Subsurface Aqueous Alteration on Ancient Mars: Implications for Habitability

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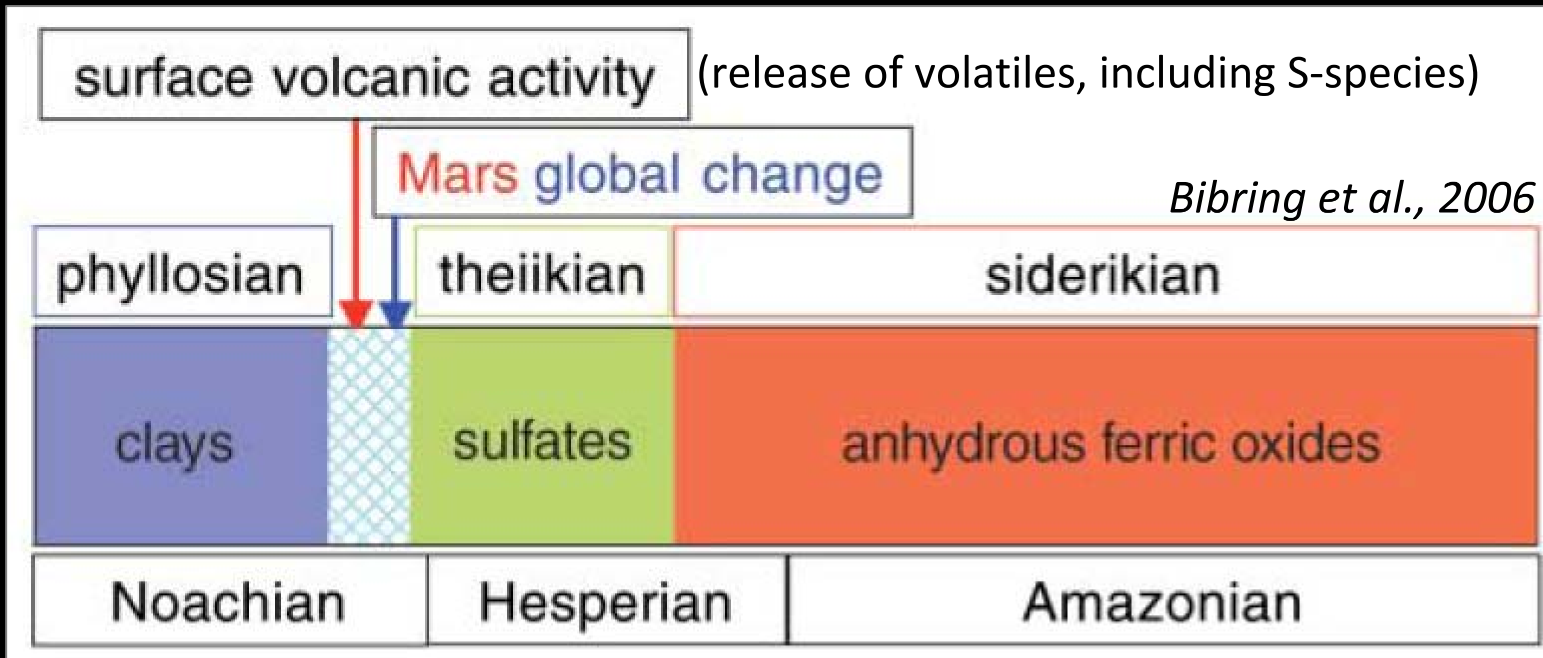
Exploring Mars Habitabiility -- 14 June 2011

Ancient



Modern

“If **phyllosilicates had formed in the subsurface**, the **Mars environment might have always been tenuous, cold, and dry**, except for transient episodes…

If instead **phyllosilicates formed at or close to the surface**, this would **require the Mars early atmosphere to be dense**. The global change to an acidic environment would then have been coupled to a rapid drop in atmospheric pressure.”

How to distinguish alteration environments?

Geochemical and Mineralogic Indicators under Chemically "Open" and "Closed" conditions and low and high Water:Rock ratios

Styles of Alteration

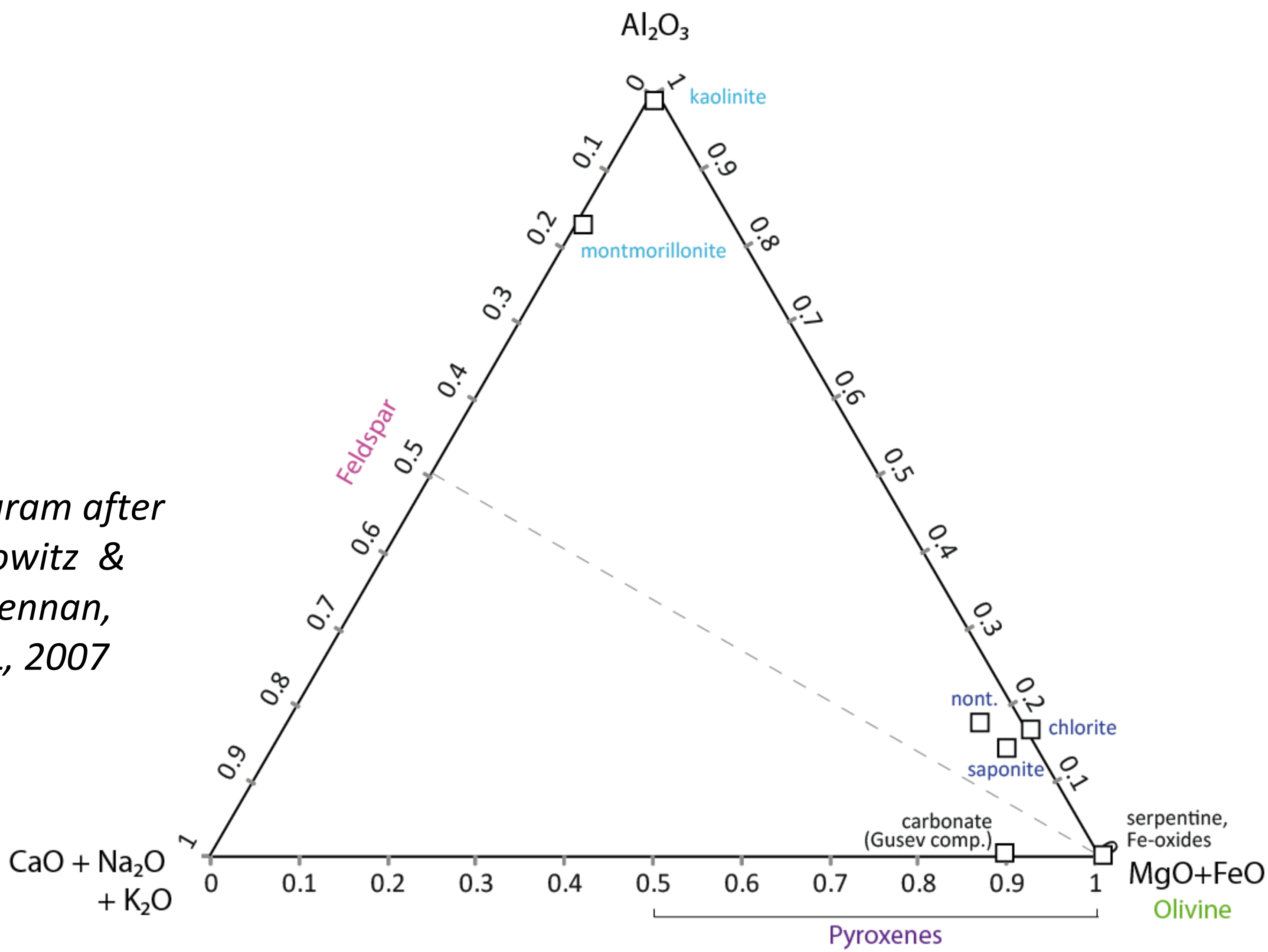
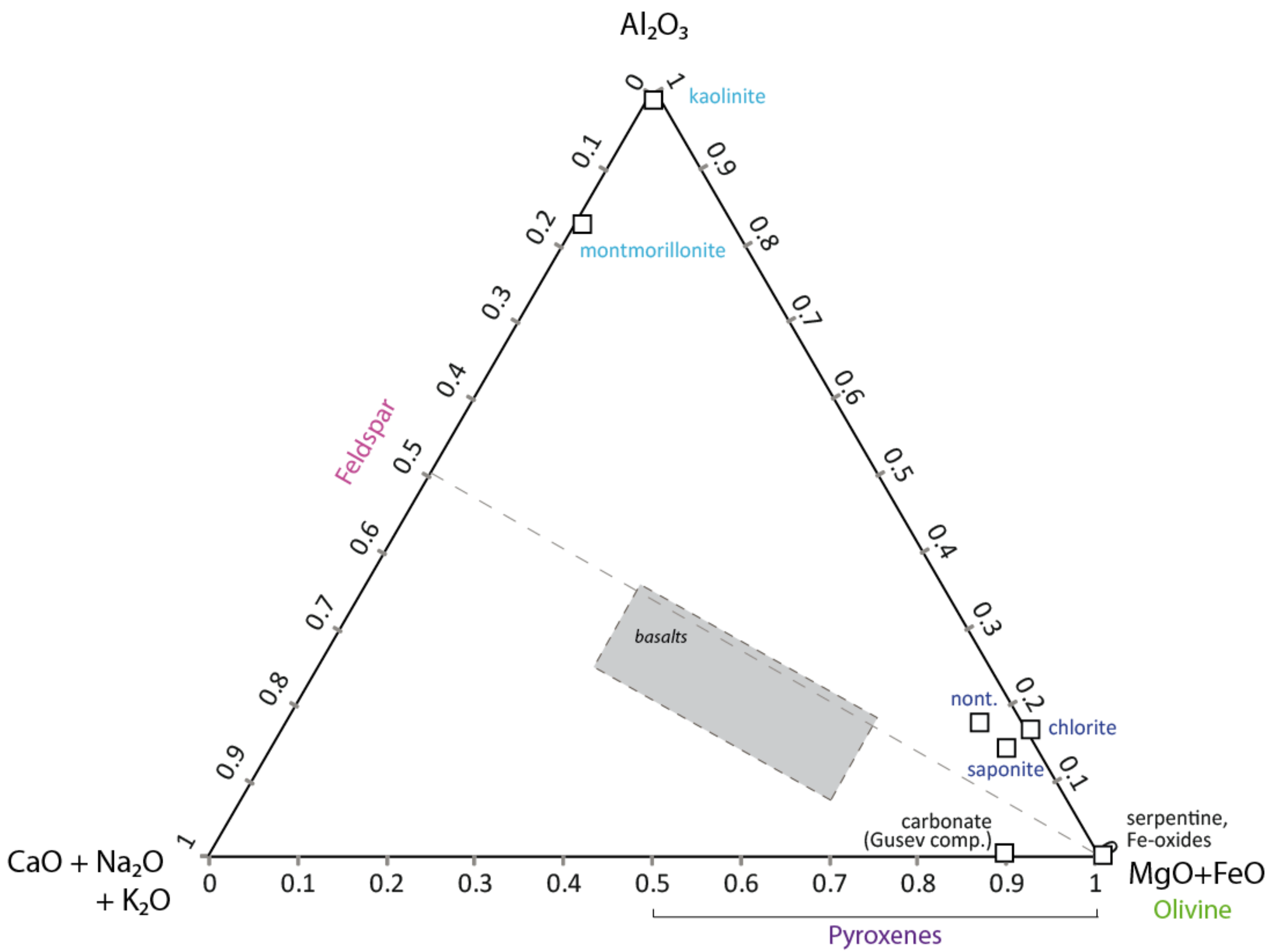


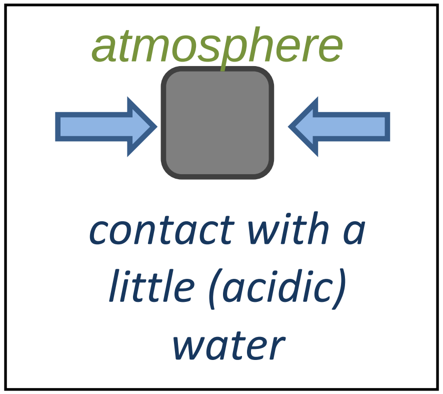
Diagram after Hurowitz & McLennan, EPSL, 2007

