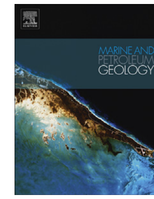
Marine and Petroleum Geology 67 (2015) 894–908

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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



Research paper

# Cold seeps at the salt front in the Lower Congo Basin I: Current methane accumulation and active seepage

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A R T I C L E   I N F O

*Article history:*
Received 25 October 2013
Received in revised form
1 April 2014
Accepted 30 July 2014
Available online 11 November 2014

*Keywords:*
Seafloor seepage
Gas migration
BSR
Salt front
Lower Congo Basin

A B S T R A C T

Active high intensity gas seepage is documented for the first time at the seaward edge of the salt occurrence in the southern Lower Congo Basin. Microbial methane release from the seafloor occurs on the crests of two 800 m high ridges formed by fault-propagation folding. Intense uplift is documented since the end of the Miocene by distinct onlapping reflections on the landward flank of these ridges. A paleo-pockmark structure suggests an onset of seepage coincident with this deformation period. High-resolution seismic imaging reveals methane migration along strata from Oligocene/Miocene fan deposits towards the ridge crests where large gas accumulations form beneath a discontinuous Bottom Simulating Reflection (BSR). Detailed mapping revealed that free gas and gas hydrate occurrences below and above the base of the gas hydrate stability zone are closely linked to sedimentary strata in the flanks of topographic ridges. Gas transport through the gas hydrate stability zone originates from the shallowest area of the BSR directly beneath the seafloor seep sites, suggesting pressure controlled venting. These sites represent the most seaward salt-related gas seepage features documented in the area and illustrate the initiation of long-lasting seepage at the front of an area of compressional tectonics at a passive continental margin.



## 1. Introduction

The seepage of gas and in particular of methane from the seafloor has been a matter of investigation for decades (Claypool and Kvenvolden, 1983; Judd and Hovland, 1992, 2007) due to its impact on the carbon cycle (Judd, 2000, 2003; Judd et al., 2002; Etiope, 2012), deep-sea fauna (Sibuet and Olu, 1998; Boetius et al., 2000; Dubilier et al., 2008) and potentially seafloor stability (Sultan et al., 2004; McConnell et al., 2012).

Ascent of fluids from the deep subsurface and escape from the seafloor has been found in various geological settings in different parts of the oceans such as in the Gulf of Mexico (Bernard et al., 1976; Brooks et al., 1986; Sassen et al., 1993; MacDonald et al., 2003; Sassen et al., 2004; Ding et al., 2008), at the Cascadia active continental margin (Suess et al., 1999; Tréhu et al., 2004; Bangs et al., 2011), and in the Black Sea (Klaucke et al., 2006; Wagner-Friedrichs et al., 2008; Römer et al., 2012a). Seafloor features associated with fluid seepage include mud volcanoes and pockmarks which are also know from various regions such as the Gulf of Mexico (Ruppel et al., 2005; Castellini et al., 2006), the Black Sea (Ivanov et al., 1996; Bohrmann et al., 2003; Wagner-Friedrichs et al., 2008), the Mediterranean Sea (Kopf and Behrmann, 2000; Huguen et al., 2004; Loncke et al., 2004; Bayon et al., 2009), the Niger Delta (Sultan et al., 2007, 2010), and the Congo Basin (Gay et al., 2006a, 2006b, 2007; Andresen and Huuse, 2011; Andresen et al., 2011). The migration of gas to the seafloor through overlying low-permeability sealing sediments is facilitated by various geologic structures (Cartwright et al., 2007), e.g. faults (Eichhubl et al., 2000; Ingram et al., 2004), gas chimneys and pipes (Cathles et al., 2010; Løseth et al., 2011) or stratigraphic conduits (Crutchley et al., 2010). In general, gases of different origin may be discharged from these structures. Microbial methane is produced in organic-rich sediments at shallow burial depths whereas thermogenic methane along with higher hydrocarbons are formed at elevated pressures and temperatures in the deeper subsurface (Rice and Claypool, 1981; Floodgate and Judd, 1992).

At relatively low temperature and high pressure within the gas hydrate stability zone (GHSZ) gas hydrates form in sediments in case methane concentrations exceed solubility (Kvenvolden, 1993;

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http://dx.doi.org/10.1016/j.marpetgeo.2014.07.032
0264-8172/

Sloan, 2003). Such hydrates might serve as a capacious, temporary near-seafloor methane reservoir which in turn, however, starts to disintegrate and to release methane when fluid supply from below decreases. Indeed, periodic fluid expulsion activity was recognized for some seepage features. Hydrate decomposition can also result from shifts in the boundaries of the GHSZ induced by increases in temperature and/or decrease in pressure. Gas hydrate decomposition was considered as trigger for slope instability (Pauli et al., 2003; Sultan et al., 2004).

Ascending fluids as well as methane from decomposing gas hydrates commonly nourish seep-associated micro- and macrofauna at the seafloor (Sibuet and Olu, 1998; Sahling et al., 2002; Sibuet and Olu-Le Roy, 2003; Knittel and Boetius, 2009). In the water column the fate of rising methane bubbles depends on its relative water depth. While most of the methane released as pure bubbles into deep waters typically gets dissolved (McGinnis et al., 2006) and microbially oxidized (Reeburgh, 2007) during ascent, part of the methane emitted into shallow water might pass the sea-atmosphere boundary (Leifer and Patro, 2002; Schmale et al., 2005) and add to the climate-affecting atmospheric methane budget.

