The early supracrustal rocks of Mars

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Surface processes on Early (Noachian) Mars

In the absence of geomorphic evidence for abundant surface water pre-3.7 Ga, we assume three processes dominate the earliest martian surface:

1. Impacts
2. Volcanism
3. Eolian reworking

Here, we explore rock accumulation and mineralogical predictions in this context.

Finally, we compare this model to observations at Mawrth Vallis.
Explosive volcanism: An dominant contributor to the martian surface

- Explosive volcanism on Mars common:
  - Lower atm pressure
  - Greater gas exsolution
  - Enhanced magma disruption
  - Higher volatile content

- Pyroclastic deposits
  - 100x finer grained
  - Greater distances
  - Clouds rise 5x higher

- Virtually every eruption (regardless of composition) of volatile-bearing magma accompanied by fine-grained pyroclastic deposit

- The Earth’s sedimentary budget contains a minimum of 30% volcaniclastic contributions (Garrels & Mackenzie, 1971)
Explosive volcanism on Mars: Observational support

- Volcanic ash deposition important in forming Friable layered deposits (FLDs)
  - Mapped by Schultz & Lutz (1988) & Hynek et al. (2003) across equatorial regions 1000s km apart

- FLDs fine-grained & thinly layered
  - Distributed over $10^5$ to $10^6$ km$^2$
  - Mostly post-Noachian

- Additional support for pyroclastic activity from Home Plate in Gusev Crater

- Many additional reports (Mouginis-Mark, 1982, 2002; Edgett, 1997; Greeley & Crown, 1990, etc.)

- Robbins et al. (2010) identify transition from explosive to effusive volcanism at about 3.5 Ga from survey of major calderas
Usually, we associate the products of explosive volcanism with either:

**A. Syndepositional alteration**

- Nearly pure smectite deposits (e.g., bentonites)
- Pre-existing water body must be spatially and temporally persistent
- Additional detrital pulses/signals?

**B. Post-depositional alteration**

- Dominated by halloysite, kaolinite, opaline SiO₂, imogolite
- Smectite rare; when present is Al-rich
The origin of smectite in pyroclastic deposits

- **Most smectite in pyroclastic deposits & soils is hydrothermally formed within volcanic vents and entrained upon eruption**
  - Mineralogy, geochemistry, $\delta^{18}$O & $\delta$D show elevated formation temperatures
  - Smectite is Fe/Mg-rich; including saponite & nontronite
  - Occurs with minor/trace chlorite, biotite, vermiculite, and C/S, etc.
  - Hydrothermal smectite deposited w/ash in localities across globe

- **Mt. St Helens 1980 deposits (Pevear et al., 1982)**
  - Largely andesitic/basaltic composition
  - Saponite in the unaltered ash reaches 10 vol. % of bulk, increasing with distance from vent
  - Total deposits >25% lithic material (i.e., entrained vent rocks)

- **Mt. Usu, Japan (Mizota & Faure, 1998)**
  - Nontronite present at >10 vol. % in unaltered ash
  - **Water-saturated zone under vents driving hydrothermal activity**
**Hydrous magmatism & hydrothermalism: Hand in hand**

- Every group of meteorites preserves evidence for magmatic hydrothermalism
- Abundant geochemical evidence for early hydrous volcanism
- When magmatic volatiles were high, degassing & hydrothermalism results
- Petrogenetic studies infer the earliest magmas were also the most volatile rich
- Thus, magmatic hydrothermal activity can be inferred to be directly proportional to volcanism
- Meteoric water may also contribute, but constraints are less clear pre-3.5 Ga

*Magmatic-hosted hydrothermal systems*

(after Henley & Ellis, 1983)
**The pyroclastic contribution to early martian sedimentary budget**

- **Significant volcanism in pre-/mid-/late-Noachian (e.g., Tharsis)**

- **Magma-water/ice interactions would have produced:**

  **Hydrothermal systems**
  
  - Dependent on nature of interaction, volatile content, crustal H$_2$O reservoir
  - Generate significant Fe/Mg-smectite & lesser chlorite, C/S, biotite, etc.
  - Clays would be transported & concentrated in air fall deposits

  **Fine-grained pyroclastics**
  
  - Entrainment of atmosphere could alter syn-eruptive ash
  - Distinct post-eruptive Al-rich weathering signal

