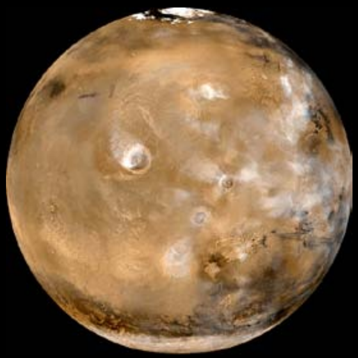
Mars Exploration Rover Mission
Observations & Implications

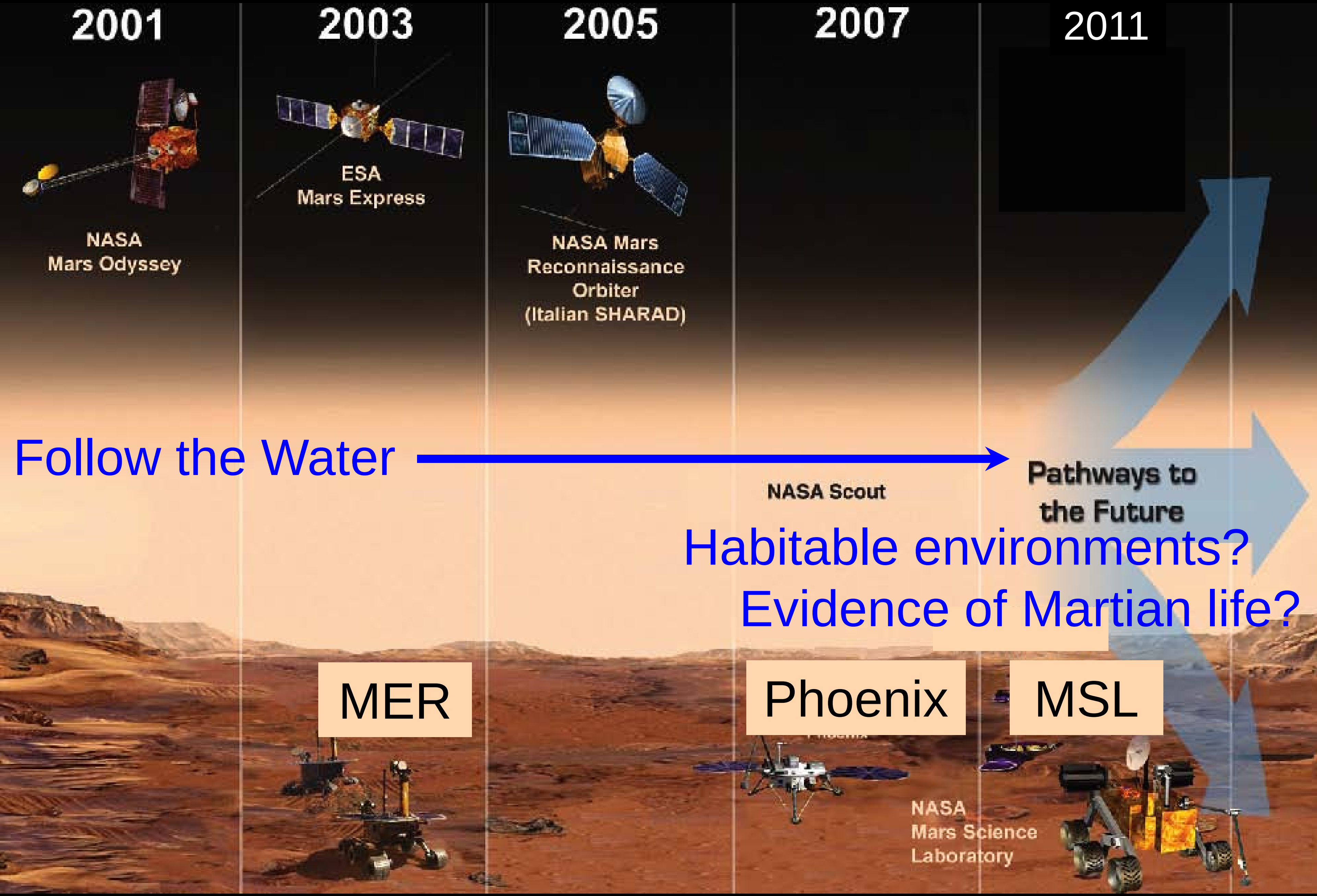


Mars today

Early Mars ?

David J. Des Marais
NASA Ames Research Center

and the MER Athena & Engineering teams


2001
2003
2005
2007
2011
NASA
Mars Odyssey
ESA
Mars Express
NASA Mars
Reconnaissance
Orbiter
(Italian SHARAD)
Follow the Water
NASA Scout
Pathways to
the Future
Habitable environments?
Evidence of Martian life?
MER
Phoenix
MSL
NASA
Mars Science
Laboratory

Conditions That Could Sustain Life on Mars: Changes Over the Eons

The Athena Science Payload

Remote Sensing Package

Pancam Mast Assembly (PMA)
Pancam
Mini-TES

In-Situ Package

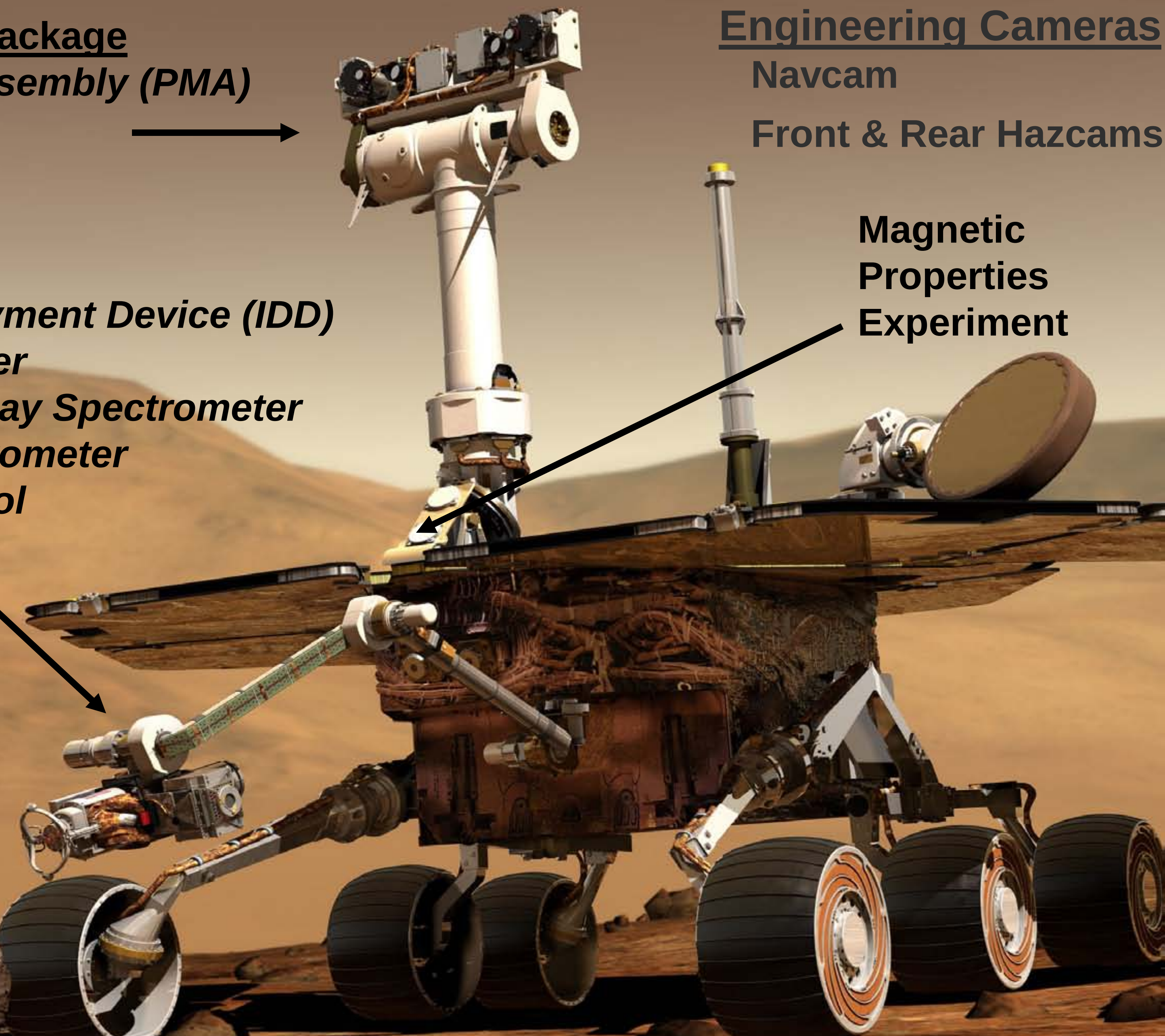
Instrument Deployment Device (IDD)
Microscopic Imager
Alpha Particle X-Ray Spectrometer
Mössbauer Spectrometer
Rock Abrasion Tool

Engineering Cameras

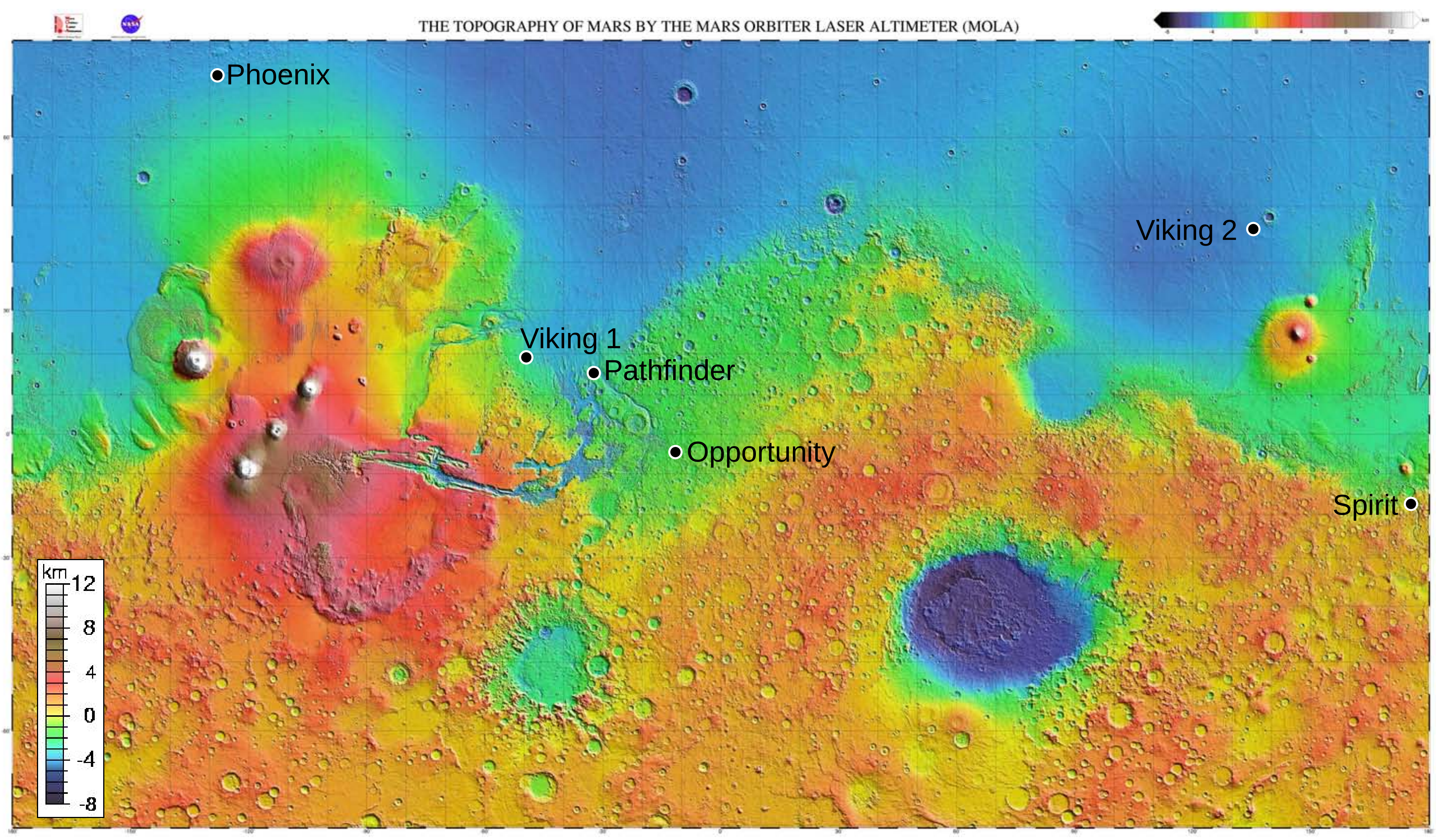
Navcam

Front & Rear Hazcams

Magnetic Properties Experiment



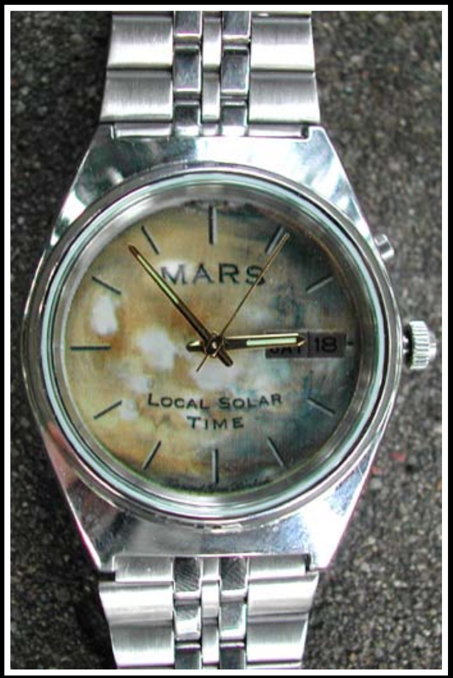
Mars Global Surveyor



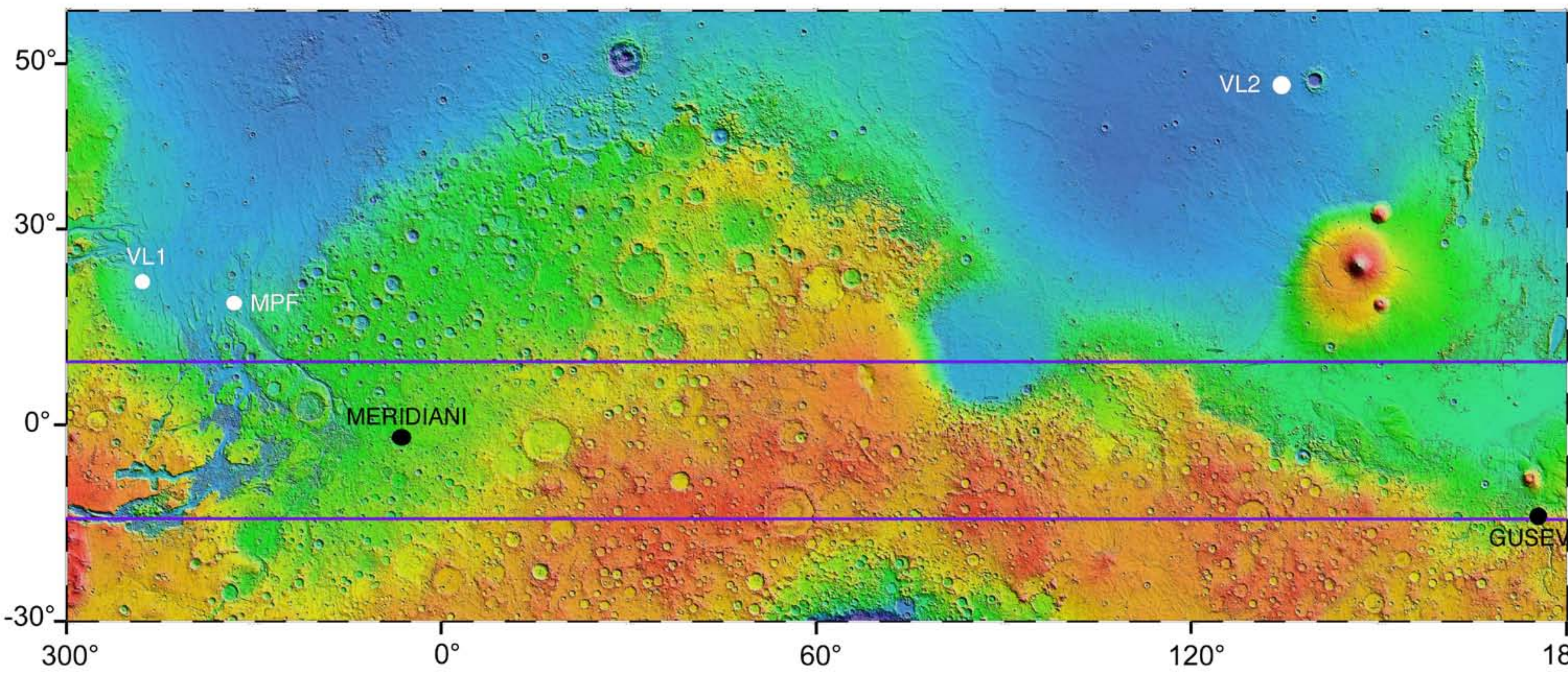

TOUCHDOWN!!
ALTITUDE
RADIUS
SPEED
GUSEV LOCAL TIME
LATITUDE
LONGITUDE
FLIGHT PATH ANGLE

MER Science Operations Working Group

MER Tactical Activity Cycle

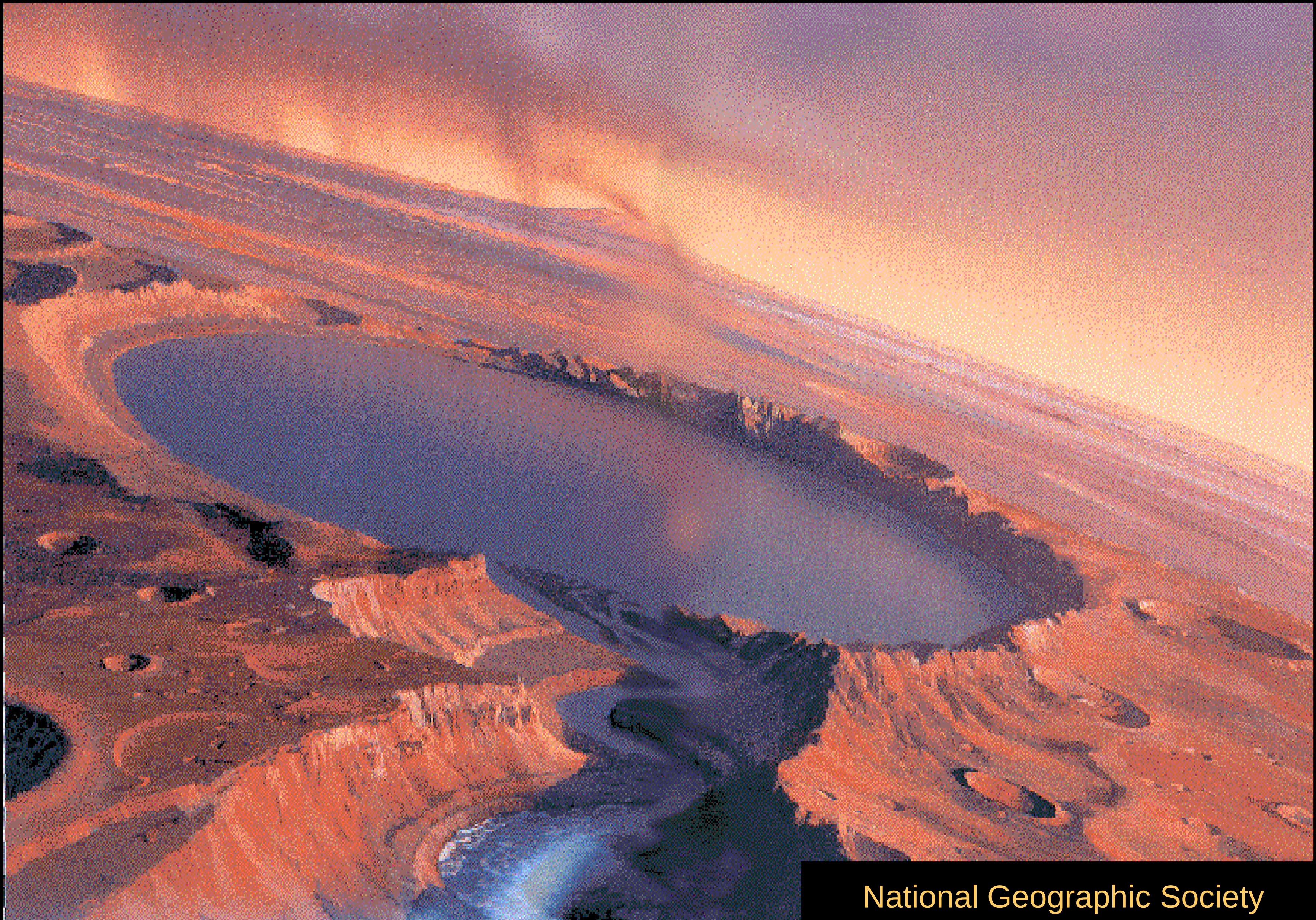


MER Landing Sites

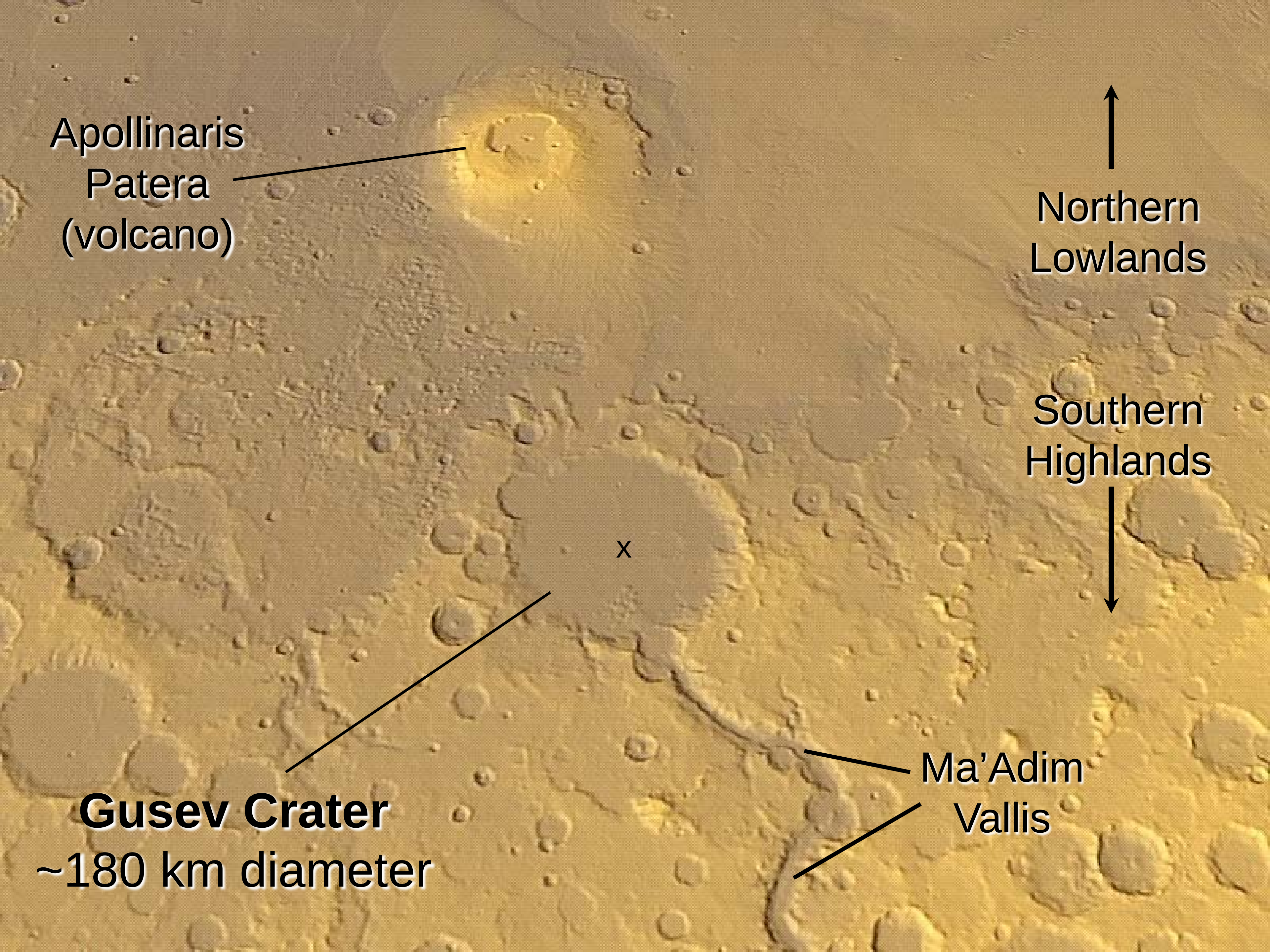


Landforms indicate that Gusev crater once harbored a lake

Note Apollinaris Patera volcano on the horizon



National Geographic Society

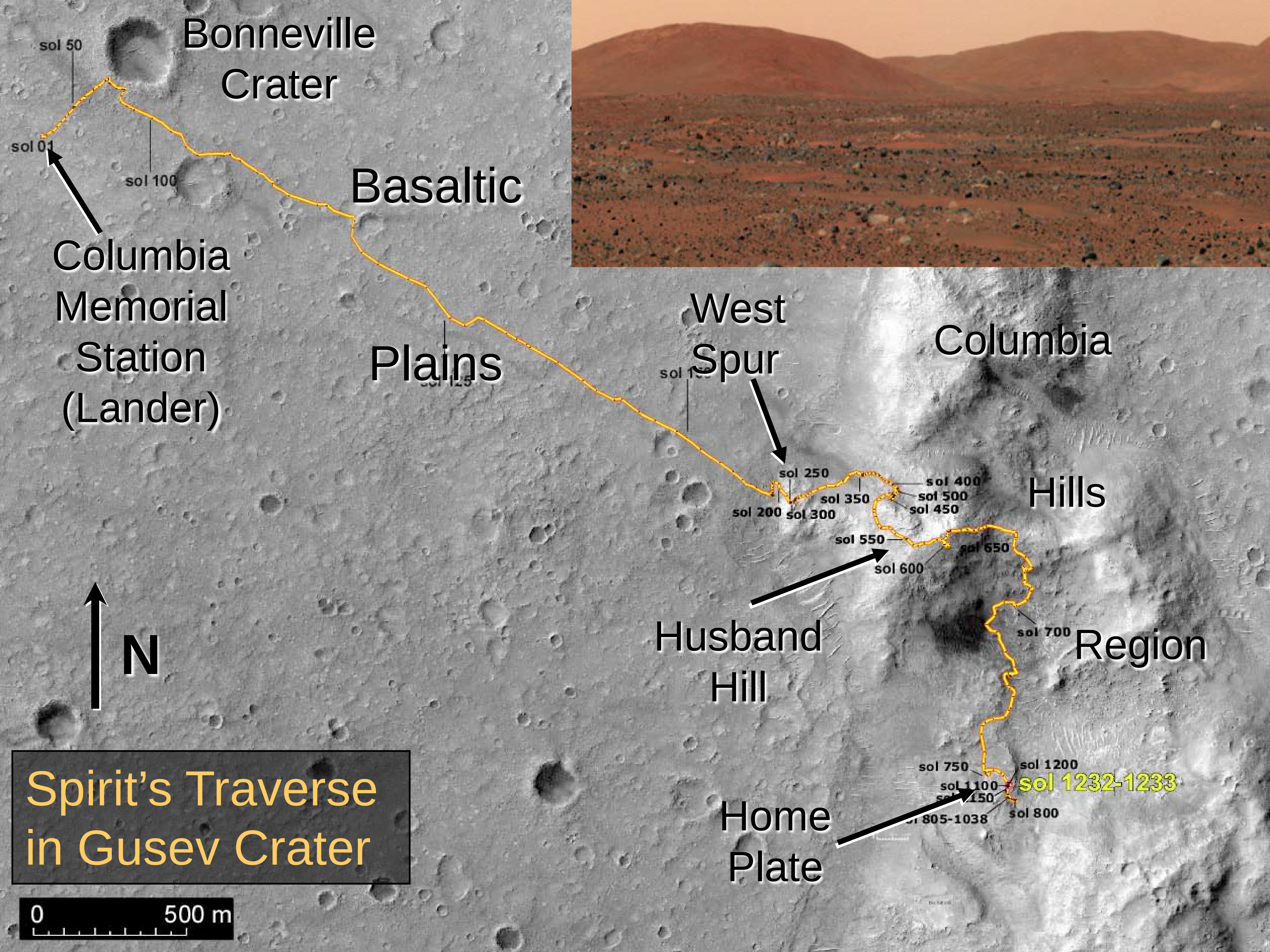

Apollinaris Patera (volcano)
Northern Lowlands
Southern Highlands
x
Ma'Adim Vallis
Gusev Crater
~180 km diameter

Sol
A004


View to southeast from Columbia Memorial Station


Sol A568
0000

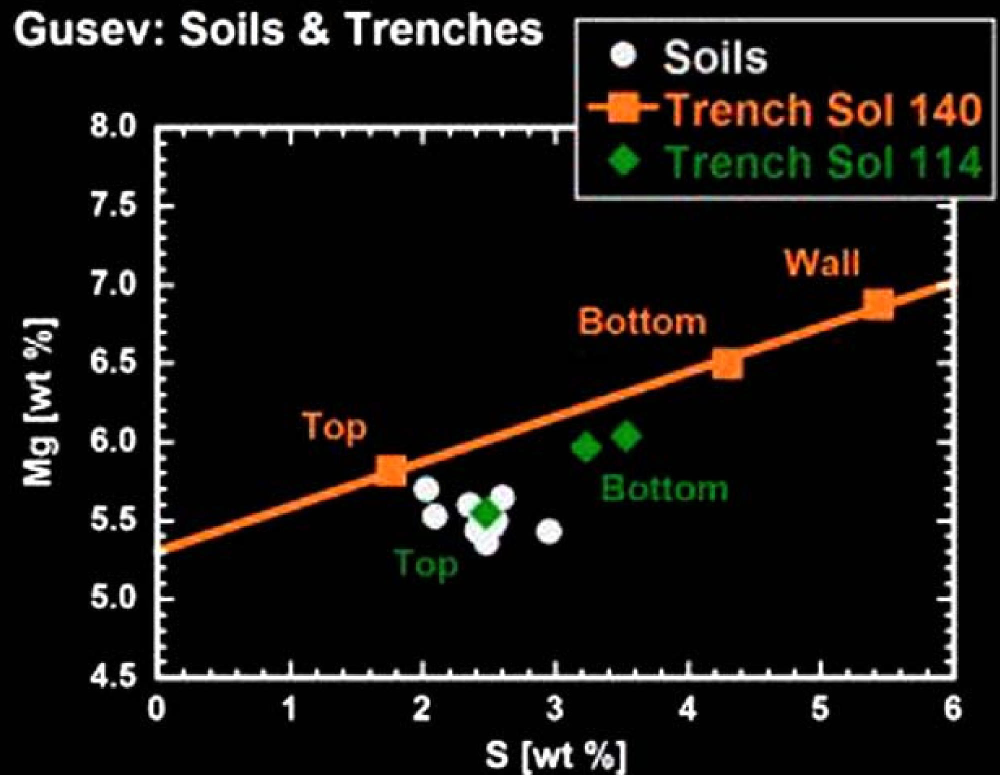
Bonneville crater, basaltic plains, Gusev crater



Bonneville Crater
sol 50
sol 01
sol 100
Columbia Memorial Station (Lander)
Basaltic Plains
West Spur
Columbia Hills Region
sol 250
sol 200
sol 300
sol 350
sol 400
sol 500
sol 450
sol 550
sol 600
sol 650
sol 700
Husband Hill
sol 750
sol 1200
sol 1232-1233
sol 1100
sol 800
Home Plate
N
Spirit's Traverse in Gusev Crater
0 500 m

The Boroughs Trench

Sol 140

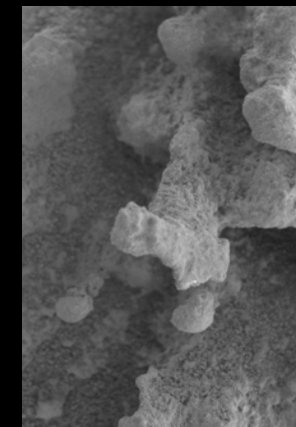


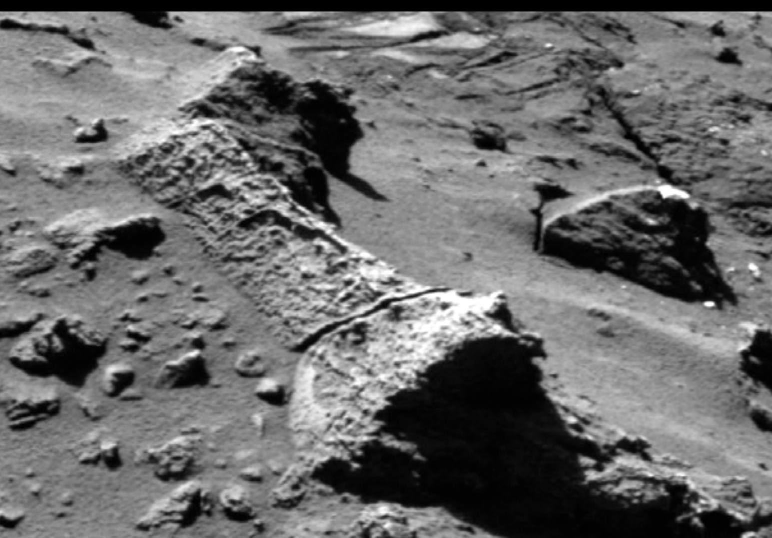
Local enrichment of Mg and S
Local low Cl / S values
Aqueous mobilization of solubles (>10^6 yr BP?)

