

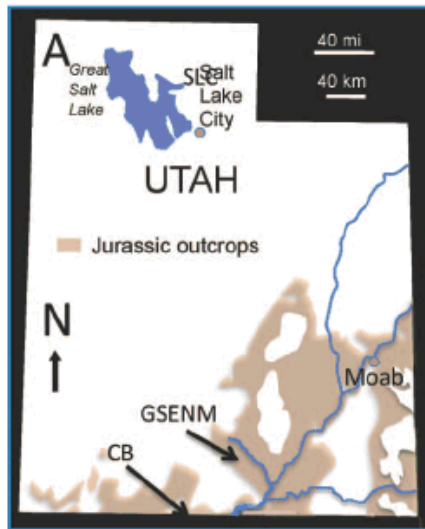
Constraining paleo-hydrologic flow fields from iron oxide cementation patterns

Yifeng Wang¹, Marjorie A. Chan² and Enrique Merino³

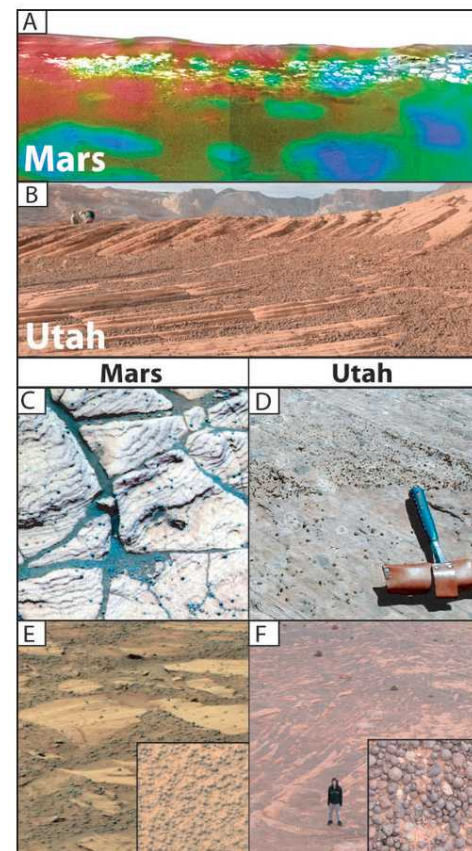
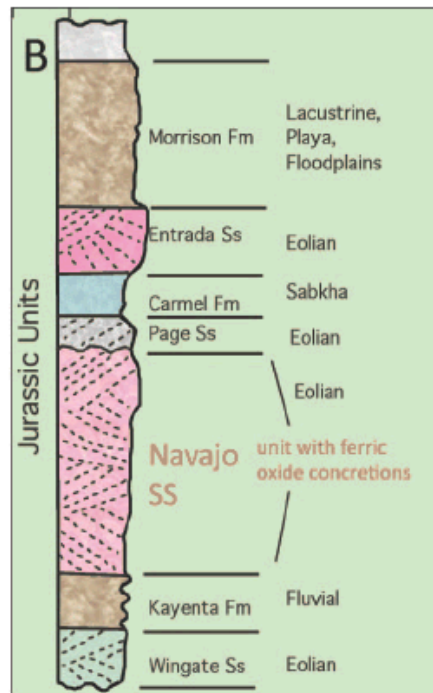
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Chan et al. (2012)

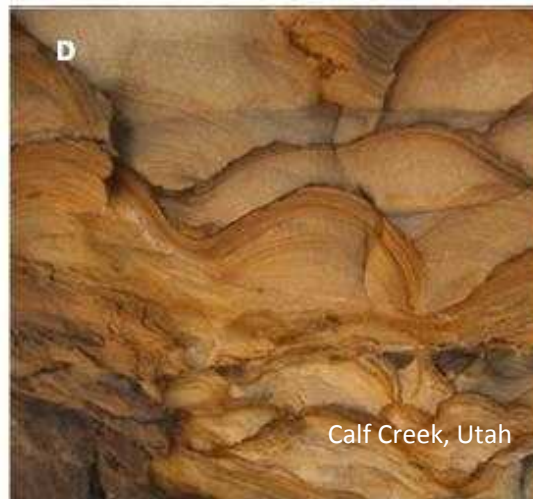
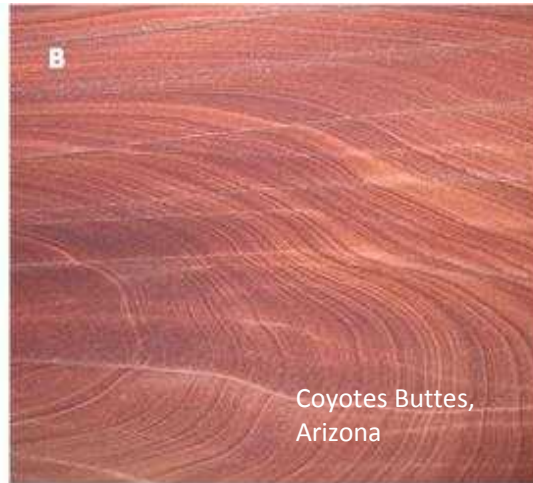


Chan et al. (2005)

Table 1 Comparison between characteristics of the Utah analogue and proposed characteristics of the system on Mars.

