Oil & Natural Gas Technology

DOE Award No.: DE-FE0009897

Quarterly Research Performance Progress Report (Period ending 12/31/2015)

Hydrate-Bearing Clayey Sediments: Morphology, Physical Properties, Production and Engineering/Geological Implications

Project Period (10/1/2012 to 9/30/2016)

Submitted by:
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Office of Fossil Energy

DISCLAIMER:

ACCOMPLISHMENTS

Context – Goals. *Fine grained sediments host more than 90% of the global gas hydrate accumulations. Yet, hydrate formation in clayey sediments is least understood and characterized. This research focuses on* <u>*hydrate bearing clayey sediments*</u>*. The goals of this research are (1) to gain a fundamental understanding of hydrate formation and ensuing morphology, (2) to develop laboratory techniques to emulate "natural" formations, (3) to assess and develop analytical tools to predict physical properties, (4) to evaluate engineering and geological implications, and (5) to advance gas production alternatives to recover methane from these sediments.*

Accomplished

The main accomplishments for this period include:

- Formation of gas hydrate in fine-grained sediments
  - Hydrate formation in sediments after long-time pressurization
  - Time-lapse monitoring hydrate formation with X-ray projection
- Topology of gas hydrate in fine-grained sediments
- Physical properties through numerical experiments
  - Thermal conduction
  - Hydraulic conduction
  - Stiffness and strain field
- Effect of heterogeneity on small-strain stiffness
- Gas migration in soft sediments
  - Experimental setup and preliminary results

Plan - Next reporting period

1. Advance understanding of crystal-sediment interaction.
2. Advance numerical experiments to predict properties.
3. Extend study of gas migration

RESEARCH IN PROGRESS

Slurry: Hydrate formation by cooling specimen after long-term pressurization

Two tests are conducted within this formation process. First, a bentonite slurry prepared at a water content of 2000% was pressurized for 20 days before the temperature was lowered into hydrate stability field. The first X-ray image in Figure 1 shows that hydrate formed above the sediment, extracted water from it, and eventually invaded the sediment. Additional images show the evolution during heating and dissociation (including gas bubble entrapment in the slurry).

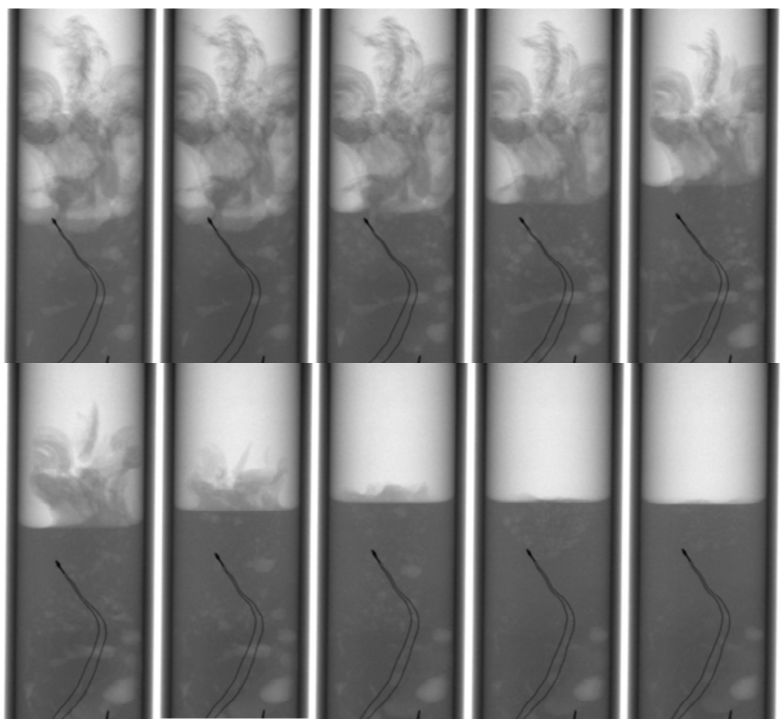

Figure 1: Soft bentonite slurry. The first image captures the end of hydrate formation. Other images show time-lapse for dissociation during heating

The second test involves a denser bentonite specimen prepared at water content of 300%. It is pressurized for 10 days, then cooling is imposed by circulating cooling fluid through a tube wrapped around the high pressure chamber. The evolution of the process is monitored using with X-ray projections (rather than tomography). Figure 2 shows hydrate formation using X-ray images. Once again, formation projects above the sediment and eventually invades the medium. Notice the structure and high porosity in fresh hydrate. Figure 3 captures the evolution sediment during dissociation and remnant gas filled fractures.

