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TRANSIENT NUMERICAL MODELS OF WELL-CHARACTERIZED GAS HYDRATE RESERVOIRS IN A RANGE OF GEOLOGIC SETTINGS

C. Ruppel and J. Nimblett[1]
School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA

The effort to compile data from gas hydrate provinces in a variety of geologic settings (e.g., active and passive continental margins, salt basins, permafrost regions) continuously provides new examples of the relationship between hydrate occurrences and lithology, stratigraphy, availability of organic matter, location of chemosynthetic communities and cold seeps, vigor of gas and fluid flow and biological activity, and other parameters. At the same time, this emphasis on documenting the disparate manifestations of gas hydrate occurrences sometimes detracts from attempts to understand the commonality amongst hydrate provinces and the fundamental physical, chemical, and biological processes that control their evolution.

Numerical modeling, with its emphasis on evaluating the relative importance of various processes (e.g., advection vs. diffusion) or parameters (e.g., permeability vs. methane supply), has proved to be a useful tool in gaining more fundamental insight into hydrate reservoir dynamics. In this study, we apply several generations of numerical models developed at Georgia Tech to data from diverse geologic settings (e.g., Gulf of Mexico, Hydrate Ridge, Costa Rican and Nankai margins, Blake Ridge). The goal of the study is to understand how to couple geological observations to numerical models as a predictive tool for evaluating the evolution of gas hydrate reservoirs at multiple spatial (pore to regional) and temporal (years to millennia) scales. We also examine the changes in marine hydrate reservoirs subject to conditions that range from slow geologic change (e.g., sedimentation, subsidence) to rapid climate change.

In our previous work, we argued for a process-oriented classification of gas hydrate provinces, instead of relying on tectonic setting, dominant sediment type, or key hydrate-forming gas. The “flux-based framework” we advocated provided a means for categorizing hydrate provinces along a spectrum from low, diffuse flux (e.g., Blake Ridge) to regionally high advective flux (e.g., Gulf of Mexico). Zones of focused high flux can be superposed on provinces within any part of this spectrum, reflecting tectonic, lithologic, and hydrologic heterogeneity. The previous work also demonstrated that 3 fluxes--methane, energy, and heat--control the key characteristics of mature marine gas hydrate reservoirs and showed that even relatively simple models can link basic geological observables to first order quantification of these fluxes.

[1] Now at Shell International Exploration and Production, Inc.

