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SEISMIC ANALYSIS OF COLD SEEPS AS PROSPECTIVE ZONES ON OFFSHORE BARREIRINHAS BASIN, BRAZILIAN EQUATORIAL MARGIN

By

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ANÁLISE SÍSMICA DE COLD SEEPS COMO ZONAS DE PROSPECÇÃO NA PORÇÃO OFFSHORE DA BACIA DE BARREIRINHAS, MARGEM EQUATORIAL BRASILEIRA

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ABSTRACT

The Brazilian Equatorial Margin (BEM) is an oblique-transform segment with counterparts in the Gulf of Guinea in West Africa. Both margins are inherited from the Pangea breakup and hence opening of the Equatorial Atlantic Ocean. These areas have been studied as new exploratory frontiers due to petroleum systems found in deep- and ultra-deep waters. The Barreirinhas Basin, located at the central portion of the BEM, has counterparts with the oil and gas producers Ivory Coast and Tano basins. Nevertheless, no relevant reserves were identified in the Barreirinhas Basin yet, moreover due to the poor study in respect to the petroleum systems. This present study aims to identify cold seeps in shallow strata and associated with hydrocarbon migration, indicating possible hydrocarbon accumulations along the offshore Barreirinhas Basin. Investigation was made through conventional 2D seismic reflection in post-stack time migration with additional use of seismic attributes. The results comprise the identification of cold seeps associated with hydrocarbon migration, including leaking faults, gas chimneys, pockmarks, hydrocarbon-derived diagenetic zone (HRDZ), bottom simulating reflectors (BSR), and deep-water mounds. Regional morphologic and stratigraphic structures constrain the zones of cold seep occurrences. In the eastern lower continental slope and continental rise, regional normal faults control cold seep formation. On the central to northern sectors of the continental rise and abyssal plain, several deep-water mounds are sourced by gas chimneys and faults. Gravitational gliding systems are dominated by normal faults and negative flower structures that produce cold seeps on proximal regions, defining the extensional domain. These structural controls are related to the compressional domain of the distal portion, where the decollement zones and series of faults and folds are correlated to pockmarks and deep-water mounds. Near to the western compressional domain, igneous intrusions control the development of leaking faults, gas chimneys, bright spots, and pockmarks. These hydrocarbon-derived structures indicate potential petroleum systems in the Albian to Turonian-Oligocene tectono-sedimentary sequences in the central sector of the BEM. However, more refined techniques are needed to confirm the presence of active hydrocarbon seepage and/or storage. Likewise, the Barreirinhas Basin can be a vast field to the petroleum industry and scientific research, with the latter specially focusing in the nature of the deep-water mounds, endowed of great potential for the geobiology.

Keywords: leakage/seepage structures; hydrocarbon migration; pockmark; deep-water mounds

RESUMO

A margem equatorial brasileira (MEB) é um segmento oblíquo-transformante com equivalentes geológicos no Golfo da Guiné, África Ocidental. Ambas as margens são oriundas da separação da Pangéia e consequente abertura do Oceano Atlântico Equatorial. Essas áreas têm sido estudadas como novas fronteiras exploratórias pela descoberta de sistemas petrolíferos em águas profundas e ultra-profundas. A Bacia de Barreirinhas, localizada na porção central da MEB, tem equivalentes geológicos com as bacias produtoras de óleo e gás da Costa do Marfim e Tano. Apesar disso, ainda não foram identificadas reservas relevantes na Bacia de Barreirinhas, ainda mais por ser pobremente estudadas em respeito aos sistemas petrolíferos. Este presente estudo visa identificar cold seeps em estratos rasos e associadas à migração de hidrocarbonetos, indicando possíveis acumulações de hidrocarbonetos ao longo da porção imersa da Bacia de Barreirinhas. A investigação foi feita através de sísmica de reflexão convencional 2D em migração temporal pós-empilhamento, com uso adicional de atributos sísmicos. Os resultados do estudo compreendem a identificação de cold seeps associados à migração de hidrocarbonetos, incluindo falhas com escape de fluidos, chaminés de gás, pockmarks, hydrocarbon-derived diagenetic zone (HRDZ), bottom simulating reflectors (BSR) e mounds de águas profundas. Estruturas regionais morfológicas e estratigráficas compreendem as zonas de ocorrências de cold seeps. No talude continental inferior e elevação continental do setor leste, falhas normais regionais controlam a formação de cold seeps. No setor central ao setentrional da elevação continental e planície abissal, diversos mounds de águas profundas são abastecidos por chaminés de gás e falhas. Sistemas de células gravitacionais são dominados por falhas normais e estruturas em flor negativa que produzem cold seeps nas regiões proximais, definindo o domínio extensional. Esses controles estruturais são relacionados ao domínio compressional da porção distal, onde as zonas de descolamento e séries de falhas e dobras são correlacionadas à pockmarks e mounds de águas profundas. Próximo ao domínio compressional ocidental, intrusões ígneas controlam o desenvolvimento de falhas carreadoras de fluidos, chaminés de gás, bright spots e pockmarks. Essas estruturas derivadas de hidrocarbonetos indicam potenciais sistemas petrolíferos em sequências tectono-sedimentares do Albiano ao Turoniano-Oligoceno no setor central da MEB. No entanto, técnicas mais refinadas são necessárias para confirmar a presença de ativa percolação e/ou acumulação de hidrocarbonetos. Assim sendo, a Bacia de Barreirinhas

pode constituir um campo vasto para a indústria do petróleo e para pesquisa científica, esta especialmente focando na natureza dos mounds de águas profundas, dotados de grande potencial para a geobiologia.

Palavras-chave: estruturas de escape/percolação; migração de hidrocarbonetos; pockmarks; mounds de águas profundas.

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1. INTRODUCTION

The Brazilian Equatorial Margin (BEM), situated in the Equatorial Atlantic Ocean, comprises a sequence of divergent and transform margin segments resulted from the Pangea breakup, which started in the Aptian (125 Ma) and completely separated at Albian (102 Ma) (Soares et al., 2007; Krueger et al., 2012; Mello et al., 2013). Five basins compose the BEM: Foz do Amazonas and Pará-Maranhão basins to the west, Barreirinhas Basin in the center, Ceará and Potiguar basins in the eastern sector. Those basins are inherited of the Equatorial Atlantic opening, with counterparts in the African conjugate margins, precisely in the Gulf of Guinea in West Africa – also called Côte d'Ivoire-Ghana Margin (de Figueiredo et al., 1983; Brownfield and Charpentier, 2006; Mullin et al., 2018; Wang et al., 2018; Montenegro et al., 2020). The evolution of the Equatorial Atlantic Ocean and assembly of the BEM and Gulf of Guinea are highly influenced by the establishment of enormous oceanic fracture zones (Romanche, Chain, Strakhov, and Saint Paul), active from the syn-rift and drift stages, to the present day (Zalán and Warme, 1985; Azevedo, 1987; Antobreh et al., 2009; Zalán, 2004; Nemčok et al., 2013; de Lépinay et al., 2016; Kuszniir et al., 2020). In the Barreirinhas Basin, the Romanche Fracture Zone (RFZ) governed the tectonic and stratigraphic evolution, practically splitting the basin into two half-grabens (sub-basins): the first one is located south of the RFZ, in shallow-waters of the continental shelf near to the shelf break; the other sub-basin is located to the north of the RFZ and extends till ultra-deep oceanic waters (Trosdorf Junior et al., 2007; de Castro and Oliveira, 2019; Montenegro et al., 2020).

Brazilian margin has vast petroleum reserves, especially in the eastern continental margin – South Atlantic – within which the Pre-salt giant play being one of the most prolific petroleum systems worldwide in deep- and ultra-deep waters. In contrast, the Equatorial Atlantic is earning special notoriety as a new exploratory frontier. Recently, large hydrocarbon reserves were found, mainly in deep- and ultra-deep waters of the Africa-South America conjugate margins: Venus, Mercury, and Jupiter fields (Sierra Leone–Liberia Basin, Conn and Rodriguez, 2011; Kong et al., 2018); Baobab, Espoir, Paon, Rossignol, Foxtrot, Lion, Panthere, Gazelle, Marlin, Belier, Acajou, Ibex, Kossipo, and Pelican (Ivory Coast Basin, MacGregor et al., 2003; Brownfield and Charpentier, 2006); Tano, Belier, Sankofa, Gye Nyam, Hess, Odum, Teak, Tweneboa, Enyenra, Ntomme, and Jubilee field (Tano Basin, MacGregor et al., 2003; Brownfield and Charpentier, 2006; Dailly et al., 2013; Tetteh, 2016); Saltpond Field (Saltpond Basin, Appenteng et al., 2013; Adda et

al., 2015); Lomé Field (Keta Basin, Brownfield and Charpentier, 2006; Welch, 2008; Tyrrell et al., 2017); Aje, Epiya, and Sémé Field (Benin Basin, Haack et al., 2000; Kaki et al., 2013; Ola and Olabode, 2019; Nwizug-bee, 2020); El Furrial, Quiriquire, Boquerón, El Tejero, El Carito, Carito Oeste, and Santa Barbara fields (Eastern Venezuela Basin, Carnevali, 1991; Erlich and Barrett, 1992; Salvador and Leon, 1992; Aguado et al., 1993; Colmenares and Smith, 1997; Porras and Campos, 2001; Roure et al., 2003; Acosta et al., 2005); Zaedyus, Payara, Snoek, Turbot, Ranger, Pacora, Longtail, Hammerhead, Pluma, Tilapia, Haimara, Yellowtail, Tripletail, Mako, Sapakara, and Liza fields (Guyana-Suriname Basin, Platon, 2017; Maia de Almeida et al., 2020; Varga et al., 2021); Xaréu, Atum, Espada, Curimã, and Pecém fields (Ceará Basin, Maia de Almeida, 2018; Maia de Almeida et al., 2020; Oliveira et al., 2020); Pitu field (Potiguar Basin, Wang et al., 2018; da Silva et al., 2021).

These discoveries and the exploratory success triggered several investigations aiming to find new reserves in both South America-West Africa margins. Analogously, the possibility of new discoveries in the BEM is feasible due to its correlated tectono-stratigraphic evolution (Schiefelbein et al., 2000; Mello et al., 2013; Wang et al., 2018; Oliveira et al., 2020; da Cruz et al., 2021). Particularly, the Barreirinhas, Ivory Coast, and Tano basins constituted a conjugate margin, sharing genetic processes and similarities during their respective evolution (Basile et al., 1993, 2005; Soares et al., 2007; Antobreh et al., 2009; Pellegrini & Ribeiro, 2018; Wang et al., 2018; de Castro and Oliveira, 2019; Lunn, 2019).

Hydrocarbon leakage has been documented worldwide (Hovland et al., 2010; Maestrelli et al., 2017a; Suess, 2020). Source layers are submitted to high pore-fluid pressure, exceeding the sum of the lithostatic pressure and the tensile strength (Cosgrove, 2001, as cited by Cartwright and Santamarina, 2015). Overpressure is responsible for hydraulic fracturing in the overburden, breaking the seal integrity and leaking hydrocarbons through a network of fractures, faults, chimneys, and pipes (Plaza-Faverola, 2010; Cartwright and Santamarina, 2015; Maestrelli et al., 2017a; Zhang et al., 2018). Several parameters can lead to overpressure release, including tectonic activity, sedimentary loading, rapid sedimentation, burial conditions, dewatering, sea-level changes, tides, storms, gas hydrate formation and dissociation, glaciation and deglaciation cycles (Cole et al., 2000; Dimitrov, 2002; Oliveira et al., 2008; Hovland et al., 2010; Ma et al., 2021; Suess, 2014). Usually, leakage occurs vertically towards the surface, with very limited lateral movement. Actually,

the majority of hydrocarbon accumulations are affected by some degree of leakage related to seal failure (tectonic activity, fracking) and low-integrity sealing (facies changes, juxtaposition of porous layers) (Cowley and O'Brien, 2000). The volume of leakage can damage submarine infrastructure, drain the reservoir partially or completely, and release hydrocarbons within the water and atmosphere (Hovland and Judd, 1992; Whelan et al., 2005; Skarke et al., 2014; Cartwright and Santamarina, 2015; Maestrelli et al., 2017a; Roelofse et al., 2020).

Hydrocarbon seepage is a common phenomenon reported in onshore environments, continental shelves, active and passive continental margins, and deep-water settings (Hovland and Judd, 1988, 1992; Dimitrov, 2002; Suess, 2014; Li et al., 2021). Vertical fluid flow moves upward in such a manner very similar to leakage, carrying hydrocarbons of depths ranging from shallow subsurface to several kilometres deep. Seepage may reach the surface, forming the so-called cold seeps, and a variety of seafloor morphologies, including depressions, craters, and mounds (Hovland, 2012; Chen et al., 2014; Smith and Coffin, 2014; Suess, 2020). Sometimes, gas venting from the seafloor may generate hydroacoustic flares in the water column (Taylor et al., 2000; Greene et al., 2006; Skarke et al., 2014; Spatola et al., 2017; Li et al., 2021). Furthermore, cold seeps represent transport pathways for dissolved chemical nutrients, sustaining complex food chain for marine life (Hovland, 2012; Suess, 2014, 2020).

Cold seeps are identified in features such as faults, gas chimneys, pockmarks, bottom simulating reflectors, hydrocarbon-related diagenetic zones, seafloor mounds, mud diapirs, mud volcanoes, and so forth (Figure 1.1). They are associated with hydrocarbon migration and hence classified as DHI – direct hydrocarbon indicator – very important in the prospection and production of oil- and gas-bearing fields (Chapman et al., 2004; Plaza-Faverola, 2010; Hovland et al., 2010; Nandi and Samanta, 2011; Serié et al., 2012; Allen and Allen, 2013; Su et al., 2016; Zhang et al., 2018; Goulart et al., 2019; Roelofse et al., 2020; Van Ngo & Ferguson, 2020; Ma et al., 2021; Zhong et al., 2021). Firstly, DHIs are identified based on seismic data, then validated by geochemical survey before a well is drilled.

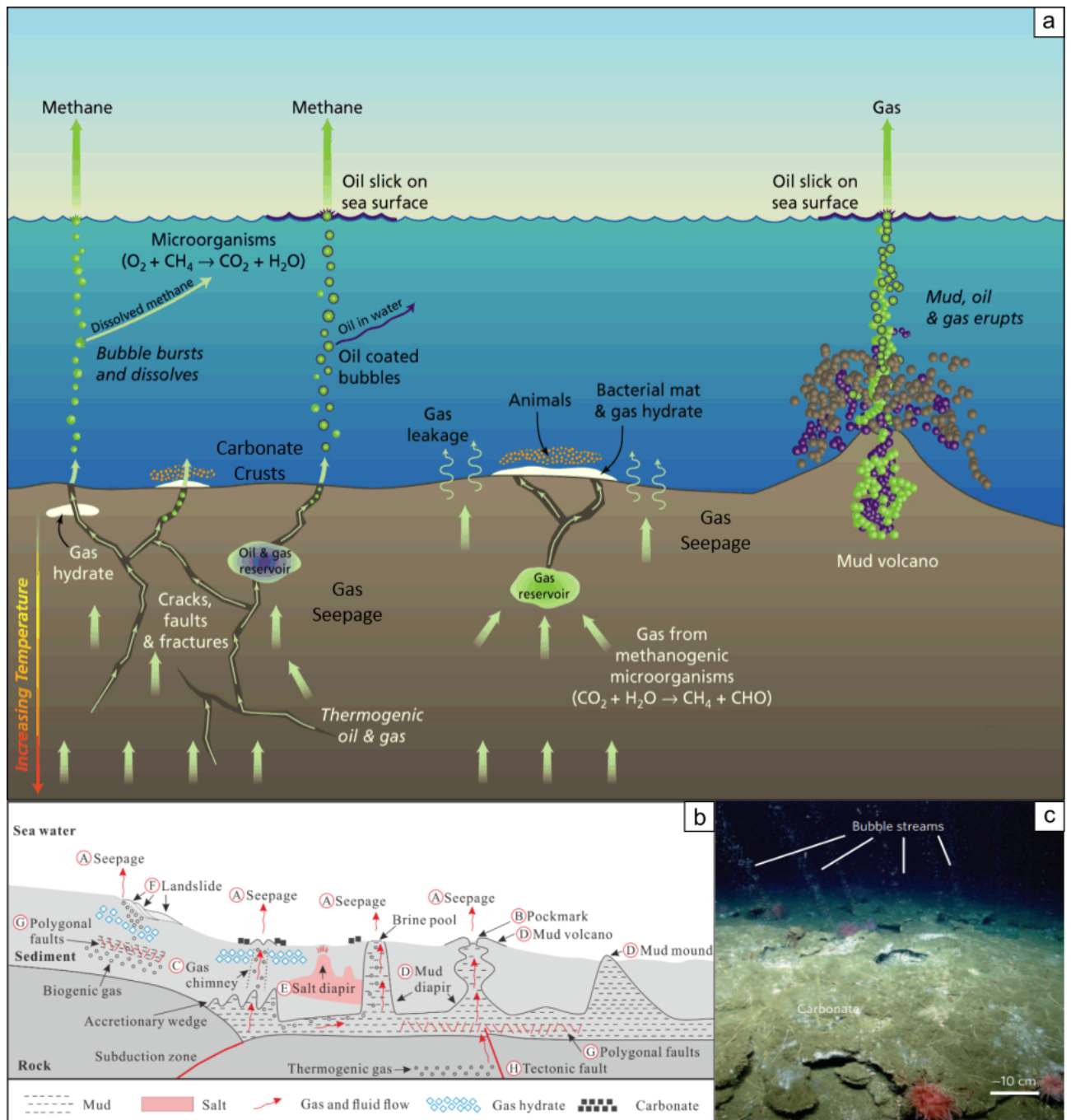


Figure 1.1 Common cold seeps features. (a) Scheme of integrated fluid migration in the vicinity of the Green Canyon area, on the upper continental slope of northern Gulf of Mexico. Hydrocarbon leaks from shallow reservoirs through cracks, faults, and fractures, forming gas hydrates pockets, chemosynthetic communities, carbonate crusts, gas plumes, and giant mud volcanoes. (b) Compilation of several expressions related to hydrocarbon leakage/seepage. (c) Image from ROV showing carbonate crusts, living colonies, and methane plumes found ~ 425 m deep on upper continental slope, near Norfolk Canyon, between Cape Hatteras and Mid-Atlantic Bight. Offshore Virginia, northern US Atlantic margin. (Modified from Whelan et al., 2005; Skarke et al., 2014; Ma et al., 2021).

Faults are important conduits for hydrocarbon leakage/seepage (Suess et al., 2001; Whelan et al., 2005; Greene et al., 2006; Sarkar et al., 2012; Cartwright and Santamarina, 2015; Suess, 2020; Van Ngo & Ferguson, 2020). Within a reservoir, when the seal integrity is sufficiently reduced, fluids start to leak and faults act as pathways of hydrocarbon migration. Gas chimneys are very associated with faults, either remobilizing fluids and sediments and cutting throughout the stratigraphy (Cowley and O'Brien, 2000; Maestrelli et al., 2017a). When huge volumes of plastic mud are involved, piercing geological features known as mud diapirs may form (Dimitrov, 2002; Li et al., 2013; He et al., 2016; Zhang et al., 2018; Li et al., 2021). Faults, gas chimneys, and mud diapirs are capable to reach the seafloor and form depressions known as pockmarks (Hovland and Judd, 1988; Cole et al., 2000; Taylor et al., 2000; Sarkar et al., 2012; Chen et al., 2014; Roelofse et al., 2020). These features are widespread identified in basins worldwide, seen isolated or in clusters, ranging in size from meters to craters of hundreds of meters wide, and meters to tens of meters deep (Hovland et al., 2010; Hovland, 2012; Suess, 2020).

Within continental slopes and continental rises, with minor distribution in shelves and abyssal plains, bottom simulating reflectors (BSRs) are a common feature associated with hydrocarbon seepage and migration (Li et al., 2013; Yu et al., 2014; Zhang et al., 2018; Suess, 2020). BSRs delineate the boundary between above gas hydrate-bearing strata and underlying free gas (Suess et al., 1999; Chapman et al., 2004; Satyavani et al., 2005; Schroot et al., 2005; Roberts et al., 2006). The gas hydrate stability zone (GHSZ) is the denomination of the area where gas hydrates are stable. The hydrate phase-changes are related to a thermobaric field and occur in very specific stability conditions in the subsurface (Berndt et al., 2004; Yu et al., 2014; Su et al., 2016). Another ordinary hydrocarbon migration feature is the hydrocarbon-related diagenetic zone (HRDZ). Symbiont sulfate-reducing bacteria and methane-oxidising archaea are responsible for anaerobic oxidation of methane and authigenic carbonate precipitation, forming chemosynthetic communities, carbonate cementation, hardgrounds, concretions, nodules, crusts, etc (Roberts et al., 1990, 2006; Hovland, 2002; Han et al., 2004; León et al., 2007; Gong et al., 2010; Chen et al., 2014; Smith and Coffin, 2014; Camerlenghi, 2018; Zhong et al., 2021).

A variety of positive seafloor morphologies are genetically related to hydrocarbon migration. Mud volcanoes may form by sedimentary and tectonic loading originated from compressional forces, high sediment rates, and stacking of overpressured muddy deposits

enriched in water and hydrocarbons, generating mounds of hundreds to thousands of meters long, and tens to hundreds meters high (Dimitrov, 2002; Chiu et al., 2006; Deville, 2009; He et al., 2016; Spatola et al., 2017; Li et al., 2021; Zhong et al., 2021). Another feature built by hydrocarbons is gas hydrate mounds, also called hydrate mounds or pingoes (Hovland and Svensen, 2006; Serié et al., 2012; Macelloni et al., 2013; Somoza et al., 2014; Wilson et al., 2014; Yang et al., 2021; Zhang et al., 2021). High-flux of light gas hydrate infiltrates porous layers through chimneys, faults and fractures, causing doming due to upward movement of less dense hydrate-bearing strata (Hovland, 2012; Liu et al., 2020; Hovland and Roy, 2022). Furthermore, carbonate buildups have been reported associated with cold seeps (Whelan et al., 2005; Burgess et al., 2013; Skarke et al., 2014; Suess, 2014; Li et al., 2021; Zhong et al., 2021). These features hold a wide range of morphologies, including carbonate mounds, mud mounds, reefs, attached carbonate platforms, isolate carbonate platforms, and so forth.

Deep-water reefs are found in hypoxic, aphotic, and cold waters in depths ranging from dozens to thousands of metres deep (Hovland et al., 1994b; Hovland, 2008, 2012; Rodriguez-Martinez et al., 2011; Veeken & Moerkerken, 2013). They form carbonate mud mounds constituted by deep-water communities in similar way to that of tropical barrier-reefs, although the deep-water reefs tend to be considerably smaller, and the food-chain based on chemosynthesis, where nutrients are proven from hydrocarbons supplied by cold seeps, hydrothermal vents, and ocean upwellings (Roberts and Aharon, 1994; Mienert et al., 2004; Roberts et al., 2006; León et al., 2007; Paull et al., 2008; Maignien et al., 2010; Rodriguez-Martinez et al., 2011; Templer et al., 2011; Wheeler et al., 2011; Ceramicola et al., 2018; Lo Iacono et al., 2018; Zhou and Pratt, 2019). Nevertheless, Hovland et al. (1994b) and Talukder et al. (2007) point out that is very difficult to differentiate between the various types of seafloor mounds based only on seismic sections, without more refined techniques such as drilling, collected samples, ROV and AUV surveys. In this study, there is a lack of core data and high frequency seismic, hampering the exact determination of the mounded features (mud volcanoes, hydrate mounds, carbonate buildups, carbonate mud mounds), so the collective term mound is used.

Seismic analyses are essential to understand the natural processes involved in tectono-sedimentary evolution, stratigraphy and hence the formation of oil and gas. In this context, the BEM is viewed as a new exploratory frontier, target of prospection and finding of new hydrocarbon reserves, especially after recent discoveries in several sectors of the

conjugate margin. Nevertheless, there are a lack of knowledge about the Barreirinhas Basin petroleum systems, particularly on deep-waters. This study examines the offshore Barreirinhas Basin, investigated through conventional 2D seismic, with additional use of RMS amplitude, instantaneous amplitude, instantaneous frequency, and chaos seismic attributes. They are extensively used in the oil industry to reduce exploratory risks by optimizing the conventional seismic lines (Fathiyah Jamaludin et al., 2016; Goulart et al., 2019; Obiadi et al., 2019; Conti and Oliva, 2021). The objectives are to map the distribution of cold seeps, and identify their pathways of hydrocarbon migration and respective structural-stratigraphic controls. Based on a comparison between the occurrence of cold seeps features on Barreirinhas Basin and the context of petroleum systems of the conjugate African margin, this study might support the potential prospective zones for hydrocarbon accumulation and migration on the offshore petroleum systems.

2. GEOLOGICAL SETTING

2.1 Brazilian Equatorial Margin

The Pangea breakup, started in Aptian and extended to the final of Albian, built extensive transform margin segments on both edges of the Equatorial Atlantic (Figure 2.1). Shear and suture zones on West Gondwana, inherited from Late Proterozoic Brasiliano/Pan-African Orogen (720-540 Ma), are described as weakness zones, promoting the development of the several basins (Szatmari et al., 1987; Antobreh et al., 2009; Davison et al., 2016; Maia de Almeida, 2018; Bempong et al., 2019; Lunn, 2019). In West Africa, also called Côte d'Ivoire-Ghana Margin, the Gulf of Guinea comprises the countries Liberia, Ivory Coast, Ghana, Togo, Benin, and western Nigeria (Niger Delta) (Brownfield and Charpentier, 2006; Jianping et al., 2010; Montenegro et al., 2020). Several oblique transform basins developed in the Gulf of Guinea, including Sierra Leone-Liberia, Deep Ivorian (sub-basins of Ivory Coast, Tano, and Grand Bassam), Saltpond-Central, Keta, and Benin basins (Lamarche et al., 1997; de Matos, 2000; Brownfield and Charpentier, 2006; Tari, 2006; Jianping et al., 2010; Bempong et al., 2019; Lunn, 2019; Fea et al., 2022). The South America conjugate margin developed the BEM segment, composed of the Foz do Amazonas, Pará-Maranhão, Barreirinhas, Ceará, and Potiguar basins. Figure 2.2 shows two stages of conjugate Barreirinhas-Ivorian-Tano and Ceará-Saltpond basins opening; red and black dashed lines represent inferred lineaments, as the Gondwana suture zone and São Luís Craton edges, taken as weakness zones during the intracontinental breakup. The resultant pull-apart basins exhibit the proto-oceanic fracture zones from the mid-ocean shearing, basin-sidewall faults NW/SE and NE/SW trending, in the BEM and Côte d'Ivoire-Ghana Margin, respectively (Antobreh et al., 2009; Lunn, 2019).

All the BEM rift segments are characterized by dextral deformation, trending E-W, triggered due to strike-slip tectonics in the ocean fracture zones (Romanche, Chain, Saint Paul, and Strakhov) (Szatmari et al., 1987). Hence, the BEM and the African conjugate margin are part of the oblique transform margins, with strong right-lateral and normal components (de Figueiredo et al., 1983; de Matos, 2000; Nemčok et al., 2013; Mullin et al., 2018; de Castro and Oliveira, 2019; Kusznir et al., 2020; da Silva et al., 2021). Particularly in Barreirinhas, the RFZ constitutes one of the megastructures that segment the Mid-Atlantic Ridge, approximately 3200 km long, extending in both directions of the

Brazilian-African conjugate margins (Tavares et al, 2020). The fault offset generated by the strike-slip component can reach 1000 km.

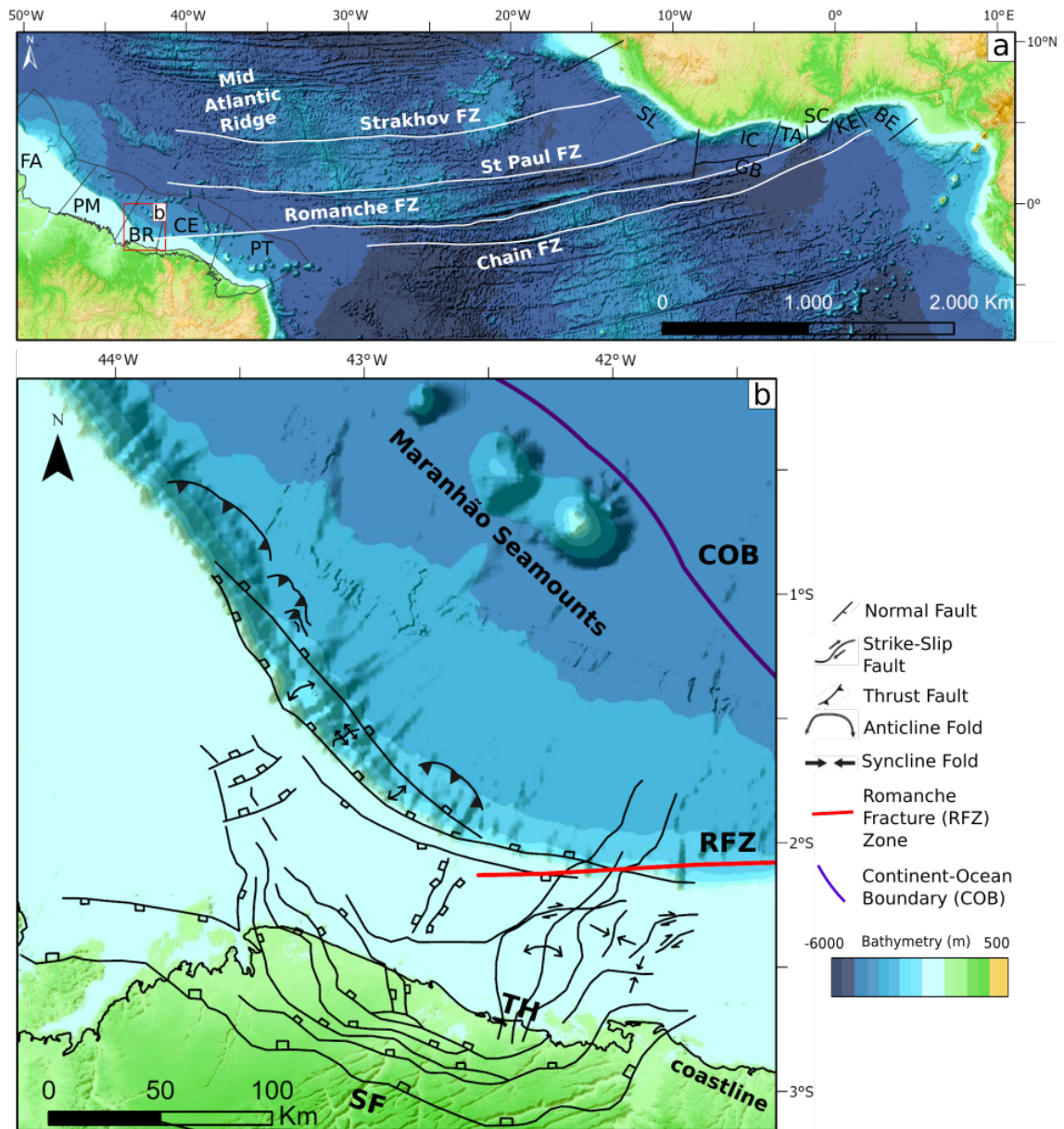


Figure 2.1 Regional map of the Equatorial Atlantic and Conjugate Margins. (a) Bathymetric map evidencing the Mid-Atlantic Ridge, respective oceanic fracture zones (FZ), and BEM-West Africa basins. (b) Simplified geological map of the Barreirinhas Basin, delineating the main structural domains and bathymetry. Basins: BE – Benin; BR – Barreirinhas; CE – Ceará; FA – Foz do Amazonas; GB – Grand Bassam; IC – Ivory Coast; KE – Keta; PM – Pará-Maranhão; PT – Potiguar; SC – Saltpond-Central; SL – Sierra Leone-Liberia; TA – Tano. Structures: SF – Sobradinho Fault; TH – Tutóia High. The bathymetry was extracted from the Nippon Foundation – GEBCO Seabed 2030 project. Structural data compiled from Morrison et al., 2000; Vasconcelos et al., 2004; Veiga et al., 2005; Krueger et al., 2012; Oliveira et al., 2012; Jovane et al., 2016; Maia de Almeida et al., 2020; Montenegro et al., 2020; Oliveira et al., 2020; Tavares et al., 2020).

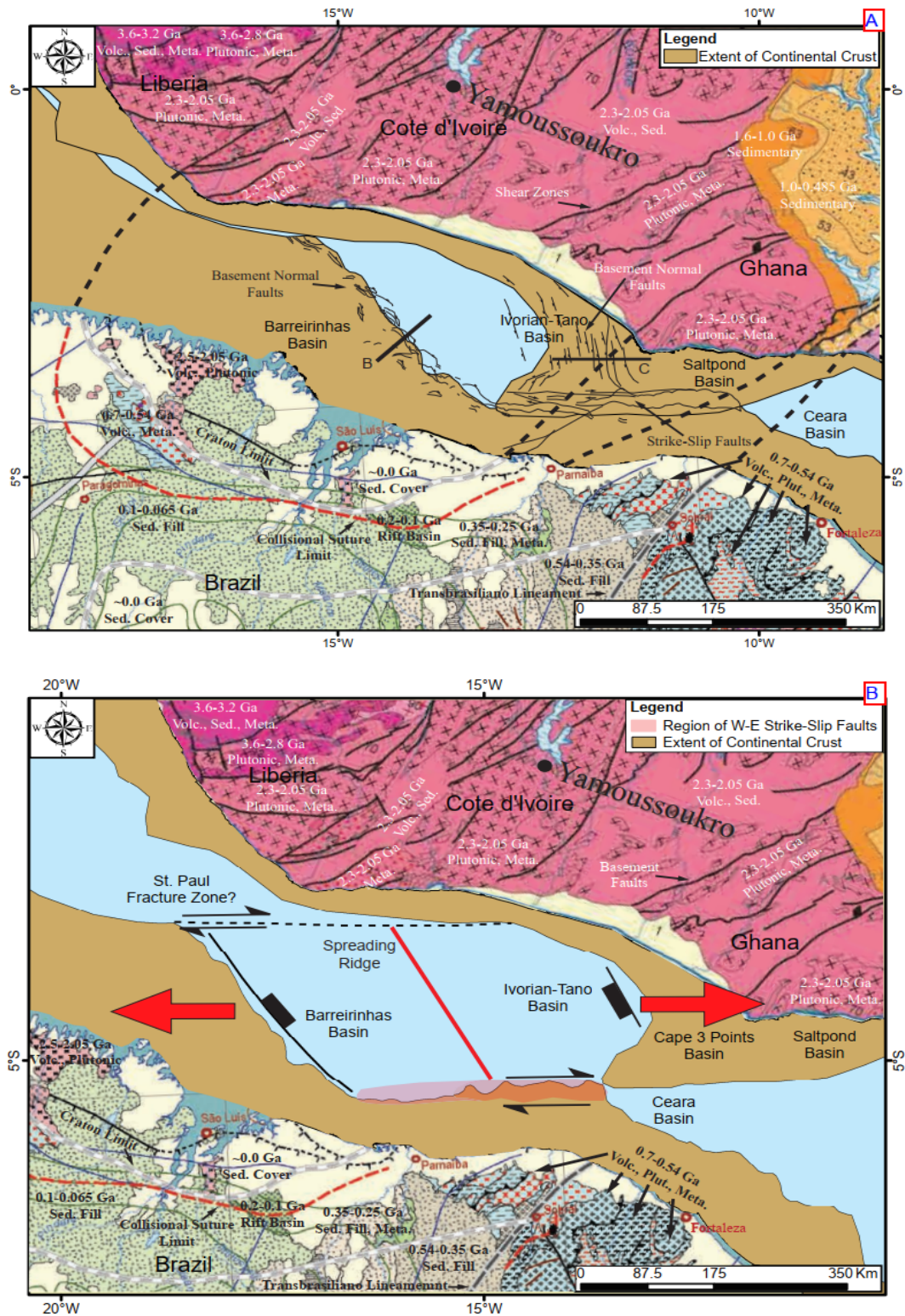


Figure 2.2 Paleogeography and tectonic evolution of the Barreirinhas-Tano and Ceará-Saltpond proto-basins, showing the principal structural, geometric, and tectonic settings. Tectonic plate reconstructions at 111.5 Ma (A) and at 103.3 Ma (B). (Adapted from Antobreh et al., 2009; Krueger, 2012; Dailly et al., 2013; Cordani et al., 2016; Thiéblemont and Chene, 2016; Lunn, 2019).

