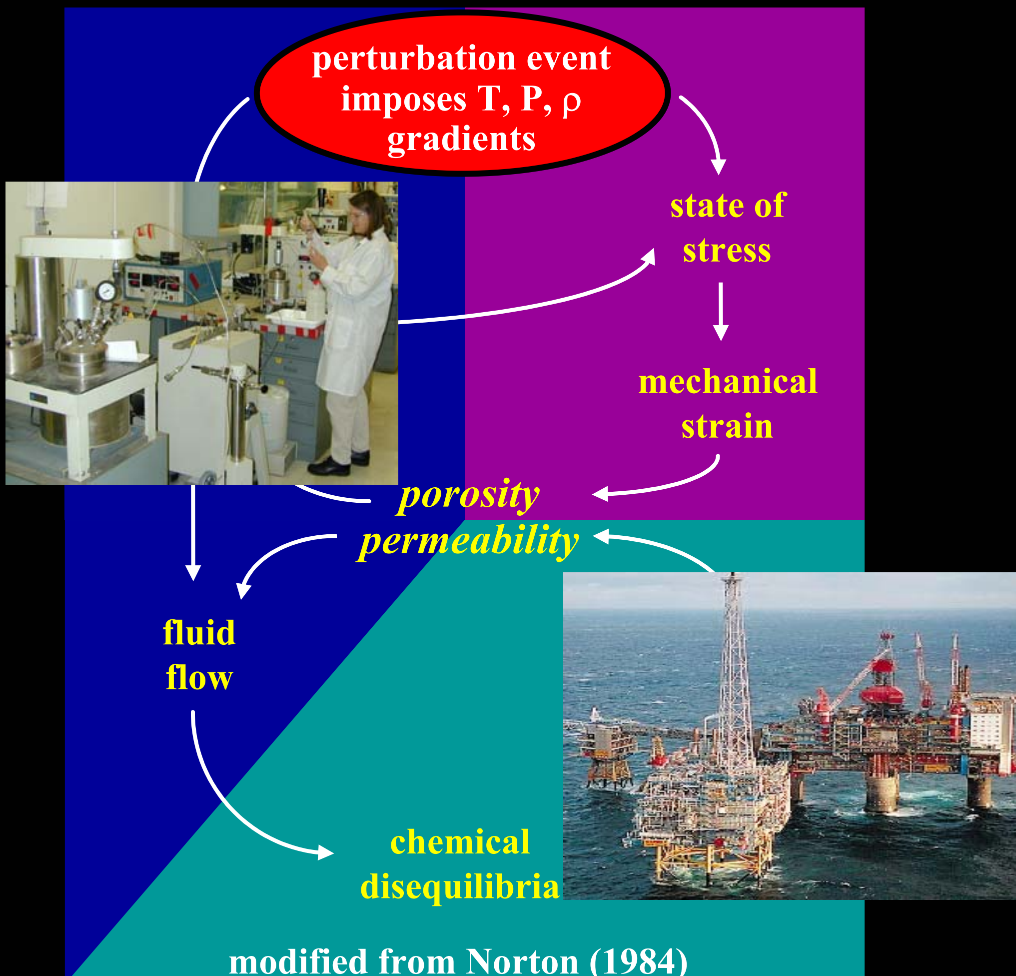
Requirements & challenges for modeling the isolation performance of geologic CO_2 storage



James W. Johnson

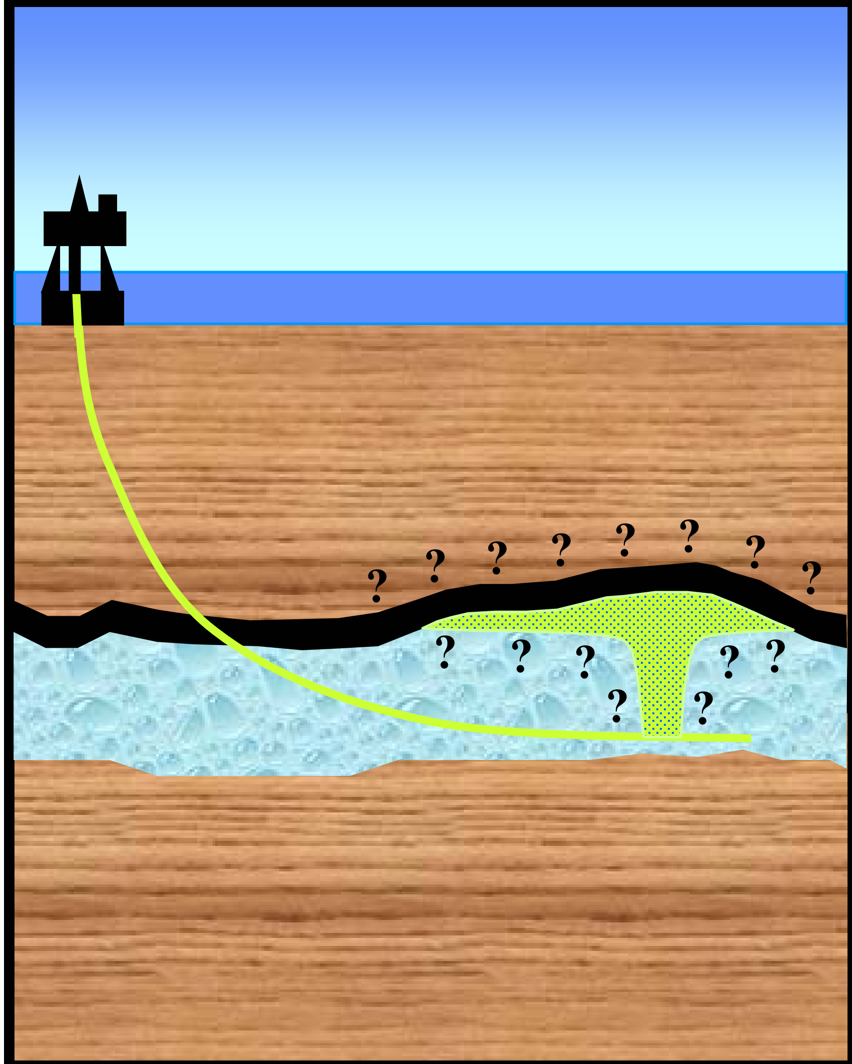
Lawrence Livermore National Laboratory
Livermore, CA

