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**Pressure-Temperature-Salinity Influences on Gas Hydrate Stability in Sediments of the
Mallik Gas Hydrate Reservoir, Mackenzie Delta, Canada**

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The Mallik 2002 Gas Hydrate Production Research Well Program succeeded in conducting the first scientifically constrained production tests of a natural gas hydrate reservoir, using both pressure reduction and thermal stimulation techniques. Testing was conducted on the site of Imperial Oil Limited’s Mallik exploration lease in the Mackenzie Delta, Northwest Territories, Canada (see Dallimore et al. 2004). A Modular Dynamics Tester (MDT) was employed to conduct a series of 6 pressure draw-down tests targeting specific intervals within the Mallik gas hydrate reservoir (which extends from about 890 m to 1107 m depth), followed by a single thermal stimulation test of a 13 m interval between 907 and 920 m, conducted over a 5-day period. In addition, a detailed ground temperature profile of the reservoir was obtained using Distributed Temperature Sensing technology (Henninges et al., 2004).

A reliable assessment of the reservoir response to these stimuli requires an adequate understanding of the *in situ* stability of gas hydrates throughout the reservoir. Essentially, the local *in situ* stability condition determines the magnitude of the pressure reduction and/or temperature increase required to force gas hydrate crystal to dissociate into its constituent liquid water and free gas phases. Characterization of the *in-situ* stability of gas hydrate within the target reservoir is crucial to the design of more rigorous and extensive production tests anticipated in the near future. This in turn has significant implications for the development of technically feasible strategies (i.e. the mechanisms employed and configurations used to force gas hydrate dissociation) and for managing the economics of gas hydrate production (e.g. the cost of the energy input vs. the value of energy produced).

Laboratory experiments were conducted on 4 sediment samples recovered from the Mallik 5L-38 Production Research Well to characterize *in situ* stability conditions of gas hydrate at various locations within the Mallik reservoir. The original *in situ* gas hydrate content of the test specimens had been completely dissociated prior to their arrival at the GSC laboratories in Ottawa. The measured pore water salinity of the individual samples ranged from about ~7 ppt to a high of about 50 ppt (Table 1).

Table 1: Selected properties of test sands recovered from the Mallik 5L-38 research well

Specimen	Recovery depth (m)	Sedimentary Unit	Water content (w%)	Measured ¹ bulk salinity (ppt)	GH sat. % (inferred from logs)	GH sat. % (calc. from P-T-salinity data)
1	921	1	16.5	<10	~80	84
2	1022	4a	20.6	35-40	<10	33
3	1097	5	19.2	~25	60-65	58
4	1123	5	21.3	~50	0	15

¹ measurement on core sample in the vicinity of specimen sub-sampling location

¹ Lewis and Collett (in preparation)

Gas hydrate was formed or re-formed in each sediment specimen using a GSC reactor cell specifically designed for tracking pressure-temperature (P-T) equilibrium conditions within a porous medium. Note that specimens 2 and 4 contained little or no gas hydrate *in situ*, although in the lab significant amounts of gas hydrate were grown in each. Specimen 4 was recovered from a slightly greater depth than the lowermost observed gas hydrate occurrence, in a location at which local P-T-salinity conditions were unfavorable for gas hydrate formation. Specimen 3 was recovered from a sand interbed within a silt-dominant sedimentary unit considered to be relatively impermeable to gas. Following the hydrate formation stage, specimens 1 through 3 were stabilized at their respective *in situ* pressure and temperature conditions (i.e. corresponding to the depth of sample recovery). Note that in order to form gas hydrate in specimen 4 it was necessary to cool the specimen well below its assumed *in situ* temperature (Figure 1).

