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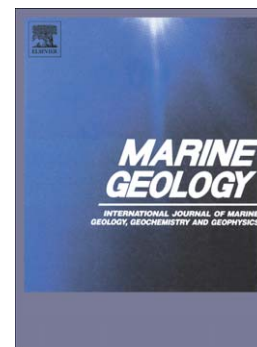
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Geological controls on focused fluid flow associated with seafloor seeps in the Lower Congo Basin

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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, 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 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 Elverhøi, 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 generally 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 (Cole et al., 2000), have migrated upward and are now preferentially trapped within the Oligo-Miocene silty-sandy channels (Gay et al., 2006b), constituting the most prolific hydrocarbon reservoirs in this area (Burwood, 1999). From early Pliocene time to present, the shelf and the slope were deeply incised (about 1000 m in the central part of the study area) by a canyon of the proto-Congo River (**Fig. 1**). The Zaire Canyon continues all the way down to the basin floor at 4000 m water depth (Jansen et al., 1984; Uenzelmann-Neben, 1998; Savoye et al., 2000), where it grades into the Zaire channel.

One of the main tectonic features of the West African margin is the gravitational sliding of post-rift sediments 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 (**Fig. 2**): an extensional domain on the upper slope, and a contractional domain located downslope (Duval et al., 1992; Rouby et al., 2002; Fort et al., 2004). The basinward translation of the post-rift sequence over the Aptian salt layer is balanced by compression and salt extrusion along reverse faults at the toe of the slope, creating the Angola Escarpment (**Fig. 2**).

3. Data and methods

The bathymetry of the Congo-Angola basin was surveyed during the 1992-1993 GUINNESS and 1998-2000 ZAIANGO (ZAIRE-ANGOLA) projects. The main objective was to map and investigate the Pliocene/Quaternary sedimentary history of the slope and deep sea fan (Savoye et al., 2000). The

bathymetric/multibeam map was acquired with a Simrad EM12 dual bathymetric and acoustic imagery. At 3000 m water depth, the processing of EM12 data provides a final terrain numerical grid with a 100x100 m horizontal grid and a vertical resolution of +/- 10 m. The primary objective was to create a mosaicked backscatter image from the multibeam data. After reprocessing, the final backscatter map is composed of pixels of 50x50 m each. The multibeam/backscatter data displayed in this study (**Fig. 3**) cover an area of about 12000 km².

The interpretation of the bathymetric/multibeam data was performed in combination with high-resolution 3D-exploration seismic data provided by TOTAL. The 3D-dataset selected for this study covers an area of 3300 km² with a line spacing of 12,5 m and a CDP distance of 12,5 m. The acquisition was performed using a dual 1530 cubic inch airgun, towed at a 3,5 m depth, fired at a 12,5 m interval and operated at 100 Hz. The data were loaded in an interactive seismic interpretation workstation and interpreted with the SISIMAGE software developed by TOTAL.

Additional data from the Leg ODP175 on the West African Margin (Wefer et al., 1998) and from recent studies in the Lower Congo Basin (Valle et al., 2001) provide useful information on stratigraphy, sedimentation rates and mechanical properties of sediments.

4. Seafloor backscatter analysis

The multibeam backscatter imagery, which extends from approximately 10° to 12° E and from 5° to 6° S in the study area, shows high backscatter anomalies that are oblique or overlap the ship tracks, indicating they are not data acquisition noise (**Fig. 3**). These high backscatter features fall into several categories by appearance: large sub-circular to ovoid areas, linear to curvilinear bands, and irregular to rounded patches (**Fig. 3**).

Wide sub-circular and ovoid areas are almost always associated with topographic mounds, which are part of the Angola escarpment salt diapir ridge.

The continuous meandering strip that crosscuts the study area from about east to west corresponds to the bottom of the Zaire channel turbiditic system (Babonneau et al., 2002), which is in the extension of the Zaire canyon further upslope. Both steep flanks of the canyon can be imaged on the backscatter mosaic and they are separated from the main channel axis by low backscatter reflectivity interpreted as abandoned terraces (Babonneau et al., 2004).

Rounded features are typically a few hundred meters wide and the most common appearance is one with nearly uniformly medium to high backscatter all across the features. The highest backscatter anomalies are observed in the centre of the depression. Such circular features are commonly interpreted as pockmarks (Hovland and Judd, 1988), the depression owing to fluid escape at the seabed. On the Congo-Angola margin pockmarks exist in a depth range of approximately 400-3000 m, and they appear as black patches on the backscatter mosaic (**Fig. 3**). In the area covered by the 3D seismic data, we identified 194 pockmarks on the multibeam side-scan imagery, with an average density of 5,9 pockmarks per 100 km².

5. Pockmarks, fluid pipes and BSR on 3D seismic data

The morphology of the pockmarks, their distribution and orientation are clearly revealed by a dip map of the seafloor based on the 3D seismic dataset (**Fig. 4**; see **Fig. 3** for location). They range from 100 m up to 800 m in diameter, and from a few meters to 40 m in depth. Most of them have a circular shape in map view, but the largest pockmarks are elongated in one main direction. Detailed displays of 3D seismic data show that these large pockmarks are irregular and sometimes link to several amplitude anomalies underneath suggesting that they have formed from the coalescence of several smaller pockmarks. On the 3D seismic data-derived dip map of seafloor, we counted 672 pockmarks, with an average density of 20,4 pockmarks per 100 km². This means that only 29% of the pockmarks visible in the 3D seismic data could be identified from the backscatter imagery (depending on the resolution of both datasets: see discussion part for further details).

Free gas can easily be interpreted from seismic records because even small amounts of gas within pore space significantly decrease the acoustic impedance of sediments and create anomalies such as acoustic turbidity, enhanced reflections (bright spots, flags) and acoustic blanking (wipe out) (Anderson and Hampton, 1980; Judd and Hovland, 1992; Schroot et al., 2005). In the Lower Congo Basin numerous seismic profiles through pockmarks show two levels of acoustic anomalies, vertically elongated under the main depression (**Fig. 5**). The deep anomaly is an inverted cone shape in cross section and marked by lower amplitude reflectors and acoustic turbidity. On both sides of this region the bright reflectors shift upward. This pull-up may be due to fluid movement (structural) or to velocity effects caused by hydrate/carbonate cementing within the overlying pipe corresponding to the shallow anomaly. The pipe is ovoid in shape with depressed high-amplitude reflectors considered as a reduction of the seismic velocities (pull-down effects), even if this could be real depressions due to fluid expulsion (ancient pockmarks ?). Such acoustic anomalies are also

called seismic chimneys and could be indicative of fluid flow from deeper levels (Hovland and Judd, 1988; Judd et al., 1992; Hempel et al., 1994; Heggland, 1997; Tingdahl et al., 2001; Ligtenberg, 2005).

At 250 ms TWT below seafloor, a high-amplitude reflection, parallel to the seafloor and characterized by a reversed polarity compared to the seafloor reflection (**Fig. 5**), is interpreted as a Bottom Simulating Reflector (BSR). It can be observed all over the Lower Congo Basin (Cunningham and Lindholm, 2000). It corresponds to the lower thermodynamic limit of the gas-hydrate stability zone (Shipley et al., 1979). On the seismic profile CD (**Fig. 5**), the BSR is deflected upward directly beneath the pockmark depressions, suggesting a localized positive heatflow anomaly (Wood et al., 2002), which is consistent with an ascending movement of fluids through the gas-hydrate layers creating seismic chimneys (Lucazeau et al., 2004).

6. Pockmarks related to tectonic features

6.1. Normal faults

In the north-eastern part of the study area, the seabed is affected by curved depressions, 5 to 8 km long and a few meters deep. They are oriented NW-SE, parallel to the Cretaceous carbonate platform (Anderson et al., 2000). The dip map of Area 1 (see **Fig. 4 for location**) shows a continuous curved depression, 300 m wide and 20 m deep, at about 800 m water depth. The seismic profile EF (**Fig. 6c**) shows that this depression is related to a basinward, i.e. SW-dipping, normal fault. Such normal faults are located in the extensional domain created by gravitational sliding of the sedimentary cover over the Aptian salt. Five pockmarks have been identified along the fault depression on the seafloor dip map (**Fig. 6a**). However, only one of them is visible on the backscatter map (**Fig. 6b**). Associated with the pockmarks, there are acoustic disturbances on the seismic data. They have the shape of narrow vertical columns, 75 m wide, that seem to branch off the fault plane at about 150 ms TWT below seafloor. This suggests that the normal faults channel fluids upward from deep reservoirs, such as upper Miocene turbiditic channels (Gay et al., 2006b).

In the northeastern part of the study area (Area 2: see **Fig. 4 for location**), at about 400 m water depth, two circular structures, 200 to 400 m wide and about 30 m high, are visible both on the dip map of seafloor as dome-like structures and on the multibeam reflectivity map as black patches (**Fig. 7a & 7b**). A sediment core collected from within the main dome-like structure shows carbonate-rich sediments and debris of cold-water corals interbedded with hemipelagic muds (Gay, 2002). The seismic profile GH (**Fig. 7c**)

reveals that they are located just above a deep-buried turbiditic channel that shows a rollover anticline at the hanging wall of a west-dipping normal fault.

Despite the less permeable nature of the Quaternary-Pliocene sequence, this interval is affected by tight polygonal faults that have possibly channeled fluids from the west-dipping normal fault and fed the fluid seep site (**Fig. 7d**). In this area the gravity-driven normal fault does not affect the seabed. However, fluids coming from the upper turbiditic Miocene channels reach the seabed to form seafloor fluid seeps. In this case, polygonal faults act as a shortcut, as they represent preferential pathways for fluid migration with a high drainage potential at the node of three contiguous polygonal cells (Gay et al., 2004).

6.2. Salt diapirs

Diapirism and its association with fluid migration and gas-hydrate occurrences is relatively well documented for Blake Ridge (Dillon et al., 1983; Taylor et al., 2000), in the Fair Way Basin (Auzende et al., 2000), in the Gulf of Mexico (McManus and Hanor, 1993; Smith Enos and Kyle, 2002) and on the western continental margin of India (Satyavani et al., 2005). In general, subsurface diapirs play a dominant role in the development of a growth fault network that provides major conduits for the upward migration of fluids and hydrocarbons to the seafloor (Roberts et al., 1992; Sager et al., 2003). The multibeam data from the Lower Congo Basin, at water depths ranging between 3000 m and 3200 m, show an elongated diapiric ridge with a trend of N160. This ridge corresponds to the Angola Escarpment south of the Zaire canyon (**Fig. 1, 3 and 4**). In this area, numerous shallow subseafloor salt diapirs are expressed on the seafloor as circular to ovoid, 1 to 5 km wide features. This is due to steep angles on the diapir flanks compared to the regional seafloor. In Area 3 (**Fig. 4**), a large number of circular areas of anomalous dip are visible on top of the salt diapir mounds (**Fig. 8a**). Some cores taken within these areas have shown evidence of thermogenic oil and gas (Total, pers. comm.) and these depressions are interpreted to be associated with fluid seeps (pockmarks). However, only some pockmarks appear as high backscatter (black) patches on the multibeam acoustic map (**Fig. 8b**), indicating that most of them are now inactive.

Numerous other salt diapirs show seafloor expression further north on the right (north) side of the Zaire canyon. In Area 4 (**Fig. 4**) a large number of pockmarks is concentrated on the top of a normal fault network associated with collapse above a diapir crest (**Fig. 9a**) and only some of them appear as high backscatter anomalies on the multibeam reflectivity map (**Fig. 9b**). The seismic profile IJ (**Fig. 9c**) shows

that the pockmarks are fed by fluid pipes characterized by high amplitude reflections. The base of the pipes seems to branch on a BSR with free gas beneath it.

Similar diapirs, pockmarks and BSRs have been reported offshore Nigeria (Heggland, 1997; Hovland et al., 1997; Graue, 2000). The rapid ascending movement of a salt diapir does not allow the thermal equilibrium to be re-established and this may generate overpressure due to the sub-adiabatic uplift of the surrounding reservoirs and to the decrease of the lithostatic pressure from depth Z1 to Z2 (**Fig. 9d**). In such diapiric environments, fluid migration may be enhanced 1) by the collapse of sediments above the diapir head (Paull et al., 1993), 2) by a localized positive heat-flow anomaly along the diapir axis and in surrounding sediments (Xie et al., 2001; Lucazeau et al., 2004), 3) by the convection of fluid around and over the diapir induced by the thermal anomaly (Fu and Aharon, 1998; Cartwright et al., 2001), 4) by permeability changes due to remineralization through precipitation from salt rich fluids, in particular barium and salt exchanges (Roberts, 1999) and 5) by hydraulic faulting at the top of overpressured uplifted reservoirs.

7. Pockmarks related to erosional surfaces

The ZAIANGO 1 and 2 cruises surveyed a large part of the Zaire Fan (Savoye et al., 2000; Droz et al., 2003) and showed that the fan surface is characterized by a multitude of inactive channel-levee systems (**Fig. 3**). Most of the channels and palaeochannels are meandering with variable sinuosity. The youngest and still active channel-levee system is located in the axial part of the fan and has been entirely surveyed down to the distal fan at 5000 m water depth. The shelf and the slope are deeply incised by the Zaire canyon from East to West, reaching a maximum relief of 1300 m near the shelf break and gradually decreasing toward the toe of the slope (Babonneau et al., 2002).

7.1. Active Canyons

Area 5 is located south of the Zaire Canyon, north of the Angola Escarpment, at 1700-1900 m water depth (**Fig. 4**). The dip map of seafloor in this area shows meanders at the bottom of the canyon and smooth flanks (**Fig. 10a**). The meanders are bordered by terraces that are locally discontinuous due to erosional processes within the canyon. The detailed analysis of the morphology, the seismic structure and the recent sedimentation along the Zaire upper-fan valley show that terraces are inner levees confined within the incised valley (Babonneau et al., 2004). Many terraces correspond to the infilling of abandoned meanders,

and aggradation by deposition of turbiditic sequences due to current overspill in the Zaire Canyon. A large number of pockmarks exist on the terraces, at the foot of the canyon flanks. They are 200-800 m wide, elongated, and located along the base of the main scarp of the canyon flanks indicating that the scarp-terrace discontinuity may have played a role in focusing fluids discharge (**Fig. 10a**). The lack of any high backscatter anomaly on the multibeam reflectivity map indicates that they are now inactive (**Fig. 10b**).

7.2. *Palaeo-canyons*

The present Zaire Canyon is the last erosional episode of a series of incision-infill cycles that started in the Pliocene. During these successive events, the canyon moved laterally creating a large valley, 15 km wide, whereas the present canyon is 5 to 8 km wide. In Area 6 (**Fig. 4**), the northern border of the valley is marked by a slope break, almost parallel to the canyon axis, visible on the dip map of the seafloor (**Fig. 11a**). This slope break is the result of differential compaction between recently deposited sediments within palaeo-canyons and the surrounding sediments on the open slope. The seismic profile KL shows a BSR which tracks the seafloor below the present Zaire Canyon, indicating equilibrium of hydrates below the canyon (**Fig. 11c**). This means also that the canyon has been active for long enough to allow hydrates to be in thermodynamical equilibrium below it (Lucazeau et al., 2004). A large number of fluid pipes, bright spots and free gas beneath the BSR have been identified in this area. The slope break is highlighted by aligned pockmarks on the seafloor. Several of these pockmarks are visible both on the dip map and on the multibeam reflectivity map (**Fig. 11a and 11b**). The pockmarks are aligned over a steep erosional surface of a palaeo-canyon that incises into the upper Miocene sediments (**Fig. 11c and 11d**). They are associated with underlying chimneys that root on the erosional surface. As previously shown in the Lower Congo Basin, fluids are likely originate from Miocene palaeo-channels (Gay et al., 2006b). A plausible scenario consistent with known hydrocarbon accumulations in the LCB and this cross-section is that fluids migrate laterally and upsection along dipping permeable stratigraphic units, and more vertically along erosional unconformities or faults. The fluid chimneys appear to originate at a pinch-out of a turbiditic sequence, probably silty-sandy, on the erosional surface (**Fig. 11d**).

