Gas Production from Hydrate Bearing Sediments: Geomechanical Implications

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The gas hydrates resource pyramid (FITI, Fall 2006) identifies coarse-grained lithologies like sands as the most economically favorable hydrate-bearing sediments for future gas production. Yet, the largest fraction of total gas hydrate resources resides in fine-grained sediments at relatively low saturations, and producing substantial gas from such deposits has long been considered prohibitively costly and technically difficult. Using a combined experimental and numerical approach, the gas hydrates research team at Georgia Tech has investigated phenomena that may affect gas production from sand-hosted hydrates and studied factors that may augment the prospects for gas production from hydrates in fine-grained sediments. This article summarizes the interplay between sediment geomechanics and gas production from hydrate-bearing sediments, with particular focus on fine-grained sediments.

Hydrate Bearing Sediments

A compilation of pressure and temperature conditions for selected gas hydrate provinces is shown in Figure 1. The zone in which methane hydrate could potentially occur within the sediment is bounded by hydrostatic pressure at the seafloor on the left and the phase transformation boundary calculated for 3.5% salinity on the right. In addition to salinity, factors such as pore size and the presence of other hydrate-formers affect the phase transformation.

Grain size distribution. There is an inherent link between mineralogy and

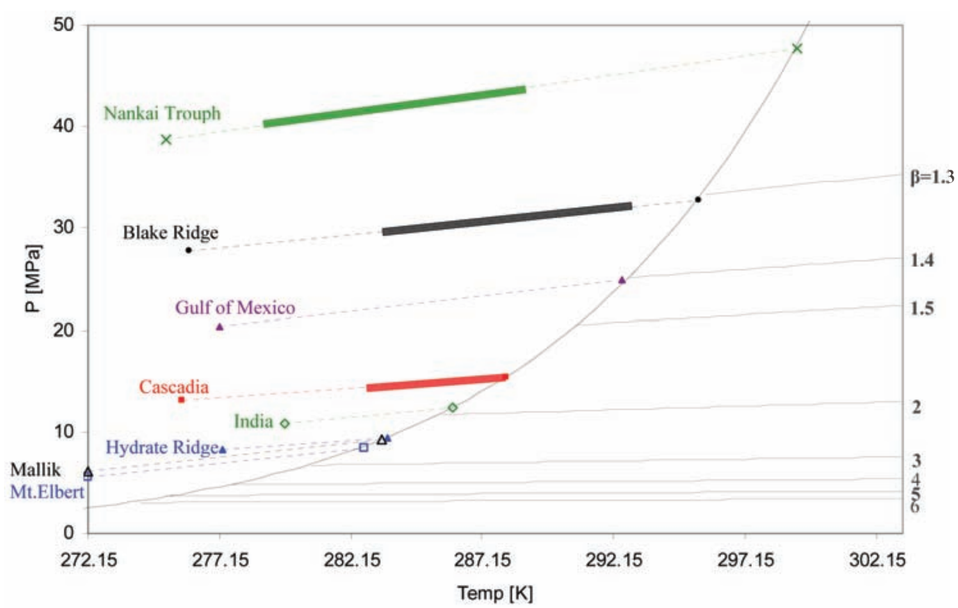


Figure 1. Pressure and temperature conditions for selected hydrate reservoirs. Dashed lines show the range of potential hydrate occurrence in the sediments, and thick lines correspond to depth range over which hydrate was inferred to occur based on downhole logs. Thin solid lines to the right of the phase boundary show various hydrate-to-fluid expansion ratios β=Vfluid/Vhyd.

grain size. Most submicron-size grains are made of clay minerals and are formed through chemical processes (e.g., fine-grained layers in Gulf of Mexico, Krishna-Godavari basin, and Blake Ridge). Grains larger than about 50μm are non-clay minerals and have formed through mechanical processes (e.g., coarse-grained layers in Mt. Elbert, Mallik Mackenzie Delta, and Nankai Trough). Biological activity may contribute shell fragments and microfossils to the sediments, leading to a dual porosity medium (e.g., Blake Ridge and East Sea). Smaller or thinner grains exhibit higher specific surface, higher amount of adsorbed water per volume, higher plasticity, and higher dependency on electrical interaction forces.