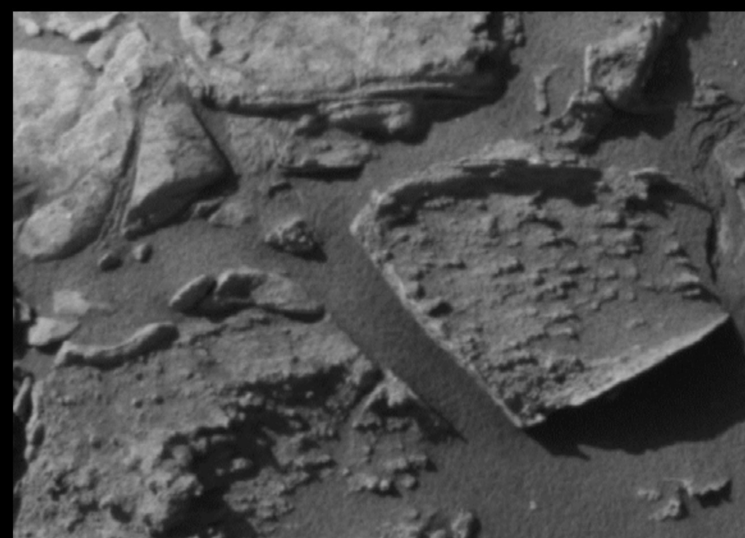
Rock Weathering Stages, Gusev Crater

isochemical weathering

Columbia Hills
Gusev crater





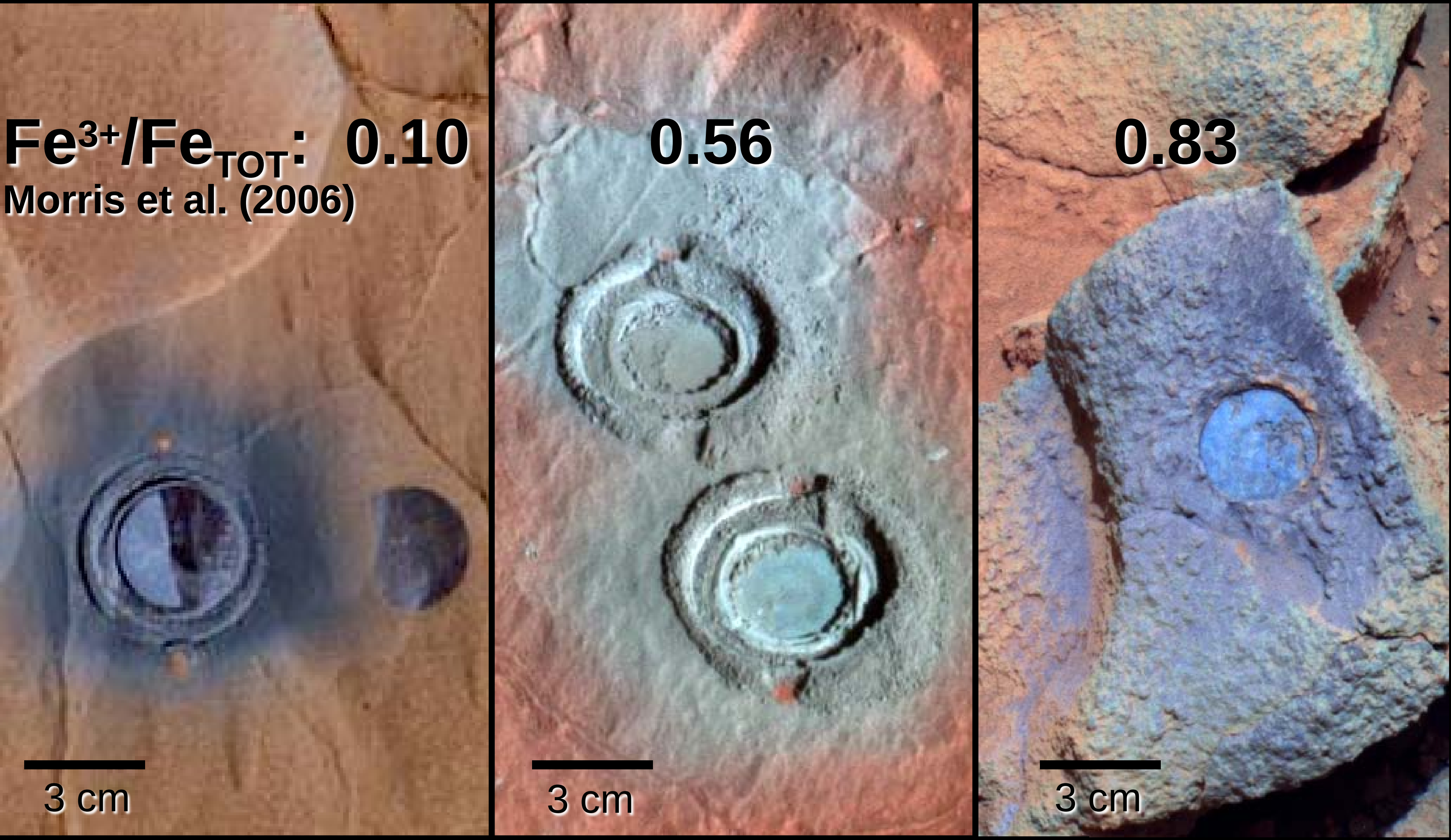


Mars Hill
Death Valley

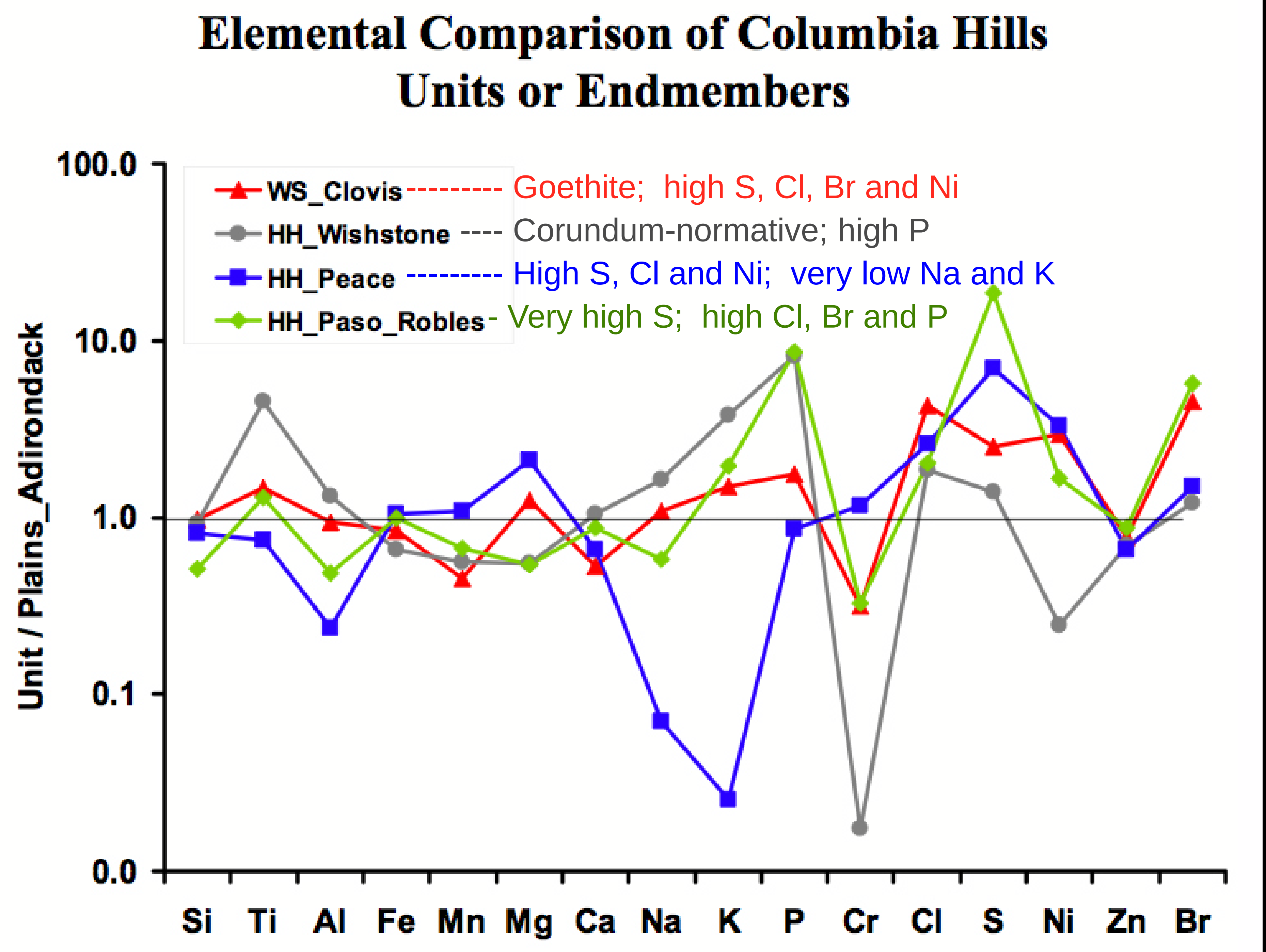
Jim Rice (2005)

Spirit Rover on Cumberland Ridge, Husband Hill

Husband Hill: evidence of aqueous iron oxidation

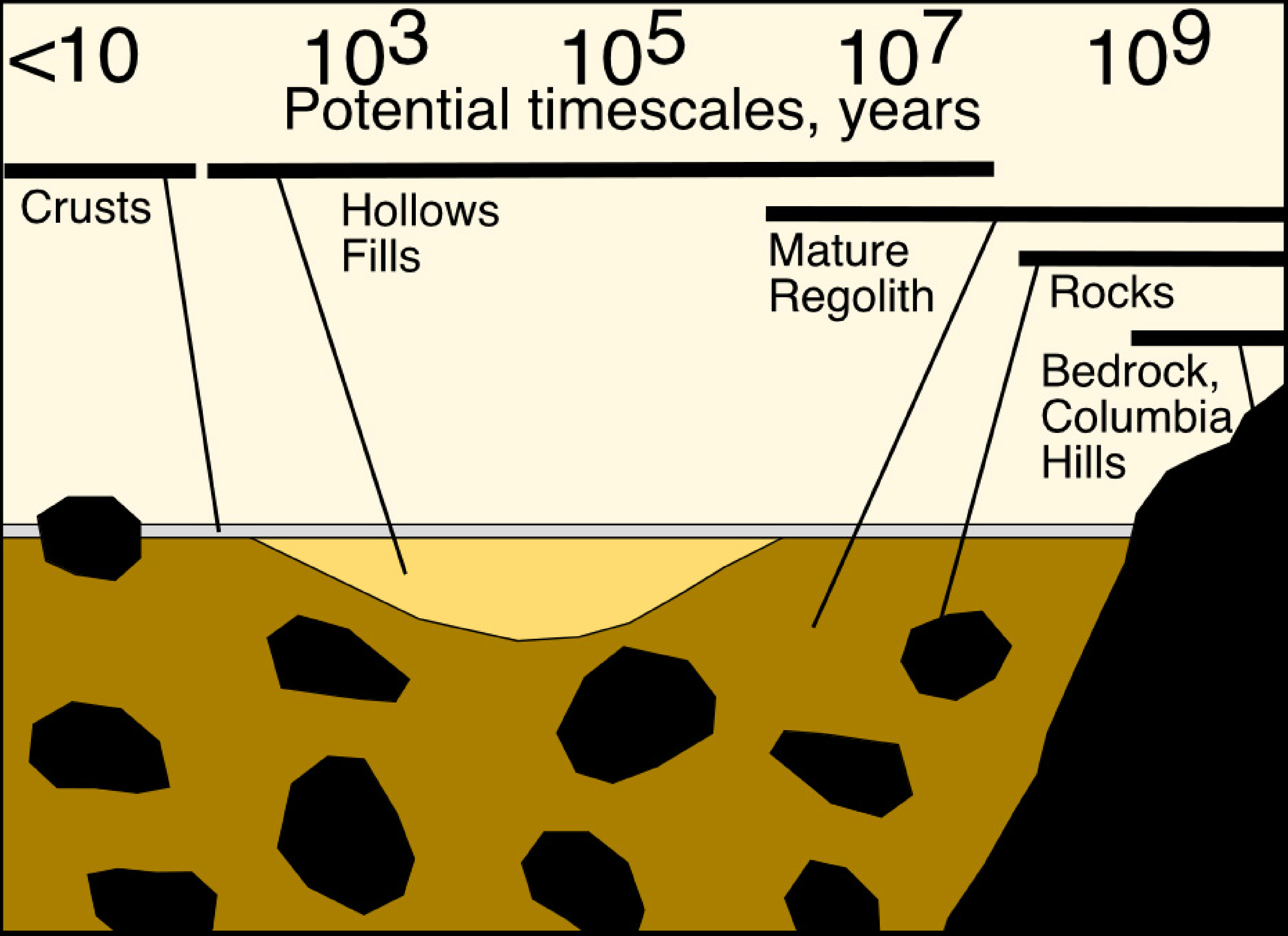


Mazatzal basalt, plains Wooly Patch, West Spur Watchtower, Husband Hill



Elemental Comparison of Columbia Hills
Units or Endmembers
WS_Clovis --------- Goethite; high S, Cl, Br and Ni
HH_Wishstone ---- Corundum-normative; high P
HH_Peace --------- High S, Cl and Ni; very low Na and K
HH_Paso_Robles - Very high S; high Cl, Br and P
Unit / Plains_Adirondack
100.0
10.0
1.0
0.1
0.0
Si
Ti
Al
Fe
Mn
Mg
Ca
Na
K
P
Cr
Cl
S
Ni
Zn
Br

Gusev Crater Materials



Indicators of Liquid Water in the Past

Low availability

Plains

Fresh volcanic rocks largely unaltered by water

Soil horizons with insoluble minerals uniformly mixed with soluble salts

Soil profiles indicating vertically-migrated soluble salts

Rock surfaces, cracks and vugs showing alteration

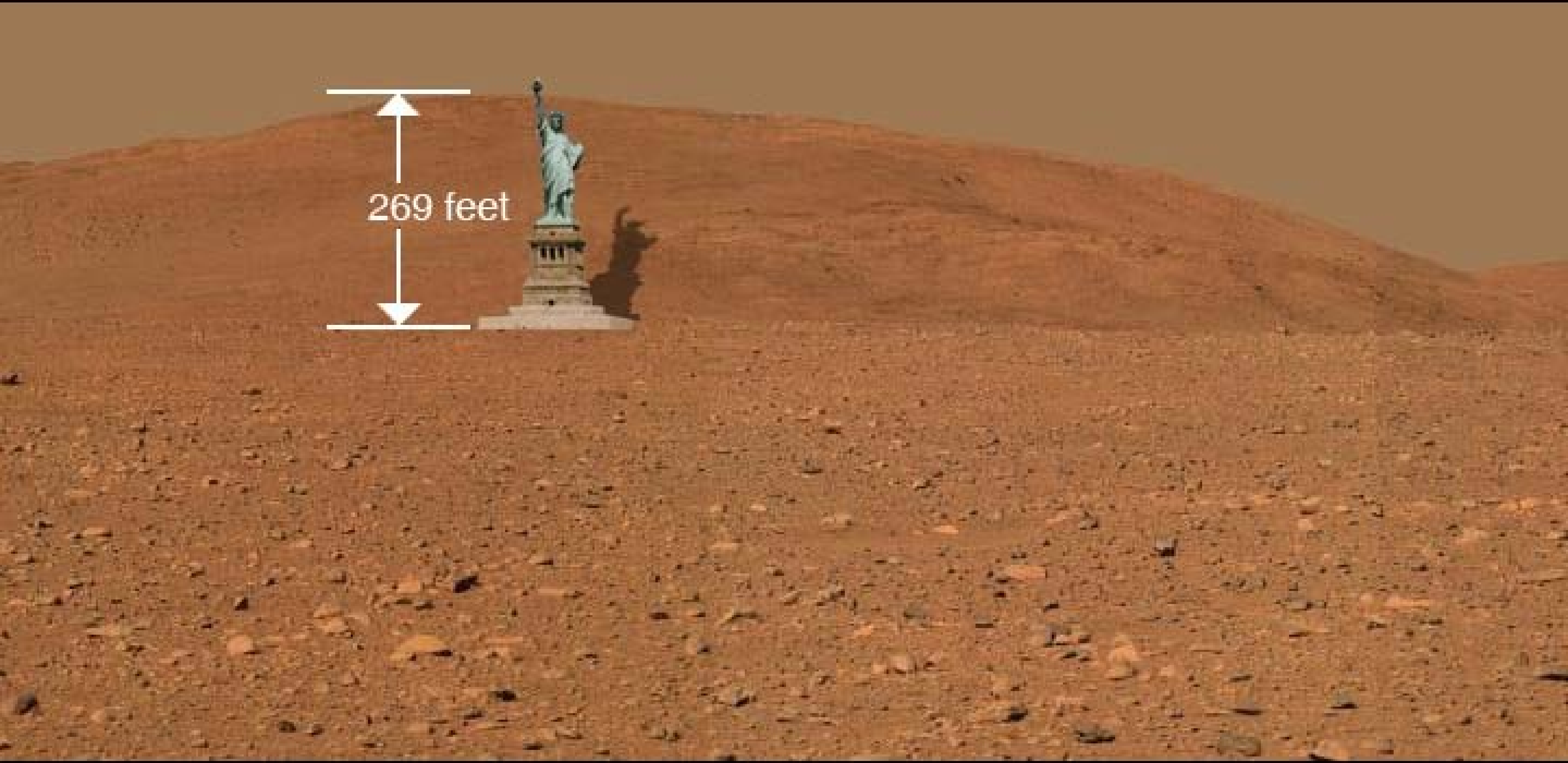
Soil profiles showing weathering *in situ*

Rocks largely altered to weathering products but retaining near-original elemental abundances

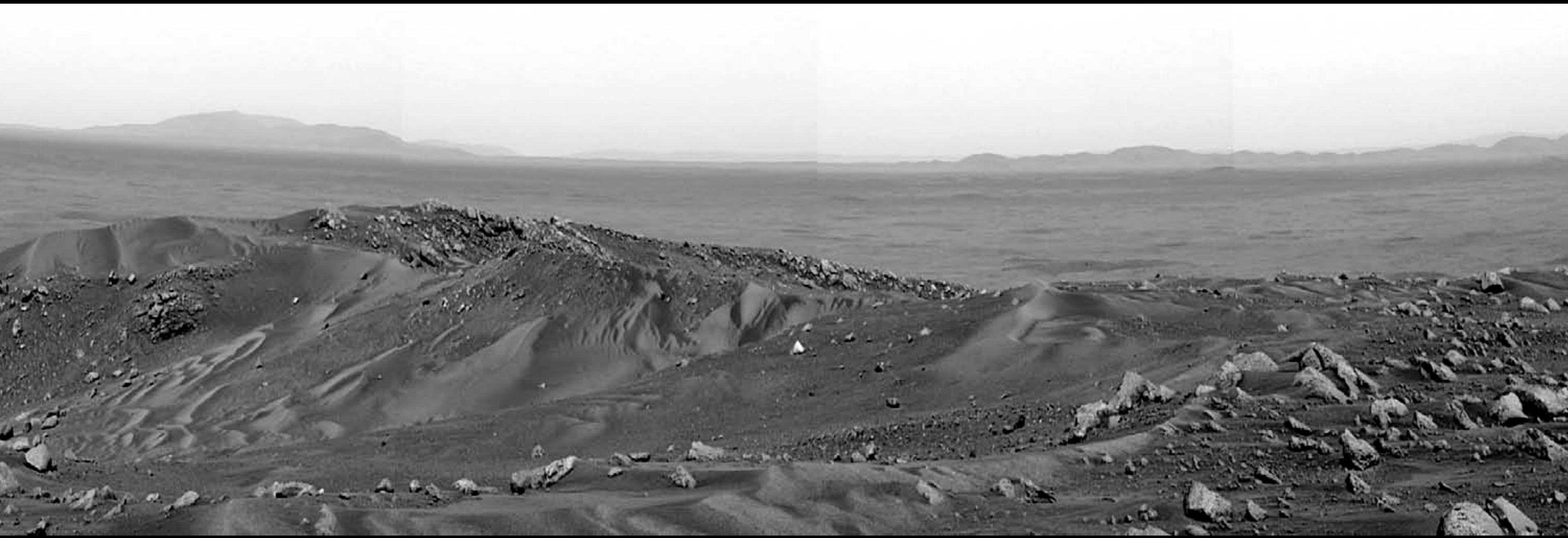
Rocks or soils indicating extensive alteration and transport of components by liquid water

High availability

Husband Hill
Inner Basin



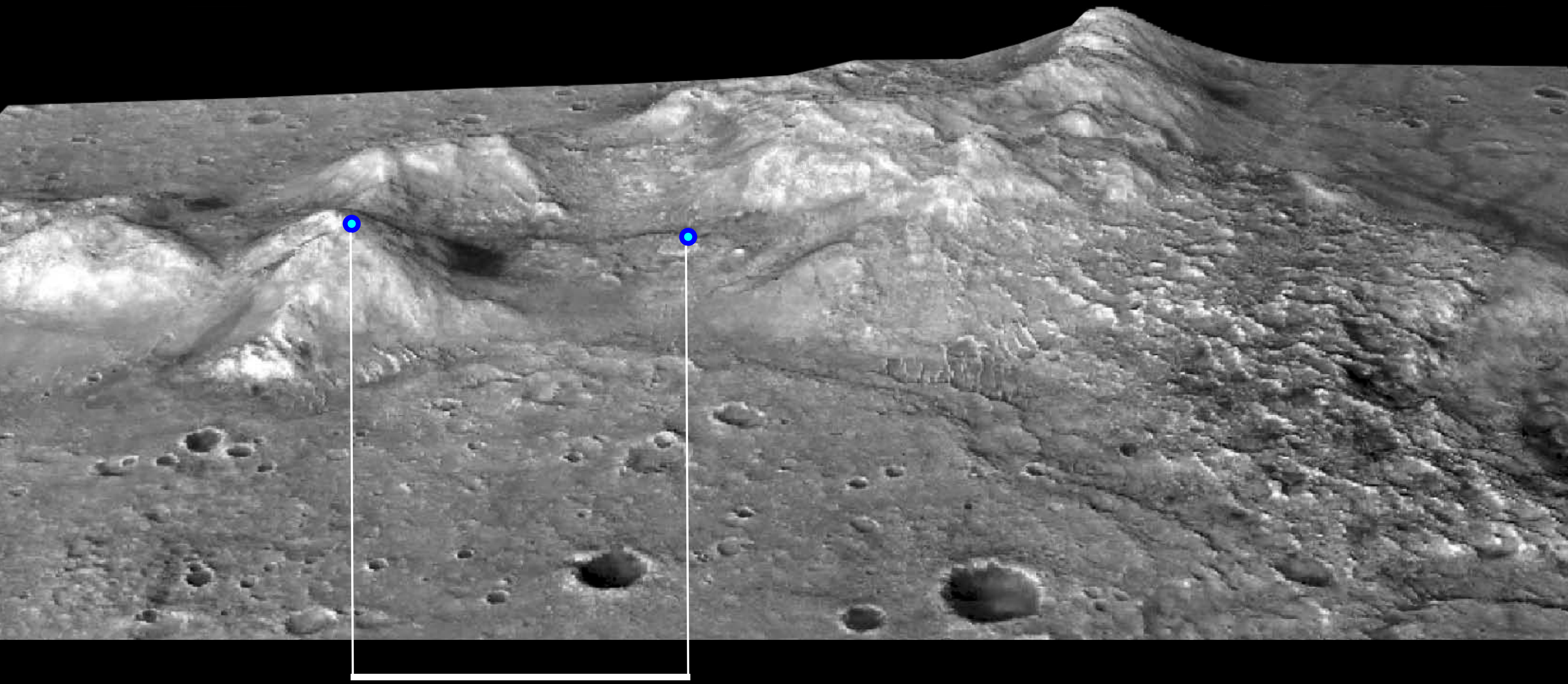
Husband Hill, Gusev Crater

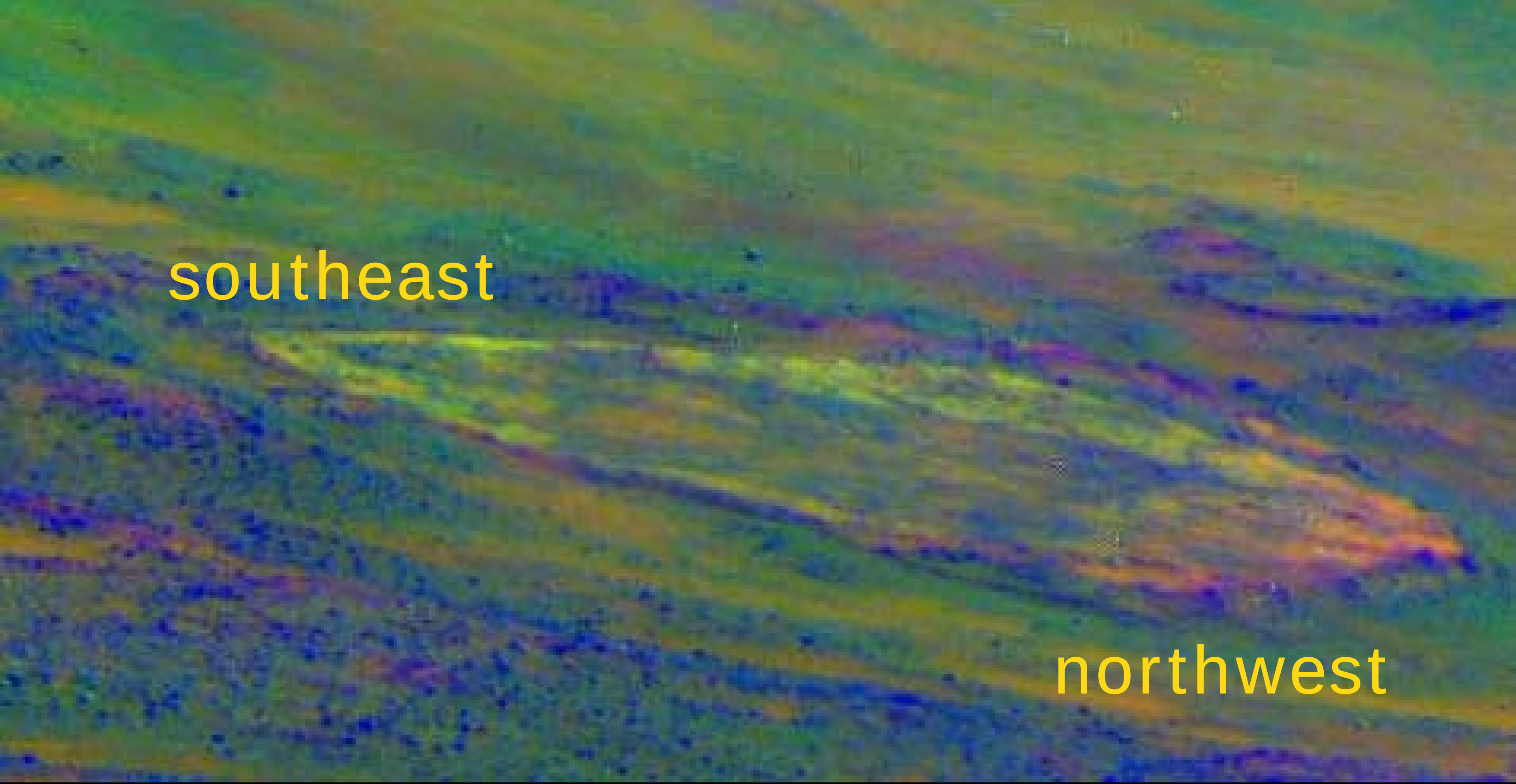


“Top of the World”
Husband Hill summit, view to East
Sol 581

Columbia Hills viewed from the west

(MRO HiRISE stereo images)

