“A Mars 2020 Mission to Columbia Hills: Risk minimization through ground truth”

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Spirit imagery from Columbia Hills allow ground-truthed mapping of contacts and strikes and dips of varied strata.
Spirit analyses allow ground-truthed identification of rock compositions

**Stratigraphic column**

- **Vesicular basalt (Irvine Class), with basal polymict conglomerate and volcaniclastic sandstone/tuff**
- **Folding**
  - HP2: Fine-grained, planar to cross-bedded, Aeolian sandstone
  - HP1: Medium- to coarse-grained pyroclastics
  - Nodular/digitate opaline silica (local, as elongate ridges)
  - Buff-colored platy unit
  - Light-toned, fine-grained, vesicular, olivine basalt

- **Plunging syncline, anticline**
- **Strike and dip direction of bedding**

Includes observations from Squyres et al., 2007: Science
Arvidson et al., 2008: JGR
Crumpler et al., 2011: JGR
Ruff et al., 2011: JGR and others
Home Plate is an erosional remnant of an originally more widespread unit.

Legend

- Traverse Path

[Image of Martian surface with labeled features: Home Plate, Mitcheltree Ridge, Von Braun, Goddard, Oberth]
Event stratigraphy of the Columbia Hills

Spirit analyses provided ground-truthed identification of major units and their relationships, which can be extrapolated across whole area.

Adirondack Class (Plains basalt west): Olivine picrobasalt (3.6 Ga)

Inner Basin: mixed volcanic, volcaniclastic and sedimentary units

Algonquin Class: Olivine-bearing picritic tephra (north and south)

Wishstone Class: Hawiite tephra with NE-SW bedding strike: (and associated other classes);

Possible basement in floor of impact crater

Minor hydrous alteration (atmospheric)

carbonate alteration (Comanche Class)

aqueous and sulfate alteration (Watchtower Class)
What is the age of the nodular/digitate opaline silica deposits around Home Plate?

Opaline silica: older than HP

Opaline silica: younger than HP

HP2: Aeolian sandstone
HP1: Volcanoclastics
Buff-colored platy unit
Silicify HP1
HP1 is not altered when adjacent to the nodular/digitate opaline silica; thus the opaline silica is younger than BHPU and older than HP1.
Nodular/digitate opaline silica occurrences are consistent with their being part of the stratigraphy, as it is folded together with the other bedded units.

This relationship is also consistent with the acid-sulfate alteration observed for the buff-colored platy unit.

Its absence from “Backstop” area is consistent with an overlying unconformity of flat-lying Irvine Class vesicular basalt.

**Stratigraphic column**

- Irvine Class vesicular alkaline basalt, with basal conglomerate
- HP2: Aeolian sandstone
- HP1: volcaniclastic rocks
- Nodular/digitate opaline silica
- Buff-colored platy unit (ash)
- Light-toned, fine-grained, vesicular, olivine basalt
McCool Hill mass waste deposit:  
A subaqueous landslide

Oldest unit of the Inner Basin
Event stratigraphy of the Columbia Hills

- **Adirondack Class** (Plains basalt west): Olivine picrobasalt (3.6 Ga)
  - Irvine Class: Vesicular alkali basalt; with basal conglomerate
  - Aeolian sandstone
  - Barnhill Class: alkaline volcaniclastics
  - Nodular/digitate opaline silica
  - Halley Class Buff-coloured platy unit
  - Vesicular basalt
  - Sediments, with subaqueous landslide: Ma'Adim Vallis flooding?
- **Algonquin Class**: Olivine-bearing picritic tephra (north and south)
  - Flows?
  - Volcanic domes?
- **Wishstone Class**: Hawaiite tephra with NE-SW bedding strike:
  - (and associated other classes);
- **Uplift and erosion**
  - Possible basement in floor of impact crater

- Impact crater w. exposed basement (?)
- Aqueous alteration
- Carbonate alteration
- Subaqueous landslide
- Sulfate alteration
- Flows?
- Volcanic domes?
Jezero: A fluvial-deltaic system

- Diverse geologic units in clear stratigraphic context (Ehlmann et al., 2008a; Goudge et al., 2015).
- Long-lived delta
- Fe-Mg smectite clays may contain organics
Clear stratigraphic context...
Volcanic floor unit interpreted as younger than the delta

Volcanic floor unit embays delta deposit.  
Goudge et al. [2012, 2015]
Lobate margins

Craters of the Moon, Idaho

Gusev Crater

CTX

Older friable unit

Younger flow unit

M O A T

~3 m

Lobate margins

Moats

Lobate margins

Younger flow unit

Older friable unit

EARTH

MARS

5 km
Could the delta lie on the Volcanic floor unit?