	Utah	Mars
Host rock	Fine- to medium-grained (0.06–0.65 mm) quartz arenite	Fine-grained sedimentary ⁹
Fe source	Haematite grain coatings	Oxidized basalt (Fe ³⁺) ²³ , orthopyroxene (Fe ²⁺) ⁹ , other?
Fe mobilizing fluids	Reducing (± hydrocarbons)	CO ₂ (ref. 24), acidic brine ²⁵ , other?
Precipitating fluids	Oxidizing groundwater	Oxidizing groundwater
Concretion cements	Haematite (± goethite), carbonates (with no haematite)	Haematite ¹
Haematite characteristics		
<i>In situ</i> distribution	Internal within beds, along faults, fractures, joints	Internal ¹
Accumulations	Resistant surface concentrations, topographic lows	Surface layers, shallow depressions ¹
Geometry	Spherules + others based on host texture	Spherules ¹
Boundaries	Sharp to diffuse	Sharp ⁹ , diffuse?
Crystals	Fine (<10 μm) to coarse (>10 μm) pore-fill cement	Pure and crystalline ²

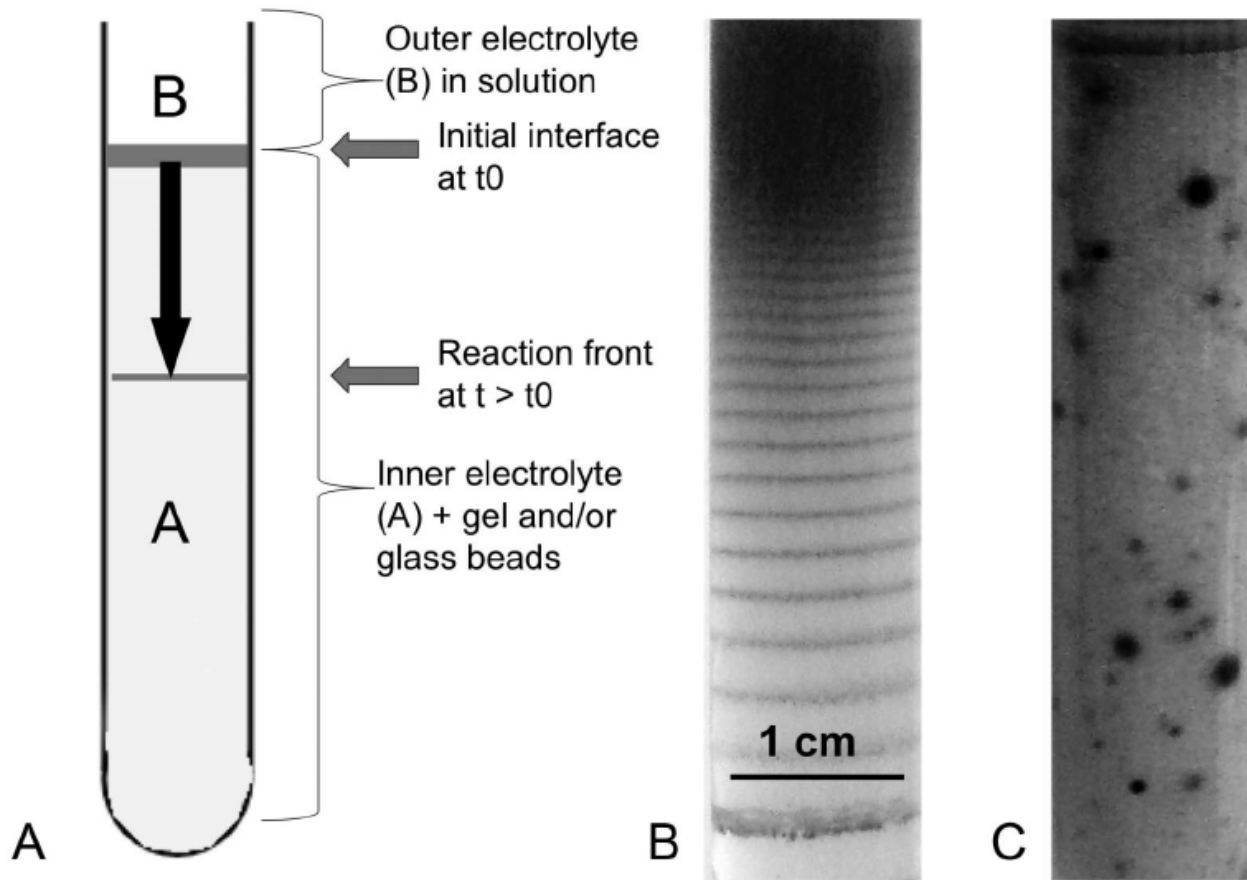
Formation of iron oxide concretion nodules and bands in Jurassic Navajo fine-grained eolian sandstone