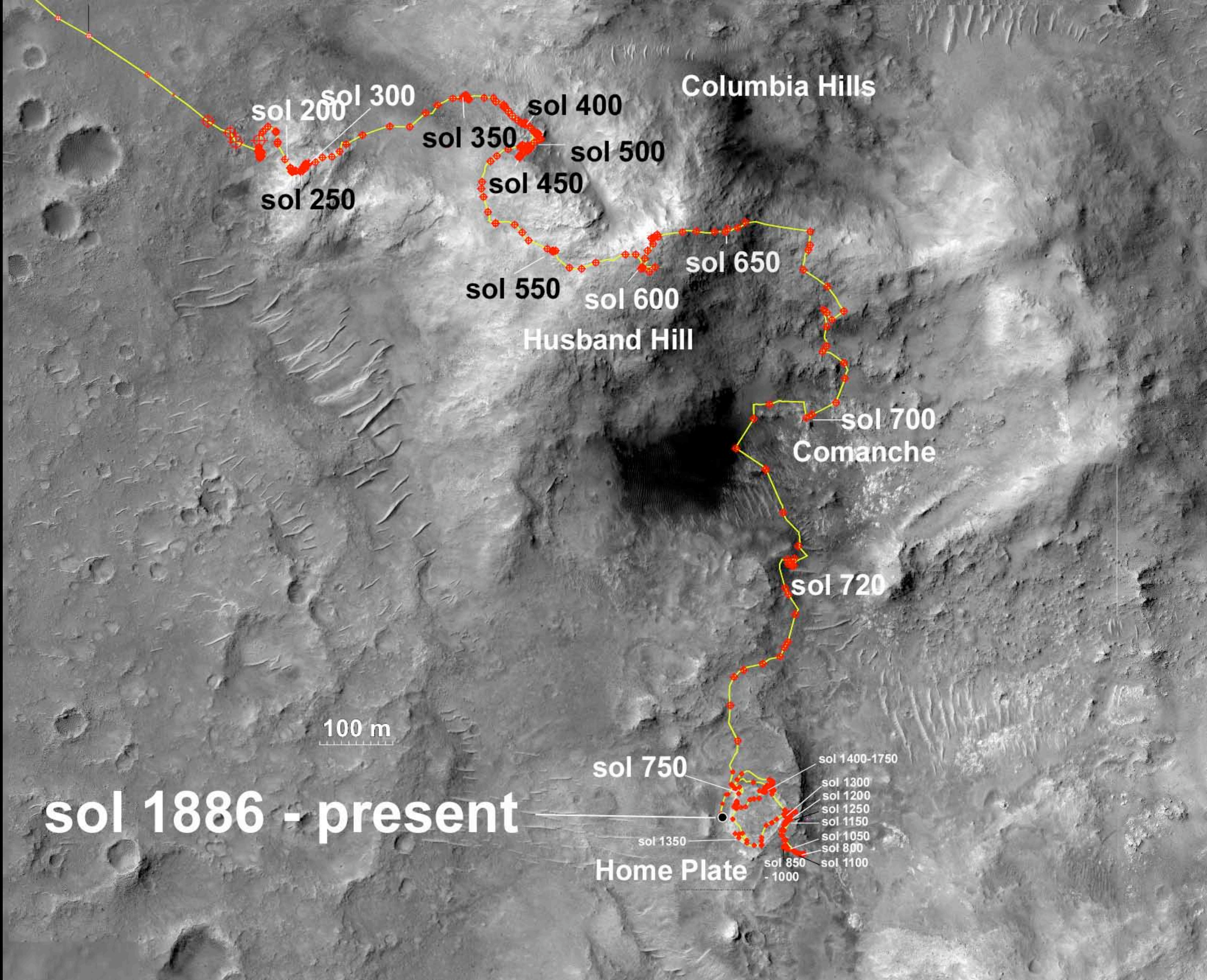


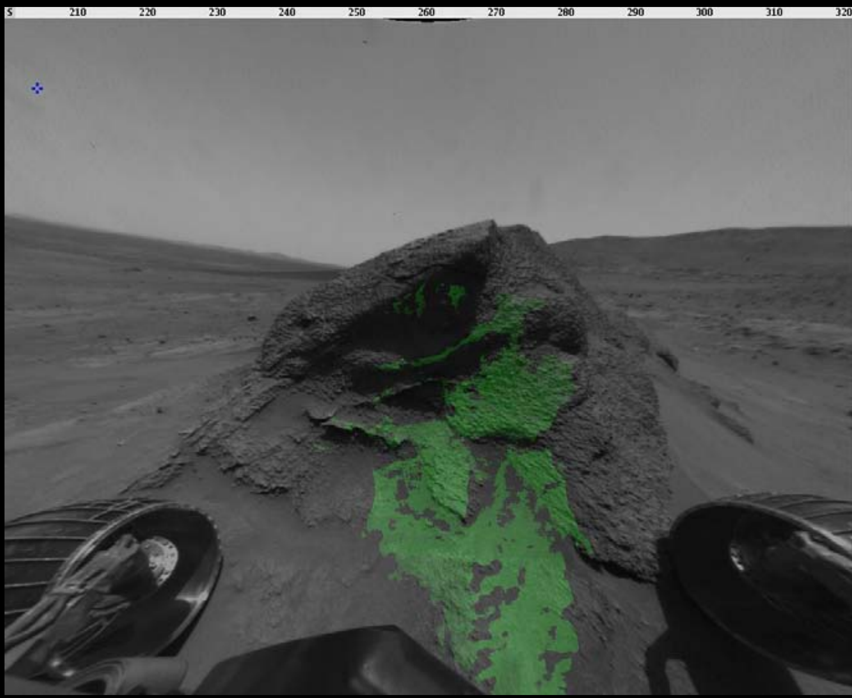


Home Plate

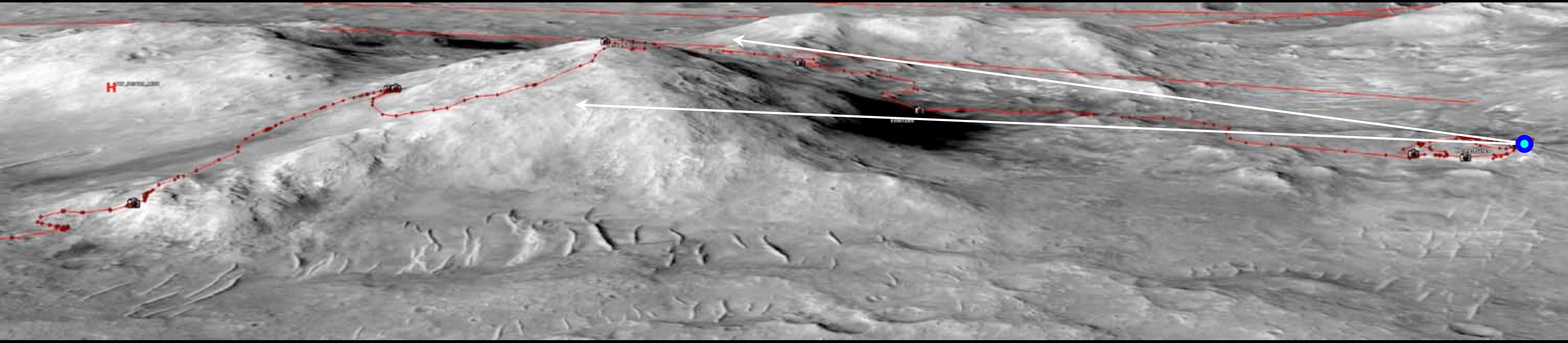
90 m diameter, ~1 to 2 m height

View looking south from Husband Hill summit
Spirit Pancam vis/NIR false color image


Columbia Hills
sol 200
sol 300
sol 400
sol 350
sol 500
sol 450
sol 250
sol 650
sol 550
sol 600
Husband Hill
sol 700
Comanche
sol 720
100 m
sol 750
sol 1400-1750
sol 1300
sol 1200
sol 1250
sol 1150
sol 1050
sol 800
sol 1100
sol 1886 - present
sol 1350
Home Plate
sol 850
- 1000



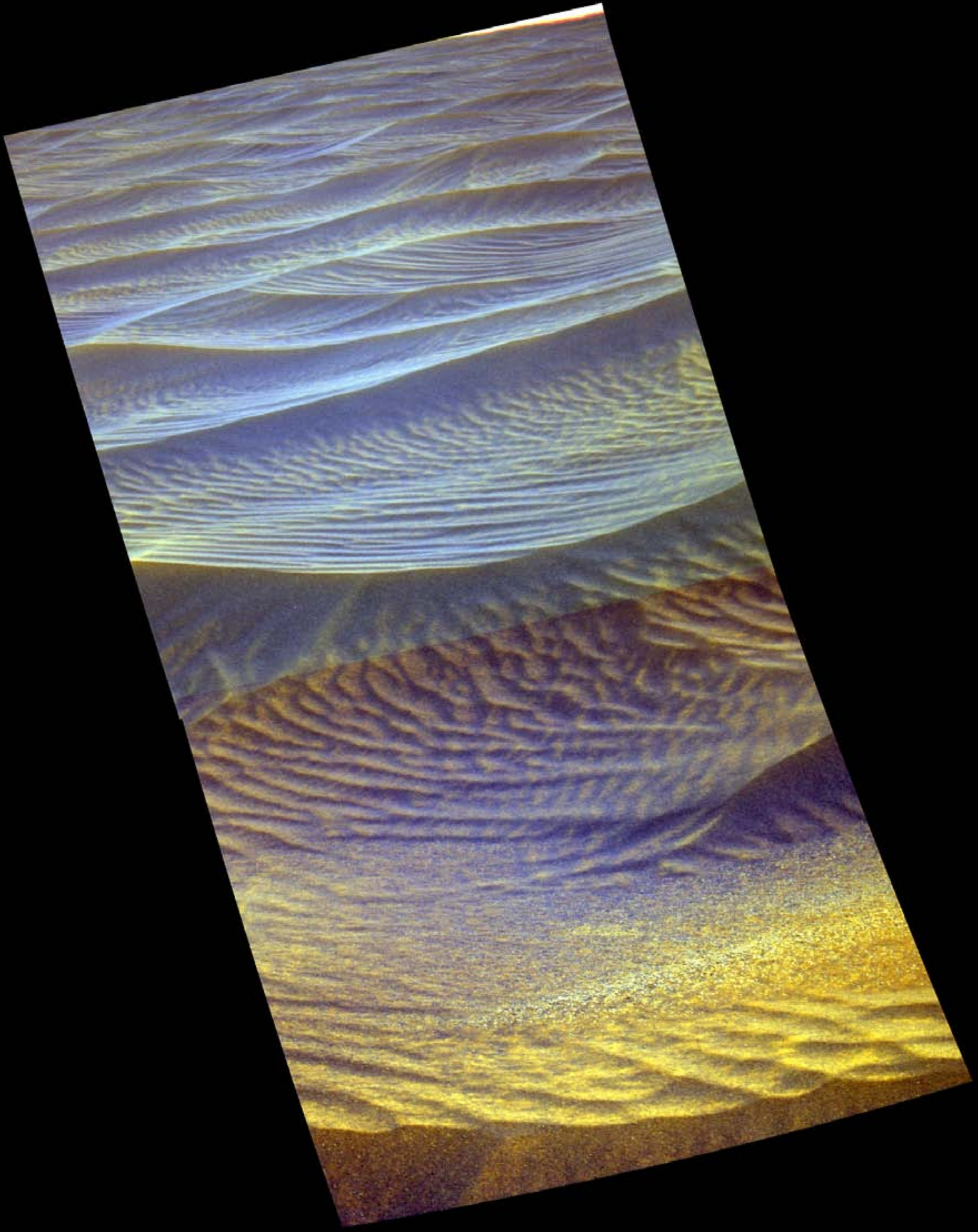
Comanche outcrop



Orbiter view
(MRO HiRISE)

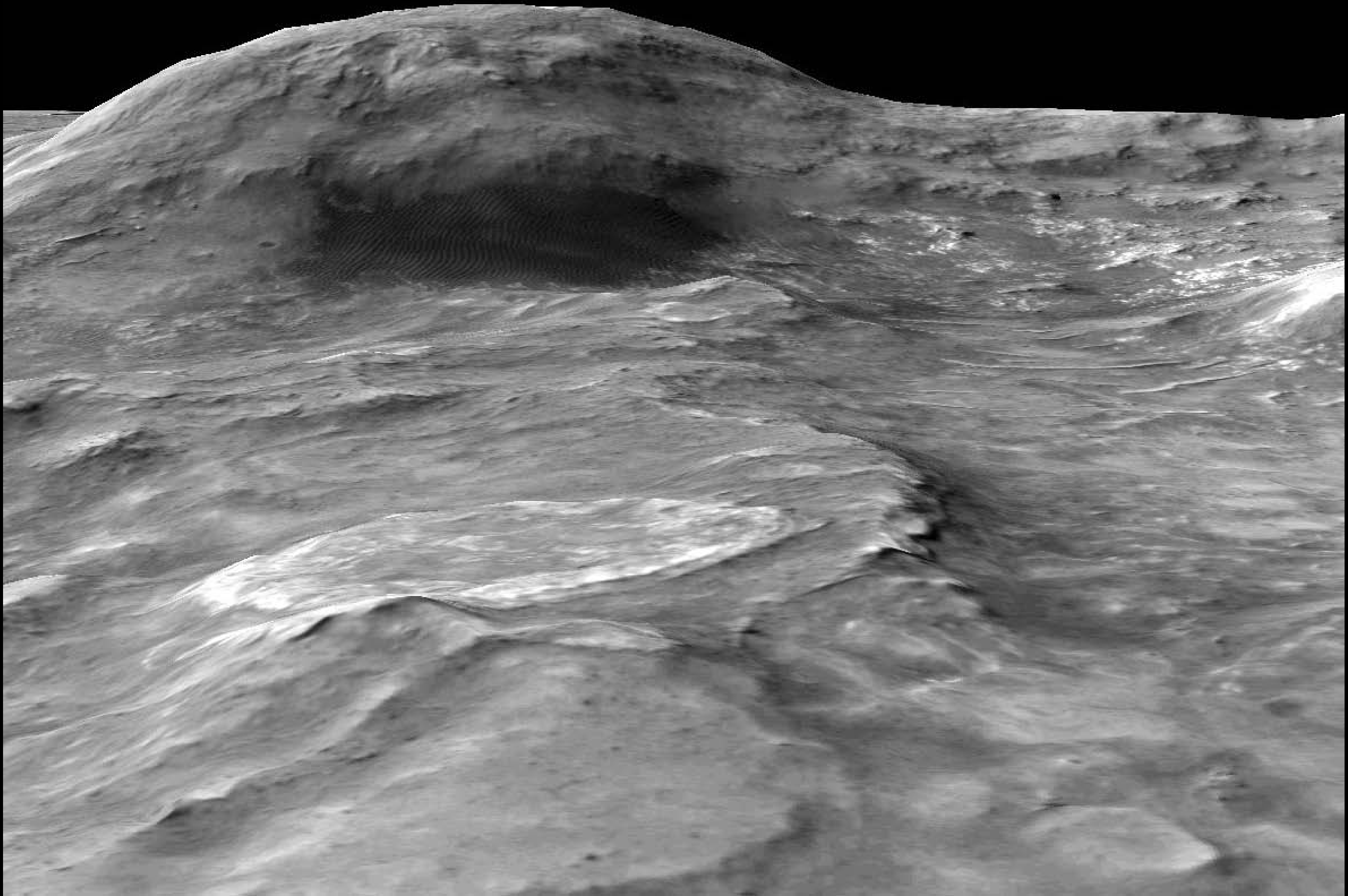
Husband Hill and Inner Basin

ground view
(MER Pancam)



El Dorado

MRO HiRISE, Looking North



Inner Basin volcanism and hydrothermal activity

Orcadas, vesicular basalt

Tyrone

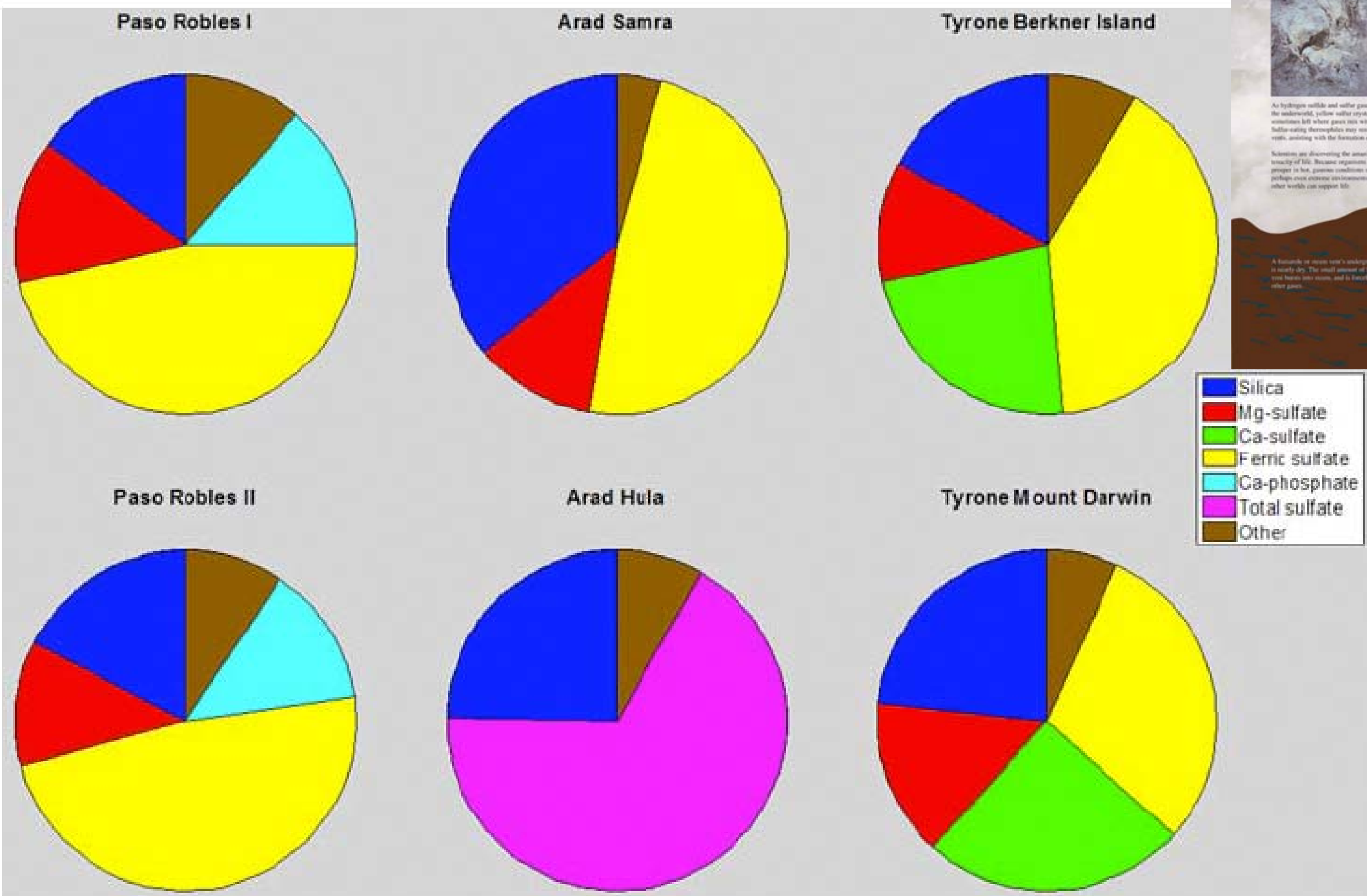
Arad

aqueous deposits rich in Fe, Mg and S

Sulfur-rich light-toned soils

A. Yen et al., JGR (2008)

YEN ET AL.: HYDROTHERMAL PROCESSES AT GUSEV CRATER



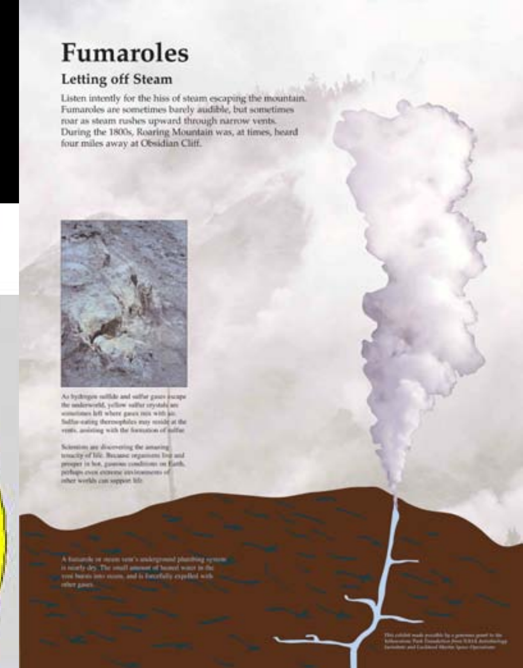


Figure 14. Derived compositions of the Paso Robles class samples after removal of basaltic soil contamination (based on Table 5). "Other" represents the remaining constituents after depicted phases and basaltic soil are removed. The available constraints on the Arad Hula sample prevent an accurate subdivision of the "total sulfate" wedge.

An integrated view of the chemistry and mineralogy of martian soils

The mineralogical and elemental compositions of the martian soil are indicators of chemical and physical weathering processes. Using data from the Mars Exploration Rovers, we show that bright dust deposits on opposite sides of the planet are part of a global unit and not dominated by the composition of local rocks. Dark soil deposits at both sites have similar basaltic mineralogies, and could reflect either a global component or the general similarity in the compositions of the rocks from which they were derived. Increased levels of bromine are consistent with mobilization of soluble salts by thin films of liquid water, but the presence of olivine in analysed soil samples indicates that the extent of aqueous alteration of soils has been limited. Nickel abundances are enhanced at the immediate surface and indicate that the upper few millimetres of soil could contain up to one per cent meteoritic material.

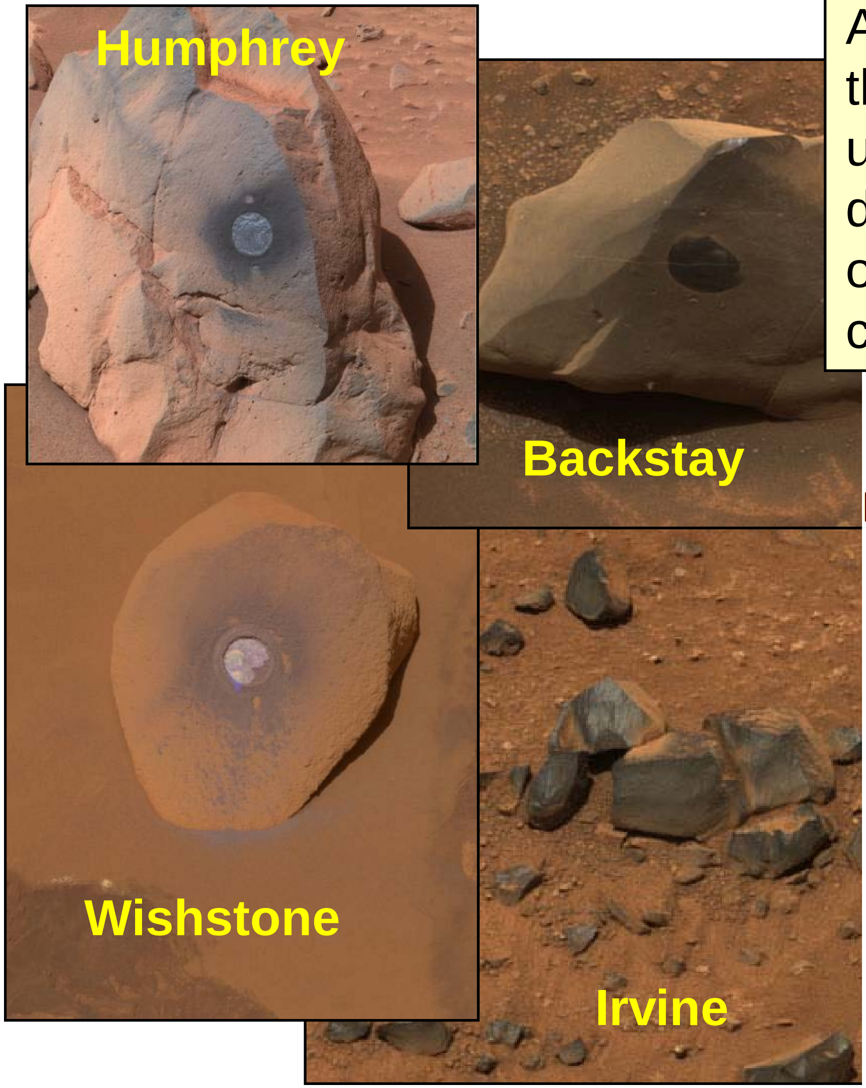
Table 1 | Endmember components of martian soils

Site	Soil component	Description	Figure	Representative APXS/Mössbauer Targets*	Sol(s)
Gusev crater	Bright dust	Global unit	1a	Gusev/First Soil	14
				Sugar Loaf Flats/Soil 1	65
				Deserts/Gobi 1	68-71
				Truckin Flats/Accelerator	126
	Dark soil	Similar to dark soil at Meridiani	1b	Bear Paw/Panda New	73-74
				Santa Anita/Seattle Slew	135
				Shredded/Dark 4	158
	Bedform armour	Abundant magnetite	1c	Arena/Crest	41
				Angel Flats/Halo 01	45
	Lithic fragments	Abundant magnetite	1d	Ramp Flats/Soil 1	44
				Wrinkle/Ridge 1 (Mössbauer only)	54
Meridiani Planum	Bright dust	Global unit	1e	Mont Blanc/Les Hauches (surface)	59-60
				Hilltop/McDonnell (surface)	123
				Big Dig/Hema Trench 1 (subsurface)	24-25
				PhotoTIDD/Nougat (subsurface)	89-90
	Dark soil	Similar to dark soil at Gusev	1f	Millstone/Dahlia	165-167
				Auk/Auk RAT	237-238
	Spherules	Haematite concretions	1g	Dog Park/Jack Russell	80
				PhotoTIDD/Fred Ripple	91
	Clasts (mostly angular/vesiculated)	Possibly basaltic	1h	Not yet analysed	-

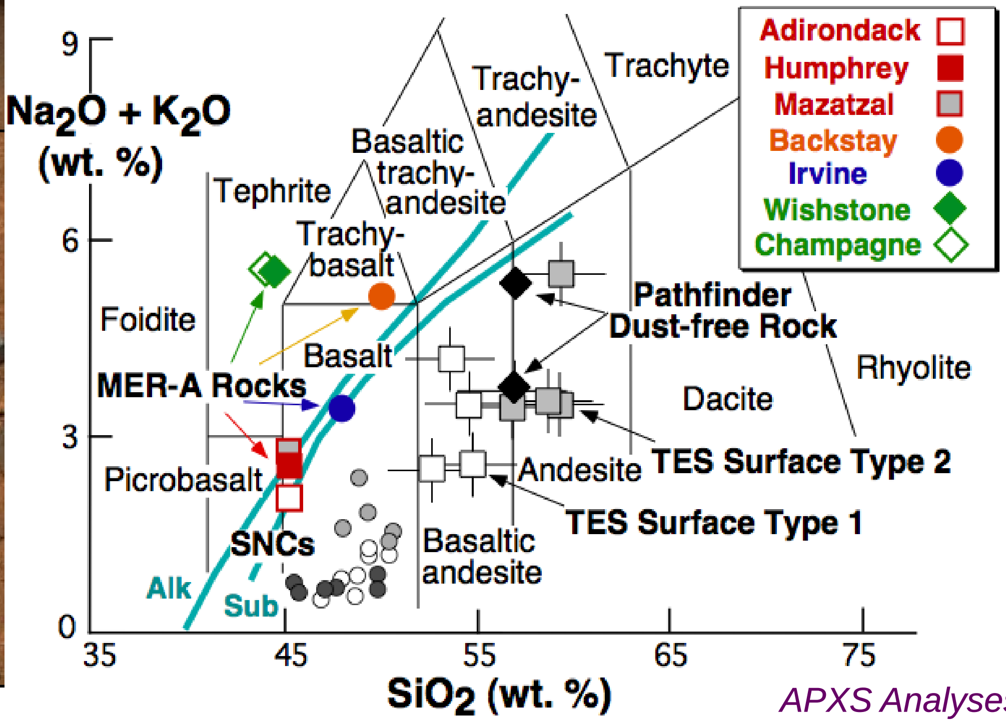
*MER APXS data used in analyses are tabulated in Supplementary Tables A, B and C.

A. Yen et al., Nature (2005)

Sample Types: Igneous Rocks



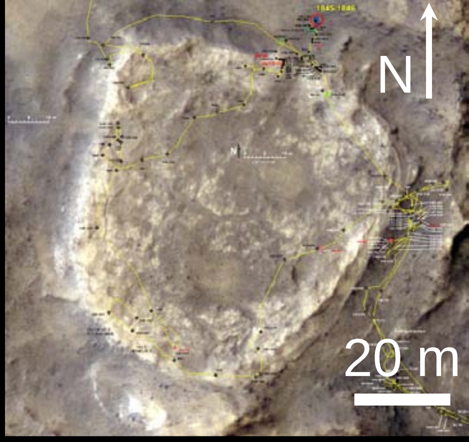
Analysis of this suite of rocks shows that they are alkaline volcanics, which formed under different conditions or from a very different starting composition than the bulk of martian rocks. This sheds light on the complexity of the martian interior.



