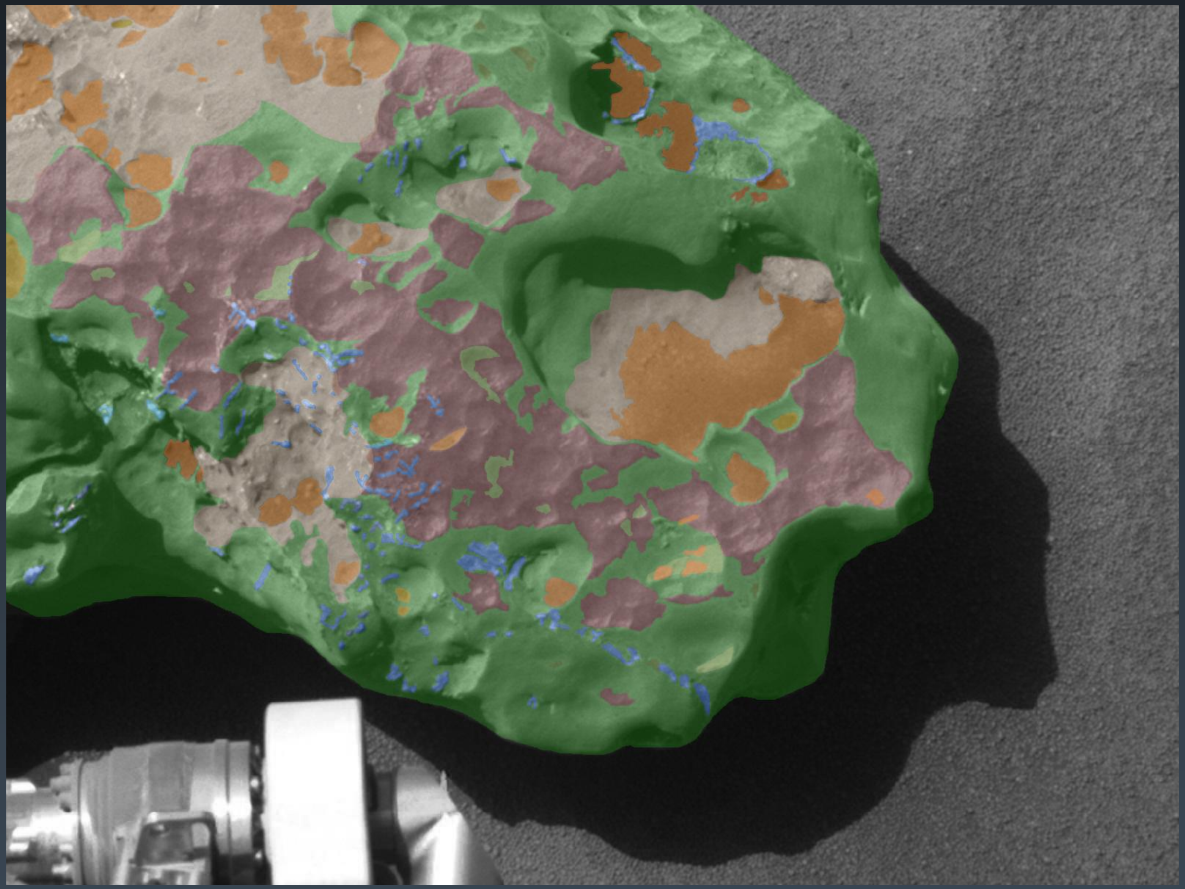
Meteorite Weathering on Mars — Updates on Exogenic Iron Survivability Biases and Micro-mapping of Meridiani Planum Block Island MI Mosaics



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Overview

- Meteorites found on Mars provide complementary insights into chemical and physical surface alteration processes.
- Spirit, Opportunity, and Curiosity have now discovered 23 confirmed and candidate meteorites at their respective rover landing sites (15 appear to be irons).
- The challenge is to identify and separate features resulting from:
  - Ablation (pre-fall); speaks to freshness of sample. Includes regmaglypts, pits, grooving, fusion crusts.
  - Weathering (post-fall); reflects surface processes/exposure histories. Includes acidic corrosion, aeolian scouring, oxide production.
- This talk will touch upon:
  1. The importance of getting the regmaglypt question right;
  2. Qualitative comparisons with curated meteorites. [A quantitative morphometric comparison study using 3D imaging and digital processing of terrestrial analogs has been proposed as Task 1 in a recent MDAP]; and
  3. Ventifact analog comparisons for a possible boring process.

Introduction to Martian Meteoritics

- *Traditional thinking about meteorite relevance*
  - parent body formation and solar system evolution
  - pre-solar nebula/ISM formation environments;
  - stellar nucleosynthesis and galactic chemistry

- Finding non-indigenous rocks on other planets forces us to rethink meteoritical definitions/language and generalize to the concept of “exogenites” throughout the solar system

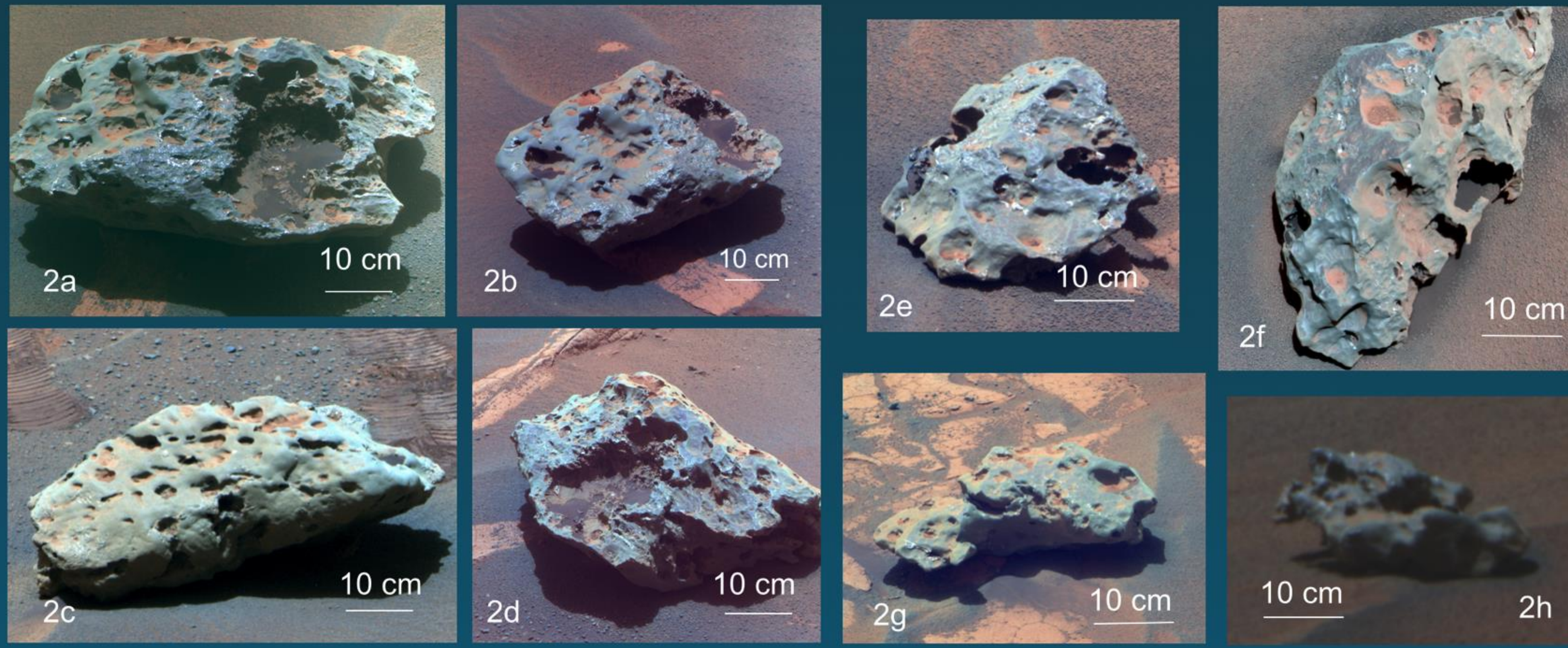
Several outstanding questions in Mars science encompass an exogenic dimension ...

- Source of organics in martian soils (*ref*);
- Source of nickel in martian soils (*ref*);
- Atmospheric methane source (*ref*);
- As a potential food source for microbes (*Fries et al., 2009*);

Non-Mars-Specific Science	***In Situ*, Mars-Specific Science**
Type frequency distributions and variations between Earth and Mars finds	Constraints on the martian atmospheric density [Chappelow and Sharpton, 2006; Chappelow and Golombek, 2010].
Delivery dynamics (soft landings vs. hypervelocity impact)	Assisting with martian habitability assessments [e.g., Steele et al., 1999].
Compositional variability among main-belt asteroids	Understanding better the contributions of extraterrestrial materials to martian soils and sedimentary rocks [Yen et al., 2005; 06].
Unanticipated applications	Witness samples for weathering and climate history assessment [Ashley et al., 2011].
	Improving our understanding of impact processes and relative age dating on Mars [Golombek and Chappelow, 2010].
	Overlap with recent impact studies (seismicity/InSight mission, abs. 259-12)

Partial Iron Inventory

Figures 2a through 2d (right) present Block Island as viewed from the north, east, south, and west, respectively. Note large, cavernous pit on western (right) third of the north side in 2a. Mackinac Island, Shelter Island, Oileán Ruaidh, and Ireland, are presented in figures 2e, 2f, 2g, and 2h, respectively. Image credits: NASA/JPL/Pancam/MI.



Lebanon A and B, Gale crater

Zong Shan and Alan Hills, Gusev crater

Two new finds within last six months ~

Egg Rock; Low Ridge, Gusev crater *NASA/JPL/Mastcam*

Ames Knob; Low Ridge, Gusev crater *NASA/JPL/Mastcam*

- Either very different compositionally, or they have been subjected to different weathering processes (unlikely given their close proximity).
- Evidence for taxonomic diversity, which should caution against pairing assumptions, and support measurements in future.

See poster #2258, Meslin et al., Thursday poster session.