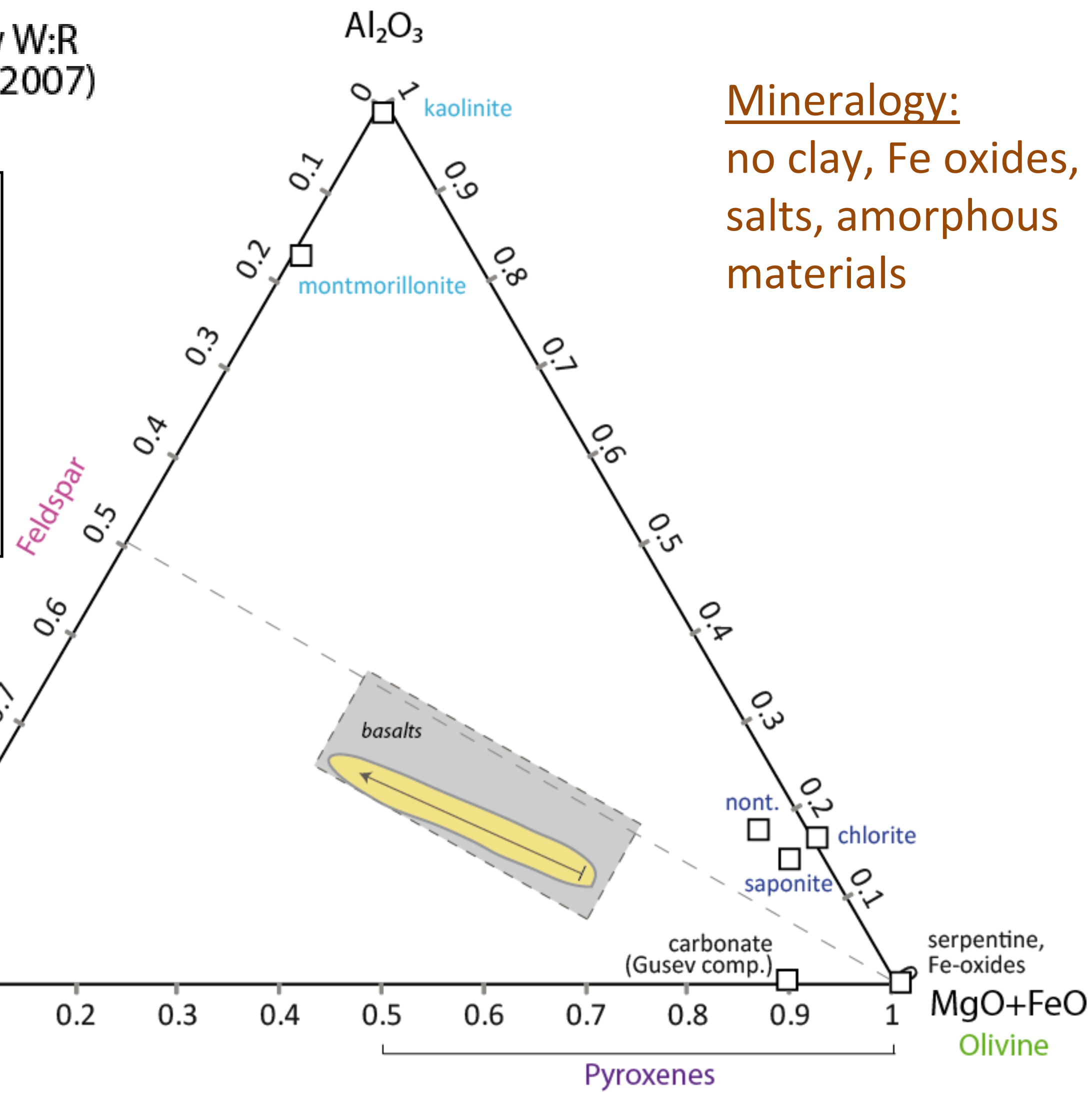
Styles of Alteration



Styles of Alteration to form <not clay>

- Near-surface, acidic, low W:R (Hurowitz & McLennan, 2007)

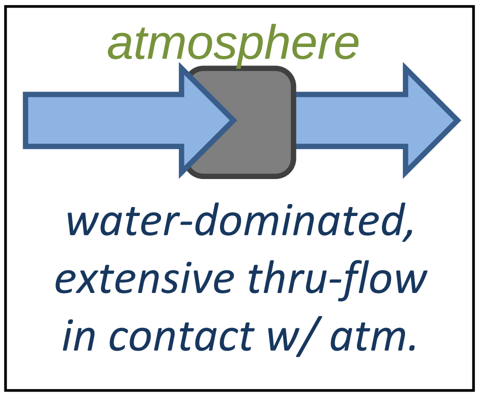


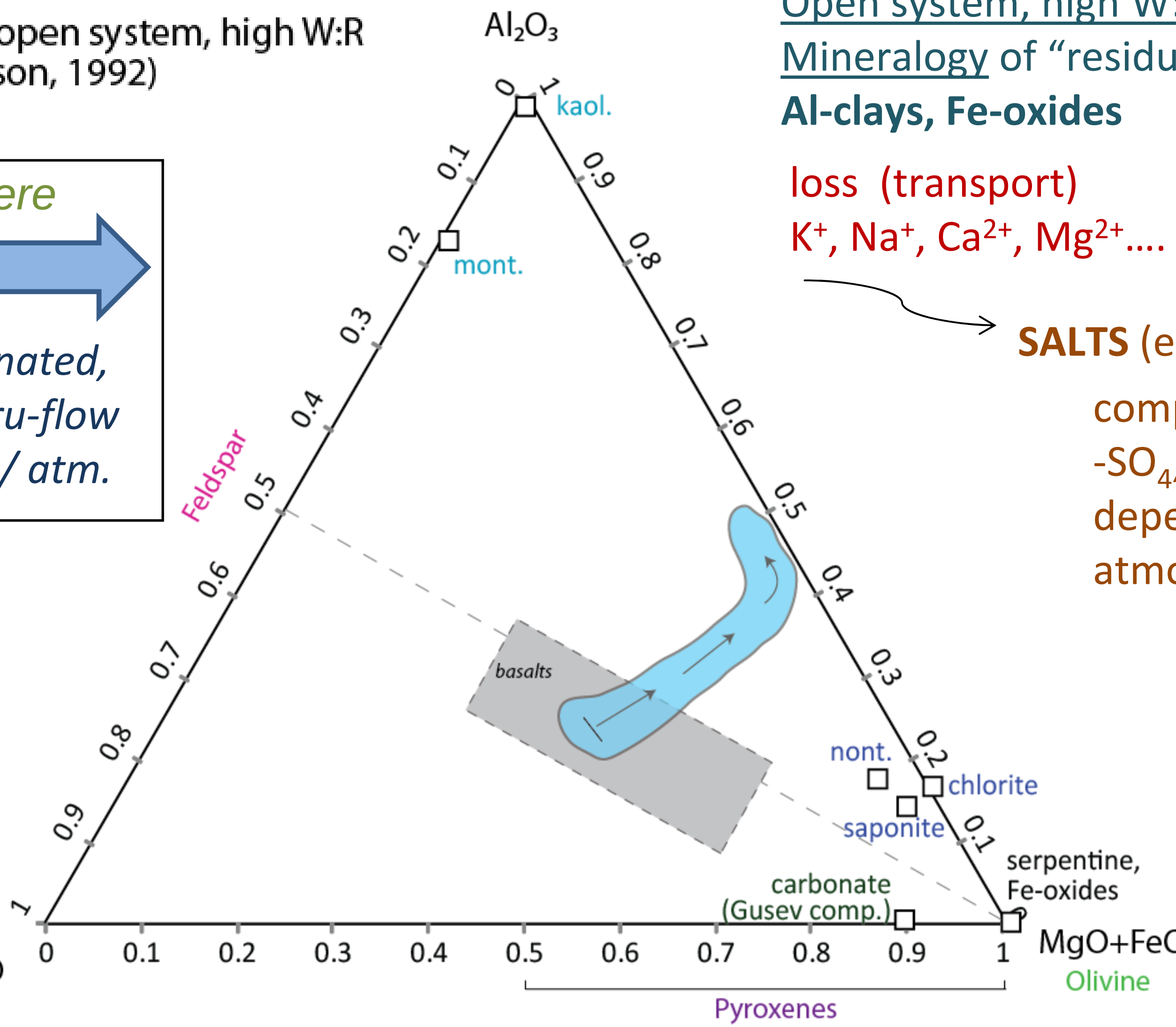


<u>Mineralogy:</u>
no clay, Fe oxides, salts, amorphous materials

Styles of Alteration to form Clays

Near-surface, open system, high W:R (Nesbitt & Wilson, 1992)





Open system, high W:R

Mineralogy of "residue":

Al-clays, Fe-oxides

loss (transport)

K^+, Na^+, Ca^{2+}, Mg^{2+}....

SALTS (elsewhere)

composition…
$-SO_4$, -Cl, $-CO_3$, depends on atmosphere

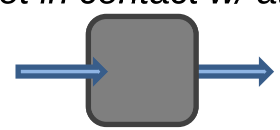
Styles of Alteration to form Clays

Open system, high W:R, near surface
(Nesbitt & Wilson, 1992)

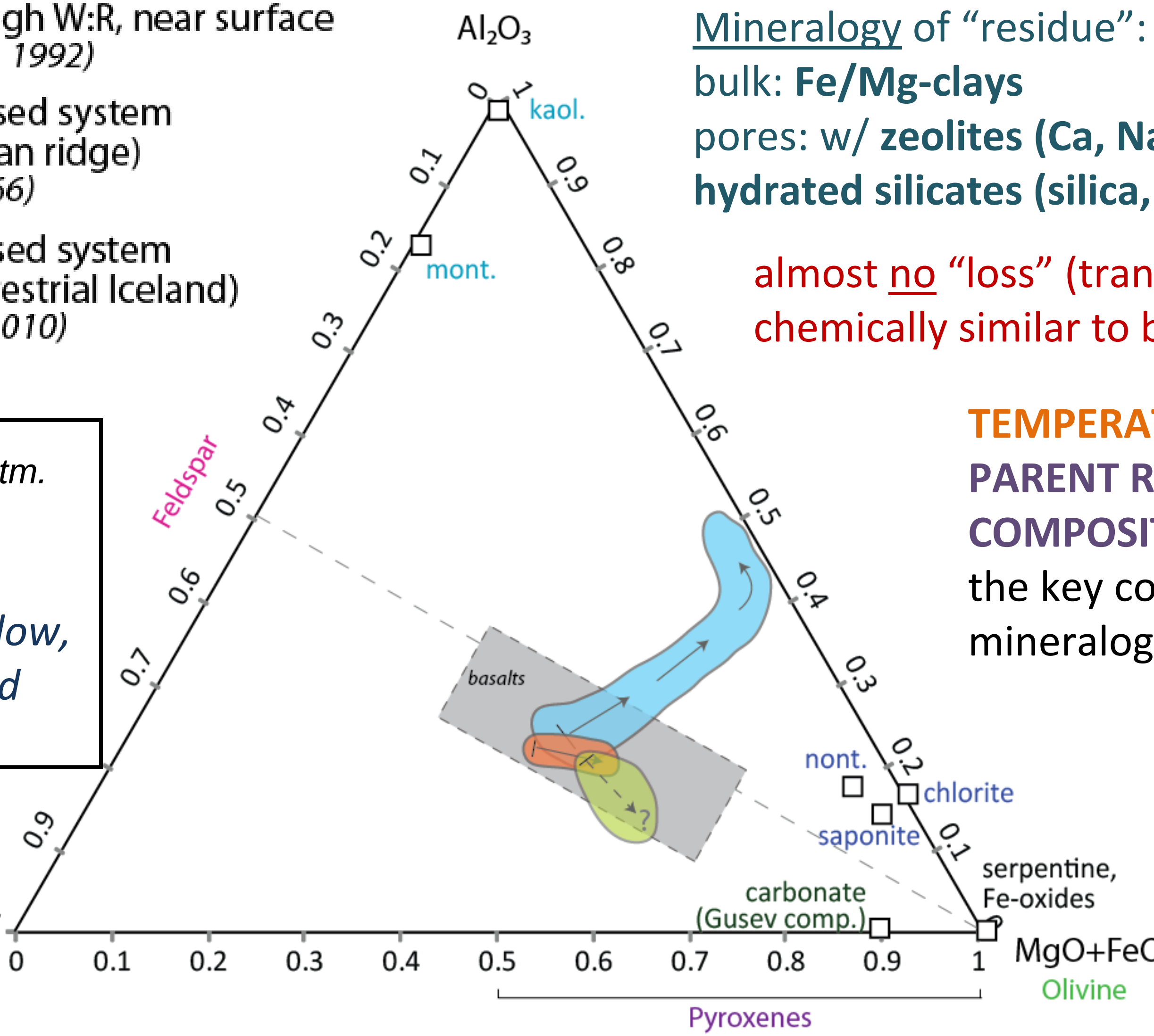
Subsurface, closed system
(hydroT alt. ocean ridge)
(Cann & Vine, 1966)