8. Pockmarks related to buried sedimentary bodies

8.1. Shallow buried palaeochannel

On the northern side of the Zaire Canyon (Area 7: **Fig. 4**), a large number of pockmarks are aligned along a sinuous belt from the southeast to the northwest (**Fig. 12a**). They are 100 to 800 m wide with a maximum depth of about 40 m. They are regularly spaced about 300 m apart, but some of them have formed from the coalescence of several smaller pockmarks. Despite the number of pockmarks visible on the seafloor dip map, relatively few of them appear as high backscatter anomalies on the multibeam reflectivity map (**Fig. 12b**). On the seismic profile MN (**Fig. 12c**), the reflectors below the pockmarks appear deflected downward. They are not continuous and they are disturbed by acoustic blanking probably due to a recent ascending movement of fluids. These vertical anomalies are commonly interpreted as chimneys for ascending fluids from deeper levels (**Fig. 12d**). Systematic mapping of this area reveals that all chimneys root in an underlying turbiditic palaeochannel (Gay et al., 2003) and the pockmarks on the seafloor mimic the meandering track of the palaeochannel.

The large number of pockmarks and their size represent an extensive system of dewatering from a shallow buried channel reservoir as demonstrated in the Black Sea (Naudts et al., 2006). They have probably expelled large quantities of pore fluids and biogenic gas previously trapped in the silty-sandy channel. This kind of fluid expulsion related to a palaeochannel is also described on the Niger delta front (Davies, 2003), where sediments are mobilized leading to sand injections within the overlying sediments and creating hummocky-depressional structures instead of pockmarks, and in the Black Sea (Naudts et al., 2006), where seeps occur along the margins of filled channels and in association with cut-and-fill delta deposits, corresponding probably to the initiation of dewatering or sand injections. These studies show that initial fluid migration pathways may be initiated early during the burial history of a sedimentary body. Such conduits may be re-used at greater depth by thermogenic fluids coming from source rocks (Gay et al., 2006a).

8.2. Deep buried palaeochannels

In the northern part of the study area (Area 8: **Fig. 4**), some pockmarks have been identified on the modern seafloor both on the seafloor dip map derived from 3D seismic data and on multibeam imagery (**Fig. 13a and 13b**), indicating that they are still active. This has been confirmed by geochemical analyses conducted on cores taken within four of these pockmarks showing evidence of thermogenic fluids (Gay et

al., 2006a). The seismic profile OP shows a clear spatial relationship between a pockmark, an underlying chimney, the BSR and an upper Miocene turbiditic channel (**Fig. 13c and 13d**). In the Lower Congo Basin, turbidite sands are associated with four main stages of deposition (Oligocene, lower, middle and upper Miocene) (Gay et al., 2006b), whereas only three stages have been identified further south in the Angola basin (Anderson et al., 2000). Where the Oligocene-Miocene turbiditic channels are vertically stacked, thermogenic fluids ascending from deeper source rocks can migrate from one channel to the next and they are progressively concentrated in the upper Miocene channels.

Syn-depositional major faults located above turbiditic sand bodies may periodically act as main vertical fluid escape pathways (Lonergan et al., 2000). As the base of the polygonal faults reaches the upper Miocene interval (Gay et al., 2004), they are probably connected locally to the syn-depositional faults, allowing fluids to migrate upward. The migration of fluids through the impermeable Pliocene–present cover leads to chimney development, free gas accumulation beneath hydrates, BSR occurrence over turbiditic channels and pockmark formation at the seabed.

9. Discussion

The evaluation of seafloor fluid seeps in a sedimentary basin requires a thorough understanding of the parameters that control the migration and the accumulation of fluids before redistribution to the seabed. The origin of shallow fluids (0-3000 m water depth) is commonly attributed to biogenic and/or thermogenic processes (Tissot and Welte, 1984). In both cases, the fluids are derived from organic matter either as the result of bacterial activity or of thermogenic processes, which are dependent on temperature and pressure. Different driving forces for fluid migration have been hypothesized including hydrocarbon generation, differential compaction, and tectonic compression. One way to understand these mechanisms, both as a process and in terms of timing, is through the use of basin modeling methods, commonly applied by the petroleum industry. However, such an approach does not take into account local heterogeneities observed in sedimentary basins. Geochemical analyses conducted on cores taken within seafloor pockmarks of the Lower Congo Basin have led to the conclusion that expelled fluids are a mix of biogenic and thermogenic gases and oil (methane and heavier hydrocarbons) coming from Oligo-Miocene turbiditic reservoirs (Gay et al., 2006a; Gay et al., 2006b). This observation suggests that the fluid migration history is not as simple as stated by basin-scale models of sedimentary basins. Moreover, despite the fact that very low permeability hemipelagic sediments overlying the Oligo-Miocene sequence should act as a seal barrier preventing further upward

migrations (Davis, 1992; Lee and Chough, 2003), the occurrence of deep thermogenic fluids at the present day seafloor indicates that deep source fluids do somehow bypass the thick mud-dominated Pliocene seal.

9.1. *Fluid seeps imaging ambiguities*

The topographic expression of fluid expulsion at the seafloor commonly includes build-ups, such as mud volcanoes/diapirs (and maybe carbonate mounds), and depressions, such as pockmarks (Hovland and Judd, 1988; Roberts et al., 1990; Kaluza and Doyle, 1996; Sager et al., 2003; Somoza et al., 2003; Loncke et al., 2004; Zitter et al., 2005; León et al., 2006). Most often these fluid expulsion features are recognized by their effects on the physiography of the seafloor and acoustic properties of near-surface sediments because both chemosynthetic communities and authigenic carbonates, that are commonly associated with them, may cause higher acoustic impedance and roughness than in the surrounding seafloor (Kaluza and Doyle, 1996; Sager et al., 1999; Vogt et al., 1999; Yun et al., 1999; Orange et al., 2002; Johnson et al., 2003; Klaucke et al., 2006). Such anomalies are usually the result of a near total reflection of sound owing to a hard sea bottom or attenuation owing to dispersion of the sound waves by gas bubbles (Behrens, 1988; Anderson and Bryant, 1990). In the Lower Congo Basin, numerous morphological anomalies are imaged on both the 3D seismic dip map and the backscatter imagery. However, video records from ROV dives show that some of the fluid seeps lack direct evidence of modern chemosynthetic activity or fluid leakage. Such seeps are interpreted to be now inactive seeps and to be no longer fed by fluids (Greene et al., 1999; Stakes et al., 1999). Gravity cores taken during the ZAIANGO cruises (Savoye et al., 2000) show that authigenic carbonates and shell debris are now buried in shallow sediments where pockmarks still appear as black patches on backscatter imagery. This means that both active and recently active (but presently dormant) seep sites may create anomalies on backscatter data that can not be distinguished from each other.

The backscatter energy recorded on EM12 multibeam data is a function of several parameters including a surface effect (micro-topography changes, steep angles or roughness) and a volumetric effect (porosity, bulk density or compaction rate) that can only be calibrated from regional slope (Johnson and Helferty, 1990; Kenyon, 1992; Blondel and Murton, 1997; Cochrane and Lafferty, 2002). Furthermore, the multibeam backscatter signal may penetrate up to 10 m in mud-rich sediments and up to 4 m in sand-rich sediments (Liu, 1997). The high impedance combined with a high roughness of buried carbonate pavements and/or domes and shells within pockmarks will cause a strong reverberation and return a large amount of backscatter energy (Sager et al., 2003). Finally, the amplitude anomaly of multibeam data depends mainly on

the presence of carbonate building and chemosynthetic fauna in the first 10 m below the bottom of the depression. We propose here several correlations between backscatter imagery response and seafloor chemo-biological facies (A to E) depending on the extent and recency of fluid expulsion activity (**Fig. 14**). Moreover, an episodic activity of fluid escape may allow more than one generation of seafloor fluid seep to form (MacDonald et al., 2000) and a low backscatter may correspond to a dormant site (Sager et al., 2003), which could be reactivated, for instance, by loading owing to sediment dynamics at the seabed (i.e. turbidite deposits) or to human activity (i.e. pipe-line or platform anchor).

Such a model is a good approach to understand the seabed organization of fluid seeps and to define whether these fluid seeps are active or not. Using this model, a high backscatter anomaly indicates that fluid expulsion is active (chemosynthetic fauna and/or carbonate buildups present at the seabed) or has been recently active (dead or dormant site characterized by buried chemosynthetic fauna and/or carbonate buildups within the upper 10 m). This has to be verified by in situ visual observations or geochemical sampling. The model may explain why only 194 pockmarks (29%) have been identified on backscatter imagery, where 672 were recognized on the dip seafloor map derived from 3D seismic data. Even if the smallest pockmark identified on 3D seismic data is 200 m wide, this difference may be partly caused by different lateral resolutions between multibeam data (100x100 m) and 3D seismic data (12,5x12,5 m).

9.2. Comparison between different types of pockmarks

Of all identified seeps in the Lower Congo Basin, more than 99% are located in water depths deeper than 545-575 m (Areas 1 and 3 to 7) where they are clustered in certain morphologically determined locations, with only a few seeps were identified above this depth (Area 2). A recent study conducted in the Lower Congo Basin has shown that this depth (545 to 575 m water depth depending on bottom water temperature shift from winter to summer) corresponds to the outcrop of the BGHSZ (Base of the Gas Hydrate Stability Zone) at the seabed (Sultan et al., 2004). Even if gas hydrates are usually considered impermeable due to their ice-like nature, we have shown here that pockmarks occurring below 545-575 m water depth are commonly developing over a BSR. We have previously shown in the area that the BSR shifts upward near the chimneys, indicating an active fluid flow into the gas hydrate stability zone (Gay et al., 2006b), even if free gas cannot easily move through the GHSZ without freezing into hydrates contributing to stop the flux. This observation strongly suggests a focused fluid flow rather than a diffuse fluid flow through the hemipelagic seal in the Lower Congo Basin.

Different mechanisms have been proposed for the driving forces that control the movement of fluids and the migration pathways that lead to the formation of modern seeps. However, in the Lower Congo Basin there can be only two reasons for fluids to cross the permeability barrier formed by less permeable gas hydrates hosted within layer-parallel mud-dominated low permeability Pliocene-Quaternary sediments. One reason may be a continuous feeding of the free gas zone by deeper fluids leading to overpressure below gas hydrates. Once the pore fluid pressure below or at the base of the GHSZ reaches the overlying lithostatic pressure, fluids and free gas will be periodically released, as shown for the fault valve behavior (Sibson, 1992), creating pipes and seabed pockmarks. Another explanation is that the presence of a widespread polygonal fault system affecting the Pliocene-Quaternary sequence (Gay et al., 2004) may provide vertical fluid escape pathways (Gay et al., 2004; Trincardi et al., 2004; Hansen et al., 2005). The periodic release of fluids, which either exceed lithostatic pressure or a critical pore throat capillary tension, may explain why only a small percentage (29%) of pockmarks have an anomalous backscatter, suggesting that they are active or they have been recently active. Furthermore, based on video records during ROV dives, sediment and water sampling, and gravity cores analysis, we have shown that less than 2-3 % of the pockmarks are really active in terms of fluid release in the water column associated with living endemic fauna at the seabed and mineralogical precipitation (carbonate domes and pavements, pyrite, tubular concretions). This suggests that we are now in a dormant period in terms of fluid release and that the rate of fluid expulsions has been even much higher recently to create such number of pockmarks at the seabed.

These observations show that fluid migration in the Lower Congo Basin depends mainly on two processes or their combination: 1) the gas hydrate system that inhibits fluid and gas migration and 2) the polygonal fault systems that favour fluid migration when fluids are periodically released.

9.3. Geochemical constraints on the origin of fluids

Geochemical analyses of near-bottom water and shallow sediments within pockmarks have revealed variable dissolved methane concentrations up to 400 nl/l, which are 30-40 times the oceanic background (Charlou et al., 2004). However, even if isotopic analyses ($\delta^{13}\text{C} = -70$ to -86% relative to PDB) indicate a primarily microbial origin for the CH_4 (Brooks et al., 1984; Tissot and Welte, 1984) generated through bacterial CO_2 reduction (Claypool and Kaplan, 1974), GC-MS analyses containing clearly recognizable oil fingerprints, elevated baselines ($\text{UCM} > 20 \mu\text{g/g}$), a broad molecular weight range of n-alkanes with little odd-even preference, extract yields and relatively high fluorescence intensities ($4000 < \text{Imax TSF} < 21,000$)

could also be interpreted as an indication of the presence of thermogenic hydrocarbons (Gay et al., 2006a). The thermogenic signal is tenuous because of the biodegradation, which mainly depends on the time these hydrocarbon have spent in various reservoirs, such as buried turbiditic channels, gas hydrates and free gas trapped below it, and on the oxidization by bacteria in the first 10 m below seafloor, in the aerobic zone and in the sulphate reducing interval (Claypool and Kaplan, 1974; Bernard, 1979; Devol and Ahmed, 1981; Wenger and Isaksen, 2002). Nevertheless, geochemical analyses suggests that fluids reaching the seabed can be interpreted as a mix of biogenic and thermogenic gases and oils.

However, even if the geochemical sampling is selected at favourable sites (within pockmarks overlying deep chimneys), a thermogenic co-signature of fluids in shallow sediments does not guarantee the presence of petroleum reservoir directly below the seafloor fluid seep. In this study, we have shown that deep thermogenic fluids may be driven along both lateral and steep discontinuities affecting the sedimentary column, such as major tectonic faults, shallow polygonal faults, erosional surfaces, and may be temporarily stored in various reservoirs and traps, such as salt diapirs, anticlinal structures, and shallow and deep buried turbiditic channels along which fluids can be remobilized.

9.4. Model of fluid seeps organization and fluid pathways

Despite the fact that faults and fractures have been widely recognized as primary conduits for fluid migration in mid-ocean ridge vents and in convergent margins (Ritger et al., 1987; Kulm and Suess, 1990), the control that such faults and discontinuities of stratigraphic, structural and diagenetic origin exert on subsurface pathways of fluid migration is still poorly understood and requires further constraints (Parnell, 2003; Campbell, 2006). Based on a very large dataset extending from 300 to 2500 m water depth, we propose a 3D model of fluid migration on a continental passive margin where the distribution of seafloor fluid seeps is directly related to buried underlying features, such as major faults (normal and reverse), polygonal faults, salt diapirs, erosional surfaces (canyons and palaeo-canyons), shallow buried palaeochannels and deep buried stacked channels (**Fig. 15**). In this model, the ability of hydrate-rich sediments to inhibit upward fluid migration is balanced by the occurrence of shallow polygonal fault intervals in fine-grained sediments, which help fluid expulsion from deeper in the section, but their location helps control the actual location of a seep.