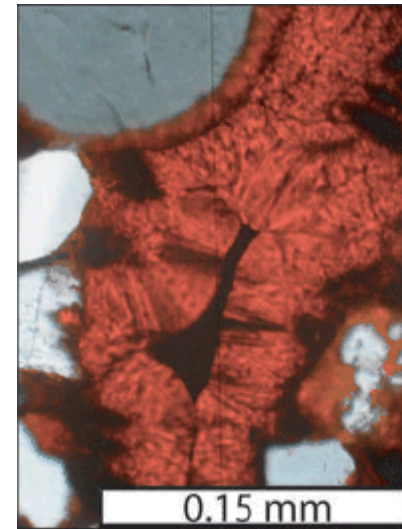
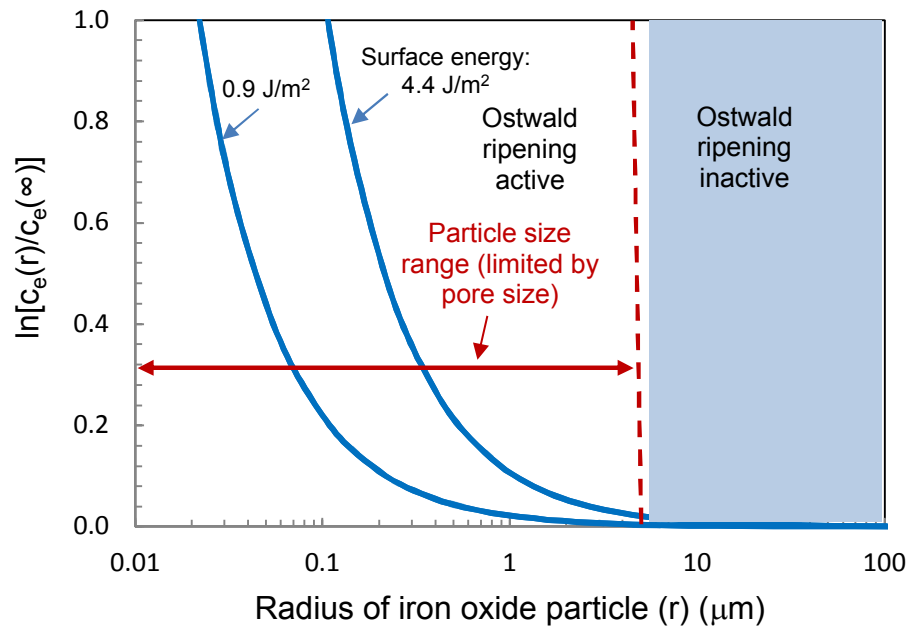
Why?

- *Nested pattern scales of 2-3 orders*
- *Pervasive in a large space (kilometers)*
- *Geometrical transitions*

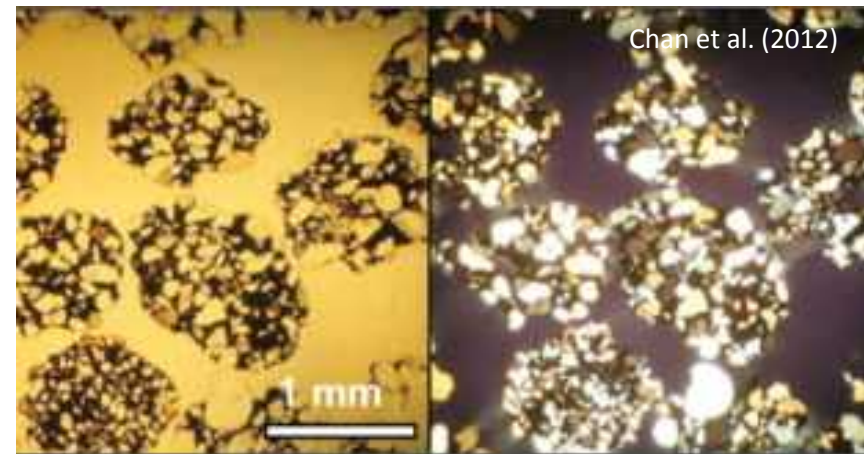
Classic Liesegang banding (counter diffusion)



Chan et al. (2012)



Confined Ostwald Ripening



New Mechanism

Ostwald ripening

+

Confinement

+

Advection

Self-organization

Patterns autonomously emerge from internal dynamics of a system through a positive feedback.

Confinement

Local solubility depends on mineral distribution in neighborhood.