2.2 Barreirinhas Basin

The Barreirinhas Basin is a sedimentary basin located in northeastern Brazil, inserted in the context of the BEM, between latitude 0° and 3° S, and longitude 42° W and 44° W (Trosdtorf Junior et al., 2007). The area encompasses 46000 km², being 37500 km² offshore and 8500 km² onshore; the sediment thickness reaches 4-6 km (Tavares et al., 2020). According to Mohriak (2003), Trosdtorf Junior et al. (2007), and Júnior et al. (2008), the Barreirinhas Basin is limited in the east by the Tutóia High, which delimits the boundary in relation to the Ceará Basin; in the south, the Sobradinho Fault Zone and Sobradinho Platform define the boundary with the crystalline basement; in the western and northwestern corner there is no clear geological boundary in concern to the Pará-Maranhão Basin, usually the frontier between both basins being arbitrarily established by the 44° W meridian.

As mentioned by Trosdtorf Junior et al. (2007), the Barreirinhas Basin's tectono-sedimentary evolution can be analyzed in the following stages: pre-rift (Paleozoic), rift/sag (Aptian to Albian), and drift (Late Albian to Recent). The South American Platform was first submitted by intense extensional deformation and crustal stretching in the Paleozoic, forming the Parnaíba Basin. This sag basin captured sediments from São Luís Craton and Gurupi Belt from the north. The tectono-stratigraphic evolution of the Barreirinhas Basin began in the Devonian, when crystalline basement structures formed and caught shales and sandstones from the Canindé Group, establishing the pre-rift stage.

The syn-rift stage corresponds to the Pangea breakup, starting on Aptian (125 Ma) and extending till Albian (102 Ma), setting up the conjugate margins of Barreirinhas (Brazil), Côte d'Ivoire (Ivory Coast) and Tano (Ghana) basins (Basile et al., 1993; Soares et al., 2007; Mello et al., 2013; Pellegrini & Ribeiro, 2018) (Figure 2.2). The rift beginning generated stretching and thinning of the lithosphere due to the mechanical subsidence and normal listric faulting arranged in backstepping, with depocenters formed in E to ENE trending rhombic grabens, filled with 4-6 km thick non-marine sediments (Davison et al., 2016; Montenegro et al., 2020).

Rifting process stopped in 112 Ma, forming anoxic salt lagoons in a sag setting (Codó Formation); then, another rift pulse started and kept until 102 Ma, when the BEM and West Africa were completely separated, establishing a breakup discordance (Soares et al., 2007; Antobreh et al., 2009). It was raised an ocean connection amidst the South and Central Atlantic, around 100-90 Ma, demarcating the onset of the drift stage. Trosdtorf

Junior et al. (2007) identified three main depositional sequences within the drift stage, developing in transgressive-regressive cycles: first, Late Albian-Cenomanian prevailing carbonate sedimentation (Caju Group); secondly, the establishment of a passive margin and drowning of the carbonate platform originated Turonian-Oligocene siliciclastic deposition (Humberto de Campos Group). In the Eocene, localized magmatism has intruded on the offshore Barreirinhas Basin (Appendix 34 to 36) (Trosdorf Junior et al., 2007; Lunn, 2019); thirdly, Miocene to recent marine transgression returns to the carbonate deposition (Pirabas Formation), with relative absence of relevant fluvial sediment charging also contributing to the carbonate sedimentation (Alves, 2018). The resultant maximum flooding surface is eroded with the coastal progradation and fluvial drainages, building sandstones, argillites and unconsolidated argillaceous sediments of the Barreiras Formation (Trosdorf Junior et al., 2007).

Transtensional regime in Barreirinhas Basin developed a relatively narrow continental margin of only ~160 km, steep continental slope, and an abrupt transition (~20 km) among continental and oceanic crusts. Low magma production during initial rifting stages, development of negative flower structures, wipeout seismic zones, and rotated blocks are typical of these oblique transform margins (Basile, 2015). In some places of Barreirinhas Basin exist transpression motion, originating positive flower structures and inversion of normal faults (Zalán, 2004). Those features are explained by diachronous subsidence and uplift events due to the transtension and transpression acting in different segments of the conjugate margin (de Lépinay et al., 2016; Lunn, 2019). Also, the BEM does not have the evaporitic transitional sequence of the Aptian and neither salt tectonics (Zalán, 2004). Furthermore, the rifting initiated later than the eastern margin of Brazil (Sztatmari et al., 1987; de Matos, 2000; Pellegrini & Ribeiro, 2018).

Strata deformation at Barreirinhas Basin is controlled due to the oblique-transform continental margin characteristics, in response to different stages of the tectono-stratigraphic evolution and the RFZ influence that acted during all those stages. The RFZ segments the Barreirinhas Basin in two sub-basins (Mesner and Wooldridge, 1964; de Castro and Oliveira, 2019; Montenegro et al., 2020). The first one is situated south of RFZ, in the onshore portion until shallow-waters near the shelf break, in a typical rift pattern. Here, the grabens and horsts formation are controlled owing to high-angle normal listric faults, synthetic, south-dipping. Also, at Albian to Cenomanian (~100 Ma), alterations in plate movement vectors must have acted, promoting transpression of the rifted margin

(Zalán and Warme, 1985; Azevedo, 1987), resulting in an approximately 500 km long and 70 km wide fold and thrust region on BEM-West Africa Conjugate Margin (Davison et al., 2016). This folded zone is characterized by landward-verging and ENE- to NE-trending asymmetric anticlines and thrusts, with minor parasitic asymmetric folds on the long seaward-dipping fold limbs. The second basin is located north of RFZ, from near the shelf break until abyssal deep-waters. This section constitutes a classic passive margin inherited from thermal subsidence, with north-dipping normal faults (de Castro and Oliveira, 2019). In the Cenozoic, systems of normal and thrust faults and gravity tectonics affect all the post-Cretaceous units and current sediments (Trosdorf Junior et al., 2007; Krueger et al., 2012). Series of grabens are filled with thick strata deformed by thrusts and imbricate fans, expressed in Cretaceous drift sequences in periods of relative tectonic quiescence.

The existence of a gravitational gliding system, linked to extensional-compressional domains, have been reported occurring on the deep-waters of Barreirinhas Basin (Zalán, 2011; Krueger et al., 2012; Oliveira et al., 2012). “Gravity gliding is defined as the rigid translation of a body down a slope, with displacement vectors parallel to the detachment plane” (Rowan et al., 2004), resulted of mass movements. Zalán (2009) subdivides gravitational gliding systems in three structural domains and Oliveira et al. (2012) applied this concept on the Barreirinhas Basin (Figure 2.3). The extensional domain is proximal and predominate synthetic listric normal faults, seaward-dipping, in conjunction with minor landward-dipping antithetic planar normal faults. Growth faults are generated due to the listric faults, thickening strata on the flanks and thinning onto the tops of rollover structures. In the transitional or translational domain there are superimposed styles of deformation with both normal and thrust faults originating detached folds and growth anticlines. The compressional domain is a 40 km wide distal zone of imbricate thrusting and folding (Appendix 18, 28, 29, 30, 31, and 33).

All the structural domains have the main faults inherited from underlying basal detachments (Oliveira et al., 2012). These detachments are caused by shales of probably Turonian age (Zalán, 2011). Shales present rheological behavior similar to salt, flowing vertically and laterally due to bulk densities contrasts with the overburden rocks and fluid overpressure (dewatering, hydrocarbon generation) (Oliveira et al., 2008). Also, shale volume and mobility vary according to lithostatic pressure and rates of burial, sedimentary

loading, and overpressure generation (Morley and Guerin, 1996, as cited in Oliveira et al., 2008).

Zalán (2011) and Oliveira et al. (2012) characterized the structural style of the gravitational gliding system as typical thin-skinned tectonics. In this situation, deformation practically does not affect the basement. A basal sole thrust or decollement separates the basement from the sedimentary cover, where the strain is concentrated (Fossen, 2010). Zalán (2009) defined a model of shale-detached gravitational system where gliding occurs along the decollement surface; moderated overpressurized shales are not capable to form diapirs and hence there is no deformation in the gliding allochthonous rocks (Figure 2.3). Wu and Bally (2000) assert that gravitational fold belts associated with shale detachment display asymmetric basinward-vergent imbrication zones and fault-related folds.

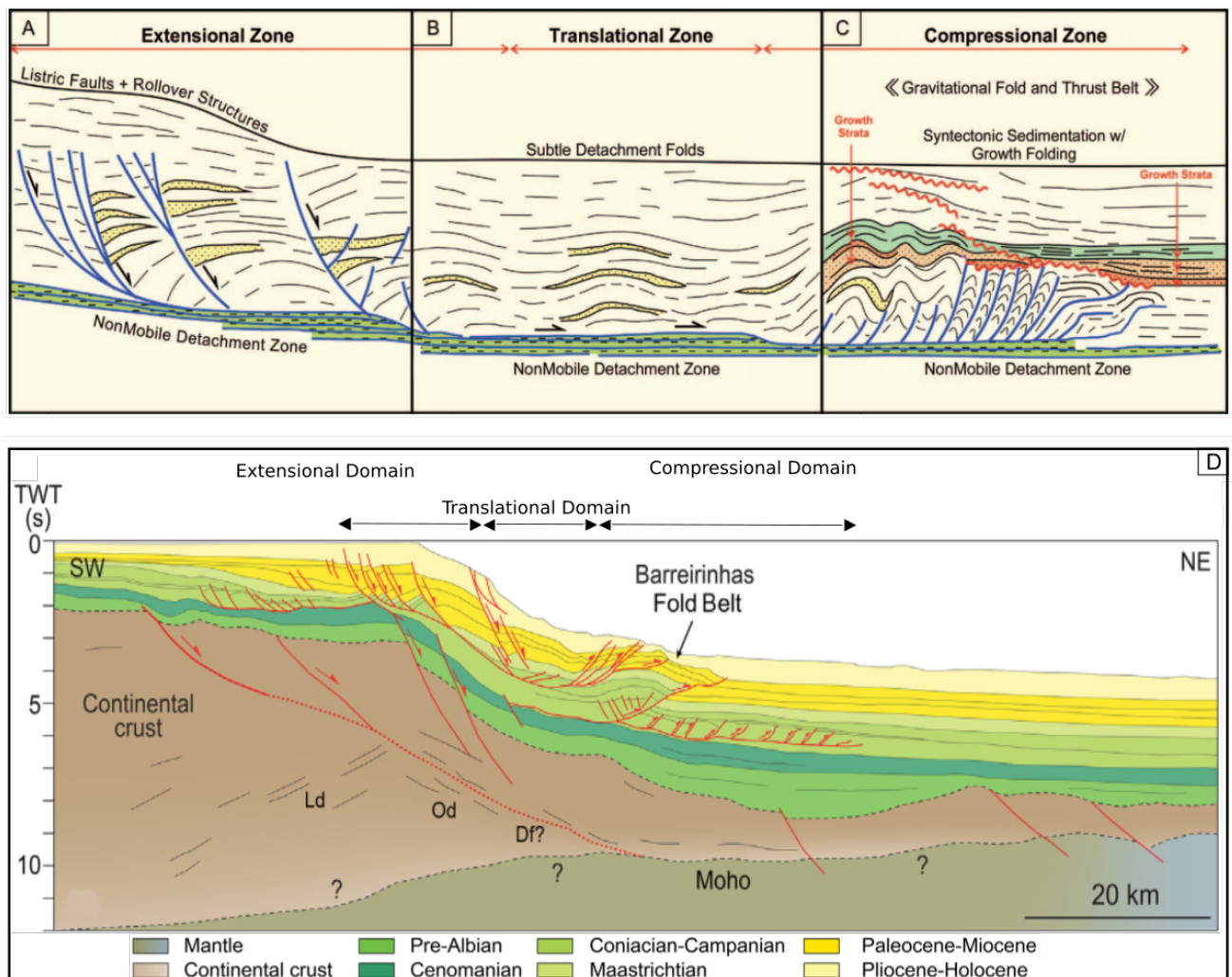


Figure 2.3 Comparison between a shale-dominated tectonic system (A, B, C) with the gravitational gliding system of Barreirinhas Basin (D). The correlated domains show match structures from the model above. Gliding occurs through the three domains related to the detachment zone. Ld and

Od are landward and oceanward dipping basement reflectors, respectively; Df is detachment fault. (Adapted from Zalán, 2009; Krueger et al., 2012; Oliveira et al., 2012; Tamara et al., 2020).

The compressional domain of the gravitational gliding system built a highly complex fold and thrust belt in the region of lower continental slope and continental rise. Conte and Oliva (2021) identified imbricate thrust faults branching upward from the decollement level. Oliveira et al. (2012) revealed the landward migration of depocenters due to the overlapping of the thrusts developed in backstepping sequence, with the pattern of younger thrusts growing in the hanging wall of the older thrusts, although out-of-sequence thrusts are locally observed. This piggy-back manner suggests that the total amount of shortening exceeded the total amount of stretching in the basal layers, whilst in the upper layers the stretching was bigger than shortening. Also, the decollement zone is intrinsically associated with fault-related folding, including the imbricate thrusts, ramp-and-flat thrusts, backthrusts, pop-ups, detachment folds, fault-propagation folds, and fault-bending folds (Zalán, 2005; Conte and Oliva, 2021).

Several explanations have been made to explain the building of the gravitational gliding system in Barreirinhas Basin. Oliveira et al. (2012) applied numerical and physical modeling, confirming the development of faults and folds upon the detachment surface. The authors proposed the combination of sedimentary loading, slope gradient, overpressurized shales, and RFZ tectonic influence as the driving mechanisms of the gravitational gliding system.

Another explanation comes from the South America plate tectonic deformation. The Andes orogenic belt's distant uplift indirectly influenced the sedimentation of Barreirinhas Basin, due to the increase in sedimentation rate and gravitational processes (Krueger et al., 2012). This is explained by the deflection of the course of the Amazon River. Previously, the Amazon has debouched in the Pacific Ocean. However, the Andes uplift in the western South America diverted the river flow, passing to runoff toward the Atlantic Ocean. Several drainages associated with the Amazon also deviated, drastically elevating the sediment charging on the BEM (Alves, 2018). In areas with thicker sedimentary stacking due to the increased sedimentary rate, such as the Amazon Cone, the additional weight of the sedimentary pile causes loading, depressing the lithosphere in response to flexural subsidence. In the Barreirinhas Basin, the huge increment in sedimentary rate is expressed mainly by the Travosas Formation. The combination of steep continental slope with high sedimentation rate creates instabilities. Hence, the sediment stacking weight

deformed the continental rise, contributing to the gravitational gliding, decollements, slides, slumps, and mega-slumps.

2.3 Stratigraphy

The Barreirinhas Basin's stratigraphy (see stratigraphic chart in the Figure 2.4) is highlighted in the following units:

2.3.1 Crystalline Basement

Pre-Cambrian unit formed by granitoids, meta-volcanics and schists from Archean São Luís Craton, and gneisses, granitoids, meta-volcanics and meta-sedimentary rocks of Neoproterozoic Gurupi Belt integrates the basement (Tamara et al., 2020).

2.3.2 Canindé Group

Constituted by sandstones and shales from Parnaíba Basin, formed in the pre-rift stage during Devonian, fed by sediments sourced from cratonic areas and adjacent orogens – São Luís Craton and Gurupi Belt, respectively. The Canindé Group encompasses transgressive/regressive sequences of Itaim, Pimenteiras and Cabeças formations (Mohriak, 2003; Trosdorf Junior et al., 2007; Júnior et al., 2008, 2011).

2.3.3 Innominate

An innominate Aptian sedimentary package of roughly 1200 m thick represents the initial stage of rifting, with classic siliciclastic deposition of conglomerates, sandstones, and shales of alluvial, fluvial, and lacustrine settings (Soares et al., 2007; Trosdorf Junior et al., 2007).

2.3.4 Codó Formation

In the final of Aptian (112 Ma), a brief rifting interruption makes a sag with marine incursion, creating shallow seas and anoxic salt lagoons, forming evaporites, calcilutites, and shales (Soares et al., 2007; Trosdorf Junior et al., 2007).

2.3.5 Canárias Group

Composed of shales and sandstones from deltaic to marine environments at 112-100 Ma, in Albian (Corrêa & Truckenbrodt, 1988; Mohriak, 2003; Júnior et al., 2008). The

Canárias Group is subdivided into the following formations: Arpoador, Bom Gosto, Tutóia, Barro Duro, Preguiças, and Bonfim. On the top of Canárias Group there's a breakup discordance, delimiting the separation between western Africa and the BEM (Soares et al., 2007; Trosdorf Junior et al., 2007; Krueger et al., 2012).

Arpoador Formation: represented by progradation of dark gray shales at the upper continental slope, toward the lower continental slope.

Bom Gosto Formation: composed of coarse-grained sandstones and gray sandstones from turbiditic fans at the continental slope.

Tutóia Formation: constituted by sandstones and dark gray shales formed in pro-delta.

Barro Duro Formation: composed of medium-grained sandstones and gray sandstones from delta fans.

Preguiças Formation: deep-waters in continental slope progressively become shallower till form a carbonate platform, depositing calcilutites, marls and shales.

Bonfim Formation: establishment of high-energy carbonate platform generated bioclastic calcarenites and oncolitic calcarenites.

2.3.6 Caju Group

After the separation between Africa and the BEM, it was raised an ocean connection amidst the South and Central Atlantic, demarcating the onset of the drift stage (Soares et al., 2007; Trosdorf Junior et al., 2007; Júnior et al., 2011). From Late Albian to Turonian (~100-90 Ma), carbonates of the Caju Group were lithified in neritic environments, alternating conditions of low and high energy. The Caju Group is branched in the Preguiças, Bonfim, and Peria formations.

Preguiças Formation: continuity of the carbonate platform, depositing calcilutites, marls, and shales.

Bonfim Formation: continuity of high energy carbonate platform, forming bioclastic calcarenites and oncolitic calcarenites.

Peria Formation: fluvial-deltaic to pro-delta environment built carbonates and sandstones.

2.3.7 Humberto de Campos Group

The continuity of drift stage is marked by Humberto de Campos Group, extending from

Turonian to Oligocene (90-22 Ma). It is characterized by thick successions of shales and turbidites, deposited in passive margin forcefully influenced by mass movements. Siliciclastics sediments prograde from the continental shelf to steep continental slope and abyssal zone. The Humberto de Campos Group is subdivided in the Areinhas, Ilha de Santana and Travosas formations (Mohriak, 2003; Soares et al., 2007; Júnior et al., 2008; Zalán, 2015; Pellegrini & Ribeiro, 2018).

Areinhas Formation: high-energy deltaic to shallow shelf environment deposited coarse-grained sandstones.

Ilha de Santana Formation: carbonates lithified in high-energy shallow platform.

Travosas Formation: progradation of shales and sandstones at upper slope until deep-waters, forming huge packages of turbidites developed due to high sedimentation rates, slope instabilities and gravity tectonics.

2.3.8 Pirabas Formation

At the top of the Humberto de Campos Group, carbonates have been deposited in transgressive carbonate platforms at Miocene to recent (Mesner and Wooldridge, 1964; Soares et al., 2007; Mohriak, 2003).

2.3.9 Barreiras Formation

Progradation of depositional coastal systems and fluvial drainages built sandstones, argillites, and unconsolidated argillaceous sediments (Soares et al., 2007; Trosdorf Junior et al., 2007; Júnior et al., 2011).

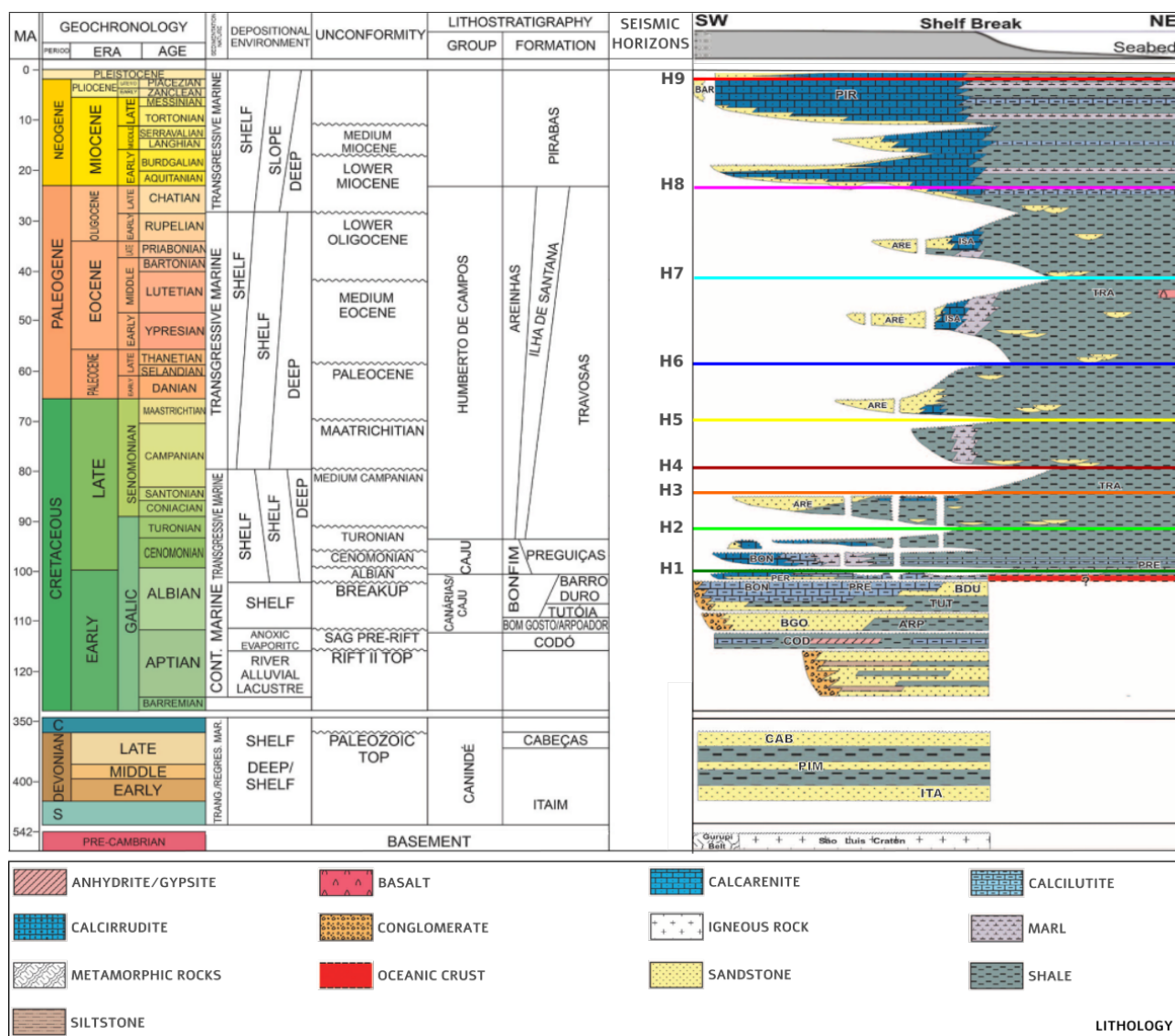


Figure 2.4 Stratigraphic chart and determined seismic horizons (H1-H9) of the Barreirinhas Basin. (Modified from Trosdorf Junior et al., 2007, and Oliveira et al., 2012).

2.4 Petroleum Systems

The Barreirinhas Basin petroleum systems comprise small onshore production, localized stratigraphically on the Paleozoic pre-rift sequence (Azevedo, 1987). Currently, new efforts are being made to attain knowledge of the probabilities of finding oil and gas reserves. On the offshore portion, some clues include (Noguti, 1964; Pellegrini & Ribeiro, 2018; Pereira et al., 2018): great sedimentation rates and relief escarpment that generate mass movements with thick turbiditic layers that can act as good reservoir rocks; extensional faults on shelf break and upper slope, jointly with extensive thrusts on the lower slope to the abyssal plain, possibly acting as fluid conduits and traps; black shales (mainly from Aptian to Turonian) enriched in organic matter, formed in the global event of

ocean anoxia, when basins worldwide record petroleum systems; drilling in deep-water regions, allied with geochemical surveys, that indicated the presence of light hydrocarbons.

In previous studies (Azevedo, 1987; Ferreira, 2013; Davison et al., 2016; Pellegrini & Ribeiro, 2018; Pereira et al., 2018), the petroleum system elements recorded are summarized: source rocks in shales of Canindé Group (Devonian, pre-rift sequence), Codó Formation (Aptian, sag sequence), Preguiças Formation (Cenomanian/Turonian, drift sequence), and Travosas Formation (Turonian, drift sequence). The organic matter content range from 3% to 24% in shales of Codó Formation, with thickness greater than 80 m (Ferreira, 2013); reservoir rocks in sandstones of Bom Gosto, Tutóia and Barro Duro formations (Canárias Group, Albian, syn-rift sequence), and sandy turbidites of Travosas Formation (Turonian to Oligocene, drift sequence), where, in all units, the porosity can be greater than 20%. Additionally, it is believed that the Travosas Formation contains both source and reservoir rocks, with pinch-out depositional traps and muddy to silty sealing rocks. Pellegrini & Ribeiro (2018) argue that those reservoir sandstones and turbidites are disposed of in thin layers on the continental shelf, in progradant clinoforms with internal configuration varying from oblique tangential to sigmoidal oblique. On the shelf break, the sandstones and turbidites are deposited in rollover anticlines associated to listric faults. Also, they can be found in deep-waters, forming large bodies related to mass movements. Pellegrini & Ribeiro (2018) suggested that turbiditic reservoirs accumulated hydrocarbons from Codó, Preguiças and Travosas formations.

Comparatively, the main petroleum systems on the conjugate Ivory Coast Basin are constituted of Cretaceous reservoir and source rocks (Figure 2.5). The syn-rift stage began in the Aptian (125 Ma) and at the Middle Aptian claystones source rocks were deposited within continental, lacustrine, and marginal marine settings (Chierici, 1996; Morrison et al., 2000; Mello et al., 2013). Another pulse of rifting started and deposited black laminated shales as source rocks and conglomeratic to coarse-grained sandstones as reservoirs (i.e., Foxtrot field), in fluvial, fluvio-deltaic, to lacustrine environments from Lower to Middle Albian (Mattick, 1982; MacGregor et al., 2003). On the Upper Albian, Espoir and Lion oil fields register black shales, sandy turbidites, and tar sands formed in deltaic and marine transgressive paleoenvironments (Morrison et al., 2000; Brownfield and Charpentier, 2006). The Late Albian (102 Ma) is marked by the final of syn-rift stage and hence complete separation of South America-West Africa conjugate margins (Blarez and

Masclé, 1988; Basile et al., 1993; Soares et al., 2007). Cenomanian-Turonian (around 100-90 Ma) are characterized by seafloor spreading and formation of a mid-oceanic ridge, assembling the Equatorial Atlantic (Blarez and Masclé, 1988; Trosdorf Junior et al., 2007; Scarselli et al., 2018). The Ivory Coast Basin underwent in the post transform stage, with thermal subsidence developing a passive margin, generating oblique-slip faults with an en echelon folds at their upper tips (Morrison et al., 2000; Kelly and Doust, 2016; Scarselli et al., 2018). Moreover, Cenomanian-Turonian times record the global event of anoxia, depositing organic-rich black shales (Brownfield and Charpentier, 2006; Kelly and Doust, 2016). Cenomanian reservoirs (Panthere and Gazelle fields) corresponds to fluvial conglomerates and sandstones (Morrison et al., 2000; Fea et al., 2022). Coarse-grained sandstones form Turonian reservoirs (Paon Field) (Mattick, 1982). On the Coniacian, there are source and reservoir rocks in marine shales and turbidites (Belier oil field), respectively, associated with submarine fans and channels (Brownfield and Charpentier, 2006; Jianping et al., 2010). Through Campanian to Maastrichtian have formed sandy reservoirs (Ibex and Lion fields) on the continental shelf (Morrison et al., 2000; Adeoye et al., 2020).

The tectono-stratigraphic evolution of the conjugate Tano Basin is strongly correlated with the Ivory Coast Basin, as both has been considered sub-basins of the Deep Ivorian Basin. In the Tano Basin, the Albian is characterized by important tectonic activity, with ENE–WSW trending sheared margin forming the Ivory-Ghana Marginal Ridge (Figure 2.5), probably starting in Middle Albian (Basile et al., 1993, 2005; Antobreh et al. 2009). Marginal ridges represent basement highs, parallel to the transform fault on continental-ocean boundaries, formed by the strike-slip motion along the mid-ocean ridge (Basile, 2015; de Lépinay et al., 2016). The proximal region is affected by syn-rift en échelon fault blocks that spreads towards the northern depocenter, with NW–SE-trending fabric controlling structural highs within a sequence of transtensional horsetail extensional faults (Tari, 2006; Antobreh et al. 2009). The formed grabens captured sediments of lakes, rivers, deltas, and shallow marine environments, forming shales as source rocks and sandstones as reservoir rocks, very often been interbedded (Tano field) (MacGregor et al., 2003; Tari, 2006; Tetteh, 2016; Gyasi, 2017). Conforming Dailly et al. (2013), at the Cenomanian, after the separation from South America, a large transpressional ridge (South Dixcove Ridge) bounded the northern transtensional depocenter, resulting in the creation of a south depocenter dominated by transpressional fold and thrust belt. Post-rift ponded deep-water clastic sequences coming from the Ghanian shelf accumulated north of South Dixcove

Ridge, forming extensive petroleum plays from Late Cretaceous to Paleogene. The global event of anoxia contributed to the deposition of organic-rich black shales from Cenomanian to Turonian (Brownfield and Charpentier, 2006; Tari, 2006; Bempong et al., 2019). In the same period, sandstone reservoirs were found, including the giant Jubilee field, formed by stacking of turbidites filling lower-slope amalgamated channels and fan packages systems (Sills and Agyapong, 2012; Dailly et al., 2013; Tetteh, 2016). From Coniacian to Maastrichtian, several deep-waters source and reservoir rocks were found within slope turbidites, submarine fan complexes, and infilling channels, as recognized in the Santonian (Tweneboa, Enyenra, and Ntomme) and Campanian (Teak and Odum) fields (Basile et al., 2005; Brownfield and Charpentier, 2006; Tari, 2006; Tetteh, 2016; Gyasi, 2017).

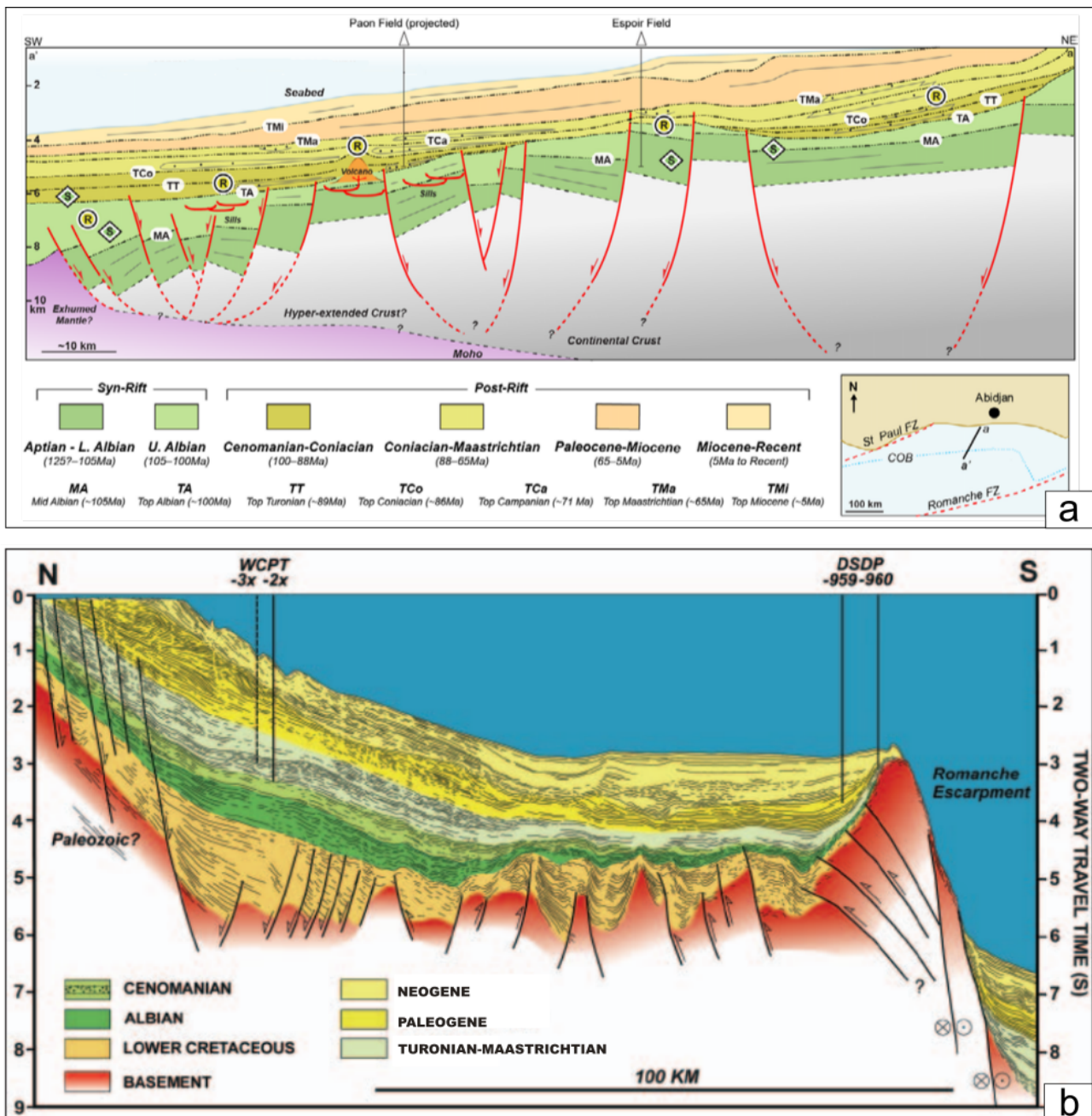


Figure 2.5 Regional seismic section of the African conjugate margin. (a) Section of proximal Ivory Coast Basin showing faulted blocks, stratigraphy of syn-rift and post-rift sequences, source rocks (green lozenge), reservoirs (yellow circles), and locations of the Espoir and Paon fields. (b) Seismic profile through the Ivory Coast-Ghana Ridge reflecting the stratigraphy, normal fault blocks, and thrusts that separate the northern and southern sections of the Tano Basin. (Modified from Brownfield and Charpentier, 2006; Tari, 2006; Scarselli et al., 2018)

3. MATERIALS AND METHODS

3.1 Database

The seismic dataset and the well logs were provided by ANP (Agência Nacional do Petróleo – Brazilian Oil, Gas, and Biofuel Agency) through the Project Barreirinhas Basin Crustal Evolution – Northeast Brazilian Equatorial Margin (UFRN/PETROBRAS/CENPES/PDEP/GEOTEC – 2018/00087-2). The multi-channel seismic profiles were acquired in 2000 year, using the conventional seismic reflection method. The seismic profiles were obtained throughout the Barreirinhas Basin offshore zone (Figure 3.1) as a product of a main grid of 2D dip and strike lines spaced by 4 km, transverse and longitudinal to the coastline, respectively, with minor oblique 2D grids, totalizing 45.000 km². Data processing was taken in Post-stack time migration (PSTM) with images shown in two-way travel time (TWT), in milliseconds, and reversed polarity (SEG convention) with red reflectors attributed to positive polarity and blue reflectors corresponding to negative polarity.

