Reactive Transport Modeling of Long-Term Cap Rock Integrity During CO_2 Injection for EOR or Saline-Aquifer Storage

James W. Johnson*
John J. Nitao
Joseph P. Morris
Stephen C. Blair

Lawrence Livermore National Laboratory

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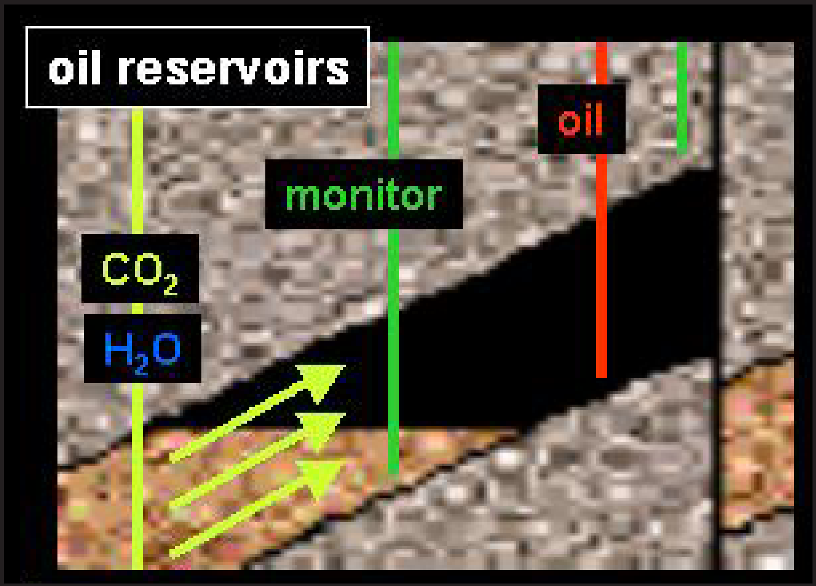
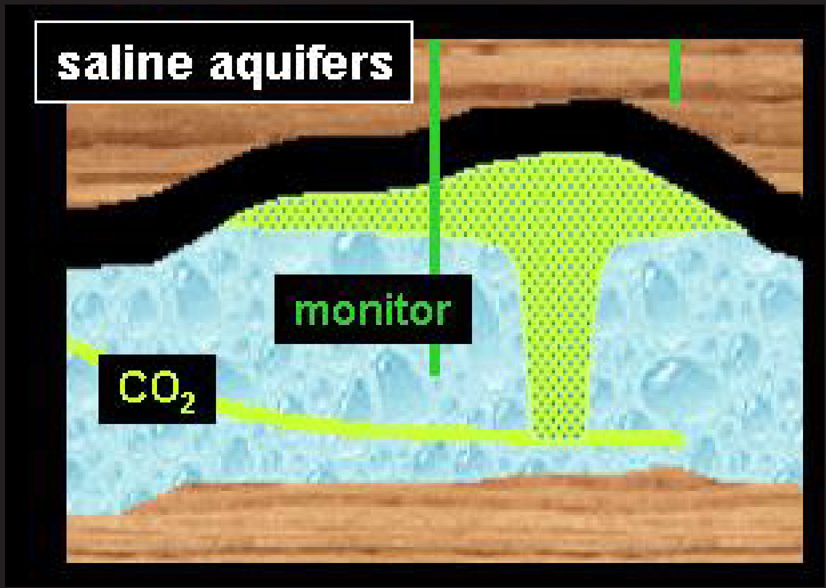
*corresponding author:
jwjohnson@llnl.gov

1. Abstract

CO_2 injection for EOR or saline-aquifer storage leads to concomitant geochemical alteration and geomechanical deformation of the cap rock, enhancing or degrading its seal integrity depending on the relative effectiveness of these interdependent processes. Injection-triggered mineral dissolution/precipitation reactions within typical shales continuously reduce microfracture apertures, while pressure and dependent effective-stress evolution first rapidly increase then slowly constrict them. Using our reactive transport simulator (NUFT), supporting geochemical databases and software (GEMBOCHS, SUPCRT92), and distinct-element geomechanical model (LDEC), we have evaluated the net effect of these initially opposing contributions to long-term cap-rock integrity, the single most important constraint on long-term isolation performance.