Images courtesy Hap McSween

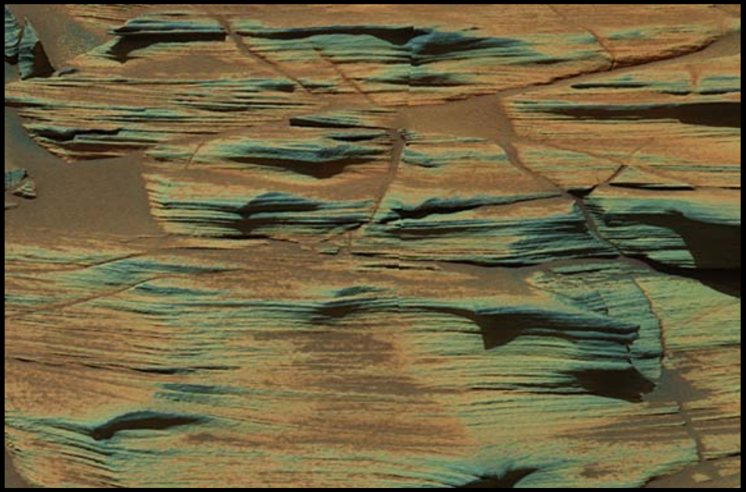
APXS Analyses (Gellert et al., 2006)

Discoveries at Home Plate



Rock textures
pyroclastic, aeolian

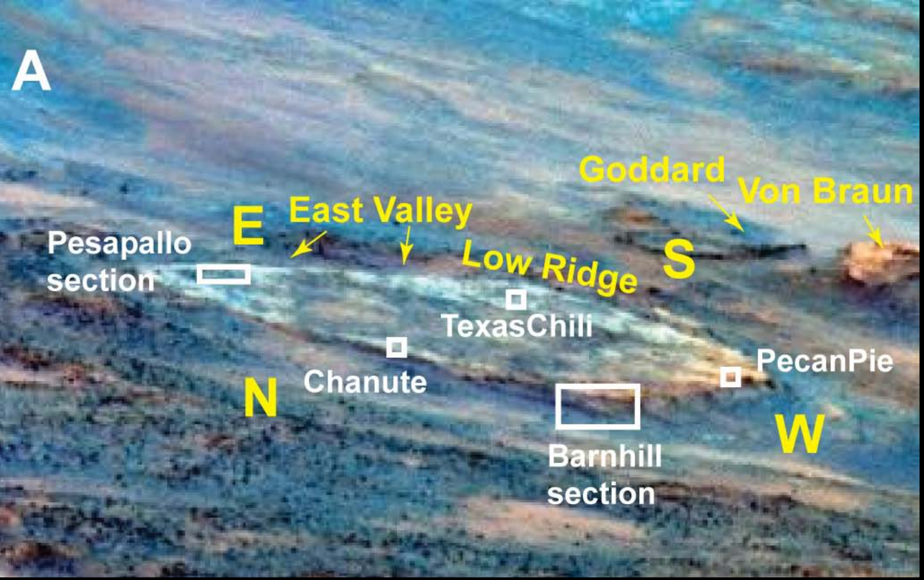
Elements
HIGH Na, Mg, Zn, Ge, Cl, and Br : hydrothermal brine

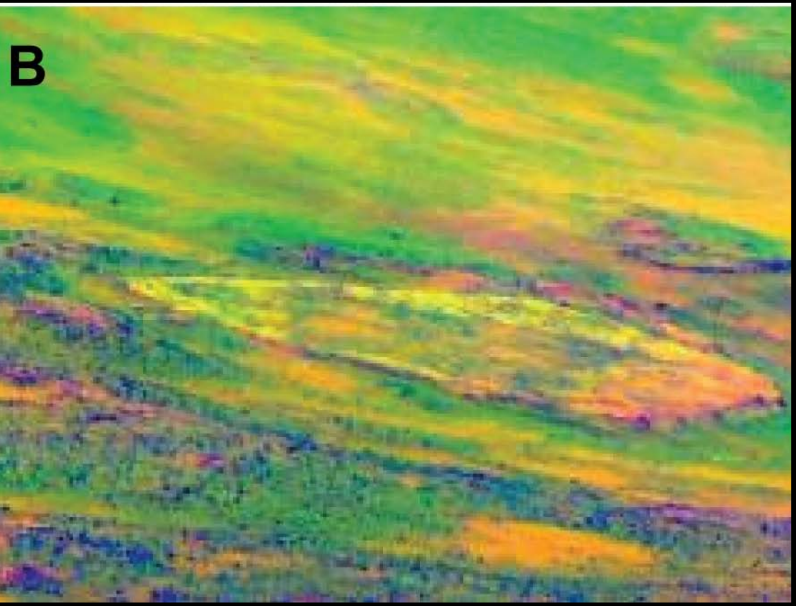


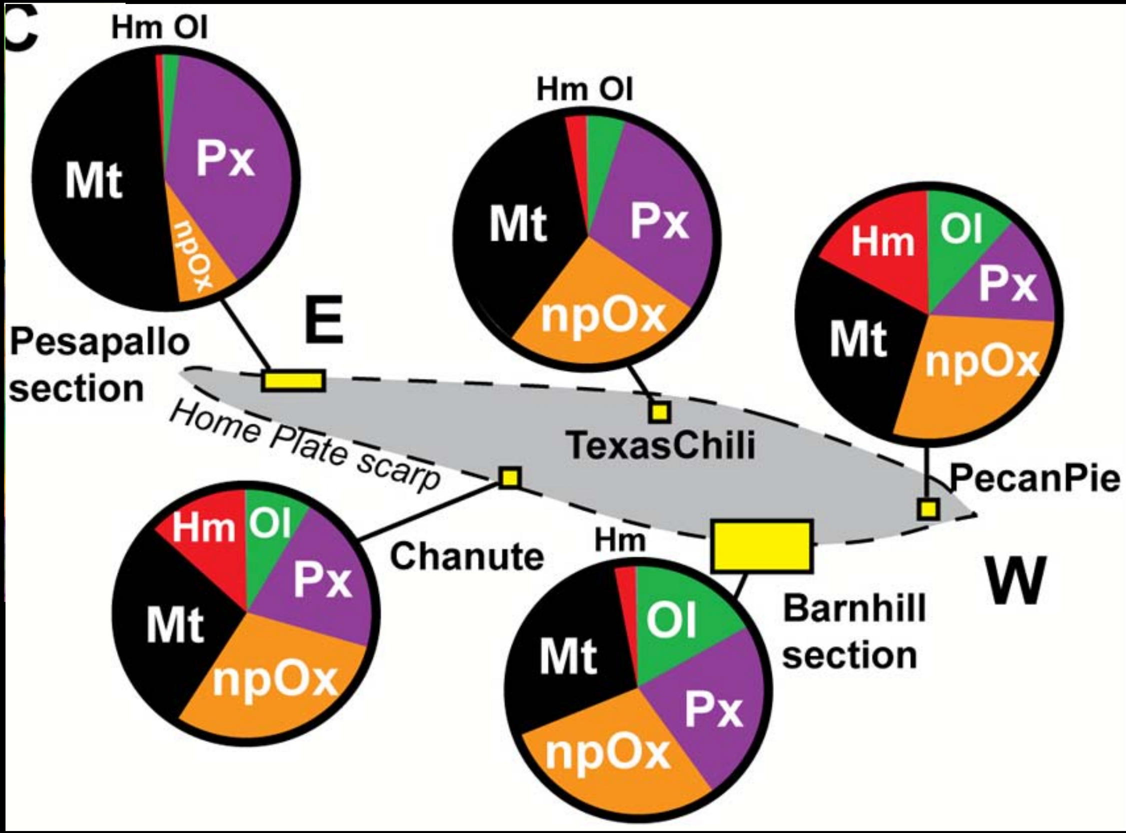
Reworked pyroclastic deposits

Spectral, Mineralogical, and Geochemical Variations Across Home Plate, Gusev Crater, Mars Indicate High and Low Temperature Alteration

M. Schmidt, et al. (2009)



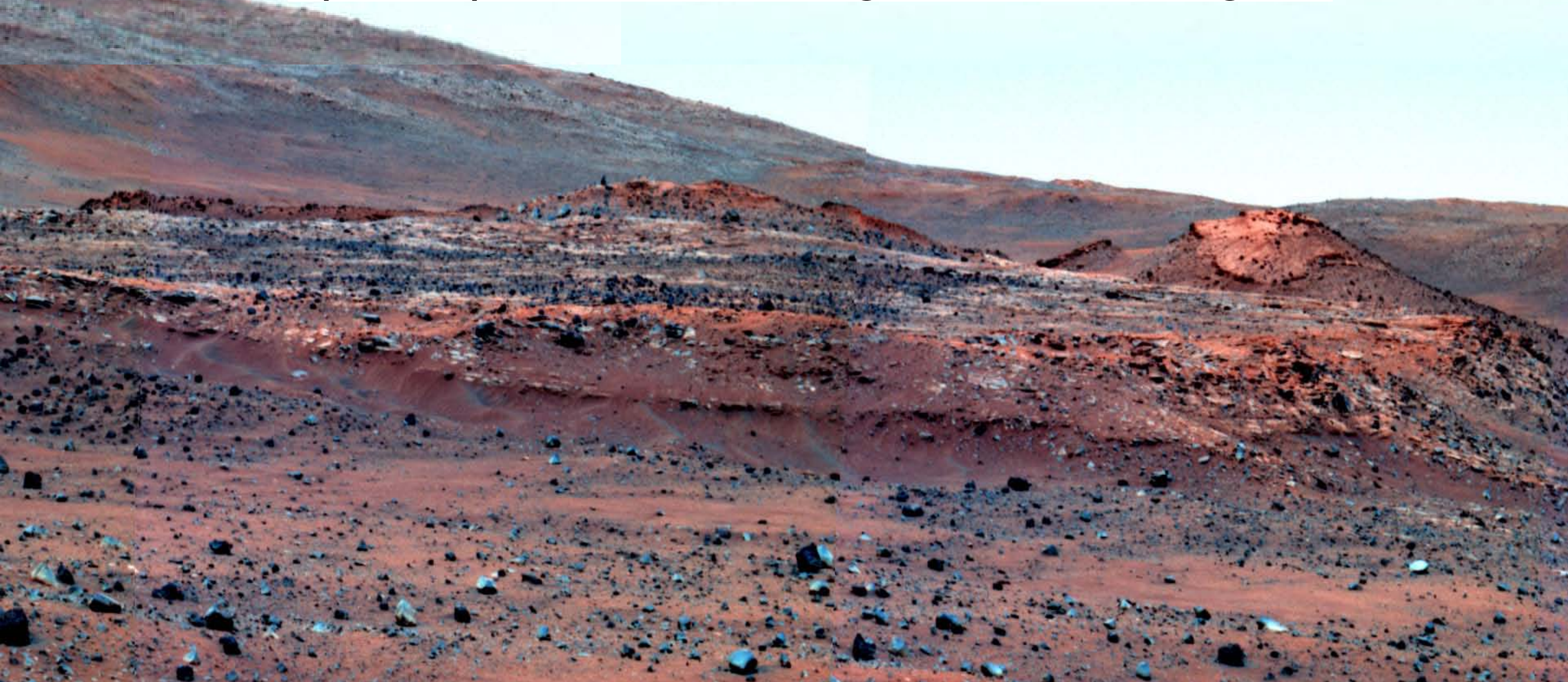




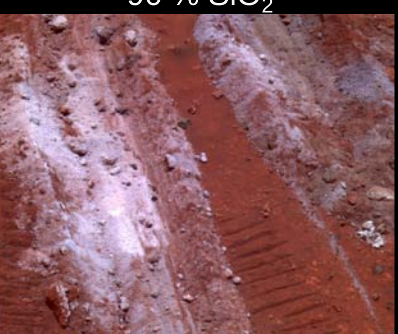
HP east side witnessed thermal alteration event(s)

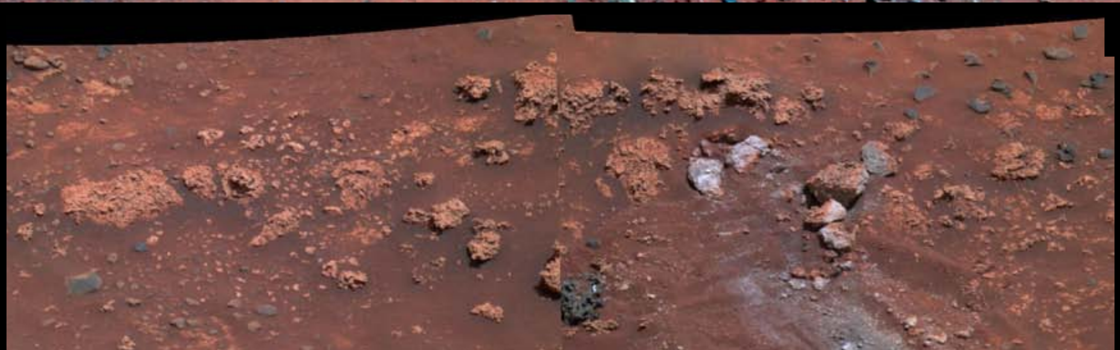
Discoveries at Home Plate

pure opaline silica along E, N & W margins



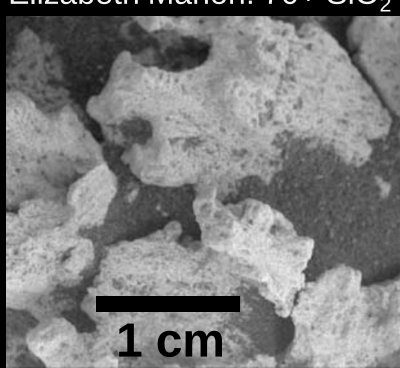
Kenosha Comets: 90 % SiO_2



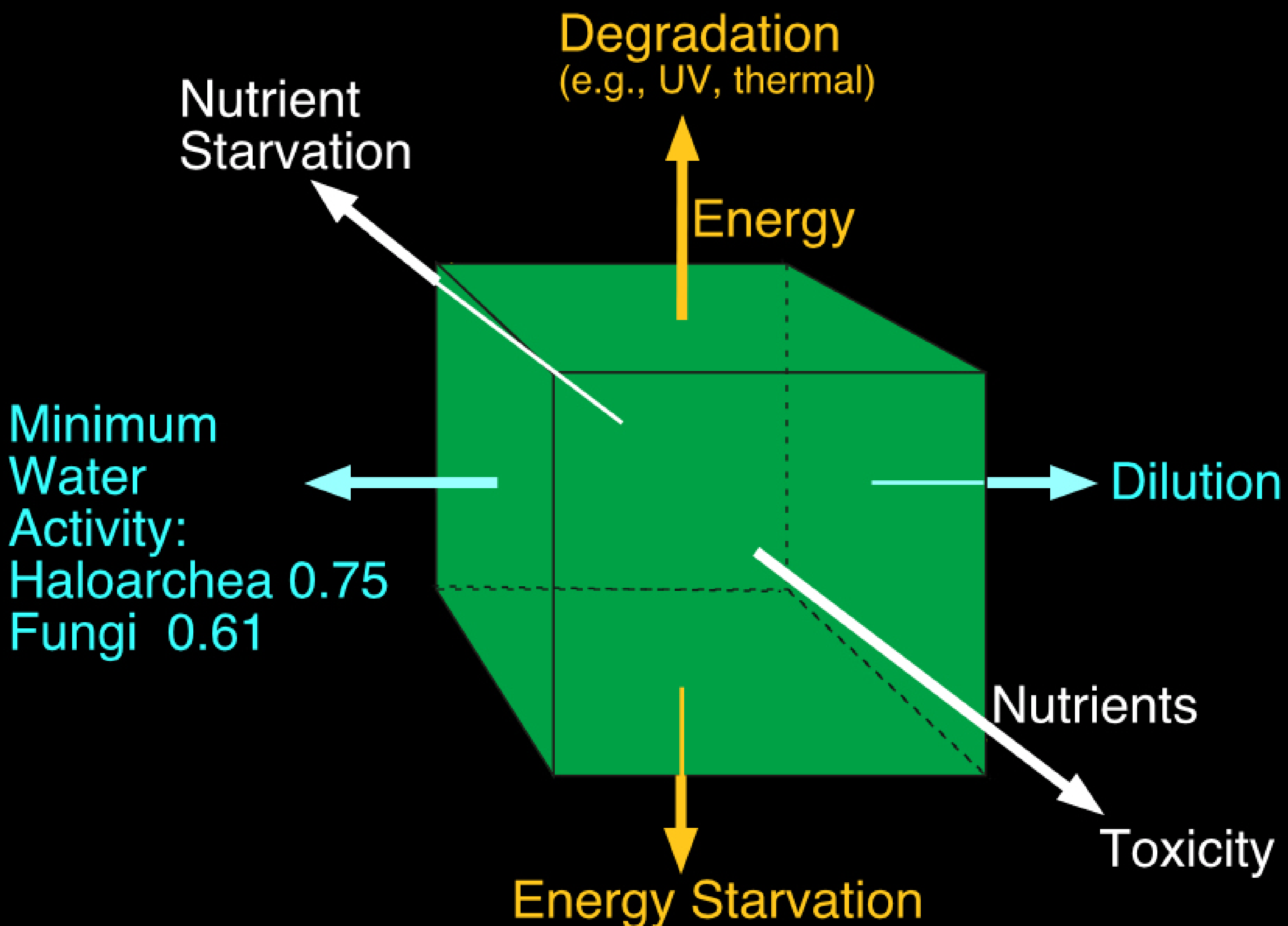


Elizabeth Warren & friends: 70+ % SiO_2

Elizabeth Mahon: 70+ SiO_2



Range of Conditions that Sustain Life



Chemical Energy for Life

Oxidation-reduction reactions can sustain life, even without photosynthesis

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Oxidants: O_2; CO_2; minerals/fluids with SO_x, Fe^{3+}, NO_x, etc.

Reductants: H_2; C_{red}; minerals/fluids with S_{red}, NH_4^+, Fe^{2+} or other reduced species

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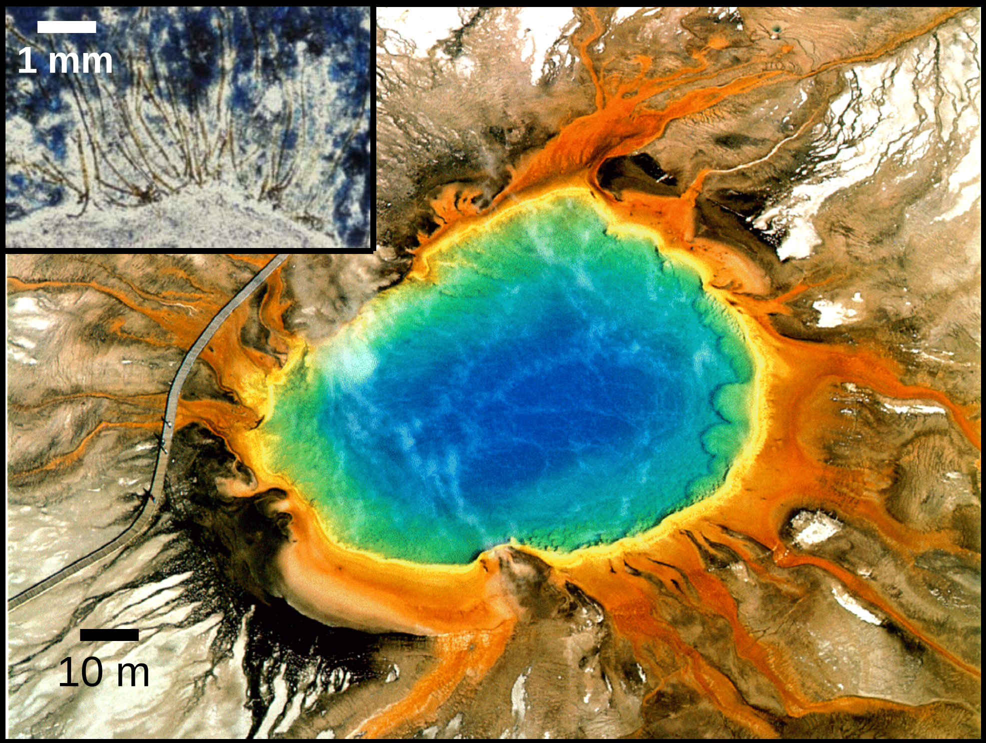
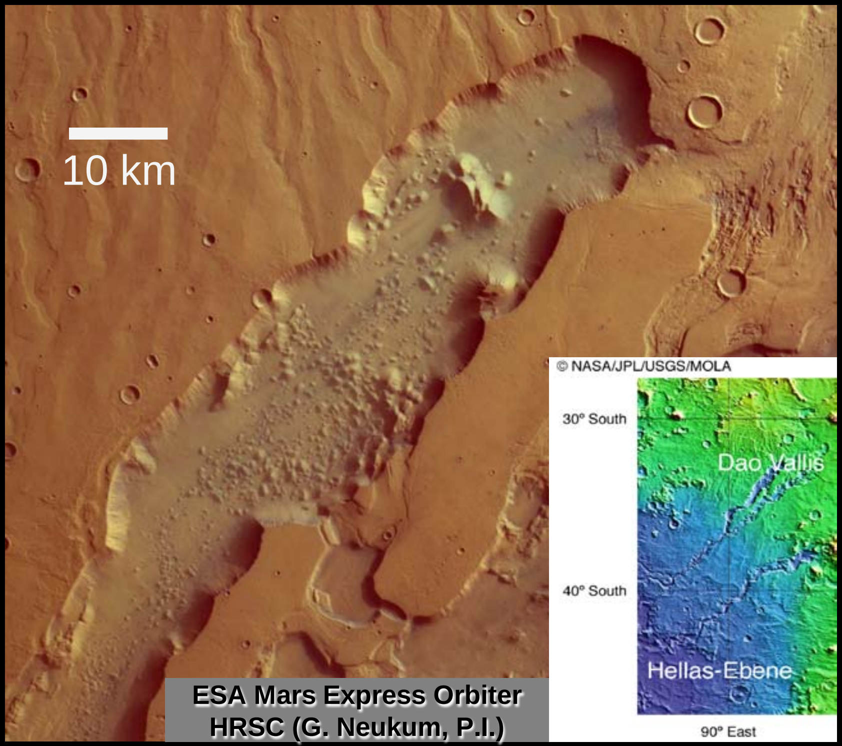
Minerals must be identified comprehensively and definitively to search for potential habitats and life

Hydrothermal sites on Mars are ideal to search for evidence of life (Walter & Des Marais, 1993)





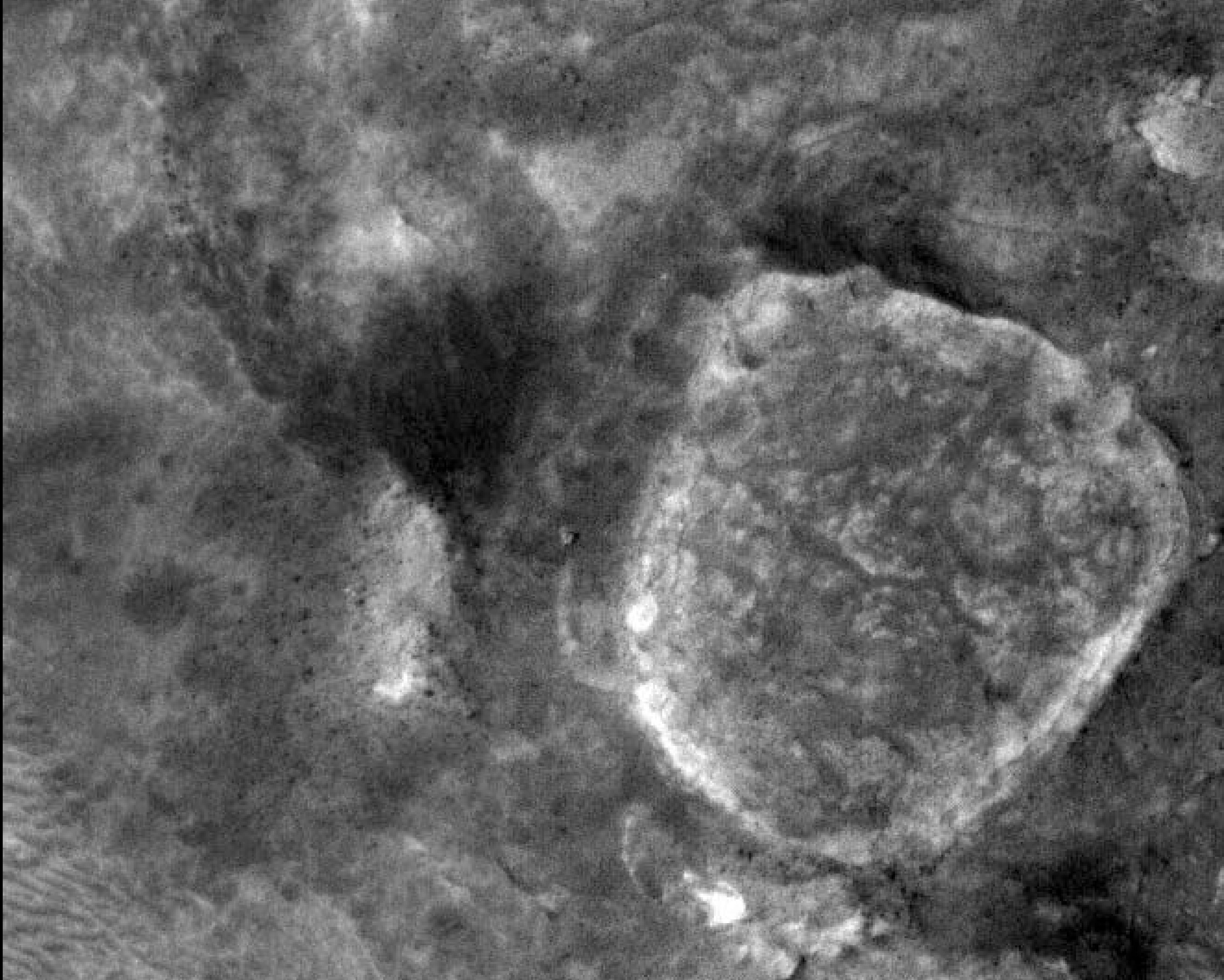
"Oases": sources of near-surface water

Reduced chemical species provide sources of energy for life

Mineral deposits preserve evidence of environments and life

Range of conditions sustains large diversity of biota

Sites of ancient spring deposits might have been found already



Sciencexpress Report

Identification of Carbonate-Rich Outcrops on Mars by the Spirit Rover

Richard V. Morris,[1*] Steven W. Ruff,[2] Ralf Gellert,[3] Douglas W. Ming,[1] Raymond E. Arvidson,[4] Benton C. Clark,[5] D. C. Golden,[6] Kirsten Siebach,[4] Göstar Klingelhöfer,[7] Christian Schröder,[8] Iris Fleischer,[7] Albert S. Yen,[9] Steven W. Squyres[10]

[1]NASA Johnson Space Center, Houston, TX 77058, USA. [2]Arizona State University, Tempe, AZ 85287, USA. [3]University of Guelph, Guelph, Ontario, Canada. [4]Washington University in Saint Louis, St. Louis, MO 63130, USA. [5]Space Sciences Institute, Boulder, CO 80301, USA. [6]ESCG-Hamilton Sundstrand, Houston TX 77058, USA. [7]Johannes Gutenberg-Universität, Mainz, Germany. [8]University of Bayreuth and Eberhard Karls University of Tübingen, Tübingen, Germany. [9]Jet Propulsion Laboratory, Pasadena, CA 91109, USA. [10]Cornell University, Ithaca, NY 14853, USA.

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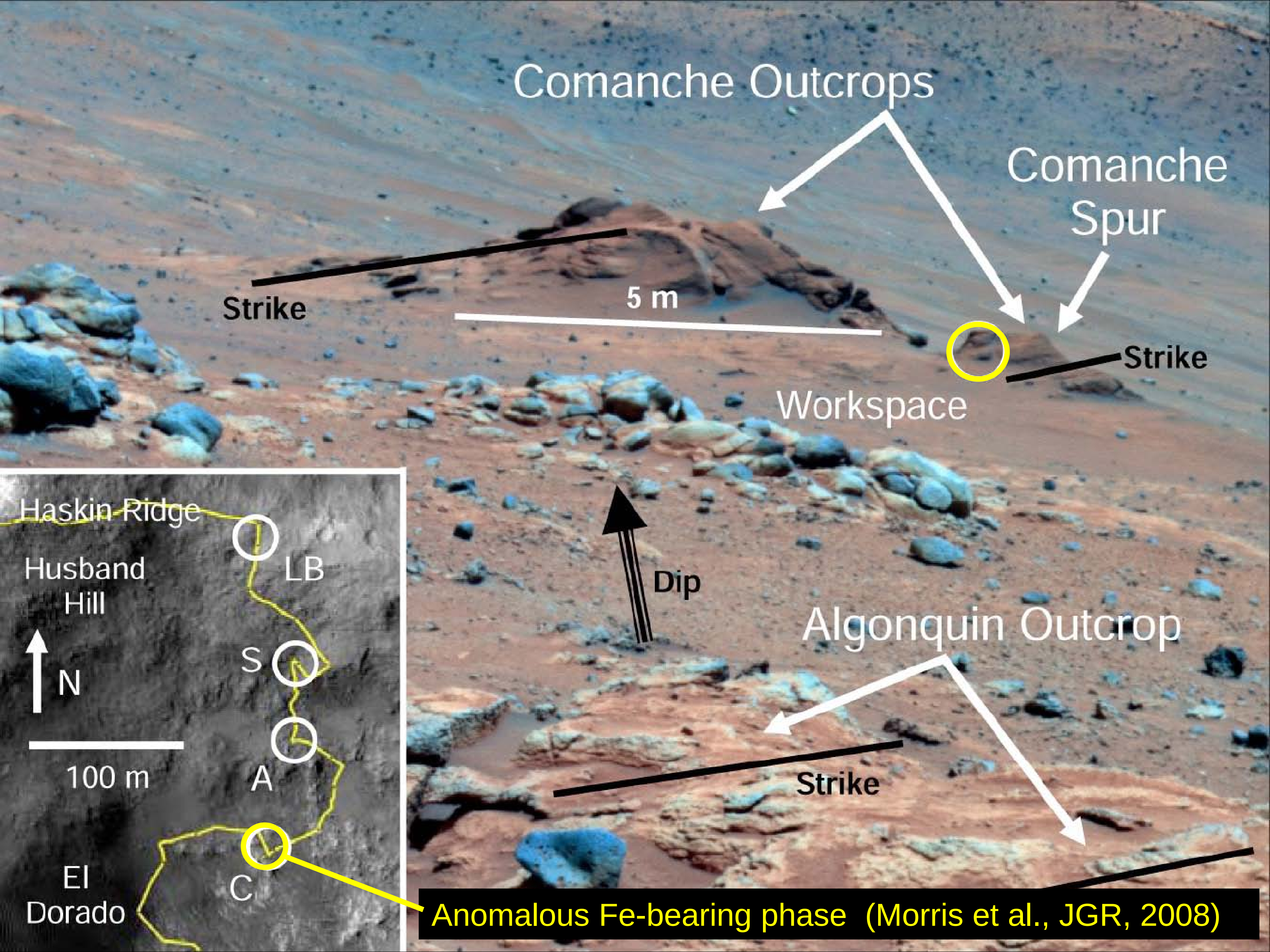
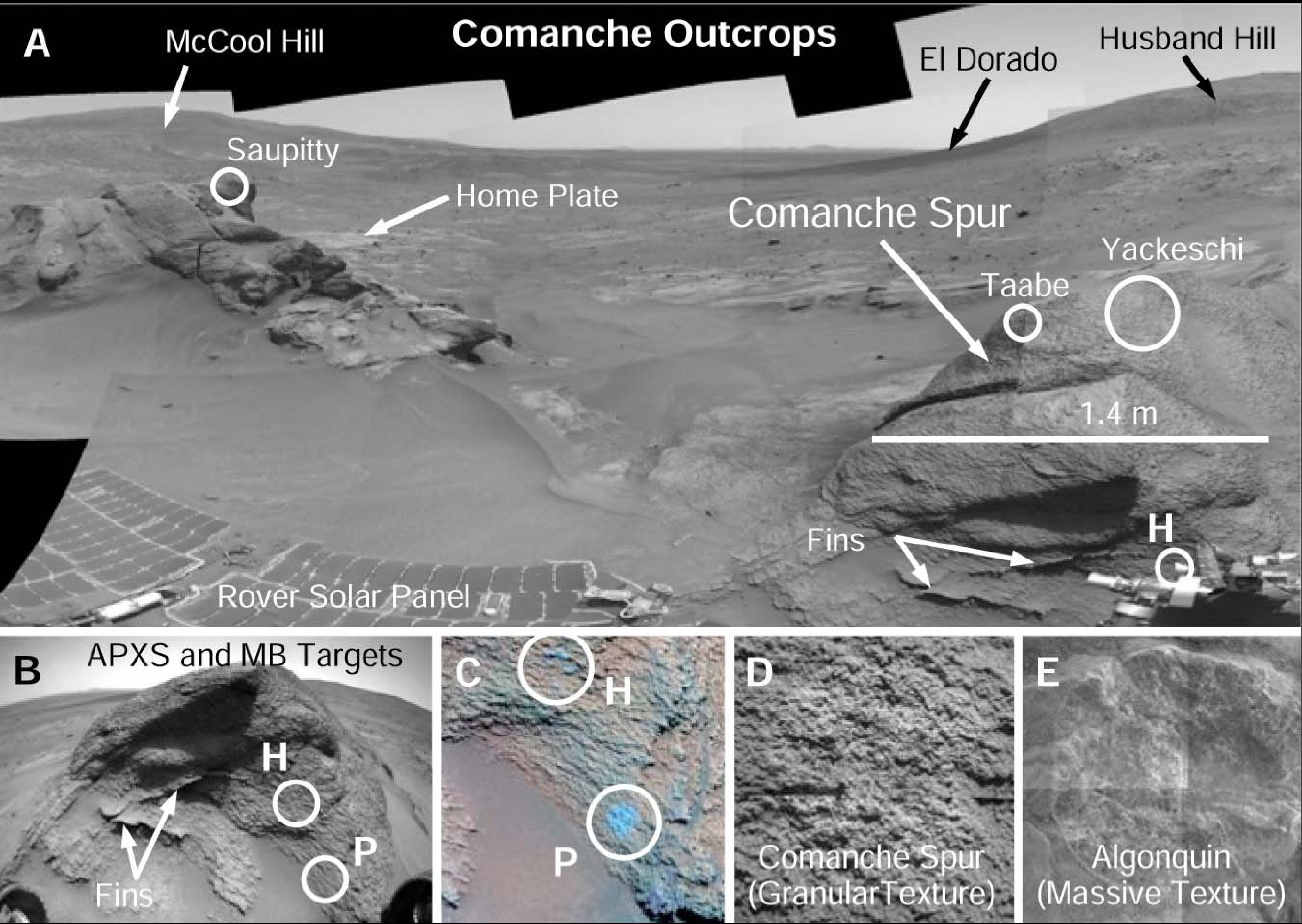
Decades of speculation about a warmer, wetter Mars climate in the planet's first billion years call upon a denser CO_2-rich atmosphere than at present. Such an atmosphere should have led to the formation of outcrops rich in carbonate minerals, for which evidence has been sparse. Using the Mars Exploration Rover (MER) Spirit, we have now identified outcrops rich in Mg-Fe carbonate (16 to 34 wt.%) in the Columbia Hills of Gusev crater. Its composition approximates the average composition of the carbonate globules in Martian meteorite ALH 84001. The Gusev carbonate probably precipitated from carbonate-bearing solutions under hydrothermal conditions at near-neutral pH in association with volcanic activity during the Noachian era.

