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Research paper

Sampling disturbance in hydrate-bearing sediment pressure cores: NGHP-01 expedition, Krishna–Godavari Basin example

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ABSTRACT

Sampling natural sediments causes unavoidable disturbance as recovered sediments experience changes in stress and strain during drilling, core recovery, transportation, handling, and early stages of testing. In hydrate-bearing sediments, the potential for sampling disturbance may be aggravated, since pressure and temperature changes can lead to hydrate dissociation and gas exsolution. Pressure core technology attempts to recover and characterize hydrate-bearing sediments while preserving them under in situ pressure and temperature conditions, which is an essential requirement to assess the mechanical, physical, chemical, and biological properties of natural hydrate-bearing sediments. Previous studies on near-surface sampling effects are extended in this study to evaluate additional sampling disturbances relevant to hydrate-bearing sediments: (1) hydrate dissociation due to mechanical extension, (2) negative pore pressure generation during unloading (Mandel–Cryer effect), (3) secondary hydrate formation, (4) changes in hydrate mass as a function of changes in pressure and temperature within the stability field, (5) hydrate anomalous preservation and its benefits for pressure core handling and testing, and (6) relaxation/aging following sampling. Results provide valuable insight to sampler design, coring and operation procedures, high pressure chamber design, and pressure core testing techniques.

1. Introduction

The 2006 Indian National Gas Hydrate Program (NGHP) Expedition 01 was conducted to investigate geological and geochemical controls on gas hydrate occurrence offshore of the Indian Peninsula and along the Andaman convergent margin (Collett et al., 2006). Hydrate saturation estimated from compressional wave velocity, electrical resistivity logs, and X-ray computed tomography vary from $S_h < 5\%$ to as high as $S_h = \sim 80\%$ (Lee and Collett, 2009; Shankar and Riedel, 2011).

The eastern continental margin of India formed as the result of rifting between India and the rest of East Gondwanaland (Australia/Antarctica) in the Late Jurassic and Early Cretaceous. Plate reconstructions place the eastern Indian margin adjacent to Enderby Land in East Antarctica with the northern margin of "Greater India" along the western margin of Australia (Bastia and Nayak, 2006; Krishna et al., 2000). The Krishna–Godavari Basin came into existence following rifting along eastern continental margin of Indian Craton in the early Mesozoic. The Krishna–Godavari Basin contains about 5 km of sediments with several depositional sequences, ranging in age from Late Carboniferous to Pleistocene (Bastia and Nayak, 2006). Sediment input to the Bay of Bengal is dominated by the Ganges–Brahmaputra River system, resulting in the development of the Bengal Fan. Isopach maps show 8–10 km of sediment at the location of the NGHP-01 drill sites established in the Krishna–Godavari Basin. The sedimentary section in the Krishna–Godavari Basin is dominated by clay-rich sediments, with little evidence of significant input of coarser-grain sediments (Basu, 1990). Studies of conventional hydrocarbon systems in the Krishna–Godavari Basin have revealed that preserved organic matter in Paleocene and Cretaceous sedimentary section has led to the accumulation of significant conventional gas and gas-condensate fields in the basin (Banerjie et al., 1994). However, the gas hydrates sampled during NGHP-01 contain mostly methane derived from microbial sources (Collett et al., 2008).

For the most part, gas hydrate formation in the Krishna–Godavari Basin has developed by grain-displacement processes and has yielded gas hydrate in the form of nodules, veins, and lenses (Rees et al., 2011); this hydrate morphology is inherently caused by high capillary forces associated with the hydrate–water

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interface in fine-grained sediments (Clennell et al., 1999; Dai et al., 2012; Henry et al., 1999). Capillary pressure effects in these sediments also constrain the thickness of the hydrate stability zone at the sites in the Krishna–Godavari Basin. The equilibrium gas hydrate temperature depression ΔT_{dep} in a cylindrical pore space can be estimated as (Kwon et al., 2008):

$$\Delta T_{dep} = -\frac{2}{d_{pore}}\left(\frac{\gamma_{hw} m_h \cos\theta}{\rho_h L_f}\right) T_{bulk} \quad (1)$$

where γ_{hw} and θ are the surface tension and contact angle between hydrate and water, m_h and ρ_h are the molecular weight and density of hydrate, L_f is the latent heat of hydrate dissociation, and T_{bulk} is the equilibrium temperature in unconfined bulk solution. The pore size d_{pore} depends on sediment void ratio e, specific surface S_s, and mineral mass density ρ_m as: $d_{pore} = 2e/(\rho_m S_s)$, and the void ratio e changes with depth as $e = e_{100} + C_c \log(\sigma'/\text{kPa})$, where e_{100} and C_c are sediment-dependent parameters (Burland, 1990). Figure 1 shows the altered hydrate stability boundaries that could be anticipated in the Krishna–Godavari Basin for three common clay minerals identified in the basin, each with distinct specific surface and compressibility: kaolinite, illite, and montmorillonite. In agreement with predictions in Figure 1, reported depths to the base of the hydrate stability zone in clay- to silt-rich sediments can vary between 100 m and 200 m from expected conditions in coarser-grain sand-rich systems (Collett et al., 2008). Contrary to coarse sediments, such as those encountered in Alaska permafrost settings (Dai et al., 2011), pore size as it relates to the presence of fine-grained sediments at Krishna–Godavari can restrict the thickness of the hydrate stability zone.