No lobate flow fronts
No moats

Eroded shape of delta mesas could be by wind

Could the delta lie on the Volcanic floor unit?
Delta deposits

Delta and delta remnants lie on volcanic floor unit

Lobate flow front

Volcanic floor unit

Olivine-carbonate unit

After erosion

Volcanic floor unit

Original deposition

VFU
Jezero: A fluvial-deltaic system

- Diverse geologic units in clear stratigraphic context (Ehlmann et al., 2008a; Goudge et al., 2015).
- Long-lived delta?
- Fe-Mg smectite clays; derived through transport from basement hinterland.

Volcanic floor
Delta sediments
Olivine-carbonate
Altered basement

No aqueous alteration of volcanic floor unit

A covering delta may explain the young crater age of the VFU = c. 1-1.4 Ga (Kinch et al., 2017: 3rd landing site workshop)

Fewer craters on VFU near delta

Goudge et al. [2015]
Thus, a reliance on this model is...

Small delta
Long-lived?
Type of metabolism? Phototrophic unlikely...
Low organic concentration?
Youngest unit, thus susceptible to radiation damage...

Risky!
NE Syrtis Major – land of many mesas

(Syrtis Major Volcanics)

Feature-bearing slope unit

(Raised boxwork ridges)

Capping unit

Olivine-carbonate Fractured unit

Fe-Mg phyllosilicate-bearing basement unit

mesas

Bramble et al., 2017: Icarus

No alteration

Partial/Local alteration

Strong alteration

a

Midway

52 km

NE Syrtis

35 km

52 km

Midway

NE Syrtis

NE Syrtis Major Volcanics

Lava

MOLA elevation (m)

Al-clay (interpolated)

Fe/Mg smectites-pyroxene

Fe/Mg smectites-pyroxene

Olivine-carbonate

Layered sulfates

sand

Ehlmann and Mustard, 2012

Northeast Syrtis Major CTX mosaic

10 km
Clear stratigraphy of 3 main units, *but all mesas show the same units*: low geological diversity.

(Bramble et al., 2017: Icarus 293)
Investigation of megabreccia will gain information on the “magnetic field, geochronology, and petrogenesis” of pre-Isidis basement.
Sudbury Impact, Canada

Vredefort Impact Structure, S. Africa
(largest on Earth)

Isidis Basin, Mars

Pseudotachylyte-hosted breccia

Shattercones

Shocked zircons, \( T > 1676^\circ C \)

Disturbed isotopic systems

50 µm

Pre-Isidis “basement” at NE Syrtis, Midway, Jezero will be significantly compromised by the Isidis impact event:

The stated goals of gaining information on the “magnetic field, geochronology, and petrogenesis” of basement from isidis breccia blocks is RISKY!

Pb-loss

Kamo et al. 1996: EPSL

Mustard et al., 2009: JGR 114
<table>
<thead>
<tr>
<th>Age</th>
<th>Rock type</th>
<th>Alteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6 Ga</td>
<td>Capping mafic unit</td>
<td></td>
</tr>
<tr>
<td>3.83 Ga</td>
<td>Capping mafic unit</td>
<td></td>
</tr>
<tr>
<td>3.96 Ga</td>
<td>Regional Olivine-carbonate</td>
<td></td>
</tr>
<tr>
<td>c. 3.7 Ga</td>
<td>Inner Basin sediments, southern delta; Ma’Adim flooding?</td>
<td></td>
</tr>
<tr>
<td>3.4 Ga</td>
<td>Debris flow</td>
<td></td>
</tr>
<tr>
<td>3.6 Ga</td>
<td>Plains Basalt: olivine picrobasalt</td>
<td>Folding (Pingo formation?)</td>
</tr>
<tr>
<td>3.96 Ga</td>
<td>Isidis Impact event</td>
<td></td>
</tr>
<tr>
<td>3.96 Ga</td>
<td>Fe-Mg smectite basement unit, with raised ridges</td>
<td></td>
</tr>
<tr>
<td>3.4 Ga</td>
<td>Algonquin Class: Olivine ferropicrite; Comanche Class: Olivine-carbonate</td>
<td>CO₂</td>
</tr>
<tr>
<td>3.4 Ga</td>
<td>Clovis class: basaltic sediments</td>
<td>K</td>
</tr>
<tr>
<td>3.4 Ga</td>
<td>Peace class: ultramafic sediments</td>
<td></td>
</tr>
<tr>
<td>3.4 Ga</td>
<td>Wishstone Class: plag-rich Hawaiite, and altered equivalents (Watchtower, Independence)</td>
<td>A/S, Sm</td>
</tr>
<tr>
<td>?</td>
<td>Exposed basement (in crater floor)</td>
<td></td>
</tr>
</tbody>
</table>
COLUMBIA HILLS

