

# 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. © 2005 Elsevier B.V. All rights reserved.

**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<sup>2</sup> 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 SIS-MAGE 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 SIS-MAGE 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

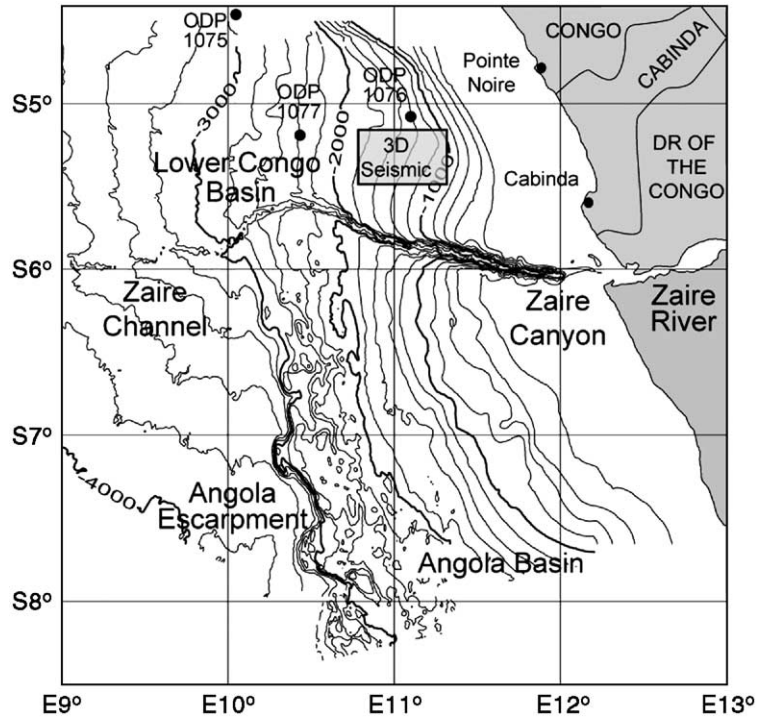


Fig. 1. Bathymetric map of the Lower Congo Basin issued from the EM12 multibeam acquisition (ZAIANGO project, 1998–2000). This map shows the Zaire system from the Zaire estuary to the basin at 4000 m water depth. The 3D seismic data set used in this study (shaded rectangle) is located on the slope, between 950 and 1850 m water depth, north of the Zaire canyon. The three sites of the ODP Leg 175 in this zone are indicated.

km wide (Fig. 3). We have then considered the average value of “Chaotism” within each interval previously identified on seismic that allows to determine four different levels of turbiditic palaeochannels.

2.2. The “Fault” attribute

Fluid chimneys are commonly characterized by two superposed acoustic anomalies (Fig. 4). They may rep-

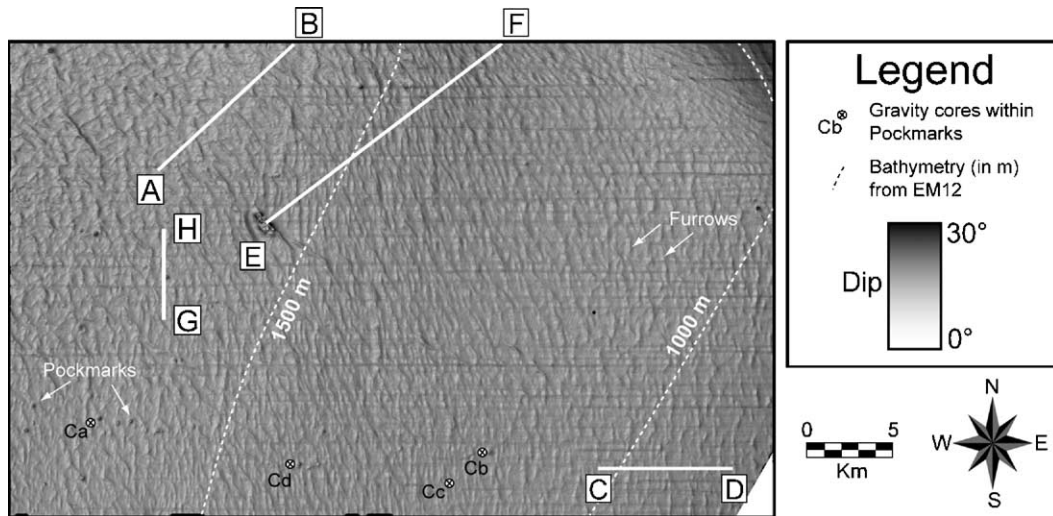


Fig. 2. Dip map of seafloor in the Lower Congo Basin, calculated from the 3D data. A dip map is the derived surface of an isochron map that illuminates, from white to black, horizontal to inclined surfaces, respectively. This map illustrates the seafloor facies characterized by pockmarks and furrows. The white lines represent seismic profiles issued from the 3D seismic data set used in this study. The bathymetry issued from the EM12 multibeam acquisition is reported. Geochemical analyses conducted on cores Ca, Cb, Cc and Cd within four pockmarks show evidence of thermogenic hydrocarbons.

