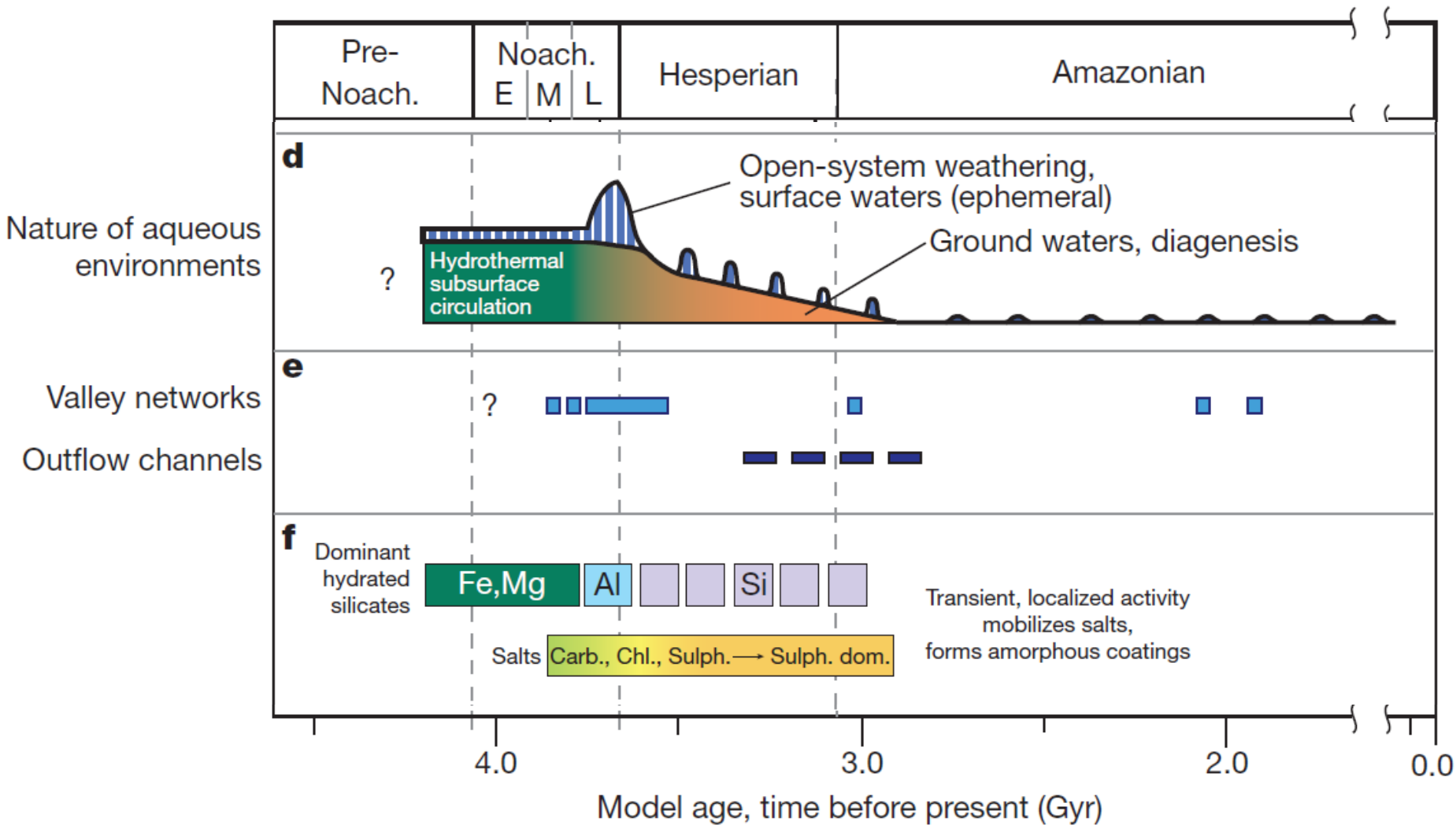
Habitable Environments of Ancient Mars: Deciphering the Rock Record

John Grotzinger

Modern Mars: Recurring Slope Lineae

McEwan et al., 2014

Mars Timeline: Water-related environments

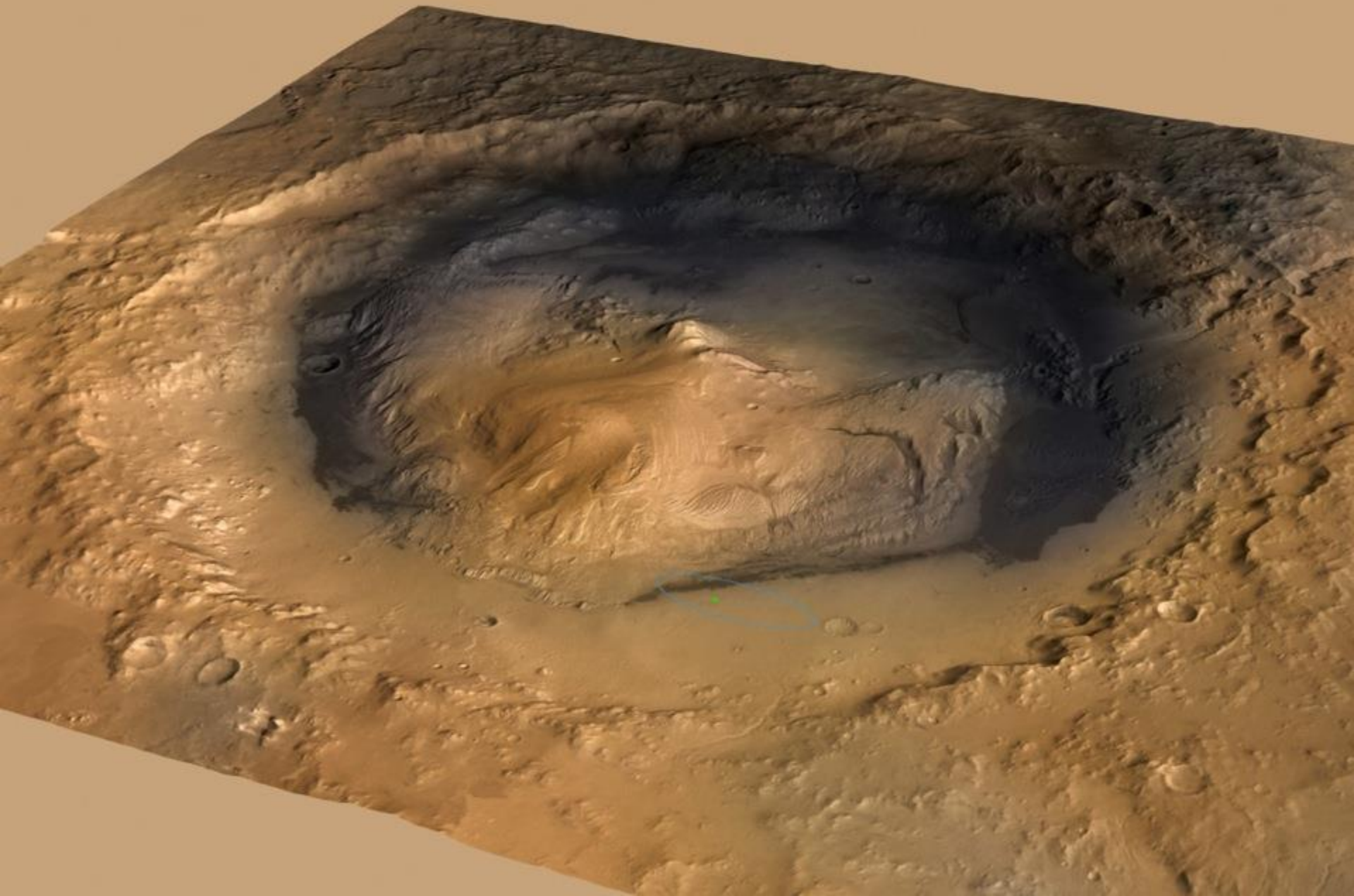


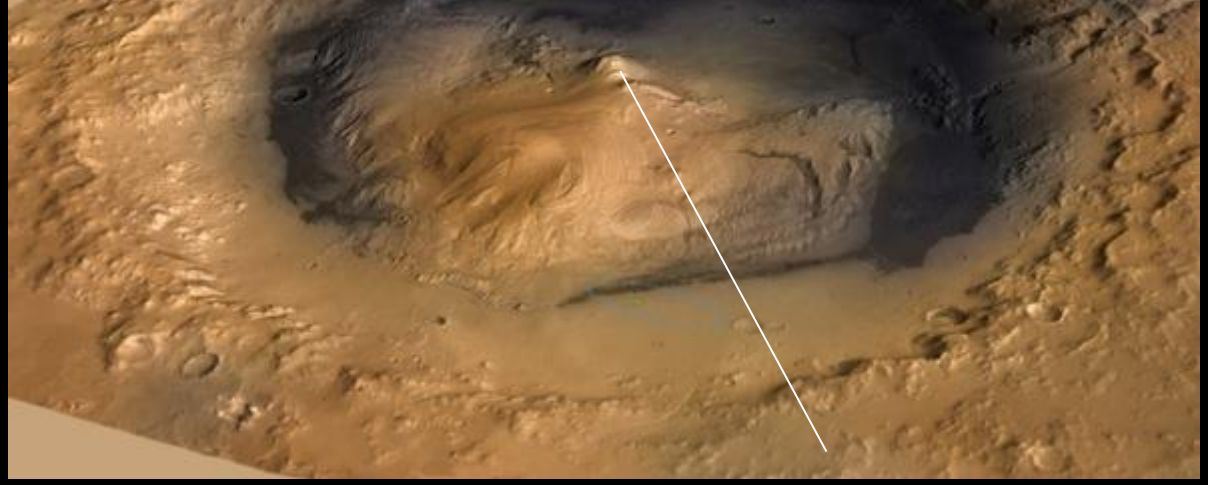
Ehlmann et al., 2011, Nature

Rethinking Ancient Mars

- "Mars is a volcanic planet". But…
  - Layered rocks can be sedimentary.
  - Sedimentary basins are chemical reactors: heat + fluid flow → aqueous minerals
  - Sedimentary rocks are the archive of Earth's early biosphere record.
- "Mars is a glacial planet". But…
  - No landed mission has ever encountered glacial landforms. Sedimentary deposits lack glacial features.
  - Mars was apparently wet enough, and warm enough, for liquid water to be stable at surface for 10^4 - 10^6 years.
- "Noachian → Hesperian was a global acidization event". But…
  - Meridiani (Opportunity rover) was acidic. Gale crater (Curiosity rover) was not.
  - The largest river system on Mars only formed clays despite spanning N→H boundary. No evidence of layered sulfates in younger history.
- When considering biomarker preservation, texture and petrogenesis are as important as mineralogy.
- *Need more (small, cheap) rovers, assigned to "boutique" missions.*

