LBNL Studies on the Geomechanical Performance of Hydrate-Bearing Sediments

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  - ➢ LBNL's objective, role and contribution
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- ❑ **LBNL ACTIVITIES**
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  - ➢ Task description
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INTRODUCTION: Overall Project Objective

PROJECT TEAM: TAMU, UCB, LBNL

- **OVERALL OBJECTIVE:** To develop the necessary knowledge base and quantitative predictive capability for the description of geomechanical performance of HBS

- **HBS geomechanical properties:** Affected by
  - Gas production from hydrates
  - Thermal loading of HBS intersected by rising warm fluids in wells: Production from deeper formations
  - Mechanical loading (structures supported by/ anchored in HBS)

INTRODUCTION: Issues

- **RESULTS**
  - P, T and S changes
    - Geomechanical changes of HBS
    - Interactions with hydraulic and thermal properties/behavior
  - Hydrate depletion: Transfer of loads to porous medium
    - Displacement
    - Subsidence
    - Failure/Fracturing
- **Potentially adverse effects on:**
  - Wellbore stability
  - Structural integrity and stability of the HBS: consequences for structures supported by (or anchored in) them
  - Issues affecting both permafrost and marine deposits, but CRITICAL in marine systems

STATEMENT OF THE PROBLEM

❑ CURRENT STATUS

- Significant uncertainties and HBS stability concerns
  - Potentially catastrophic economic consequences
  - Health and safety issues
- Well placement and seafloor structures (platforms) non-optimal: strongly influenced by the presence of hydrates - AVOIDANCE
- Embryonic state of knowledge of the geomechanical behavior of HBS
- Geomechanical behavior must be accounted for in the design of facilities operating in HBS
- Reliable quantitative predictions are critically important to allow safe operations in HBS and to allow resource recovery from HBS

STATEMENT OF THE PROBLEM
Knowledge requirements for reliable predictions

- **Hydraulic, thermal and phase transition processes in HBS**
  - **Reliable quantitative relationships (YES, in progress)**
  - **Corresponding parameters (YES, in progress)**
  - **Integrated hydrate behavior models in geologic media (YES)**
- **Geomechanical behavior of HBS**
  - **Reliable quantitative relationships (NO)**
  - **Corresponding parameters (NO)**
  - **Integrated generic geomechanical models (YES)**
- **Interrelations between hydraulic, thermal, phase transition and geomechanical processes**
  - **Reliable quantitative relationships (NO - extrapolation possible?)**
  - **Corresponding parameters (NO - extrapolation possible?)**
  - **Coupled models (YES: TOUGH+/FLAC3D - LBNL work)**

LBNL's Role and Approach: 2006

❑ OBJECTIVE (Single Task for FY2006)

To couple a robust numerical simulator of hydrate behavior in geologic media (TOUGH+/HYDRATE) with a commercial geomechanical code (FLAC3D), thus developing a numerical code for the concurrent analysis of flow, thermal, thermodynamic and geomechanical behavior of HBS.

❑ Fully-coupled processes a NECESSITY

- **Original TOUGH+/HYDRATE did not include robust geomechanical capabilities (pore compressibility only)**
- **TOUGH+/HYDRATE output could conceivably be used as an input to a geomechanical code such as FLAC3D in a sequential mode: NOT ADVISABLE - inherently inaccurate**
- **Extremely non-linear processes**
- **Interrelated processes**

STATEMENT OF THE PROBLEM

Integrated model of hydrate behavior

- TOUGH+: Next generation of TOUGH2 family of codes - General-purpose multiphase, multicomponent model for simulation of fluid and heat flow and transport in porous and fractured media
- TOUGH+/HYDRATE (T+H) code [*Moridis et al., 2005*]: Describes the non-isothermal hydrate dissociation/formation, CH_4 flow, and phase behavior
- Most advanced code of its kind: incorporates current state-of-the-art of knowledge of hydraulic, thermal and phase transition processes in HBS

Methane hydrates

$CH_4.N_mH_20 = CH_4 + N_mH_20(l,i)$, $5.75 \leq N_m \leq 7.4$

Second-gas hydrates (*)

$G.N_GH_20 = G + N_G\, H_20(l,i)$, $G = C_\nu H_{2\nu+2}, H_2S, CO_2, N_2$

Binary hydrates (*)

$\chi_m[CH_4.N_mH_20\,]\ \chi_G\ [G.N_GH_20\,]$, $\chi_m+\chi_G = 1$

(*): Included but deactivated in TOUGH-Fx/HYDRATE

STATEMENT OF THE PROBLEM

TOUGH+/HYDRATE CODE

1. Components

- (1) H_2O
- (2) CH_4
- (3) Hydrate (*)
- (4) Salt
- (5) Inhibitor
- (6) Heat

Components in red: Minimum necessary
(*): For kinetic dissociation

26 Possible phase combinations

2. Phases

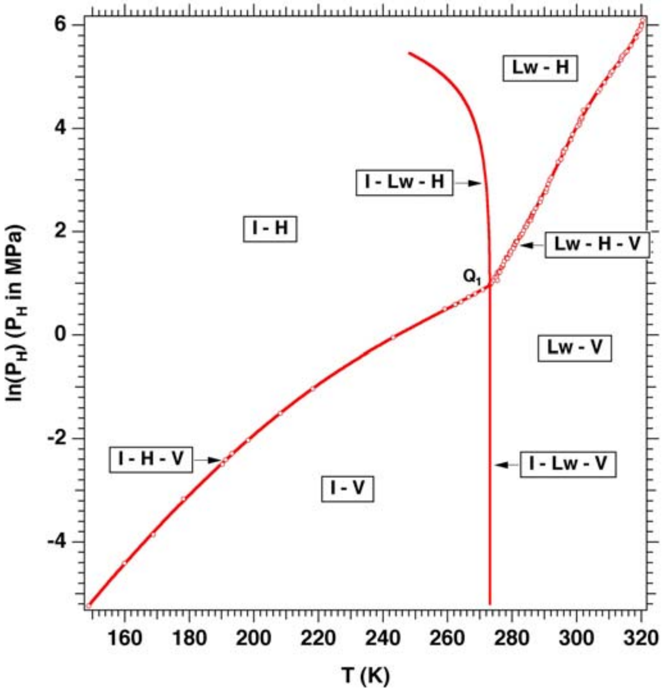
(1) Aqueous
H_2O, CH_4, CH_4, S, I

(2) Gas
CH_4, H_2O, I

(3) Solid-Hydrate
$CH_4.N_mH_20$

(4) Solid-Ice
H_2O

New hydration P-T relationships



TOUGH+/Hydrate capable of handling (a) equilibrium or kinetic dissociation, and (b) all possible dissociation mechanisms (depressurization, thermal stimulation, inhibitor effects, combinations)

LBNL's Approach

Coupling TOUGH+/HYDRATE with FLAC3D

- **The FLAC3D code**
  - State-of-the-art geomechanical model
  - Widely used in soil and rock mechanics engineering, and for scientific research in academia
  - Built-in constitutive mechanical models suitable for soil and rocks, including
    - Elastoplastic models for quasistatic yield and failure analysis
    - Viscoplastic models for time dependent (creep) analysis
    - Models for strain-hardening/softening plasticity for HBS
    - Accepts user-defined constitutive models

- **Reasons for FLAC3D**
  - Wealth of geomechanical options available in the model
  - Wide acceptance by the scientific community
  - LBNL's familiarity with this model (extensive Yucca Mountain TOUGH2/FLAC work)

