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Distribution and origin of natural gas leakage in the Colorado Basin, offshore Argentina Margin, South America: seismic interpretation and 3D basin modelling

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ABSTRACT

The detailed analysis of a dense 2D seismic reflection dataset and data from 8 exploration wells, allowed us to identify, map out and characterize possible indications of past and present-day hydrocarbon leakage (i.e. gas chimneys, gas pockets, and seafloor mounds and pockmarks) on the continental shelf and slope of the Colorado Basin, offshore Argentina, where Permian, Jurassic and Early Cretaceous source rocks are potentially present and may be currently mature. Identified gas leakage features, developed both in the syn-rift and post-rift successions, were also analysed in relation to the structural the stratigraphic elements of the basin. A family of seabed pockmarks, located close to an array of submarine channels, was identified on the distal slope of the basin. These pockmarks are overlying a series of sub-vertical to vertical seismic chimneys in the subsurface. A calibrated basin-wide 3D petroleum system model comprising generation and migration of hydrocarbons was carried out and compared with the observations from the seismic analysis. Preliminary results from this model indicate that although syn-rift and early Cretaceous source rock (SR) intervals may be depleted in the central areas of the basin, an active kitchen from the Aptian SR may be present below the slope areas. Hydrocarbon migration pathways predicted by the 3D model (Hybrid method) coincide with the interpreted seismic chimneys underlying the observed seabed slope pockmarks. Hence, our results indicate that thermogenic gas may be currently generated in the distal slope of the basin from mature early post-rift source rocks within the Early Cretaceous (Aptian) sequences and migrates vertically, due to seal failure, through the stratigraphic column. This migrating thermogenic gas is feeding the seafloor pockmarks identified in the distal slope of the basin, although up-dip lateral migration along stratigraphic layers to the more proximal slope areas cannot be ruled out. The present work represents the first published study integrating detailed seismic analysis and 3D basin modelling linking observed gas-leakage indicators and associated seepage pathways, to their relative abundance, distribution and feeding systems offshore Argentina's continental margin.

KEYWORDS **Passive continental margin. Gas leakage. Oil migration. South Atlantic. Pockmarks. Seismic chimneys.**

INTRODUCTION

Hydrocarbon leakage is a process recognized to occur, in varying intensities along passive continental margins of the Earth, where hydrocarbon release into the hydrosphere and atmosphere, or sequestration within the sediments, takes place (*e.g.* Gay *et al.*, 2007; Hempel *et al.*, 1994; Hornbach *et al.*, 2007; Hovland, 2000; Judd and Hovland, 2007; Kvenvolden & Rogers, 2005; Loncke *et al.*, 2004; Sager *et al.*, 2003). Kvenvolden and Rogers (2005) showed that continental shelf regions play a key role regarding the amount of natural gas emission worldwide. Recently investigations started to focus on the understanding of the subsurface processes controlling gaseous emanations in continental margins (Berndt, 2005; Gay *et al.*, 2007, Anka *et al.* 2012 and references therein). The emissions are produced either by biogenic gas generation (Judd *et al.*, 1997) or by thermogenic hydrocarbon generation from buried source rocks (Heggland, 1997; MacDonald *et al.*, 2000; Mazurenko *et al.*, 2002). In many cases, marine gas-hydrate dissociation has been put forward as an important gas releasing mechanism (Collett, 2002; Cole *et al.*, 2000; Mienert *et al.*, 2005; Van Rensbergen *et al.*, 2002; Wood *et al.*, 2002). Seafloor features, such as mud volcanoes, pockmarks and carbonate/mud mounds, or subsurface features like gas chimneys, polygonal faults, and bright spots imaged in seismic reflection data, have been recognized to be indicators of active natural gas migration/leakage from deeper sources/reservoirs (*e.g.* Berndt, 2005; Gay *et al.*, 2007; Hornbach *et al.*, 2007; Hovland, 2005; Hovland and Judd, 1988; Hovland and Svensen, 2006; Leon *et al.*, 2006: Naeth *et al.*, 2005; Orange *et al.*, 1999; Orange *et al.*, 2002; Schroot *et al.*, 2005). Several authors have recognized and mapped these features along the west African continental margin, on the eastern South Atlantic (Ben Avraham *et al.*, 2002; Charlou *et al.*, 2004; Gay *et al.*, 2006; Graue, 2000; Pilcher and Argent, 2007). More recently, detailed study on gas chimneys and pockmarks occurrence was carried out in the South African Orange Basin (Kuhlmann *et al.*, 2010; Boyd *et al.* 2009, Hartwig *et al.* 2012), which is the conjugate basin of the Argentine Colorado Basin (Lawver *et al.*, 1998; Unternehr *et al.*, 1988). To the best of our knowledge, the present work represents the first integrated study of both seismic analysis and 3D basin modelling linking observed gas leakage indicators, their relative abundance, distribution with the possible deep feeding systems and associated migration pathways in the Colorado Basin, offshore Argentina. Hence, it complements not only previous studies on the petroleum system in this area (*e.g.* Bushnell *et al.* 2000, Vayssaire *et al.* 2007, Marcano Romero *et al.* 2013), but also provides a comprehensive view of the hydrocarbon plumbing system of the basin.

DATASET AND METHODOLOGY

The study area is located in the Colorado Basin and covers approximately 95.000 km2 (Fig. 1). Based on a previous published study (Loegering *et al.* 2013) and the detailed analysis of a dense 2D seismic reflection dataset and data from 8 exploration wells, we reconstruct the geological evolution of the basin and identify, map out and characterize all possible indications of past and present-day hydrocarbon leakage (*i.e.* gas chimneys, gas pockets, mounds, and seafloor pockmarks) on the continental shelf and slope of the basin. The 2D seismic reflection grid comprises about 30.000 km of seismic lines and were kindly provided by Petrobras Argentina S.A. and the Federal Institute of Geo-resources Germany (BGR). Direct evidence of hydrocarbons in the basin was obtained in a deep sea piston coring survey which showed thermogenic gas contents (Vayssaire *et al.*, 2007). There is also recent evidence of active migration/leakage from reservoirs along the Argentine margin, in the form of hydrocarbon seeps observed on the seafloor of the Colorado Basin (Mancilla *et al.*, 2001).

To evaluate the seafloor seeps in a sedimentary basin it is necessary to understand the parameters that control the migration and accumulation of the fluids within the sedimentary column before they escape through the seafloor. Therefore the most important questions to answer are: Where do the fluids come from? When did the fluids evolve? To where do the fluids migrate? In order to address these questions a careful understanding of the morphological, lithological, stratigraphic and tectonic setting of a sedimentary basin is necessary. In addition, with the aim of evaluating possible fluid flow pathways we built a calibrated basin-wide 3D petroleum system model comprising generation and migration of hydrocarbons, using the commercial software PetroMod™ (Schlumberger) and the numerical results were then compared with the observations from the seismic analysis.

RESULTS

Natural gas leakage - occurrence and characterization

The distribution of liquid/gas hydrocarbon-leakage features is considered to allow the identification of potential migration pathways in the basin (Anka *et al.* 2012 and references therein). In this sense, a systematic mapping of the paleo- and present-day features, including seabed mounds and pockmarks, seismic pipes and interpreted gas chimneys, observed in the seismic profiles was carried out in the Colorado basin. Their distribution was analyzed in relation to the structural and stratigraphic elements present within the syn-rift

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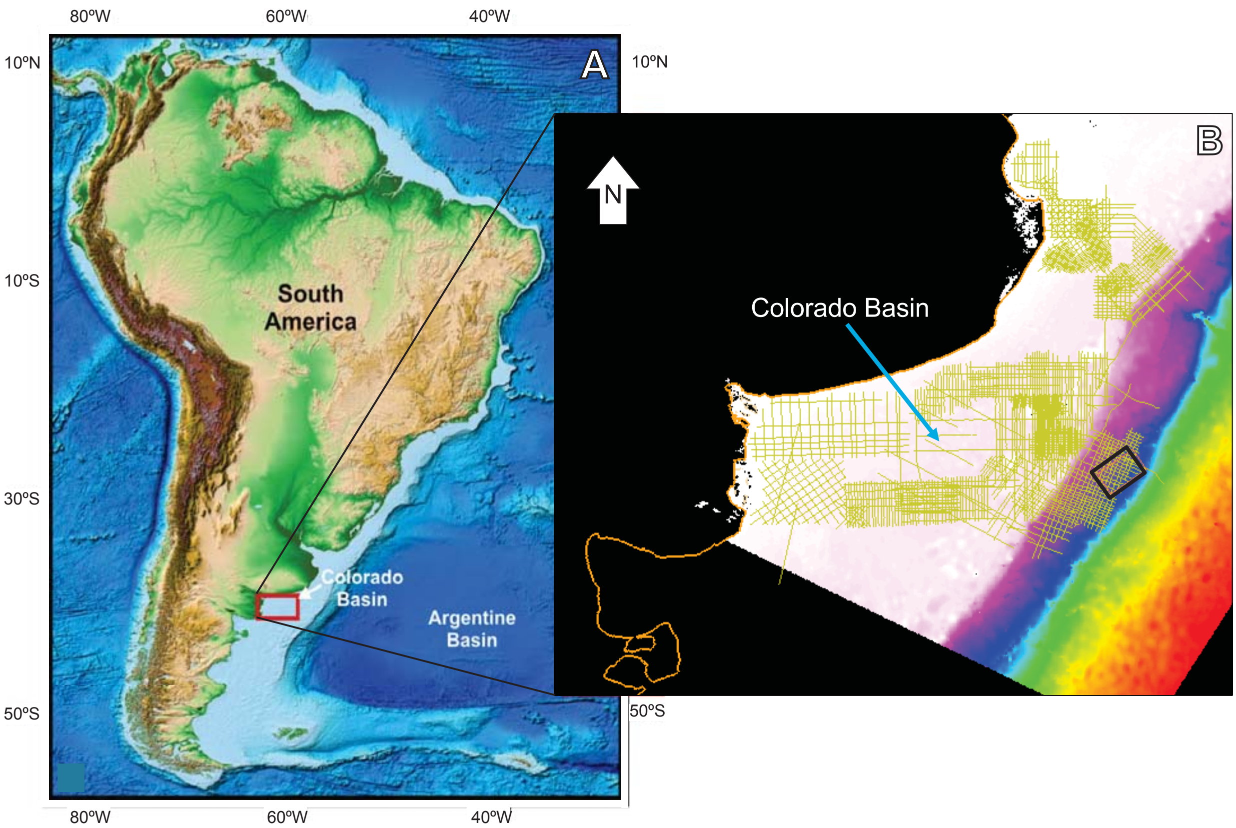

