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Earth and Planetary Science Letters

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Letters

Sedimentological control on saturation distribution in Arctic gas-hydrate-bearing sands

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ARTICLE INFO

Article history:

Received 2 May 2011

Received in revised form

2 June 2012

Accepted 11 June 2012

Editor: P. DeMenocal

Available online 7 July 2012

Keywords:

Mount Elbert well

GHSZ

gas hydrate

capillary entry pressure

ABSTRACT

A mechanistic model is proposed to predict/explain hydrate saturation distribution in “converted free gas” hydrate reservoirs in sub-permafrost formations in the Arctic. This 1-D model assumes that a gas column accumulates and subsequently is converted to hydrate. The processes considered are the volume change during hydrate formation and consequent fluid phase transport within the column, the descent of the base of gas hydrate stability zone through the column, and sedimentological variations with depth. Crucially, the latter enable disconnection of the gas column during hydrate formation, which leads to substantial variation in hydrate saturation distribution. One form of variation observed in Arctic hydrate reservoirs is that zones of very low hydrate saturations are interspersed abruptly between zones of large hydrate saturations. The model was applied to data from Mount Elbert well, a gas hydrate stratigraphic test well drilled in the Milne Point area of the Alaska North Slope. The model is consistent with observations from the well log and interpretations of seismic anomalies in the area. The model also predicts that a considerable amount of fluid (of order one pore volume of gaseous and/or aqueous phases) must migrate within or into the gas column during hydrate formation. This paper offers the first explanatory model of its kind that addresses “converted free gas reservoirs” from a new angle: the effect of volume change during hydrate formation combined with capillary entry pressure variation versus depth.

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1. Introduction

Prospecting for gas hydrates as a resource has only recently begun to adopt the perspective of exploring for petroleum systems (Collett et al., 2009). Gas hydrates are formed at low temperatures and generally high pressures (e.g. temperatures below 25 °C and pressures greater than 1.5 MPa for natural gas hydrates) which are typical of relatively shallow depths in oceanic sediments (Kvenvolden, 1988; Koh et al., 2002) or deeper sediments in the Arctic (Collett, 1993).

In deep ocean sediments hydrates occur in various morphologies (Sloan, 1998; Waite et al., 2009). Hydrates have been observed as disseminated grains filling pores (Dallimore and Collett, 2005; Fujii et al., 2008) and as complex networks of filled fractures and veins in fine grained sediments (Hadley et al., 2008; Holland et al., 2008). Beneath the Indian Ocean (offshore India) most of the recovered gas hydrate was found to exist in “combination reservoirs”, characterized as either pore-filling grains or as fracture-filling (in clay dominated sediments) (Collett et al., 2009).

In the Arctic such as Alaska’s North Slope (ANS), strata several meters thick, containing large saturations (65–75%) of gas hydrate are often separated by layers of varying thickness that contain little or no hydrate (Boswell et al., 2011). In addition, gas hydrates in permafrost regions have been commonly reported to occur with pore-filling morphology in sand-rich sediments (Dallimore and Collett, 2005).

Hydrate formation in sediments, especially in marine environments, has been subject to series of analyses. Predictive models of the process can be divided into two categories: (A) models assuming formation of hydrate from methane dissolved in water in which accumulation is driven by methane-saturated water entering the gas hydrate stability zone (GHSZ) or by providing methane from a biogenic source (Hyndman and Davis, 1992; Ginsburg, 1998; Xu and Ruppel, 1999; Buffett, 2000; Hensen and Wallmann, 2005; Bhatnagar et al., 2007) and (B) models assuming formation of hydrate at the interface between gaseous and aqueous phases in which accumulation is driven by methane gas phase entering the GHSZ (Torres et al., 2004; Liu and Flemings, 2006, 2007). One motivation for the latter class of models was that observed chloride concentrations and gas hydrate distributions could not be explained without assuming transport of free gas through GHSZ (Torres et al., 2004).

The model categories (A) and (B) address marine hydrate reservoirs. While there is no comparably mechanistic model of

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Nomenclature

D_{10} , D_{50} , D_{60}	10th, 50th and 60th percentile of grain size distribution, respectively (L)
g	gravitational acceleration (LT^{-2})
K	hydraulic conductivity (LT^{-1})
K_{trans}	total phase (gas+aqueous) volume transported per unit volume of hydrate formed (dimensionless)
k	permeability (L^2)
MW	molecular weight (M/M)
N	hydration number
n	number of moles (M)
P , P_c	phase pressure, and capillary pressure, respectively ($ML^{-1}T^{-2}$)
$P_{c,entry}$	capillary entry pressure ($ML^{-1}T^{-2}$)
R_n	gas phase molar ratio of transported phases (dimensionless)
R_v	gas phase volume ratio of transported phases (dimensionless)
r_{avg} , r_{eq}	average radius and equivalent radius, respectively (L)
S	saturation (dimensionless)
S_{gr}	residual gas saturation (dimensionless)
$S_{w,irr}$	irreducible water saturation (dimensionless)

T	temperature (Θ)
U	coefficient of uniformity (dimensionless)
V	volume (L^3)
\bar{V}	molar volume (L^3M^{-1})
z	depth (L)
ρ	density (ML^{-3})
σ	interfacial tension (MT^{-2})
μ	dynamic viscosity ($ML^{-1}T^{-1}$)
Δn	transported number of moles (M)
ΔV	transported volume (L^3)