5th Annual Conf. Carbon Capture & Sequestration
May 8-11, 2006
Alexandria, VA

Ultimate technical goal

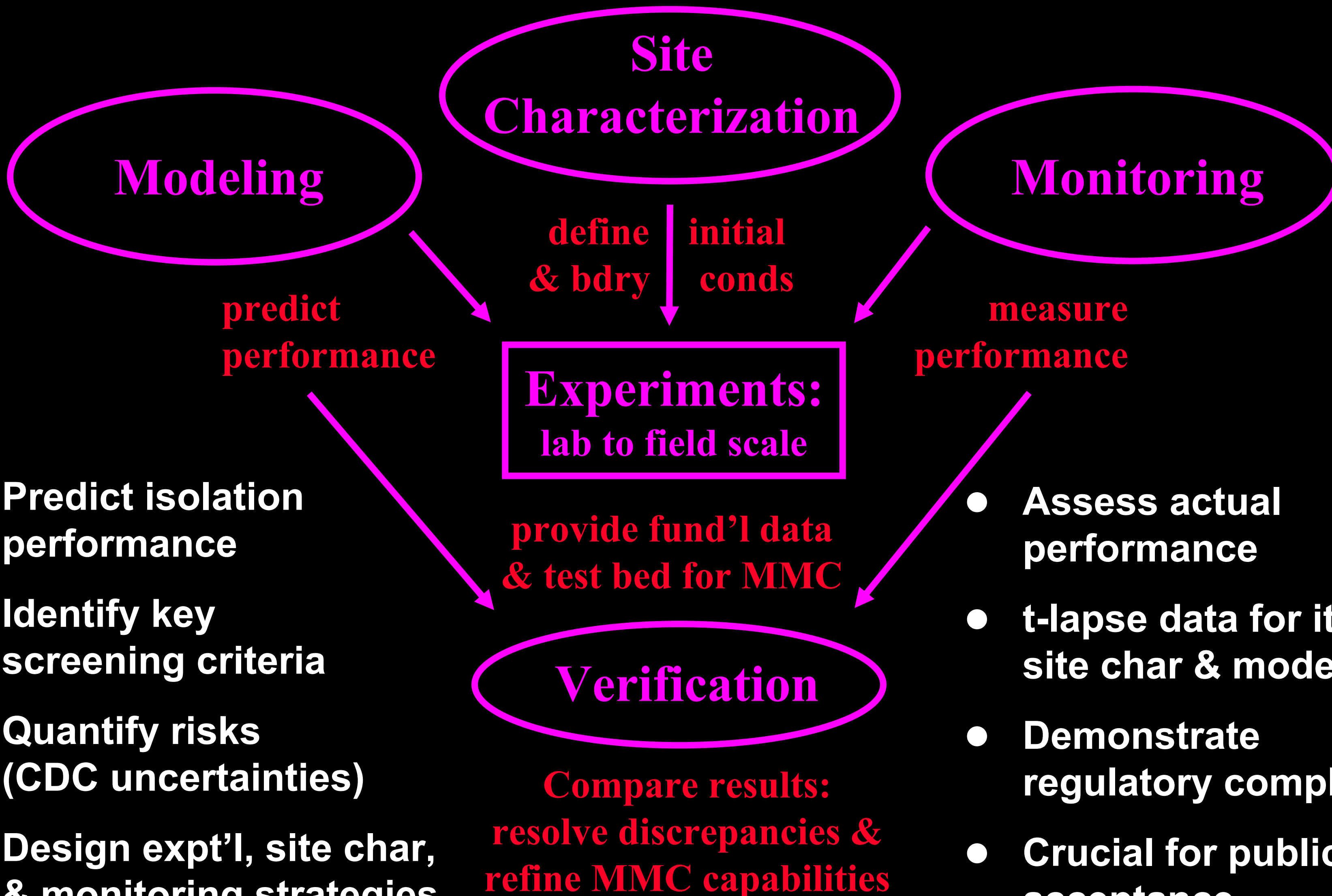
- **Develop two fundamental abilities**
  - ✓ Match injection-stream & disposal-site chars such that requisite isolation performance is *predicted* by advanced modeling capabilities
  - ✓ Match site chars, modeling results, and monitoring techniques such that predicted isolation performance can be *verified*
- **Injection-stream characteristics**
  - ✓ Projected incremental/total flux, impurity comps/concs, #/spacing of injection wells
- **Site components & characteristics**
  - ✓ Target reservoir(s), cap rock(s), localized wellbore environment, & overburden
  - ✓ Myriad hydrological, compositional, geo-mechanical, dimensional, & structural props
- **"Requisite" isolation performance**
  - ✓ That which provides regulatory compliance