Conventional seismic operates using low frequencies, imaging rough rugosity areas in deep-waters, and it is largely applied in petroleum industry. Multi-channel seismic uses multiple source-receiver pairs to image the same point; each shot records several offsets, generating different midpoints. The imaging of these distinct mid-points are combined into a common mid-point (CMP), gathering seismic traces stacked together to build one trace for each common mid-point. In PSTM, the stacking is assumed to be zero-offset. This stacking optimizes the signal-to-noise ratio through the signal amplification and filtering of random and incoherent noise.

Petrel E&P Software Platform was utilized to seismic interpretation, based on the concepts of seismic stratigraphy established by Mitchum et al. (1977), Allen (1982), and Catuneanu (2006). Measurements are taken in time, in milliseconds (ms), for vertical strata, and in metres (m) for horizontal scale. Seismic-to-well tie was used for calibration of the seismic interpretation, correlating subsurface measurements obtained at a wellbore, measured in depth, with seismic data measured in time. Sonic logs were utilized to convert data from distance to time. Seven wells were provided by ANP, five located in the continental shelf and two in the deep basin. The well's information of continental shelf were extrapolated to deep-waters. Nine chronostratigraphic seismic horizons (Figure 2.4) were established through biostratigraphy and seismic-to-well tie, analyzing seismic facies

and patterns of reflectors termination, amplitude, geometry, continuity, thickness, and frequency. Additionally, seismic attributes (RMS Amplitude, instantaneous amplitude, instantaneous frequency, and chaos) were applied via the “Volume Attributes” command in the seismic interpretation tab of Petrel Software. RMS Amplitude and instantaneous amplitude enhanced amplitude anomalies caused by BSRs, GHSZs, free gas zones, gas pockets, and HRDZs. Instantaneous frequency optimized the visualization of low-frequencies in free gas zones, GHSZs, gas chimneys, and faults. Chaos attribute improved recognition of chaotic facies of fluid migration pathways, faults, and gas chimneys.

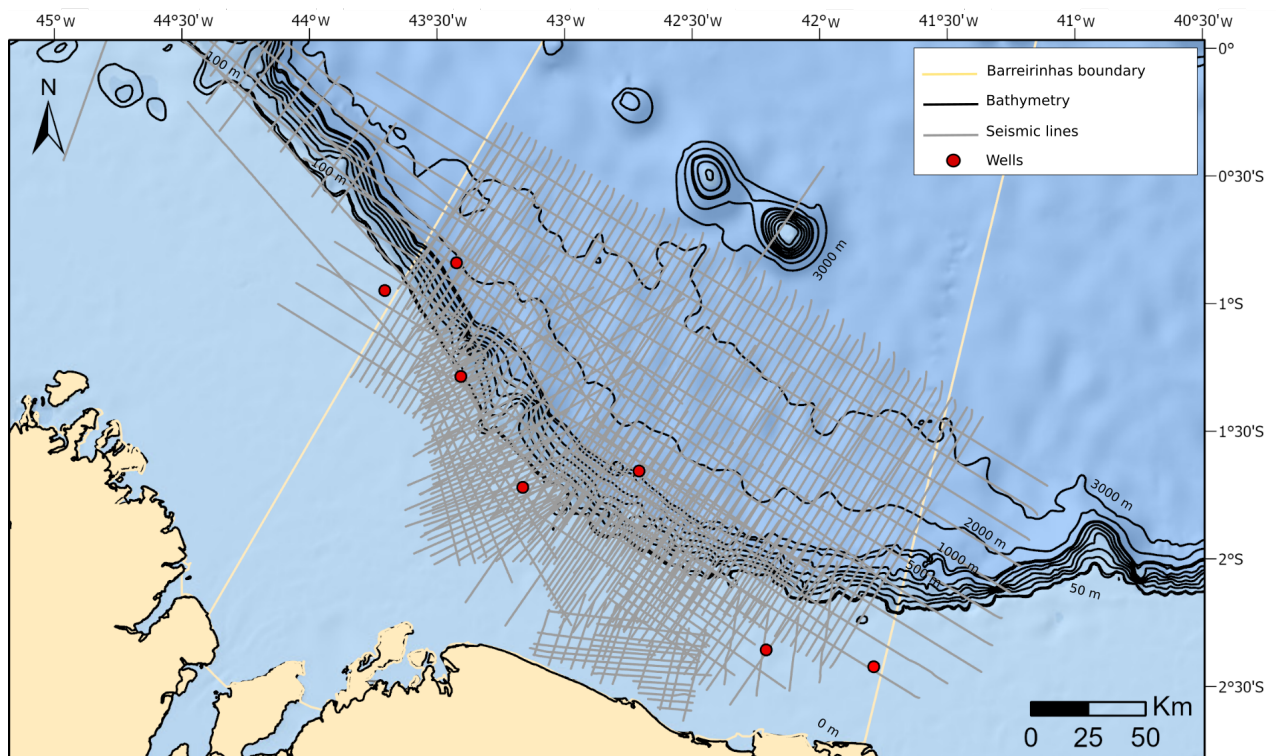


Figure 3.1 Map of 2D seismic lines and wells of the Barreirinhas Basin. Structural features can be accessed in Figure 2.1. The wells were provided by ANP (Agência Nacional do Petróleo – Brazilian Oil, Gas, and Biofuel Agency), and the bathymetry was extracted from CPRM (Brazilian Geological Survey) through the works of Ladeira Neto and Roza (2013) and Becker et al. (2009). Uninterpreted seismic sections are present in the Appendix.

3.2 Seismic Reflection Method

The seismic methods are based on the emission and propagation of seismic waves through materials. Seismic is applied in subsurface indirect investigation in geoscience, imaging a determinate terrain via reflected acoustic signals. According to Selley et al.

(2005) and Catuneanu (2006), seismic reflection is the method most commonly utilized in the exploration of hydrocarbons worldwide.

In a seismic survey, a grid of linear profiles is delimited on target areas, resulting in a bidimensional configuration of seismic lines (two-way travel time vs. horizontal distance). The basic operational principle consists of seismic waves emitted by a source, transmitted through material means (rocks and sediments, called reflectors), and reflected until being captured by seismic receivers – geophones on land surveys and hydrophones in aqueous bodies. The distance between the pair source-receiver is known as an offset; Two-Way Travel Time (TWT) is the designation given for the elapsed time from the emitting source to the seismic receivers and returned signal. Through the TWT it is obtained the reflectors depth; seismic trace is the denomination for the elapsed time from the source-receiver pair during the electric pulse trajectory. Continuously repeating the acquisition process, it established the images of local configurations, as seen in the Figure 3.2, that illustrate a marine seismic survey and the aforementioned concepts.

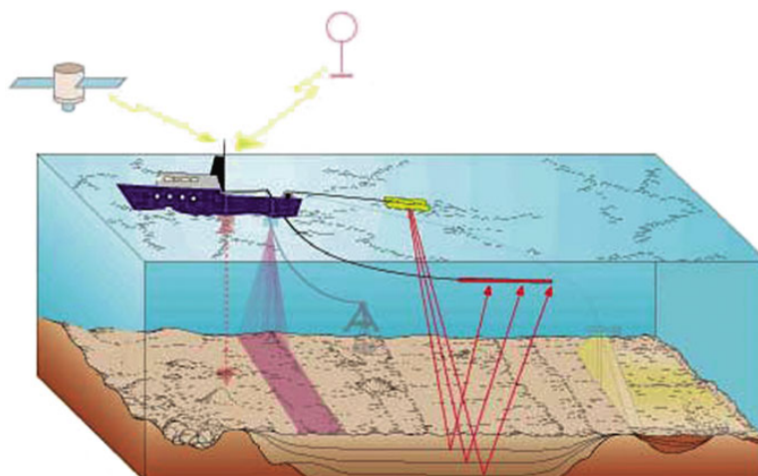


Figure 3.2 Scheme of a marine seismic survey and representation of seismic sources, receivers, reflections, offsets, and the sea bottom. (Extracted from Mondol, 2010)

The imaging generated by the seismic method it is originated due to the interaction of acoustic waves with the physical properties of the material means. Firstly, the electric pulse emitted from the seismic source has the geometry and wavefront affected by the wave polarity (direction of the main deflection), frequency (number of oscillations per second), amplitude (related to the wave deflection and energy of the source), and propagation velocity. Except for the frequency, all the aforementioned parameters vary according to the substrate heterogeneities. These contrasts are caused due to the acoustic impedance, defined by the propagation velocity multiplied by the material mean

density, representing the strength of the material against the wave propagation. The transmitted pulses reflection occurs due to the differences in porosity, cementation, clay content, compaction, and fluid saturation of the medium (Selley et al., 2005; Catuneanu, 2006). The generated impedance contrast shows strata boundaries, discontinuities, faults, folds, and anyone appreciated geometric variation; the larger the medium acoustic impedance discrepancy, the greater will be the reflected energy, that is, the imaging will present a bigger amplitude of the signal. For example, the crystalline basement – higher amplitude – is easily evidenced against the supracrustal rocks. According to Veeken & Moerkerken (2013), the capitation of a seismic reflection directly depends on the impedance contrast, expressed by the reflection coefficient “R” in the function of velocity V and density ρ , both related to changes in wave propagation in different material means. The mathematical expression is:

$$R = (\rho_2 V_2 - \rho_1 V_1) / (\rho_2 V_2 + \rho_1 V_1)$$

The P waves (longitudinal primary waves) and S waves (transverse secondary waves) are the most important waves acting in the seismic method. The propagation velocity of seismic waves is proportional to the elastic properties of the medium. As the wavefront advances throughout an object, the wave pulse undergoes pressure changes due to the force exerted upon the object. In an aqueous medium, the velocity is influenced by temperature, pressure, salinity, and fluid density. Generally, the average speed of sound in water is 1500 m/s, but varying with some physical-chemical parameters. According to IHO (2005), a 1°C variation in water temperature achieves a variation approximately of 4,5 m/s in the propagation of speed of sound; fluctuation of 1 ‰ in water salinity produces a rate of variation in speed of sound of approximately 1,3 m/s; for each 100 meters water depth (about 10 ATM pressure), the rate of variation of sound velocity is 1,6 m/s. As denoted by this data, these physical-chemical parameters have considerable influence on the measurement of velocity on oceans. It must be considered that the propagation of sound velocity is affected by: temperature, which has a variable range according to the latitude, season and daily hour; the great thermohaline circulation conveyor belt created by temperature and salinity contrasts of ocean currents; canyons and seamounts that usually deflect and accelerate the ocean currents; commonly occurrence of stratified waters, indicating that different depths show contrasting values of temperature and salinity – meromixis. Nevertheless, limnology recognizes the existence of seasonal mixtures of stratified waters during a year. It could be a single one, double or many phases of mixing,

respectively known as monomictic, dimictic and polymictic water body (Renaut and Gierlowski-Kordesch, 2010); with respect to rocks and sediments, the sound velocity is changed by the porosity, cementation, fluid type and content, depth, and discontinuities.

On the seismic scale is used the time domain (TWT), normally in seconds, to make measurements of strata thickness through the formula $c = 2 \times Z/\Delta t$, where c is the sound velocity in the medium, Z is the depth, and Δt its the time variation. With respect to the vertical scale, as previously observed, many factors are can alter the velocity, hence the convenience of using time units as a linear measure. In relation to the horizontal scale, this is dictated by the sources and receivers arrangement and by the vessel velocity.

The seismic resolution is known as the object's imaging rank. The smaller the identified object, the higher the resolution and the detail of the generated image will be. According to Bjørlykke (2010), the vertical resolution only separates two reflectors on contact if each one has a minimum thickness of $\lambda/4$ (a quarter of the wavelength). By the wave motion equation, $\lambda = c/f$, where λ is the wavelength, c is the velocity, and f the frequency, it is observed that higher vertical resolution depends of higher frequencies, whereas smaller vertical resolutions needs of lower frequencies; already, the horizontal resolution is ideal for determination of seismic reflectors discontinuities (Severiano Ribeiro, 2001). As mentioned by Bjørlykke (2010), reflectors are imaged in horizontal resolution when they are within the Fresnel zone. Otherwise, they cannot be detected by the seismic waves. This zone is dependent on the range and frequency, where the wavefront interferes constructively and is detected as a single signal. On a reflection plane and with transducers both emitting and receiving, the Fresnel zone has circular geometry and is defined by the following formula:

$$R_f = \sqrt{\frac{\lambda Z}{2}}$$

where R_f is the Fresnel's zone radius, λ is the wavelength, and Z is the reflector depth. As the horizontal resolution is directly influenced by the frequency f_c and velocity V , the formula can be re-written as follows:

$$R_f = \sqrt{\frac{VZ}{2f_c}}$$

Conventional seismic is largely utilized in the petroleum industry due to penetration on the bottom rugosity, using high energy and frequencies lower than 100 Hz. Airguns,

arrangements of compressed air cannons, are the most adopted equipment in the petroleum industry, followed by sparkers (Souza & Tessler, 2006). Airguns trigger airshots in the water; the compression and propagation of waves are responsible for signal generation. The shots are blasted at the same point, generating clearer signals. Usually, it uses frequencies of about 60 Hz, penetrating 4 to 5 km below the seafloor. More sophisticated airguns reach 300-400 Hz frequencies, imaging until 700 km. Some disadvantages of this method include: inefficiency in operating in deep-waters, low control of signal direction, maintenance and operation complexity, and disturbance of marine life.

3.3 Seismic Interpretation

Interpretation of seismic profiles is an integrate recognition and study of lithologies, morphostructures, discontinuities, geometry, and fluid content of surface/subsurface rocks. Its results are directly applied in research of regional and local geology, basin analysis, tectonics and structural modeling, petroleum systems, mineral resources surveys, etc. The main parameters of seismic interpretation (Mondol, 2010) are summarized as: 1) reflection amplitudes related to the impedance contrast within layers. The higher the reflector impedance, the stronger the reflection generated; 2) reflectors spacing, as the measurable distance between two layers – strata thickness – in distance unit or TWT; 3) propagation velocity, associated with the porosity, density, fluid type and content of a rock or sediment; 4) reflectors continuity, in response to the depositional environment and energy variation of transport agents; 5) configuration, in the function of reflectors geometry, indicative of systems tracts, erosion and tectonics; 6) instantaneous phase, directly related to the seismic traces; even more, Mondol (2010) correlates these seismic interpretation parameters to four main systematic seismic analyses: structural, attributes, seismofacies, and sequences. Each one of them is briefly summarized in the following paragraphs.

The seismic structural analysis diagnoses the occurrence of faults, folds, lineaments, deep crustal structure, low-velocity zones, Moho discontinuity and anyone elements studied by structural geology and geotectonic. Faults are characterized by loss of amplitude signal. Scarps, offsets and dislocations are more easily identifiable in the fault delineation. These elements are set to support the creation of polygons and modelling for qualitative and quantitative studies of kinematics, tectonics, fluid migration, reservoirs, etc.

Seismic attributes are geologic, geometric and physical characteristics of imaged rocks, such as amplitude, polarity, instantaneous phase, continuity, dip, velocity, frequency,

density, permeability, porosity, thermal conductivity, etc. The aim of seismic attributes analysis is the construction of digital models that facilitate visualization of sedimentary sequences, fluid migration, reservoir production, kriging, etc. Using the advantage of big data statistic, complex 3D or 4D geological models are created through advanced softwares.

With the development of the seismic method, relating it with the big area of stratigraphy, it was established the seismostratigraphy or seismic stratigraphy (Mitchum et al., 1977; Catuneanu, 2006). It considers the external geometry as seen in seismic lines, to deduce about the depositional systems. A seismic profile is subdivided into seismic units according to the temporal scale. This is correlated to a depositional sequence, defined by Mitchum (1977) and Bjørlykke (2010) as a stratigraphic unit composed of a succession of strata genetically correlated, bounded at top and base by unconformities or correlative conformities. Such boundaries are indicative of changes in the sedimentation process. The stratigraphic sequences are identifiable in the seismic by the reflector terminations (Figure 3.3). The baselap is generated by gradual sedimentation overlying a layer. If the strata prograde into the basin, their terminations are characterized by downlaps. In contrast, a termination against an inclined surface or producing horizontal terminations is called onlap; toplap is tangential terminations of strata at the top. If forms a pronounced erosive surface yields an erosional toplap; abrupt terminations forming erosive discordances are erosional truncations.

The seismic facies analysis explores the approach of seismic stratigraphy, determining reflection patterns through appreciation of the amplitude, geometry, continuity, and thickness of the reflectors. The seismic facies have a parallel in relation to the stratigraphic bedding, directly inherited by the lithology, energy of transport, and paleoenvironmental reconstruction (see the configurations of Figure 3.3). Transparent reflectors indicate homogeneous layers (*i.e.*, evaporites, pelites). Chaotic reflection can be found in convolute bedding, mass movements, igneous rocks, gassy sediments, and where else signal degradation occurs or bottom rugosities. Parallel, undulated, or sigmoidal reflectors are associated with environment energy, sedimentary supply, flow competence, etc.

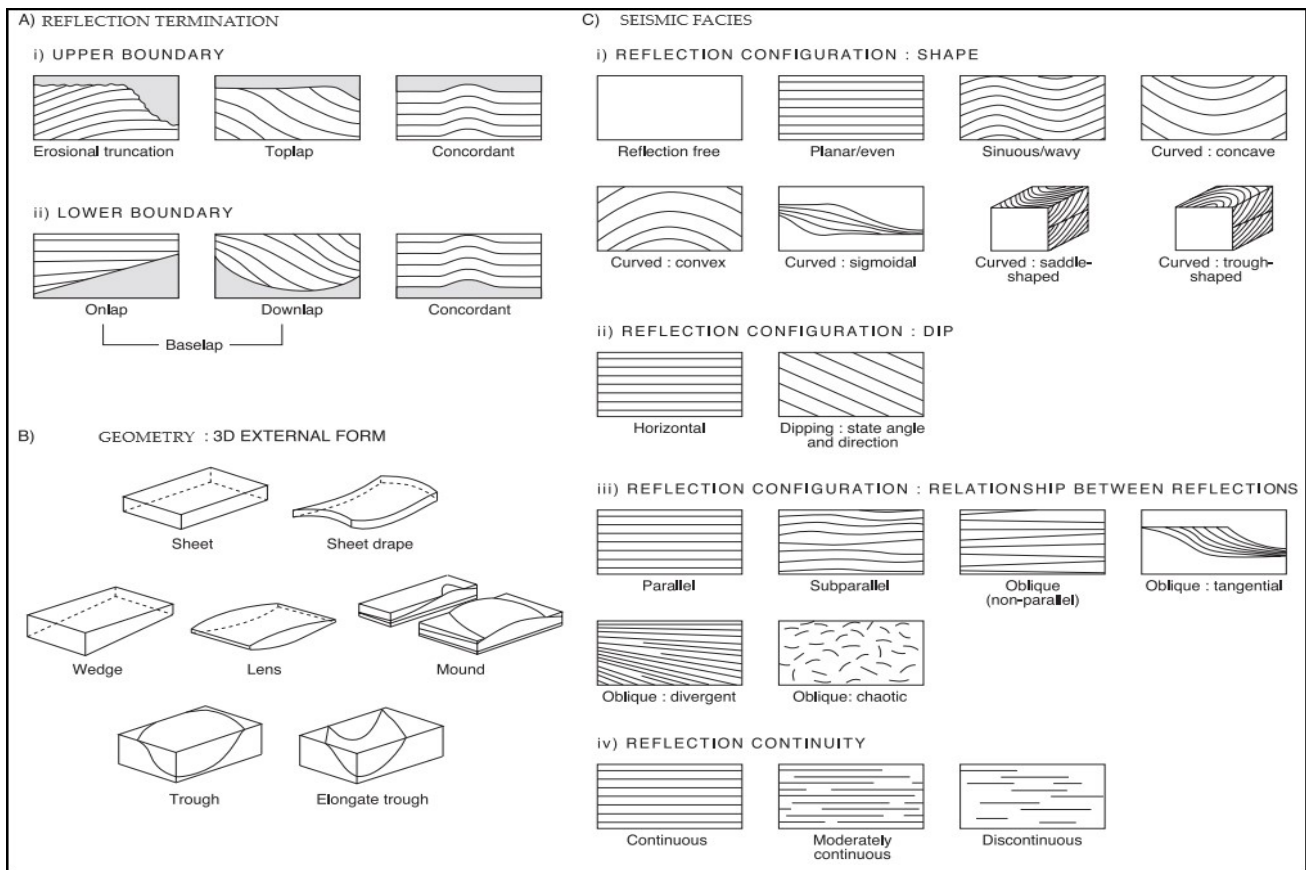


Figure 3.3 Seismic patterns of reflectors configuration, termination, geometry, facies, and continuity. (Modified from Campbell, 1967; Mitchum et al., 1977; Allen, 1982; Neal, 2004)

A seismic profile study is applied to interpret the sedimentary basin fill through the seismic sequences analysis, due to the correlation among sedimentary rate, subsidence rate, and environmental energy (Bjørlykke, 2010). This analysis is correspondent to sequence stratigraphy. For Catuneanu (2006), sequence stratigraphy is a modern method of stratigraphic analysis developed through the integration of multidisciplinary methods (sedimentology, facies analysis, geomorphology, geophysics, absolute and relative dating, basin analysis), focusing on stratal stacking pattern and surfaces that mark changes or breaks in sedimentation style. These surfaces – seismic horizons – include unconformities, correlative conformities, maximum regressive and maximum flooding surfaces that designate sedimentation and tectonic regime changes, both in a regional context and in interrelations between depositional systems and architectural elements. Thereby, sequence stratigraphy has a more robust approach to how stratigraphic units, system tracts, and sedimentary deposits correlate in time and space.

In a sedimentary basin, sedimentation control is given by the interaction among eustasy and tectonics, governed by marine transgressions and regressions, subsidence and uplift,

creating accommodation. The depositional trends (normal regression, forced regression, and transgression) result from the interplay between sedimentation and accommodation. This determines if the sedimentary sequences are in aggradation, degradation, progradation, retrogradation, or a combination of these (Catuneanu, 2006).

3.4 Seismic Attributes

As aforementioned, seismic attributes are part of the seismic interpretation, exploring geologic, geometric, and physical characteristics of the materials, better highlighting the stratigraphic and structural rock features, bottom formations, and discontinuities from the vicinity. They are extensively used in the oil industry to reduce exploratory risks by optimizing the conventional seismic lines (Fathiyah Jamaludin et al., 2016; Goulart et al., 2019; Obidi et al., 2019; Conti and Oliva, 2021). The seismic attributes explored in this study are Root-Mean-Square (RMS) Amplitude, Instantaneous Amplitude, Instantaneous Frequency, and Chaos.

3.4.1 RMS Amplitude

In seismic attributes, amplitude accounts for the magnitude of the seismic traces values or trace envelope, being the RMS Amplitude represented by the variation of the average energy in an interval among horizons. In other words, the internal energy of the seismic reflectors (Neves, 2020). “The root mean square Amplitude A_{RMS} is usually obtained from the seismic trace $f(t)$ within a defined window with a width equal N of samples” (Ismail et al., 2020). The expression of the RMS Amplitude A_{RMS} , in the function of the seismic trace $f(t)$, is given below, where N is the number of samples, and $A(i)$ is the amplitude of i samples:

$$A_{RMS(t)} = \sqrt{\frac{1}{N} \sum_{i=1}^N A(i)^2}$$

As noted by the above equation, RMS Amplitude is convenient to evidence high amplitudes due to the values being squared before averaging, useful to identify amplitude anomalies generated by BSRs, bright spots, gas pockets, gas-rich sands, and porosity changes owing to the high concentration of gas hydrate (Shukla et al., 2012; Ismail et al., 2020; Neves, 2020). Plaza-Faverola (2010), in her research about gas hydrate in Norway, characterized Pliocene/Quaternary sedimentary sequences using RMS Amplitude to highlight gassy sediments infilling depressions at the base of a BSR (Figure 3.4).

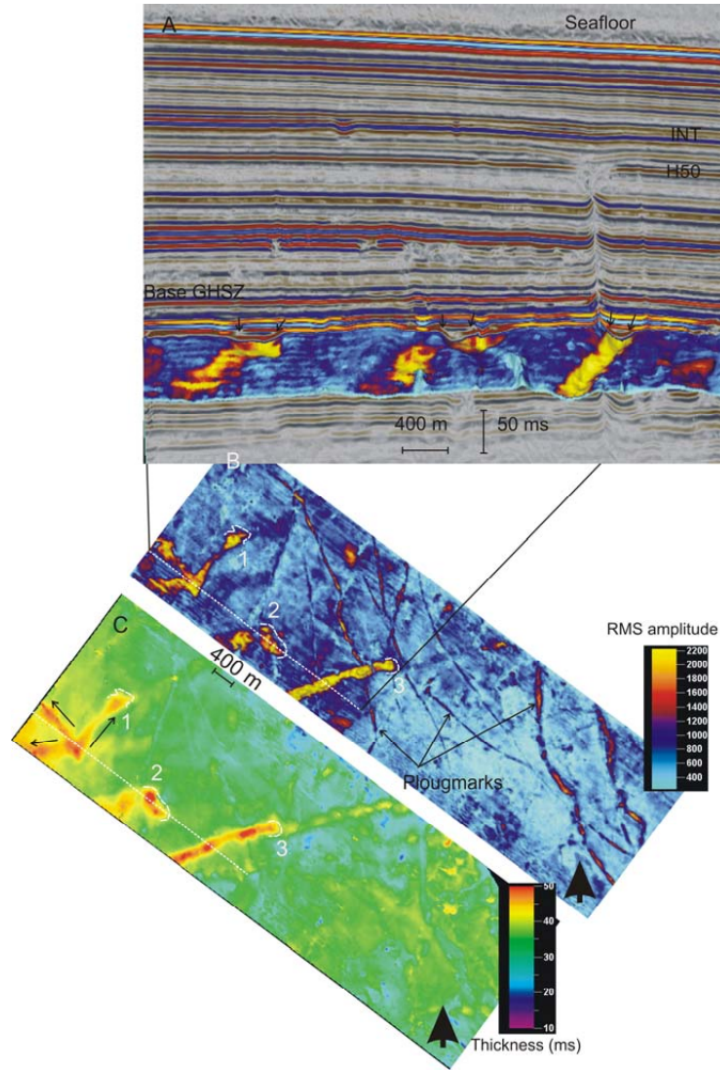


Figure 3.4 RMS Amplitude applied in fluid migration of hydrate system, Nyegga, mid-Norwegian continental margin. (A) Seismic sections 2D and 3D showing gas chimneys linked to depressions beneath the gas hydrate stability zone (GHSZ). Arrows denote depressions infill; INT and H50 are important reflectors. (B) RMS attribute evidencing the depressions (1, 2, 3) and ploughmarks produced by icebergs scour. (C) Thickness distribution of sedimentary infilling. (Extracted from Plaza-Faverola, 2010)

3.4.2 Instantaneous Amplitude

Reflection Strength, Amplitude Envelope, Instantaneous Envelope, or Instantaneous Amplitude are the same denominations of the seismic attribute that mean total instantaneous energy (Neves, 2020). The Instantaneous Amplitude $A(t)$ is given by the seismic trace $f(t)$ and the quadrature trace $q(t)$, according to the equation below:

$$A(t) = (f(t)^2 + q(t)^2)^{\frac{1}{2}}$$

It recognizes variations in acoustic impedance, highlighting amplitude anomalies (Figure 3.5) present in gas-rich layers, BSRs, and bright spots (Ismail et al., 2020; Neves, 2020). Above BSRs, a blanking zone is seen due to the hydrate-bearing sediments that display weak reflections and relatively small acoustic impedance contrasts. Instantaneous amplitude is extensively applied to identify the amplitude loss above BSRs and hence the pathways and infilling of gas hydrates in shallow porous sands (Taylor et al., 2000; Satyavani et al., 2005; Li et al., 2013).

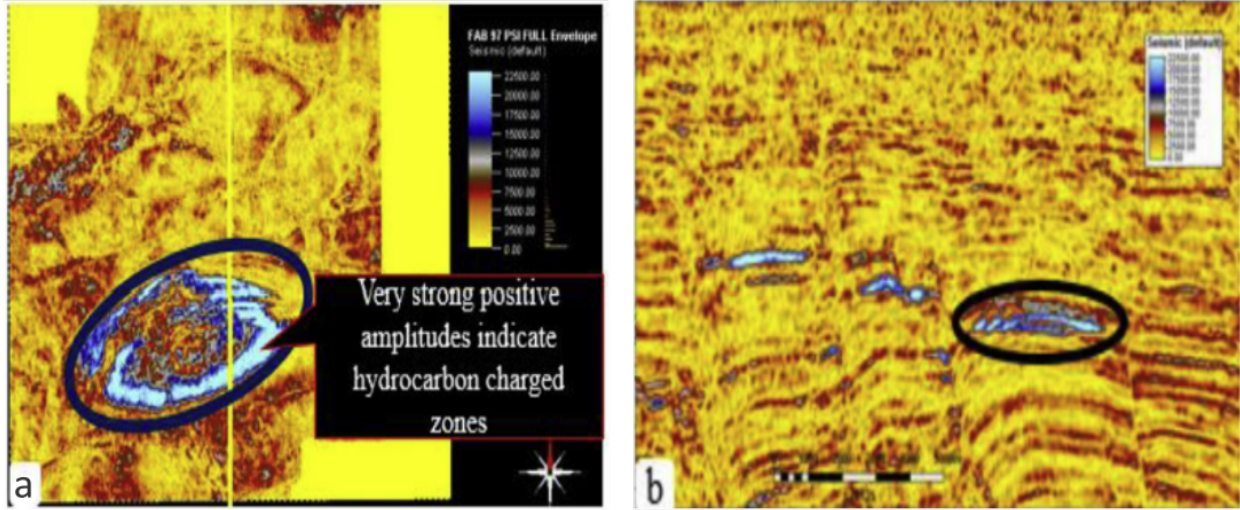


Figure 3.5 Instantaneous Amplitude used to visualize high amplitudes produced by hydrocarbon-charged reservoir in porous sand. The bright spots were detected in time-slicing (a) and 2D (b) sections. Fabianski Field, onshore Niger Delta, Nigeria. (Modified from Obiadi et al., 2019)

3.4.3 Instantaneous Frequency

One of the most used complex seismic trace attributes is the Instantaneous Frequency, defined by Xing et al. (2019) as “the frequency of the sinusoid that matches the seismic trace in a small window about a given time, for a relatively constant envelope”. According to Wang et al. (2013) and Xing et al. (2019), the instantaneous frequency $IF(t)$ is the time derivative of the instantaneous phase $IP(t)$, in hertz, as seen below:

$$IP(t) = \arctan (y(t) / x(t))$$

$$IF(t) = \frac{1}{2\pi} \frac{x(t)y'(t) - x'(t)y(t)}{x^2(t) + y^2(t)}$$

where $x(t)$ is the seismic trace, $y(t)$ is the Hilbert transform of $x(t)$, $x'(t)$ is the derivative of $x(t)$, and $y'(t)$ is the derivative of $y(t)$. Instantaneous frequency is used to analyze seismic attenuation and frequency oscillations, highlighting high attenuation and lower frequencies of stratigraphic discontinuities, faults, fractures, hydrocarbon leakage/seepage, gas chimneys, free gas zones, mud diapirs, mud volcanoes, etc (Xing et al., 2019; Neves, 2020; Zhong et al., 2021) (Figure 3.6). These features are very different from the usually higher frequencies of host rocks. In the case of BSRs, below it is seen higher attenuation and low frequency produced by free gas, contrasting with lower attenuation and absorption of high frequencies by gas hydrates-bearing sands above it (Satyavani et al., 2005; Li et al., 2013). Also, the instantaneous frequency can be applied to identify bed thickness and thin-bed tuning (Ahmed, 2001; Xing et al., 2019).