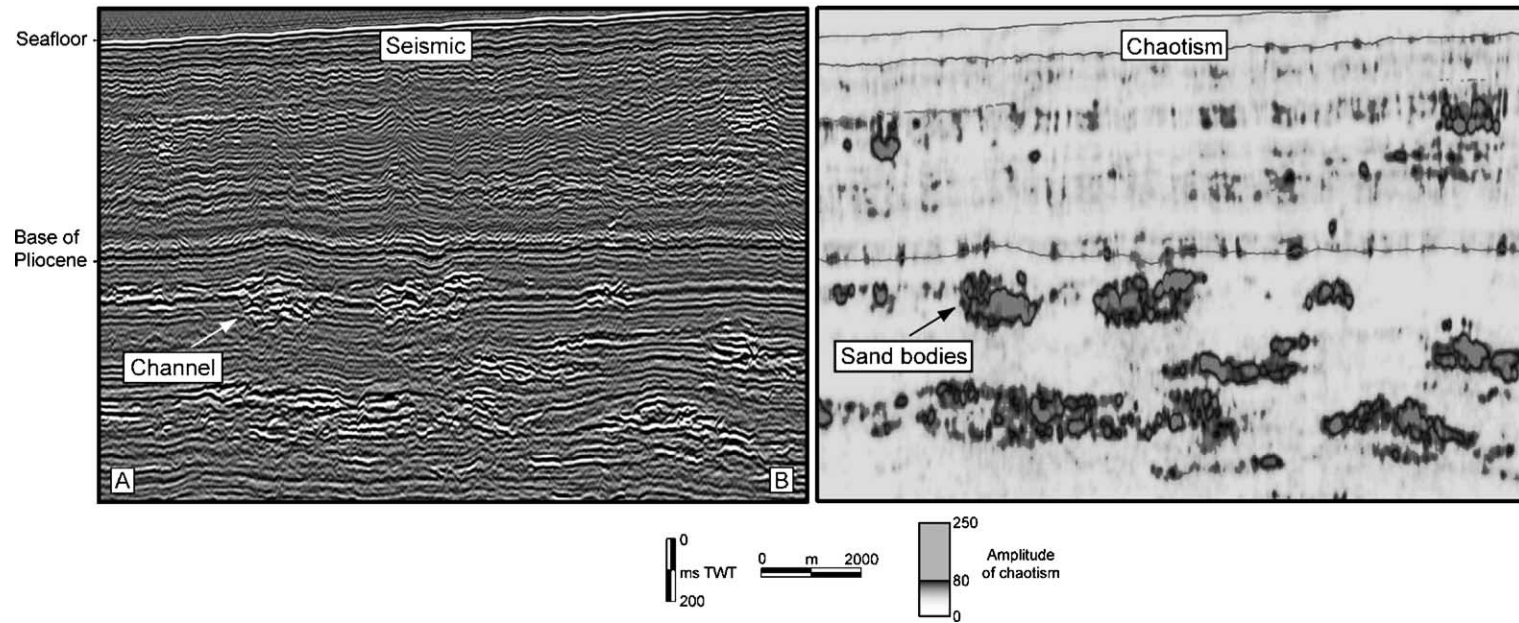


Fig. 3. Seismic profile AB showing discontinuous high-amplitude reflectors interpreted as turbiditic palaeochannels within the Oligocene–Miocene Interval. 3D seismic allows to calculate other attributes such as “Chaotism”. The turbiditic palaeochannels, now well individualized with this attribute, are easily mappable by automatic picking.

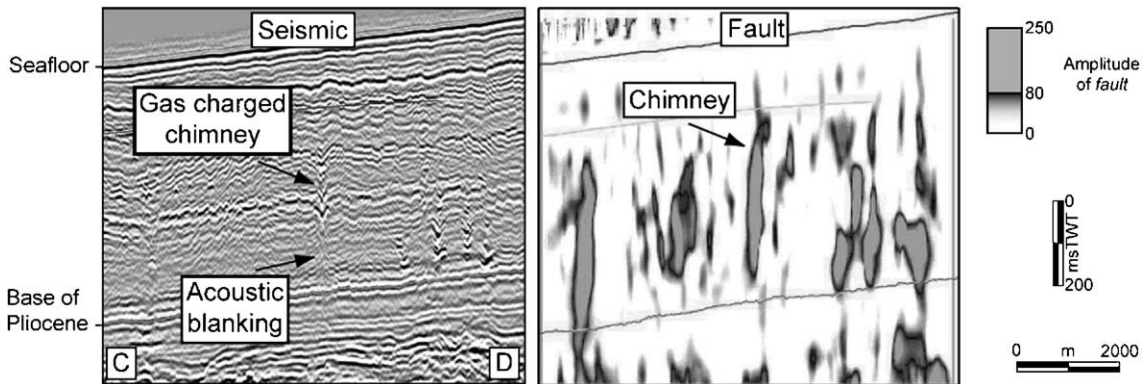


Fig. 4. Seismic profile CD showing seismic chimneys of migrating fluids. These chimneys are characterized by a shallow part, with high-amplitude depressed reflectors interpreted as gas-charged chimneys, and a deep part that corresponds to a fade-out of the reflectors in an inverted cone shape interpreted as an acoustic turbidity. As described for palaeochannels, these objects are very difficult to extract from the 3D block. Here, the “Fault” attribute is used and allows to individualize vertical discontinuities such as seismic chimneys.

resent present migration of fluids in the sedimentary column (Heggland, 1998; Hempel et al., 1994; Tingdahl et al., 2001). The shallowest anomaly is vertically elongated and ovoid in shape, 50–250 ms TWT high and 50–150 m wide. On seismic profiles, these anomalies are underlined by depressed high-amplitude reflectors interpreted as a reduction of the seismic velocities (pull-down effects) through a gas-charged column. Similarly to the “Chaotism” attribute, the SISMAGE software allows to calculate the “Fault” amplitude of a 3D seismic block. It is based on vertical discontinuities of reflectors and the fluid chimneys appear as homogeneous vertically elongated columns easily mappable by automatic processes. The seismic profile CD shows that they may connect down to turbiditic palaeochannels and may act as a preferential drain for deep fluid migrations (Fig. 4).

### 3. Geologic setting

The 3D seismic data set is located on the slope (950–1850 m water depth) of the Lower Congo Basin (LCB). The LCB is one of the numerous sub-basins of the West African passive margin developing during the opening of the South Atlantic Ocean at early Cretaceous (Jansen et al., 1984a; Marton et al., 2000). Subsequent to large accumulations of evaporites (up to 1000 m) during the mid-Aptian time (Karner et al., 1997), the post-rift stratigraphy is characterized by two superposed seismic architectures that reflect a major change in ocean circulation and climate (Seranne 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 a stable climate (greenhouse period) (Seranne, 1999).

This interval is characterized by Tertiary source rocks that produce thermogenic oils and gases through cracking of organic matter (Burwood, 1999) (Fig. 5).

From early Oligocene to Present time, the sedimentation was dominated by the progradation of a terrigenous wedge that reflect high-amplitude/high-frequency sea-level changes and an alternating drier and wetter climate. These high-frequency alternating climatic conditions have caused deep incision and erosion. The large amounts of terrigenous material has led to the formation of the Zaire system, a large turbiditic submarine fan characterized by numerous turbiditic palaeochannels (Brice et al., 1982; Droz et al., 1996; Uchupi, 1992). A portion of this fan system is preserved in the Oligocene–Miocene interval imaged in the 3D seismic volume discussed here. Updip migration of deeper thermogenic fluids (Gay et al., in press) are preferentially trapped in these coarse-grained (likely silty-sandy) palaeochannels, which now serve as hydrocarbon reservoirs (Burwood, 1999).