LBNL's Approach: Initial Concept

Coupling TOUGH+/HYDRATE with FLAC3D

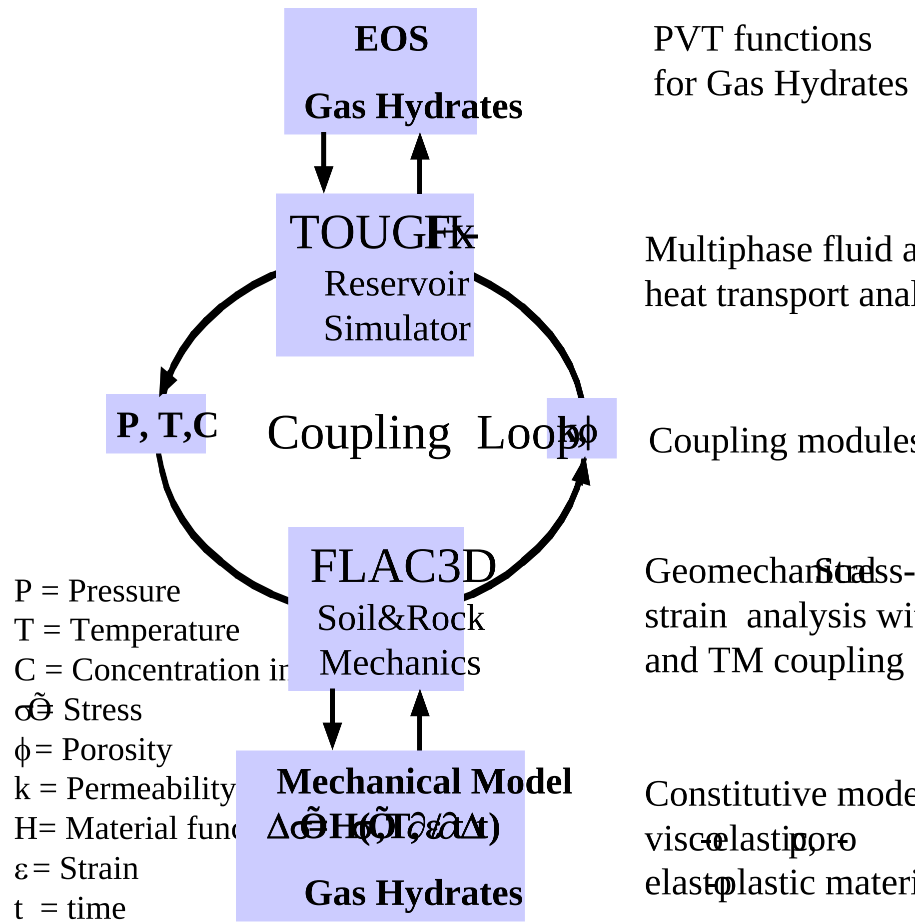
FLOW OF INFORMATION IN THE COUPLED CODE

1. **The TOUGH+/HYDRATE simulations export the thermal, hydrological, thermodynamic, phase and flow parameters needed by FLAC3D.**

2. **FLAC3D computes and exports the mechanical stress and strain.**

3. **Relating stress and strain to domain deformation and changes in the hydraulic and thermal properties, a new TOUGH+/HYDRATE simulation (using the updated system properties, conditions and behavior, yields an updated solution)**

4. **The process 1 to 3 is repeated.**



Subtask 1.1

Development of FLAC3D Routines (2/1/06 - 5/30/06)

DELIVERABLE: *FLAC3D and associated routines, ready to be integrated into the coupled geomechanical model.*

- **Develop FLAC3D-FISH routines describing the geomechanical behavior of HBS as a function of phase saturations, P, T and inhibitors (e.g., salts): assumptions and approximations**
  - **New conceptual models (to be developed by TAMU and UCB) will be incorporated**
- **Develop FLAC3D-FISH routines calculating coupled geomechanical effects in the geologic media of HBS and describing deformation caused by thermal strain, effective stress or swelling/shrinkage in response to changes in the concentration of inhibitors.**
- **Develop FLAC3D-FISH routines for**
  - **reading the HBS-specific inputs**
  - **reading the TOUGH+/HYDRATE outputs from external files**
  - **creating standardized output files (to be read by TOUGH-Fx/HYDRATE for property update)**

Subtask 1.2

Modification/Extension of TOUGH+/HYDRATE (2/1/06 - 5/30/06)

DELIVERABLE: *Modified/Expanded T+H code, ready to be integrated into the coupled geomechanical model.*

- **Develop T+H routines for**
  - **reading the FLAC3D outputs from external files**
  - **creating standardized output files (to be read by FLAC3D)**
- **Develop T+H routines of models relating changes in the hydraulic properties of the porous medium to changes in stress and strain (inputs provided by the FLAC3D simulation).**
- **Expand T+H routines describing the response of the wettability behavior and thermal properties to changes in the hydraulic properties.**

CHALLENGE: Maintain generic structure of unified core code

Subtask 1.2 (Cont.)

- Modify the current T+H computational processes:
  i. deactivation of the standard treatment of permeability as a region-wide constant
  ii. deactivation of the standard model of porosity as a region-wide variable affected by pore compressibility and expansivity
  iii. replacement of (i) and (ii) by the full models of evolving permeability and porosity as functions of hydraulic, thermal and mechanical changes

- Modify/expand the standard T+H code to handle the *explicit-sequential* and *implicit-sequential* options of parameter updating in the course of the simulation.

- Modify/expand the standard T+H grid handling to account for domain deformation (subsidence and expansion)
  - Option #1: Equation of movement of solid grains
  - Option #2: Deforming grid

Subtask 1.3

Development of the TOUGH-Fx/FLAC3D Synchronization and Interaction Interface (6/15/06 - 7/15/06)

DELIVERABLE: ***Software interface for coupling and synchronizing the T+H and FLAC3D codes.***

- **Rendered UNNECESSARY by using a more advanced code architecture: The entire FLAC3D code is called as a simple C subroutine from within T+H (instead of the initial concept of synchronized execution of two interacting codes)**
  - **Drastically enhanced flexibility**
  - **Significantly simpler code structure, shorter and faster code**
  - **The generic structure of the core TOUGH+ code is maintained**

Subtask 1.4

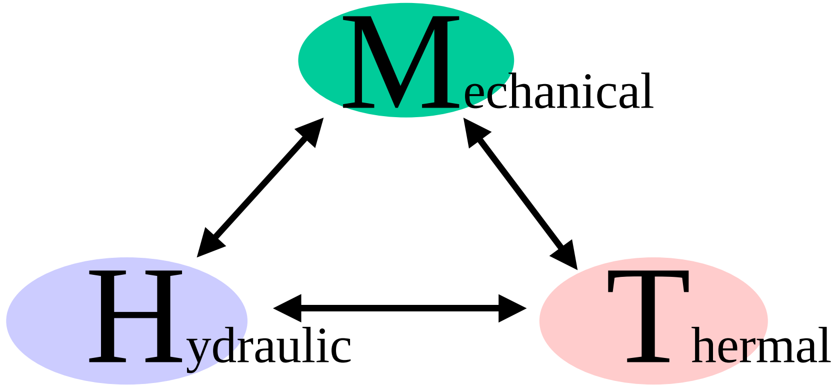
Component Integration and Testing of the Coupled Geomechanical Model T+H/FLAC (7/15/06 - 9/30/06)

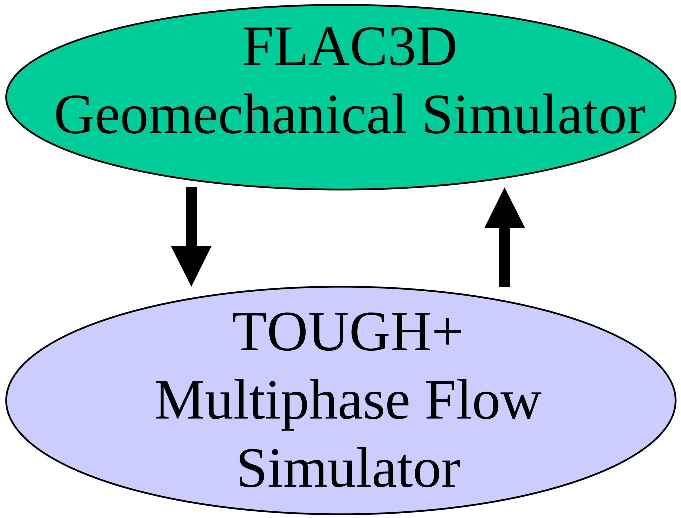
***DELIVERABLE:** The coupled geomechanical model T+H/FLAC, with the corresponding User's Manual.*

- **Integration of the software developed and modified in Subtasks 1.1 to 1.3:**
  - **Seamless interaction of components**
  - **Full access to components for application and further development**
  - **Code testing in a set of synthetic problems**
- **Requirements for code use:**
  - **A commercial FLAC3D license (unrestricted use, derivative product development)**
  - **A license for the modified T+H code**
  - **Knowledge of the T+H and FLAC3D codes**