2. Geologic settings for CO_2-flood EOR and saline-aquifer storage



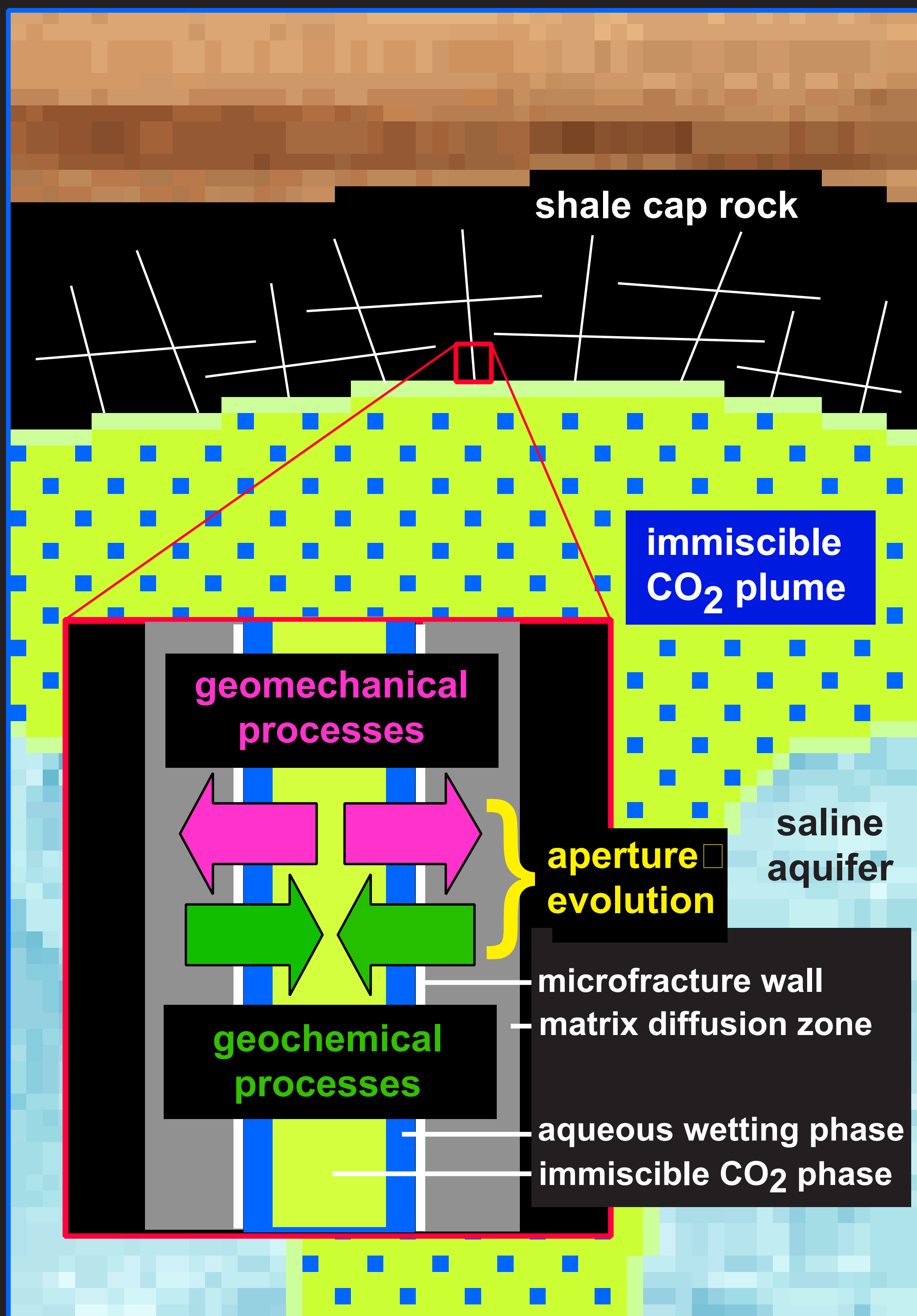


Hydrocarbon phase present
Compartmentalized systems
Rel. low perm (10s-100s md)

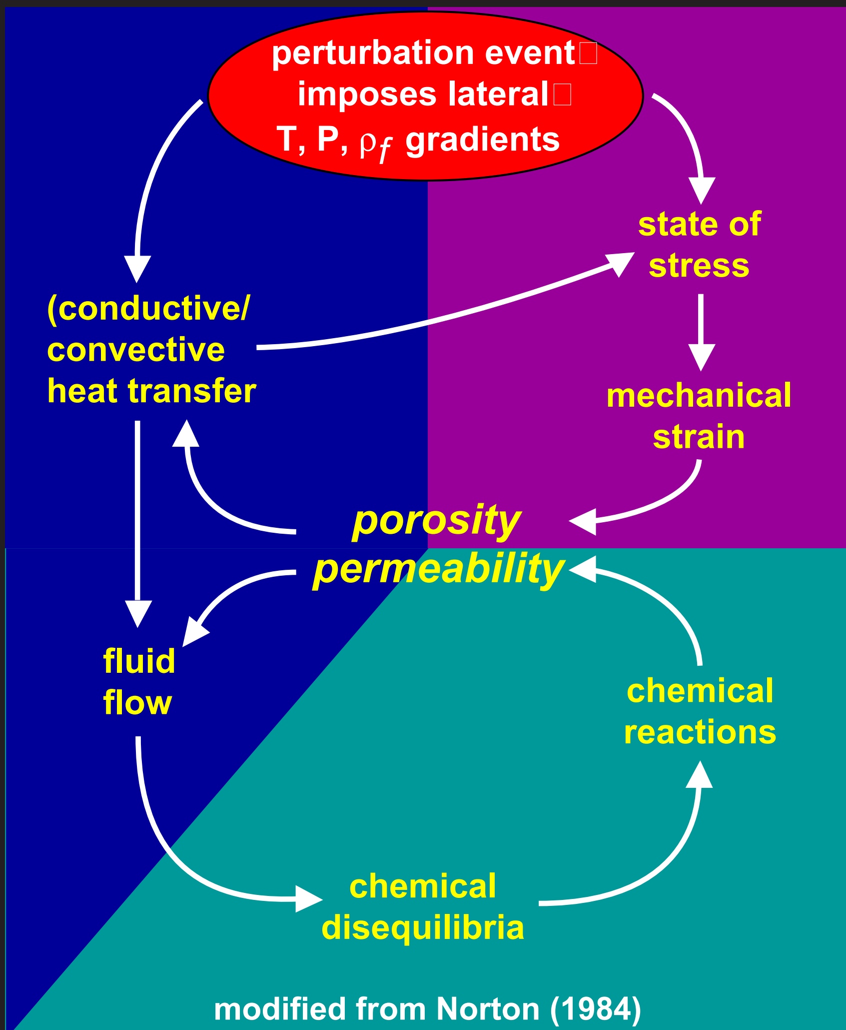
Hydrocarbon phase absent
Laterally extensive systems
Rel. high perm (100s-1000s md)

Fluid-mineral reactions are similar for water-wet oil reservoirs & saline aquifers

3. Long-term cap rock integrity hinges on the relative effectiveness of concomitant geochemical and geomechanical processes



