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Identification and numerical modelling of hydrocarbon leakage in the Lower Congo Basin: Implications on the genesis of km-wide seafloor mounded structures

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ABSTRACT

We present a combined approach of interpretation of 2D seismic-reflection data and numerical modelling of hydrocarbon generation and migration across the southern slope of the Lower Congo Basin, in order to investigate the factors controlling timing and distribution of hydrocarbon leakage in this area. We identified three main families of past and present-day leakage features: (1) Mid-Upper Miocene seismic chimneys concentrated basinwards and ending up on buried pockmarks, (2) Plio-Pleistocene chimneys, rather clustered to the east of the study area and ending up in seafloor pockmarks, and (3) fewer scattered chimneys identified within the Miocene sequences ending up in shallow enhanced reflectors ("Flat spots"). Stratigraphic and structural elements seem to control the distribution of these features. At least two major events of leakage occurred during the Middle–Late Miocene and intermittently during the Pliocene-Present. External factors as sediment supply are associated to the Miocene leakage event, whilst internal structural elements probably triggered the Pliocene to present-day leakage.

A major seabed morphological feature, represented by a margin-paralleled belt of more than 1-km-wide mounds, was identified above growth faults to the east of the study area. Data-constrained 2D HC generation and migration modelling suggests a genetic link between these structures and vertical migration/leakage of thermogenic methane sourced from either currently mature Oligo-Miocene source rocks or secondary cracking and further expulsion from over-mature Upper-Cretaceous source rocks. Hence, the mounds are likely to represent a lineation of methane-derived carbonate build-ups. Despite the natural limitations of a 2D migration model, when combined and calibrated with observations from seismic data, it can be used as a valid tool to assess petroleum migration routes in sedimentary basins. To the best of our knowledge, this is the first integrated approach combining both seismic observations and numerical modelling carried out in the Angola basin.

1. Introduction

Leakage of liquid and gaseous hydrocarbons (HC) through focused fluid flow is a process recognized to occur, in varying intensities, along most continental passive margins, where both carbon trapping within the sediments and/or intense carbon release into the hydrosphere and atmosphere may take place e.g. (Hempel et al., 1994; Hornbach et al., 2007; Hovland and Judd, 1988; Roberts and Carney, 1997; Sager et al., 2003).

Seafloor features, such as mud volcanoes, pockmarks, carbonate mounds, and polygonal faults have been recognized to be the surface indicators of both dewatering and active leakage of natural gas from deeper sources and reservoirs (e.g. Berndt, 2005; Gay et al., 2007; Hovland, 2005; Leon et al., 2006; Orange et al., 2002). These surface indicators are usually linked to subsurface expressions of active hydrocarbon migration as seismic chimneys, pipes, and bright spots (i.e. Andresen et al., 2011; Ben Avraham et al., 2002; Charlou et al., 2004; Graue, 2000). Recognition of similar features in buried sediments can indicate the occurrence of past hydrocarbon leakage events staggered through time, which in turn may be related to particular events on the basin history as sea-level changes, tectonic uplifts and erosions, or even glacial–interglacial cycles. Additionally, since hydrocarbon (HC) seepage can be a source of greenhouse gases (such as thermogenic methane) to the ocean and atmosphere, quantification of this process could help understanding the potential influence of this process on Earth's climate history.

On the other hand, submarine cold seeps derived from HC leakage are often associated with the presence of carbonate mounds in deep marine settings (Hornbach et al., 2007; Hovland et al., 2005; Judd and Hovland, 2007). The microbial activity associated with the anaerobic oxidation of migrating thermogenic fluids (mostly methane) in the bacterial sulphate reduction zone (Suess and Whiticar, 1989) can lead to the precipitation of authigenic carbonates as crusts or concretions at the sediment–water interface (Hovland, 1990; Jørgensen

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and Boetius, 2007; Ritger et al., 1987). Such hydrocarbon-derived hardgrounds may act as the foundation for a carbonate mound build-up (Naeth et al., 2005 and references therein). Seepage of HC from the reservoirs into seawater can also be enhanced by the presence of permeable faults and fractures.

Past and Present-day indicators of liquid and gaseous HC leakage as pockmark belts, giant pockmarks and gas chimneys have been reported all along offshore western African margins (e.g. Cunningham and Lindholm, 2000; Kuhlmann et al., 2011; Pilcher and Argent, 2007) and in particular off-shore the Congo/Angola margins, where evidence of direct leakage from the reservoirs to the seafloor have been found to the North of the Congo submarine Canyon, in the Lower Congo Basin (LCB) (Andresen et al., 2011; Gay et al., 2006 and references therein). However, the deep systems that feed the seeps in this basin are rarely addressed, much less by numerical simulation of leaking HC or quantification of leaked volumes through this process. Relatively recent studies in the north Atlantic and on the western South Africa margin have shown that location and timing of HC-leakage expressions, such as carbonate mounds giant pockmarks, and gas chimneys, could be explained by Petroleum System Modelling (PSM) results (Boyd et al., 2011; Huvenne et al., 2007; Kuhlmann et al., 2011; Naeth et al., 2005; Paton et al., 2007).