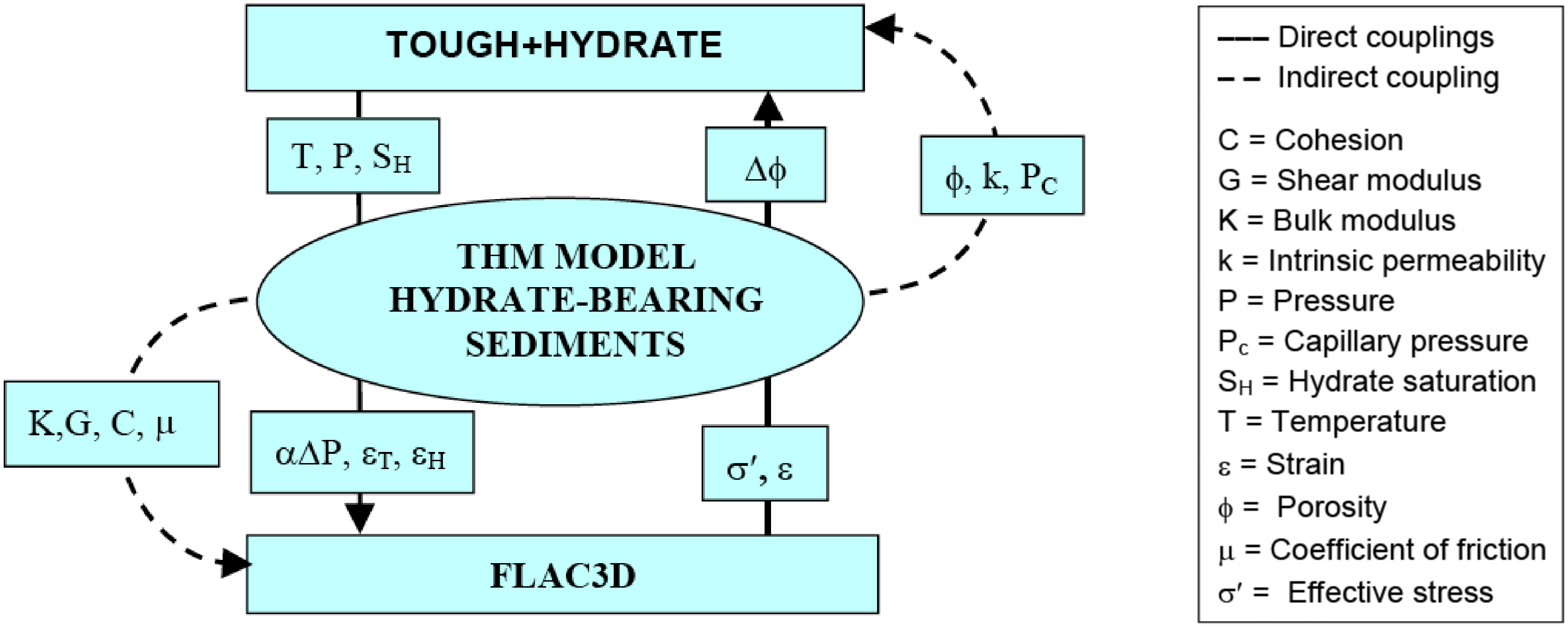
Final Result: The T+H/FLAC Model

Development of the First THM Fully Coupled Numerical Model of its Kind





Coupled THM Numerical Model



The two codes coupled through a **coupled THM model of HBS**:

Direct couplings: Pore volume change, effective stress, thermal strain, and swelling

Indirect couplings: Changes in mechanical and hydraulic properties

Coupled Geomechanical Numerical Model

Coupling Schemes

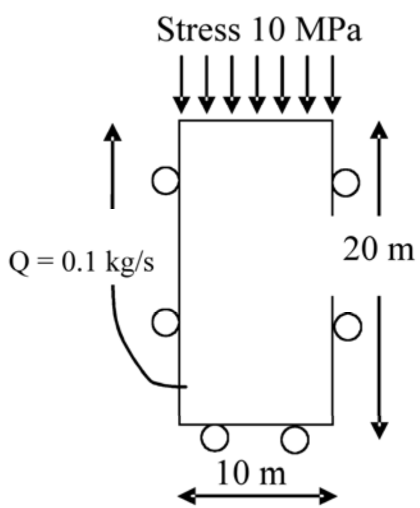
Geomechanical processes are invoked from TOUGH+ using a a desired coupling scheme (a user option):

- **Jacobian**: the highest level of iterative coupling in which geomechanical changes in porosity and permeability is considered in the calculation of the full Jacobian matrix within TOUGH+
- **Iterative**: the porosity and permeability is corrected for geomechanical changes once at the beginning of each iteration, based on the state at the previous iteration.
- **Time-step:** the porosity and permeability is corrected once each time step.

Numerical Test of HBS Mechanical Behavior During Methane Production

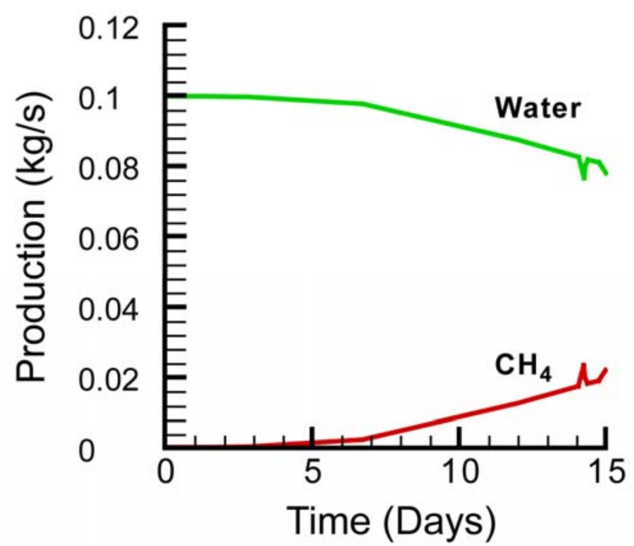
An example

- Pressure, temperature, and stress conditions corespondent to an **oceanic HBS**
- Simulate constant rate production for 15 days
- Horizontal well system



Initial Conditions:

Temperature ≈ 12.5 °C
Pressure ≈ 9.7 MPa
Vertical stress ≈ 10 MPa
Horizontal stress ≈ 10 MPa
Hydrate saturation ≈ 0.5
Water saturation ≈ 0.5

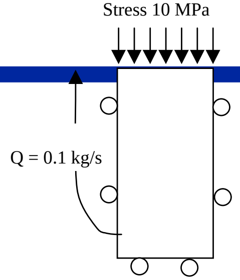


Numerical Test of HBS Mechanical Behavior During Methane Production

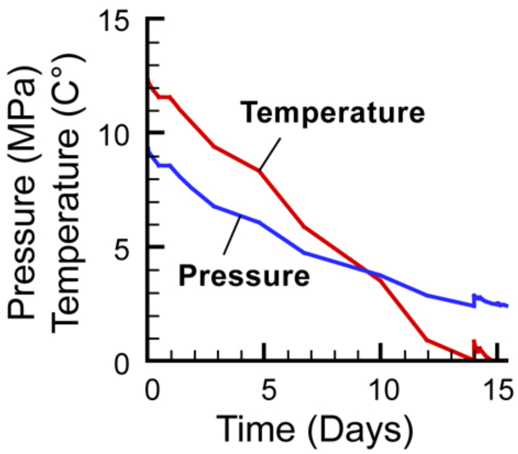
Geomechanical properties

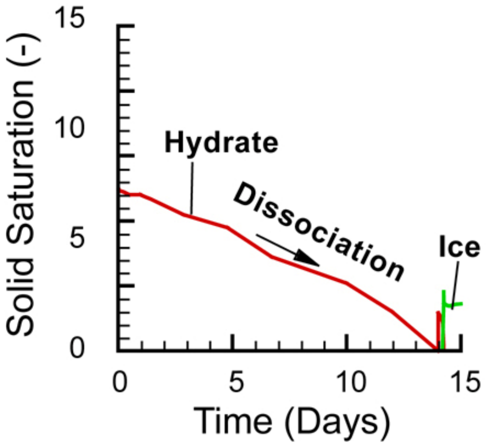
- The geomechanical properties of the HBS were taken from recent laboratory experiments on hydrate bearing Toyoura Sand (Matsui et al., 2005)
- Based on Matsui et al. (2005) as well as other recently published experimental data, the mechanical properties of the sediment were corrected for pore-filling solid content (hydrate and ice)
- At the initial conditions, with a hydrate saturation of about 50%, the initial bulk and shear modula were 375 and 343 MPa, respectively
- For a Mohr-Coulomb constitutive failure model, the hydrate dependent cohesion was initially 1.13 MPa

Numerical Test of HBS Mechanical Behavior During Methane Production



Simulation output





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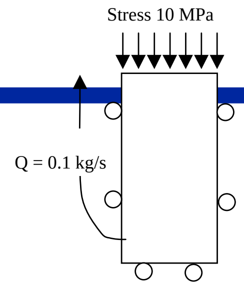

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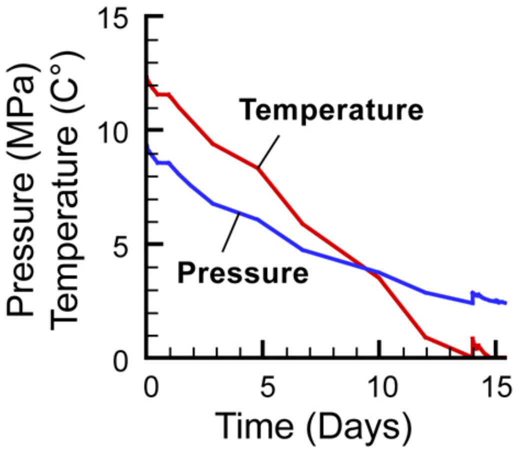