Here we show the setting of active gas seepage at the seaward termination of the salt-induced deformation in the Lower Congo Basin (LCB) using multichannel seismic and other acoustic data sets. The LCB has been investigated widely for seafloor seepage on the upper and middle slope; however, the area of the seaward boundary of deposited evaporites, i.e., the salt front, has not yet been in the focus of research. This study investigates two individual active seepage sites and describes their detailed geological setting and evolution including their supply with gas from the sedimentary succession. The accumulation of gas and its association with the gas hydrate stability zone are examined in detail. A concurrent study (Wenau et al., 2015) further extends into the wider vicinity of the salt front and considers the structural setting of numerous potential seepage sites and the evolution of their activity through geologic time.

### 1.1. Geological evolution and setting of the Lower Congo Basin

The study area is located in the Lower Congo Basin in the eastern South Atlantic (Fig. 1). The passive Angola continental margin was formed by the rifting within Gondwana which started in the Late Jurassic and subsequently led to the separation of South America from Africa through seafloor spreading (Norton and Sclater, 1979; Uchupi, 1989; Marton et al., 2000; Moulin et al., 2010). Since then, its geological evolution has been dominated by active salt tectonics of Lower Cretaceous (Aptian) evaporites and large-scale sedimentary input from the Congo River.

The pre-salt sedimentary wedge to the east of the spreading axis is constructed of lacustrine syn-rift deposits (Rabinowitz and LaBrecque, 1979; Brun and Fort, 2004) and a sag basin infill accumulating towards the end of the rifting phase in the Lower Cretaceous (Late Barremian to Early Aptian) (Jackson et al., 2000; Marton et al., 2000; Brun and Fort, 2004). The Aptian transgression and subsequent closure of the basin led to the deposition of salt over a 50 to more than 200 km wide belt along the margin (Rabinowitz and LaBrecque, 1979; Marton et al., 2000). The slope of the spreading margin in conjunction with an overburden by margin sedimentation has initiated basinward salt movement. The deformation induced by the originally 1.4 km thick Aptian salt layer affected the subsequent Upper Cretaceous and Cenozoic sedimentation through large-scale salt displacement, subsequent sediment deformation and creation of accommodation space (Marton et al., 2000).

The Angola passive continental margin can generally be classified into several distinct domains with respect to the style of deformation of the salt layer and overlying sediments. It can be subdivided into an extensional domain on the shelf and upper slope, characterized by salt deflation (Duval et al., 1992; Marton et al., 2000), a translational domain on the middle slope, and a compressive domain on the lower slope showing salt accumulation. The study area is located within the compressional zone on the lower slope at ~2500 m water depth in the vicinity of the salt front, i.e., the seaward boundary of salt in the sedimentary succession (Marton et al., 2000, 2004). The compressional domain on the lower slope is dominated by shallow allochthonous salt bodies ('salt canopies') (Marton et al., 2000), along with massive salt accumulating through seaward movement of the salt (Brun and Fort, 2004). The Angola escarpment which is present as an 800 m high topographic feature to the south of our study area marks the seaward termination of salt tectonics on the margin (Cramez and Jackson, 2000). The study area is underlain by an inflating salt glacier which was emplaced in the Upper Cretaceous and has been deforming the overlying sediments since its burial in the Eocene (Marton et al., 2004). This inflation and an associated salt thrust are responsible for the seafloor topography in the study area (Marton et al., 2004).

The deep sea fan of the Congo River has been active since the Early Oligocene and terminates today basinward of the salt front to the NW of the study area, but shifted location through geologic time (Manley and Flood, 1989; Cramez and Jackson, 2000; Anka et al., 2009; Savoye et al., 2009). Fan sedimentation since the Oligocene is dominated by deposition of turbidite lobes, channels and levees on large parts of the continental slope intercalated with sea level-controlled hemipelagic sedimentation (Broucke et al., 2004). Oligocene to Miocene depocenters, which have been sourced by a network of channels and lobes, are located to the SE and the NW of the modern Congo River mouth (Anka et al., 2009). These deposits show a thickness of several hundred milliseconds TWT on the lower slope with basinward-increasing thickness of >1500 ms TWT (Anka et al., 2009). Such fan deposits have been reported to host hydrocarbons accumulated from deeper source layers (Gay et al., 2006b).

During the late Miocene the Angola continental margin was subjected to margin tilting and the formation of pronounced salt-induced topography, which caused the northward migration of fan deposits and the formation of the Congo Canyon around the Miocene–Pliocene boundary. This left the slope without direct turbiditic sediment input, but with dominating hemipelagic slope sedimentation from Pliocene to recent times (Anka et al., 2009). This shift from channel-related to slope hemipelagic deposits at the end of the Miocene has been documented in several areas on the Angola continental margin south of the modern Congo Canyon (Anderson et al., 2000; Kolla et al., 2001; Anka et al., 2009). Pliocene to modern sediments are characterized by pervasive small-scale extensional faults forming polygonal cells which are related to pore water expulsion during sediment dewatering and potentially facilitate gas seepage (Cartwright and Lonergan, 1996; Gay et al., 2004; Andresen and Huuse, 2011).

Today, the Angola continental margin is known for hydrocarbon production and the presence of substantial hydrocarbon reservoirs (Fraser et al., 2005; Beglinger et al., 2012). Source rocks for hydrocarbons comprise pre-salt lacustrine deposits such as the Early Cretaceous Bucomazi formation and post-salt strata such as the Late Cretaceous Iabe, the Eocene Landana and the Oligocene Malembo formations (Burwood, 1999; Figueiredo et al., 2010). Migration of fluids is facilitated by faults and other salt-induced structural features such as diapirs and turtle-backs. Prominent host rocks for hydrocarbons are Oligocene to Miocene channel fills which are present in structural lows between individual diapirs and on the basinward side of listric faults (Fraser et al., 2005; Gay et al.,