Gale Crater and Mt. Sharp



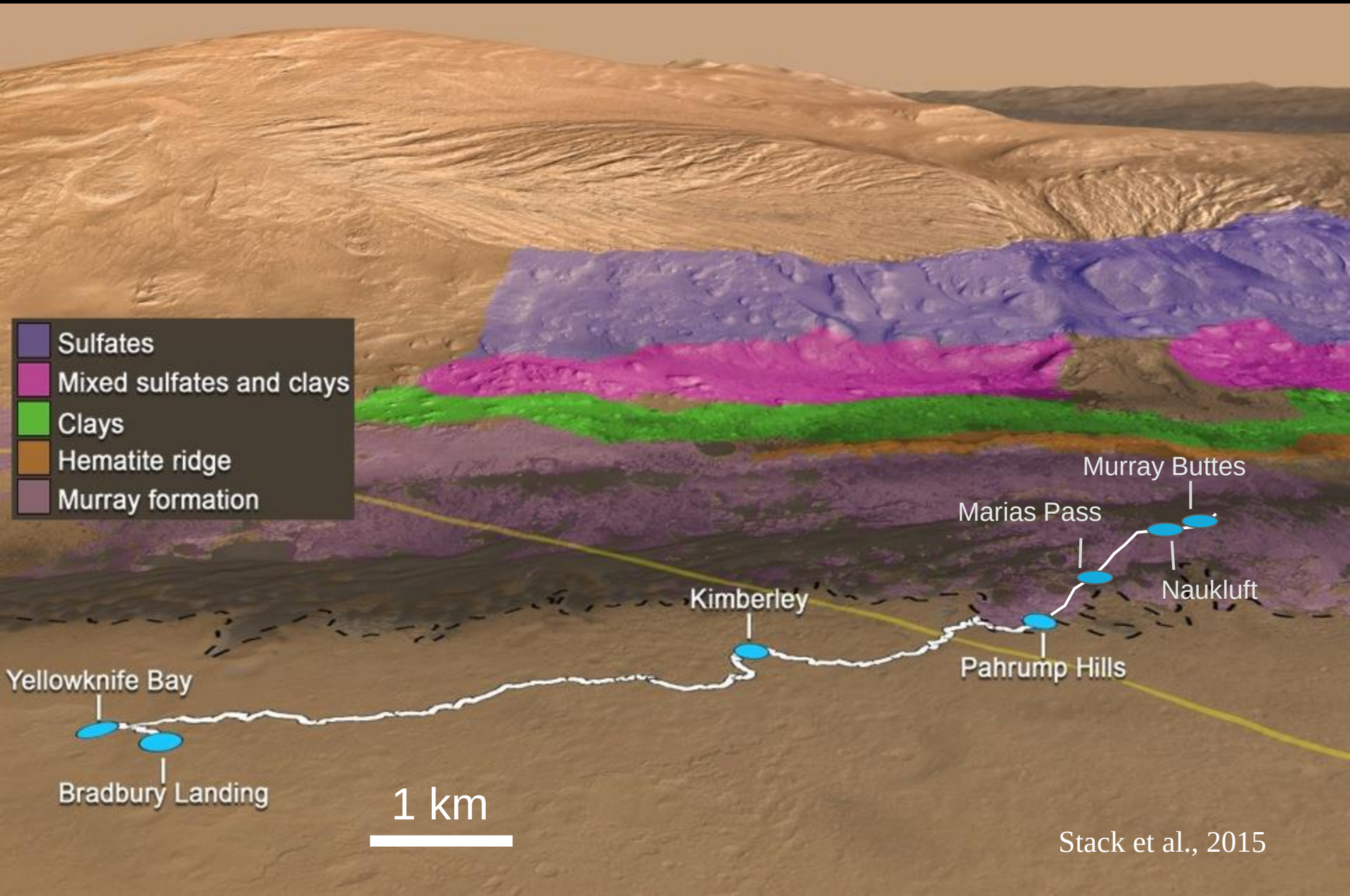


Original topography
Current topography
Conglomerate
Sandstone
Mudstone
Clay-bearing unit + hematite-bearing unit
Clay/sulfate-bearing unit + sulfate-bearing unit
Eolian strata?
Pre-impact bedrock
? Sedimentary rock?
1,000
0
-1,000
-2,000
-3,000
-4,000
-5,000
-6,000
?
?
?
15 km

