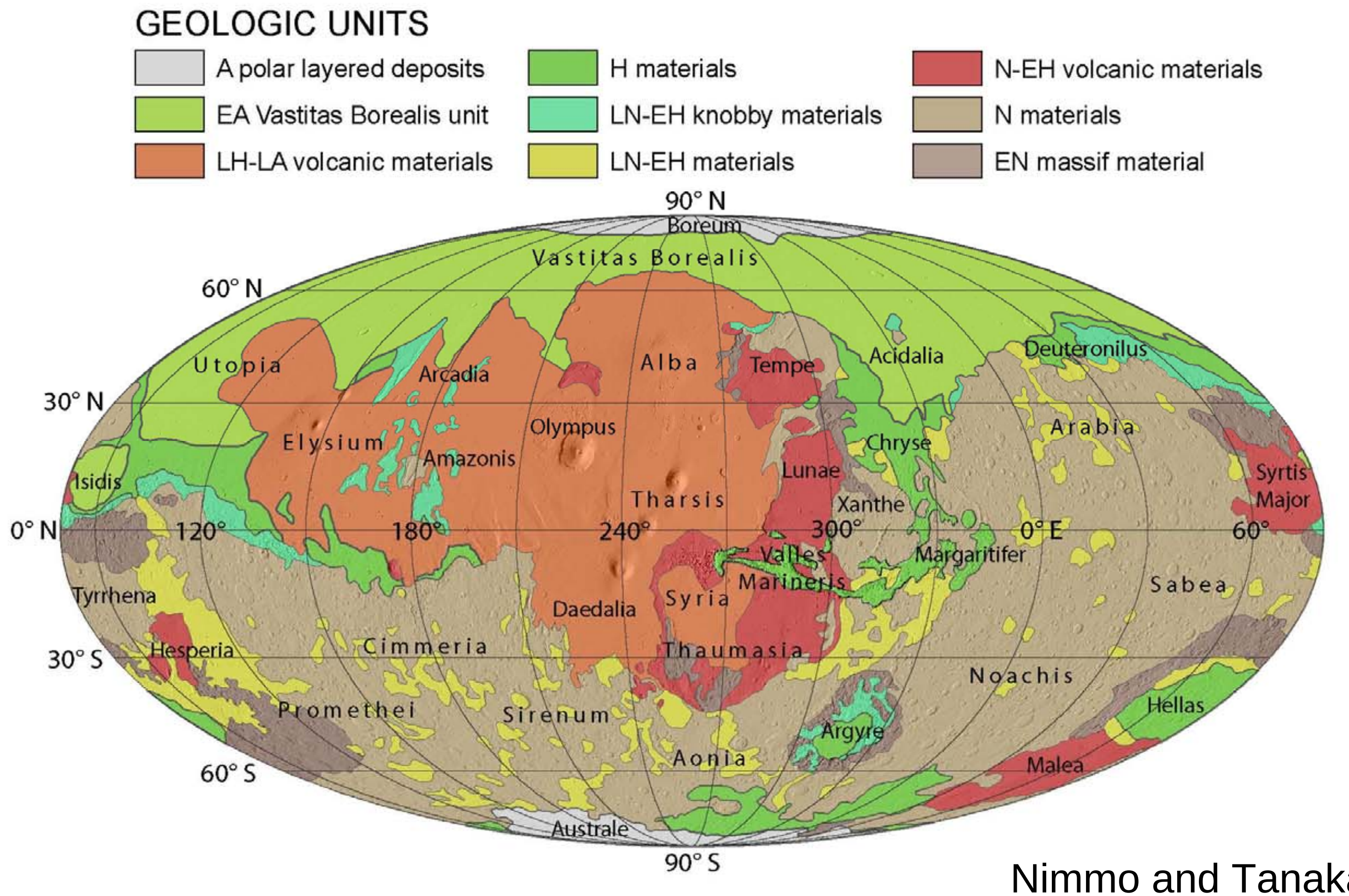
Mineralogy-based Chronostratigraphy for Mars

Bibring et al., 2006



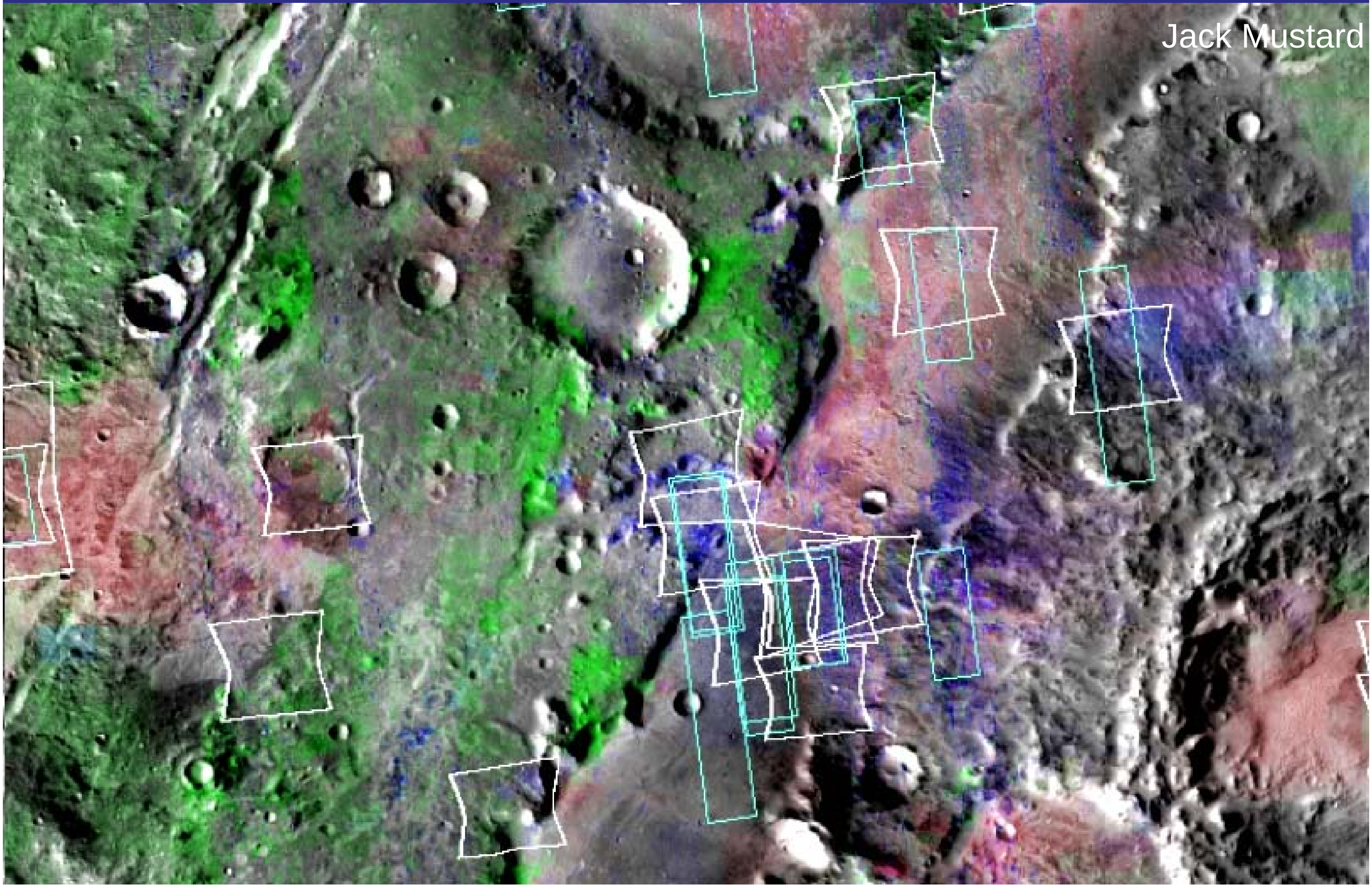
- Major Step Forward
- Based on physical properties that show apparent temporal evolution
- Testable based on *in situ* measurements

