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Stress-induced chemical waves in sediment burial diagenesis

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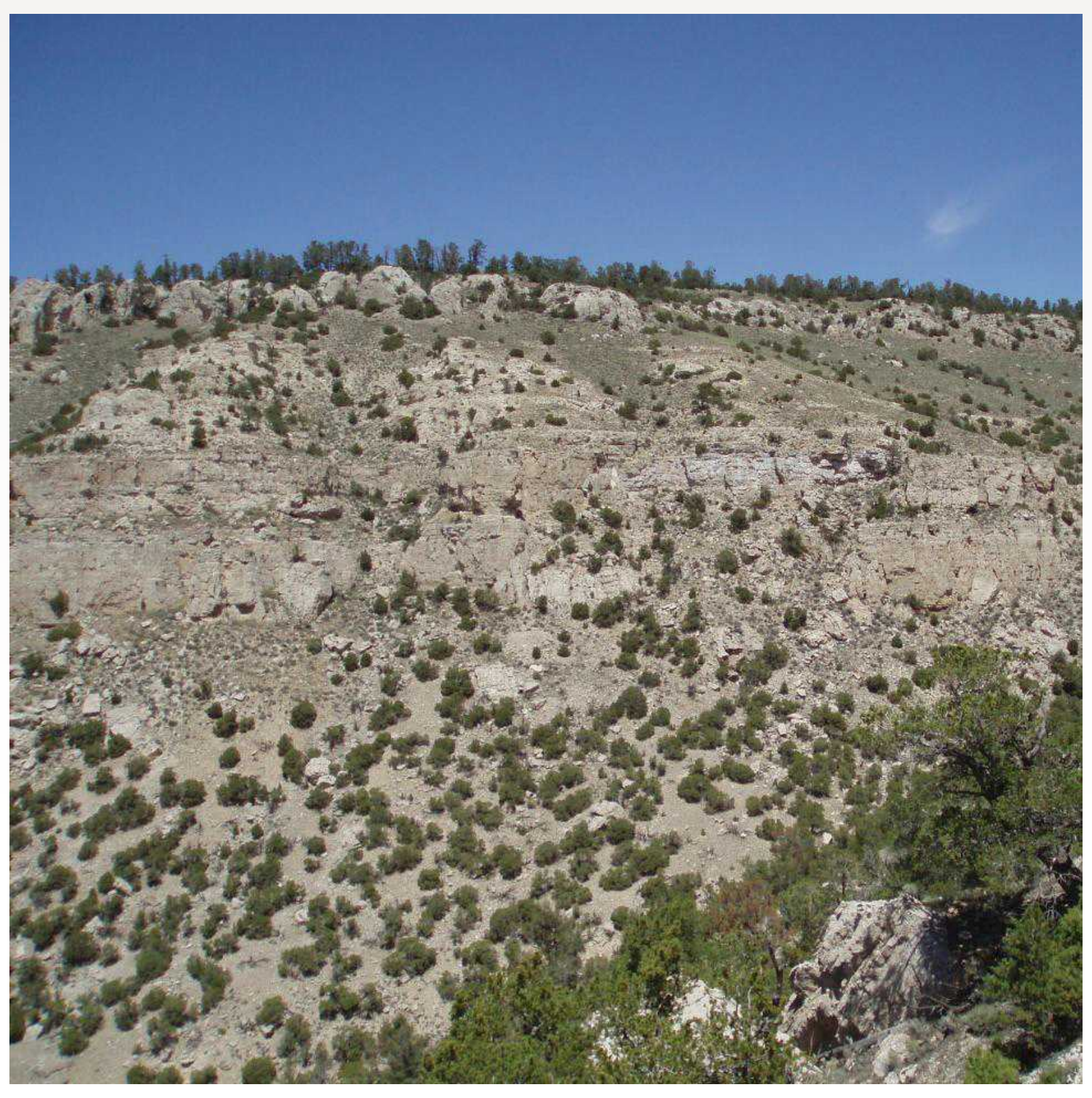
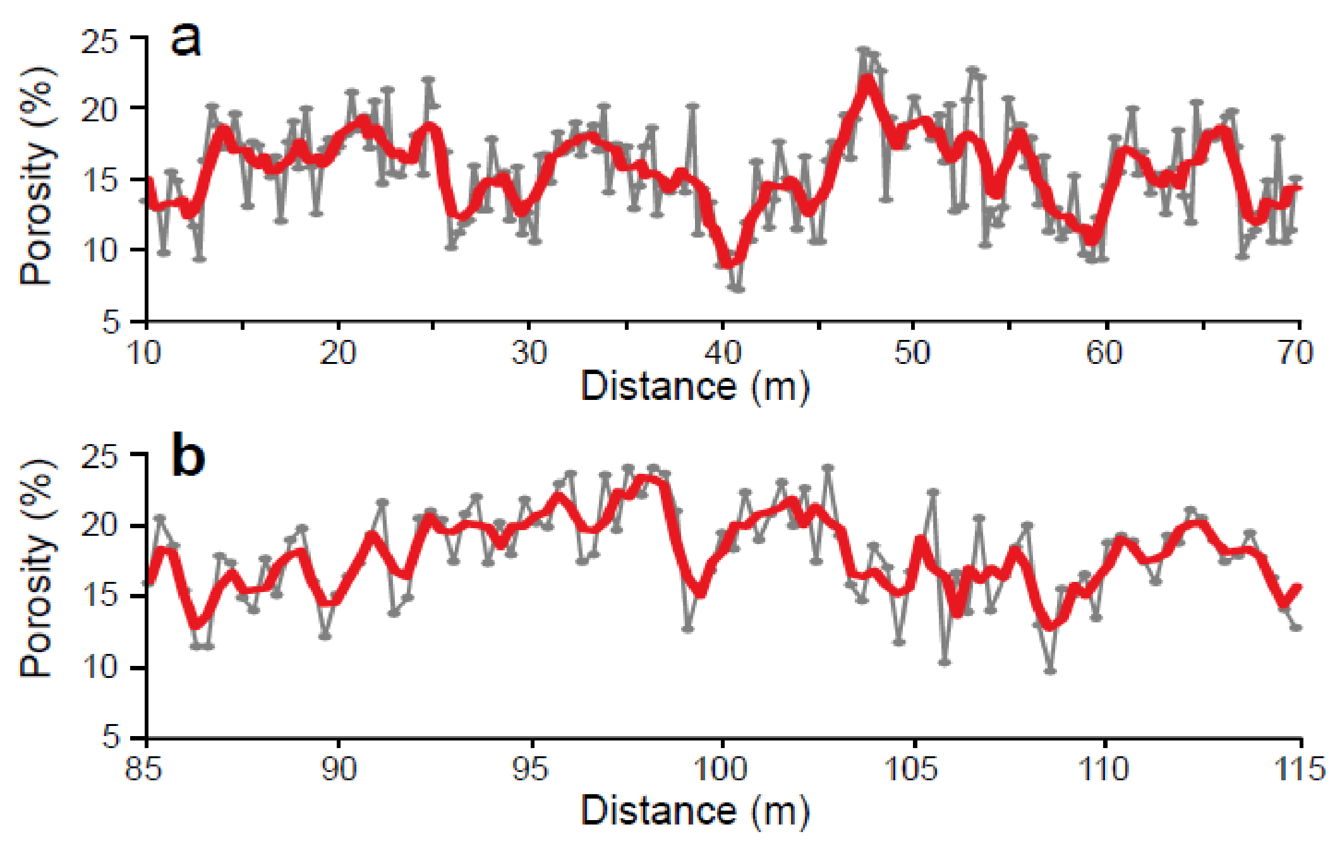