Fundamental components of long-term isolation performance



- **Capacity (incremental & cumulative mass)**
  - ✓ Res dims/depth, por/perm mag/het, resid satn, ambient flow field
  - ✓ Must demonstrate for ER credits
- **Density (areal & volumetric footprint)**
  - ✓ Depth, struct, seqn partitioning among geochem & residual trapping mechs
  - ✓ Spatial extent of monitoring programs
- **Containment (hydrodynamic seal capacity)**
  - ✓ Cap-rock/wellbore integrity as f(geochem/geomech processes)
  - ✓ Must demo for regulatory compliance
- **Risk (uncertainty limits on CDC estimates)**
  - ✓ Economic: +/- ER credits & spatial extent of monitoring responsibility
  - ✓ Environmental: +/- resume & impact of potential leakage mechanisms

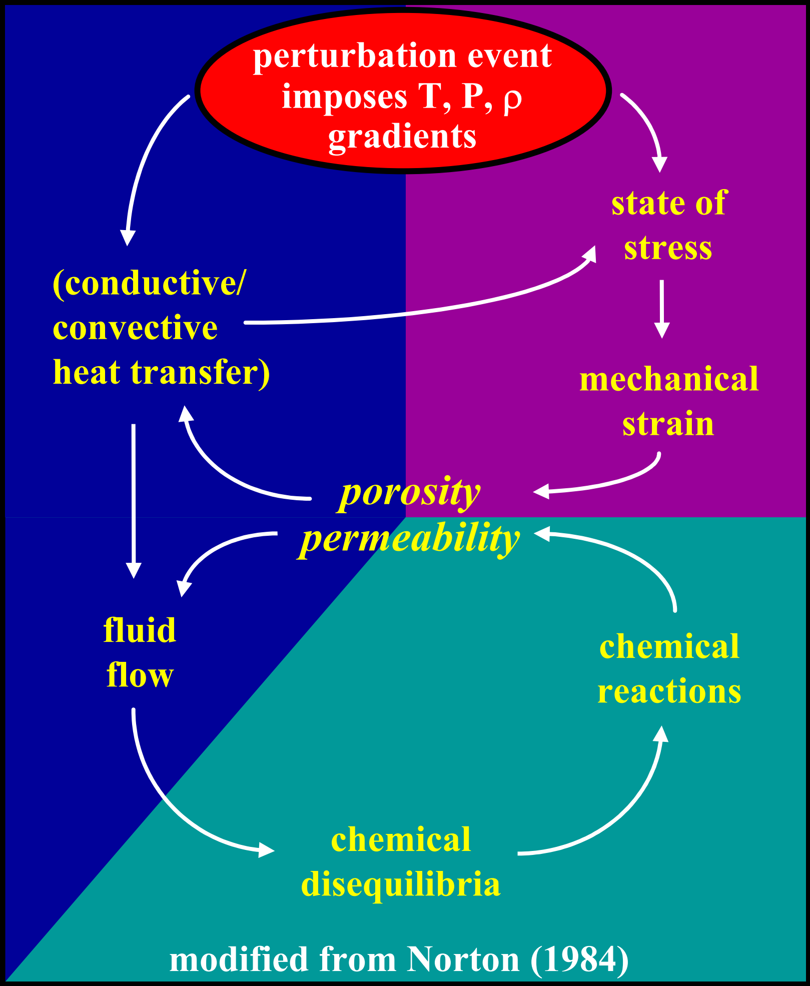
Requisite integrated technology portfolio for geologic CO_2 storage



- Predict isolation performance
- Identify key screening criteria
- Quantify risks (CDC uncertainties)
- Design expt'l, site char, & monitoring strategies

- Assess actual performance
- t-lapse data for iterative site char & modeling
- Demonstrate regulatory compliance
- Crucial for public acceptance

Modeling the integrated processes & isolation performance of geologic CO_2 storage