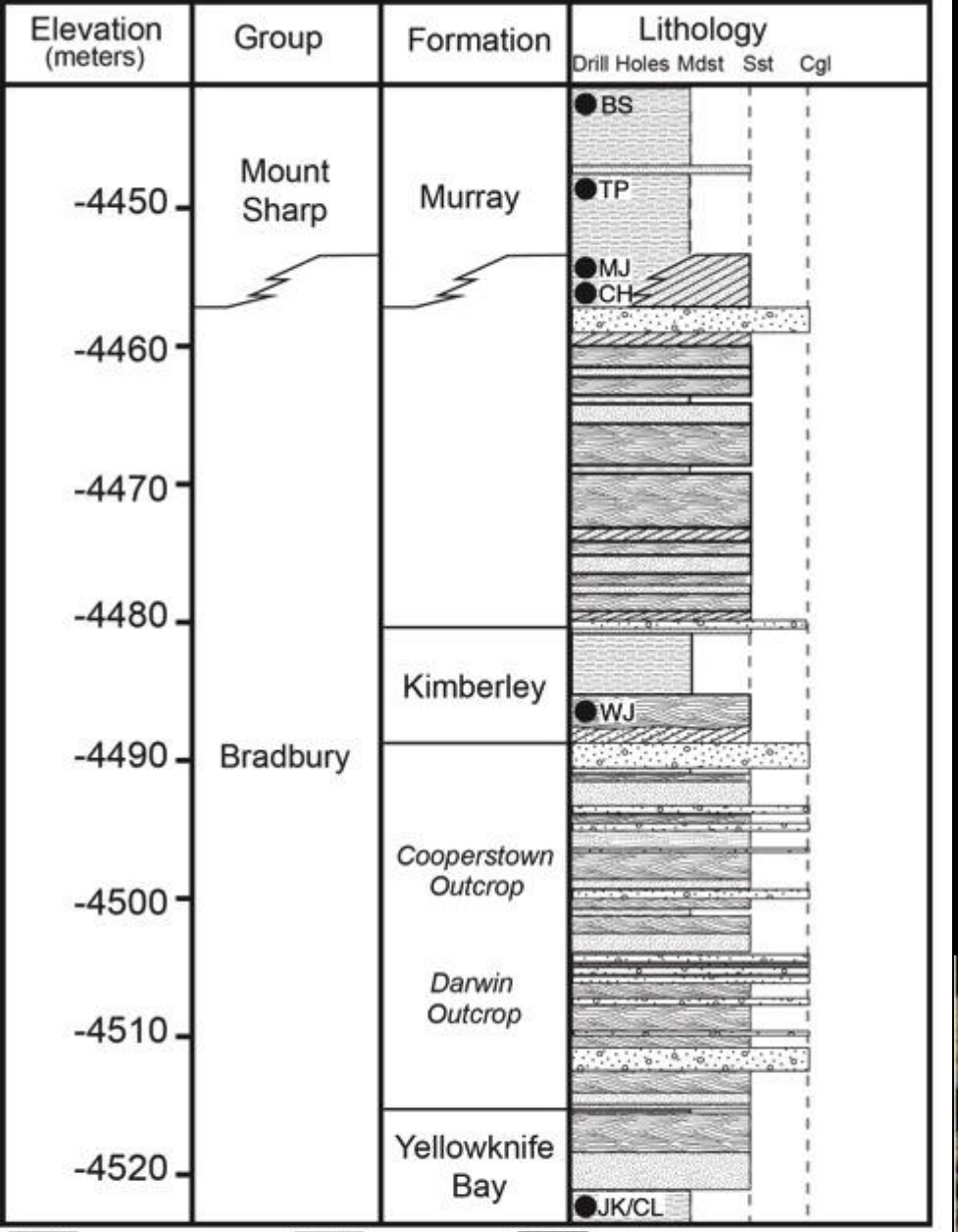
Grotzinger et al., 2016

Looking South to Mount Sharp

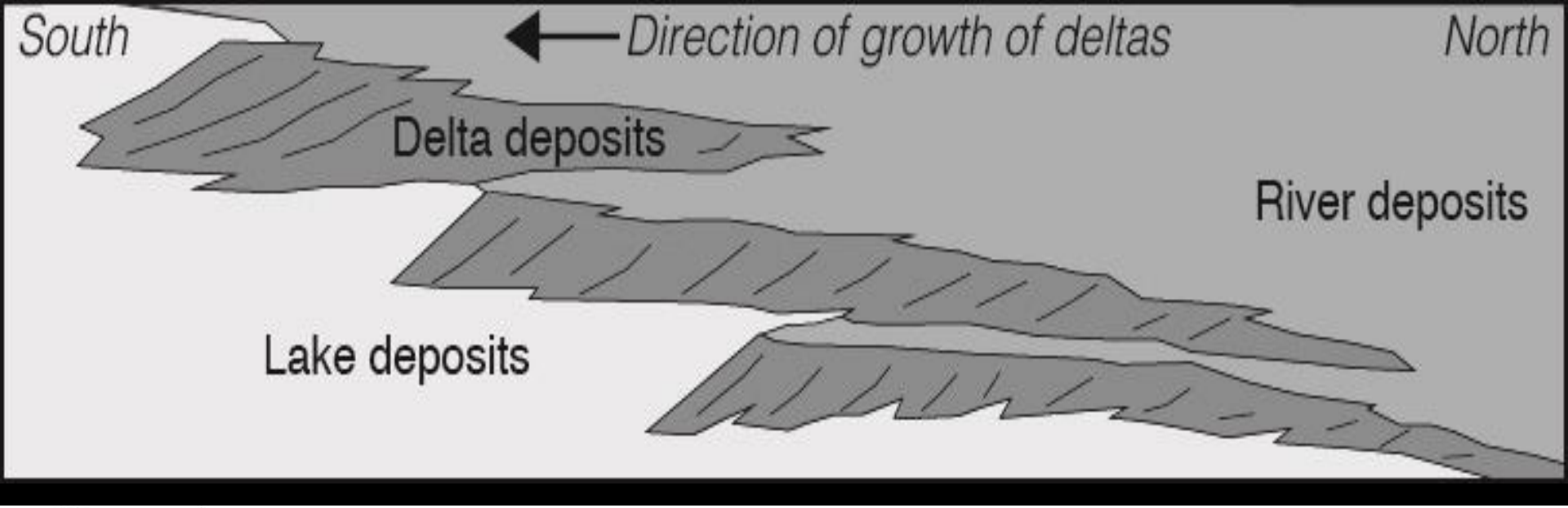
Mineral Stratigraphy, lower Mt. Sharp

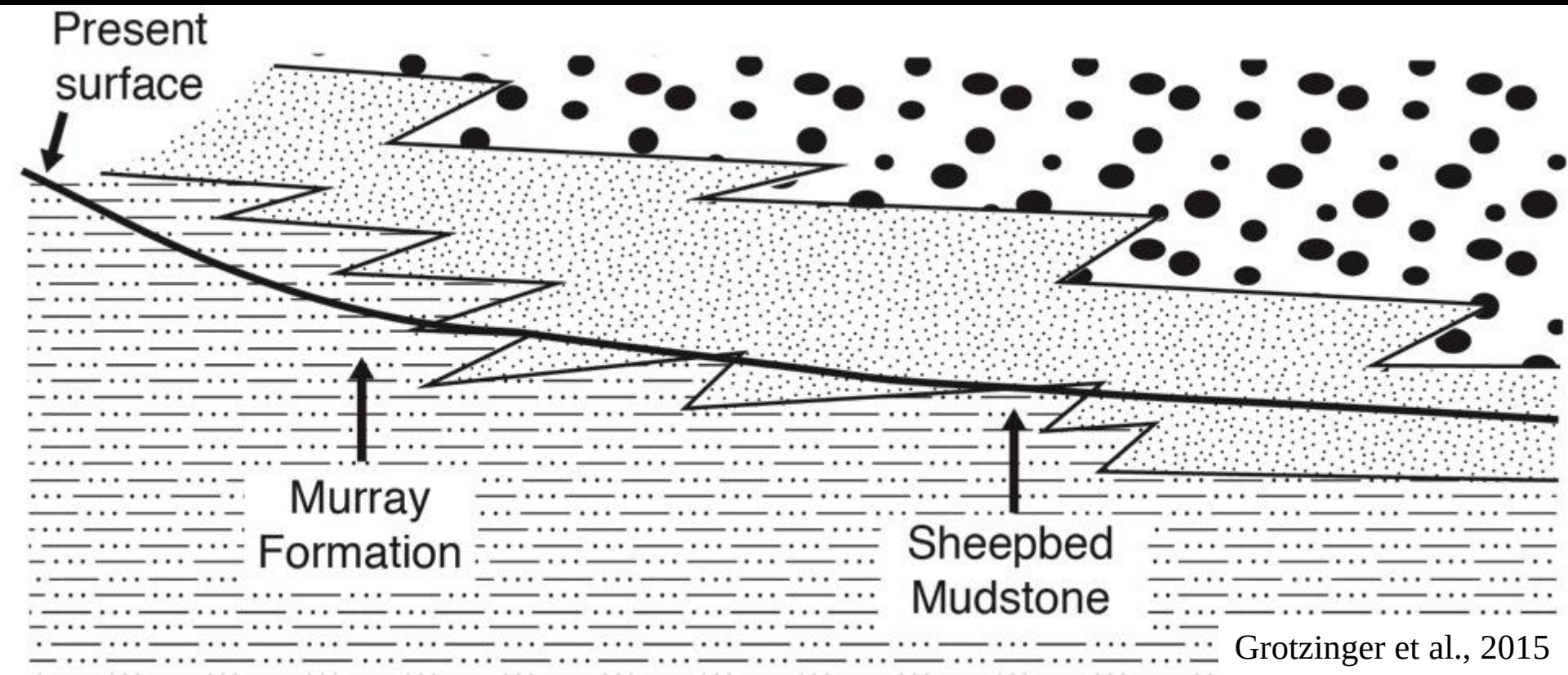


Stack et al., 2015

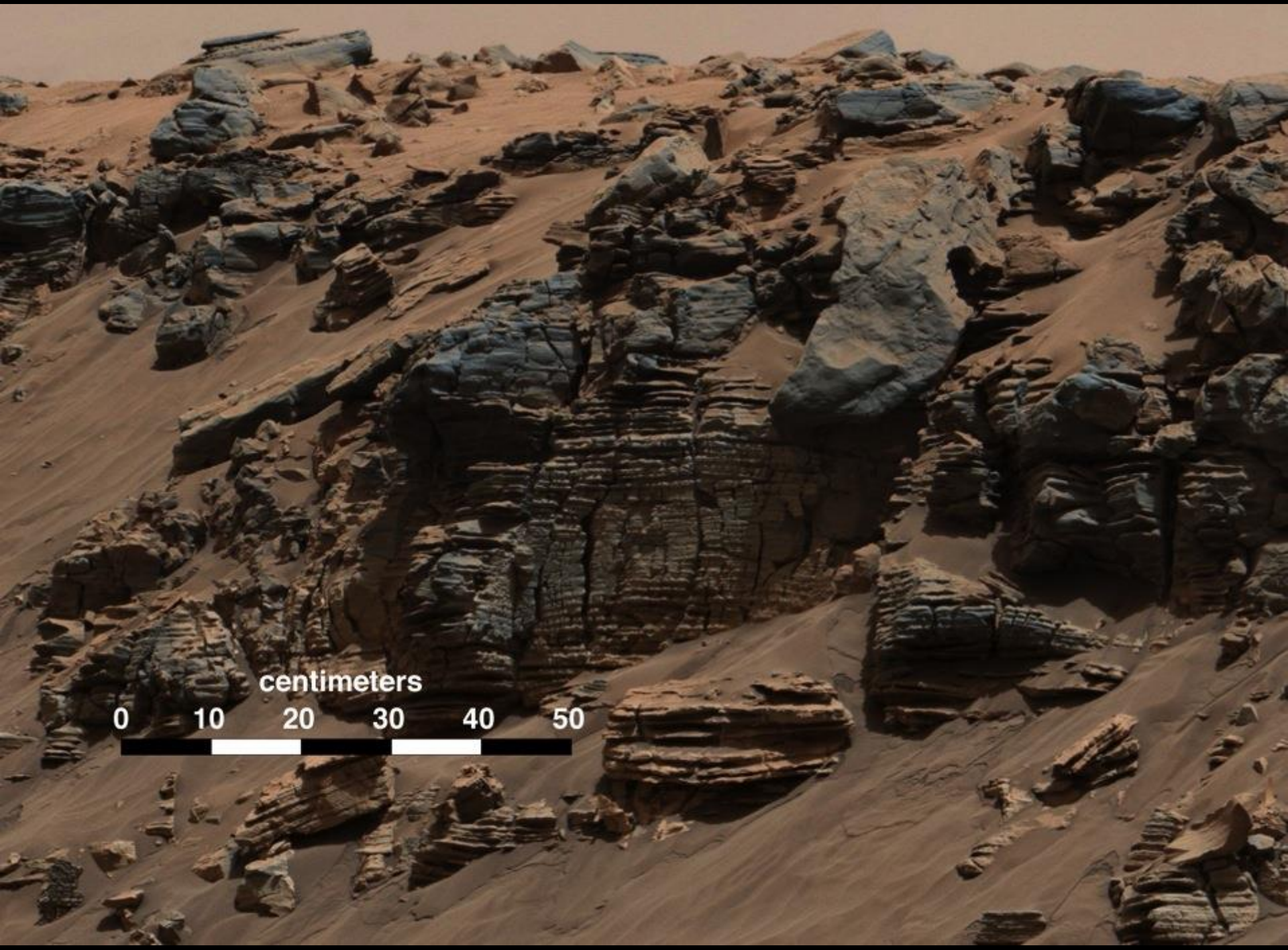


Williams et al., 2016





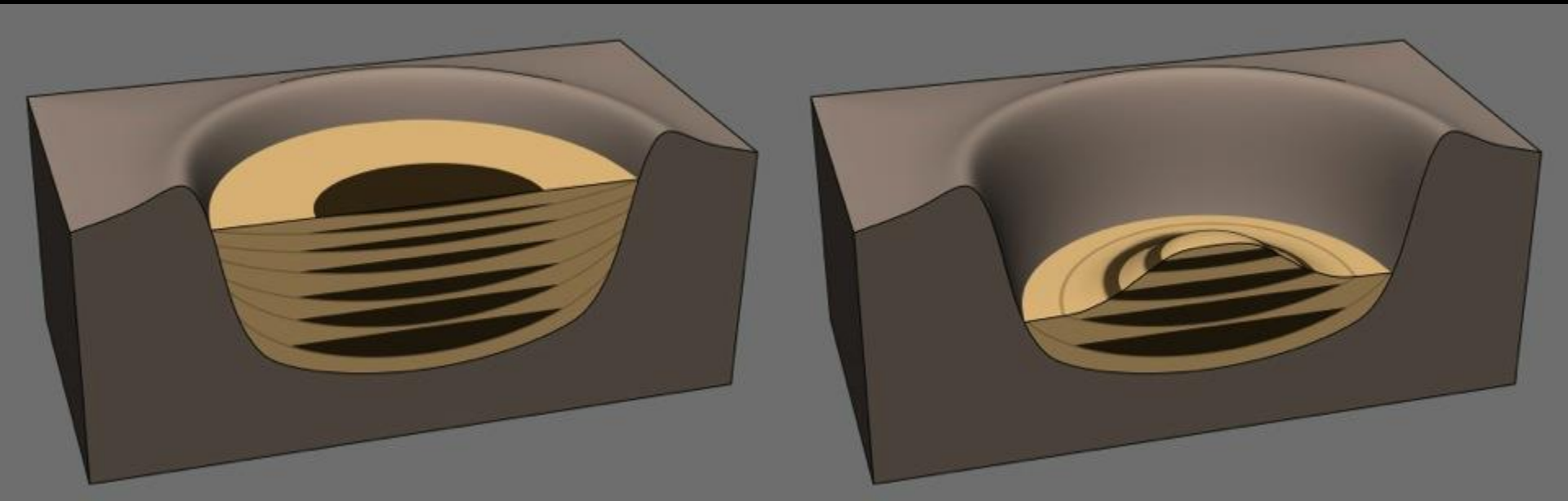
Grotzinger et al., 2015


centimeters