FIGURE 1. A) Location of the Colorado Basin in the South Atlantic, offshore Argentina (red rectangle). B) 2D seismic grid of the Colorado Basin with 2D bathymetry and borehole locations (white dots) used in this study.

and post-rift successions. The presence of free gas in the sediments can be interpreted from seismic sections since even small amounts of free gas in the pore space (ca. 3%) of the sediments reduce the acoustic impedance and create "acoustic turbidity", enhanced reflections (*i.e.* bright spots) (Ostanin *et al.* 2012a, 2013), "acoustic blanking" (Judd and Hovland, 2007; Schroot *et al.*, 2005), seismic pipes (Løseth *et al.*, 2009; Hustoft *et al.*, 2007), and hydrocarbon related diagenetic zones (O'Brien *et al.*, 2005). Additionally, surface indicators related to gas exhalations include mud volcanoes, authigenic carbonate crusts, mounds and pockmarks (Anka *et al.* 2012 and references therein) which in many cases can be identified in seismic sections.

Seismic depressions - seafloor pockmarks and channels

Pockmarks are known to occur in a variety of marine environments from estuarine to marine shelf, slope and abyssal plain settings and have been recorded at all water depths from <2 m to ~5000 m (Hovland and Judd, 1988). They are usually described as circular or near-circular depressions, generally of 2 to 200 m in diameter and up to 35 m deep (Fader, 1991; Haskell *et al.*, 1999; Hovland and Judd, 1988). Mega-pockmarks, described by Pilcher and Argent (2007) in the Gabon and Equatorial Guinea Basins at the West African continental margin, are the largest known contemporary pockmarks. They are greater than 200 m and extend up to 1500 m in diameter. In order to distinguish between seafloor pockmarks and submarine channels on 2D seismic sections, circular to near-circular seafloor depressions were compared against known pockmarks and channels mapped on high-resolution bathymetry available from the study area (Fig. 2A). This approach allowed us to define the seismic characteristics of the two types of seabed features in order to clearly distinguish them through 2D seismic interpretation.

Identified pockmarks have a diameter ranging from 100 m up to 1400 m (Fig. 2B), are between 15 m to 150 m deep (Fig. 2B), and occur associated to submarine channels on the slope of the basin (Fig. 2C). In contrast to pockmarks, the submarine channels are near funnel-shaped to irregular depressions with much larger sizes, from 500 m up to 6.000 m in width and 20 m to 500 m in depth (Fig. 2D). Besides the difference in dimensions, pockmarks were classified as such when they show an uppermost continuous reflector (high-amplitude reflection) similar to the seafloor (Fig. 3A and 3E), which could be the result of bacterial mat and/or carbonate crust formation, or carbonate cemented

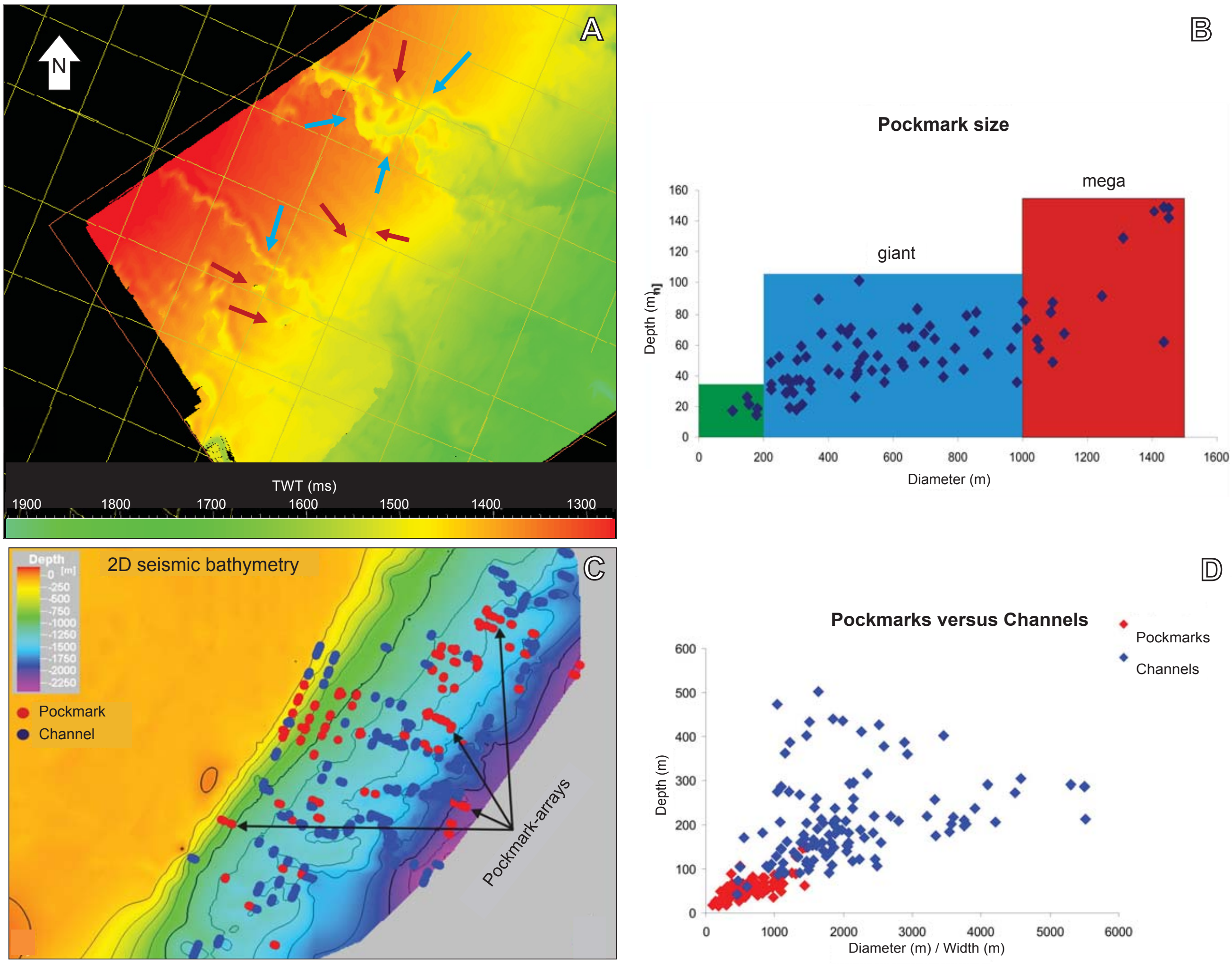

FIGURE 2. A) 3D seismic high resolution bathymetry and locations of pockmarks (red arrows) and channels (blue arrows). (See location in fig. 1). B) Size ranges of pockmarks C) Location of seafloor pockmarks (red dots) and submarine channels (blue dots) at the slope D) Comparison between the dimensions of seafloor pockmarks versus submarine channels. Continues on the next page.

sediments (Hovland and Judd, 1988; Sibuet *et al*. 1988). In contrast, the submarine channels present eroded, truncated sediments on the channel walls, where no continuous reflections (low-amplitude reflection) exist (Fig. 3B). The parameters used to distinguish between pockmarks and channels are thus seismic reflection characteristics, diameter/width ratio, and depth (Fig. 3C). The pockmarks occur as isolated structures and/or as an array of pockmarks (Fig. 2C).