Subsurface, closed system
(hydroT alt., terrestrial Iceland)
(Ehlmann et al., 2010)

not in contact w/ atm.



little water thru-flow, rock-dominated



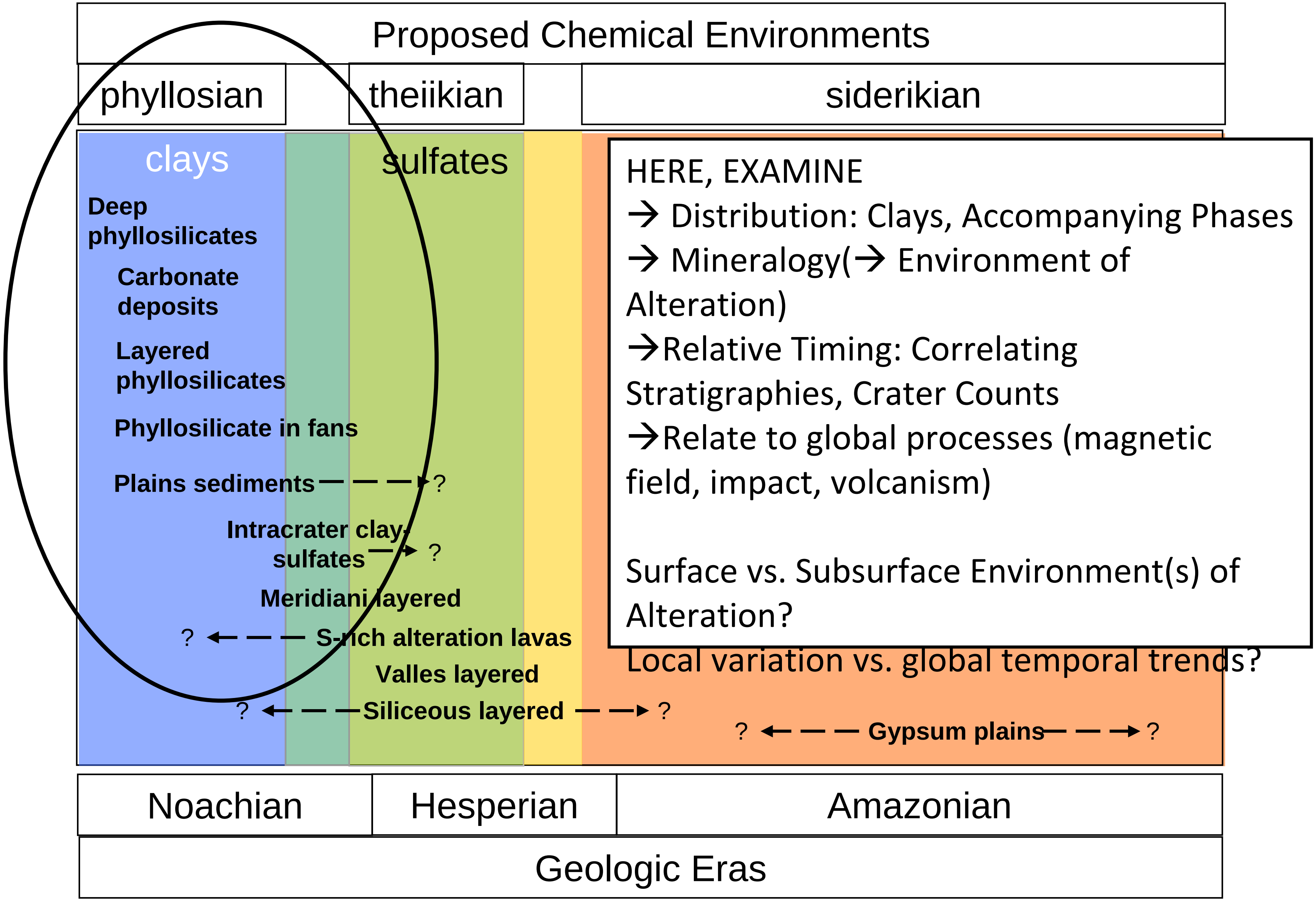
Low W:R, closed system

Mineralogy of "residue":
bulk: **Fe/Mg-clays**
pores: w/ **zeolites (Ca, Na),** other **hydrated silicates (silica, prehnite)**

almost no "loss" (transport), chemically similar to basalt

TEMPERATURE, PARENT ROCK COMPOSITION are the key controls on mineralogy

Adapted from Murchie et al., JGR, 2009 with mineralogic epochs from Bibring et al., 2006



A *meta-analysis* of CRISM data

DATA SOURCES

- Surveyed targeted images (18-40m/pixel)
- Compiled data from the literature when a complete list of alteration minerals found within a CRISM targeted image was reported by the authors

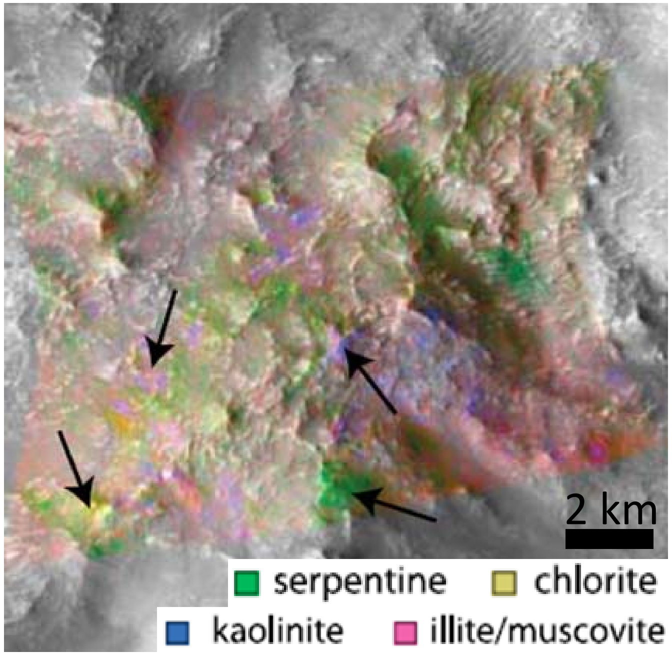
DATASET

- Lat/Lon of image center (images within +/- 15km count as 1 image)
- Kept track of present/absence of phyllosilicate and which accompanying phases
- Defined setting: "crustal", "clay in stratigraphy", "sedimentary"

Number of Data Points	Reference
1	Baldridge et al., 2009, *GRL*
6	Buczkowski et al., 2010, *JGR*
6	Buczkowski et al., 2010, *LPSC*
91	Carter et al., 2010, *Science*
75	Ehlmann et al., 2009, *JGR*
119	surveyed as part of Ehlmann et al., 2010, *GRL*
240	surveyed as part of Fraeman et al., 2009, *LPSC*
5	Glotch et al., 2010, *GRL*
1	Michalski & Niles, 2010, *Nature Geosci.*
26	McKeown et al., 2009, *JGR*
2	Milliken et al., 2010, *GRL*
4	Milliken and Bish, 2010, *Phil. Trans.*
2	Murchie et al., 2009, *JGR*
1	Mustard & Ehlmann, 2011, *LPSC*
31	Noe Dobrea et al., 2010, *JGR*
2	Roach et al., 2010, *Icarus*
5	Wiseman et al., 2010, *JGR*
1	Wiseman et al., 2008, *GRL*
21	Wray et al., 2011, *JGR*
639	**TOTAL**

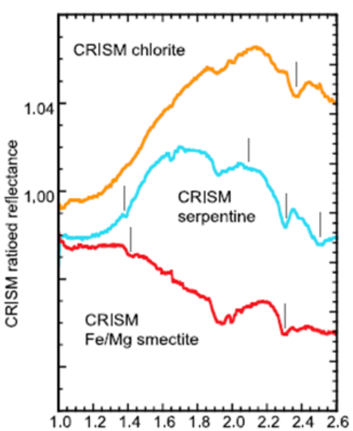
"Crustal Clays"

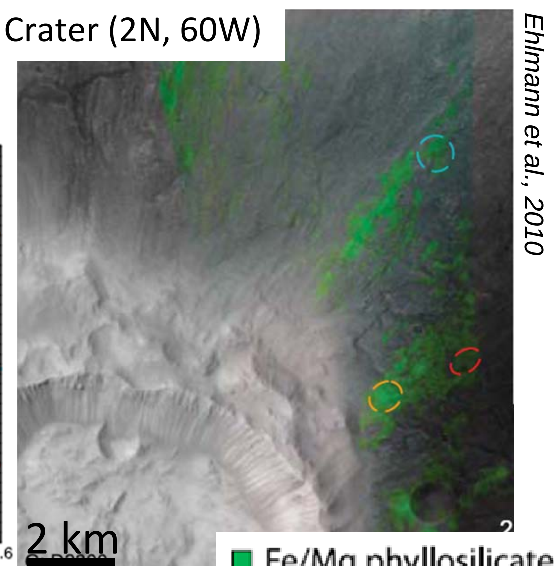
i. Exposed Ancient Crust, e.g. in the Claritas Rise



Ehlmann et al., 2010

ii. Craters, e.g. Chia Crater (2N, 60W)

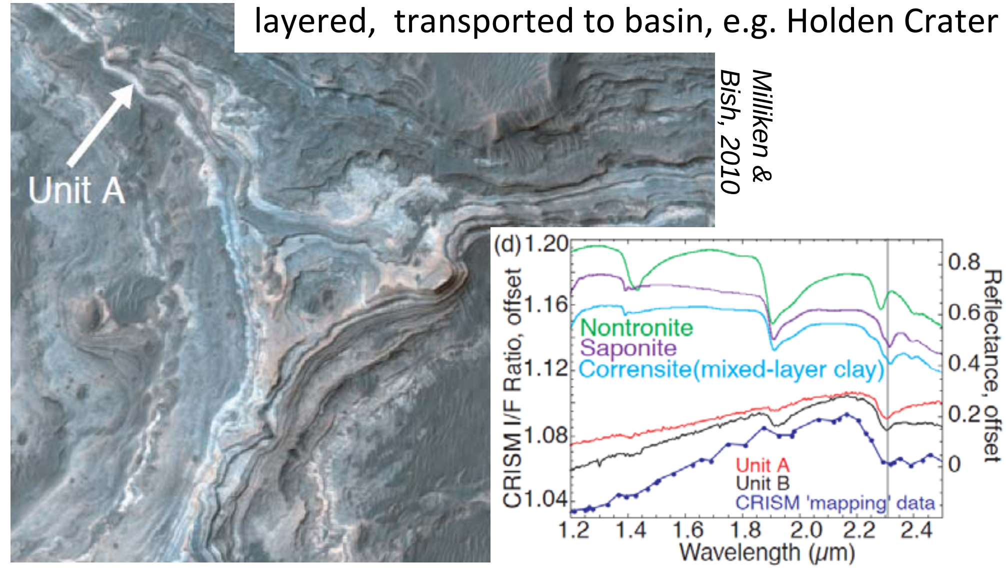




Ehlmann et al., 2010

"Sedimentary Clays"

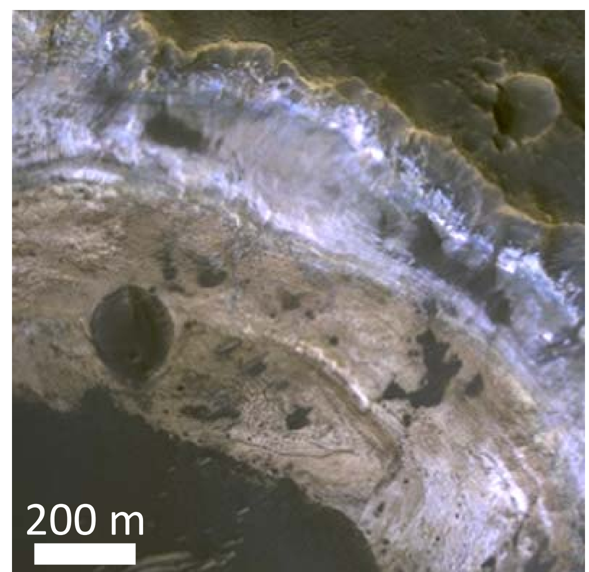
layered, transported to basin, e.g. Holden Crater