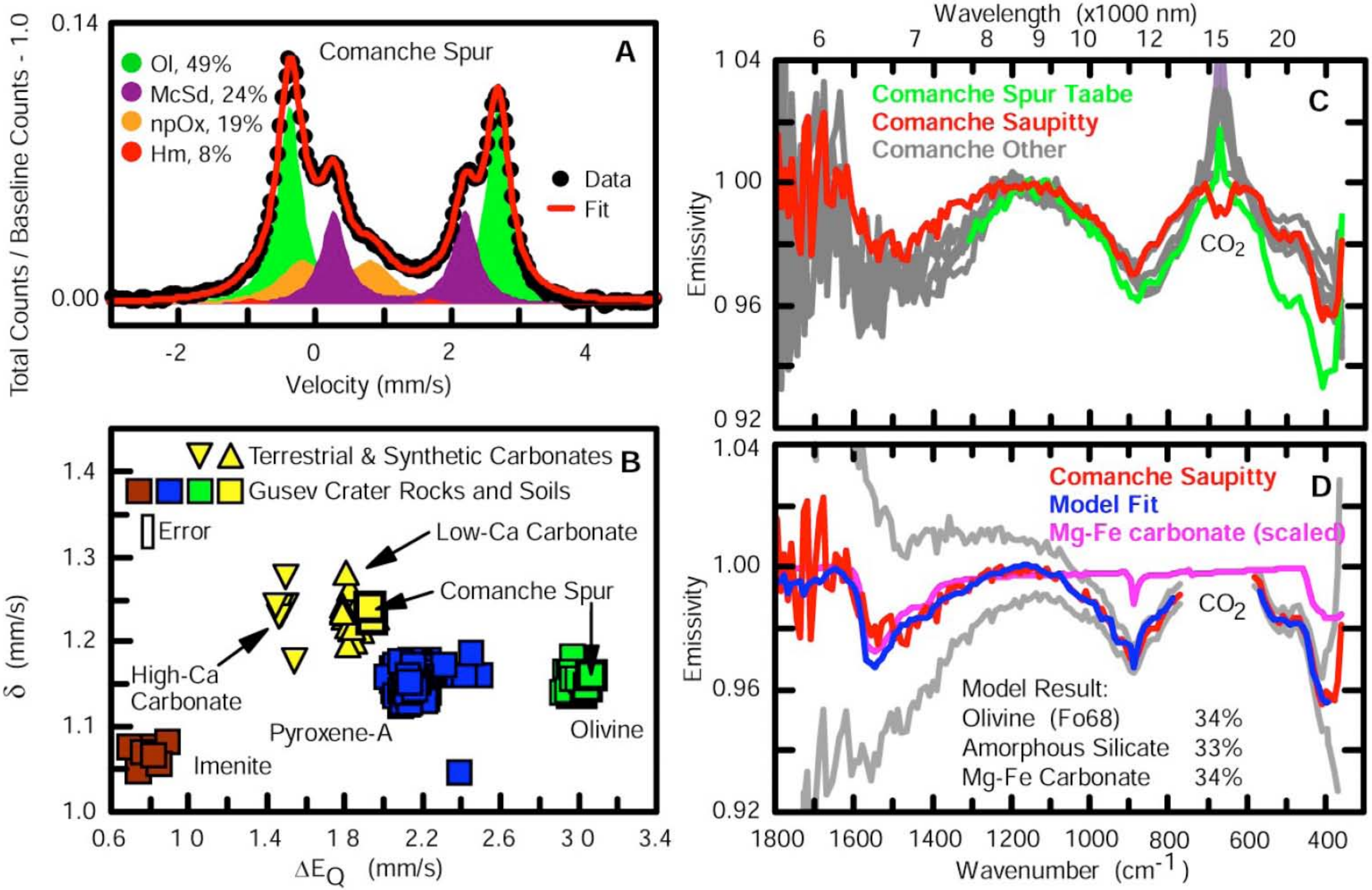
at Gusev crater (*16*). A series of benches (Fig. 1) with olivine-rich outcrops were encountered and analyzed by Spirit's instruments (*19*, *21*). The Comanche outcrops with their granular surface textures (grain sizes ~0.5 to 1.0 mm) are erosional remnants that are draped over the older and more massive Algonquin and other olivine- and pyroxene-rich outcrops (Figs. 1 and 2). They have layering whose bedding is roughly conformal with local topography, consistent with a volcaniclastic origin, and have fracture-filling deposits that have withstood aeolian erosion better than the surrounding materials, forming raised fins (Figs. 1 and 2).

Spirit's Mössbauer (MB) spectrometer provides information about Fe mineralogy and distribution of Fe among Fe-bearing phases and oxidation states (*22*). The



Comanche Outcrops
Comanche Spur
Strike
5 m
Strike
Workspace
Haskin Ridge
Husband Hill
LB
N
S
A
100 m
C
El Dorado
Dip
Algonquin Outcrop
Strike
Anomalous Fe-bearing phase (Morris et al., JGR, 2008)


A
Comanche Outcrops
McCool Hill
El Dorado
Husband Hill
Saupitty
Home Plate
Comanche Spur
Yackeschi
Taabe
1.4 m
Fins
H
Rover Solar Panel
B
APXS and MB Targets
H
P
Fins
C
H
P
D
Comanche Spur
(GranularTexture)
E
Algonquin
(Massive Texture)



Also: APXS data accurately estimated the abundance of an undetected element (carbon)

Following the Energy: Chemical Sources

Both mafic and ultramafic rocks occur at Gusev & water has altered some. Ultramafic rock alteration can yield phyllosilicates, magnetite, hematite & H_2. Aqueous reactions with Fe^{2+} can yield energy.

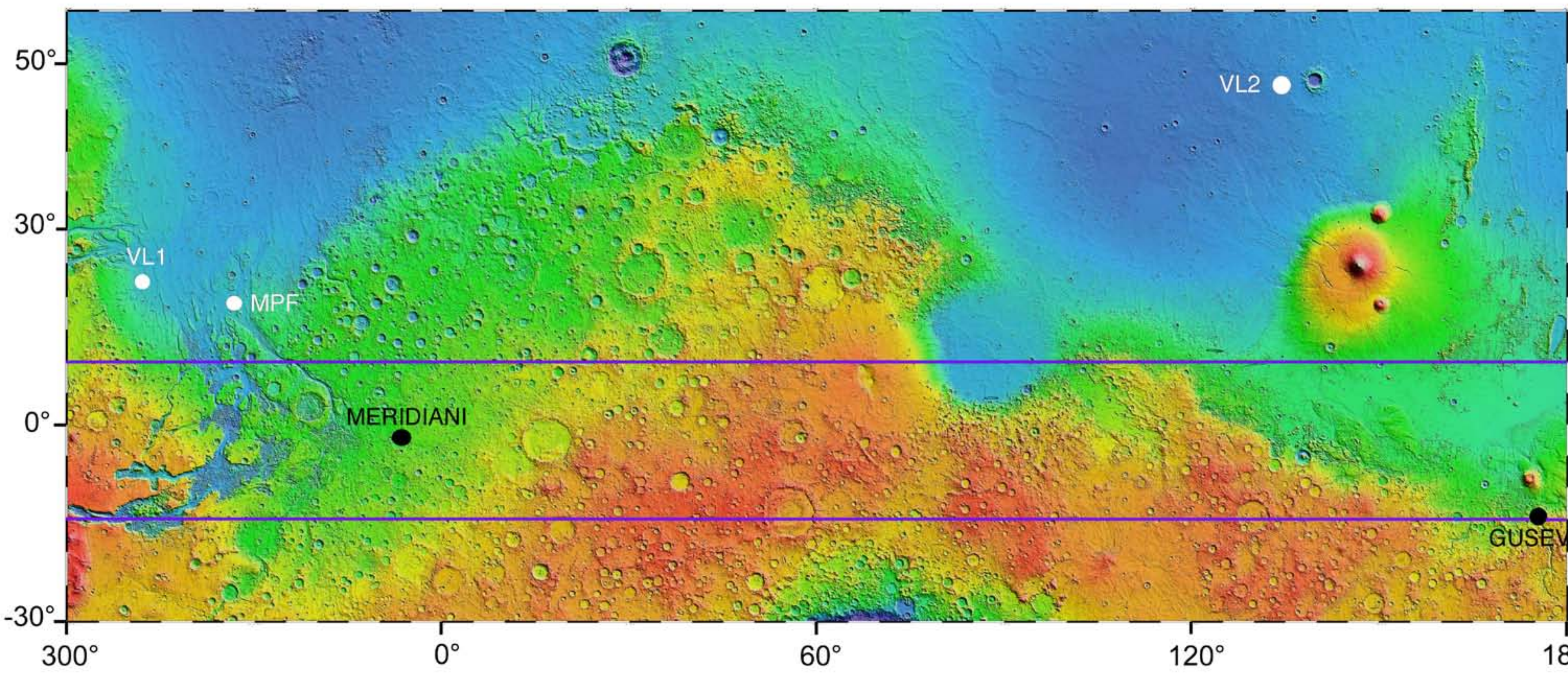
"Excess S" in some deposits indicates added H_2S, S^o or SO_x. Their redox reactions can yield energy.

Volcanism & impacts probably led to aqueous events.

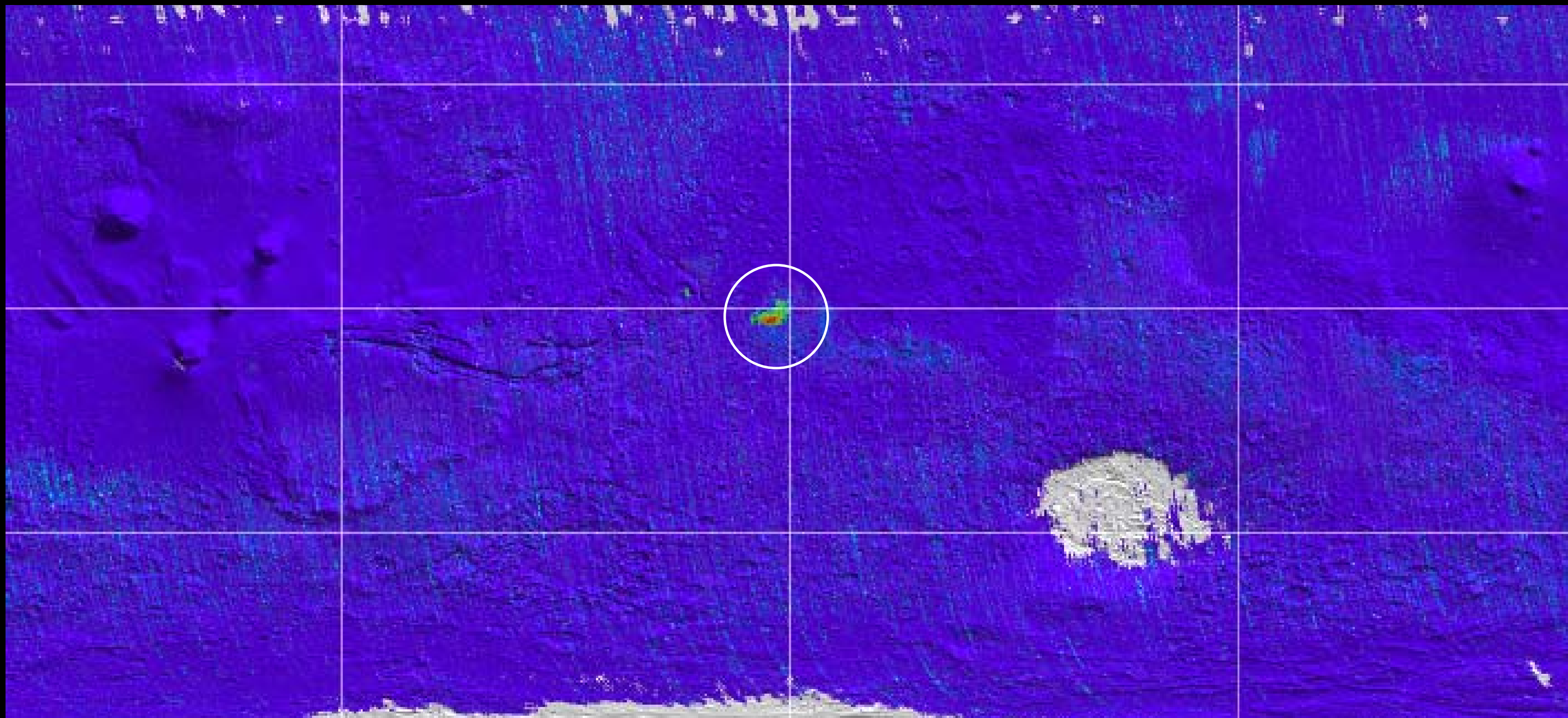
For much of Martian history, reduced materials reacted with strong oxidants. Such reactions have high energy yields.

Spirit conceivably has found evidence of the above scenarios. Subsurface events could have persisted longer than surface events.

MER Landing Sites



Coarse-grained hematite (Fe_2O_3) at Meridiani Planum
a “beacon” indicating past liquid water?