Current Mars meteorites and meteorite candidate inventory

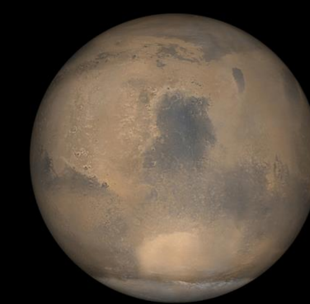
Meteorite	Rover	First sol encountered	Type (suspected or confirmed)	Instrumentation employed
Heat Shield Rock*	Opportunity	339	IAB complex iron	MTES/Pancam/APXS/MB/MI
Block Island	Opportunity	1961	IAB complex iron	Pancam/APXS/MB/MI
Shelter Island	Opportunity	2022	IAB complex iron	Pancam/APXS/MB/MI
Mackinac Island	Opportunity	2034	iron	PancamNavcam
Oileán Ruaidh	Opportunity	2368	iron	PancamNavcam
Ireland	Opportunity	2374	iron	PancamNavcam
Bingag Cave	Opportunity	2642	iron	PancamNavcam
Dia Island	Opportunity	2642	iron	PancamNavcam
Allan Hills	Spirit	858	iron	MTES/Pancam/Navcam
Zhong Shan	Spirit	858	iron	MTES/Pancam/Navcam
Lebanon	Curiosity	634	iron	Mastcam/ChemCam RMI
Lebanon B	Curiosity	634	iron	Mastcam/ChemCam RMI
Littleton	Curiosity	634	iron	Mastcam/ChemCam RMI
Egg Rock	Curiosity	1505	iron	Mastcam/LIBS
Ames Knob	Curiosity	1577	iron	Mastcam/LIBS
Barberton	Opportunity	121	stony-iron	PancamNavcam
Santa Catarina	Opportunity	1034	stony-iron	MTES/Pancam/APXS/MB/MI
Joacaba	Opportunity	1046	stony-iron	MTES/Navcam
Mafra	Opportunity	1151	stony-iron	MTES/Navcam
Paloma	Opportunity	1190	stony-iron	MTES/Navcam
Santorini	Opportunity	1713	stony-iron	Pancam/APXS/MB/MI
Kasos	Opportunity	1889	stony-iron	Pancam/APXS/MB/MI
Canegrass	Opportunity	3346	stony	Pancam/Navcam

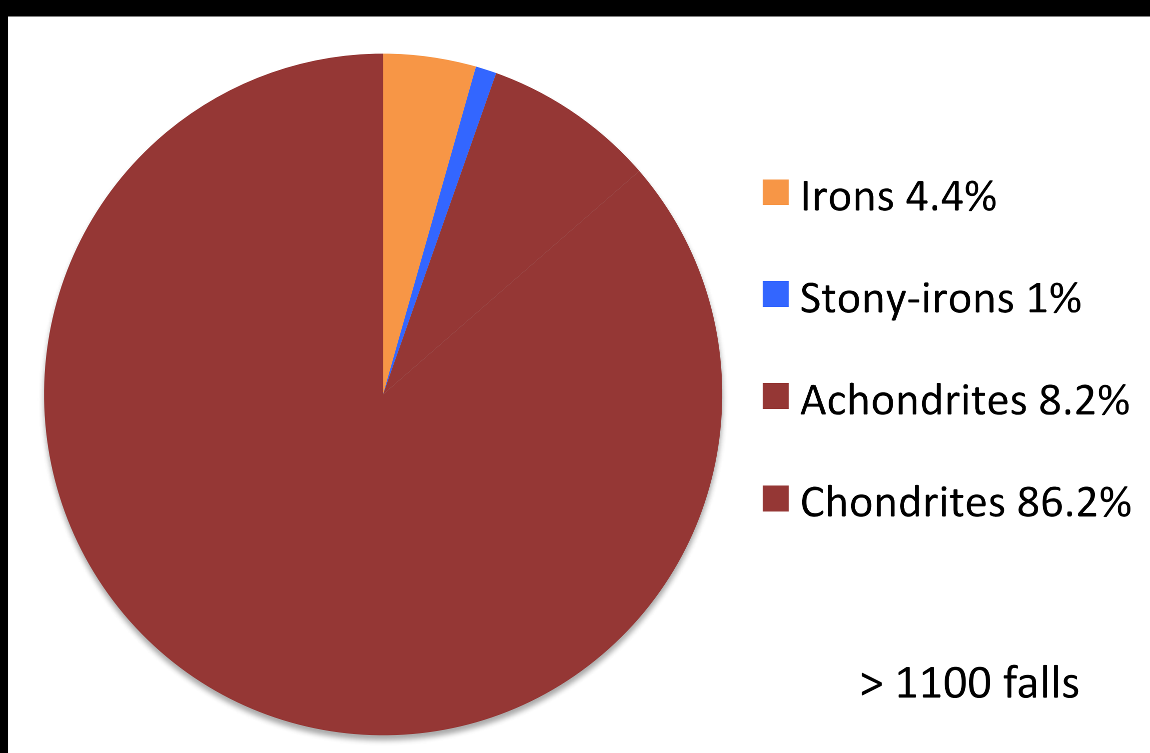
* Official name: Meridiani Planum; [*Connolly et al.,* 2006]