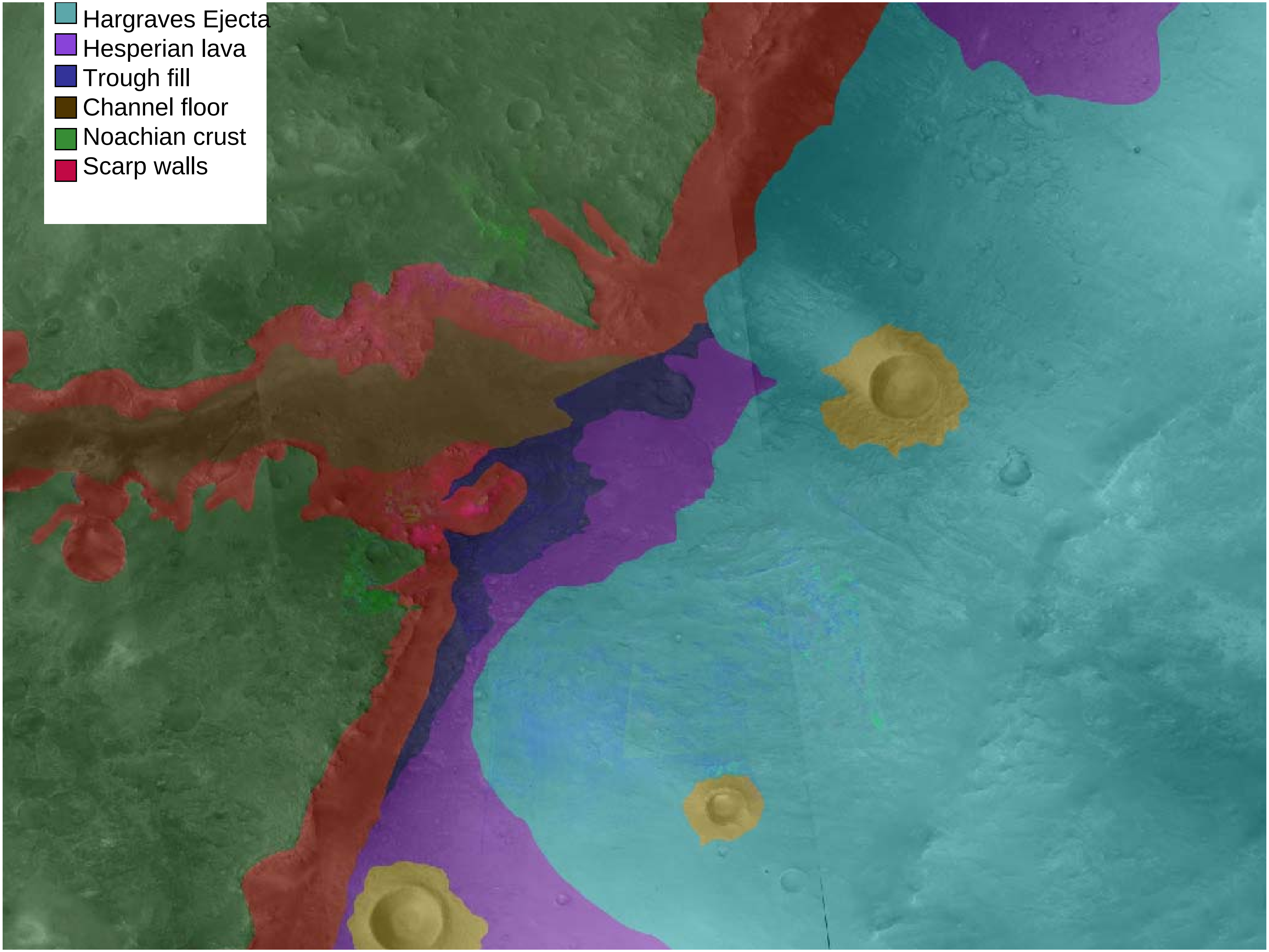
Generalized Mars Geology



Nimmo and Tanaka, 2005

Noachian Crust: Nili Fossae

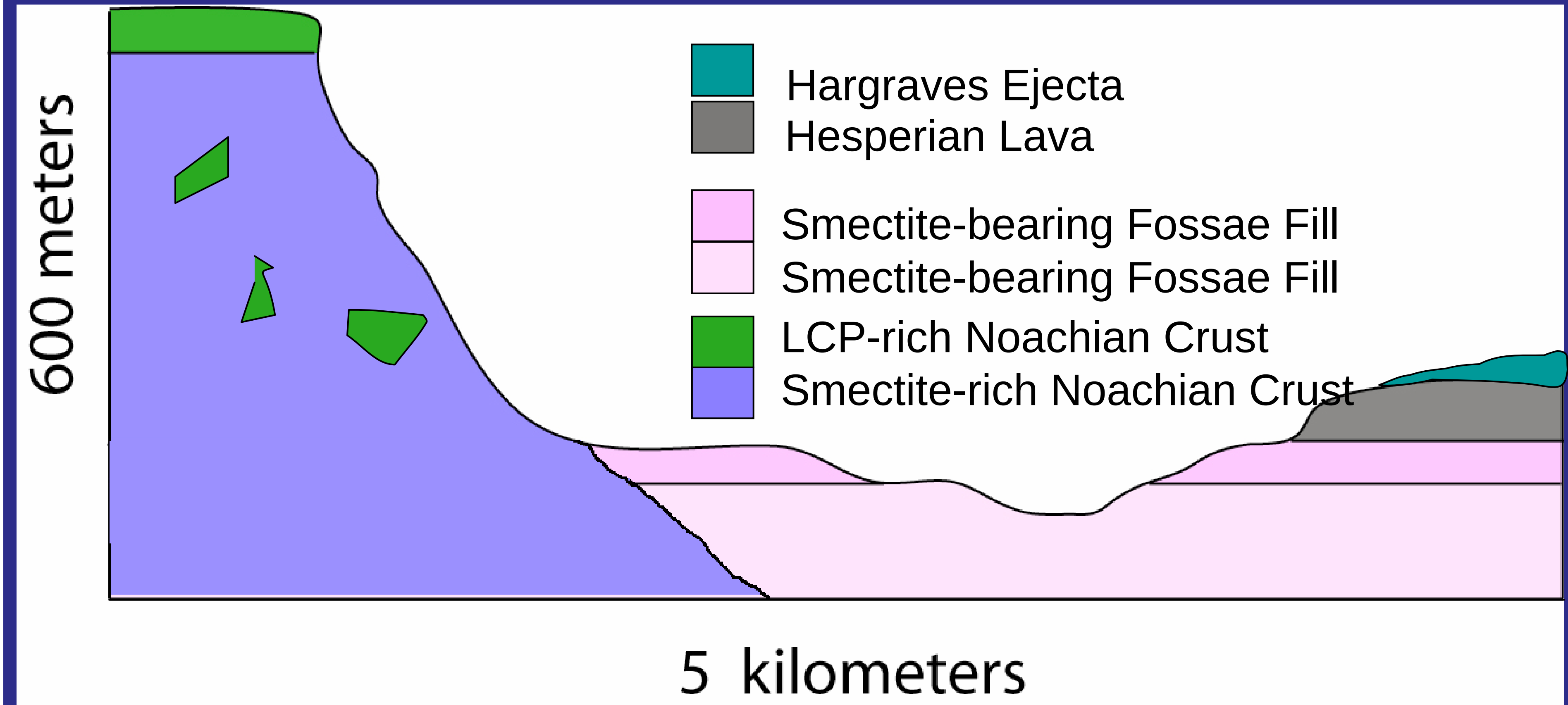




Hargraves Ejecta
Hesperian lava
Trough fill
Channel floor
Noachian crust
Scarp walls

Generalized stratigraphy, amenable for dating

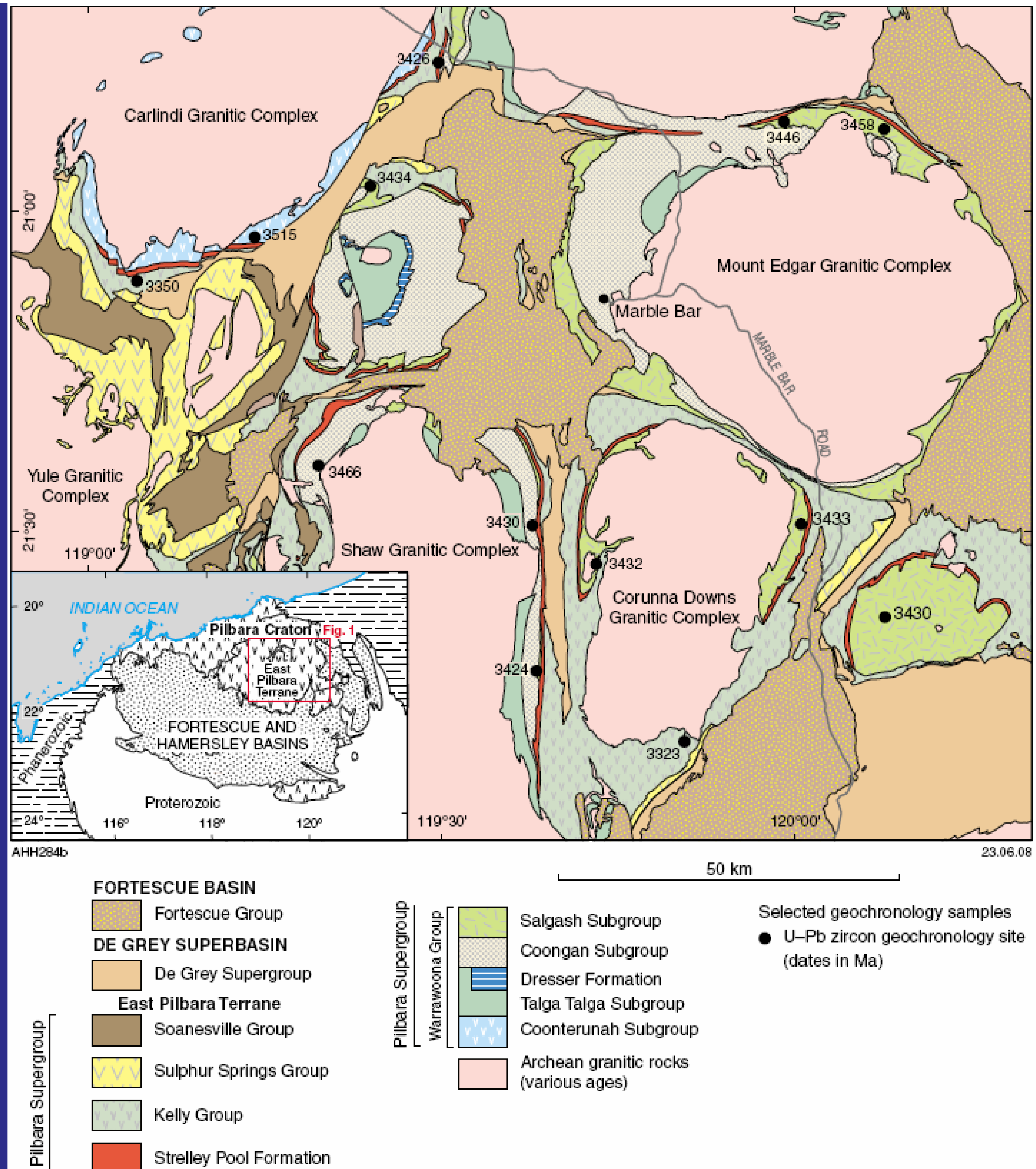
1)Hesperian lava
2)Phyllosilicates in Trough (Hesperian)
3)“Classic” Noachian crystalline rocks
4)Altered equivalents of Noachian crystalline rocks



(Representative vertical and horizontal distances, not to scale)