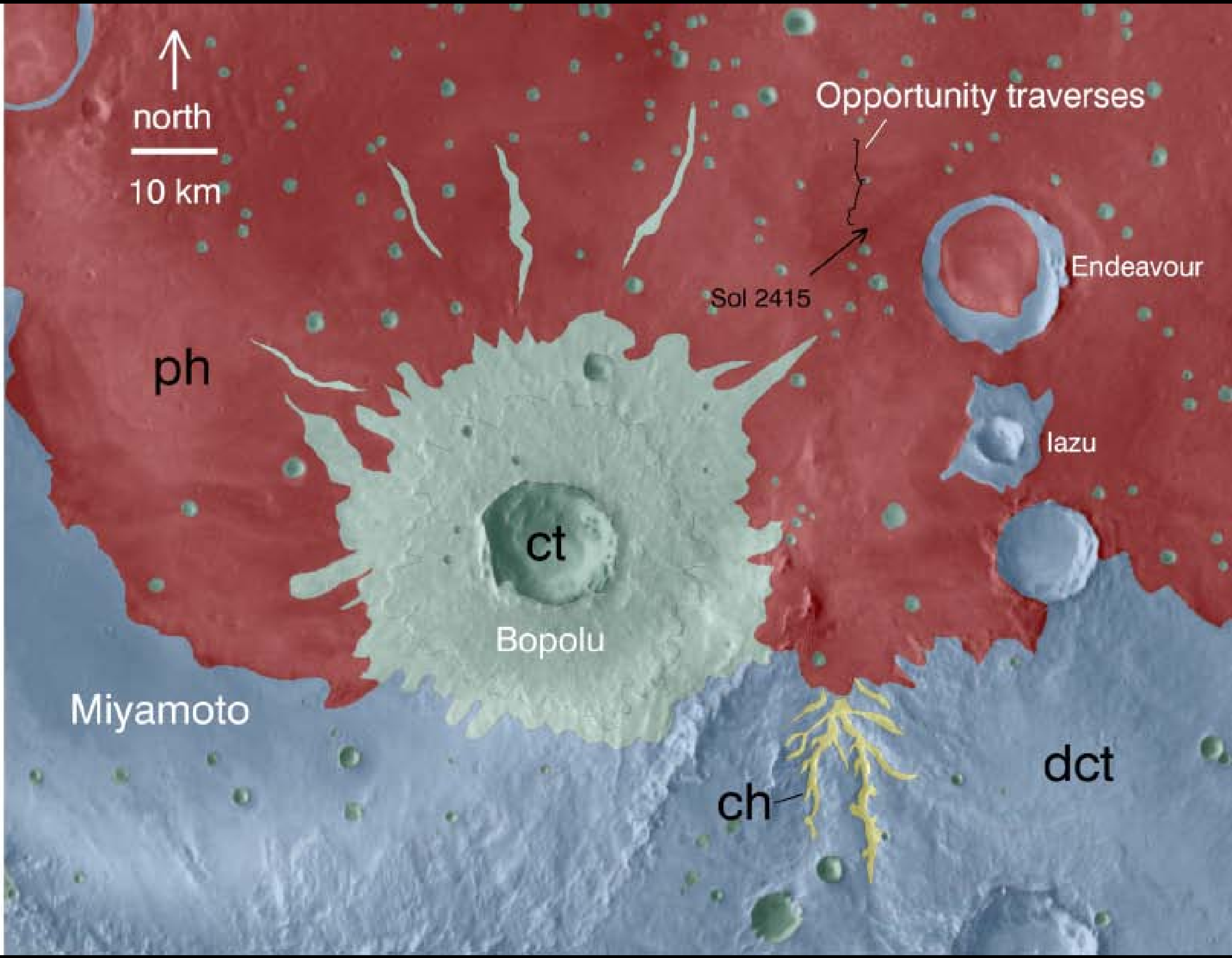
Meridiani Planum Geologic Setting

ct-post Noachian craters

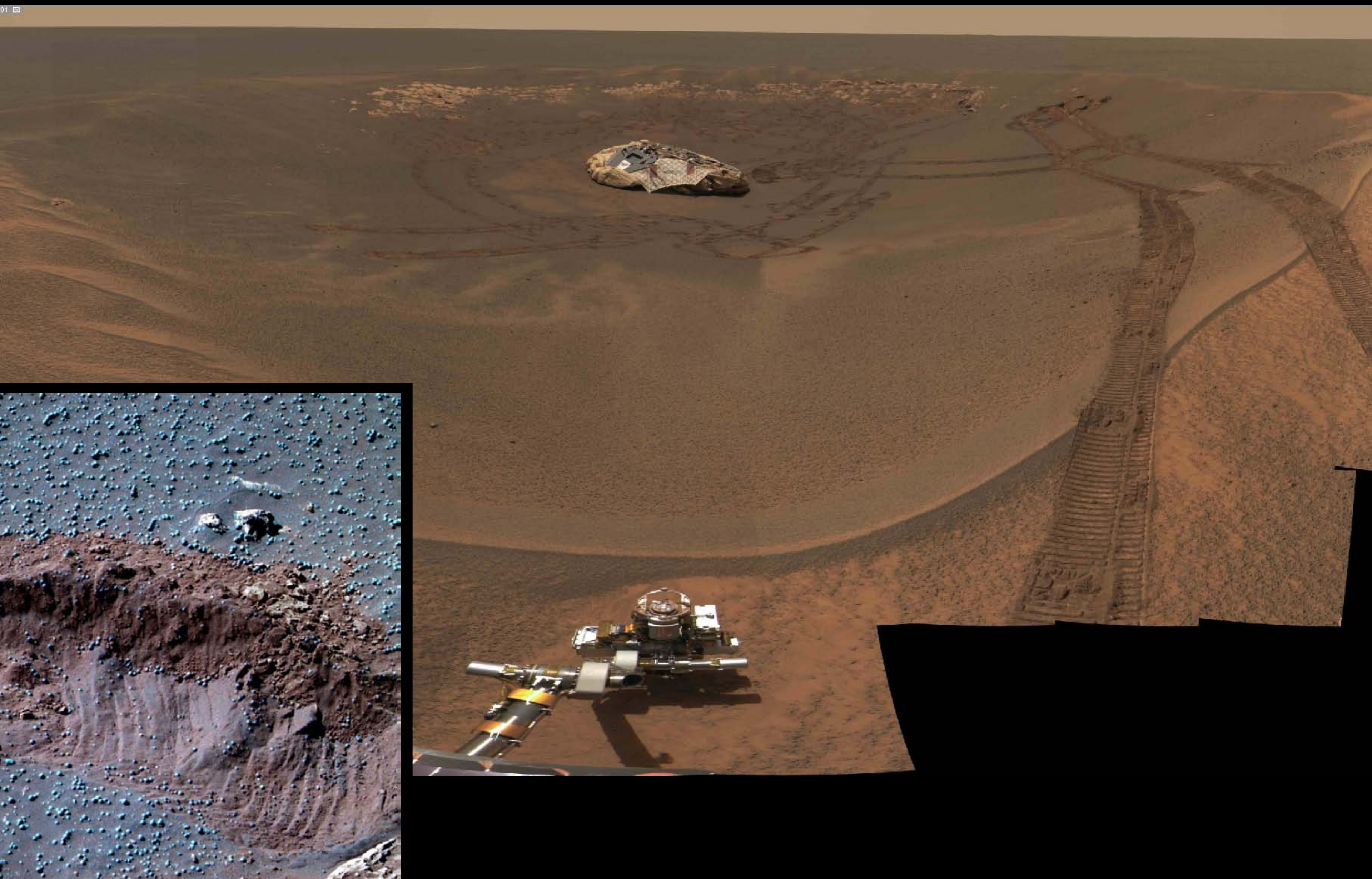
ph-hematite-bearing plains

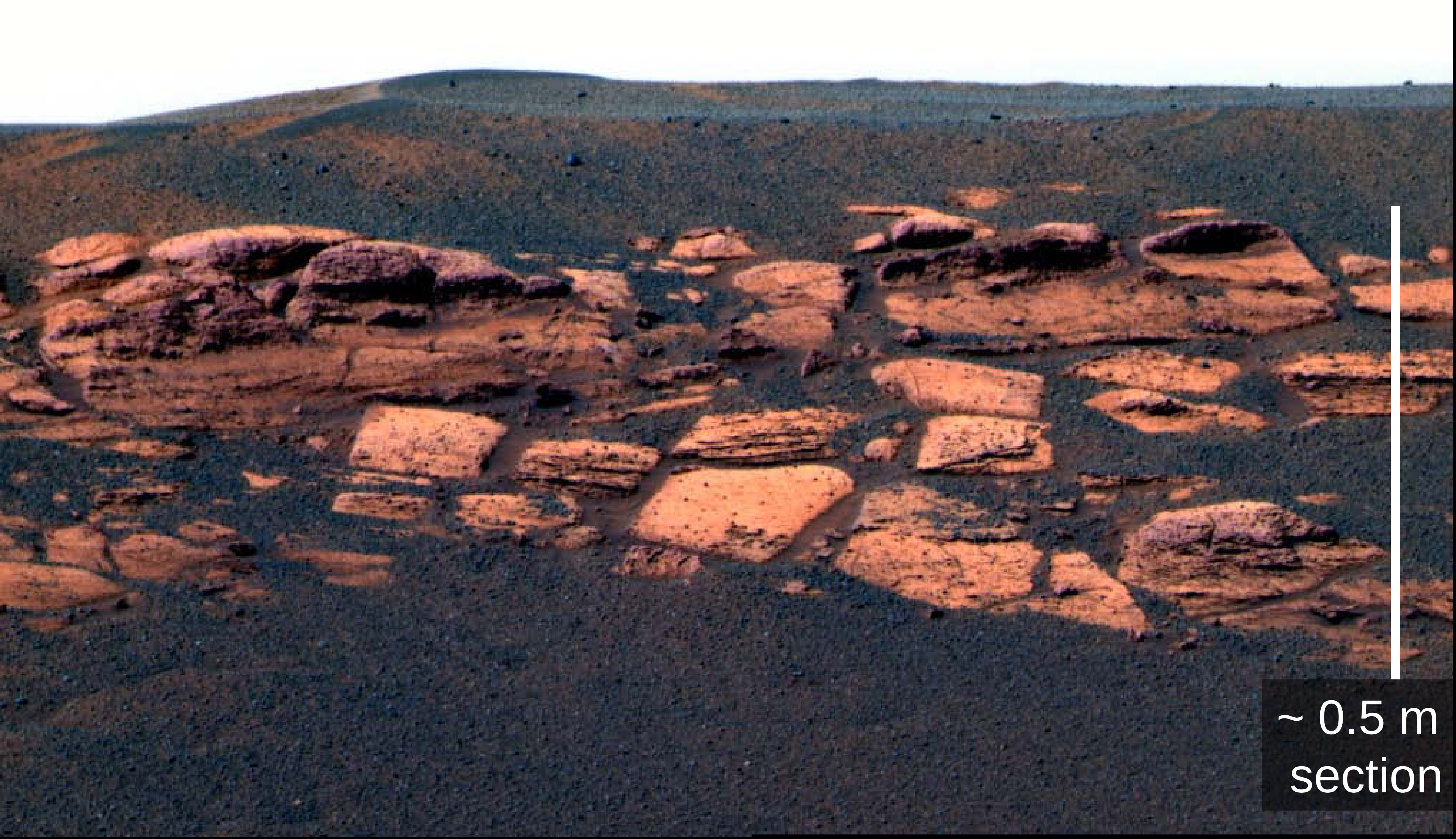
ch-channel

dct-Noachian cratered terrain



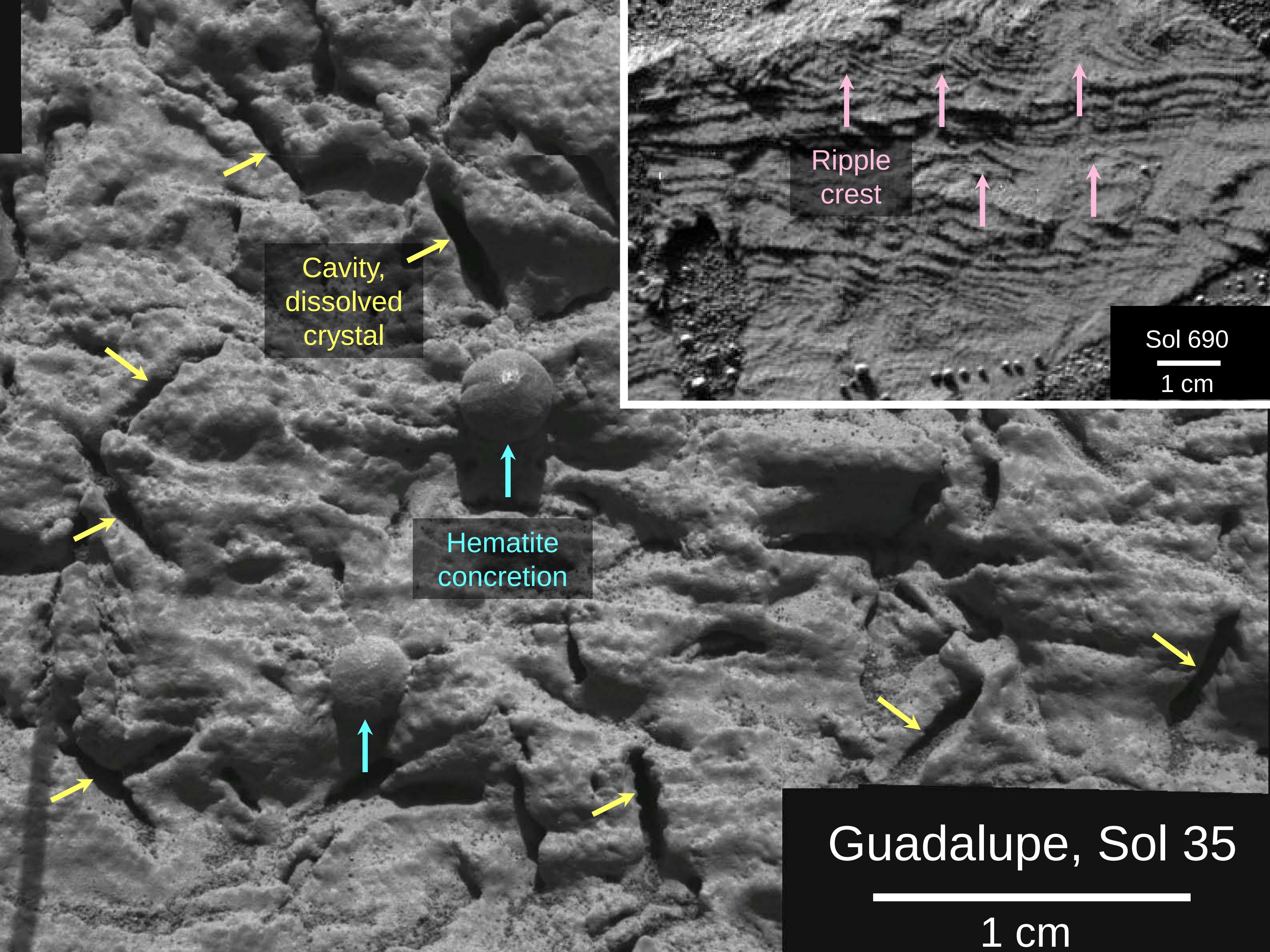
Eagle Crater, Meridiani Planum

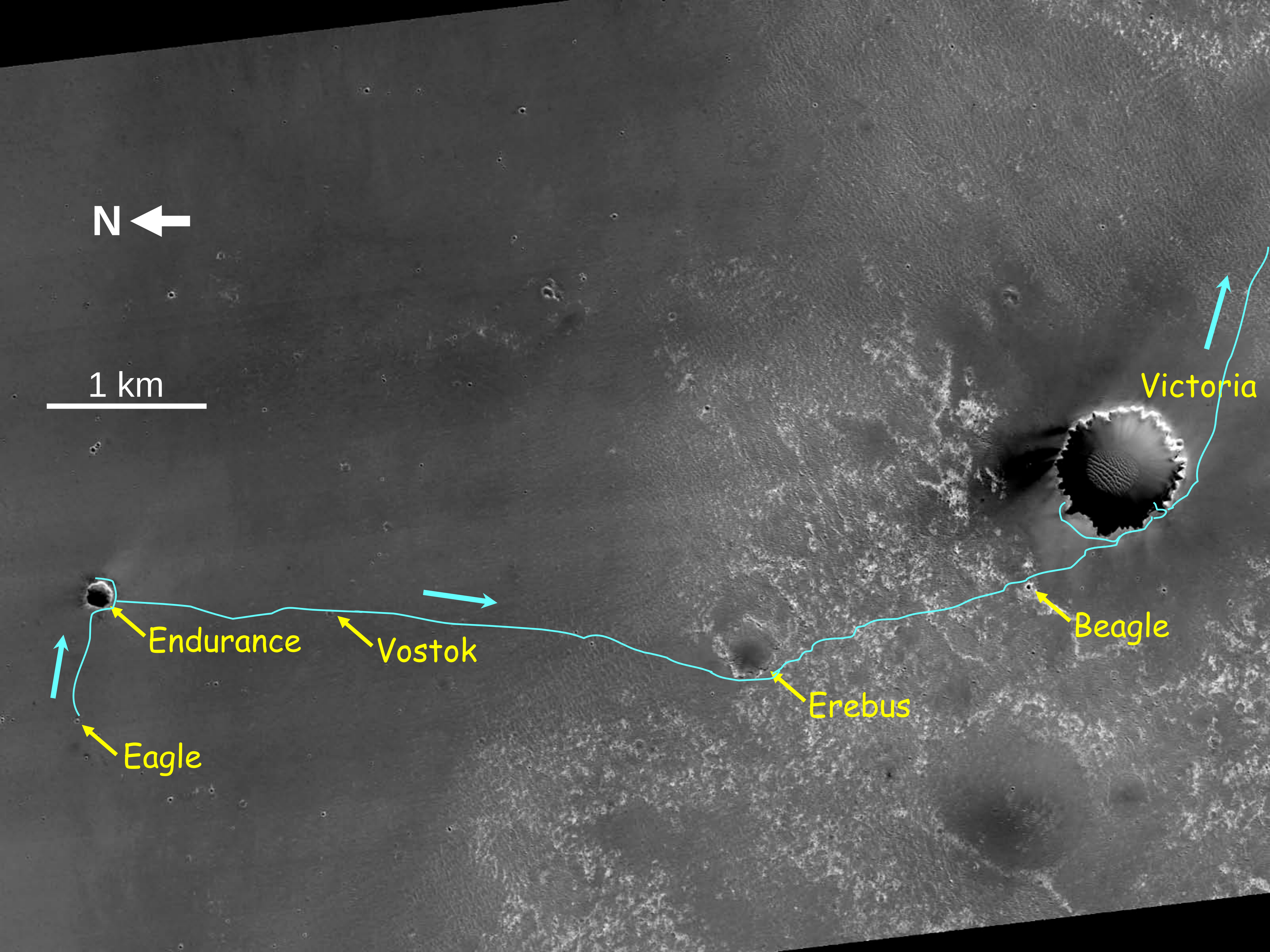




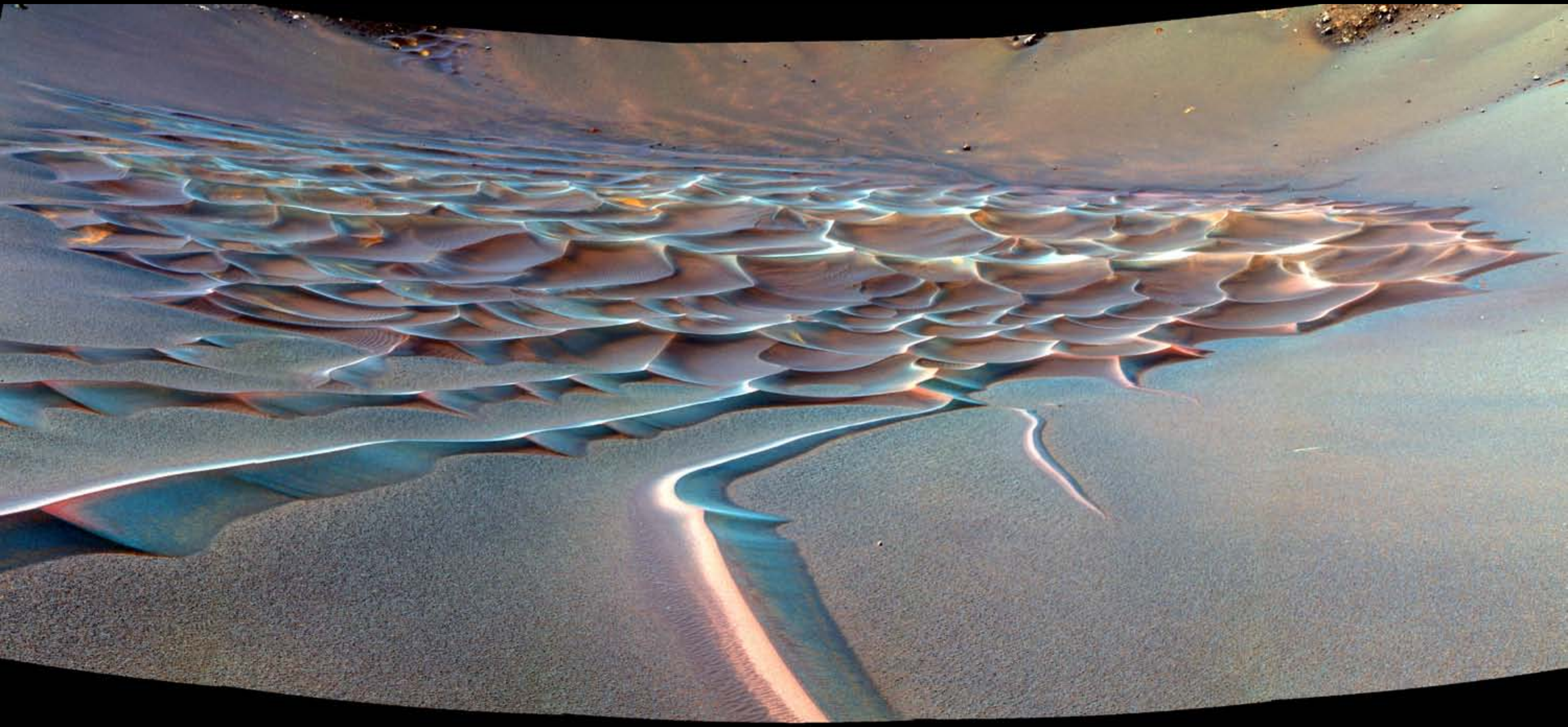
Sulfate-rich
evaporite deposits !

Abundant soluble sulfate minerals
Hematite-rich diagenetic concretions
Finely-laminated festoon cross-beds
Jarosite (acidic conditions)
Remobilization of soluble salts


Ripple
crest
Sol 690
1 cm
Cavity,
dissolved
crystal
Hematite
concretion
Guadalupe, Sol 35
1 cm

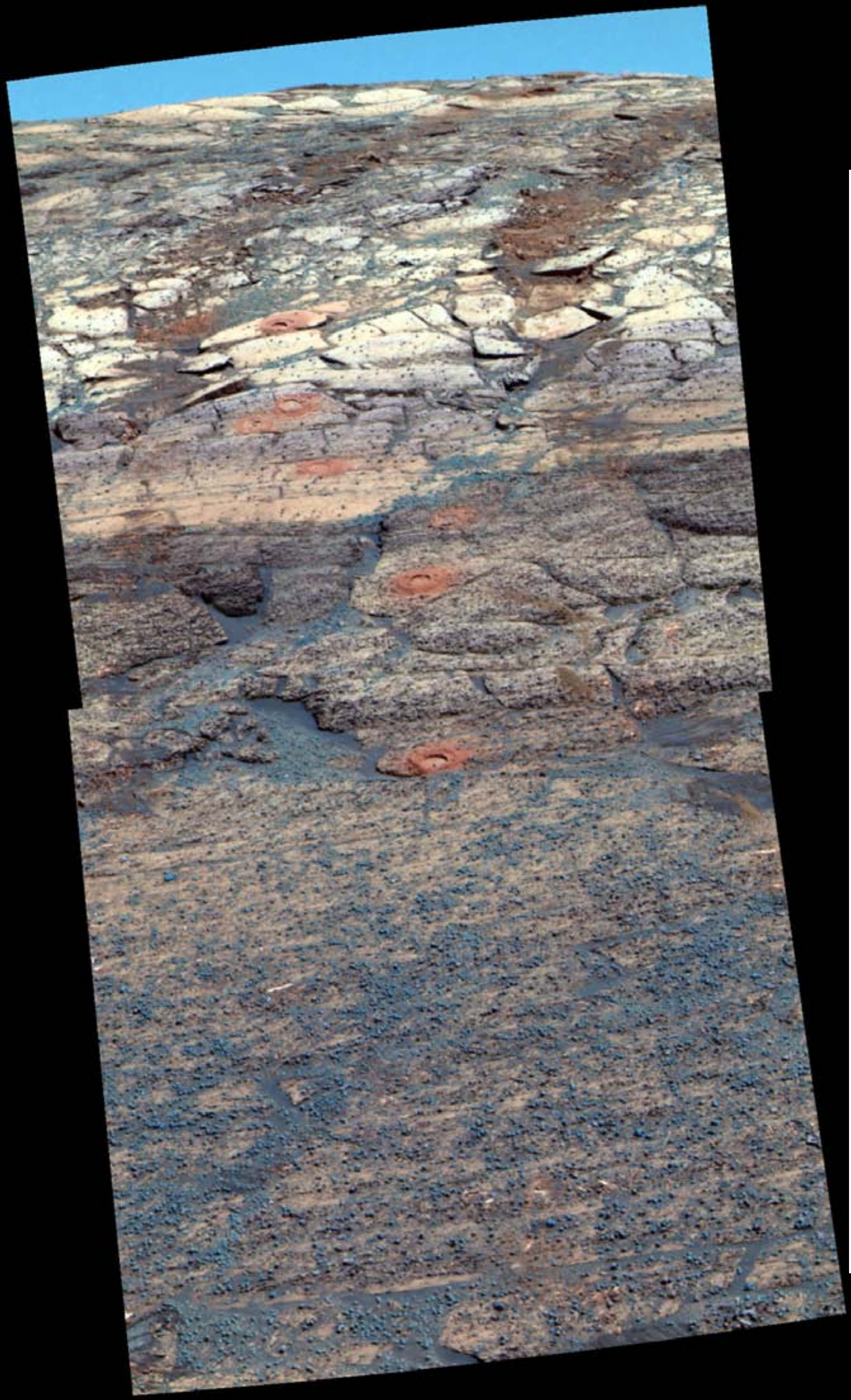


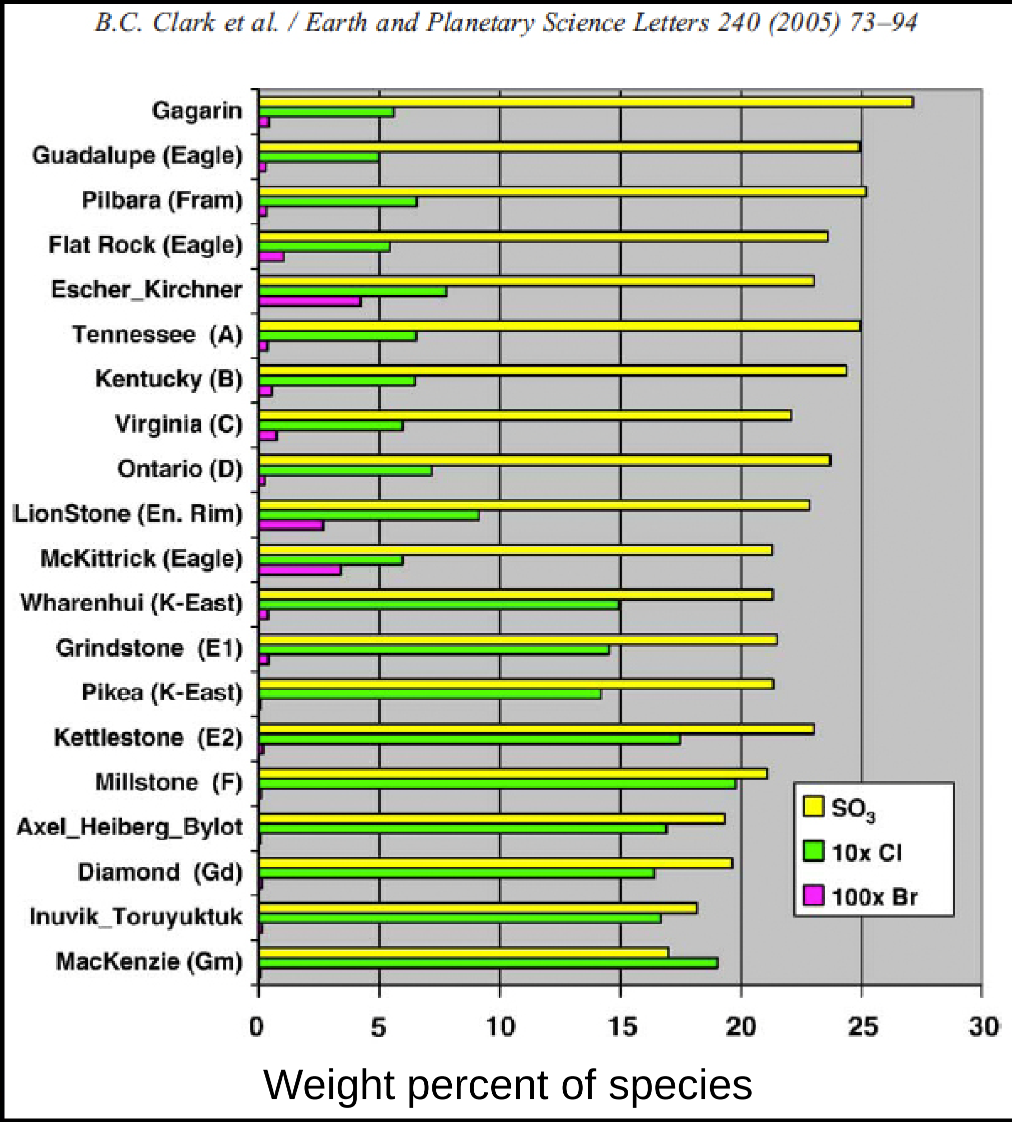
N
1 km
Victoria
Beagle
Endurance
Vostok
Erebus
Eagle



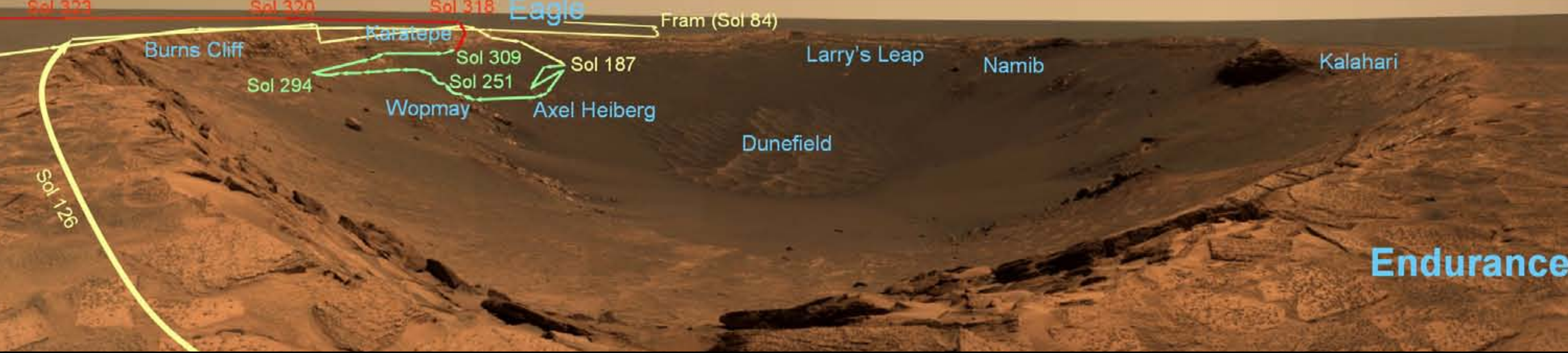
Aeolian drift deposits, Endurance crater

Evidence for redistribution of soluble salts by groundwater intrusion(s)





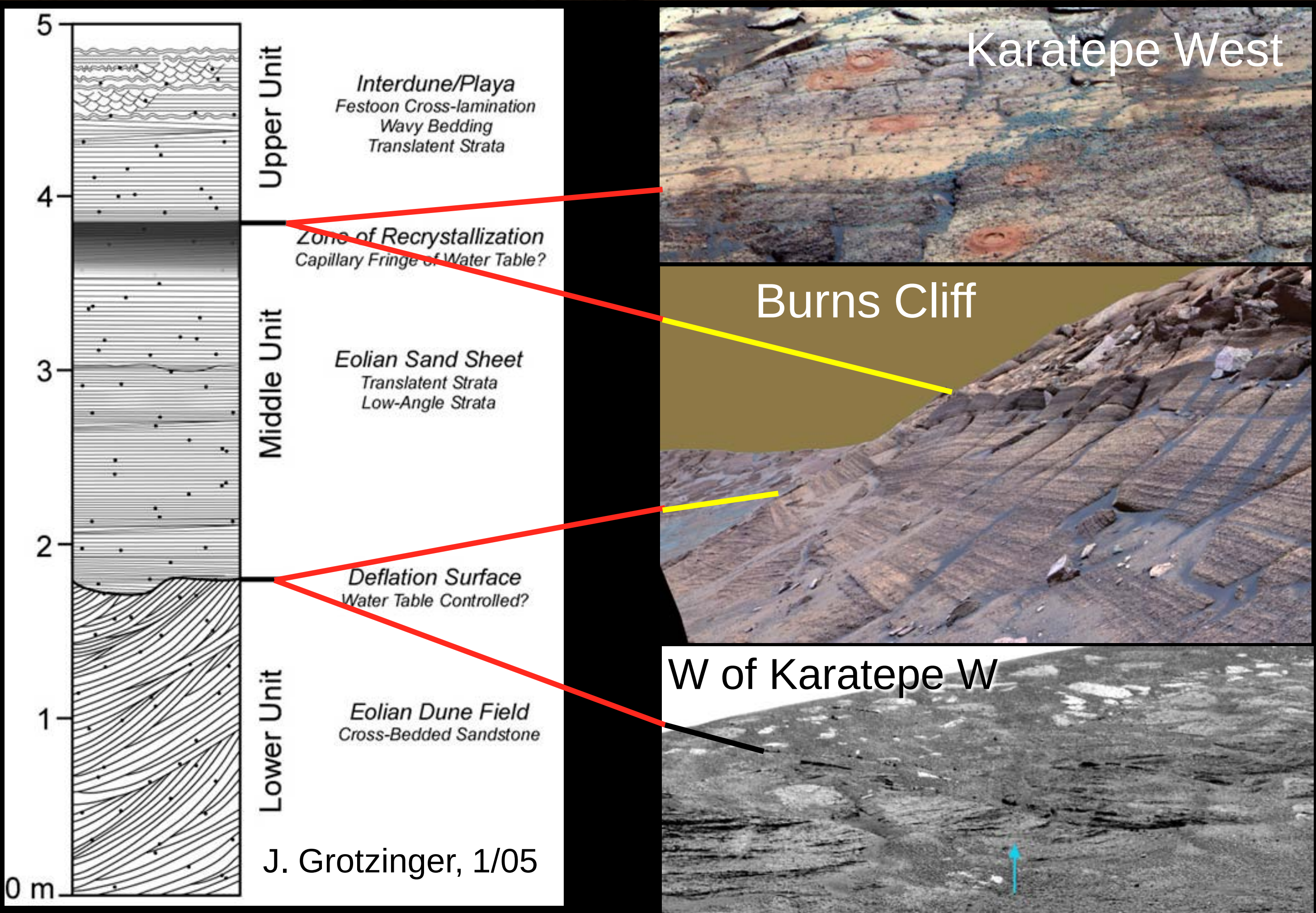
Clark et al., EPSL (2005)



Endurance Crater

160 m diameter
14 m deep

evidence
of ancient
sand dunes,
wet sand sheets
& playa lakes



Deposition and diagenesis of sulfate-rich bedrock at the MER Meridiani site

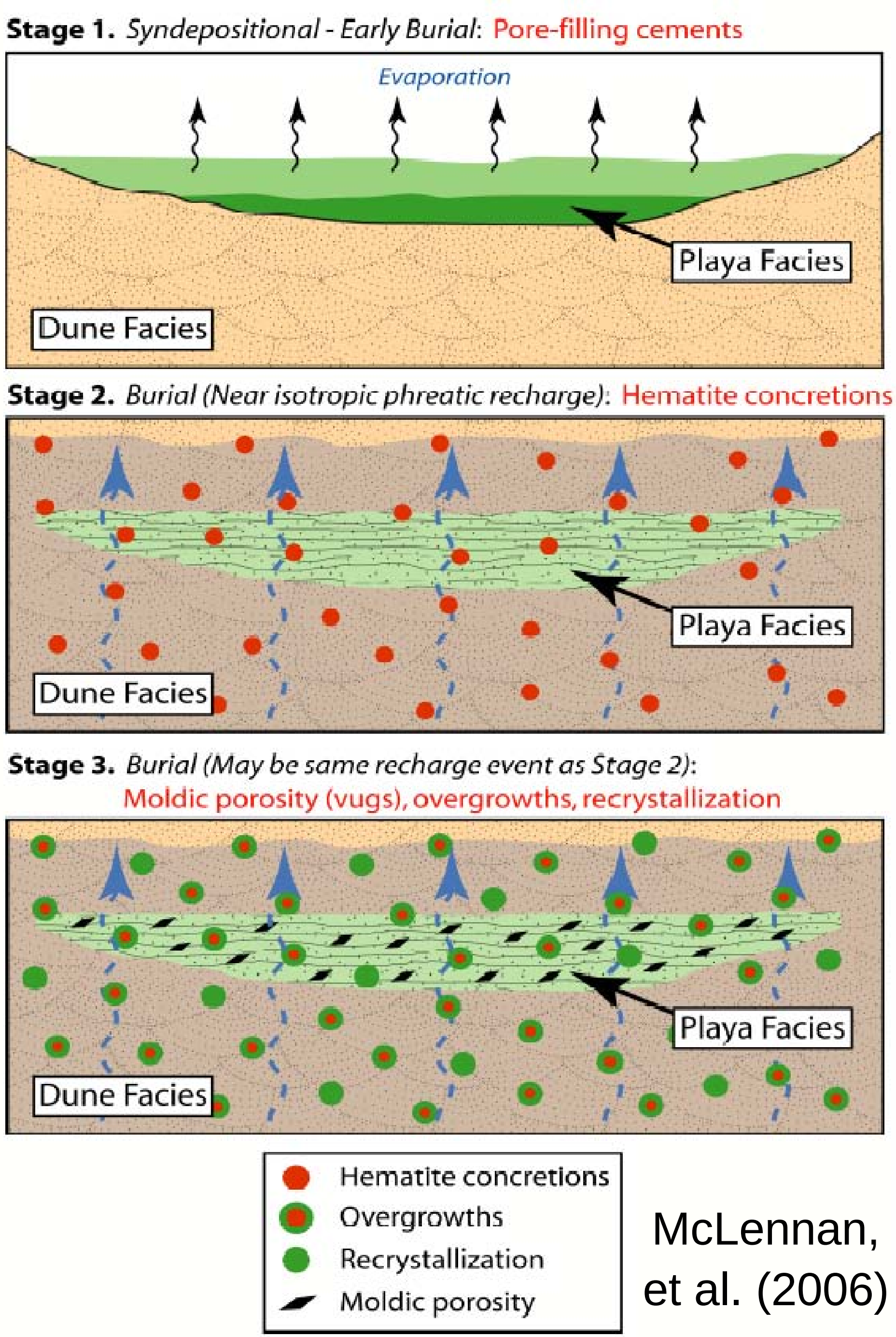


Fig. 2. Simplified model of diagenetic history.

McLennan, et al. (2006)

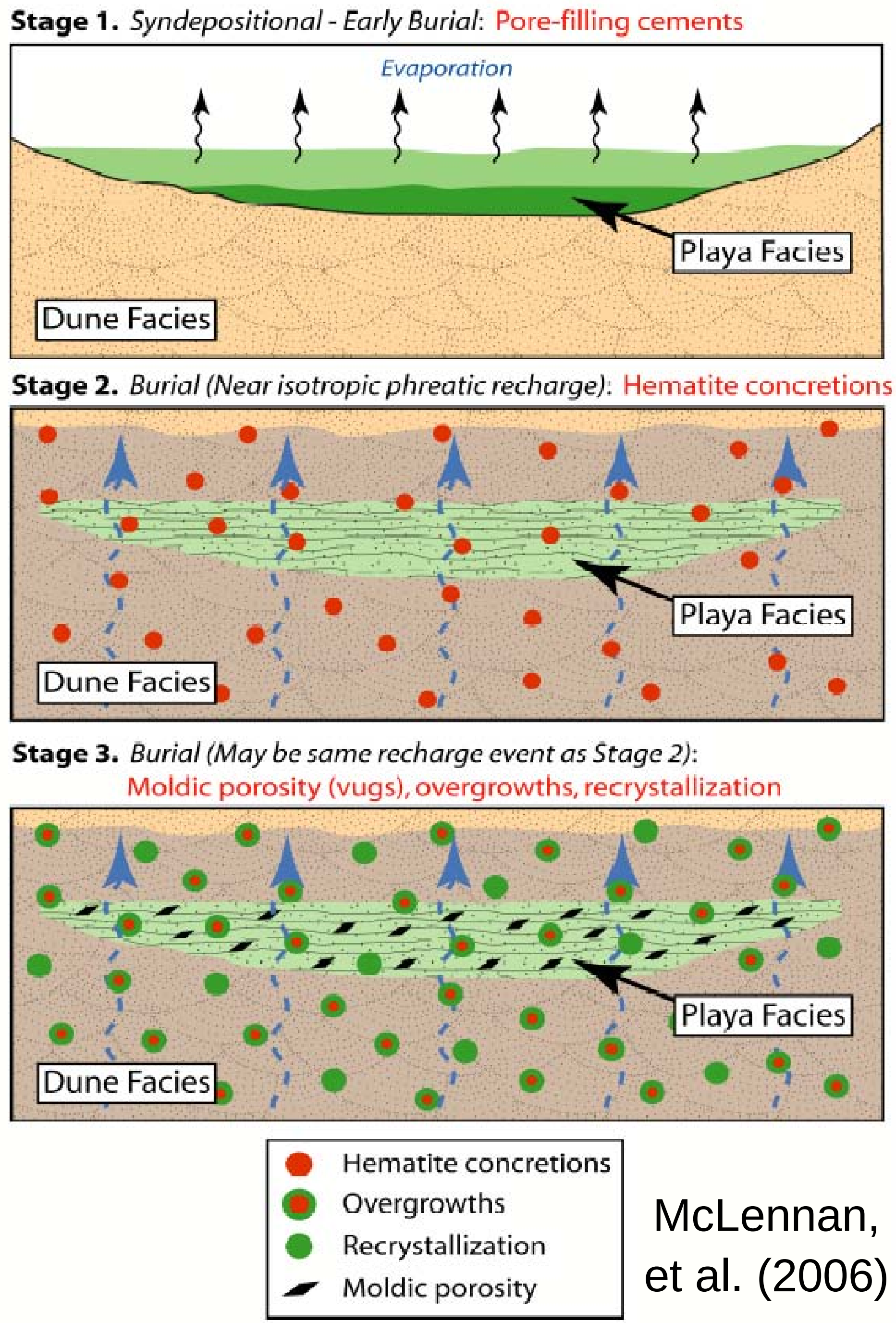
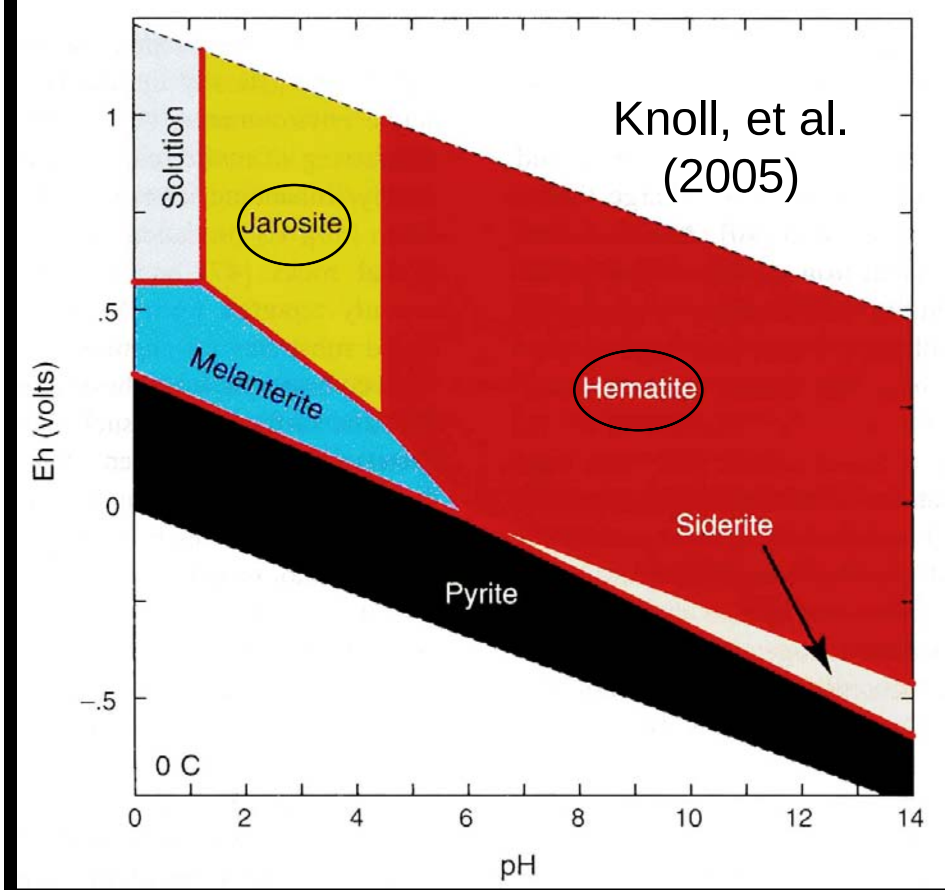


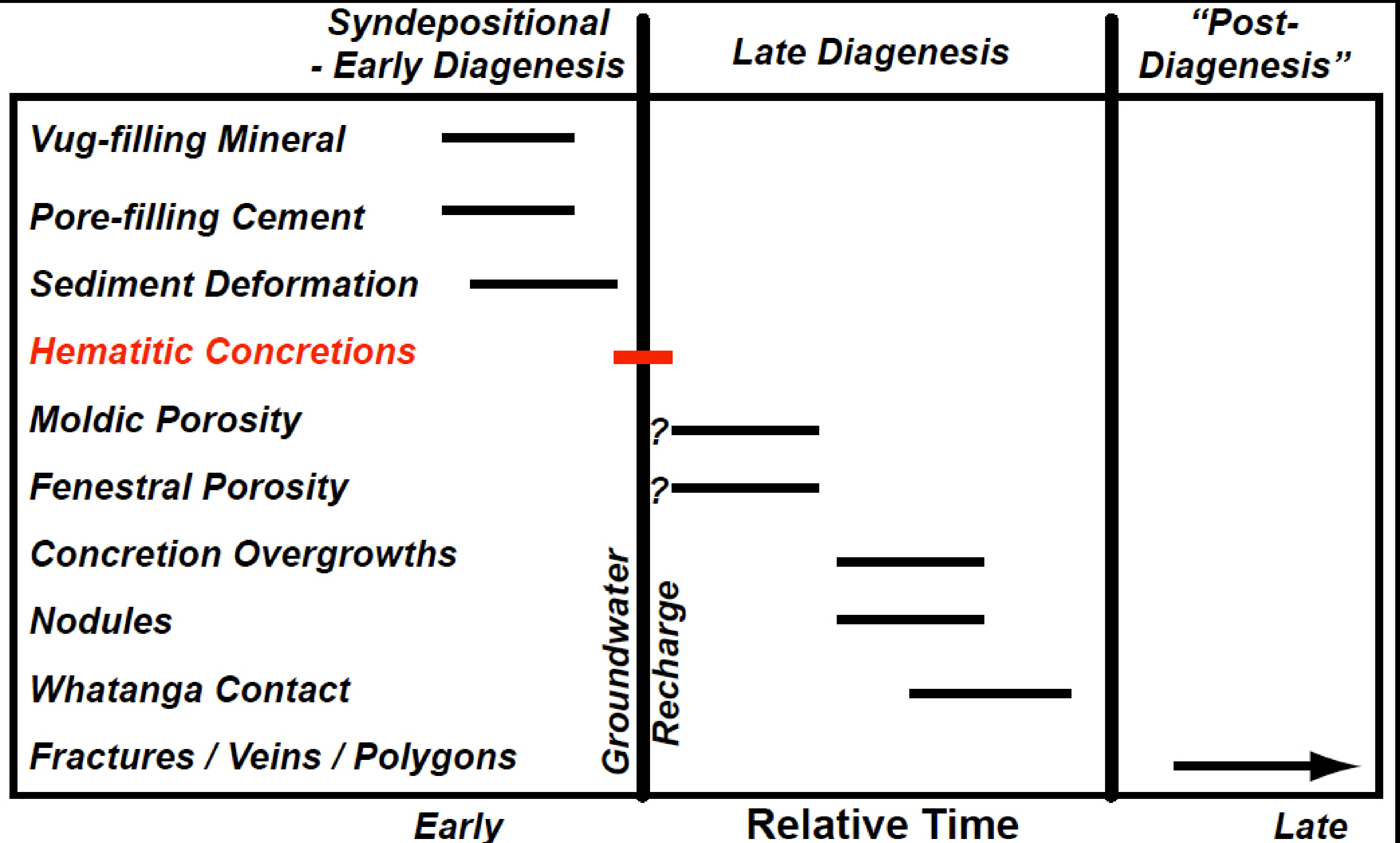
Fig. 2. Simplified model of diagenetic history.

