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Pore fluid geochemistry from the Mount Elbert Gas Hydrate Stratigraphic Test Well, Alaska North Slope

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ABSTRACT

The BPXA-DOE-USGS Mount Elbert Gas Hydrate Stratigraphic Test Well was drilled and cored from 606.5 to 760.1 m on the North Slope of Alaska, to evaluate the occurrence, distribution and formation of gas hydrate in sediments below the base of the ice-bearing permafrost. Both the dissolved chloride and the isotopic composition of the water co-vary in the gas hydrate-bearing zones, consistent with gas hydrate dissociation during core recovery, and they provide independent indicators to constrain the zone of gas hydrate occurrence. Analyses of chloride and water isotope data indicate that an observed increase in salinity towards the top of the cored section reflects the presence of residual fluids from ion exclusion during ice formation at the base of the permafrost layer. These salinity changes are the main factor controlling major and minor ion distributions in the Mount Elbert Well. The resulting background chloride can be simulated with a one-dimensional diffusion model, and the results suggest that the ion exclusion at the top of the cored section reflects deepening of the permafrost layer following the last glaciation (~100 kyr), consistent with published thermal models. Gas hydrate saturation values estimated from dissolved chloride agree with estimates based on logging data when the gas hydrate occupies more than 20% of the pore space; the correlation is less robust at lower saturation values. The highest gas hydrate concentrations at the Mount Elbert Well are clearly associated with coarse-grained sedimentary sections, as expected from theoretical calculations and field observations in marine and other arctic sediment cores.

1. Introduction

Gas hydrates, crystalline substances composed of water and gas (Sloan, 1998), have long been known to occur in Arctic permafrost areas (e.g. Makogon et al., 1972; Bily and Dick, 1974; Galate and Goodman, 1982; Collett, 1993; Collett et al., 2008). In a recent effort from the U.S. Geological Survey and the Bureau of Land Management, a detailed geological and geophysical analysis was used to map the spatial distribution of the gas hydrate stability zone and assess the gas hydrate accumulations in the Alaska North Slope, within an area that extends from the National Petroleum Reserve of Alaska (NPRA) on the west, through the Alaska National Wildlife Refuge (ANWR) on the east (Collett et al., 2008).

The Alaska North Slope (ANS) is an east–west elongate basin that extends from the Brooks Range to the Arctic Ocean and that has accumulated sediment ranging in age from Mississippian through Quaternary (Fig. 1). Three principal sedimentary sequences have been identified in this region: the Ellesmerian (Mississippian through Triassic); the Beaufortian (Jurassic through early Cretaceous) and the Brookian (middle Cretaceous to Recent) (Bird, 1987, 1991; Mull et al., 2003). The Ellesmerian sediments were derived from a northern source area and deposited in a passive margin setting. The development of the Brooks Range compressional orogen began in late Jurassic and early Cretaceous (Fuis et al., 1997). The Beaufortian sequence is characterized by mud dominated sediment, with interbedded sandstone and shales and marks the end of passive sedimentation; its sediment source was local or from the north. The present Arctic Ocean opened in the mid to late Cretaceous, and clastic input shifted from the north to the south as a result of plate rotation, faulting and uplift of the Brooks Range. The deposition of the Brookian sequence began with proximal fan delta and turbidites, and succeeding prodelta and deltaic systems filled the newly formed Coville foreland basin from the south-west to the north-east. Stratigraphic correlations with previous outcrop

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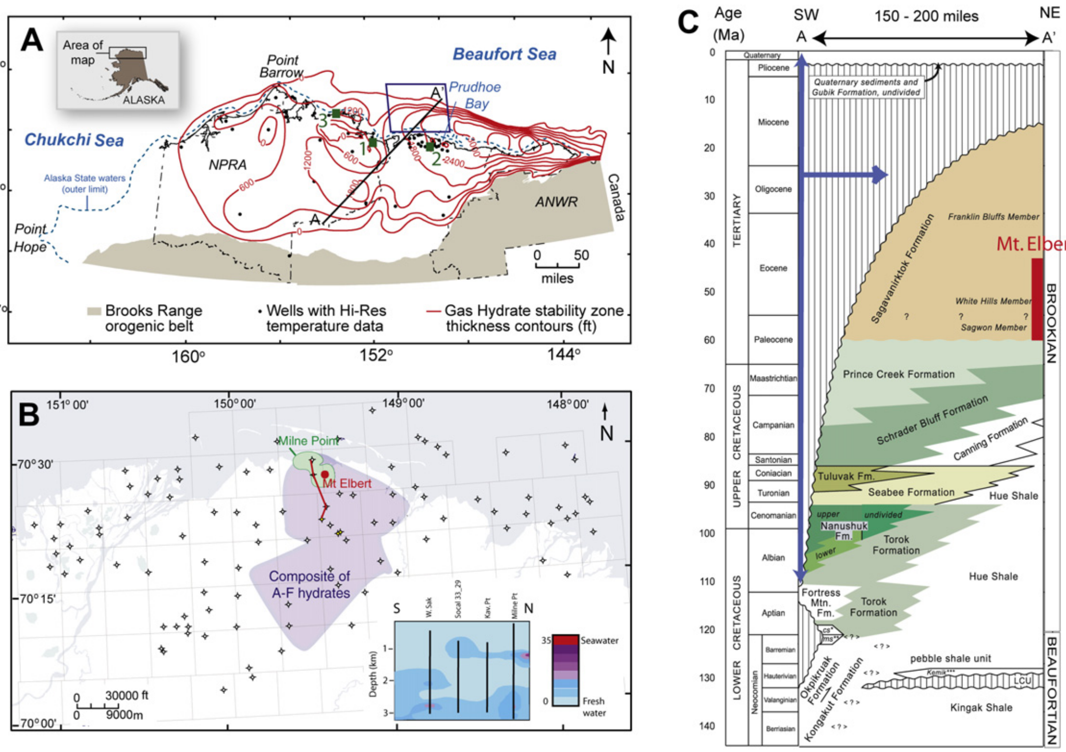