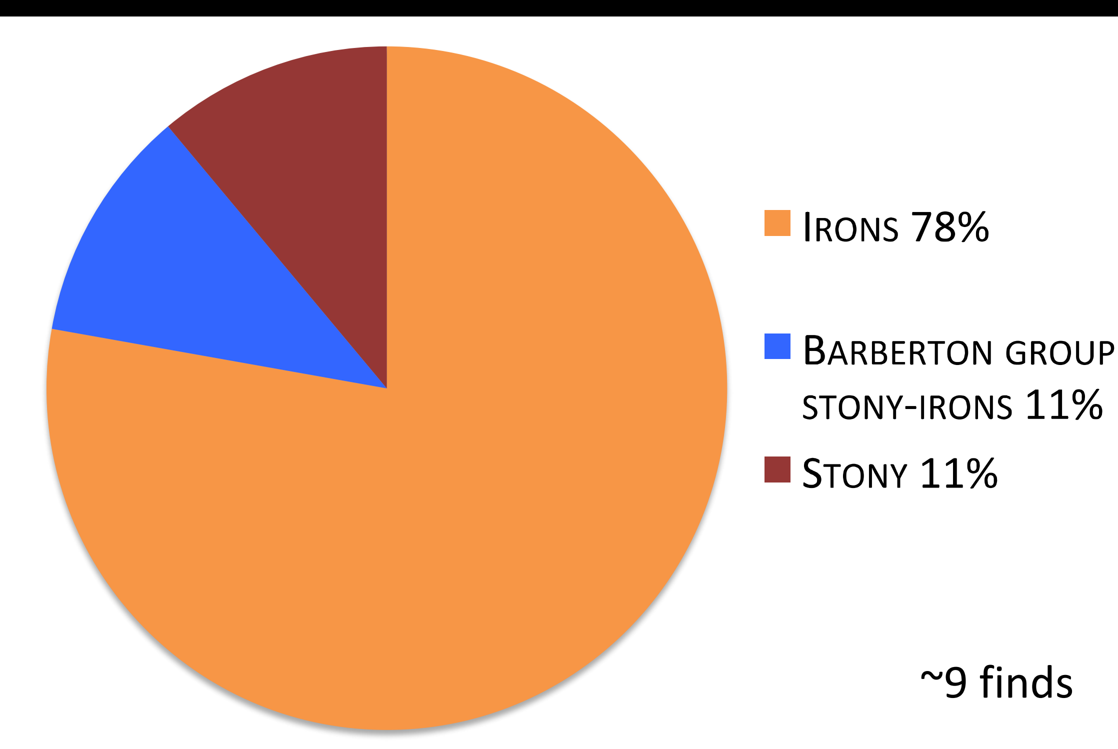
Interplanetary comparison

Earth Falls

Martian Finds



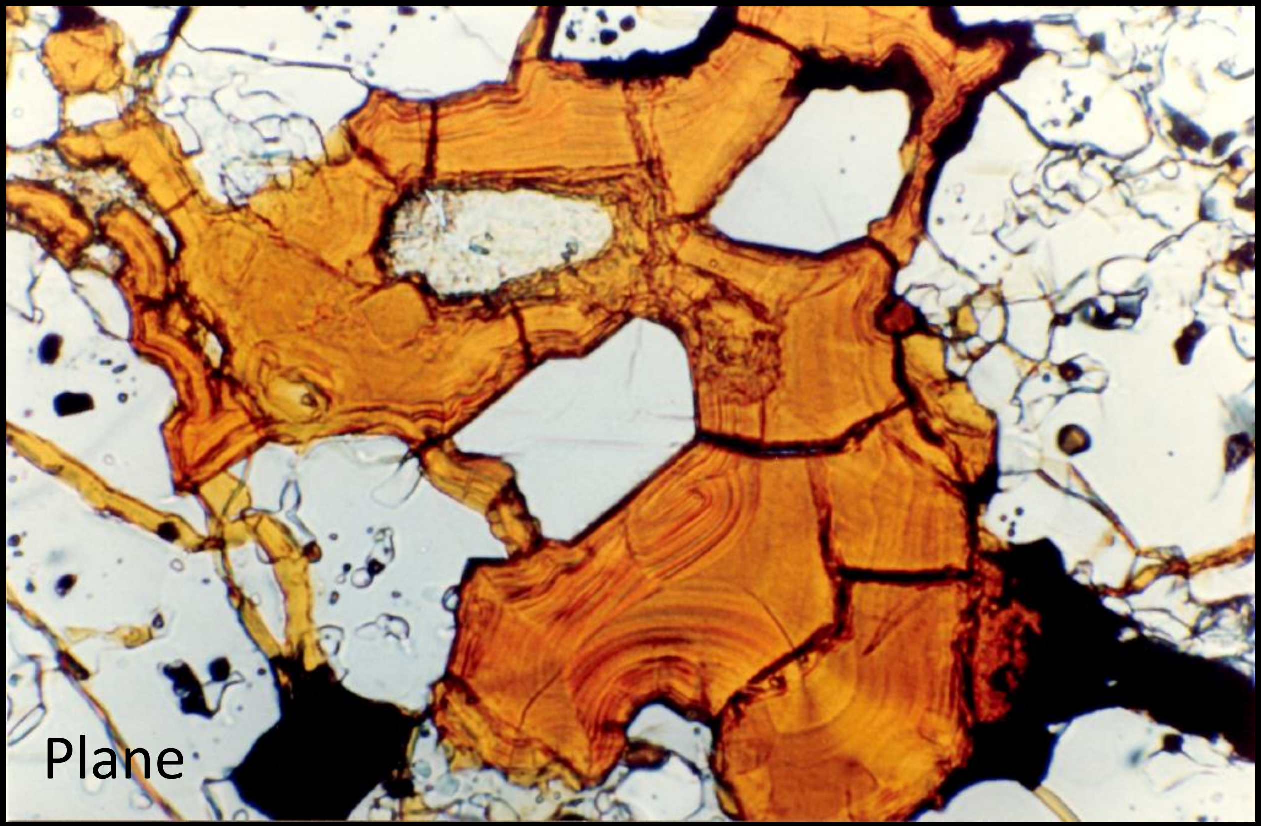


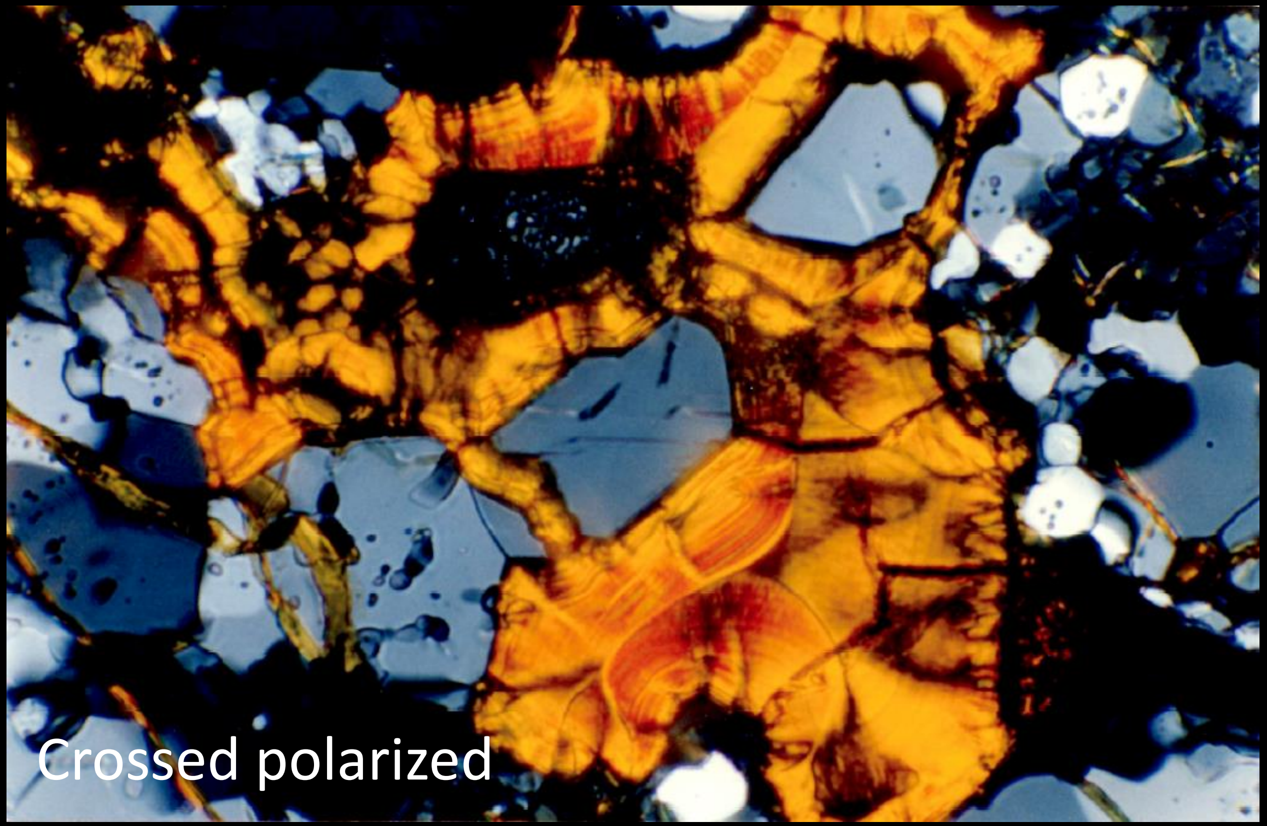


Possible Sources of Anomalous Iron Bias

- Survivability biases (may favor stronger irons over weaker stony meteorites during EDL; atmospheric passage and impact)
- Selection biases favor iron identification (just as on Earth) because — largely a function of size when rover operations and science objectives tend to prefer cobble-sized and larger rocks.
  - ✓ Fragmentation from post-fall weathering may enhance this

Antarctic Ordinary Chondrite Weathering





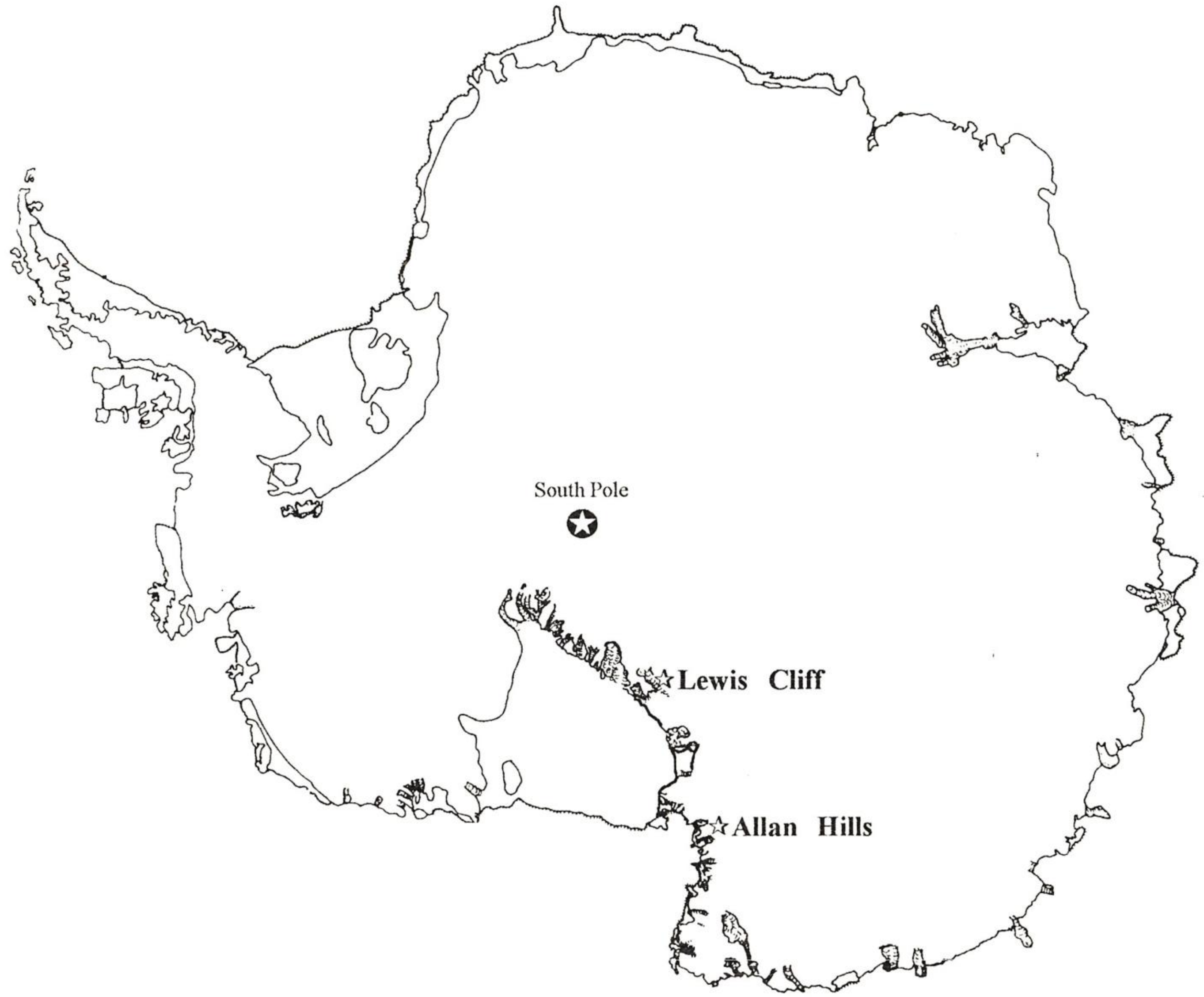
ALH77271, 28. Frame dimensions 160 x 240 microns

Carichic in reflected. Slide is 1 x 1 ¾ inches

Curatorial Weathering

Incipient re-oxidation of the bare metal portion (grey-toned right side) of a sandblasted 10 kg Canyon Diablo sample (images collected at ~2- to 4-year intervals).

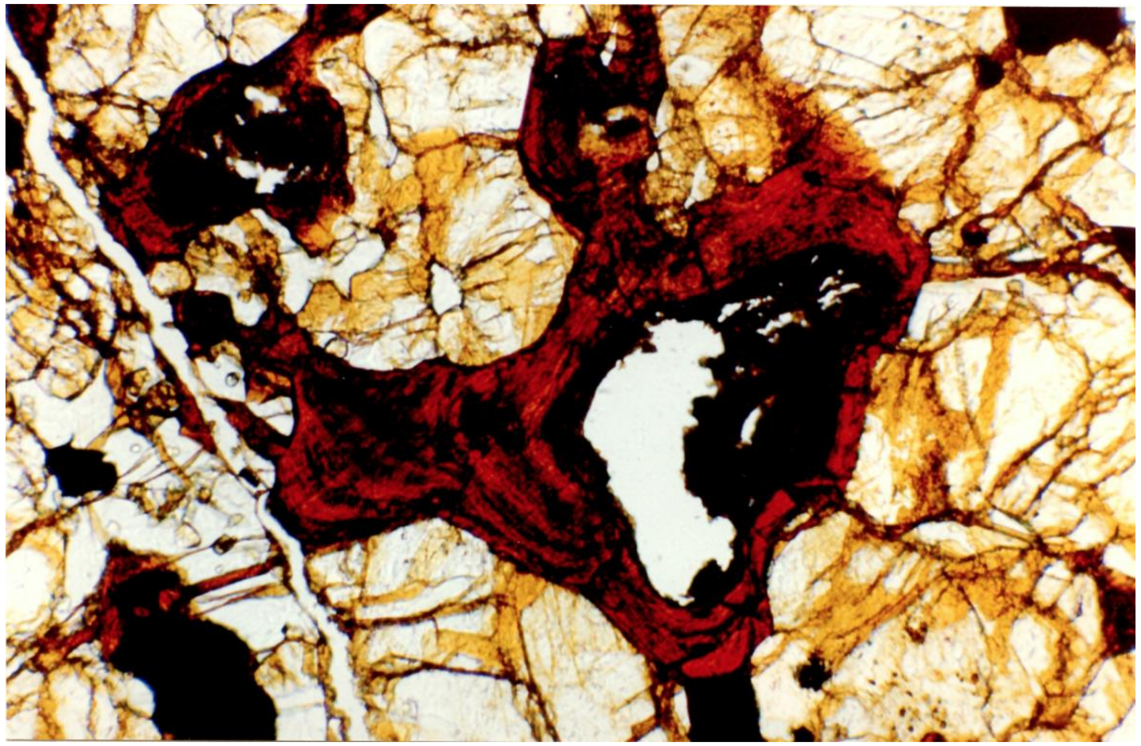
Insights from Antarctica using 19 weathering category C ordinary chondrites