0
10
20
30
40
50

Ancient Lake Beds

Mars (cm-scale)

Earth (cm-scale)

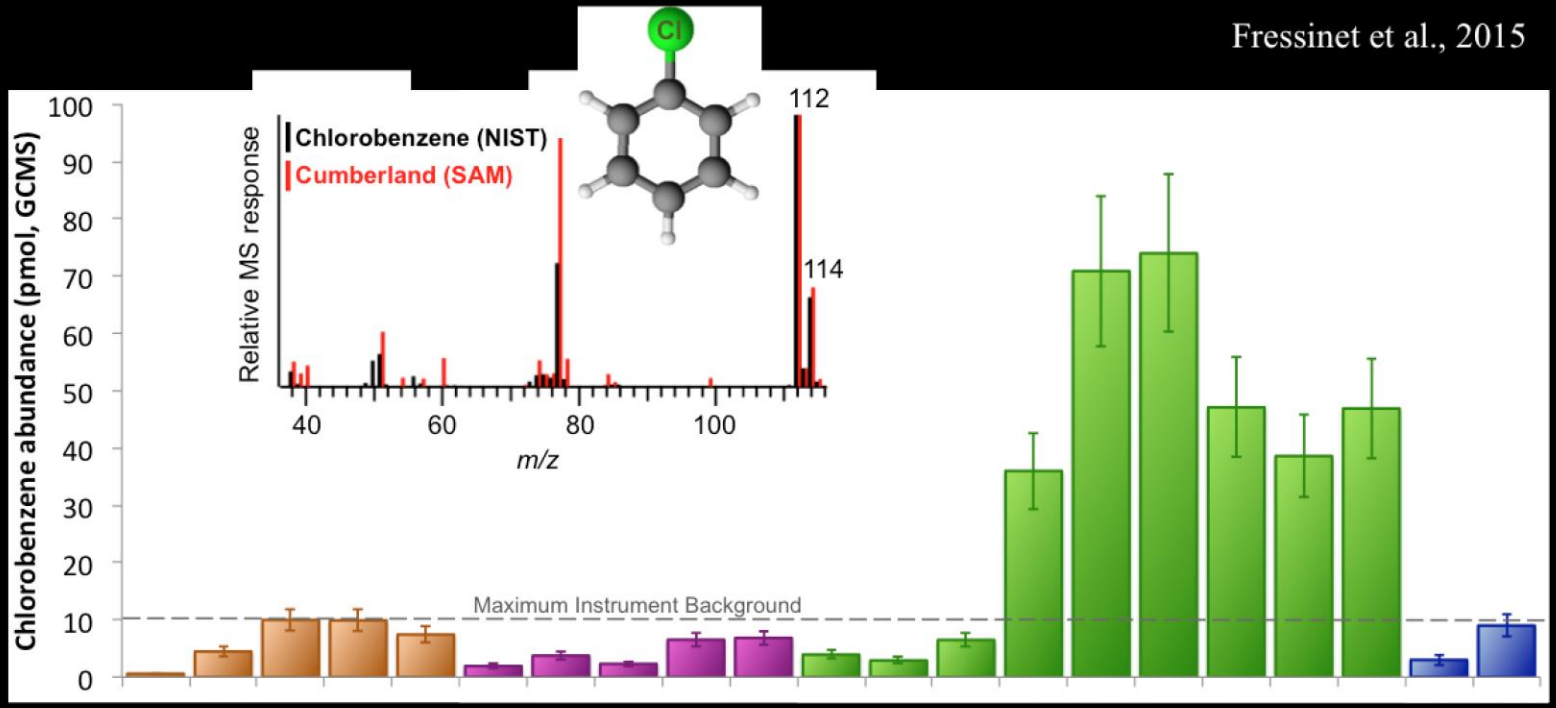


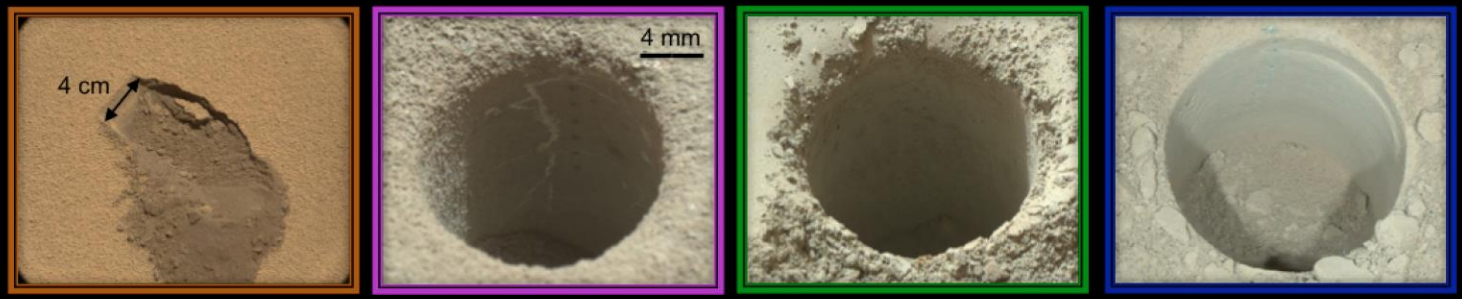
Mineral	Rocknest	John Klein
Plagioclase (~An50)	43%	30%
Olivine (~Fo58)	20.5%	4.4%
Augite	16.7%	6.2%
Pigeonite	11.4%	5.2%
Magnetite	1.8%	10%
Anhydrite	1.4%	4.5%
Pyrhotite	-	1.5%
Smectite	-	20-30%
Amorphous material	25-40%	20%