J. Mustard

Earth's
Late Noachian Crust
Pilbara, Australia

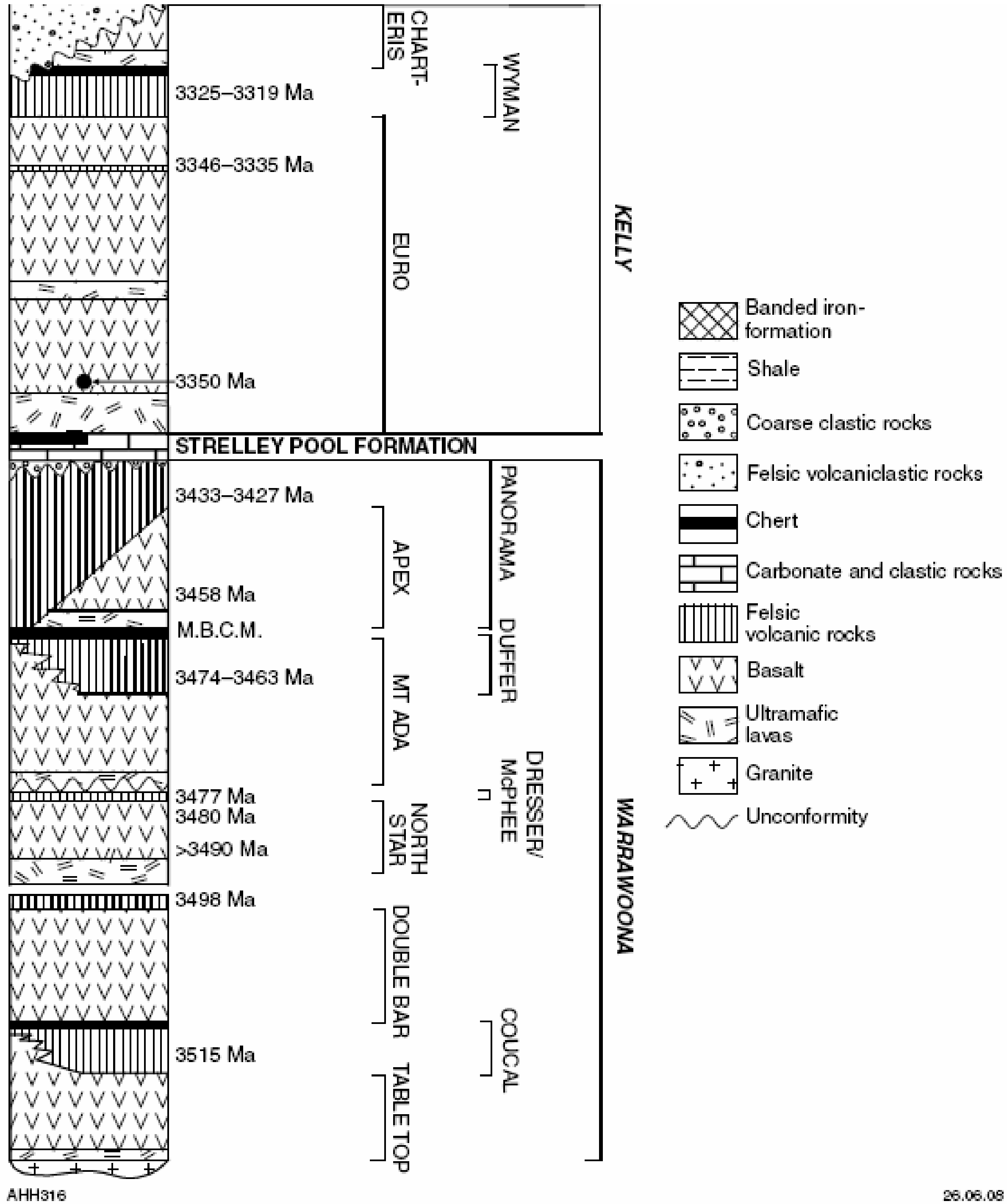


Van Kronendonk et. al, 2008

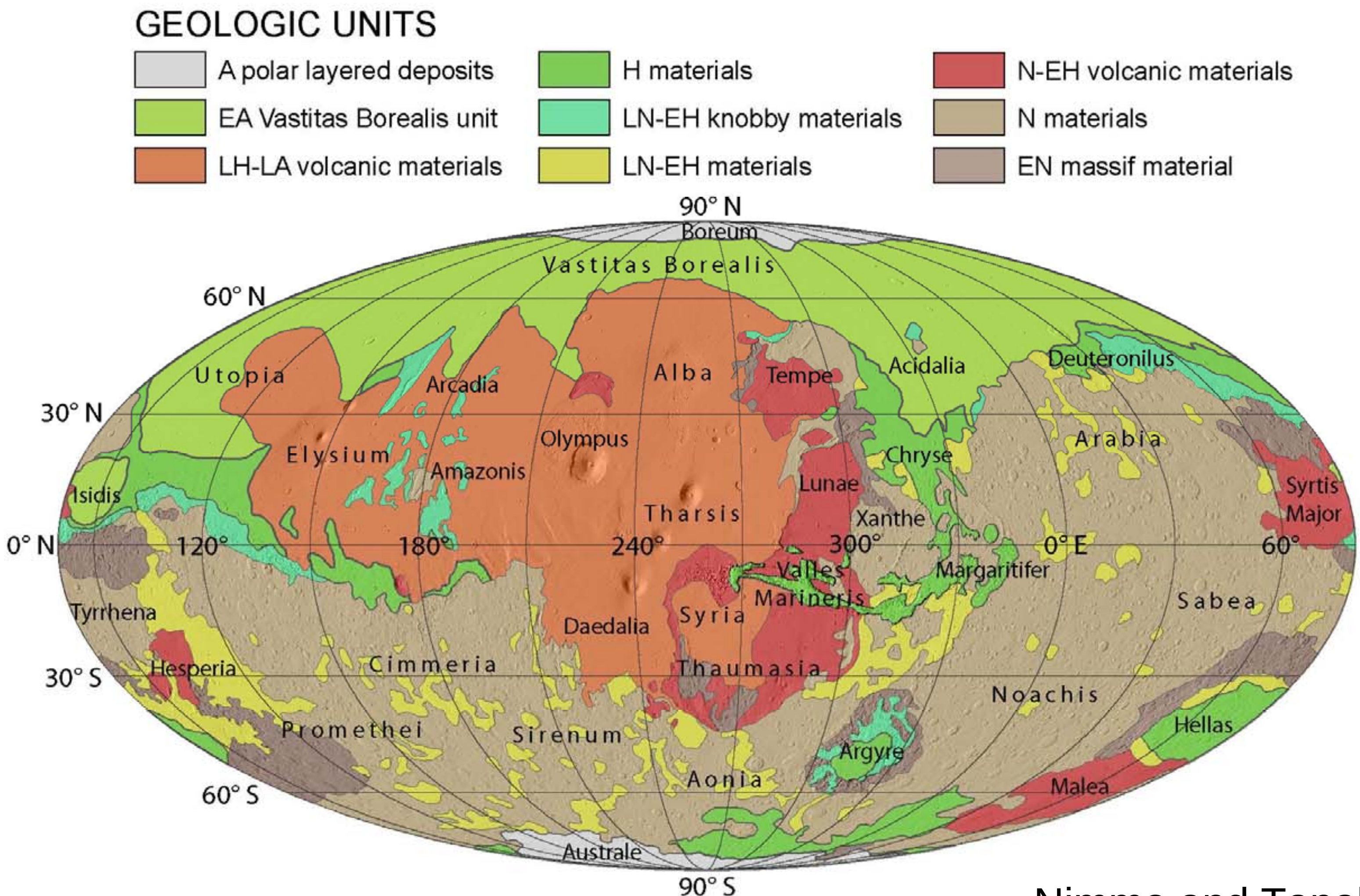
Pilbara Chronostratigraphy

- High resolution geochronology sorted out the stratigraphic relationships

Van Kronendonk et. al, 2008



Generalized Mars Geology

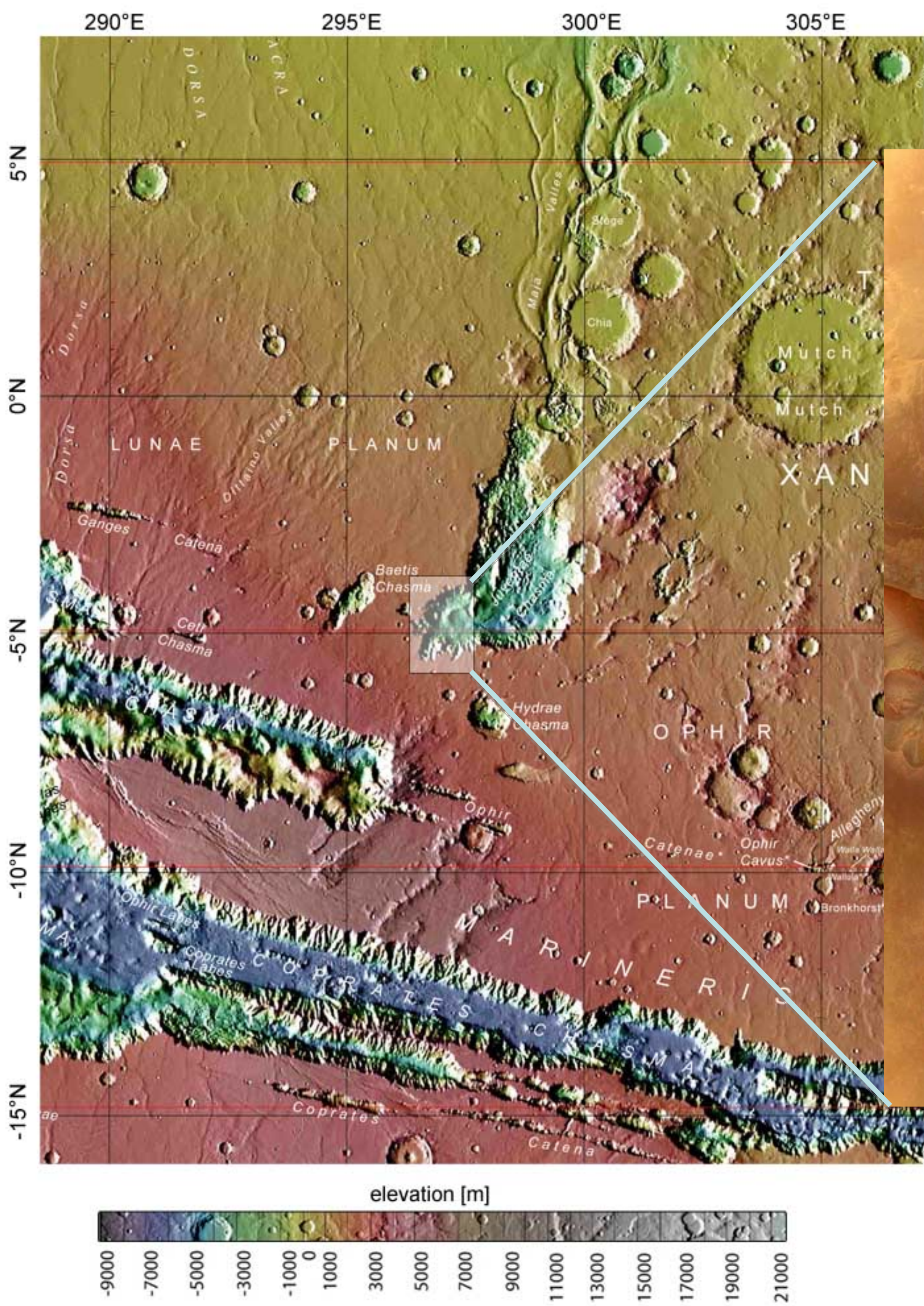


Nimmo and Tanaka, 2005

Layered Rocks: Regional Sequences

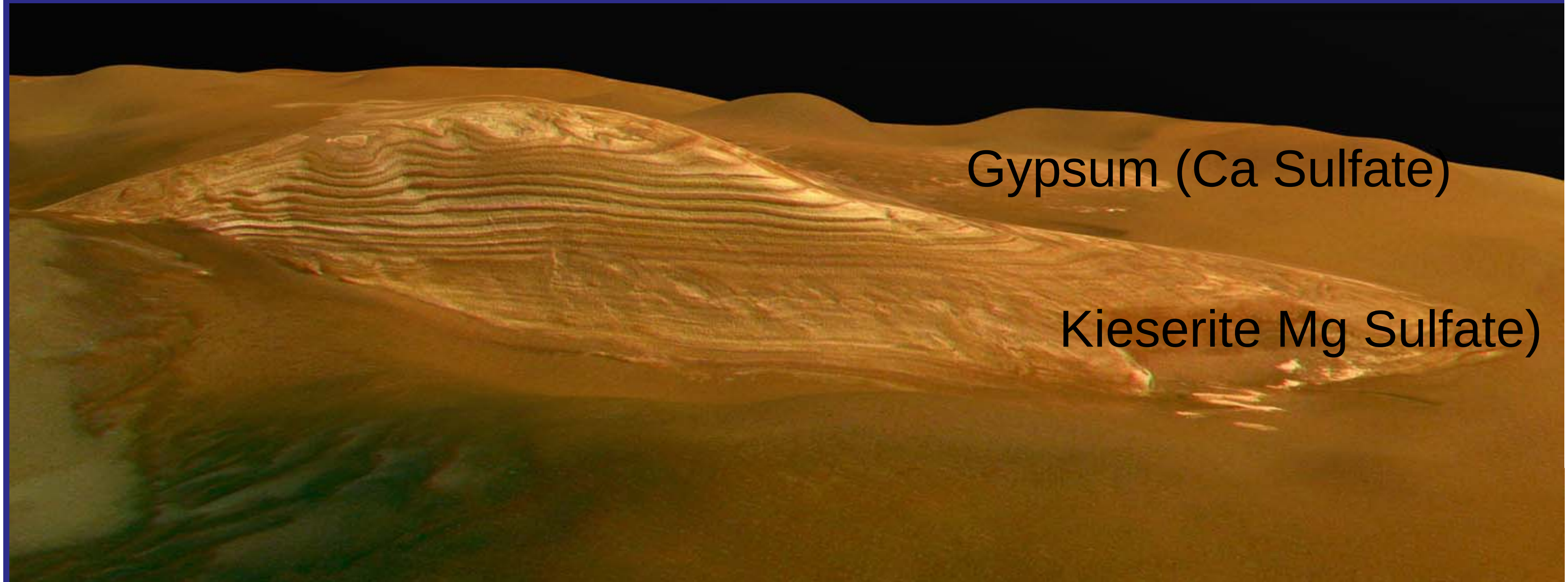
- Extend for 100s of km
- Simple stratal geometries, bit local truncation
- Dominated by sulfates or no diagnostic spectral response. Locally phyllosilicate rich

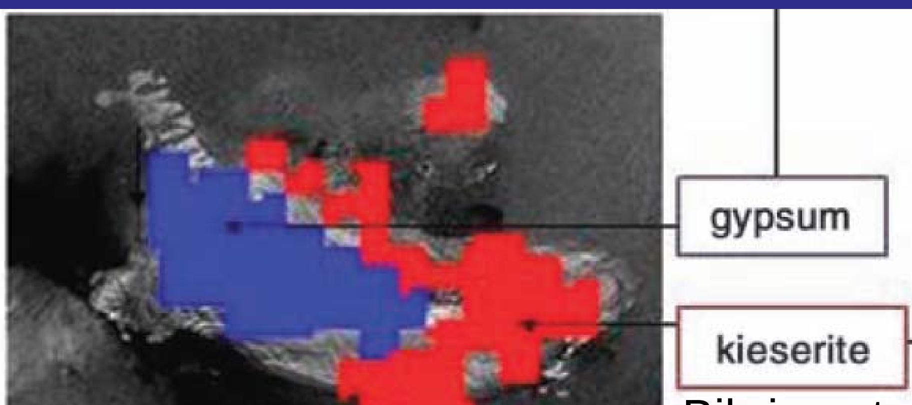
Juventae Chasma



Example of Layered Sulfates
Headwaters of Maja Valles
Floor Around -2 km Elevation
4.5° S, 297.5° E