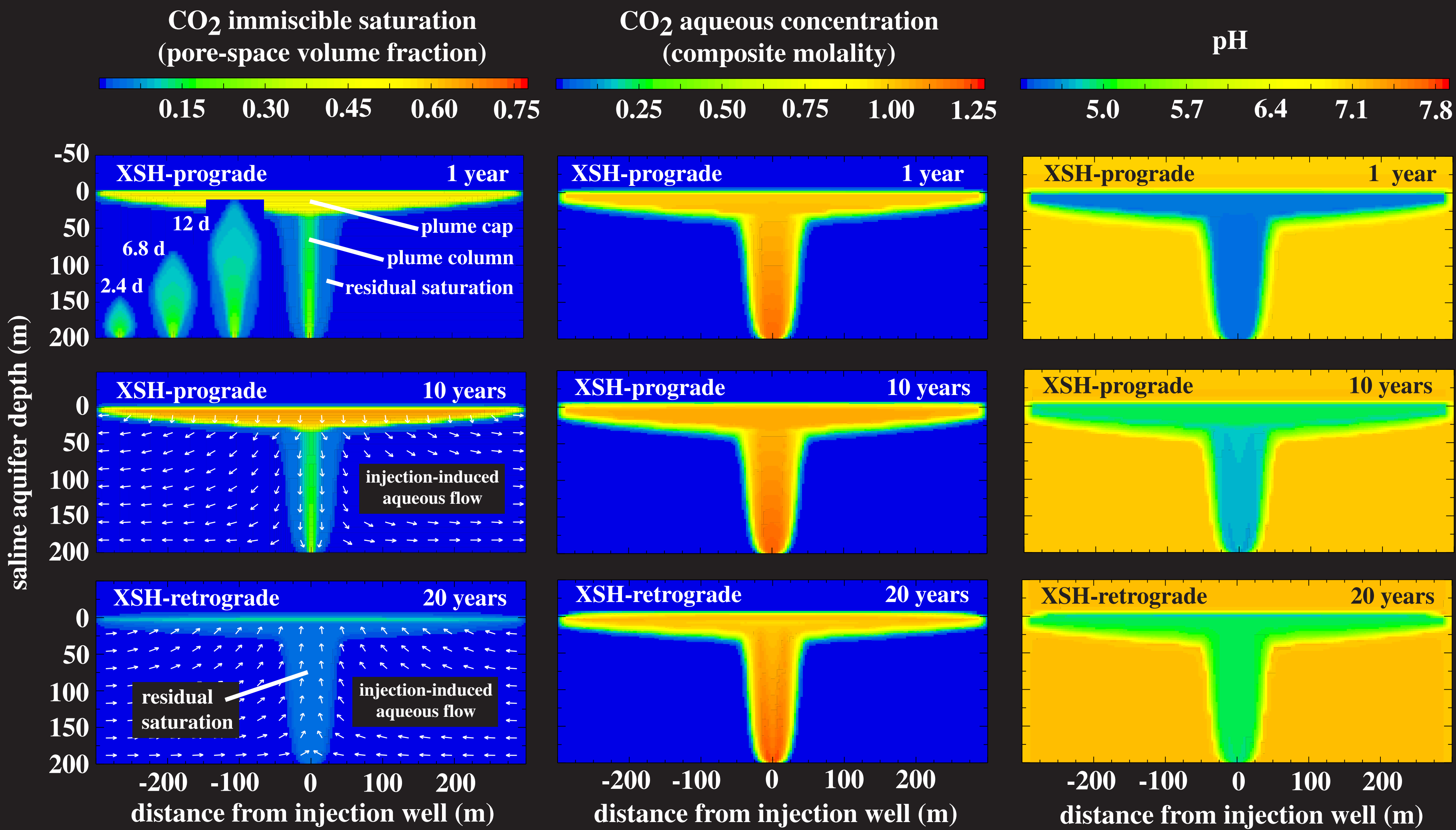
4. Reactive transport modeling: an advanced simulation capability for geologic systems



Schematic depiction of coupled processes

Time-integrated effects: magma-hydrothermal system

5. NUFT simulation of saline-aquifer storage at Sleipner: immiscible CO_2 migration, solubility trapping, and pH evolution



In the near-field environment at Sleipner, roughly 85% by mass of injected CO_2 remains as a migrating immiscible fluid phase during the prograde regime

Roughly 15% of injected CO_2 dissloves into formation waters; this prograde extent of solubility trapping is maintained during the retrograde phase by residual sat'n

Acidic conditions imposed by CO_2 injection and maintained by residual saturation are slowly moderated by silicate dissolution

6a. Solubility trapping and pH evolution

(5) $CO_2(f) + H_2O \Leftrightarrow CO_2(aq) + H_2O \Leftrightarrow HCO_3^- + H^+$

6b. Mineral trapping: four mechanisms

(7) $KAlSi_3O_8 + Na^+ + CO_2(aq) + H_2O \Leftrightarrow NaAlCO_3(OH)_2 + 3\ SiO_2 + K^+$

K-feldspar; $\Delta V_r = +17\%$; dawsonite; qtz/ch/cr

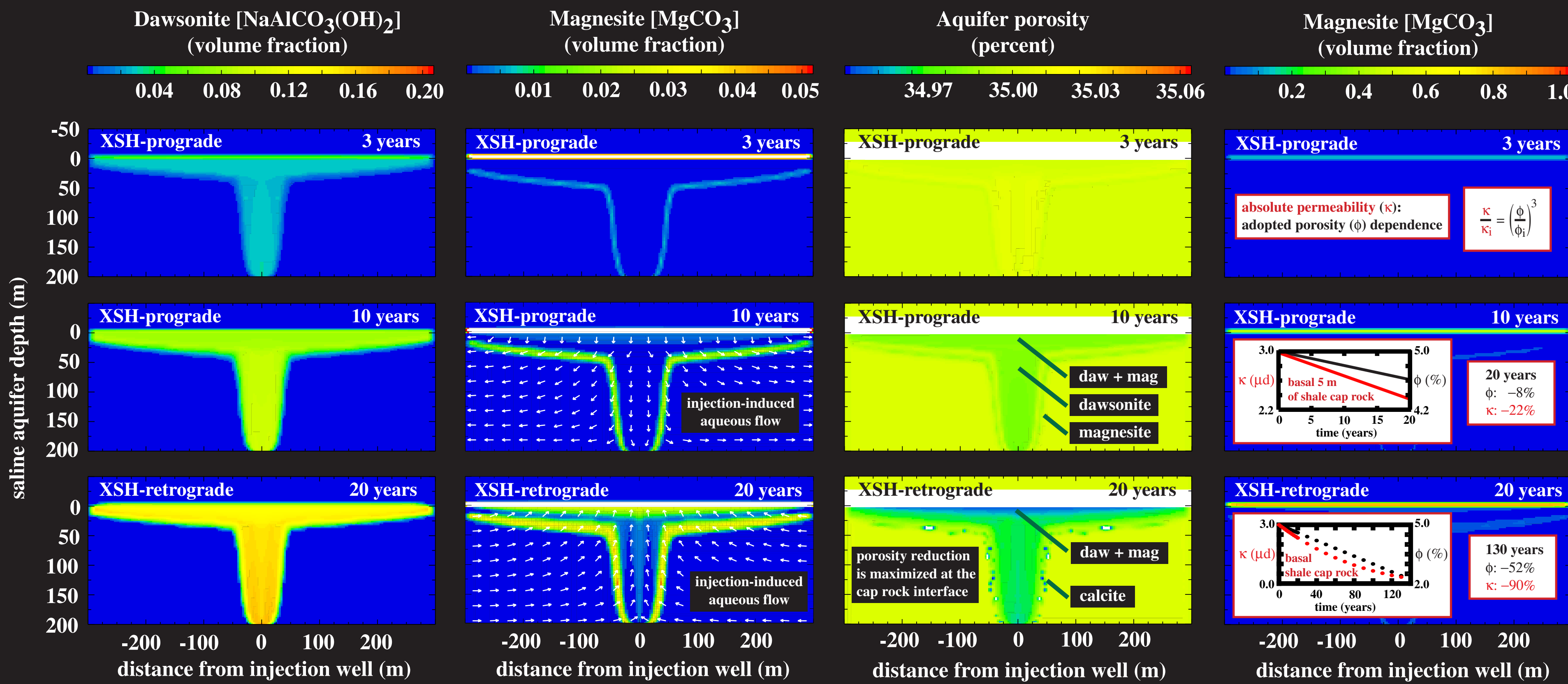
(7) $Mg^{+2} + CO_2(aq) + H_2O \Leftrightarrow MgCO_3 + 2\ H^+$ (distinct precipitation mechanisms along upper and lateral plume boundaries)

