Earth and Planetary Science Letters 423 (2015) 202–209

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

An irregular feather-edge and potential outcrop of marine gas hydrate along the Mauritanian margin

Richard J. Davies [a,*], Jinxiu Yang [b,c], Ang Li [c], Simon Mathias [c], Richard Hobbs [c]

[a] *School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, Tyne and Wear, NE1 7RU, UK*
[b] *Research Institute of Unconventional Oil & Gas and New Energy, China University of Petroleum (Huadong), No. 66 Changjiang West Road, Huangdao District, Qingdao, Shandong, 266555, China*
[c] *Centre for Research into Earth Energy Systems (CeREES), Department of Earth Sciences, Durham University, Science Labs, Durham DH1 3LE, UK*

ARTICLE INFO

Article history:
Received 16 July 2014
Received in revised form 4 April 2015
Accepted 9 April 2015
Available online 17 May 2015
Editor: J. Lynch-Stieglitz

Keywords:
hydrate
seabed
dissociation
warming
reflection
gas

ABSTRACT

The dissociation of marine hydrate that surrounds continental margins is thought to be an agent for past and future climate change. As the water depth decreases landwards, the base of the hydrate stability zone progressively shallows until hydrate can occur at or immediately below the seabed where an increase in bottom water temperature can cause dissociation. But the true extent of these most vulnerable hydrate deposits is unknown. Here we use exceptional quality three-dimensional (3-D) seismic reflection imagery offshore of Mauritania that reveals a rare example of a bottom simulating reflection (BSR) that intersects the seabed and delineates the feather-edge of hydrate. The BSR intersects the seabed at the ∼636 m isobath but along the 32 km of the margin analysed, the intersection is highly irregular. Intersections and seismic evidence for hydrate less than ∼4.3 m below the seabed occur in seven small, localised areas that are 0.02–0.45 km^2 in extent. We propose gas flux below the dipping base of the hydrate to these places has been particularly effective. The intersections are separated by recessions in the BSR where it terminates below the seabed, seawards of the 636 m isobath. Recessions are areas where the concentration of hydrate is very low or hydrate is absent. They are regions that have been bypassed by gas that has migrated landwards along the base of the hydrate or via hydraulic fractures that pass vertically through the hydrate stability zone and terminate at pockmarks at the seabed. An irregular feather-edge of marine hydrate may be typical of other margins.

1. Introduction

Marine gas hydrate is a solid compound of water and gas that occurs in many settings, including sediment surrounding deep water continental margins. The stability of hydrate is related to temperature and pressure (P–T) and in these settings the progressive landward reduction in water depth causes the base of the gas hydrate stability zone (BHSZ) to shallow and intersect the seabed. This configuration results in a potential hydrate zone that thins in a landward direction (Dickens, 2001; Milkov and Sassen, 2000) that has been termed the feather-edge of marine hydrate (Fig. 1A; Ruppel, 2011).

The feather-edge holds ∼3.5% (Ruppel, 2011) of the estimated $\sim 7 \times 10^2$ to $\sim 1.27 \times 10^4$ Gt of carbon held in marine hydrates (Dickens, 2011). Where the BHSZ intersects the seabed, hydrate may occur at the sediment–water interface (e.g. Egorov et al., 1999) or because of the anaerobic oxidation of the methane, just below it (Barnes and Goldberg, 1976). Past, rapid climate perturbations have been attributed to several different phenomena, including the dissociation of marine hydrate (Dickens et al., 1995). Warming of the seabed in the feather-edge domain could cause dissociation after only a few decades, because of the proximity of the hydrate to the seabed (Thatcher et al., 2013). Dissociation could even be seasonal (Berndt et al., 2014) or associated with changes in seabed temperature caused by upwelling currents (see Hagen, 2001). Methane release has been documented at the feather-edge of marine hydrate offshore of Svalbard (Westbrook et al., 2009; Berndt et al., 2014) and the eastern North American margin (Phrampus and Hornbach, 2012; Skarke et al., 2014).

Although hydrate dissociation has long been proposed as a mechanism for climate change (e.g. Dickens et al., 1995) and there is potential evidence for dissociation on some margins, descriptions of the feather-edge using seismic reflection data lack detail (Ben-Avraham et al., 2002; Coffin et al., 2007; Phrampus and Hornbach, 2012). This is because they are based upon widely spaced

* Corresponding author.
E-mail address: richard.davies@ncl.ac.uk (R.J. Davies).

