Deciphering the Spectral Evidence for Serpentinization of Martian Basement Materials

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Mars 2020 Landing Site Workshop

Solar System Exploration Seminar

5 Aug 2015

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1. Pilbara as a Mars Analog

Stromatolites and Ultramafic Rocks

2. Spectra of Martian Basement

Talc-carbonate hypothesis, Olivine and Mg-OH at Nili Fossae

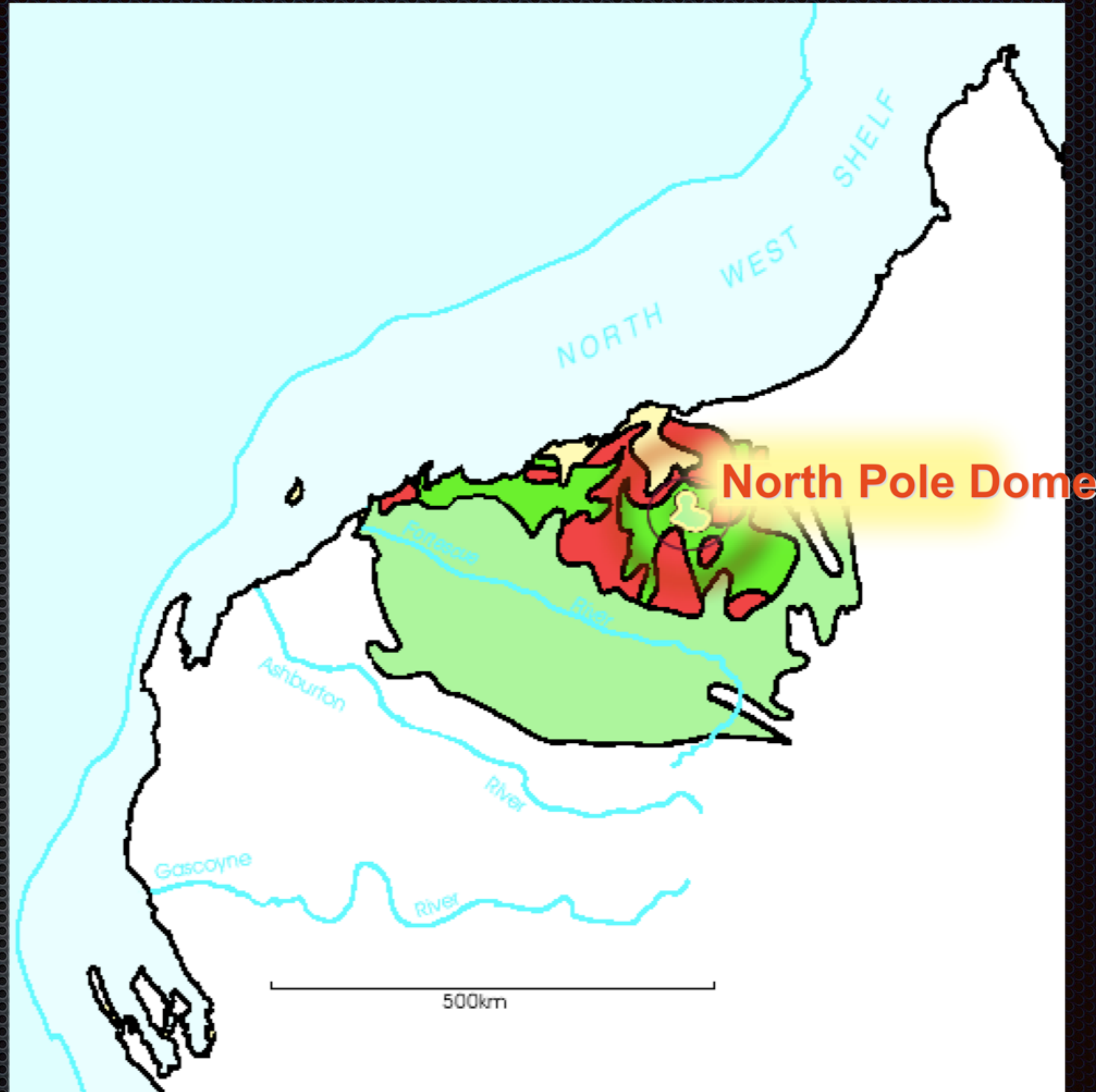
3. Serpentinization Ansatz

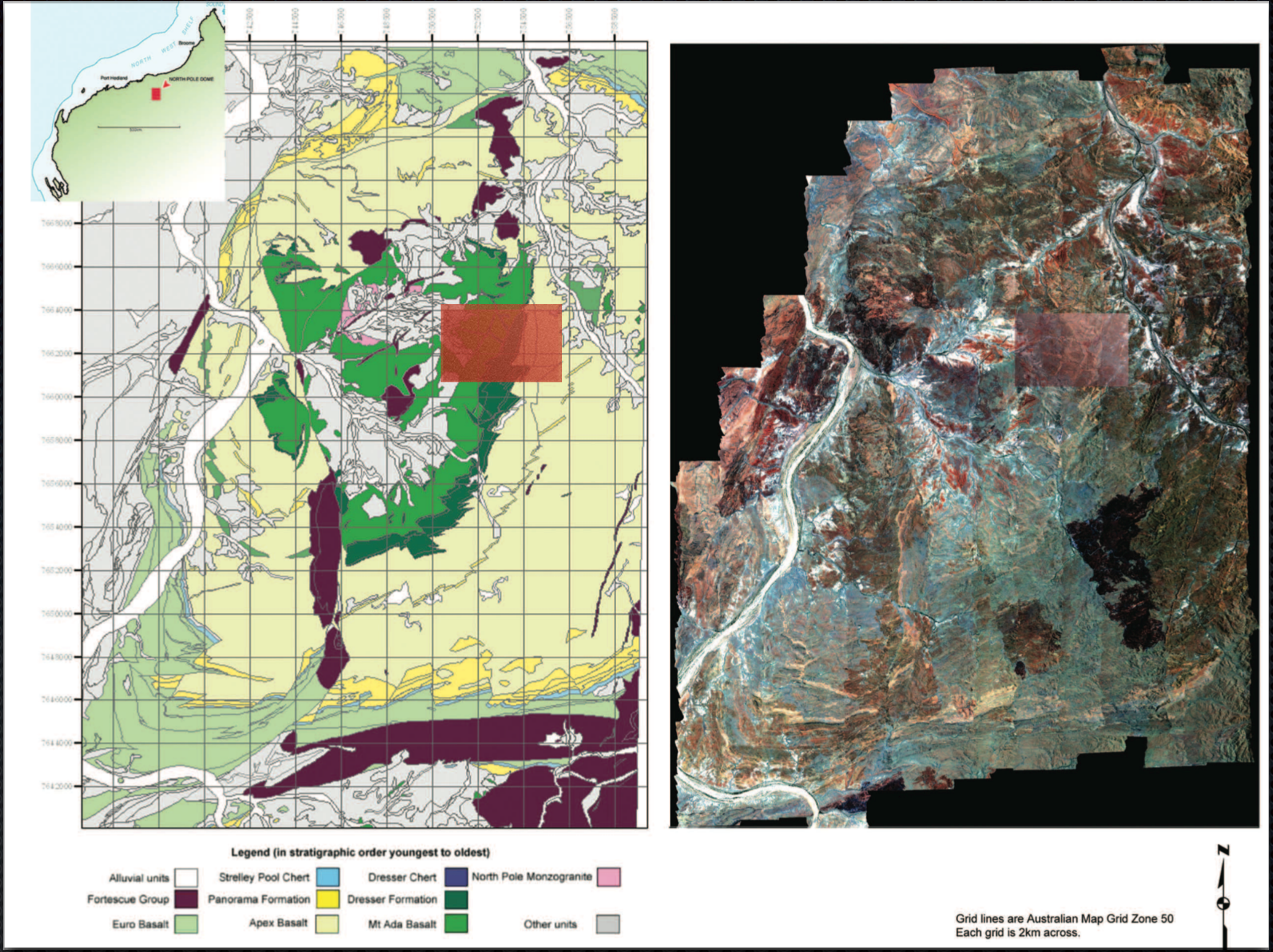
Hydrated and Carbonated Hydrothermal models

