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)
Chemostatigraphy (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 + Geochronometer

Fossil | Mineral | Isotope | Zircon | Jarosite?
Geologic Time Scale: Circa 1860

Diversity

Caenozoic life

Mesozoic life

Palaeozoic life

Geologic time

Cretaceous-Tertiary

Permian-Triassic

John Phillips (1860)
Mars Time Scale, Surfaces and Ages  Hartmann and Neukum, 2002

Young: Amazonis Planitia
- "fresh" lava flows
- rare craters

Old: Isidis Planitia
- abundant craters
- eolian "resurfacing"
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

GEOLOGIC UNITS
- A: polar layered deposits
- EA: Vastitas Borealis unit
- LH-LA: volcanic materials
- H: materials
- LN-EH knobby materials
- LN-EH: materials
- N: materials
- EN: massif material

Nimmo and Tanaka, 2005
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

**Diagram:***

- **Surface volcanic activity**
  - Mars global change
  - Phyllosian
  - Thelikian
  - Siderikian
  - Clays
  - Sulfates
  - Anhydrous ferric oxides

**Periods:**
- Noachian
- Hesperian
- Amazonian
Generalized Mars Geology

Nimmo and Tanaka, 2005
Noachian Crust: Nili Fossae

Jack Mustard
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

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
Example of Layered Sulfates
Headwaters of Maja Valles
Floor Around -2 km Elevation
4.5° S, 297.5° E
Juventae Chasma: Hesperian Layered Deposits

Gypsum (Ca Sulfate)

Kieserite Mg Sulfate)

Stratigraphic Transition - Minerals with Different Solubilities

Bibring et al. 2005
Candor Chasma: Layers can be Deformed
Candor Chasma: Folded Layers are Sulfates

- Polyhydrated sulfate
- Monohydrated sulfate

L. Roach/J. Mustard
Layered Rocks: Arabia

• Widespread over huge region
• Well-bedded, relatively uniform bed thickness
• No strong spectral responses identified
When structural tilts and topographic effects are removed, the sections in Arabia Terra are remarkably cyclic.
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 (50 kyr) do not explain the signal
  - Obliquity forcing implies a moderate deposition rate of 100 $\mu$ 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

Malin and Edgett, 2003
Deltaic Deposits in Craters: Phyllosilicates at Jezero

Olivine
Fe/Mg smectite and/or carbonate
Mafic rock

Ehlmann et al., 2008
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

Locations of exposed light-toned strata

opaline silica
clays
Fe-sulfates

R. Milliken
Blue tones = sulfates
Green tones = clays

CRISM on HiRISE

Next Slide
THE LATEMAR CONTROVERSY

ZIRCON U/Pb DATES

Mundil et al. (2003)

241.7 $^{+1.5}_{-0.7}$ Ma

- 0.5 m.y.

241.2 $^{+0.7}_{-0.6}$ Ma

1.4 m.y.

242.6 $^{+0.7}_{-0.7}$ Ma

240.4 $^{+0.5}_{-0.5}$ Ma

HUNGARY (Palfy et al. 2003)

Crassus Subzone, N.I.A. Subzone

0 to 4.7 m.y.

> 9.3 m.y.

ANd./and Subzone

LPF=Lower Platform Facies
LCF=Lower Cyclic Facies
MTF=Middle Tepee Facies
UCF=Upper Cyclic Facies
UTF=Upper Tepee Facies

MILANKOVITCH

Preto et al. (2001, 2003)

445 m

3.1 m.y.

265 m

ORBITAL calibration: 51.4 m/My

Biozones
(Manfrin et al. in review)

LITZON

LADINIAN ANISIAN

vusian Subzone
Crassus Subzone

LPF LCF MTF UCF UTF

0 to 4.7 m.y.

2.0 to 4.7 m.y.

2.0 to 4.7 m.y.

Biozones
(Manfrin et al. in review)

Lithozones
(Egenhoff et al. 1999)

LPF=Lower Platform Facies
LCF=Lower Cyclic Facies
MTF=Middle Tepee Facies
UCF=Upper Cyclic Facies
UTF=Upper Tepee Facies
Double-check the ages…

Mundil et al., 2003

LA 81
241.7 $\pm$ 1.5/-0.7 Ma

LA 53
241.2 $\pm$ 0.7/-0.6 Ma

LA 5/6
MIT, in progress
241.94 $\pm$ 0.06 Ma

LAT 30
241.64 $\pm$ 0.08 Ma

LA-LL
242.23 $\pm$ 0.06 Ma
Home Plate: Noachian? Hesperian?
How do these rocks relate to the Columbia Hills and hi-Si rocks?

Fine-grained, well-rounded, well-sorted sandstone with low-angle to trough cross-bedding. Interpreted as eolian reworking of underlying pyroclastic sediments.

Sharp Contact
Massive, finer-grained pyroclastic deposit. Recticulate fracture network (elutriation?). Probable bomb at base of interval.

Crudely-stratified, coarse pyroclastic deposit. Grains subrounded, poorly sorted.

Contact Inferred
The Inevitability of Record Failure

Erebus Crater
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.