Some of the identified seafloor pockmarks and pockmark-arrays seem to be controlled by structural elements since (1) they occur at the slope in the hanging wall of rift-initiated and reactivated faults, which terminate in the Lower Tertiary sequences, and (2) several near-circular depressions developed locally in the hanging wall of post-rift normal faults affecting the Upper Cretaceous (Colorado Fm. of Campanian age) and Lower Tertiary (Pedro Luro Fm. of Paleocene age) units at the distal slope area, where a vertically-faulted interval with dense fault spacing has been identified (Fig. 3D). As similar sets of depressions occur along several neighbouring lines at the slope, they have been interpreted to represent pockmark-sets along these faults (Fig. 2C). In the area where these pockmarks occur, high-amplitude reflectors within the upper part of the Colorado Fm., between the Tertiary/Cretaceous bounding faults, suggest possible gas accumulation in these levels (Fig. 4A and 4B). In addition, diffuse high-amplitude reflectors observed within the Elvira Fm. (Eocene) are associated with recent pockmarks, suggesting possible gas accumulations in this unit (Fig. 3F). Furthermore, ancient or buried pockmarks and large channel-complexes can be observed at the slope between the Elvira Fm. and informal Caotico Unit (Fig. 5A and 5B).

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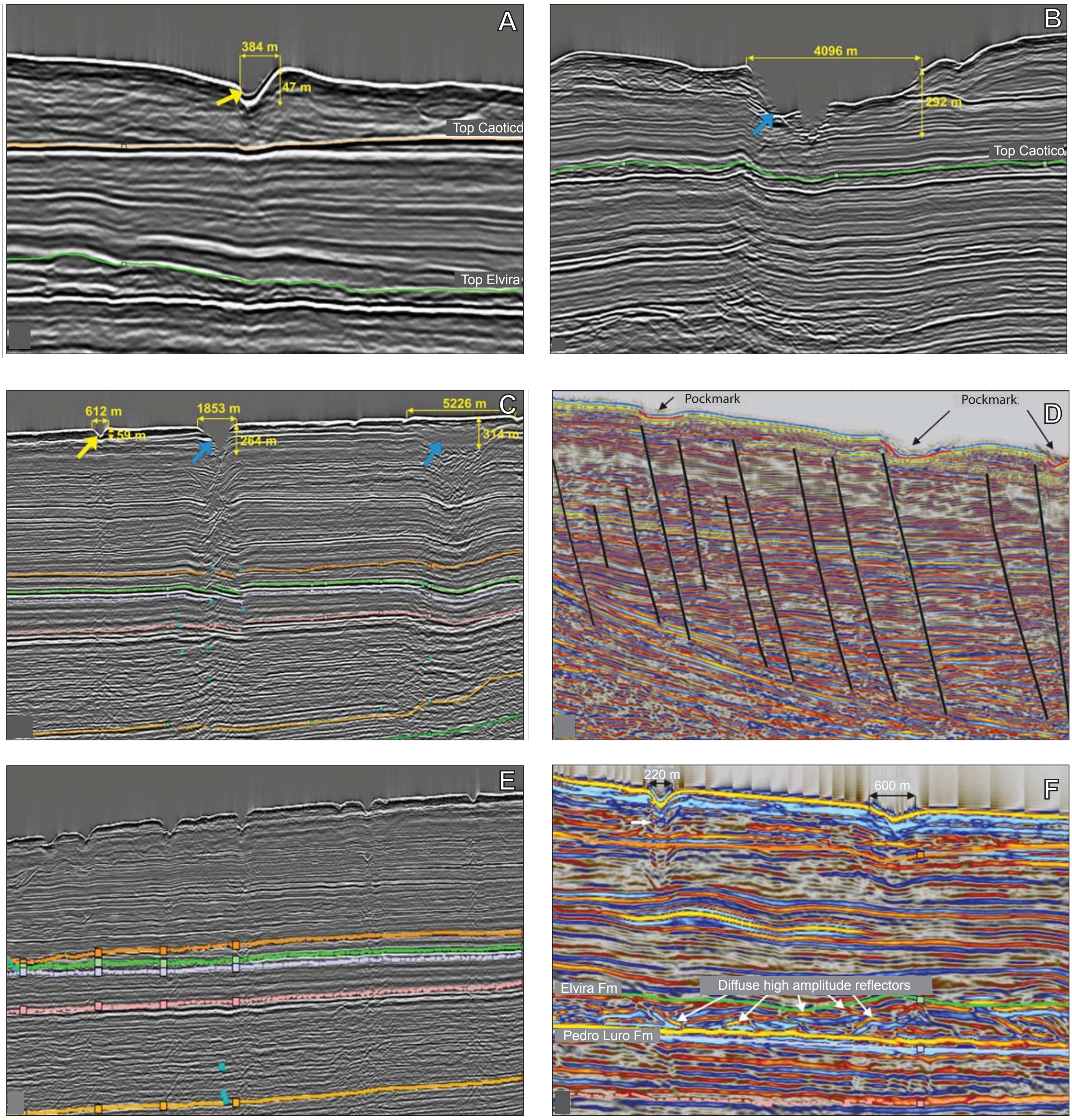

FIGURE 3. A) The pockmark (yellow arrow) shows an upper-most continuous reflection (high-amplitude reflection) similar to the seafloor. B) The channel (blue arrow) shows eroded, truncated sediments on the channel walls, where no continuous reflection (low-amplitude reflection) exists. C) Comparison of submarine channels (blue arrows) and a seafloor pockmark (yellow arrow), these features are known to be pockmarks and channels from the high resolution bathymetry. D) Extensional faults with pockmarks (black arrows) at the hanging wall of these faults. E) Circular or near circular depressions of pockmarks and the internally continuous reflection similar to the seafloor. F) Diffuse high-amplitude reflectors within the Elvira Formation and free migration of gas resulting in seafloor depressions.

Seismic expressions - seafloor mounds

In addition to the pockmarks, seafloor mounds and buried mounds are identified in the slope of the Colorado Basin (Fig. 6A). The mounds present distinctive conical topographic structures and are therefore distinct on seismic data (Fig. 6B). Identified seafloor mounds have a width (diameter) raging from about 750 m to more than 1000 m and are between 50 m to 150 m high (Fig. 6B). Mounds within the Pedro Luro Fm. are buried under thick layers of sediments and are sealed by the Eocene sequences (Fig. 6C). A mounded structure