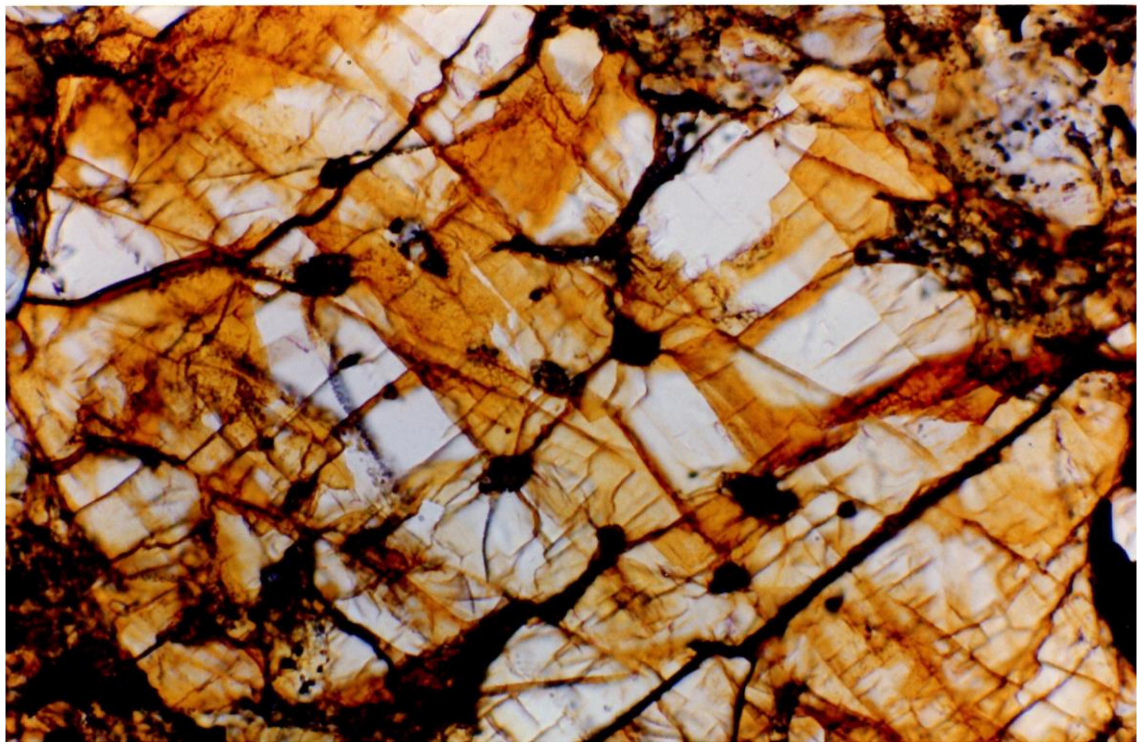
Specimen	Group and type
ALHA81031	L3
ALHA77230	L4
ALHA81027	L6
ALHA77004	H4
ALHA77208	H4
ALHA77225	H4
ALHA77226	H4
ALHA77232	H4
ALHA77233	H4
ALHA77182	H5
ALHA79025	H5
ALHA79029	H5
ALHA84075	H5
ALHA85025	H5
ALHA77271	H6
ALHA77288	H6
ALHA84082	H6
LEW85322*	H6
LEW86015	H6
Carichic	H6

Ordinary chondrites comprise ≈ 82% of Earth falls – some of the most diverse chemical weathering mechanisms should be found among this suite