Pore size. Grain size distribution determines pore size. In clayey sediments, the mean pore diameter dp can be related to the sediment specific surface Ss and porosity n, $dp=2n/[(1-n)\rho Ss]$. In sands, the percentage of fine grains (passing sieve #200) is a critical indicator of pore size, as shown in Table 1: (1) "clean" sands lack fines; (2) even a small percentage of fines may drastically affect the hydraulic properties of sands, and (3) as low as ~15% of fines may fill all pores and strongly affect both the hydraulic and stress-strain properties of sands.

Fluid conductivity and gas entry pressure. Pore size governs hydraulic conductivity (Kozeny-Carman and Hazen equations) and gas entry pressure (Laplace equation). These two physical parameters control the spatial distribution of hydrate in reservoirs, affect the selection of gas production strategies, and define ensuing geomechanical effects.

Hydrate concentration and spatial distribution. How did hydrate form? Methane invades the sediment in gas phase when the gas pressure exceeds the gas entry pressure at pore throats. Therefore, hydrate formation from gas phase should be expected in coarse-grained sediments that are connected to high permeability faults or a gas source; hydrate saturation may be water-limited in this case. Low viscosity gas invasion into a water-saturated sediment is essentially unstable and viscous fingering is anticipated. On the other hand, forced gas invasion will cause fracture formation in clayey sediments if the gas entry pressure exceeds the sediment effective stress (first-order estimate for unconsolidated sediments –Figure 2a). Similar physical processes apply to the development of hydrate lenses in fine grained sediments. The initial interconnectivity of segregated hydrate lenses and nodules observed in fine grained hydrate bearing sediments will facilitate gas production from these otherwise low permeability sediments.

Hydrate formation from dissolved gas is inherently gas-limited due to the low solubility of methane in water compared to the high gas content in hydrate. Dissolved methane transport combines diffusive and advective contributions. The contribution of advective transport will prevail in most cases (except in high specific surface, low hydraulic conductivity sediments) and will bias hydrate accumulation towards the coarser and cleaner layers. Therefore, clean sand layers with high hydrate saturation may be found between sand layers that contain some fines and almost no hydrate, even though all these layers are within the stability field. This situation has been observed in the recent Chevron/DOE JIP Gulf of Mexico drilling, at Mount Elbert, and at the Nankai Trough.

Reservoir morphology. At the macro-scale, fluid flow and hydrate accumulation are related to large scale geometric characteristics, the subsurface geo-plumbing (faults, pipes and dipping layers), and trapping conditions which include self-sealing hydrate formation.

Gas Production: Geomechanical Implications and Emergent Phenomena

Potential geomechanical implications associated with gas production depend on both pore-scale and macro-scale reservoir characteristics (see Table 1). Consequently, these must be taken into consideration for the selection of optimal gas production strategies.

Fluid volume expansion during gas production. Iso-expansion lines are shown to the right of the phase boundary in Figure 1. There are two volume expansion components: (1) a pronounced increase in volume just across the phase boundary so that an initial hydrate volume Vo immediately inside the stability field converts into a fluid volume βVo immediately outside the stability field, e.g., β~2.5 for the PT conditions of Hydrate Ridge; and (2) volume change due to thermal change and depressurization, e.g., β~1.3 just to cross the phase boundary at Blake Ridge, but increases to β~5 if depressurized to P=3.7 MPa at T=275 K. Such a large change in volume implies high fluid flow if drained conditions prevail (e.g., depressurization driven production) or the generation of very elevated fluid pressure if dissociation is enforced under undrained conditions (e.g., rate of dissociation higher than the rate of pore pressure dissipation in thermally-driven production).