In this contribution we have carried out a combined approach of analysis of observations from seismic reflection data and numerical modelling of generation and migration of hydrocarbons, in order to address the timing and possible controlling factors of HC leakage in the Lower Congo Basin (LCB). The study area is located off-shore the north-central Angolan margin in West Africa and it comprises an area of nearly 10,500 km^2 between the shelf and the slope of the LCB basin (Fig. 1a–b). Particular efforts were placed on investigating the possible origin of a conspicuous seafloor km-wide margin-paralleled mounded lineation identified to the south of the remarkable Congo submarine Canyon (Fig. 1c) and whether these features may be derived from HC migration and seep.

2. General geologic evolution and petroleum system elements

The Angola passive margin resulted from rifting of Gondwana during the Late Jurassic to Neocomian and currently host immense hydrocarbon reserves (Brice et al., 1982; Emery and Uchupi, 1984; Karner et al., 1997; Marton et al., 2000; Teisserenc and Villemin, 1989; Uchupi, 1989).

Fig. 2 depicts the general stratigraphy and main tectonic events of the Lower Congo Basin, which contains a Lower Cretaceous clastic

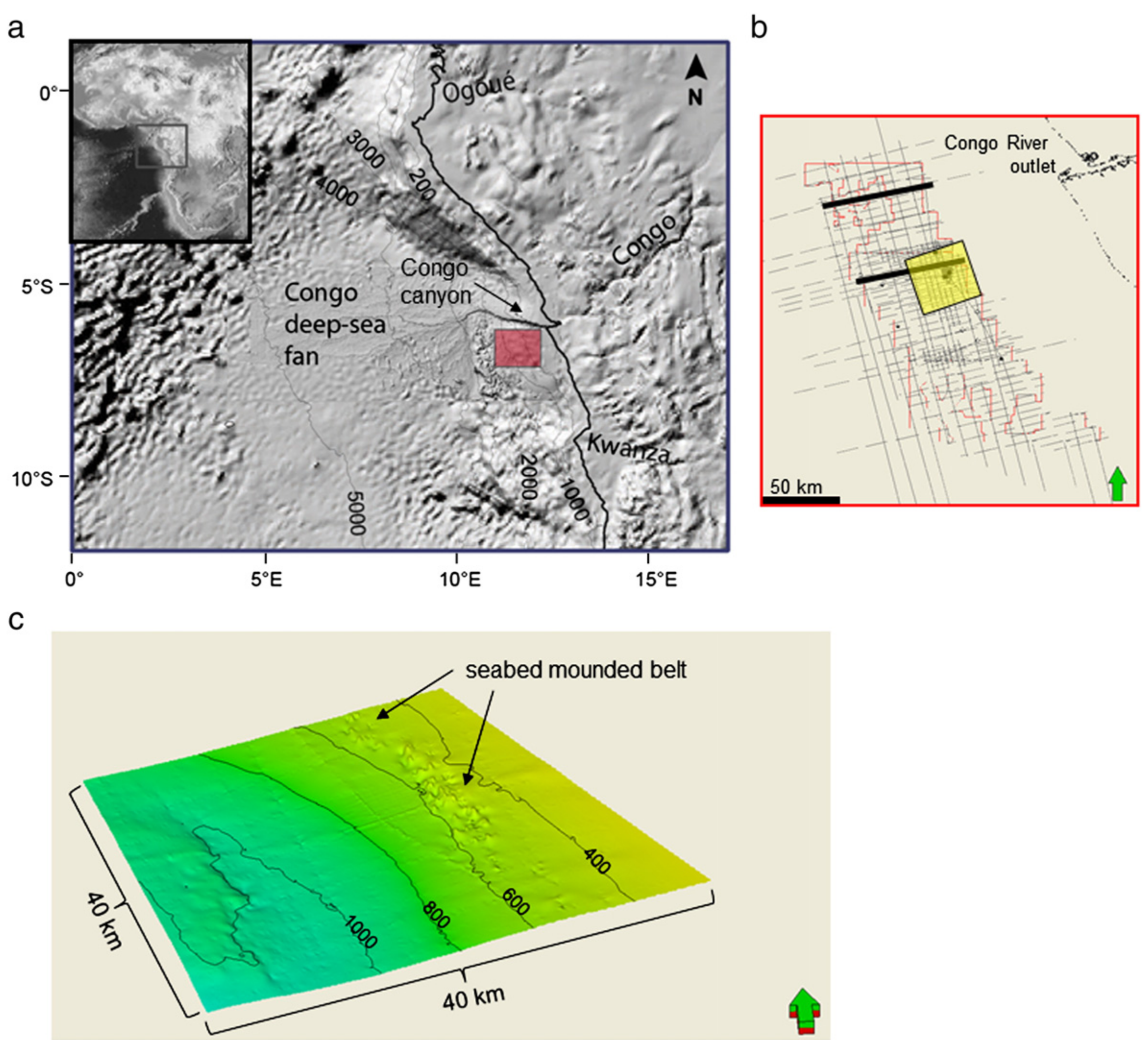

Fig. 1. a) Bathymetric maps of the study area, off-shore the Congo–Angola passive margin. b) Detailed TWT bathymetry of a portion of the study area showing a mounded belt parallel to the margin between 400 and 600 ms (twt) (see location in 1c). c) 2D seismic reflection dataset interpreted in this work (yellow square corresponds to area in Fig. 1b, bold lines represent approximate locations of the two modelled sections).