magnesite

(7) $KAlSi_3O_8 + 2.5\ Mg_5Al_2Si_3O_{10}(OH)_8 + 12.5\ CO_2(aq) \Leftrightarrow KAl_3Si_3O_{10}(OH)_2 + 1.5\ Al_2Si_2O_5(OH)_4 + 12.5\ MgCO_3 + 4.5\ SiO_2 + 6H_2O$

K-feldspar; Mg-chlorite; $\Delta V_r = +19\%$; muscovite; kaolinite; magnesite; qtz/ch

7. NUFT simulation of saline-aquifer storage at Sleipner: mineral trapping maintains CO_2 injectivity and significantly enhances cap rock integrity



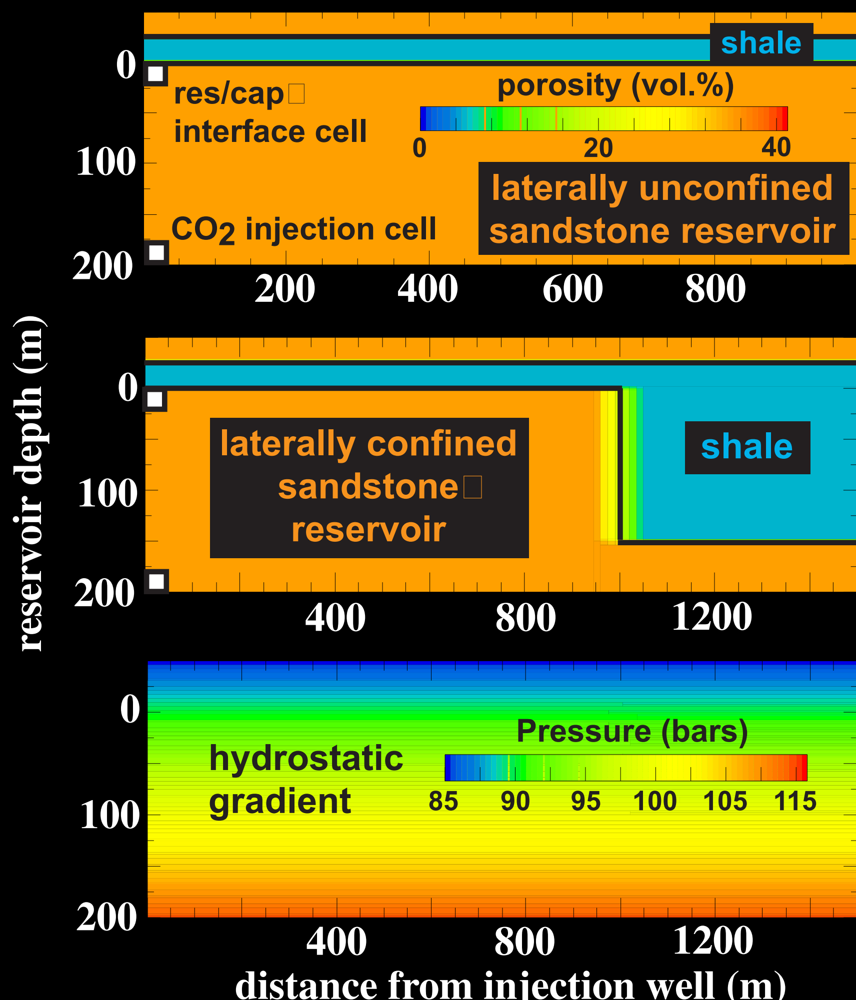
Intra-plume dawsonite cementation will be characteristic of saline-aquifer disposal; a continental-scale natural analog of this process has been documented in Australia (Baker, 1995)

Calcite-group carbonate rind forms along upper and lateral plume boundaries, volumetrically limited by Ca-Fe-Mg concs within the aquifer source region

For Utsira-like compositions, coupled mineral diss/pptn does not appreciably affect aquifer porosity; thus, CO_2 injectivity is maintained and collapse structures do not form

Mineral trapping is most extensive in shales (high conc Fe-Mg-rich clays); although <1% of injected CO_2 is mineral trapped, cap rock integrity is significantly enhanced