1. Pilbara as a Mars Analog

Stromatolites and Ultramafic Rocks

Pilbara region of Western Australia





North Pole Dome Mars analog

1. Brown et al (2005) showed the stromatolite bearing, hydrothermally altered North Pole Dome region of the Pilbara is a good analog for Mars
2. Showed how talc was an easily detectable ultramafic mineral

Hyperspectral imaging spectroscopy of a Mars analogue environment at the North Pole Dome, Pilbara Craton, Western Australia

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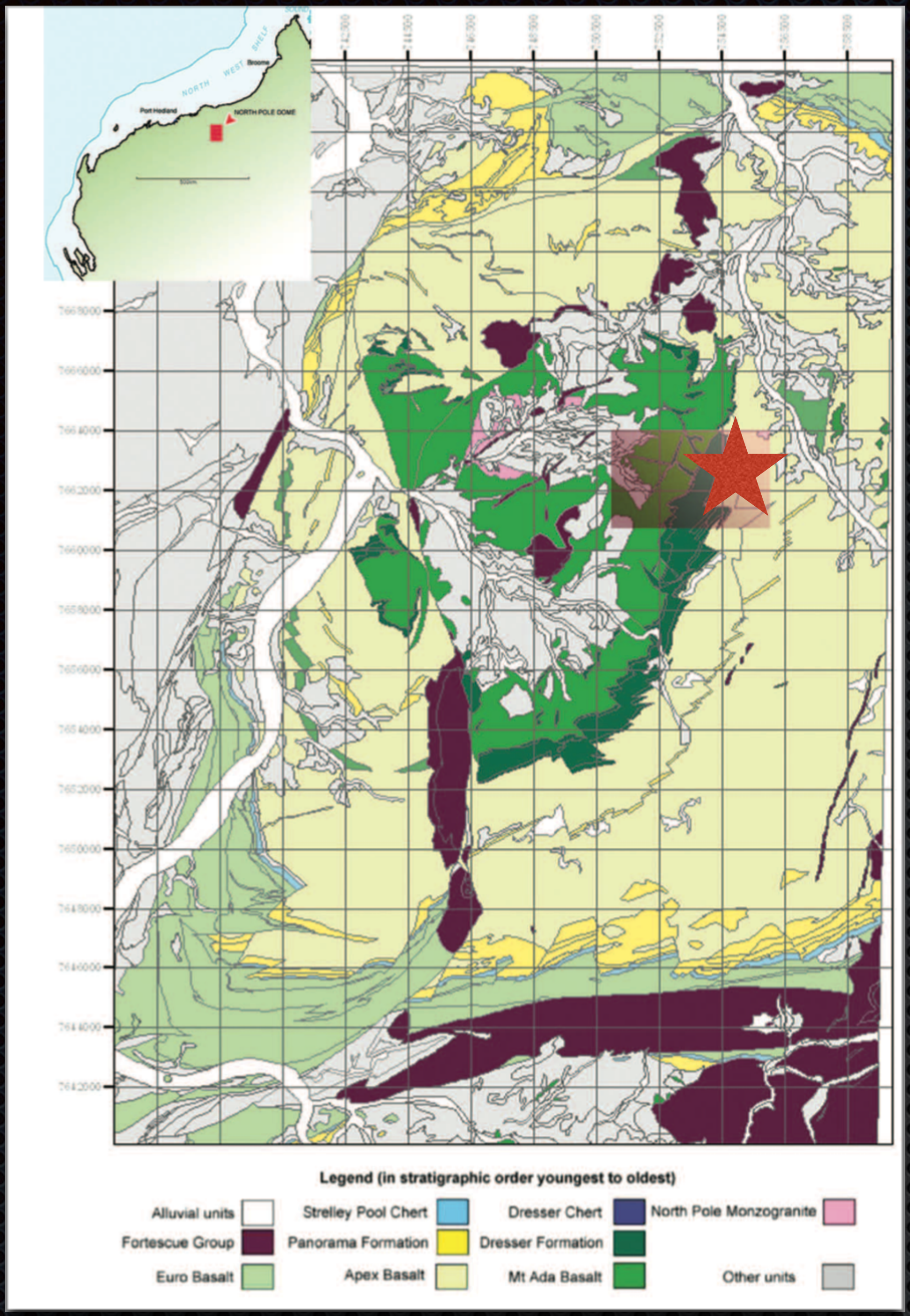
A visible and near infrared (VNIR) to shortwave infrared (SWIR) hyperspectral dataset of the Early Archaean North Pole Dome, Pilbara Craton, Western Australia, has been analysed for indications of hydrothermal alteration. Occurrence maps of hydrothermal alteration minerals were produced. It was found that using a spatial resolution on the ground of approximately 5 m and spectral coverage from 0.4 to 2.5 μm was sufficient to delineate several hydrothermal alteration zones and associated veins, including phyllic, serpentinitic and chloritic alteration. These results suggest this level of spectral and spatial resolution would be ideal for localising shallow epithermal activity, should such activity have existed, on the surface of Mars.

Pilbara as a Mars analog

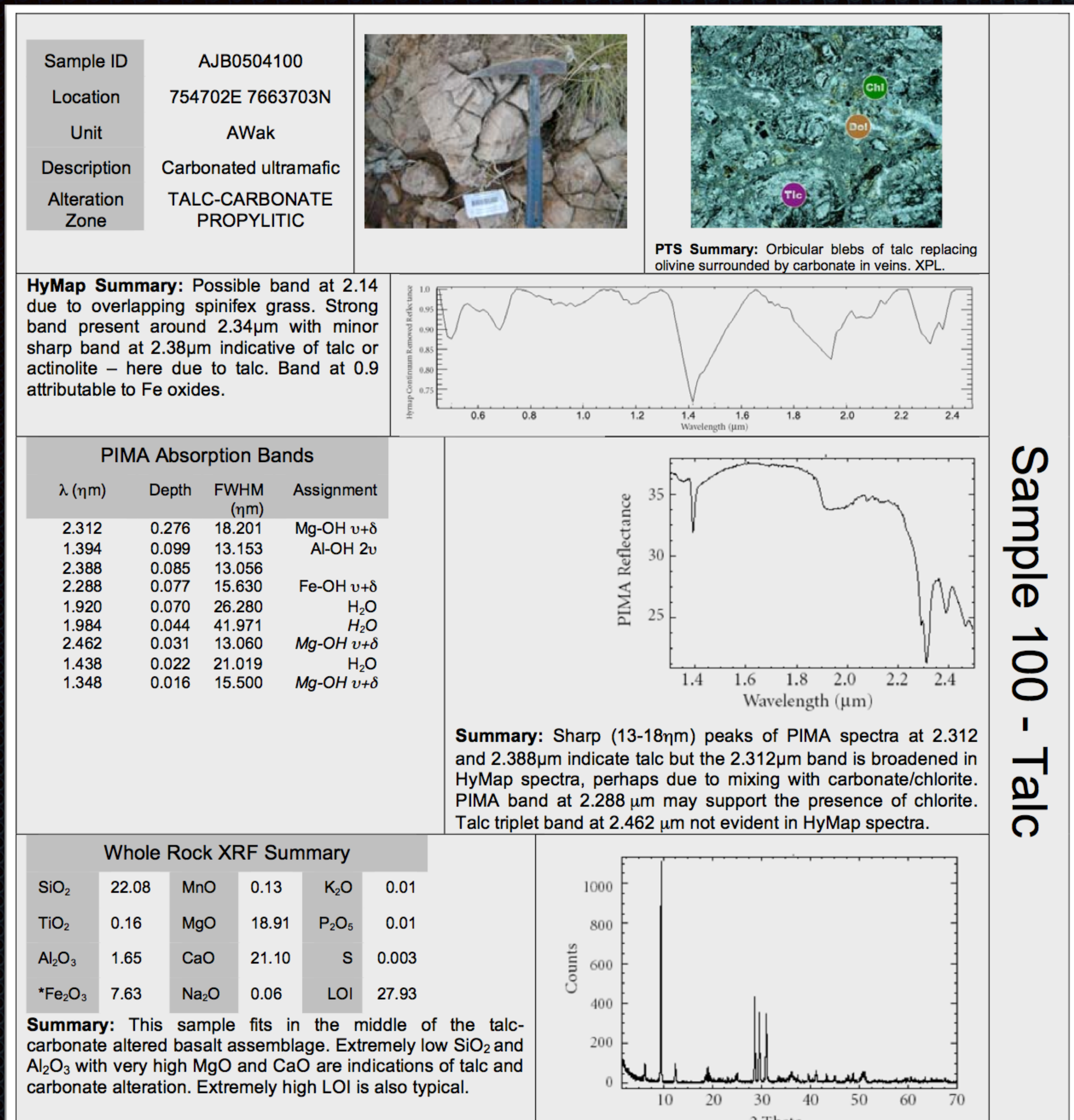
1. Brown et al 2005 showed how the stromatolite bearing, hydrothermally altered North Pole Dome region of the Pilbara is a good analog for Mars
2. Showed how talc was an easily detectable ultramafic mineral