Juventae Chasma: Hesperian Layered Deposits

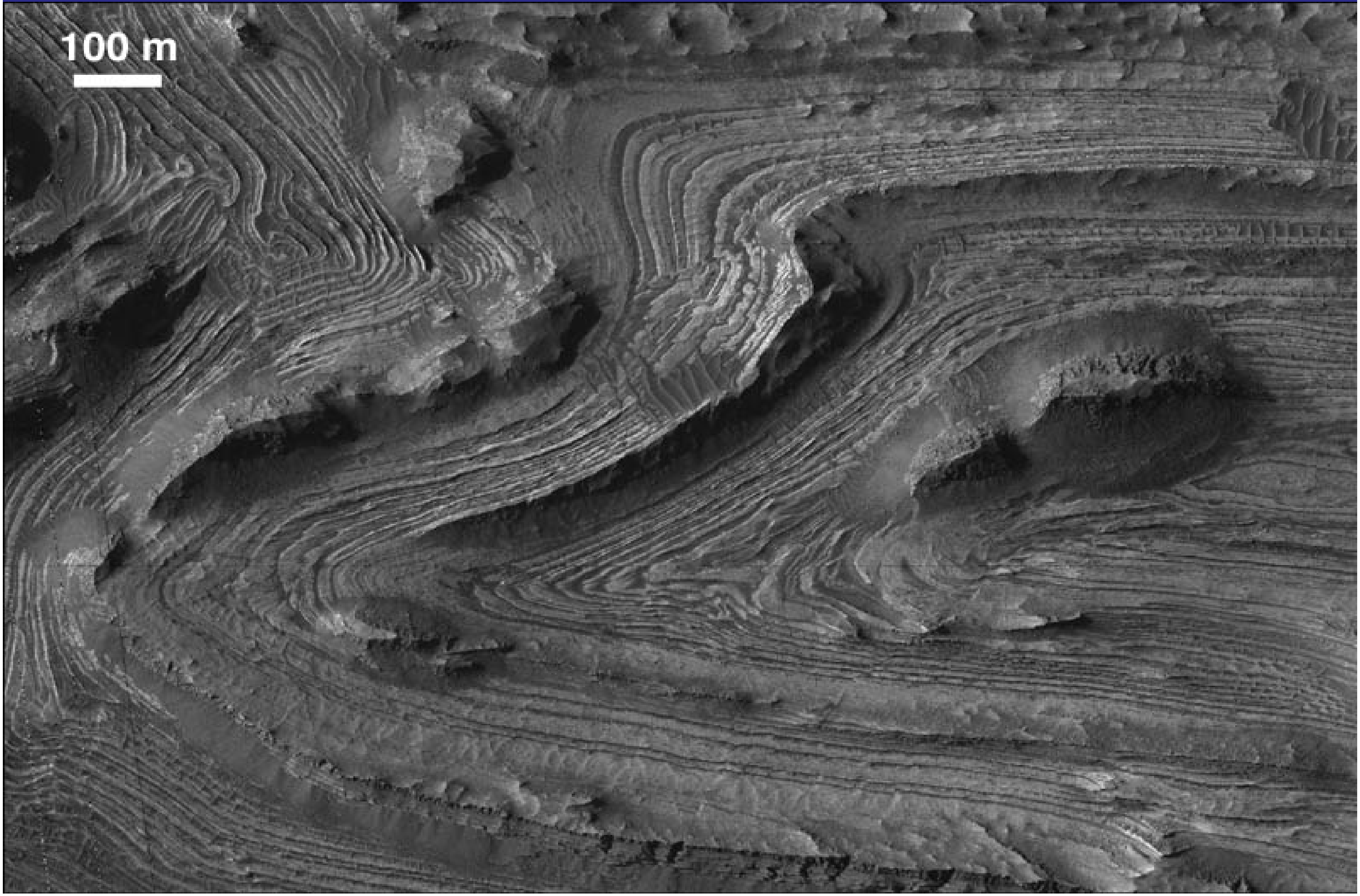




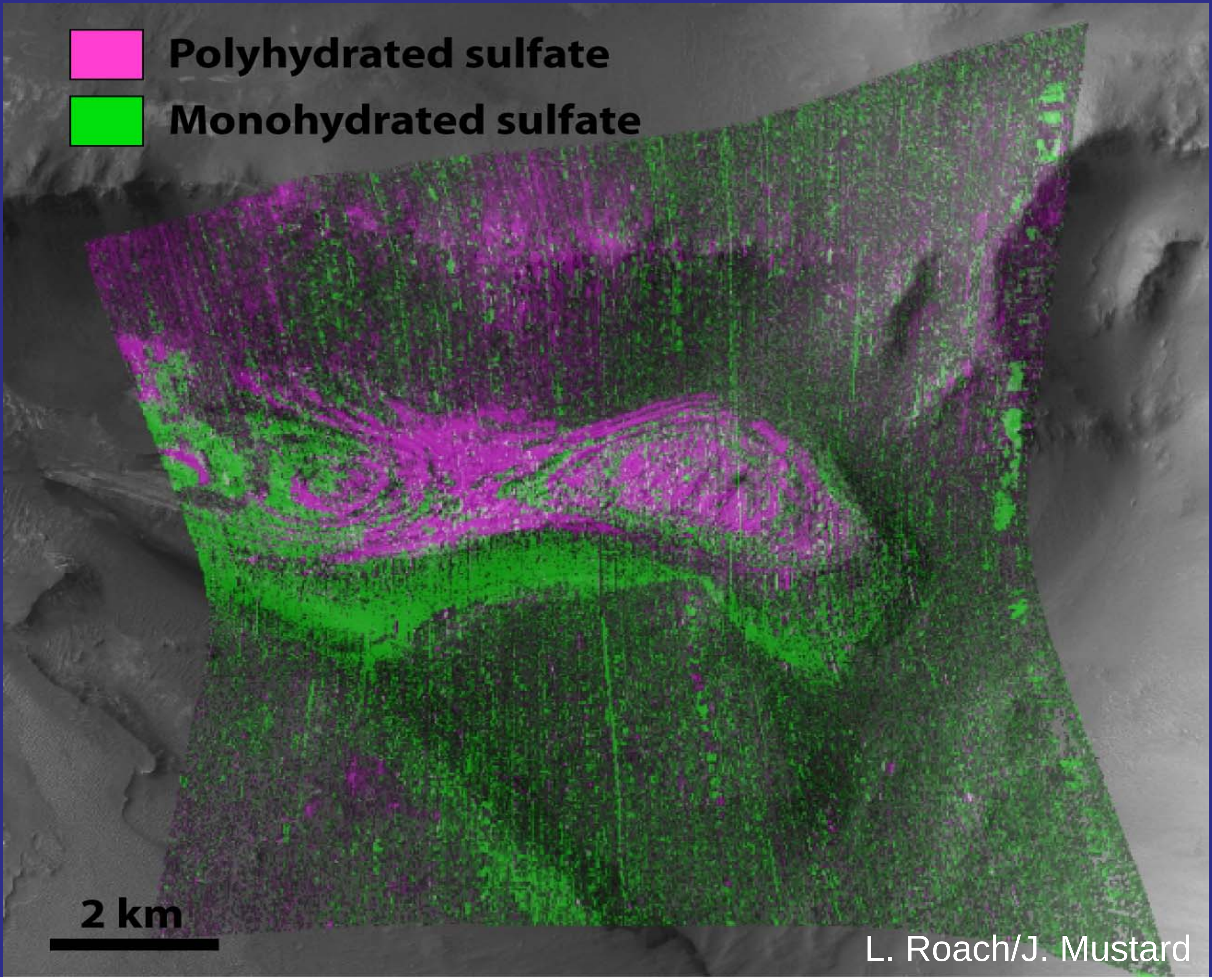
Bibring et al. 2005

Stratigraphic Transition - Minerals with Different Solubilities

Candor Chasma: Layers can be Deformed



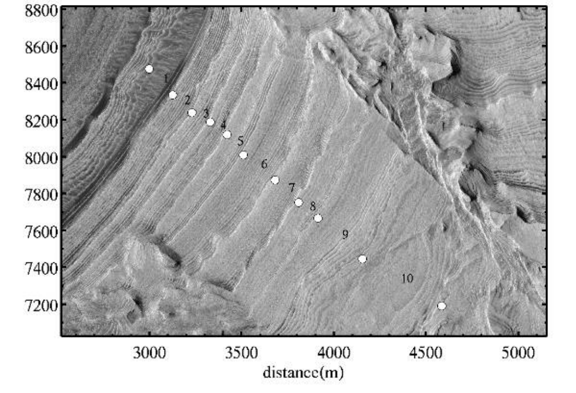
Candor Chasma: Folded Layers are Sulfates



Layered Rocks: Arabia

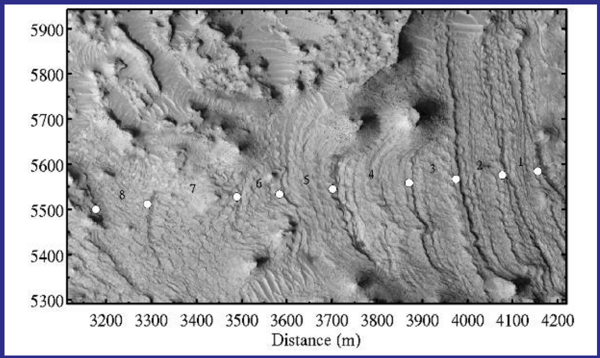
- Widespread over huge region
- Well-bedded, relatively uniform bed thickness
- No strong spectral responses identified