Further south, in the Angola Basin (Block 4), turbidite sands are commonly associated with three major turbidite-bearing depositional sequences (Anderson et al., 2000): the 17.5–15.5 Ma sequence (Burdigalian, early Miocene), the 8.2–6.3 Ma sequence (Tortonian, Late Miocene), and the 6.3–5.5 Ma sequence (Messinian, Late Miocene). Based on geological interpretations of 3D seismic profiles in the study area described here, we identify four levels of distinct turbiditic palaeochannels within the Oligocene–Miocene interval (Fig. 5):

- Level 1: Base Pliocene/Base Pliocene+260 ms TWT
- Level 2: Base Pliocene+260 ms TWT/Base Pliocene+430 ms TWT

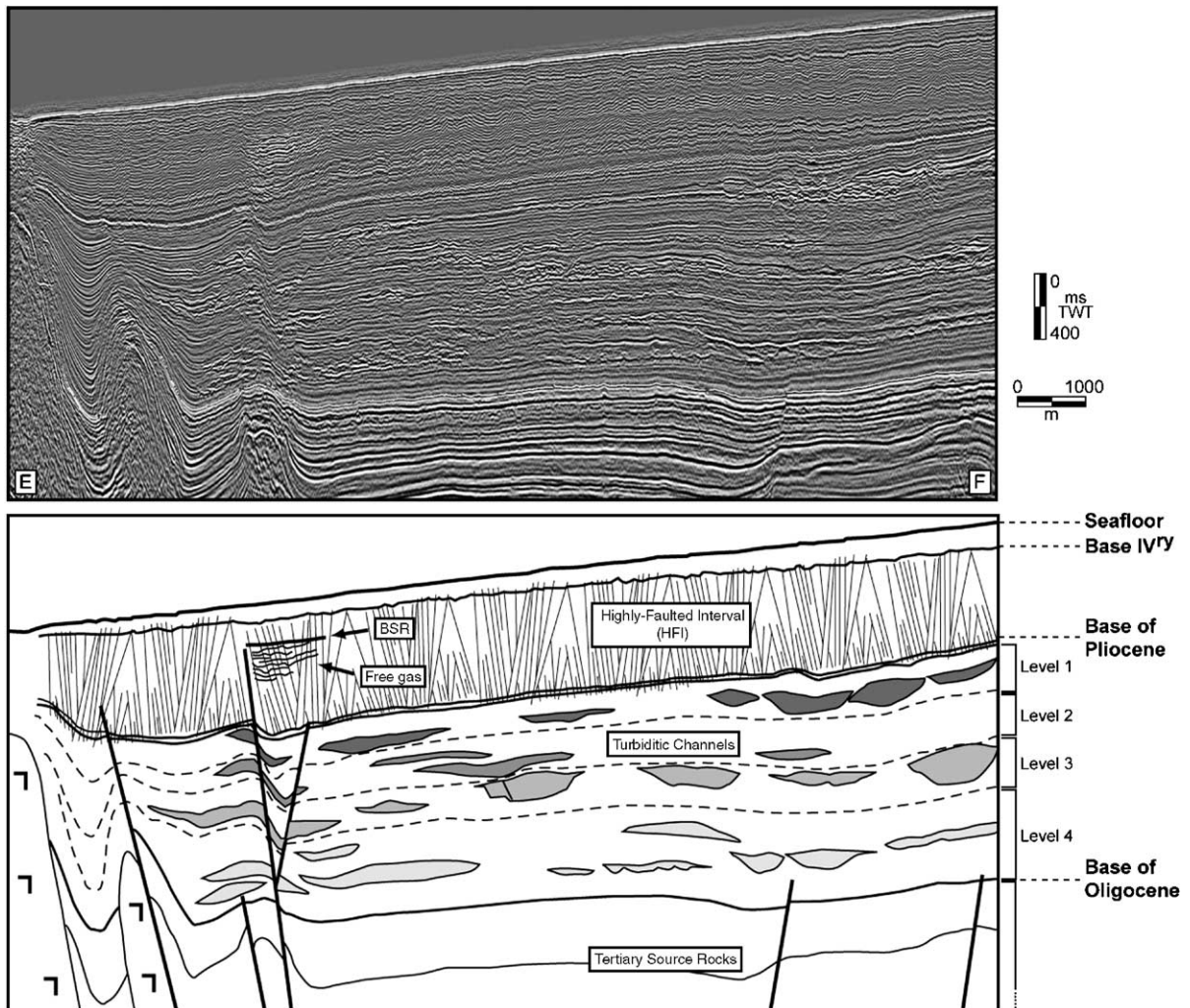


Fig. 5. Seismic profile EF. The post-rift stratigraphy is characterized by two superposed seismic architecture: (1) an Albian to Eocene sequence containing the source rocks and (2) an Oligocene to Present sequence containing the reservoirs (turbiditic palaeochannels) and the sedimentary cover (affected by a highly faulted interval). Deep thermogenic fluids migrating from the source rock are preferentially entrapped into the coarse-grained (sand/silt infills) palaeochannels, playing the role of reservoirs.

- Level 3: Base Pliocene+430 ms TWT/Base Pliocene+640 ms TWT
- Level 4: Base Pliocene+640 ms TWT/Base Oligocene.

From early Pliocene time to Present, the shelf and the slope are deeply incised by a canyon that directly connects the Congo River with the basin floor at the toe of the continental slope, down to 4000 m water depth (Babonneau et al., 2002). During the ODP Leg 175, three sites were drilled at varying positions from the shelf break (sites 1075, 1076 and 1077) within the LCB. The lithostratigraphy of Late Neogene sediments suggests that turbidity currents played a minimal role in transporting sediment within the LCB (Girardeau et

al., 1998; Pufahl and Wefer, 2001). Presumably, the sediments trapped into the canyon were carried far onto the lower fan, starving the shelf of coarse detritus (Jansen et al., 1984b; Uenzelmann-Neben, 1998; Savoye et al., 2000). Only fine muddy sediments not confined to the canyon are delivered to the LCB, perhaps from riverine plumes, through sedimentation by aggregates and in fecal pellets (Wefer et al., 1998; Cooper, 1999) and mixed with hemipelagic sediments on the continental shelf and slope. The Pliocene–Present interval plays the role of a seal cover above the Oligocene–Miocene turbiditic interval (Burwood, 1999) (Fig. 5).