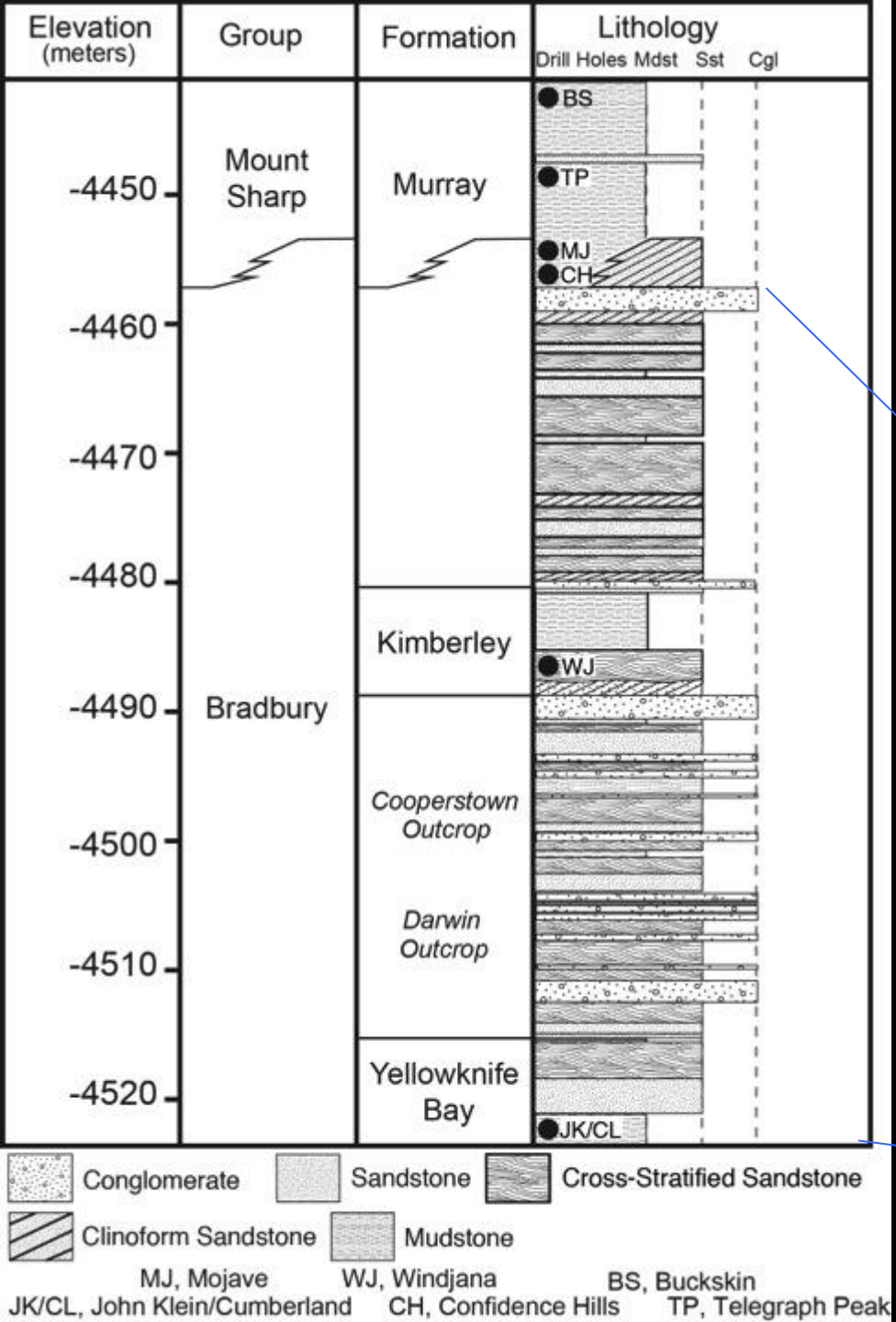
Vaniman et al., 2014

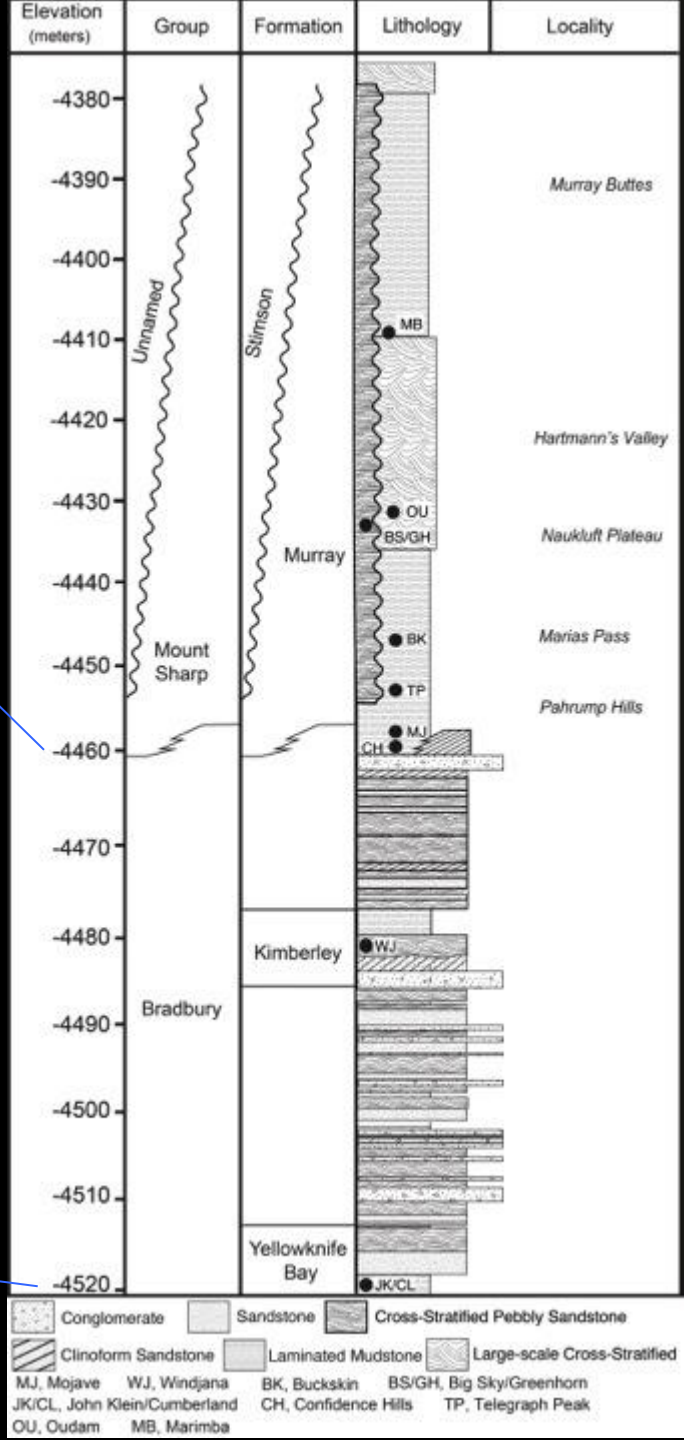
Organic Compounds in Rocks

Fressinet et al., 2015



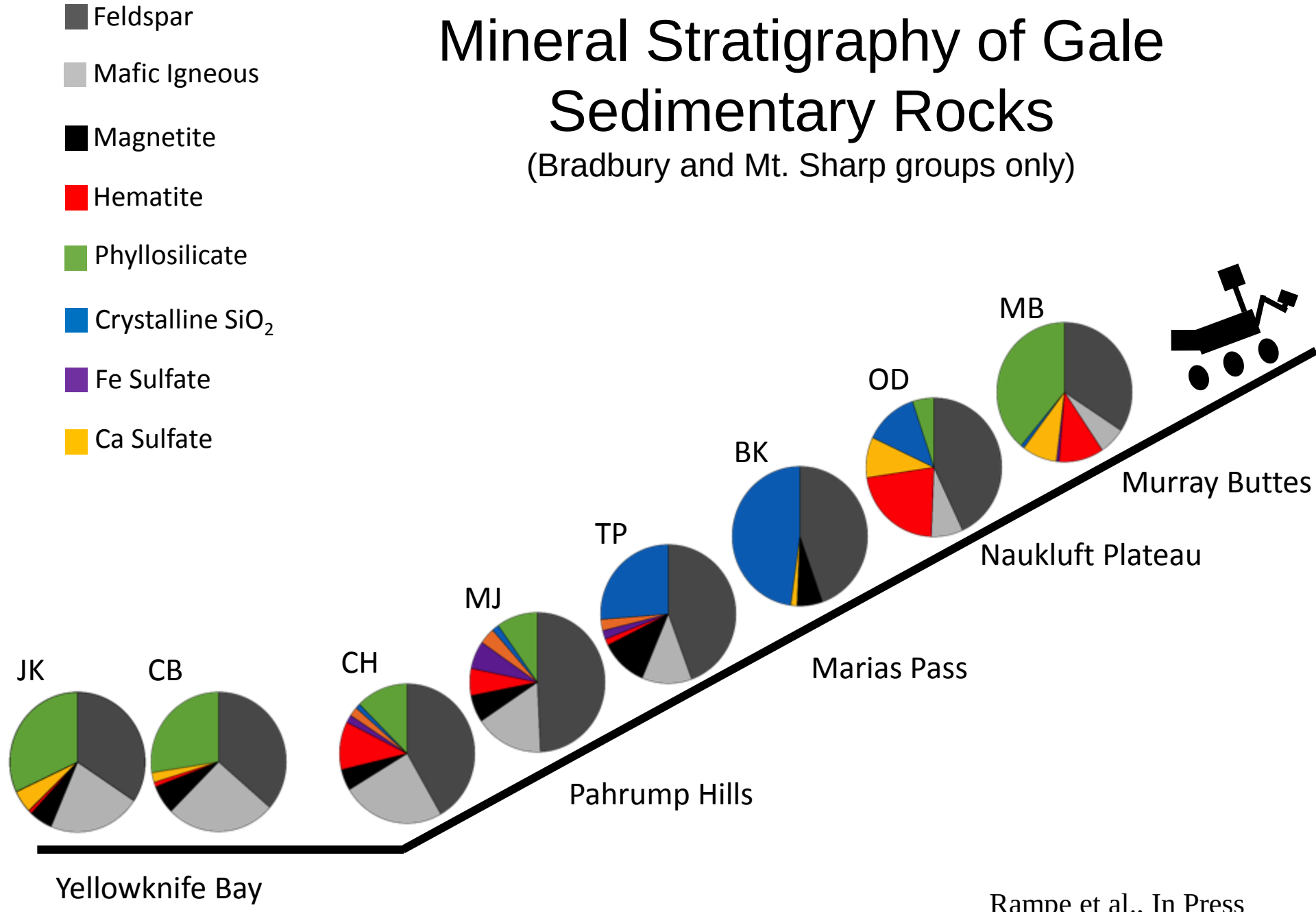



Elevation (meters)
Group
Formation
Lithology
Drill Holes Mdst Sst Cgl
-4450
-4460
-4470
-4480
-4490
-4500
-4510
-4520
Mount Sharp
Bradbury
Murray
Kimberley
Cooperstown Outcrop
Darwin Outcrop
Yellowknife Bay
BS
TP
MJ
CH
WJ
JK/CL
Conglomerate
Sandstone
Cross-Stratified Sandstone
Clinoform Sandstone
Mudstone
MJ, Mojave
WJ, Windjana
BS, Buckskin
JK/CL, John Klein/Cumberland
CH, Confidence Hills
TP, Telegraph Peak


Elevation (meters)
Group
Formation
Lithology
Locality
-4380
-4390
-4400
-4410
-4420
-4430
-4440
-4450
-4460
-4470
-4480
-4490
-4500
-4510
-4520
Unnamed
Stimson
Mount Sharp
Murray
Kimberley
Bradbury
Yellowknife Bay
MB
OU
BS/GH
BK
TP
MJ
CH
WJ
JK/CL
Murray Buttes
Hartmann's Valley
Naukluft Plateau
Marias Pass
Pahrump Hills
Conglomerate
Sandstone
Cross-Stratified Pebbly Sandstone
Clinoform Sandstone
Laminated Mudstone
Large-scale Cross-Stratified
MJ, Mojave
WJ, Windjana
BK, Buckskin
BS/GH, Big Sky/Greenhorn
JK/CL, John Klein/Cumberland
CH, Confidence Hills
TP, Telegraph Peak
OU, Oudam
MB, Marimba