8. Simulation domains for comparing CO_2-flood EOR and saline aquifer settings



Laterally unconfined sandstone reservoir

- Saline aquifer storage
- Sleipner-like setting

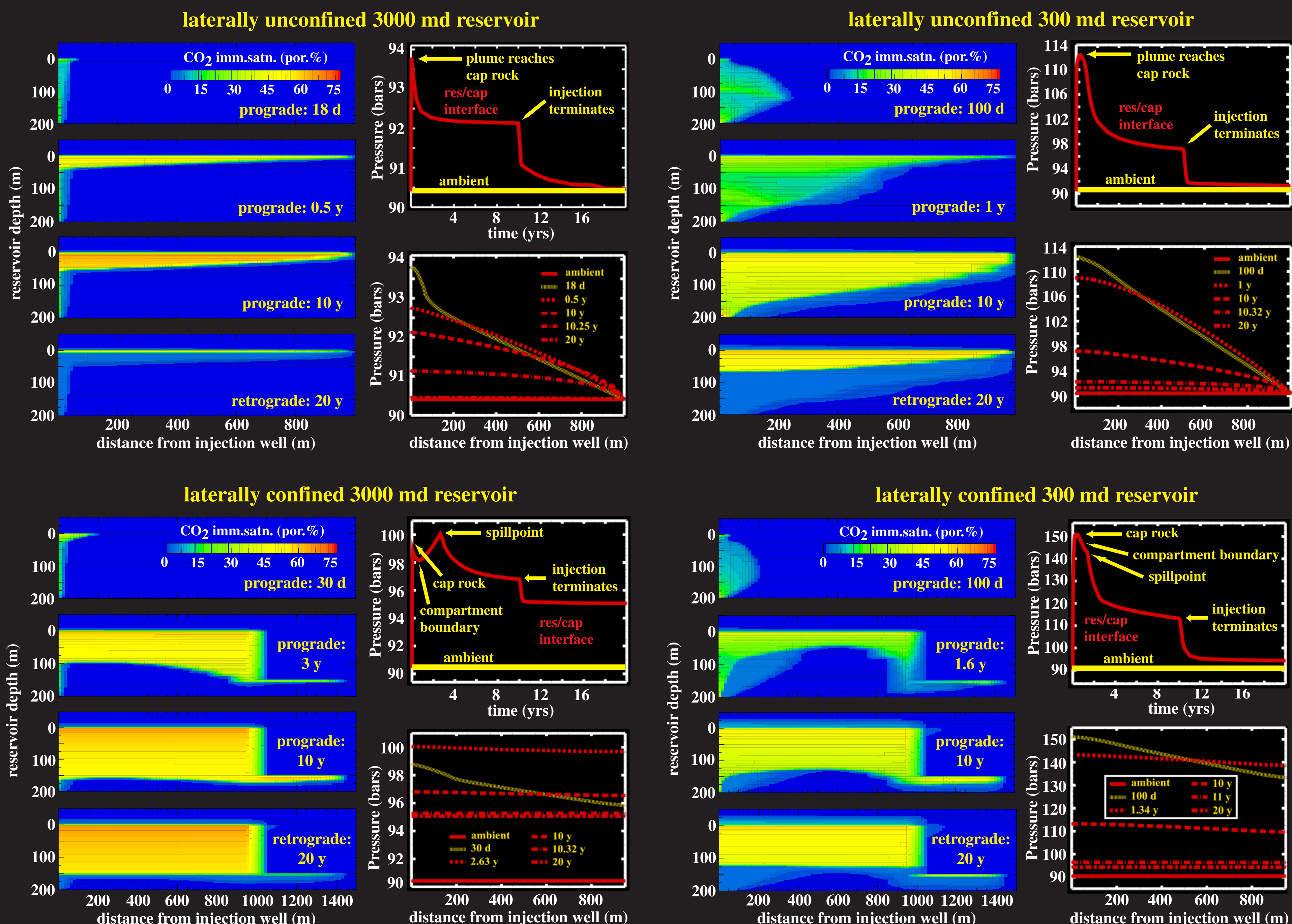
Laterally confined sandstone reservoir

- Depleted oil/gas reservoir storage
- CO_2-flood EOR/seq'n setting

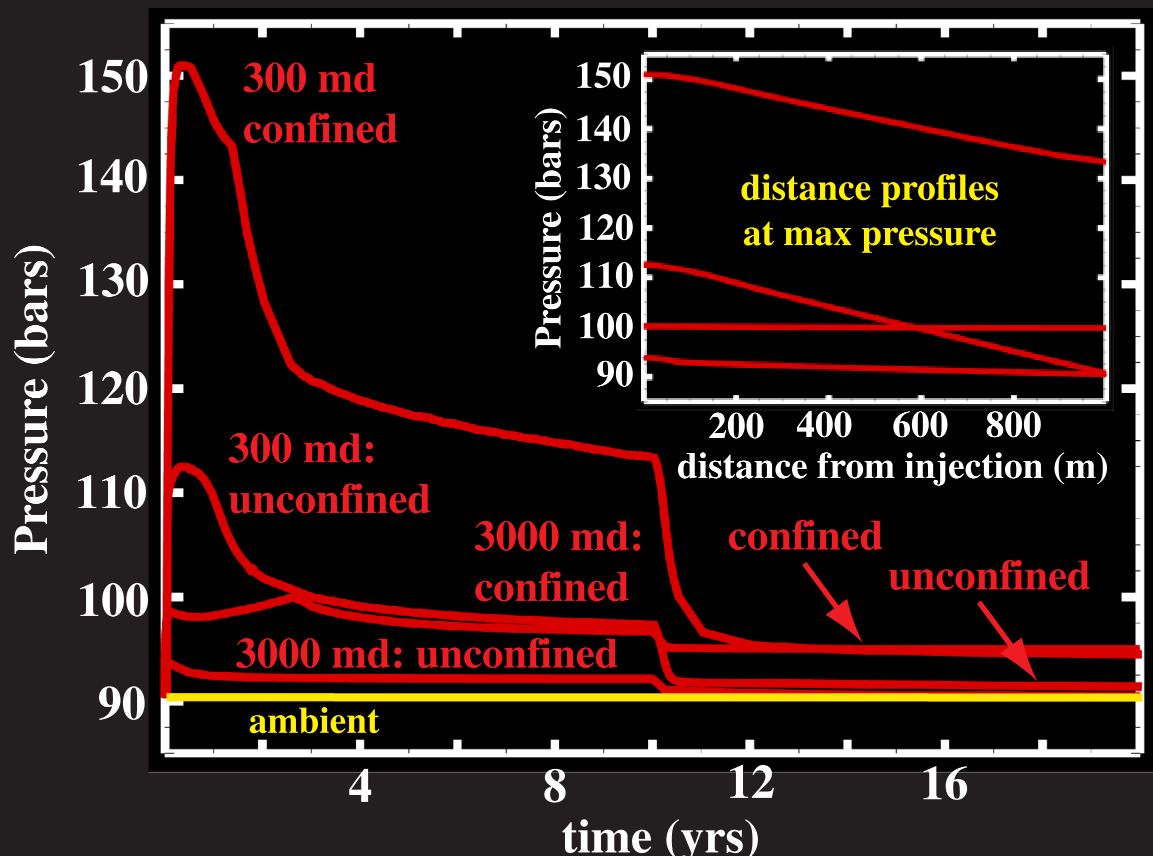
System commonalities

- Shale perm: 3 μd
- Reservoir perm: 300 and 3000 md
- CO_2 injection rate: 5000 ton/yr
- T = 37°C, P_h = 85-110 bars