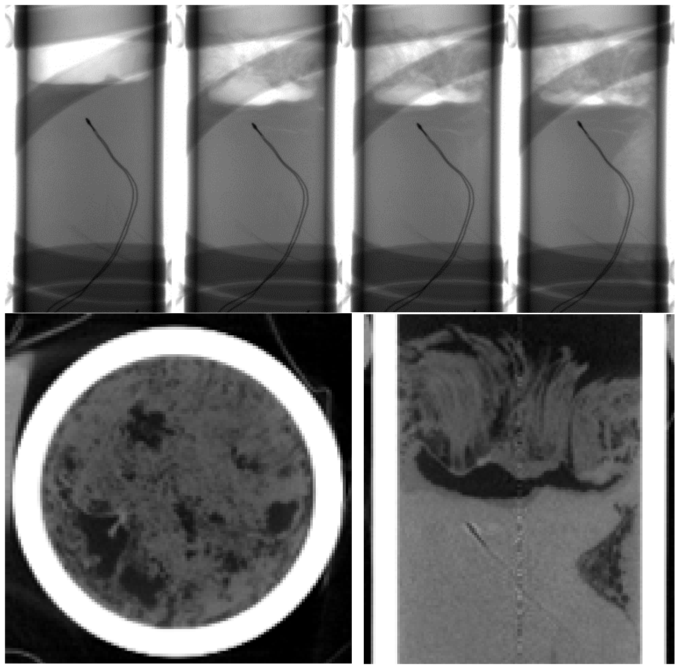

Figure 2: Dense paste - Hydrate formation

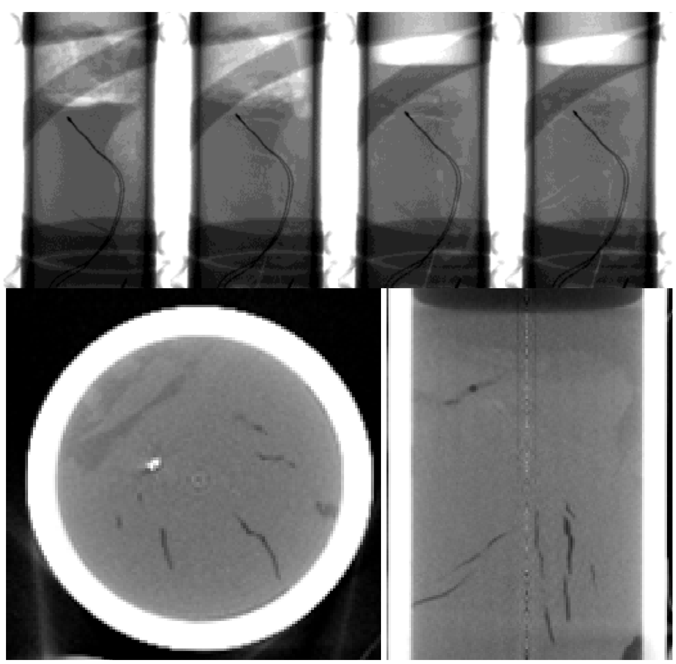

Figure 3: Dense paste - Hydrate dissociation process and specimen 3D structure

Gas Migration in Soft Sediments—Experimental Setup

A complementary experiment was designed to study gas migration in soft sediments, in view of both hydrate formation as well as gas production. The experiment used transparent soil: a Mohr-Coulomb particulate medium where fumed silica is mixed with mineral oil to render it transparent (Figure 4-a). The square chamber is place within a specially designed frame with a pneumatic cylinder to consolidate/compact the sediment to any desired stress state. Gas is injected from the bottom through a unique injection needle designed to prevent clogging. The injection pressure is recorded using a high resolution pressure transducer. Two cameras record in time-lapse mode the evolution of gas invasion (Figure 4-b).

