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Formation history and physical properties of sediments from the Mount Elbert Gas Hydrate Stratigraphic Test Well, Alaska North Slope

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A B S T R A C T

The synthesis of available geological information and surface temperature evolution in the Alaska North Slope region suggests that: biogenic and deeper thermogenic gases migrated through fault networks and preferentially invaded coarse-grained layers that have relatively high hydraulic conductivity and low gas entry pressures; hydrate started forming before the beginning of the permafrost; eventually, the permafrost deepened and any remaining free water froze so that ice and hydrate may coexist at some elevations. The single tested specimen (depth 620.47–620.62 m) from the D unit consists of uncemented quartzitic fine sand with a high fraction of fines (56% by mass finer than sieve #200). The as-received specimen shows no evidence of gas present. The surface texture of sediment grains is compatible with a fluvial-deltaic sedimentation environment and shows no signs of glacial entrainment. Tests conducted on sediments with and without THF hydrates show that effective stress, porosity, and hydrate saturation are the major controls on the mechanical and geophysical properties. Previously derived relationships between these variables and mechanical/geophysical parameters properly fit the measurements gathered with Mount Elbert specimens at different hydrate saturations and effective stress levels. We show that these measurements can be combined with index properties and empirical geomechanical relationships to estimate engineering design parameters. Volumetric strains measured during hydrate dissociation vanish at 2–4 MPa; therefore, minimal volumetric strains are anticipated during gas production at the Mount Elbert well. However, volume changes could increase if extensive grain crushing takes place during depressurization-driven production strategies, if the sediment has unexpectedly high in situ porosity associated to the formation history, or if fines migration and clogging cause a situation of sustained sand production.

1. Introduction

Pressure and temperature constrain the formation of gas hydrates to permafrost regions and marine sediments in continental margins (Kvenvolden and Lorenson, 2001). This manuscript documents a study of hydrate-bearing sediments in permafrost. The site is about 400 km north of the Arctic Circle on the coastal plain of Alaska North Slope (Hunter et al., 2011). First, we investigate the local geology and the formation history of the permafrost and hydrate phase. Then we report results of a comprehensive experimental characterization study conducted on a single specimen recovered from the BPXA-DOE-USGS Mount Elbert Gas Hydrate Stratigraphic Test Well (Mount Elbert well): parameters include index properties, geotechnical and geophysical characteristics obtained for the "undisturbed" sample and subsequent remolded specimens with and without THF hydrate. Finally, we explore potential implications related to gas production.

2. Hydrate and permafrost in Alaska North Slope

2.1. Site geology

The sediments at the Alaska North Slope are grouped into Franklinian, Ellesmerian and Brookian sequences in relation to tectonic episodes and lithologic characteristics (Lerand, 1973; Grantz et al., 1975). The Franklinian sequence consists of metamorphosed clastic and carbonate rocks (Reiser et al., 1978). The Ellesmerian sequence records the northward retreat of the coast line and the shallow-marine and nonmarine clastic sedimentation (Collett et al., 1988). And the Brookian sequence records a series of tectonic events: uplift of the Brook Range, subsidence of the Colville trough, and the formation of the Barrow arch caused by the

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northward downwarping of the Colville trough (Grantz et al., 1979; Collett et al., 1988; Bird, 1999). Currently, the Barrow arch is approximately parallel to the present shoreline and controls the occurrence of numerous oil and gas fields including the Milne Point Unit (Grantz et al., 1975; Collett et al., 1988). Gas hydrate prospects at Milne Point Unit are found in the sand layers of the fluvial-deltaic Sagavanirktok Formation within the Brookian sequence. This complex formation includes structural compartmentalization and faults that may serve as gas migration pathways from deeper hydrocarbon reservoirs (Hennes, 2004; Casavant et al., 2004; Hunter et al., 2005).

The stratigraphy at the Mount Elbert well exhibits a stacked sequence of fluvial, deltaic and nearshore marine sands with interbedded layers of both terrestrial and marine shales (Rose et al., 2011). Gas hydrates are found in two primary horizons at the Mount Elbert well. The C unit consists of 16 meters of gas hydrate-bearing sands (depth: ~650 m to ~666 m), and the shallower D unit which consists of 14 meters of gas hydrate-bearing sands (depth: ~614 m to ~628 m). The sediment tested in this study was recovered from the D unit. Both layers have relatively high hydrate saturation ranging from $S_{hyd} = 60-75\%$; this estimate is based on analyses of well log data (Lee and Collett, 2011) and pore water geochemistry (Torres et al., 2011).

Isotopic compositional analysis shows the coexistence of thermogenic and biogenic gases at the Alaska North Slope (Collett et al., 1988; Valin and Collett, 1992; Lorenson et al., 2008). This points to two general scenarios for gas hydrate formation. One theory assumes that a pre-existing gas reservoir was converted into hydrate after favorable changes in temperature and pressure. The other suggests that gas migrated upwards into the stability zone and then formed hydrate. In particular, biogenic and/or deeper thermogenic free gases may have migrated upward through Eileen fault (Carman and Hardwick, 1983; Masterson et al., 2001; Lorenson et al., 2008). Various sealing and trapping mechanisms have been proposed, such as structured fault closures (Collett et al., 1988; Hunter et al., 2005), low permeability marine siltstone layers (Collett et al., 1988,1990; Collett, 1993), permafrost (Pratt, 1979; Jamison et al., 1980; Downey, 1984), previously formed hydrate itself (Hunter et al., 2005), or concentrated deposits of peat or coal seams (Pratt, 1979).

