Marine and Petroleum Geology 58 (2014) 99–116

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Anomalous porosity preservation and preferential accumulation of gas hydrate in the Andaman accretionary wedge, NGHP-01 site 17A

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ARTICLE INFO

Article history:
Received 30 November 2013
Received in revised form
22 April 2014
Accepted 23 April 2014
Available online 6 June 2014

Keywords:
Porosity
Permeability
Grain size
Indian Ocean
Gas hydrate
Saturation
Volcanic ash
Carbonate

ABSTRACT

In addition to well established properties that control the presence or absence of the hydrate stability zone, such as pressure, temperature, and salinity, additional parameters appear to influence the concentration of gas hydrate in host sediments. The stratigraphic record at Site 17A in the Andaman Sea, eastern Indian Ocean, illustrates the need to better understand the role pore-scale phenomena play in the distribution and presence of marine gas hydrates in a variety of subsurface settings. In this paper we integrate field-generated datasets with newly acquired sedimentology, physical property, imaging and geochemical data with mineral saturation and ion activity products of key mineral phases such as amorphous silica and calcite, to document the presence and nature of secondary precipitates that contributed to anomalous porosity preservation at Site 17A in the Andaman Sea. This study demonstrates the importance of grain-scale subsurface heterogeneities in controlling the occurrence and distribution of concentrated gas hydrate accumulations in marine sediments, and document the importance that increased permeability and enhanced porosity play in supporting gas concentrations sufficient to support gas hydrate formation. The grain scale relationships between porosity, permeability, and gas hydrate saturation documented at Site 17A likely offer insights into what may control the occurrence and distribution of gas hydrate in other sedimentary settings.

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1. Introduction

Natural gas hydrates, ice-like crystalline compounds composed of water molecules surrounding molecules of natural gas, occur in a variety of geologic environments. Most commonly, natural gas hydrates (NGHs) are found in marine sediments where conditions supporting the formation of the gas hydrate stability zone (GHSZ) exist, including high pressures and low temperatures (Sloan and Koh, 2008) and abundant methane to establish the clathrate structure. Globally, estimates of NGH occurrences vary, (Frye, 2008; Frye et al., 2013; Johnson, 2011; Kvenvolden, 1988; Kvenvolden and Lorenson, 2000; MacDonald, 1990; Max et al., 2006; Milkov, 2004), however most estimates agree that significant abundances of organic carbon are trapped in NGH accumulations predominantly as methane gas (250,000 to 1,250,000 trillion cubic feet). In the marine environment, sediments in the GHSZ are often associated with slope and basin settings. These settings are dominantly composed of fine-grained silt and clay lithofacies with generally low vertical permeability, and pore fluids are frequently under-

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http://dx.doi.org/10.1016/j.marpetgeo.2014.04.009
0264-8172/Published by Elsevier Ltd.

saturated with respect to methane, the most common natural gas found in hydrate systems on Earth (Sloan and Koh, 2008). As a result, while the conditions for the GHSZ may be widely present in appropriate marine settings, the distribution of NGH in the subsurface is neither ubiquitous nor uniform.

Field and laboratory studies have shown that the controls on the distribution and occurrence of NGH in marine sediments vary and are largely tied to site-specific factors including but not limited to, sediment composition and grain size, the nature and volume of the gas source, pathways and mode of gas migration, pore-fluid chemistry, and the porosity and permeability of the host strata. Studies from regions such as the Cascadia Margin (Malinverno, 2010; Malinverno et al., 2008; Torres et al., 2008; Trehu et al., 2004), the Gulf of Mexico (Boswell et al., 2012; Collett et al., 2012; Cook and Malinverno, 2013; Lee et al., 2012), and Nankai trough (Uchida et al., 2009) have demonstrated that NGH will preferentially form at higher concentrations in more porous and permeable sedimentary layers, such as sand and volcanic ash beds. There is growing evidence that properties such as grain size, composition, and gas migration may contribute to complex distributions of gas hydrate saturation within porous-permeable reservoirs themselves (Boswell et al., 2011, 2012; Collett et al., 2011, 2012; Lee and Collett, 2011; Lee et al., 2012; Rose et al., 2011). Field, modeling, and laboratory studies (Kneafsey et al., 2009; Lu et al., 2011; Malinverno, 2010; Shankar and Riedel, 2013; Torres et al., 2008) indicated that for the majority of marine systems, which are dominantly fine-grained with discrete, well-constrained porous and permeable layers, a general relationship exists between higher NGH saturations and grain size of the host sediment. However, studies of NGH accumulations both onshore (Collett et al., 2012; Rose et al., 2011) and offshore (Bahk et al., 2011, 2014, 2013; Collett et al., 2012; Torres et al., 2008) increasingly illustrate that hydrate distribution within the GHSZ does not always have a simple relationship with grain size.