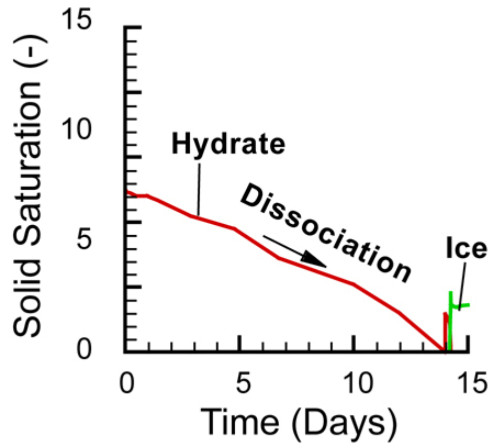

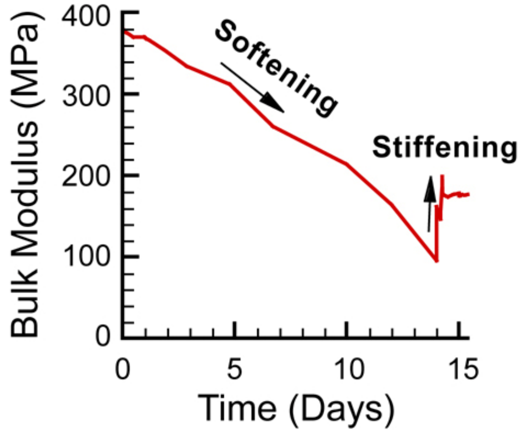

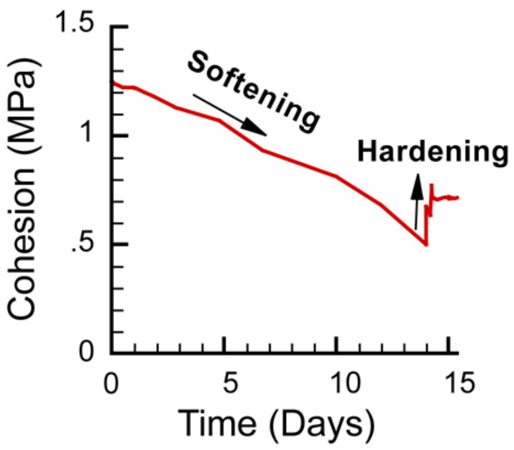

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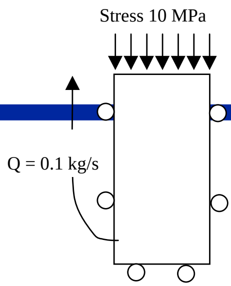
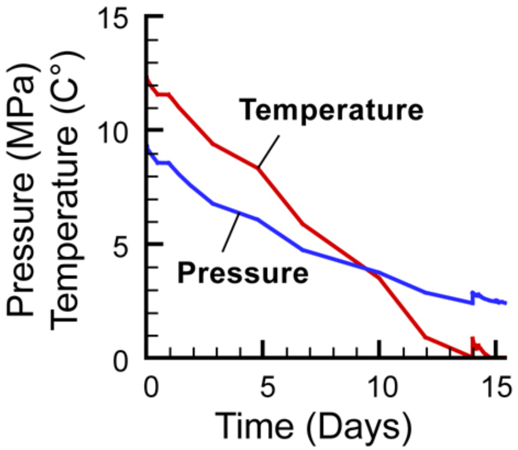
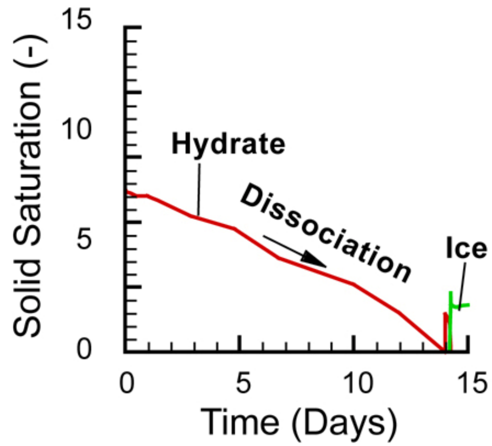
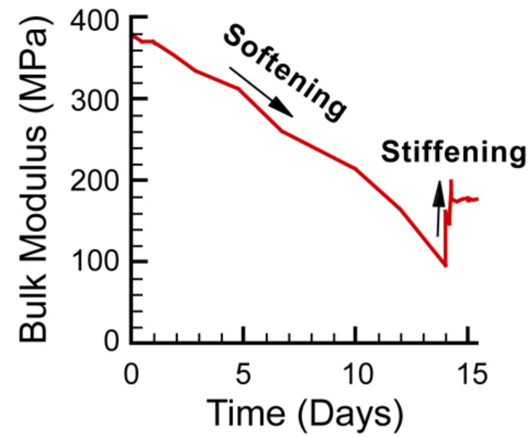
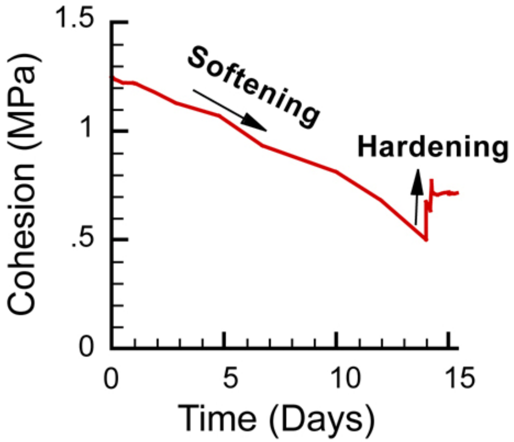