Governing equations

Mass continuity for iron dissolved

$$\frac{\partial(\phi C)}{\partial t} = \vec{\nabla} \cdot [D(\phi)\vec{\nabla}C + K(\phi)C\vec{\nabla}P] - \frac{\partial Q}{\partial t}$$

Flow field

$$\frac{\partial\phi}{\partial t} = \vec{\nabla} \cdot [K(\phi)\vec{\nabla}P]$$

Mineral precipitation

$$\frac{\partial Q}{\partial t} = R_p$$

Porosity evolution

$$\phi = \phi_0 - QV_m$$

Textural dependent solubility

$$\tilde{Q}(\vec{r}, t) = \iiint Q(\vec{r}', t)K_r(\vec{r} - \vec{r}')dX'dY'dZ'$$

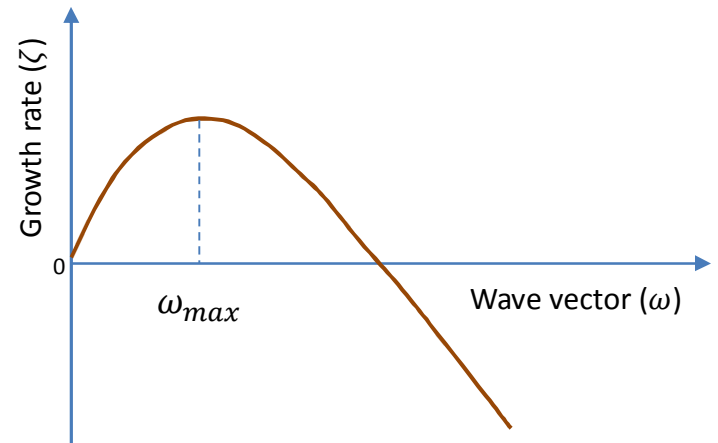
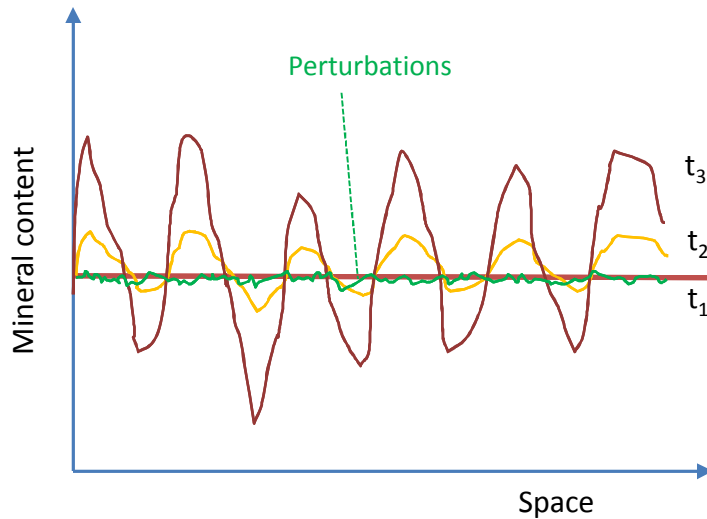
$$\tilde{Q} \approx Q + B\nabla^2 Q$$