High increase in fluid pressure ➔ gas driven fractures. The potentially high increase in fluid pressure in thermally stimulated or chemically driven production (including CO_2-CH_4 replacement) can cause gas driven fractures (Figure 2b) and the development of high permeability paths that can facilitate gas production in fine-grained sediments or in coarse grained sediments with fines. A proper understanding of these gas-related phenomena requires an effective stress formulation.

A **B** **C**

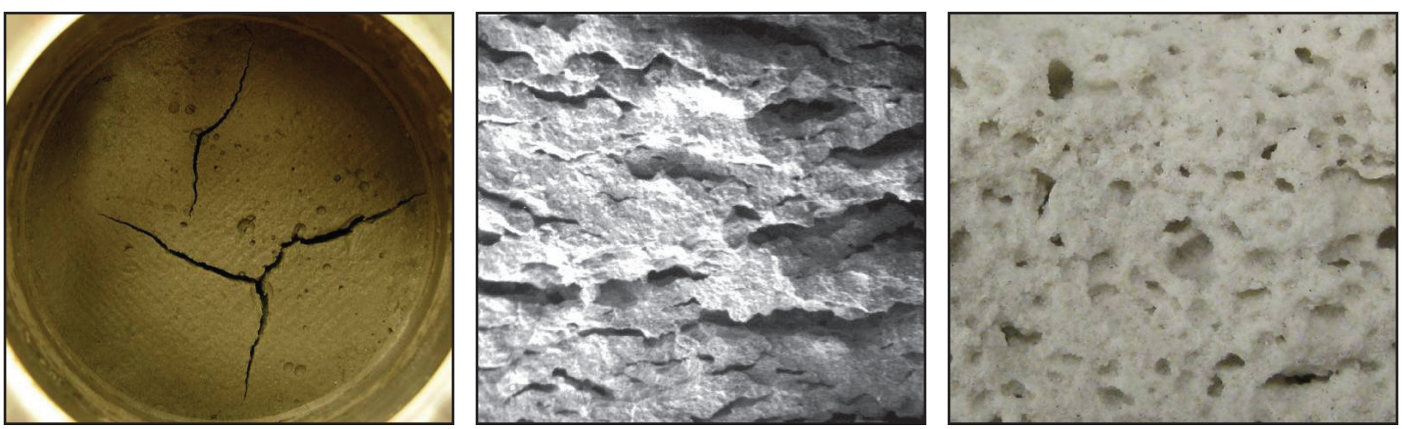


Figure 2. Gas production in fine-grained sediments. (a) Water saturated montmorillonite paste subjected to forced gas invasion. The cracks initiate in the largest pores. Image scale= 100 mm (collaboration with H. Shin). (b) Water saturated kaolin paste subjected to fast internal heating to cause vapor generation faster than pressure dissipation. The sediment becomes pervasively fractured. Image scale= 10 mm. (c) CO_2 hydrate bearing sand with 3% kaolinite by weight. The presence of fines affects gas production and a vuggy sediment fabric develops during depressurization. Image scale= 20 mm (collaboration with J.W. Jung and C. Tsouris).

Sediment volume contraction during gas production. Distributed hydrate augments the stability of the sediment granular skeleton, particularly when the hydrate saturation exceeds Shyd > ~0.4. Therefore, hydrate loss during free-draining gas production will cause sediment volume contraction that is proportional to the initial hydrate saturation and the sediment compressibility. In addition, there is volume contraction associated to the dissociation of segregated hydrate in lenses and nodules.

The other contribution to sediment volume contraction is related to the increase in effective stress $\sigma'=\sigma-u$ in depressurization strategies, i.e., lowering the fluid pressure u under constant total boundary stresses σ. The effect is more pronounced near the production well, meaning that higher volume contraction will take place at shorter radial distances. This radial gradient in volume contraction causes an increase in shear stress, and the sediment will evolve towards the "critical state porosity" near the production well.