9. NUFT simulation of immiscible CO_2 migration and the associated pressure perturbation as a function of reservoir permeability and lateral confinement



10. NUFT simulation of P evolution at the reservoir/cap rock interface

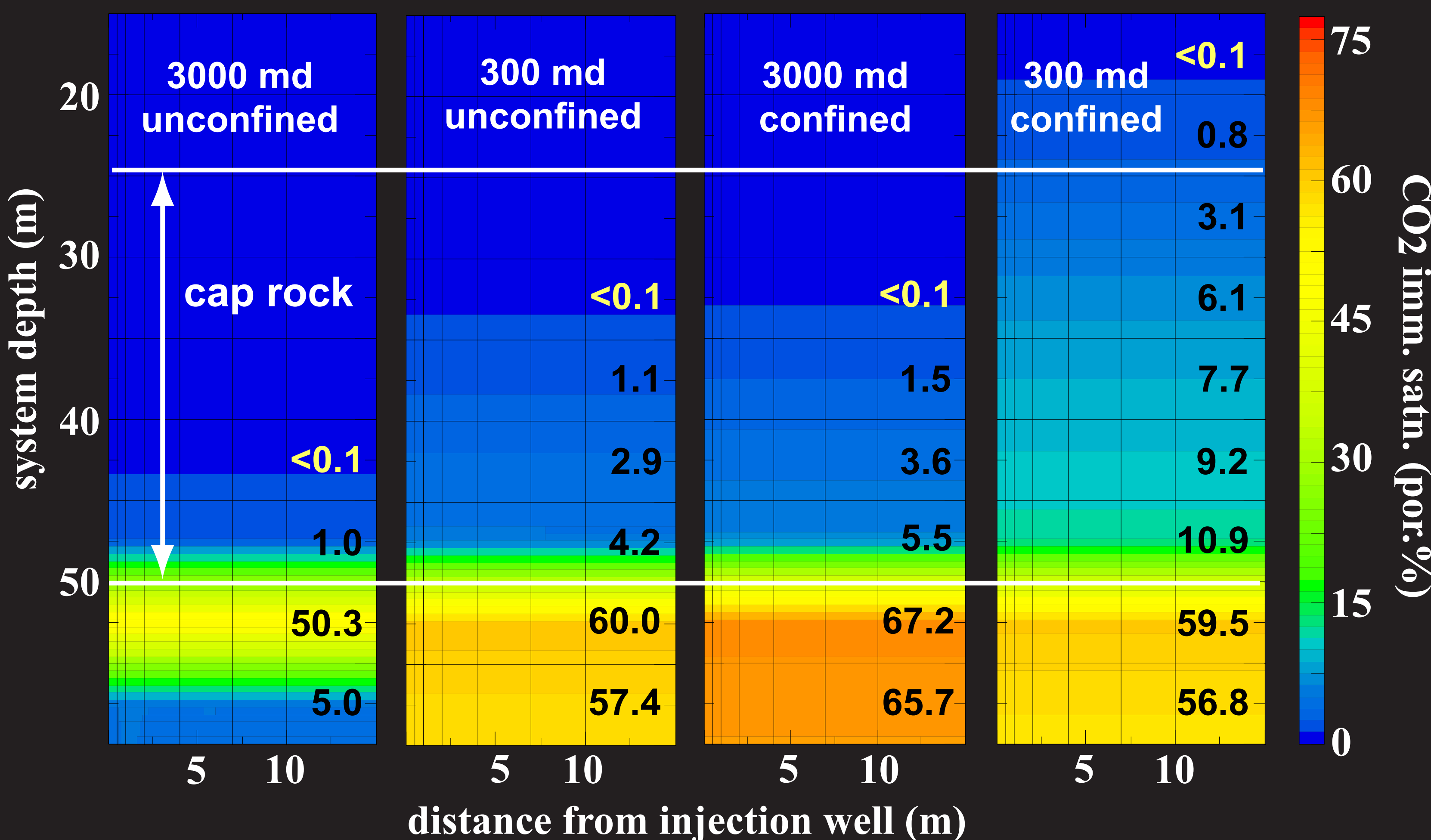


P spike as plume ascends to cap rock

