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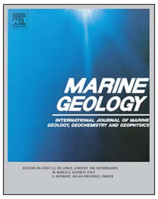

Relationship between fluid-escape pipes and hydrate distribution in offshore Sabah (NW Borneo)

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ABSTRACT

Fluid-escape pipes represent seismic evidence for the focused cross-stratal migration of fluids. In natural gas hydrate systems, these features serve both as conduits for methane-rich fluids and as preferred locations for the formation of gas hydrates. In this study, 3D seismic, well-log and core data from offshore Sabah (NW Borneo) are used to investigate the controls on the occurrence of fluid-escape pipes and their impact on hydrate distribution in a system dominated by the vertical leakage of thermogenic hydrocarbons.

The pipes are observed within a gas hydrate stability zone (GHSZ) that extends 100 m below a bottom simulating reflector (BSR), located at 155 m below the seafloor (mbsf). Pipes are restricted to an area with evidence of free gas-bearing sediments, suggesting a causative link where the free gas promotes the build-up of critical fluid pressures. The stacking of the upper terminus of fluid-escape pipes at discrete stratigraphic intervals suggests that fluid flow to the seabed has been episodically enhanced. Possible triggers for cyclical increases of pore fluid pressures are sea-level and temperature fluctuations, tectonic activity and gas leakage from deep reservoirs.

This fluid flow system further impacts the gas hydrate distribution. The fluid-escape pipes can be locations where hydrates occur at high concentrations up to the seafloor if the pipe is presently active. Therefore, the observed up-bending of the stratigraphic reflections along the pipes are interpreted as a combination of a net volume increase of the host sediment owing to hydrate formation and seismic velocity pull-up effects. Away from the pipes, hydrates do not occur until 65–152 mbsf and are present only at low to moderate concentrations. At this site of focused fluid flow, fluid-escape pipes constitute, by volume, only 7–11% of the gas hydrate occurrence zone. Nevertheless, we predict that they could host between 20 and 50% of the whole hydrate volume. It is therefore likely that, in similar systems, a volumetrically significant portion of the total hydrate reservoir is hosted within fluid-escape pipes. The distribution of these features should thus be considered as a critical parameter for hydrate volume estimates.

1. Introduction

In fine-grained sequences, the migration of hydrocarbon-rich fluids often occurs through vertical to sub-vertical pathways which may terminate at the seafloor as pockmarks, mounds and mud-volcanoes (Hustoft et al., 2007; Judd and Hovland, 2007). Fluid-escape pipes are vertical to sub-vertical elongated zones having a width ranging from a few tens to a few hundred metres, with a seismic character disrupting an otherwise continuous stratigraphy (Cartwright and Santamarina, 2015). Similar but occasionally larger features have also been referred to as gas/fluid-escape chimneys, although there is considerable latitude in the use of these terms (Løseth et al., 2009; Bertoni et al., 2017).

These hydrocarbon migration phenomena can be further influenced by natural gas hydrates, whose stability is controlled by the in-situ thermobaric conditions, pore water salinity, pore-network geometry and chemical composition of the gas involved in the hydrate formation (Collett et al., 2009). These factors define the thickness of the gas hydrate stability zone (GHSZ), commonly overlying a volume of free gas-bearing sediments, termed the free gas zone (FGZ). The upper boundary of the FGZ is frequently imaged in seismic data as a bottom-simulating reflector (BSR) (Holbrook et al., 1996; Haacke et al., 2007; Shedd et al., 2012).

The analysis of seismic reflection data from various basins has revealed that hydrocarbon gases migrate throughout the GHSZ along

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pipe-like conduits (Gorman et al., 2002; Gay et al., 2006; Riedel et al., 2006; Plaza-Faverola et al., 2011). Geophysical models and direct sampling have shown that hydrates accumulate at extremely elevated saturations along these pipe-like conduits, in the form of pure grain-displacing lenses and veins (Westbrook et al., 2008; Plaza-Faverola et al., 2010; Chun et al., 2011; Torres et al., 2011; Attias et al., 2016; Matsumoto et al., 2017). Given the high concentration of hydrates potentially stored within these features, it is important to understand better their seismic-scale expression, as well as the factors controlling their distribution and activity.

The intensity of fluid flow across the GHSZ varies at short time-scales (e.g. days-years) and scales of thousands to hundreds of thousand years. In this latter case, major triggers for fluid flow are global sea-level and temperature fluctuations, ice sheets loading and unloading, and the regional tectonic activity (e.g. Hustoft et al., 2010; Andresen and Huuse, 2011; Plaza-Faverola et al., 2011, 2015; Andreassen et al., 2017). These events can induce hydrate dissociation, leakage of fluids from deep reservoirs and submarine landslides along continental slopes (Vogt and Jung, 2002; López et al., 2010; Berndt et al., 2012; Riboulot et al., 2013).

Furthermore, in the presence of leaky thermogenic petroleum systems, hydrocarbons heavier than methane (C_{2+}) can be incorporated into structure II (S_{II}) and structure H (S_H) hydrates. In such cases, the thickness of the GHSZ is increased, and S_{II} and S_H hydrates may occur below BSRs (Sassen et al., 2001b; Lu et al., 2007; Hadley et al., 2008; Paganoni et al., 2016; Liang et al., 2017).

The deepwater fold and thrust belt offshore Sabah (NW Borneo) provides an ideal location for the study of the natural gas hydrate systems fed by leaky thermogenically-sourced reservoirs (Warren et al., 2010). In this study, we extend the analysis of the natural gas hydrate system at the crest of the bathymetric ridge overlying the Gumusut-Kakap hydrocarbon accumulation (cf. Hadley et al., 2008; Paganoni et al., 2016), located in this region, with new observations and interpretations. Our main aim is to characterise the seismic expression of fluid flow across the GHSZ, in order to evaluate the controls on the occurrence and on the genesis of fluid flow features interpreted as fluid-escape pipes, as well as the potential triggers for their formation and their impact on the distribution of gas hydrates.