Tectonic deformation controls the up-dip migration of fluid and gases from the deep basins to the margins along faults and discontinuities. The fluid migration is triggered by the interaction of several

processes including: 1) pore fluid overpressure: sand-rich turbiditic channels embedded within fine-grained sealing layers can preserve porosity, delay lithification and favour liquefaction and upward fluid migration (Osborne and Swarbrick, 1997); 2) overpressure in sand-rich reservoirs affected by hydrocarbon charges (Yu and Lerche, 1996); 3) earthquakes; 4) differential compaction and folding across a thick sand body, that may generate upward propagating fractures at its edges, and downward propagating cracks over its crest (Cosgrove and Hillier, 2000; Lonergan et al., 2000).

Even though such triggering processes can not be clearly defined here, the model of seafloor fluid seeps organization provides a major tool in identifying the geometry of flow pathways and of the underlying buried bodies where the fluids are originate. This qualitative model can provide insight into shallow geohydrologic processes of both passive and active continental margins.

10. Conclusion

During the ZAIANGO project, we have collected bottom video records using ROV dives, sediment and water for geochemical analysis, and gravity cores above some high backscatter (black) patches, 100 to 800 m wide, previously identified on the extensive EM12 reflectivity map acquired in the Congo/Angola Basin (Savoye et al., 2000). Although all these circular backscatter anomalies were not explored, one of the main results of this collaborative project is that these anomalies are commonly associated with localized fluid seeps within negative-relief (pockmarks) and positive-relief (mounds) dip anomalies (Olu-Le Roy et al., 2003; Charlou et al., 2004; Ondreas et al., 2005; Gay et al., 2006c). In this study, we examined geophysical signatures of numerous bathymetric and backscatter anomalies based on backscatter imagery coupled with 3D seismic datasets in the Lower Congo Basin, from 300 m to 2500 m water depth, that we have interpreted as fluid seep sites. We have shown that:

- 1) the seabed organization of fluid seeps clearly relates to the location and the geometry of underlying buried reservoirs/traps where the fluids are originating from ;

- 2) discontinuities in the sedimentary section, such as faults, salt diapirs, erosional surfaces (active canyons and palaeo-canyons), polygonal faults, or buried chimneys may channelize deep fluids during migration and may allow fluids to migrate both laterally and vertically;

- 2) sedimentary structures, such as shallow and deep turbiditic channels or sandy/silty layers, and gas hydrates may behave as either conduits or intermediate reservoirs, concentrating fluids before redistribution.

Despite the fact that gas hydrates may act as a regional seal in the area, a widespread polygonal fault system allows fluids to migrate upwards resulting in a patchy distribution of seafloor pockmarks and mounds. Only a third part of the pockmarks identified on 3D seismic data are imaged on the backscatter map, indicating that these high backscatter pockmarks are potentially active at the present day (the multibeam signal penetrates up to 10m in soft sediments or 4m in sand-rich sediments for a 12 KHz source). However, ROV dives and geochemical analyses have shown that only a few of these high backscatter pockmarks are currently active at the seabed (less than 2-3 %); the remaining high backscatter pockmarks or mounds are dormant, but show indications of recent activity in the 10m below the mudline. This suggests that we are now in a period of relative quiescence in terms of fluid seepage (low amount of active pockmarks vs total number of imaged pockmarks), but they have been periodically reactivated. The proposed 3D model of the plumbing system of a continental margin would help to define where these fluid seeps are supposed to occur in the near future, which is relevant for the risk assessment in offshore operations and for the global carbon budget as methane and carbon dioxide are the two main fluids escaping at the seabed.

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12. References

- Abrams, M.A., 1992. Geophysical and geochemical evidence for subsurface hydrocarbon leakage in the Bering Sea, Alaska. *Mar. Pet. Geol.* 9, 208-221.
- Anderson, A.L., Bryant, W.R., 1990. Gassy Sediment Occurrence and Properties: Northern Gulf of Mexico. *Geo-Mar. Lett.* 10, 209-220.
- Anderson, A.L., Hampton, L.D., 1980. Acoustics of gas bearing sediment. *JASA* 67, 1865-1903.
- Anderson, J.E., Cartwright, J., Drysdall, S.J., Vivian, N., 2000. Controls on turbidite sand deposition during gravity-driven extension of a passive margin: examples from Miocene sediments in Block 4, Angola. *Mar. Pet. Geol.* 17, 1165-1203.
- Auzende, J.M., van de Beuque, S., Dickens, G.R., Francois, C., Lavoy, Y., Voutary, O., Exon, N., 2000. Deep sea diapirs and bottom simulating reflector in Fairway Basin (SW Pacific). *Mar. Geophys. Res.* 21, 579-587.
- Babonneau, N., Savoye, B., Cremer, M., Bez, M., 2004. Multiple terraces within the deep incised Zaire Valley (ZaiAngo Project): are they confined levees? In: Lomas, S.A., P. Joseph (Eds.), *Confined turbidite systems*. Geological Society of London Special Publication 222, pp. 91-114.

- 520 Babonneau, N., Savoye, B., Cremer, M., Klein, B., 2002. Morphology and architecture of the present canyon
521 and channel system of the Zaire deep-sea fan. *Mar. Pet. Geol.* 19, 445-467.
- 522 Baraza, J., Ercilla, G., 1996. Gas-charged sediments and large pockmark-like features on the Gulf of Cadiz
523 slope (SW Spain). *Mar. Pet. Geol.* 13, 253-261.
- 524 Behrens, E.W., 1988. Geology of a continental slope oil seep, northern Gulf of Mexico. *AAPG Bull.* 72,
525 105-114.
- 526 Bentahila, Y., Hebrard, O., Ben Othman, D., Luck, J.-M., Séranne, M., Lopez, M., 2005. Gulf of Guinea
527 continental slope and Congo (Zaire) deep-sea fan: Sr–Pb isotopic constraints on sediments
528 provenance from ZaiAngo cores. *Mar. Geol.* 226, 323-332.
- 529 Bernard, B.B., 1979. Methane in marine sediments. *Deep Sea Res.* 26A, 429-443.
- 530 Berndt, C., 2005. Focused fluid flow in passive continental margins. *Phil. Trans. Roy. Soc. A* 363, 2855-
531 2871.
- 532 Blondel, P., Murton, B.J., 1997. *Handbook of Seafloor Sonar Imagery*. Wiley, New York, 314 pp.
- 533 Boe, R., Rise, L., Ottesen, D., 1998. Elongate depressions on the southern slope of the Norwegian trench
534 (Skagerrak) : morphology and evolution. *Mar. Geol.* 146, 191-203.
- 535 Brice, S.E., Cochran, M.D., Pardo, G., Edwards, A.D., 1982. Tectonics and Sedimentation of the South
536 Atlantic Rift Sequence: Cabinda, Angola. In: Drake, W.A. (Ed.), *Studies in Continental Margin*
537 *Geology*. AAPG Memoir 34, pp. 5-18.
- 538 Brooks, J.M., Kennicutt, M.C., Fay, R.R., McDonald, T.J., 1984. Thermogenic gas hydrates in the Gulf of
539 Mexico. *Science* 225, 409-411.
- 540 Brown, A., 2000. Evaluation of possible gas microseepage mechanisms. *AAPG Bull.* 84, 1775-1789.
- 541 Burwood, R., 1999. Angola: source rock control for Lower Congo Coastal and Kwanza Basin petroleum
542 systems. In: Cameron, N.R., Bate, R.H., Clure, V.S. (Eds.), *The Oil and Gas Habitats of the South*
543 *Atlantic*. Geological Society of London Special Publication 153, pp. 181-184.
- 544 Campbell, K.A., 2006. Hydrocarbon seep and hydrothermal vent paleoenvironments and paleontology: Past
545 developments and future research directions. *Palaeogeogr. Palaeoclim. Palaeoecol.* 232, 362– 407.
- 546 Cartwright, J., Stewart, S., Clark, J., 2001. Salt dissolution and salt-related deformation of the Forth
547 Approaches Basin, UK North Sea. *Mar. Pet. Geol.* 18, 757-778.
- 548 Charlou, J.L., Donval, J.-P., Fouquet, Y., Ondréas, H., Knoery, J., Cochonat, P., Levaché, D., Poirier, Y.,
549 Jean-Baptiste, P., Fourré, E., Chazallon, B., ZAIROV-Leg 2 scientific party, 2004. Physical and
550 Geochemical characteristics of gas hydrates and associated methane plumes in the Congo-Angola
551 Basin. *Chem. Geol.* 205, 405-425.
- 552 Cifci, G., Dondurur, D., Ergün, M., 2003. Deep and shallow structures of large pockmarks in the Turkish
553 shelf, Eastern Black Sea. *Geo-Mar. Lett.* 23, 311-322.
- 554 Claypool, G.E., Kaplan, I.R., 1974. The origin and distribution of methane in marine sediments. In: Kaplan,
555 I.R. (Ed.), *Natural Gases in Marine Sediments*. Plenum Press, New York, pp. 99-139.
- 556 Cochonat, P., Cadet, J.-P., Lallemand, S.J., Mazzoti, S., Nouzé, H., Fouchet, C., Foucher, J.-P., 2002. Slope
557 instabilities and gravity processes in fluid migration and tectonically active environment in the
558 eastern Nankai accretionary wedge (KAICO-Tokai'96 cruise). *Mar. Geol.* 187, 193-202.
- 559 Cochran, G.R., Lafferty, K.D., 2002. Use of acoustic classification of sidescan sonar data for mapping
560 benthic habitat in the northern Channel Islands, California. *Cont. Shelf Res.* 22, 683-690.
- 561 Cole, G.A., Requejo, A.G., Ormerod, D., Yu, Z., Clifford, A., 2000. Petroleum geochemical assessment of
562 the Lower Congo Basin. In: Mello, M.R., Katz, B.J. (Eds.), *Petroleum Systems of South Atlantic*
563 *Margins*. AAPG Memoir 73, pp. 325-339.
- 564 Cosgrove, J.W., Hillier, R.D., 2000. Forced-fold development within Tertiary sediments of the Alba Field,
565 UKCS; evidence of differential compaction and post-depositional sandstone remobilization. In:
566 Cosgrove, J.W., Ameen, M.S. (Eds.), *Forced folds and fractures*. Geological Society of London
567 Special Publication 169, pp. 61-71.
- 568 Cunningham, R., Lindholm, R.M., 2000. Seismic evidence for widespread gas hydrate formation, offshore
569 West Africa. In: Mello, M.R., Katz, B.J. (Eds.), *Petroleum systems of South Atlantic margins*.
570 AAPG Memoir 73, pp. 93-105.
- 571 Davies, R.J., 2003. Kilometer-scale fluidization structures formed during early burial of a deep-water slope
572 channel on the Niger Delta. *Geology*, 31, 949-952.
- 573 Davis, A.M., 1992. Shallow gas: an overview. *Cont. Shelf Res.* 12, 1077-1079.
- 574 Devol, A.H., Ahmed, S.I., 1981. Are high rates of sulfate reduction associated with anaerobic oxidation of
575 methane ? *Nature* 291, 407-408.
- 576 Dillon, W.P., Popenoe, P., Grow, J.A., Klitgord, K.D., Swift, B.A., Paull, C.K., 1983. Growth faulting and
577 salt diapirism: their relationship and control in the Carolina Trough, eastern North America. *Margin*
578 *Geol.* 34, 21-46.

- Dimitrov, L., Woodside, J., 2003. Deep sea pockmarks environments in the eastern Mediterranean. *Mar. Geol.* 195, 263-276.
- Droz, L., Marsset, T., Ondreas, H., Lopez, M., Savoye, B., Spy-Anderson, F-L., 2003. Architecture of an active mud-rich turbidite system: The Zaire Fan (Congo-Angola margin southeast Atlantic): Results from ZaiAngo 1 and 2 cruises. *AAPG Bull.* 87, 1145-1168.
- Droz, L., Rigaut, F., Cochonat, P., Tofani, R., 1996. Morphology and recent evolution of the Zaire turbidite system (Gulf of Guinea). *GSA Bull.* 108, 253-269.
- Duval, B., Cramez, C., Jackson, M.P.A., 1992. Raft tectonics in the Kwanza basin, Angola. *Mar. Pet. Geol.* 9, 389-404.
- Eichhubl, P., Greene, H.G., Naehr, T., Maher, N., 2000. Structural control of fluid flow: offshore fluid seepage in the Santa Barbara Basin, California. *J. Geoch. Expl.* 69/70, 545-549.
- Elverhøi, A., De Blasio, F.V., Butt, F.A., Issler, D., Harbitz, C.B., Engvik, L., Solheim, A., Marr, J., 2002. Submarine mass-wasting on glacially influenced continental slopes - processes and dynamics. In: Dowdeswell, J.A., O'Cofaigh, C. (Eds.), *Glacier-influenced Sedimentation on high Latitude Continental Margins*. Geological Society of London Special Publication 203, pp. 73-87.
- Evans, D., King, E.L., Kenyon, N.H., Brett, C., Wallis, D., 1996. Evidence for long-term instability in the Storegga Slide region off western Norway. *Mar. Geol.* 130, 281-292.
- Fort, X., Brun, J.-P., Chauvel, F., 2004. Contraction induced by block rotation above salt (Angolan margin). *Mar. Pet. Geol.* 21, 1281-1294.
- Fu, B. Aharon, P., 1998. Sources of hydrocarbon-rich fluids advecting on the seafloor in the northern Gulf of Mexico. *AAPG Bull.* 82, 1781.
- Gay, A., 2002. Les marqueurs géologiques de la migration et de l'expulsion des fluides sédimentaires sur le plancher des marges passives matures. Exemples dans le Bassin du Congo., Université des Sciences et Technologies, Thèse Université de Lille 1, France, 426 pp.
- Gay, A., Lopez, M., Cochonat, P., Levaché, D., Sermondadaz, G., Séranne, M., 2006a. Evidences of early to late fluid migration from an upper Miocene turbiditic channel revealed by 3D seismic coupled to geochemical sampling within seafloor pockmarks, Lower Congo Basin. *Mar. Pet. Geol.* 23, 387-399.
- Gay, A., Lopez, M., Cochonat, P., Séranne, M., Levaché, D., Sermondadaz, G., 2006b. Isolated seafloor pockmarks linked to BSRs, fluid chimneys, polygonal faults and stacked Oligocene-Miocene turbiditic palaeochannels in the Lower Congo Basin. *Mar. Geol.* 226, 25-40.
- Gay, A., Lopez, M., Cochonat, P., Sermondadaz, G., 2004. Polygonal faults-furrows system related to early stages of compaction - Upper Miocene to present sediments of the Lower Congo Basin. *Bas. Res.* 16, 101-116.
- Gay, A., Lopez, M., Cochonat, P., Sultan, N., Cauquil, E., Brigaud, F., 2003. Sinuous pockmark belt as indicator of a shallow buried turbiditic channel on the lower slope of the Congo Basin, West African Margin. In: Van Rensbergen, P., Hillis, R.R., Maltman, A.J., Morley, C.K. (Eds.), *Subsurface Sediment Mobilization*. Geological Society of London Special Publication 216, pp. 173-189.
- Gay, A., Lopez, M., Ondreas, H., Charlou, J.L., Sermondadaz, G., Cochonat, P., 2006c. Seafloor facies related to upward methane flux within a Giant Pockmark of the Lower Congo Basin. *Mar. Geol.* 226, 81-95.
- Graue, K., 2000. Mud volcanoes in deepwater Nigeria. *Mar. Pet. Geol.* 17, 959-974.
- Greene, H.G., Yoklavich, M.M., Starr, R.M., O'Connell, V.M., Wakefield, W.W., Sullivan, D.E., McRea Jr, J.E., Cailliet, G.M., 1999. A classification scheme for deep seafloor habitats. *Oceanologica Acta* 22, 663-678.
- Guiraud, R., Maurin, J., 1992. Early Cretaceous rifts of Western and Central Africa: An Overview. *Tectonophysics* 213, 153-168.
- Hansen, J.P.V., Cartwright, J.A., Huuse, M., Clausen, O.R., 2005. 3D seismic expression of fluid migration and mud remobilization on the Gjallar Ridge, offshore mid-Norway. *Bas. Res.* 17, 123-139.
- Heggland, R., 1997. Detection of gas migration from a deep source by the use of exploration 3D seismic data. *Mar. Geol.* 13, 41-47.
- Hempel, P., Spiess, V., Schreiber, R., 1994. Expulsion of shallow gas in the Skagerrak- Evidence from subbottom profiling, seismic, hydroacoustical and geochemical data. *Est. Coast. Shelf Sc.* 38, 583-601.
- Hovland, M., 1981. Characteristics of pockmarks in the Norwegian trench. *Mar. Geol.* 39, 103-117.
- Hovland, M., Gallagher, J., Clennell, M.D., Lekvam, K., 1997. Gas hydrate and free gas volumes in marine sediments: Example from the Niger Delta front. *Mar. Pet. Geol.* 14, 245-255.
- Hovland, M., Judd, J., 1988. Seabed pockmarks and seepages. *Impact on Geology, Biology and Marine Environment*. Graham and Trotman, London, 293 pp.