One of the main tectonic features of the West African margin is the gravitational sliding of post-rift sedi-

ments above a décollement layer made up of Aptian evaporites (Duval et al., 1992; Lundin, 1992; Liro and Cohen, 1995). In the Lower Congo Basin, gravitational processes created two structural domains each about 100 km wide: an extensional domain on the upper slope and a compressive domain located downslope that are partly active today. The extensional domain is locally associated with large amounts of extension across listric faults creating individual rafts and grabens (Burlot, 1975; Duval et al., 1992; Rouby et al., 2002).

## 4. Results

### 4.1. Seismic expression of fluid migration

In the southern part of the study area, the seismic profile GH crosses a single pockmark and its underlying chimney, which is characterized by downward deflected high-amplitude reflectors (Fig. 6). The chimney is disrupted by a high-amplitude reflection parallel to the seafloor located 200–300 ms TWT below the seafloor. This reflection is interpreted as a bottom-simulating reflector (BSR), which corresponds to the lower thermodynamic limit of the gas-hydrate stability zone (Shipley

et al., 1979; Kvenvolden and Barnard, 1983; Hyndman and Spence, 1992) or to the top of the free-gas zone beneath the hydrates (MacKay et al., 1994). BSRs are characterized by a reverse polarity compared to the seafloor reflection, indicating a decrease in seismic impedance and, therefore, of seismic velocity. This contrast in impedance is probably due to the presence of free gas entrapped below the gas hydrate stability zone, and the BSR can be considered as the interface between high-velocity gas hydrates and the underlying gas-charged sediments with low seismic velocities (MacKay et al., 1994). The seismic profile GH shows that the BSR is deflected upward directly beneath the seismic chimney and the seafloor pockmark. This upward deflection of the BSR suggests a localized positive heat flow anomaly, which could be due to an ascending movement of fluids through the sedimentary column (De Batist et al., 2002).

All seismic profiles within the study area show a highly faulted interval (HFI) in the first 0–800 ms TWT below seafloor (Fig. 6). The HFI (described in detail in Gay et al., 2004) is characterized by numerous closely spaced normal faults, which have small offsets (5–30 m) and an average spacing (100–500 m). These faults draw large polygons in plan view, ranging from 1 km to

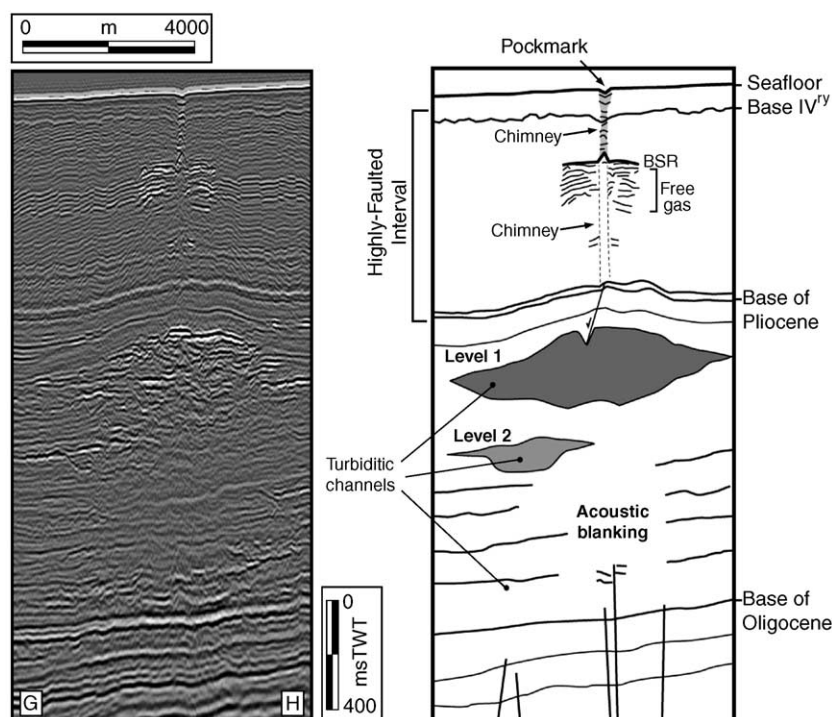


Fig. 6. Seismic profile GH across a single pockmark. The chimney under the pockmark is disrupted by a high-amplitude reflection parallel to the seafloor, which is interpreted as a BSR. This seismic profile shows that the BSR is deflected upward, suggesting a localized positive heat flow anomaly and an ascending movement of fluids. The Pliocene to Present interval is affected by a highly faulted interval (HFI). We consider that this interval can act as a major process for driving up fluids entrapped within underlying Oligocene–Miocene turbiditic palaeochannels.

3 km. Since the first recognition of a polygonal fault system in the Leper Clay of Belgium (Henriet et al., 1991), numerous examples of layer-bound polygonal fault systems have been described worldwide from 3D seismic data (Klitgord and Grow, 1980; Poag et al., 1987; Cartwright, 1994; Oldham and Gibbins, 1995; Cartwright and Lonergan, 1997; Cartwright and Dewhurst, 1998; Lonergan et al., 1998a,b). Due to the fine-grained lithology of Pliocene–Recent sediments and the map view polygonal network of faults, we suspect the HFI results from layer-parallel volumetric contraction of fine-grained sediments leading to the pore fluids escape (Cartwright and Lonergan, 1996). Although sand bodies located above rift-related basin-forming faults appear especially susceptible to act as major vertical fluid escape pathways (Lonergan et al., 2000), we consider that the highly faulted interval may compromise the seal capacity of the Pliocene sedimentary cover. The polygonal faults may act as a major process for driving up fluids entrapped within underlying Oligocene–Miocene turbiditic palaeochannels (Gay et al., *in press*).

The Oligocene–Miocene turbiditic palaeochannels appear on the seismic as high-amplitude packages with strongly scoured/erosional bases indicating deposition in a largely channelized environment (Fig. 6). To the south, where these palaeochannels have been cored (Anderson et al., 2000), massive sands often form the basal units of sequences that grade upwards into a succession of horizontally laminated fine sands and silts, overlain by wavy, lenticular bedded silts and interbedded muds. Anderson et al. (2000) have shown that dewatering structures are common and in some cases may have resulted in total homogenization of the sands. An alternative model for the lack of clearly defined sedimentary structures in the sands and grading within these beds is rapid deposition from suspension in a high-density turbidite flow (Lowe, 1982). The fining-upwards sequences consisting of more thinly bedded fine sands and silts are interpreted as classic fine- to medium-grained, low- to medium-density turbidite deposits (Bouma sequences: Bouma, 1962).