Talc carbonate deposits

Note bright, friable nature of talc on right

Located above Dresser formation in the N. Pole Dome



Sample ID	AJB0504100
Location	754702E 7663703N
Unit	AWak
Description	Carbonated ultramafic
Alteration Zone	TALC-CARBONATE PROPYLITIC

PTS Summary: Orbicular blebs of talc replacing olivine surrounded by carbonate in veins. XPL.

HyMap Summary: Possible band at 2.14 due to overlapping spinifex grass. Strong band present around 2.34µm with minor sharp band at 2.38µm indicative of talc or actinolite – here due to talc. Band at 0.9 attributable to Fe oxides.

PIMA Absorption Bands

λ (ηm)	Depth	FWHM (ηm)	Assignment
2.312	0.276	18.201	Mg-OH υ+δ
1.394	0.099	13.153	Al-OH 2υ
2.388	0.085	13.056	
2.288	0.077	15.630	Fe-OH υ+δ
1.920	0.070	26.280	H_2O
1.984	0.044	41.971	H_2O
2.462	0.031	13.060	Mg-OH υ+δ
1.438	0.022	21.019	H_2O
1.348	0.016	15.500	Mg-OH υ+δ

Summary: Sharp (13-18ηm) peaks of PIMA spectra at 2.312 and 2.388µm indicate talc but the 2.312µm band is broadened in HyMap spectra, perhaps due to mixing with carbonate/chlorite. PIMA band at 2.288 µm may support the presence of chlorite. Talc triplet band at 2.462 µm not evident in HyMap spectra.

Whole Rock XRF Summary

SiO_2	22.08	MnO	0.13	K_2O	0.01
TiO_2	0.16	MgO	18.91	P_2O_5	0.01
Al_2O_3	1.65	CaO	21.10	S	0.003
*Fe_2O_3	7.63	Na_2O	0.06	LOI	27.93

Summary: This sample fits in the middle of the talc-carbonate altered basalt assemblage. Extremely low SiO_2 and Al_2O_3 with very high MgO and CaO are indications of talc and carbonate alteration. Extremely high LOI is also typical.

Sample 100 - Talc

Talc-carbonate Sample from Pilbara

Ref: Brown (2006) PhD thesis (online)

Note: 1. XRD shows strong 9.38 A spacing

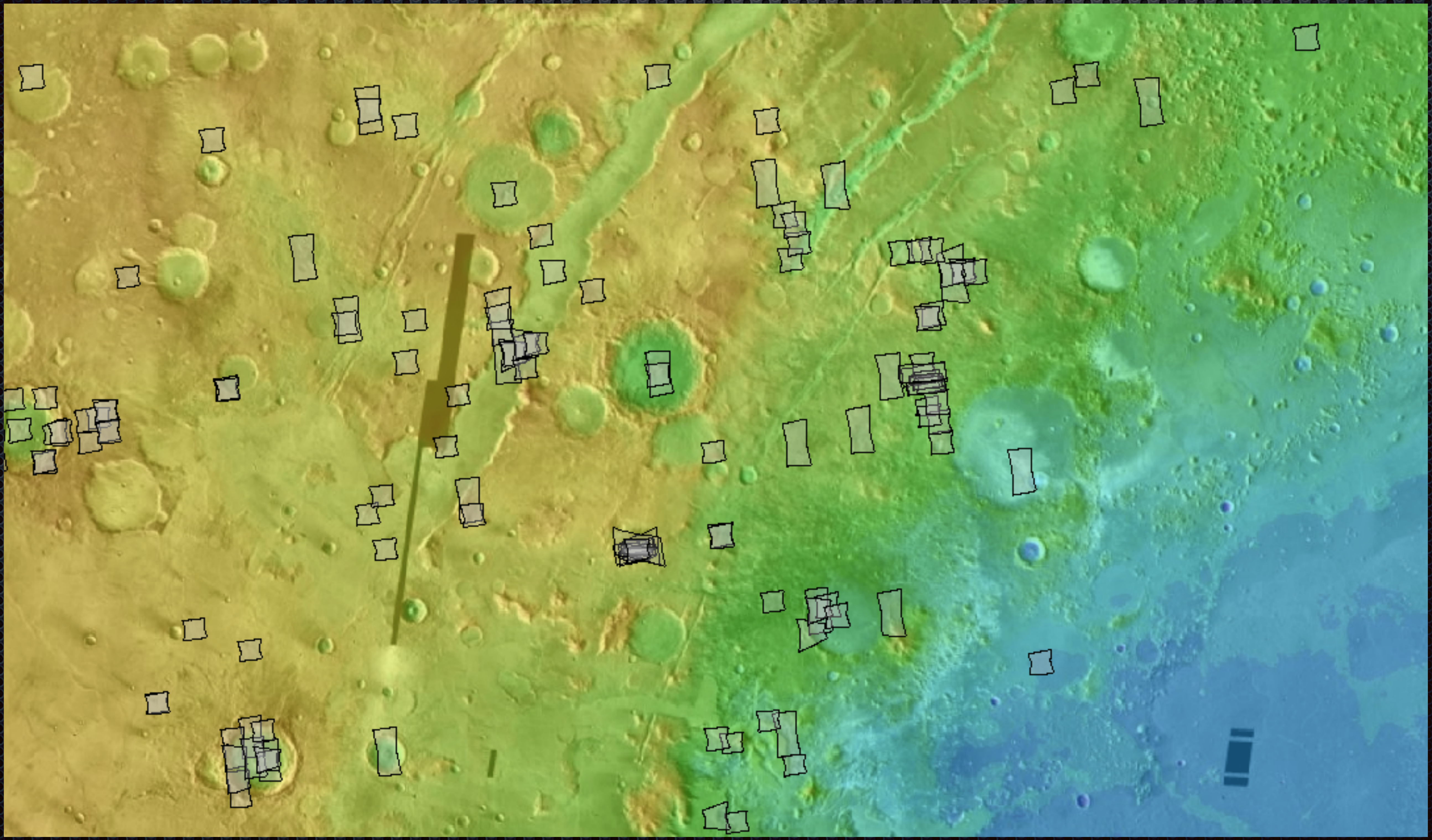
2. third band in lab spectrum not apparent in airborne

3. Talc replacing olivine with Dolomite

2. Spectra of Martian Basement

Talc-carbonate hypothesis, Olivine and Mg-OH at Nili Fossae

Nili Fossae



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Science 19 December 2008:
Vol. 322 no. 5909 pp. 1828–1832
DOI: 10.1126/science.1164759

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REPORT

Orbital Identification of Carbonate-Bearing Rocks on Mars

Bethany L. Ehlmann[1], John F. Mustard[1], Scott L. Murchie[2], Francois Poulet[3], Janice L. Bishop[4], Adrian J. Brown[4], Wendy M. Calvin[5], Roger N. Clark[6], David J. Des Marais[7], Ralph E. Milliken[8], Leah H. Roach[1], Ted L. Roush[7], Gregg A. Swayze[6], James J. Wray[9]

+ Author Affiliations

ABSTRACT

Geochemical models for Mars predict carbonate formation during aqueous alteration. Carbonate-bearing rocks had not previously been detected on Mars' surface, but Mars Reconnaissance Orbiter mapping reveals a regional rock layer with near-infrared spectral characteristics that are consistent

CRISM finds carbonate at Nili

Ref: Ehlmann et al. 2008, No other exposed large carbonate deposits on Mars found to date.