- Jansen, J.H., Van Weering, T.C.E., Gieles, R. Van Ipresen, J., 1984. Middle and Late Quaternary oceanography and climatology of the ZAIRE-Congo fan and the adjacent eastern Angola Basin. *Neth. J. Sea Res.* 17, 201-249.
- Johnson, H.P., Helferty, M., 1990. The geological interpretation of side-scan sonar. *Review Geoph.* 28, 357-380.
- Johnson, J.E., Goldfinger, C., Suess, E., 2003. Geophysical constraints on the surface distribution of authigenic carbonates across the Hydrate Ridge region, Cascadia Margin. *Mar. Geol.* 202, 79-120.
- Josenhans, H.W., King, L.H., Fader, G.B., 1978. A side-scan sonar mosaic of pockmarks on the Scotian shelf. *Can. J. Earth Sc.* 15, 831-840.
- Judd, A., Long, D., Sankey, M., 1992. Pockmark formation and activity, UK block 15/25, North Sea. *Bull. Geol. Soc. Denmark*, 41, 34-49.
- Judd, A.G., Hovland, M., 1992. The evidence of shallow gas in marine sediments. *Cont. Shelf Res.* 12, 1081-1095.
- Judd, A.G., Hovland, M., Dimitrov, L.I., Garcia Gil, S., Jukes, V., 2002. The geological methane budget at continental margins and its influence on climate change. *Geofluids* 2, 109-126.
- Kaluza, M.J., Doyle, E.H., 1996. Detecting fluid migration in shallow sediments: continental slope environment, Gulf of Mexico. In: Schumacher, D., Abrams, M.A. (Eds), *Hydrocarbon Migration and its Near-surface Expression*. AAPG Memoir 66, Tulsa, OK, pp. 15-26.
- Karner, G.D., Driscoll, N.W., 1998. Tectonic setting of the Marnes-Noires/Falcao source rocks of the Congo and Angolan continental margins. *AAPG bull.*, 82, 1928.
- Karner, G.D., Driscoll, N.W., Barker, D.H.N., 2003. Syn-rift region subsidence across the West African continental margin; the role of lower plate ductile extension. In: Arthur, T., MacGregor, D.S., Cameron, N.R. (Eds), *Petroleum geology of Africa; new themes and developing technologies*. Geological Society of London Special Publication 207, pp. 105-129.
- Kelley, J.T., Dickson, S.M., Belknap, D.F., Barnhardt, W.A., Henderson, M., 1994. Giant sea-bed pockmarks: evidence for gas escape from Belfast Bay, Maine. *Geology* 22, 59-62.
- Kenyon, N.H., 1992. Speculations on the geological causes of backscatter variation on GLORIA sonographs from the Mississippi and De Soto fans, Gulf of Mexico. *Geo-Mar. Lett.* 12, 24-32.
- King, L.H., MacLean, B., 1970. Pockmarks on the Scotian shelf. *GSA Bull.* 81, 3141-3148.
- Klaucke, I., Sahling, H., Weinrebe, W., Blinova, V., Bürk, D., Lursmanashvili, N., Bohrmann, G., 2006. Acoustic investigation of cold seeps offshore Georgia, eastern Black Sea. *Mar. Geol.* 231, 51-67.
- Kulm, L.D., Suess, E., 1990. Relationship between carbonate deposits and fluid venting: Oregon accretionary prism. *JGR* 95, 8899-8915.
- Lee, S.H., Chough, S.K., 2003. Distribution and origin of shallow gas in deep-sea sediments of the Ulleung Basin, East Sea (Sea of Japan). *Geo-Mar. Lett.* 22, 204-209.
- León, R., Somoza, L., Medialdea, T., Maestro, A., Díaz-del-Río, V., Fernández-Puga, M.C., 2006. Classification of sea-floor features associated with methane seeps along the Gulf of Cadiz continental margin. *Deep-Sea Research II* 53, 1464-1481.
- Ligtenberg, H., 2005. Detection of fluid migration pathways in seismic data: implications for fault seal analysis. *Bas. Res.* 17, 141-153.
- Liro, L.M., Cohen, R., 1995. Salt deformation history and postsalt structural trends, offshore southern Gabon, west Africa. In: Jackson, M.P.A., Roberts, D.G., Snelson, S. (Eds), *Salt tectonics: a global perspective*. AAPG Memoir 65, pp. 323-331.
- Liu, J.-Y., 1997. *Surficial Geological Characteristics of the Alaminos Canyon*, Gulf of Mexico, Texas A&M University, College Station, TX, 142 pp.
- Loncke, L., Mascle, J., Fanil Scientific Party, 2004. Mud volcanoes, gas chimneys, pockmarks and mounds in the Nile deep-sea fan (Eastern Mediterranean): geophysical evidences. *Mar. Pet. Geol.* 21, 669-689.
- Lonergan, L., Lee, N., Johnson, H.D., Cartwright, J., Jolly, R., 2000. Remobilization and Injection in Deepwater Depositional Systems: Implications for Reservoir Architecture and Prediction, Deep-Water Reservoirs of the World, December 3-6. GCSSEPM Foundation 20th Annual Research Conference, pp. 515-532.
- Lucazeau, F., Brigaud, F., Bouroulllec, J.-L., 2004. High-resolution heat flow density in the Lower Congo Basin. *Geoch. Geoph. Geosys.* - G3, 5.
- Lundin, E.R., 1992. Thin-skinned extensional tectonics on a salt detachment, northern Kwanza basin, Angola. *Mar. Pet. Geol.* 9, 405-411.
- MacDonald, I.R., Buthman, D.B., Sager, W.W., Peccini, M.B., Guinasso Jr., N.L., 2000. Pulsed flow from a Gulf of Mexico mud volcano. *Geology* 28, 907-910.

- 695 Marton, L.G., Tari, G.C., Lehmann, C.T., 2000. Evolution of the Angola passive Margin, West Africa, with
696 Emphasis on Post-Salt Structural Styles. In: Moriak, W., Talwani, M. (Eds), Atlantic Rifts and
697 Continental Margins. AGU, Washington DC, pp. 129-149.
- 698 McManus, K.M., Hanor, J.S., 1993. Diagenetic evidence for massive evaporite dissolution, fluid flow, and
699 mass transfer in the Louisiana Gulf Coast. *Geology* 21, 727-730.
- 700 Naudts, L., Greinert, J., Artemov, Y., Staelens, P., Poort, J., Van Rensbergen, P., De Batist, M., 2006.
701 Geological and morphological setting of 2778 methane seeps in the Dnepr paleo-delta, northwestern
702 Black Sea. *Mar. Geol.* 227, 177-199.
- 703 Olu-Le Roy, K., Nadalig, T., Caprais, J.C., Fifis, A., Fabri, M.-C., Ondréas, H., Sibuet, M., 2003. Spatial
704 variability of the chemosynthetic fauna, chemical environment and microbial communities on a giant
705 pockmark in the Gulf of Guinea, 10th Deep-Sea Biology Symposium, Oregon Coast, U.S.A.
- 706 Ondreas, H., Olu, K., Fouquet, Y., Charlou, J.L., Gay, A., Dennielou, B., Donval, J.P., Fifis, A., Nadalig, T.,
707 Cochonat, P., Cauquil, E., Bourillet, J.-F., Le Moigne, M., Sibuet, M., 2005. Integrated "in situ"
708 study of a deep giant pockmark on the Congo-Angola margin. *Geo-Mar. Lett.* 25, 281-292.
- 709 Orange, D.L., Greene, H.G., Reed, D., Martin, J.B., McHugh, C.M., Ryan, W.B.F., Maher, N., Stakes, D.,
710 Barry, J., 1999. Widespread fluid expulsion on a translational continental margin: Mud volcanoes,
711 fault zones, headless canyons, and organic-rich substrate in Monterey Bay, California. *GSA Bull.*
712 111, 992-1009.
- 713 Orange, D.L., Yun, J., Maher, N., Barry, J., Greene, G., 2002. Tracking California seafloor seeps with
714 bathymetry, backscatter and ROVs. *Cont. Shelf Res.* 22, 2273-2290.
- 715 Osborne, M.J., Swarbrick, R.E., 1997. Mechanisms for generating overpressure in sedimentary basins; a
716 reevaluation. *AAPG Bull.* 81, 1023-1041.
- 717 Parnell, J., 2003. Fluid seeps at continental margins: towards an integrated plumbing system. *Geofluids* 2,
718 57-61.
- 719 Paull, C., Spiess, F., Ussler III, W., Borowski, W., 1993. Natural gas venting associated with gas hydrate
720 capped diapirs on the Carolina continental rise, Abstract of AGU, San Francisco, pp. 174.
- 721 Prior, D.B., Coleman, J.B., 1984. Submarine slope instability. In: Brunsten, D., Prior, D.B. (Eds), *Slope*
722 *Instability*. Wiley, New York, pp. 419-455.
- 723 Ritger, S.D., Carson, B., Suess, E., 1987. Methane-derived authigenic carbonates formed by subduction-
724 induced pore water expulsion along the Oregon/Washington margin. *GSA bull.* 98, 147-156.
- 725 Roberts, H.H., 1999. Surficial fluid/gas expulsion features on the Gulf of Mexico continental margin with
726 special emphasis on gas hydrates. *AAPG Bull.* 83, 1336-1337.
- 727 Roberts, H.H., Aharon, P., Carney, R.S., Larkin, J., Sassen, R., 1990. Sea Floor Responses to Hydrocarbon
728 Seeps, Louisiana Continental Slope. *Geo-Mar. Lett.* 10, 232-243.
- 729 Roberts, H.H., Cook, D.J., Sheedlo, M.K., 1992. Hydrocarbon seeps of the Louisiana continental slope:
730 Seismic signature and seafloor response. *Transactions Gulf Coast Association of Geological*
731 *Societies* 42, 349-360.
- 732 Rollet, N., Logan, G.A., Kennard, J.M., O'Brien, P.E., Jones, A.T., Sexton, M., 2006. Characterisation and
733 correlation of active hydrocarbon seepage using geophysical data sets: An example from the tropical,
734 carbonate Yampi Shelf, Northwest Australia. *Mar. Pet. Geol.* 23, 145-164.
- 735 Rouby, D., Raillard, S., Guillocheau, F., Bouroulec, R., Nalpas, T., 2002. Kinematics of a growth fault/raft
736 system on the West African margin using 3-D restoration. *J. Struct. Geol.* 24, 783-796.
- 737 Sager, W.W., Lee, C.S., McDonald, I.R., Schroeder, W.W., 1999. High-frequency near-bottom acoustic
738 reflection signatures of hydrocarbon seeps on the Northern Gulf of Mexico continental slope. *Geo-*
739 *Mar. Lett.* 18, 267-276.
- 740 Sager, W.W., Mac Donald, I.R., Hou, R., 2003. Geophysical signatures of mud mounds at hydrocarbon seeps
741 on the Louisiana continental slope, northern Gulf of Mexico. *Mar. Geol.* 198, 97-132.
- 742 Satyavani, N., Thakur, N.K., Aravind Kumar, N., Reddi, S.I., 2005. Migration of methane at the diapiric
743 structure of the western continental margin of India. *Mar. Geol.* 219, 19-25.
- 744 Savoye, B., Cochonat, P., Apprioual, R., Bain, O., Baltzer, A., Bellec, V., Beuzard, P., Bourillet, J.-F.,
745 Cagna, R., Cremer, M., Crussion, A., Dennielou, B., Diebler, D., Droz, L., Ennes, J.-C., Floch, G.,
746 Guimar, M., Harmegnies, F., Kerbrat, R., Klein, B., Kuhn, H., Landuré, J.-Y., Lasnier, C., Le
747 Drezen, E., Le Formal, J.-P., Lopez, M., Loubrieu, B., Marsset, T., Migeon, S., Normand, A., Nouzé,
748 H., Ondréas, H., Pelleau, P., Saget, P., Séranne, M., Sibuet, J.-C., Tofani, R., Voisset, M., 2000.
749 Structure et évolution récente de l'éventail turbiditique du Zaïre: premier résultats scientifiques des
750 missions d'exploration Zaiango 1 et 2 (Marge Congo-Angola). *CRAS* 331, 211-220.
- 751 Schroot, B.M., Klaver, G.T., Schüttenhelm, R.T.E., 2005. Surface and subsurface expressions of gas seepage
752 to the seabed - examples from the Southern North Sea. *Mar. Pet. Geol.* 22, 499-515.