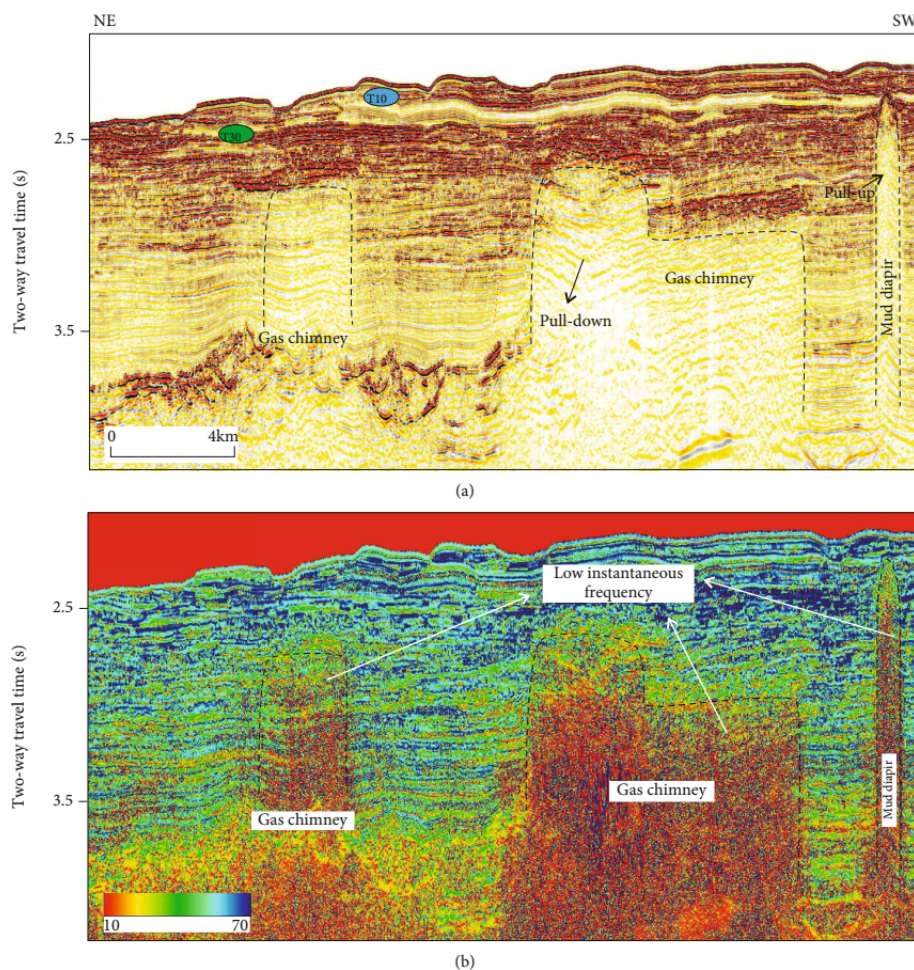


Figure 3.6 Instantaneous frequency profile evidencing Paleogene to Miocene strata fluid migration through gas chimneys and mud diapir on the continental slope. (a) Seismic section. Colored circles represent important horizons. (b) Contrast of low frequency in vertical zones by upward leakage. Shenhu Area, Baiyun Sag, Pearl River Mouth Basin, South China Sea. (Extracted from Zhong et al., 2021)

3.4.4 Chaos

The Chaos attribute discriminates the chaoticness of the dip and azimuth estimation method (Koson et al., 2014). According to Randen et al. (2001) and Chopra and Marfurt (2016), the Chaos measure starts analyzing a point on the reflector; the normal in such point is obtained by calculating the local gradient, characterized by partial derivative for each dimension. Considering the expected large variations on the gradient, a dominating orientation is measured based on the eigenanalysis of the 3×3 gradient structure tensor ∇x , with respective times t , as seen below:

$$\nabla x(t_1, t_2, t_3) = \begin{bmatrix} \frac{\partial x(t_1, t_2, t_3)}{\partial t_1} \\ \frac{\partial x(t_1, t_2, t_3)}{\partial t_2} \\ \frac{\partial x(t_1, t_2, t_3)}{\partial t_3} \end{bmatrix}$$

This covariance matrix is decomposed into eigenvectors (three main gradients directions) and eigenvalues (magnitude). The eigenvector with the highest eigenvalue defines the dominating orientation, corresponding to the local orientation estimate, normal to a local plane of constant amplitude waveforms; the data are completely chaotic if the eigenvalues are equivalent.

Chaoticness is characterized by reflector disruption. It is found in faults, fractures, angular unconformities, channel sand bodies, mass-transport complexes, karst surfaces, salt structures, turbidites, gas leakage, mud diapirs, etc (Koson et al., 2014; Ismail et al., 2020). Mass movements, channel infill and turbidites usually deposit poorly-sorted sediments randomly, causing chaotic reflections; faults, fractures zones, and karst collapse generate reflector disruption; scattering and signal deterioration are produced by gas due to the fluctuation of compressional wave velocity. Chaos attribute easily enhances the visualization of faults, conduits, gas chimneys, and BSRs by the upward gas migration signal diffusion (Figure 3.7).

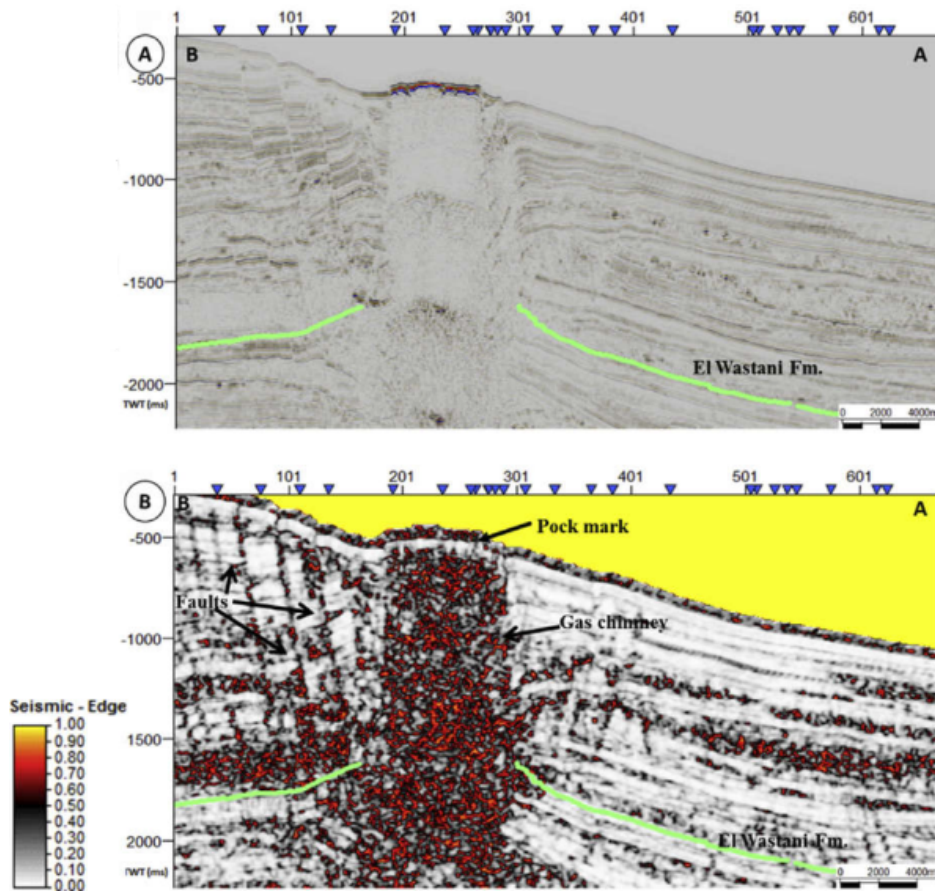


Figure 3.7 Seismic section (A) and Chaos attribute (B) showing fluid migration of the offshore gas reservoir (Lower Miocene to Lower Pliocene), localized within the El Wastani Formation. A network of faults and gas chimney are responsible for gas leakage, forming a pockmark on the seafloor. Scarab Field, Nile Delta, Egypt. (Modified from Ismail et al., 2019)

4. STATE OF ART

4.1 Bottom Simulating Reflectors

The hydrocarbons are naturally encountered in different states of matter, transported and accumulated in diverse aqueous bodies such as rivers, lakes, seas and oceans. Within sedimentary basins, hydrocarbons are preferentially concentrated in specific temperature and pressure stability zones. At subsurface with conditions of low temperature and high pressure, gas hydrates may form; they are also called clathrate hydrates or methane hydrates, described as ice-like solid substances composed of gas, mainly methane, trapped within water molecules lattices (Hovland and Judd, 1988; Chapman et al., 2004; Li et al., 2013; Yu et al., 2014; Su et al., 2016). Gas hydrates occur broadly interspersed within shallow sediment piles, muddy fluids, little pockets, and small channels, being stable in favorable conditions of the Gas Hydrate Stability Zone (GHSZ). The depth and thickness of the GHSZ are influenced by the geothermal gradient, bottom water temperature, pore water salinity, gas hydrate composition, pressure of the water column, and lithostatic pressure (Chapman et al., 2004; Hovland et al., 2005; Plaza-Faverola, 2010; Li et al., 2013; Skarke et al., 2014; Somoza et al., 2014; Neves, 2020; Roelofse et al., 2020). Small alterations of the equilibrium state, such as subtle changes in sea-level and sediment discharge, can drive gas dissociation, especially when topographic gradients exist as in continental slopes and canyons (Hovland and Judd, 1988; Roberts and Carney, 1997; Suess et al., 1999, 2001; Roberts et al., 2010). Such conditions are triggered by the generation of landslides, slumps and associated mass movements (Hovland et al., 1993; Aloisi et al., 2001; Grotzinger et al., 2010; Moore et al., 2018; Ma et al., 2021). Also, the mass movements or seismic activity can provoke gas dissociation.

High-amplitude reflectors with reversed polarity in relation to the seafloor are known as Bottom Simulating Reflectors (BSRs), commonly occurring at the base of GHSZ (Appendix 9, 11, 15, 17, 20, and 21) (Suess et al., 1999; Satyavani et al., 2005; Roberts et al., 2006; Serié et al., 2012; Skarke et al., 2014), demarcating the limit of gas clathrates stability. BSRs are widespread found in continental slopes and continental rises, with minor distribution in shelves or abyssal plains. Generally, the BSRs are seen crosscutting the stratigraphy because they are the expression of a thermobaric field, not a stratigraphic or structural control (Berndt et al., 2004; Yu et al., 2014; Su et al., 2016; Neves, 2020). Normally, the BSRs depict the phase change between overlying gas hydrates and free gas

below; seismic attributes interpretation displays smooth reflections, high velocities and relatively small acoustic impedance contrasts in the hydrate-bearing sediments upon BSRs (Hovland and Judd, 1988; Cowley and O'Brien, 2000; Chapman et al., 2004; Plaza-Faverola, 2010; Li et al., 2013; Yu et al., 2014; Su et al., 2016; Clairmont et al., 2021). Those weak reflections are explained by Taylor et al. (2000) due to the amplitude blanking. The gas hydrates usually accumulate in high porosity – low velocity – sediments, increasing the velocity due to the hydrate-bearing strata (Hovland and Curzi, 1989; Talukder et al., 2007; Paull et al., 2008; Serié et al., 2012; Shukla et al., 2012; Wilson et al., 2014; Camerlenghi, 2018). This velocity increment reduces the acoustic impedance contrast within two strata of different porosity, decreasing the reflection amplitude in the hydrate-bearing sediments above BSRs; underlying the BSRs, the pattern of free gas seismic attributes is different, represented by enhanced reflection, low velocity and low frequency (Figure 4.1). Although this research focuses on gas-bearing BSRs, the most common BSRs are related to the diagenesis of silicate sediments – smectite to illite conversion and opal-A, opal-CT and quartz transformations. Both diagenetic and gas-bearing BSRs can be differentiated. Diagenetic BSRs occur in silicate-rich strata, usually deeper and with greater temperature than the gas-bearing BSRs, showing positive acoustic impedance contrast between siliceous sediments and the same polarity in relation to the seafloor. Gas-related BSRs occur in gassy sediments, in shallower and cooler zones, showing negative acoustic impedance contrast, and reversed polarity. Nevertheless, it's difficult to determine the BSR nature only using seismic data, because the sediment composition does not always show significant contrasts, and neither is enough information about physical-chemical conditions. Also, in smooth slope surfaces, the small angle of cross-cutting between strata hamper the polarity visualization, because cross-cutting events are superimposed above and below the analyzed reflectors. More information can be accessed in Berndt et al. (2004).

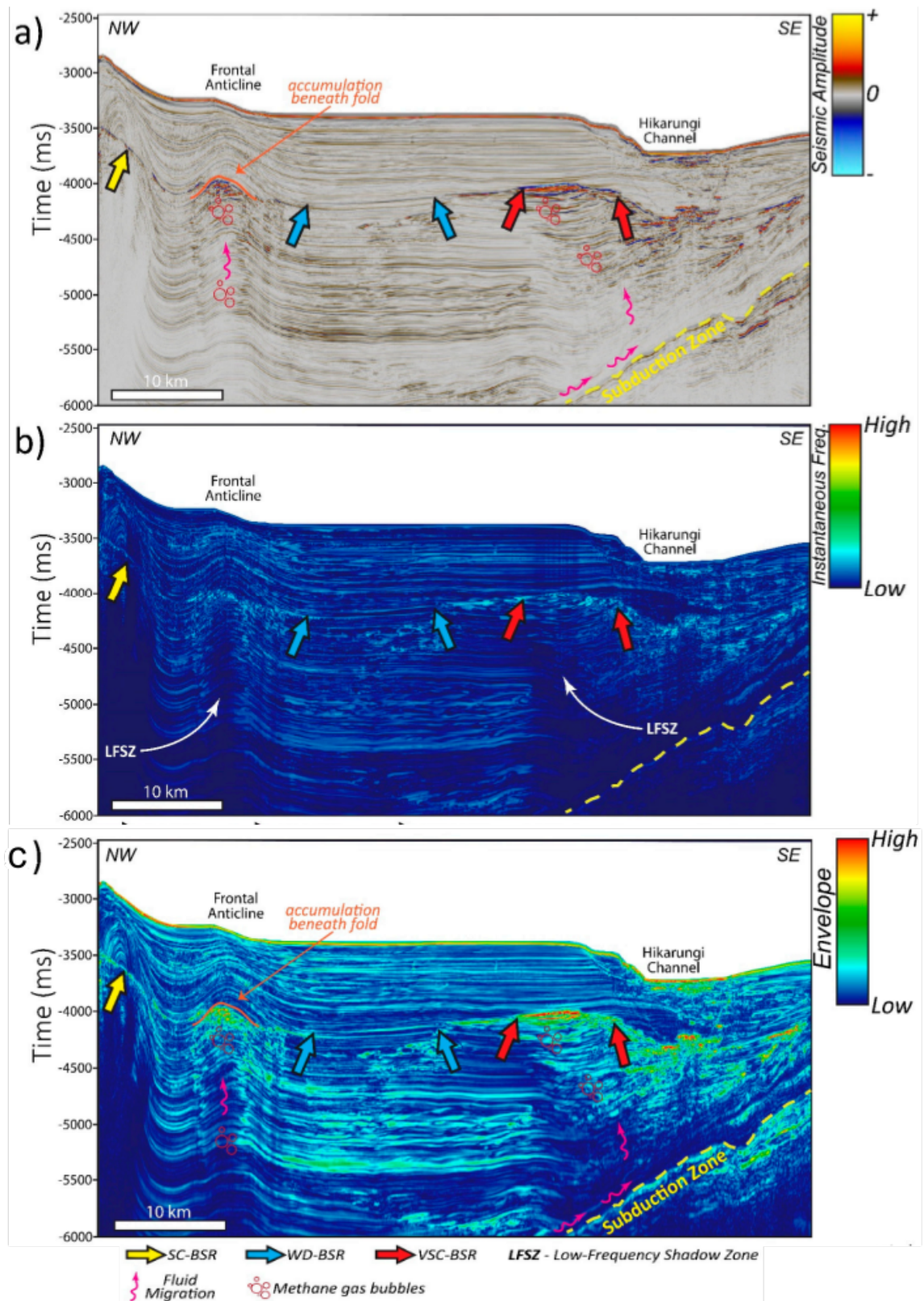


Figure 4.1 Neogene deep-water strata result from deposition within a subducting-related accretionary wedge. Three BSRs are depicted; SC (strong continuous); WD (weak discontinuous); and VSC (very strong continuous). (a) Seismic section displaying a Pleistocene to recent fluid migration zone. (b) Low-Frequency Shadow Zone (LSFZ) located below folded strata, visualized by instantaneous frequency attribute. Low frequency is caused by signal attenuation and is

characteristic of the free gas zone. (c) Envelope showing high amplitude on the BSR. The amplitude is weaker above BSR due to the amplitude blanking performed by gas hydrate-bearing sediments. Frontal Anticline and Hikurangi Channel, Pegasus Basin, New Zealand. (Modified from Clairmont et al., 2021)

4.2 Gas Chimney

Gas chimneys are a type of fluid escape structure in which fluids pass through different media (Appendix 10). They percolate discontinuities such as faults and fractures, remobilizing sediments and fluids of deeper sections, moving upward, and may reach the seafloor/lake bottom (Schroot et al., 2005; Kang et al., 2013; Somoza et al., 2014; Yu et al., 2014; Su et al., 2016; Ismail et al., 2020). It can create its own way of migration through fluids in overpressure that destabilize soft layers, causing fracking (Hovland et al., 2010; Plaza-Faverola, 2010; Callow et al., 2021). In sedimentary basins, gas chimneys delineate gas migration, cutting the stratigraphic layers from source rocks towards high integrity seals, or even bypassing the seal rocks, pumping gas to the surface (Plaza-Faverola, 2010; Cartwright and Santamarina, 2015; Goulart & de Castro, 2021). The gas chimney base is known as the root, while the top is called the terminus (Maestrelli et al., 2017a); from root to terminus, it can have hundreds of meters long, sometimes reaching a few thousand of meters (Van Rensbergen et al., 2007; Ivanov et al., 2009; Zhang et al., 2018). The chimney width varies from tens to hundreds of meters. In seismic sections, gas chimneys are identified by low amplitude, low frequency, chaotic pattern, and discordance in relation to the sedimentary strata, generally vertical or sub-vertical (Figure 4.2). Sometimes it causes pull-down in the strata, depending on alterations of compressional wave velocity (Spatola et al., 2017). All of these features are explained by the propagation of seismic waves. Given the nature of the fluid migration in sedimentary basins through a faults network and/or interconnected fractures, backscattering is generated by diffusion of the seismic signal (Cole et al., 2000; IHO, 2005; Riboulot et al., 2016; Ceramicola et al., 2018; Ismail et al., 2019). This disturbance is visualized by the chaotic and low amplitude reflections, typical of gas chimneys. For more information about gas chimneys is recommended to access Maestrelli et al. (2017a) and Goulart & de Castro (2021).

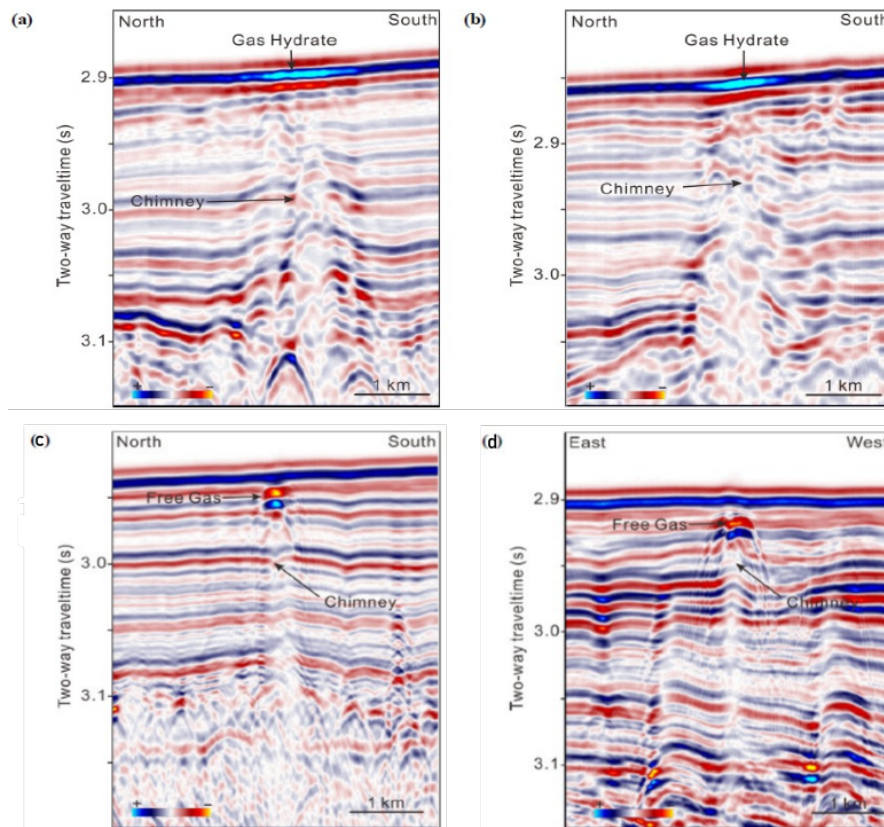


Figure 4.2 Gas chimneys identified by chaotic, low amplitude, vertical reflectors. Fluids are transported through the chimneys, forming amplitude anomalies on shallow subsurface recognized as gas hydrates (a) and (b) or free gas (c) and (d) below the gas hydrate zone. Cheonbu Formation, Ulleung Basin, East Sea, South Korea. (Extracted from Kang et al., 2013)

4.3 Pockmark

Pockmarks are circular or elliptic depressions localized on the surface of sediments in marine, estuarine, and lacustrine settings (Appendix 13 and 16) (Whelan et al., 2005; Suess, 2014; Maestrelli et al., 2017a; Spatola et al., 2017; Goulart et al., 2019). Pockmarks are widespread identified in basins worldwide. They have been isolated or in clusters, ranging in size from meters to hundreds of meters wide, and meters to tens of meters deep (Hovland et al., 1987, 2005; Pilcher and Argent, 2007; Hovland, 2012; Mascle et al., 2014; Durán and Guillén, 2018). Giant ones may form craters, reaching a few kilometers wide and more than 100 m deep, probably resulting from the coalescence of some other pockmarks (Pilcher and Argent, 2007; Newman et al., 2008; Ceramicola et al., 2018). Its formation is explained by the expulsion of overpressurized pore fluids in continuous escape from shallow reservoirs or violent events (Hovland and Judd, 1988; Hovland et al., 1993, 2010; Cole et al., 2000; Schroot et al., 2005; Chiu et al., 2006; Callow

et al., 2021). The depressions size is related to the amount of overpressure, fluid volume, and composition (especially hydrocarbons and mud); it can be enlarged by continuous fluid flow, collapsed crater scarp, and coalescence of nearby depressions (Suess, 2014; Durán and Guillén, 2018; Ceramicola et al., 2018; Moore, et al., 2018; Mountjoy and Micallef, 2018). Also, depressions can be buried or overprinted by structure collapse, slumping borders, and high sediment infilling. Pockmarks are genetically related to active fluid migrations and gas plumes, sourced by muddy water, gas hydrates pockets, biogenic gas degraded by bacterial decomposition, and thermogenic gas (Hovland et al., 1987; Hovland and Judd, 1992; Roberts and Carney, 1997; Berndt et al., 2004; Suess, 2014; Riboulot et al., 2016). In seismic sections, pockmarks are mostly seen in the terminus of gas chimneys and associated with mud volcanoes, mud diapirs, and authigenic carbonates (Hovland and Judd, 1988; Suess et al., 2001; Hovland et al., 2005; Zhang et al., 2018; Ismail et al., 2020; Roelofse et al., 2020). The seismic signature is smooth depressions on the seabed (Figure 4.3), particularly common in continental slopes, canyons, deltas or other environments that supply enough organic matter and sediment overburden.

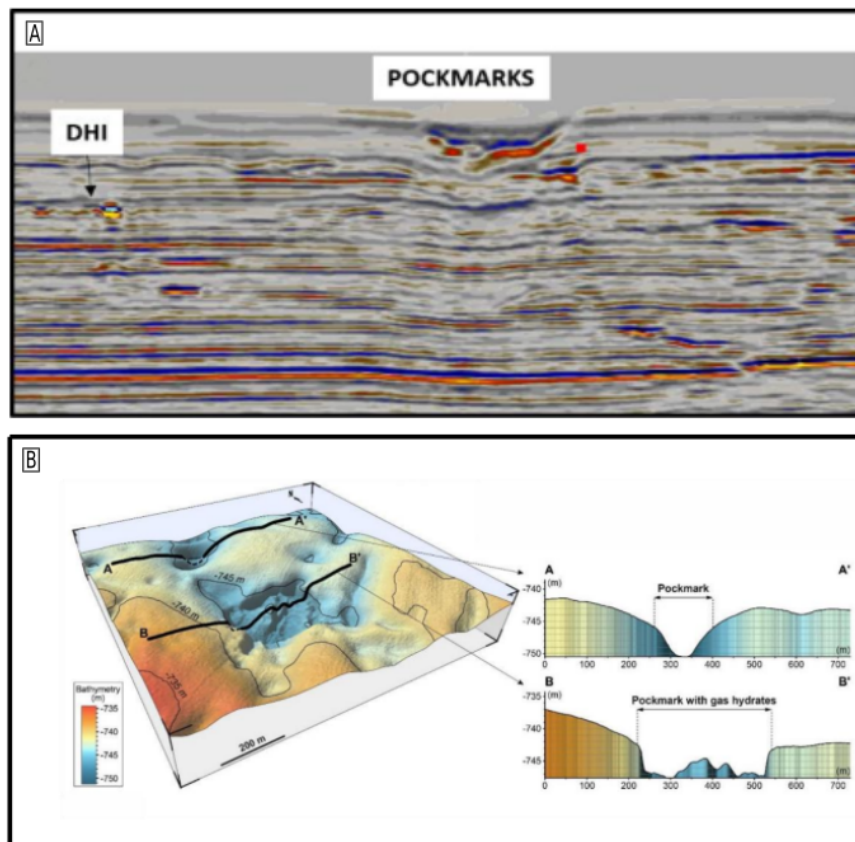


Figure 4.3 Pockmarks developed on the seafloor. (A) Cross-section view on 2D seismic of a depression 1.25 km wide and 17 m deep. A direct hydrocarbon indicator (DHI) is seen aside from

the pockmark as a bright spot resulting from gas hydrate accumulation. Malay Basin, Malaysia. (B) Bathymetric 3D and 2D map of pockmarks. The features are localized on the middle continental slope and result from hydrocarbon reservoir fluid migration through mud diapirs, gas hydrate dissolution and dissociation. Niger Delta, Nigeria. (Modified from Fathiyah Jamaludin et al., 2016, and Riboulot et al., 2016)

4.4 Hydrocarbon-Related Diagenetic Zone

At shallow depths below the seafloor, ranging from a few centimeters to tens of meters, exists a sulfate-methane transition zone, representing an interface between a superior layer called sulfate-reduction zone and the underlying methane-bearing zone. At the sulfate-methane transition zone, a microbial consortium made by sulfate-reducing bacteria and methane-oxidising archaea is responsible for the anaerobic oxidation of methane (Han et al., 2004; León et al., 2007; Skarke et al., 2014; Suess, 2020). “Methano-trophic archaea oxidize methane anaerobically via sulfate reduction, releasing CO₂ in the pore water, with production of bicarbonate ion (HCO³⁻) that induces oversaturation of the pore water with respect to carbonate minerals” (Camerlenghi, 2018). This process induces intense authigenic carbonate precipitation, forming carbonate cementation, hardgrounds, buildups, mounds, chimneys, concretions, nodules, crusts, etc (Hovland, 2002; Whelan et al., 2005; Roberts et al., 2006; León et al., 2007; Smith and Coffin, 2014; Suess, 2014). At or near the seafloor, in both reducing and oxidizing environments, slow methane seepage builds microbial mats with abundant carbonate precipitation; in moderate to high methane escape conduits, the conditions are favorable to the development of scattered carbonates outcrops and even higher biodiversity, including chemosynthetic mussels and tube worms (Suess et al., 2001; Roberts et al., 2006; Ivanov et al., 2009; Gong et al., 2010; Skarke et al., 2014; Ma et al., 2021). In this context, Hydrocarbon-Related Diagenetic Zone (HRDZ) are regions of authigenic carbonate production due to the microbial degradation of hydrocarbons. They form by hydrocarbon leakage from reservoirs throughout faults and chimneys, reaching usually sandy aquifers (Cowley and O’Brien, 2000; Smith and Coffin, 2014). Seismically, HRDZs are recognized by high amplitude due to the intense carbonate precipitation and hard substrates, positive polarity, pull-up, and stack response degradation (Figure 4.4, Appendix 27). Also, HRDZs change the seafloor morphology and are associated with faults, gas chimneys, pockmarks, mud volcanoes, and gas seeps, frequently covering faults and chimneys with carbonate crusts (Cowley and O’Brien, 2000;

Roberts et al., 2006; Goulart et al., 2019; Suess, 2020; Goulart & de Castro, 2021). More information about issues can be found in Camerlenghi (2018).

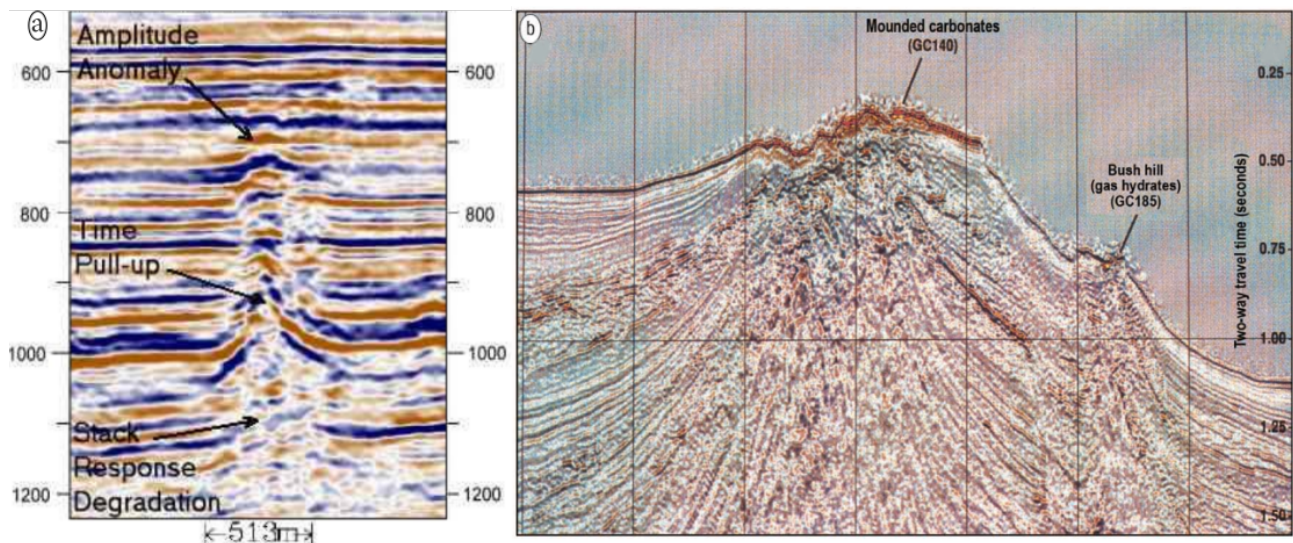


Figure 4.4 Seismic sections exhibiting HRDZs. (A) HRDZ produced by Miocene-Pliocene faults that disrupt seal integrity and leak gas from Mesozoic reservoirs to the Eocene Grebe Formation. Tahbilk gas field, southern Vulcan Sub-basin, Bonaparte Basin, Australia. (B) Very high amplitude due to HRDZs formed by authigenic carbonate mounds and hardgrounds that create peaks on the seafloor. GC140 and GC185 represent sites on the continental slope that present slow fluid migration. Green Canyon, Gulf of Mexico. (Modified from Cowley and O'Brien, 2000, and Roberts et al., 2006)

4.5 Carbonate Buildup

Carbonate buildups are designated as carbonate bodies, laterally restricted, forming topographic highs, and holding a wide range of morphologies (Burgess et al., 2013; Rankey et al., 2019; Słonka and Krzywiec, 2019). Several types of carbonate buildups can be classified according to various aspects, including carbonate mounds or mud mounds, reefs, attached carbonate platforms, isolate carbonate platforms, and so forth. The carbonate mounds are positive topographic features composed of fine-grained carbonate, usually biogenic muddy particles either detrital and microbial, occurring in photic shallow-water to aphotic deep-water settings (Aretz and Webb, 2003; Rodriguez-Martinez et al., 2011; Rejas et al., 2015; Zhou and Pratt, 2019) (Figure 4.5). A remarkable example of carbonate mound is the Waulsortian mudbanks of Ireland.

The reefs are classified as complex bioconstructions made by diverse reef-building organisms (corals, bryozoans, bivalves, sponges, red algae, green algae, etc) that

accumulate significant biologically produced calcium carbonate deposits (Aretz and Webb, 2003; James and Wood, 2010; Browne et al., 2021) (Figure 4.5). Reefs are very abundant in tropical shallow-waters, devoid of significant siliciclastic input, and with optimal conditions of temperature, salinity, sunlight, and nutrients. Biostromes and bioherms (patch reefs) are widespread in tidal flats, lagoons, carbonate platforms, and carbonate ramps (Grotzinger et al., 2010). Reefs also occur significantly in cold-and deep-waters (Rodriguez-Martinez et al., 2011; Hovland, 2012). Deep-water reefs are found in water depths below the photic zone from dozens to thousands of metres deep (Hovland, 2008; Veeken & Moerkerken, 2013). They are constituted by deep-water corals, tube worms, bivalves, polychaetes, gorgonians, crustaceans, bryozoans, echinoderms, brachiopods, etc) in a similar way that of tropical barrier-reefs, although the deep-water reefs tend to be considerably smaller and the food-chain based on chemosynthesis (Ceramicola et al., 2018; Lo Iacono et al., 2018). The Great Barrier Reef of Australia is the most spectacular tropical reefal structure; an excellent example of deep-water reef is the coral reefs of La Gaviera Canyon, Cantabria Sea (Sánchez et al., 2014).

Carbonate platforms are geological entities characterized by high biological productivity that produces carbonate bodies in diverse shallow-water settings, such as tidal flats, continental shelves, and continental slopes. They have a variety of complex geomorphological expressions, forming rimmed and non-rimmed shelves, ramps, epeiric platforms, and banks (Nichols, 2009; Brigaud et al., 2014). The combination of different mechanisms are responsible for the carbonate factory development, including temperature, salinity, limited siliciclastic supply, climate, nutrients, oceanic currents, tectonics, eustasy, and so forth (Pomar, 2001; Catuneanu, 2006; Paumard et al., 2017). Deposits within carbonate platforms range from small patch reefs to barrier reefs reaching kilometres to tens of kilometres (Williams et al., 2011). Attached carbonate platforms are those formed within carbonate shelves connected to a landmass (Bosence, 2005) such as the Amapá carbonate platform on the Amazon continental margin of Brazil (Cruz et al., 2019). This type of platform is commonly bordered by barrier reefs, growing up along the shelf break or shelf rim, protecting the internal environments to the action of high-energy waves and storms (Veeken & Moerkerken 2013). Patch reefs are prone to buildup in those protected lagoons, characterized by low-energy settling muddy facies. In counterparts, isolated carbonate platforms are identified as detached buildups formed in shallow-water environments, including tidal flats, reefs, lagoons, and bordering slopes (Burgess et al., 2013; Rankey et al., 2019). Isolate platforms are installed in rift continental margins and

volcanic islands, generating flat-topped morphologies surrounded by deep-waters (Read, 1985; Bosence, 2005). When a subsiding volcano is colonized by reef-building organisms, it forms an atoll. Those features are broadly circular, with a protected lagoon behind barrier reefs. Slope facies are developed on the flanks, depositing talus and carbonate debris that extend to very deep-waters. The Great Bahama Bank (Newell and Rigby, 1957; Harris et al., 2015) is a spectacular isolated carbonate platform.