$$C_e = C_e^0 e^{f(\tilde{Q})/RT}$$

Reaction kinetics

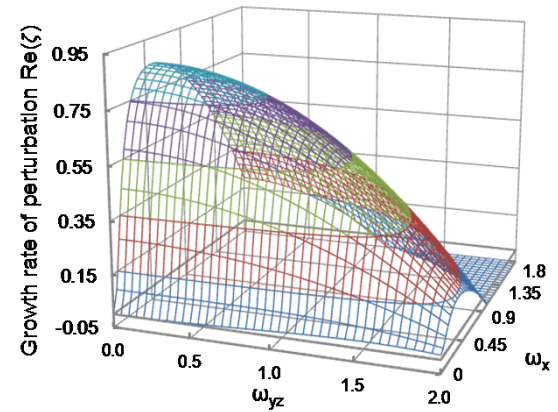
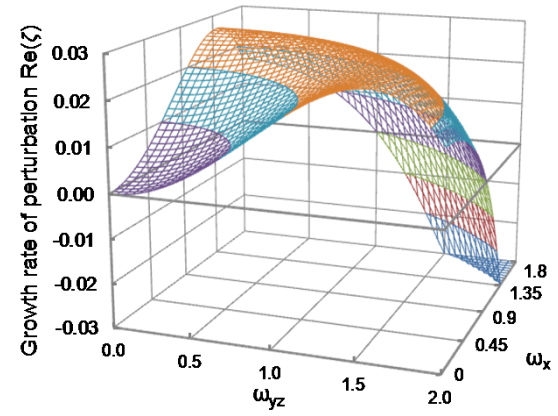
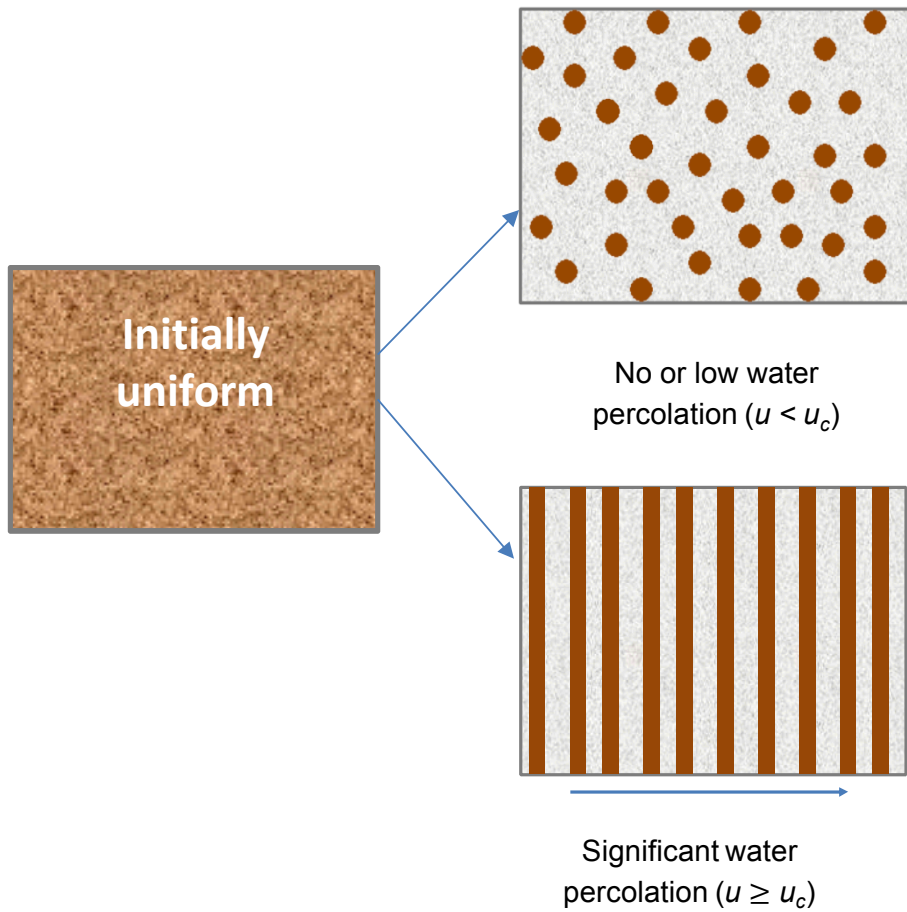
$$R_p = kS\phi^{\frac{2}{3}}(C - C_e)$$

A pattern can emerge from fluctuations.

