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Deepwater canyons: An escape route for methane sealed by methane hydrate

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ABSTRACT

Three-dimensional seismic imaging and modelling of gas hydrates from offshore of west Africa (Mauritania) shows that submarine canyons on stable continental slopes can capture and release methane that is sealed by methane hydrate. We demonstrate this by focussing on a canyon which is ~200 km long, 2.4 to 3.1 km wide, up to 550 m deep and has canyon walls that dip at 25°-30°. Incision of the canyon causes cooling of the surrounding sediment and deepening of the base of the methane hydrate stability zone. The base of the hydrate deepens by up to 550 m and also dips at 25°–30°, parallel to the canyon margins. It forms a continuous or semi-continuous wall of lower permeability sediment that can be mapped along the canyon margins on the basis of aligned high amplitude reflection terminations. Theoretically these methane barriers could extend for 10 s to 100 s of kilometres parallel to both canyon walls. Several free gas accumulations are sealed laterally in this way in a canyon margin free gas zone. Large failures of the sides of the canyon, remove the lower permeability hydrate, allowing free methane to leak. Globally, submarine canyons and marine gas hydrates occur in similar places on continental margins and canyons incise to depths that are comparable with the position of base of the methane hydrate stability zone. Therefore deepening of the base of the hydrate as a result of the cooling effect of canyons should be common and this mechanism for methane trapping and release could be generally applicable to present and past marine methane hydrates.

1. Introduction

Methane release from gas hydrates has been proposed as a mechanism for past (Dickens et al., 1995; Hesselbo et al., 2000) and potentially future climate change (Kennett et al., 2000). Methane can be stored as a hydrate (e.g. Kvenvolden, 1993) and as free gas in porous strata sealed below the hydrate in a free gas zone (FGZ) (e.g. Dillon et al., 1980; Hornbach et al., 2004). The transition between the gas hydrate and the free gas zone corresponds to the base of the gas hydrate stability zone (BHSZ) and is commonly marked by a high amplitude, negative polarity seismic reflection or reflection terminations that align parallel to the seabed (Field and Kvenvolden, 1985). This is commonly termed a bottom simulating reflection (BSR).

There are several potential leak mechanisms for methane within hydrate and sealed below it in the FGZ, some could operate globally and others locally. Global climate change could cause hydrate to dissociate due to increased seabed temperature (Dickens, 2001; Westbrook et al., 2009). Alternatively sea-level fall causes hydrostatic pressure to drop and induces hydrate dissociation (e.g. Kvenvolden, 1993). There are several local mechanisms that have also been proposed. Localised hydrate dissociation may cause slope failure causing additional methane release (e.g. Kvenvolden, 1993). The thickness of the FGZ below the hydrate can increase until it is critically pressured, triggering the failure of the hydrate seal (Flemings et al., 2003; Hornbach et al., 2004). Methane from beneath the hydrate could also bypass the gas hydrate along faults and gas chimneys (Gorman et al., 2002). Lastly, deepwater currents could erode gas hydrate (Bangs et al., 2010; Holbrook et al., 2002). But some methane hydrates are hosted on stable slopes which are clearly susceptible to dissociation and methane escape due to global mechanisms but lack any evidence for local leak mechanisms.

In this paper we focus on the role of canyons on stable continental margin slopes for trapping and escape of methane. Canyons are common on continental slopes and at least 660 major deepwater canyons have been identified to date (De Leo et al., 2010). They can form landward (Popescu et al., 2004) but usually basinward of the shelf break, at water depths of 100 to 4500 m (De Leo et al., 2010) and are 10–1000 m deep (e.g. Deptuck et al., 2007; Gay et al., 2007; Popescu et al., 2004). Methane hydrate forms in marine sediment where the water depth is about 400 m (Milkov and Sassen, 2002). As water depth increases the base of the hydrate stability zone deepens and is usually located 0–500 m below the seabed (Davies and Clarke, 2010; Dickens, 2001). Therefore methane hydrates and canyons occupy similar positions on continental slopes and island margins (Fig. 1) and the bases of methane hydrate deposits and the bases of canyons form at comparable depths below the seabed (Fig. 1) (Lüdmann et al., 2004, their Fig. 3). We analyse one example of the co-existence of a canyon and hydrate on the west African margin, offshore of

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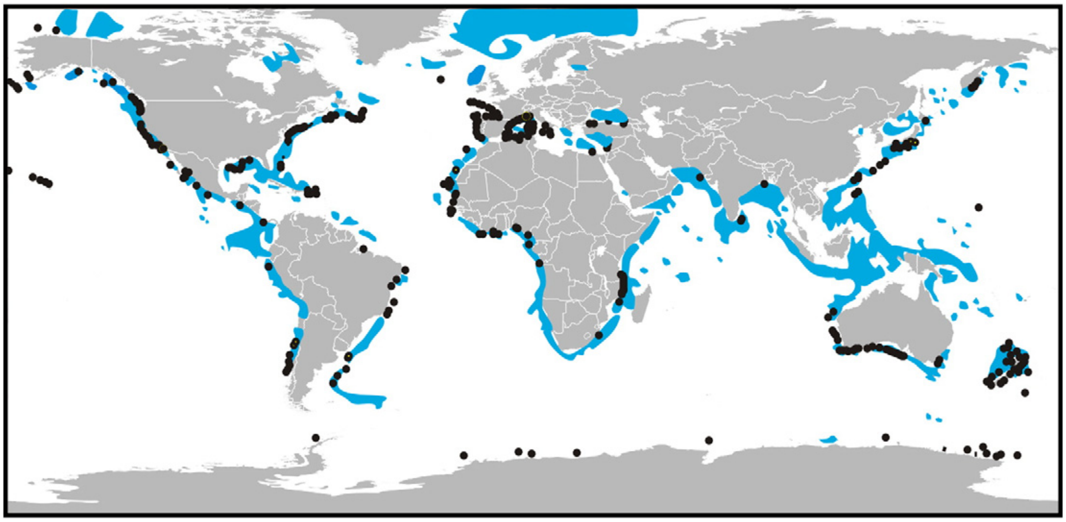

Fig. 1. Map of the globe showing the predicted location of methane hydrate (blue) in water depths<3000 m (after Klauda and Sandler, 2005) and the known locations of 660 canyons (black dots) — after De Leo et al. (2010).