Antarctic Ordinary Chondrite Weathering

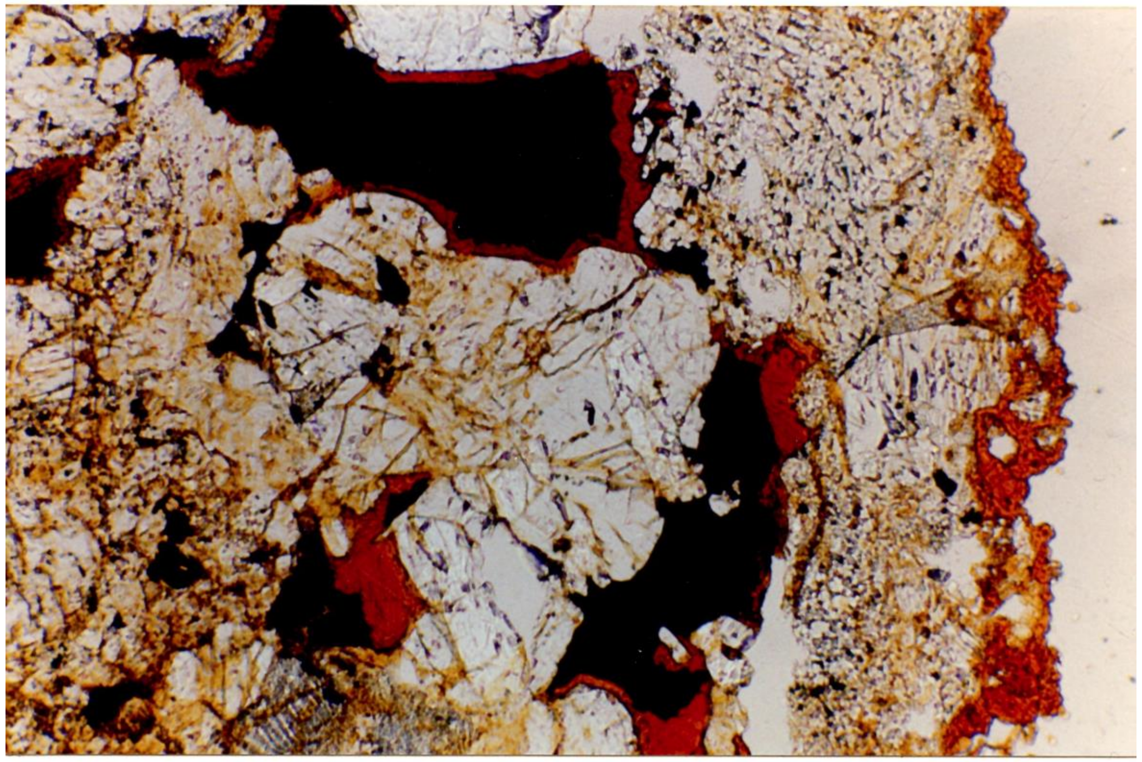


ALH81027,26; 400 x 600 µm



LEW86015,10; 400 x 600 µm

LEW86015,10; 400 x 600 µm



ALH84086075,7; 400 x 600 µm

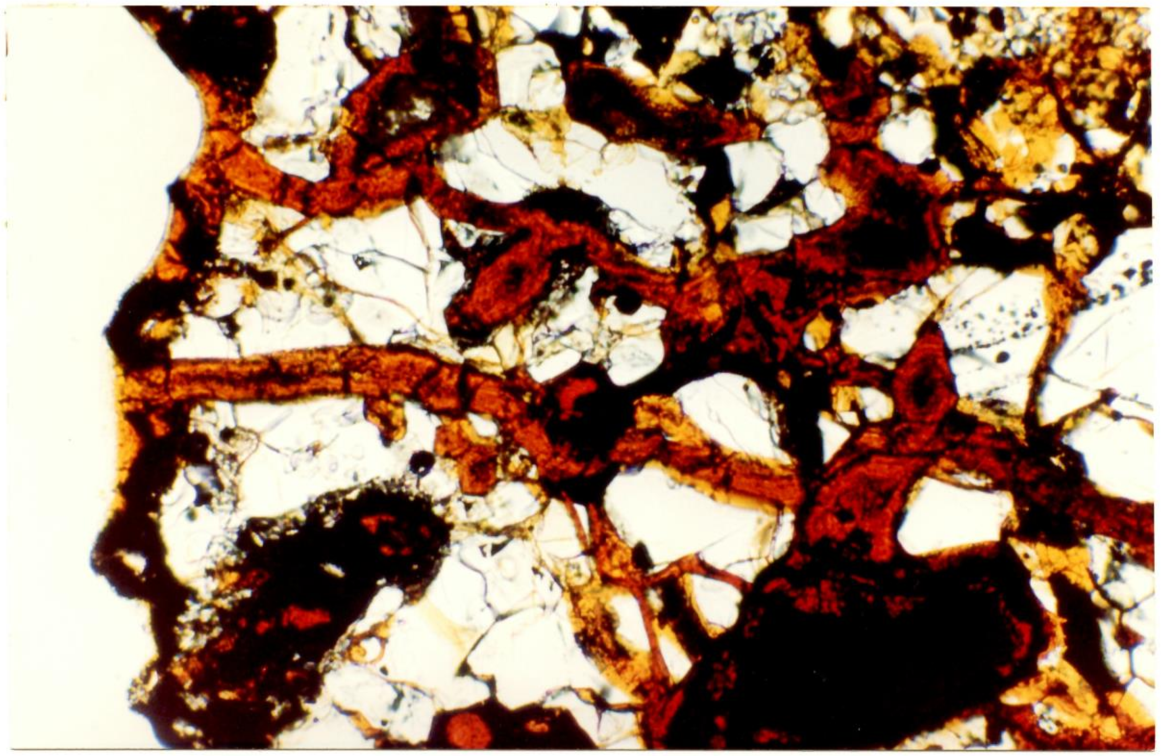
Modal opaque mineral percentages

Meteorite	Class	Modal % opaque				Reference
		Fe-Ni	Troilite	Chromite	Total	
L Chondrites						
Junction, Texas	L5d	4	8	0.7	12.7	Ehlmann & Keil, 1987
Qidong, China	L5d	4.7	4.3	nr	9	Wang & Ruben, 1987
Bayard	L5	6.4	nr	nr	6.4	Struempler & Kaelin, 1987
Reliegos	L5	6.1	nr	nr	6.1	McCoy et al., 1990
Roosevelt County 025	L5a	1.3	6.2	nr	7.5	Pen et al., 1990
Roosevelt County 028	L5a	3.9	6.5	nr	10.4	Pen et al., 1990
Roosevelt County 066	L5a	0	1.6	nr	1.6	Pen et al., 1990
Roosevelt County 067	L5a	1.3	4.6	nr	5.9	Pen et al., 1990
Roosevelt County 068	L5a	0.4	3	nr	3.4	Pen et al., 1990
Roosevelt County 069	L5a	0.4	3.5	nr	3.9	Pen et al., 1990
Roosevelt County 074	L5(S3)	Trace	1.5	nr	1.5	McCoy et al., 1993
Roosevelt County 076	L4(S3)	3.7	4.6	nr	8.3	McCoy et al., 1993
Roosevelt County 077	L4(S2)	Trace	6.6	nr	6.6	McCoy et al., 1993
Roosevelt County 078	L4(S2)	2	6.2	nr	8.2	Gomes & Keil, 1980
		Normative % opaque				
Average values		7.5	6.1	0.6	14.4*	Dodd, 1981
H Chondrites						
Olton, Texas	H	11.2	4	nr	15.2	Keil et al., 1990
Dalhart, Texas	H5a	1	3	nr	4	Ehlman & Keil, 1987
Rosebud, Texas	H5c	8	4	nr	12	Ehlman & Keil, 1987
Cranfills Gap, Texas	H6c	1	4	nr	5	Ehlman & Keil, 1987
Ingella Station	H5a	13.6	5.4	nr	19	McCoy & Keil, 1988
Molina	H5	21.1	7	0.7	28.8	McCoy et al., 1990
Guarena	H6	20.7	4.8	1.1	26.6	McCoy et al., 1990
Olmedilla de Alaron	H5	20.9	nr	nr	20.9	McCoy et al., 1990
Springer, Oklahoma	H5(S3)	15	5.3	nr	20.3	Ehlman & Keil, 1992
Roosevelt County 073	H5(S2)	1.9	4.6	nr	6.5	McCoy el al., 1993
Anton, Texas	H4b	19	8	nr	27	Ehlman & Keil, 1987
Venus, Texas	H4d	15	8	nr	23	Ehlman & Keil, 1987
Hashima	H4	8.2	5.8	nr	14	Hohino & Suea, 1992
Allen, Texas	H4(S2)	8	oxides	nr	8	Ehlman & Keil, 1992
May Day, Kansas	H4(S2)	14.5	4.7	nr	19.2	Ehlman & Keil, 1992
Pony Creek, Texas	H4(S3)	8.1	5.4	nr	13.5	Ehlman & Keil, 1992
		Normative % opaque				
Average values		18.6	5.3	0.6	24.7*	Dodd, 1981

Fe-Ni = Iron-nickel metal
nr = Not reported
Many of the low values are low because of weathering
* includes ilmenite

Average Fe-Ni and Sulfide abundances:

L's – 13.6 %
H's – 24 %



X-Ray diffraction (ALH84075,7; ALH77182,21; ALH77271, 27):

Goethite, akaganéite, maghemite

Thermal emission spectroscopy LEW86015,10:

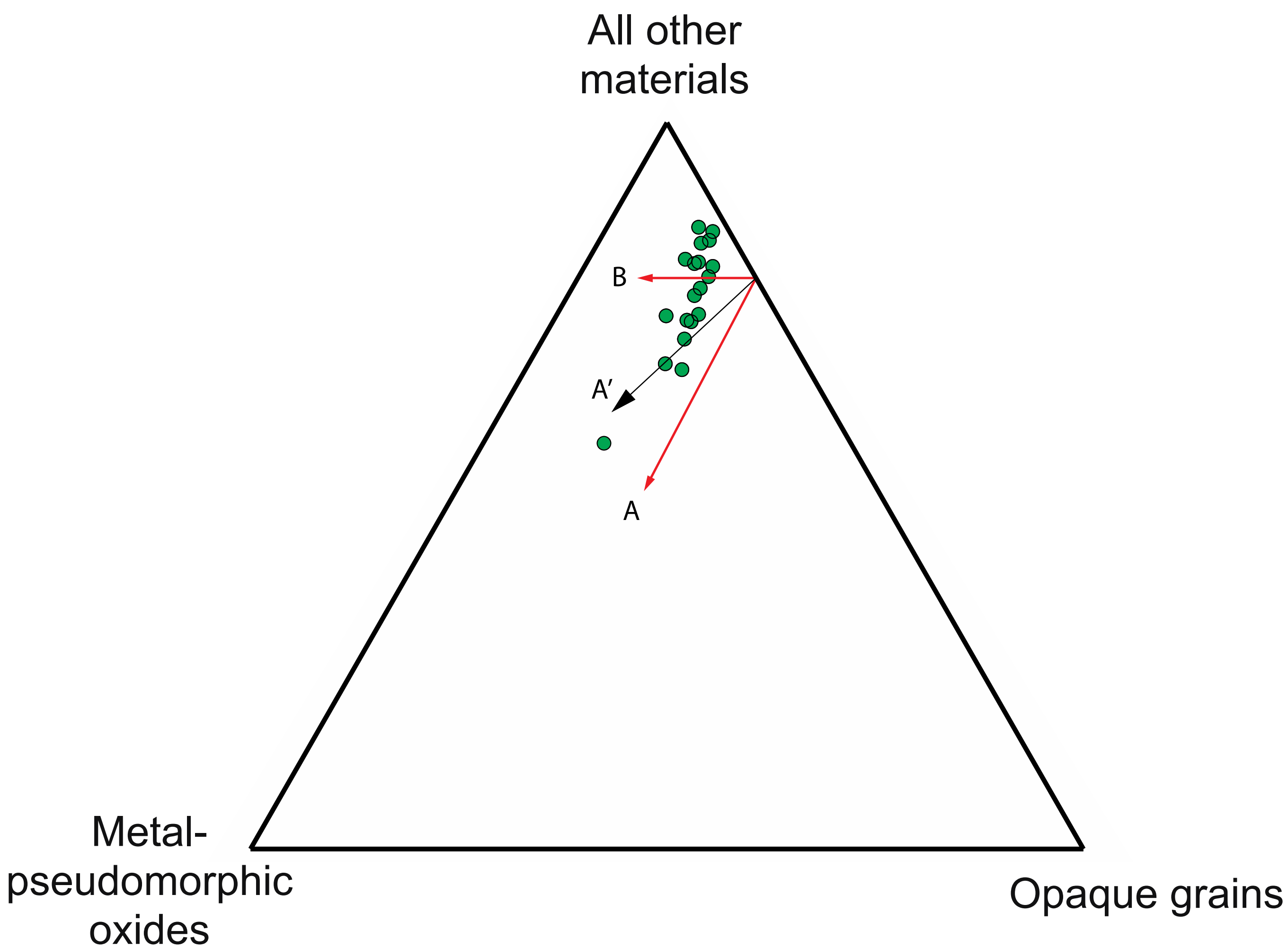
Lepidocrocite

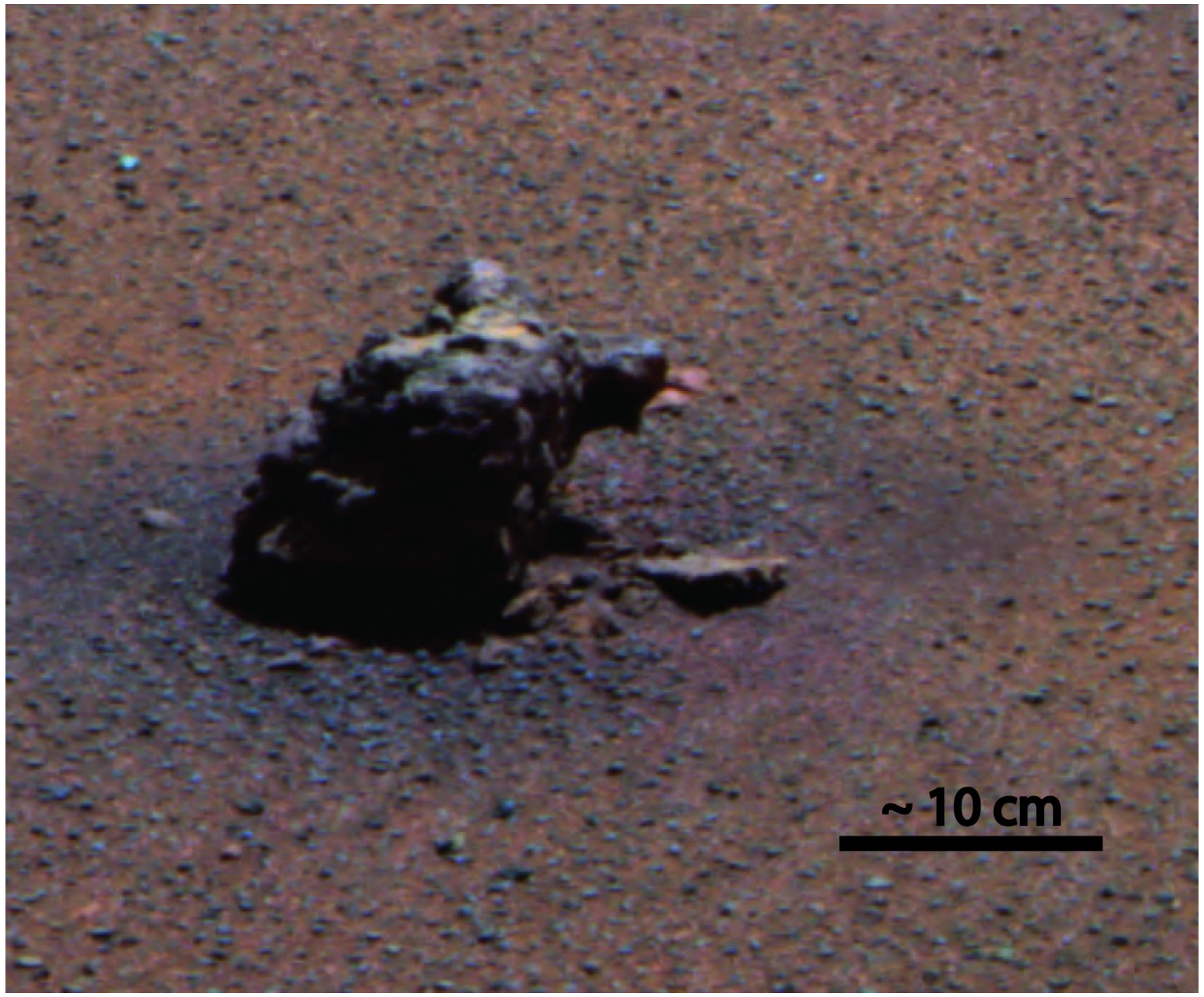
Calculation of primary and secondary mineral volume percent differences

