Marine Geology 380 (2016) 264–271

Contents lists available at ScienceDirect

Marine Geology

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

Gas trapped below hydrate as a primer for submarine slope failures

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ARTICLE INFO

Article history:
Received 10 September 2015
Received in revised form 4 April 2016
Accepted 17 April 2016
Available online 20 April 2016

Keywords:
BSR
Gas accumulation
Submarine failure
Buoyancy
Gas hydrate

ABSTRACT

Interpretation of a three-dimensional (3-D) seismic dataset from offshore of Mauritania reveals a shear zone at the base of a partially developed slope failure. The shear zone is at a depth of ~220 m below the seabed, immediately above a hydrate bottom simulating reflector (BSR). We propose that a paleo-gas accumulation trapped below hydrate was the primer for what would have been a substantial submarine slope failure of ~220 m thickness, covering ~50 km^2. This is based on the following observations: (a) the shear surface is, at the level of seismic resolution, coincident with some present gas accumulations located immediately below sediment that hosts hydrate; (b) there are remnants of a more extensive paleo gas accumulation that would have generated sufficient buoyancy pressure for the shear surface to be critically stressed and therefore primed the failure; (c) seismic pipes are a common seismic feature within the studied succession but absent in the area of the shear zone, which supports the hypothesis that a high gas column could have existed. This is a rare example of a shear zone that did not lead to the complete development of a slope failure. It provides the first seismic evidence that the buoyancy effect of gas below the hydrate rather than the hydrate dissociation is also a viable mechanism for large-scale slope failures.

1. Introduction

Gas hydrates are ice-like crystalline compounds, each with a gas molecule trapped by a rigid cage of water molecules (Sloan, 1998). Their occurrence is controlled by the appropriate combination of pressure and temperature conditions (Kvenvolden, 1993). They occur mostly in permafrost regions and on continental slopes where the water depth is greater than 500 m (Kvenvolden, 1993; Brown et al., 1996). The base of the hydrate stability zone (HSZ) is commonly marked approximately by a BSR on seismic reflection data. Typically, it is a high amplitude reflection with the opposite polarity to the seabed. It can cross-cut stratal reflections and mimic the geometry of the seafloor (Shipley et al., 1979).

Gas hydrates are considered to have the potential to trigger submarine slope failures, an important type of geohazard (Kvenvolden, 1993; Lane and Taylor, 2002). Furthermore, the methane-dominated gases, which are thought to be liberated during failure by the removal of the overlying sediments, could escape into the seawater and potentially the atmosphere (Paull et al., 2002; Skarke et al., 2014). Methane is a potent greenhouse gas and its release from hydrate may contribute to the concentration of methane in the atmosphere (Kennett et al., 2003). Generally, two mechanisms for failure initiation associated with hydrates have been proposed (McIver, 1982; Booth et al., 1994; Sultan et al., 2004; Bunz et al., 2005; Bull et al., 2009b). Firstly, near the level of the BSR large volumes of water and gas could be released during hydrate dissociation when the base of the HSZ shifts upwards. This potentially causes liquefaction of the sediment within the zone where dissociation occurred (McIver, 1982; Sultan et al., 2004; Xu and Germanovich, 2006). The final product of such a process can include submarine slides with the gas-bearing sediment ejected laterally or glide planes and remobilized hydrated sediment transported along them (McIver, 1982). The second mechanism involves buoyancy provided by an inter-connected gas column underlying the incipient failure plane (McIver, 1982; Berndt et al., 2012). But a spatial relationship between the BSR, the gas column trapped below the hydrate in a free gas zone (FGZ) and a submarine failure has never been documented.

The objective of this paper is to describe the architecture of a shear zone for a partially developed failure and interpret a probable underlying paleo gas accumulation that was likely to have been trapped by the hydrate. These spatial relationships have not been identified to our knowledge before and are used here to support our theory on the potential role of gas buoyancy rather than hydrate dissociation as a mechanism for priming slope failures.

2. Geological setting

The study area is located on the passive continental margin of West Africa, ~75 km offshore of Mauritania, where sedimentary features include gullies, canyons and mass transport deposits developing on a

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http://dx.doi.org/10.1016/j.margeo.2016.04.010
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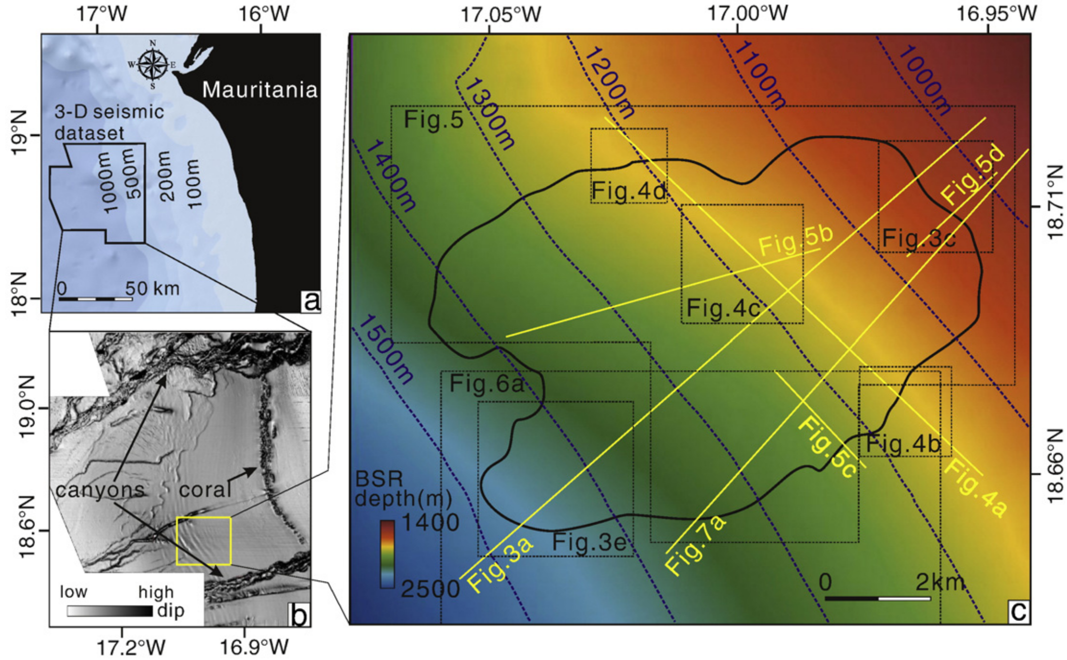