- Séranne, M., 1999. Early Oligocene stratigraphic turnover on the west Africa continental margin: a signature of the Tertiary greenhouse-to-icehouse transition ? *Terra Nova* 11, 135-140.
- Séranne, M., Seguret, M., Fauchier, M., 1992. Seismic super-units and post-rift evolution of the continental passive margin of southern Gabon. *Bull. SGF* 163, 135-146.
- Shaw, J., Courtney, R.C., Currie, J.R., 1997. Marine geology of St. George's Bay, Newfoundland, as interpreted from multibeam bathymetry and back-scatter data. *Geo-Mar. Lett.* 17, 188-194.
- Shipley, T.H., Houston, M.H., Buffler, R.T., Shaub, F.J., McMillen, K.J., Ladd, J.W., Worzel, J.L., 1979. Seismic evidence for widespread possible occurrence of gas-hydrate horizons or continental slopes and rises. *AAPG Bull.* 63, 2204-2213.
- Sibson, R.H., 1992. Implications of fault-valve behaviour for rupture nucleation and recurrence. *Tectonophysics* 211, 283-293.
- Sibuet, M., 2003. Cold seep communities on continental margins; structure and quantitative distribution relative to geological and fluid venting patterns. In: Wefer, G., Billett, D., Hebbeln, D., Jorgensen, B.B., Schlueter, M., van Weering, T.C.E. (Eds), *Ocean margin systems*. Springer-Verlag, Bremen, pp. 235-251.
- Smith Enos, J., Kyle, J.R., 2002. Diagenesis of the Carrizo sandstone at Butler State Salt Dome, East Texas Basin, U.S.A: Evidence for fluid-sediment interaction near halokinetic structures. *J. Sed. Res.* 72, 58-81.
- Solheim, A., Elverhoi, A., 1993. Gas-related sea floor craters in the Barents Sea. *Geo-Mar. Lett.* 13, 235-243.
- Somoza, L., Diaz-del-Rio, V., Leon, P., Ivanov, M., Fernandez-Puga, M.C., Gardner, J., Hernandez-Molina, F.J., Pinheiro, L.M., Rodero, J., Lobato, A., Maestro, A., Vazquez, J.T., Medialdea, T., Fernandez-Salas, L.M., 2003. Seabed morphology and hydrocarbon seepage in the Gulf of Cadiz mud volcano area: Acoustic imagery, multibeam and ultra-high resolution seismic data. *Mar. Geol.* 195, 153-176.
- Soter, S., 1999. Macroscopic seismic anomalies and submarine pockmarks in the Corinth-Patras rift, Greece. *Tectonophysics* 308, 275-290.
- Stakes, D.S., Orange, D., Paduan, J.B., Salamy, K.A., Maher, N., 1999. Cold-seeps and authigenic carbonate formation in Monterey Bay, California. *Mar. Geol.* 159, 93-109.
- Sultan, N., Cochonat, P., Bourillet, J.-F., Cayocca, F., 2001. Evaluation of the risk of marine slope instability: a pseudo-3D approach for application to large areas. *Mar. Georesources Geotech.* 19, 107-133.
- Sultan, N., Foucher, J.-P., Cochonat, P., Tonnerre, T., Bourillete, J.-F., Ondreas, H., Cauquil, E., Grauls, D., 2004. Dynamics of gas hydrate: case of the Congo continental slope. *Mar. Geol.* 206, 1-18.
- Taylor, M.H., Dillon, W.P., Pecher, I.A., 2000. Trapping and migration of methane associated with the gas hydrate stability zone at the Blake Ridge Diapir: new insights from seismic data. *Mar. Geol.* 164, 79-89.
- Tingdahl, K.M., Bril, A.H., de Groot, P.F., 2001. Improving seismic chimney detection using directional attributes. *J. Pet. Sc. Eng.* 29, 205-211.
- Tissot, B.P., Welte, D.H., 1984. *Petroleum formation and occurrence*. Springer, Berlin.
- Trincardi, F., Cattaneo, A., Correggiari, A., Ridente, D., 2004. Evidence of soft sediment deformation, fluid escape, sediment failure and regional weak layers within the late Quaternary mud deposits of the Adriatic Sea. *Mar. Geol.* 213, 91-119.
- Uchupi, E., 1992. Angola Basin: Geohistory and Construction of the Continental Rise. In: Poag, C.W., De Graciansky, P.A. (Eds), *Geologic Evolution of Atlantic Continental Rifts*. Nostrand Reinhold, New York, pp. 77-99.
- Uenzelmann-Neben, G., 1998. Neogene sedimentation history of the Congo Fan. *Mar. Pet. Geol.* 15, 635-650.
- Valle, P.J., Gjelberg, J.G., Helland-Hansen, W., 2001. Tectonostratigraphic development in the eastern Lower Congo Basin, offshore Angola, West Africa. *Mar. Pet. Geol.* 18, 909-927.
- Vogt, P.R., Gerdner, J., Crane, K., Sundvor, E., Bowles, F., Cherkashev, G., 1999. Ground-truthing 11- to 12-kHz side-scan sonar imagery in the Norwegian-Greenland Sea: Part I: Pockmarks on the Vestnesa Ridge and Storegga slide margin. *Geo-Mar. Lett.* 19, 97-110.
- Wefer, G., Berger, W.H., Richter, C., 1998. Facies patterns and authigenic minerals of upwelling deposits off Southwest Africa, *Proceedings of the Ocean Drilling Program. Initial Report*, pp. 487-504.
- Wenger, L.M., Isaksen, G.H., 2002. Control of hydrocarbon seepage intensity on level of biodegradation in sea bottom sediments. *Org. Geoch.* 33, 1277-1292.
- Werner, F., 1978. Depressions in mud sediments (Eckernfoerde Bay, Baltic Sea) related to sub-bottom and currents. *Meyniana* 30, 99-104.
- Whiticar, M.J., Werner, F., 1981. Pockmarks: Submarine vents of natural gas or freshwater seeps ? *Geo-Mar. Lett.* 1, 193-199.

- Wood, W.T., Gettrust, J.F., Chapman, N.R., Spence, G.D., Hyndman, R.D., 2002. Decreased stability of methane hydrates in marine sediments owing to phase-boundary roughness. *Nature* 420, 656-660.
- Xie, X., Li, S., Dong, W., Hu, Z., 2001. Evidence for episodic expulsion of hot fluids along faults near diapiric structures of the Yinggehai Basin, South China Sea. *Mar. Pet. Geol.* 18, 715-728.
- Yu, Z., Lerche, I., 1996. Modelling abnormal pressure development in sandstone/shale basins. *Mar. Pet. Geol.* 13, 179-193.
- Yun, J.W., Orange, D.L., Field, M.E., 1999. Subsurface gas offshore of northern California and its link to submarine geomorphology. *Mar. Geol.* 154, 357-368.
- Zitter, T., Huguen, C., Woodside, J., 2005. Geology of mud volcanoes in the eastern Mediterranean from combined sidescan sonar and submersible surveys. *Deep-Sea Research I* 52, 457-475.

13. List of figures:

Figure 1: Bathymetric map off Congo, extending from the Zaire estuary to the deep sea fan, acquired during GUINNESS (1992-1993) and ZAIANGO (1998-2000) projects. The shaded rectangle represents the EM12 multibeam coverage used in this study. The three sites of ODP Leg 175 are indicated.

Figure 2: Line drawing of the profile AB. The post-rift stratigraphy is characterized by two levels of seismic architectures: (1) an Albian to Eocene sequence containing the source rocks and (2) an Oligocene to Present sequence containing the reservoirs (turbiditic channels) and the sedimentary cover (affected by polygonal faults). Deep thermogenic fluids migrating from the source rocks are preferentially trapped into the silty-sandy channels (Burwood, 1999).

Figure 3: (to download a larger version, click on this link: www.elsevier_website) Multibeam backscatter mosaic of the Lower Congo Basin (see Fig. 1 for location). Dark areas represent strong acoustic backscatter (BS), whereas lighter areas show low backscatter. The meandering strip crossing the study from East to West corresponds to the modern Zaire canyon and channel. Wide circular features correspond to salt diapirs in shallow sediments or outcropping at the seabed, which are part of the Angola escarpment. Smaller rounded black patches are interpreted to be due to features associated with active or recent fluid seepage (pockmarks and mounds).

Figure 4: Seafloor Dip map derived from the 3D seismic dataset (see Fig. 3 for location). The grey-scale ranges from white that represent flat surfaces (0°) to black corresponding to steep angles (30°). White rectangles represent areas 1 to 7 detailed in later figures. Fluid seeps are clearly visible on this map

where they appear as negative-relief circular depressions (pockmarks) or positive-relief circular domes (mounds) distributed all along the slope.

Figure 5: Seismic profile CD (see Fig. 4 for location). This profile show two superimposed acoustic anomalies, vertically elongated under the pockmarks. The deep anomaly is characterized by low amplitude acoustic turbidity, whereas the shallow anomaly is ovoid in shape with depressed high-amplitude reflectors. Such acoustic anomalies are commonly called seismic chimneys or fluid pipes, and could be indicative of fluid flow from deeper levels.

Figure 6: Top left: Dip map of seafloor in Area 1 (see Fig. 4 for location) derived from 3D seismic data, showing aligned pockmarks on a fault scarp outcropping at the seabed. Top right: Multibeam backscatter imagery in Area 1 on which only one pockmark is visible as a medium amplitude backscatter. Bottom: Seismic profile EF extracted from 3D seismic data and its interpreted line-drawing. This profile shows that a major fault is cutting an upper Miocene channel-levee system, which may provide a source of thermogenic fluids. Note that the seafloor pockmarks occur on the hanging-wall of this southwest-dipping normal fault, and can be tied via vertical acoustic anomalies to the fault zone at a depth of 150 msTWT.

Figure 7: Top left: Dip map of seafloor in Area 2 (see Fig. 4 for location) derived from 3D seismic data, showing two mounds that have been identified as reefs using ROV dives. Top right: Multibeam backscatter imagery in Area 2 on which two high backscatter anomalies are visible. Bottom: Seismic profile GH extracted from 3D seismic data and its interpreted line-drawing. Similar to Area 1, this system is located over a major fault that cuts an upper Miocene turbiditic channel. In this case, polygonal faults may provide a preferential conduit for fluids to reach the seafloor.

Figure 8: Left: Dip map of seafloor in Area 3 (see Fig. 4 for location) derived from 3D seismic data, showing negative-relief dip anomalies (pockmarks) on the top of salt diapirs. Right: Multibeam backscatter imagery in Area 3 showing only a few backscatter anomalies associated with the pockmarks, indicating that these features are not active, and have not been active recently (except for those identified on both datasets).

Figure 9: Top left: Dip map of seafloor in Area 4 (see Fig. 4 for location) derived from 3D seismic data, showing pockmarks located on faults scarps with subtle bathymetric signature that are radially arranged. Top right: Multibeam backscatter imagery in Area 3 where the pockmarks appear as high reflectivity (black) patches. Bottom: Seismic profile IJ extracted from 3D seismic data. This profile shows that the pockmarks are located over a salt diapir. Fluids may have migrated along the faults associated with the top of the dome structure, due to the collapse of sediments above the top of the salt.

Figure 10: Left: Dip map of seafloor in Area 5 (see Fig. 4 for location) derived from 3D seismic data, showing pockmarks located at the toe of the Zaire canyon flanks. Right: Multibeam backscatter imagery in Area 5 shows no backscatter anomalies associated with the pockmarks, indicating that these features are not active, and have not been active recently.

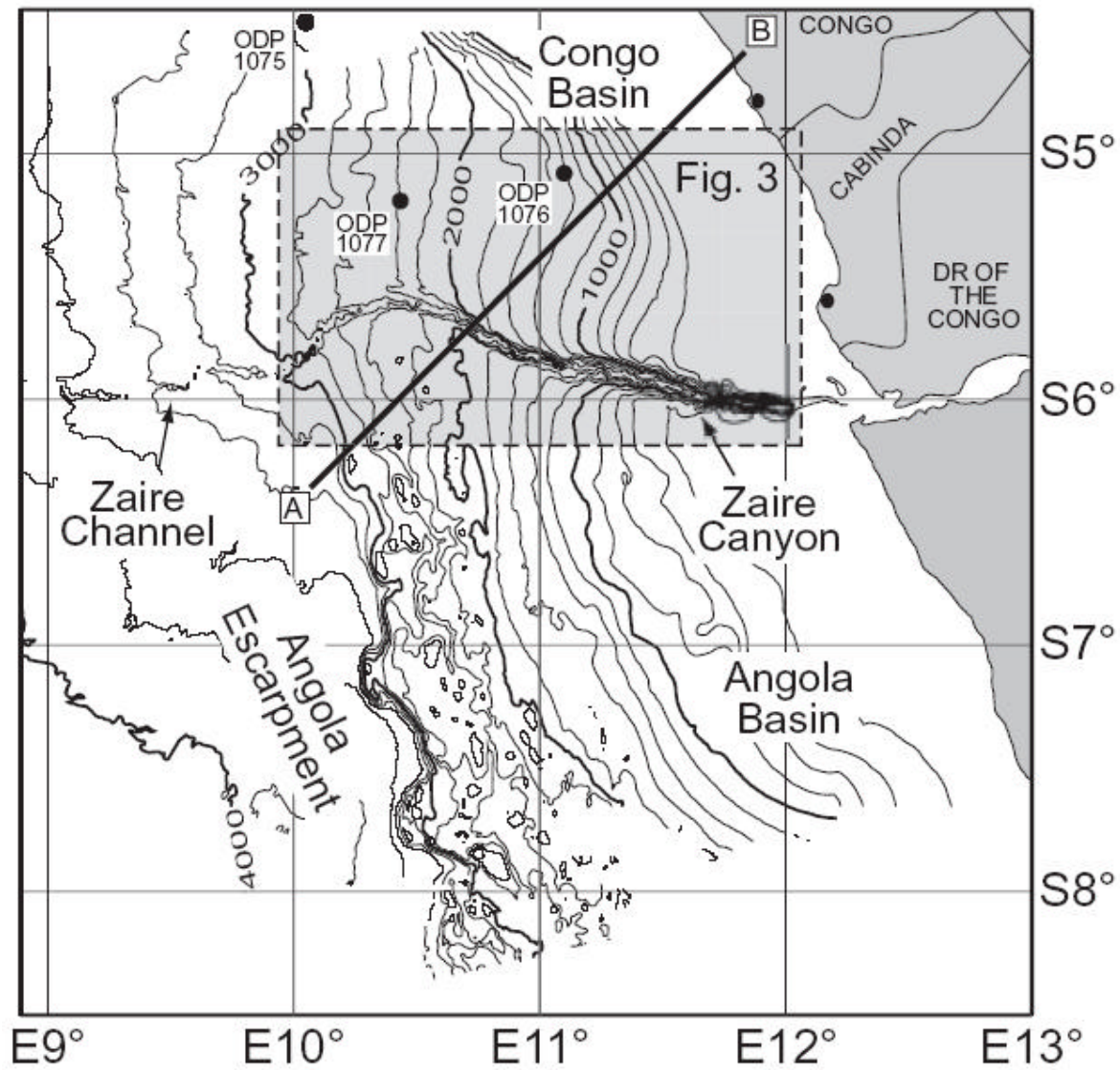
Figure 11: Top left: Dip map of seafloor in Area 6 (see Fig. 4 for location) derived from 3D seismic data, showing numerous pockmarks aligned on a trend parallel to the Zaire canyon axis. Top right: Multibeam backscatter imagery in Area 6 showing that only some of the pockmarks are characterized by high backscatter. Bottom: Seismic profile KL extracted from 3D seismic data and its interpreted line-drawing. The seismic profile shows that the stacked seismic anomalies interpreted to be a fluid/gas chimney is located over an erosional surface corresponding to a palaeo-flank of the Zaire Canyon. Fluids may have migrated laterally from Miocene turbiditic channels to be trapped below the erosional surface dipping towards the modern canyon. Fluids may migrate up below the unconformity but may break out further up section to migrate to the seabed.