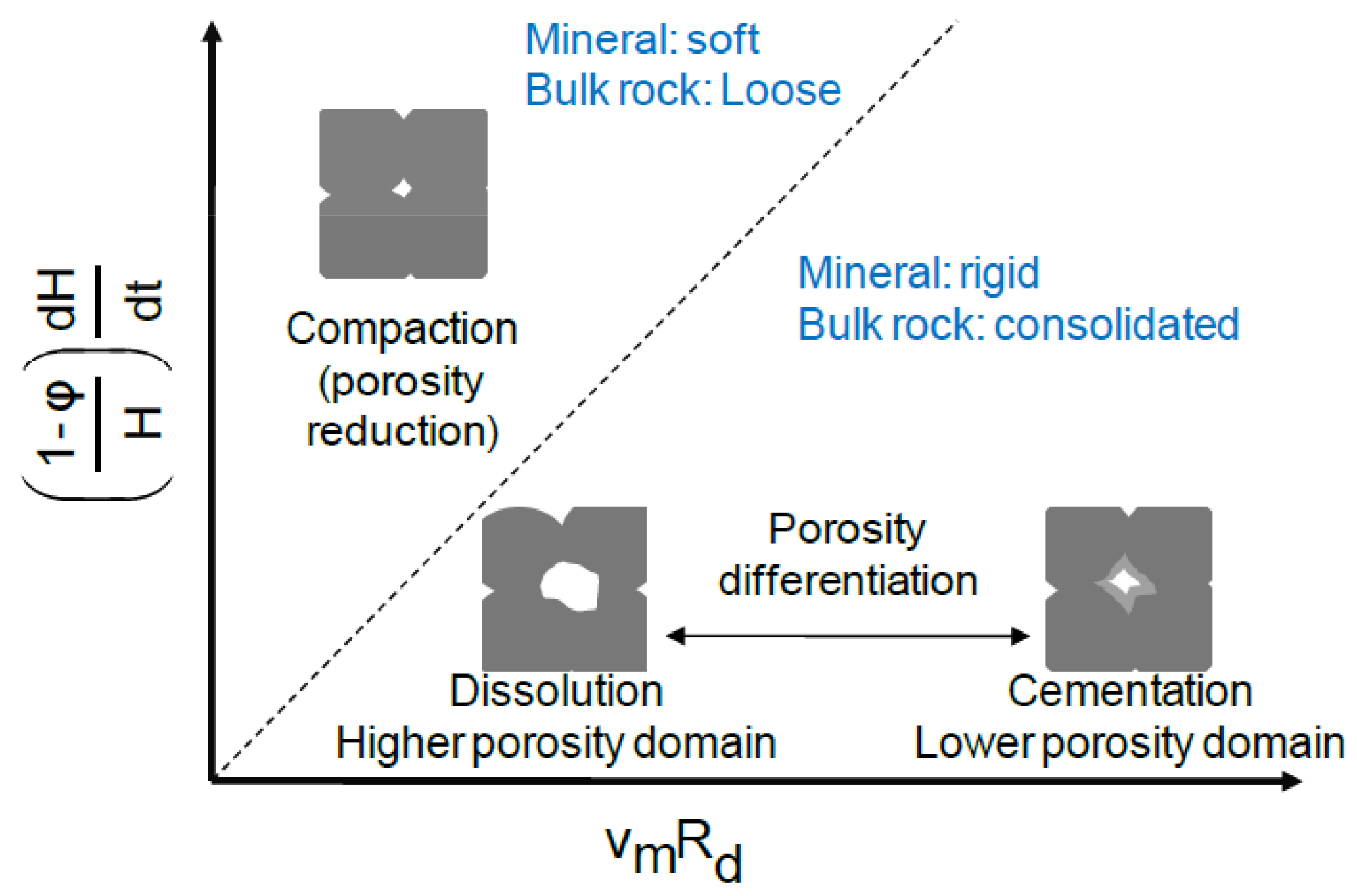
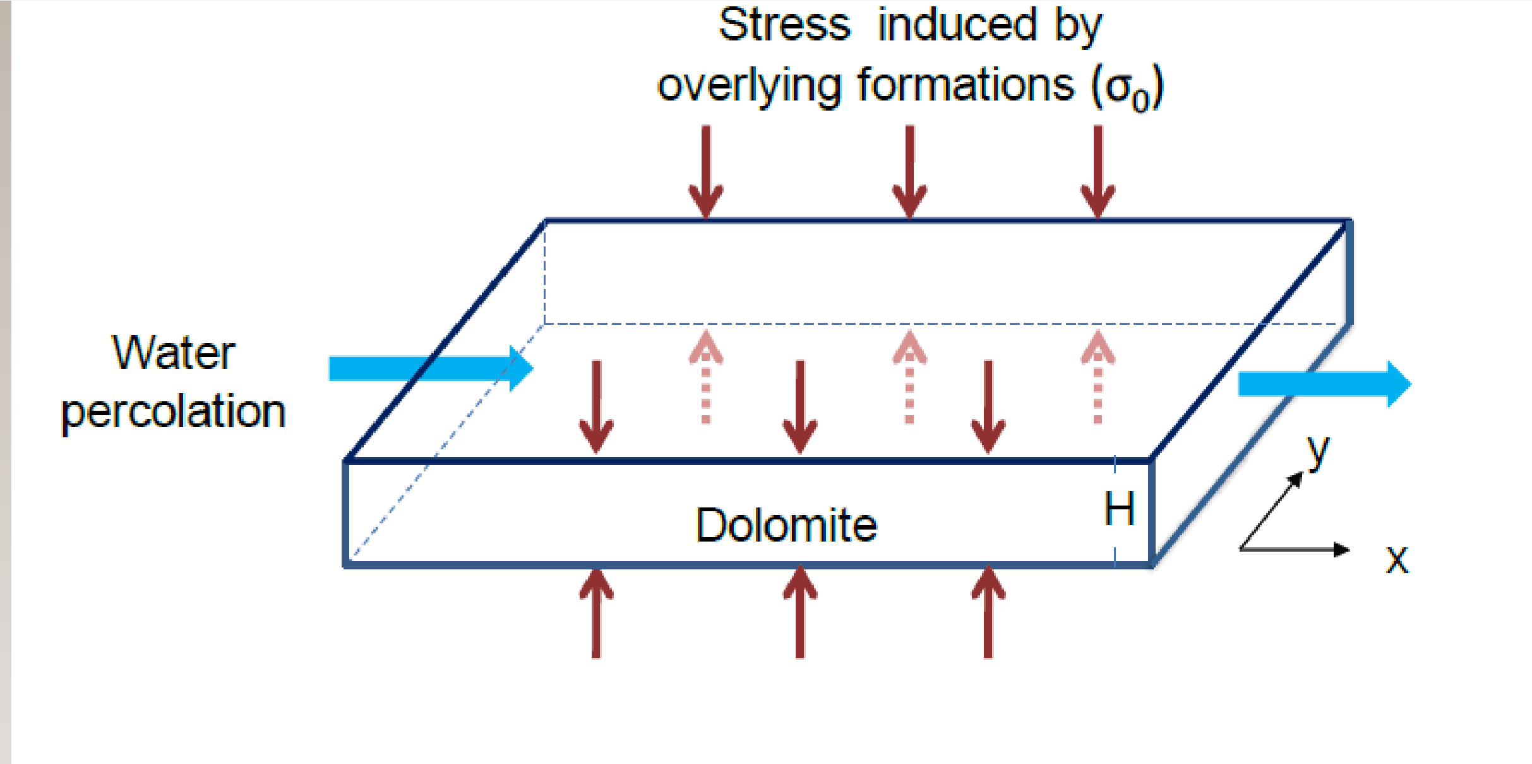
Summary