McLennan, et al. (2006)

Deposition and diagenesis of sulfate-rich bedrock at the MER Meridiani site



Knoll, et al. (2005)



Indicates multiple & persistent groundwater episodes

McLennan et al., EPSL (2005)

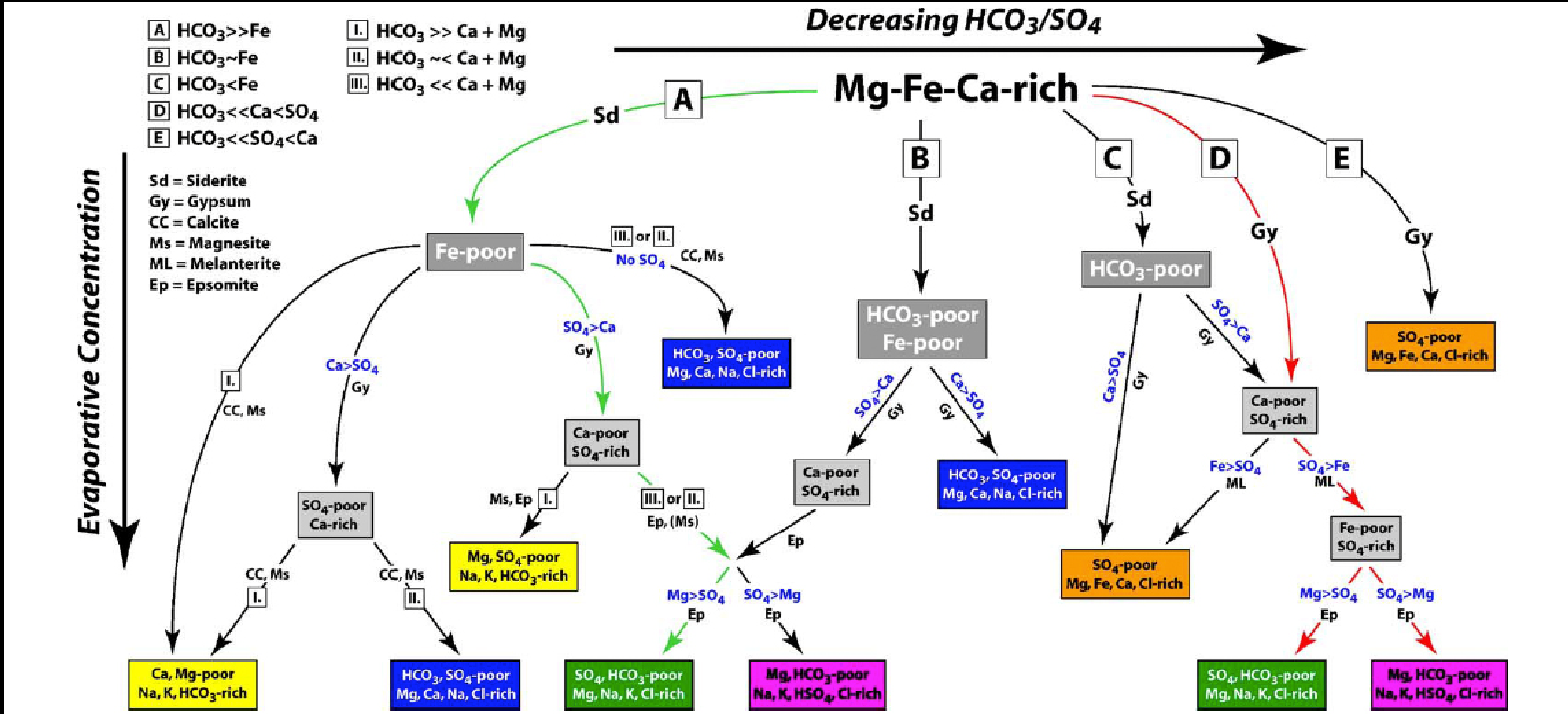


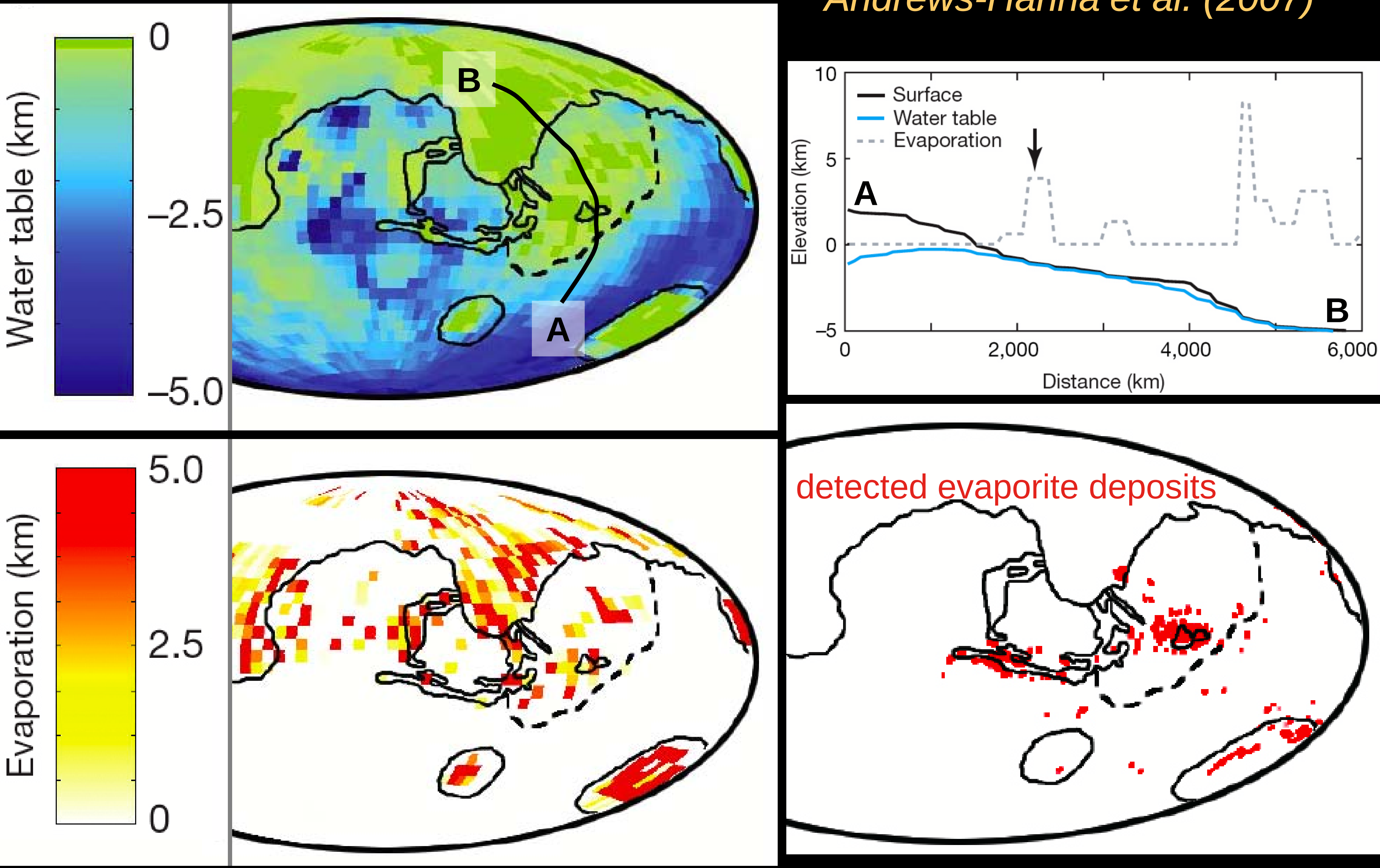
Fig. 2. Flow chart for the chemical evolution of evaporating fluids derived by basaltic weathering. Evaporative concentration increases downward and the relative amount of HCO_3^- to SO_4^{2-} decreases to the right. Precipitates causing chemical divides are indicated as are conditions leading to chemical fractionation from mineral precipitation. The resulting brines and their characteristics are described in boxes. The precipitation pathways for the Nakhla (green arrows) and Meridiani Planum (red arrows) evaporite assemblages correspond to two distinct geochemical environments for saline mineral formation on Mars.

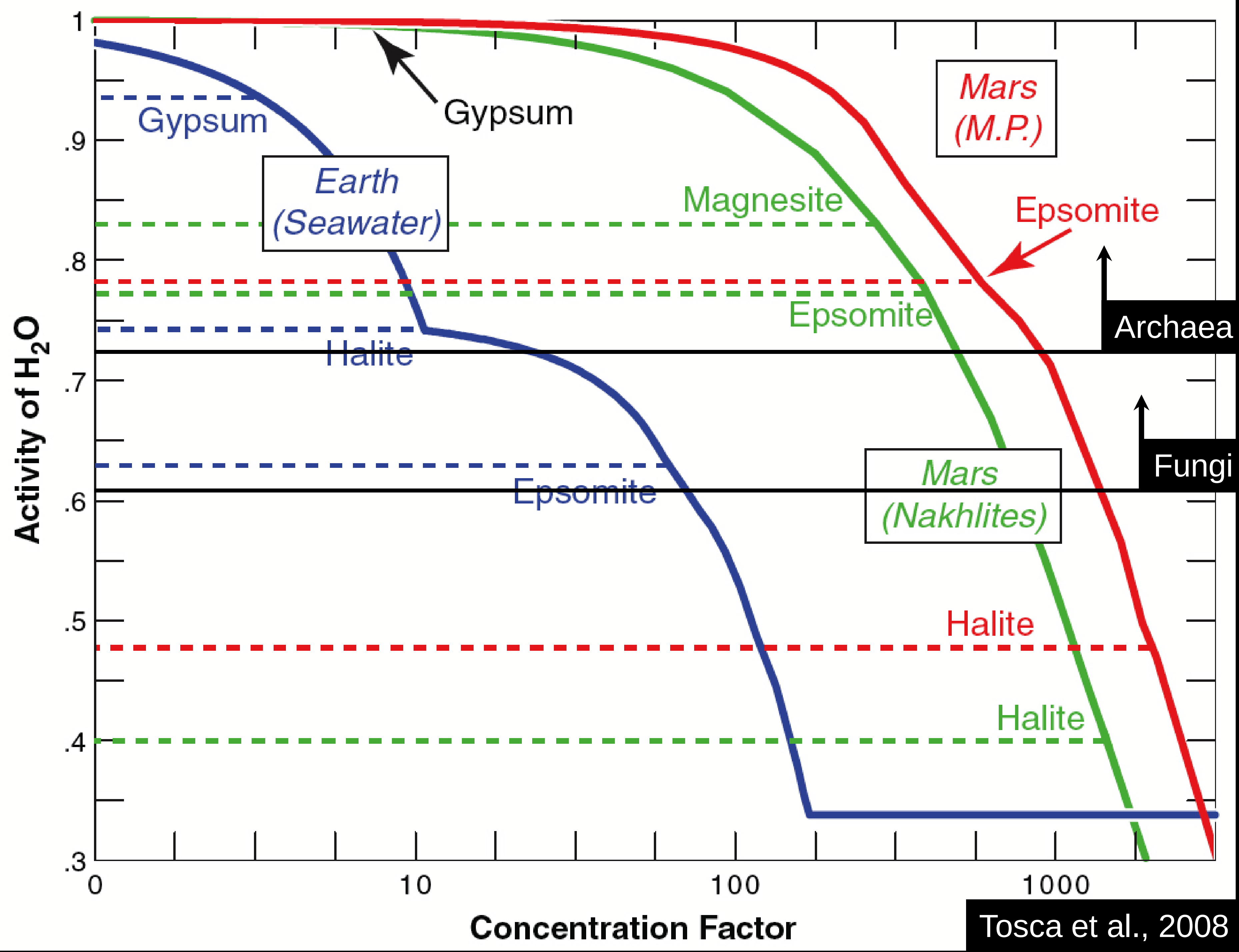
Brine type	Symbol	Characteristics	Typical precipitates
TYPE I	Ca, Mg, SO_4-poor Na, K, HCO_3-rich	Acid brine (pH 3–4), Na > K - Bicarbonate brine	Nahcolite, kalicinite
TYPE II	HCO_3, SO_4-poor Mg, Ca, Na, Cl-rich	Acid brine (pH 0–2), Mg > Ca > Na - Chloride brine	Halite, sylvite, bischofite, antarcticite
TYPE III	SO_4-poor Mg, Fe, Ca, Cl-rich	Acid brine (pH 0–2), Mg > Fe > Ca -Chloride brine	Halite, sylvite, bischofite, antarcticite
TYPE IV	SO_4, HCO_3-poor Mg, Na, K, Cl-rich	Acid brine (pH 0–2), Mg > Na > K - Chloride brine	Halite, sylvite, bischofite
TYPE V	Mg, HCO_3-poor Na, K, HSO_4, Cl-rich	Acid brine (pH 0–2), Na > K > HSO_4 - Chloride brine	Bloedite, polyhalite, glauberite, thenardite

Tosca et al., EPSL (2006)

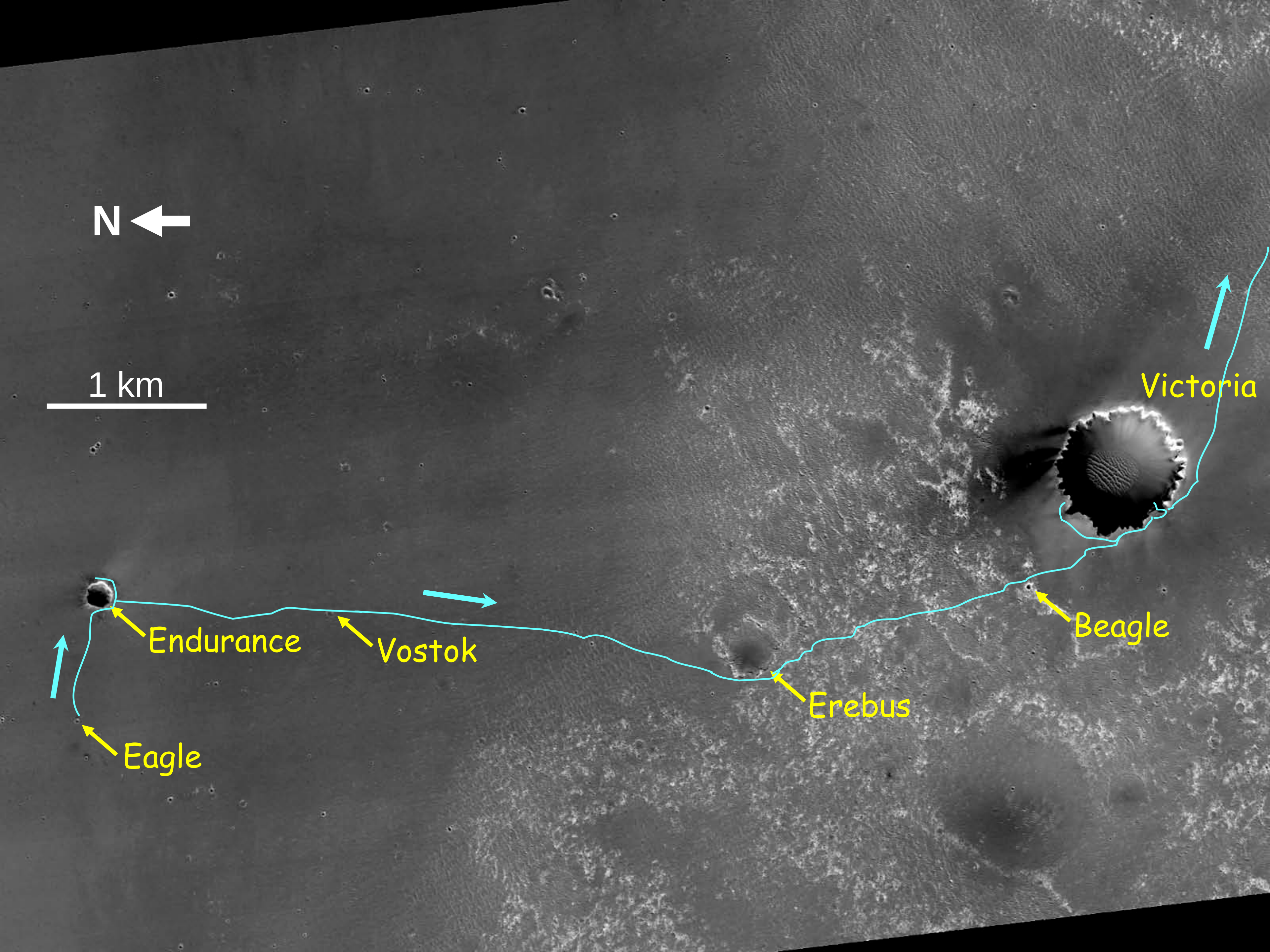
Meridiani Planum and the Global Hydrology of Mars

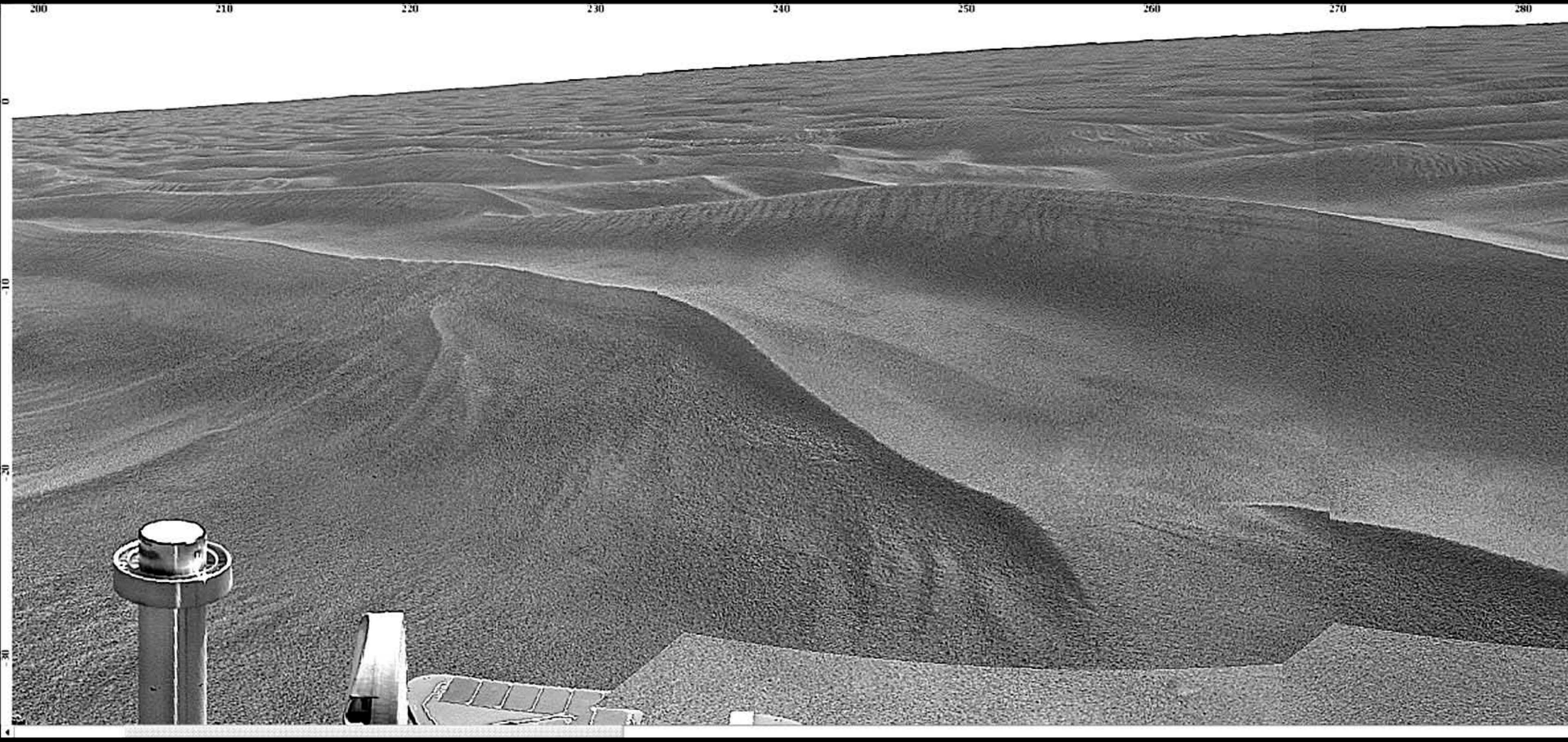
Andrews-Hanna et al. (2007)





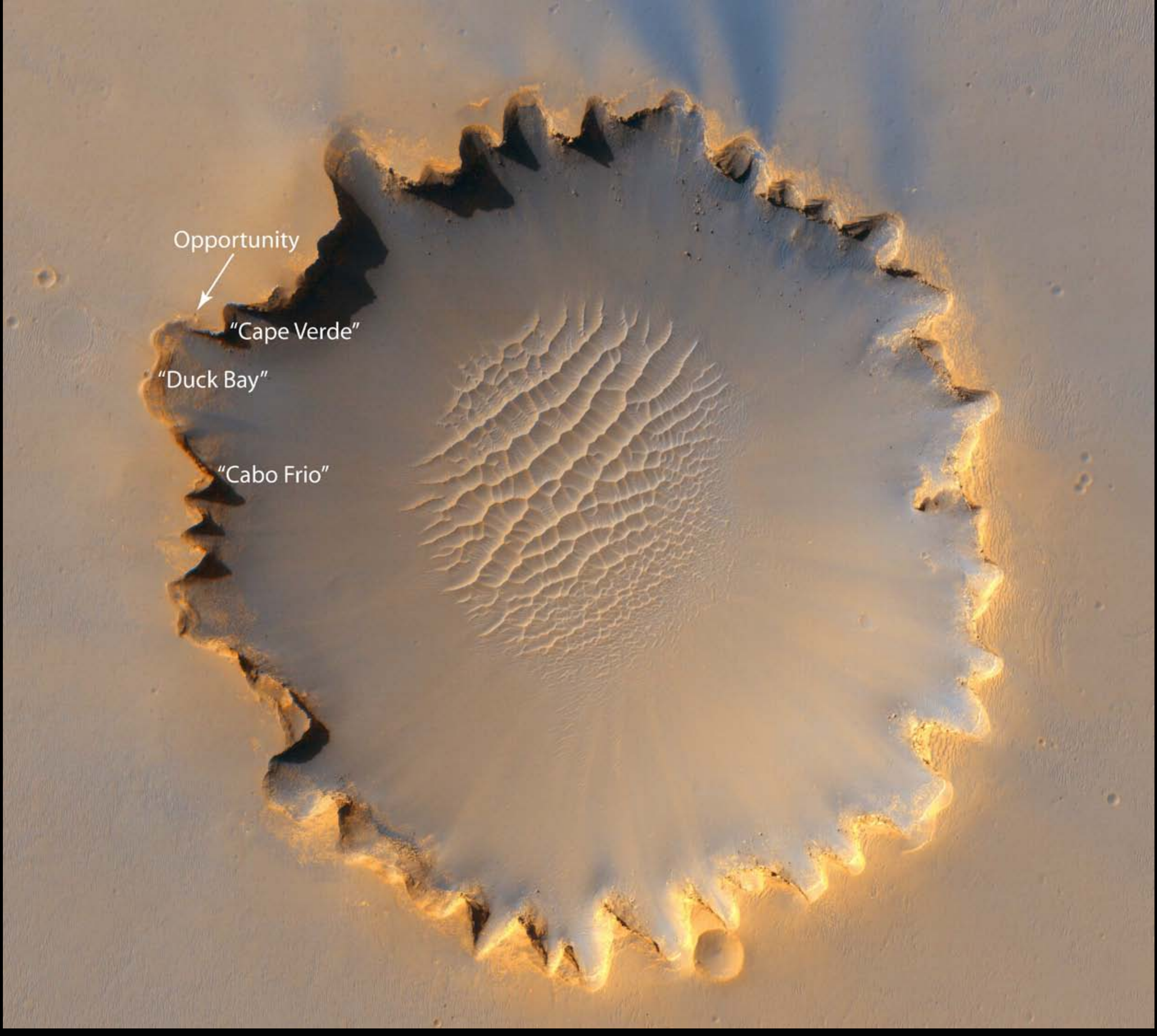
1
.9
.8
.7
.6
.5
.4
.3
0
10
100
1000
Activity of H_2O
Concentration Factor
Gypsum
Gypsum
Earth
(Seawater)
Magnesite
Epsomite
Halite
Epsomite
Mars
(M.P.)
Epsomite
Archaea
Fungi
Mars
(Nakhlites)
Halite
Halite
Tosca et al., 2008


N
1 km
Victoria
Endurance
Vostok
Erebus
Beagle
Eagle



Opportunity’s “months at sea”

destination: Victoria crater, 750 m diameter, 70 m deep


Opportunity
“Cape Verde”
“Duck Bay”
“Cabo Frio”


Victoria Crater
Cape St. Vincent
super-resolution image

OPPORTUNITY’S KEY FINDINGS:

Abundant soluble sulfate minerals
Hematite-rich diagenetic concretions
Finely-laminated festoon cross-beds
Acidic conditions (e.g., jarosite)
Remobilization of soluble salts
Playa lakes, sand sheets, dunes
Persistent near-surface water