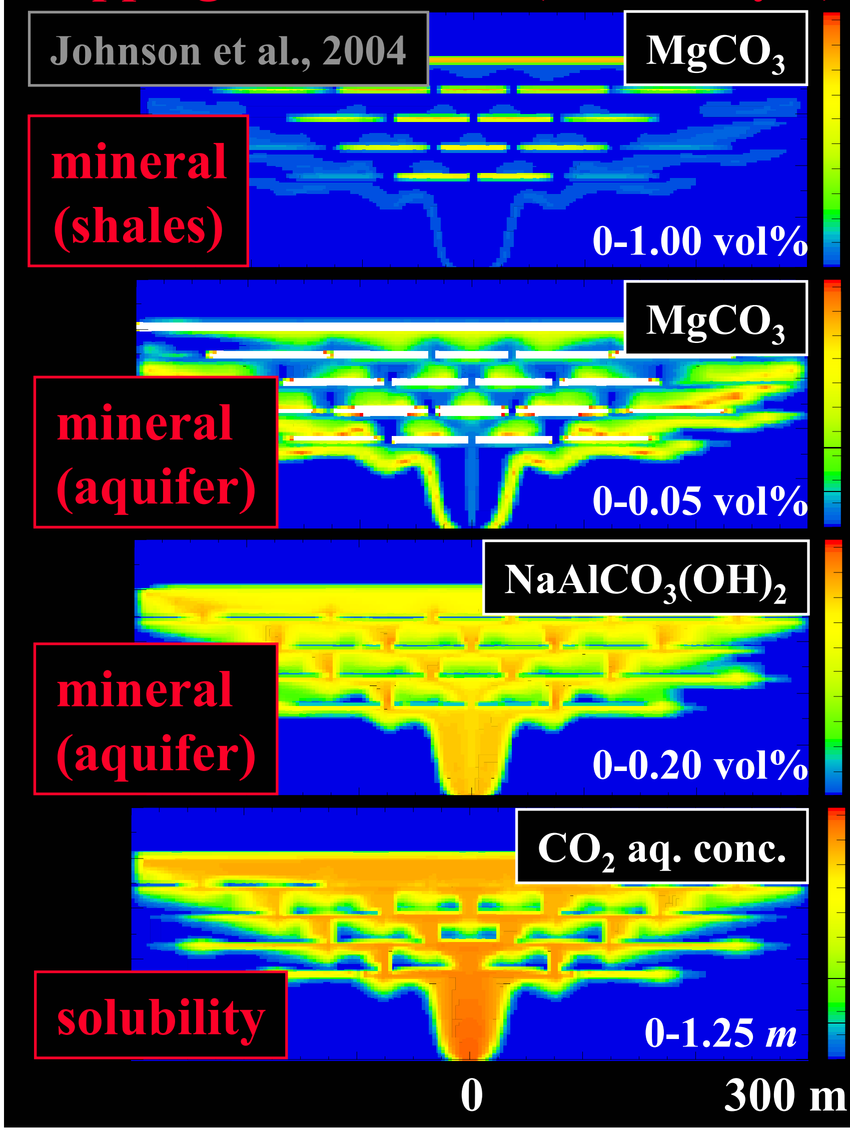
- **Process quantification requires theoretical geoscience expertise**
  - ✓ Mathematical reps, numerical methods
- **Practical implementation requires computational expertise & facilities**
  - ✓ Software, solvers, hardware, visualizn
- **Applications require diverse system-specific field & experimental data to represent:**
  - ✓ Initial & boundary conditions: Site characterization data that define the physical domain
  - ✓ Dynamic system evolution: Site-independent data that underpin the process models

Fundamental Challenges for modeling

- **Ultimate goal**
  - ✓ Develop ability to match injection-stream & disposal-site chars such that requisite isolation performance is *predicted*
- **Challenges**
  - ✓ Identify key screening criteria that facilitate such correlations (CDC components)
  - ✓ Quantify & reduce the uncertainties that surround such predictions (R component)
- **Potential screening criteria**
  - ✓ Myriad hydrological, compositional, structural, & dimensional properties
- **Sources of uncertainty**
  - ✓ Process & process coupling: rep'n & accur.
  - ✓ Site-independent data: accuracy
  - ✓ Site characterization: accuracy -- spatial distribution of heterogeneous properties

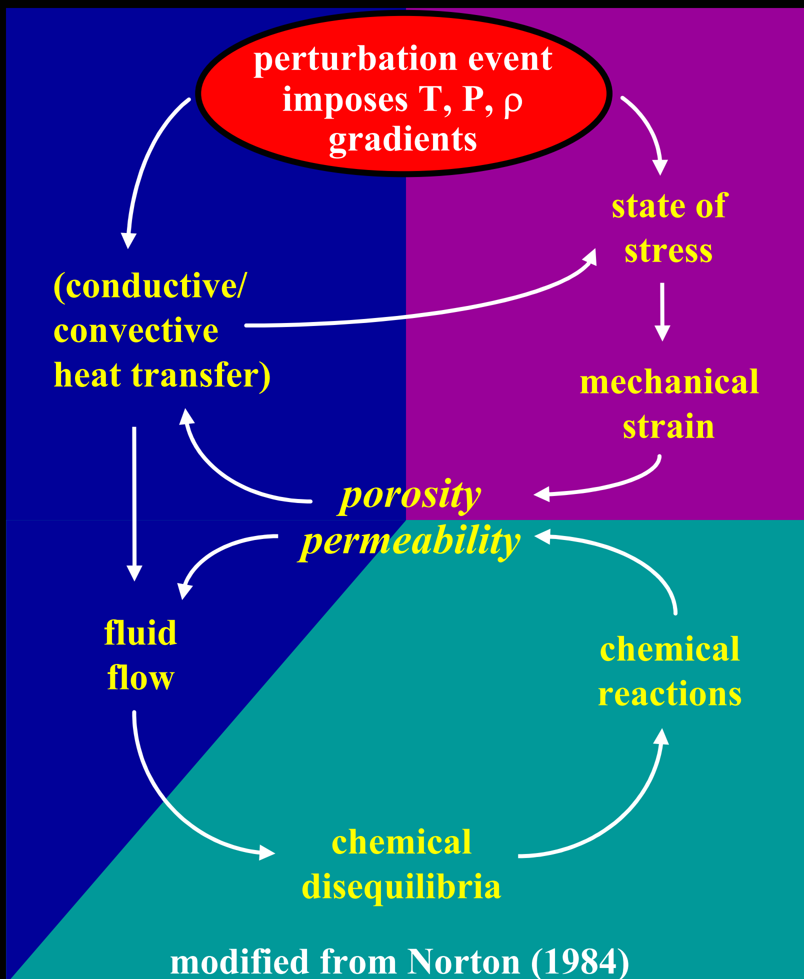
Identification of screening criteria for optimized source/sink matching

trapping mechanisms (DSH: 20 yrs)