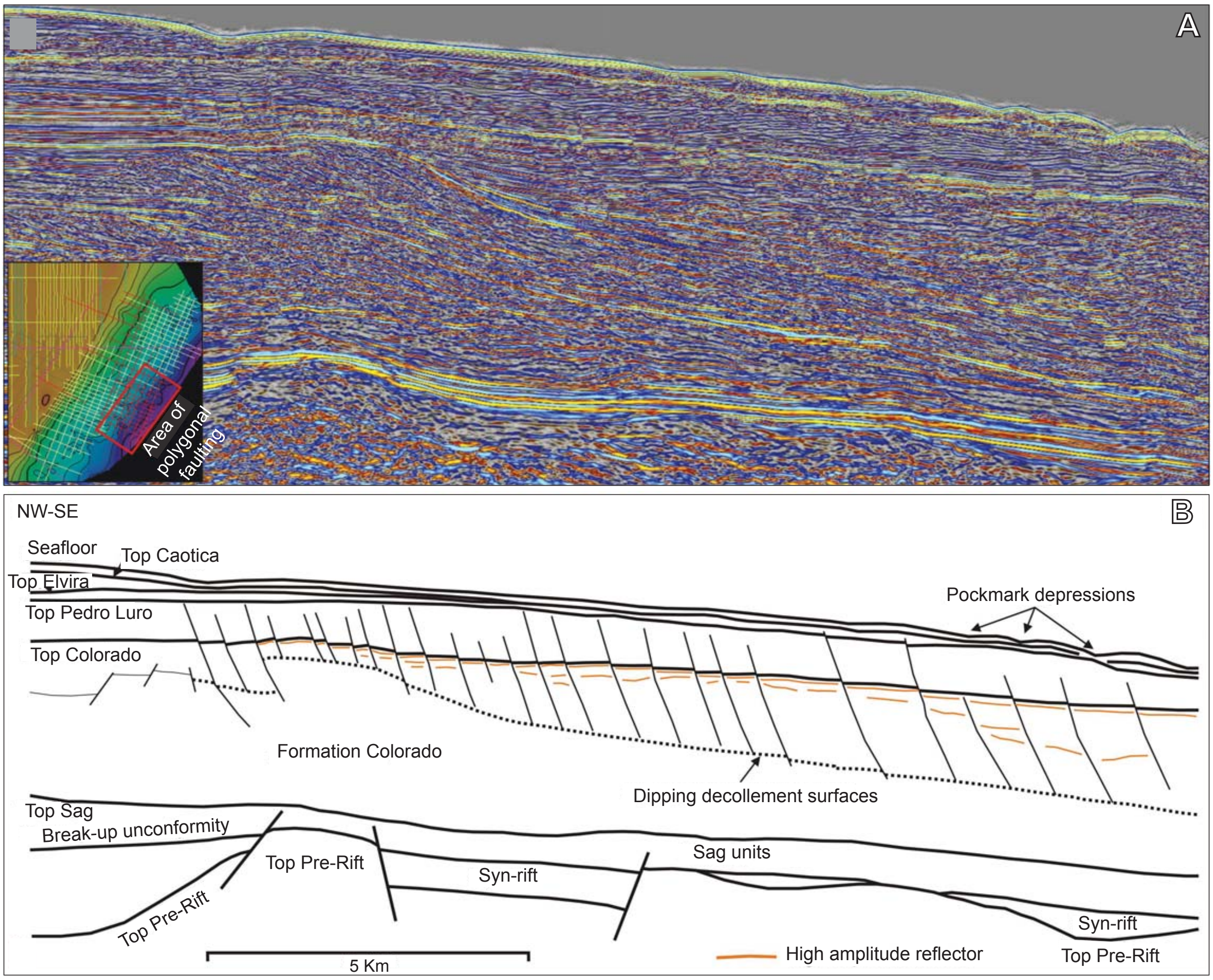

FIGURE 4. A) Uninterpreted seismic profile and B) line drawing depicting a highly-faulted interval identified within the Colorado (Campanian) and Pedro Luro (Paleocene) Fms. in the distal slope region of the basin. High-amplitude reflectors within the upper part of the Colorado Fm., between the Tertiary/Cretaceous bounding faults, suggest gas accumulation at these levels.

similar to the latter was drilled by an exploration well in the centre area of the basin and it turned out to be of volcanic origin.

Amplitude variations in seismic data - seismic chimneys and pipes

Seismic chimneys seen in seismic reflection data are vertical to near-vertical columns of noisy seismic character, interpreted as scattered energy caused by zones of focused gas saturation (Gay *et al.*, 2007; Schroot *et al.*, 2005). These are characterised by low trace-to-trace coherency, low amplitude reflections, pull-down anomalies, bright spots and highly variable dip- and azimuth of seismic reflections (Ostanin *et al.*, 2012a). The most distinct features are vertical pipes where the seismic signal is strongly disturbed and acoustic blanking and pull-down effects, as well as bright spots, all of which may indicate vertical movement and accumulation of gas (Fig. 6B and 6C). The diameter of the identified seismic pipes ranges from 20 m up to 2000 m. Based on their distribution they were classified in two populations (Fig. 7A): i) Population 1 is concentrated in the central part of the basin and apparently is mainly controlled by the stratigraphy, with pipes rooting in syn-rift sequences and terminating in the Elvira Fm. (Fig. 7B). Although the features from these population were initially interpreted as resulting from migrating gas, a nearby drilled well showed that they are rather related to the presence of overlying volcanic mounds (Fig. 6C); ii) Population 2 is concentrated in the slope of the basin, where rift-controlled faults and reactivated faults occur (Fig. 7A and 7C). These seismic pipes are interpreted as gas chimneys. The gas seems to be migrating through the

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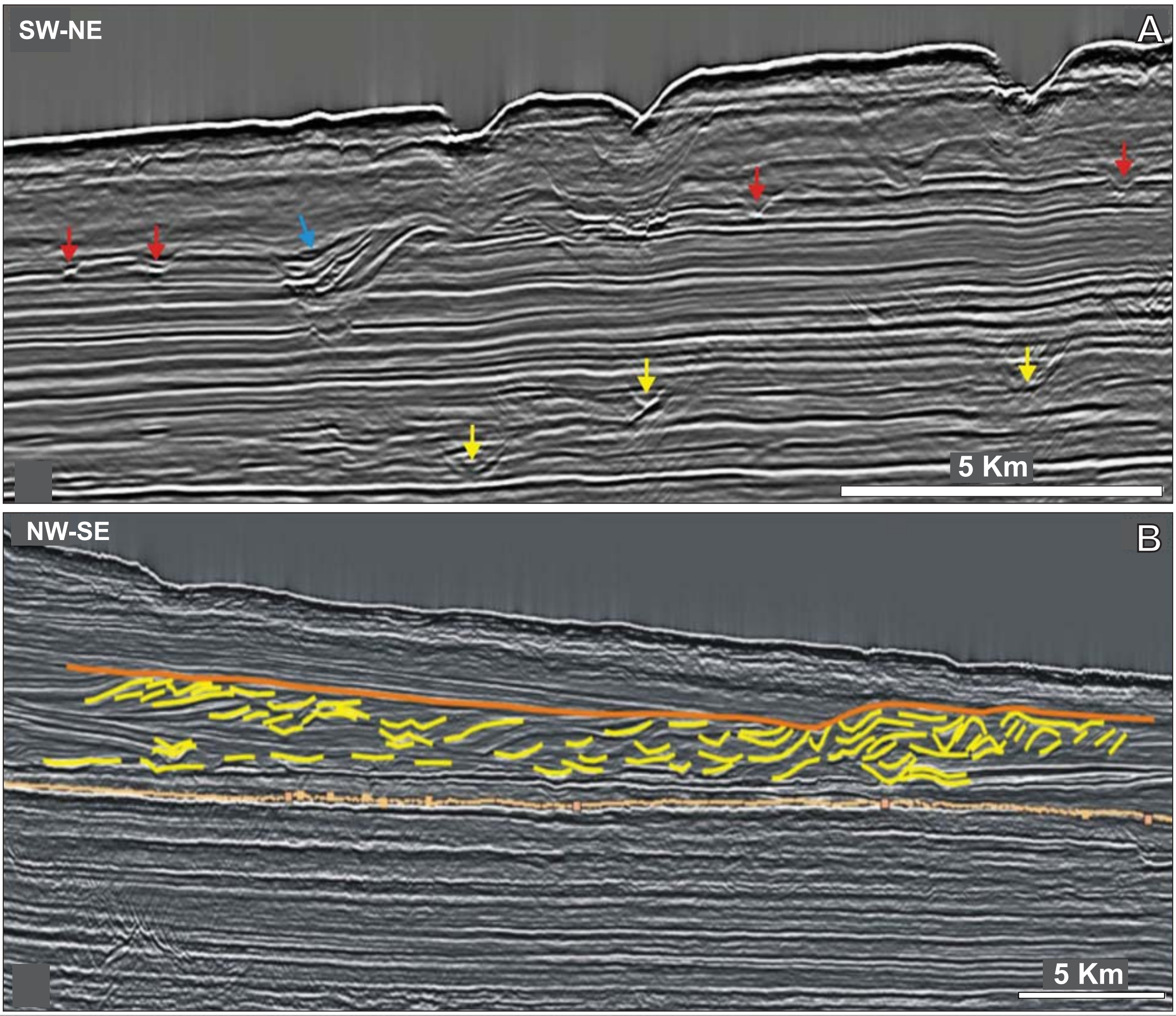

FIGURE 5. A) Paleo-pockmarks (red arrows) and paleo-channels (blue arrow) at the slope within the Barranca Fm. (Miocene). Yellow arrows indicate multiple of seafloor depressions. B) A base of slope channel system is presented, showing many densely spaced individual channels and vertical and lateral aggradational styles. The whole system is up to 40 km wide and 400 m thick. This system overlies the Elvira Formation. Yellow lines represent interpreted channel incisions, light orange represents the Eocene (Elvira Fm.) basement cover contact and dull orange represents the channel surface (Oligocene).

sedimentary column probably along these faults. In this case, the gas chimneys seem to be rooted in the Early Cretaceous sedimentary layers and terminate either in the Elvira Fm. or reach up to the present-day seafloor (Fig. 3F and 7D). The reactivated faults breach post-rift sealing sequences, allowing fluids to flow vertically or sub-vertically across otherwise sealing lithologies. Such migration pathways are documented by indications of gas chimneys occurring in close relationship to the faults (Fig. 7C). On the other hand, some chimneys are rather controlled by the stratigraphy and the gas migrates freely within the sedimentary column and results either in pockmark-like depressions on the seafloor (Fig. 7D and 7E) or seafloor mounds (Fig. 6B). Additionally, some other kind of gas escape indicators, such as seismic wipe-out zones, are observed (Fig. 7F). There are, however, no indications for a bottom-simulating-reflector (BSR) which would point to the presence of gas hydrate in this basin.