Mineral crystal system	Unit cell axial dimensions (Å) a	b	c	Z	Unit cell volume (Å³)	Unit cell volume (m³)	No. of unit cells in one mol UC(m³) x 6.023E23/Z	V_{prod}/V_{react} after 100 percent oxidation*
Kamacite (iso)	2.86	2.86	2.86	2	23.394	2.33940E-29	7.0451E-06	Kamacite » goethite: 3.027
Taenite (iso)	3.56	3.56	3.56	4	45.118	4.51180E-29	6.79364E-06	Taenite » goethite: 3.139
Goethite (orth)	4.65	10.02	3.04	4	141.642	1.41642E-28	2.13277E-05	NA
Hematite (hex)	5.04	5.04	13.76	6	349.526	3.49526E-28	3.50866E-05	Kamacite » hematite: 4.980

* Increase is upper limit, based on hypothetical pure iron primary phase
NA = not applicable
UC = unit cell
Kamacite » goethite = weathering reaction from primary to secondary mineral

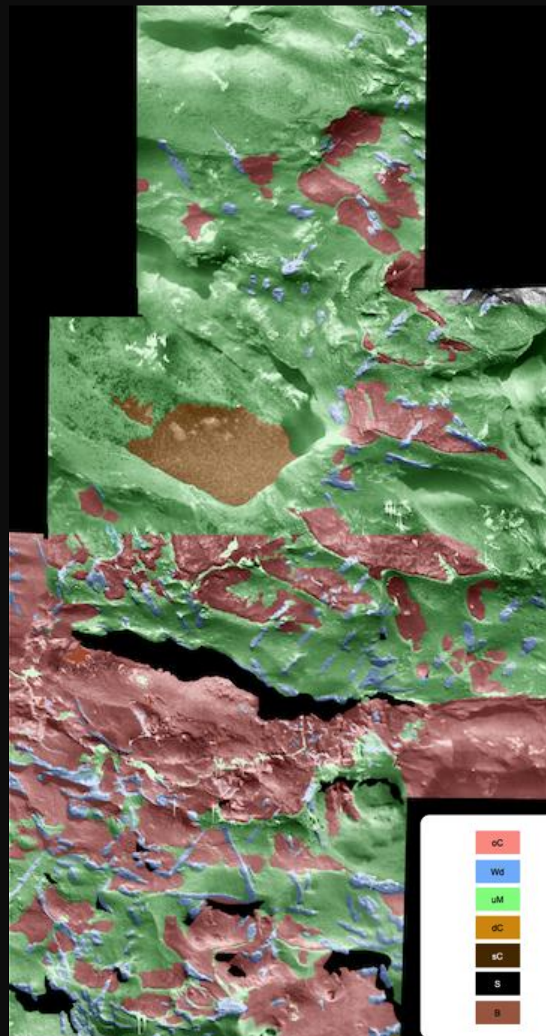
Small fragments of dark material litter the Meridiani plains, and are also found around the rims of Resolution, Discovery, and Concepción craters.

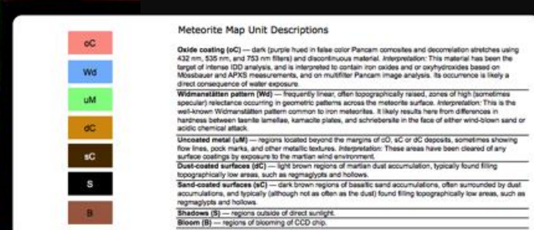


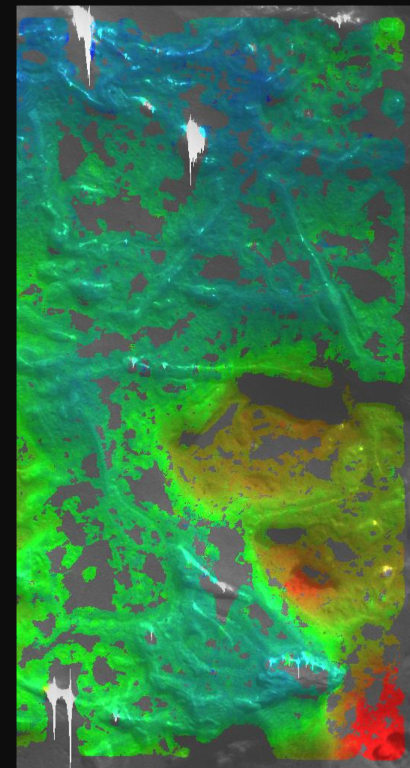


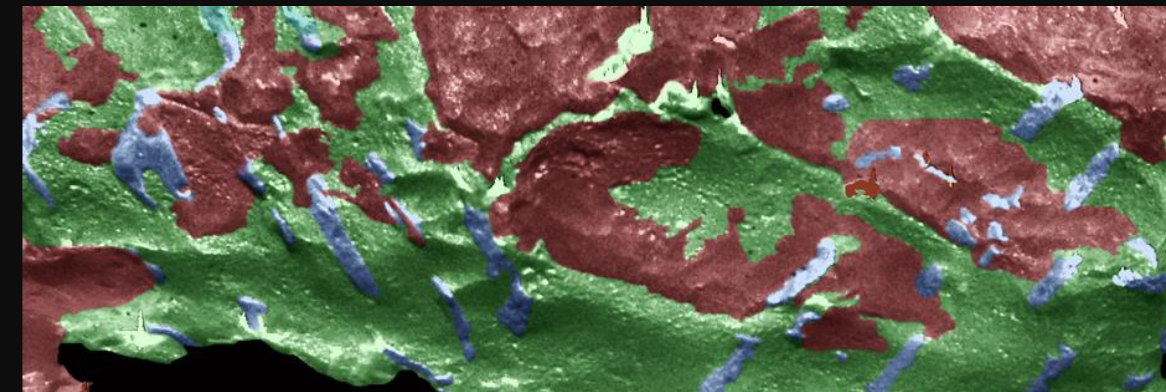
False color Pancam of Canegrass; sol 3346

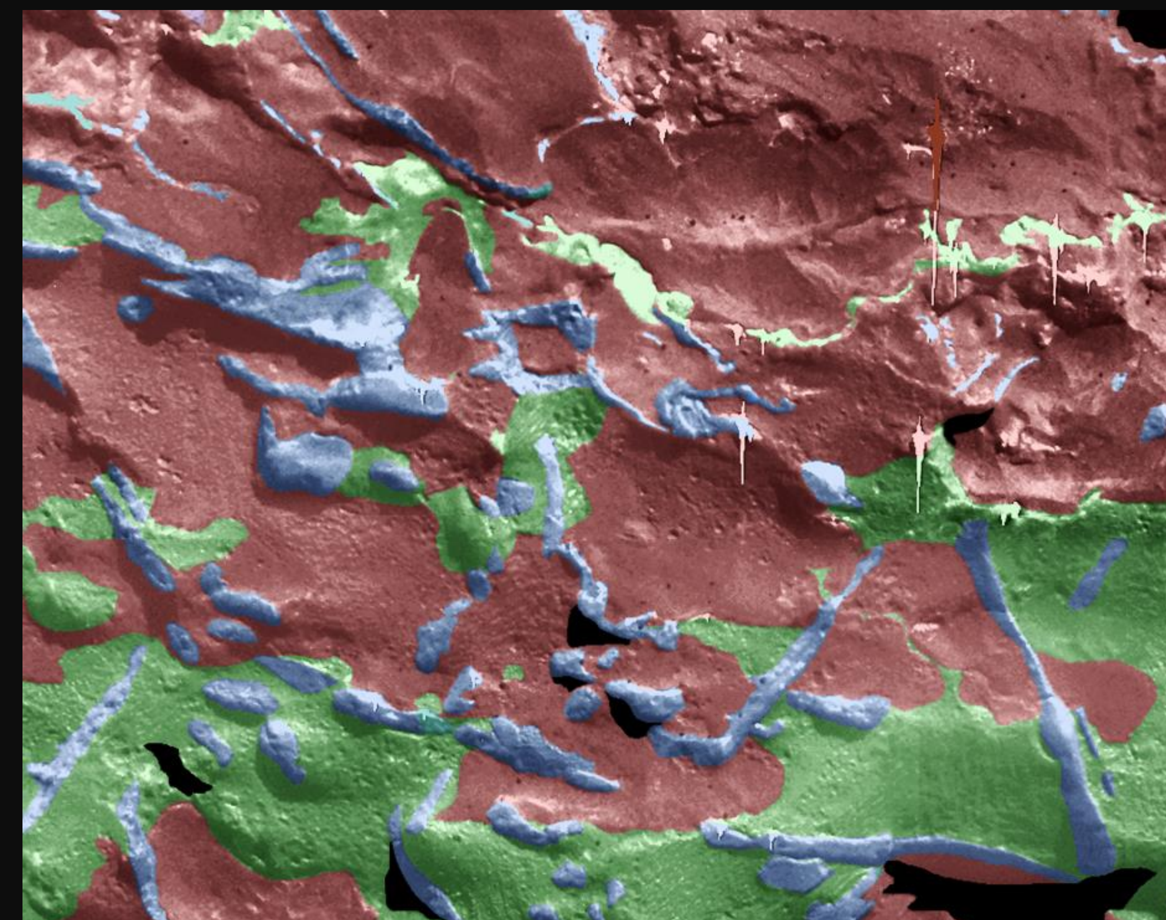
In both hot and cold desert environments We see evidence of this "passivation" effect … A metastable state of cessation, but one which encourages fragmentation, and produces differences in H vs L chondrite size and abundance in Antarctica.