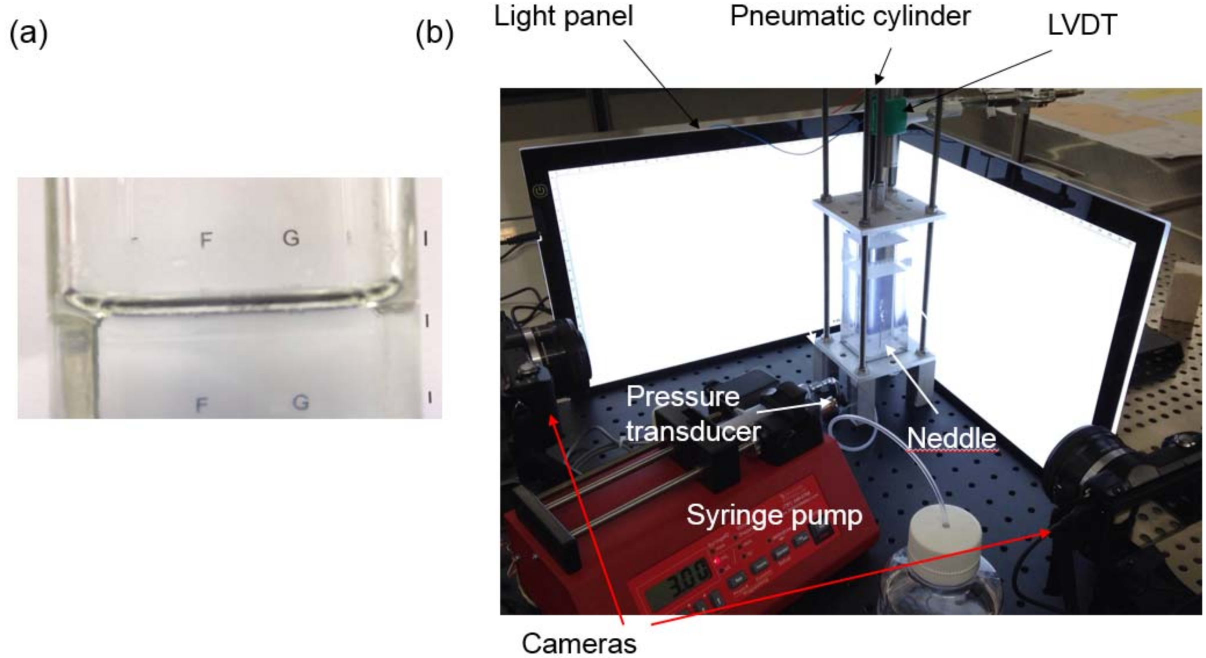

Figure 4. Transparent soil and experimental setup.

Results

Tests have been conducted at different states of stress. Figure 5 shows the geometry of gas inclusions in soils subjected to different effective stress levels 0.2 kPa and 4 kPa. Gas invades in two different patterns: gas finger/chimney at low effective stress and gas fracture or open-mode discontinuity at high effective stress.

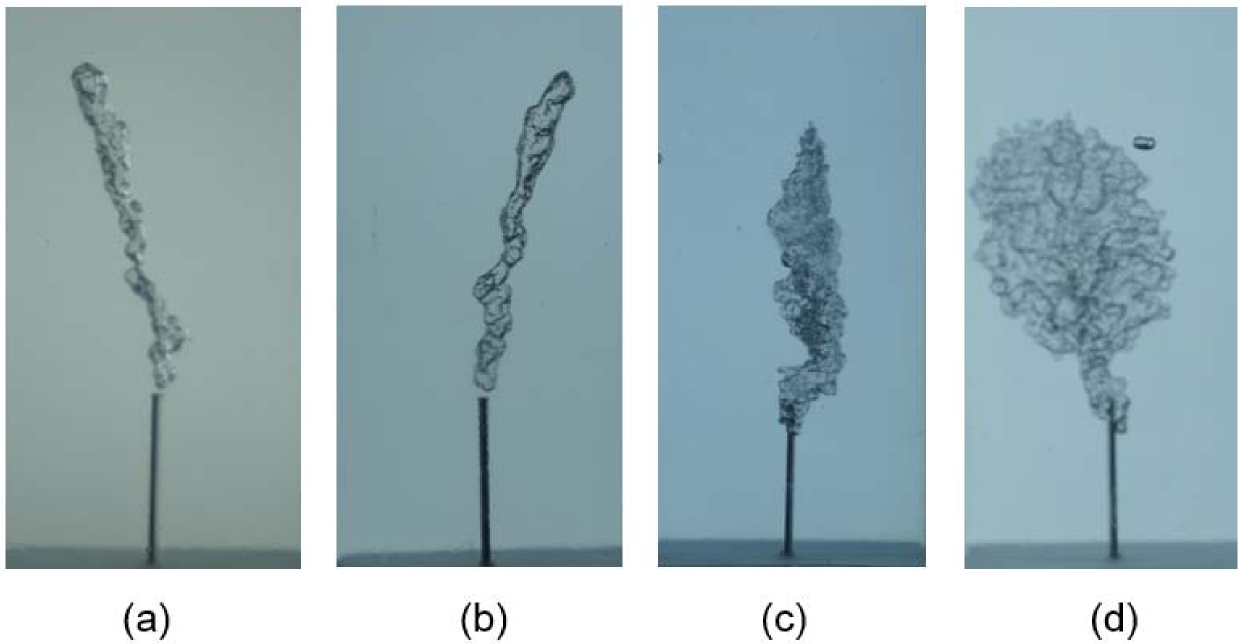

Figure 5. Invasion patterns: (a&b) front and side views of gas inclusion in a sediment subjected to 0.2 kPa, and (c&d) for a sediment consolidated to ~4kPa.