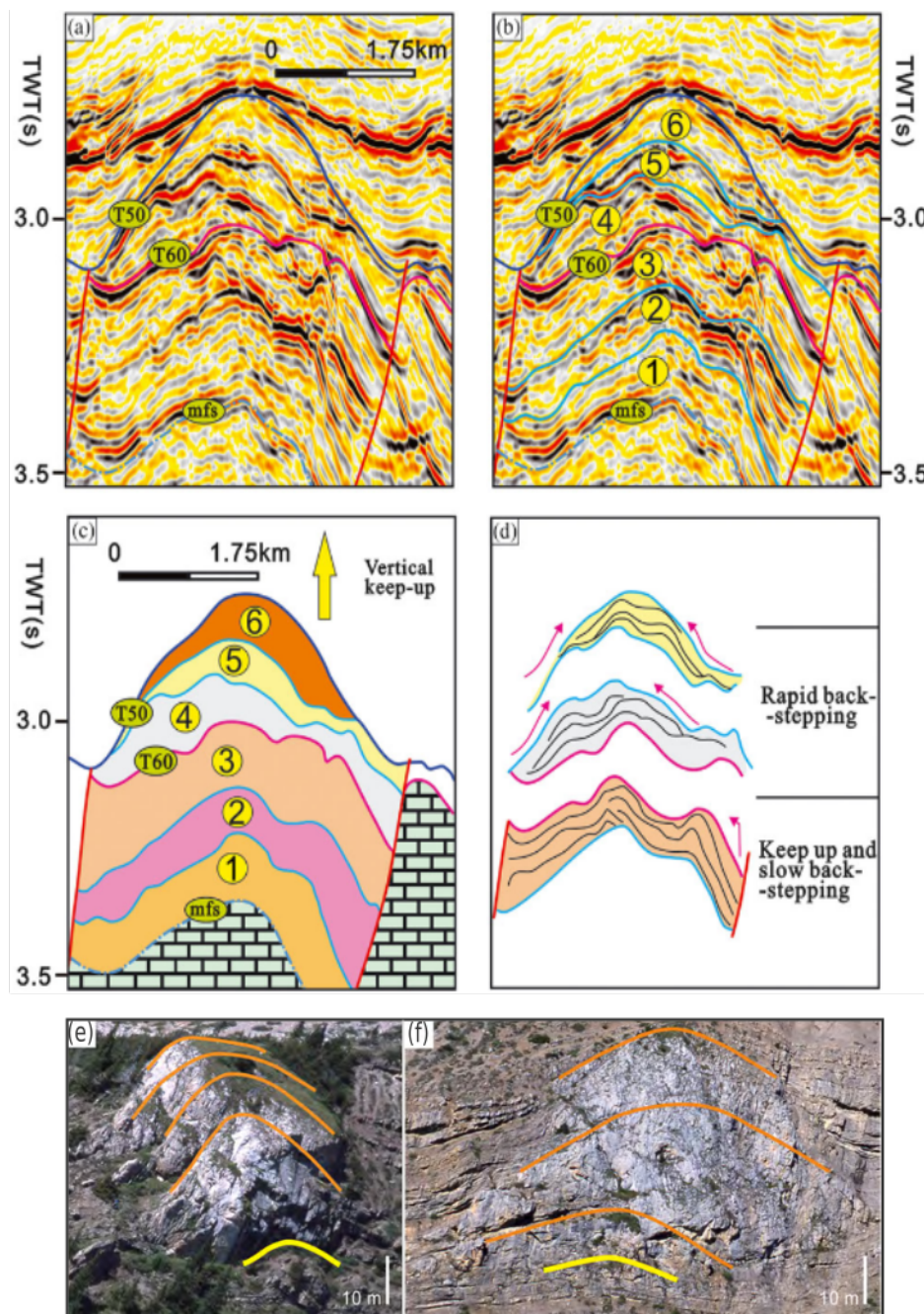


Figure 4.5 Examples of carbonate buildups. (a) to (d) represents seismic sections and configurations of Upper Oligocene–Lower Miocene reefs. 1 to 6 are reef-building units showing

keep-up and backstepping depositional trends, developed inside a faulted block of the carbonate platform. T50 and T60 are chronostratigraphic horizons, and mfs is the maximum flooding surface. Liyue Basin, South China Sea. (e) and (f) are outcrops of Upper Devonian carbonate mud mounds formed within a carbonate ramp. Yellow lines are the mounds' base and orange lines are the growth stages. The mounds show aggradational stacking pattern deposited in deep-waters around the storm-wave base, within the photic zone that preserved stromatactis and bacterial mats. Mount Hawk Formation, southern Rocky Mountains, Alberta, Canada. (Modified from Du et al., 2019, and Zhou and Pratt., 2019)

Many times, the terminologies about carbonate buildups cited above are used interchangeably, because the carbonate factory is very complex and can flourish in diverse settings. Hovland et al. (1994b) described seabed mounds on Porcupine Basin and Vulcan sub-Basin as carbonate knolls or bioherms. Veeken & Moerkerken (2013) used deep-water reefs or carbonate mounds for features on the eastern margin of the Rockall Trough, offshore NW Ireland. Sánchez et al. (2014) named the cold-water coral reefs of the Avilés Canyon System, Cantabrian Sea, as carbonate mounds. In the present study, there are a lack of core data and high frequency seismic, hampering the exact determination of mounded features; the interest is to analyze the deep-water carbonate formations of mid-lower slope and abyssal plain, hence the applied terminology is carbonate mud mound or simply the generalized therm carbonate buildup, although the mounds possibly can be related to mud volcanoes, deep-water reefs and bioherms.

Deep-water carbonate mounds have been recognized in several places worldwide, varying in geological context, shape, size, and depth (Appendix 22 to 26). Hovland et al. (1994b) identified mounds in Porcupine Basin, western Ireland, ranging from 100-1800 m across and 50-175 m high, occurring in water depths of 650-1000 m; on Vulcan sub-Basin, northwest Australia, they range from 100-1100 m across and occur in shallower water depths of 200-350 m. In the southwestern Rockall Trough, Ireland, carbonate mounds are found in water depths of 500-1000 m (Mienert et al., 2004). Henriot et al. (2014) reported coral reefs on the western margin of the North Atlantic (water depths of 1000–1300 m) and on the slopes of the Campos Basin, Brazil (bathymetry of 570-850 m). Talukder et al. (2007) identified mud mounds on the continental slope of Nicaragua in water depths between 1000-2500 m, with more than 130 m high. León et al. (2007) described carbonate mud mounds on Guadalquivir Diapiric Ridge and Hormigas Ridge, Gulf of Cádiz, ranging from 800-1.100 m depth.

Many of the carbonate mounds in deep ocean are formed by biological activity. Diverse biota (chemosynthetic bacteria, worm *Pogonophora* sp., clams, sponges, echinoids, bivalves, polychaetes, crustaceans, bryozoans, corals *Lophelia* sp. and *Madrepora oculata*) can create rich communities (Roberts et al., 1990, 2006; Mienert et al., 2004; León et al., 2007; Maignien et al., 2010; Wheeler et al., 2011; Suess, 2014). The typical assemblage of biological calcareous ecosystems thrives in photic, oxygenated, warm, shallow-waters, where abundant cyanobacteria and green algae are responsible for photosynthesis, together with symbionts zooxantella algae that live in coral tissues. In counterparts, deep-water buildups are dramatically different, found in hypoxic, aphotic, cold waters. The common coral species *Lophelia pertusa* are widespread distributed, having been found in the North Atlantic, Indian, and Pacific Oceans, in water depths ranging from 39-3380 m, and temperatures less than 0°C (Hovland et al., 1994b; Hovland, 2008; Lo Iacono et al., 2018). These species are azooxanthellate (Maignien et al., 2010) so the basic trophic resources do not have a relation to photosynthesis. Corals, tube worms, bacteria, and diverse other beings create prolific live colonies based on chemosynthesis. The base of the food chain nutrients is proven from hydrocarbons, supplied by cold seeps, hydrothermal vents, and ocean upwellings (Hovland and Judd, 1988; Roberts and Aharon, 1994; Paull et al., 2008; Rodriguez-Martinez et al., 2011; Templer et al., 2011; Skarke et al., 2014; Zhou and Pratt, 2019). Therefore, carbonate mud mounds are intrinsically found at/or near gas chimneys, pockmarks, HRDZs, mud volcanoes, mud diapirs, salt diapirs, and hydrothermal vents, where hydrocarbon leaks from deep reservoirs from conduits such as pipes, faults and fractures (Colman et al., 2005; Whelan et al., 2005; Van Rensbergen et al., 2007; Comas et al., 2009; Henriot et al., 2014; Suess, 2020).

The generated carbonate mounds are constituted by live colonies, accumulations of coral debris, patches of authigenic carbonate crusts, bacterial mats, and scattered chimneys. Models to explain the carbonate mud mounds genesis are based on episodes of varying fluid-venting rates (Roberts et al., 1990, 2010; Roberts and Carney, 1997; Suess et al., 2001; León et al., 2007). Slow hydrocarbon seepage are likely to form intense authigenic carbonate precipitation and small bacterial carpets (Figure 4.6). Higher fluid-venting rates produces gas hydrate mounds, minor mineral precipitation, and hot-spots of biological colonies (Roberts, 2001; Whelan et al., 2005). The greatest fluid-venting rates are responsible for the formation of mud volcanoes and scarce poorly-developed communities (Hovland et al., 1994b; Roberts and Carney, 1997; Roberts, 2001; Roberts et

al., 2006). Eventually, the hydrocarbon source will be exhausted and the live colonies perishes, leaving dead coral rubble, bacterial limes, shells and tubes debris.

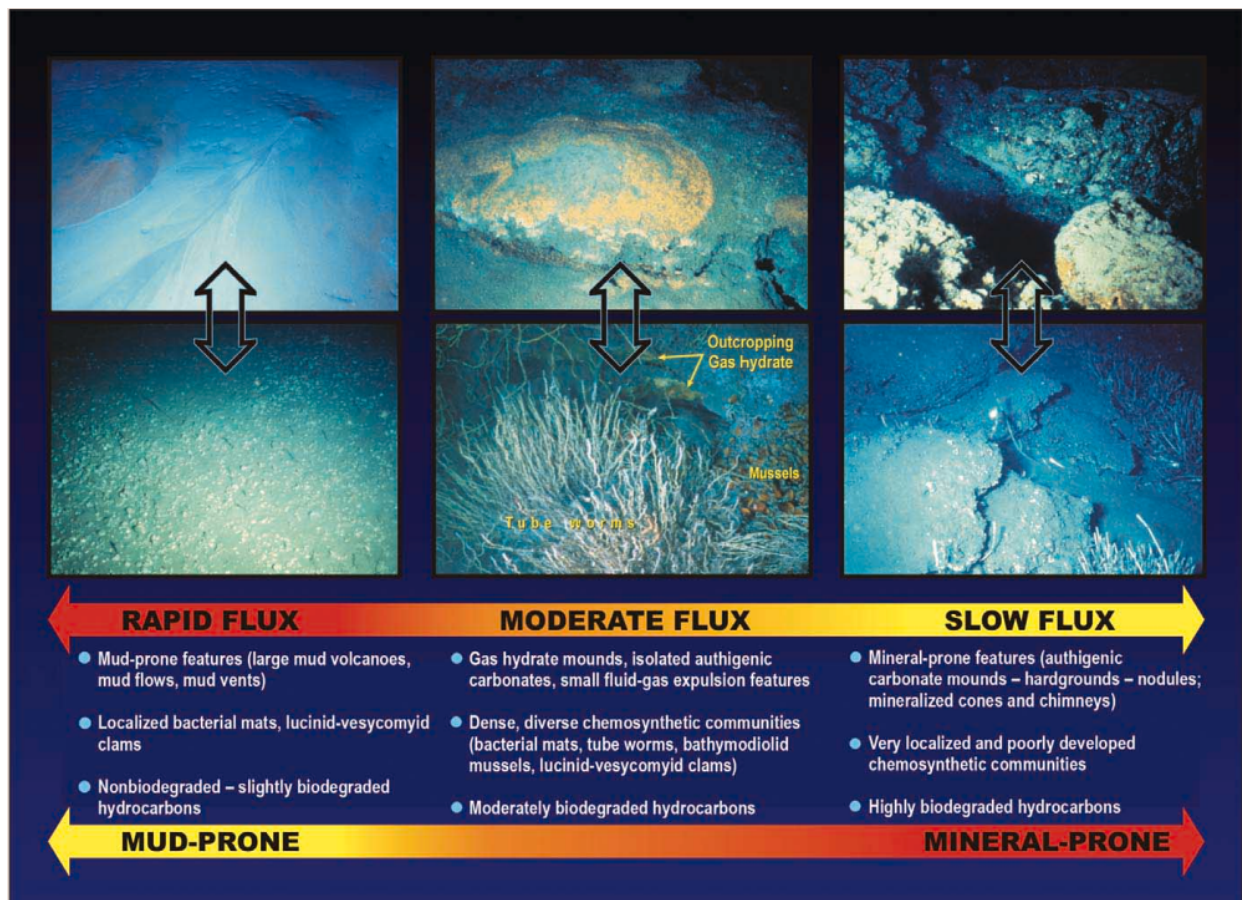


Figure 4.6 Correlation between fluid-venting and generated seafloor features. (Modified from Roberts, 2001, and Roberts et al., 2006)

On seismic sections, carbonate mud mounds are identified by the characteristic convex-up top reflections produced by the buildup, whereas the feeder conduit from below has transparent or semitransparent seismic facies (Talukder et al., 2007) (Figure 4.7). Also, carbonate rocks are likely to have higher seismic velocities than siliciclastic rocks, producing the pull-up effect (Hovland et al., 1994b). However, the correct identification of carbonate mud mounds based only on seismic sections is truly difficult due to their resemblance with igneous rocks, salt diapirs, tilted fault blocks, folds, mud volcanoes and diapirs (Burgess et al., 2013; Infante-Paez and Marfurt, 2018). Volcanoes, basement highs, and salt plugs also display pull-up effect due to their up-doming and higher seismic velocities relative to adjacent strata. Subtle distinction between those features rely on whereupon the carbonate buildups generate pull-ups within the structure, while diapirs, folds, fault blocks, and volcanoes deform the adjacent strata (Burgess et al., 2013).

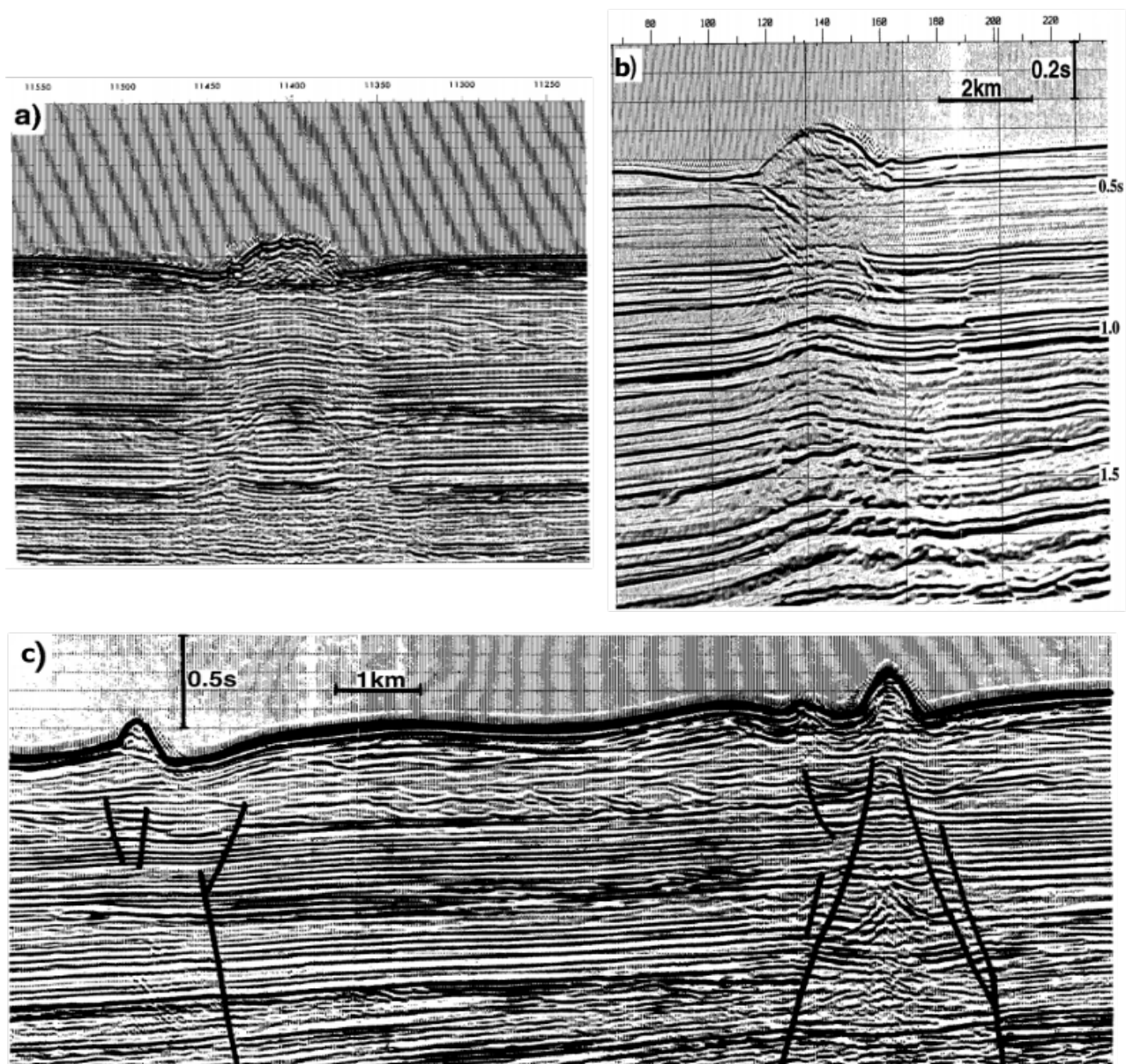


Figure 4.7 Carbonate mud mounds on deep seafloor. They present mounded topography, pull-up effect, and deep faults carrying hydrocarbons. (a) Mound 1,8 km wide at the base and located in water depth of 790 m. (b) Exemplar found at 300 m depth, with 1,1 km wide and 155 m high. Vulcan sub-basin, northwest Australia. (c) 2 mounds located over 1 km depth, with 625 m width in the base and 125 m high. (a) and (c) are placed in Porcupine Basin, western Ireland. In both locations, there are petroleum sources. The carbonate mounds are capped by living colonies of corals. (Modified from Hovland et al., 1994b)

4.6 Hydrate Mound

Gas hydrate mounds, hydrate mounds, giant gas mounds, and pingoes are different denominations of mounded features on the seafloor related to hydrate pumping (Hovland

and Svensen, 2006; Serié et al., 2012; Macelloni et al., 2013; Somoza et al., 2014; Wilson et al., 2014; Yang et al., 2021; Zhang et al., 2021). They have been reported in several places and tectonic settings, mainly along deep continental margins. On the Scotia Sea, Somoza et al. (2014) identified hydrate mounds above BSRs, where gas chimneys acted as fluid migration pathways. On the northeast edge of the Storegga slide scarp, Nyegga site, Norway, Hovland and Svensen (2006) characterized hydrate mounds on the continental slope, associated with BSR, pockmarks, vertical pipes, gas hydrates, and authigenic carbonate. Serié et al. (2012) studied the Kwanza Basin, Angola, finding hydrate mounds on the continental slope, genetically related to BSR and salt diapirism. Roberts (2001) reported features on the continental slope of Gulf of Mexico in water depths below 500 m, where moderate gas flux sites focused by salt masses and faults create local mounds and abundant biological colonies. Also in the Gulf of Mexico, on Mississippi Canyon Block and ~890 m of water column, Macelloni et al. (2013) observed similar patterns on the Woolsey Mound, where different fluid venting rates create contrasting seascapes from carbonate hardgrounds and pockmarks to vibrant chemosynthetic communities. On the continental slope of Barkley Canyon, Northern Cascadia Margin, thermogenic gas hydrate is associated with BSRs and chemosynthetic communities (Chapman et al., 2004). Freire et al. (2011) characterized gas chimneys, BSRs, mounds, and pockmarks at Umitaka Spur, Joetsu Basin, Japan Sea.

The hydrate mounds' formation is linked to physical-chemical processes in which are needed pressure of water depths exceeding ~ 400 m and temperatures less than approximately 4°C (Hovland and Roy, 2022). In these conditions, light gas hydrate infiltrates porous layers through chimneys, faults and fractures network, causing doming due to density inversion and hence upward movement of less dense hydrate-bearing strata. This process has resemblance with the serpentine, salt, and mud diapirs that are highly viscous due to their contrast in bulk density in relation to the adjacent strata (Somoza et al., 2014; Liu et al., 2020). High-flux of methane is necessary to build and maintain the mound. Eventually, the press exerted can pump gas flares into the water column (Whelan et al., 2005; Hovland, 2012; Suess, 2020).

The pingo development is intimately associated with other features correlated to hydrocarbon seepage, such as gas chimneys, pockmarks, BSRs, authigenic carbonates, chemosynthetic bacteria, and deep reefs, constituting both biological oasis on deep-waters and indicators of hydrocarbon resources (Roberts, 2001; Chapman et al., 2004; Whelan et

al., 2005; Macelloni et al., 2013; Yang et al., 2021). On seismic sections (Figure 4.8), gas hydrate mounds are characterized by a lack of internal reflections, blanking zones, or weak chaotic facies. Nevertheless, high amplitude of BSRs, free gas, and HRDZs are usually found near the mounds, as well as pull-up effects of carbonate buildup, and acoustic blanking due to hydrate-bearing strata (Liu et al., 2020; Zhang et al., 2021).

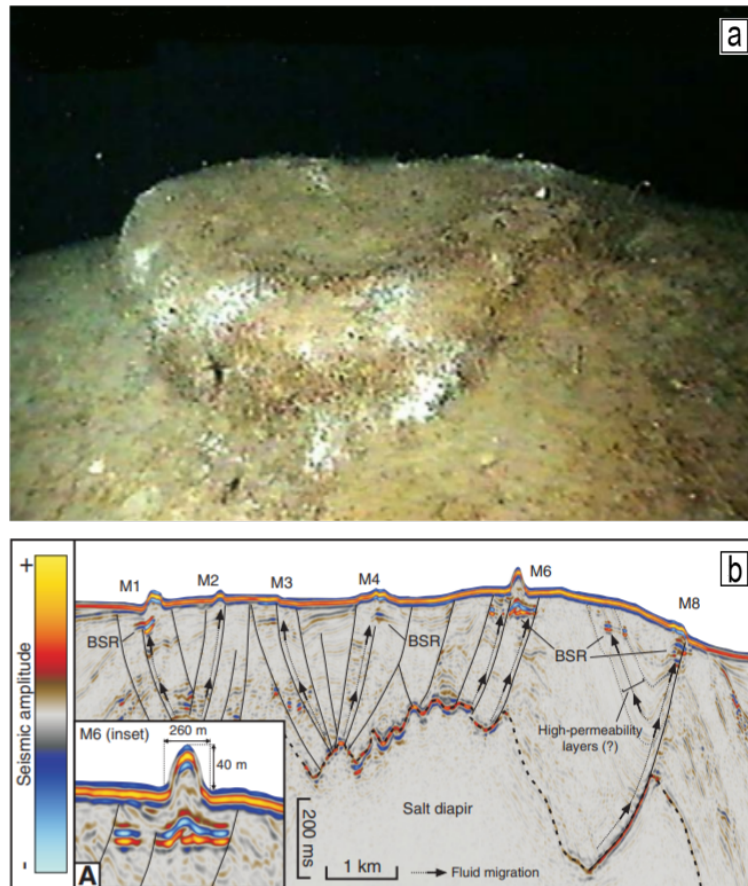


Figure 4.8 Expressions of hydrate mounds. (a) Image obtained by ROV survey, showing a small pingo 1 m across and 25 cm high. The mound has a central rim, corrosion pits, and eventual fluid spilling, indicative of sub-surface dissolution of hydrates. The feature is situated above a protuberance and the surface is covered by bacterial mats and tube worms. Storegga slide scarp, Nyegga site, Norway (b) Seismic section of the continental slope at almost 1 km depth, covered by several hydrate mounds (M1 to M8). The features can reach 80-300 m wide and 5-40 m high. They are associated with the salt structures development that creates pathways of migration through BSRs. Also, there are bacterial carpets and organic debris. Kwanza Basin, Angola. (Modified from Hovland and Svensen, 2006, and Serié et al., 2012)

4.7 Mud Volcano

Mud volcanoes are positive topographic features formed in sedimentary environments supplied by abundant sediment rates, organic matter, and water (Roberts and Carney,

1997; Aloisi et al., 2001; Suess, 2014; Ceramicola et al., 2018; Roelofse et al., 2020). They resemble cone volcanoes, although the mud volcanoes summit can have a flat top or even ponds and rims. Mud volcanoes are produced by sedimentary or tectonic loading originated from compressional forces, high sediment rates, and stacking of muddy deposits, enriched in water and hydrocarbon content, especially gassy sediments, overpressurized by burial conditions of 1.5-2 km deep (Dimitrov, 2002; Chiu et al., 2006; Suess, 2014; Ceramicola et al., 2018). They are fed by shallow sources of gas and mud transported via interconnected fractures and faults, also linked to mud diapirs, gas chimneys and pockmarks (Hovland and Judd, 1988; Hovland et al., 2005; Zhang et al., 2018). Mud volcanoes are recognized in seismic sections by the mounded topography; blank zones, chaotic pockets, and bright reflectors are seen due to gas seeping (Figure 4.9). They occur in a variety of geological contexts, both continental and marine domain, as active margins, passive margins, orogenic belts, continental slopes, abyssal plains, delta plains, etc (Camerlenghi et al., 1995; Roberts and Carney, 1997; Talukder et al., 2007; Deville, 2009; Mascle et al., 2014). Generally, they are closely related to compressional settings in which rapid sedimentation accompanied by sedimentary loading and seismic activity triggers favorable conditions for the development of mud volcanoes (Chen et al., 2014; Whelan et al., 2005; Talukder et al., 2007; Paull et al., 2008; Suess, 2020). Nevertheless, some places out of this context have been studied due to the presence of mud volcanoes, as deltas and shelves of transform and passive margins, inasmuch as they provided sufficient sedimentation (Orange et al., 1999; Kopf, 2003; León et al., 2007; Mascle et al., 2014). The size of mud volcanoes is related to the amount of sediment, fluid, and overpressure, generating mounds of hundreds to thousands of meters long, and tens to hundreds meters high (Camerlenghi et al., 1995; Martinelli and Judd, 2004; Chen et al., 2014). Most of the time, they expel flows of fluid material called mud volcano breccia. Eventually, violent eruptions will burst fluidized mud and gas flares kilometers high (Dimitrov, 2002; León et al., 2007; Deville, 2009). This highlights the mud volcanoes as one of the most critical geohazards, both in offshore exploration and onland catastrophic events (Plaza-Faverola, 2010; Ceramicola et al., 2018; Moore et al., 2018; Mountjoy and Micallef, 2018; Wan et al., 2021). Also, the entire structure is subject to slides and slumps, even in very low gradients, due to the instability of the mobile fluids and gradual feeding by gases, mostly methane. In fact, mud volcanoes are one of the greatest sources of this gas (Dimitrov, 2002; Kopf, 2003; Martinelli and Judd, 2004; Mascle et al., 2014).

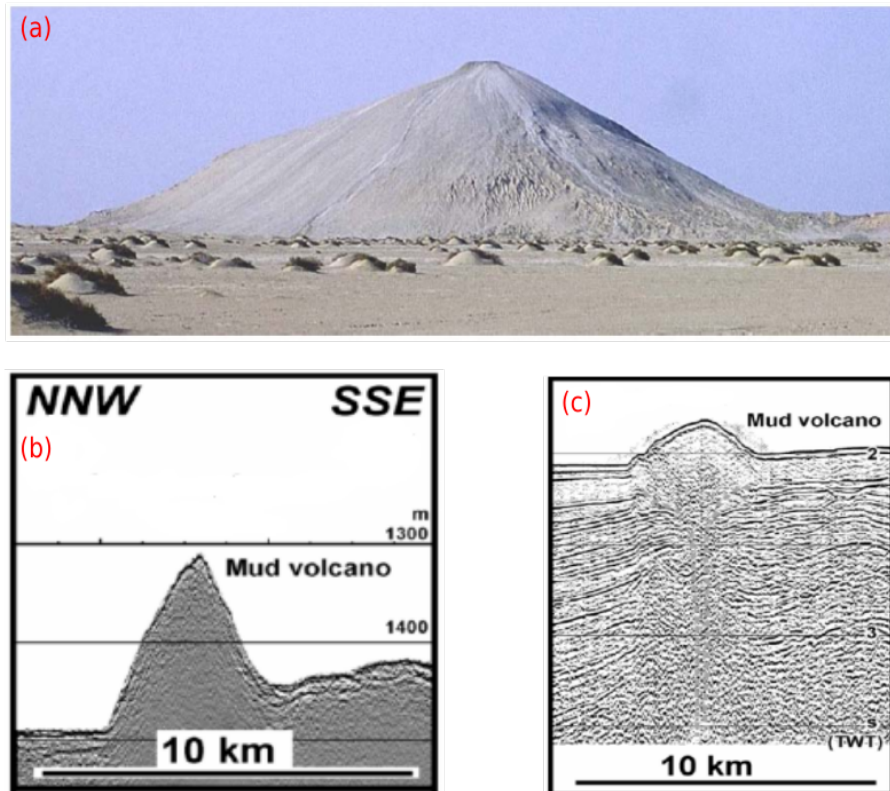


Figure 4.9 Examples of mud volcanoes. (a) Onland giant mud volcano more than 100 m high. Small peaks called gryphons are scattered on the ground. Makran accretionary prism, Pakistan. (b) Depth migrated 3.5 kHz profile showing an almost 200 m high cone-shaped mud volcano on continental slope. (c) Same section of (b) viewed on time-migrated seismic line. In this section the volcano conduit and strata piercing upward are visible. Offshore Trinidad. (Modified from Deville, 2009)

4.8 Mud Diapir

Piercing geological features composed of mud, water and gases are known as mud diapirs. They can form structures from a few kilometers to dozens of kilometers long, and <10 km wide (Camerlenghi et al., 1995; Chen et al., 2014; Wan et al., 2021). Mud diapirs and mud volcanoes are both generated due to the same processes, being called as mud diapirs when they do not expose to the surface and mud volcanoes when they do that (Orange et al., 1999; He et al., 2016; Ceramicola et al., 2018). Piercement is caused due to buoyancy forces achieved by bulk density contrast between the overburden and underlying lighter mud formation (Hovland and Judd, 1988; Hovland and Curzi, 1989; Orange et al., 1999; Satyavani et al., 2005; Talukder et al., 2007; Paull et al., 2008; Deville, 2009; Plaza-Faverola, 2010; Hovland, 2012; Camerlenghi, 2018). Strata overlying the diapirs are arched, forming high-angle brittle faults and radially arranged fractures (Chiu et

al., 2006; He et al., 2016; Zhang et al., 2020; Zhong et al., 2021). In seismic profiles, mud diapirs are recognized by the unconformable attitude in relation to the surrounding strata, identified in pull-up events, and consequent uplifting in the overburdened rocks (Figure 4.10). Therefore, the diapirs express onlap terminations on both flanks, with the summit mounded shaped (Chen et al., 2014; Zhang et al., 2018). Also, mud diapirs frequently exhibit bright spots, blank zones and signal attenuation due to the upward migration of free gas and/or gas hydrates, associated with faults and fractures network (Martinelli and Judd, 2004; Satyavani et al., 2005; Ivanov et al., 2009; Yu et al., 2014; Wan et al., 2021). Chaotic features and low instantaneous frequency are typical, differentiating from neighboring lithologies with higher instantaneous frequencies (Satyavani et al., 2005; Zhang et al., 2020; Zhong et al., 2021). Gas chimneys and mud diapirs are frequently associated in gas migration and trapping settings, subject to sedimentary loading, overpressure and faulting, being very difficult to differentiate both in conventional seismic sections. Zhang et al. (2018) established some distinct ways of recognition. Gas chimneys are usually smaller, only sometimes reaching a few kilometers long and hundreds of kilometers wide. They can create pull-down features, normally not altering the surrounding strata. Meanwhile, mud diapirs induce uplifting of the overburden due to density contrast, also forming pull-up reflections. Commonly they are bigger than chimneys, extending dozens of kilometers long and a few kilometers wide.

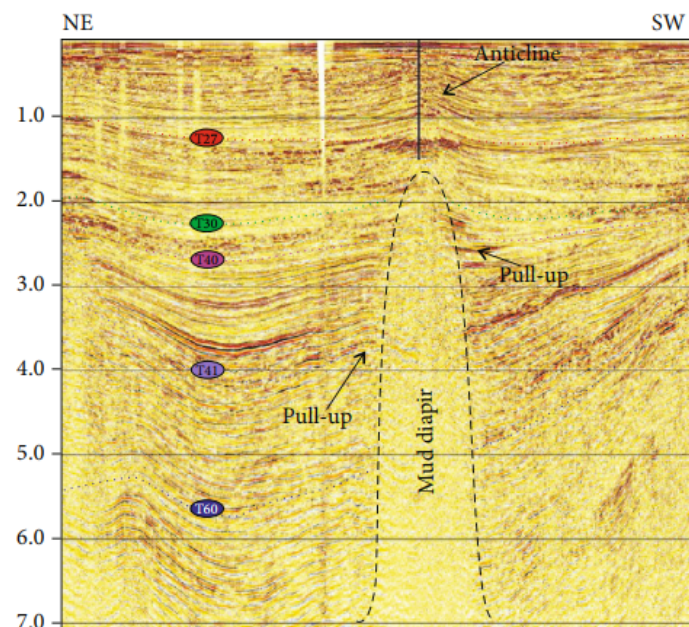


Figure 4.10 Mud diapir showing chaotic reflections, onlap on both flanks, and piercing the above sedimentary strata. It developed on Miocene Sanya Formation and reached the Pliocene upper

Yinggehai Formation. Coloured circles are seismic horizons. Yinggehai Basin, northern continental margin of South China Sea. (Modified from Zhong et al., 2021)

4.9 Fault

Faults are defined as planar or gently curved surface resulting from applied forces that generate displacement along the fault plane and allow the blocks to move relative to each other (Woyt, 2017). Fault length and offset range from millimetres to thousands of kilometres. In the seismic sections, faults are identified by low amplitude, low frequency, and chaotic reflections resulting from backscatter due to variations in the dip direction, displacement, and juxtaposition of contrasting strata. Fluid migration are intrinsically controlled by faults as they can act either as conduits or barriers to fluid flow, depending on their complex three-dimensional structure and anisotropic flow properties (Greene et al., 2006; Zhang et al., 2011; Wang et al., 2014; Jiang et al., 2015).