Both conventional and pressure cores were recovered during the 2006 NGHP-01 expedition. Five pressure cores recovered at Site NGHP-01-21 were kept at 4 °C and 13 MPa fluid pressure, and tested three months after the expedition at an onshore facility in Singapore using the Instrumented Pressure Testing Chamber (IPTC) (Yun et al., 2010). The test program included the measurement of elastic wave velocities, shear strengths, electrical conductivities, and monitored fast depressurization tests using sub-sampled core samples. X-ray images showed horizontal layering, pronounced heterogeneity from milli- to centimeter scales, with the presence of high-density nodules and both horizontal and sub-vertical gas hydrate lenses. However, the laboratory testing of all natural sediments faces inherent sampling disturbance (Hvorslev, 1949), which occur even before detailed laboratory characterizations. This manuscript reviews previous studies on sampling effects associated with near surface sediment coring and processing, demonstrates the need for pressure core technology in the study of hydrate-bearing sediments, and analyzes several emergent phenomena of the poroelastic and pressure/temperature effects on hydrate-bearing sediment cores.

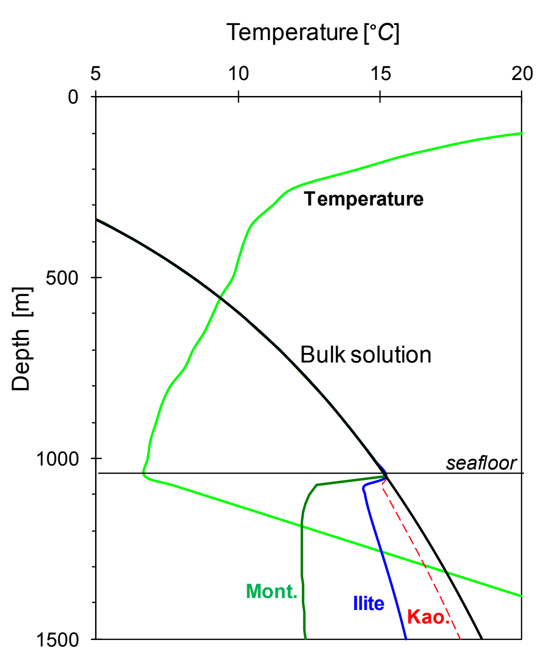

Figure 1. Pore size dependent shift in the phase boundary at Krishna–Godavari Basin site. Trends are computed for bulk solution, kaolin "Kao" ($e_{100} = 0.89$, $C_c = 0.29$), illite ($e_{100} = 2.05$, $C_c = 0.82$), and Montmorillonite "Mont." ($e_{100} = 3.06$, $C_c = 1.15$).

2. Sampling disturbance in hydrate-free sediment cores

Sampling affects the mechanical, biological, chemical, mineralogical, and lithological properties of natural sediments. Cores experience excavation unloading and friction against the corer wall, introducing unavoidable volumetric and shear strains. Figure 2 illustrates a conceptual stress-strain path that a sediment experiences during coring (Hight et al., 1992; La Rochelle et al., 1980; Ladd and DeGroot, 2003; Landon, 2007; Shogaki and Kaneko, 1994). To rationally quantify sampling disturbances, the "perfect sampling approach" considers only the unavoidable undrained removal of the deviator stress ($q \rightarrow 0$), followed by an undrained triaxial extension; and the "ideal sampling approach" considers also the effects of sequentially compression and extension along the centerline, shear strain along sampling tube walls during sampler penetration, and undrained shear stress relief during sample extrusion (Baligh, 1985; Baligh et al., 1987; Levadoux and Baligh, 1980).

2.1. Sources of sampling disturbance

Several factors account for changes in physical and mechanical properties of sampled sediments. These factors include, (1) Drilling and coring has been shown to cause changes in effective stress and

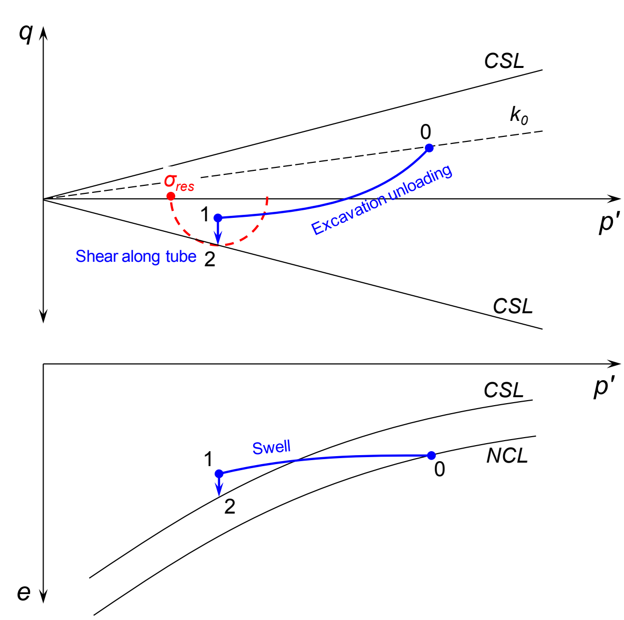

Figure 2. The stress-strain path during sampling. Cores experience excavation unloading ($0 \rightarrow 1$) and wall shear ($1 \rightarrow 2$); volumetric (shown) and shear strains are unavoidable (Note: CSL = critical state line; NCL = normal consolidation line; σ_{res} = residual stress mobilized during expansion against the sampling tube).