Figure 6 shows the pressure signature during gas injection at constant injection rate. One can identify the initial opening pressure, and successive formations/ruptures.

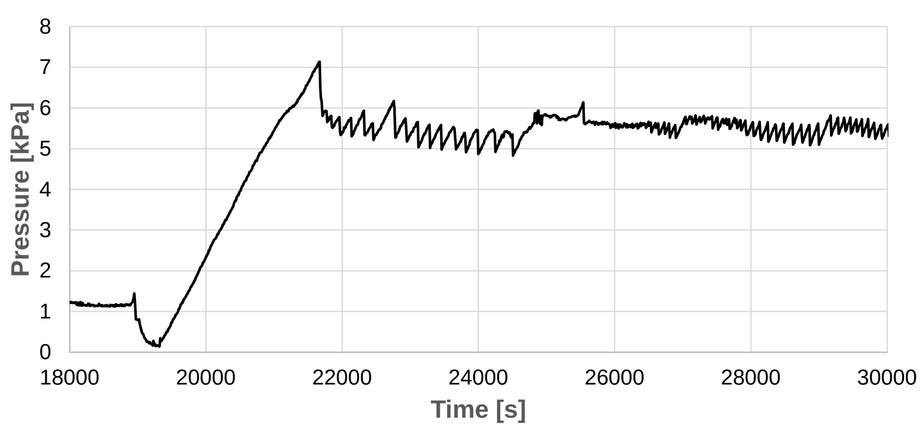

Figure 6. Gas pressure profile during gas injection into the sediment subjected to 4 kPa vertical effective stress (constant injection rate).

The impact of heterogeneity on small-strain stiffness

Hydrate in fine-grained sediments tends to manifest in pervasive lenses, which cause heterogeneity and anisotropy and affects all physical properties. One of our high pressure aluminum effective-stress cells were modified to include P- and S-wave velocity measurements concurrent with 3D X-ray images at various load conditions to observe the lens structure (Figure 7). Preliminary results using ice as an analogue show that sediments with the same amount of ice but different ice distribution can exhibit 2-3 times different velocities upon freezing (Note: this corresponds to 4-9 times difference in sediment stiffness). Future experiments will be extended to determine P- and S-wave velocities in THF hydrate-bearing clays under various stress conditions with concurrent 3D X-ray CT images of hydrate morphology.

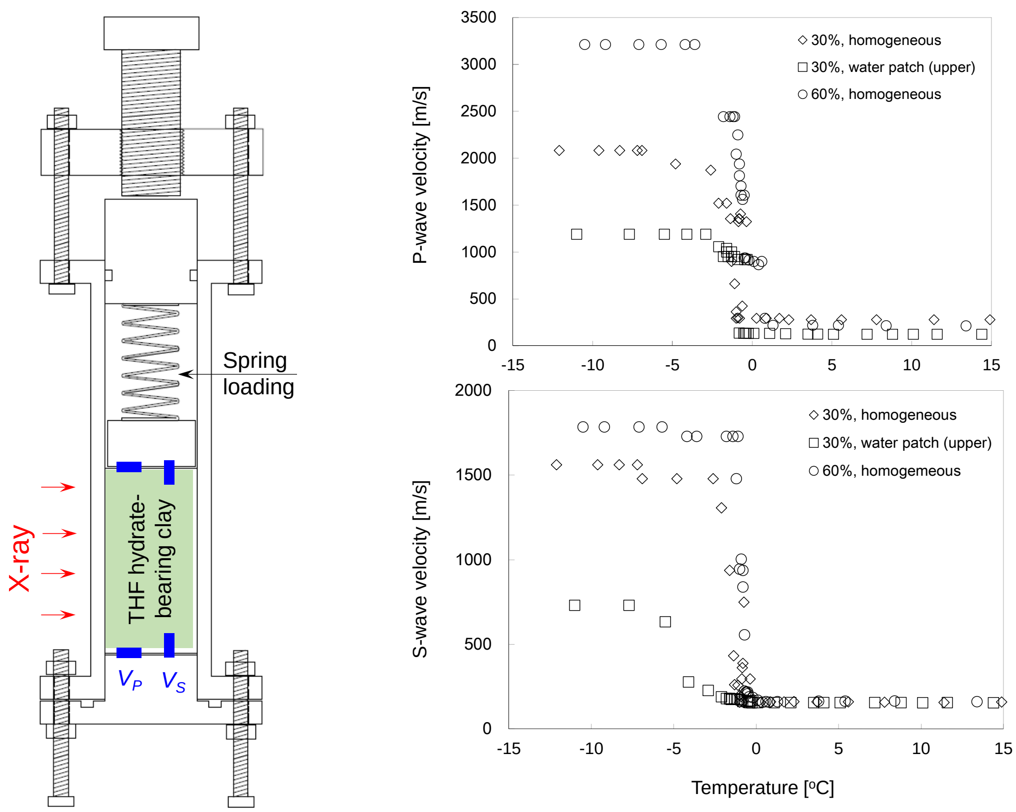

Figure 7: Impacts of hydrate morphology on small-strain stiffness of hydrate bearing sediments. The left figure shows the configuration of the high pressure aluminum device and the right two plots shows measured P- and S-wave velocities of partially water saturated soils upon freezing.