The capacity of faults to transport fluid is measured via the effectiveness of the hydraulic connectivity, evaluated by several correlated parameters such as the lithology of the faulted rocks, clay and sand content, shale smear, fault gouge, burial depth, fluid pressure, porosity, permeability, transmissivity, strike, dip angle, fault throw, stress, etc (Fossen, 2010; Zhang et al., 2011; Jiang et al., 2015). Porous rocks, such as sandstones and conglomerates, are prone to accumulate fluids, while non-porous rocks like igneous, metamorphic, and carbonatic rocks are impermeable. Nevertheless, the cataclastic deformation induced by faulting produces strain hardening in porous rocks, reducing the porosity, and strain softening in non-porous rocks, increasing the porosity (Fossen, 2010). The clay content of the faulted rock can act as a physical barrier to fluid flow. Generally, the own clay of the host rock can rotate by a drag mechanism (clay/shale smear) and incorporate in the fault core. Also, clay are added via injection of abnormally high pressures, and fault gouges form along the fault zone by attrition brecciation (Fossen, 2010). Very important to note is the juxtaposition due to the fault offset, where normally the contact sand-shale is sealing and sand-sand is non-sealing.

The effectiveness of hydrocarbon migration is a role of fault transmissivity along a network of interconnected faults and fractures. Generally, active faults are high-permeable, although fault zone heterogeneities can segment the fault surface in both sealing and transmitting parts (Moretti, 1998, as cited by Zhang et al., 2011). According to a numerical modelling proposed by Jiang et al. (2015), when the fault slip rate are greater than 20

m/Ma the fault transmissivity is high due to the expanded fault core thickness and large numbers of fractures. For values of fault slip rate less than 20 m/Ma, transmissivity diminishes and is highly dependent of shale smear, shale thickness, and fault throw. Most commercial oil and gas accumulations trapped by faults in China are related to fault sealing with fault slip rate less than 20 m/Ma (Jiang et al., 2015).

Faults constitute important pathways for hydrocarbon leakage and seepage from source rocks, reservoirs, and traps. Other conduits, such as gas chimneys, mud diapirs, and pipes, are associated with faults, disrupting hydrates-bearing layers, carrying hydrocarbons, and producing expressions on the seafloor, including pockmarks, mud volcanoes, and carbonate mounds (Hovland et al., 1994b; Dimitrov, 2002; Chiu et al., 2006; Ma et al., 2021). Authigenic carbonate usually covers fault surfaces via microbial degradation of hydrocarbons when there is an HRDZ (Cowley and O'Brien, 2000; Greene et al., 2006; Roberts et al., 2006; Smith and Coffin, 2014; Suess, 2020).

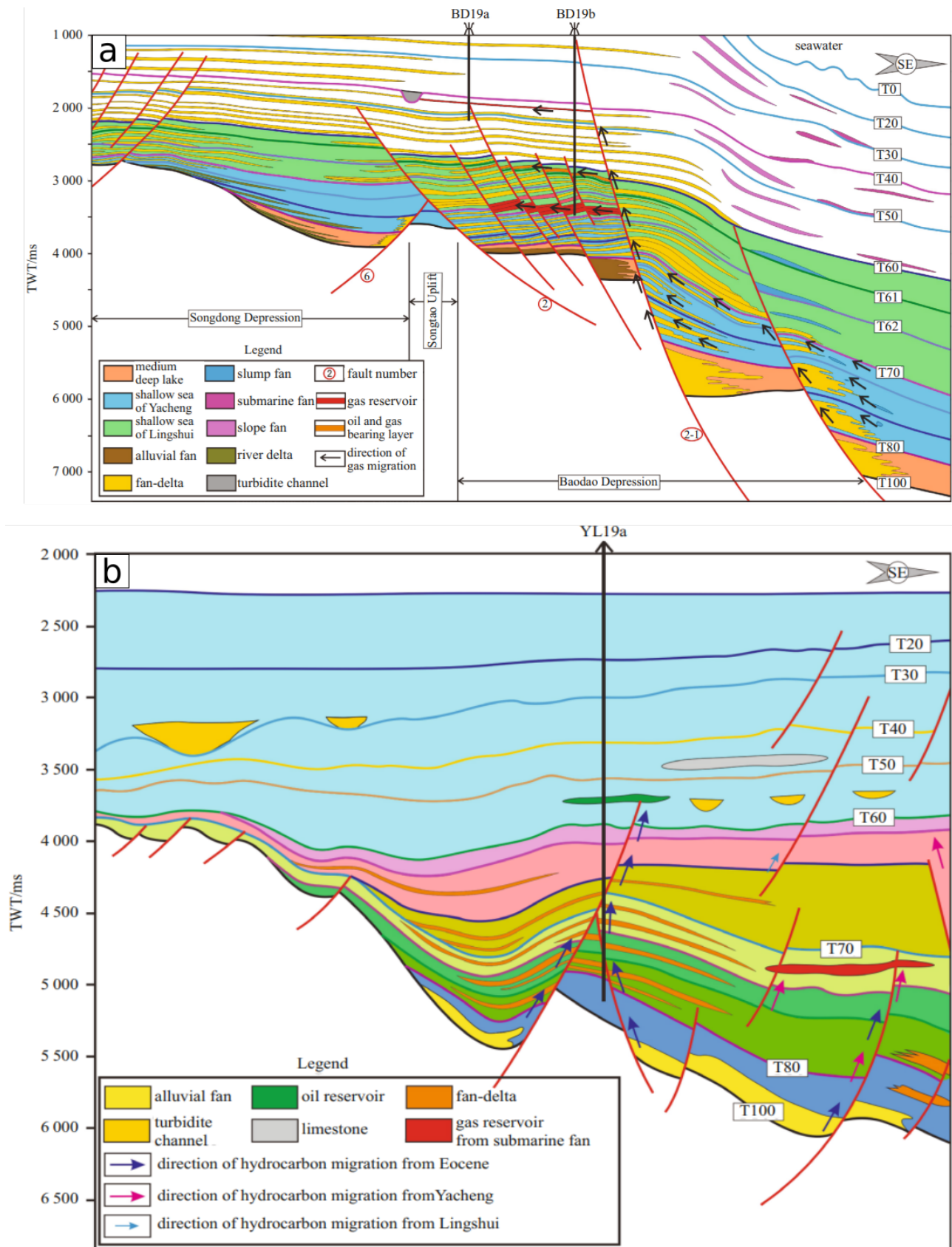


Figure 4.11 Deep-seated fault network controlling hydrocarbon migration in deep-water Qiongdongnan Basin, China. (a) Highly mature coal-bearing source rocks, composed of deep lake shales from Eocene Yacheng Formation, provide gas that migrates laterally via fan-delta

sandstones and vertically through Early-Middle Miocene faults, reaching gas pools of Meishan Formation and Lingshui Formation. Fluid flow comes from the slope zone of Baodao-Changchang Depression, passing by a faulted anticline structure controlled by a fault terrace, and reaches the sand bodies of the Songtao Uplift. There are two wells drilled and seismic horizons mapped from T100 to T0. (b) Three different sourced rocks (Eocene shales, coastal plain coal-bearing mudstones of Yacheng Formation, and shallow marine shales of Lingshui Formation) feeding two reservoirs (gas reservoir from submarine fan sands and above thin limestone oil reservoir of Sanya Formation) through interconnected fault network within the Beijiao Depression. T100 to T0 are seismic horizons and there is one borehole drilled. (Modified from Wang et al., 2014)

5. PAPER

Journal of Petroleum Science and Engineering

SHALLOW STRATA EXPRESSIONS OF LEAKAGE AND SEEPAGE STRUCTURES ASSOCIATED WITH HYDROCARBON MIGRATION: A SEISMIC ANALYSIS ON OFFSHORE BARREIRINHAS BASIN, BRAZILIAN EQUATORIAL MARGIN

--Manuscript Draft--

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Abstract:	The Brazilian Equatorial Margin is an oblique-transform segment with counterparts in the Gulf of Guinea on the West Africa Margin, inherited from the Pangea breakup. These areas are exploratory frontiers where recently petroleum systems were found in deep- and ultra-deep waters. The strike-slip Barreirinhas Basin, at the central portion of the BEM, is conjugated with the oil and gas producers Ivory Coast and Tano basins, whereas the Barreirinhas Basin has no relevant discovered petroleum reservoirs. This present study aimed to identify and map distribution patterns of leakage and seepage features in shallow strata, indicating hydrocarbon accumulations and migration along the offshore Barreirinhas Basin. The investigation used conventional 2D PSTM seismic reflection data with additional application of seismic attributes, including RMS amplitude, instantaneous amplitude, instantaneous frequency, and chaos. Diverse hydrocarbon leakage/seepage structures were identified, including leaking faults, gas chimneys, pockmarks, hydrocarbon-derived diagenetic zones, bottom simulating reflectors, and mounds. Regional morphologic and stratigraphic structures constrain the zones of cold seep occurrences formed by fluid leakage and seepage, which indicate petroleum systems. In the eastern lower continental slope and continental rise, regional normal faults and gas chimneys controls cold seep formation. On the central to northern sectors of the continental rise and abyssal plain, several deep-water mounds are linked by large gas chimneys and faults. There are gravitational gliding systems on the western and central portion of the basin, where the extensional domain is characterized by normal faults, negative flower structures, and gas chimneys that produce cold seeps on the outer shelf and upper slope. These structural controls are related to the compressional domain of the lower continental slope and continental rise, where the decollement zone and series of faults and folds are correlated to pockmarks and deep-water mounds. Near to the western compressional domain, igneous intrusions control the development of leaking faults, gas chimneys, bright spots, and pockmarks. These hydrocarbon-derived structures, cold seeps, and pathways of fluid migration in deep-water indicate potential petroleum systems in the Aptian to Turonian-Oligocene tectono-sedimentary sequences in the central sector of the Brazilian Equatorial Margin.
Suggested Reviewers:	harry roberts hrober3@lsu.edu Expertise in fluid migration within sedimentary basins martin hovland martin.hovland@ambio.no Great knowledge concerning geobiology, marine geology, and fluid seepage within

SHALLOW STRATA EXPRESSIONS OF LEAKAGE AND SEEPAGE STRUCTURES ASSOCIATED WITH HYDROCARBON MIGRATION: A SEISMIC ANALYSIS ON OFFSHORE BARREIRINHAS BASIN, BRAZILIAN EQUATORIAL MARGIN

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ABSTRACT

The Brazilian Equatorial Margin is an oblique-transform segment with counterparts in the Gulf of Guinea on the West Africa Margin, inherited from the Pangea breakup. These areas are exploratory frontiers where recently petroleum systems were found in deep- and ultra-deep waters. The strike-slip Barreirinhas Basin, at the central portion of the BEM, is conjugated with the oil and gas producers Ivory Coast and Tano basins, whereas the Barreirinhas Basin has no relevant discovered petroleum reservoirs. This present study aimed to identify and map distribution patterns of leakage and seepage features in shallow strata, indicating hydrocarbon accumulations and migration along the offshore Barreirinhas Basin. The investigation used conventional 2D PSTM seismic reflection data with additional application of seismic attributes, including RMS amplitude, instantaneous amplitude, instantaneous frequency, and chaos. Diverse hydrocarbon leakage/seepage structures were identified, including leaking faults, gas chimneys, pockmarks, hydrocarbon-derived diagenetic zones, bottom simulating reflectors, and mounds. Regional morphologic and stratigraphic structures constrain the zones of cold seep occurrences formed by fluid leakage and seepage, which indicate petroleum systems. In the eastern lower continental slope and continental rise, regional normal faults and gas chimneys controls cold seep formation. On the central to northern sectors of the continental rise and abyssal plain, several deep-water mounds are linked by large gas chimneys and faults. There are gravitational gliding systems on the western and central portion of the basin, where the extensional domain is characterized by normal faults, negative flower structures, and gas chimneys that produce cold seeps on the outer shelf and upper slope. These structural controls are related to the compressional domain of the lower continental slope and continental rise, where the decollement zone and series of faults and folds are correlated to pockmarks and deep-water mounds. Near to the western compressional domain, igneous intrusions control the development of leaking faults, gas chimneys, bright spots, and pockmarks. These hydrocarbon-derived structures, cold seeps, and pathways of fluid migration in deep-water indicate potential petroleum systems in the Albian to Turonian-Oligocene tectono-sedimentary sequences in the central sector of the Brazilian Equatorial Margin.

Keywords: Brazilian equatorial margin, leakage/seepage structures, hydrocarbon migration, cold seeps, pockmark, deep-water mounds

1. INTRODUCTION

The Brazilian Equatorial Margin (BEM) (Fig. 1) comprises a sequence of divergent and transform continental margin segments developed during the Pangea breakup, from Aptian to Albian (Soares et al., 2007; Krueger et al., 2012; de Castro et al., 2022). The Equatorial Atlantic opening built pull-apart basins in the BEM (Foz do Amazonas, Pará-Maranhão, Barreirinhas, Ceará, and Potiguar Basin) (Azevedo, 1987; Zalán, 2004), and the African counterpart basins within the conjugate Ivory Coast-Ghana Margin in the Gulf of Guinea, West Africa (Brownfield and Charpentier, 2006). Large oceanic fracture zones (Strakhov, Saint Paul, Romanche, and Chain) have an important role in the regional structural control since syn-rift and drift stages, to the present day (Montenegro et al., 2020; Tavares et al., 2020).

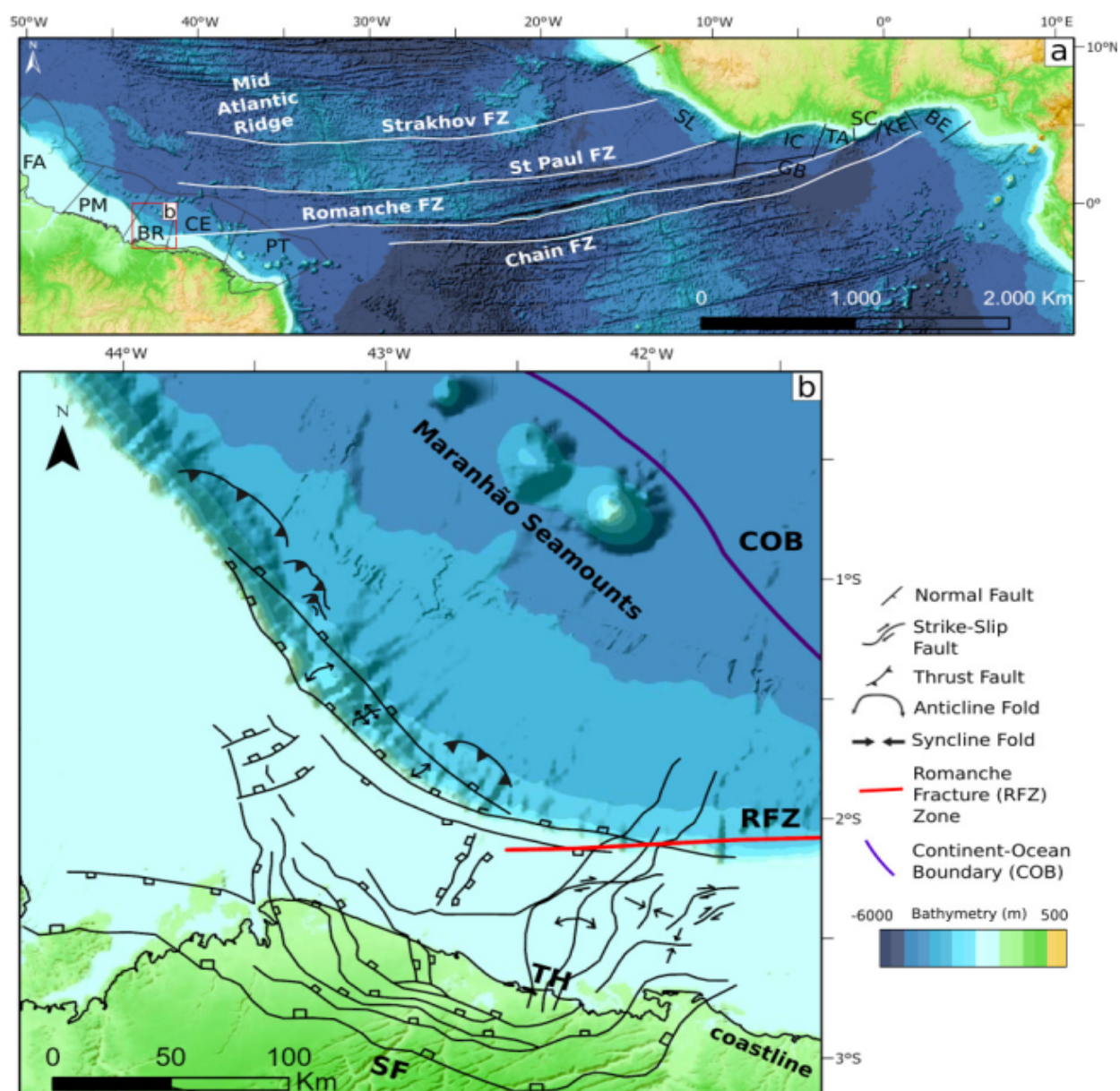


Fig. 1. Regional view of the Equatorial Atlantic and South America-West Africa Conjugate Margins. (a) Bathymetric map showing oceanic fracture zones (FZ), and marginal basins. (b) Simplified geological map of the Barreirinhas Basin with the main structural domains. Basin: BE – Benin; BR – Barreirinhas; CE – Ceará; FA – Foz do Amazonas; GB – Grand Bassam; IC – Ivory Coast; KE – Keta; PM – Pará-Maranhão; PT – Potiguar; SC – Saltpond-Central; SL – Sierra Leone-Liberia; TA – Tano. Structures: SF – Sobradinho Fault; TH – Tutóia High. The bathymetry was extracted from the Nippon Foundation – GEBCO Seabed 2030 project. Structural data compiled from Morrison et al., 2000; Vasconcelos et al., 2004; Veiga et al., 2005; Krueger et al., 2012; Oliveira et al., 2012; Jovane et al., 2016; Maia de Almeida et al., 2020; Montenegro et al., 2020; Oliveira et al., 2020; Tavares et al., 2020.

Recently, large hydrocarbon reserves were found in the Equatorial Atlantic, mainly in deep- and ultra-deep oceanic waters: Lion, Panthere, and Ibex in the Ivory Coast Basin (MacGregor et al., 2003; Brownfield and Charpentier, 2006); Tweneboa, Enyenra, Ntomme, and Jubilee field in the Tano Basin (MacGregor et al., 2003; Tetteh, 2016); El Furrial and Santa Barbara fields from the Eastern Venezuela Basin (Salvador and Leon, 1992); Zaedyus and Liza fields in the Guyana-Suriname Basin (Platon, 2017); Pecém field from the Ceará Basin (Maia de Almeida et al., 2020); Pitu field in the Potiguar Basin (da Silva et al., 2021). These discoveries triggered several investigations aiming to find new reserves in both South America-West Africa margins. However, there are only a few onshore production wells in the Barreirinhas Basin drilled in the Paleozoic pre-rift sequence (Azevedo, 1987), and most of the deep-water basin areas still poorly investigated.

The conjugate Barreirinhas, Ivory Coast, and Tano basins share genetic processes and similarities during their respective tectono-depositional evolution (Basile et al., 1993, 2005; Soares et al., 2007; Antobreh et al., 2009). Those basins do not display evaporites and salt tectonics (Zalán, 2004; Brownfield and Charpentier, 2006; Bempong et al., 2019). Besides, they have abundant source rocks formed in the global event of ocean anoxia (Noguti, 1964; Tari, 2006; Kelly and Doust, 2016). Tilted faulted blocks bear important petroleum systems in the Ivory Coast Basin (Jianping et al., 2010). According to Dailly et al. (2013), a transpressional fold and thrust belt controls extensive petroleum plays from Late Cretaceous to Paleogene in the Tano Basin, which is similar to the faulted blocks and fold and thrust belts also present in the Barreirinhas Basin (Zalán and Warme, 1985; Azevedo, 1987; Davison et al., 2016). Analogously, new discoveries in the Barreirinhas Basin are possible (Wang et al., 2018; de Castro et al., 2022).

Cold seeps, formed by fluid leakage and seepage, are indicators of active petroleum systems, hence interesting proxies for potential reservoirs, particularly on deep-water (Hovland, 2002; Zhang et al., 2021). These features are prolific along transform boundaries and strike-slip settings where fluids escape upward from hydrocarbon reservoirs (Suess, 2014, 2020). Shallow strata leakage and seepage expressions are identified in features such as faults, gas chimneys, pockmarks, bottom simulating reflectors, hydrocarbon-related diagenetic zones, seafloor mounds, mud diapirs, and mud volcanoes (Hovland and Judd, 1992; Hovland and Roy, 2022). Faults and gas chimneys act remobilizing fluids and sediments and cutting throughout the stratigraphy (Cowley and O'Brien, 2000). When high volumes of plastic mud are involved, piercing geological features known as mud diapirs may form (Dimitrov, 2002; Li et al., 2013). Faults, gas

chimneys, and mud diapirs are capable of reaching the seafloor and form depressions known as pockmarks (Hovland and Judd, 1988; Taylor et al., 2000; Chen et al., 2014). Bottom simulating reflectors (BSR) delineate the boundary between above gas hydrate-bearing strata, where the gas hydrate stability zone (GHSZ) occurs, and underlying free gas zone (Chapman et al., 2004; Satyavani et al., 2005; Roberts et al., 2006). The hydrocarbon-related diagenetic zone (HRDZ) is composed of chemosynthetic communities, carbonate cementation, hardgrounds, concretions, nodules, and crusts (Roberts et al., 1990, 2006; Hovland, 2002; León et al., 2007).

A variety of positive seafloor mounds are genetically related to hydrocarbon migration. Mud volcanoes may form by sedimentary and tectonic loading originated from compressional forces, high sedimentation rates, and stacking of overpressured muddy deposits enriched in water and hydrocarbons (Dimitrov, 2002; Chiu et al., 2006; Deville, 2009; Zhong et al., 2021). Other features built by hydrocarbons are gas hydrate mounds, also called hydrate mounds or pingoes (Hovland and Svensen, 2006; Macelloni et al., 2013; Somoza et al., 2014; Zhang et al., 2021). Furthermore, carbonate buildups have been reported associated with cold seeps (Burgess et al., 2013). These features hold a wide range of morphologies, including carbonate mounds, mud mounds, reefs, attached carbonate platforms, isolate carbonate platforms, and so forth. Nevertheless, Hovland et al. (1994b) and Talukder et al. (2007) point out the challenge of differentiate between the various types of seafloor mounds based only in seismic sections, without more refined techniques such as drilling, collected samples, remote operated vehicle (ROV), and autonomous underwater vehicle (AUV) surveys.

The cold seeps are associated with hydrocarbon leakage, seepage, and migration, hence classified as direct hydrocarbon indicator (DHI), very important in the prospection and production of oil- and gas-bearing fields (Chapman et al., 2004; Serié et al., 2012; Zhang et al., 2018; Goulart et al., 2019; Ma et al., 2021; Zhong et al., 2021). First, DHIs are identified based on seismic data, then validated by geochemical survey before a well is drilled. For example, in the Santa Barbara Basin (USA), transpressive deformation creates anticlinal traps, subsequently deformed by thrust faults that worked as conduits from leaking reservoirs, forming cold seeps composed of pockmarks and carbonate mounds (Greene et al., 2006). Cronin & Jubilee Team (2022) identified pockmark trains within canyons and submarine channels of the giant Jubilee oil field, Tano Basin (Ghana).

The present study examines the offshore Barreirinhas Basin (Fig. 1), using conventional 2D seismic, with additional use of RMS amplitude, instantaneous amplitude, instantaneous

frequency, and chaos seismic attributes. These techniques are largely applied in the oil industry to reduce exploratory risks by optimizing the interpretation of conventional seismic lines (Goulart et al., 2019; Obiadi et al., 2019; Conti and Oliva, 2021). The objectives are to map the distribution of leakage and seepage structures, identifying their pathways of migration and respective structural-stratigraphic controls. Based on a comparison between the occurrence of leakage and seepage features on Barreirinhas Basin and the context of petroleum systems of the conjugate African margin, this study might support the potential prospective zones for hydrocarbon accumulation and migration on the offshore petroleum systems.

2. GEOLOGICAL SETTING

2.1 Brazilian Equatorial Margin

The Pangea breakup, in the Lower Cretaceous, built extensive transform margin segments on both edges of the Equatorial Atlantic (Soares et al., 2007; de Castro et al., 2022). Reactivation of shear and suture zones on West Gondwana, inherited from Late Proterozoic Brasiliano/Pan-African Orogen (720-540 Ma), are described as weakness zones, which controlled the development of the several basins (Szatmari et al., 1987; Antobreh et al., 2009; Davison et al., 2016). In the Ivory Coast-Ghana Margin, several oblique-transform basins developed in the Gulf of Guinea, including Sierra Leone-Liberia, Deep Ivorian (sub-basins of Ivory Coast, Tano, and Grand Bassam), Saltpond-Central, Keta, and Benin basins (Lamarche et al., 1997; Tari, 2006; Jianping et al., 2010; Bempong et al., 2019). The BEM segment developed in the South America conjugate margin, encompassing the Foz do Amazonas, Pará-Maranhão, Barreirinhas, Ceará, and Potiguar basins (Fig 1).

All the BEM transform segments are characterized by dextral deformation, trending E-W, triggered by strike-slip tectonics along the ocean fracture zones (Szatmari et al., 1987; de Castro et al., 2022). Particularly in the Barreirinhas Basin, the Romanche Fracture Zone (RFZ) constitutes the mega-structure that segments the Mid-Atlantic Ridge, approximately 3200 km long, extending in both directions of the Brazilian-African conjugate margins (Tavares et al., 2020). The fault offset generated by the strike-slip component can reach 1000 km.

2.2 Barreirinhas Basin

The Barreirinhas Basin is a sedimentary basin located in the BEM, northeastern Brazil, between latitude 0° and 3° S, and longitude 42° W and 44° W (Trosdtorf Junior et al., 2007) (Fig. 1). The area encompasses 46000 km², being 37500 km² offshore and 8500 km² onshore. According to Mohriak (2003), Trosdtorf Junior et al. (2007), and Júnior et al. (2008), the Barreirinhas Basin is limited in the east by the Tutóia High, which delimits the boundary in relation to the Ceará Basin; in the south, the Sobradinho Fault Zone and Sobradinho Platform define the boundary with the crystalline basement; in the western and northwestern corner there is no clear geological boundary in concern to the Pará-Maranhão Basin, usually the frontier between both basins being arbitrarily established by the 44° W meridian.

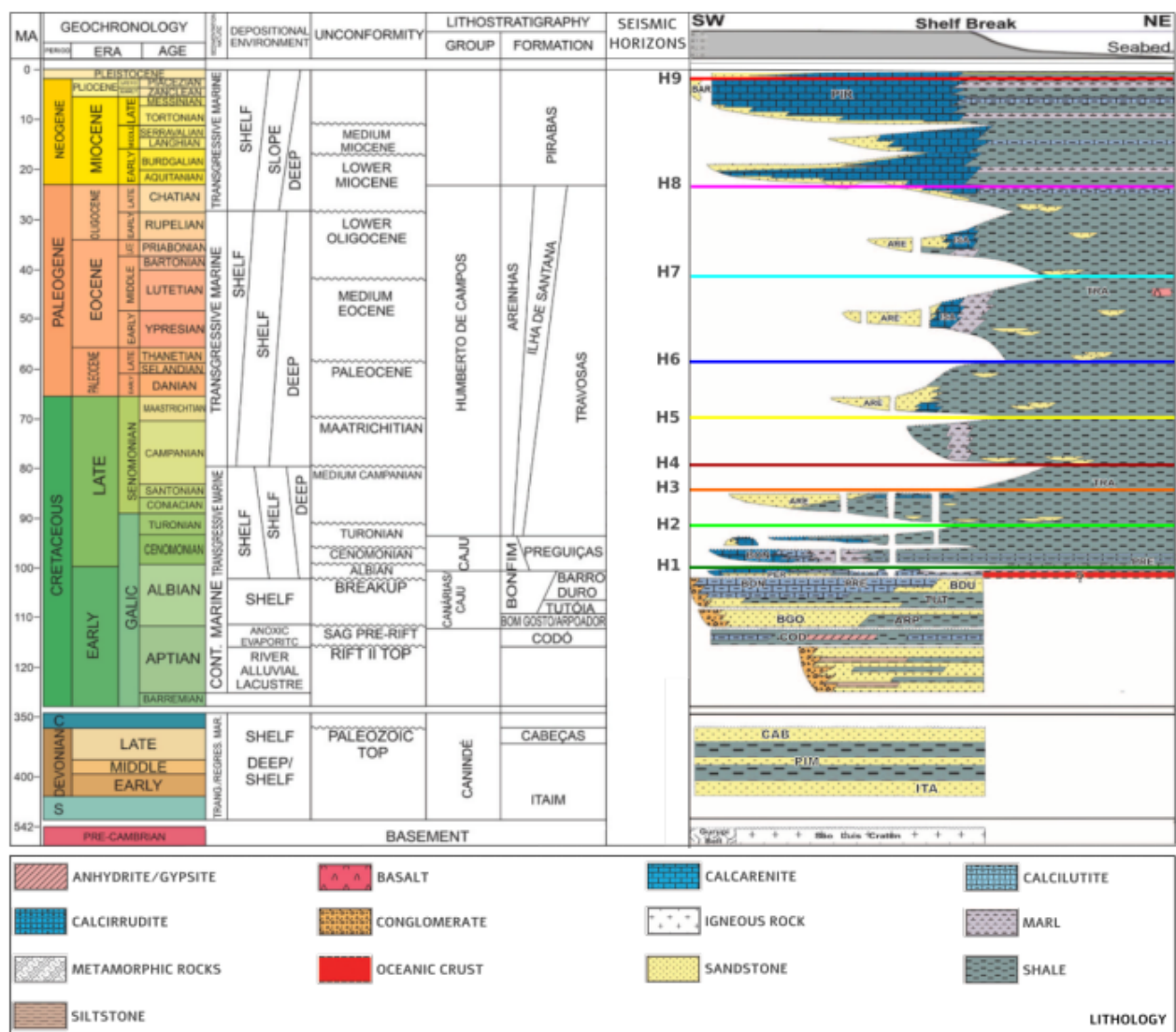
According to Trosdtorf Junior et al. (2007), the Barreirinhas Basin's tectono-sedimentary evolution (Fig. 2) can be analyzed in the following stages: pre-rift (Paleozoic), rift/sag (Aptian to Albian), and drift (Late Albian to Recent). The rift stage during the Pangea breakup started on Aptian (125 Ma) and extended till Albian (102 Ma), setting up the conjugate margins of Barreirinhas (Brazil), Ivory Coast (Ivory Coast) and Tano (Ghana) basins (Basile et al., 1993; Soares et al., 2007; Pellegrini & Ribeiro, 2018). The rifting generated stretching and thinning of the lithosphere because of normal listric faulting and mechanical subsidence, with depocenters formed in E to ENE trending rhombic grabens and filled with thick non-marine sediments (Davison et al., 2016; Montenegro et al., 2020).

The end of the rift stage was in 112 Ma, forming anoxic salt lagoons in a sag setting (Codó Formation) and endured until 102 Ma, when the BEM and West Africa were completely separated, establishing a breakup discordance (Soares et al., 2007; Antobreh et al., 2009). It was raised an ocean connection amidst South and Central Atlantic, around 100-90 Ma, demarcating the onset of the drift stage. The drift stage developed three depositional sequences within transgressive-regressive cycles: first, Late Albian-Turonian prevailing carbonate sedimentation (Caju Group); then, the establishment of a passive margin and drowning of the carbonate platform originated Turonian-Oligocene siliciclastic deposition (Humberto de Campos Group) with magmatic activity on the offshore Barreirinhas Basin during the Eocene; last, Miocene to recent marine transgression returns to the carbonate deposition (Pirabas Formation), with relative absence of relevant fluvial sediment charging. Coastal progradation and fluvial drainages built sandstones, argillites and unconsolidated argillaceous sediments of the Barreiras Formation (Trosdtorf Junior et al., 2007).

Transtensional regime in Barreirinhas Basin developed a narrow continental margin, steep continental slope, and an abrupt transition (~20 km) among continental and oceanic crusts (Basile et al., 1993; Lamarche et al., 1997; de Castro et al., 2022). Low magma production during initial rifting stages, development of negative flower structures, wipeout seismic zones and rotated blocks are typical of these oblique transform margins (Basile, 2015). Transpression style is observed locally in the Barreirinhas Basin, originating positive flower structures and inversion of normal faults (Zalán, 2004) associated with diachronous subsidence and uplift events forced by transtension and transpression regimes in different segments of the conjugate margin (de Lépinay et al., 2016). Furthermore, the BEM does not have the evaporitic transitional sequence of the Aptian and neither salt tectonics (Zalán, 2004).

The oblique-transform continental margin strain and strike-slip movements along the RFZ controlled the depositional evolution of Barreirinhas Basin. The RFZ segmented the Barreirinhas Basin in two sub-basins (Mesner and Wooldridge, 1964; Montenegro et al., 2020). At the south of RFZ, the basin comprises the continental shelf and the onshore portion in a typical rift pattern. Here, the grabens and horsts formation are controlled by high-angle normal listric faults, synthetic, south-dipping. From Albian to Cenomanian (~100 Ma), alterations in plate movement vectors must have acted, promoting transpression of the rifted margin (Zalán and Warme, 1985; Azevedo, 1987), resulting in an approximately 500 km long and 70 km wide fold and thrust region on BEM-West Africa Conjugate Margin (Davison et al., 2016). North of the RFZ, the deep-water basin developed as a classic passive margin inherited from thermal subsidence, with north-dipping normal faults (Montenegro et al., 2020). In the Cenozoic, systems of normal and thrust faults affect all the post-Cretaceous units and current sediments in periods of relative tectonic quiescence (Trosdorf Junior et al., 2007; Krueger et al., 2012).