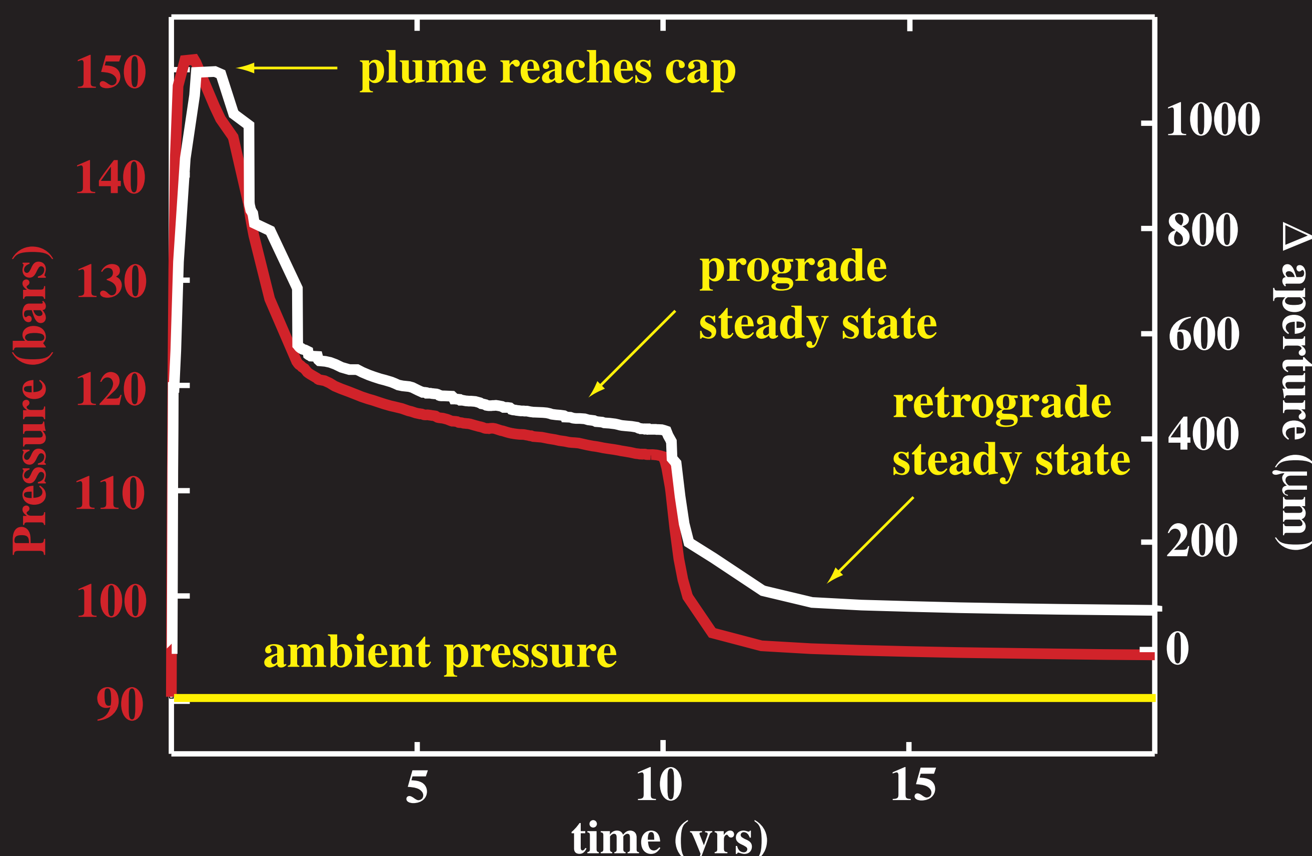
Asymptotic decay toward steady-state prograde and retrograde values

Retrograde steady-state P exceeds ambient P_h for confined systems

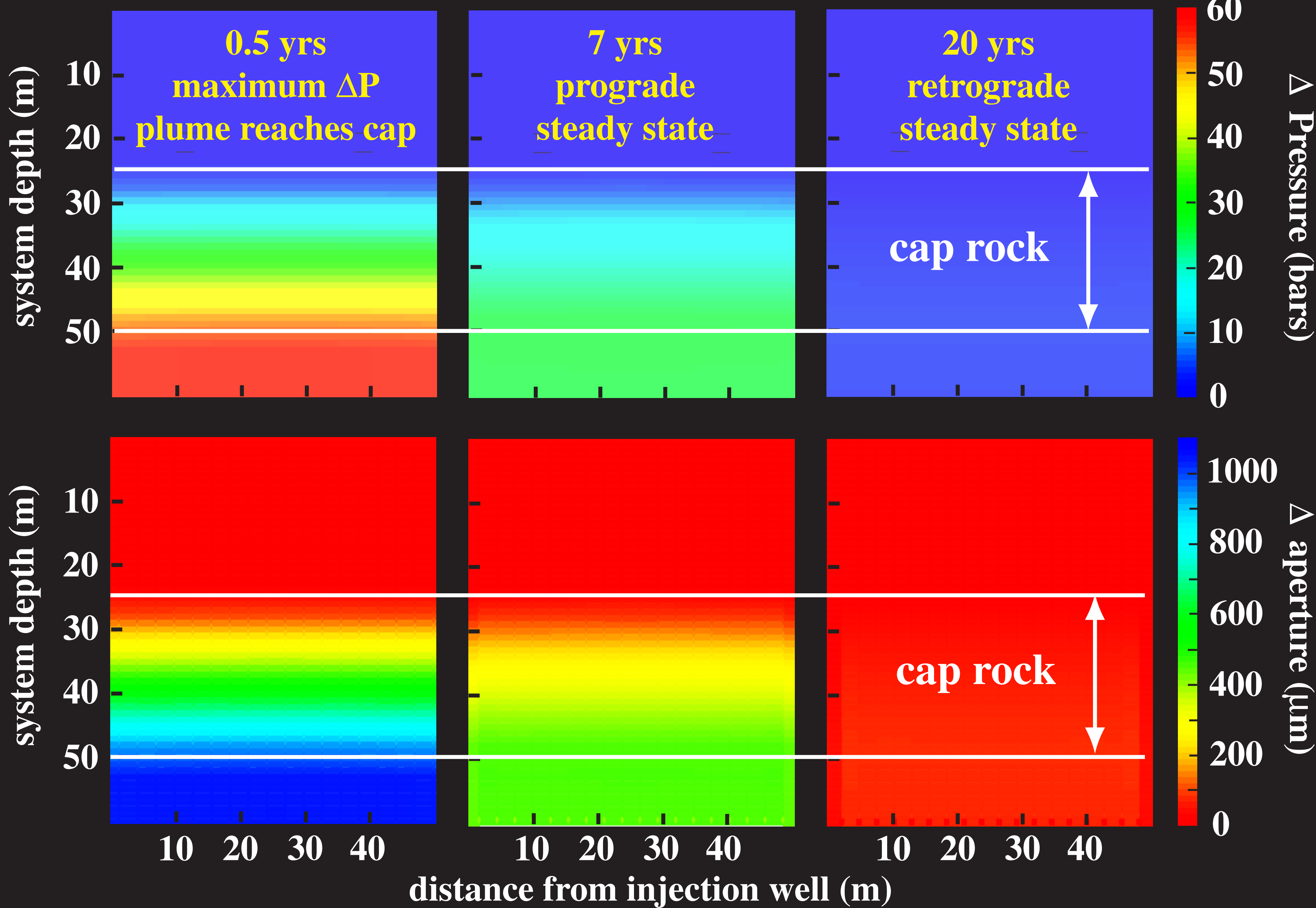
11. NUFT simulation of CO_2 migration into geomechanically undeformed cap rock through increased capillary pressure