The difficulty in interpretation strongly increases where reservoirs comprise stacked turbidite systems and such stacked reservoirs systems are relatively common phenomena (Richard and Bowman, 1998). Here, predictions of reservoir architecture based upon a single model will fail to appreciate the spatial changes in reservoir geometry and shale architecture. We resolved this problem by using a new tool based on the “Chaotism” of a seismic profile, developed by TOTAL for the SIS-MAGE software.

#### 4.2. Organization of turbiditic palaeochannels

Based on the identification of four levels of turbiditic palaeochannels on seismic profiles, we transformed the seismic block into a “Chaotism” block that allows to map these palaeochannels (see Database and processing for more details). The map view expression of the turbiditic palaeochannels (i.e., average value of “Chaotism” within the four intervals) exhibit a variety of forms including high sinuosity channels with well-developed levee systems or relatively straight channel segments (Fig. 7). Depositional processes are believed to be responsible for the dominantly linear shape and channelized cross-sectional geometry of most deep-water turbidite fan channel reservoirs. The maps of the average value of “Chaotism” within the four levels show that the overall trend of the palaeochannel complexes is ESE/WNW cutting obliquely across the major faults (i.e., normal and reverse faults due to the gravitational sliding of the post-rift sequence). In the northeastern corner of the study area, the palaeochannels are deflected to the south near the normal faults bordering an extensional graben, implying that faulting was prior or occurred during the channel development. In the centre of the study area, some palaeochannels are deflected near underlying salt diapirs, suggesting that they developed during active salt diapirism. We also notice that the current fan channel reservoir geometry is influenced by the location of extensional or compressive post-rift faults. The dominant orientation of turbidite palaeochannels corresponds to the direction of the sediment supply issued from the Zaire River mouth and is related to the progradation of the Zaire fan pro-delta across the study area.

#### 4.3. Relation between stacked palaeochannels and seismic chimneys under the BSR

The use of the “Fault” attribute allows to extract fluid chimneys from the seismic block (see Database and processing for more details). These chimneys can be projected in any 3D view as the basinward perspective view (i.e., toward the West) shown in Fig. 8. In this figure, level 1 of the upper Miocene turbiditic palaeochannels is projected on the base Pliocene and fluid chimneys from the Pliocene interval are represented. The base Pliocene is intensively deformed by structural features such as normal and reverse faults and large domes, 5–10 km wide. The domes correspond to the deformation induced by underlying salt diapirs. Some chimneys develop on the top of these domes and are attributed to a normal faulted network due to the col-

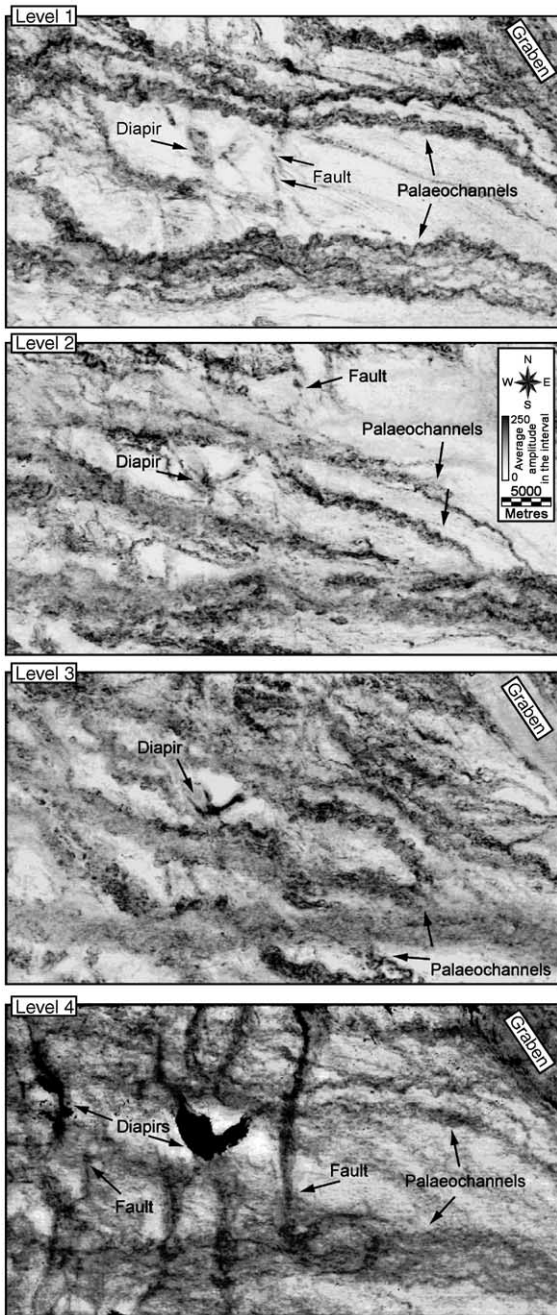


Fig. 7. “Chaotism” maps of turbiditic palaeochannels. Based on the identification on seismic profiles of four levels of turbiditic palaeochannels (levels 1–3 are Miocene and the level 4 is Oligocene), we transformed the seismic block into a “Chaotism” block using the SISIMAGE software. The average value of “Chaotism” within each interval is then calculated and projected on a map view. These maps exhibit a variety of forms including high-sinuosity channels with well-developed levee systems or relatively straight channel segments. The overall trend of the palaeochannel complexes is ESE/WNW.

lapse above the diapir crest (Stewart, 1999). Similar diapir chimneys offshore Nigeria have been discussed by Heggland (1997) and Graue (2000).

The base of the vertically elongated seismic chimneys seems to connect with meander loops of turbiditic palaeochannels. Even if this interval is projected on the base Pliocene, this statement has been verified through the 3D seismic block. However, numerous chimneys are not clearly connected to any palaeochannel of level 1. The apparent isolated chimneys, which are far from any major structure (i.e., faults, diapirs or turbiditic palaeochannels), may connect to deeper palaeochannels. In fact, all seismic chimneys take root over turbiditic palaeochannels but not always at the same level.

The map of vertically stacked palaeochannels of the four Oligo-Miocene levels shows large bands, 2–8 km wide (Fig. 9). The widest band is located in the southern part of the study area. This band is oriented EW and corresponds to the strongest stacking pattern: in this zone, three to four levels of turbiditic palaeochannels are vertically stacked. In the northern part of the study area, the bands are mainly oriented SE–NW and do not exceed 2–3 stacked levels of palaeochannels. The seismic chimneys under the BSR are consistently located above the bands of highly stacked palaeochannels, suggesting that the fluids migrate through several levels of turbiditic palaeochannels.