Lateral meter-scale periodic variations in porosity and composition are found in many dolomite strata. Such variations may embed important information about dolomite formation and transformation. Here we show that these variations could be fossilized chemical waves emerging from stress-mediated mineral-water interaction during sediment burial diagenesis. Under the overlying loading, crystals in higher porosity domains are subjected to a higher effective stress, causing pressure solution. The dissolved species diffuse to and precipitate in neighboring lower porosity domains, further reducing the porosity. This positive feedback leads to lateral porosity and compositional patterning in dolomite. The pattern geometry depends on fluid flow regimes. In a diffusion-dominated case, the low and high porosity domains alternate spatially with no directional preference, while, in the presence of an advective flow, this alternation occurs only along the flow direction, propagating like a chemical wave. Our work provides a new perspective for interpreting diagenetic signatures in sedimentary rocks. [Wang, Y. & Budd, D.A., Nature Communications 3:685 doi: 10.1038/ncomms1684 (2012)]









Governing equations

$$R_d = kS(1-\phi)(C_s - C) = kS(1-\phi)\left(C_e^0 e^{\frac{\sigma\Delta v}{RT}} - C\right)$$

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

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

$$\frac{\partial\phi}{\partial t} = v_m R_d$$

$$\psi(X,Y,t) = \iint \phi(X',Y',t)K_r(X-X',Y-Y')dX'dY'$$

$$\sigma = \alpha\sigma_0 f(\psi)$$

R_d	-	dissolution rate
k	-	reaction rate constant
C	-	concentration of dissolved dolomite species
C_s	-	solubility of dolomite
C_e^0	-	solubility of dolomite under no stress
σ	-	effective stress
σ_0	-	overlying loading
Δv	-	molar volume change of dolomite dissolution reaction
R	-	gas constant
T	-	temperature
ϕ	-	porosity
K_r	-	a kernel function

Linear stability analysis:

$$\frac{\partial\delta\phi}{\partial\tau} = (1-\phi_s)[\theta\eta(\delta\phi + \beta\nabla^2\delta\phi) - \delta c]$$

$$\phi_s^m\nabla^2\delta c - v\frac{\partial\delta c}{\partial x} + \frac{\partial\delta\phi}{\partial\tau} = 0$$

$$-\frac{(3-\phi_s)v}{\phi_s(1-\phi_s)}\frac{\partial\delta\phi}{\partial x} + \frac{\phi_s^3}{(1-\phi_s)^2}\nabla^2\delta p = 0$$