Figure 12: Top left: Dip map of seafloor in Area 7 (see Fig. 4 for location) derived from 3D seismic data, showing pockmarks aligned along a sinuous meandering trend on the seabed. Top right: Multibeam backscatter imagery in Area 7 showing that only a few pockmarks appear as high backscatter (black) patches. Bottom: Seismic profile MN extracted from 3D seismic data and its interpreted line-drawing. The pockmarks are located over the edges of a shallow buried turbiditic channel. The distribution of pockmarks mimics the meandering track of the underlying palaeochannel.

Figure 13: Top left: Dip map of seafloor in Area 8 (see Fig. 4 for location) derived from 3D seismic data showing aligned pockmarks. Top right: Multibeam backscatter imagery in Area 8 on which pockmarks appear as high backscatter anomalies. Bottom: Seismic profile OP extracted from 3D seismic data and its interpreted line-drawing. This profile shows that the pockmarks are located over a Miocene turbiditic channel. The fluids are interpreted to have migrated through the sedimentary column to be ponded below the gas hydrate layer where a BSR appear. The BSR is shifted upward, indicating an ascending movement of fluids concentrated in a pipe that projects to the seafloor pockmark.

Figure 14: Block diagrams defining five chemo-biological facies at the seabed associated with fluid seep activity (vigorosity and timing of activity relative to today). Various combinations of facies with respect to fluid escape are interpreted to explain the backscatter intensity at the seabed.

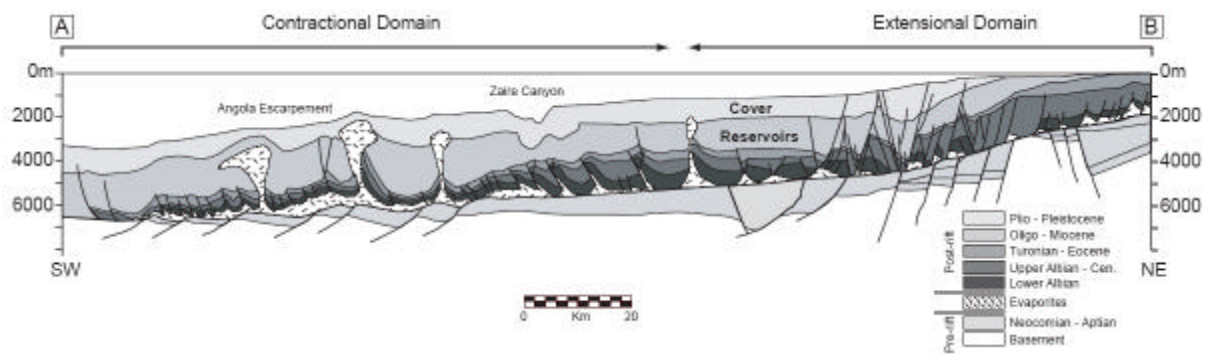
Figure 15: Conceptual 3D block diagram of a passive margin showing the plumbing systems of fluid migration. The organization of fluid seeps at the seabed is strongly dependent on the nature and shape of the buried reservoirs (i.e. turbiditic channels or salt diapirs) where the fluids originate. Their distribution is also linked to the location of major pathways, such as erosional surfaces or faults. In this model, the base of the gas hydrates stability zone tends to hinder vertical fluid migration whereas the polygonal faults may facilitate such migration.



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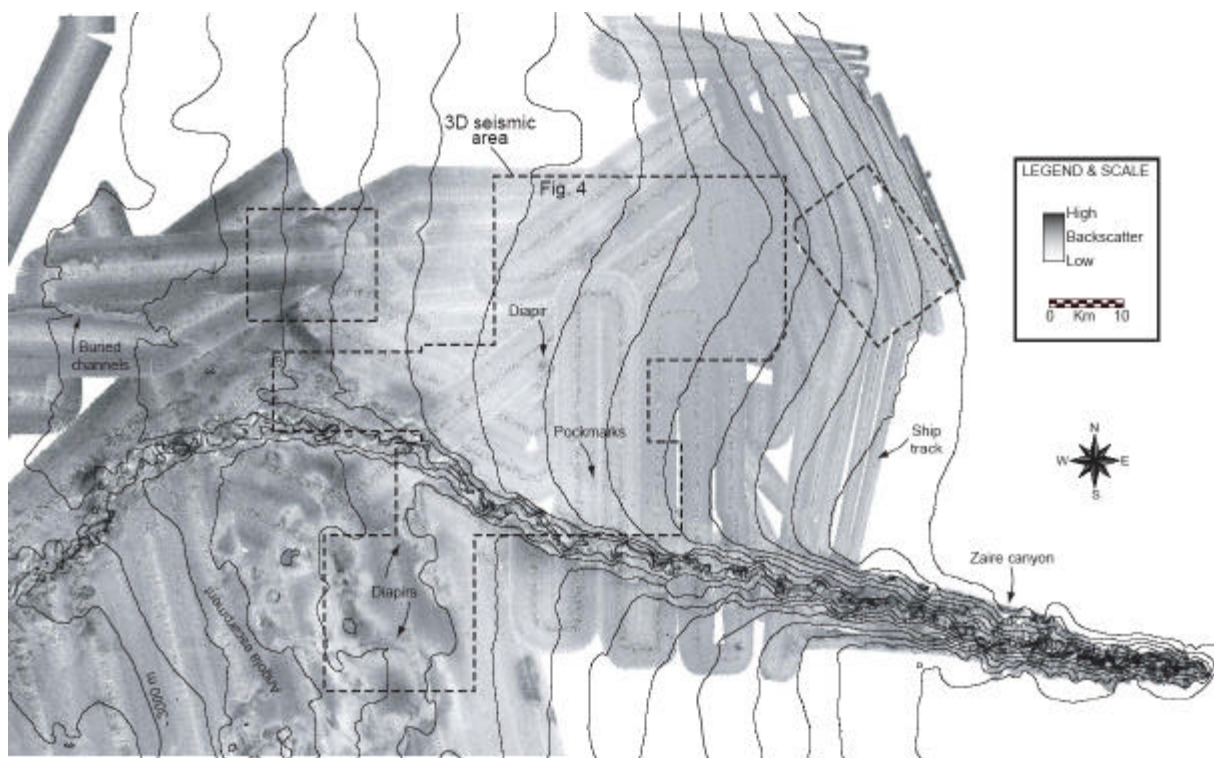
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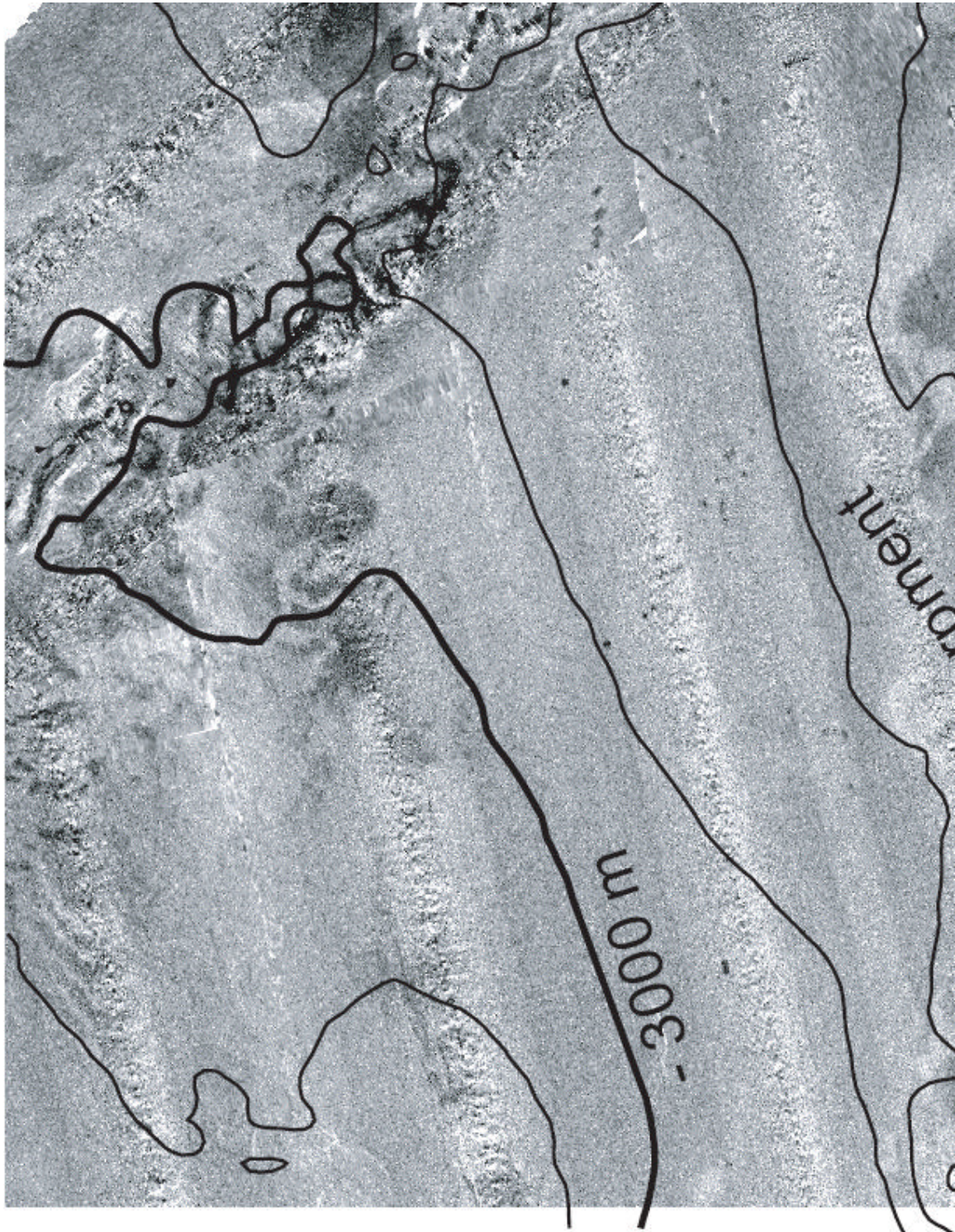


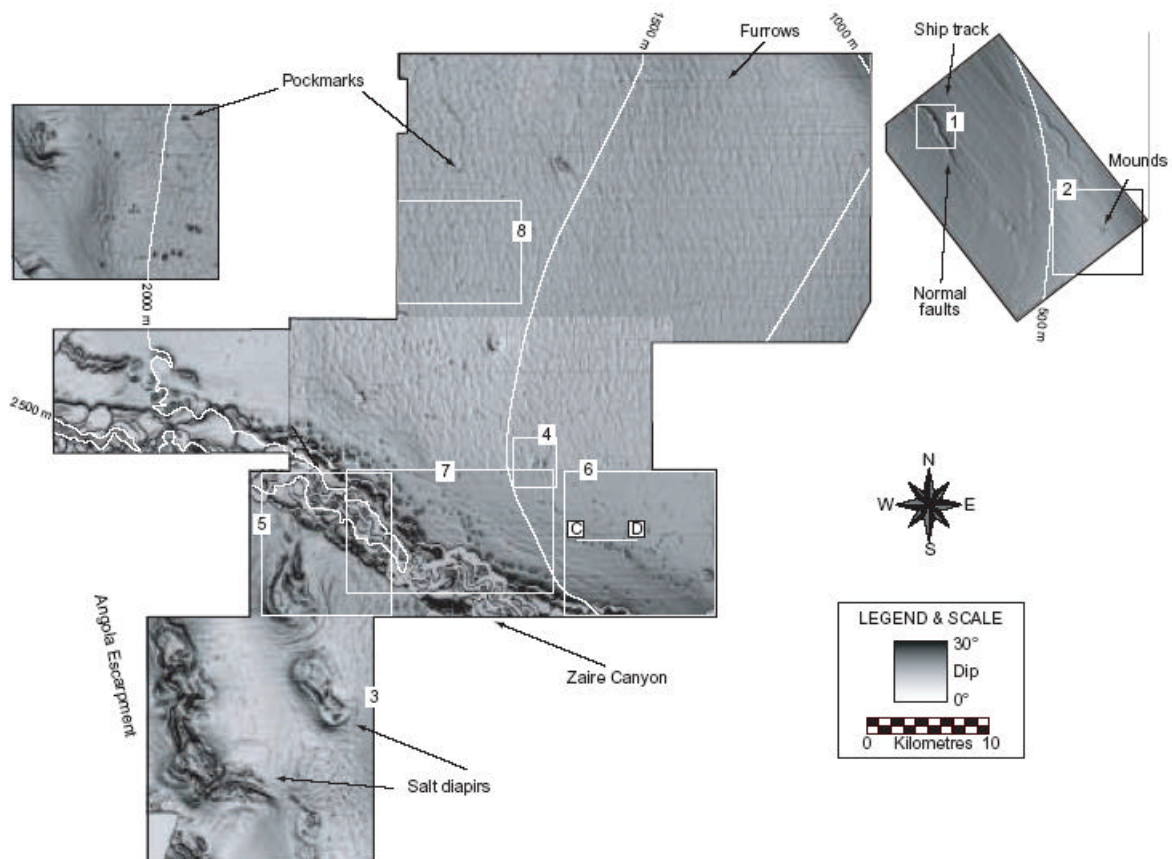
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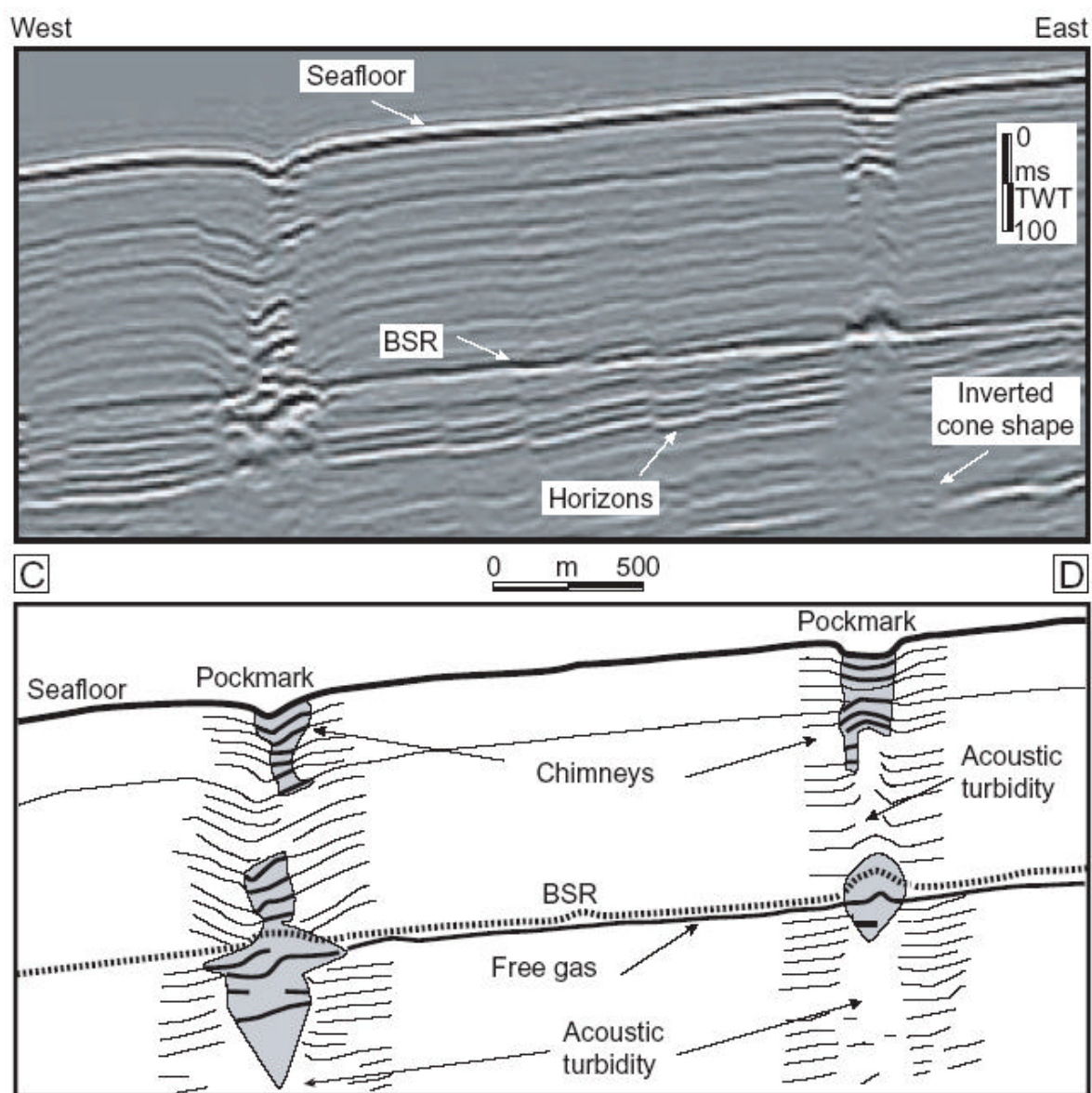