Gravitational gliding systems, linked to extensional-compressional domains, have been reported on deep-waters within the central and western portions of Barreirinhas Basin (Zalán, 2011; Krueger et al., 2012; Oliveira et al., 2012). Zalán (2009) subdivides gravitational gliding systems in three structural domains and Oliveira et al. (2012) applied this concept to the Barreirinhas Basin. The extensional domain is proximal and predominates synthetic listric normal faults, seaward-dipping, with minor landward-dipping antithetic planar normal faults. Growth and listric faults thicken strata on the flanks and thinning onto the top of rollover structures. There are superimposed styles of deformation with both normal and thrust faults originating detached folds and growth anticlines in the transitional or translational domain. The compressional domain is a 40 km wide distal zone of imbricate thrusting and folding near lower continental slope and continental rise. Krueger et al. (2012) and Oliveira et al. (2012) attribute the gravitational cells formation to the combined effect of the RFZ, steep slope, high sedimentation rates, and high pore pressure occurred during the drift stage. The RFZ influenced deformation through the extensional domain, whereas sedimentary loading deformed the toe slope, and Late Cretaceous overpressured shales formed the main detachment zone (Zalán, 2011). Such instabilities are responsible for generation of submarine landslides, mass transport, and turbidites, depositing sedimentary packages expressive both vertically and laterally (Júnior et al., 2008; Araújo et al., 2009).



3. MATERIALS AND METHODS

The seismic dataset and the well logs were provided by Brazilian Oil, Gas, and Biofuel Agency (ANP). The multi-channel seismic profiles were acquired in the 2000 year, using the conventional seismic reflection method. The seismic profiles were obtained throughout the Barreirinhas Basin offshore zone (Fig. 3) as a product of a main grid of 2D dip and strike lines spaced by 4 km, transverse and longitudinal to the coastline, respectively, with minor oblique 2D grids, with total of 45.000 km². Data processing was taken in post-stack time migration (PSTM) with seismic profiles showed in two-way travel time (TWT), in milliseconds, and reversed polarity (SEG convention) with red reflectors attributed to positive polarity and blue reflectors corresponding to negative polarity.

Petrel E&P Software Platform was used to seismic interpretation, based on the concepts of seismic stratigraphy established by Mitchum et al. (1977) and Catuneanu (2006). Measurements are taken on time, in milliseconds (ms), for vertical strata, and in meters (m) for horizontal scale. Seismic-to-well tie was used for calibration of the seismic interpretation, correlating subsurface measurements obtained at a well-bore, measured in depth, with seismic data measured in time. Sonic logs were utilized to convert data from distance to time. Seven wells were provided by ANP, five on the continental shelf and two on the continental rise. Nine chronostratigraphic seismic horizons (Fig. 2) were established through biostratigraphy and seismic-to-well tie, analyzing seismic facies and patterns of reflectors termination, amplitude, geometry, continuity, thickness, and frequency. The chronostratigraphic well's information extracted from wells of the continental shelf were extrapolated to deep-waters domain. Seismic attributes RMS Amplitude and instantaneous amplitude were applied to enhance amplitude anomalies caused by BSRs, GHSZs, free gas zones, gas pockets, and HRDZs. Instantaneous frequency optimized the visualization of low-frequencies in free gas zones, GHSZs, gas chimneys, and faults. Chaos attribute improved recognition of chaotic facies of fluid migration pathways, faults, and gas chimneys.

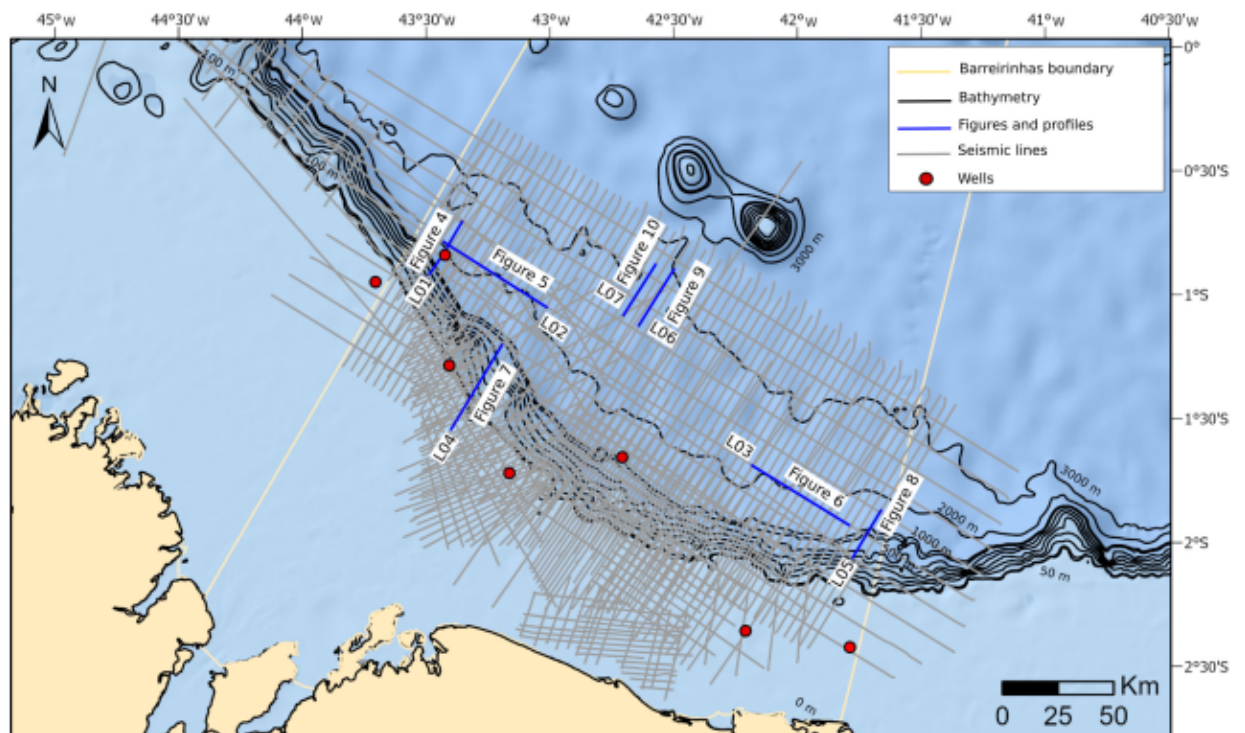


Fig. 3. Location map of the seismic lines and wells used in this study. The bathymetry was extracted from CPRM (Brazilian Geological Survey) through the works of Ladeira Neto and Roza (2013) and Becker et al. (2009).

4. RESULTS

4.1 Leakage and Seepage Features

The seismic analyses of the 2D conventional profiles throughout deep-waters of the outer shelf, continental slope, continental rise and abyssal plain of Barreirinhas Basin resulted in the identification of several shallow strata expressions of leakage and seepage associated with hydrocarbon migration. Such expressions include leaking faults, gas chimneys, BSRs, HRDZs, pockmarks and mounds. Table 1 discriminates the spatial distribution of the identified features and their main characteristics. Each one of them is contextualized in the following sections.

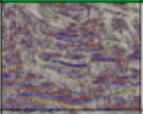
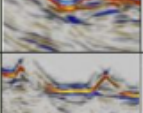
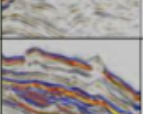
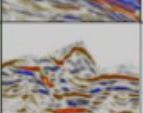
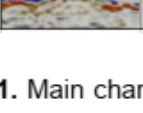
Structure	Seismic	Distribution	Characteristics
Fault		Regional faults throughout the outer shelf, shelf break, and upper slope. A fold and thrust belt occur on the central and western sector. Local faults are widespread.	Low amplitude, low frequency, pull-up, wipeout zones, bright spots, chaotic reflections. Great variety of structural styles. Association with gas chimneys, pockmarks, HRDZs, BSRs, and mounds.
Gas Chimney		Widespread through the basin, especially near the shelf break, upper slope, and on the central sector of the abyssal plain.	Low to faded amplitude, low frequency, pull-down, pull-up, chaotic reflections. Lower size on the shelf; higher size on the continental slope and basin. Directly linked to faults. Associated also with pockmarks, BSRs, mounds, and HRDZs.
Pockmark		Distributed over the studied area. Concentration on the continental slope, continental rise, and abyssal plain.	Circular to elliptical depressions. Most are small; large structures on the distal parts of the basin. Always coupled to gas chimneys or faults. Also related to mounds, HRDZs, and BSRs.
HRDZ		Present on the continental slope, mainly on the western sector. Few occurrences on the abyssal plain.	Always fed by gas chimneys and/or faults, producing small mounds and pavements with sharp peaks or more gentle rounded crests with high amplitude, pull-up effect and stack response degradation. Correlated to pockmarks, BSRs, and mounds.
BSR		Distributed over the slope, sometimes reaching the continental rise in the central and eastern sector.	High to very high amplitude, sub-parallel to the seafloor, reverse polarity, lateral continuity, crosscut the stratigraphy. Amplitude blanking and higher frequencies above. Frequency attenuation below. Disruption made by faults and chimneys. Associated to mounds, HRDZs, and pockmarks.
Mound		Abundant on the central to northern section of the continental rise and abyssal plain. Important occurrences between the lower-slope and the continental rise of the western sector. Sparse specimen scattered through other sectors of the basin.	Low amplitude, low frequency, pull-up, blank zones, bright spots, and chaotic reflections. Convex-up, rounded, cusate to cone-shaped. Usually found in clusters of small size. Giants are only present on the central abyssal plain. Always linked to chimneys and/or faults. Associations BSRs, pockmarks, and HRDZs.

Table 1. Main characteristics and distribution of structures associated with hydrocarbon migration in the Barreirinhas basin.

4.1.1 Faults

Faults constitute the most important conduits of fluid migration on the Barreirinhas Basin. Fractures and gas chimneys are also related to the faults, forming an intricate network where sedimentary sequences and hydrocarbons are remobilized from deep sources, migrate upward, and build pockmarks, HRDZs, and mounds (Figs. 4 to 10). BSRs are frequently disrupted by faults, indicating active seepage of free gas.

Identification of the faults are made by visualization of low amplitude, low frequency, chaotic reflections, variations in the dip direction, displacement, pull-up effect, and juxtaposition of different strata. Instantaneous frequency (Fig. 8c) and chaos (Figs. 5b, 8d, 9b, and 10b) highlights low frequencies and chaotic reflectors, respectively. Blank zones, wipeout zones, and bright spots are commonly seen due to the seepage of hydrocarbons and accumulation of gas hydrates (Figs. 5g, 7, and 8).

Regional faults along the whole extension of the basin include extensional faults on the outer shelf, shelf break, and upper slope (Fig. 11). Negative flower structures are also common. Sometimes thrusts develop due to inversion of normal faults and build positive flower structures. On the central and western basin, the extensional faults are linked to gravity tectonics (Figs. 4 and 5). The proximal part has an extensional style dominated by listric normal faults, seaward-dipping, with minor antithetic normal faults, landward-dipping. The distal domain built a fold and thrust belt. A first phase of compression developed a basal decollement where thrust faults have formed in piggy-back manner. Local backthrusts and kink bands also occur. Later, a second phase of compression originated another basal decollement that assembled to the older, constructing huge fault-propagation-folds and fault-bend-folds. Overlain such complex structures, pockmarks and mounds are present on the seafloor (Figs. 4 and 5).

The Figure 4 shows the older basal decollement below 5500 ms, accompanied by imbricate thrusts in piggy-back style. The second decollement is steeper upward and flattens out downward on the older one, controlling more pronounced thrusts and minor normal and thrusts faults. Drag against the hanging wall built a large asymmetric anticlinal fault-bend-fold, whose crest outcrops at the seafloor and is excavated, forming pockmarks. Active sedimentation has formed a marginal levee with pockmark upon the buried fold backlimb. An angular unconformity delimits the fold forelimb and overlies overlapping strata. The structural style showed in the left corner of the Figure 5 is very similar to the above described, with the basal decollement present above 6000 ms, developing series of imbricate thrusts, backthrusts, kink bands, pop-ups, and box folds arranged in piggy-back manner. The younger decollement is located above 5000 ms, forming a huge anticlinal fault-bend-fold terminated against onlaps of the contemporaneous sedimentation.

Local faults of the Barreirinhas Basin are correlated to canyons, deep channels, thalwegs, channel avulsion, BSRs disruption, pockmarks, HRDZs, and mounds. Large gas chimneys can have internal faults and fractures.

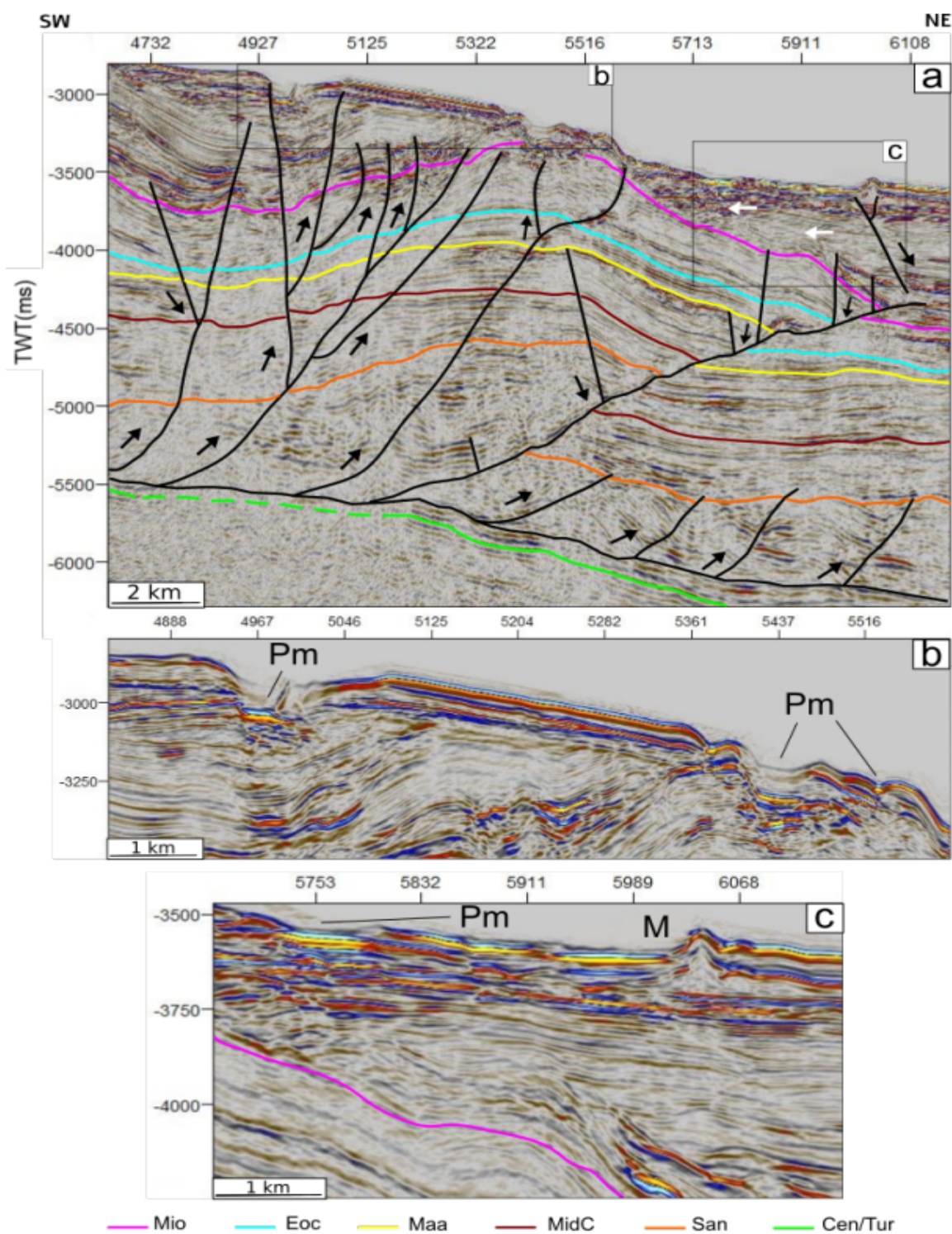


Fig. 4. Seismic profile L01 (location in Fig. 3), showing hydrocarbon migration related to gravitational cells on the transition between the lower-slope and continental rise, western sector of the Barreirinhas basin. (a) Compressional domain of the gravitational gliding system. Pockmarks (Pm) and a conic mound (M) are present on the seabottom. White arrows represent onlapping

strata, whereas black arrows represent fault vergence. (b) and (c) are zoomed boxes of the outcropping features. Seismic Horizons: Mio – H8; Eoc – H7; Maa – H5; MidC – H4; San – H3; Cen/Tur – H2.

4.1.2 Gas Chimneys

The gas chimneys are widespread in the Barreirinhas basin wherever occur fluid migration, being closely associated with faults. They are particularly abundant on the outer continental shelf near the shelf break, upper slope, and on the central sector of the abyssal plain (Fig. 11). Seismically, the gas chimneys display low to faded amplitude, low frequency, and chaotic reflections. Instantaneous amplitude (Fig. 6b) highlights the contrast of chimneys in relation to higher amplitudes, whereas instantaneous frequency (Fig. 6c) emphasizes low frequencies, and chaos (Figs. 5b, 6d, 9b, and 10b) enhances randomness produced by backscattering. Sometimes the gas chimneys create pull-down or pull-up effects due to lithology/fluid contrasts of low and high acoustic impedance, respectively. Pull-down features probably result from low density – low velocity – gas seepage, and the pull-up effect should be the result of higher velocity strata like carbonates or gas hydrate filling porous sands, which increases the rock density.

Deep channels thalwegs may be controlled by gas chimneys where occur fluid migration (Fig. 6). Pockmarks (Figs. 5 and 6), BSRs, HRDZs, and mounds (Figs. 9 and 10) are also commonly seen associated with gas chimneys. Those conduits vary in size across the continental margin. For instance, on the shelf, they reach 400-470 ms in vertical length, while on the slope they reach up to 900-1200 ms. On the abyssal plain most of gas chimneys have < 400 ms, but big ones measure an average of 1700 ms and occasionally reach more than 2300 ms in vertical length. Clearly, the size is a function of depth, related to different source layers. The gas chimney morphology is usually narrow cylindrical (80m to 500 m), varying to wider forms and gas clouds (500 m to 1900 m). On the Figure 9, the gas chimney is 2132 ms long and 1100 m wide, while the feature of the Figure 10 is 2631 ms long and 1888 m wide.

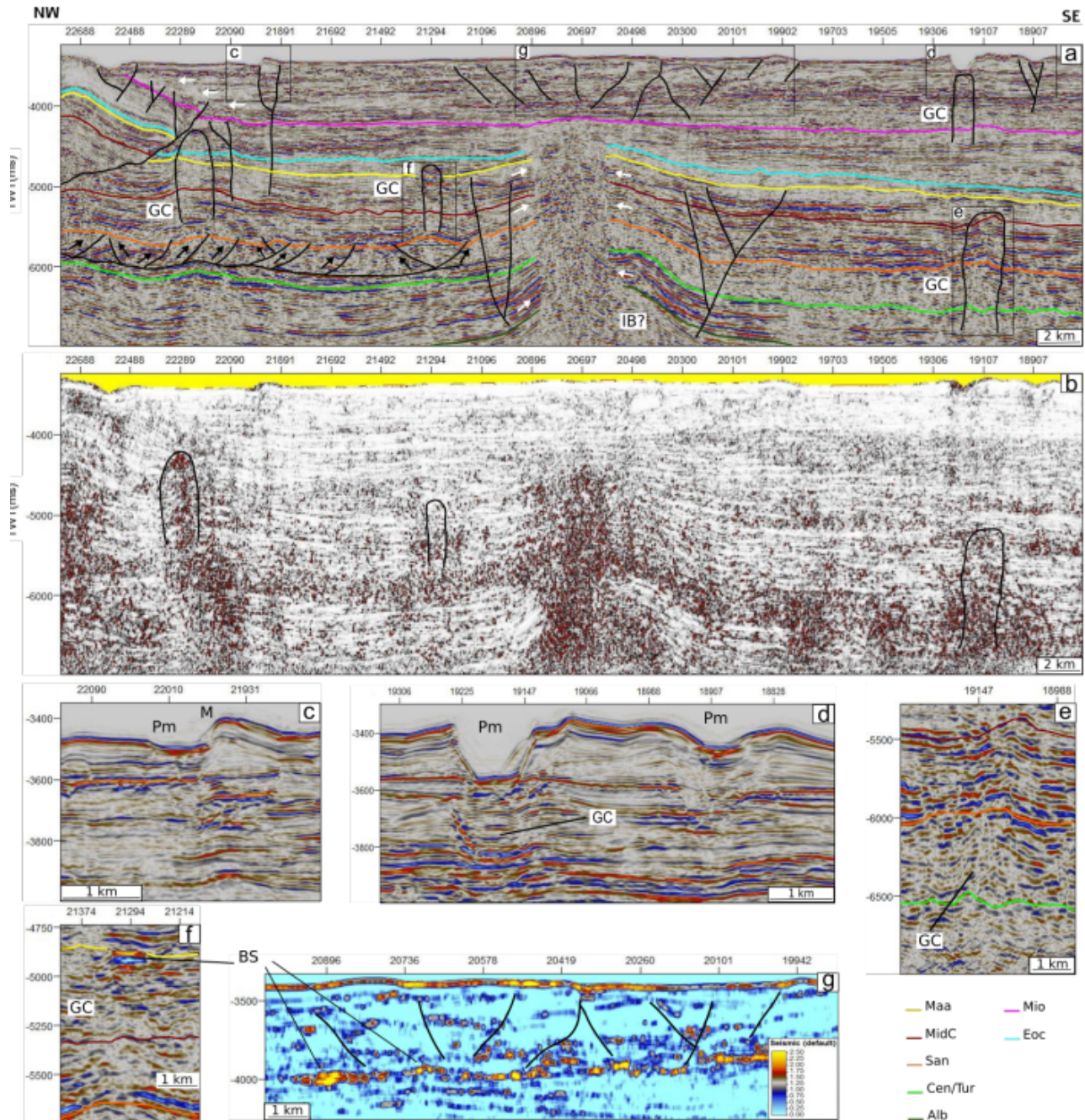


Fig. 5. Seismic profile L02 crossing the transition between the continental rise and abyssal plain in the basin western sector (location in Fig. 3). (a) A possible intrusive body (IB) is present in the center. Four cylindrical-shaped gas chimneys (GC) are also present. Black arrows represent the fault vergence. (b) both gas chimneys and faults are enhanced by the chaos attribute. (c) and (d) pockmarks (Pm) and mound (M) on the seafloor. (e) and (f) details of the gas chimneys. (g) RMS amplitude attribute of faulted region highlighting several bright spots (BS). Horizons: Mio – H8; Eoc – H7; Maa – H5; MidC – H4; San – H3; Cen/Tur – H2; Alb – H1.

4.1.3 Pockmarks

These features are distributed overall in the Barreirinhas Basin (Fig. 11), individually or in clusters, always connected with gas chimneys and/or faults. Pockmarks are notably numerous throughout the slope, commonly within canyons and deep channels thalwegs, associated with BSRs (Figs. 6 and 8) and HRDZs (Figs. 7 and 8). Agglomerations are found in different sectors of the basin; on the eastern lower slope and continental rise, pockmarks are abundant inside meandering channels and genetically related to BSRs (Fig. 6). On the central and northern abyssal plain, they are associated with mounds. Into the western edge, there is an agglomeration of pockmarks between the lower-slope and the continental rise (Figs. 4 and 5). There, a fold and thrust belt inherited from gravitational cells is cut by leaking faults and gas chimneys that create pathways for upward gas migration.

Pockmarks are recognized by circular to elliptical depressions on the surface and subsurface, linked to conduits that transport fluids upward. It is also common to have bright spots within or below the pockmarks (Figs. 6 and 8). These structures can be partially or totally buried by sediments. Most of the pockmarks are small depressions with < 500 m in diameter. Notwithstanding, there are huge pockmarks up to 1000 m in diameter, especially on the lower-slope and continental rise. The large depressions and craters usually have smaller pockmarks inside and slumping borders that partially fill the space.

The Figure 6 shows deep-water channels with large quantities of sediment and organic matter that destabilize and are carried by gas chimneys, forming pockmarks. A small pockmark is buried, whereas two other pockmarks are partially buried due to coalescence of channels that fill the depressions. On the left, the pockmark is fed by a narrow gas chimney, whereas the pockmark on the right is sourced by a wide gas chimney that forms a gas cloud. Both pockmarks are underlain by bright spots. These high-amplitude reflections probably result from gas-bearing strata.

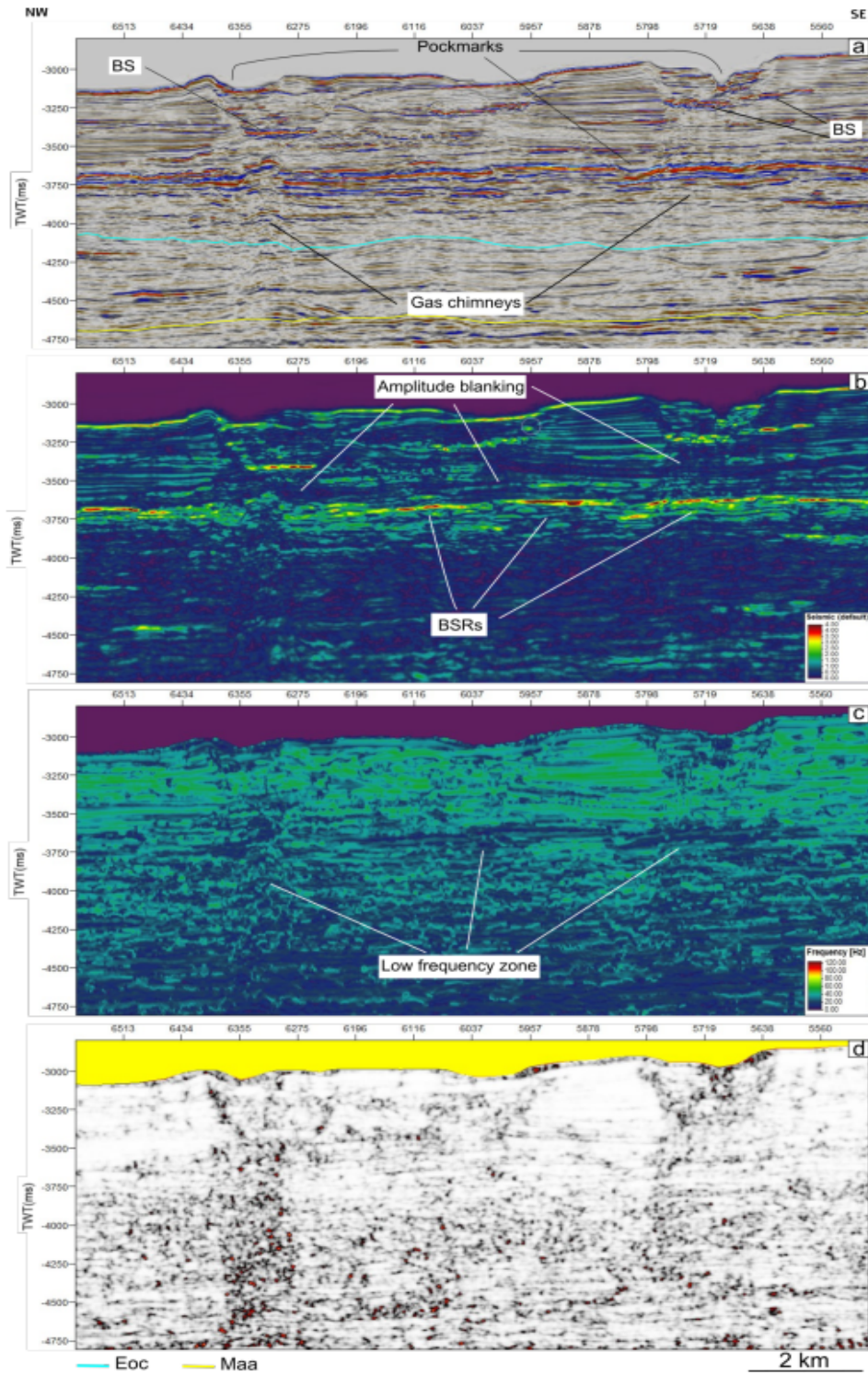


Fig. 6. Seismic profile L03 on the eastern sector of the continental rise. (a) Pockmarks associated with bottom simulating reflectors (BSRs) and gas chimneys. There are bright spots (BS) below the pockmarks. (b) small BSRs with loss of amplitude above and disrupted by gas chimneys,

highlighted by low frequency zones (c). The upward fluid migration pathway and pockmarks depressions are clearly seen with the chaos attribute (d). Horizons: Eoc – H7; Maa – H5.

4.1.4 *Hydrocarbon-Related Diagenetic Zone (HRDZ)*

HRDZs occur on the continental slope, markedly on the western sector of the Barreirinhas basin (Fig. 11). However, few occurrences are present on the continental rise. These features are always sourced by faults and gas chimneys, also associated with pockmarks, BSRs, and mounds (Fig. 8). The HRDZs display high amplitude. Where the features outcrop, they build small mounds and pavements that terminate in sharp peaks or more gentle rounded crests with the same polarity as the seafloor. Below them, pull-up effect and stack response degradation are always present (Figs. 7c and 7d). Instantaneous frequency and chaos are very useful seismic attributes to evidence low frequency and chaotic patterns generated by the fluid migration below the HRDZs (Figs. 8c and 8d).

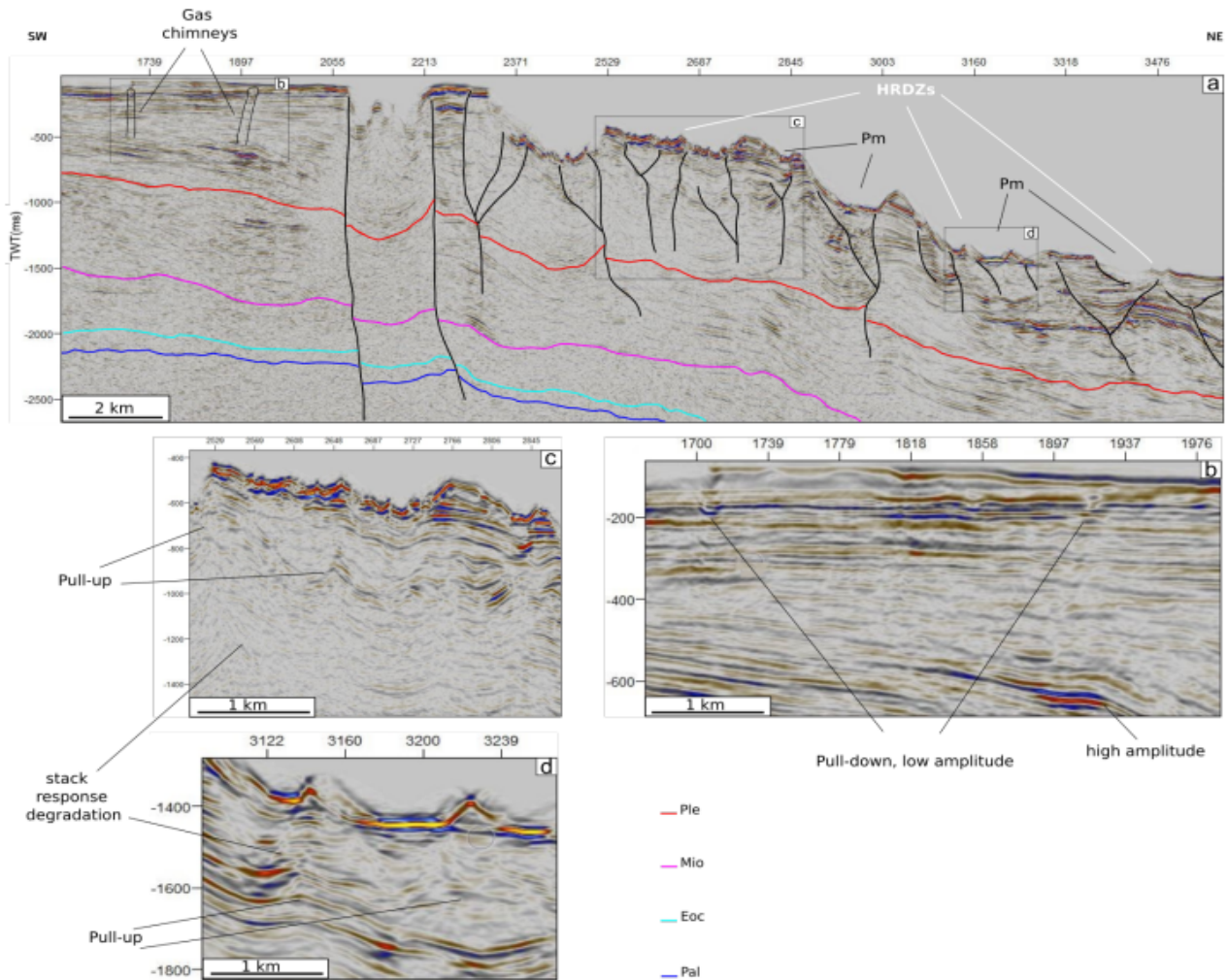


Fig. 7. Seismic profile L04 through the outer shelf-upper continental slope of the extensional domain. (a) Gas chimneys near the shelf break, hydrocarbon-related diagenetic zone (HRDZ), and pockmarks (Pm) throughout the slope. Both HRDZs and pockmarks are controlled by leaking faults. Inset in (b) shows two small, low amplitude gas chimneys with pull-down effects. High amplitude reflectors possibly been gas hydrate-bearing strata. (c) and (d) sharp, mounded HRDZs with terminations in high amplitude, pull-up effect, and stack response degradation due to the upward fluid migration. Horizons: Ple – H9; Mio – H8; Eoc – H7; Pal – H6.

4.1.5 Bottom Simulating Reflectors (BSR)

BSRs are abundant from the upper-slope to the lower-slope and continental rise, eventually spanning to the abyssal plain, mainly in the eastern sector of the Barreirinhas basin (Fig. 11). They are usually overlain by canyons, deep channels, mass movements complexes, and contourite drifts (Figs. 6 and 8). BSRs are sub-parallel to the seafloor. It is common to see them crosscutting the stratigraphy. Generally, the BSRs display high to

very high amplitude reflections and show reversed polarity. Instantaneous amplitude is useful to evidence the high amplitude anomaly and amplitude blanking above the BSRs (Figs. 6b and 8b). Instantaneous frequency highlights the low frequency below and higher frequencies upon (Figs. 6c and 8c). Most BSRs have lateral continuity, although discontinuous also occurs. Local disruptions are made by faults and gas chimneys that remobilize deep gas sources upward. In this situation, pockmarks, HRDZs, and mounds may form. Features with moderate to high amplitude, discontinuous, and underlain by smooth low frequency zone should be BSRs. Those apparently are also related to the mentioned expressions of hydrocarbon migration, but it is more difficult to clearly categorize them as BSRs.