Subscripts and superscripts

g, h, w	gaseous, hydrate, and aqueous phases, respectively
i, f	initial and final, respectively
d	dimensionless
<i>stoich</i>	associated with having the maximum possible hydrate saturation
1:1	associated with having the final hydrate saturation equal to the initial gas saturation
GWC	gas–water contact

hydrate formation for terrestrial hydrate accumulations, i.e. sub-permafrost hydrate reservoirs, in the literature, the overall process has been delineated. Boswell et al. (2011) listed several aspects of gas hydrate accumulations in the Arctic that support the interpretation of conversion of free gas accumulation to gas hydrate accumulations. The accepted scenario for Arctic hydrate reservoirs such as those of the Prudhoe Bay and Kuparuk River area in ANS is that gas first accumulated in shallow traps. A GHSZ was then established and ultimately expanded to encompass the gas reservoir in response to ancient climate cooling, i.e. imposition of Arctic conditions (Collett, 1993).

In this paper a more detailed model of the process of hydrate accumulation is proposed, based on the latter Arctic scenario. A major difference between this model and the marine models (A) and (B) is that instead of presuming fluxes of fluid(s) to the GHSZ, we presume that the base of GHSZ moves down to (and through) an existing petroleum system. Fluid flux occurs in our model (and plays an important role in determining saturation) but only as a response to BGHSZ motion. This downward movement of the BGHSZ occurred in the ANS roughly 1.8 Ma (Collett, 1993; Dai et al., 2011). For simplicity we also assume that CH_4 is the only constituent of the gas phase and the only guest molecule in the hydrate.

The motivation for a detailed process model is that the previous presentations of the above concept, i.e. descent of the GHSZ through a pre-established gas column (Collett, 1993; Boswell et al., 2011; Collett et al., 2011; Dai et al., 2011), did not explore the physical basis of how this conversion of gas accumulation to hydrate might proceed, nor did they consider implications and effects of variable geology/petrophysics as well as volume change during hydrate formation on the response of a free-gas/water system to the imposition of gas hydrate stability conditions. Observations in the well-characterized Milne Point Unit (MPU) hydrate accumulations, e.g. in Mount Elbert well, suggest that these effects could be significant. For example, large saturations of hydrate are often restricted to the upper part of the sand units (Fig. 1b). Several interpretations of rather abrupt changes between large (50–75%) and small (0–15%) saturations have been reported. In the upper hydrate-bearing sand unit of Mount Elbert well, known as Unit D (Collett, 1993), this

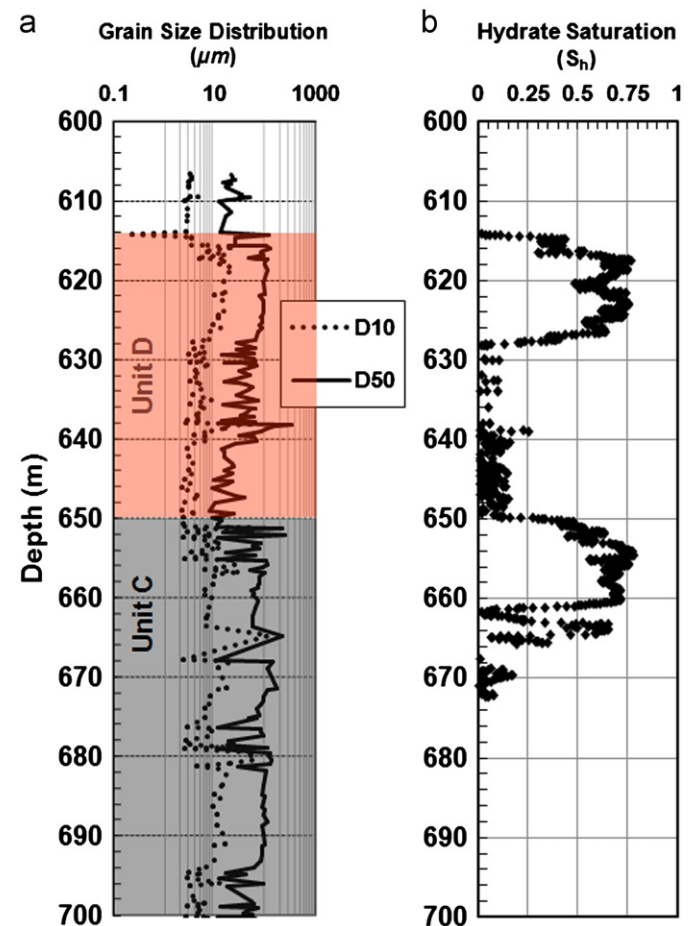


Fig. 1. Data from Mount Elbert stratigraphic test well, drilled in the Milne Point unit of Alaska North Slope: (a) 10th percentile, D_{10} , and 50th percentile, D_{50} , of grain size distribution versus depth determined from laser-grain-size analyses (Rose et al., 2011); (b) gas hydrate saturation, S_h , determined from the TCMR-repeat-pass-plus-density log based on NMR-DEN POR method (Lee and Collett, 2011). The shown interval of interest includes the informally labeled C and D units of Collett (1993).

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