Marine and Petroleum Geology 64 (2015) 31–42

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Subsea gas emissions from the Barbados Accretionary Complex

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ARTICLE INFO

Article history:
Received 4 February 2015
Accepted 6 February 2015
Available online 17 February 2015

Keywords:
Barbados
Multibeam
Water column
Marine
Geology
Hydrate
Methane
Subsea

ABSTRACT

We have identified and analyzed the affect of newly identified gas plumes in the water column from the Barbados Accretionary Complex. Multibeam echo soundings from cruise AT21-02 acquired using a Kongsberg EM122 system were used to define a region with several ~600–900 m tall gas plumes in the water column directly above cratered hummocky regions of the sea floor having relatively high backscatter at a water depth of ~1500 m. The natural gas hydrate stability zone reaches a minimum depth of ~600 m in the water column, similar to that of the tallest imaged bubble plumes, which implies hydrate shells on the gas bubbles. Tilting of the plume shows current shear in the water column, with a current direction from the northwest to southeast at 128°, a direction similar to the transport direction of North Atlantic Deep Water in this region. The source of hydrocarbons, determined from existing geochemical data, suggests the gas source was subjacent marine Cretaceous source rocks. North–south trending faults, craters and mud volcanoes associated with the gas plumes point to the presence of a deep plumbing system and indicate that gas is a driver of mud volcanism in this region. The widespread occurrence of seafloor morphology related to venting indicates that subsea emissions from the Barbados Accretionary Complex are substantial.

1. Introduction

Near vertical acoustic anomalies in the water column, associated with gas rising from the seafloor and termed acoustic “flares” are commonly identified in echograms from sonar systems (Colbo et al., 2014 and references therein). Integration of bathymetry, backscatter and water column acoustic data by modern multibeam sonar processing software provides water column features with a geological context. Shipboard, remote and autonomous vehicle operated multibeam systems are well suited as detection sensors when trying to identify and evaluate the extent and number of natural emission sites present on the seafloor, as well as for identifying anthropogenic emissions (Weber et al., 2012; Wynn et al., 2014). Repeated survey sweeps enable a time dimension that can detect temporal changes. Water current displacement of gas plumes is commonly imaged within multibeam data and can help identify deep currents and aid in focusing seafloor studies to emission sources (Schneider et al., 2010).

Cold seeps consisting of gas and fluid most commonly vent from emission sites in marine sediments on continental shelves and slopes. They vary in their rate of effusion and temperature (almost always <30 °C) depending on their sources, transport distance, and mechanisms of ascent. Subsurface geology may determine the presence of a source, migration pathways, and the location of surface features (Riedel et al., 2002; Talukder, 2012; Talukder et al., 2007). At the seafloor, emission site morphology is a result of the gas releasing mechanisms, depth of the natural gas hydrate stability zone (GHSZ), and gas flux (Naudts et al., 2010; Roberts et al., 2006). Subsea gas and fluid emission sites can be identified by their effect on surface morphology, and the formation of pockmarks/craters (Brothers et al., 2012; Chand et al., 2009; King and MacLean, 1970; Pilcher and Argent, 2007; Tinivella and Giustiniani, 2012), mud volcanoes (Bonini, 2012; Jerosch et al., 2007; Kopf, 2002; Milkov, 2000; Sager et al., 2003; Savini et al., 2009; Van Rensbergen et al., 2002; Zitter et al., 2005), natural gas hydrate (NGH, which refers to any combination of hydrocarbon gases although dominantly methane) pingoes/mounds, (Haeckel et al., 2004; Paull et al., 2007; Serié et al., 2012; Simonetti et al., 2013; Van Dover et al., 2003), although these are less common, and authigenic carbonates (Aloisi et al., 2000; Bian et al., 2013; Bohrmann et al., 1998; Johnson et al., 2003). These seafloor

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http://dx.doi.org/10.1016/j.marpetgeo.2015.02.008
0264-8172/

features not only provide a record of the surficial processes but they are also a key to diagenetic activity in the subsurface. For example, fault scarps on the seafloor may be a morphologically distinct part of the migration pathway that delivers gases, and fluids, from the lithosphere into the ocean, and potentially atmosphere.

Because of the gases and fluids released, emission sites play an important role in biological and chemical processes on the seafloor (Agirrezabala et al., 2012; Blackford et al., 2014; Cao et al., 2013; Hovland et al., 2012; Zemskaya et al., 2012). Bubble release activity, that is the volumetric and rate of gas release in natural systems varies (Greinert, 2008; Kannberg et al., 2013; Leifer et al., 2004: Leifer and MacDonald, 2003; Naudts et al., 2010; Nikolovska et al., 2008; Sauter et al., 2006; Torres et al., 2002), with the dominant control being changes in the source region and the degree of resistance to the upward force of buoyancy (Leifer et al., 2004). The pressure differential between the source and migration pathway may be great enough to rupture NGH seals (Daigle et al., 2011; Tryon et al., 2002, 1999).

Gas release activity is also influenced in shallow (<500 m) water by changes in source pressure due to currents and tides (Boles et al., 2001; Greinert et al., 2006; Linke et al., 2010; Newman et al., 2008; Torres et al., 2002). Continuous monitoring of a few sample emission sites is just beginning. 4-D monitoring would be necessary to provide a more complete picture of the temporal and volumetric variability of vent flow (Bayrakci et al., 2014).