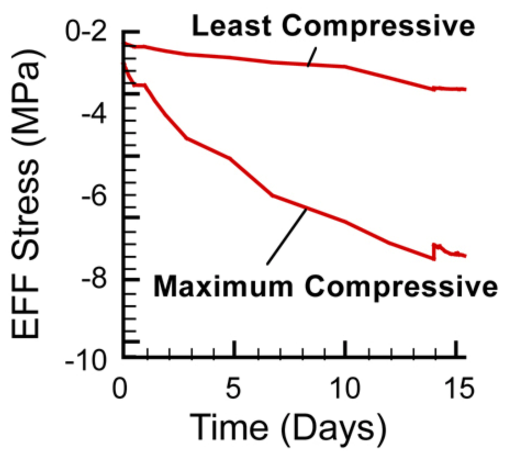
Simulation output

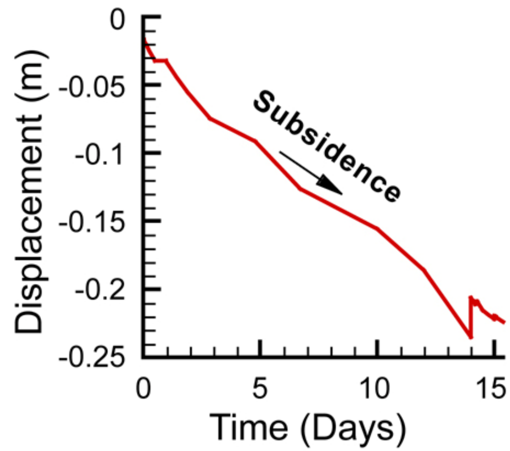












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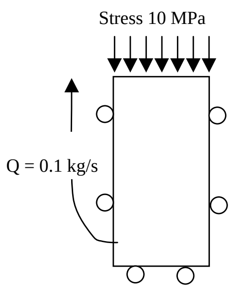
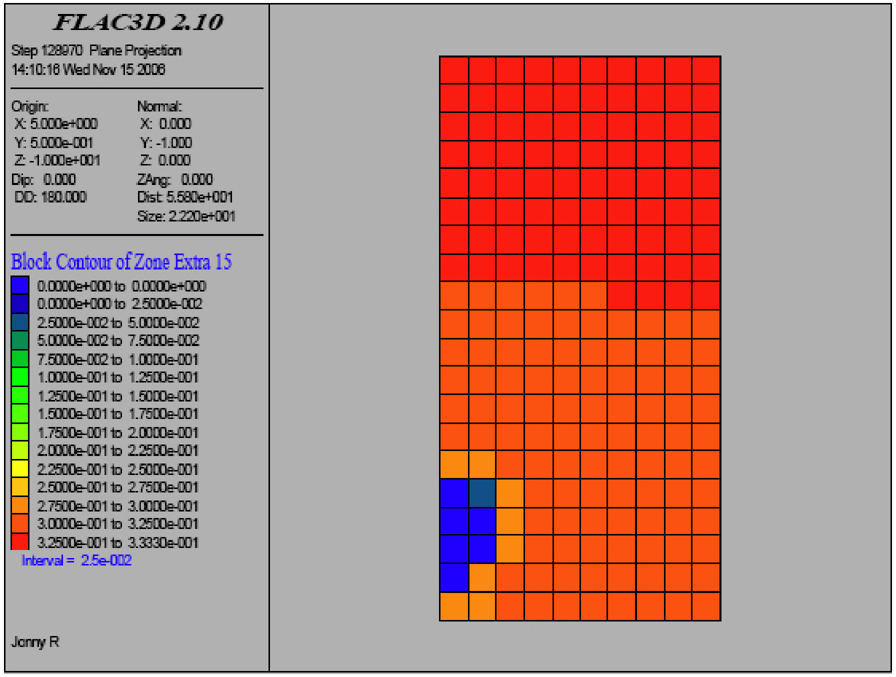
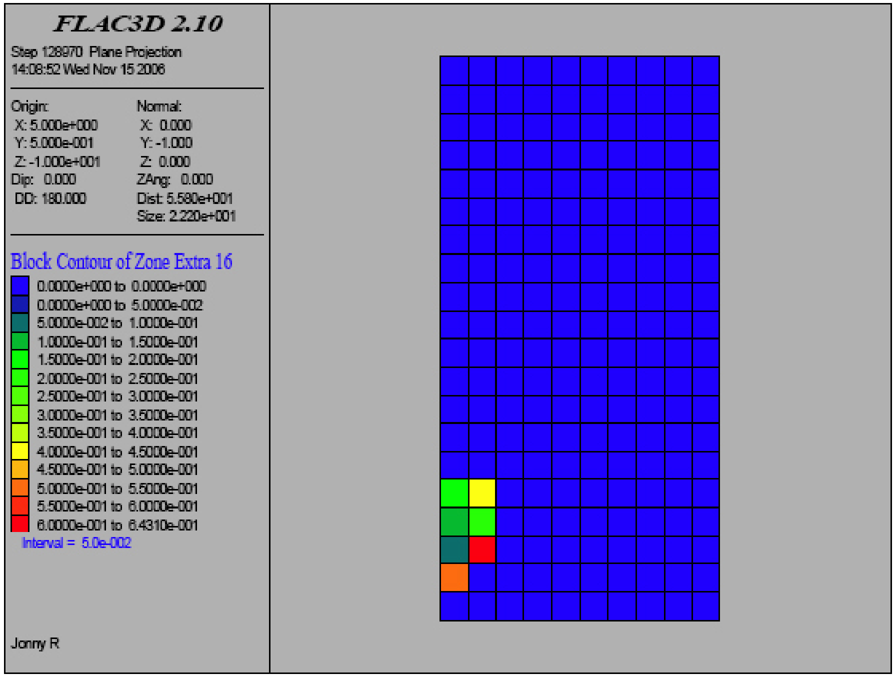


Interactive Simulation Output

Hydrate Saturation

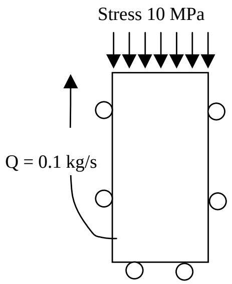


Ice Saturation



Contours after 15 days of production

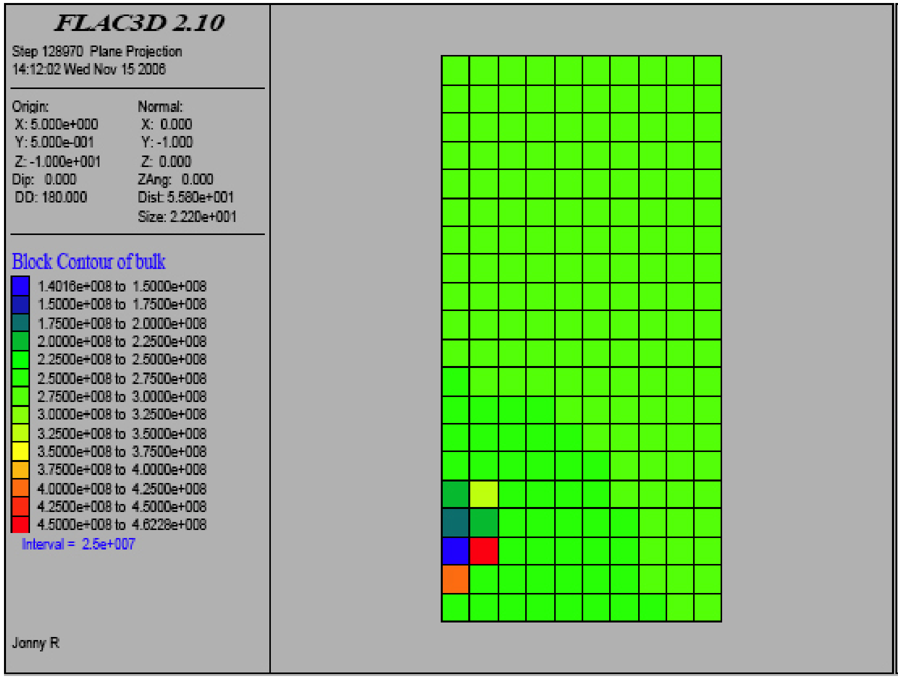
Numerical Test of HBS Mechanical Behavior During Methane Production

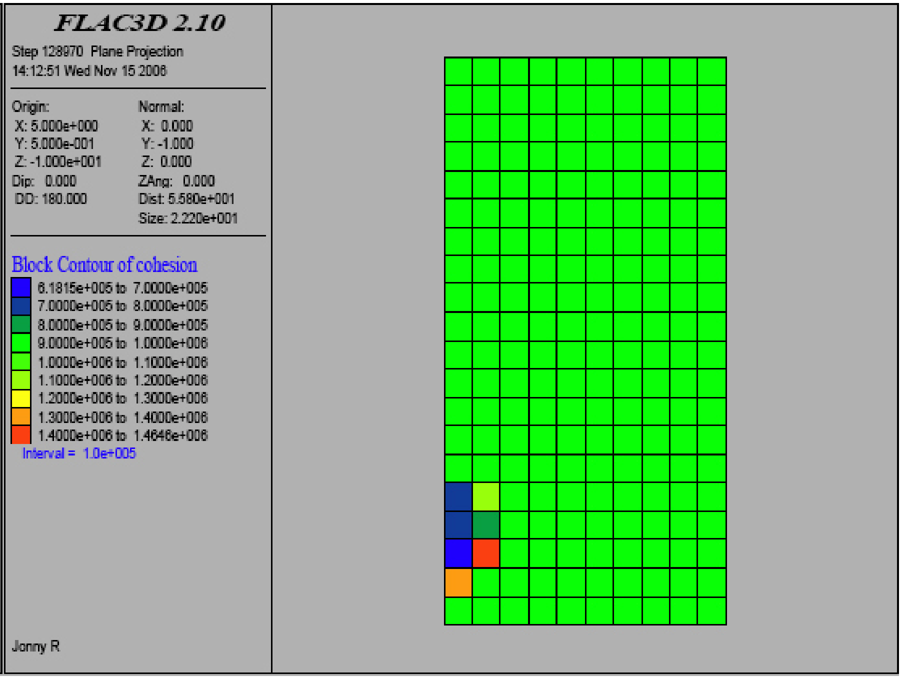


Interactive Simulation Output

Bulk Modulus

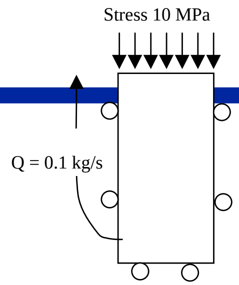
Shear Strength (cohesion)