Physical properties: Numerical Experiments

Numerical experiments consist of a hydrate lens (think and thick) within a hydrate free sediment. Studies explore hydraulic conduction, thermal conduction and mechanical response. Figure 8 shows simulations ran, for two different lens geometry

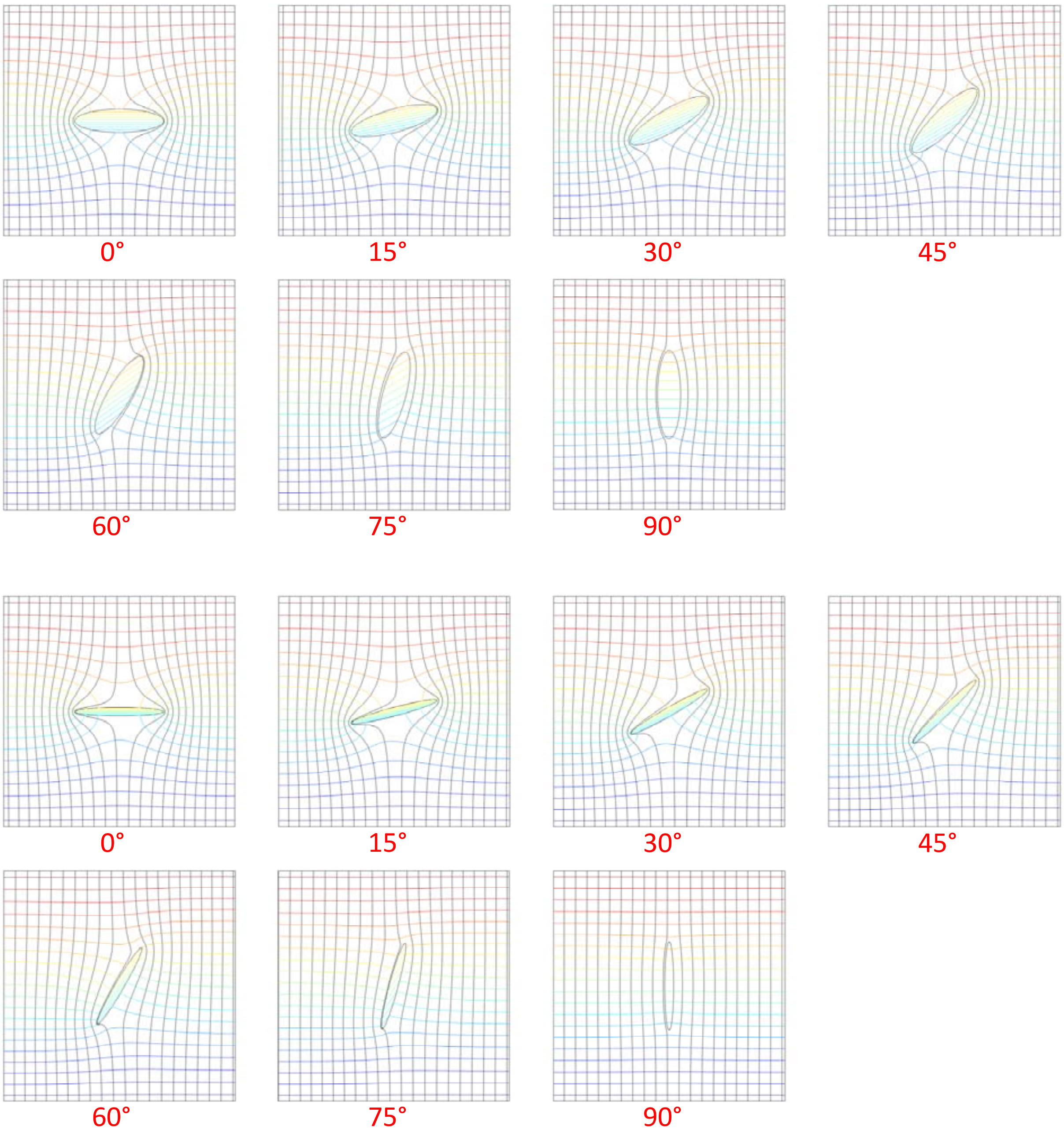

Figure 8: Hydraulic conduction - Flow lines in the presence of hydrate lenses

Figure 9 summarizes simulation results. Additional results are shown in Figure 10 and 11 for a parallel study for heat flow.