ELSEVIER

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Hydrothermal formation of Clay-Carbonate alteration assemblages in the Nili Fossae region of Mars

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ARTICLE INFO

Article history:
Received 1 February 2010
Received in revised form 8 June 2010
Accepted 9 June 2010
Available online 17 July 2010

Editor: T. Spohn

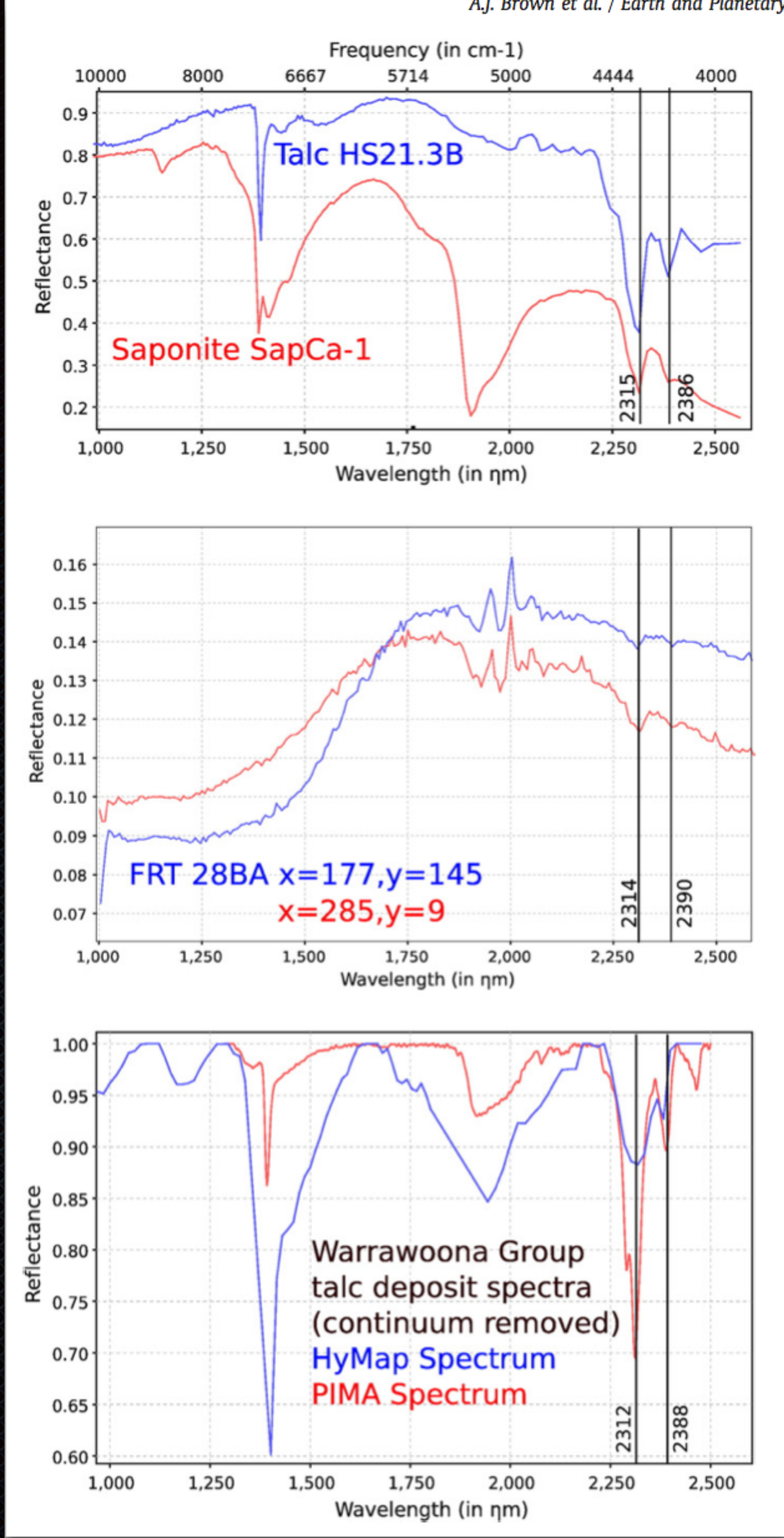
Keywords:

ABSTRACT

The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) has returned observations of the Nili Fossae region indicating the presence of Mg-carbonate in small (<10 km sq^2), relatively bright rock units that are commonly fractured (Ehlmann et al., 2008b). We have analyzed spectra from CRISM images and used co-located HiRISE images in order to further characterize these carbonate-bearing units. We applied absorption band mapping techniques to investigate a range of possible phyllosilicate and carbonate minerals that could be present in the Nili Fossae region. We also describe a clay-carbonate hydrothermal alteration mineral assemblage in the Archean Warrawoona Group of Western Australia that is a potential Earth analog to the Nili Fossae carbonate-bearing rock units. We discuss the geological and biological implications for

The Talc-carbonate hypothesis

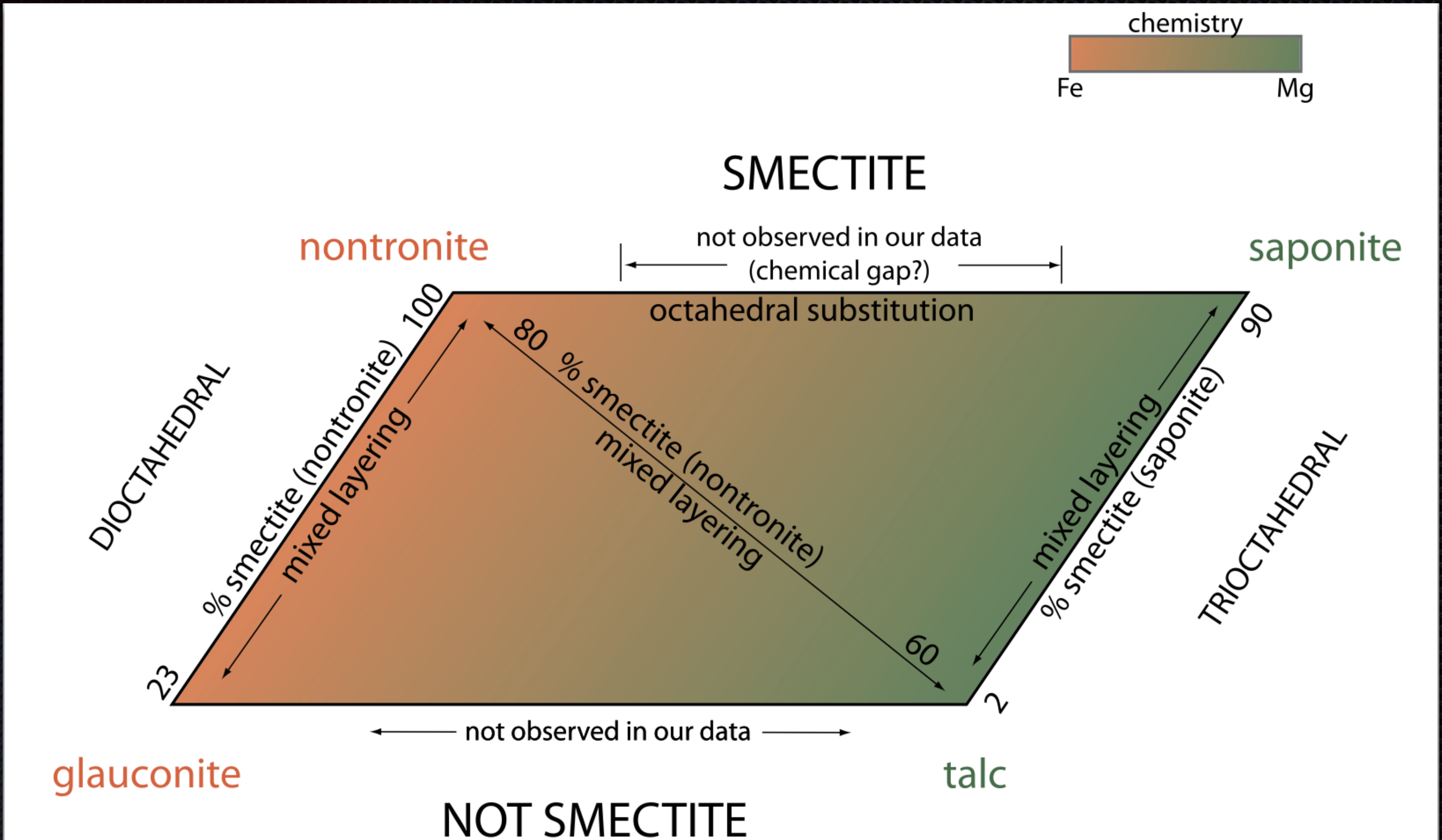
Ref: Brown et al. 2010 suggested the presence of talc in combination with carbonates at Nili Fossae, in analogy to terrestrial greenstone