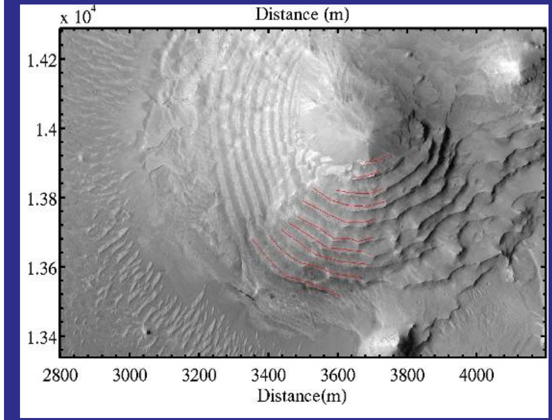
Representative Strata



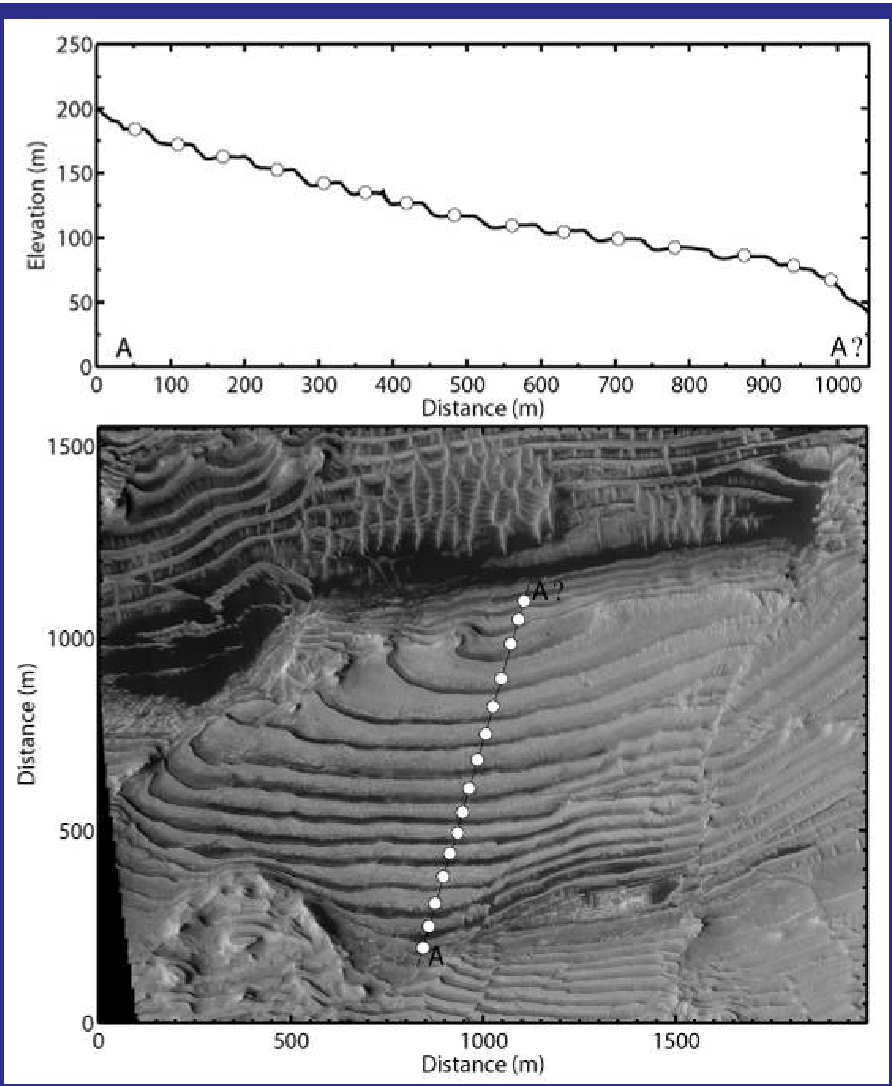
Becquerel Crater

Crommelin Crater





Unnamed Crater, 9° N, 359° E



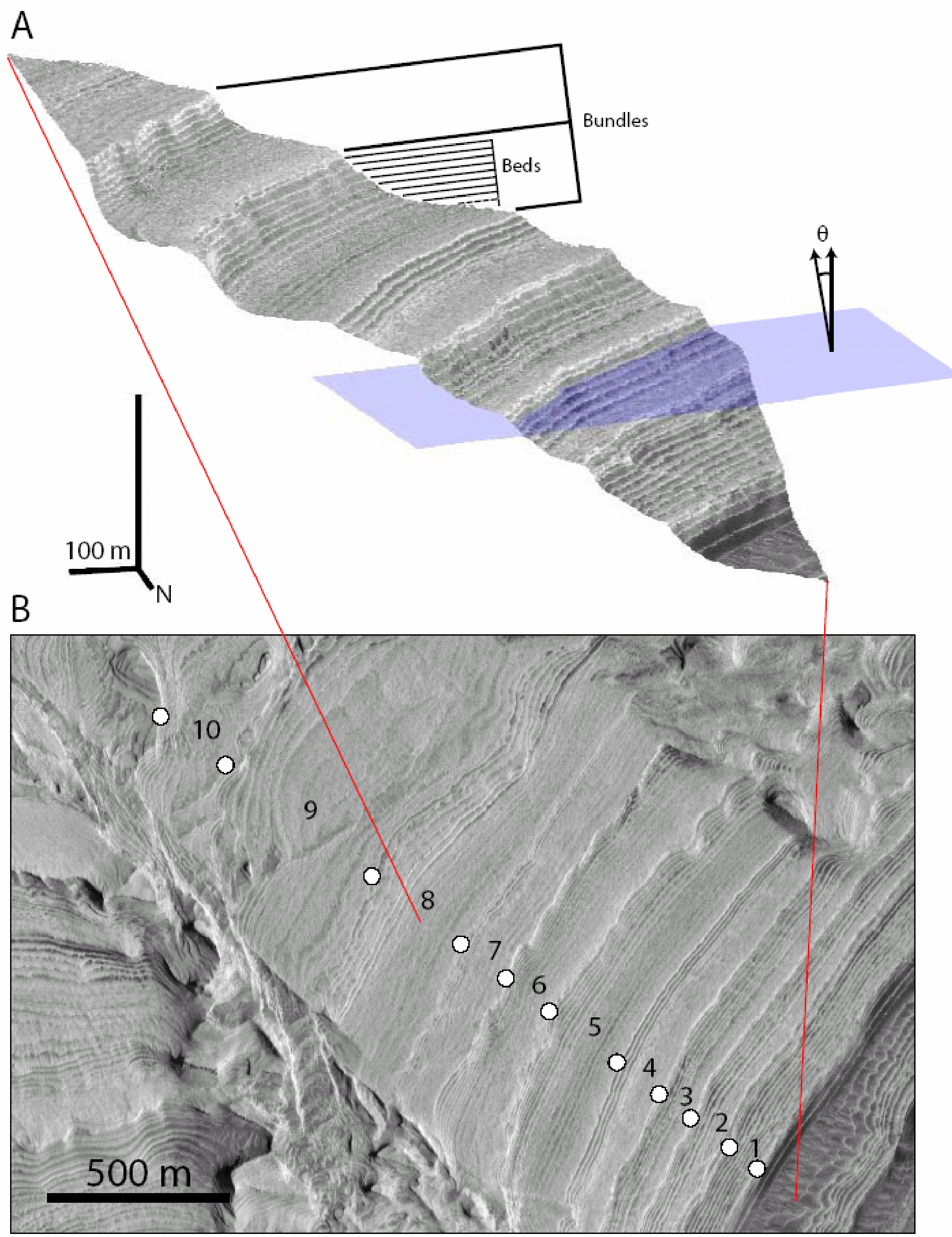
Unnamed Crater, 8° N, 353° E

Crater Name	Location	N	Mean Thickness (m)	σ (m)
Becquerel (Beds)	22°N, 352°E	66	3.6	1.0
Becquerel (Bundles)	22°N, 352°E	10	35.5	9.2
Crommelin	5°N, 350°E	8	19.6	4.0
Unnamed	8°N, 353°E	14	9.7	1.5
Unnamed	8°N, 359°E	10	12.6	2.6

Lewis et al., *Science*, Dec. 5, 2008

Becquerel crater stratigraphy

- Two scales of stratification expressed in topography
- Beds are grouped into bundles of ~10



Lewis et al., *Science*, Dec. 5 2008

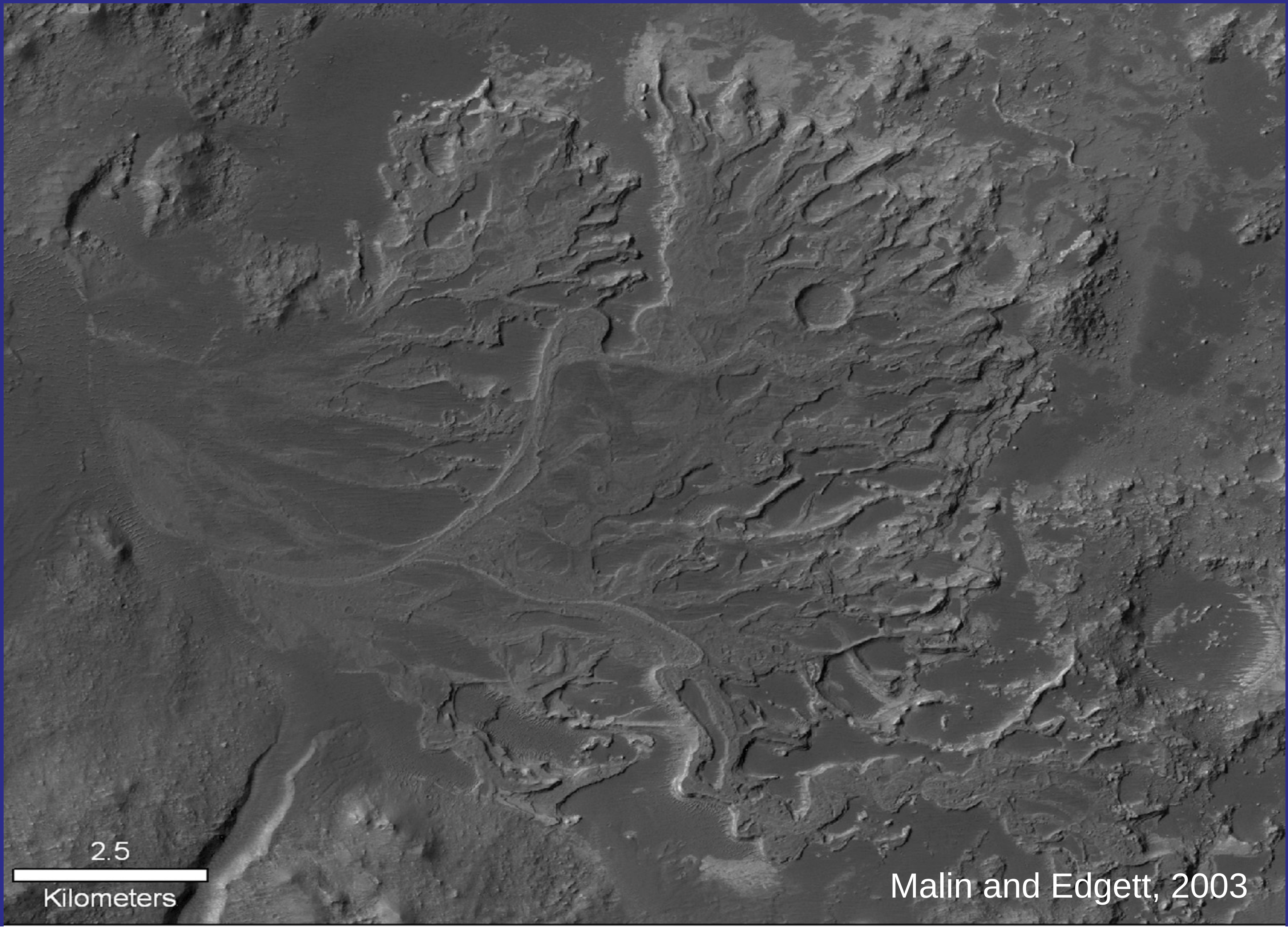
Cyclostratigraphic time scale?

- 120 kyr obliquity variations are modulated on a 1.2 Myr timescale
  - Eccentricity (120 kyr) and Precession (50kyr) do not explain the signal
  - Obliquity forcing implies a moderate deposition rate of 100 μ m/yr
- Regardless of process, this rock attribute could have value for construction of a geologic time scale for Mars
  - e.g. Strata that have 10:1 bundling vs. those that don’t, or other possible variations

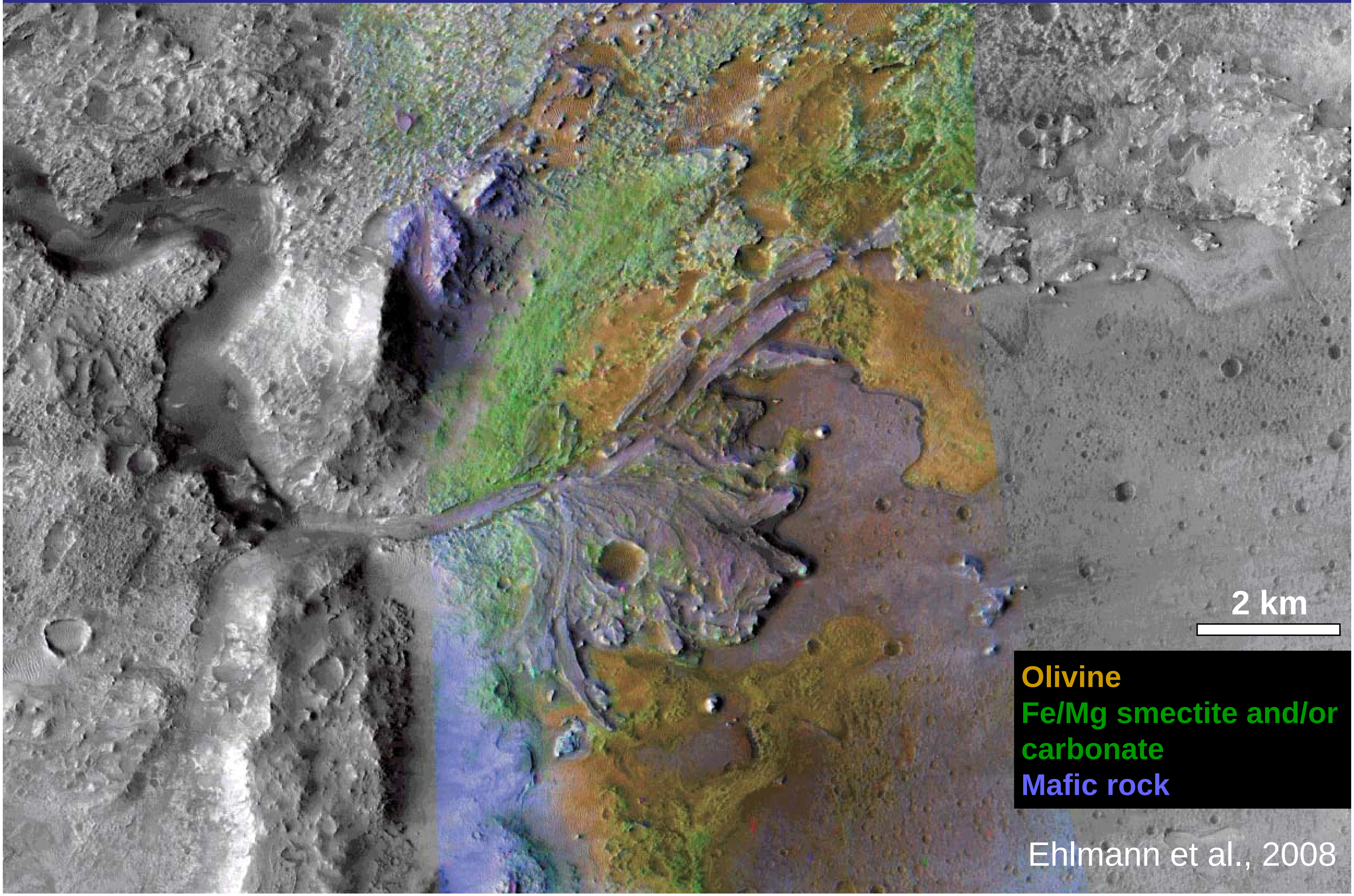
Layered Rocks: Crater infill

- Locally developed
- Complex stratal geometries
- Phyllosilicate spectral responses (no sulfates seen yet)

Deltaic Deposits in Craters: Meanders at Eberswalde



Deltaic Deposits in Craters: Phyllosilicates at Jezero

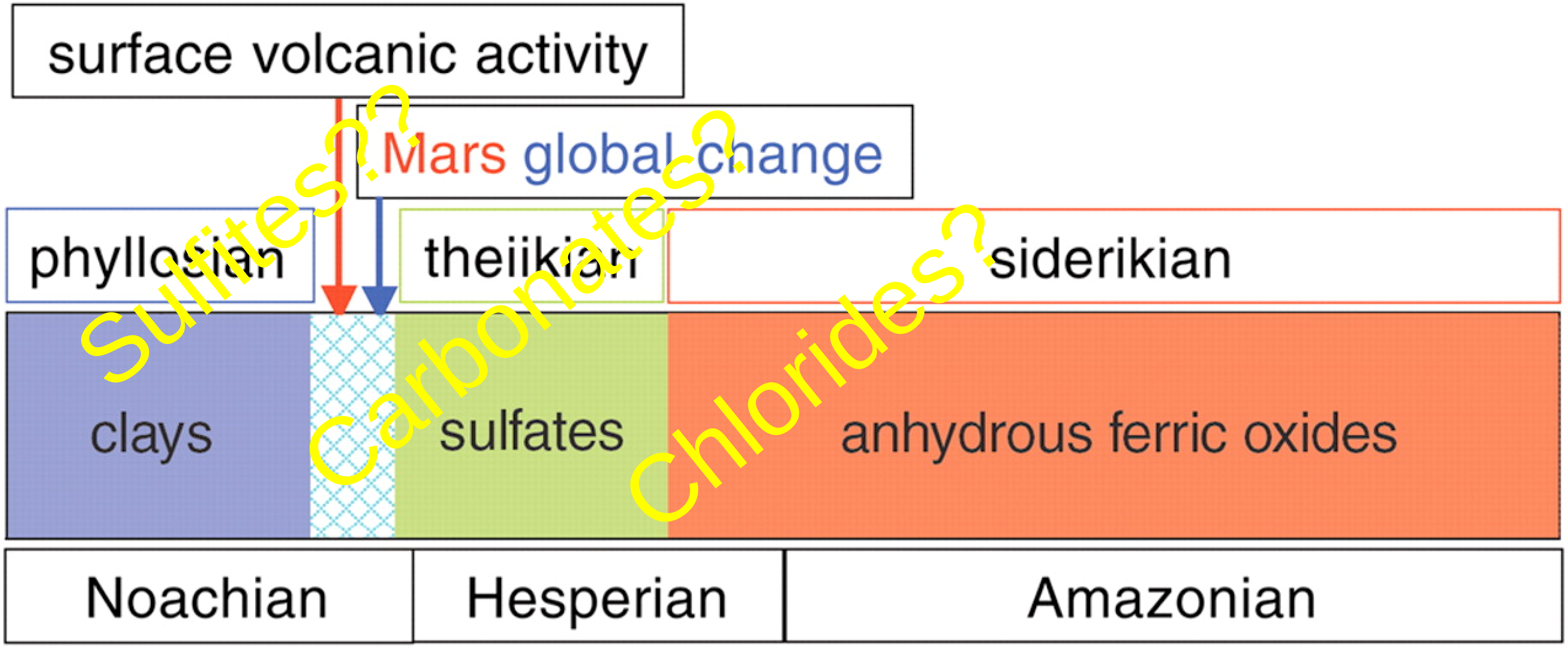


We could be in for some surprises…..