Source rock characterization and 3D Hydrocarbon Generation/ Migration model

Having discarded that Population 1 results from migration of gas, but it is rather associated to episodes of volcanics in the basin, we built up a preliminary 3D

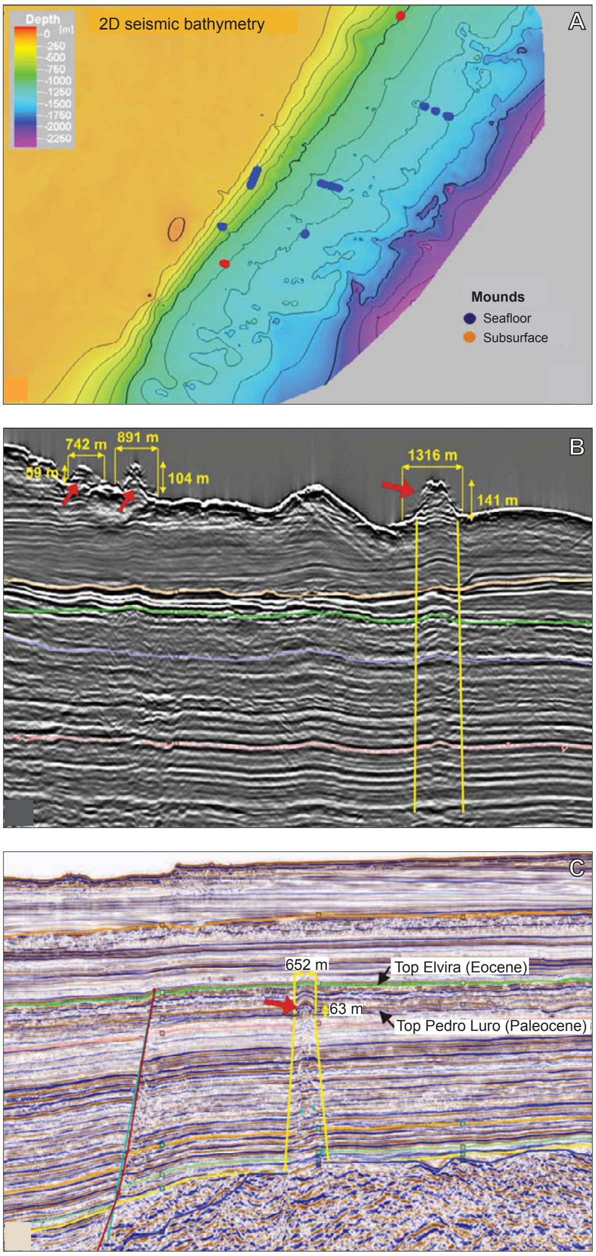

FIGURE 6. A) Location of seafloor (blue dots) and subsurface (red dots) mounds at the slope. The background displays the bathymetry from 2D seismic. B) Seafloor mounds (red arrows). Note the fluid migration path within the yellow lines, illustrating feeding of the mound by a gas chimney. C) Subsurface, paleo-mound (red arrow).

petroleum system numerically simulate in order to model the possible hydrocarbon migration paths and determine whether the seismic chimneys from population 2 might indeed result from upward migration of thermogenic gas in the slope of the basin.

Lower stratigraphic intervals in two wells were characterized with respect to their source rock potential through geochemical screening analysis which included Rock Eval, TOC measurements and Pyrolysis-Gas Chromatography (PyGC). The ratio S2/ TOC indicate good source rock quality for two samples with HIs (Hydrogen Index) values between 200 and 300 mgHC/g TOC, suggesting a mixed Type II/III kerogen albeit early mature at the well positions (Fig. 8A). The individual resolved compounds for these two samples were determined up to n-C_{30}. Horsfield (1989) related the petroleum fluid type generated under natural conditions to the alkyl chain length distribution (CLD) generated from source rocks by open system pyrolisis. This approach allows defining the petroleum type organofacies, which permits to recognize the gas and condensate, paraffinic-naphthenic-aromatic (PNA) petroleum (high and low wax variety) and paraffinic petroleum (high and low wax variety) generating potential of individual source rock samples. The two investigated samples plot in the low wax PNA oil, but very close to the transition into the gas and condensate field (Fig. 8B). Based on the geochemistry analysis, we defined three main source rocks for modelling purposes: (1) Aptian: with 4% TOC, kerogen type II, HI 300mg HC/g TOC, (2) Early Cretaceous: with 1% TOC, kerogen type III, HI 200mg HC/g TOC and (3) Late Jurassic- Early Cretaceous Syn-rift: with 4% TOC, kerogen type II, HI 300mg HC/g TOC (Fig. 9).

The stratigraphic sequence and gridded maps used as input in the model were interpreted and constructed in our previously published detailed seismo-stratigraphic analysis of the basin (for details please see Loegering *et al.* 2013). The lithological information and sedimentary facies of each unit were populated through the extrapolation of 8 exploration wells data.

An initial simulation was carried out considering an initial heat flow 80 mW/m^2 about 150 Ma, representing the basin's rifting event, which decreased exponentially to present-day values of about 55 mW/m^2. However, this initial scenario did not allow calibration of the model with borehole temperature and maturity (vitrinite reflectance) data. In a following simulation two pulses of high heat flow were considered: (1) the initial value of 80 mW/m^2 about 150 Ma representing the rifting event and a second pulse of 75 mW/m^2 around 63 Ma, which represents the local volcanism that has been reported in the basin (Fig. 10A). This scenario allowed to achieve a fairly good calibration with temperature and vitrinite reflectance data (Fig. 10B).

Preliminary results from this calibrated model indicate that Syn-rift source rocks would be currently mature to over-mature and have a present-day

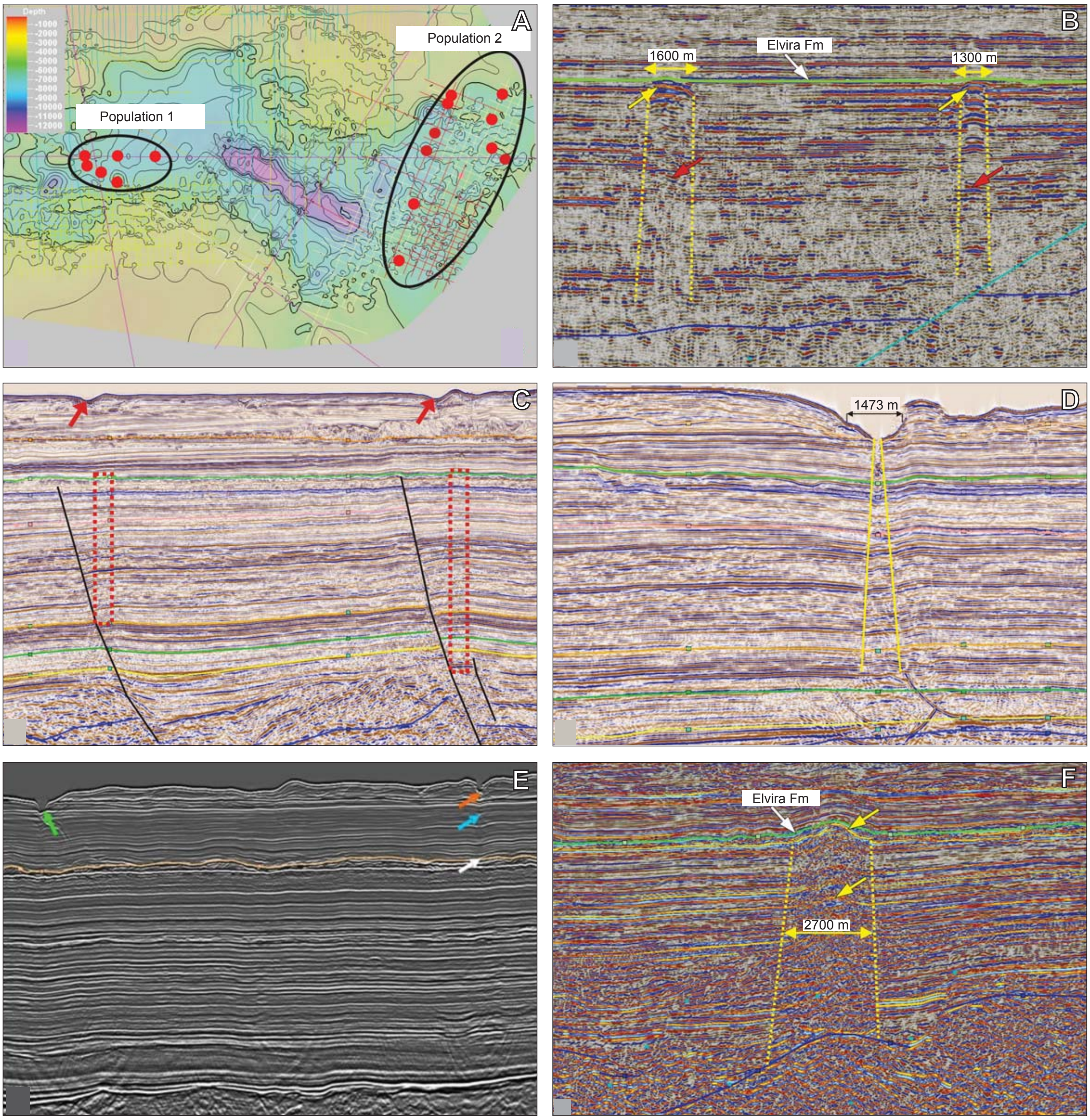

FIGURE 7. A) Location of seismic pipes in the centre and at the slope. The background displays the depth surface map of the basement. B) Seismic pipe (dotted lines). Note the bright spots (yellow arrows) at the top of the chimneys and the internal pull down effect (red arrows). The seismic pipe rooted out of the syn-rift successions. C) Extensional faults with pockmarks (red arrows). Note the fluid migration path within the red rectangles. The gas chimneys are fault related. D) Mega-pockmark and the fluid migration path within the yellow lines, illustrating feeding of the pockmark by a gas chimney. E) Possible gas-chimney (blue arrow/green arrow) feeding a pockmark (orange arrow). The chimney starts at the top of Elvira Fm. (white arrow/orange line). F) Wipe out zone (dotted line) and bright spots (yellow arrow).

transformation ratio of 100%. Similar values are also estimated for the Early Cretaceous source rock in the central and deepest areas of the basin. On the other hand, the Aptian source rock would present a transformation ratio of 100% only in a small area in the deepest part of the basin, being currently mature in most of the basin, with estimated transformation ratios ranging between 30% and 60 % (Fig. 11). The 3D migration model was carried out using the hybrid method, which combines Darcy Flow and Ray-tracing (PetroMod software). We observe that vertical hydrocarbon migration pathways are predicted from the currently mature Aptian source rock up to the seafloor in the present-day slope (Fig. 12).