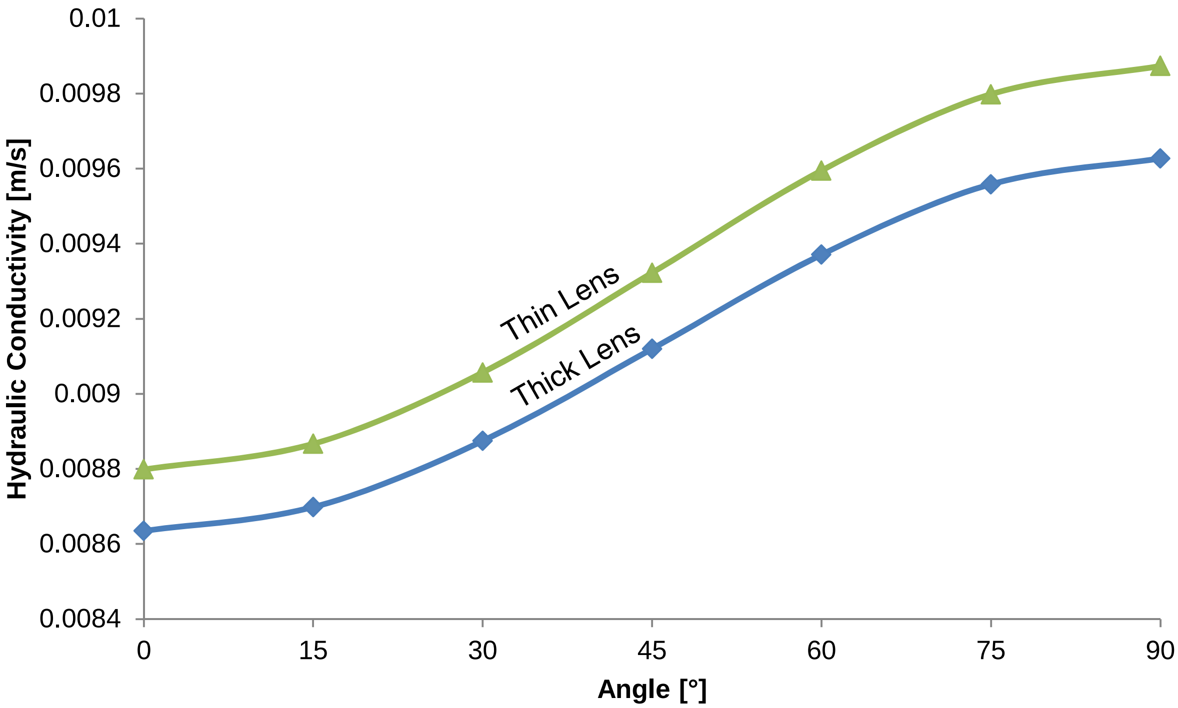

Figure 9: The effective hydraulic conductivity determined using numerical experiments as a function of inclination angle