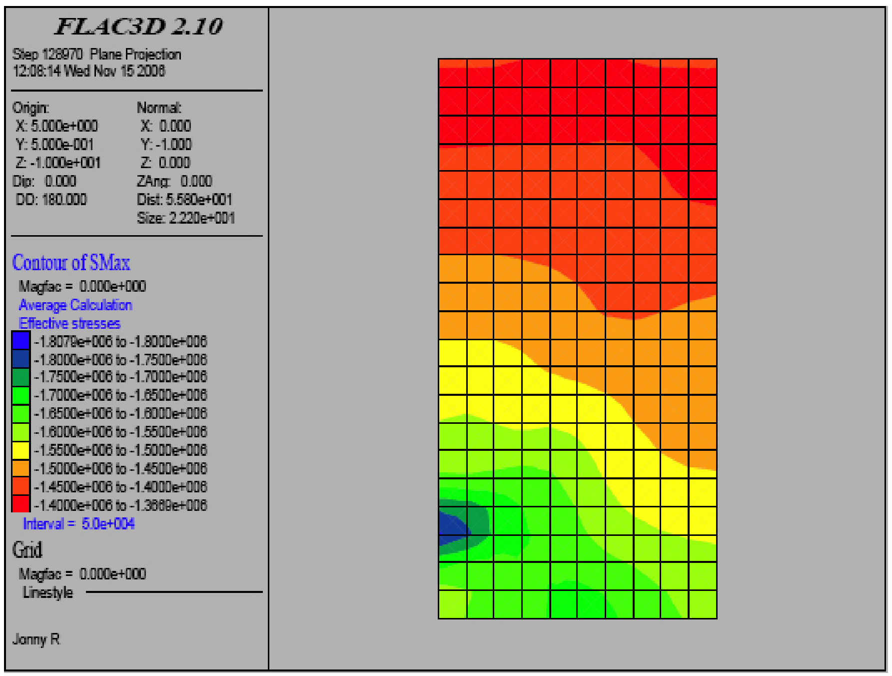
Contours after 15 days of production

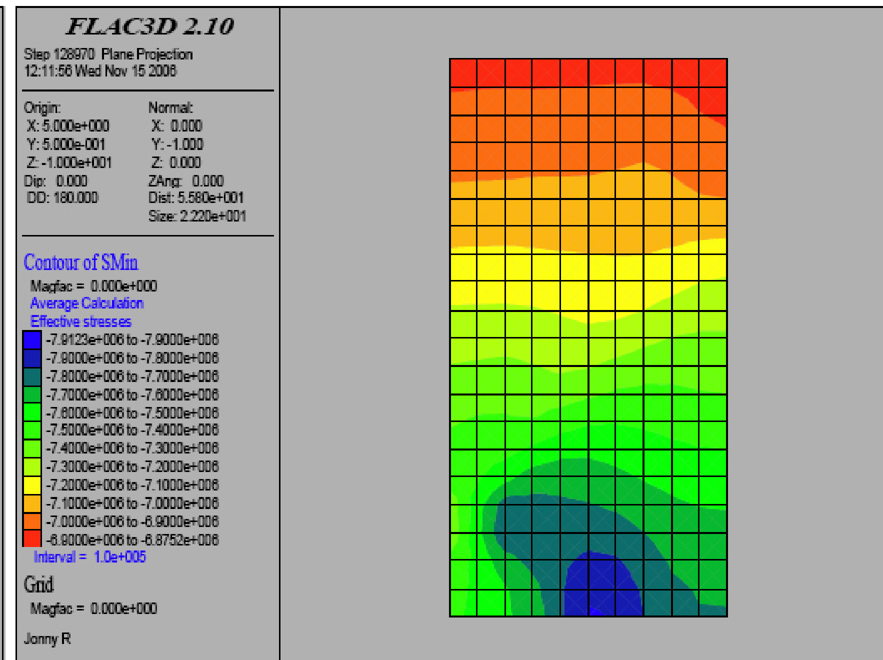
Numerical Test of HBS Mechanical Behavior During Methane Production



Interactive Simulation Output

Minimum Compressive Stress **Maximum Compressive Stress**

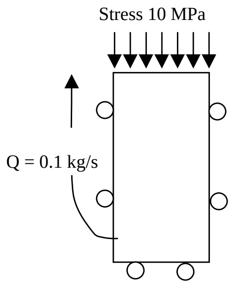




(Negative values indicate compressive stress)

Contours after 15 days of production

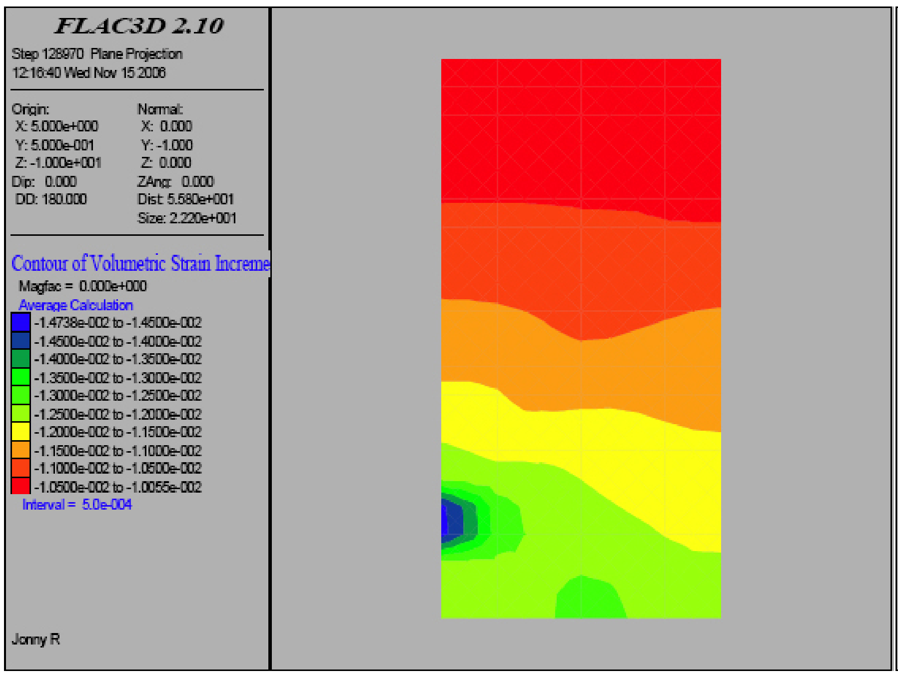
Numerical Test of HBS Mechanical Behavior During Methane Production

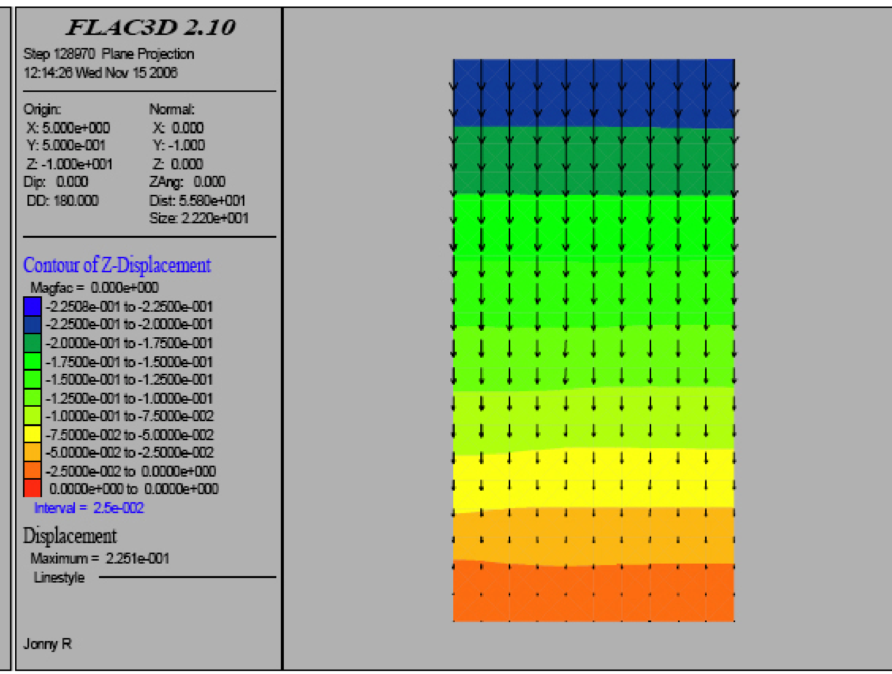


Interactive Simulation Output

Volumetric Strain

Displacements





Contours after 15 days of production

Status and Current Activities in T+H/FLAC Studies

- The couple simulator is fully operational and its capabilities have been demonstrated in a raft of synthetic problems
- Currently being applied to the description of several practical problem related to geomechanical behavior of oceanic HBS
- Three papers (two invited - 2007 OTC and SPE) describing the code and its applications to the analysis of the geomechanical behavior of HBS are in preparation:
  - Hydrate dissociation in the vicinity of the ocean floor by hot fluids rising through uninsulated pipes: Strong geomechanical changes, severe subsidence, possibility of formation fracturing, wellbore collapse and structural instability)
  - Hydrate dissociation in a deeper formation in the process of gas production: Mild geomechanical changes, no significant subsidence or loss of structural integrity
  - Effect of mechanical stress loading on hydrates caused by the anchoring of structures on the ocean bottom: No dissociation, increase in stability and structural strength (unlike ice)
  - Geomechanical processes and effects at the hydrate basal zone: analysis of conditions leading to possible oceanic hill slope landslide