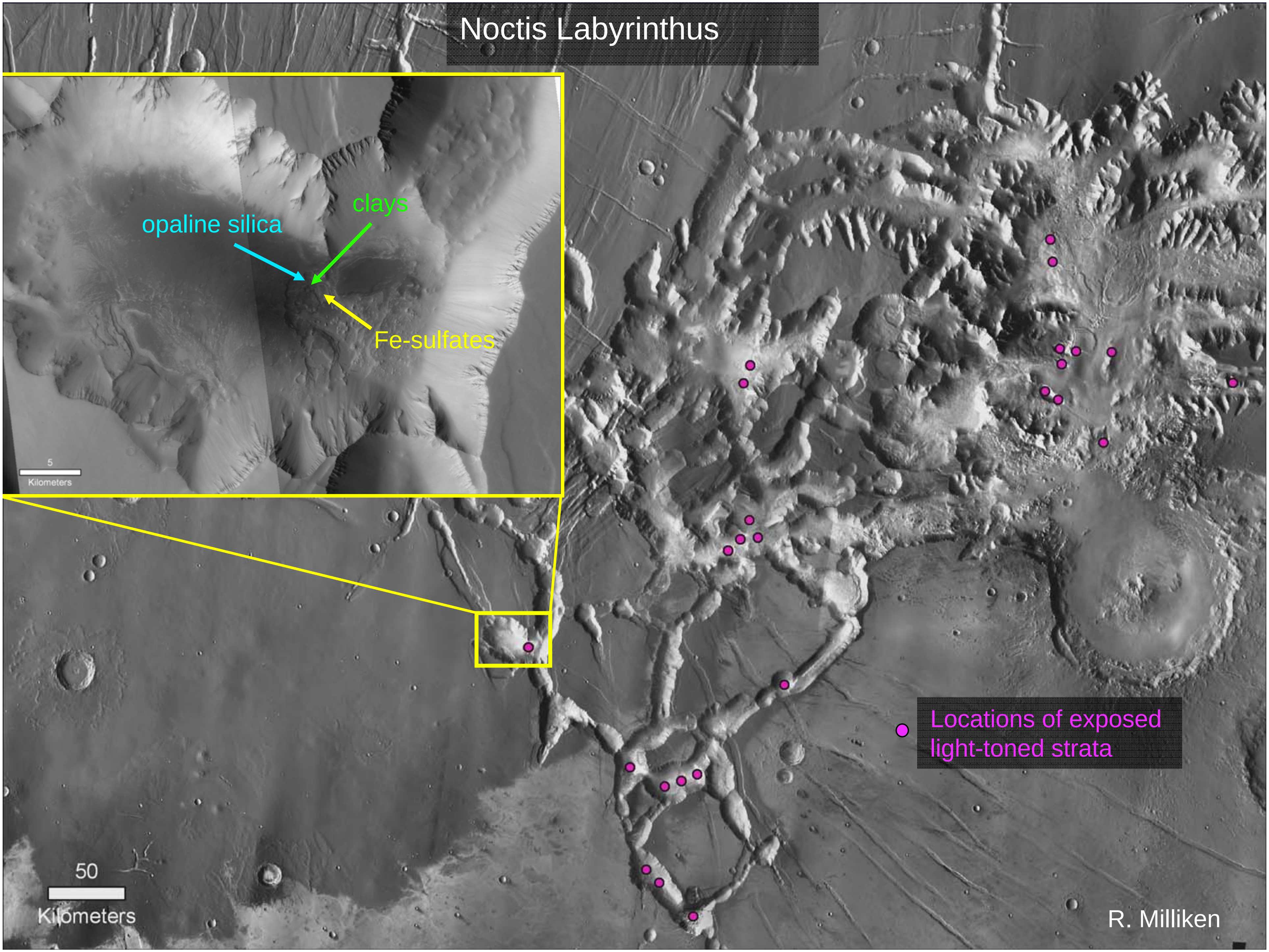
(If Earth is a guide, geochronology often refutes prevailing dogma)

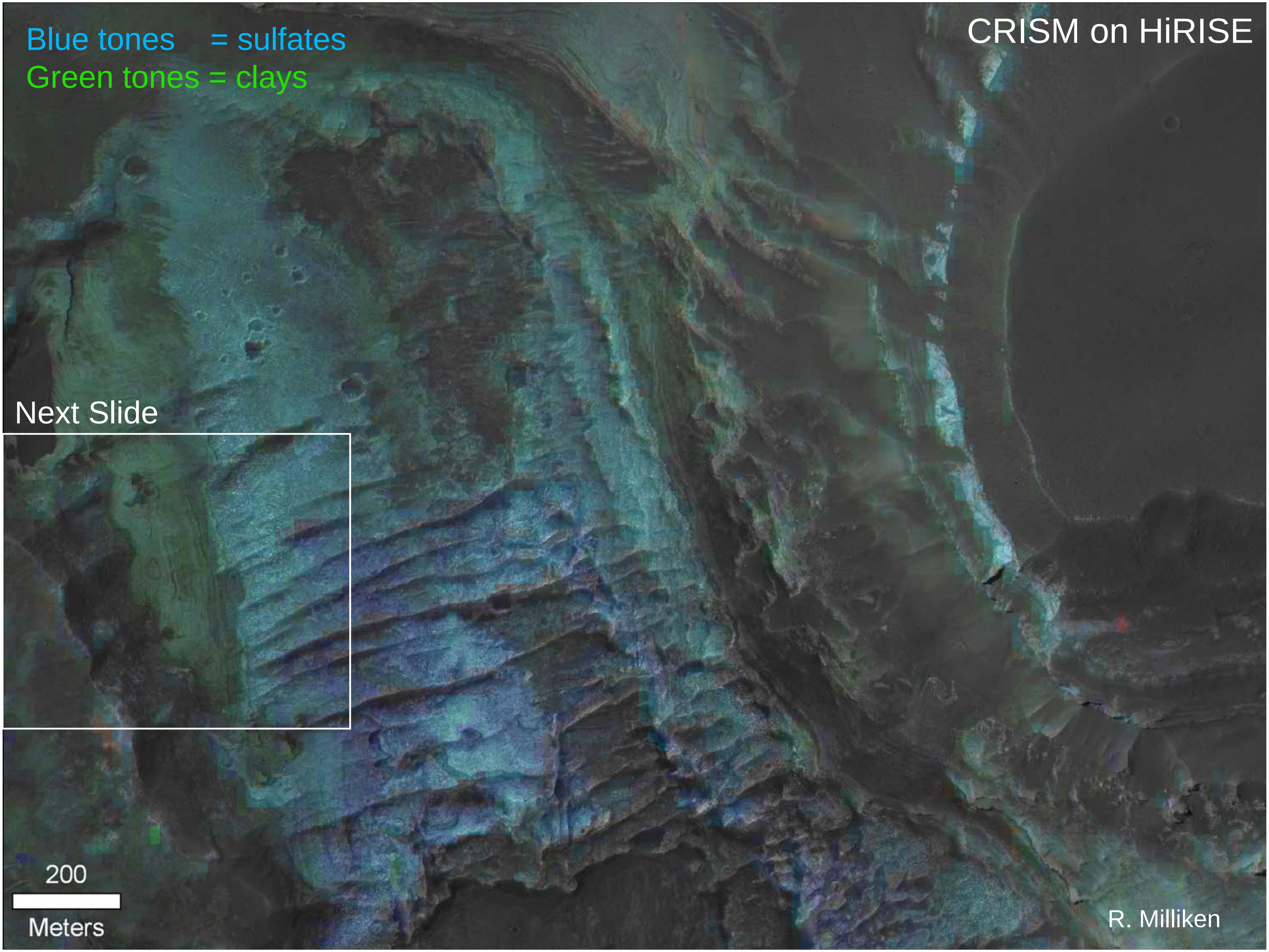
- Age of geomorphic surfaces based on crater flux models and resurfacing rates could change
- Sequence of hydrated mineral precipitation might vary
- Age of hydrated minerals may be different from what is currently assumed
- Duration of strata based on orbital tuning model could change
- A global stratigraphy will certainly bear Mars' unique imprint – mostly gaps? Weighted toward early history?

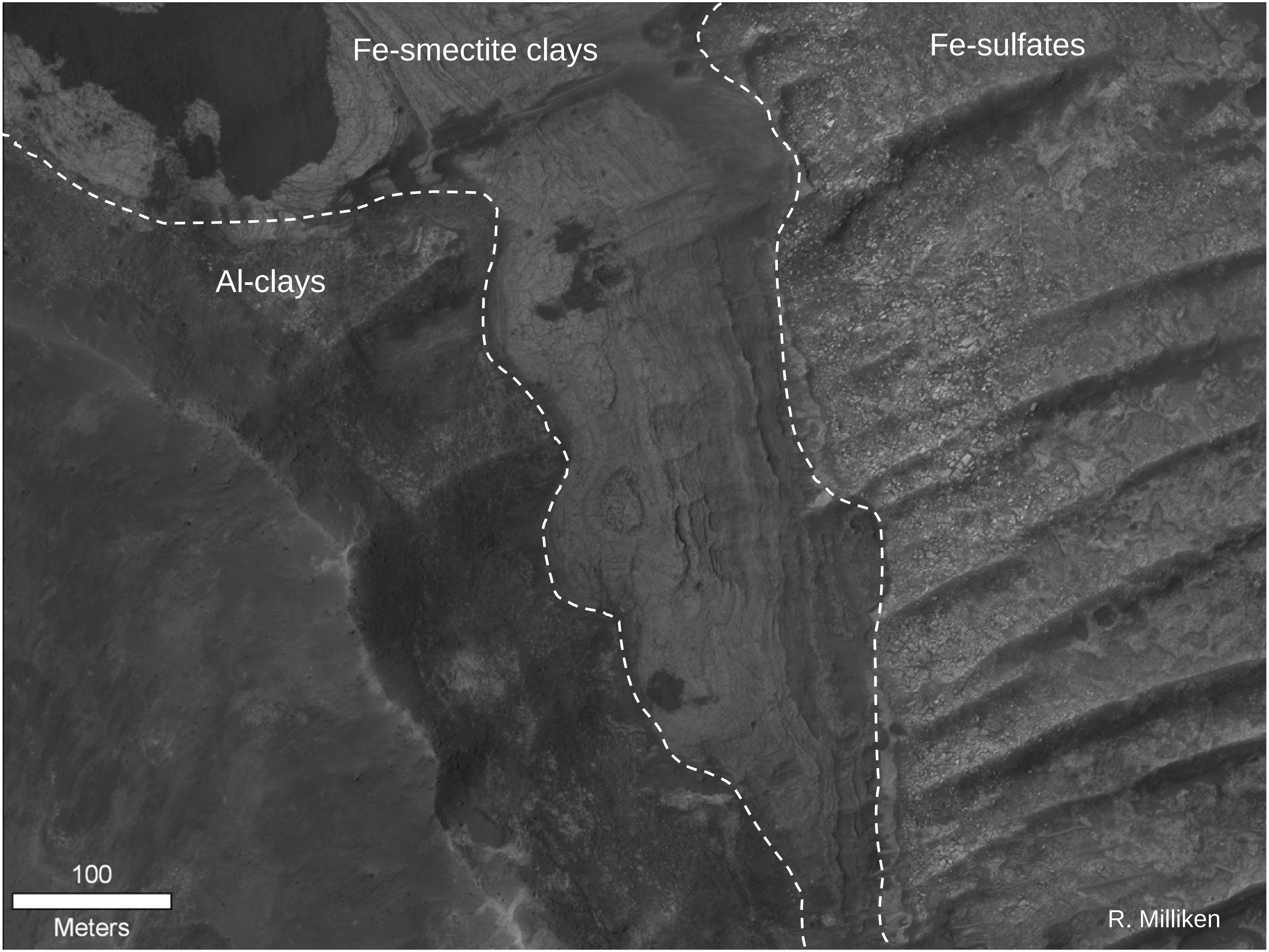
Exceptions
to Current Mineralogy-based Chronostratigraphy



- Sulfite model predicts progressive oxidation rather than acidification of Mars
- Carbonates – if Noachian in age – contradict global acidification in Hesperian
- Chlorides occur dominantly (exclusively?) in Noachian terrains, yet follow current topography (are other “Noachian” minerals younger??)