Spectral evidence for talc

Ref: Brown et al. 2006
(Pilbara remote sensing)
laid the groundwork
for the suggestion

KEY QUESTION:
Why is carbonate at Nili Fossae often associated with an Mg-OH alteration mineral?
(only exception is Jezero)



Relationship of Talc to other clays

Ref: Michalski et al. 2015, talc is 1:1 trioctahedral, non expanding (not a smectite), physically mixes with swelling smectites saponite and nontronite

JOURNAL OF GEOPHYSICAL RESEARCH: PLANETS, VOL. 118, 1858–1872, doi:10.1002/jgre.20141, 2013

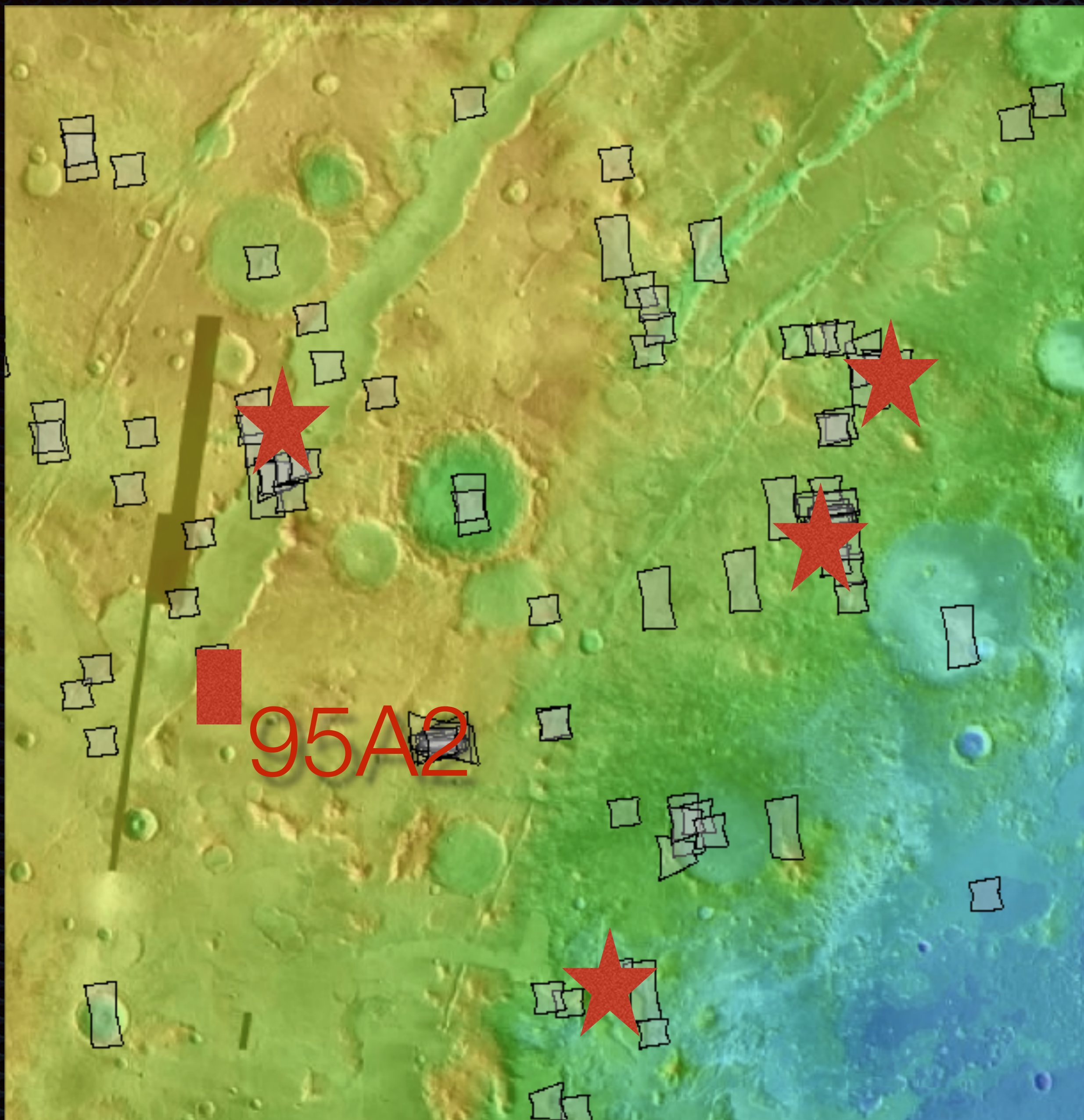
Implications for early hydrothermal environments on Mars through the spectral evidence for carbonation and chloritization reactions in the Nili Fossae region

Christina E. Viviano,[1] Jeffrey E. Moersch,[2] and Harry Y. McSween[2]