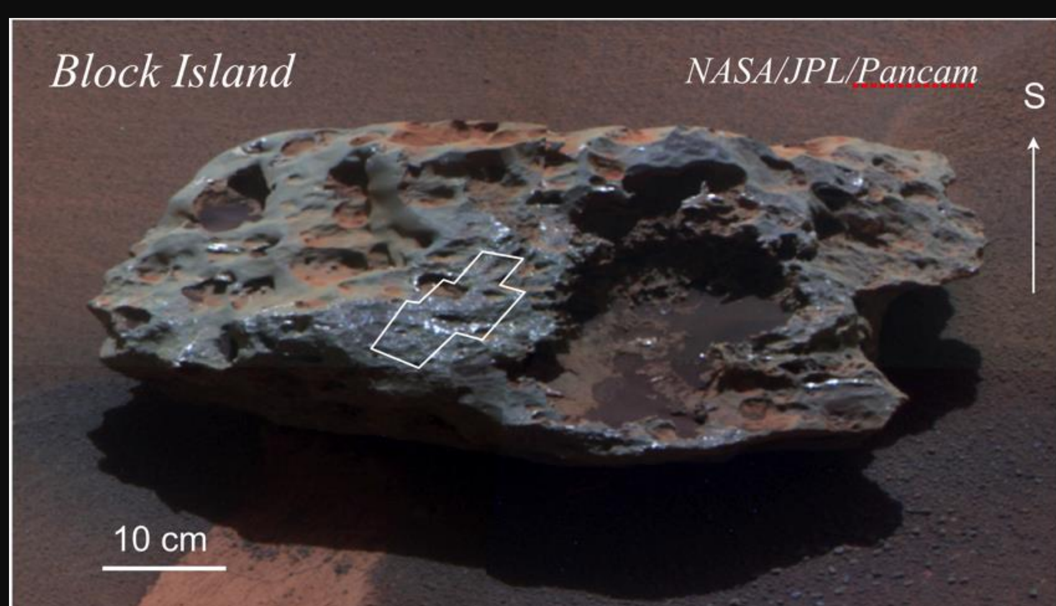






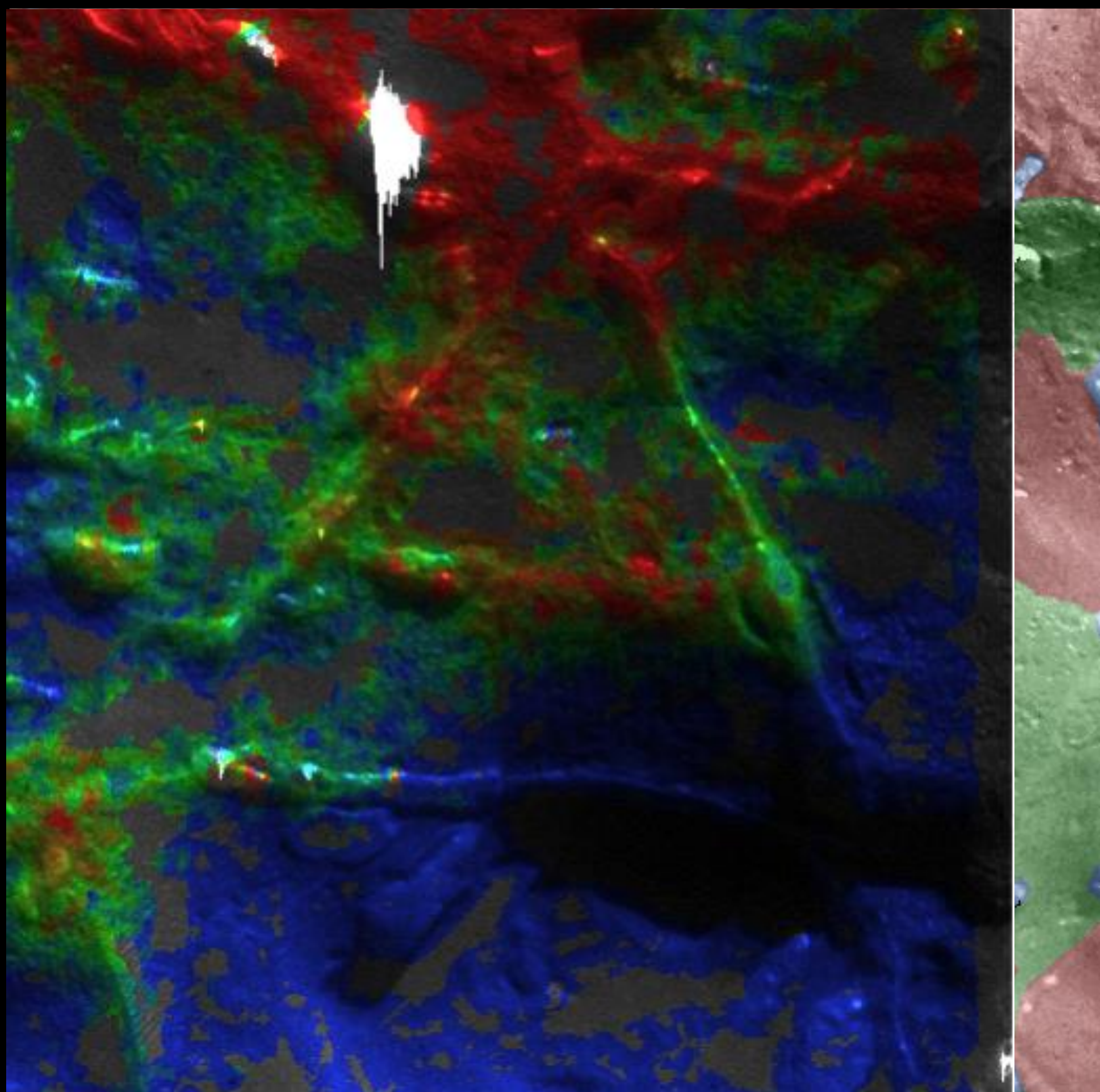




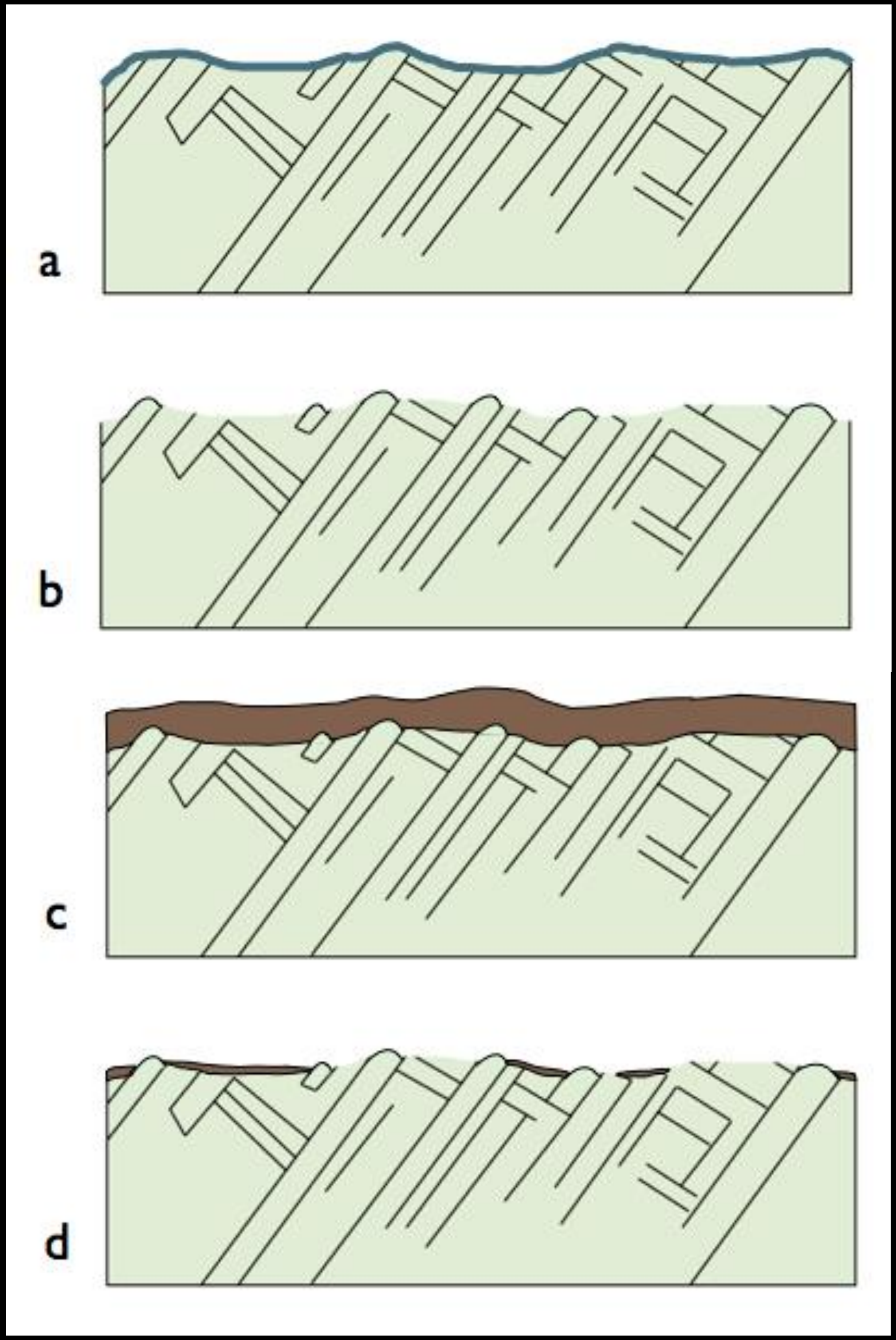


- Micro-mapping is a useful tool, which can assist understanding of features. their interrelationships, and the extent of aeolian modification.

