The deposition and alteration history of the northeast Syrtis layered sulfates

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Layered sulfates exposed over ~1000 km² beneath eroded edge of Syrtis Major lava flows
Northeast Syrtis sequence spans first billion years of Mars history

Layered sulfates record major environmental change during Noachian—Hesperian transition

- More acidic style of alteration
- Capped by un-altered Syrtis Major lavas
- Proxy for global change

MOLA topography (m)

after Ehlmann and Mustard, 2012
Layered sulfates ~ 300m thick atop basement

PSP_009217_1975 - ESP_027625_1975

View to the northwest

Syrtis Major lavas

layered sulfates
beneath dusty mantle

Olivine carbonate
Fe/Mg smectites
Oblique view (towards NE)
Layers exposed in erosional window
Oblique view (towards NE)
Boxwork fractures cover 40% of layered sulfate
## Possible mechanisms for layered sulfate formation

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### Volcanic

- **Lava flow**
  - Effusive volcanism over large area [2,4]
  - Typical thickness: 1-10 m
  - Typical scale: 10-100 km
  - Single level: black
  - Containing basin: red

- **Ash fall**
  - Airborne volcanic ash from explosive eruptions [3]
  - Typical thickness: 0.1-10 m
  - Typical scale: 100+ km
  - Single level: blank
  - Containing basin: red

- **Ash flow**
  - Pyroclastic flow deposits
  - Typical thickness: 10-100 m
  - Typical scale: 100+ km
  - Single level: black
  - Containing basin: blank

### Lacustrine (deep)

- **Lake covering the entire region**
  - Typical thickness: 0.01-1 m
  - Typical scale: 100+ km
  - Single level: black
  - Containing basin: blue

### Lacustrine (shallow)

- **Lakes in localized craters or valleys**
  - Typical thickness: 0.01-0.1 m
  - Typical scale: 1-10 km
  - Single level: black
  - Containing basin: blue

### Alluvial/ fluvial

- **River or upstream sedimentary system**
  - Typical thickness: 0.1-1 m
  - Typical scale: 0.1-1 km
  - Single level: black
  - Containing basin: blue

### Evaporite

- **Playas/ephemeral lakes, deposition by drying** [10]
  - Typical thickness: 0.01-0.1 m
  - Typical scale: 1-10 km
  - Single level: black
  - Containing basin: blue

### Aeolian

- **Wind-blown dust and sand**
  - Typical thickness: 1-10 m
  - Typical scale: 10-100 km
  - Single level: black
  - Containing basin: blue

### Glacial/ snowfall

- **Dust residue from precipitation and sublimation** [5]
  - Typical thickness: 0.01-0.1 m
  - Typical scale: 100+ km
  - Single level: blank
  - Containing basin: blue
Bedding extracted from HiRISE and CTX elevation models

- Layered sulfates dip <10º everywhere
- Poor exposure leads to high uncertainty
Minimizing orientation errors

Syrtis Major lavas

Layered sulfates

5 km
Minimizing orientation errors

Exposed bedding surface (323 m)
Principal component analysis

- Generalization of linear least squares
- Visualization of shape of input data and residuals along major axes
- Enables accounting for arbitrarily oriented errors

Long cross-section: 323 m
Short cross-section: 14 m
Residuals: 3.3 m
Orientation errors (spherical projection)
Poor fits from multiple orientation measurements

Test prior assumption that individual planes are part of a single stratigraphy...
Combining multiple planes reduces error

- Single fit over 7 km of exposure
- Contains error minima of all component planes
- Maximum residual: 6.6 m
Unconformity with capping Syrtis Major lava flows

- Near-perfectly planar strata in layered sulfates
- Dipping differently at > 3 σ level
Bedding results for layered sulfates

- Low-angle (<10°) dips everywhere
- Locally, planar stratigraphy (homoclinal) at 5-km scale
- Unconformable with overriding lavas
- Uncertain if deposited on flat surface (equipotential) or draping low-angle slope
Boxwork polygons: key markers of alteration history
Boxwork polygons: filled volume-loss fractures

No preferred orientation (no regional stress field)

Rose diagram of boxwork strike
$n = 295$ km
Boxwork polygons: filled volume-loss fractures

- Boxwork polygons at ~500 m scale
- Ridges enriched in jarosite ($K$-$Fe$-$sulfate$) with up to 30 m of relief
Boxwork polygons: filled volume-loss fractures

Often non-vertical

Can penetrate full exposed thickness of layered sulfate (*up to 200 m depth*)

*Not formed at free surface*
Polygonsal faulting: an Earth analog?

- polygonal fracture geometry
- no preferred orientation
- non-vertical dips
- penetrative but layer-bound
- ~100–1000 m scale

**Mechanism**

Compaction of *clay-rich sediments* forms *layer-bound faults* during *diagenesis and shallow burial*
Mineralization along preexisting fracture network

Alteration fronts parallel to fracture plane

Evidence of fluid flow through preexisting fractures
Fluid alteration: associated with lava flow?

High-albedo alteration halo beneath lava flow
Fluid alteration: associated with lava flow?

Alteration halo grades into boxwork fractures
Model of deposition and alteration of layered sulfates

- **Deposition** as sediments (flat-lying to draping)
- **Burial** by capping Syrtis Major lava
- **Diagenesis** and **volume-loss fracturing**
- **Fluid mineralization**
- **Differential erosion**
Model of deposition and alteration of layered sulfates

- **Deposition** as sediments (flat-lying to draping)
- **Burial** by lava
- **Diagenesis** and **volume-loss fracturing**
- **Fluid mineralization**
- **Differential erosion**

**Unconformity** masks potential history of deposition, erosion.
Alternative scenario with substantial early erosion

**Deposition** of sediments of unknown thickness (flat-lying to draping)

**Diagenesis** and **volume-loss fracturing**

Period of erosion \((\pm\text{fluid alteration})\)

**Burial** by capping Syrtis Major lava

**Fluid mineralization**

**Differential erosion**
Conclusions

• Parallel bedding at km-scale: flat or gently draping deposition (e.g. lacustrine, evaporite, or ash fall)
• Layered sulfates unconformable with capping Syrtis Major lava
• Boxwork is formed by volume-loss fracturing followed by fluid flow
• Fluid alteration likely associated with overriding lava

Ongoing work

• Regionally constrain depositional dips with further analysis of orientation errors
• Finalize mapping (mineralogy, morphology)
• Examine timing of fracturing relative to lava emplacement