Example: Response of a complex HBS system under thermal stresses

❑ SYSTEM DESCRIPTION

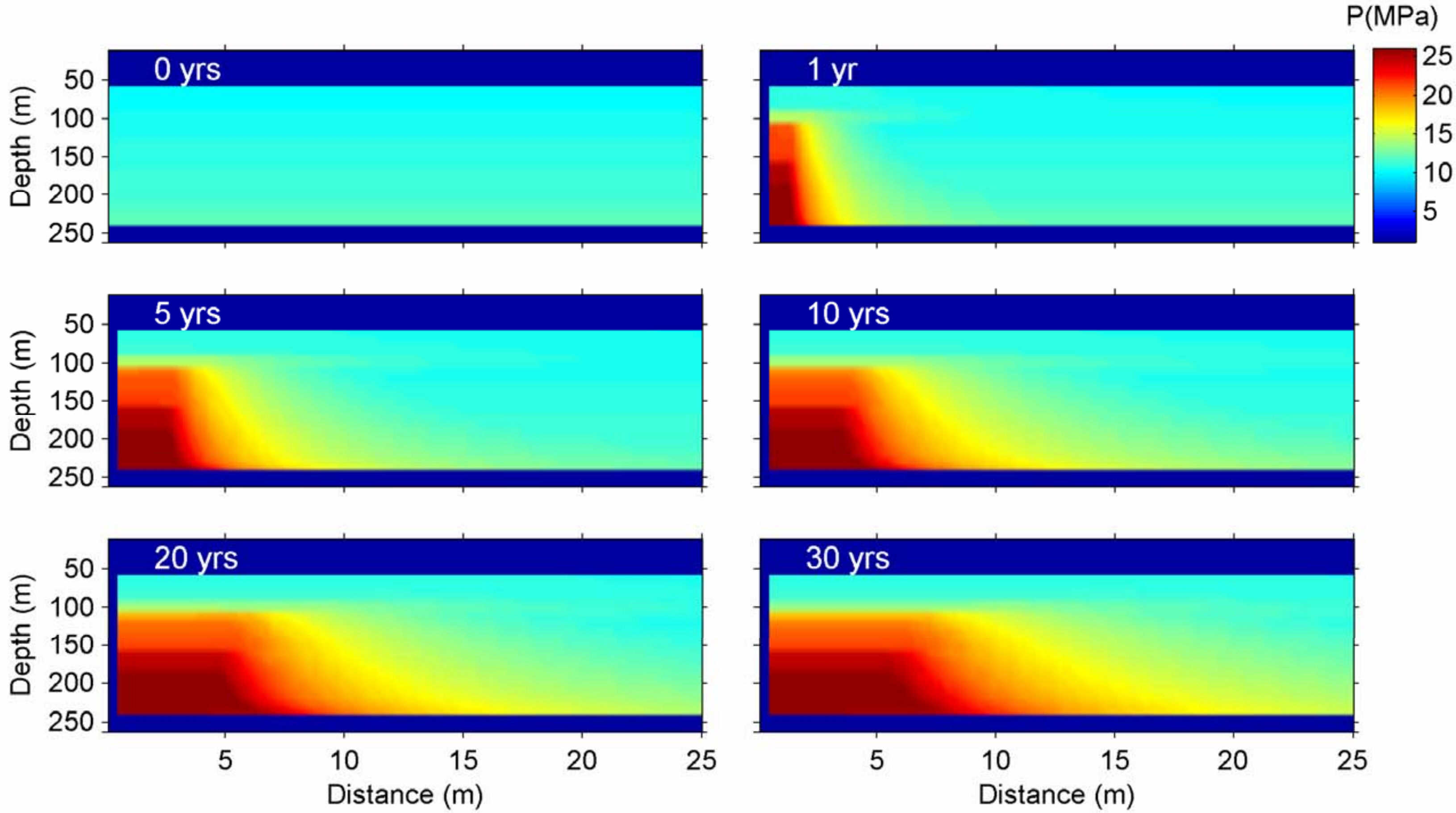
- Actual marine system
- Complex geology, involving 5 HBS layers of different properties and conditions, confined by impermeable shales
- Heating by warm reservoir fluids rising to the surface through vertical well(s)

❑ CONCERNS

- Structural stability/integrity of the well assembly - well design and well separation
- Possible fracturing of HBSs and of shale overburden and underburden
- Shale swelling by water released from hydrate dissociation

OTC-18193 (2006); OTC-18866 (2007)

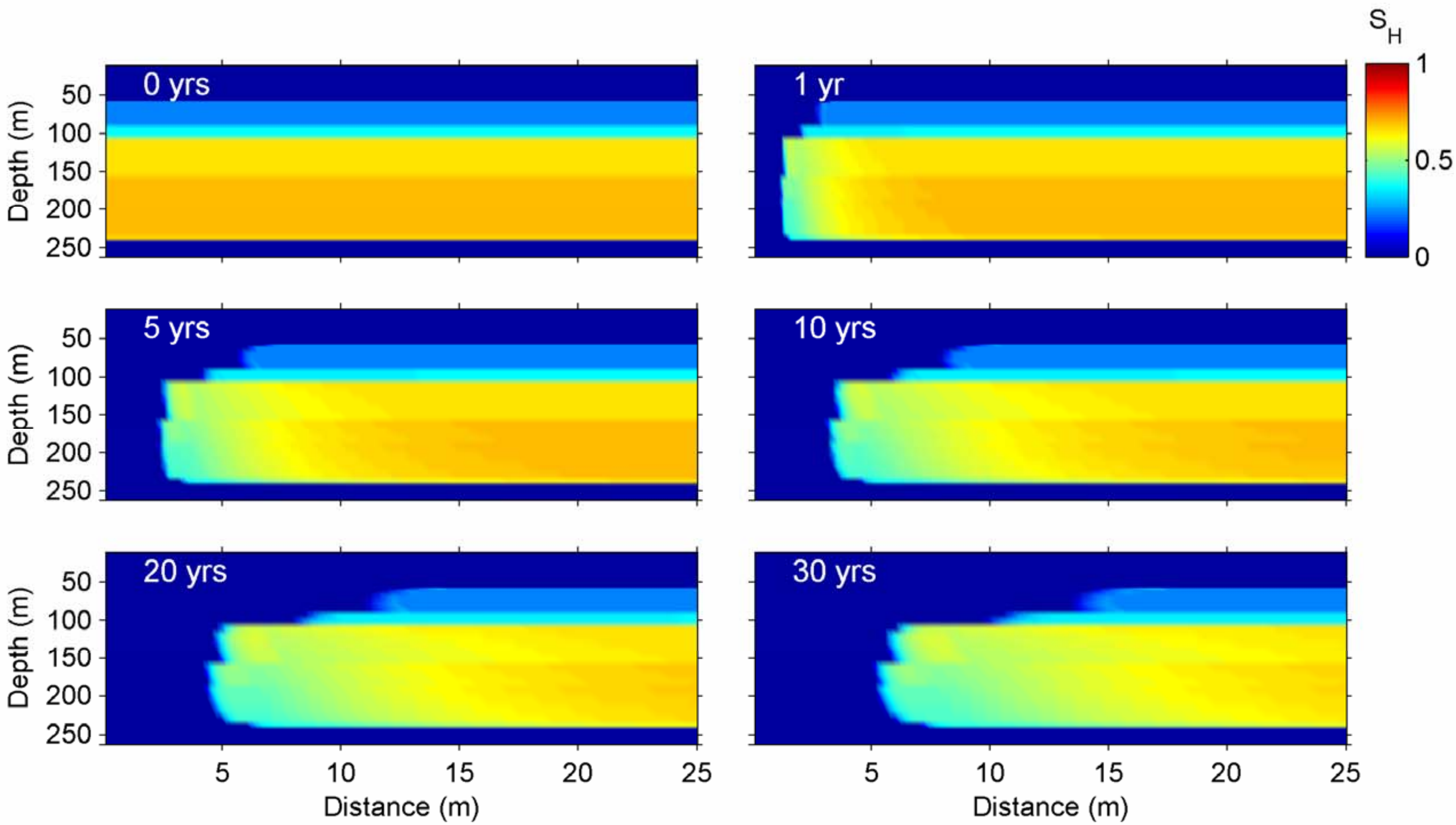
Example: Response of a complex HBS system under thermal stresses