Fig. 1. A. Map of the North Slope of Alaska, showing the extent and thickness of the gas hydrate stability zone, the Brooks Range (shaded tan), National Petroleum Reserve of Alaska (NPRA) and the Arctic National Wildlife Refuge (ANWR). Inset shows location of the study area within Alaska; green boxes depict locations of Wells 1, 2 and 3 (Fig. 6), square purple box designates the region shown in panel B; and A–A′ denotes location of stratigraphic section shown in panel C. Figure modified from Collett (1993). B. Milne Point 3D survey region showing the location of the Mount Elbert Well (red circle) within the Milne Point Unit; composite of A–F hydrates refer to gas-hydrate-bearing sand units (modified from Collett, 1993), and red line designates transect of wells where formation salinity is available from spontaneous potential logs. Inset shows salinity contours (5 ppt interval), with fresh water represented in blue and fluids approaching seawater salinities in purple (from Belanger, 2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

and subsurface studies place the section recovered in BPXA-DOE-USGS Mount Elbert Stratigraphic Test Well (the Mount Elbert Well) within the Tertiary Sagavanirktok Formation, in the younger part of the Brookian Sequence (Fig. 1C; Mull et al., 2003; Rose et al., 2011).

Sediments from the Mount Elbert Well revealed shallow marine and non-marine depositional environments of latest Paleocene and early Eocene, which span an age of about 56–49 Ma (Hunter, 2008; Rose et al., 2011). Paleoceanographic records from the central Arctic document a shift from the relatively warm Eocene conditions to a colder "ice house" environment, but the timing and progress of this cooling is not certain because of an incomplete record between the middle Eocene and the early Miocene (Moran et al., 2006). The Arctic generally cooled from about 49 to 44 Ma, although the presence of abundant planktic microfossils during this time shows that permanent sea–ice had not yet developed (Moran et al., 2006). The onset of present day ice-bearing permafrost is thought to have occurred ∼1.65 Ma (Collett, 1993). Present day ice-bearing permafrost in the ANS thickens towards the north, where the base of this frozen layer reaches 600 m (Collett and Bird, 1988).

Salinity at the time of deposition ranges from fresh to marine. Uplift and subaerial erosion during the geologic evolution of the basin is thought to have induced significant meteoric flow, which may have displaced some of the older more marine formation fluids (Hanor et al., 2004). A northward topographically driven fluid flow is thought to have been active for the last 110 Ma, as the fluvial–deltaic Brookian systems began prograding from the Brooks Range (Hanor et al., 2004; Deming, 1993).

Although many wells on the ANS have likely penetrated gas hydrate accumulations (Fig. 1A), only in a limited number of these have sufficient core and well-log data been collected to allow for the robust quantification of these accumulations, and a good understanding of the hydrologic and geochemical processes that influence their distribution. The Mount Elbert Well was drilled to a depth of 605.6 m and cored from 605.6 m to 760.1 m in the Milne Point Unit (Fig. 1B), to evaluate the occurrence, distribution and formation of gas hydrate in sediments below the base of the ice-bearing permafrost, which in this well occurs at 536.4 m (Hunter et al., 2011).

This paper summarizes the interstitial water geochemical data for this Arctic sub-permafrost environment. Of particular interest is the observation of a "reverse" salinity distribution, with freshening downcore. Chloride and water isotopes indicate that the observed distributions originate from ion exclusion that occurred during deepening of the permafrost layer following the last glaciation (∼100 kyr), consistent with thermal model predictions (Majorowicz et al., 2008). Based on these results, we inferred a background in situ chloride distribution, which was used to calculate the gas hydrate saturation in the Mount Elbert Well.

2. Methods

A challenge commonly associated with recovering pristine formation fluids from drilled sections is the potential contamination with drilling fluids. Previous drilling in the Arctic used a water based KCL/polymer, and the infiltration of these fluids was observed to significantly affect the pore water chemistry, with a resulting increase in salinity by ∼2 ppt from drill mud contamination in the Mallik 2L-38 well (Cranston, 1999), and a 25–76% increase in the dissolved potassium in the pore fluids from Mallik 5L-38 (Matsumoto et al., 2005). The amount of water associated