Mineral Stratigraphy of Gale Sedimentary Rocks

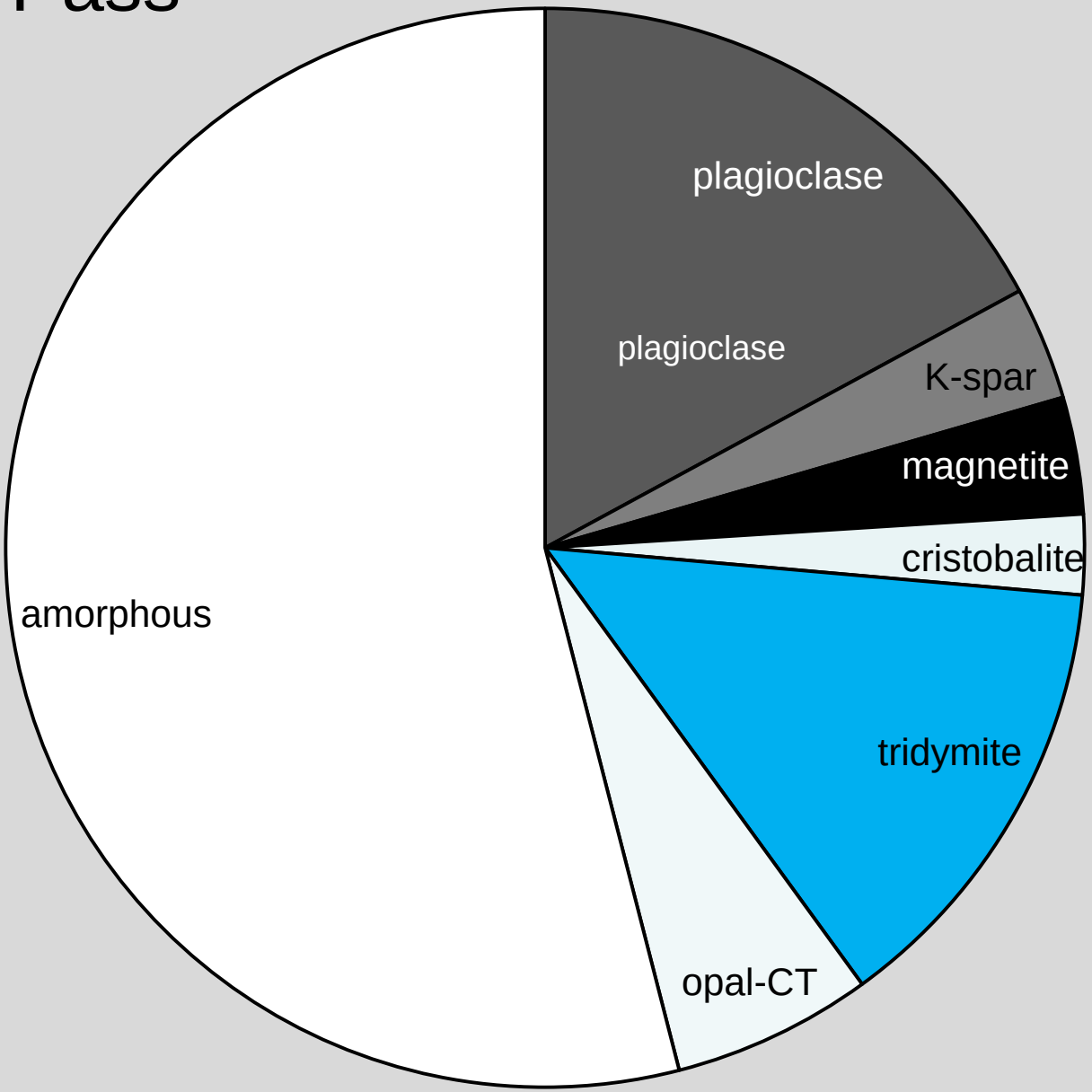
(Bradbury and Mt. Sharp groups only)



