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Geological controls on focused fluid flow associated with seafloor seeps in the Lower Congo Basin

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Abstract

A synthesis of backscatter imagery coupled with a large 3D seismic dataset in the Lower Congo Basin (LCB) reveals a patchy distribution of features interpreted to be associated with fluid seepage from 300 m to 2500 m water depth. With the exception of one region of anomalous backscatter positive-relief mounds, all inferred seep sites occur in negative-relief pockmarks. The extensive 3D seismic dataset in the LCB offers a unique opportunity to study the plumbing system that is feeding surface cold seep systems, and in general, to reconstruct the relationship between tectonics and fluid flow in continental margins. The fluid seeps in the LCB are associated with morphologically, stratigraphically or tectonically controlled focused fluid flow. The integration of the geophysical datasets, backscatter imagery coupled to 3D seismic, clearly indicates that fluid seeps are not randomly distributed, but their seabed organization reflects 1) the location of the underlying structure (reservoir or trap) where the fluids are coming from, 2) the geometry and morphology of the reservoir/trap, and 3) the discontinuities in the sedimentary column along which fluids have migrated. In the LCB seafloor pockmarks are always associated with underlying tectonic structures (fault zones, salt diapirs, polygonal faults) or buried sedimentary bodies (turbiditic channels, erosional surfaces), whereas they never occur above sub-horizontal parallel-stratified fine-grained sediments. Even if triggering processes can not be clearly defined here, we propose a model of seafloor fluid seep organization, which represents a new tool for identifying the geometry of flow pathways and the underlying buried bodies where the fluids are originating from. This qualitative 3D model provides insight into the geohydrologic processes of continental margins.

Keywords: fluid seeps; pockmarks; seepage; leakage; BSR; pipes; chimneys; gas hydrates; turbiditic channels; canyon; faults; diapirs; polygonal faults; backscatter imagery; EM12; 3D seismic

1. Introduction

Focused fluid migration in marine sediments is a widespread phenomenon which is increasingly gaining attention in the context of environmental discussions, even though it still is not well understood (Berndt, 2005). However, increased data coverage and the advent of new tools in oceanic exploration, such as backscatter imagery, multibeam swath bathymetry maps and 3D seismic data, can provide new evidence of relatively small-scale fluid seep structures on modern continental margins, and can help towards improving our understanding of the underlying processes. Fluid migration in sedimentary

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basins is an important process because 1) the input of greenhouse gases into the ocean/atmosphere system may be an important component of the atmospheric carbon budget (Judd et al., 2002), 2) the fluid expulsion at the seafloor may play a role in potential instabilities on slopes (Prior and Coleman, 1984; Evans et al., 1996; Yun et al., 1999; Cochonat et al., 2002), representing a risk for human activities (Sultan et al., 2001; Elverhøi et al., 2002), and 3) fluid expulsion sites form the basis for a plethora of chemosynthetic benthic ecosystems that play an important role in the deep marine communities (Sibuet, 2003). Fluids can follow different pathways but the occurrence of fluids and gas seepage is manifested in the Lower Congo Basin by the presence of pockmarks on the seafloor. Since their initial identification on the Scotian Shelf by King and MacLean (King and MacLean, 1970), pockmarks have been reported repeatedly during offshore hydrocarbon exploration and scientific surveys in various depositional systems at water depths ranging from 30 m to over 3000 m (for a detailed review see (Josenhans et al., 1978; Werner, 1978; Hovland, 1981; Whiticar and Werner, 1981; Hovland and Judd, 1988; Solheim and Elverhoi, 1993; Baraza and Ercilla, 1996; Rollet et al., 2006). They generally appear in unconsolidated, fine-grained sediments as cone-shaped circular or elliptical depressions, ranging from a few meters to 300 m or more in diameter and from 1 m to 80 m in depth, and they concentrate in fields extending over several square kilometers. In some cases, they have been identified along straight or circular lines correlated with glaciomarine tills (Josenhans et al., 1978; Whiticar and Werner, 1981; Kelley et al., 1994) suggesting a geological control on focused fluid flow (Eichhubl et al., 2000; Cifci et al., 2003). In particular, structural surfaces along bedrock (Shaw et al., 1997), salt diapirs (Taylor et al., 2000; Satyavani et al., 2005), and faults and faulted anticlines (Boe et al., 1998; Soter, 1999; Vogt et al., 1999; Eichhubl et al., 2000; Dimitrov and Woodside, 2003) create pathways for fluid migration. These observations suggest that discontinuities or unconformities are much more effective for fluid migration than a simple diffusive seepage through the sedimentary column (Abrams, 1992; Brown, 2000) and are responsible for focused fluid flow, fluid escape at the seafloor and pockmark development (Abrams, 1992; Orange et al., 1999). The crater-like nature of pockmarks suggests an erosional power of fluid venting (Hovland and Judd, 1988), commonly related to an overpressured buried reservoir of biogenic gases, thermogenic gases, or oil, interstitial water, or a combination of the three. However, time varying fluxes may be recorded into seafloor fluid seeps. An integrated study conducted on a giant pockmark of the Lower Congo Basin at 3200 m water depth has shown that the mineralogical, chemical, and biological facies are clearly related to upward fluid intensity (Gay et al., 2006c).

The objectives of this study are: (1) to identify the main flow pathways for shallow and deep fluids through the sedimentary column of the Congo/Angola passive margin. We integrate high-resolution 3D seismic datasets and multibeam imagery within the Lower Congo Basin to determine the main fluid pathways and to characterize the expression of fluid expulsion on the seafloor; (2) to understand the underlying structural control on focused fluid flow structures. Drawing on the extensive database, we document how different structures such as normal and reverse faults, salt diapirs, shallow and deep turbiditic channels, and erosional surfaces can lead to fluid flow focusing.

2. Geological settings

Rifting of the Congo/Angola margin started in the early Cretaceous (144–140 Ma) and culminated in the opening of the South Atlantic Ocean around 127–117 Ma (Brice et al., 1982; Jansen et al., 1984; Guiraud and Maurin, 1992; Karner and Driscoll, 1998; Marton et al., 2000; Karner et al., 2003). Two major post-rift stratigraphic units overlie a thick Aptian salt layer. They reflect a major change in ocean circulation and climate (Séranne et al., 1992). From Late Cretaceous to Early Oligocene time, an aggradational carbonate/siliciclastic ramp developed in response to low-amplitude/low-frequency sea-level changes and continuously hot climate (greenhouse period) (Séranne, 1999). This interval includes the Tertiary source rocks producing thermogenic oils and gas by cracking of organic matter (Burwood, 1999). From Early Oligocene to present time, the sedimentation is dominated by the progradation of a terrigenous wedge that reflects high-amplitude/high-frequency sea-level changes and alternating dry and wet climatic conditions. The high-frequency climate variations triggered deep incision and erosion and deposition of large amounts of terrigenous material in a turbiditic fan off Congo and Angola (Brice et al., 1982; Uchupi, 1992; Droz et al., 1996). The important spreading of the Congo plume over the canyon edge has led to the deposition of mud-dominated sediments on the slope, whereas turbidite currents are transferred to the deep-sea fan within the Zaire canyon (Bentahila et al., 2005). The Pliocene to Present sediments constitute a seal above the Oligocene–Miocene turbiditic interval (Burwood, 1999).

Thermogenic hydrocarbons, produced in the pre-salt lacustrine sequence and in the clastic sediments and marls of Albian–Cenomanian Moita Seca source rocks