#### 4.4. Relation between stacked turbidite palaeochannels, BSR, fluid chimneys and seafloor pockmarks

In the study area, all the seismic profiles show that a BSR with underlying free-gas zone occur over turbiditic palaeochannels, suggesting that gas hydrates may act as an impermeable layer, inhibiting fluid escape to the surface. The 3D seismic data allow us to map the area covered by a visible bottom-simulating reflector (BSR) on seismic (Fig. 10). In the study area, the BSR is defined by parallel bands, 2–5 km wide, dipping towards the WNW from 1800 ms TWT in the east to a maximum of about 2800 ms TWT in the west. An extensive mapping of the BSR in the Congo Basin has shown that the BSR extends from 800 m down to 3200 m water depths (Cunningham and Lindholm, 2000). As described in most basins worldwide, an active BSR parallels the seafloor. In the Lower Congo Basin, the main slope of the BSR is parallel to the seafloor slope (see Figs. 1 and 2). Finally, the BSR covers less than half of the study area. What prevails on the isochronal map of the BSR is the organization in bands oriented ESE–WNW, which are located exactly above areas of

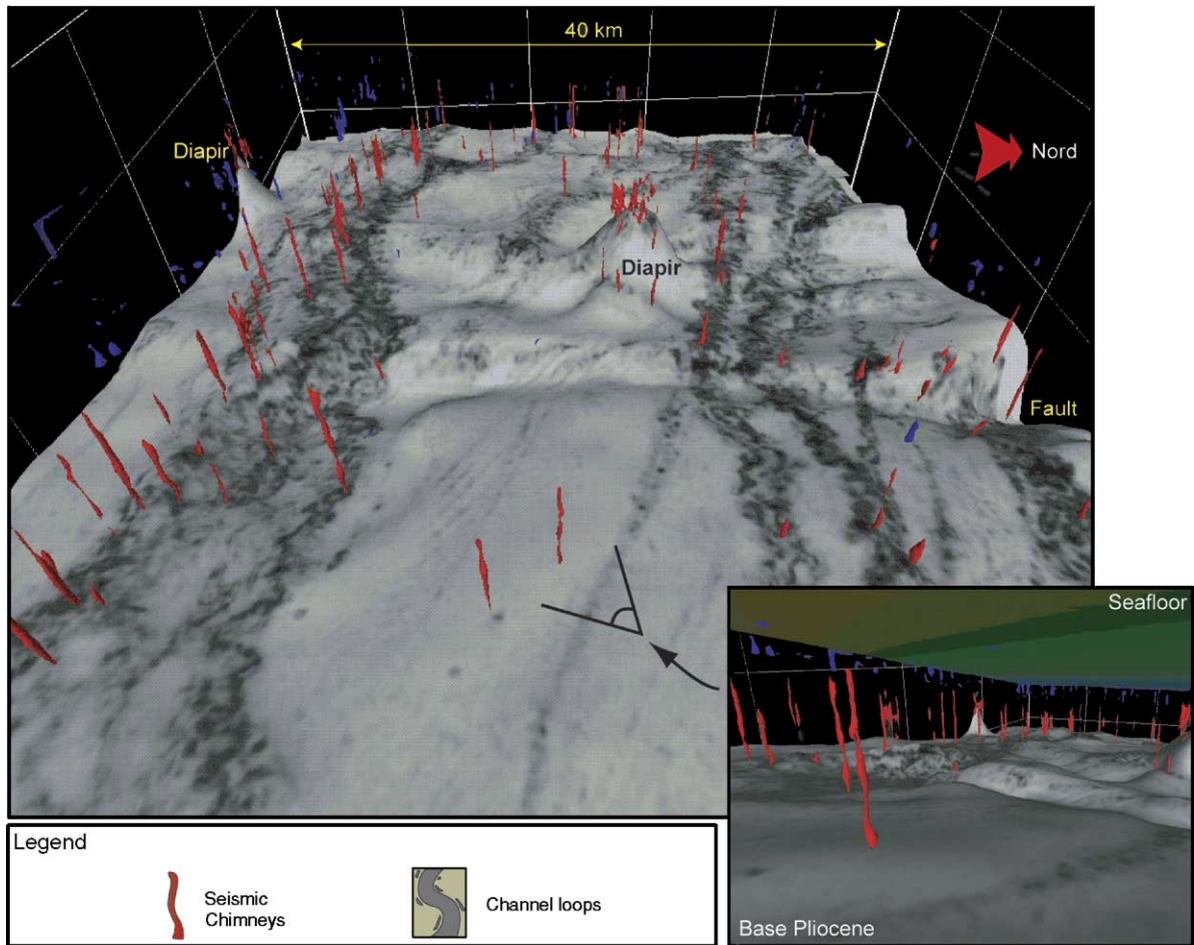


Fig. 8. Basinward perspective view within the 3D seismic block (toward the west). The level 1 of turbiditic palaeochannels is projected on the Base Pliocene (i.e., the top boundary of this level). The channel meander loops are highlighted in black while hemipelagic muds are in white. The seismic chimneys, extracted from the 3D seismic block using the “Fault” attribute, are represented. The base of the vertically elongated seismic chimneys seems to connect with meander loops of turbiditic palaeochannels. However, the apparent isolated chimneys may connect to deeper palaeochannels.

high stacking levels of turbidite palaeochannels. Furthermore, present-day seafloor pockmarks have been reported on the map of the BSR. All pockmarks with their underlying chimneys are located above the BSR, except one near 2000 m water depth. It could be due to the progradation of slope that moves the BSR basinward as the sediments are deposited. This isolated pockmark is probably inactive at the present day.