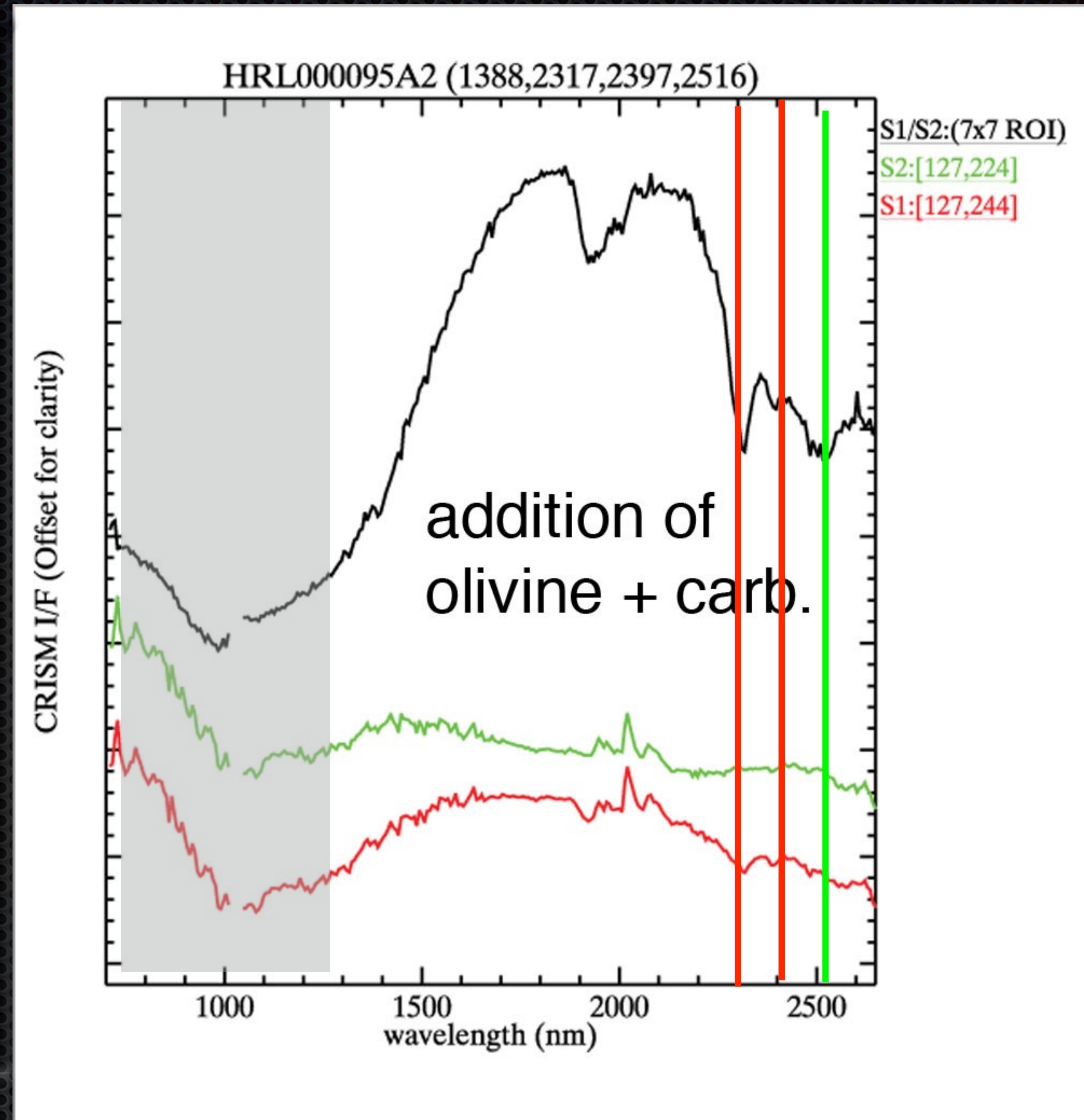
Received 18 May 2012; revised 20 July 2013; accepted 16 August 2013; published 18 September 2013.

[1] Previous identification of serpentine and magnesium carbonate in the eastern Nili Fossae region of Mars indicates hydrothermal alteration of an olivine-rich protolith. Here we characterize Fe/Mg phyllosilicates associated with these units and present spectral evidence for the presence of a talc component, distinguishable from saponite. Locations with magnesium carbonate are exclusively associated with talc-related phyllosilicates. In the westernmost portions of the Nili Fossae region, where a mafic protolith dominates, Fe/Mg phyllosilicates display spectral evidence for a wide degree of chloritization. We propose that Noachian Fe/Mg smectites were uniformly buried by Hesperian lava flows that initiated hydrothermal alteration in the eastern Nili Fossae region. The chloritization of smectites may have produced silica-rich fluids necessary for the serpentinization of olivine; temperature and depth constraints indicated by their distribution also suggest a hydrothermal system was present. The subsequent carbonation of serpentine and/or olivine in eastern Nili Fossae, while requiring an additional CO_2 source, provides an explanation for the limited occurrence of serpentine and the colocation of carbonate and talc-bearing material throughout this area. The consequence of the hypothesized carbonation reaction and the presence of serpentine provides geochemical constraints for the proportion of CO_2 present in the fluids that interacted with the protolith. If this carbonation reaction was a widespread phenomenon, it may have been an important process in the ancient Martian carbon cycle and could have provided a sink for CO_2 in the past.

Ref: Vivano et al. 2013 mapped talc throughout eastern Nili Fossae and proposed a detailed formation model



Nili Fossae Landing Sites



From Southern Nili Fossae
Courtesy of Christina Beck

3. Serpentinization Ansatz

Hydrated and Carbonated Hydrothermal Models

Serpentinization

$$\underset{\text{forsterite}}{3\,Mg_2SiO_4} + \underset{\text{aqueous silica}}{SiO_2} + 2H_2O \Rightarrow \underset{\text{serpentine}}{2Mg_3Si_2O_5(OH)_4}$$

vs. (or in addition to)

$$\underset{\text{serpentine}}{2Mg_3Si_2O_5(OH)_4} + 3CO_2 \Rightarrow \underset{\text{talc}}{Mg_3Si_4O_{10}(OH)_2} + H_2O + \underset{\text{magnesite}}{3MgCO_3}$$

Talc-Carbonatization

1. Hydrothermal alteration reaction to produce talc-carbonate

Ref. Brown et al. 2010

Both processes probably occurred, key question is how much

Meteoritical Society
Meteoritics & Planetary Science 1–14 (2014)
doi: 10.1111/maps.12330

Metamorphism in the Martian crust

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(Received 30 January 2014; revision accepted 20 May 2014)

Abstract–Compositions of basaltic and ultramafic rocks analyzed by Mars rovers and occurring as Martian meteorites allow predictions of metamorphic mineral assemblages that would form under various thermophysical conditions. Key minerals identified by remote sensing roughly constrain temperatures and pressures in the Martian crust. We use a traditional metamorphic approach (phase diagrams) to assess low-grade/hydrothermal equilibrium assemblages. Basaltic rocks should produce chlorite + actinolite + albite + silica, accompanied by laumontite, pumpellyite, prehnite, or serpentine/talc. Only prehnite-bearing assemblages have been spectrally identified on Mars, although laumontite and pumpellyite have spectra similar to other uncharacterized zeolites and phyllosilicates. Ultramafic rocks are predicted to produce serpentine, talc, and magnesite, all of which have been detected spectrally on Mars. Mineral assemblages in both basaltic and ultramafic rocks constrain fluid compositions to be H_2O-rich and CO_2-poor. We confirm the hypothesis that low-grade/hydrothermal metamorphism affected the Noachian crust on Mars, which has been excavated in large craters. We estimate the geothermal gradient (>20 °C km^{-1}) required to produce the observed assemblages. This gradient is higher than that estimated from radiogenic heat-producing elements in the crust, suggesting extra heating by regional hydrothermal activity.

Metamorphism in Martian crust

Ref: McSween et al. 2014 “Both serpentine- and talc-bearing assemblages are consistent with temperature constraints imposed by the metabasalt assemblages (<350 °C). At these temperatures, serpentine is stable with fluids having $X_{CO2}<0:1$ and talc with fluids having X_{CO2} 1/4 0:1 to 0:3.”