Rampe et al., In Press


“Marias Pass”
-73% SiO2
-Laminae are 0.5 mm thick
-Very fine grained
1 cm

Marias Pass

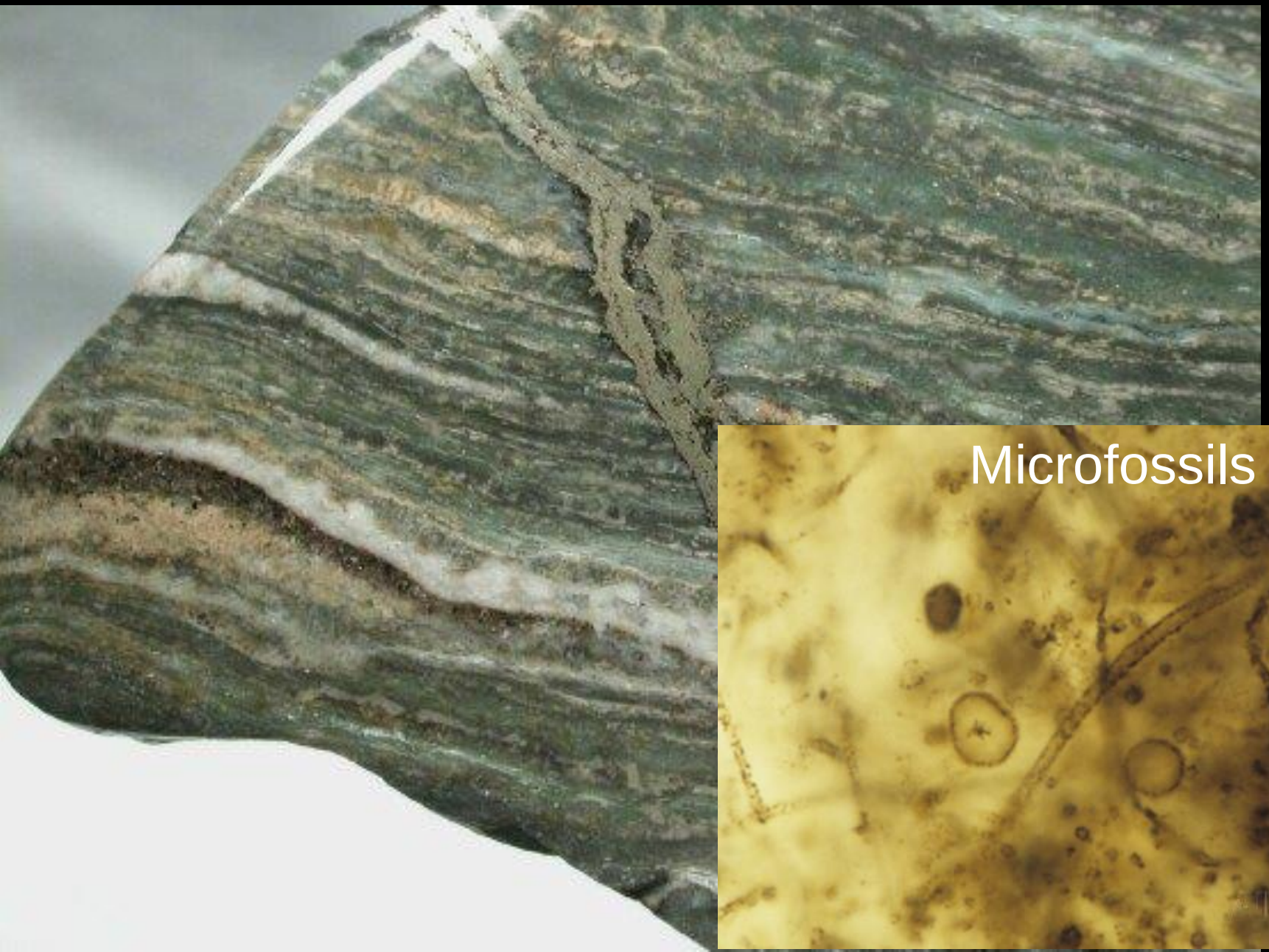


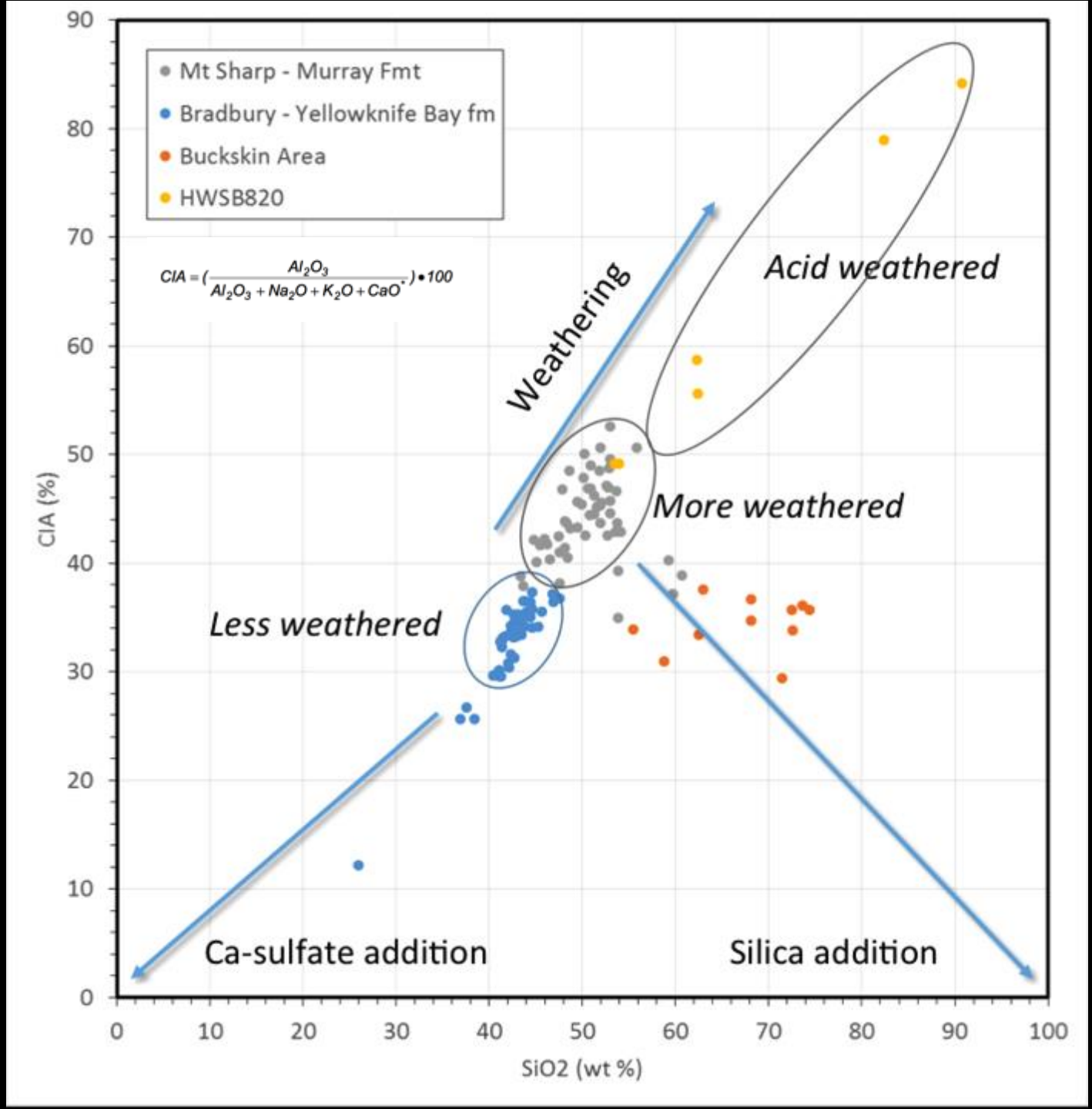
Morris et al., 2016

Precambrian Banded Iron Formation, Silica-rich Facies

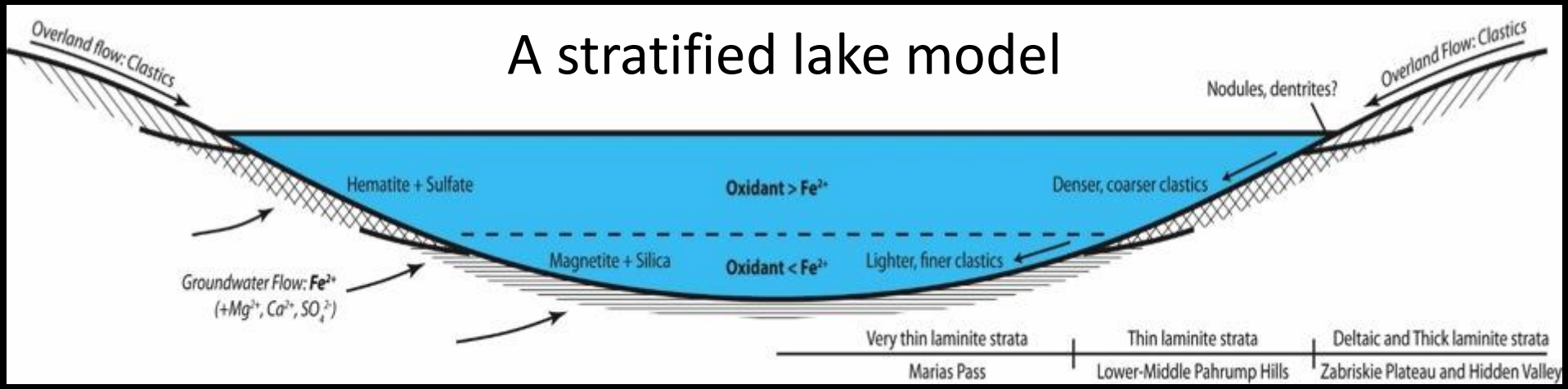
Precambrian Laminated Silica Deposit

Precambrian Laminated Silica Deposit




Mt Sharp - Murray Fmt
Bradbury - Yellowknife Bay fm
Buckskin Area
HWSB820
$CIA = (\frac{Al_2O_3}{Al_2O_3 + Na_2O + K_2O + CaO^*}) \bullet 100$
Weathering
Acid weathered
More weathered
Less weathered
Ca-sulfate addition
Silica addition
CIA (%)
SiO2 (wt %)
0
10
20
30
40
50
60
70
80
90
100

A stratified lake model



Hematite-sulfate = shallow water facies

- Nearshore sediments delivered by fluvial input; dense, mafic minerals dominate.
- Oxidant concentration (UV photons, molecular O_2) > [Fe^{2+}].
- Fe-oxidation produces hematite and acidity, eventually stabilizing minor jarosite.
- Evaporation of the lake concentrates water to produce Mg, Ca sulfates.

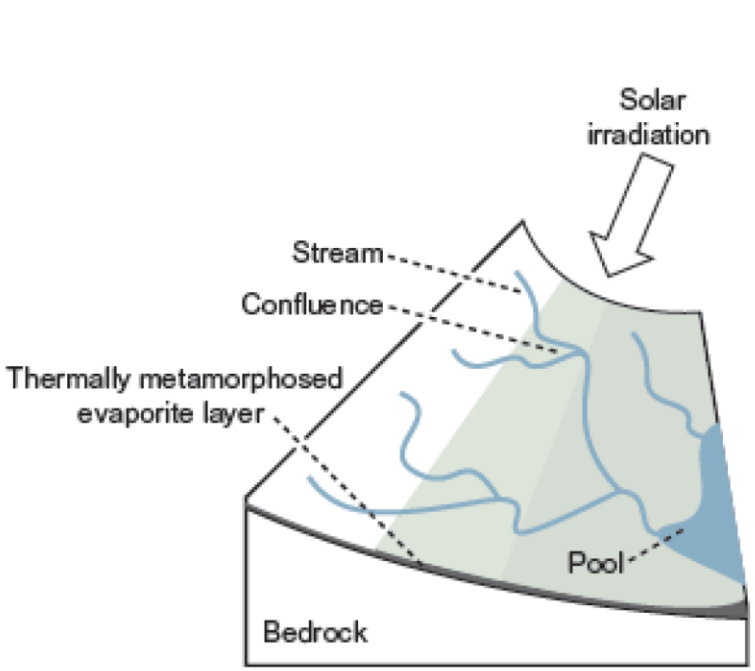
Magnetite-silica = deep water facies

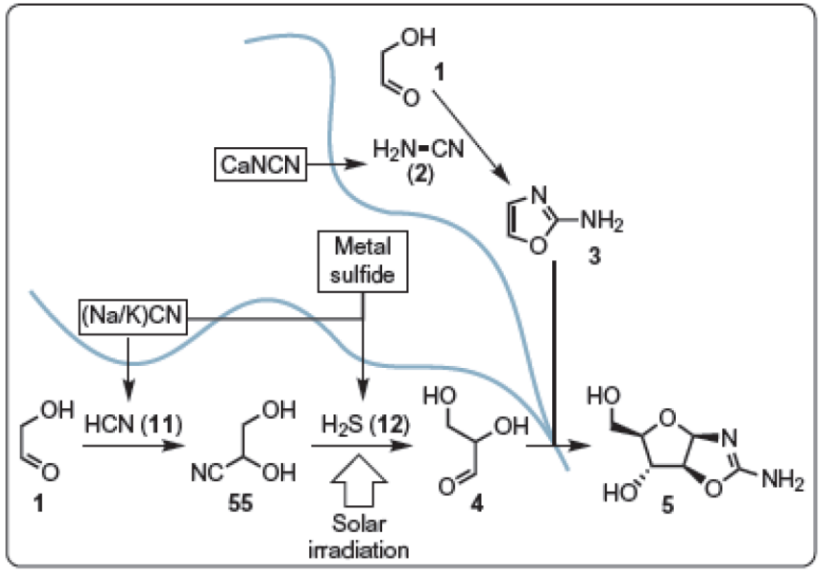
- Offshore sediments are finer, less dense clastics (crystalline silica, feldspars, perhaps some of the opaline silica)
- Oxidant concentration (UV photons, molecular O_2) < [Fe^{2+}].
- Less oxic conditions permit the precipitation of authigenic magnetite > hematite.
- Amorphous silica precipitated via interactions with silica-rich source area.

Hurowitz et al., In Review

Surface Scenario for Origin of Life

Towards a geochemical scenario: confluence





"Although it necessarily has to be painted with broad brushstrokes, the picture that emerges is of an overall reaction network developing over time in separate streams and pools…[and] the various products would be synthesized by subtle variations in the flow-chemistry history of the streams and pools."

Powner, M.W.; Gerland, B.; Sutherland, J.D. *Nature*, **2009**, *459*, 239-242.

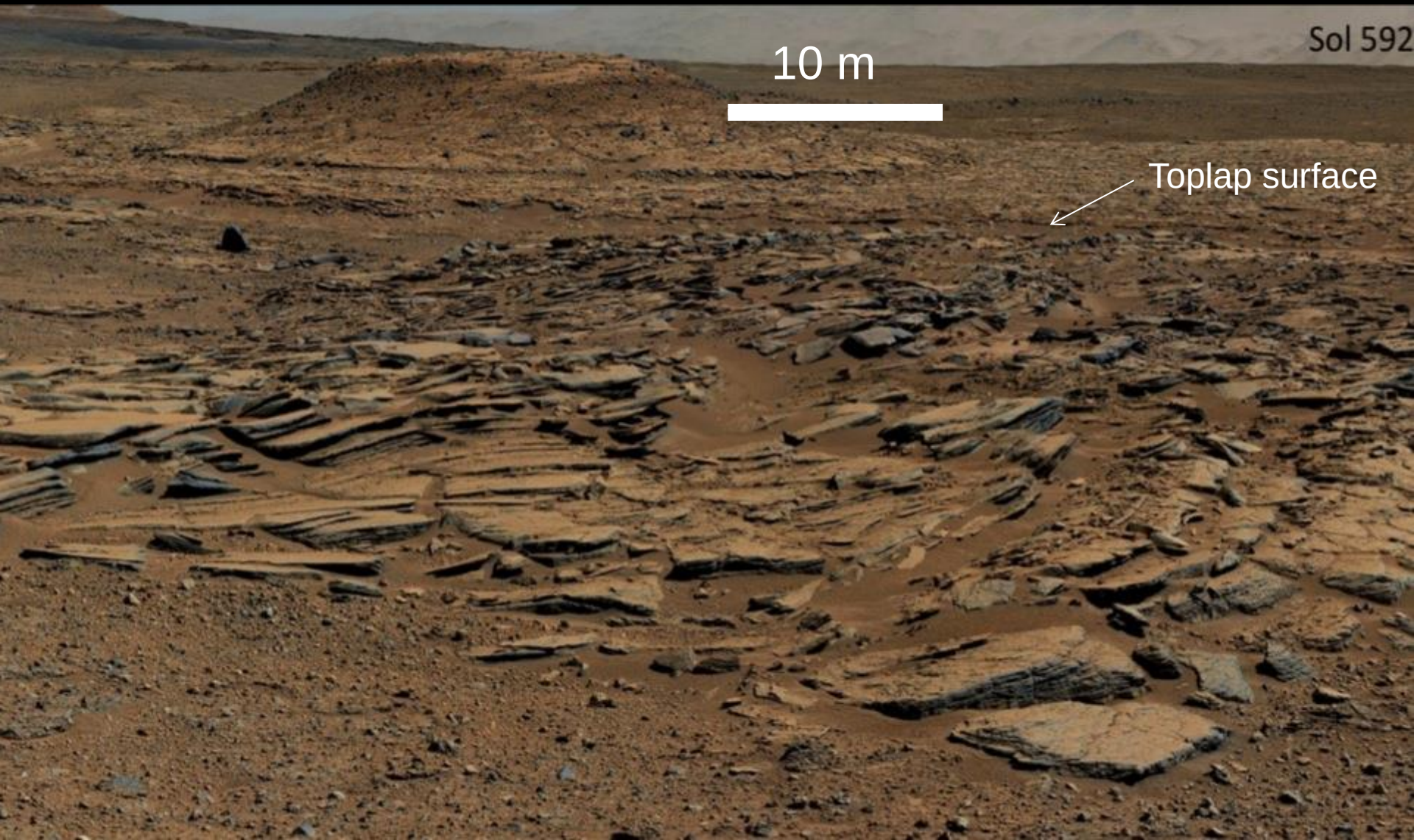
Patel, B.H.; Percivalle, C.; Ritson, D.J.; Duffy, C.D.; Sutherland, J.D.; *Nature Chemistry*, 2015, *7*, 301-307