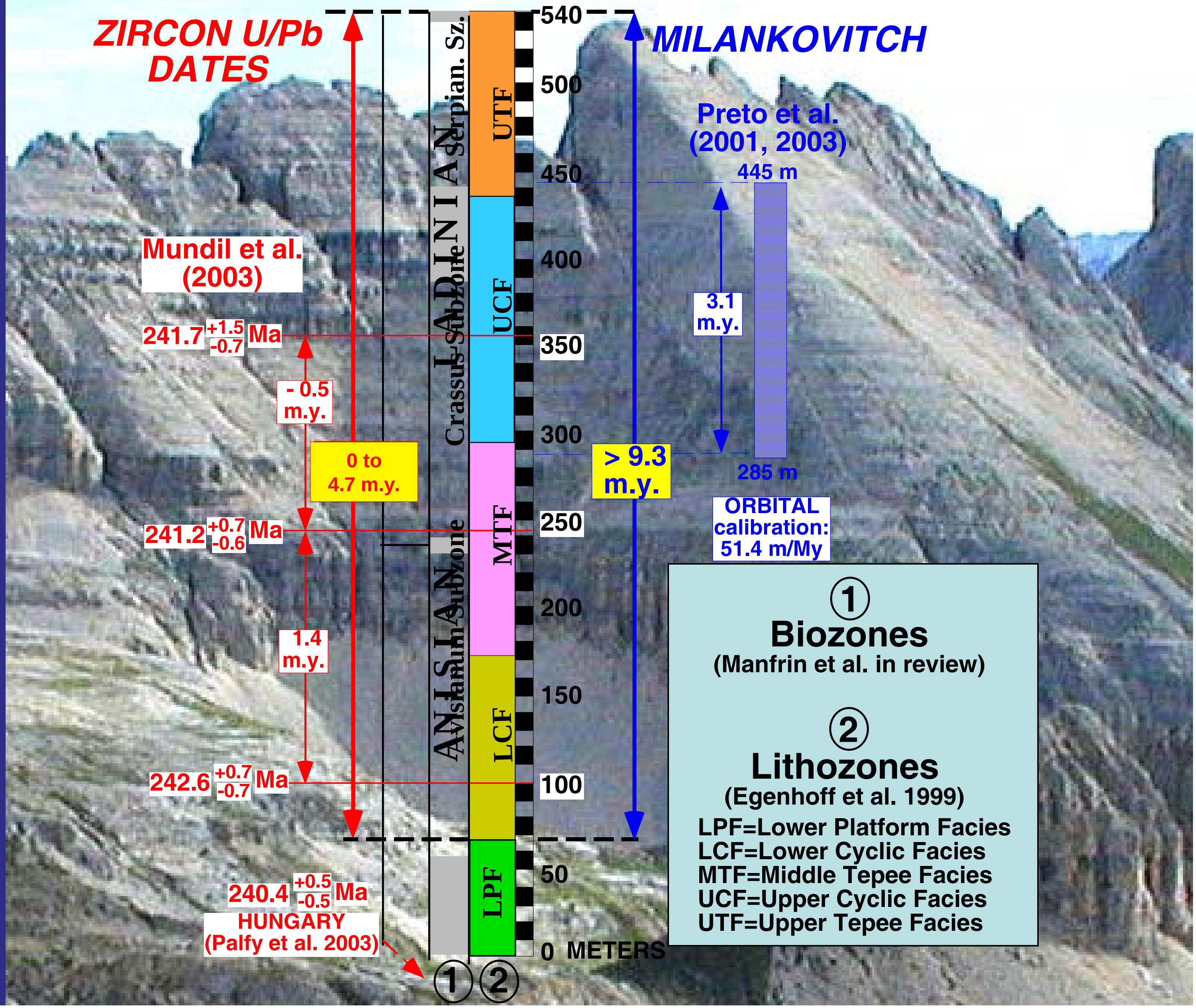

Noctis Labyrinthus
opaline silica
clays
Fe-sulfates
5
Kilometers
Locations of exposed
light-toned strata
50
Kilometers
R. Milliken


Blue tones = sulfates
Green tones = clays
CRISM on HiRISE
Next Slide
200
Meters
R. Milliken