Milliken & Bish, 2010

"Clays in Stratigraphy"

well-ordered compositional variation, e.g. Mawrth Vallis



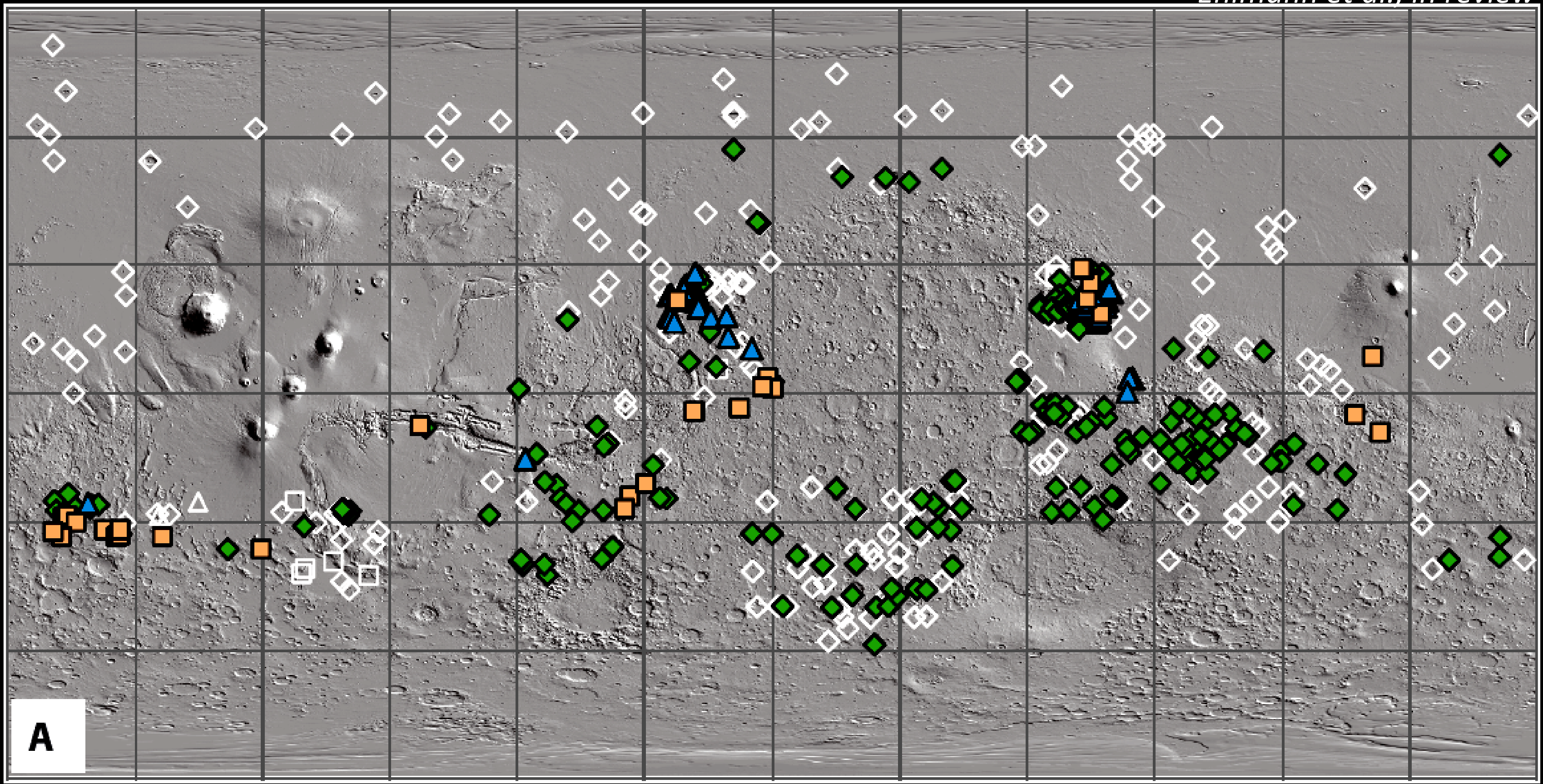
Loizeau et al. 2011

Al-clays + silica

nontronite

Global Distribution of Clay-Bearing Materials

Ehlmann et al., in review

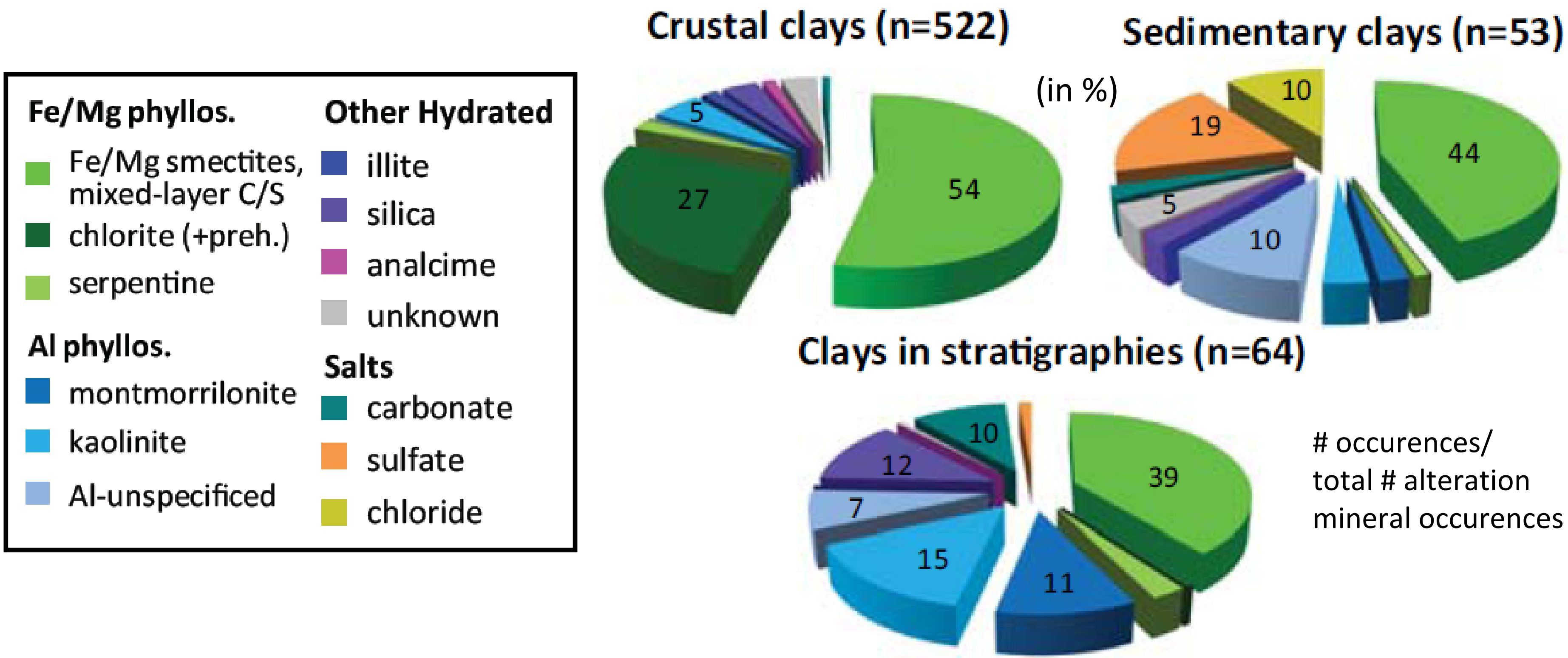


= crustal clays = sedimentary clays = clays in stratigraphy

open symbols = no clays found

→ Exposure is the principal control on mineralogy (alteration to clays was a global phenomenom)

Mineral Associations: Key Findings

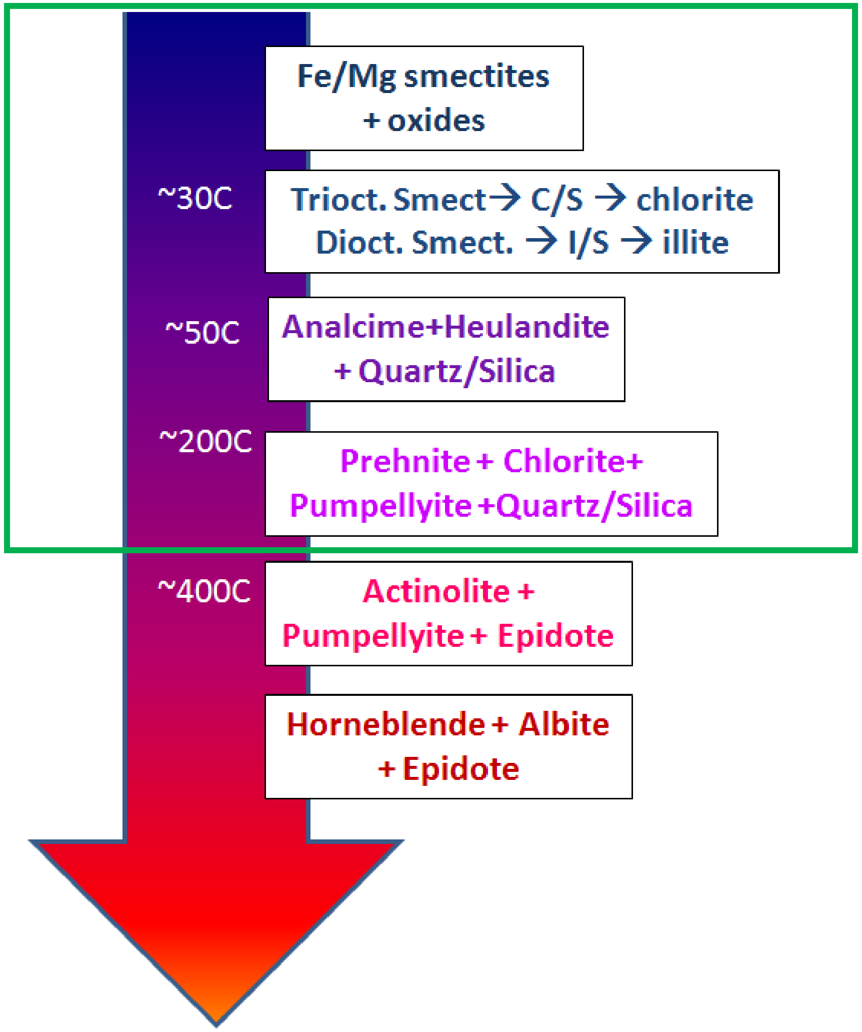


Ehlmann, et al., in review

- Fe/Mg smectites are always the most dominant clay mineral
- Phases associated with Fe/Mg smectites depend on geologic setting
  - Crustal: other hydrated silicates (prehnite, illite, analcime, silica, Al clays)
  - Sedimentary: salts + clays, more Al clays
  - in Stratigraphy: Fe/Mg smectites in stratigraphy with Al-clays or olivine-carbonate unit

Crustal Clays: Evidence of Elevated Temperature Alteration

LOW W:R ALTERATION OF BASALTIC PROTOLITH

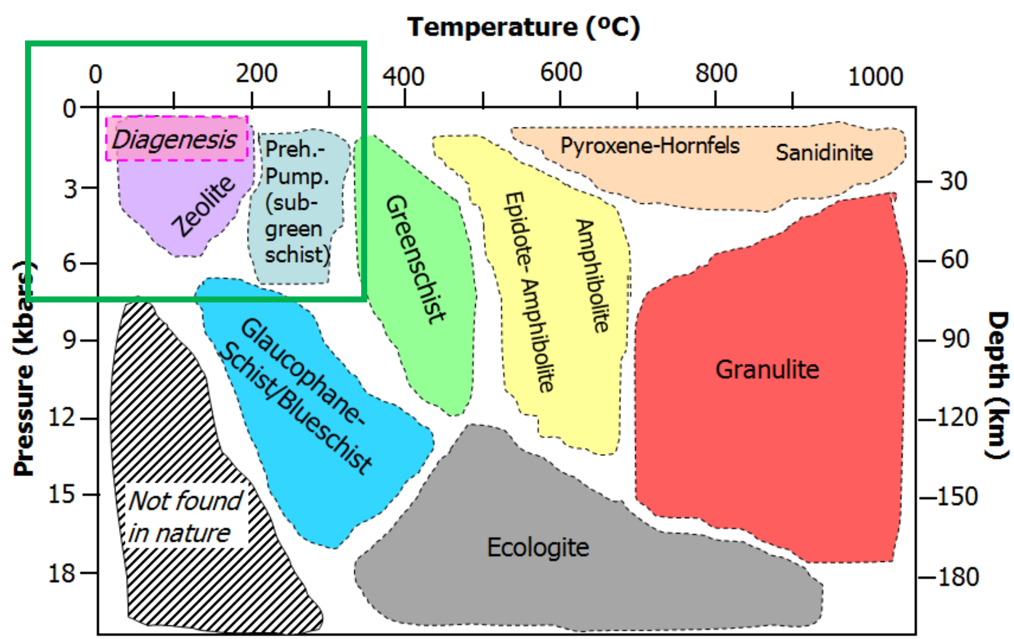


(an ultramafic composition assemblage would instead have saponite, serpentine, talc, brucite)