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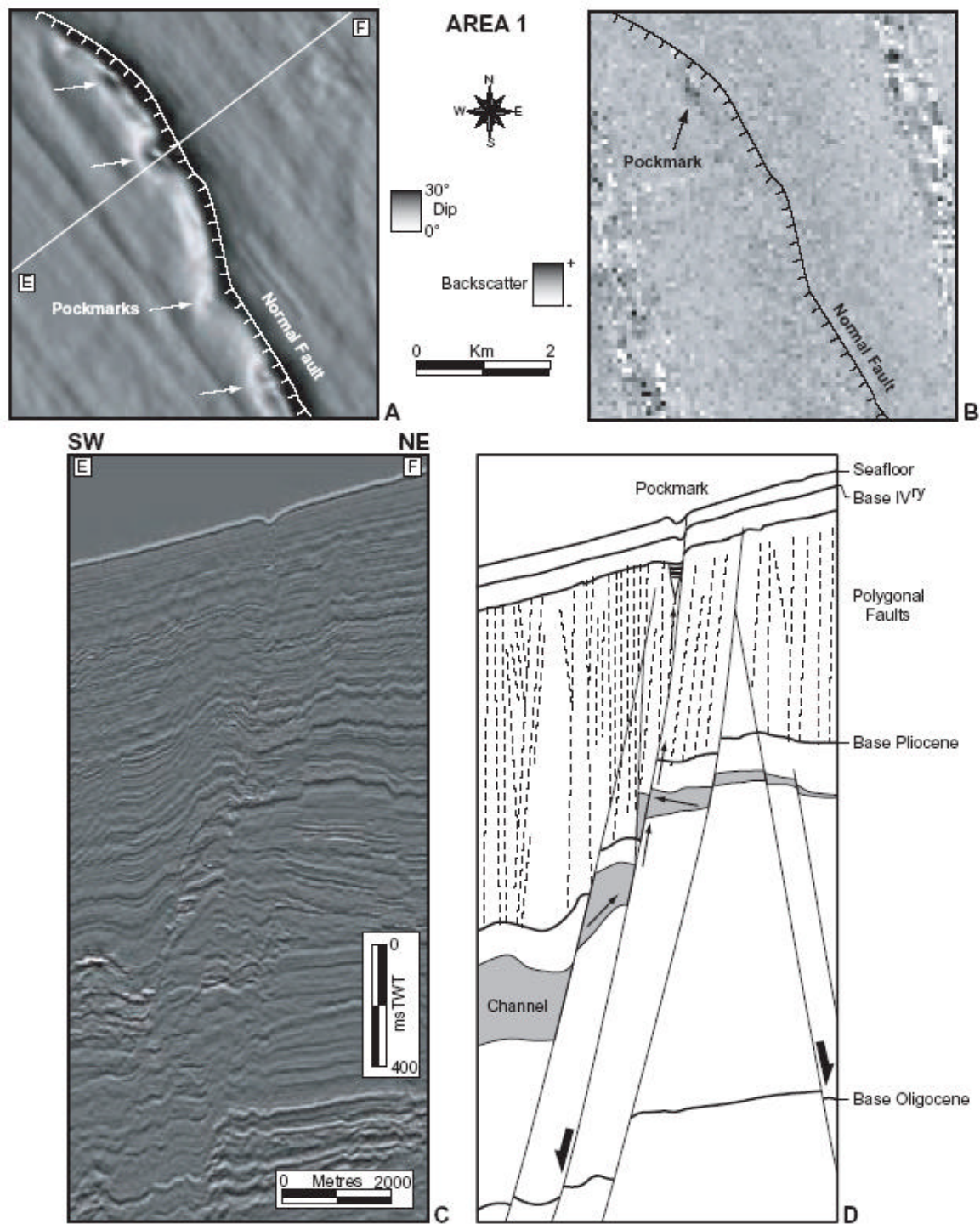
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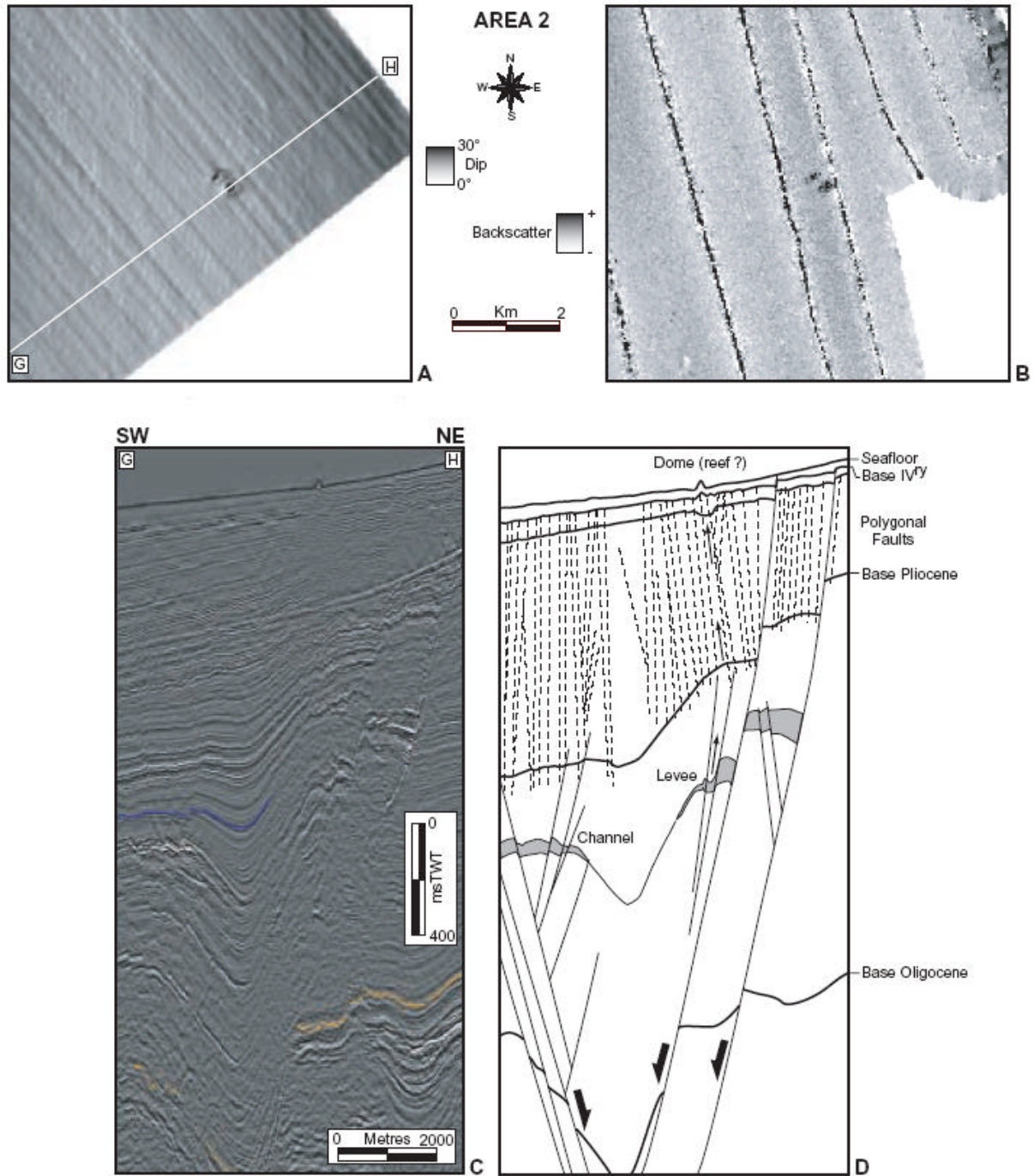
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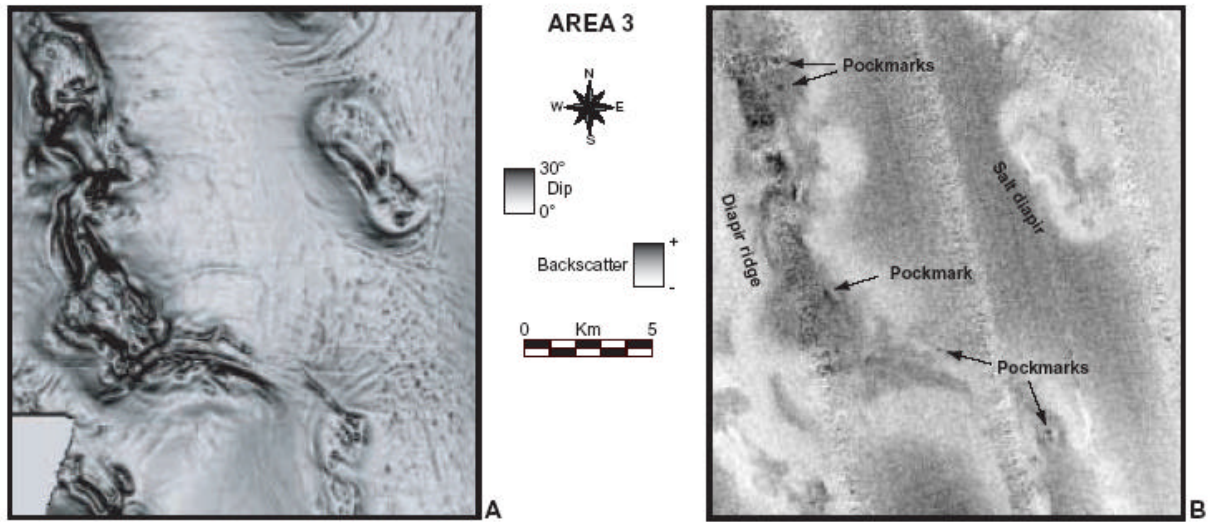
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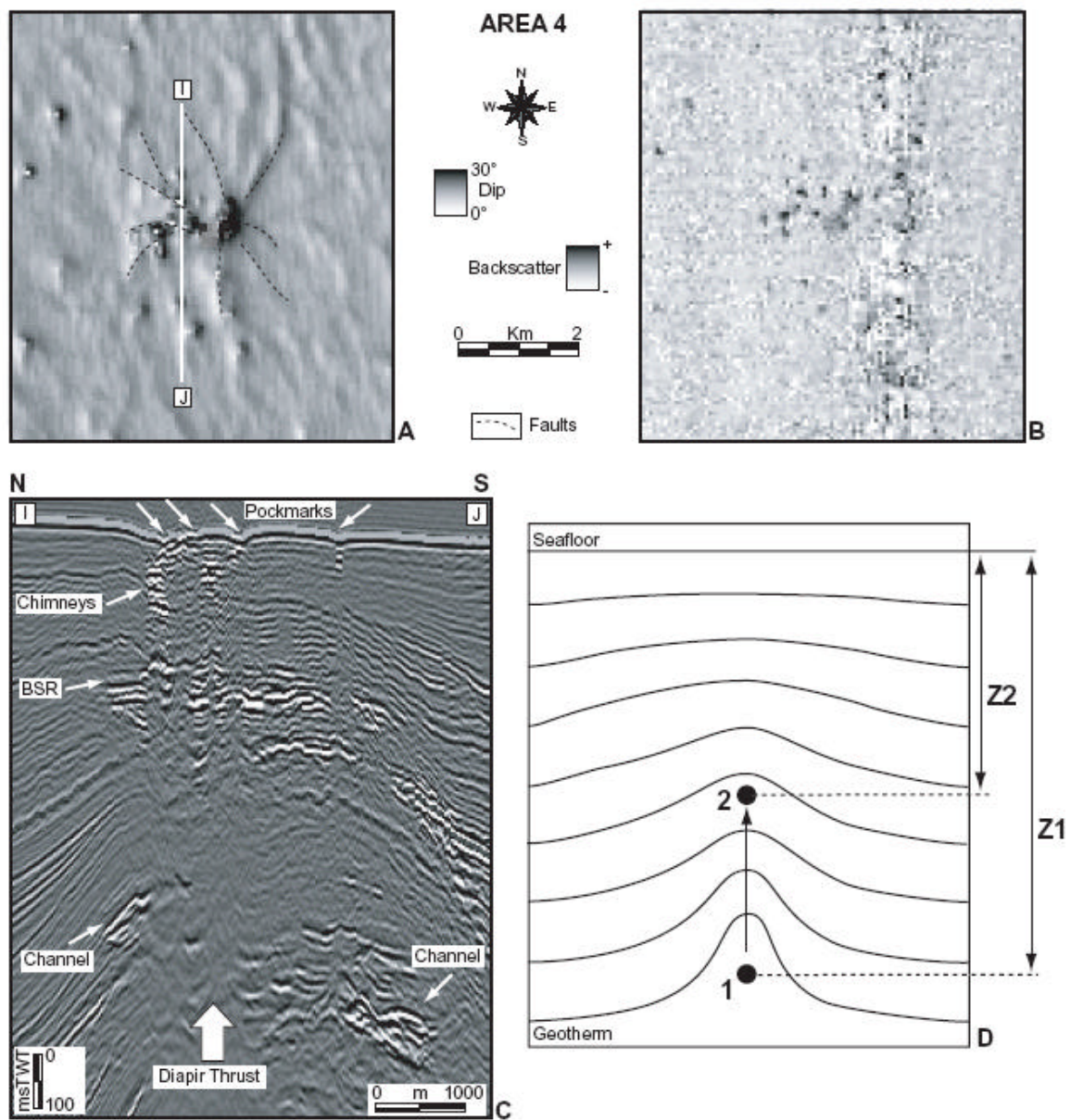
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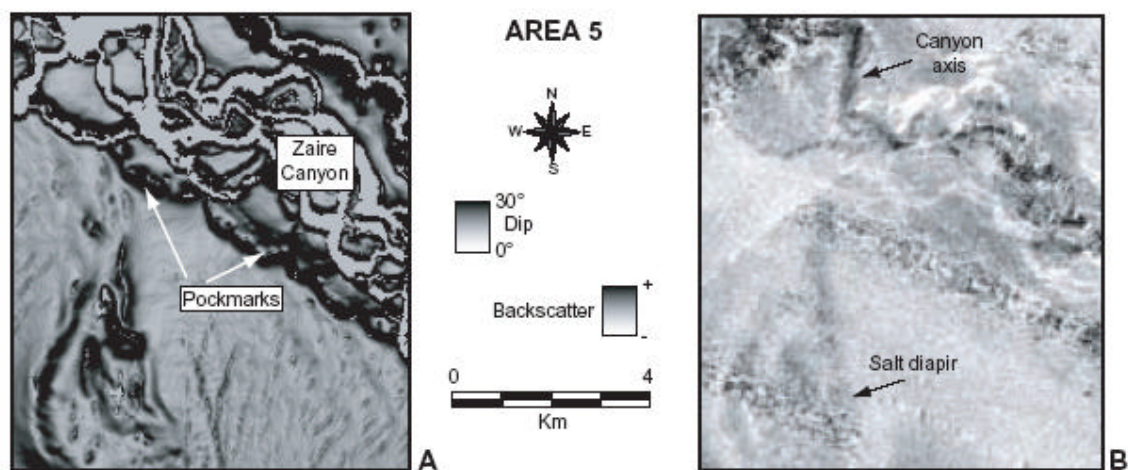
