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Isolated seafloor pockmarks linked to BSRs, fluid chimneys, polygonal faults and stacked Oligocene–Miocene turbiditic palaeochannels in the Lower Congo Basin

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Abstract

Based on high-resolution 3D seismic data sets, we document the subsurface reservoir architecture and organization of a portion of the Oligocene–Miocene stratigraphy within the Congo Basin, offshore southwestern Africa. Within the 3D seismic volume, we have identified four levels of turbiditic palaeochannels, which are separated by low-amplitude continuous reflectors interpreted as hemipelagic sediments. Geochemical analyses on sediment samples taken within overlying seafloor pockmarks reveal the presence of thermogenic gases and oils, suggesting that deep-seated fluids have migrated through both the channel deposits and the impermeable layers between them, forming a conduit to the surface. Deep thermogenic fluids produced within Cretaceous source rocks are preferentially entrapped within coarse-grained turbiditic Oligocene–Miocene palaeochannels. We show in this study that the vertical stacking pattern of turbiditic palaeochannels allows the best pathway for fluids migration. Once the fluids migrate to the upper layer (i.e., Upper Miocene) of palaeochannels, they can reach the seafloor via migration along a highly faulted interval composed of polygonal faults. They are temporarily inhibited below an interpreted 300-m-thick gas hydrate layer marked by a strong BSR on seismic profiles. Fluids accumulate under the hydrate stability zone to form a thick layer of free gas. The generation of excess pore fluid pressure in the free gas accumulation leads to the release of fluids along faults of the highly faulted interval forming pockmarks on the seafloor. Ultimately, we show in this study that fluids are progressively concentrated in the sedimentary column and aligned pockmarks on the seafloor may represent a focused fluid flow from stacked turbiditic palaeochannels.

Keywords: fluid migration; pockmarks; turbiditic palaeochannels; hydrates; pipes; fluid chimneys; BSR; polygonal faults

1. Introduction

Evidences of offshore fluid seeps at the seabed were first reported on sidescan records from the Scotian Shelf by King and MacLean (1970). Fluid seeps generally appear in unconsolidated fine-grained sediments

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as cone-shaped circular or elliptical depressions named pockmarks. They range from a few meters to 300 m or more in diameter and from 1 m to 80 m in depth. Pockmarks generally concentrate in fields extending over several square kilometers where they often appear as isolated patches named single pockmarks or "eyed pockmarks" (Hovland and Judd, 1988). 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; Ussler et al., 2003) or suggesting a structural control on fluid flow (Eichhubl et al., 2000; Paull et al., 2002; Loncke et al., 2004). In particular, structural surfaces along bedrock (Shaw et al., 1997), salt diapirs (Schmuck and Paull, 1993; Taylor et al., 2000) 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. Pockmarks are known to occur on continental slopes with gas hydrates (Bünz et al., 2003; Johnson et al., 2003; Zühlsdorff and Spieß, 2004) and in association with slides and slumps (Hovland et al., 2002; Lastras et al., 2004). These observations suggest that discontinuities and/or unconformities are more effective fluid conduits than homogeneous sections of stratigraphy that are dominated by intergranular fluid flow (Abrams, 1992; Brown, 2000) and are thus more likely the conduits responsible for pockmark development (Abrams, 1996; Orange et al., 1999). These observations suggest that the nature of fluids expelled and the organization of pockmarks on seafloor may be indicative of the depth of the reservoir and of the potential fluid migration pathways (Heggland, 1998).

Understanding fluid flow processes through sediments need first to improve our knowledge of large-scale fluid pathways and of fluid migration processes within a sedimentary basin. Our study area, located within the Lower Congo Basin (LCB), is characterized on the seafloor by groups or isolated small circular pockmarks, ranging from 100 m to 300 m in diameter, and from a few meters to a maximum of 20 m in depth (Gay et al., 2003). They seem mostly unevenly distributed and their abundance varies considerably across the area. Pockmarks develop, in particular, in areas covered by 1–3-km regularly spaced linear depressions. These furrows are interpreted as the seafloor expression of small-scale polygonal faults that cut through an underlying interval, 600 m thick, serving as shallow subsurface fluid conduits to the seafloor (Gay et al., 2004).

Seismic profiles issued from high-resolution 3D seismic data sets show that these apparent isolated pockmarks are clearly related to deep buried turbiditic palaeochannels, which may have concentrated thermogenic fluids before upward redistribution. Geochemical analyses conducted on cores within some of these pockmarks show clear evidence of deep thermogenic fluids (Gay et al., in press). In this paper, we show that the nature of expelled fluids and the location of isolated pockmarks are clearly controlled by (1) the stacking pattern of four Oligocene–Miocene turbiditic palaeochannels, (2) the presence of an impermeable gas hydrate layer, which may temporarily inhibit the fluid migration and (3) the development of an highly faulted interval (HFI) hosting polygonal faults that allow fluid migration to reach the seafloor. In frontier exploration, knowledge of reservoirs architecture and organization will constrain risk assessment, help the development of appropriate drilling strategies and improve the prediction of fluid migration pathways and seepage locations.

2. Database and processing

This study is primarily based on 3D exploration seismic data sets from the Lower Congo Basin (LCB) acquired by TOTAL (Fig. 1). The selected 3D data set covers about 2400 km^2 with a line spacing of 12.5 m and a CDP distance of 12.5 m (Fig. 2). They were loaded to a workstation and interpreted with the SISMAGE software developed by Total-Fina-Elf. 3D seismic imagery allows extraction of continuous horizons within the 3D block and calculation of seismic attributes (Brown, 1996). The automatic picking on conventional seismic profiles (i.e., seismic attribute) is suited to the interpretation of continuous horizons. Irregular sedimentary bodies or post-depositional structures, such as faults, fluid chimneys and turbiditic palaeochannels, cannot be delineated by conventional horizon picking and require the calculation of new seismic attributes.

2.1. The "Chaotism" attribute

Due to the discontinuous character of turbiditic palaeochannel infills, an automatic picking of sand bodies is difficult. New tools in the academic and petroleum exploration domains allow to individualize these chimneys from the 3D block. Based on the amplitude of reflectors and their continuity, however, the SISMAGE software developed by TOTAL does allow the calculation of the "Chaotism" amplitude attribute from a 3D seismic survey. In the derived 3D-chaotism block, turbiditic palaeochannels appear as homogeneous high-amplitude anomalies, ovoid in shape, 1–4