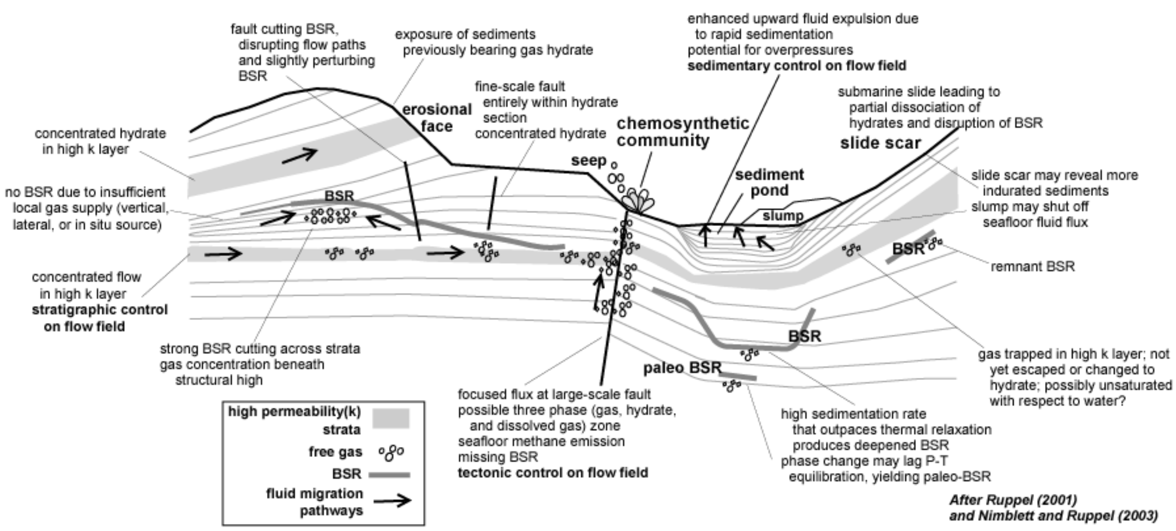
Here we refine the flux-based framework by applying transient 1D models that track how hydrate formation fundamentally alters the hydrodynamics of the gas hydrate reservoir. ODP legs and/or associated site survey work on the Nankai, Costa Rican, and Peruvian margins, on Blake Ridge and Hydrate Ridge, and in the Gulf of Mexico provide constraints on the thickness of the sulfate reduction zone (proxy for methane flux), the depth to the top of the gas hydrate zone (proxy for fluid flux), the depth to the base of the gas hydrate zone (proxy for methane flux), and BSR depth (reflecting energy flux). The age of sediments provides an upper bound for the age of the hydrate deposits, published lithologic descriptions constrain permeability, and pore water salinity profiles provide information about the in situ distribution of gas hydrate. Combining these data and other observations, we develop an initial steady-state model of each system to bracket key flux parameters. We then apply a transient permeability evolution model to each province to track the rate and locus of gas hydrate formation, to determine how flow pathways change and permeability is altered during the evolution of gas hydrate deposits, and to calculate the time for natural renewability of gas hydrate resources.

Overall, the results of the transient modeling effort bear out both anecdotal evidence and our earlier steady-state results: Higher concentrations of gas hydrate are predicted at sites dominated by more rapid advective flux. However, our transient models show that even low advective flux may produce large concentrations of gas hydrate, depending on the age of the province, the predominant flow pathways (faults vs. porous media), and the supply of hydrate constituents.

Table of hydrate provinces investigated in the transient 1-D modeling studies.

	Peru	**Costa Rica**	**Nankai**	**Hydrate Ridge**	**Blake Ridge**	**Gulf of Mexico**
Locations	ODP sites 685 and 688	ODP sites 1040 and 1041	ODP sites 808 and 1178	ODP Leg 204	ODP sites 994 and 997	Garden Banks 388; Green Canyon 185; Miss. Canyon 852/853
Sediments	Diatomaceous mud	Clay, with some ash; variegated	variegated	variegated	hemipelagic ooze	clay
Hydrate recovery	X		X	X	X	X
Pore water freshening	X	X	X	X	X	
BSR	X	(X)	X	X	X	

We also report on a new generation of pseudo-2D transient models that quantify the response of gas hydrate reservoirs to climate change, subsidence, uplift, sedimentation, and erosion. Unlike some previous studies, these models fully account for the pressure-temperature dependence of methane solubility, including tracking solubility changes during events that perturb the reservoir. Evolving methane solubility within the gas hydrate zone can lead to formation of new hydrate or dissociation of extant hydrate deposits and the occurrence of zones in which hydrate may first dissociate and then reform before re-dissociating. We apply these new models to well-constrained active margin (Peru) and passive margin (Blake Ridge) gas hydrate systems to provide insight into the processes that contribute to the lateral heterogeneity in hydrate and free gas distribution and BSR strength in mature reservoirs. We also extend these models to demonstrate that the likely impact of climate change events on marine hydrate reservoirs is significantly less catastrophic than advocated by many researchers.



This figure, which was first formulated by Ruppel for the Hydrogeology Proposal Planning Group within the Ocean Drilling Program, qualitatively demonstrates the lateral heterogeneity in the hydrodynamics of a marine gas hydrate reservoir and how various processes may contribute to the distribution of free gas and gas hydrate. The left side of this figure was published by Nimblett and Ruppel in 2003 in the Journal of Geophysical Research as part of a transient modeling study.

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