The Intergovernmental Panel on Climate Change has estimated that natural emissions of methane into the atmosphere from faults, fractured rocks and the seafloor is 40–60 Tg yr^{-1}, or 15–20 % of global emissions, (Denman et al., 2007; Kvenvolden and Rogers, 2005) but there is a high degree of uncertainty in the location and clustering of emission site locations, numbers and volumes of gases involved. This is important because present-day atmospheric methane levels are higher than the past ~650 ka and increasing (Spahni et al., 2005; Nisbet et al., 2014). Estimates of NGH volumes on Earth and Mars (Max et al., 2013; Milkov, 2004) and the quantities of gas delivered into the oceans and atmosphere (Fisher et al., 2011; Leifer et al., 2004) from the subsurface vary widely. This leads to a high degree of uncertainty over the potential impact that NGH have on the climate system, and whether a proportion of the gases vented from the seafloor could be partly responsible for changes in the climate system observed during Earth's history, e.g., ocean acidification and intensification of greenhouse conditions (Dawson et al., 2011; Jones et al., 2010; Max et al., 2006; McGuire and Maslin, 2012; Phrampus and Hornbach, 2012; Skarke et al., 2014; Smith et al., 2014).

The GHSZ is the reservoir zone for unconventional NGH concentrations that sequester migrating, and *in-situ* (e.g., biogenic) gases and fluids (Max and Johnson, 2014) that might otherwise reach the seafloor. Release of the constituent gas and fresh water phases may occur when the gas trap beneath the GHSZ boundary is breached, for instance by faulting or sediment failure, Conversion of NGH will take place when seafloor warming reaches the lower part of the GHSZ or when sea level falls and pressure reduces. Failure of the trap integrity has been postulated from reflection seismic evidence to release large quantities of natural gas from the seafloor (Dillon et al., 2001).

The base of the GHSZ frequently appears in seismic data as an ocean bottom simulating reflector (BSR) with opposite polarity to that seen at the seafloor (Hyndman and Spence, 1992; Shipley et al., 1979). Prominent BSR indicates the presence of a low pressure wave free gas zone immediately below the GHSZ. Gas molecules within the GHSZ are presumed to be largely contained within solid NGH. The presence of BSR alone is not evidence for the existence of NGH concentrations.

A variety of technologies can be used to indirectly detect the presence of gas and fluid emissions from the seafloor. These include hydrographic surveys for particle rich or dissolved methane-rich thermal plumes (German et al., 2010; Baker and German, 2004), heat flow measurements (e.g. Lister, 1980; Fisher and Becker, 1991) and high-resolution seafloor imaging (e.g. De Beukelaer et al., 2003; Sahling et al., 2008; Klaucke et al., 2008). Both focused and diffuse gas and fluid emissions can be identified.

Water depths in the study area are deep enough for NGH to be stable. Combined with the availability of hydrate-forming gases, NGH can be anticipated within the GHSZ locally, although large concentrations will depend on the existence of fortuitously located sands. We have not identified NGH within the sediments in the area. We report the first use of high-resolution multibeam echo sounder data that includes water column data to identify subsea gas emissions in the offshore Barbados region.

2. Study area and background

The study area is located ~100 km southeast of Barbados along the Barbados Ridge, part of the Barbados Accretionary Complex (BAC) (Fig. 1). This region forms the eastern margin of the Caribbean Plate where the South and North American plates are being subducted beneath the BAC (Burke, 1988). Approximately 20 km of east–west shortened Quaternary – Miocene sediments, that are largely detached from the down-going slab, overly the detachment (Moore and Shipley, 1988). The sediments thicken toward the south as a consequence of increasing sediment burden and accretionary material flux originating from the ancestral and present-day Orinoco delta and its distal deep sea fan complexes (Westbrook et al., 1984). Two main bottom currents exist that help to shape the sediment bodies on the continental rise (Embley and Langseth, 1977): the North Atlantic Deep Water, that flows toward the southeast; and the Antarctic Bottom Water, that flows toward the northwest (Fig. 1). On the seafloor of the Barbados Ridge, the structural grain is dominantly north–south and mud volcanoes with diameters ranging up to ~8 km and craters are common (Fig. 1). Mud volcanoes, craters and faults have been mapped across the accretionary prism (Fig. 1) and natural gas emissions from the seafloor are spatially associated with mud diapirs (Brown and Westbrook, 1988; Körber et al., 2014) but previously, active gas emissions into the water column have neither been identified in this region nor associated with vent locations.

The composition of gases released from the emissions sites has not been measured *in-situ* in the study area. Geochemical inversion of hydrocarbon gases and liquids found in boreholes and natural seeps on Barbados indicates they are of a thermogenic origin and derived from marine Cretaceous source rocks (Hill and Schenk, 2005). On Trinidad and its surrounding offshore areas the gases are predominantly thermogenic mixed with a biogenic fraction (Battani et al., 2010; Deville et al., 2003a; Pohlman et al., 2009). Accordingly, the source of gas released from the seafloor is likely to be organic-rich shales that are part of the BAC, coupled with biogenic gas produced in the shallower subsurface.

NGH has been interpreted to be common in the study area. BSR, was used to indicate the presence of NGH (Brown and Westbrook, 1988; Deville et al., 2006, 2010; Marcelle-De Silva et al., 2012; Martin et al., 1996), but since the drilling on the Blake Ridge proved NGH with no underlying BSR and BSR with no overlying NGH (Holbrook, 2001), it is better understood that the negative impedance marker of the BSR is dominated by the presence of low Vp gas-enriched sediments, as has been shown by acoustic modeling (Max, 1990). NGH was recovered at a depth of 1 m in core KS20 collected ~200 km north of the study area (Martin et al., 1996).