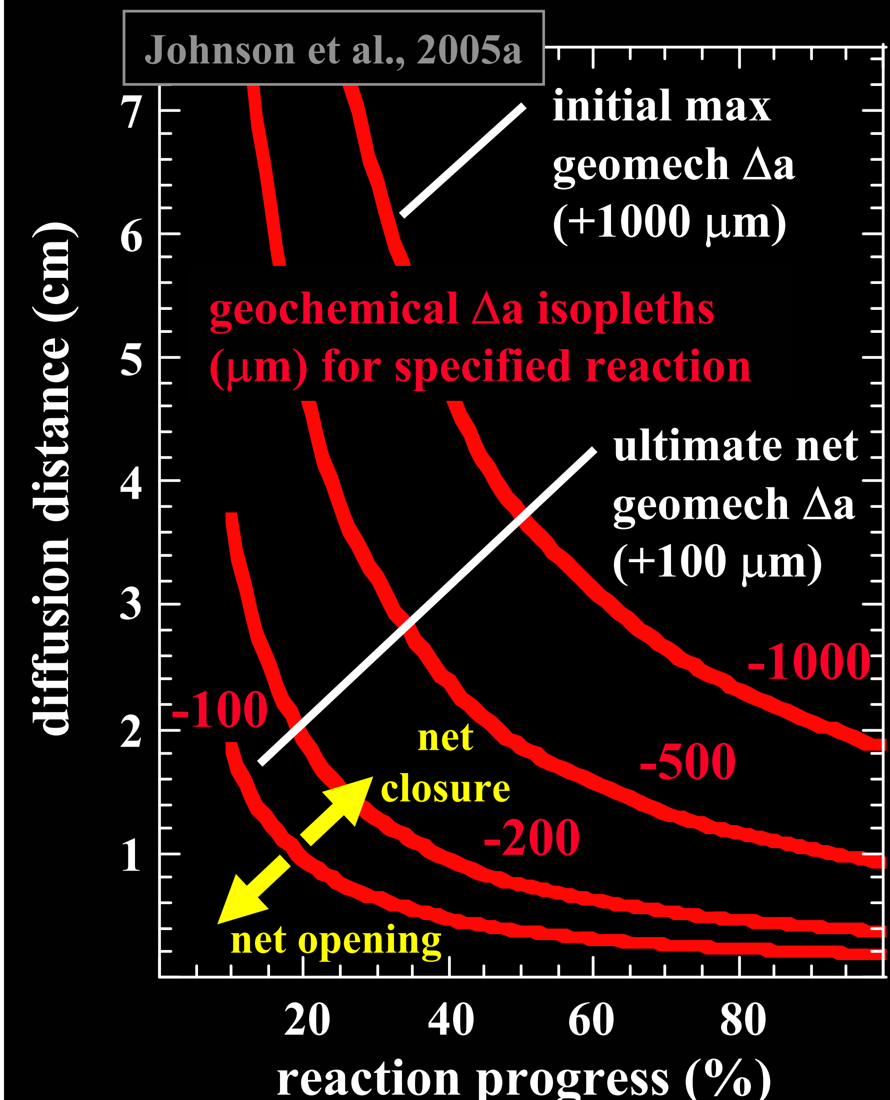
- **Approach: quantify CDC sensitivity to the range of key property variations**
- **Compositional**
  - ✓ CO_2 impurities: e.g., SO_X, NO_X, CH_4, H_2S
  - ✓ Res/cap-rock min: carb-forming cations
  - ✓ Ambient fluids: aqueous & HC phases
  - ✓ Wellbore environs: mud, cement, casing
- **Hydrological**
  - ✓ CO_2 & ambient fluid fluxes
  - ✓ Poros/perm of res/cap-rock/wellbore envs
  - ✓ Residual saturations: CO_2, aqueous, HC
- **Structural**
  - ✓ Res lateral cont; res/cap interface topog.
- **Depth & geothermal gradient (P-T conds)**
  - ✓ Eq. ref. frame for chem mass transfer
  - ✓ Fluid-phase density contrasts