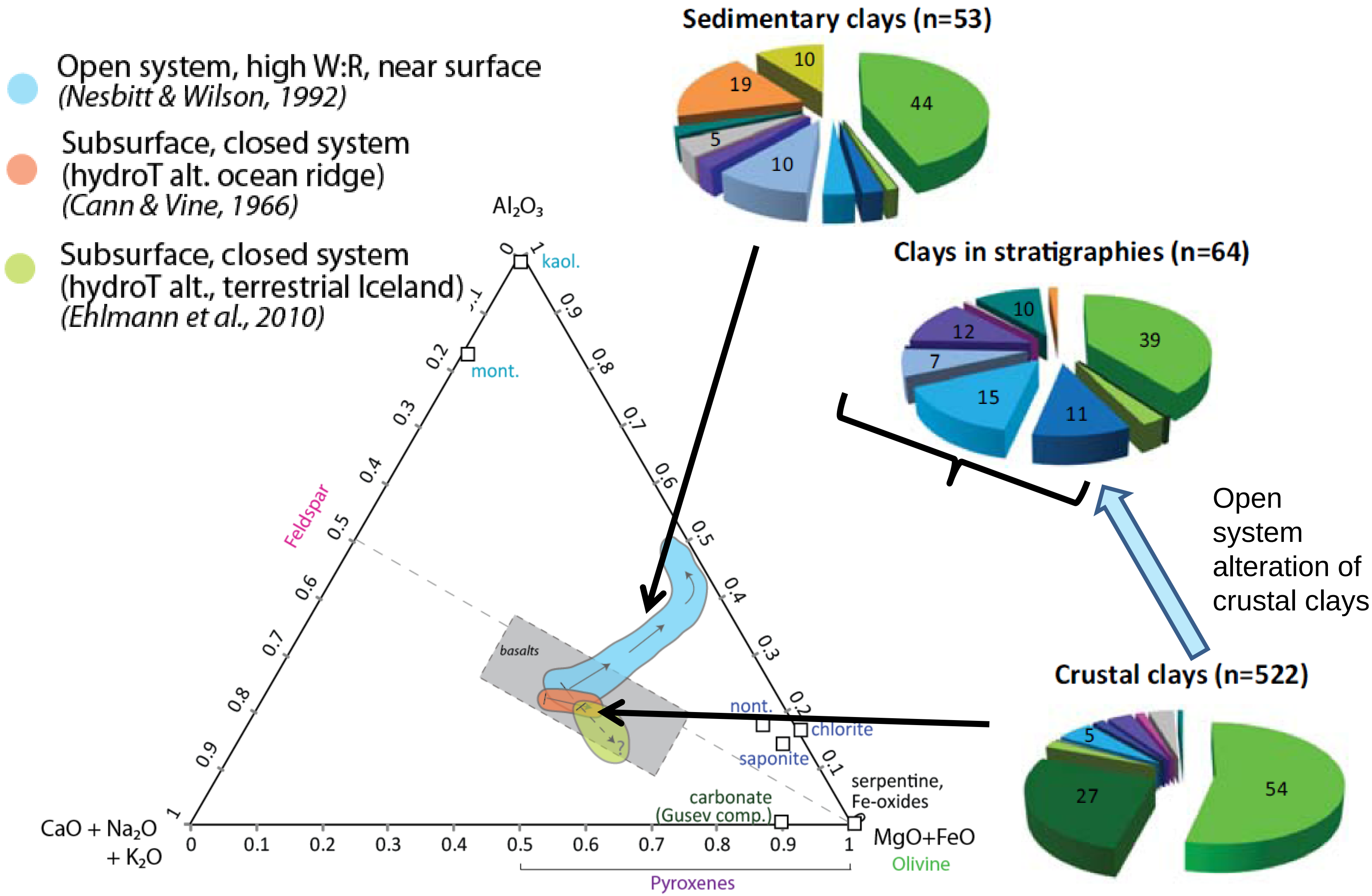
synthesizing Cann, 1979; Meunier, 2005; Frey & Robinson, 1999; Arkai et al., 2003; Philpotts & Aguee, 2009

- Mineral assemblages are consistent with low W:R ratio formation by
  - Hydrothermal alteration
  - Low-grade metamorphism
  - Deuteric formation (e.g. lava cooling)

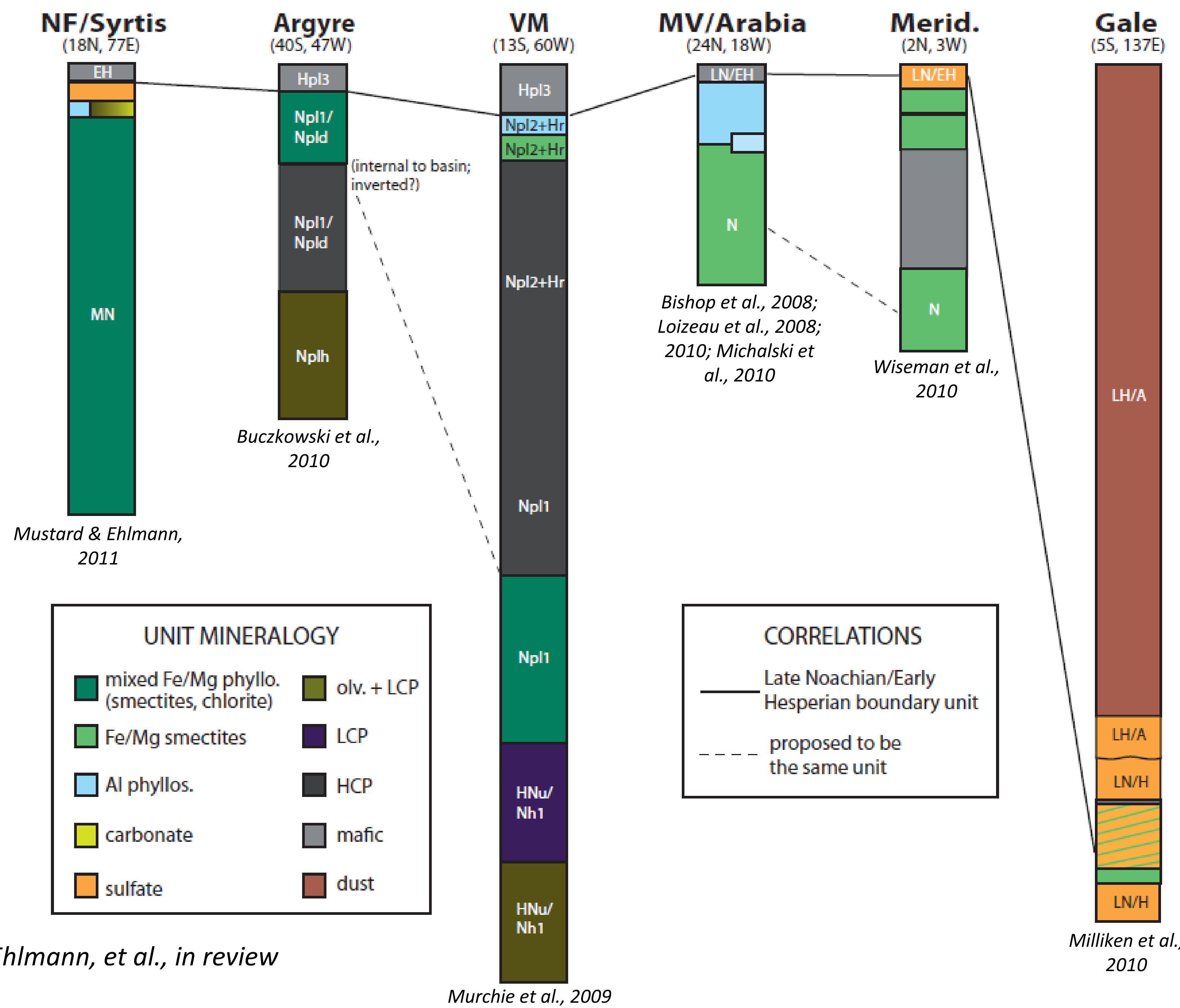
Ehlmann et al., forthcoming, Clays & Clay Minerals



Styles of Alteration to form Clays



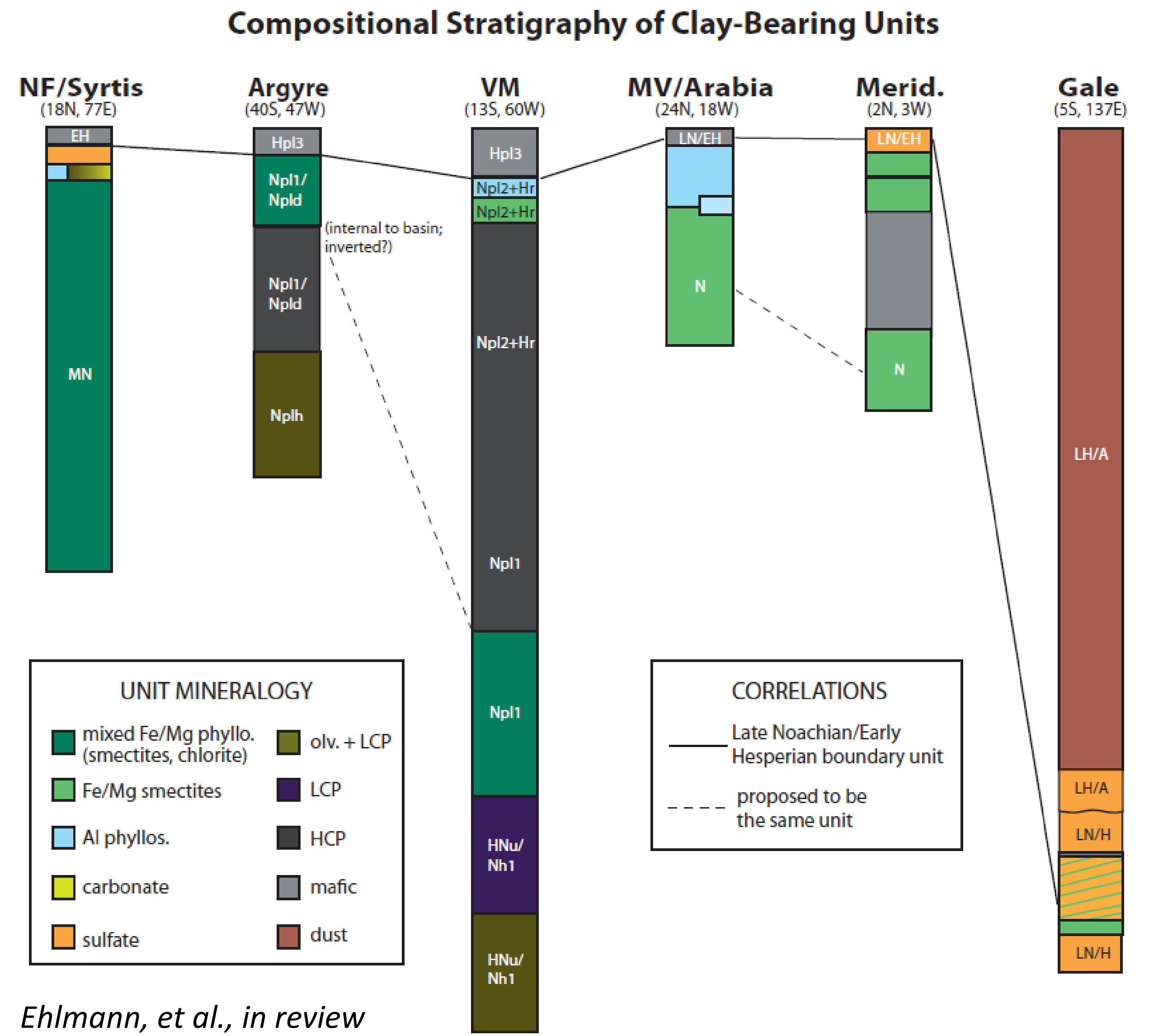
Compositional Stratigraphy of Clay-Bearing Units