2.2. Hydrate formation history

We combine various sources of information to reconstruct the evolution of the stratigraphy, ground surface, base of the ice-bearing permafrost, and potential gas hydrate stability zone at the Mount Elbert region. Data sources include: (1) logging data gathered for the Mount Elbert well, (2) stratigraphic and geologic information from the Alaska North Slope (Reimnitz et al., 1972; Bird, 1981,1999; Collett et al., 1988; Valin and Collett, 1992; Frederiksen et al., 1998; Inks et al., 2008), and (3) information on permafrost and ground surface temperature (Wolfe, 1980; Wolfe and Upchurch, 1987; Wolfe, 1994; Brigham and Miller, 1983; Parrish et al., 1987; Spicer and Chapman, 1990; Elias and Matthews, 2002; Matheus et al., 2003; Kaufman et al., 2004; Bujak Research International, 2008). We make the following assumptions:

- Continuous permafrost starts when the mean annual ground surface temperature is lower than $-5\,^{\circ}C$ (Brown, 1970). Thereafter, we place the base of the ice-bearing permafrost BIPF following Lunardini (1995) and Osterkamp and Gosink (1991).
- The temperature at the BIPF is assumed to be $-1\,^{\circ}C$, based on both logging data ($-1 \pm 0.5\,^{\circ}C$, Lachenbruch et al., 1982) and salt concentration (12.7 g/L, reported later in this manuscript) which induces a $-0.8\,^{\circ}C$ freezing point depression (Andersland and Ladanyi, 2004).
- The temperature within the permafrost increases with depth above the BIPF following a linear geothermal gradient of $1.64\,^{\circ}C/100$ m (Lachenbruch et al., 1982). Centennial fluctuations of the surface temperature can cause an anomalous temperature profile in the upper 160 m at Prudhoe Bay (Lachenbruch et al., 1982).
- The temperature beneath the BIPF is computed assuming that oscillations in the depth of the permafrost have a period much longer than the thermal diffusion time. Thus, we assume a time-constant, linear geothermal gradient below the permafrost ($3.56\,^{\circ}C/100$ m − from logging data in Collett et al., 2008; corroborated with data at other wells in the Alaska North Slope − refer to Lachenbruch et al., 1982; Collett et al., 1988, and Collett, 1993).
- The fluid pressure is hydrostatic and the water table is assumed at the ground surface. This assumption is based on the proximity of the Mount Elbert site to the coast line, evidence of hydrate formation before the permafrost (to be shown later in this section), and confirmatory fluid pressure data found in Collett (1993).
- The methane hydrate stability zone is computed with the pressure–temperature conditions assumed above. We use the equation by Sloan and Koh (2008) to compute the phase boundary for pure methane gas hydrate, but we modify it to fit data points generated using the HWHYD software; for temperature higher than $0\,^{\circ}C$, the equation is $P\ [\text{kPa}] = \exp(40.234 - 8860/T\ [\text{K}])$. The effect of salt concentration on methane hydrate stability is also considered in this computation following Sloan and Koh (2008).

The computed depth-time evolution for hydrate and permafrost are summarized in Fig. 1. These results indicate that current hydrate-bearing sediments could have formed almost a million years before the onset of permafrost at Mount Elbert. The hydrate stability zone thickened as the base of the permafrost deepened. In fact, the permafrost invaded the pre-existing gas hydrate zone; therefore, ice and hydrate may coexist throughout the superposition depth. These results are compatible with hydrate formation sustained by the upwards migration of deep thermogenic gases, which became trapped together with shallower biogenic gases within the current gas hydrate stability zone and converted into hydrate as ground surface cooled in the Pleistocene epoch. Pre-existing free gas and high-conductivity faults can explain the high hydrate saturations found on the North Slope.

We can anticipate that preferential hydrate accumulation in the coarse-grained C and D units is due to either advective flow favored through the more permeable coarse-grained layers (methane transport dissolved in water), or gas invasion due to the low capillary entry pressures in coarse-grained layers with low fines content (methane transport in gas phase).

Could pore size shift pressure–temperature PT stability conditions in layers with high fines content and explain the absence of hydrate in these layers? We explore this situation taking into consideration the pressure–temperature conditions in Fig. 1. The void ratio with depth is computed using the standard 1D consolidation theory $e = e_{100} + C_c \log(\sigma'/\text{kPa})$ where e_{100} and C_c are sediment-dependent parameters (Burland, 1990). Pore size d_{pore} depends on void ratio and specific surface S_s and can be estimated as $d_{pore} = \alpha \times e/(S_s \times \rho)$ where ρ is the mineral mass density and α varies from $\alpha = 2$ for parallel face-to-face configuration to $\alpha = 6.2$ for edge-to-face aggregation of platy particles. Finally, the equilibrium temperature shift ΔT_{dep} due to pore size is computed for