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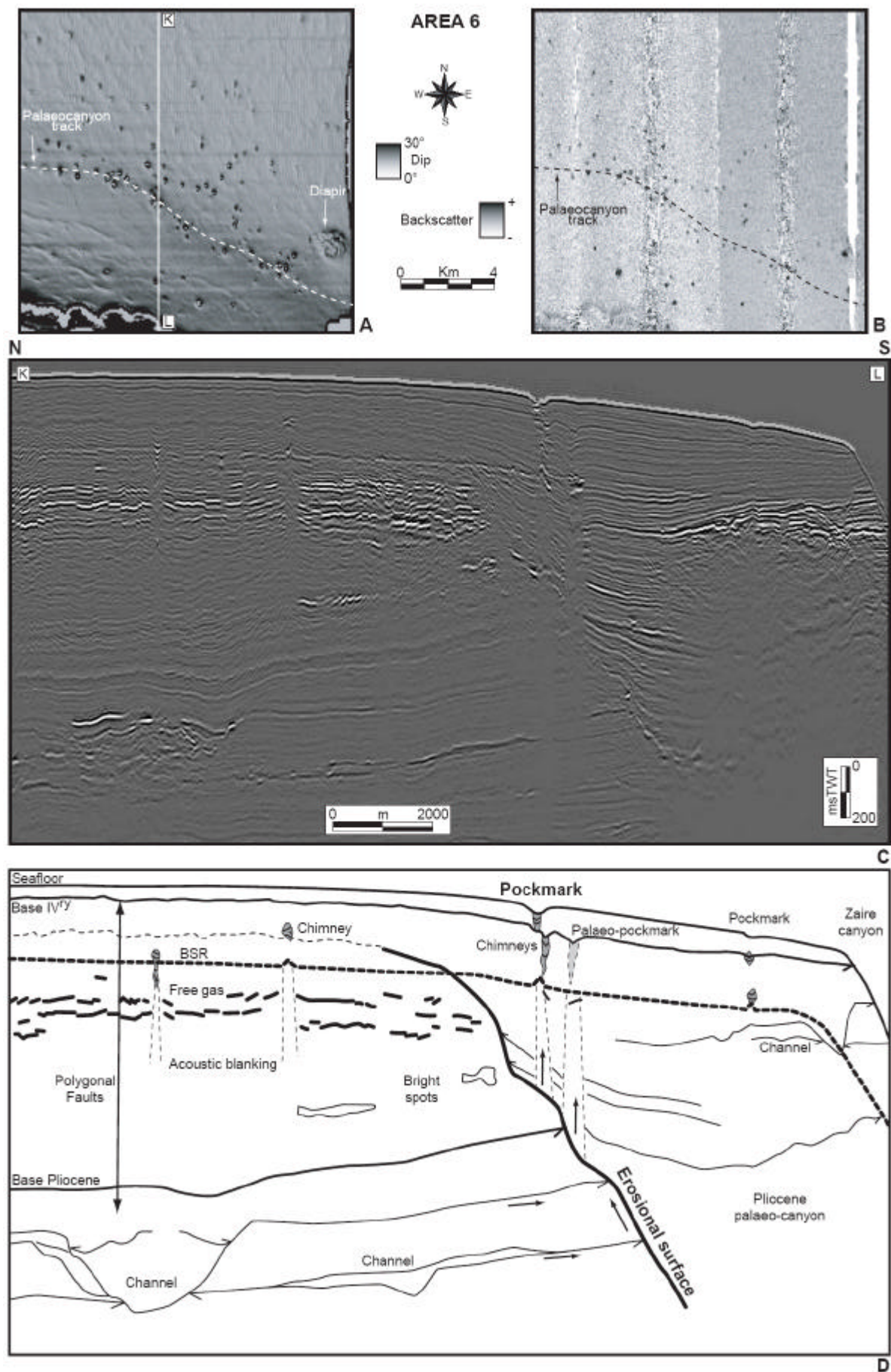
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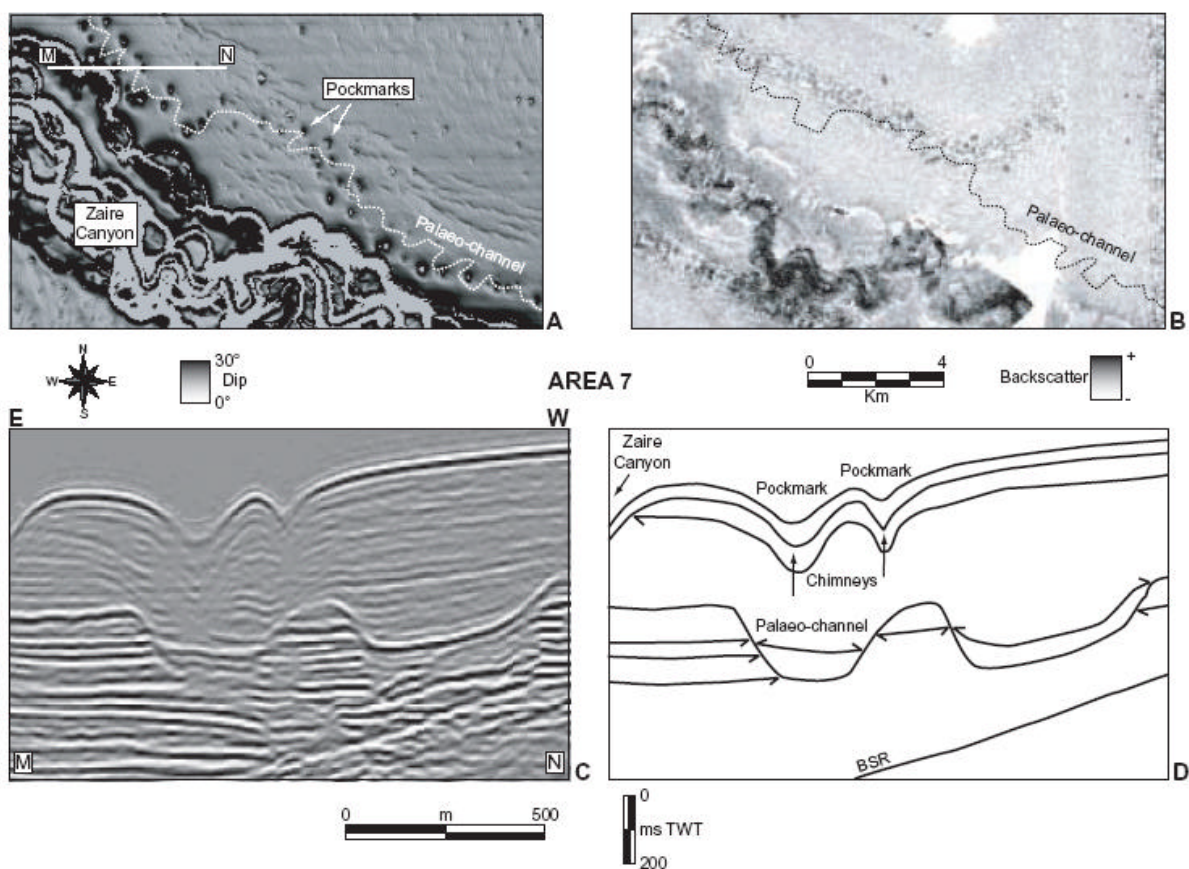
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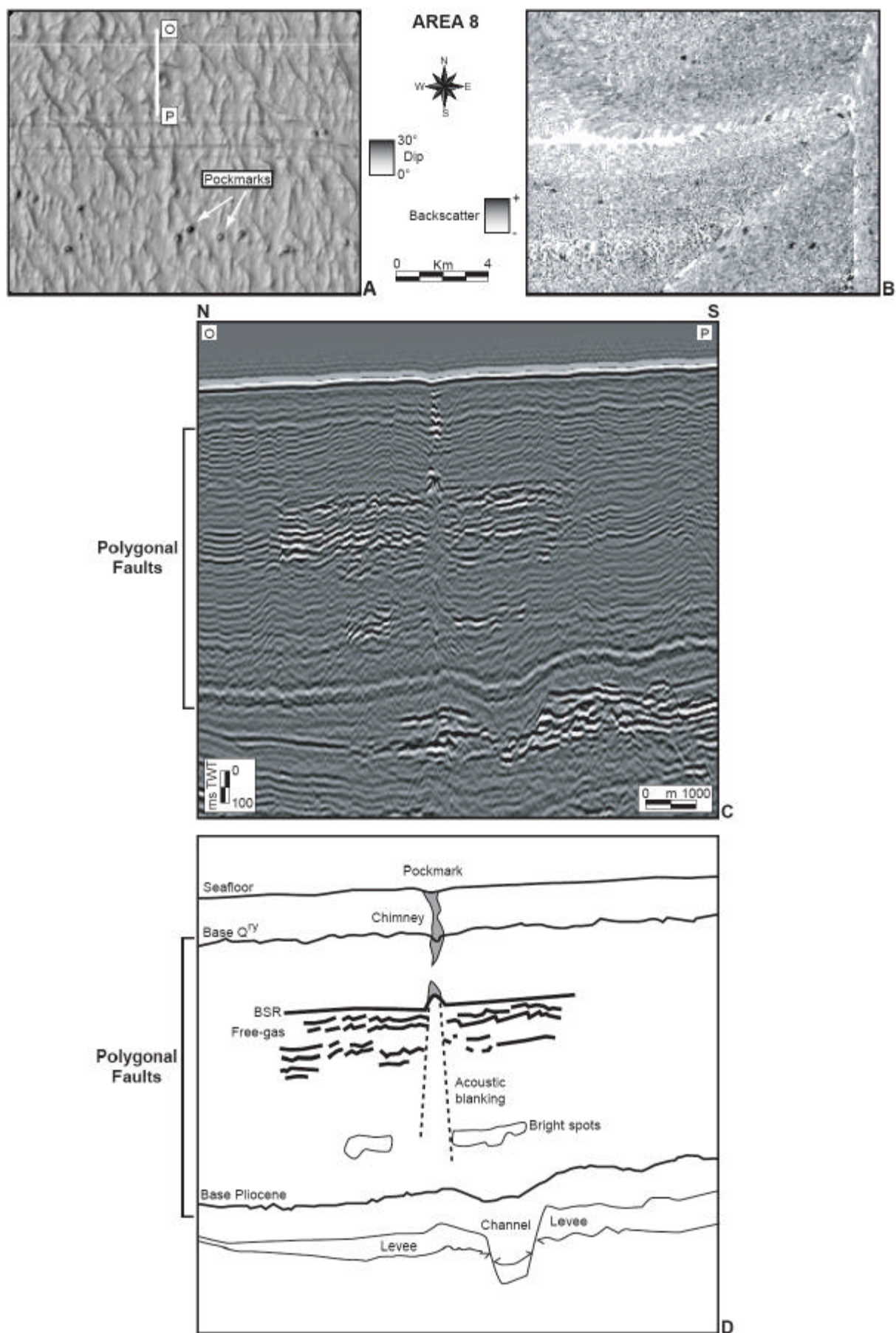
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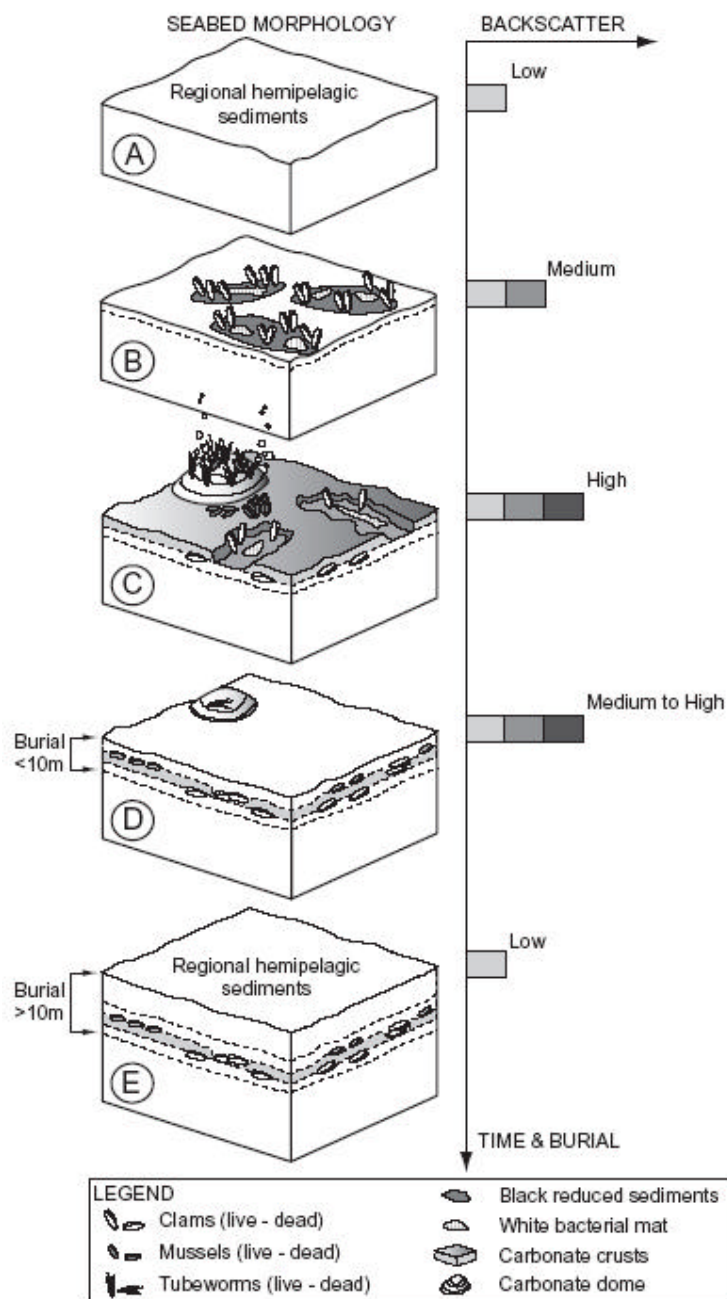




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