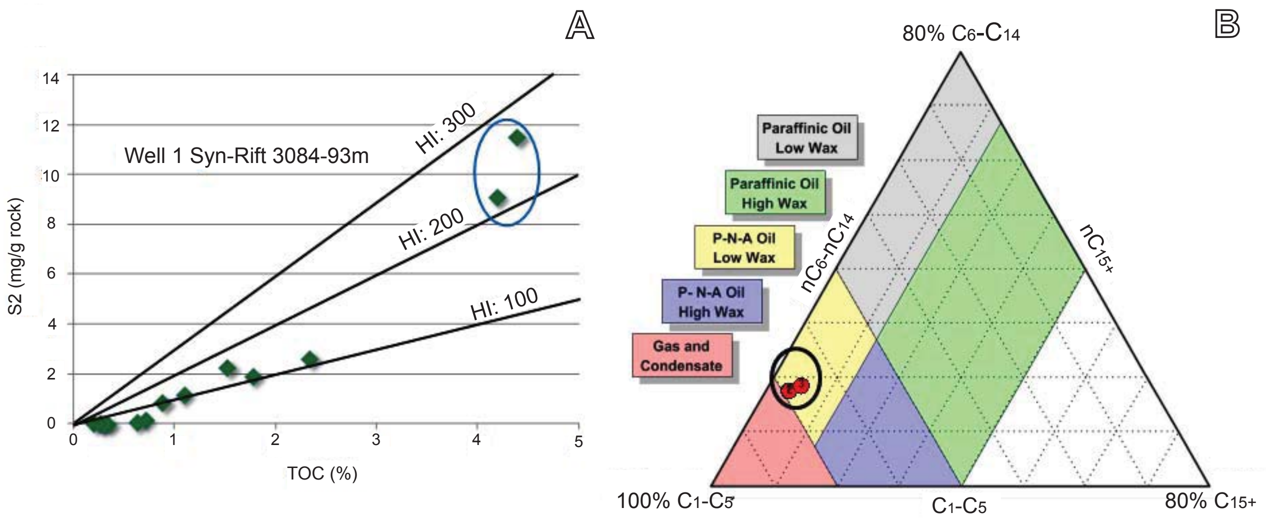

FIGURE 8. A) Results from Rock Eval analysis for samples of lower stratigraphic intervals in two wells. HIs values between 200 and 300 mgHC/g TOC for TOC > 4% indicate a good source rock quality B) Petroleum type organofacies prediction according to Horsfield 1989, based on the individual resolved compounds (up to n-C_{30}). The two samples with highest HIs (red dots) plot in the transition from low wax paraffinic-naphthenic-aromatic

DISCUSSION

Gas chimneys, pockmarks and mounds – causes and consequences

Evolution of passive continental margins play an important role with respect to hydrocarbon leakage and natural gas emissions (*e.g*. Kvenvolden and Rogers 2005, Anka *et al*. 2012). These phenomena have been described for a variety of settings in the South Atlantic: the equatorial West African continental shelf (Pilcher and Argent 2007), the western African Margin offshore Angola (Gay *et al*., 2006; 2007), the South African offshore Orange Basin (Kuhlmann *et al*., 2010, Hartwig *et al*. 2012), and the southernmost-western South Atlantic Argentine Malvinas Basin (Richards *et al*., 2006, Baristeas *et al*. 2012). The mapping of gas related indicators reveals the spatial distribution of gas chimneys and diffuse gas leakage and their relation to the geological and structural setting in the eastern centre and the slope area of the Colorado Basin, offshore Argentina. However, to interpret and detect related surface features like pockmarks and mounds together with

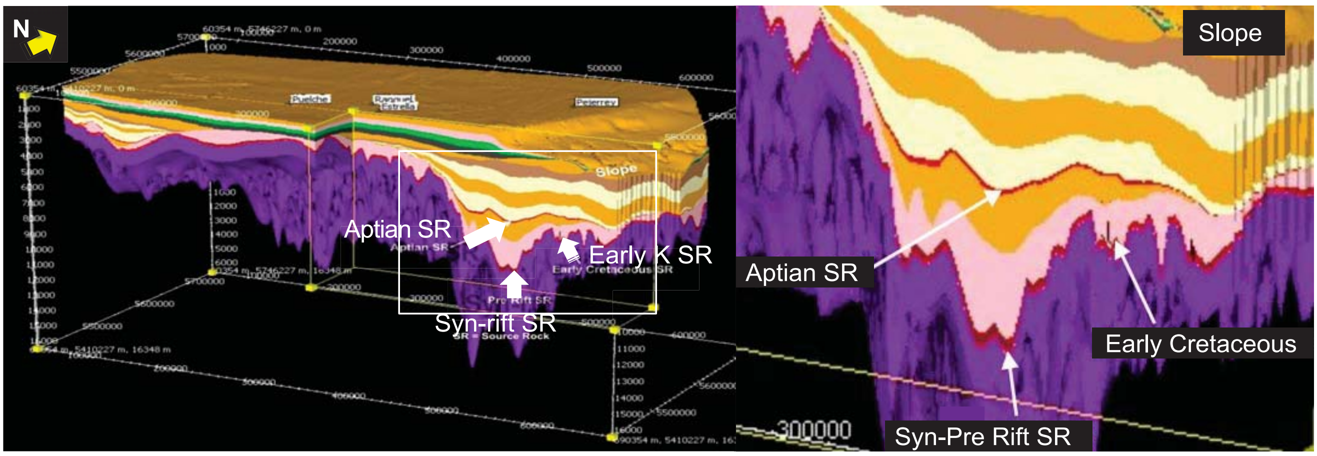

FIGURE 9. 3D basin model of the Colorado Basin depicting the present-day structure and the stratigraphy as well as the main source rock intervals defined within the model. See text for details.

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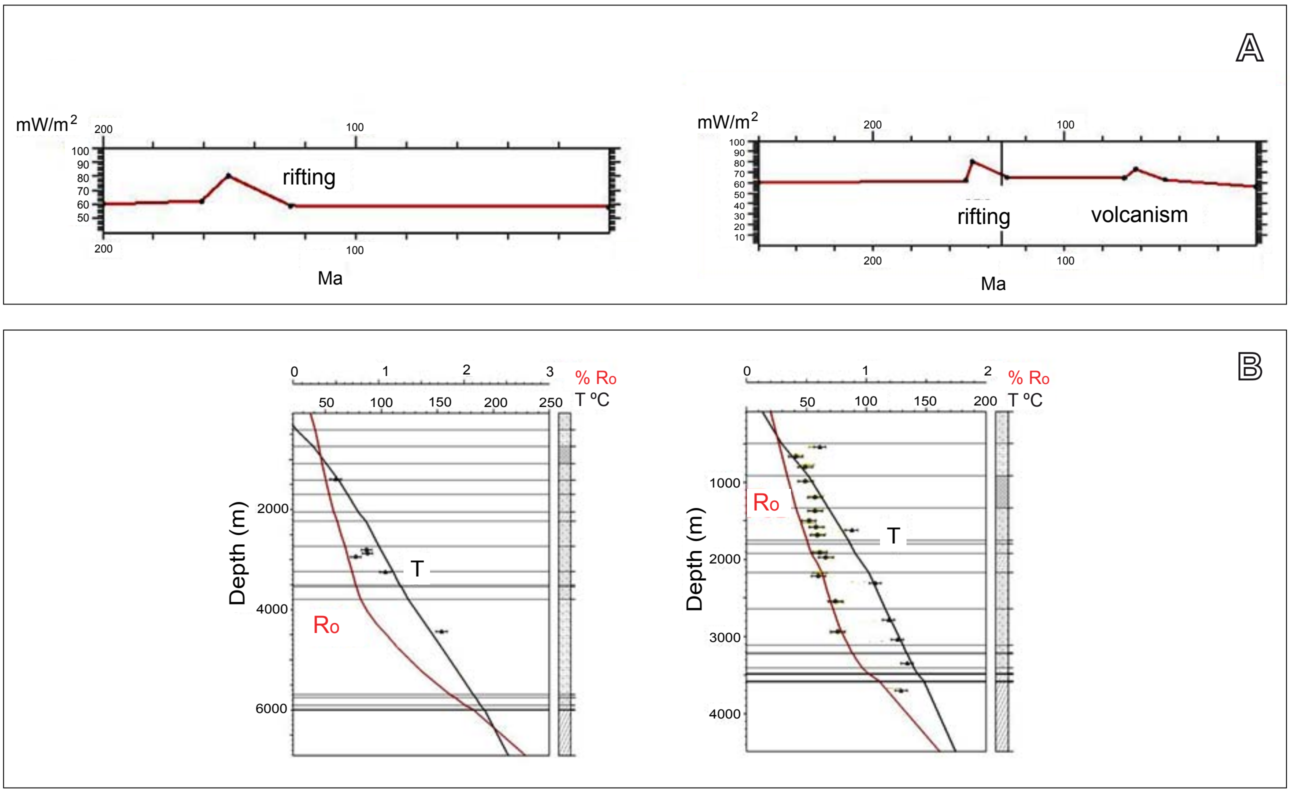