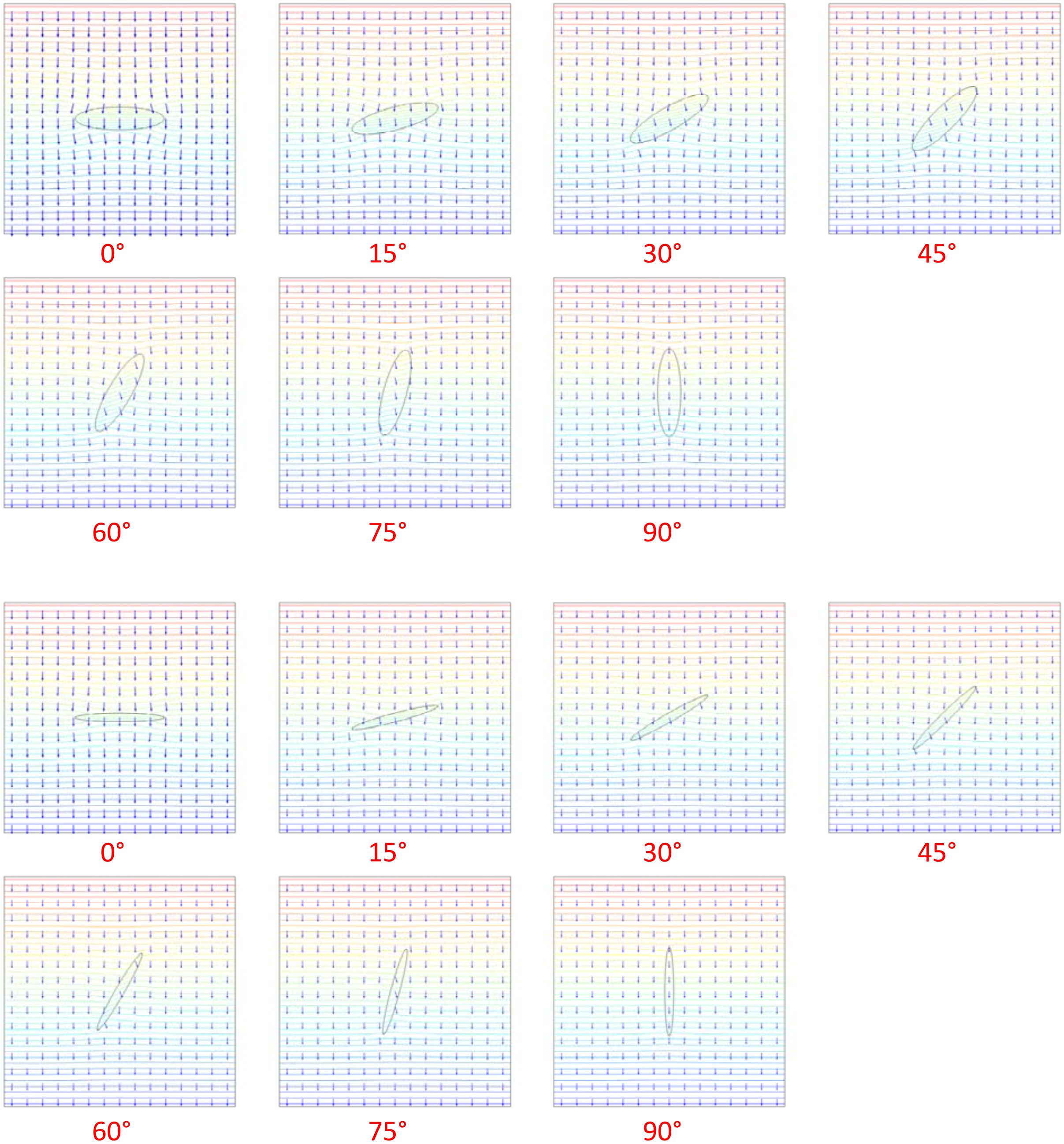

Figure 10: Thermal flow net with hydrate lens inclusion

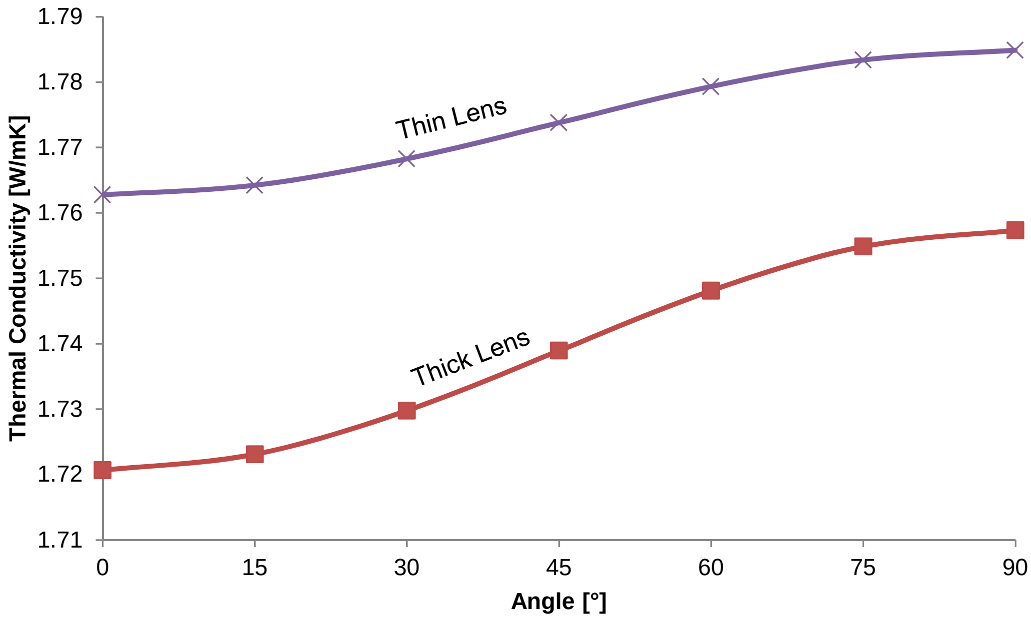

Figure 11: The effective medium hydraulic conductivity calculated versus inclination angle

Finally, Figure 12 shows the effect of the presence of the less on the stress field and the ensuing stress concentration due to the stiff lens inclusion.