- **The total amount of pyroclastic clay delivery to surface is a function of:**
  
  - Frequency & extent of magmatic-hydrothermal & syn-eruptive alteration (dependent on volatiles)
  - Efficiency of explosive delivery & transport

- **Volumetrically significant flux of newly formed clay available for impact/physical reworking**
A model for pyroclastic contributions to surface mineralogy

1. Magmatic-hosted hydrothermalism

   - Meteoric H$_2$O?
   - 300°C
   - 250°C
   - 200°C

   (after Henley & Ellis, 1983)

2. Explosive volcanism

   - Fragmentation surface
   - Wall rock entrainment
   - Exsolution surface
   - Hydrothermal mineralisation

   (after Wilson et al., 1980)

3. Transport and deposition

   - Eruption cloud turbulence-supported
   - Wind turbulence-supported
   - Fallout deposits
   - Ash flows, ash clouds, pyro. surges, etc.
   - Boil-up

   (after Fisher & Schmincke, 1984)
How much & how far? Ash transport and particle size segregation

- Atmospheric winds could carry <10µm particles several 1000 km
- Ordovician ash beds in E. US distributed over 5 x 10^6 km²
- Significant atmospheric residence time (up to 4 years on Earth)
- Smectite & other clays present in ash concentrated in the <2µm fraction w/ increasing transport distance
  - e.g., Mt. St. Helens ash deposits as a function of distance from source

(Hynek et al., 2003)
**Implications for “layered” phyllosilicates (e.g., Mawrth Vallis)**

- **Mawrth Vallis:**
  - Aerially extensive (>10^6 km^2)
  - Mineralogy consistent within stratigraphic units
  - Temporally significant
    - Buried impact craters
  - Compositional stratigraphy observed elsewhere
    - Eridania, Noachis, Valles Marineris

- **A significant pyroclastic contribution is capable of explaining:**
  - Persistent & extensive distribution
  - Disparity between TES & OMEGA/CRISM
  - **Fe/Mg assemblage:** Largely derived from volcanic/impact hydrothermal sources
  - **Al assemblage:** Largely derived from weathering pre-deposited fine-grained glassy tephra

*(Michalski et al., 2010)*
A model for rock accumulation on early Mars (esp. at Mawrth)

- Heterogeneous physical processing; consistent mineralogy
  - Rock accumulation primarily driven by impact processes, eolian reworking
  - Predicts heterogeneous mineralogical distribution
  - Continuous pyroclastic delivery & eolian reworking homogenizes mineralogy in time & space

- Caveats:
  - Does not exclude other modes of neoformation, but may well be dominant
  - **Abundances:** do we understand clay production in hydrothermal & magma-volatile interaction on Mars? We may be lacking suitable analogs.
**Conclusions (1)**

- Weathering of pyroclastic material produces a distinct Al-rich assemblage dominated by: halloysite, imogolite, opaline SiO₂, kaolinite and lesser Al-smectite (e.g., beidellite)

- Pyroclastic delivery of clay-bearing material is a common source of Fe/Mg-smectite (and other Fe/Mg 2:1 phases) in ash fall tephra deposits on Earth

- Volcanic-hosted hydrothermal systems on Mars, or syn-eruptive alteration of volatile-rich pyroclastics could represent a significant flux of Fe/Mg clay to the early surface of Mars

- Ash transport is an effective mechanism for Fe/Mg clay contribution to the early martian sedimentary record:
  - Provide significant mineralogical overprint to complex processes

- If true, a large portion of clay mineralogy on Mars may record the spatial and temporal history of volatile-magma interaction during the earliest portion of martian history
Conclusions (2)

• This model does not require a significant role for surface water on early (Noachian) Mars. Later alteration of upper stratigraphy (presuming an Fe/Mg-rich protolith) could date to any post-depositional period.

• We view magmatic hydrothermalism (& explosive volcanism) as waning in response to decreasing magmatic volatile load and perhaps decreasing subsurface water/ice.

• We view the earliest supracrustal rocks on Mars as receiving two dominant contributions to mineralogy:

  1. Impacts
     – Require pre-existing water to drive hydrothermalism
     – May suffer from low-temperature overprinting as system “dies out”

  2. Pyroclastic volcanism
     – Records conditions of magmatic hydrothermalism
     – Mineralogical contributions & delivery will correlate with high volatile load

• Eolian mixing will act to homogenise these two components