$$\delta c = \delta\hat{c}e^{i(\omega_1 x+\omega_2 y)+\zeta\tau}$$

$$\delta\phi = \delta\hat{\phi}e^{i(\omega_1 x+\omega_2 y)+\zeta\tau}$$

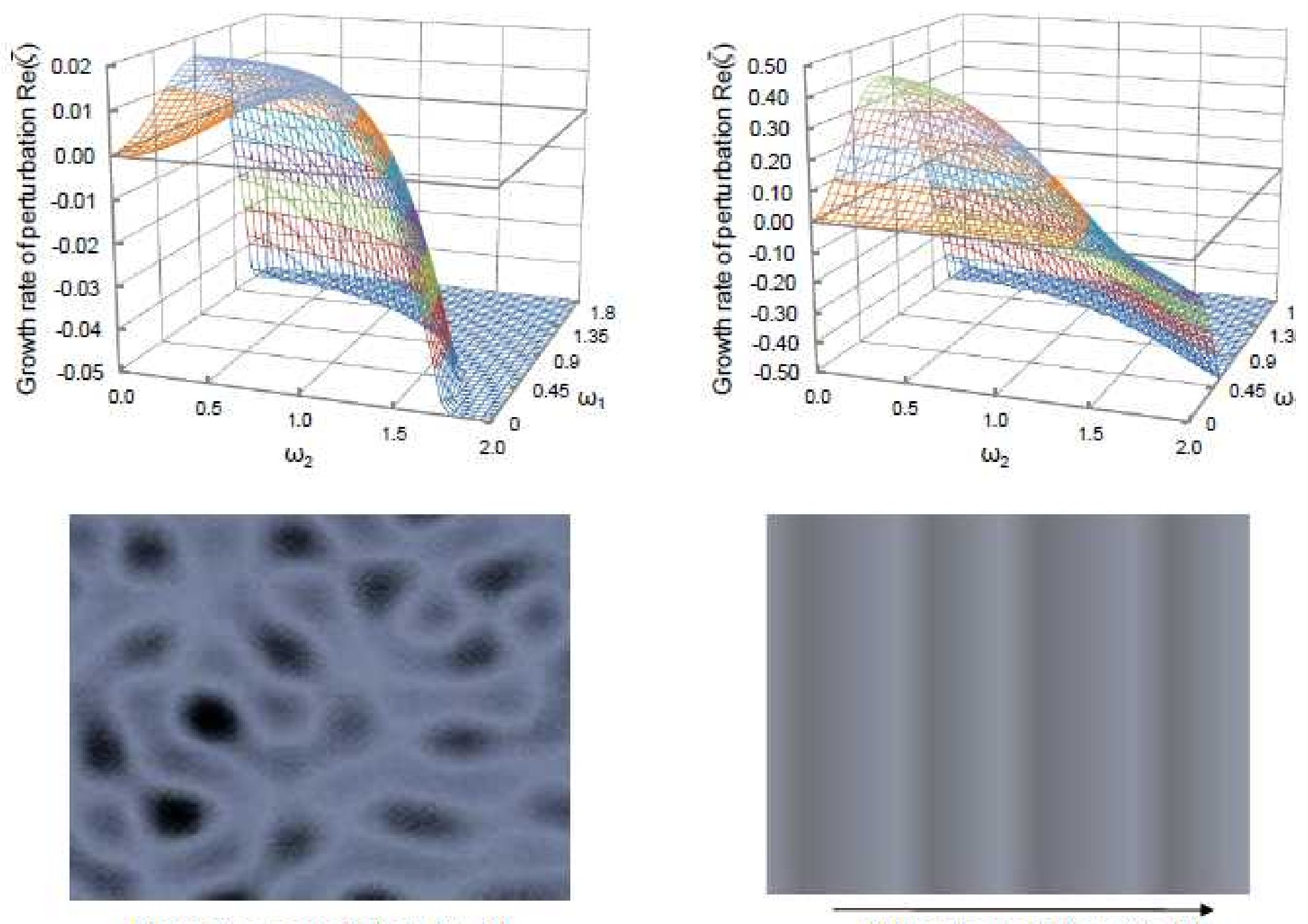
$$\delta p = \delta\hat{p}e^{i(\omega_1 x+\omega_2 y)+\zeta\tau}$$

$$Re(\zeta) = \frac{\theta\eta(1-\phi_s)[1-\beta(\omega_1^2+\omega_2^2)]\{\phi_s^m(\omega_1^2+\omega_2^2)[1-\phi_s+\phi_s^m(\omega_1^2+\omega_2^2)]+v^2\omega_1^2\}}{[1-\phi_s+\phi_s^m(\omega_1^2+\omega_2^2)]^2+v^2\omega_1^2}$$