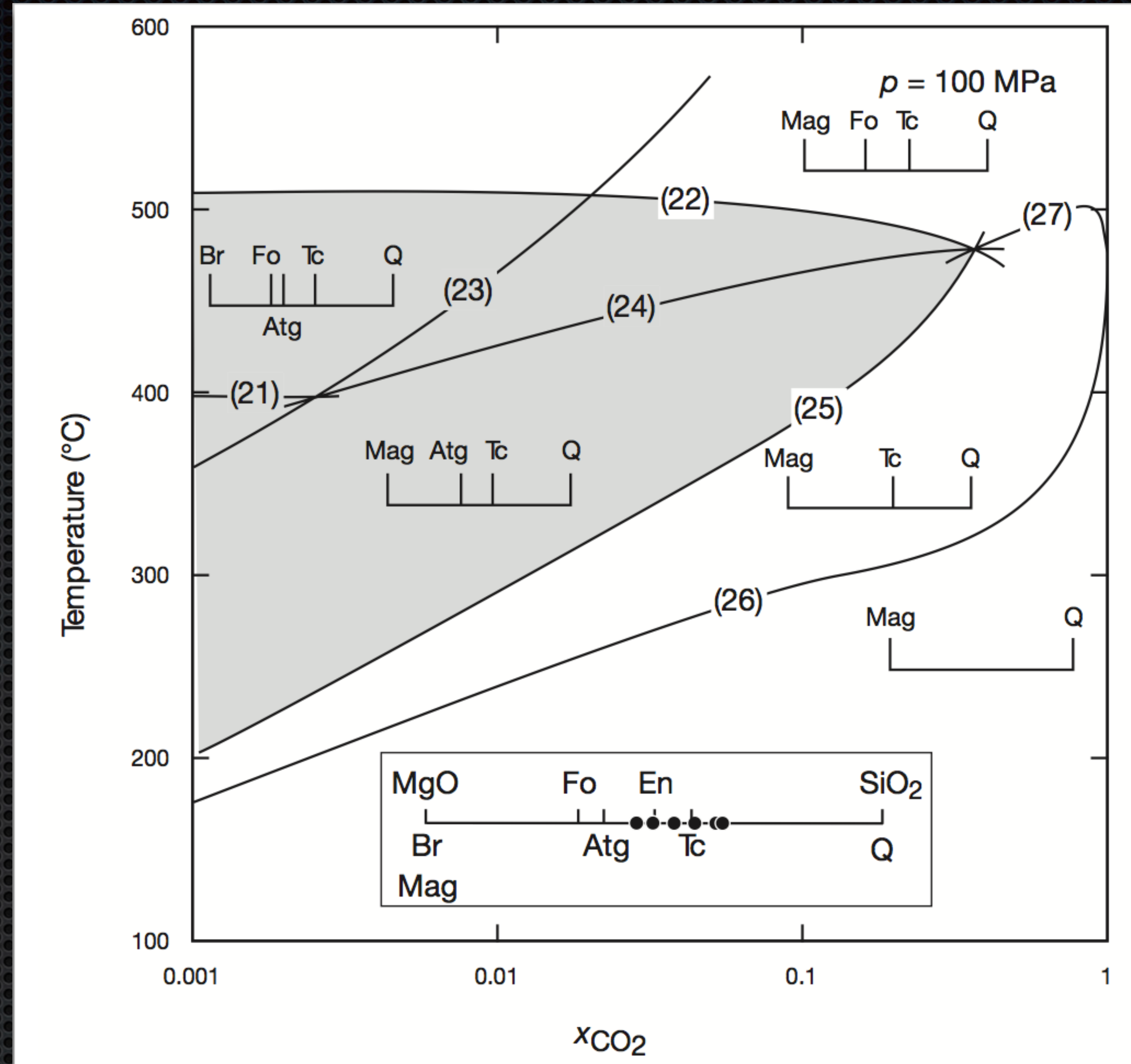
Formation of talc vs. serpentine

Table 2. Reactions in metamorphosed ultramafic rocks at low grade.

Reactions in Figs. 4 and 5:

(11) Liz + Tc = Atg
(12) Atg + Br = Liz
(13) Atg + Br = Fo + H_2O
(14) Atg = Fo + Tc + H_2O
(15) Br + CO_2 = Mag + H_2O
(16) Mag + Atg = Fo + H_2O + CO_2
(17) Mag + Tc = Atg + CO_2
(18) Mag + Qtz + H_2O = Tc + CO_2
(19) Mag + Tc = Fo + H_2O + CO_2

Mineral abbreviations: Liz = lizardite, Tc = talc, Atg = antigorite, Br = brucite, Fo = forsterite, Mag = magnesite.



Ref: McSween et al. 2014 "Both serpentine- and talc-bearing assemblages are consistent with temperature constraints imposed by the metabasalt assemblages (<350 °C). At these temperatures, serpentine is stable with fluids having XCO2<0:1 and talc with fluids having XCO2 = 0.1 to 0.3."

* Calculations are at P=1kbar, this is reached 10km deep in Martian crust
* Heating by diagenesis is insufficient

Metamorphism in the Martian crust

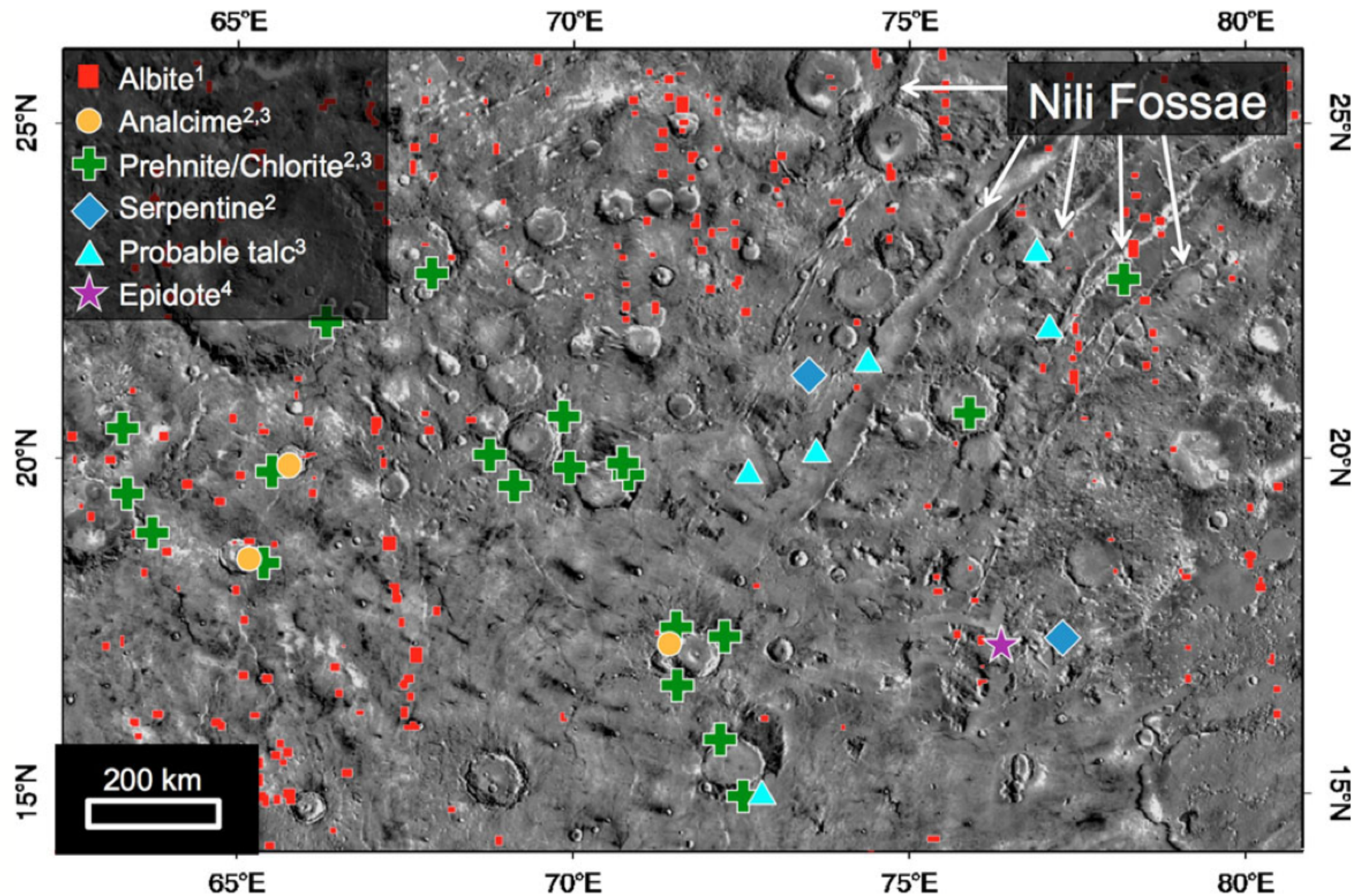


Fig. 6. THEMIS daytime infrared mosaic of the region west of Nili Fossae studied using CRISM, OMEGA, and TES spec by Ehlmann et al. (2009). CRISM-mapped occurrences of analcime (Ehlmann et al. 2009; Viviano et al. 2013), and TES pixels which the plagioclase is primarily albite (Milam et al. 2010) are shown. Prehnite, chlorite, and serpentine detections are fr Ehlmann et al. (2009), talc from Viviano et al. (2013), and epidote from Carter et al. (2013).