Pressure Distribution

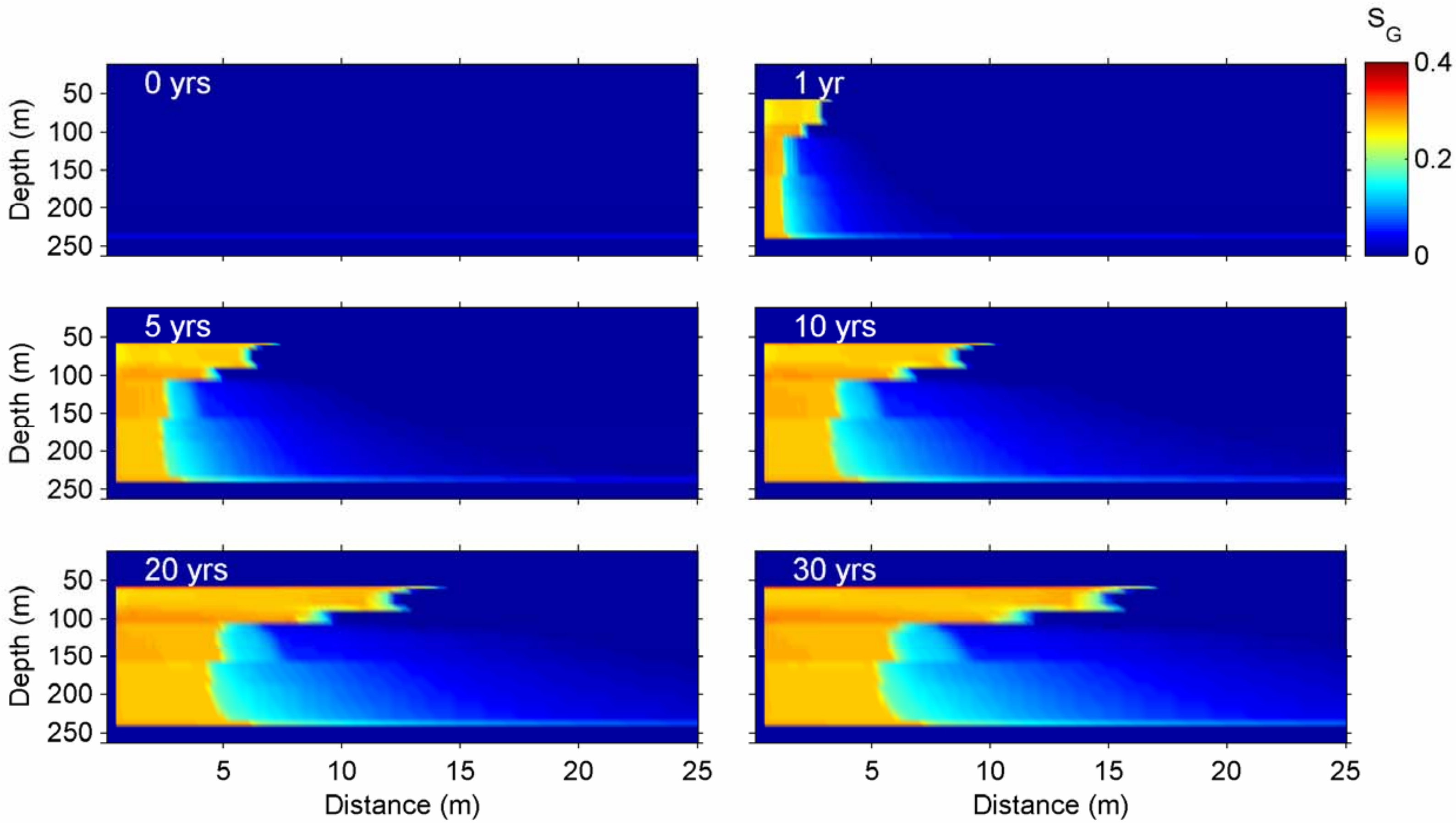
25,000 elements

Example: Response of a complex HBS system under thermal stresses



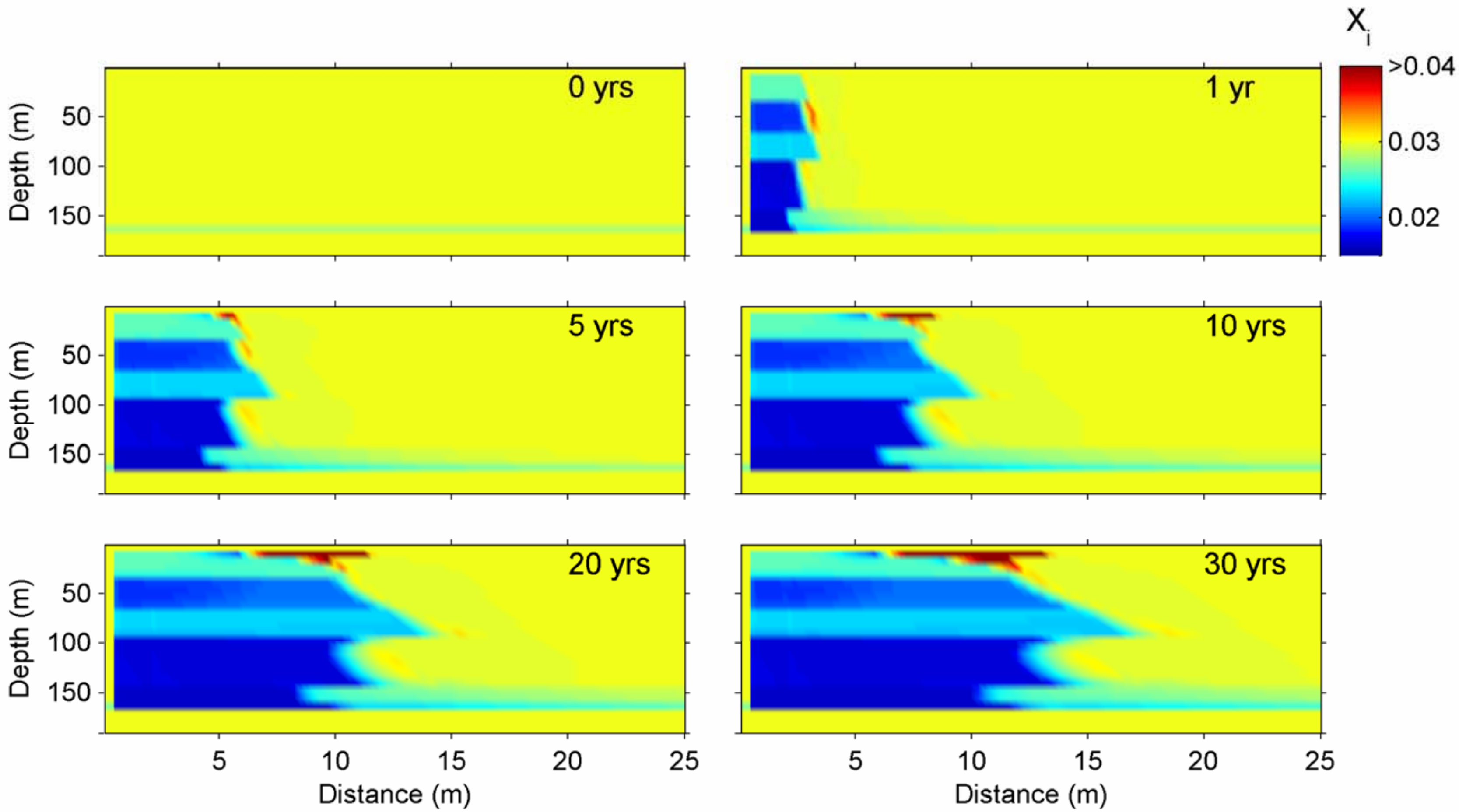
Hydrate Saturation Distribution

Example: Response of a complex HBS system under thermal stresses



Gas Saturation Distribution

Example: Response of a complex HBS system under thermal stresses



Salinity Distribution: Implications and complications

Challenges and Future Activities in T+H/FLAC Studies

- **The coupled code is slow because of**
  - **Fundamental physical and mathematical reasons**
    - Interrelated and strongly coupled physical processes
    - Steep solution fronts that persist over time (solutions do not become diffusive over time, may actually become more difficult)
    - Short-term phenomena and processes that cannot be bypassed
    - Evolving heterogeneity
  - **Large computational requirements**
    - Continuous property updating
    - Complexity and large demands during the iterative solution of the geomechanical equations
    - Large number of time steps
  - **Computational limitations**
    - Interaction between T+H and FLAC3D occurs through external files: an extremely slow process

Challenges and Future Activities in T+H/FLAC Studies

- **Need to accelerate solutions**
  - Direct access to FLAC3D memory (discussions with ITASCA)
  - Test FLAC3D (v3.1), with built-in parallel processing
  - Parallel version of TOUGH+/HYDRATE
- **Incorporation of additional geomechanical options**
  - Fundamental models
  - Empirical models
- **Availability of appropriate parameter values**
  - To be provided from laboratory studies
  - Relevance of model hinges on the availability and validity of such parameters

LBNL: PROJECT TIMELINE AND ACTIVITIES

- **FY2006:** Exclusive focus on development of coupled geomechanical model
  - Fundamental knowledge gaps will persist
  - "Placeholders" for geomechanical process description and corresponding parameters
  - Use of assumptions, extrapolations and approximations
- **FY2007:** Focus on laboratory studies
  - Develop fundamental geomechanical relationships
  - Estimate important parameters
  - Corresponding code updating - incorporation of fundamental information developed from lab studies and by other project participants (or any other source)
- **FY2008:** Focus on providing support/coordination to team users
  - Limited level of effort
  - Minor code updating

FY2007 Laboratory Studies

- **Task 1:** Determination of HBS Geomechanical Properties
  - Synthetic samples, possibly natural samples
  - Tri-axial compression tests (Mohr-Coulomb failure envelope)
  - Variable conditions, concurrent CT scanning
- **Task 2:** Determination of the Geophysical Signature of HBS Undergoing Thermo-mechanical Changes
  - Seismic/acoustic system behavior
  - Signature to track dissociation, identify regions of weakness

FY2007 Laboratory Studies

QuickTime™ and a
Graphics decompressor
are needed to see this picture.

New short-core resonant bar apparatus at LBNL. For isotropic rocks and sediments, their compressional and shear wave velocities and attenuation (or complex Young's modulus and shear modulus) can be determined at frequencies near one kilohertz.