Current challenges in developing robust process models



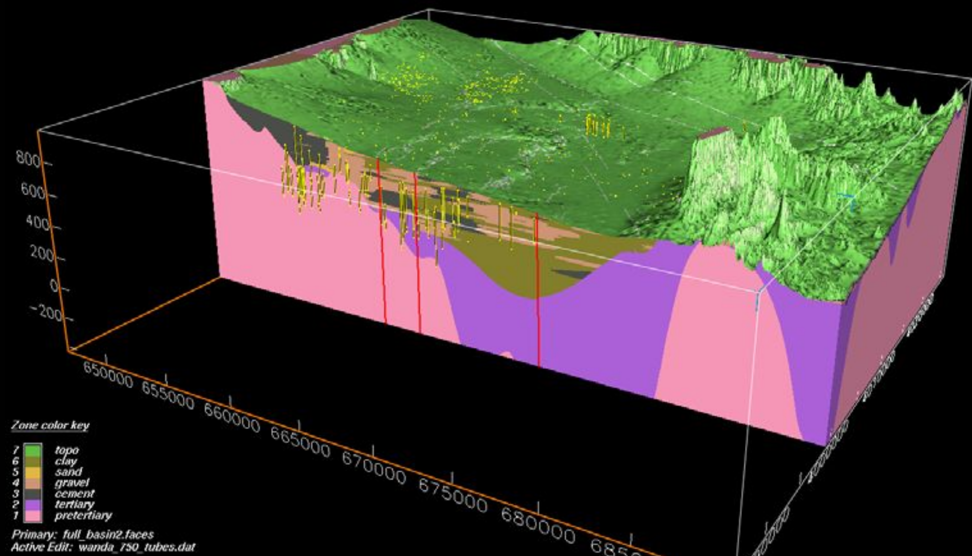
- **Multiphase flow processes**
  - ✓ Fm H_2O, impure CO_2, HC (liq, gas)
  - ✓ EOS, visc, 2-3 phase relative perm
  - ✓ Residual saturation descriptions
  - ✓ Hysteretic capillary pressure functions
- **Geochemical processes**
  - ✓ Equilibrium reference frame: well-estb
  - ✓ Intra-fl & fl/min mass transfer: less mature
  - ✓ Min diss/pptn kinetics (processes & data): nucl & growth, near-equil rates, SSA
  - ✓ CO_2 impurities; H_2O solub in “immisc” CO_2
  - ✓ CO_2 crit phenom; biogeochem procesess
  - ✓ *Perm(continuum-rep poros(min diss/pptn))*
- **Geomechanical processes**
  - ✓ Effective stress(P_f, total stress)
  - ✓ Stress-strain rels: aper(P_f, frac stiff(aper))
  - ✓ *Perm(DEM-rep poros(aper))*

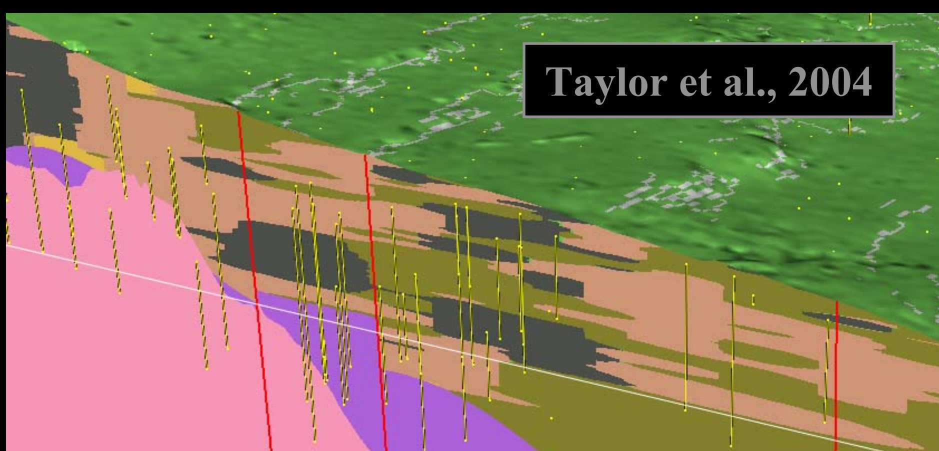
Current challenges in developing seamless process coupling



- **Multiphase flow/geochem interface**
  - ✓ Chemical affinity(aq., CO_2, HC flow)
  - ✓ Min diss/pptn; convective mixing
  - ✓ Fm H_2O dens(CO_2 solub; min diss/ppt)
  - ✓ Rel effect: flow, min diss/ppt, conv mix
  - ✓ Flow(geochem-dep perm)
- **Multiphase flow/geomech interface**
  - ✓ Effective stress(P_f(CO_2 influx))
  - ✓ Flow(geomech-dep perm)
  - ✓ Interfacing continuum & DEM models
- **Geochem/Geomech interface**
  - ✓ Geomech props(composition)
  - ✓ Perm(geochem/geomech components)
  - ✓ Rel rates/mags of indiv components
  - ✓ Interfacing continuum & DEM models

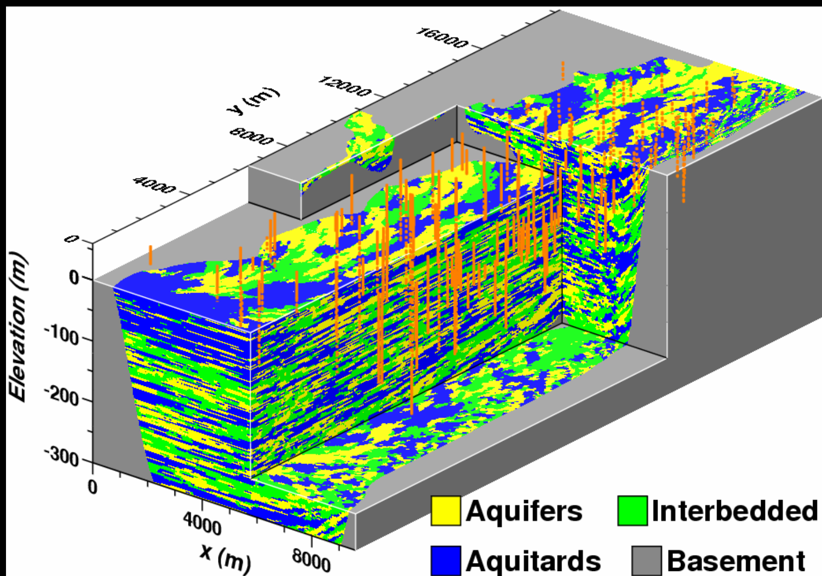
The up-scale/down-scale challenge of transitioning from lab- to field-scale models