Fig. 1. (a) Extent of the area covered by the 3-D seismic dataset and its location in relation to the bathymetry of the continental margin. (b) Dip magnitude map of the seabed revealing the main sedimentary features at the seabed. The yellow box shows the location of the study area. (c) Outline of the incompletely developed failure. The present BSR (its depth is marked in color map) is spatially sub-parallel to the seafloor (contours indicated by dashed lines).

slope with an angle of 1°–3° (Krastel et al., 2006) (Fig. 1). The composition of these hemi-pelagic sediments is dominated by silt-sized quartz and clay, which was mostly derived from the aeolian sediment transported from Sahara Desert (Krastel et al., 2006; Antobreh and Krastel, 2007; Henrich et al., 2008). There are other significant slope failures along the Mauritanian continental margin, for example the Mauritania slide. The area of the seafloor affected by it is ~30,000 km^2 (Henrich et al., 2008).

Several exploration wells have been drilled up dip from the landward termination of the hydrate as this region is a hydrocarbon province (Vear, 2005). To the south of the study area, Aptian, Cenomanian, Turonian and Danian mudstones are the possible hydrocarbon source rocks (Vear, 2005). According to the previous research, gas migrates vertically along a wide variety of pathways (e.g. gravity-driven faults or seismic pipes), indicated by localized or widespread high amplitude anomalies on the seismic reflection data (Davies and Clarke, 2010; Yang and Davies, 2013; Yang et al., 2013).

3. Seismic dataset and methodology

The 3-D seismic data, which cover an area of ~4000 km^2, have been processed by multiple suppression and post-stack time migration. These data are displayed in two-way-travel time (TWTT). The velocity is likely to be ~1800 m/s and the dominant frequency of seismic data is ~50 Hz, which together yields a vertical resolution of ~9 m (one quarter of the wavelength of the dominant frequency). The final bin spacing is 25 m × 25 m. The positive acoustic impedance is recorded as a seismic trough. The seismic response of an increase in acoustic impedance is a red–black reflection, like that of the seabed.

Four reflections have been selected as they allow the relationships between the lower boundary of the shear zone, the underlying FGZ, the seabed and the present BSR to be analyzed. The seismic attributes of these reflections have been displayed using root-mean-square (RMS) amplitude maps and dip magnitude maps. RMS is defined as the square root of the average of the squares of the original amplitudes in an analysis window. RMS amplitude maps provide information on the distribution of high amplitudes but disregard their seismic polarity. Therefore, they are useful for mapping the BSR which is an interface with a moderate to high acoustic impedance contrast. Dip-magnitude maps highlight structural features, such as faults and pockmarks (Brown, 2010; Moss and Cartwright, 2010a; Ho et al., 2012; Yang et al., 2013).

4. Observations

4.1. Seismic pipes

There are 30 seismic pipes, examples of which can be seen in the seismic cross section (Fig. 2a–d). On the seismic profile the typical internal features of these pipes are acoustic wipe-out or localized enhanced amplitude reflections bending upwards or downwards (Fig. 2a–d). Their bases are somewhat unclear but whether their tops terminate at or above BSR is easily discerned (Fig. 2a–d). The locations of these pipes are revealed by a dip-magnitude map which shows the positive or negative relief at the intersection between the pipes and the stratal reflections (Fig. 2e). More than half of these pipes are located to the northwest of the shear zone (Fig. 2e).

The seismic pipe is a sub-cylindrical fracture cluster that allows vertical fluid migration to by-pass the less permeable sediment (Cartwright et al., 2007; Moss and Cartwright, 2010b). Its genesis is commonly associated with overpressured pore fluid (Cartwright, 2007; Cartwright and Santamarina, 2015). The occurrence of pipes has been extensively documented in the Lower Congo Basin (Gay et al., 2006), at the Scotian Shelf (Hovland and Judd, 1988), the Vestnesa Ridge (Petersen et al., 2010), offshore NW-Svalbard (Hustoft et al., 2009), Mauritania (Davies and Clarke, 2010), Norway (Hustoft et al., 2010), Namibia (Moss and Cartwright, 2010b), and Nigeria (Løseth et al., 2011).

4.2. Architecture of the shear zone

The shear zone is recognized on the basis of a number of the characteristic deformational features. In dip-parallel cross sections the down-dip displacement of the sediment is consistently tens of meters. The upper and lower boundaries are parallel (Fig. 3a) and merge with