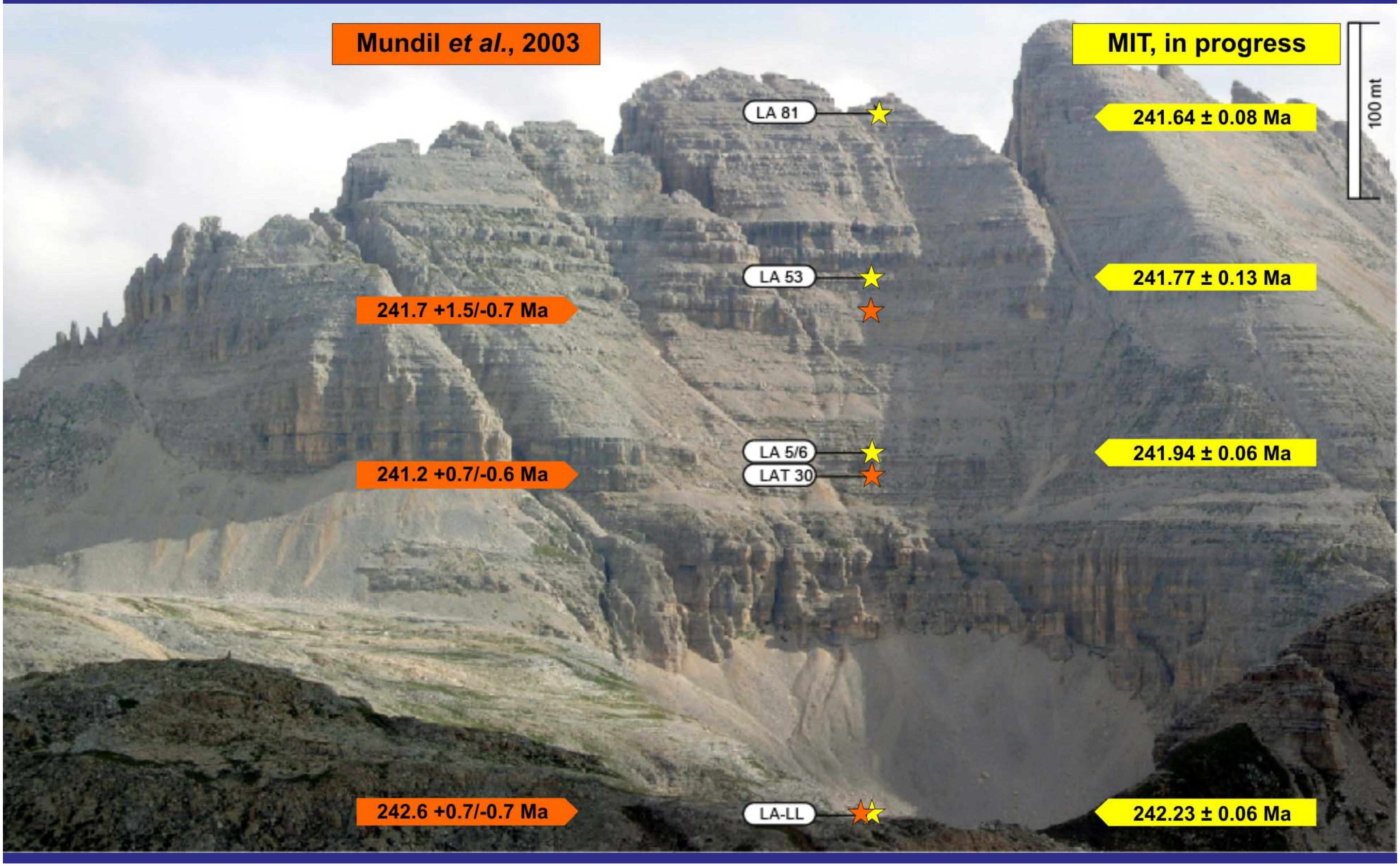

Fe-smectite clays
Fe-sulfates
Al-clays
100
Meters
R. Milliken

Latemar Dolomite: Triassic Cyclostratigraphy

THE LATEMAR CONTROVERSY

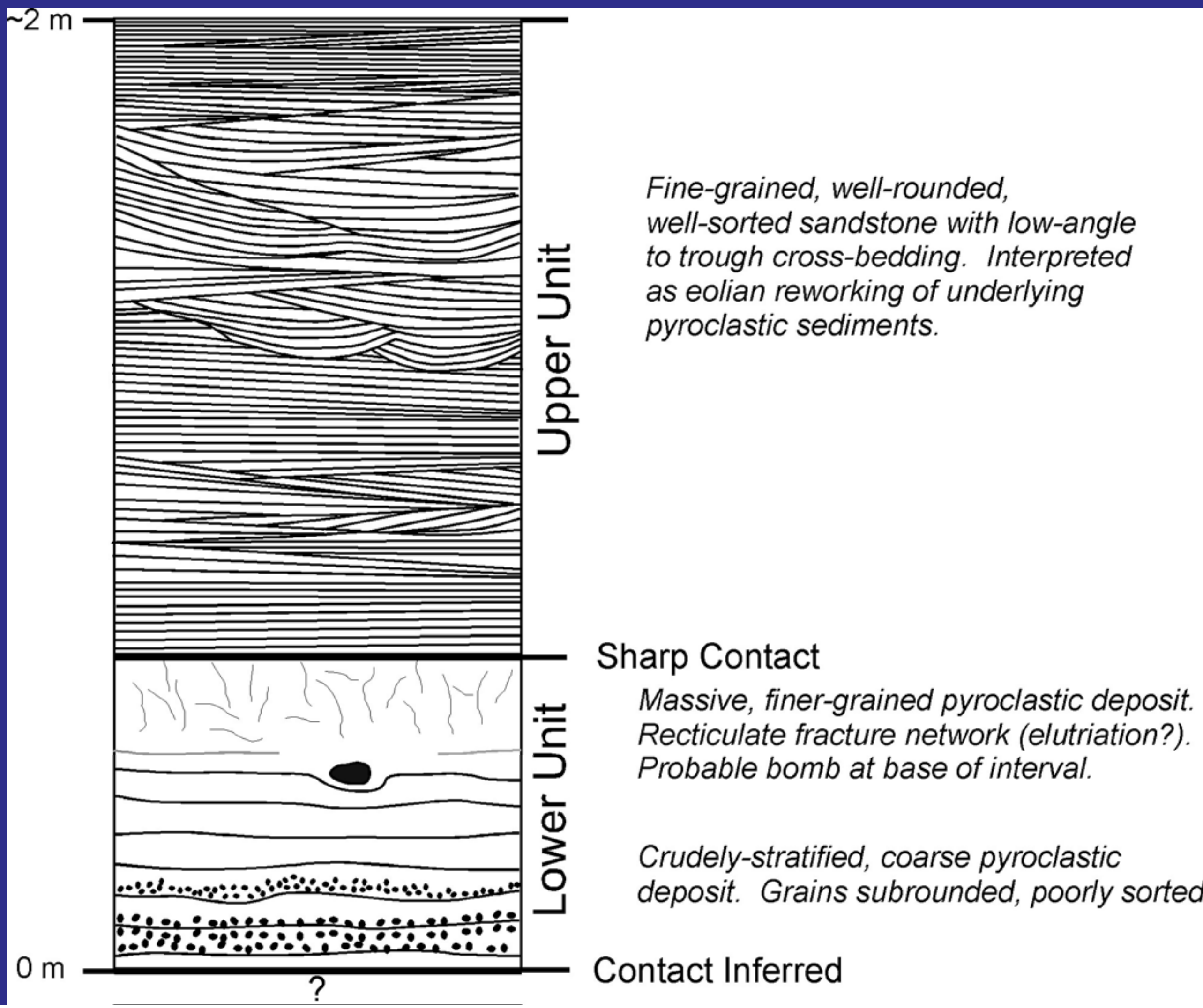


Double-check the ages…

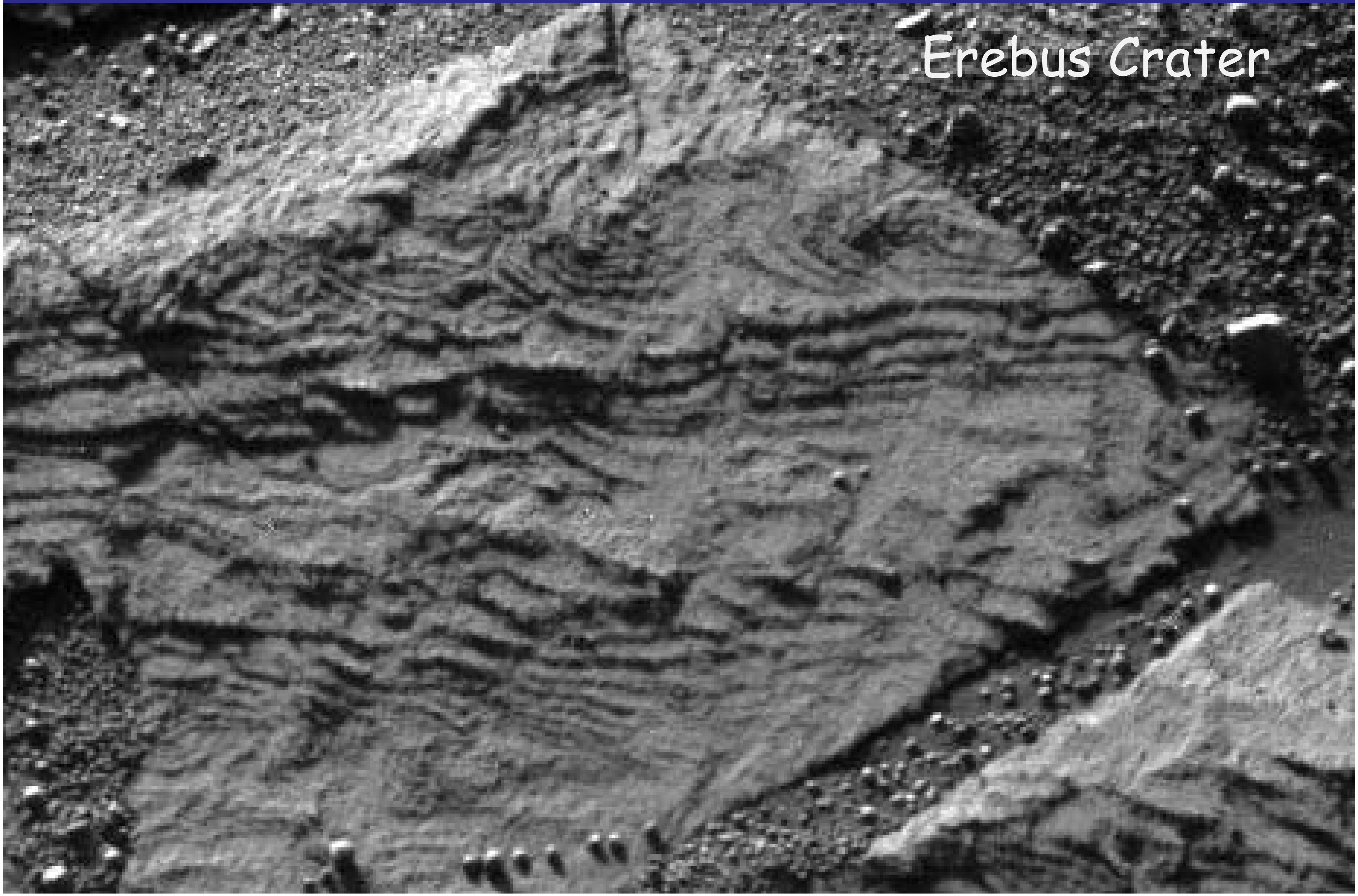


Home Plate: Noachian? Hesperian?

How do these rocks relate to the Columbia Hills and hi-Si rocks?



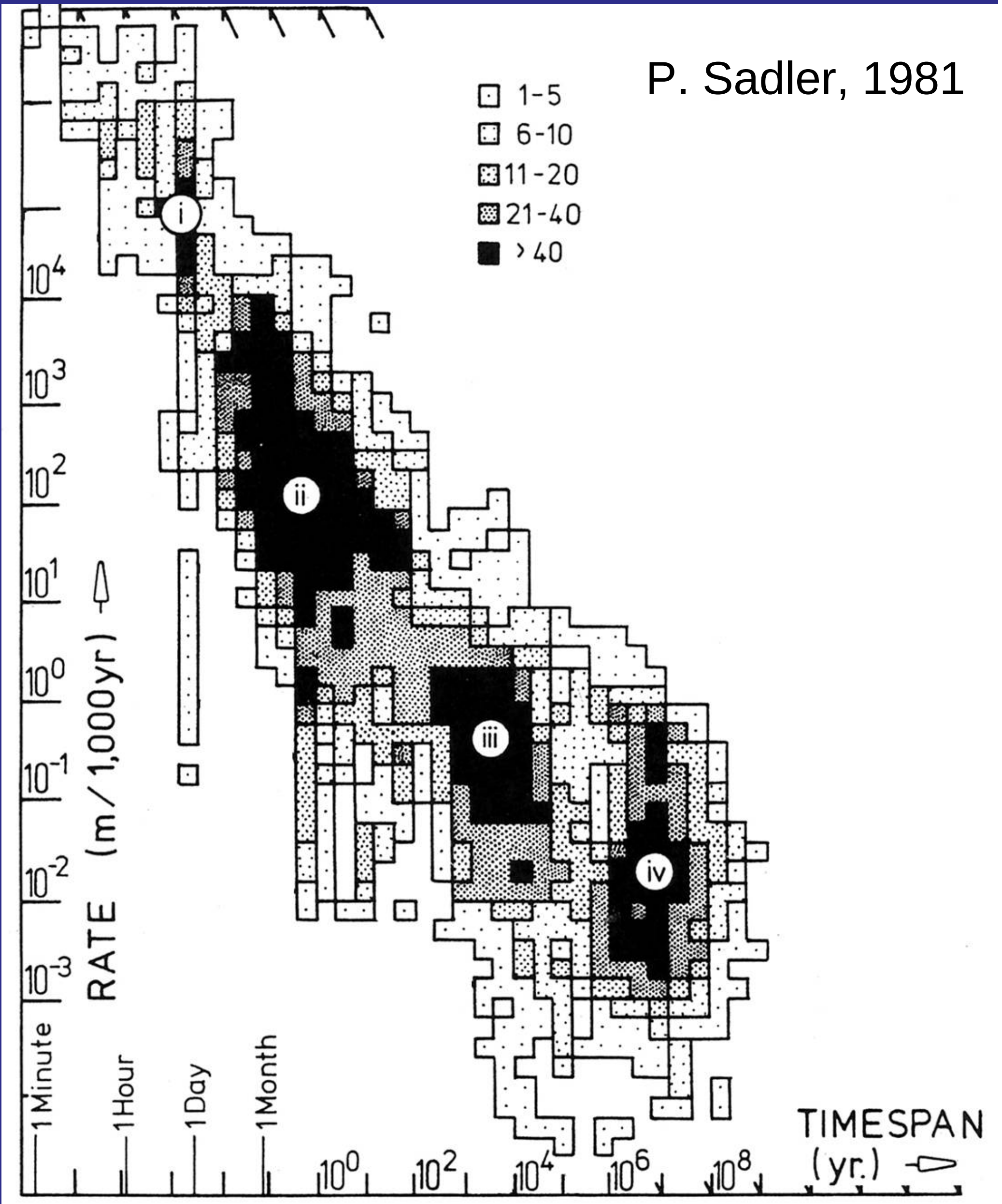
The Inevitability of Record Failure



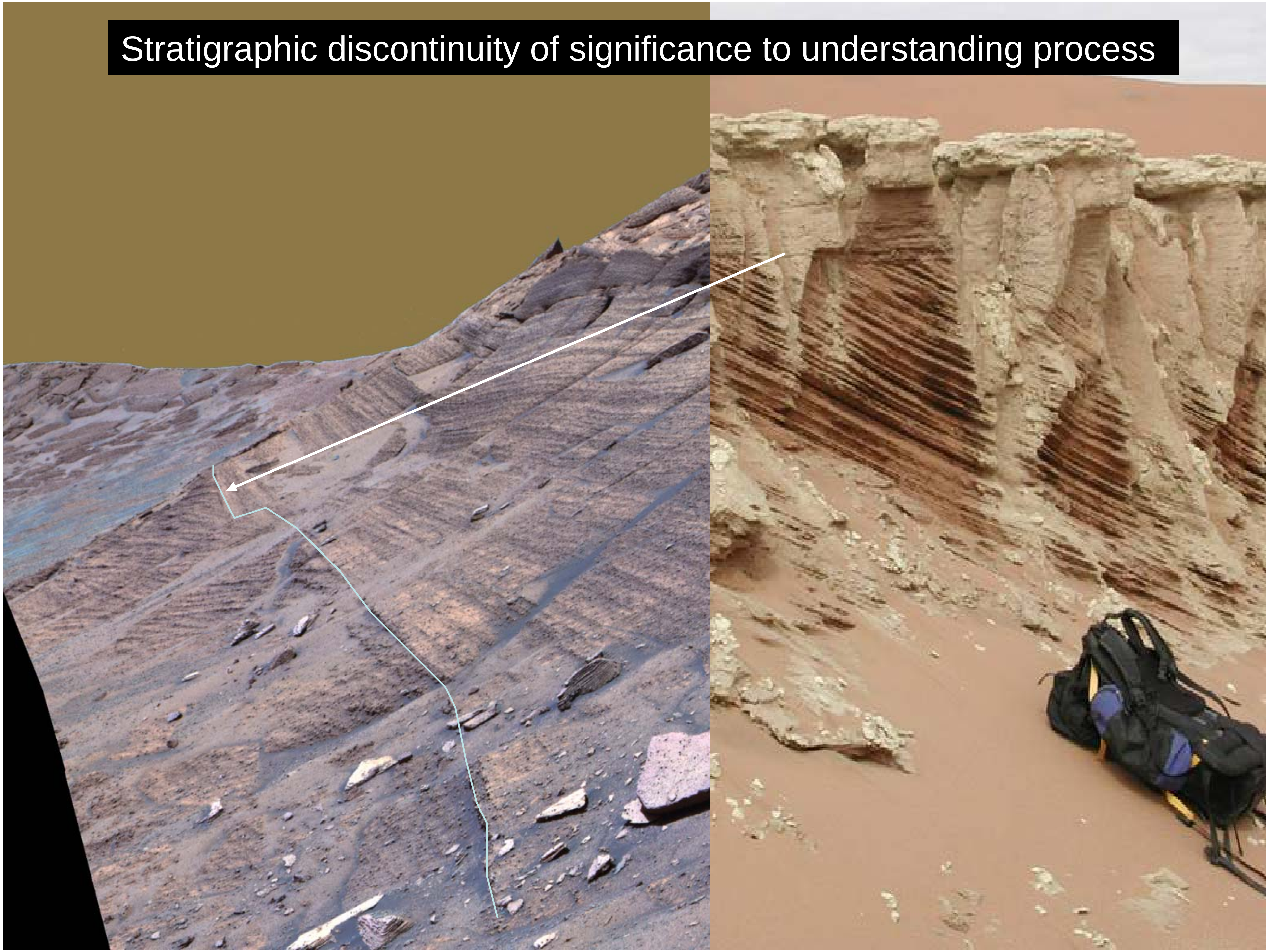
The Inevitability of Record Failure

- Sediment accumulation rate as a function of time interval sampled
- Time vs. Rate dependent on:
  - Measurement error
  - Compaction
  - Episodic sedimentation/erosion

P. Sadler, 1981



Stratigraphic discontinuity of significance to understanding process



Mars Bedrock Stratigraphy: Future Tasks

- Establish local chronostratigraphies using HiRISE/CTX, and CRISM/OMEGA data. Search for more regional to global patterns (Current missions are starting to do this)

- Check for spatial dependencies on mineral diversity and abundances. Find the key “type” sections where the clearest cross-cutting relations are exposed, or the thickest strata which show the greatest diversity. MSL will greatly expand the work started by MER.

- Fly mass spectrometer to location where geomorphic surfaces, primary minerals, secondary minerals, and other materials (dust, sand, etc) could be dated. No dates, no rates…or calibrated history. Establishment of thermal conditions?

- Need to understand “resurfacing” processes: saltation abrasion, blanketing by dust and sand, channel incision, glacial scouring.