Ref: McSween et al 2014 showing a new map of hydrothermal classes including the talc findings

‘Talc Carbonate Hypothesis’ A Distilled Model

$$\underset{\text{serpentine}}{2Mg_3Si_2O_5(OH)_4} + 3CO_2 \Rightarrow \underset{\text{talc}}{Mg_3Si_4O_{10}(OH)_2} + H_2O + \underset{\text{magnesite}}{3MgCO_3}$$

Two (maybe three) step process:

1. Emplacement of a pre-Fossae formation (~3.9Ga) ultramafic (komatiite) lava flow across eastern Nili Fossae
2. This flow was buried and later altered by CO_2 rich fluids in a low grade metamorphic event accompanied by some degree of heating

(3.)These rocks were later exhumed

THE SYSTEM $MgO—SiO_2—H_2O$

Expand

N. L BOWEN and O. F TUTTLE

Abstract

Equilibrium in the system $MgO—SiO_2—H_2O$ has been determined at temperatures up to 1000°C and at maximum pressures of water vapor varying from 15,000 lbs/in^2 at this maximum temperature, to 30,000 lbs/in^2 in the range 900°—600°C, and 40,000 lbs/in^2 in the range 600°–300°C. Thus were fixed the univariant pressure-temperature curves of the following five reactions: I. serpentine + brucite forsterite + vapor, II. serpentine forsterite + talc + vapor, III. forsterite + talc =; enstatite + vapor, IV. talc enstatite + quartz + vapor, and V. brucite periclase + vapor. Pure magnesian serpentine has a maximum temperature of existence at approximately 500°C, varying only about 10° in the whole range of pressure 2000 to 40,000 lbs/in^2. Forsterite is stable in contact with water vapor down to a temperature of about 430°C (at 15,000 lbs/in^2). Only below that temperature is it transformed into serpentine and brucite. Iron-bearing olivines are stable in contact with water vapor down to still lower temperatures.

No liquid is formed in any composition of the system throughout the range of temperatures and pressures at which experiments were conducted, a condition which remains unchanged when the mixtures have upwards of 7 per cent FeO.

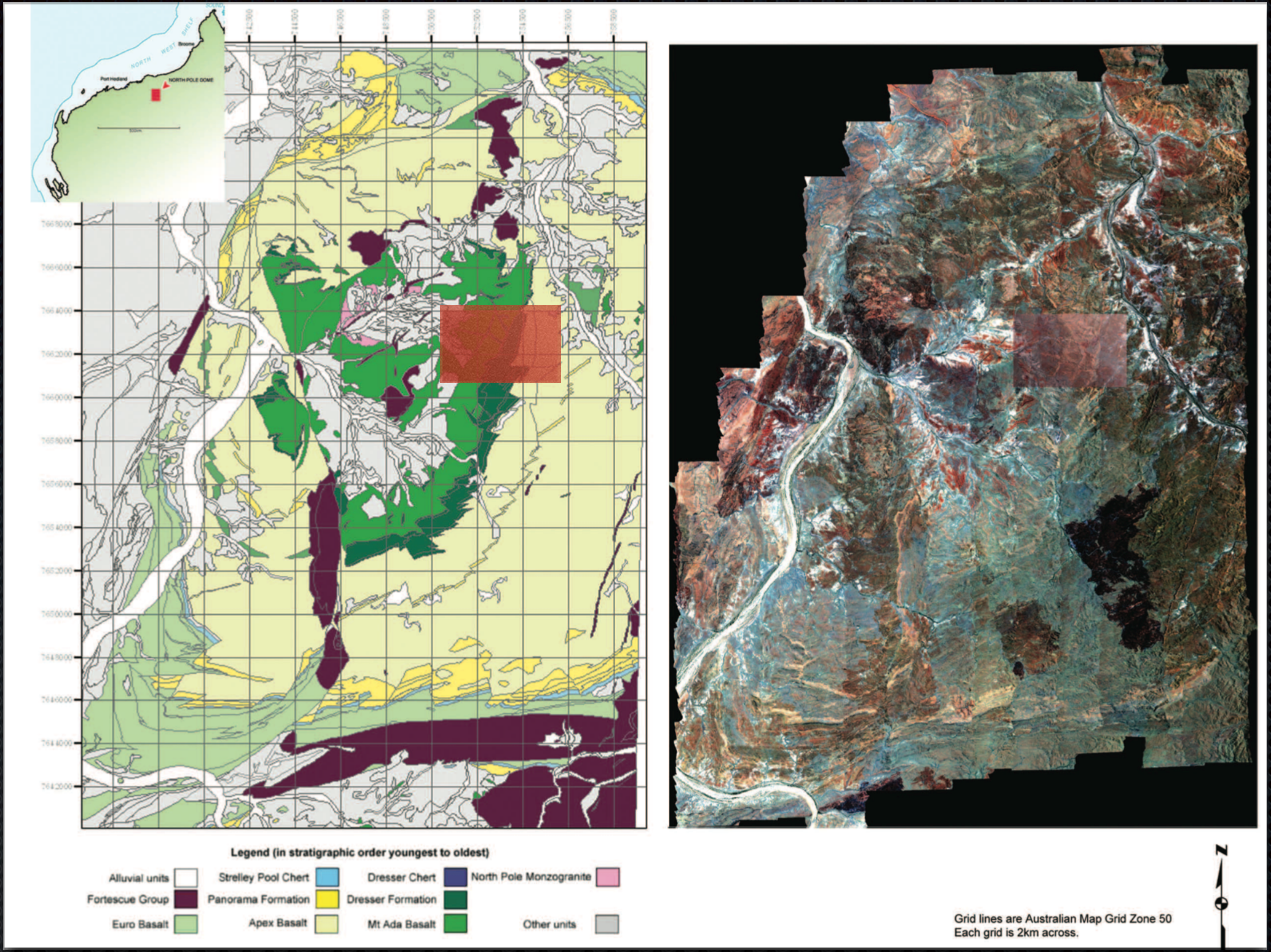
There is consequently no likelihood that any magma can exist that can be called a serpentine magma and certainly no possibility of its existence below 1000°C. There seems no escape from the conclusion that ultramafics can be intruded only in the solid state.

Q. But can komatiite form on the surface of Mars?

Ref. Bowen and Tuttle 1948, this phase diagram was misleading.

A. We don't yet know. But two points are germane.

1. Nili Fossae is the place it would be preserved.
2. if we found out it would have implications for rocky planets everywhere.
3. This is falsifiable by looking for spinifex textures or cumulate textures



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Astrobiology Questions to be addressed by Mars 2020 Rover at Nili Fossae

1. **Late Noachian conditions**. Was the Noachian habitable? How was the carbonate at Nili emplaced?
2. **Organic Preservation.** Are there recognizable signs of thin chert/silicic inter layers or sediments that might preserve biosignatures below the talc-carbonate layer?
3. **Energy source**. Was the heat and water source for Mg-OH alteration? 1. Exhalative? 2. Contact/Intrusive? 3. Magmatic? 4. Impact? Was it available for origin of life?
4. **Talc vs. serpentine.** How much of each phase precipitated and under what conditions? Was burial required?
5. **Syrtis.** What is the nature of the 'spectrally featureless' cap rock? Can we use it for crater count calibration?
6. **Isidus.** What part has been played by Isidus in the mineralogy of Nili Fossae? Are the carbonates pre or post Isidis?