2. Data and methods

The seismic data shown in this research was acquired in Block K offshore Sabah by Shell (Fig. 1a, b) and consists of a high-resolution 3D seismic post-stack dataset, covering a region of ~37 km^2, at water depths between ~850 and ~1250 m. The vertical resolution of this dataset is approximately 5 m, for seismic velocities between 1500 and 1650 m/s for the first 200 ms TWT below the seafloor. The dominant frequency of these data is higher than 100 Hz in the first ~200 ms TWT below the seafloor. However, it is frequently less than ~50 Hz within zones interpreted as free gas-bearing sediments, where the vertical resolution decreases. A lower resolution dataset (45 Hz dominant frequency), having a vertical resolution of approximately 10 m and covering a broader area (~890 km^2) further provides the necessary framework for the regional structural setting and to image deeper structures. The inline and crossline spacing of the high- and low-resolution dataset are of 6.25 and 25 m, respectively. Lateral resolution is taken as being comprised between the bin spacing and the dominant wavelength, with a 6.25–20 m range for the high-resolution dataset and in a 25–50 m range for the low-resolution one (Cartwright and Huuse, 2005).

Following a North American polarity convention, both these datasets have been phase-shifted by -90° for the seismic interpretation. An increase in the acoustic impedance is termed a positive or '*hard reflection*' (e.g. the seafloor), expressed in the wiggle-traces as a trough followed by a peak and displayed in seismic cross-sections as a red-blue combination. Vice-versa, an opposite character is displayed by a decrease in the acoustic impedance, which results in a negative reflection, termed a '*soft reflection*' (e.g. the top of a free gas accumulation).

The seismic data were interpreted with the Petrel E & P Software Platform, and the area of interest is located at the crest of a prominent bathymetric ridge overlying the Gumusut-Kakap hydrocarbon accumulation. Key stratigraphic horizons, as well as faults and various features indicative of fluid flow, have been mapped and interpreted (cf. Løseth et al., 2009; Andresen, 2012). The extraction of specific seismic attributes, including amplitude (e.g. RMS amplitude) and dip-related (e.g. dip and variance) attributes, was performed on vertical seismic sections and specific stratigraphic horizons. Amplitude-related attributes are useful in detecting anomalies associated with gas (i.e. soft reflections), gas hydrates or authigenic carbonates (i.e. hard reflections) (cf. Roberts et al., 2006; Judd and Hovland, 2007). Dip-related attributed are used to identify features with discordant or irregular geometries with respect to the background, like faults and other zones of cross-stratal fluid-flow (e.g. Ligtenberg, 2005; Plaza-Faverola et al., 2012). Depth measurements from the seismic data were based on seismic interval velocities ranging between 1500 and 1700 m/s and are accompanied by the associated TWT measurements throughout the text.

In this study, the seismic data are integrated with wireline acoustic logs acquired with the Cross-Multipole Array Acoustic log from Baker Hughes (XMAC) at the borehole location named DC_E (see Fig. 2 for location). The quality of the borehole is assessed with a 6-arm caliper. This data has been previously used, in conjunction with a density log obtained while drilling with the Halliburton tool, to create a synthetic seismogram used to tie the well with the seismic data. An abrupt decrease in the wireline P-wave velocity at approximately 155 m below the seafloor (mbsf) was associated with a BSR while the presence of gas hydrates was constrained with core data at DC_E and resistivity LWD measurements at DC_E and in other three sites (M_1, DC_F and L_2, see Fig. 2) (Paganoni et al., 2016). All four boreholes were drilled within an area characterised by abundant evidence of free gas, located at the crest of the bathymetric ridge overlying the Gumusut-Kakap accumulation. However, none of these boreholes passed through a fluid escape pipe.

The phase-shift deep smoothed resistivity measurements, acquired while drilling with the EWR®-Phase 4 multiarray propagation tool, were used at these sites to extrapolate the gas hydrate saturation (*Sh*, % of pore space) (Paganoni et al., 2016). In this work, we present averaged and smoothed *Sh* profiles along these four boreholes, to provide a general view of the hydrate distribution and saturation in the area. An additional constraint on hydrate saturation and methane fluxes comes from the chlorinity anomalies measured in cores retrieved at DC_E (see Paganoni et al., 2016), and from the pore water sulphate concentrations at the same location. The pore water chlorinity and sulphate content measurements were made by titration with silver nitrate (error = ± 1%) and by barium sulphate nephelometry (error = ± 2%), respectively, on pore water samples obtained by squeezing selected core plugs in a press. The core plugs for sulphate measurements have been retrieved with a core liner whereas samples for chlorinity measurements were obtained with the Fugro Pressure Corer, Fugro Corer and Shelby tube systems. *Sh* from chlorinity measurements has been estimated by comparing the measured chlorinity with a '*baseline*' trend, extrapolated empirically (Ussler and Paull, 2001; Paganoni et al., 2016). A further LWD resistivity profile, obtained at a borehole site named site M_2, drilled at the crest of the bathymetric ridge but outside areas of shallow free gas occurrence, will be shown (Fig. 2). This information is used to evaluate if hydrates, at this location, occur without any evidence of free gas.

The well-log and core data are used to evaluate the volumetric distribution of gas hydrates outside the vertical zones of cross-stratal focused fluid flow interpreted as fluid-escape pipes. The hydrate concentration within fluid-escape pipes in this study area is unknown, but drilling information and modelling of geophysical data from other gas