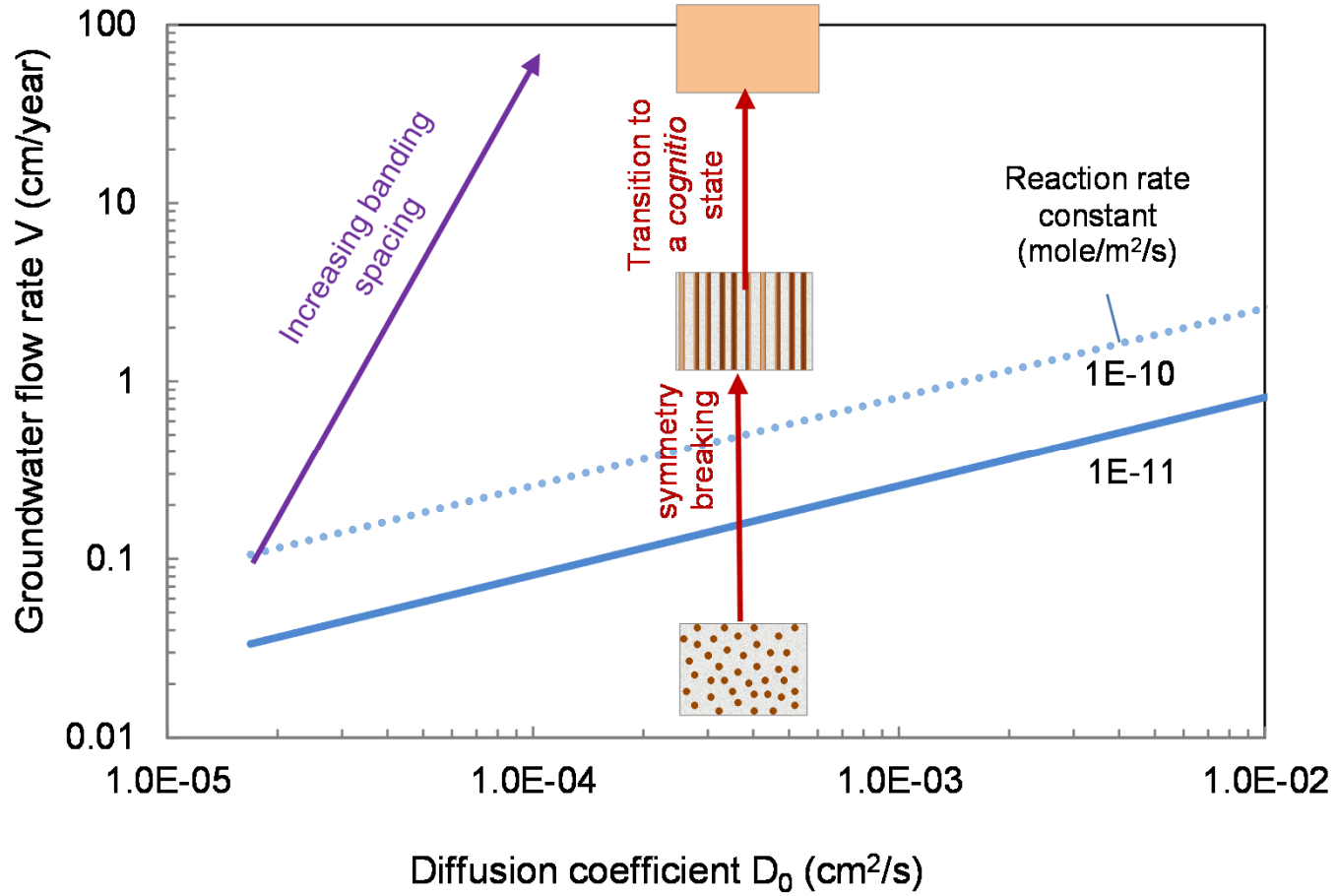


Perturbation: $\delta q = \delta \hat{q} e^{i\omega + \zeta \tau}$

Self-organized iron cementation pattern

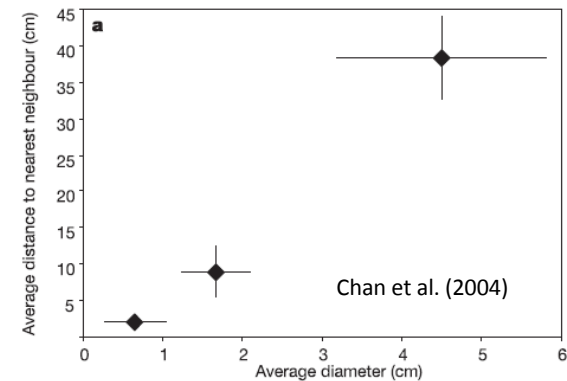


Symmetry breaking and pattern transition

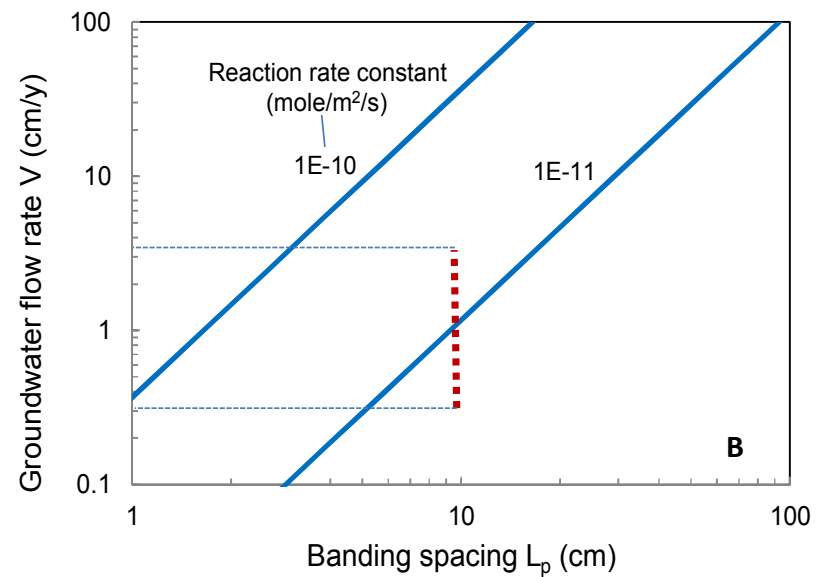
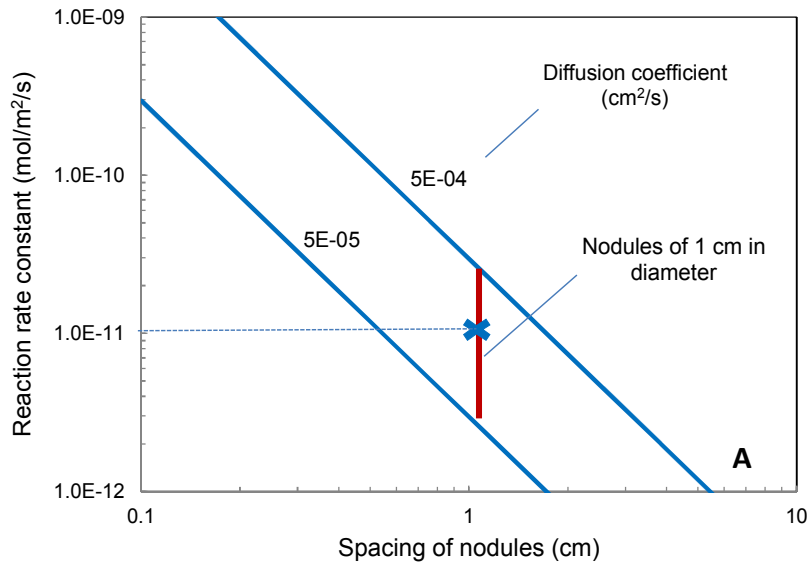