http://dx.doi.org/10.1016/j.epsl.2015.04.013

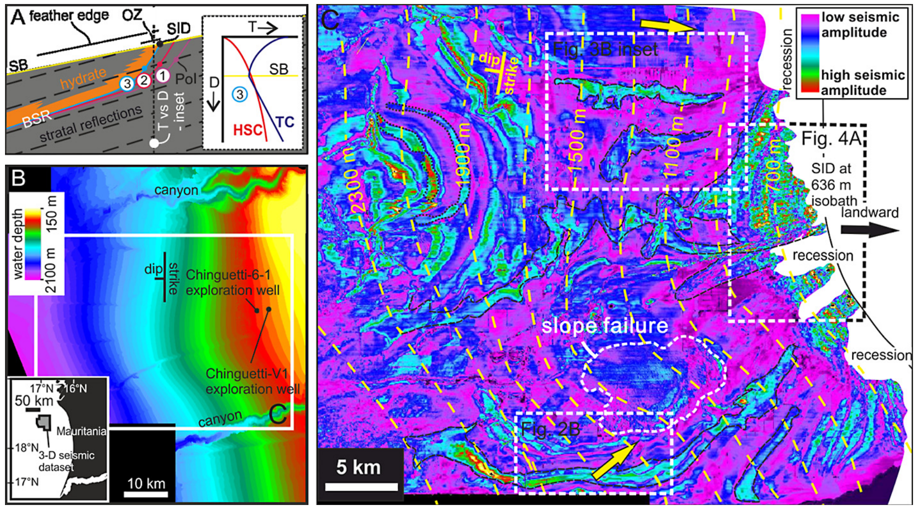

Fig. 1. A: Schematic of the feather-edge region and outcrop zone, showing positions of three hypothetical BSRs (1, 2 and 3) shifting as a response to warming of the seabed. SID – seabed intersection depth and PoI – point of intersection (in this and subsequent figures). Inset – schematic graph of temperature (T) against depth (D) for when the BSR is located at position 3, showing the hydrate stability curve (HSC) and temperature curve (TC). SB – seabed and OZ – outcrop zone on this and subsequent figures. B: Map of the seabed in metres, imaged by the 3-D seismic dataset. Inset – location map for the study area. C: RMS seismic amplitude map of the BSR showing bands of high seismic amplitude and localised intersections of the BSR with the seabed at the SID. Dashed yellow lines – depth contours for the BSR relative to sea level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

two-dimensional (2-D) seismic lines and there are no borehole calibrations. Key questions remain; for instance, regarding the amount of hydrate that is vulnerable, whether it occurs consistently along continental margins and how gas migrates to sustain it. Here we provide the first 3-D seismic description of the feather-edge of marine hydrate, based upon the mapping of a BSR that intersects the seabed. We describe the evidence for outcropping of hydrate and consider how gas sustains hydrate in these settings.

2. Hydrate and the feather-edge

In addition to P–T conditions, hydrate formation is controlled by the concentration of dissolved gas, which needs to be higher than its solubility in pore water (Xu and Ruppel, 1999). The BHSZ can coincide with the base of a hydrate accumulation, although this is not necessarily the case (Xu and Ruppel, 1999) and it may or may not be marked by a BSR (e.g. Dillon et al., 1980).

BSRs in hydrate provinces, including this one, are recognised as high-amplitude, negative polarity reflections, usually caused by the velocity contrast between sediment partially saturated with hydrate above it and sediment partially saturated with free gas below it (Field and Kvenvolden, 1985). The minimum saturation of hydrate in sediment required to cause a moderate or significant increase in acoustic impedance is unclear. It could be as little as 2% (Helgerud et al., 1999), 14% (Hu et al., 2014) or in excess of 40% (Carcione and Tinivella, 2000). The saturation of hydrate within the hydrate stability zone can be highly variable, with the highest saturations often occurring in porous sands, permeable layers and faults (e.g. Malinverno et al., 2008). This heterogeneity may be one of several factors that determine how the hydrate manifests itself where it outcrops at seabed.

We define the feather-edge of gas hydrate, also referred to as the hydrate wedge (Gorman and Senger, 2010), as the region where the BHSZ starts to shallow and intersects the seabed because of a progressive landward reduction in water depth (Fig. 1A). Since hydrate formation and dissociation are closely linked to the ambient P–T conditions, the intersection should be at a consistent depth along the margin, often ∼300–600 m (e.g. Milkov and Sassen, 2000). But this is also dependent on the composition of hydrocarbons in the hydrate with the shallower intersections occurring where methane is accompanied by other hydrocarbon gases (Milkov and Sassen, 2000). Seawards of the intersection, hydrate could exist at the seabed (e.g. Egorov et al., 1999; MacDonald et al., 1994) in an outcrop zone (Fig. 1A).

Evidence for the feather-edge of marine gas hydrate has been detected using 2-D seismic data for example on the margins of South Africa (Ben-Avraham et al., 2002 – e.g. their Fig. 2) and Chile (Coffin et al., 2007) the North Island of New Zealand (Crutchley et al., 2010). Off West Svalbard, there is evidence for a feather-edge on the basis of gas flares that occur only landwards of the 396 m isobath (Chabert et al., 2011; Sarker et al., 2012; Westbrook et al., 2009). In the northwest Black Sea, Naudts et al. (2006) described gas plumes that occur landwards of the 725 m isobath and similar observations are also made off the northern US Atlantic margin (Skarke et al., 2014).

In terms of how gas migrates to the landward limit of marine hydrate, at the West Svalbard feather-edge, Thatcher et al. (2013) proposed that gas migrates vertically through fractures towards the BHSZ; laterally within seaward-dipping permeable strata or along the base of the hydrate. At this feather-edge, carbonates at gas seeps indicate venting has been occurring for >3000 yr (Berndt et al., 2014). Large-scale 2-D modelling of the feather-edge on this margin shows that warming could cause methane release near the landward limit of the top of the hydrate stability zone (Reagan and Moridis, 2009).

3. Seismic data and geological setting

The offshore Mauritania 3-D seismic survey was processed by several steps including multiple suppression and post-stack time migration. The dominant frequency of this data at the depth of the hydrate is ∼50 Hz. The typical seismic velocity at the depth of investigation is ∼1700 $m\,s^{-1}$ and therefore 100 milliseconds two-way-travel time (ms TWT) on seismic sections is equivalent to approximately 85 m. The final bin spacing of the seismic grid is 25 × 25 m. The data are minimum phase and a negative acoustic impedance contrast is represented as a black–red (negative polarity) reflection. Amplitude maps are all root mean square (RMS – see Brown, 2010) on the reflection itself, rather than over a time window.