FIGURE 10. A) Two heat flow history scenarios used in the model: the initial value of 80 mW/m² about 150 Ma representing the rifting event (left) and an additional second pulse of 75 mW/m² around 63 Ma representing the local volcanism that has been reported in the basin (right) . The latter provided the best calibration with borehole data. B) Calibration with temperature (T) and vitrinite reflectance (Ro) data from boreholes achieved from using the two-heat-flow pulse scenario from fig. 9A (right).

their supposed migration pathways, further 3D seismic data along with more detailed bathymetric/multi beam surveys would be required. In the following, we discuss the observations made on hydrocarbon leakage in the eastern Colorado Basin (Figs. 2, 6 and 7) and compare them with other parts of the basin and with similar features on the conjugate Orange Basin.

Present and past seepage indicators are documented at the top of the Pedro Luro Fm. as paleo-mounds (Fig. 6C), within the Barranca Final Fm. (Miocene) as several paleo-pockmarks (Fig. 5A), and at the present day seafloor as pockmarks and mounds (Fig. 2C, 3A, 3C, 3D, 3E, 3F and 6A, 6B, 6C). Most of the chimneys and/or seismic pipes reach up to the Elvira Fm. or to the seafloor (Fig. 6B, 6C, 7B to 7F). The seismic pipes of population 1 (Fig. 7A) seem to be rooted in the syn-rift sequences on the continental shelf in the centre of the basin and extend into the post-rift successions. Since the deepest syn-rift deposits are located at about 7000 m depth, a possible hydrocarbon contribution from a thermogenic source was initially speculated. However, the mounded features associated to these seismic pipes can also be related to different compaction above hard-bodies compared to the adjacent lithologies. Such hard-bodies in this area of the basin may be linked to volcanism, rather than to gas migration, based on the presence of volcanic rocks reported by nearby exploration wells (Lesta *et al.*, 1978), where Palaeocene basalts have been encountered within the Pedro Luro Fm. Additionally, the migration model (Fig. 12) does not predict hydrocarbon migration paths in that area, thus ruling out a thermogenic origin for these features.

The chimneys of population 2 (Fig. 7A) seem to be rooted in the post-rift (Aptian) sequences at the slope of the basin (Fig. 13). These chimneys are controlled by structural elements and either terminate in the Elvira Fm. or migrate freely through the sedimentary column and reach the seafloor resulting in pockmark depressions and seafloor mounds. Hartwig *et al.* (2012) found that in the conjugated Orange Basin a large field of buried paleo-seafloor pockmarks and related fluid flow features are associated with underlying tectonic structures (gravitational slope fault zones), mass transport deposits, buried sedimentary bodies (turbiditic channels) or erosional surfaces. The vertically-faulted interval within the Colorado (Campanian) and

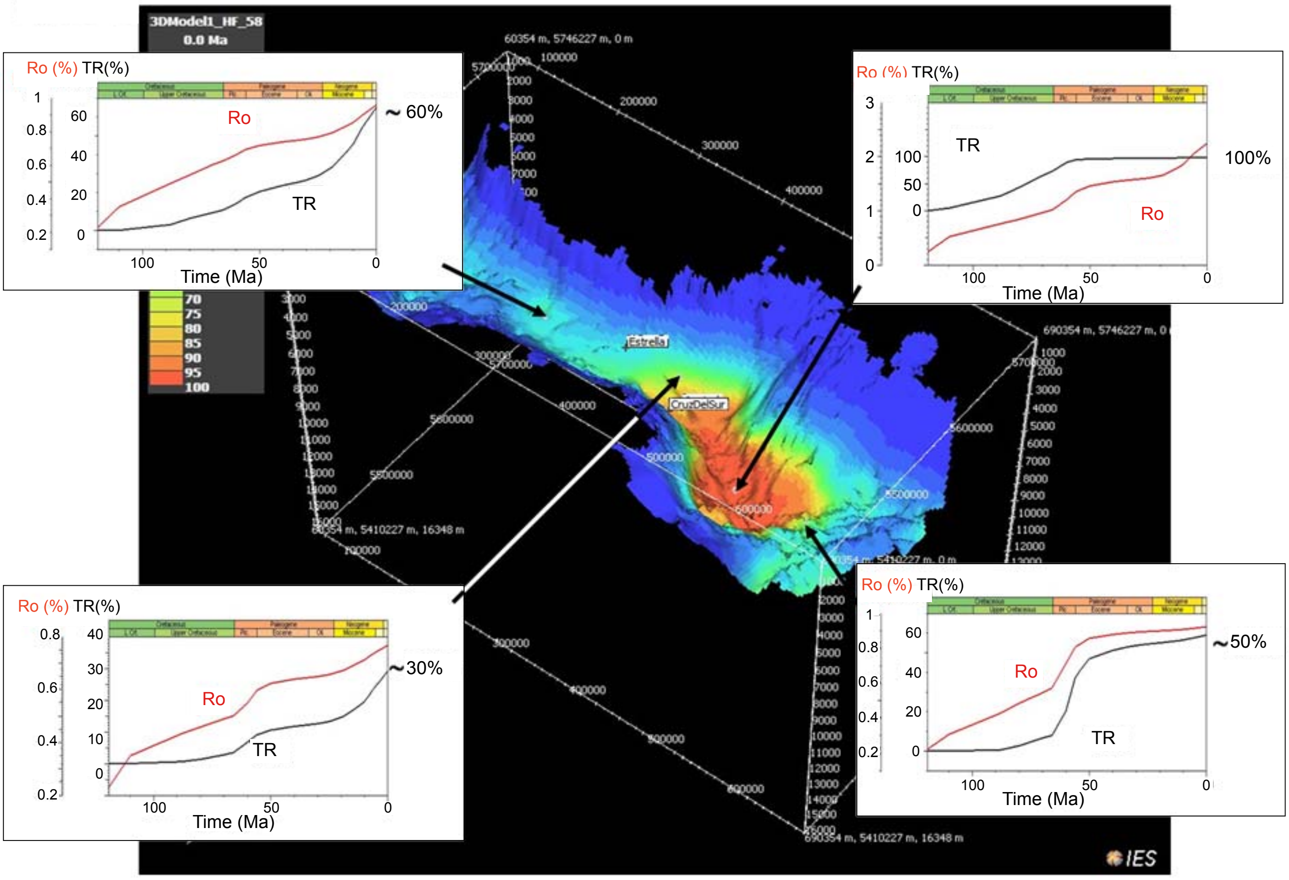

FIGURE 11. 3D generation model results depicting the maturation history of the Aptian source rocks. Transformation ratio (black line) and vitrinite reflectance (red line) over time.

Pedro Luro (Paleocene) Fms. at the distal slope region of the basin (Fig. 4) is related to gravitational tectonics as well as marginal slumping and intersect the Upper Cretaceous to Lower Tertiary sediments. These faults could breach Paleocene/Eocene sealing sequences, allowing fluids to flow vertically or sub-vertically across the seal. Seafloor depressions at the hanging wall of these faults have been interpreted as pockmarks in the Colorado Basin. Similar depressions have been observed in a number of seismic lines where the pockmarks appear to be aligned with the faults (Fig. 3D and 4A), supporting the proposed fluid conductive nature of the system. A comparable pockmark population is also reported in the slope area of the Orange Basin (Kuhlmann *et al.*, 2010; Hartwig *et al.*, 2012).

Pockmarks related to faults have been described in the eastern South Atlantic as well (Gay *et al.,* 2007; Pilcher and Argent, 2007) and are often stated to act as pathways for fluid migration. The high-amplitude reflectors within the south-eastern Upper Cretaceous wedge is interpreted as an indicator of the presence of gas accumulation at the distal slope (Fig. 4). The accumulation of gas suggests that either an impermeable layer of the Pedro Luro Fm. (Paleocene) prevents a further direct migration along the faults or that the faults are closed. Although, the faults are associated with the described conduits for active gas seepage, no direct migration of gas (*i.e.* gas chimney) has been observed along them. In contrast, at the proximal slope of the Colorado Basin, rift-controlled subvertical extensional faults are common and the gas migrated vertically beside them. Pathways are rooted in the post-rift sediments and terminate in the Elvira Fm. (Fig. 7C and Fig. 13). Thus, diffuse gas migration appears to occur along the faults with further horizontal migration within the Elvira Fm., where diffuse high-amplitude reflectors suggest gas accumulation (Fig. 3F).