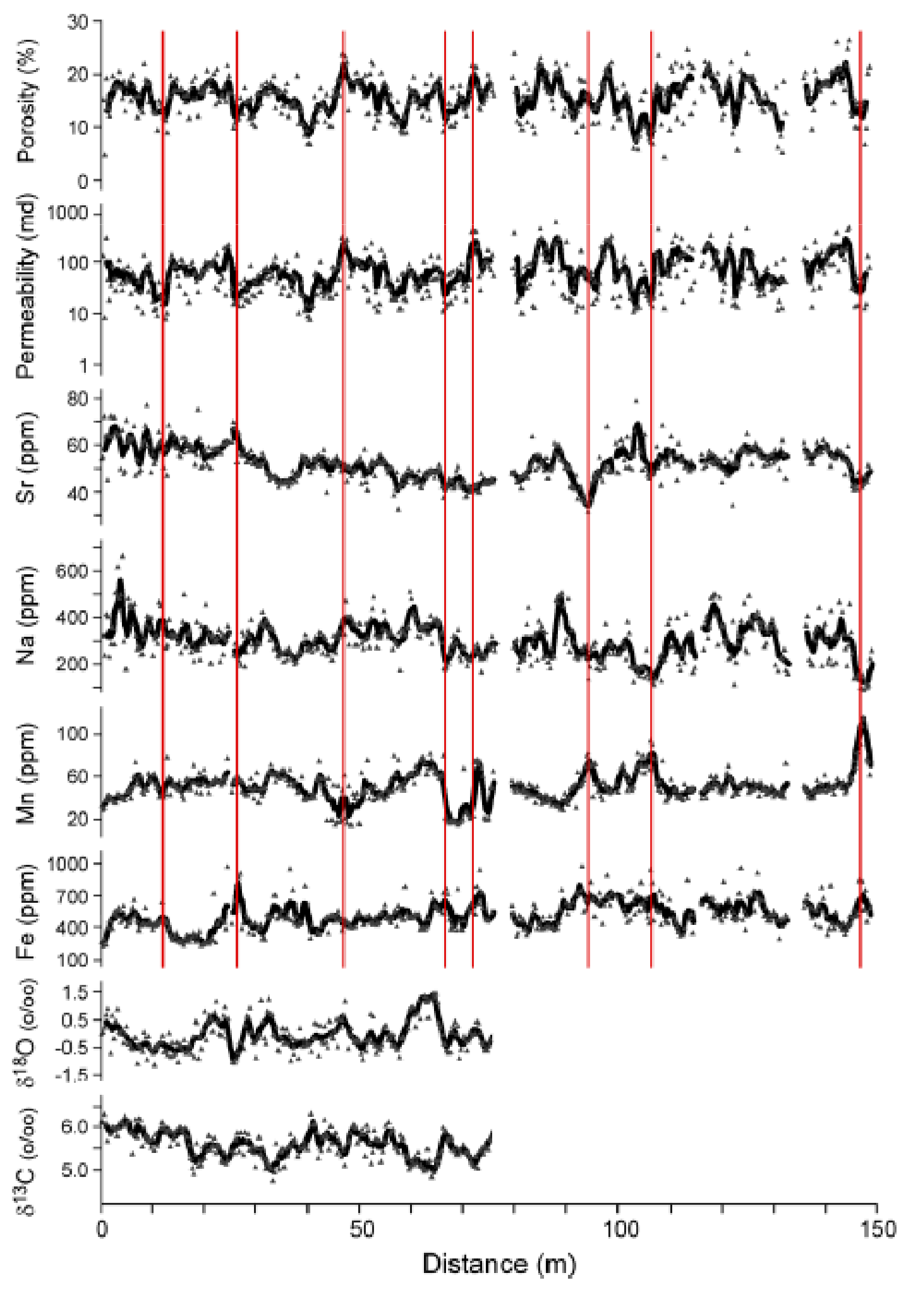
$$Im(\zeta) = \frac{\theta\eta v(1-\phi_s)^2\omega_1[1-\beta(\omega_1^2+\omega_2^2)]}{[1-\phi_s+\phi_s^m(\omega_1^2+\omega_2^2)]^2+v^2\omega_1^2}$$

$L_p \approx 2\pi\sqrt{\frac{2\beta D_0\phi_s}{kS(1-\phi_s)}}$ for a no flow case

$L_p \approx 2\pi\sqrt{\frac{vD_0\phi_s}{kS(1-\phi_s)}}$ for a flow case with $v > 0.1$



No water percolation (v =0)   Water percolation (v > 0)



Implications

An accurate prediction of the scale and geometry of lateral porosity and permeability variations is of great interest for reservoir engineering. Numerical simulations show that fingering, sweep-efficiency and breakthrough time in enhanced oil recovery are sensitive to such variations. Such effects may also be important for subsurface carbon dioxide sequestration and storage. A linear stability analysis indicates that horizontal permeability variations may enhance supercritical CO_2 dissolution in deep brine aquifers and dramatically change the qualitative behavior of the buoyancy flow of CO_2 in such environments. Furthermore, lateral porosity variations may create localized stagnant domains that may affect the transport of chemical species in subsurface environments. Small scale porosity variations have been found to have a significant impact on radionuclide transport in dolomite formations. Our work indicates that a large portion of such variations may originate from self-organized sediment diagenesis and therefore are probably predictable.

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