## 5. Discussion

### 5.1. Vertical fluid migration through turbiditic palaeochannels

Due to the high porosity of silts and sands, which we interpreted in our study area to compose the palaeochannel infills, the Oligo-Miocene palaeochannels may

concentrate thermogenic fluids migrating from the productive underlying source rocks (Burwood, 1999). The palaeochannels are acting as effective longitudinal drains for the fluids to migrate (Tokunaga, 2000; Gay et al., 2003). As shown by Lonergan et al. (2000) and Gay et al. (in press), injections and fluid escape occurred early within the burial history before significant compaction. Syn-depositional major faults located above turbiditic sand bodies may periodically act as main vertical fluid escape pathways (Lonergan et al., 2000). However, the main problem is the ability of fluids to migrate from a sand body to another and that depends on several parameters:

- 1) Vertical stacking of palaeochannels: The turbiditic palaeochannels have regionally persistent surfaces that separate sandstone-dominated lithologies from

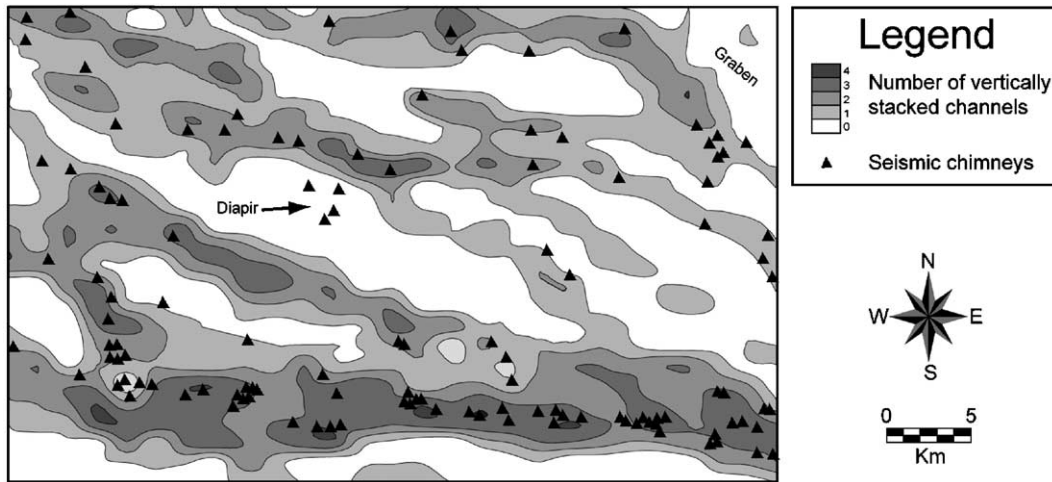


Fig. 9. Frequency map of vertical stacked palaeochannels. The triangles represent the position of seismic chimney under the BSR. This figure shows large bands, 2–8 km wide, of stacked palaeochannels. In the south of the study area, the bands are mainly oriented EW, while they are oriented SE–NW in the north. The seismic chimneys under the BSR are consistently located above the bands of highly stacked palaeochannels, suggesting that the fluids migrate through several levels of turbiditic palaeochannels.

overlying shale-dominated lithologies. The seismic expression of this change is marked by low-amplitude and moderately continuous seismic facies overlying high-amplitude and variable continuity seismic facies. This transition is interpreted as an abandonment surface, which marks a geologically abrupt end of deepwater sand deposition (Jennette et al., 2003).

2) Lithology: the coarse nature of deposits (grain flows, debris-flows or high-density turbidity currents) determines the ability of fluids to migrate longitudinally through turbiditic palaeochannels (Gay et al., 2003).

- 3) Connectivity: Sand-rich intrusions, such as sill and dykes, may represent a preferential pathway for fluids to connect turbiditic palaeochannels (Lonergan et al., 2000).
- 4) Overpressure: Overpressure development in sedimentary basins is directly related to lithology, sedimentation rate, thermal expansion of fluids, transformation of clay minerals and hydrocarbon generation or bacterial methanogenesis (Yu and Lerche, 1996). Among these factors, sedimentary facies and sedimentation rates are of primary importance in controlling fluid pressure development in a basin.



Fig. 10. Isochronal map of a bottom simulating reflector (BSR) visible on 3D seismic sections in the study area. The BSR is dipping towards the WNW and parallels the seafloor slope. Present-day seafloor pockmarks (white circles) with their underlying chimneys are located above the BSR and above areas of high stacking levels of turbidite palaeochannels. This indicates that the fluid pathways are directly linked to the organization of sedimentary bodies (i.e., palaeochannels) and/or to the structuration of the basin.

5) Differential compaction: The vertical stacking of sand-rich turbiditic palaeochannels leads to the formation of a large-amplitude (i.e., 10 km) anticline due to differential compaction during burial (see Fig. 6).

In our study area, pockmarks are developing on the modern seafloor. Most of them are still active and present evidences of thermogenic fluids. This means that the above conditions are gathered: the fluids can migrate upward through the four levels of palaeochannels and reach the top of anticlines.

### 5.2. Fluid storage under the hydrate layer

Due to the ice-like nature of gas hydrates, hydrate-rich sediments may form a barrier to fluid flow, which inhibits sediment consolidation and can lead to the development of excess pore pressures at the BSR. Decomposition can also lead to a local reduction in shear strength at the BSR, so they could play an important role during slope failure (Booth et al., 1994). Gas migrating from underlying turbiditic palaeochannels may be trapped in anticline strata that are crosscut and capped at their updip ends by the base of the gas hydrate sediment (Dillon et al., 1980) leading to the occurrence of a BSR which mimics the stacked underlying palaeochannels. This is the case in our study area in which the BSR occurs at the top of the anticline structures, indicating that free gas is trapped beneath it.

### 5.3. Migration through the highly faulted interval

Although the hydrate layer tends to temporarily inhibit fluid migration, a rapid increase of the overburden pressure can lead to the generation of excess pore fluid pressures (Bolton and Maltman, 1998), and fluids can escape from the free-gas zone through the highly faulted interval, creating pockmarks on seafloor (Cole et al., 2000). A mechanism that would be very effective in mobilizing large volumes of fluids is the addition of another fluid, such as migrating hydrocarbons from deep source rocks into the sealed system (Jenkins, 1930; Gay et al., 2003; Brooke et al., 1995). In this case, pockmarks form in such fine sediments and not in sandy sediments as reported by Hovland in the North Sea (Hovland and Judd, 1988). A detailed study of the organization of faults and furrows shows that the pockmarks are consistently located at the intersection of three neighboring hexagons (Gay et al., 2004). The triple junction of three neighboring hexagonal cells

represents a preferential pathway for upward fluid migration from deeper levels. Consequently, the HFI represents an interval with a high drainage potential for pore fluids. In this context, the fluids migrating from deeper levels are preferentially driven through this interval along the pre-existing faults affecting all the HFI.

### 5.4. Geochemical evidences of deep thermogenic fluids

Geochemical analysis conducted on cores Ca and Cd (see Fig. 1 for location) within shallow sediments of pockmarks over the upper Miocene palaeochannel show strong evidences of a mix of biogenic methane and deep thermogenic fluids (methane and heavier hydrocarbons) (Gay et al., in press). The presence of thermogenic fluid within shallow sediments of cores Ca and Cd represents an evidence of thermogenic fluid migration from the reservoir (Söderberg and Flodén, 1992) up to the seafloor through the highly faulted interval.