“So much more to explore”
Event stratigraphy of the Columbia Hills

**Adirondack Class** (Plains basalt west): Olivine picrobasalt (3.6 Ga)
- Irvine Class: Vesicular alkali basalt; with basal conglomerate
- Aeolian sandstone
- Barnhill Class: Tuffaceous rocks
- Nodular/digitate opaline silica
- Halley Class: Buff-coloured platy unit
- Vesicular basalt
- Sediments, with subaqueous landslide: Ma’Adim Vallis flooding?

**Algonquin Class**: Olivine-bearing picritic tephra (north and south)
- Flows?
- Volcanic domes?

**Wishstone Class**: Hawaite tephra with NE-SW bedding strike:
(and associated other classes);

**Uplift and erosion**

Possible basement in floor of impact crater

- Impact crater w. exposed basement(?)
- Carbonate alteration
- Aqueous alteration
- Phyllosilicate alteration
- Subaqueous landslide
- Sulfate alteration
- Smooth, deeply fractured terrain
- Subaerial alteration
- Aqueous alteration
- Erosion
- Folding
- Inner Basin
- Low water/rock, sulfate alteration
- Carbonate alteration (Comanche Class)
- Aquous and sulfate alteration (Watchtower Class)

Minor hydrous alteration (atmospheric)
Geological history of Columbia Hills, Gusev Crater

- Gusev crater
- Wishstone Class tephra
- Algonquin Class volcanics
- Ma’Adim Vallis flooding
- Home Plate volcanic plumes
- Irvine Class volcanics
- Adirondack Class volcanics

- CO2
- H2O
- Sulfate alteration
- Hot springs
- Pingo
- Plains basalts
- Ash drapes terrain
- Hydrothermal plumbing

- ~4 Ga
  Early Noachian
- ~3.8 Ga
  Warm/wet period
- ~3.6 - 3.5 Ga
  Late Hesperian
Tara’s diagram

After Ehlmann et al., 2016
No outcrop/Scree and dust-filled valley

Home Plate

Vesicular Basalt

Volcaniclasticsandstone/tuff

Sedimentary onlap

C. S. Lewis

Roger Zelazny

Unconformity

Dipping bedding

Home Plate (HP2)

Unconformity

“Backstop”

http://homepage.ufp.pt/biblioteca/Seismic/Pages/Page19.htm
Organic matter is often highly concentrated and well preserved in offshore deltaic environments [on Earth]…


Jezero delta is small: it ain’t no Amazon

Slide courtesy of Joshua Bergmark, UNSW
NE Syrtis Major – land of many mesas

Capping Mafic Rock
Olivine–Carbonate Formation
LCP-bearing Mounds
Clay-rich basement

2 km
Kaolinite may \textbf{NOT} be a realistic target
Event stratigraphy of the Columbia Hills

New analyses suggest period of standing water at onset of Inner Basin succession

- **Adirondack Class** (Plains basalt west): Olivine picrobasalt (3.6 Ga)

- **Irvine Class**: Vesicular alkali basalt; with basal conglomerate

- **Aeolian sandstone**

- **Barnhill Class**: Tuffaceous rocks

- **Nodular/digitate opaline silica**

- **Halley Class**: Buff-coloured platy unit

- **Vesicular basalt**

- **Algonquin Class**: Olivine-bearing picritic tephra (north and south)

- **Wishstone Class**: Hawaiiite tephra with NE-SW bedding strike: (and associated other classes);

**Uplift and erosion**

- **Minor hydrous alteration (atmospheric)**

- **Low water/rock, sulfate alteration**

- **Carbonate alteration (Comanche Class)**

- **Aqueous and sulfate alteration (Watchtower Class)**

**Erosion**

**Folding**

**Subaqueous landslides**

**Wave-cut benches**

**Volcanic domes**

**Possible basement in floor of impact crater**
**Terrestrial** mass waste deposits have distinctly different features:

- Radial cracks
- Scarps
- Transverse cracks
- Toe lobes
South side Husband Hill

Wave-cut benches?

Wave-cut bench, Sydney, Australia

Cross-section
Columbia Hills, Gusev Crater

Spirit Rover path

Home Plate

Extremely diverse terrain

NASA/JPL Digital elevation model