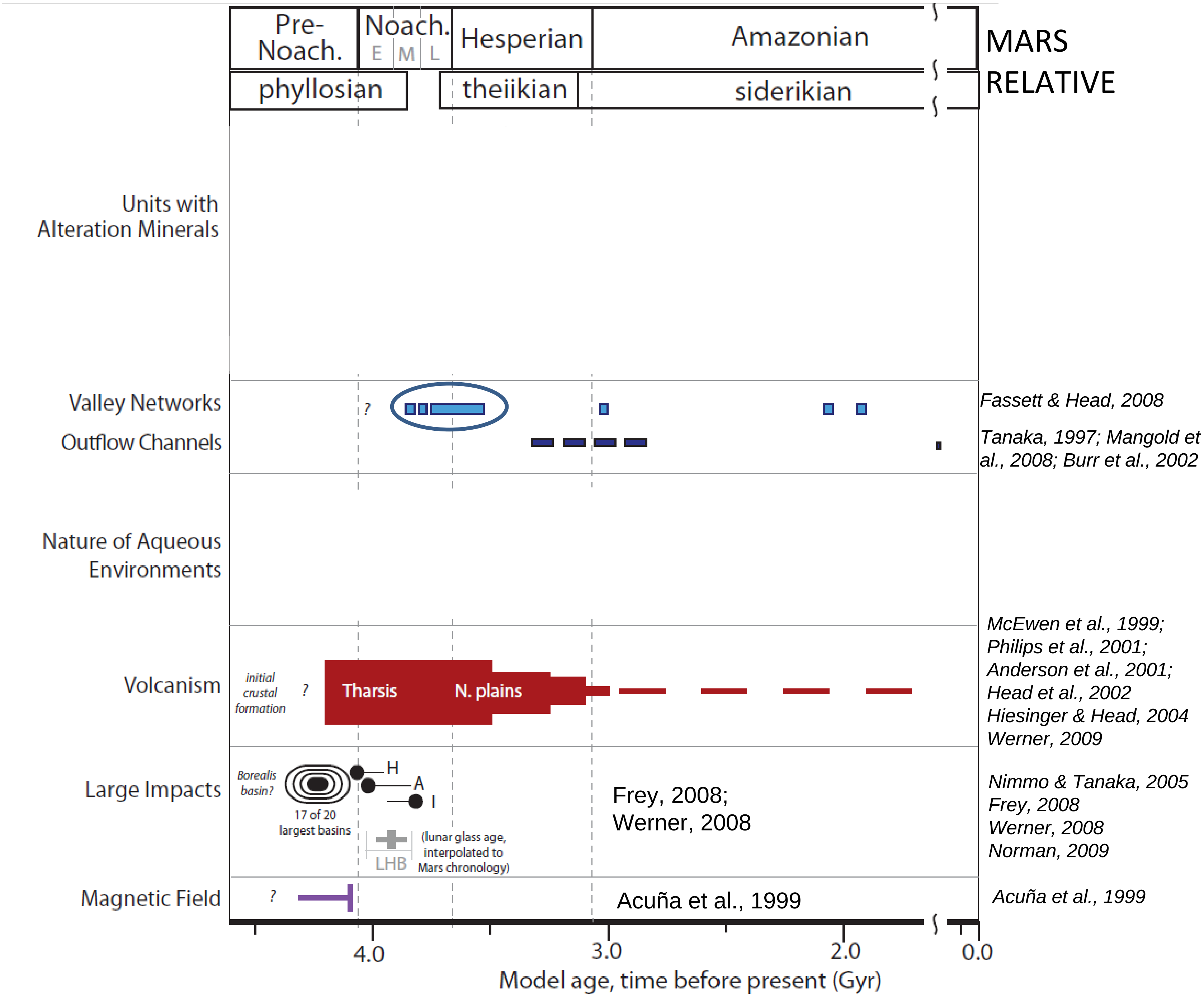
Ehlmann, et al., in review

KEY POINTS

- No clays after crater count age corresponding to LN/EH
- Al clays always atop Fe/Mg phyllosilicates
- Fe/Mg phyllos. (smectite, chlorite, mixtures) comprise thick lower layers
- *but* not usually volumetrically abundant and many thick, deep units have no signs of alteration visible from orbit



Ehlmann, et al., in review



Pre-Noach.
Noach.
E M L
Hesperian
Amazonian
MARS RELATIVE
phyllosian
theiikian
siderikian
Units with Alteration Minerals
Valley Networks
Outflow Channels
Fassett & Head, 2008
Tanaka, 1997; Mangold et al., 2008; Burr et al., 2002
Nature of Aqueous Environments
Volcanism
initial crustal formation
?
Tharsis
N. plains
McEwen et al., 1999; Philips et al., 2001; Anderson et al., 2001; Head et al., 2002 Hiesinger & Head, 2004 Werner, 2009
Large Impacts
Borealis basin?
17 of 20 largest basins
H
A
I
LHB
(lunar glass age, interpolated to Mars chronology)
Frey, 2008; Werner, 2008
Nimmo & Tanaka, 2005 Frey, 2008 Werner, 2008 Norman, 2009
Magnetic Field
Acuña et al., 1999
Acuña et al., 1999
4.0
3.0
2.0
0.0
Model age, time before present (Gyr)

Mars Sedimentary Clays

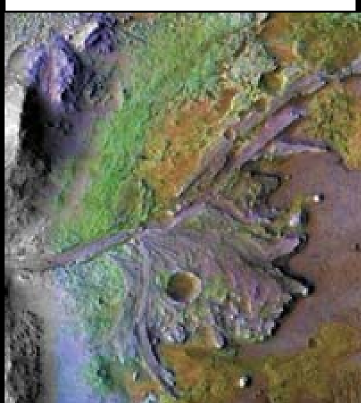
Timing of all of these is predominately: Late-Noachian to Early-Hesperian

[Fassett & Head, 2005; 2008a; 2008b – Glotch et al., 2010 – Osterloo et al., 2010 – Wray et al., 2011 – Swayze, Ehlmann, Milliken, Poulet et al., in prep.]

Diversity in alteration products, settings implies diversity in water chemistry

JEZERO

Open-basin
Fe/Mg clay,
Mg carbonate

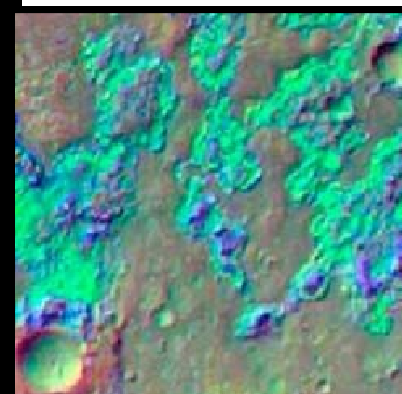


EBERSWALDE, HOLDEN

Open?-basin
Fe/Mg clay

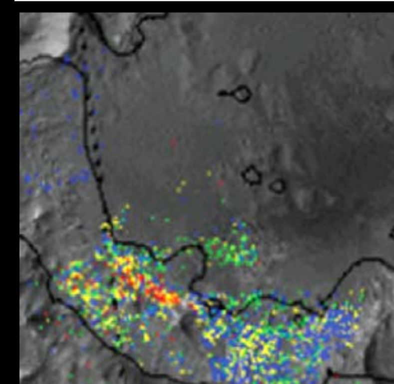
TERRA SIRENUM BASINS

Closed?-basin
Chloride salts overlying, Fe/Mg clays

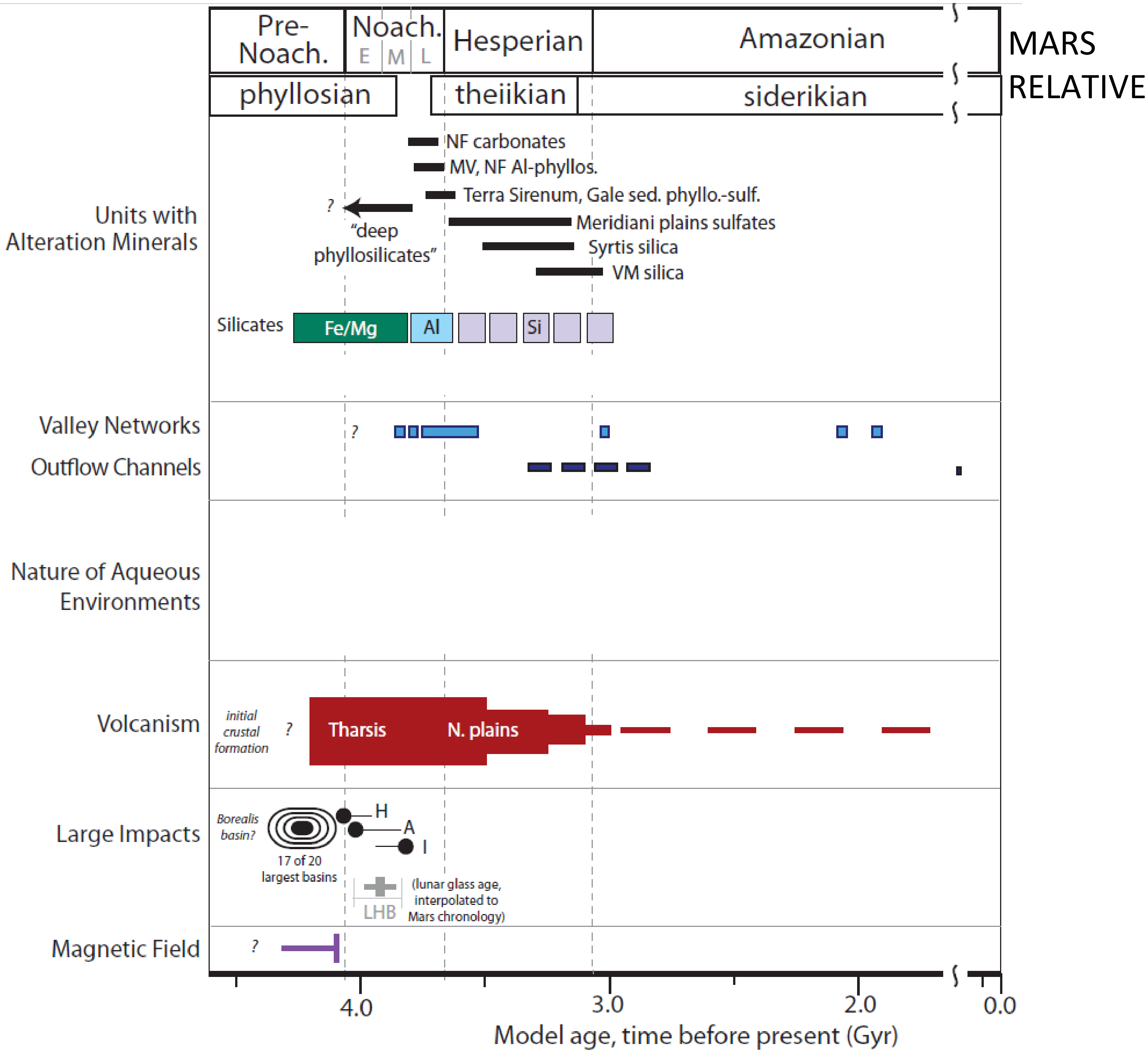


COLUMBUS , CROSS

Closed-basin
Al (, Fe/Mg) clays and sulfates (incl. jarosite, alunite)