Mauritania. We use three-dimensional (3D) seismic data and modelling to consider the impact of canyon development on hydrate formation, and evaluate the role of canyons as an alternative mechanism for the capture and release of methane that is sealed by gas hydrate.

2. Geological setting and data

The Mauritanian continental slope is characterised by major slide complexes, shelf cutting gullies and canyons (Henrich et al., 2010; Krastel et al., 2006) – Fig. 2a. Sedimentation occurs as a result of debris flows, turbidity currents and hemi-pelagic settling (Henrich et al., 2010). The Mauritania slide complex, covers 34,000 km^2 and is 165 ka old (Krastel et al., 2006). But significant sections of this and other margins show no evidence of major slide complexes or leak along faults and the ~2000 km^2 study area upon which we focus is instead characterised by major canyons (Fig. 2b). The canyons are at least 165 ka old (Krastel et al., 2006) and assuming a constant sedimentation rate they probably incise through Recent to Quaternary age (~2.5 m.y) sediments. A representative canyon (termed canyon 1, Fig. 2b) is ~200 km long (Krastel et al., 2006) and within the study area it is 2.4 to 3.1 km wide, 400–550 m deep. The canyon walls dip at 25°–30°. A 30.5 km length of it is imaged by the 3D seismic survey (Fig. 2b). The closest boreholes are the Chinguetti V1 and Chinguetti-6-1 hydrocarbon exploration wells located within the area covered by the 3D seismic data and they show that the stratigraphy within which the methane hydrate is located is Recent to Pliocene in age (Vear, 2005). Cores of the uppermost 10 m of the succession ~100 km to the north, on the margins of Timiris Canyon show that the sediment comprises of foraminiferous and terrigenous mud and siliciclastic turbidites (Henrich et al., 2010). The 3D seismic data were acquired in 1999 and 2000 for hydrocarbon exploration using a towed streamer. They were processed using a standard sequence of steps including multiple suppression and post-stack time migration and displayed in two-way-travel time. Seismic line spacing is 25 m. The vertical resolution (one quarter of the seismic wavelength) is ~10 m for the studied interval. Red-black and black-red reflections correspond to increases and decreases in acoustic impedance respectively.

3. Seismic observations

The base of gas hydrate (Fig. 3ab) has been interpreted on the basis of aligned amplitude terminations or a cross cutting reflection (herein termed the BSR) over an area of 1880 km^2 (Davies and Clarke, 2010). Below it are a number of anomalously high amplitude reflections that have been interpreted to represent gas accumulations (Davies and Clarke, 2010). The BSR can be mapped on the 3D seismic data with confidence on both on sides of canyon 1. At canyon 1 the BSR deepens significantly, tracking its margins and dipping at 25°–30° (Fig. 4abc). We cannot map it below the canyon. Five stacked amplitude anomalies that have the opposite polarity to the seabed reflection (black–red) terminate ~0.5 km from the canyon margin (black arrows on Fig. 4b). This is demonstrated for the shallowest of these (marked by a blue dashed line in Figs. 4bc) which has a remarkably consistent lateral termination at a distance of ~0.5 km from the canyon margin (yellow dashed line in Fig. 4a). The anomaly does not have an obvious sedimentary planform and no clear relationship to structure, such as a consistent updip or downdip extent. There are no faults penetrating the interval where these reflections are identified. There is evidence for similar high amplitude reflections along the opposing canyon margin which also terminate at the same distance from the canyon wall (yellow dashed line on opposing margin in Fig. 4ac).

Some sections of the canyon margins are characterised by extensional faults that have curved planforms. The failure planes are listric and sole out to become bedding parallel before intersecting the canyon wall. In the study area we identify two significant failures (canyon wall failures 1 and 2 — Fig. 5abcd). The headscarps for the failures intersect the seabed at a distance of between 0.45 and 1.3 km from the canyon margin (e.g. Fig. 5bcd). The failure scarp is also not draped by sediment that is seismically resolvable. Similar scale canyons and canyon margin failures are imaged at the Timiris Canyon approximately 100 km to the North (Henrich et al., 2010). We note that where canyon wall failures 1 and 2 occur the BSR reflection and the amplitude anomalies seen elsewhere (e.g. Fig. 4abc) are not identified.

4. Modelling

The downward deflection of the BSR could be due to the resetting of the BHSZ as a result of the canyon development. To test this we have predicted its position at steady state. We used the hydrate stability curve for pure methane given by Moridis (2003) with a correction for sea water salinity of 35 wt.%. Because of the shallow burial depths, pore pressure in the sediment surrounding the canyon was assumed to be hydrostatic and the temperature was calculated by direct solution of the steady-state heat conduction equation

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} = 0 \quad (1)$$