Deep Fractures: Subsurface Habitability

Conclusions

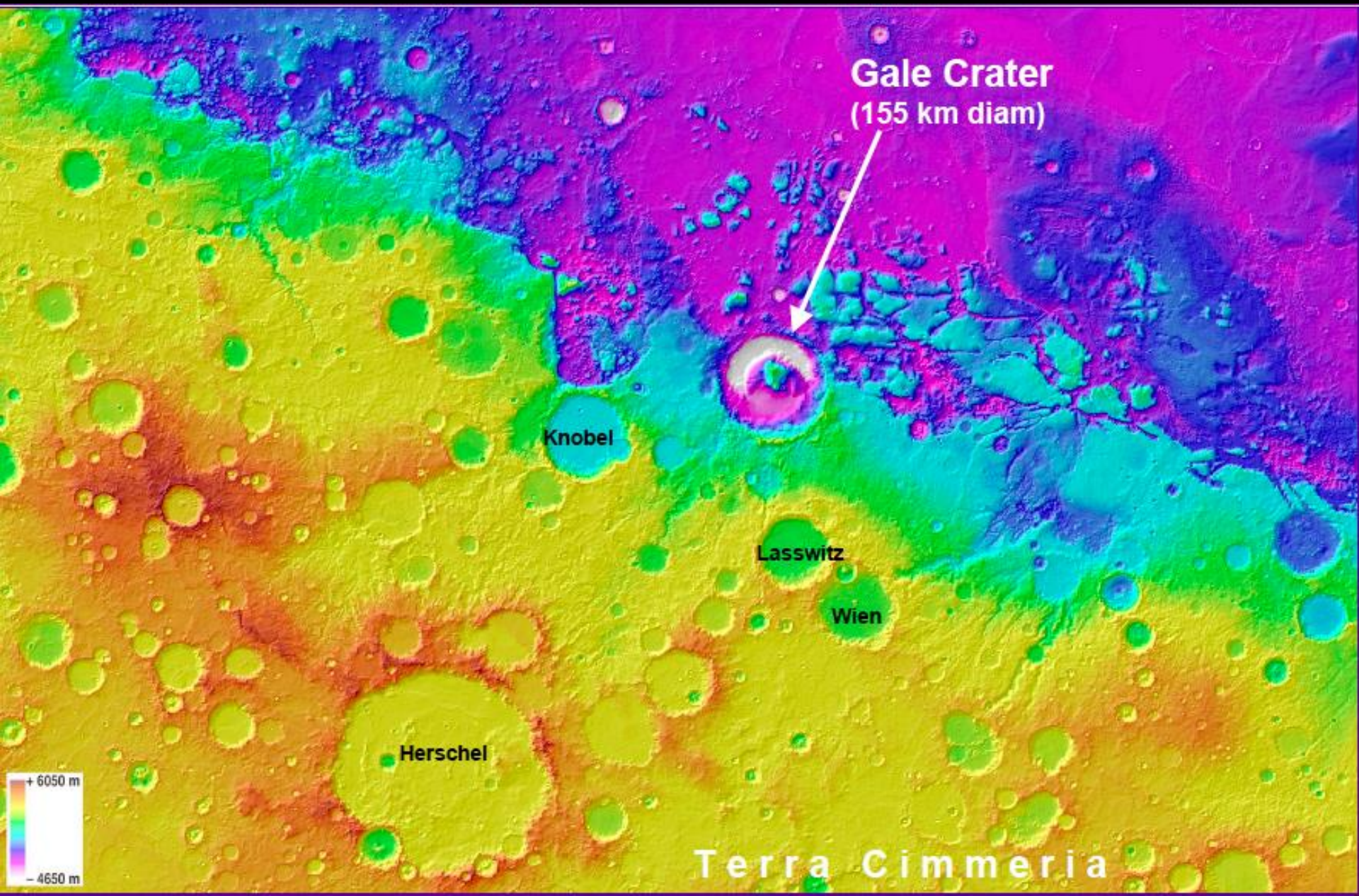
- Gale crater contained a long-lived ancient lake fed by surface waters derived from *low-elevation* highlands, and also groundwater.
- Mineral compositions show unexpected and surprising diversity in Murray formation, representing environmental differentiation over geologically brief time scales
- High silica compositions inconsistent with acid weathering, via minerals, major/minor elements.
- Opaline silica may have precipitated as early diagenetic sediment, or directly from water column to form finely laminated mudstone.
- These rocks provide compelling evidence for habitability, and remarkably Earth-like analogs for biosignature preservation.
- Boutique missions – look for borates, cyanide salts, etc.

Clinoform Sandstone (View to West)



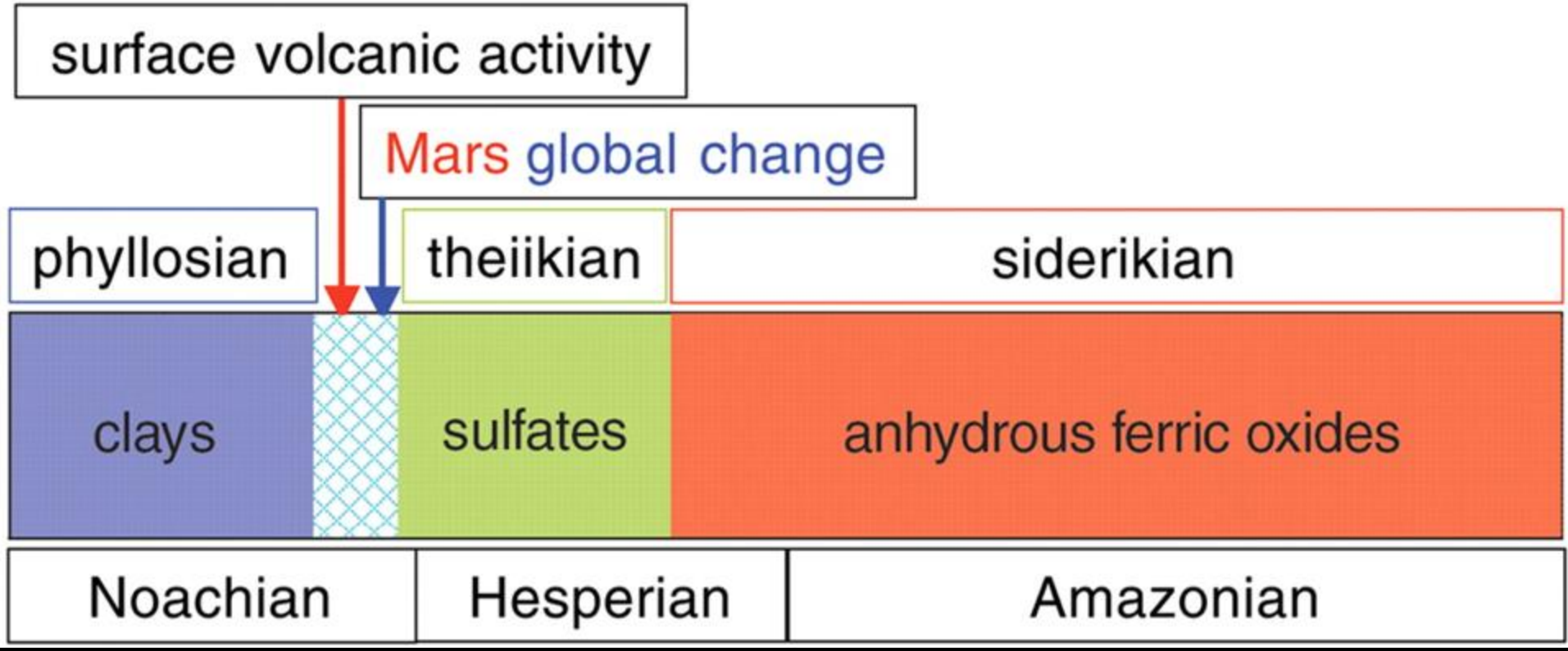
Pliocene Deltas, Caspian Sea, Azerbaijan

Gale is on the Dichotomy Boundary



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
- *But like all time scales is now in need of revision*

Toward a Global Stratigraphy For Mars

(Grotzinger and Milliken, SEPM, 2012)