Alkaline ⟷ Acidic



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Noach.
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Hesperian
Amazonian
MARS RELATIVE
phyllosian
theiikian
siderikian
NF carbonates
MV, NF Al-phyllos.
Terra Sirenum, Gale sed. phyllo.-sulf.
Meridiani plains sulfates
Syrtis silica
VM silica
?
"deep phyllosilicates"
Units with Alteration Minerals
Silicates
Fe/Mg
Al
Si
Valley Networks
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Nature of Aqueous Environments
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17 of 20 largest basins
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3.0
2.0
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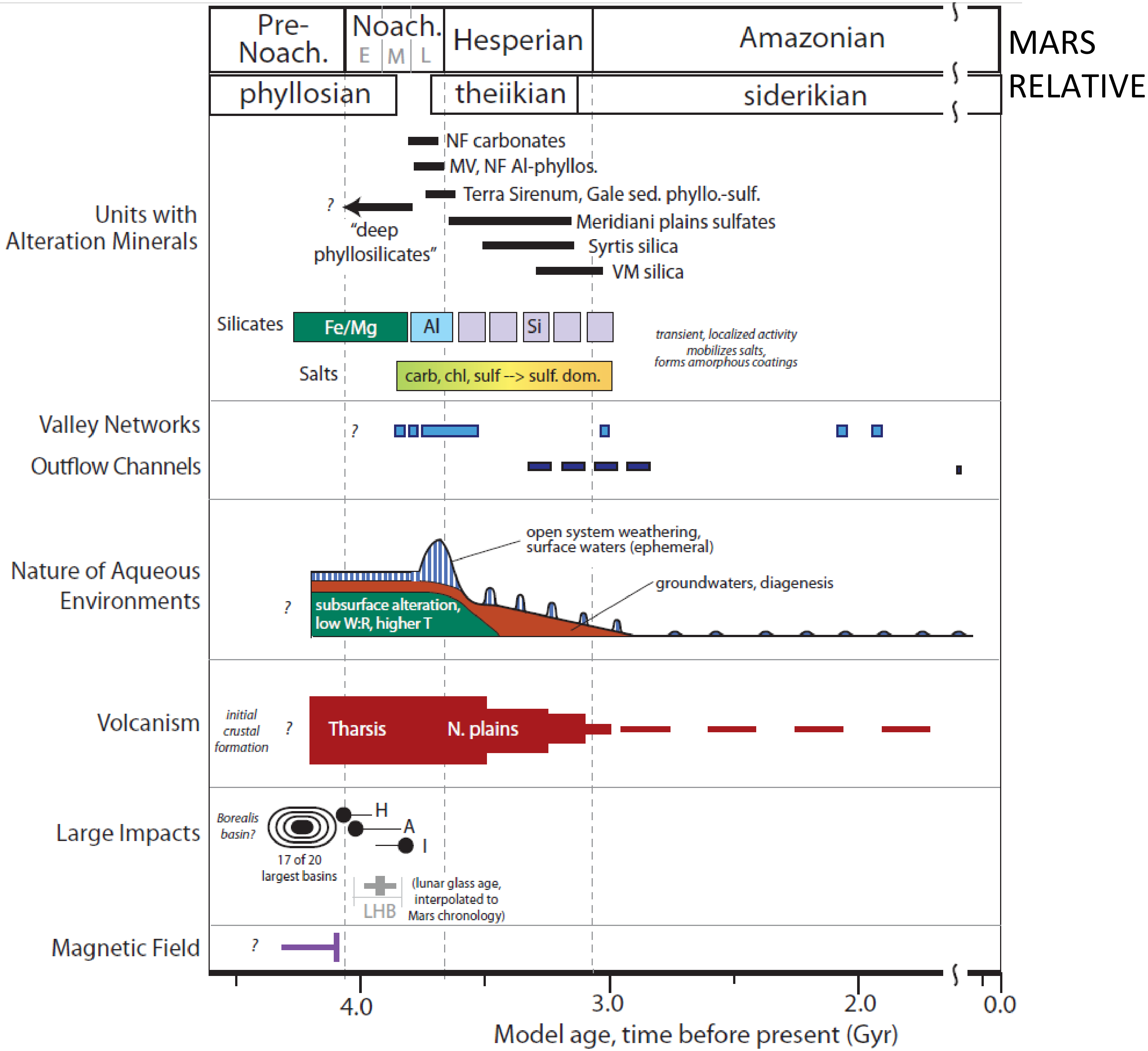
Model age, time before present (Gyr)



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Meridiani plains sulfates
Syrtis silica
VM silica
?
"deep phyllosilicates"
Silicates
Fe/Mg
Al
Si
transient, localized activity mobilizes salts, forms amorphous coatings
Salts
carb, chl, sulf --> sulf. dom.
Valley Networks
?
Outflow Channels
Nature of Aqueous Environments
open system weathering, surface waters (ephemeral)
groundwaters, diagenesis
?
subsurface alteration, low W:R, higher T
Volcanism
initial crustal formation
?
Tharsis
N. plains
Large Impacts
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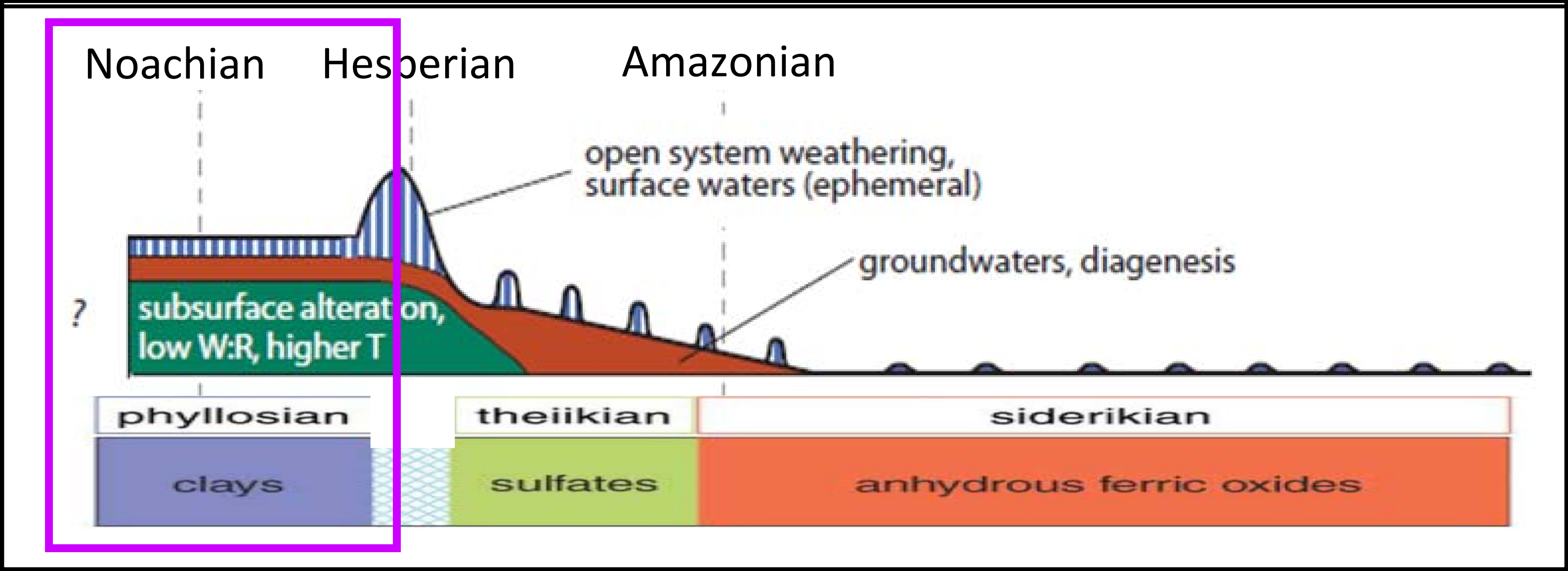


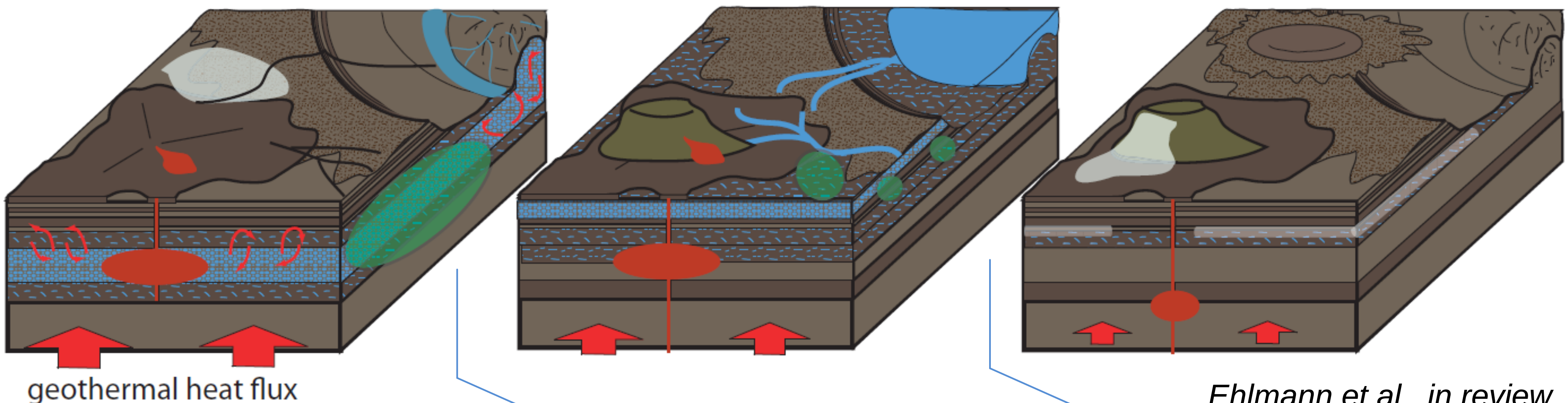
- Most clay minerals—Fe/Mg phyllosilicate-bearing units deep in the crust—formed in the subsurface at low W:R in closed systems at temperatures ranging from ambient to low-grade hydrothermal (<300ºC).
- Mechanism is consistent with
  - observed mineral assemblages of Fe/Mg smecites and chlorite, which form under anoxic, alkaline, high pH conditions
  - presence of the accompanying phases prehnite, analcime, serpentine and illite or muscovite, which form in diagenesis and/or in low-grade metamorphic/hydrothermal systems
  - the pervasive presence of clay minerals in large volumes of Mars' deepest exposed crustal materials (globally widespread) in spite of
  - elemental abundances and thermal infrared data consistent with dominance of primary minerals by weight fraction (*Taylor et al., 2010; Glotch et al., 2010*)
  - the morphology of Noachian fluvial valleys indicating hyperarid surface conditions except during the late Noachian, when episodic, high-magnitude floods incised numerhighland valley systems (*Irwin et al., 2005; Howard et al., 2005; Barnhart et al., 2009*).

Inferred Environments

1. Global phyllosilicate formation (MN. & earlier)

2. Late-stage enhanced surface waters/alteration (LN/EH)

3. Modern Mars (LH→present)



Ehlmann et al., in review

-Largely closed crustal system, low W:R ratio
→ Assemblages of diverse phases with Fe/Mg phyllosilicates in low-grade hydrothermal/metamorphic/ diagenetic conditions
permits but ***does not require significant surface water***

-High W:R open-system leaching (ice/permafrost melt, precipitation)
-Varying acidity
→ Al clay + silica formation near the surface at large scales
→ precipitation of various salts

-colder, dryer
-very small amounts of water (in time or space)
→only local scale salt and silica precipitation/ mobility

Further Hypothesis Testing: 'Most Clays Formed in the Subsurface'

1. **direct *in-situ* detection of** hydrothermal/metamorphic **indicator minerals** or interstratified clays
2. **elemental abundances of clay-bearing materials are little-changed** from that of basalt (indicative of low W:R style)
3. **textures of clay-bearing materials with alteration phases concentrated in veins and vesicles** (similar to that observed in Mars meteorites)
4. **isotopic data** (from H, C, O) **show elevated formation temperatures** for minerals
5. (indirect) measured isotopic ratios and calculation of loss rates of **atmospheric gases that indicate a continuously thin atmosphere**

Implications

- Early enhanced rates of crustal cooling
  - Explanation for early topographic feature preservation, e.g. Parmentier & Zuber, 2007
- Possibly significant sequestration of volatiles in the crust
- **Early atmosphere does not need to be thick, nor surface warm**
  - Transient liquid waters only, (e.g. from large-scale volcanic-gas release: Johnson et al., 2008; Phillips et al., 2001)
- **Crustal environments may be the oldest, most stable, and longest aqueous (habitable) environments on Mars**
  - Habitability of low W:R hydrothermal/metamorphic systems?
  - Concentration of the products of life for detectability?
  - Mars' biosphere is/was a deep biosphere?

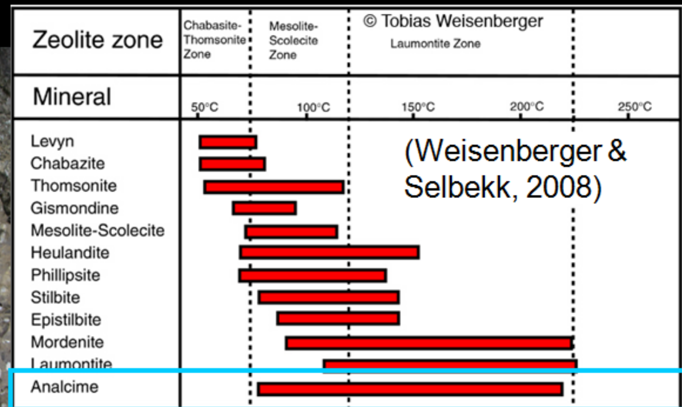
EXTRAS

For CRISM images with clay-bearing materials, % with…

	Alteration Phase	Crustal (% sites)	Sedimentary (% sites)	in Stratigraphy (% sites)
Fe/Mg CLAYS	*Fe/Mg smectite*	77.6	84.4	95.1
	Chlorite/prehnite	39.0	0	1.6
	Serpentine	3.1	0	6.6
Al CLAYS	*Montmorillonite*	3.9	4.4	26.2
	Kaolinite	7.7	6.7	36.1
	Al-phyllo (unspecified)	0	20.0	18.0
OTHER HYDRATED SILICATE	*Illite*	2.3	0	0
	Silica	5.4	4.4	29.5
	Analcime	1.9	0	0
	Other Hydrated (unspecified)	5.4	8.9	1.6
SALTS	*Carbonate*	1.2	4.4	24.6
	Sulfate	0	35.6	3.3
	Chloride	0	20.0	0