Mechanical/chemical alteration sequence



NASA/JPL/MI

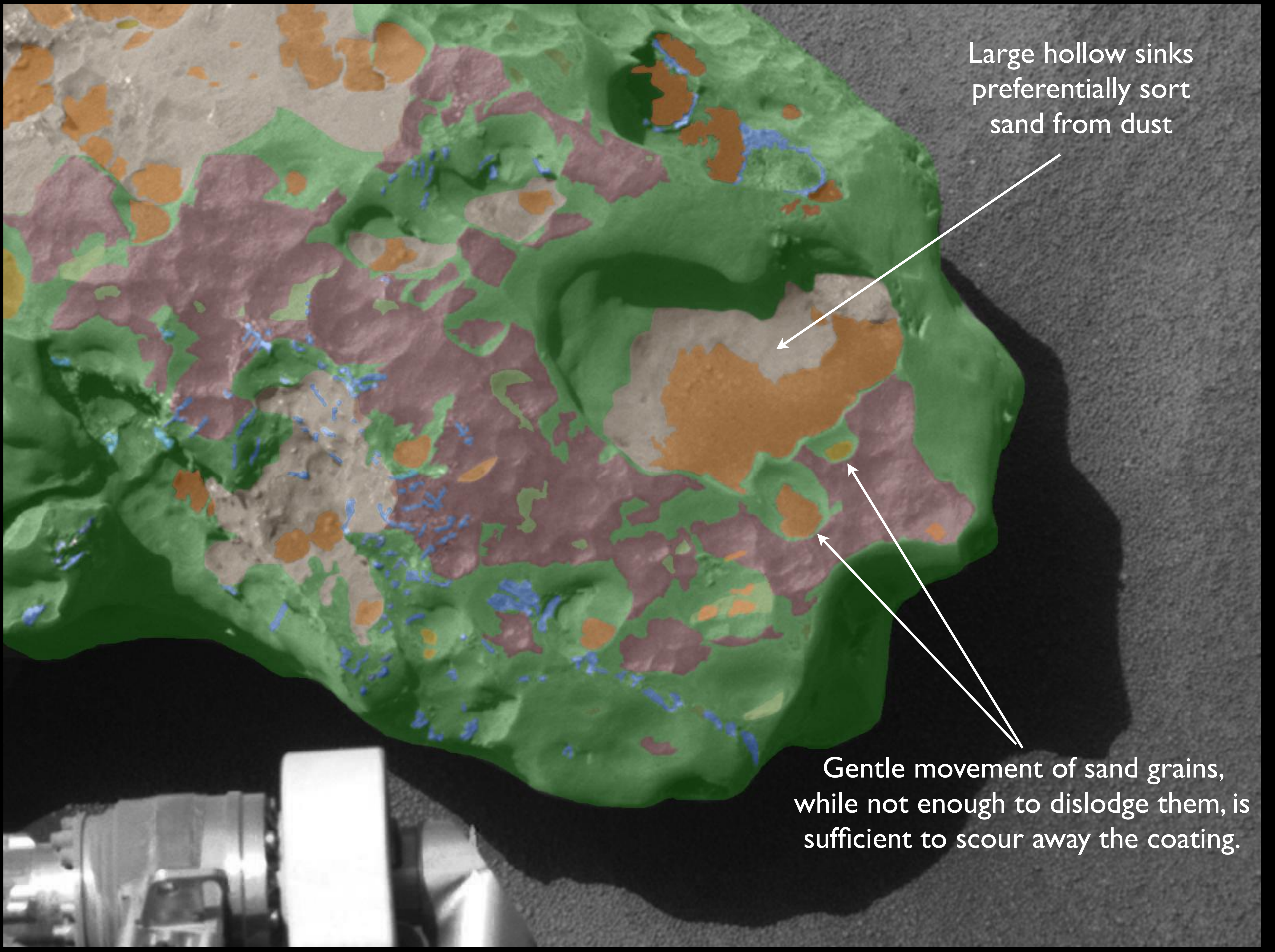


New fall

wind exposure

water exposure

wind re-exposure


Large hollow sinks preferentially sort sand from dust
Gentle movement of sand grains, while not enough to dislodge them, is sufficient to scour away the coating.

Summary

Recent oxide production from mineral-water interaction near the martian equator is supported by:

- Cross-cutting relationships between oxide coating and Widmantatten patterns on weathered meteorites; in combination with
- Evidence that oxide coating is structurally weak and is being removed in the current epoch.

Survivability bias (not selection bias) is supported as the mechanism for anomalous iron meteorite surface abundance by:

- Serendipitous discovery of iron meteorites in work volume of rover

Supported by the Canegrass observation, it appears that weathering may contribute significantly to population statistics.

Consideration for <u>*chondritic*</u> witness sample return justified?

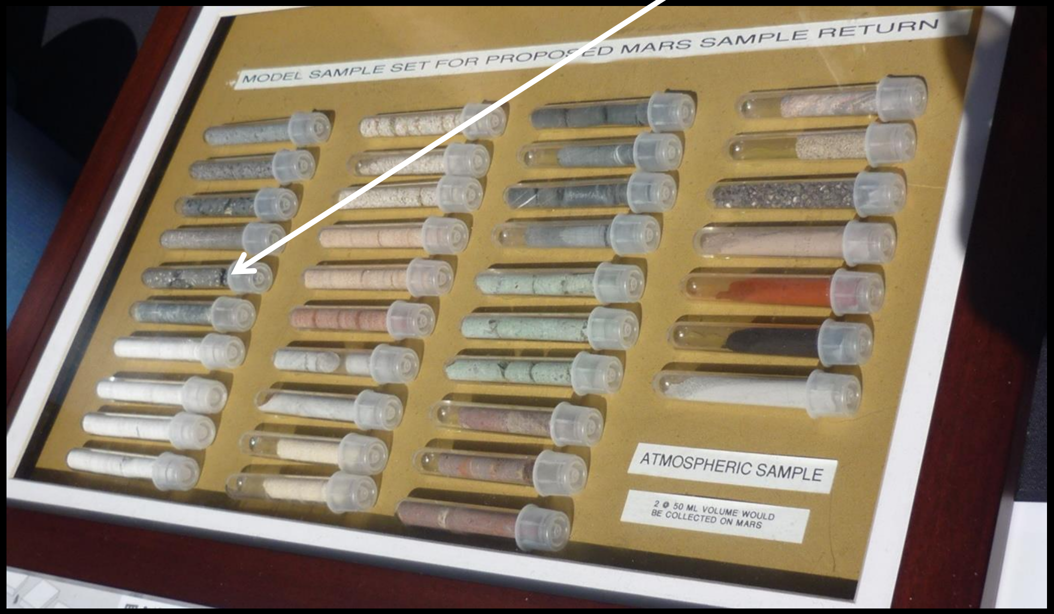
<u>*"Obviously, allocating precious return mass to a meteorite would require a strong justification for the hypothesis being tested,"*</u> [MEPAG, 2008].

Feasibility study required:

1. *would involve major and trace element analyses for suites of unweathered "super-analog" samples for comparison with hot and cold Mars-analog-desert-weathered meteorites of the same types.*

2. *Subtle mineral-water interaction effects and secondary mineral products in a returned chondrite could be compared directly to the Earth-based analogs.*

One carefully selected, non-indigenous "weathering reference sample"



Backup Slides

Meteorite Weathering on Mars

- Most meteorite finds are likely to have arrived during post-Noachian epochs
- Known starting conditions with unique mineralogies, chemistries, textures, and physical properties.
- Where weathering intensities may be subtle or undetectable for indigenous rocks, they may be conspicuous in this responsive material (*e.g. high-temperature mineral content, often unequilibrated, strong thermodynamic drivers toward chemical alteration)*.
- Chemically altered meteorites at MER/MSL locations are significant because of their low latitudes
- Paleoclimatic insights, with possibility for addressing the Amazonian

Modal Analytical Results

Specimen	Point count #1; 500 points: Opaque	Unstained	Total Oxides	Point count #2; 500 points: OPL	Non-OPL	OPL/(OPL + Opaques) x 100	OPL + Opaques
ALHA81031,19	11.0	32.8	56.2	3.4	52.8	23.6	14.4
ALHA77230,48	13.0	30.4	56.6	2.0	54.6	13.3	15.0
ALHA81027,26	12.4	8.8	78.8	4.2	74.6	25.3	16.6
ALHA77004,22	13.4	25.8	60.8	5.8	55.0	30.2	19.2
ALHA77208,29	16.6	23.6	59.8	10.8	49.0	39.4	27.4
ALHA77225,18	15.4	29.0	55.6	4.4	51.2	22.2	19.8
ALHA77226,37	15.2	16.6	68.2	8.6	59.6	36.1	23.8
ALHA77232,16	13.2	22.6	64.2	3.0	61.2	18.5	16.2
ALHA77233,21	13.0	23.2	63.8	6.4	57.4	33.0	19.4
ALHA77182,36*	10.4	48.2	41.4	26.4	15.0	71.7	36.8
ALHA79025,16	15.4	33.8	50.8	7.4	43.4	32.5	22.8
ALHA79029,21	11.6	19.2	69.2	7.2	62.0	38.3	18.8
ALHA84075,7*	15.6	10.2	74.2	5.6	68.6	26.4	21.2
ALHA85025,10	17.0	37.0	46.0	12.8	33.2	43.0	29.8
ALHA77271,28*	13.2	28.4	58.4	13.4	45.0	50.4	26.6
ALHA77288,34	16.0	26.2	57.8	11.2	46.6	41.2	27.2
ALHA84082,9	18.8	27.4	53.8	15.2	38.6	44.7	34.0
LEW85322,11	16.4	65.6	18.0	16.8	1.2	50.6	33.2
LEW86015,10	17.0	13.4	69.6	9.4	60.2	35.6	26.4
Arithmetic mean	14.5	27.5	58.1	9.2	48.9	35.6	23.6
Standard deviation	2.2	12.9	13.1	5.8	17.2	13.2	6.5
Varience	5.0	165.7	170.7	33.6	294.9	173.0	42.1

The two oxide counts in point count #2 represent the breakdown of the total oxides count of point count #1
All modal values in percents
* corresponding bulk samples used in XRD analysis

Consideration for sample return justified?

- Irons are suicidal; only chondritic meteorites should be considered!
- An ability to study the surface-volatile interaction histories of materials with well known starting mineralogies, chemistries (isotopic and elemental), and textures.
- Laboratory comparison and contrasting of relative rates of different alteration mechanisms within the suite of weathering effects detectable would be huge.
- Determining the post fall, martian residence time will be important for providing constraints on martian weathering behavior. Both cosmogenic stable nuclides and radionuclides have been discussed for the martian situation [Nishiizumi and Reedy, 2000]. The ^{10}Be-^{26}Al-^{21}Ne isotope system should be useful for determining exposure ages for rocks at Mars.