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**Heterogeneity and Strength of Natural Gas Hydrate-Bearing Sediments**

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We investigate the effect of natural gas hydrates on the strength of the host sediments in two different geological settings — Hydrate Ridge off of the U.S. Oregon coast, drilled during Ocean Drilling Program Leg 204, and the MacKenzie Delta in the Canadian NW Territories, drilled during the Mallik 2002 program — which have important similarities and differences. Hydrate Ridge is a NE-SW trending bathymetric high and consists of hemipelagic muds and turbidites, both moderately deformed by tectonic compression and fracturing associated with trench subduction and the formation of an accretionary prism. The hydrate-bearing sediments in this location are clay-rich and have 40-80% porosity. The Mallik site is located on the flanks of a shallow anticline of deltaic sandstone and shale deposits that are laterally continuous and relatively non-deformed. The hydrate-bearing sediments in this location are sandy and have 20-50% porosity. Coring in both locations recovered natural gas hydrate samples. We utilize geophysical logging data to measure the in situ properties of these formations and to estimate and compare the strength of the hydrate-bearing to the underlying water-bearing sediments. We also observe the distribution of gas hydrate in these sediments and consider its relative heterogeneity in these different depositional settings.

Geophysical logging and Logging-While-Drilling (LWD) tools were used to measure formation resistivity, acoustic velocity, and density as a function of depth at several drill sites in these environments. In particular, tools that record images of electrical resistivity allow for the delineation of the shape, geometrical distribution, and orientation of pores and structures filled with hydrate as a function of azimuth around the well bore. In addition, LWD data are acquired only minutes after the formation is drilled, limiting the extent of hydrate dissociation on the measured in situ properties. At the Mallik 5-L site, well logs and LWD data indicate that sandy formations contain hydrate saturations with up to 90% of the open pore space and appear relatively homogeneous in the vicinity of the borehole. In contrast, at ODP Site 1250 on Hydrate Ridge, clay-bearing sediments contain only 5-10% hydrate saturation, on average, but appear in asymmetric patchy zones and fractures that are distributed around the borehole with localized saturation of hydrate up to 50% of the pore space (Janik et al., 2003). Patchy hydrate distribution occurs throughout the GHSZ and at all of the sites drilled on Hydrate Ridge. In Figure 1, the resistivity images illustrate the relative heterogeneity of the hydrate distribution in Mallik 5-L and Site 1250 over 100-m intervals towards the base of each GHSZ. The hydrate saturation estimated from the wireline resistivity log (Collett et al., 2003; Collett et al., 2004) and the natural gamma ray log, which indicate the clay content of the formation, are also displayed in Figure 1. Hydrate is concentrated in sand layers in Mallik 5-L (low gamma ray), whereas there is no change in gamma ray with increasing hydrate saturation (or below the GHSZ) at Site 1250.

We compute the bulk modulus  $K$  from the measured  $V_p$ ,  $V_s$ , and density logs over the lower GHSZ interval and below in Mallik 5-L and at ODP Site 1250 (Figure 1). This computation measures the incompressibility of the formation to elastic strain, and provides an indication of the dynamic strength of the formation in the hydrate-bearing and water-bearing formations across the hydrate-water phase boundary. In hydrate-bearing sediments,  $K$  values appear to vary considerably ( $K \sim 18\text{MPa}$  in Mallik 5-L and  $K \sim 4.5\text{MPa}$  at Site 1250). Note that the hydrate saturations are 4-15 times higher in Mallik 5-L. At both sites, as expected, the average  $K$  value is also consistently higher in hydrate- than in water-bearing sediments.  $K$  decreases below the GHSZ by  $>50\%$  in Mallik 5-L and by  $\sim 12.5\%$  at Site 1250, and without lithological or other environmental changes in either hole. This drop in  $K$  can therefore be attributed to the absence of gas hydrate in both environments. Consequently, we infer that the strengthening effect of hydrate in the sands at Mallik is at least 4 times greater than in the clay-rich sediments on Hydrate Ridge. Given the very high hydrate saturation and relatively homogeneous distribution of hydrate in Mallik 5-L, this result does not come as a surprise.

Recent evidence from other studies confirms the apparent strengthening in hydrate-bearing formations at these locations. On Hydrate Ridge, borehole breakouts (elongations in the cross sectional shape of the borehole) were detected using LWD images at three sites located on the flanks of the ridge and towards the continental coastline. No breakouts were observed at sites on the trench side (west) of Hydrate Ridge. Based on the orientation of the breakouts, the direction of the in situ maximum horizontal stress ( $S_{Hmax}$ ) can be determined and is consistent with the regional tectonic and ridge uplift stresses. Moreover, in the vicinity of the ridge summit, precise measurements of the breakouts width, in conjunction with information from laboratory tests on core samples, provide constraints on  $S_{Hmax}$  and  $S_{Hmin}$  (the minimum horizontal stress) magnitudes at the depths where breakouts occur. Using these results, Janik et al (2004) estimate a lower limit of formation strength for the overlying hydrate-bearing sediments where the formation is strong enough to impede the formation of breakouts. At the Mallik site, the thick sandstone at the base of the GHSZ contains both hydrate- and water-filled pores depending on depth (i.e., above/below the phase boundary). Acoustic velocities are high and isotropic within the GHSZ, but velocity anisotropy of  $\sim 10\%$  is observed below the boundary. Plona et al (2003) suggest that the anisotropy is stress-induced as a result of mechanical elongation of the borehole (similar to borehole breakouts) in a direction consistent with the regional  $S_{Hmax}$  orientation. The water-bearing sand below the GHSZ is significantly weaker than the hydrate-filled sand above, which is strong enough to impede hole deformation.

In summary, at both ODP Site 1250 and Mallik 5-L: (1) the strengthening effect of hydrate impedes borehole deformation where it would otherwise be present, and (2) the bulk modulus decreases significantly below the GHSZ. Depending on the geological setting, therefore, the dissociation of hydrate near the base of the GHSZ and subsequent weakening of the in situ formation would likely promote borehole deformation and formation weakening in these same formations. Quantifying the in situ strength of the host formation is therefore essential to understand the likelihood of dissociation-induced sediment failure and/or borehole collapse. For drilling in gas hydrate settings, especially for inclined and/or horizontal holes, we suggest that comprehensive laboratory experiments and formation tests are undertaken to establish the strength and stability of the host sedimentary environment.

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Figure 1. Geophysical logging and image data from Mallik 5-L and ODP Site 1250, illustrating the properties of hydrate- and water-bearing formations above and below the GHSZ's, respectively.