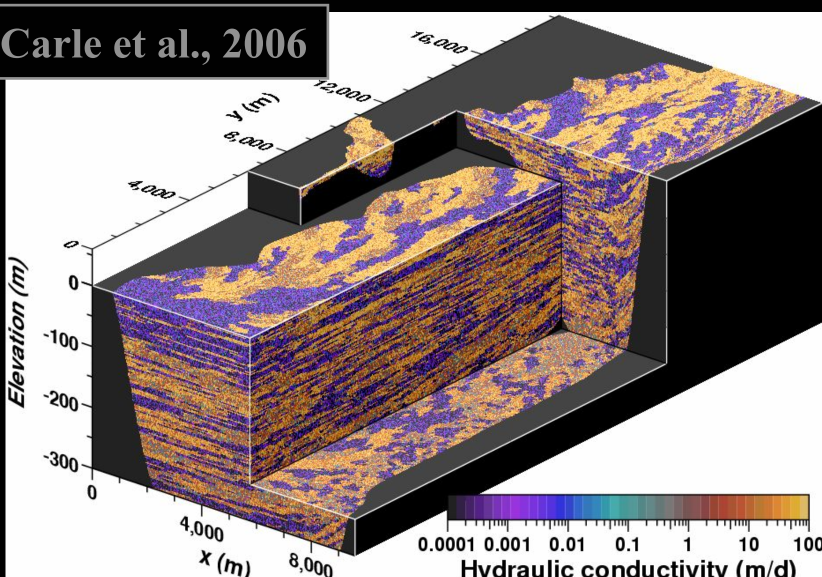


- **Lab-scale simulations**
  - ✓ Init/bdry conds are <u>established</u>: por/perm, comp, flow, P-T, stress
  - ✓ Perturbation event often observed & sampled <u>directly</u> *in situ* in its entirety
  - ✓ Mass/ener redistribution processes often can be evaluated <u>independently</u>
  - ✓ Resolution of prediction/observation discrepancies: model fine-tuning
- **Field-scale simulations**
  - ✓ Init/bdry conds are <u>poorly known:</u> sparse sampling, extreme heterog.
  - ✓ Perturbation event is observed <u>indirectly</u> and sampled at intervals
  - ✓ Mass/energy redistribution processes must be evaluated in <u>integrated</u> form
  - ✓ Resolution of prediction/observation discrepancies: improved site char & process/computational scaling

Quantifying & reducing the uncertainty of site characterization

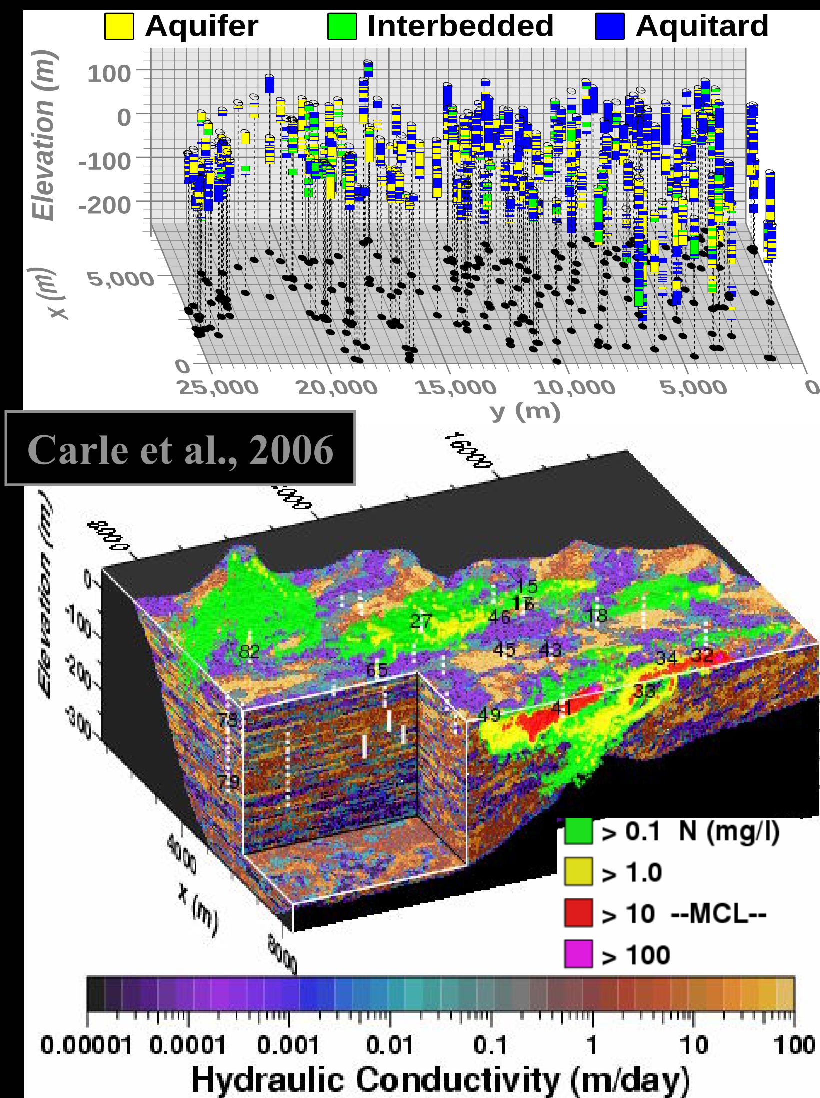


Carle et al., 2006



- **Fundamental challenge of field-scale performance prediction**
- **Requires three-pronged approach:**
  - ✓ Maximize data density & diversity
  - ✓ Develop improved methods for extracting maximum value from raw data
  - ✓ Repeatedly refine site char efforts by integrating new info from monitoring pgms
- **Improved methods**
  - ✓ Advanced *in situ* fluid sampling techs
  - ✓ Detailed compositional analyses of core
  - ✓ Facies-based transitional prob. approach for inter-well stratigraphic interpolation
  - ✓ Continuous stochastic random field approach for intra-stratum heterogeneity
- **Monitoring data**
  - ✓ Often delineates local high/low perm zones that are undetectable *a priori*