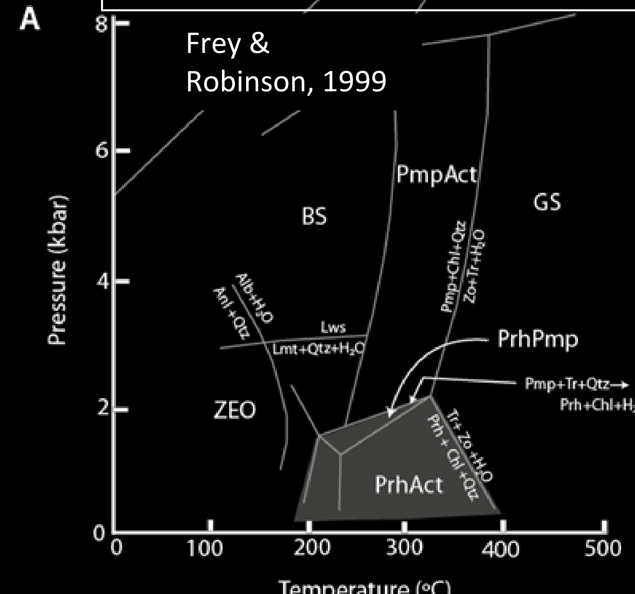
Mineral Indicators of Elevated Temperature

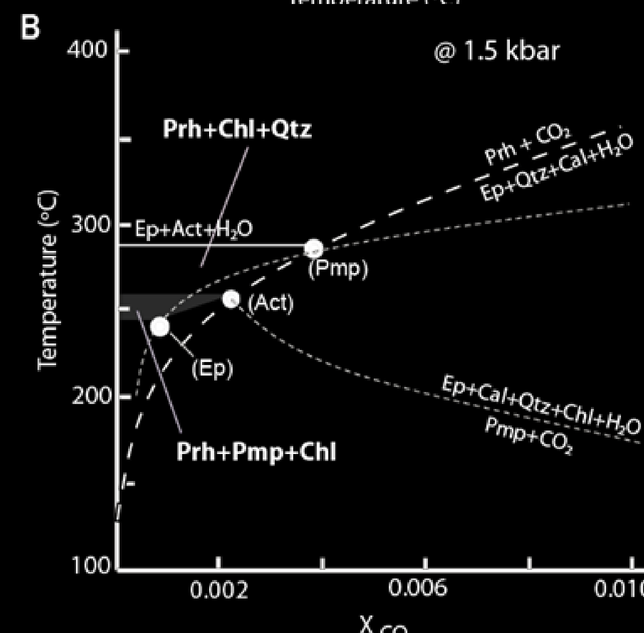
ANALCIME: 50-250ºC

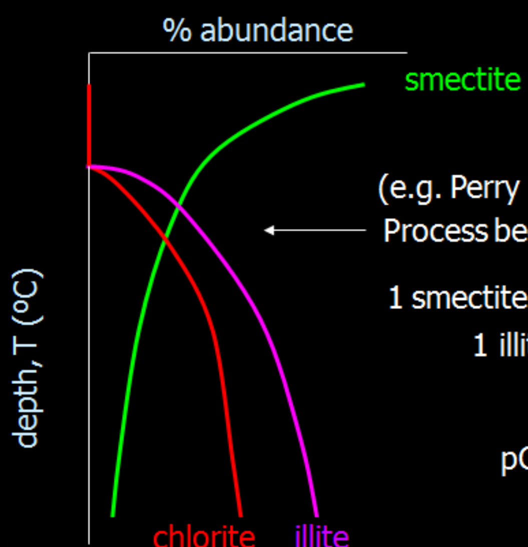


Zeolitized basalt, Iceland

PREHNITE: 200-400ºC







ILLITE/MUSCOVITE: >50ºC

(e.g. Perry & Hower, 1970)

← Process begins **T ~ 50-80ºC**

1 smectite + K^+ →

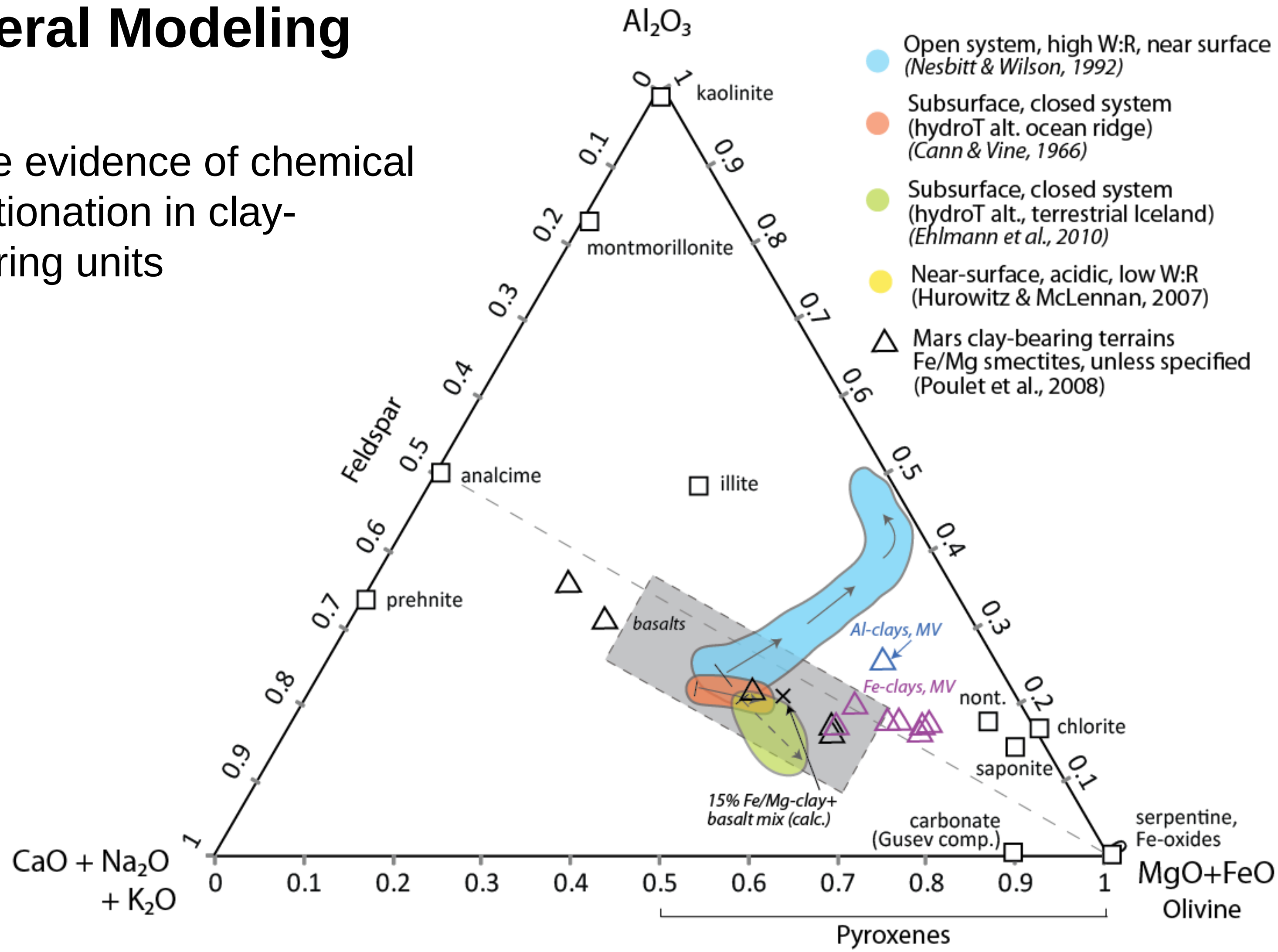
1 illite + Na^+ + Ca^{2+} + Si^{4+} + Fe^{2+} + Mg^{2+} + H_2O

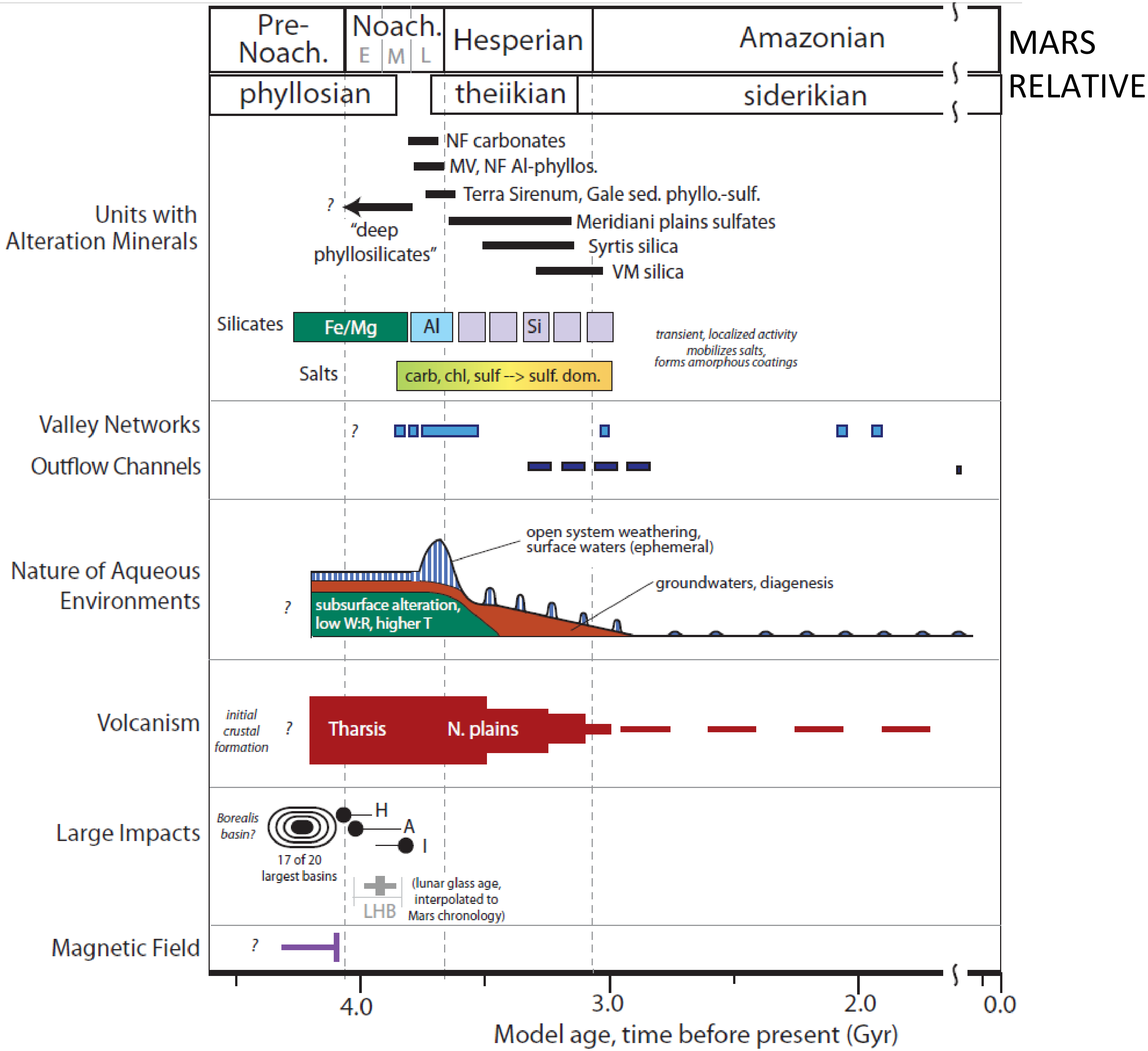
pCO_2
- high → carbonates (Ca, Mg, Fe)
- low → Fe-rich chlorites

Ehlmann et al., JGR, 2009; CCM, in review

VNIR Quantitative Mineral Modeling

Little evidence of chemical fractionation in clay-bearing units





Pre-Noach.
Noach.
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MARS RELATIVE
phyllosian
theiikian
siderikian
Units with Alteration Minerals
NF carbonates
MV, NF Al-phyllos.
Terra Sirenum, Gale sed. phyllo.-sulf.
Meridiani plains sulfates
Syrtis silica
VM silica
?
"deep phyllosilicates"
Silicates
Fe/Mg
Al
Si
Salts
carb, chl, sulf --> sulf. dom.
transient, localized activity mobilizes salts, forms amorphous coatings
Valley Networks
Outflow Channels
?
Nature of Aqueous Environments
open system weathering, surface waters (ephemeral)
groundwaters, diagenesis
subsurface alteration, low W:R, higher T
?
Volcanism
initial crustal formation
?
Tharsis
N. plains
Large Impacts
Borealis basin?
17 of 20 largest basins
H
A
I
LHB
(lunar glass age, interpolated to Mars chronology)
Magnetic Field
?
4.0
3.0
2.0
0.0
Model age, time before present (Gyr)