Model predictions & testing against observations

- *Volume of space involved (kilometers)*
 - *Field evidence indicates the involvement of groundwater flow (Potter, 2010; Nielson & Chan, 2009).*
- *Size of patterns: 1 mm – 30 cm (predicted)*
 - *Nodules: millimeters to centimeters*
 - *Bands: mm to submeters*
- *Time scale: tens to a few thousand years (predicted)*
 - *< 3000 years (Lake Brown, Australia)*
- *Correlation of nodule size with spacing*
 - *Positive correlation*
- *Pattern transition & superimposition*
 - *For example, nodules to bands or vice versa*
- *Diagenetic environments*
 - *Dry, hot*
 - *Sulfate rich acidic water*



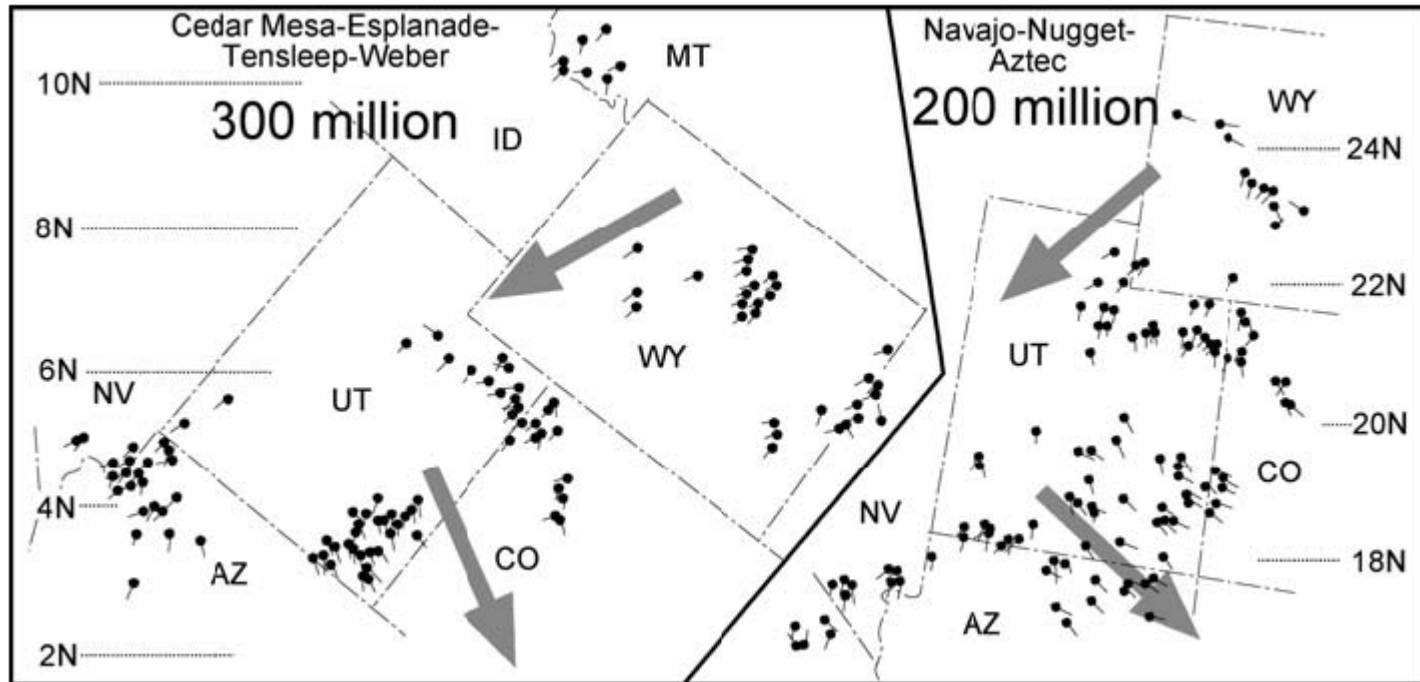
Constraining paleo-hydrologic flow fields from iron oxide cementation patterns



$$L_p \approx 2\pi \sqrt{\frac{2\beta D_0 \phi_s}{kS\phi_s^{2/3}}} \text{ for scaled flow velocity } u \leq u_c$$

$$L_p \approx 2\pi \sqrt{\frac{uD_0 \phi_s}{kS\phi_s^{2/3}}} \text{ for scaled flow velocity } u > u_c$$