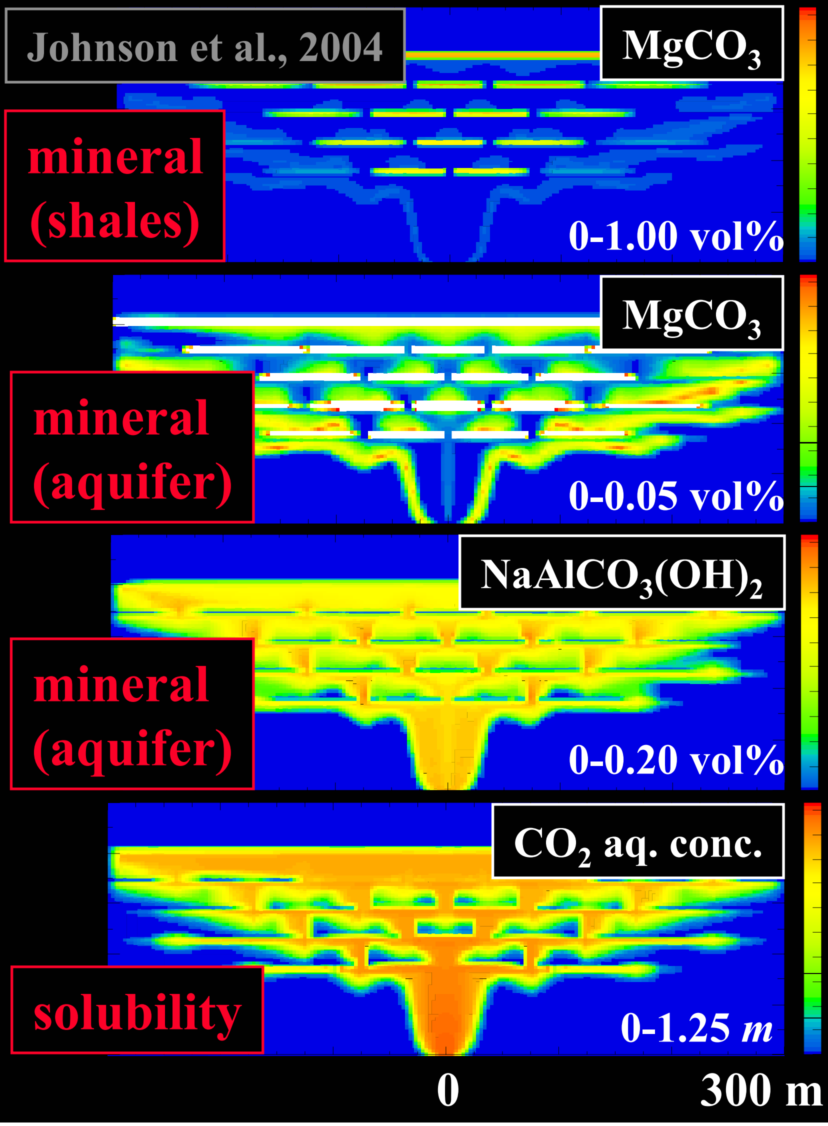
Requisite integration of site characterization, modeling, & monitoring activities



- **Expt-calibrated predictive models**
  - ✓ Screening criteria for isolation performance
  - ✓ Define & prioritize site char activities
- **Site characterization**
  - ✓ Sparse raw data for geostatistical methods
  - ✓ Core (high-res vert), seismic (rel low-res 3D)
- **Geostatistical methods**
  - ✓ 3D heterogeneous property distributions
  - ✓ Perm: spatial framework of CO_2 migration
  - ✓ Comp: efficacy of geochem trapping mechs
- **Site geologic model**
  - ✓ Import to EarthVision & predictive models
- **Model & monitor isolation performance**
- **Minimize prediction/mmt discrepancies**
  - ✓ Iterative staged refinement of het prop dists that honor *all* data (Ramirez et al., 2006)

Next-generation reactive transport modeling of long-term isolation performance to:

trapping mechanisms (DSH: 20 yrs)



- **Quantify impurity constraints (sep reqmts)**
  - ✓ Site integrity as f(SO_x, NO_x, CH_4, H_2S)
  - ✓ Define max non-deleterious limits
- **Optimize source/sink matching (perf rank)**
  - ✓ Identify key screening criteria
  - ✓ Maximize CDC performance
- **Optimize filling strategies (impl. schemes)**
  - ✓ #, spacing, geom, influx rates/duration of CO_2 (+/- associated H_2O) injection wells
- **Quantify & minimize CDC uncertainty (risk)**
  - ✓ Expt-calibrated process models & coupling, site-indep data, site characterization
- **Design monitoring programs**
  - ✓ Identify appropriate technology suite
  - ✓ Determine imaging/sampling locs/freqs
- **Interface with atmos & ocean models**
  - ✓ Seamless tracking of pot'l release scenarios