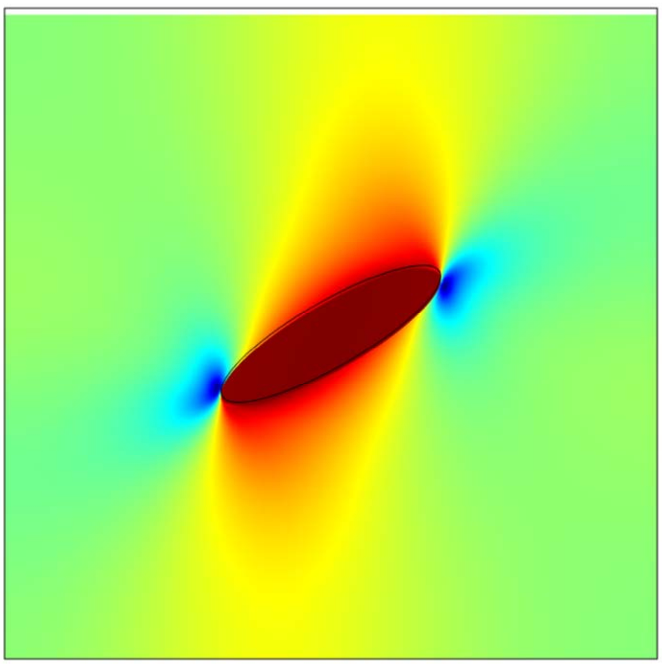

Figure 12: Stress distribution within a sediment specimen with a hydrate lens inside

MILESTONE LOG

Milestone	Planed completion date	Actual completion date	Verification method	Comments
Literature review	5/2013	5/2013	Report	
Preliminary laboratory proto-col	8/2013	8/2013	Report (with preliminary val-idation data)	
Cells for Micro-CT	8/2013	8/2013	Report (with first images)	
Compilation of CT images: segregated hydrate in clayey sediments	8/2014	8/2014	Report (with images)	
Preliminary experimental studies on gas production	12/2014	12/2014	Report (with images)	
Analytical/numerical study of 2-media physical properties	5/2015	5/2015	Report (with analytical and numerical data)	Additional studies in progress
Experimental studies on gas production	12/2015	12/2015	Report (with data)	Additional studies in progress
Early numerical results related to gas production	5/2016	In progress	Report	
Comprehensive results (in-cludes Implications)	9/2016	In progress	Comprehensive Report	

PRODUCTS

- **Publications & Presentations:**

  In progress

- **Website:** Publications and key presentations are included in http://pmrl.ce.gatech.edu/ (for academic purposes only)
- **Technologies or techniques:** X-ray tomographer and X-ray transparent pressure vessel
- **Inventions, patent applications, and/or licenses:** None at this point.
- **Other products:** None at this point.

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

Research Team: The current team involves:

- Liang Lei (PhD student)
- Zhonghao Sun (PhD student)
- Sheng Dai (Assistant Professor)
- Carlos Santamarina (Professor)

IMPACT

Understanding of fine grained hydrate-bearing sediments.

CHANGES/PROBLEMS:

None at this point.

SPECIAL REPORTING REQUIREMENTS:

We are progressing towards all goals for this project.

BUDGETARY INFORMATION:

As of the end of this research period, expenditures are summarized in the following table.

Note: in our academic cycle, higher expenditures typically take place during the summer quarter.

Baseline Reporting Quarter DE-FE009897	Budget Period 3						Budget Period 4			
	Q2		Q3		Q4		Q1		Q2	
	1/1/15 - 3/31/15		4/1/15 - 6/30/15		7/1/15 - 9/30/15		10/1/15 - 12/31/15		1/1/16 - 3/31/16	
	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total	Q1	Cumulative Total	Q2	Cumulative Total
Baseline Cost Plan										
Federal Share	40,059	381,086	40,059	421,145	40,059	461,204	41,547	502,751	41,547	544,299
Non-Federal Share	11,587	111,860	11,587	123,447	11,587	135,034	11,935	146,969	11,935	158,904
Total Planned	51,647	492,945	51,647	544,592	51,647	596,238	53,482	649,720	53,482	703,203
Actual Incurred Cost										
Federal Share	56,843	389,933	35,283	425,216	13,942	439,158	35,751	474,910		
Non-Federal Share	36,582	137,278	0	137,278	0	137,278	18,537	155,815		
Total Incurred Costs	93,425	527,211	35,283	562,494	13,942	576,436	54,289	630,725		
Variance										
Federal Share	16,784	8,848	-4,776	4,071	-26,117	-22,046	-5,796	-27,842		
Non-Federal Share	24,995	25,419	-11,587	13,831	-11,587	2,244	6,602	8,846		
Total Variance	41,779	34,266	-16,364	17,903	-37,705	-19,802	806	-18,995		

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