Clayton and Hay (1994) proposed that faults buried deeper than 200 m act as seals and not as migration pathways as the horizontal stress is normally sufficient to close them, unless they are kept open by sufficiently high pore fluid pressure or sandy lithologies next to the fault plane. However, Berndt *et al.* (2003) and more recently Ostanin *et al.* (2012b) have shown that an effective hydrocarbon plumbing system can be driven both by

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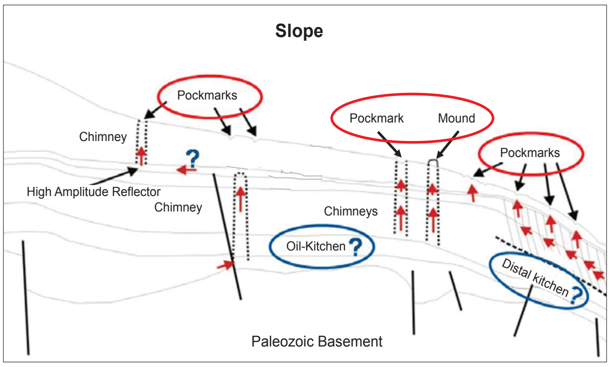

FIGURE 13. Schematic diagram of the plumbing system in the Colorado Basin illustrating the possible migration pathways at the slope of the basin.

regional tectonic faults and local polygonal networks acting as flow conduits for the migrating hydrocarbons in the Barents Sea. The interpreted stratigraphic controlled gas chimneys in Colorado Basin occur within one of the main depocenters. The gas appears to migrate directly through the sediments with no structural elements that might facilitate fluid flow. Similar structures are reported within the main depocenter in the Orange Basin (Kuhlmann *et al.*, 2010) where the gas also seems to move up freely through the sedimentary column with no structural control.

Potential migration pathways

As mentioned above, the seismic pipes of population 1 do not coincide neither with the present-day seafloor gas leakage features (pockmarks and mounds) identified in the slope nor with the predicted migration paths from the 3D model. Considering the reported presence of volcanics at the same stratigraphic level where these chimneys end up, it is proposed here that they are not genetically related to migration of gas. However, a possible genetic hypothesis for the other buried chimneys identified in the upper slope is that they could result from up-dip lateral migration of thermogenic gas generated in the distal slope from mature early post-rift source rocks (Aptian) (Fig. 13). At this location the gas (chimneys of population 2) could migrate vertically either related to the rift-controlled, sub-vertical faults, as well as within the vertically-faulted interval or through the sedimentary column, terminating in the Elvira Fm. or reaching the seafloor as pockmarks or mounds. The results from the 3D basin model indicate that vertical migration from ongoing hydrocarbon generation in the Aptian source rock is indeed possible (Figs. 11 and 12) without intervention of faults acting as conduits. Moreover, the modelled migration paths coincide with the observed seismic chimneys of population 2 and reach up to

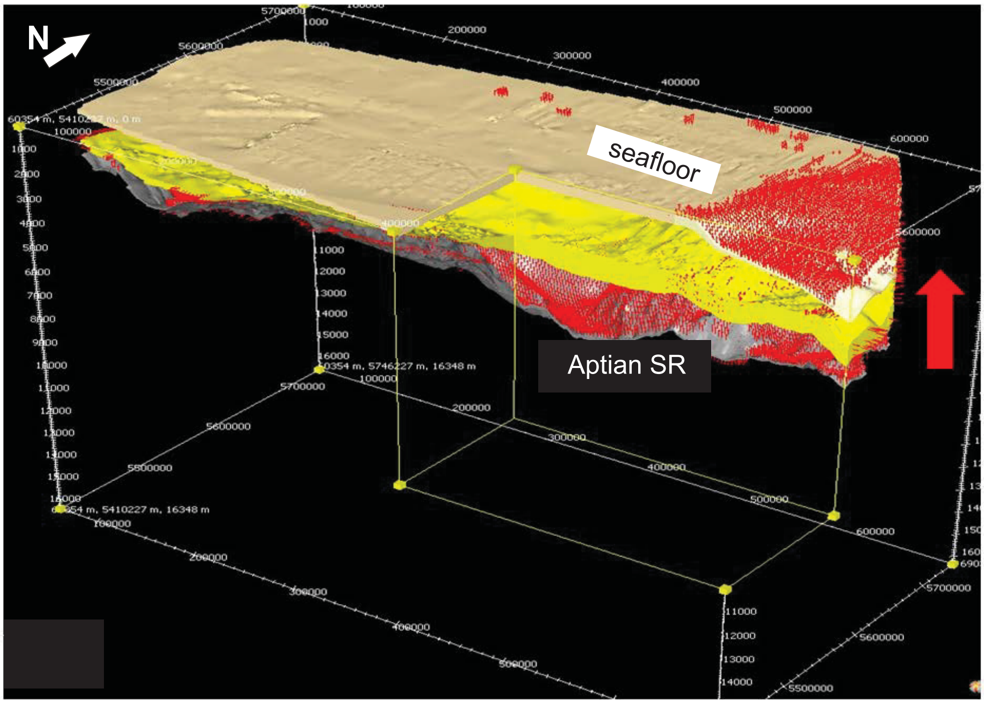

FIGURE 13. Basin-wide 3D migration model (hybrid method) depicting predicted thermogenic gas vertical-migration pathways (red arrows) from the currently mature Aptian source rock below the present-day slope.

the seafloor feeding the observed seabed pockmarks on the slope of the basin.

Integration of these results clearly points out to the existence of an active petroleum system in the slope of the Colorado basin, but also to a high risk of seal failure. If the Elvira seal is broken, the gas may migrate freely through the sedimentary column into the hydrosphere. In order to achieve seal failure, the height of the gas column must overcome the capillary pressure of the sealing rocks of the Pedro Luro and Elvira Fms. The questions probably regardingthe amount of gas leaked the seafloor, the continuity of gas fluxes, into the influence of the Cretaceous and Tertiary sediment loading and unloading through progradation and erosion remain to be addressed in detail in future works.

At the moment, the plays identified in the Colorado Basin are all structural and located mainly in the eastern edge of the Colorado Basin (Bushnell *et al*., 2000; Rodriguez *et al*., 2008), but no wells penetrate the syn-rift sedimentary rocks on the central graben of the eastern Colorado Basin. This study provides evidences of potential vertical migration pathways occurring throughout the sedimentary column or to shallower stratigraphic traps. The Elvira Fm. is likely to have provided the major drainage control in the basin since its deposition. Nevertheless, this unit does not appear tight enough across the entire basin as some of the identified chimneys reach up to the seafloor. The interpreted sandstone lithologies in the Colorado Fm. are suitable for allowing vertical migration of hydrocarbons. Aplin and Larter (2005) affirmed that most of the world hydrocarbon has migrated vertically through large thicknesses of fine-grained sediments, which supports our analysis of the seismic dataset and modelling results.

CONCLUSIONS

Gas leakage indicators have been identified and mapped in the Colorado Basin by detailed seismic interpretation and their relation to structural elements was analysed. Further 3D basin modelling comprising petroleum generation and migration was carried out and calibrated with observations from wells and seismic data. It is proposed here that thermogenic gas is currently being generated in the distal slope of the basin from mature early post-rift source rocks within the Early Cretaceous (Aptian) sequences and migrates vertically, due to seal failure, through the stratigraphic column feeding seafloor pockmarks identified in the distal slope of the basin. Additional up-dip lateral migration along stratigraphic layers of the Elvira Fm. and the Colorado Fm. to more proximal areas of the slope cannot be ruled out. At these more proximal location the gas could then migrate vertically either through the rift-controlled sub-vertical faults, as well as within the highly-dense vertically-faulted interval, or through the sedimentary column, terminating in the Elvira Fm. or reaching the seafloor and resulting in the observed pockmarks or mounds. In some cases the gas could also migrate horizontally below the Elvira seal (Eocene) as supported by the identification of diffuse high-amplitude reflectors within the seal. Hence, the Elvira Fm. probably provided the major drainage control in the basin since its deposition. Nevertheless, this unit does not appear tight across the entire basin and high risk of failure could be predicted in the distal slope.

Rather than describing known petroleum systems, this study examined the potential petroleum systems that may be present in the offshore distal parts of the basin. Exploration of the deep water plays in Argentina certainly remains one of the most important frontier areas to be explored in South America. Future exploration activities in the area should provide better insights on the potential of Jurassic and Early Cretaceous source rocks, as well as more data to characterize the distal source rock intervals and improve the numerical modeling of petroleum generation and migration in the basin.

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