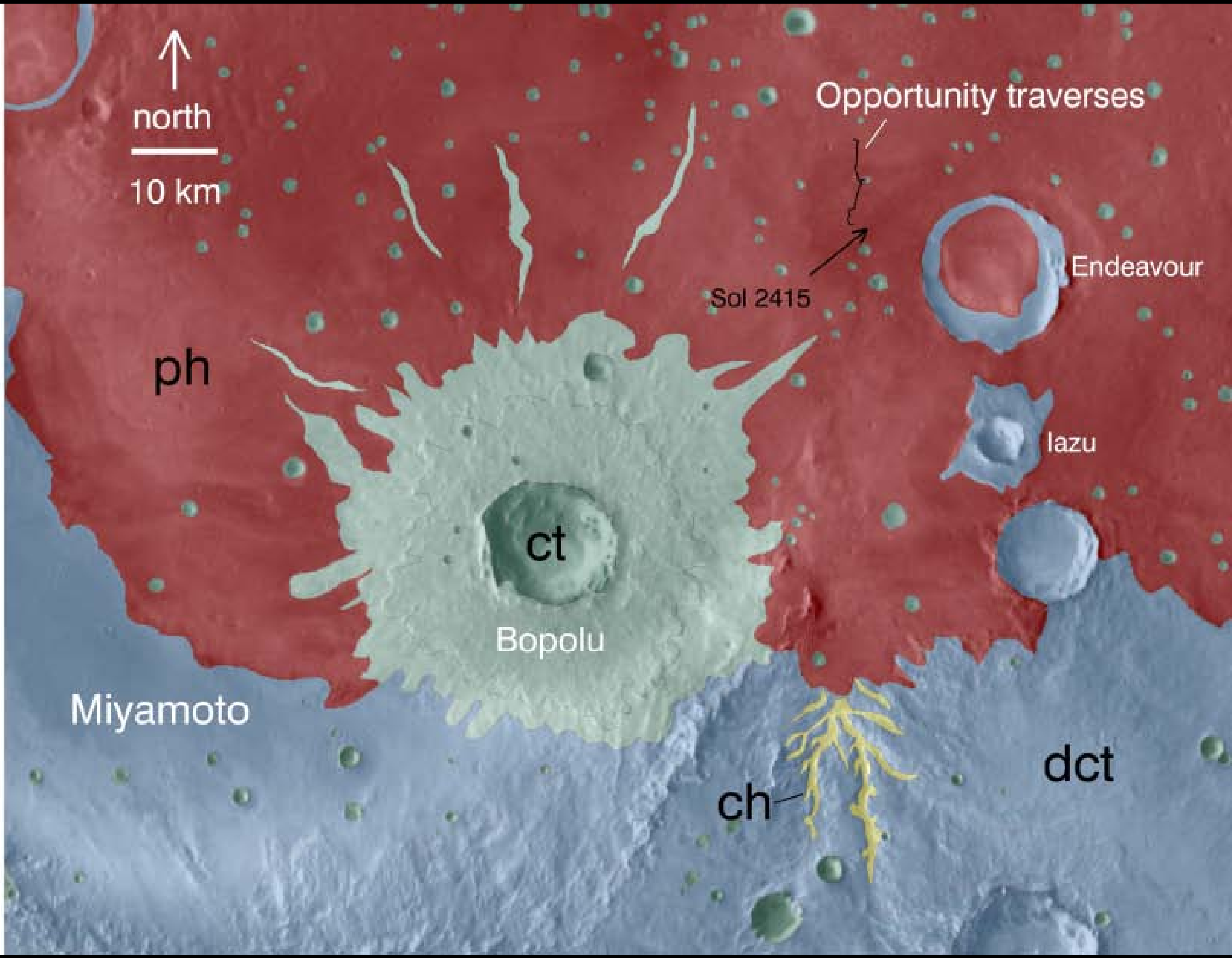
Meridiani Planum Geologic Setting

ct-post Noachian craters

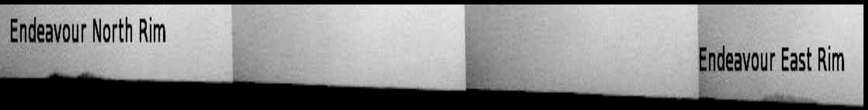
ph-hematite-bearing plains

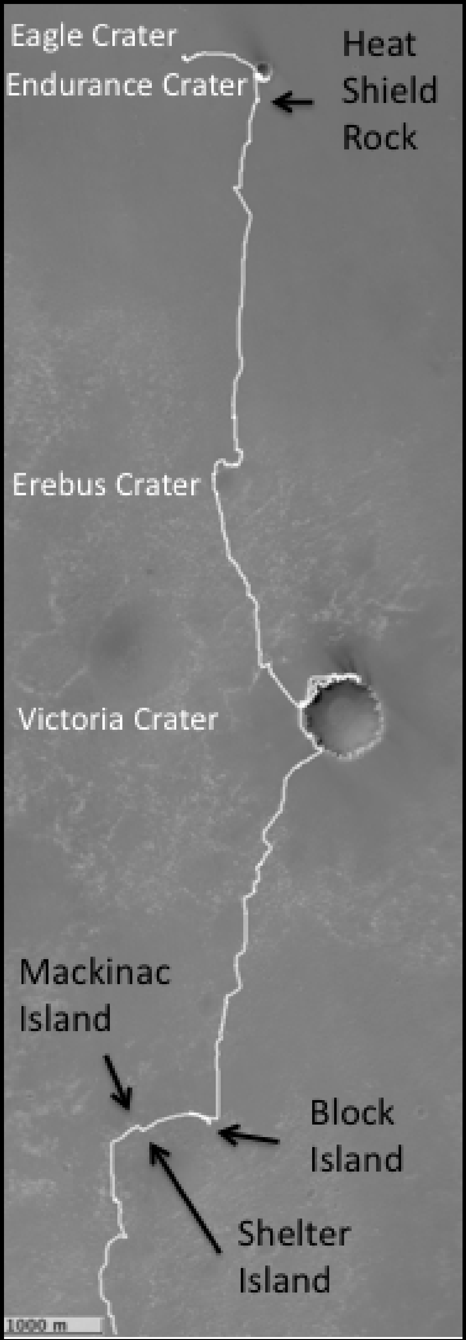
ch-channel

dct-Noachian cratered terrain



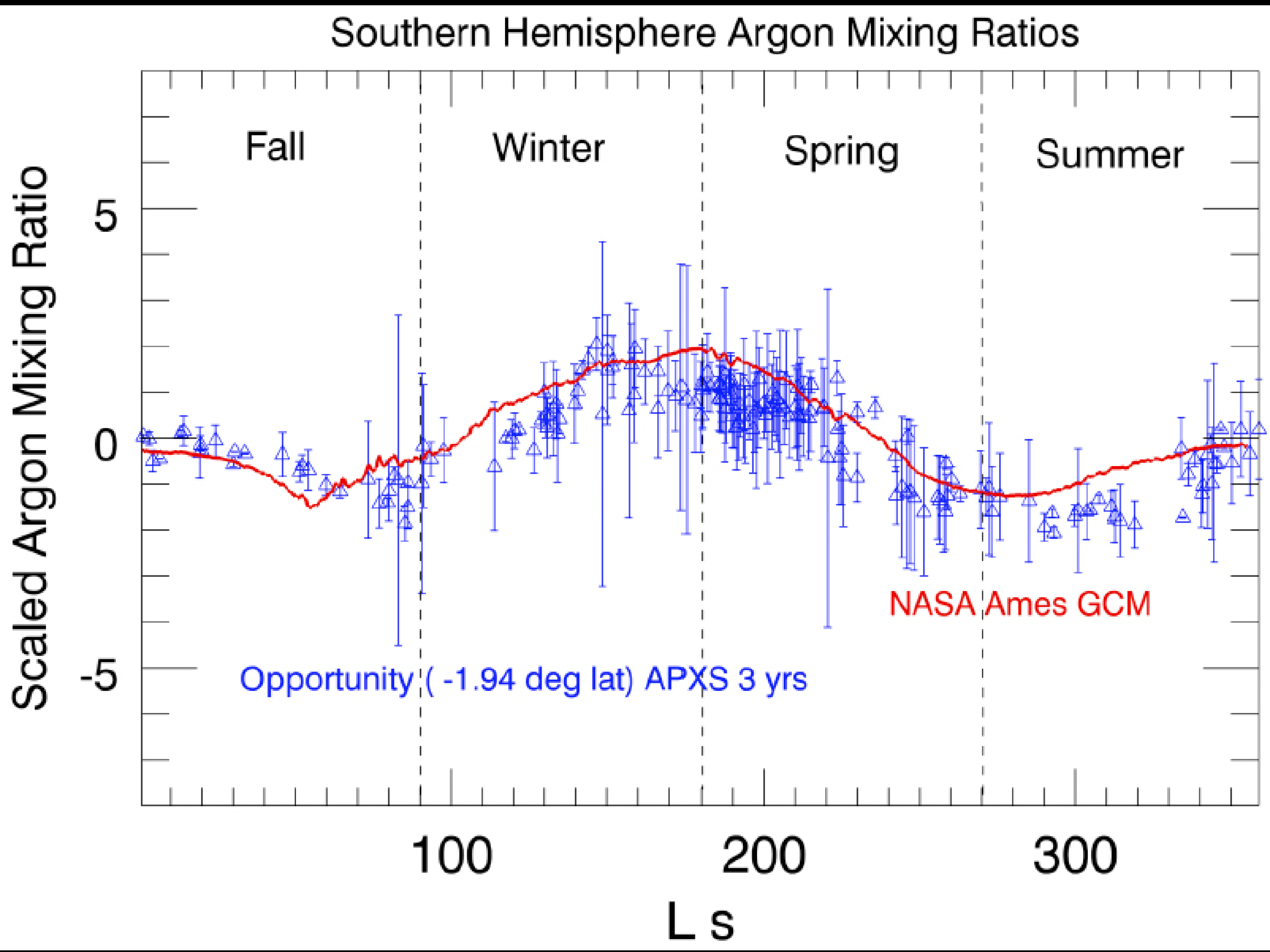
Endeavour Crater on the Horizon…



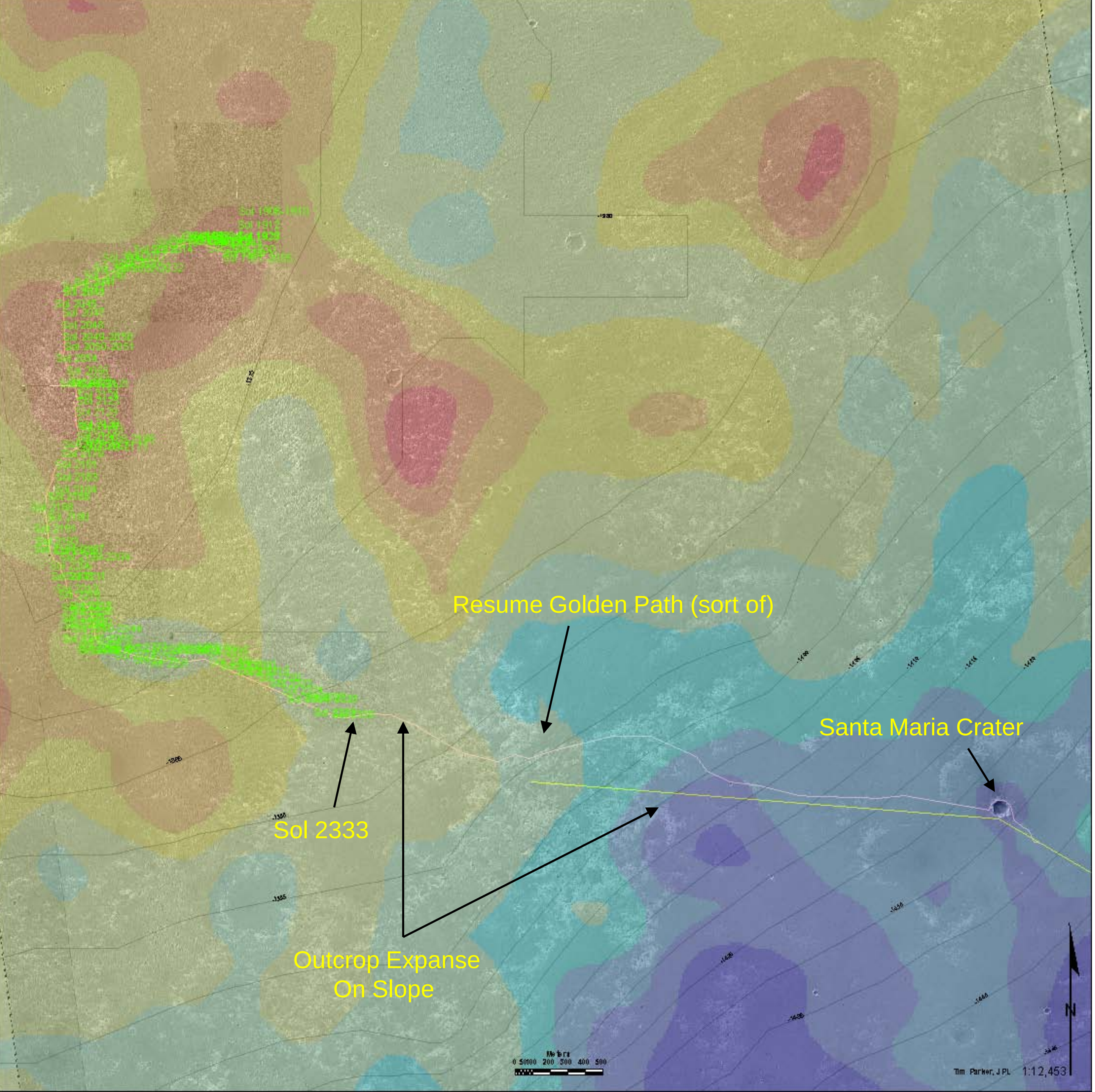


* Four Large Nickel Iron Meteorites, 3 IAB Irons
* All Smooth Surfaces w/Hollows Likely Regmaglypts
* Record Atmospheric Ablation
* Landed <2 km/s, Not Hypervelocity Impact
* Atmosphere Dense Enough to Land Large Iron Meteorites? *
  - Are Irons Part of Same Fall? “Paired”
  - Where are Large Stony Meteorites?
* Small Meteorites Expected [Bland & Smith, 2000]

* Chappelow & Golombek: Landing Meteorites



Southern Hemisphere Argon Mixing Ratios
Fall
Winter
Spring
Summer
5
0
-5
Scaled Argon Mixing Ratio
100
200
300
L s
NASA Ames GCM
Opportunity (-1.94 deg lat) APXS 3 yrs

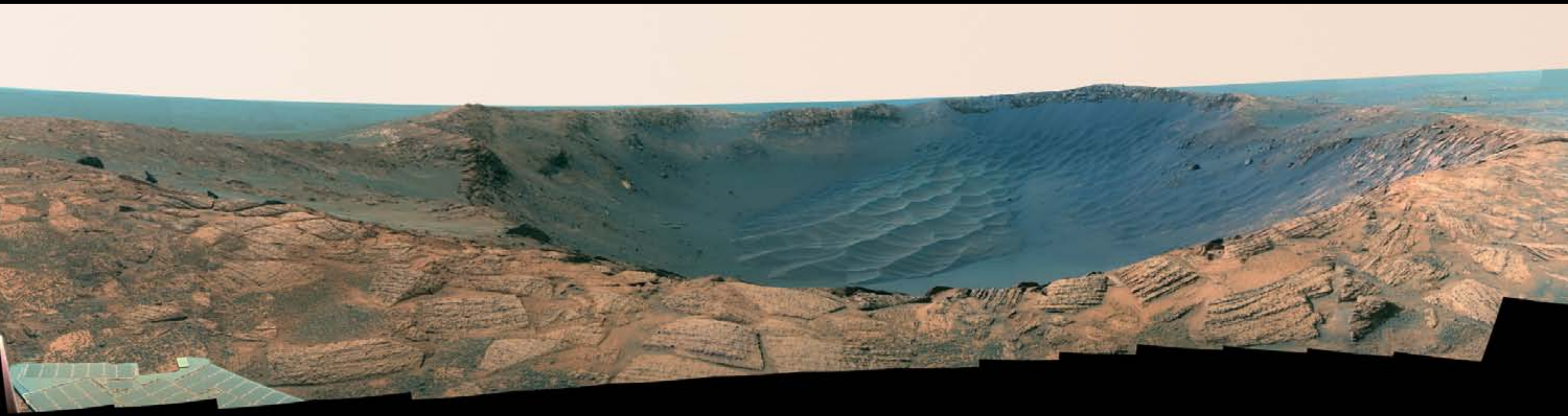


Science along the Pink/Golden Path

Entire Pink Path

(HRSC DEM/MOLA contours)

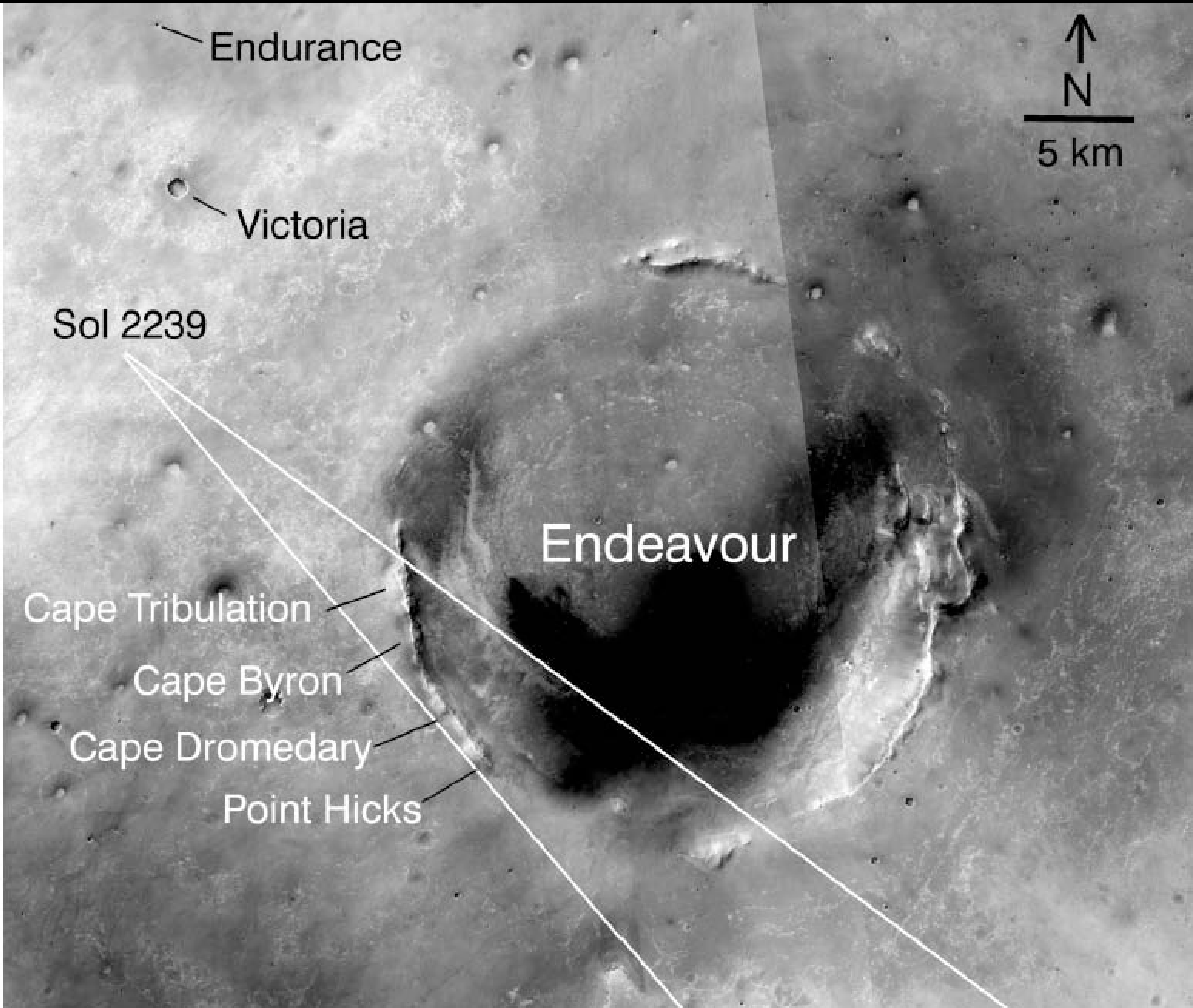
Adjustments in path made to visit outcrop contacts (“festoons”), gravel banks, fresh craters

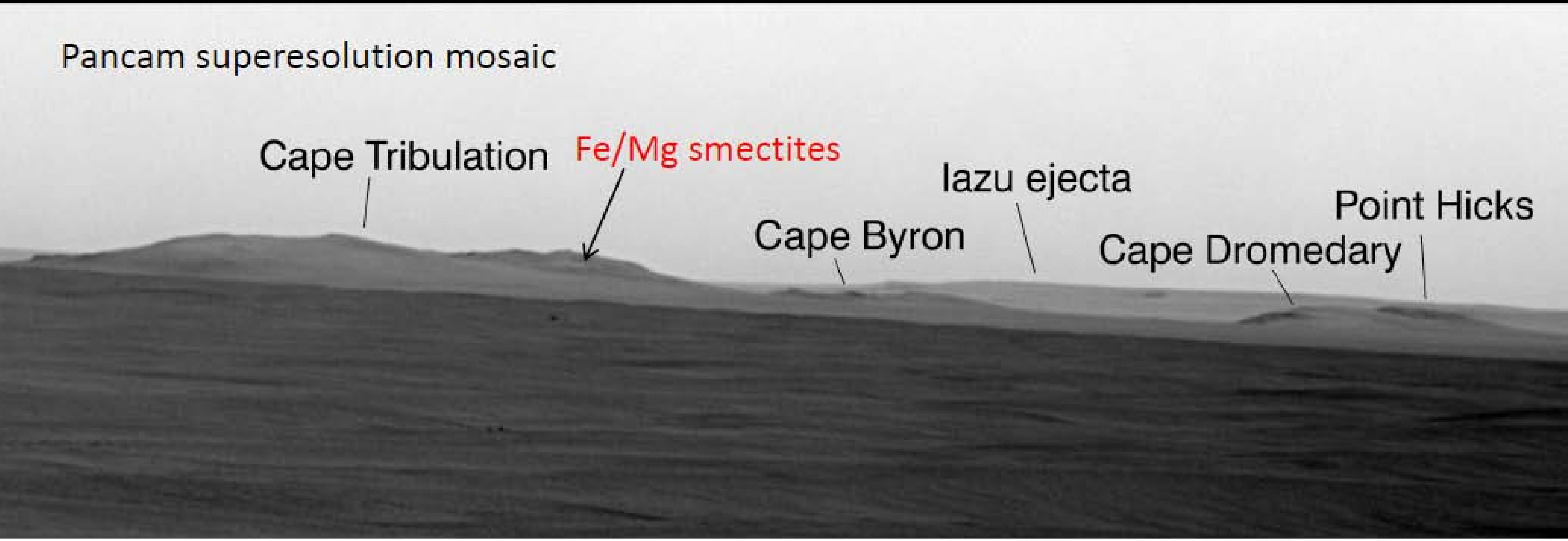


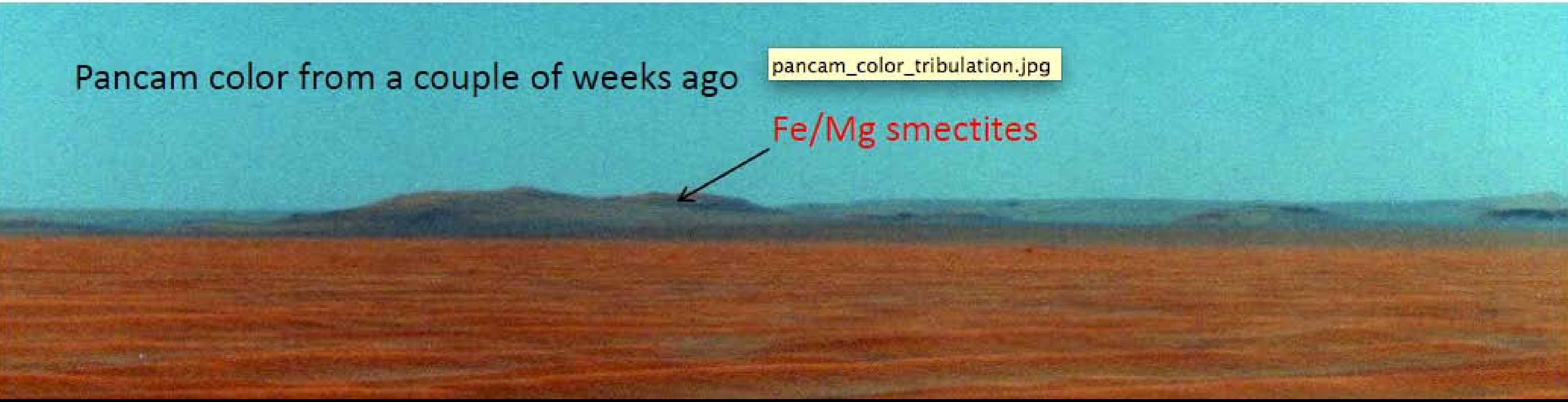
Santa Maria crater, Meridiani Planum
Sol 2539

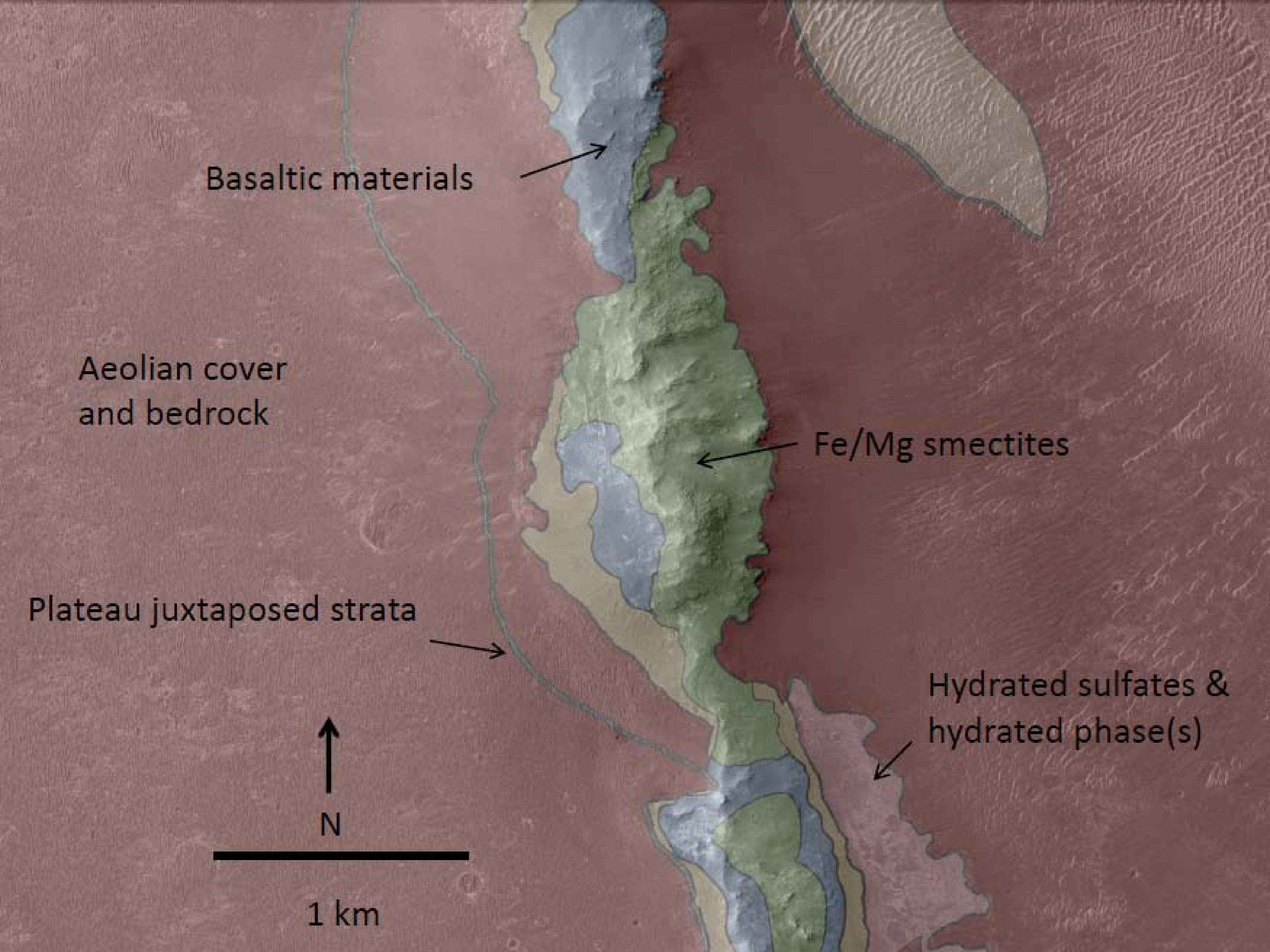
CTX image

White lines show Pancam coverage next slide

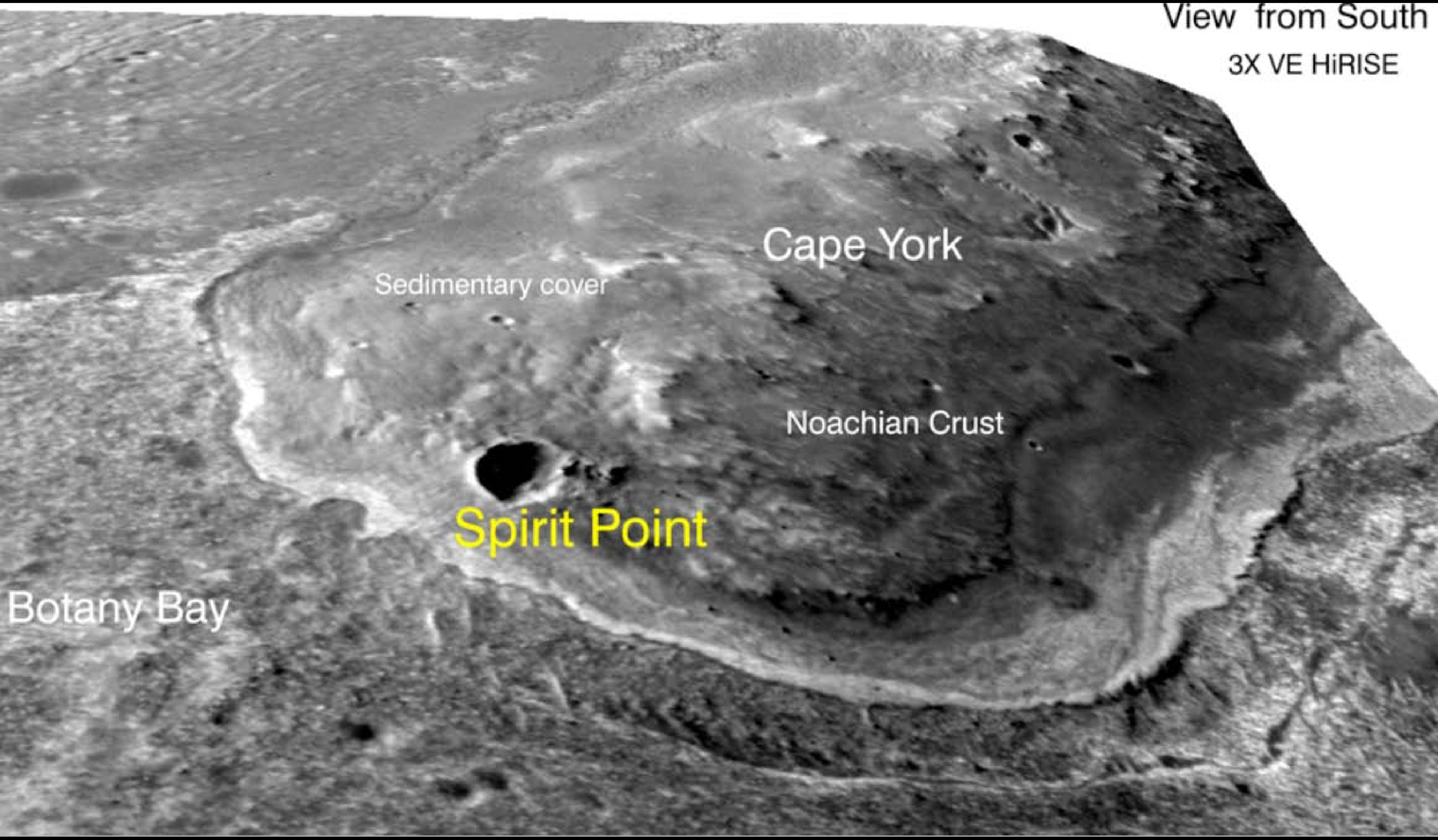



Pancam superesolution mosaic
Cape Tribulation
Fe/Mg smectites
Iazu ejecta
Cape Byron
Point Hicks
Cape Dromedary

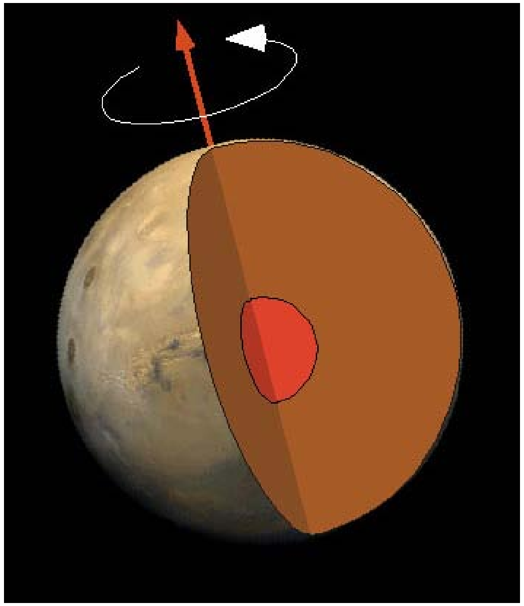

Pancam color from a couple of weeks ago
pancam_color_tribulation.jpg
Fe/Mg smectites



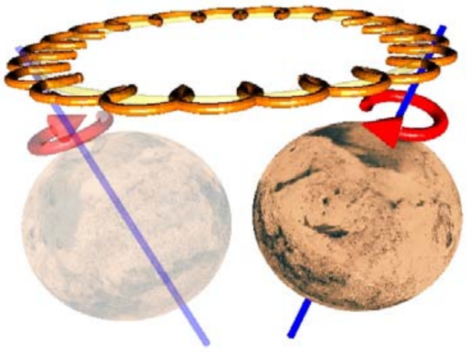
Basaltic materials
Aeolian cover
and bedrock
Fe/Mg smectites
Plateau juxtaposed strata
Hydrated sulfates &
hydrated phase(s)
N
1 km


View from South
3X VE HiRISE
Cape York
Sedimentary cover
Noachian Crust
Spirit Point
Botany Bay

MER Radio Science: Martian Core



- Science objectives are to determine size, state, and density of Mars core.
  - Provide insight into evolution of terrestrial planets.
  - Provide information on whether Mars could ever have had a global magnetic field, enhancing probability of life.
- Core parameters are derived from determining time-dependent spin-axis direction (precession/nutation).
  - Two-way Doppler tracking of fixed lander gives spin axis direction at time of track.
    - Normally, Doppler tracking of rovers determines varying position of rover, not spin axis direction.
- MER tracking over many months can:
  - Improve precession estimate by a factor of ~5.
  - Possibly observe free-core nutation, giving core state (liquid/solid).




Still looking forward to more tomorrows ….

End…

Importance of systems engineering testing:
Dress rehearsal for the Rock Abrasion Tool (RAT)