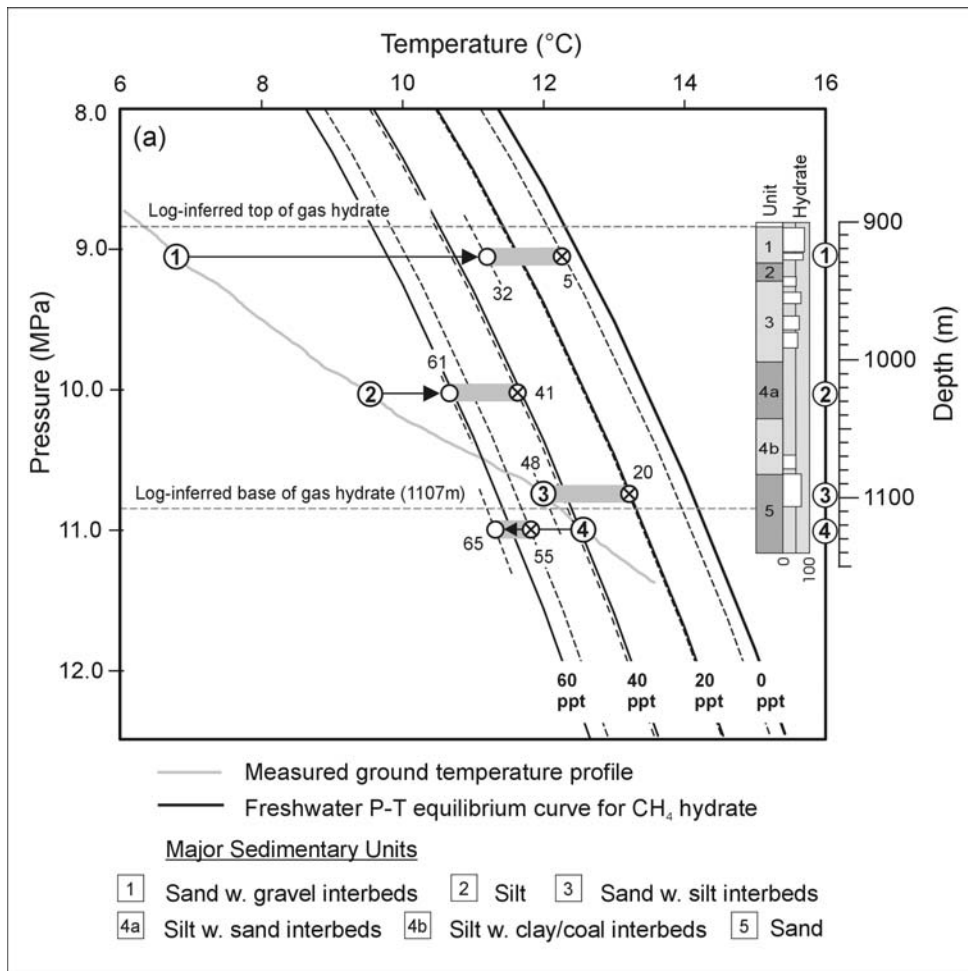


Figure 1: *In situ* stability conditions of methane hydrate in sandy sediments from the gas-hydrate-bearing interval at Mallik 5L-38. Specimens 1, 3, & 4 were recovered from sand-dominated sedimentary units. Specimen 2 was taken from a sand interbed within a silt-dominated zone (Unit 4a). Theoretical P-T stability curves for methane hydrate are presented for salinities of 0, 20, 40, & 60 ppt. Numbered circles represent the *in situ* pressure-temperature condition for each specimen, as inferred from the recovery depth and the ground temperature profile. Open circles indicate P-T-salinity condition at the onset of gas hydrate instability during temperature forcing. Arrows indicate the magnitude of temperature offset between *in situ* conditions and the gas hydrate instability threshold. Circle "X" symbols indicate the P-T-salinity condition upon complete dissociation of gas hydrate, assuming the maintenance of constant pressure throughout the dissociation period. In each case the shaded bands indicate a region of "quasi-stability" within which gas hydrate exists in continuous equilibrium with evolving pressure-temperature-salinity conditions.

Dissociation of the gas hydrate content of each sample was subsequently forced by gradually increasing the temperature within the test cell over a period of several hours. Complete dissociation occurred within about 2-4 hours of initiation, across a temperature range spanning about 2-4 C°. Results indicate that the dissociation of gas hydrate in saline sediments is characterized by a continuous shift in the instantaneous P-T equilibrium threshold for gas hydrate stability, corresponding to progressively lower values of pore water salinity as “fresh” water is released from the dissociating hydrate crystal. In such cases, the transition between gas hydrate stability/instability does not occur across a discrete P-T threshold as generally assumed, but rather extends across a P-T region or field (shaded bands in Figure 1) bounded by the separate P-T equilibrium curves correspond to the bulk salinity value of the host sediment and the locally elevated pore water salinity in the presence of gas hydrate. We may conclude, therefore, that gas hydrate existing within this P-T region is in strict terms neither stable nor unstable, but rather exists in continuous 3-phase equilibrium (L-V-H) conditioned by local pore water salinity. This “quasi-stable” gas hydrate would be highly sensitive to even small changes in pressure and/or temperature (and/or salinity), resulting either in new hydrate growth (assuming the availability of sufficient free gas) or partial dissociation of existing gas hydrate.