The research presented here takes advantage of sediment core and borehole related data recovered by drilling at Site 17 in the Andaman Sea during the Indian National Gas Hydrate Program Expedition 1 (NGHP-01) in 2006, to investigate reservoir-scale controls on gas hydrate distribution. From the cored borehole, Site 17A, we recovered low concentrations of NGH throughout most of the GHSZ, however, higher NGH saturations were consistently observed within the more porous and permeable volcanic ash-bearing intervals (Collett et al., 2008). To enhance our understanding of the mechanisms that lead to the observed NGH distribution, we conducted additional analyses lithology (including composition and grain size), and dissolved silica and calcium. We used a scanning electron microscope (SEM) with a back-scatter electron detector (BSE) and energy dispersive spectroscopy (EDS) to conduct image and compositional analyses of select sediment samples at Site 17A. These data were integrated with field lithostratigraphic and post-cruise datasets in order to evaluate the role that sediment composition, texture, and the occurrence and distribution of secondary precipitates play in enhancing gas hydrate saturation at Site 17A.

We show that the porosity profile observed in borehole geophysical data and physical properties measured in core samples (Collett et al., 2008) at Site 17A relative to the expected profile (see Hamilton, 1976) for a calcareous nannofossil ooze is anomalous. In particular, at Site 17A the porosity profile is enhanced relative to expected porosity from 225 m below seafloor (mbsf) to total depth (TD) of the well as a result of secondary mineral precipitates. When this relationship is evaluated against grain size measurements for the entire sediment core interval, and gas hydrate saturations (Collett et al., 2008), we show that hydrate occurrence greater than 10% of the pore volume preferentially occurs in coarser grained, and more well sorted lithofacies. This relationship illustrates the complex balance and lithology-driven controls on hydrate accumulations of higher concentrations.

2. Geologic setting

2.1. Tectonic and sedimentary setting

The Andaman-Sunda basin formed as a result of subduction of the Indian Plate beneath the Sunda Plate over the past ~65 Ma (Pal et al., 2003) (Fig. 1). The Andaman Island Arc complex lies in the central portion of the 5000 km long Burma-Sunda-Java subduction complex (Pal et al., 2003). NGHP-01 Site 17A (Fig. 1) is located within the accretionary wedge along the Andaman-Sunda portion of this complex near the plate boundary between the Indian Plate and the Sunda Plate (Curray, 1979; Curray, 2005; Curray and Moore, 1974). East of the Andaman-Sunda arc complex, backarc extension, initiated between 11 and 4 Ma resulted in the present day Andaman basin (Pal et al., 2003; Raju et al., 2007; Rodolfo, 1969). The Andaman-Sunda wedge, forearc, and back-arc, is dominated by regional reverse, extensional, and transform faults that strike roughly parallel with the north–south axis of the Andaman Trench (Krishna and Sanu, 2002; Rodolfo, 1969). In addition, tectonic folds of varying amplitude are also pervasive throughout the western portion of the region. These compressional folds are part of the accretionary wedge, which lies between the extensional Eastern Margin Fault and compressional Diligent Fault (Cochran, 2010). NGHP-01 Site 17A (Fig. 1) sits near the crest of a broad anticlinal fold which is underlain by the Diligent Fault in the Andaman accretionary wedge to the east of Little Andaman Island (Cochran, 2010; Collett et al., 2008).

Deposition in the northern portion of the Andaman basin is dominated by siliciclastic sedimentation. These include Miocene to recent age deposits, primarily sourced from the Irrawaddy Delta system (Mohan et al., 2006). Irrawaddy siliciclastics are delivered from the northern shelf into the Andaman basin primarily via turbidity flows. However, bathymetric complexities, including the Andaman-Nicobar Ridge that lies between the deltaic source and the Nicobar Deep, may restrict the transport of Irrawaddy derived sediments to the northern Andaman basin. The lithologic sequence at NGHP-01 Site 17A, situated in the Andaman wedge, is dominated by pelagic (biogenic dominated) sedimentation (Collett et al., 2008; Cawthern et al., 2014), receiving little to no coarse siliciclastics from the adjacent land masses (Fig. 1). Structural down warping on the outboard side of the Andaman margin results in a low geothermal gradient and marine biogenic organic matter present throughout the section supports methane production (Johnson et al., 2014). Both of these conditions support the occurrence of an anomalously thick GHSZ in this basin, which at NGHP-01 Site 17A extends from the seafloor to 605 mbsf (Collett et al., 2008).

Drilling and coring at Site 17 confirmed the presence of methane hydrate-bearing sediments and provided information about the conditions that produced these accumulations (Collett et al., 2008). The dominant lithologies observed in cores recovered from NGHP-01 Site 17A were biogenic oozes. The sedimentary record throughout the Andaman Basin is also punctuated by distinct, volcanic ash beds recording the volcanic history of the arc from the Cenozoic to the present (Cawthern et al., 2010; Rodolfo, 1969). The ash layers at Site 17A that serve as the dominant host lithology for NGH occurrences are related to volcanic activity in the Andaman region since the Miocene (Cawthern et al., 2010; Collett et al., 2008).