### 5.5. Model of fluids migrating from stacked turbidite palaeochannels

We propose for the Lower Congo Basin a model of fluid migration through the sedimentary column which takes into account two kinds of sedimentation (Fig. 11): (1) a turbiditic sedimentation building channel–levee systems on the slope and (2) a hemipelagic sedimentation which tends to seal the first one.

Deep thermogenic fluids produced within Cretaceous source rocks are preferentially entrapped within the sandy bodies of turbiditic Oligocene–Miocene palaeochannels. They can migrate from a palaeochannel level to another one along faults which develop at the crest of the channel–levee system or along sand sill and dykes (Lonergan et al., 2000; Gay et al., 2003). The vertical stacking pattern of turbiditic palaeochannels allows the best pathway for fluids migration, as migration pathways (chimneys) are more concentrated when underlain by three to four stacked palaeochannels. Once the fluids migrate to upper layer (Layer 1) of palaeochannels, they can reach the seafloor via migration along closely spaced normal faults of the highly faulted interval. They are temporarily inhibited below an interpreted 300-m-thick gas hydrate layer and accumulate under the hydrate stability zone to form a thick layer of free gas. In this case, the main factors controlling fluid entrapment is the presence of impermeable layers of hydrates leading to the generation of excess pore fluid pressure in

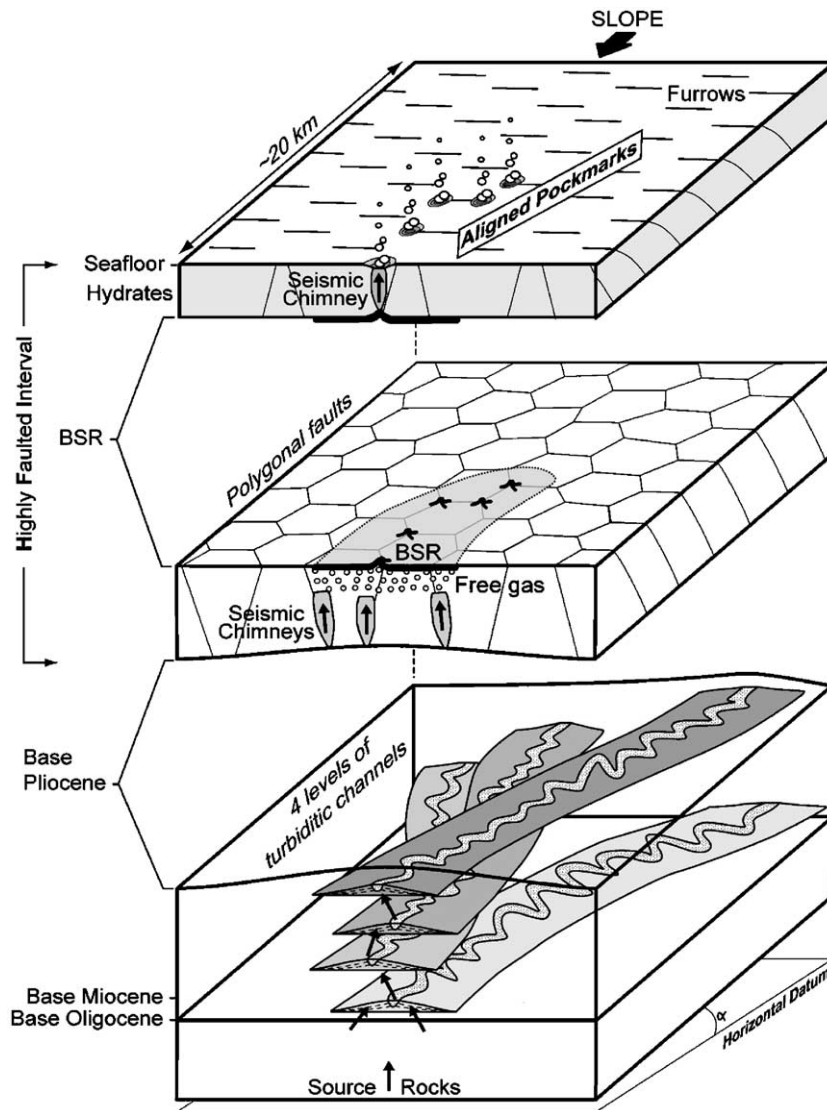


Fig. 11. Schematic block diagram illustrating the likely relationship between stacked palaeochannels within the Oligocene–Miocene interval, the seismic chimneys under the BSR that concentrate fluids under the impermeable layer of hydrates, the seismic chimneys over the BSR and seafloor pockmarks. Ultimately, in this model, fluids migrating through a large area are progressively concentrated to reach the seafloor at one point discharge site.

the underlying free gas accumulation. The free gas can escape up to the seafloor along faults of the highly faulted interval forming pockmarks on the seafloor (Fig. 11). Although these pockmarks seem isolated, they are clearly related to stacked Oligocene–Miocene turbiditic palaeochannels.

## 6. Conclusion

This detailed study of pockmarks within the Lower Congo Basin shows that the fluid migration history is complex due to the interrelation of tectonic features and sedimentary bodies. We show in this study that present-

day seafloor pockmarks which seem isolated are most often related to:

- 1) Underlying gas-charged chimneys and these chimneys are located at the triple junction of three neighboring polygonal faults;
- 2) A BSR still visible on seismic section. The BSR shifts upward near the overlying chimney, indicating an active fluid flow into the gas hydrate stability zone;
- 3) A large number of seismic chimneys above the BSR. These chimneys allow to feed the free-gas zone under the hydrate layer;

4) Stacked Oligocene–Miocene turbiditic palaeochannels. Due to differential compaction during burial, this stacking leads to the formation of a large anticline, about 10 km wide, driving fluids at the crest.

The main restriction of this model is that the present-day thermogenic fluid seepage on seafloor depends on an immediately underlying Mesozoic rift basin with an active petroleum system containing high-quality source rocks, which reaches the peak maturity at or about the same time as the mud-dominated Pliocene–Quaternary sediments were being deposited over the Oligo–Miocene turbiditic palaeochannels.

However, this system might follow the fault-valve behavior developed by Sibson (1992) and the fluid could escape periodically through the highly faulted interval (HFI). Such cycling could be recorded (mineralogically and/or biologically) within these pockmarks. Further sampling and exploration are needed to address this issue.

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