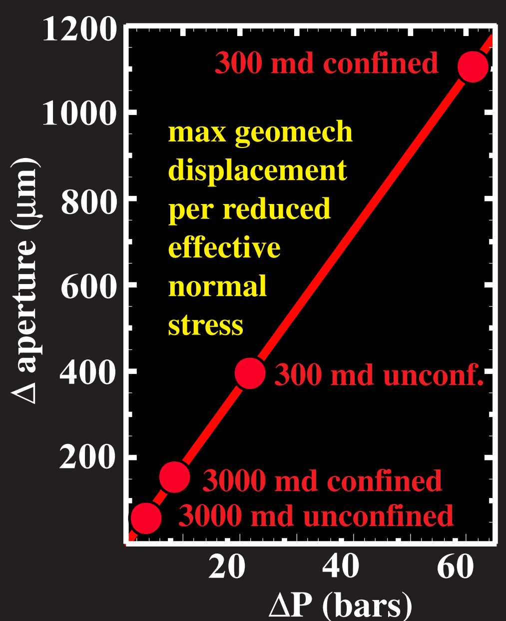
12. LDEC simulation of aperture evolution at the reservoir/cap rock interface: laterally confined 300 md reservoir

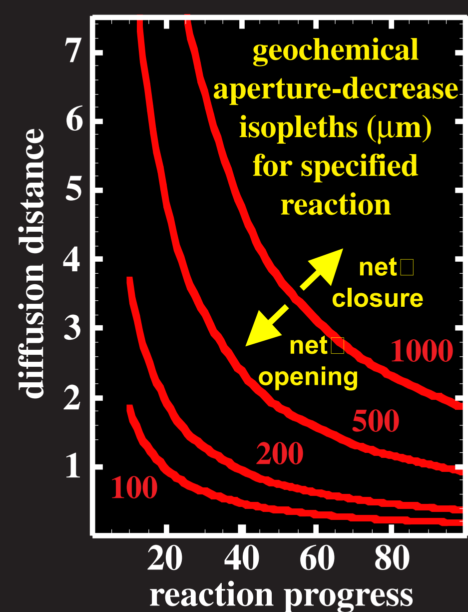


13. LDEC simulation of aperture evolution within and immediately surrounding the cap rock: laterally confined 300 md reservoir



14. Conceptual framework for geochemical counterbalancing of geomechanical effects





Magnitude of aperture change due to a specific diss/pptn reaction depends on:

- Vol. frac. reactant min. assemblage
- Vol. change of reaction
- Extent of reaction progress
- Effective diffusion distance

K-feld + Mg-chl + CO_2(aq) <==> magnesite + musc + kaol + silica (6b.)

- Vol. frac.: 0.1425
- ΔV_r = +19%
- Representative, yet conservative example reaction
- Natural analog has been documented (Watson et al., 2002)

15. Summary

Long-term cap rock integrity represents the single most important constraint on the long-term isolation performance of subsurface CO_2 storage sites. Ultimate enhancement or degradation of seal integrity hinges on the relative effectiveness of concomitant geochemical alteration and geomechanical deformation. Reactive transport modeling has shown that for typical shale cap rocks, geochemical processes slowly but continuously enhance isolation performance, while geomechanical processes at first rapidly degrade and then slowly improve it. The extent to which initial geomechanical degradation may occur (and overwhelm early geochemical enhancement) has been shown inversely proportional to reservoir permeability and lateral continuity. Hence, such degradation is expected to be most severe in tight compartmentalized CO_2-flood EOR settings, and of least consequence in Sleipner-like saline aquifer disposal sites.

A conceptual framework that permits comparison of initially opposing geochemical and geomechanical contributions to long-term cap rock integrity has been introduced. Diffusion length and reaction progress constraints derived from this framework suggest that ultimate geochemical counterbalancing of geomechanical effects is feasible. As a result, this counterbalance process represents a potentially important mechanism for re-establishing seal integrity in certain engineered storage settings and for initially establishing such integrity in specific natural CO_2 reservoirs.

16. References

Baker, J.C., Bai, G.P., Hamilton, P.J., Golding, S.D., and Keene, J.B., 1995, Continental-scale magmatic carbon-dioxide seepage recorded by dawsonite in the Bowen-Gunnedah-Sydney Basin, Eastern Australia: J. Sed. Res., Sec. A - Sed. Petrol. Processes, v. 65, n. 3., p. 522-530

Johnson, J.W., Nitao, J.J., Morris, J.P., and Blair, S.C., 2003, Reactive transport modeling of geohazards associated with CO_2 injection for EOR and geologic sequestration: Proc. Offshore Technology Conf.

Johnson, J.W., Nitao, J.J., and Steefel, C.I., and Knauss, K.G., 2003, Reactive transport modeling of CO_2 storage in saline aquifers to elucidate fundamental processes, trapping mechanisms, and sequestration partitioning: in Geol Soc. London Spec. Pub. "Geologic storage of carbon dioxide for emissions reduction: technology", Baines, S.J., Worden, R.H., and Gale, J., eds. (accepted).

Johnson, J.W., Nitao, J.J., Steefel, C.I., and Knauss, K.G., 2001, Reactive transport modeling of geologic CO_2 sequestration in saline aquifers: Proc. First Natl. Conf. Carbon Seqn.

Johnson, J.W., Oelkers, E.H., and Helgeson, H.C., 1992, SUPCRT92: A software package for calculating the standard molal thermodynamic properties of minerals, gases, aqueous species, and reactions from 1 to 5000 bars and 0 to 1000 ^{o}C: Comp. Geosci., v. 18, n. 7, p. 899-947.

Morris, J.P., Glenn, L.A., and Blair, S.C., 2002, The distinct element method--application to structures in jointed rock, Lecture Notes Comp. Sci. Engr., v. 26, p. 291-306.

Nitao, J.J., 1998, Reference manual for the NUFT flow and transport code, version 2.0: LLNL, UCRL-MA-130651, 55 p.

Watson, M.N., Zwingmann, N., and Lemon, N.M., 2002, The Ladbroke Grove-Katnook carbon dioxide natural laboratory: A recent CO_2 accumulation in a lithic sandstone reservoir, Proc. GHGT-6.