The experiments also suggest that there is a salinity-imposed limit to gas hydrate growth in saline sediments, as the expulsion of salts during the crystallization process increases the concentration of salts in the remaining pore waters to a point beyond which continued formation of gas hydrate cannot be sustained. For the specimens tested, the degree of gas hydrate saturation achieved was directly correlated to the bulk pore water salinity of specimen, with a distinct linear relation being apparent (Figure 2). The gas hydrate saturation values achieved in the experiments (black bars) are derived from an estimate of the amount of pore water that must have crystallized in order to produce the level of salt concentration indicated by the data, as calculated from the inferred salinity values just prior to and following the dissociation of the gas hydrate content of each test specimen (Figure 1). Subject to the constraints of the prevailing P-T conditions within the Mallik reservoir, the capacity of the sediments to host gas hydrate can be expressed as a simple mathematical relation, such that:

$$Sr_{MAX} = -1.3527x + 88.42$$

Where: Sr_{MAX} = salinity-imposed limit on gas hydrate saturation
 x = bulk pore water salinity

The log-inferred estimates of *in situ* gas hydrate saturation (grey bars) at the depth of recovery of specimens 1 and 3 are in good agreement with saturation levels achieved in the laboratory, being close to the specified salinity-imposed limit. We have previously noted that the

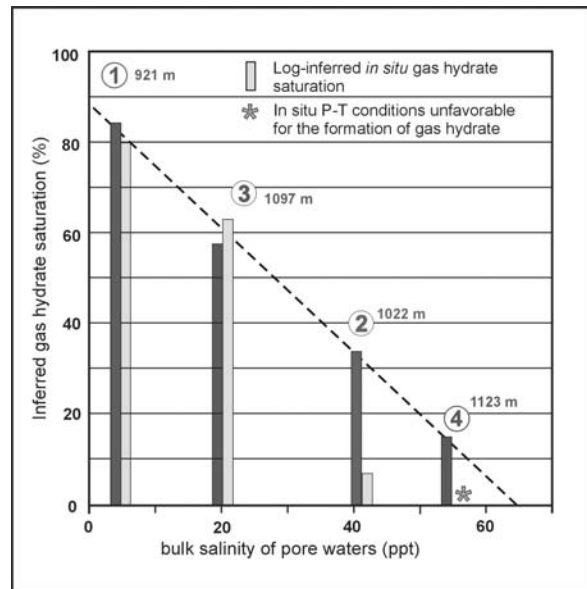


Figure 2: Relation between gas hydrate saturation and bulk pore water bulk salinity

low *in situ* saturation levels associated with specimens 2 and 4 are probably due to other constraining factors. Extrapolation of the above relation suggests that even for very low bulk salinity values we are unlikely to observe gas hydrate saturation values greater than about 85-90%, a value that is in fact representative of the upper limit of gas hydrate saturation inferred from well log data at Mallik (Lewis and Collett, 2004). This simple model also suggests that no gas hydrate can form in sediments for which the bulk pore water salinity exceeds about 65 ppt, although these limits probably vary somewhat for natural reservoirs having distinctly different geothermal and/or geopressure regimes.

In summary, experiments conducted on core samples recovered from the Mallik 2002 gas Hydrate Production Research Well indicate that pore water salinity exerts a major influence on the *in situ* stability of gas hydrate within reservoir sediments. Our research suggests that the conventional notion of fixed upper and lower boundaries for methane hydrate stability/instability in natural gas hydrate-bearing reservoirs may be inadequate, rather it is likely that gas hydrate may exist at or near its stability threshold at many locations within the reservoir. Furthermore, pore water salinity appears to impose limits on capacity of sediments to host gas hydrate, with a direct relation apparent between the hydrate saturation levels achieved in sediments of varying salinity. These conclusions have significant implications for the specification of reservoir production characteristics and engineering design parameters, as well as for the development of a geologic model for understanding gas hydrate accumulation and free gas migration within the Mallik reservoir.

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