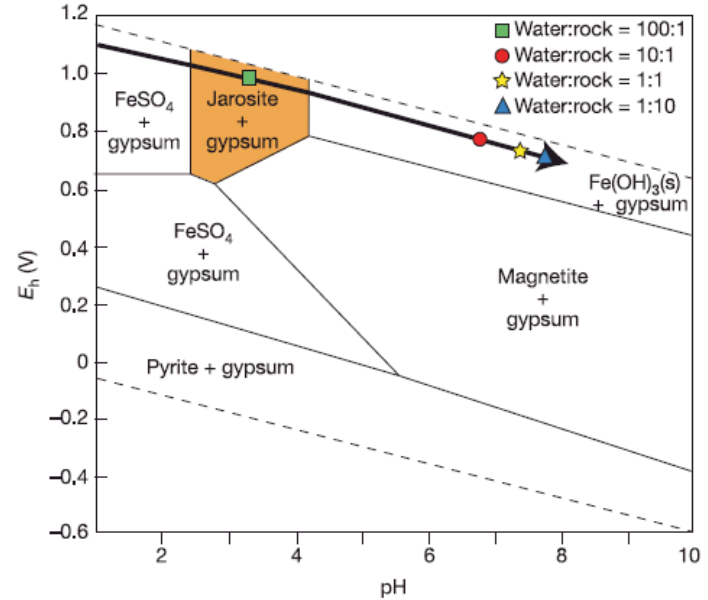
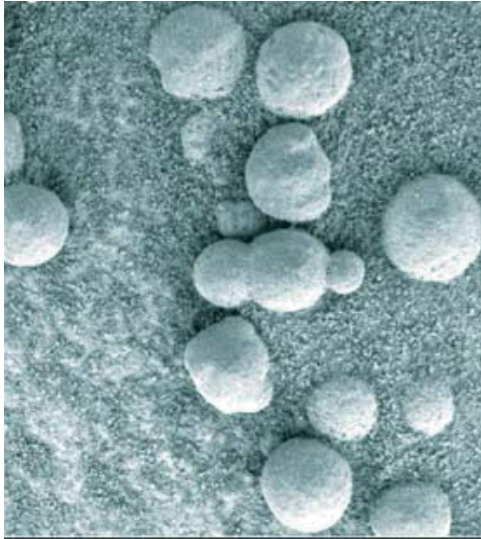
Implication to the measurements of paleomagnetism



Rowe et al. (2007)

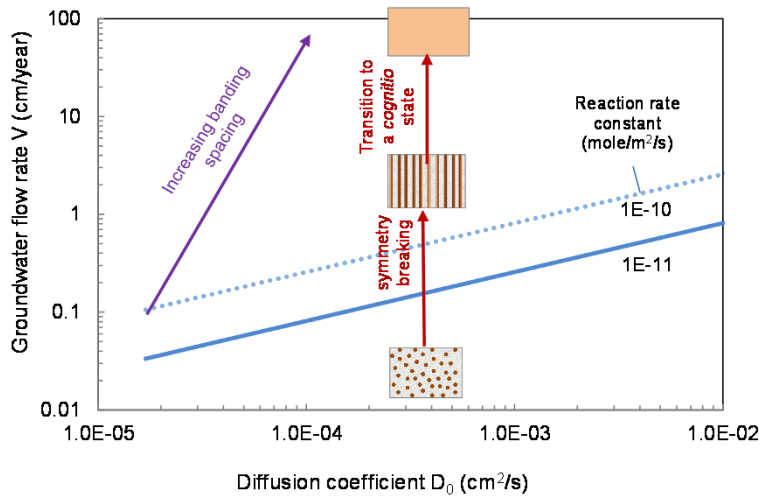
*Recently acquired magnetism in Navajo sandstone
(Johnson, 1976)*

Implication to extraterrestrial search for life



Madden et al. (2004)

Since a persistent water circulation is generally required for a sustainable subsurface life, a site with the presence of iron oxide bands, if any exists, may offer a better chance for detecting biosignatures on the Mars.



Summary

- *Iron oxide precipitation in fine-grained red beds displays complex pattern formation, including nodulation and banding.*
- *Hematite nodules have also been found at the Meridiani Planum site on the Mars and interpreted as evidence for the ancient presence of water on the red planet.*
- *Such patterns can autonomously emerge from a previously unrecognized Ostwald ripening mechanism.*
- *A pattern transition from nodules to bands can result from symmetry breaking triggered by groundwater advection.*
- *Nodules tend to develop under nearly stagnant hydrologic conditions, while repetitive bands form in the presence of persistent water flows.*
- *Since water circulation is a prerequisite for a sustainable subsurface life, a site with the presence of iron oxide precipitation bands, if any exists, may offer a better chance for detecting extraterrestrial biosignatures on the Mars.*

Acknowledgment

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This work is partly supported by DOE Sandia LDRD Program. Chan's effort was an outgrowth of work supported by the National Aeronautics and Space Administration under grant NNG06G110G (to Chan) issued through the Mars Fundamental Research Program.