Crushing, fines migration, clogging, and sand production. The increase in effective stress beyond the sediment yield stress will cause grain crushing in silty and sandy reservoirs. Existing sediment fines and fine particles newly created by crushing can migrate during gas production. Fines migration is controlled by particle size, the ratio of migrating particle size to pore constriction size, and the spatial variability of the flow velocity field. Migrating particles may form bridges at pore throats and a clogging annular ring around the production well, thereby limiting fluid flow and potentially triggering sustained sand production.

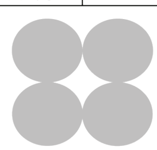
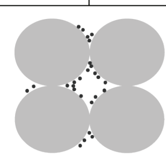
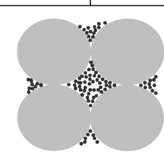
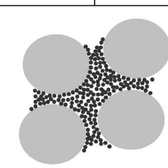
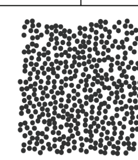
	Clean sand		Sand with some fines		Transition sediment		Silty or clayey sand		Silt or clay	
	Sand	Fines	Sand	Fines	Sand	Fines	Sand	Fines	Sand	Fines
	100 %	0 %	> 93%	< 7%	~85%	~15%	< 85 %	> 15%	0 %	100 %
Sediment fabric	 $d_{pore} \sim 0.4\, d_{grain}$								 $d_{pore} = \frac{2n}{(1-n)S_s\rho}$	
Sediment properties *(without hydrates)*	Stiffness, strength, and hydraulic conductivity: ***sand controlled***		Stiffness, strength: ***sand controlled*** Hydraulic conductivity: ***fines may affect***		Stiffness and strength: ***sand controlled*** Hydraulic conductivity: ***fines controlled***		Stiffness, strength, and hydraulic conductivity: ***fines controlled***			
Hydrate habit	$S_h < 20\%$ Pore filling $S_h > 40\%$ Frame building						Finely disseminated, nodules, layers, lenses			
Reservoir	Mallik Mackenzie Delta (Canada), Mount Albert (Alaska), Nankai Trough (Japan)						Blake Ridge (SC), KG Basin (India), Gulf of Mx (LA), East Sea (Korea), Hydrate Ridge (OR)			
	$S_{hyd} < \sim 0.8$						$S_{hyd} < 0.1\text{-}0.25$			
Gas production: Potential phenomena	sand production		clogging (implications may include high excess fluid pressure and gas driven fractures), sand production				high excess fluid pressure, gas driven fractures, high volumetric strain			

Table 1. Sediment characteristics and physical properties - Potential phenomena during gas production

Coupled processes. The emergence of unanticipated phenomena is one of the main concerns in the development of new engineering solutions. From this perspective, coupled hydro-thermo-chemo-mechanical processes pose the greatest uncertainty given their inherent complexity, as demonstrated by the following sequence of causally related processes: heating, dissociation, freshening, changes in inter-particle electrical forces, volume change, compatibility of deformation, and changes in stress state. Conversely, coupled processes may present the best opportunities for producing gas, for example by inducing the spontaneous internal formation of gas-driven fractures that increase the hydraulic conductivity of clayey sediments.

Summary

Grain size distribution determines (1) pore size, gas entry pressure, and hydraulic conductivity; (2) hydrate growth, distribution and eventual hydrate saturation; (3) the feasibility of producing gas, the selection of production strategy, and the necessary technology; and (4) potential production-related outcomes. The particle size or specific surface of the finest 5%-to-10% sediment fraction largely controls these properties and processes.

The very pronounced volume expansion that accompanies hydrate dissociation has different consequences depending on the production method and the reservoir lithologies. Thermal stimulation may lead to extensive gas-driven fracturing in fine grained sediments and in coarse sediments with fines-filled porosity. These fractures facilitate gas production from low hydraulic conductivity sediments. Depressurization, the favored method of gas production from coarse-grained sediments, may lead to grain crushing near the wellbore, fines migration, and eventual clogging. While safe production strategies can be engineered to accommodate known processes and reservoir conditions, special attention should be placed to anticipate phenomena that can emerge from complex hydro-thermo-chemo-mechanical coupled processes.

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