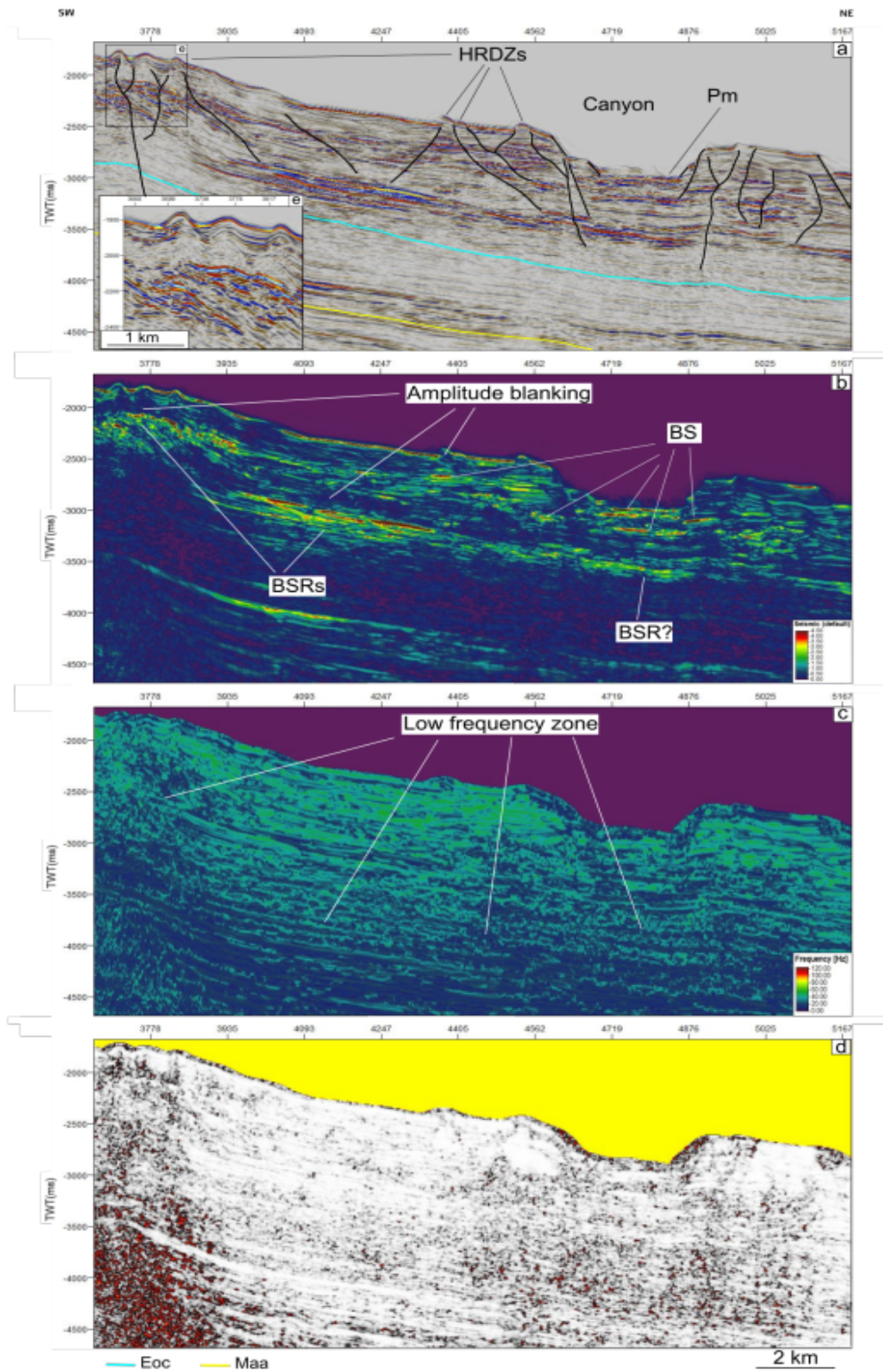


Fig. 8. Seismic profile L05 showing cold seeps on the lower continental slope. (a) pockmark (Pm) within the canyon area, two bottom simulating reflectors (BSRs) on the left, and several

hydrocarbon-related diagenetic zone (HRDZ). (b) a possible BSR underneath the pockmark displays high amplitude and reverse polarity in relation to the seafloor, and is overlaid by amplitude blanking highlighted using the instantaneous amplitude attribute. (c) instantaneous frequency attribute revealing frequency attenuation zone below the BSRs. (d) chaos attribute indicates free gas feeding mounded HRDZs (e). Bright spots (BS) (b) and high frequency reflections (c) below the canyon and adjacent HRDZs are indicative of gas hydrate charging. Horizons: Eoc – H7; Maa – H5.

4.1.6 Mounds

In the central to northern sector of the continental rise and abyssal plain, there is a profusion of mounds (Figs. 9, 10, and 11). Important occurrences are also present between the lower-slope and continental rise of the basin western sector, related to the gravitational cells and contemporaneous deposition (Figs. 4 and 5). Minor mounds are scattered through other sectors of the abyssal plain, continental rise, lower-slope, and middle-slope.

All the mounds are found in deep-waters, ranging from 760 m to 3250 m. They form positive topographic features, convex-up, with varied morphologies, from rounded, cusped to cone-shaped. Faults can act displacing the mounds, making their geometry even more complex. The mounds are commonly seen in clusters, connected to faults, fractures and gas chimneys. Associations with pockmarks and BSRs are also common. Seismically, the bodies display low amplitude, low frequency, pull-up, and chaotic reflections. Instantaneous frequency and chaos (Figs. 9b and 10b) enhance the visualization of low frequencies and random reflectors. Both mounds and conduits can show weak reflections, although lack of internal reflections are also reported. Blank zones and bright spots are common. The feeding conduits have pull-up effects only within the structure, and deformation of the adjacent strata is incipient or absent.

The mounds' size varies greatly. Most have < 400 m wide and < 100 ms high. Giant mounds greater than 2500 m in diameter and > 400 ms high are found on the central sector of the abyssal plain, as the mound 458 ms high and 2745 m wide showed in the Figure 10. Clearly the size of the features arising the seafloor is a function of depth and proportional to the bulk material conducted by the faults, fractures and gas chimneys.

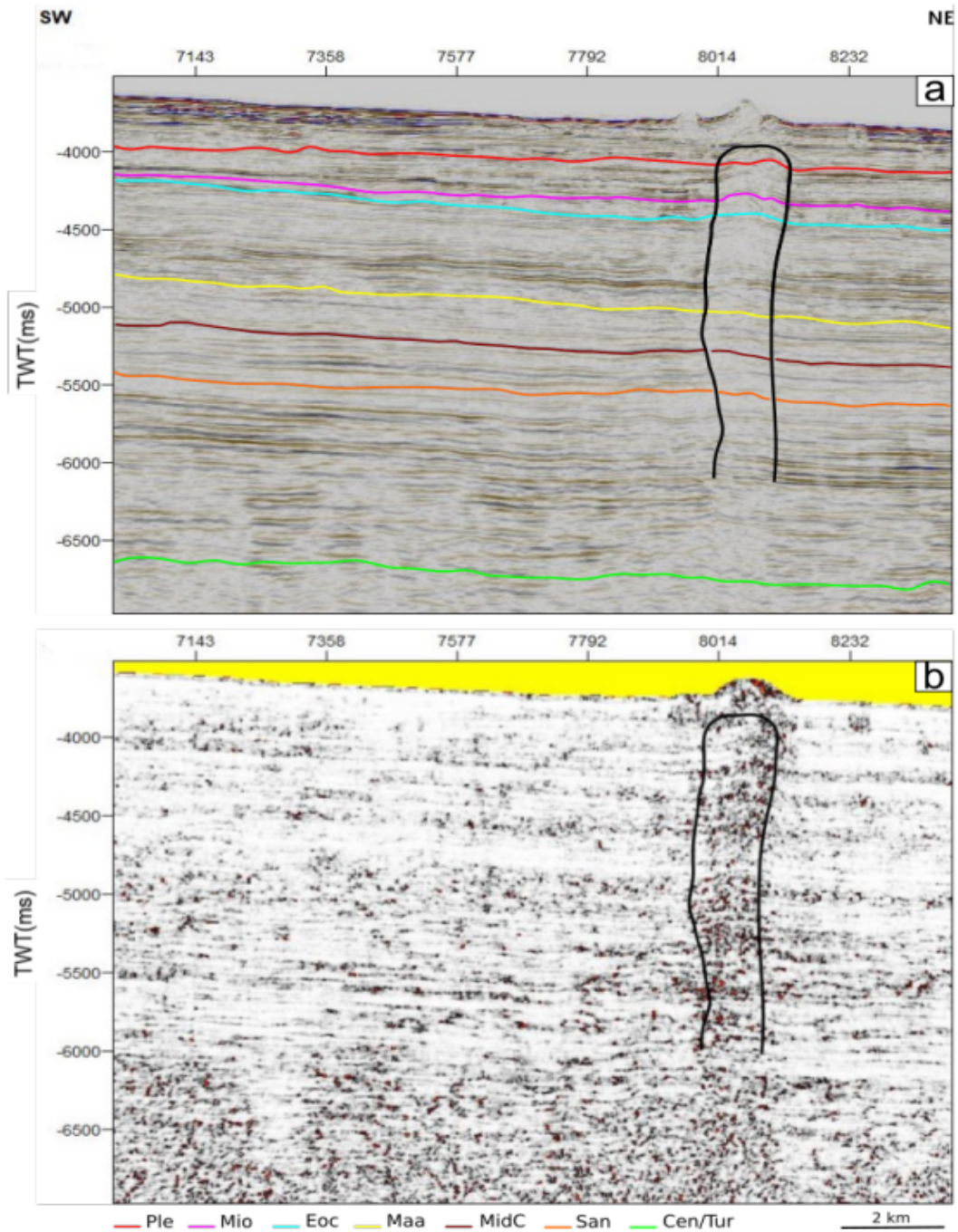


Fig. 9. Seismic profile L06 showing deep-water mounds outcropping on the seafloor. The mounds are located in ~ 2,84 km water depth in the central sector of the abyssal plain. They are fed by a huge gas chimney. (a) Both mounds and chimney display weak, low amplitude, and chaotic reflections. (b) Chaos attribute highlights internal faults, fractures, and pull-up events within the chimney that reflects the upward fluid migration. Horizons: Ple – H9; Mio – H8; Eoc – H7; Maa – H5; MidC – H4; San – H3; Cen/Tur – H2.

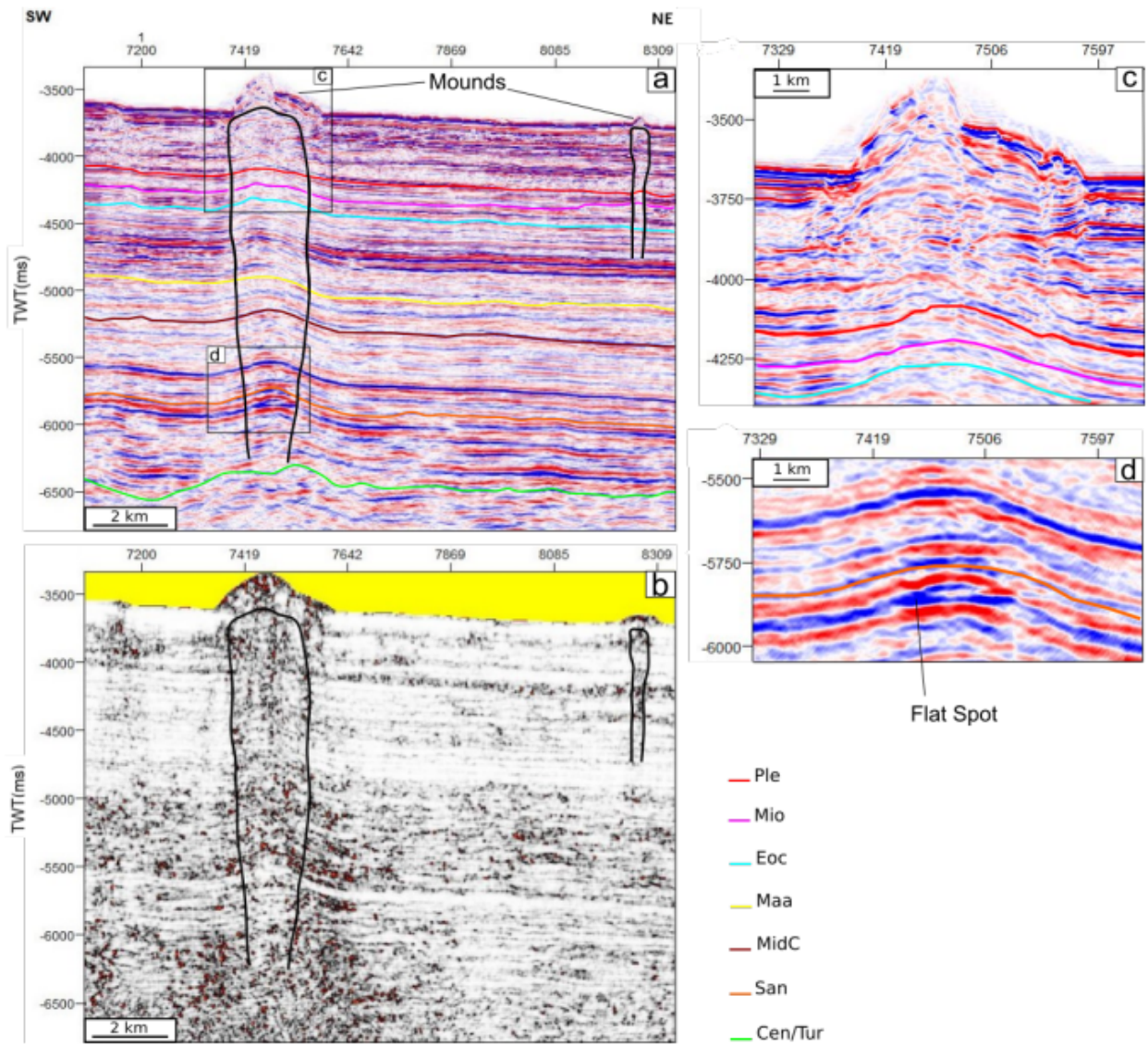


Fig. 10. Seismic profile L07 showing giant mound located in 2,76 km of water depth within the abyssal plain. The seismic section (a) and chaos attribute (b) show an expressive mound sourced by a deep gas chimney. Internal faults, fractures, and pull-up are clearly seen inside the chimney. On the right, a smaller conduit fed a shallow muddy stratum above high amplitude reflectors, forming a small mound on the seafloor. Zoomed box (c) depicts the giant mound appearance, and (d) exhibits an antiform strata with flat spot, evidencing hydrocarbon accumulation. Horizons: Ple – H9; Mio – H8; Eoc – H7; Maa – H5; MidC – H4; San – H3; Cen/Tur – H2.

5. DISCUSSION

5.1 Leakage and Seepage Structures Controls, Mapping, and Implications for the Petroleum Systems

The spatial distribution of the shallow structures derived from hydrocarbon migration and the major structural controls are shown in Figure 11. In the Barreirinhas Basin, leakage and seepage structures are concentrated in four regions: 1) the western gravitational gliding system; 2) neighboring areas of igneous intrusions; 3) the transition of the continental slope and the continental rise on the east; and 4) the central to northern sector of the continental rise and abyssal plain.

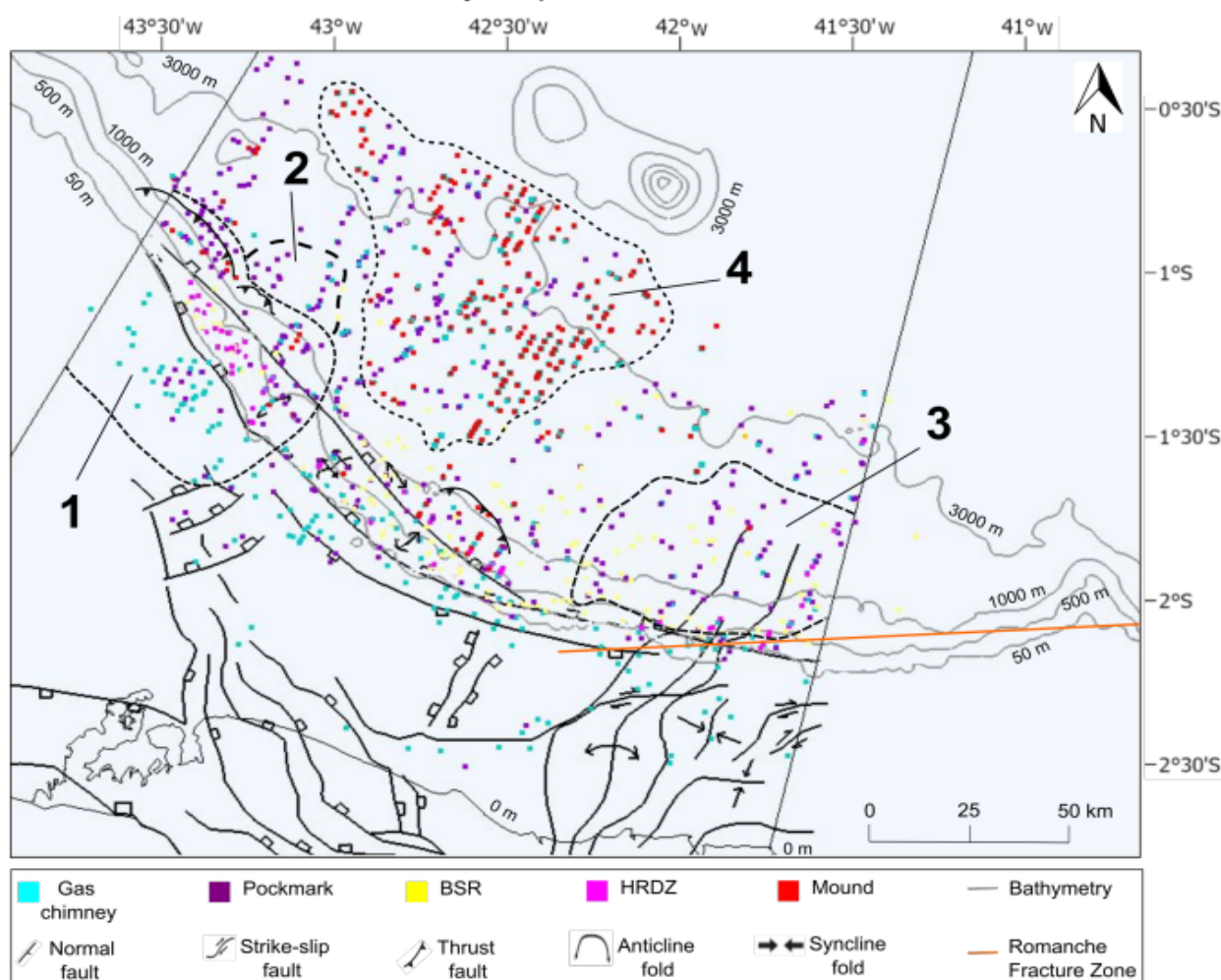


Fig. 11. Spatial distribution of leakage and seepage features in the offshore Barreirinhas Basin. The features are not in scale. Dashed lines represent the main target zones, corresponding to the western gravitational gliding system (1), igneous intrusions (2), eastern basin (3), and central to northern basin (4). Bathymetry was extracted from the Brazilian Geological Survey (CPRM,

Ladeira Neto and Roza, 2013), while the structural data were compiled from Vasconcelos et al. (2004), Krueger et al. (2012), Oliveira et al. (2012), and Tavares et al. (2020). Wells, seismic lines, and geological setting can be accessed in Figures 1 and 3.

5.1.1 Gravitational Gliding System

In the central and western regions of the Barreirinhas Basin, the RFZ tectonic deformation affects the transition between the continental shelf and the deep-water basin, part of the extensional domain of the gravitational gliding system with thin-skinned tectonics structural style (Fig 11) (Zalán, 2011; Krueger et al., 2012; Oliveira et al., 2012). Extensional faults and negative flower structures control the deposition on the outer shelf, shelf break, and upper slope. Those faults catch the prograding sediments and display broad wipeout zones (Montenegro et al., 2020). The faults are expressed as synthetic, listric, seaward-dipping, with minor landward-dipping, antithetic faults (Fig. 7). Such interactions create rollovers and growth anticlines with thickened strata. The narrow continental margin (~160 km), steep continental slope (> 6°), and high sedimentation rates generate instabilities from the upper slope to the distal regions, depositing very thick packages of slides, slumps, debrites, and turbidites (Soares et al., 2007; Júnior et al., 2008; Krueger et al., 2012).

Faults are the main structures for cold seeps formation in the Barreirinhas Basin. Both faults and gas chimneys control the migration of hydrocarbons, producing small pockmarks, HRDZs, and BSR disruption (Fig. 7). The faulted blocks of the extensional domain may have significant exploratory potential (Oliveira et al., 2008, 2012; Wang et al., 2018). Rollovers and growth anticlines might comprise source and/or reservoir rocks that leak and form cold seeps on the surface (Oliveira et al., 2012). Figure 7 shows gas chimneys forming within prograding post-Pleistocene sedimentary units on the outer-shelf, near to the shelf break. The features on the upper slope are also above the Pleistocene unconformity, but regional faults can also serve as fluid conduits of deeper sources. Pellegrini & Ribeiro (2018) described sandstones and turbidites belonging to Travosas Formation (Late Cretaceous-Paleogene), formed by prograding clinoforms of the shelf and shelf border, as possible hydrocarbon prospects.

The HRDZs in Barreirinhas Basin are indicators of active hydrocarbon leakage (Figs. 7 and 8) and may be the product of slow to moderate methane flux, considering the scheme proposed by Roberts (2001) and Roberts et al. (2006). They are produced by microbial degradation of hydrocarbons, precipitating authigenic carbonate that forms the high

amplitude on seismic reflectors and rough surfaces on the seafloor (Fig. 7d) (Hovland, 2002; Suess, 2014). Pull-up effects below the HRDZs (Fig. 7c) relate to the propagation of seismic waves through high velocity carbonates. Those carbonates can also cover fault surfaces (Camerlenghi, 2018; Suess, 2020). Stack response degradation is due to scattering and signal deterioration produced by fluid seeping (Cowley and O'Brien, 2000). Slow methane fluxes are prone to form abundant carbonate precipitation with some microbial mats, whereas moderate methane fluxes are favorable to the development of scattered carbonate outcrops and higher biodiversity (Suess et al., 2001; Ma et al., 2021).

A short area between the middle- and lower-slope comprises both extensional and compressional deformation, representing the transitional domain of the gravitational gliding system. The compressional domain extends to the transition between the lower-slope and continental rise, building a 40 km-wide fold and thrust belt. This domain is characterized by two phases of decollement formation and propagation of fault-related folding (Fig. 4). The first phase was probably triggered by overpressure of Turonian shales (Zalán, 2011). Oliveira et al. (2008) explain that shales present rheological behavior similar to salt, flowing vertically and laterally. The resultant shale-detached gravitational system (Zalán, 2009) formed a decollement surface where faults and folds developed upon the detachment surface (Oliveira et al., 2012). Complex geometric correlated structures express imbricate thrusts, ramp-and-flat thrusts, backthrusts, kink bands, pop-ups, box folds, detachment folds, fault-propagation-folds, and fault-bend-folds (Figs. 4 and 5).

Active sedimentation overlying the compressional domain is confirmed by channel levees and onlapping strata, and erosion is also reported by excavation of the fold hinge (Figs. 4 and 5). Gas chimneys, pockmarks, and mounds are found near or immediately above faults and folds, suggesting an active hydrocarbon leakage (Figs. 4b, 4c, 5c, and 5f). The compressional domain of the gravitational gliding system is an important prospect and many oil reservoirs were found worldwide (Oliveira et al., 2008; Zalán, 2011; Conte and Oliva, 2021). Detachment zones may act as fluid conduits, together with a series of faults (Zalán, 2011; Oliveira et al., 2012). Structural traps possibly can be created by fault-related folding and pop-ups (Oliveira et al., 2012; Conti and Oliva, 2021). Traces of gas were reported in turbidites of the Travosas Formation in the compressional region, as well (Conte and Oliva, 2021). Nevertheless, the gravitational gliding system on the central part of the basin has very similar characteristics, but it is significantly smoother in relation to the western system, hence developing smaller cold seeps.

Canyons, submarine channels, and pockmarks are very associated. Benjamim et al. (2015) described pockmarks created by fluid expulsion from fluid conduits associated with deep channels within canyon areas in the Niger Delta continental slope. Gay et al. (2003) explains that channels are preferential fluid migration pathways. This situation may occur at the gravitational gliding system of Barreirinhas Basin. Figure 7 presents canyons and pockmarks controlled by faults. Here, pockmarks and HRDZs are resulted of fluid migration. The pockmarks on Figures 4b and 5d are within channels and are underlain by long faults and gas chimney, respectively. Those fluid conduits may act controlling the channels (Gay et al., 2003, 2006). Pockmarks associated with mounds are also found near to the channels (Figs 4c and 5c), corroborating with the presence of active fluid migration.

5.1.2 Igneous Intrusions

On the western sector of the abyssal plain, near to the boundary of the gravitational gliding system (Fig. 11), apparent igneous intrusions are present (Fig. 5). This local magmatism has intruded on the offshore Barreirinhas Basin in the Eocene (Trosdorf Junior et al., 2007). The features are seismically characterized by very chaotic reflections, faulted borders, onlap terminations on both edges, discordant attitude, and draping of the adjacent strata. These characteristics together are good indicators of the magmatic origin of such features (Zuo and Fan, 2011; Infante-Paez and Marfurt, 2018).

Igneous rocks are frequently misinterpreted as salt rocks, folds, and sedimentary conduits (Infante-Paez and Marfurt, 2018). Nevertheless, the decollement present on salt structures is absent. Neither hinge zone of folds was observed. In addition, the large diameter of the features is not compatible with gas chimneys or mud diapirs.

The possible intrusive body of Figure 5 is very near to the first decollement and series of thrusts of the compressional domain of the gravitational gliding system. Gas chimneys on both sides of the intrusion (Figs. 5e and 5f), faults and several bright spots above it (Fig. 5g), and pockmarks in its vicinity (Fig. 5d) suggest an active petroleum system. Heat from intrusions is capable of inducing thermal maturity for hydrocarbon generation, making the host rocks into which these igneous bodies intruded become exploration targets (Infante-Paez and Marfurt, 2018). The piercement of the forceful intrusion also generates migration pathways on the host rock through faults and fractures (Delpino and Bermúdez, 2009), as that can be the case of the faulted borders and faulting above the intrusion (Fig. 5). Igneous rocks can also form traps for hydrocarbon accumulation (Goulart & de Castro, 2021). More rarely, fractured magmatic rock can produce a very atypical petroleum system

(Delpino and Bermúdez, 2009; Zuo and Fan, 2011). Rodriguez Monreal et al. (2009) described such occurrence in Neuquen Basin, Argentina, where immature source rocks were intruded by up to 600 m thick laccoliths, forming commercial oil reservoirs in sandstones, carbonates, and fractured igneous rocks. Oliveira et al. (2020) suggest reservoirs associated with igneous intrusions in the Ceará Basin, east of the Barreirinhas Basin. Accordingly, igneous intrusion in Barreirinhas Basin may influence thermal maturity, migration, and trapping for petroleum systems.

5.1.3 Eastern Basin

The most pronounced interaction between faults, canyons, and deep channels are found on the eastern sector of the basin (Fig. 11), where there are numerous channels that spreads through the continental rise and abyssal plain (Figs. 6 and 8). Canyons and deep channels, from the outer shelf to the continental rise, are highly controlled by faults on forming canyons scarps, terraces, and inter-canyons areas. Channels and drainages can be diverted by faults, promoting abandoned meanders (channel avulsion). Marginal levees can also be affected.

The continental slope is characterized by continuous BSRs associated with HRDZs, some small mounds, pockmarks, gas chimneys, and leaking faults, especially on the lower-slope where pockmarks and gas chimneys are bigger. Seismic attributes allowed the identification of the BSRs (Figs. 6 and 8). Instantaneous amplitude confirmed the amplitude loss upon the BSRs and therefore the gas hydrates charging shallow porous sands (Taylor et al., 2000; Berndt et al., 2004; Satyavani et al., 2005; Obiadi et al., 2019). Instantaneous frequency underneath the BSRs validated free gas due to the higher attenuation and low frequencies, contrasting with lower attenuation and absorption of high frequencies from the overlying gas hydrate-bearing sands (Satyavani et al., 2005; Li et al., 2013; Clairmont et al., 2021; Zhong et al., 2021). These occurrences indicate the presence of gas hydrates infilling the uppermost sedimentary packages (*i.e.*, prograding clinoforms, contourite drifts, sandy channels, marginal levees, turbidites, mass transport complexes) within the GHSZ. Nevertheless, the underlain free gas can migrate upward through chimneys and faults and might form accumulations. When such discontinuities cut across canyons and deep channels overlying BSRs, they create the most pronounced sites of gas seepage (Fig. 8).

BSRs reach the continental rise on the eastern sector of the Barreirinhas Basin (Fig. 11). This region is characterized by abundant meandering channels, laterally extensive,

with many distributaries and marginal levees. It is common to see channels and drainages diverted by faults, erosion of abandoned meanders, channel avulsion, and amalgamation. The complex depositional system can be explained by the combination of regional normal faults, a narrow continental margin, steep continental slope, and high sedimentary rates (Mohriak, 2003; Júnior et al., 2008). The Travosas Formation (Turonian-Oligocene) represents the most expressive sedimentary package of the basin, composed of siliciclastic-carbonatic rocks prograding from the continental shelf to ultra-deep waters, forming very thick turbiditic layers (Soares et al., 2007; Krueger et al., 2012). Such amount of sediments probably fed the deep basin with also a contribution of contemporaneous sedimentation.

Gas chimneys passed through pre-Maastrichtian sedimentary sequences (Fig. 6), suggesting they are likely from the Travosas Formation. Bright spots near to the cold seeps are feasible to be gas pockets and gas-rich sands (Fig. 6) (Shukla et al., 2012; Ismail et al., 2020). The pockmarks can be partially or totally filled with mass of sediments brought by channels that deposit through slumping borders, alternating with regular pelagic sedimentation. Craters of big size result from coalescence of many pockmarks and collapse of the crater scarps (Pilcher and Argent, 2007; Hovland, 2012). Moreover, to create those large craters it is necessary a continuous fluid flow, in this case sourced by BSRs and gas chimneys (Fig. 6), indicative of an active petroleum system (Suess, 2014). Authigenic carbonates and chemosynthetic biota are frequently described occurring within large pockmarks (Hovland et al., 2005; Hovland and Judd, 1988; Suess et al., 2001; Zhang et al., 2018).

The genesis of the submarine channels in the eastern sector of the Barreirinhas Basin are correlated to pockmarks and fluid conduits. Pockmark formation may result from gravity processes and gas hydrate dissolution and dissociation, where fluid conduits are responsible for fluid migration (Pilcher and Argent, 2007; Camerlenghi, A., 2018). Continuous pockmark erosion through bottom currents, gravity-driven processes, and turbidity currents may enlarge the depressions, conditioning channel formation (Andresen et al., 2008). Cronin & Jubilee Team (2022) described submarine channels developed over pockmark trains in the Jubilee Field, Tano Basin (Ghana), a counterpart of Barreirinhas Basin. The authors pointed out that gas escape and gravitational processes formed the pockmarks, subsequently excavated and driving preferential pathways to the slope channel complexes. Analogously, the giant pockmarks of the eastern Barreirinhas Basin may control channel formation in this region. Figure 6 shows a buried pockmark overlaid by bigger pockmarks associated with channels. The gas chimneys may have acted

carrying fluids from the BRSs, conditioning the pockmarks formation. Thereafter, the deep channels might have evolved from the relict depressions.

5.1.4 Central and Northern Basin

The central and northern sectors of the continental rise and abyssal plain (Fig. 11) have experienced more relative tectonic quiescence (Montenegro et al., 2020). Huge fine-grained packages, laterally extensive, are formed by hemipelagic sedimentation and mass transport deposits that fill the depocenters of these sectors. Extensive turbidites packages can be generated by high sedimentation rates and relief escarpment from the proximal part of the basin, reaching the abyssal plain. Large slides and slumps are observed spreading on the seamounts foot.

Numerous deep-water mounds are fed by long chimneys and faults (Fig. 9). The fine-grained fraction of these extensive packages is presumably mobilized by the conduits as a fluidized mass, jointly with water and hydrocarbons, to form the convex-up topographic highs on the surface (Suess, 2014, 2020). The biggest mounds have conduits built after the Cenomanian-Turonian and pre-Santonian unconformities, indicating that the fluids are leaking from source rocks deposited within this age interval (Figs. 9 and 10). However, there are numerous smaller conduits fed by younger strata, suggesting different sources. Pockmarks, bright spots, networks of faults, fractures, and gas chimneys, with signal attenuation and chaotic reflections, indicate the upward fluid migration. Likewise, the flat spot within the conduit (Fig. 10) supports the evidence of hydrocarbon migration and accumulation.

Regards to the composition of the mounds, one can conclude that the identification of these conspicuous features is very difficult based only in 2D seismic section due to their resemblance with igneous rocks, hydrothermal vents, and salt diapirs (Burgess et al., 2013; Infante-Paez and Marfurt, 2018). Hydrothermal vents occur in magma-rich continental margins such as the Karoo Basin in South Africa and the Vøring Basin in Norway (Svensen et al., 2006). Salt diapirs are found where there is halokinesis, as the Campos Basin in Brazil (Mohriak, 2003). The Barreirinhas Basin does not have salt tectonics and is magma-poor, with magmatism on the offshore zone observed into the Maranhão seamounts to the north and a small area on far west (Zalán, 2004; Trosdortf Junior et al., 2007). High amplitude reflections characteristic of igneous rocks were not observed. Both mounds and conduits usually display continuous reflections with low amplitude, contrasting with broad chaotic or lack of internal reflections in hydrothermal

vents, salt, and igneous rocks (Infante-Paez and Marfurt, 2018). Moreover, overall deformation of the adjacent strata is incipient or absent. Therefore, the origin of mounds from mud and hydrocarbons fluid mass is more realistic, even more with the presence of pockmarks (Fig. 5c). In this case, the hypothesis of carbonate buildups agrees with the predominance of this rock type in the Barreirinhas Basin. Furthermore, the mounds are normally accompanied by pull-up effects in the seismic profiles, especially in high velocity and density carbonates comparing with other sedimentary rocks (Burgess et al., 2013). As carbonate buildups, the tropical reefs, attached carbonate platforms, and isolate carbonate platforms are discarded due to the mounds are found in deep-waters, ranging from 760 m to 3250 m. The most plausible is that the features are carbonate mounds as those described by Hovland et al. (1994b) and Talukder et al. (2007).

Hovland et al. (1994b) identified mounds as carbonate knolls or bioherms in Porcupine Basin, western Ireland, ranging from 100 to 1800 m across and 50-175 m high, occurring in water depths of 650-1000 m. Talukder et al. (2007) called the features more than 130 m high as mud mounds on the continental slope of Nicaragua in water depths between 1000-2500 m. Many of the carbonate mounds in the deep ocean are formed by biological activity, such as chemosynthetic bacteria, bivalves, and corals (Roberts et al., 1990, 2006; Suess, 2014). These deep-water reefs and bioherms are found in hypoxic, aphotic, and cold waters without photosynthesis (Hovland, 2008, 2012; Rodriguez-Martinez et al., 2011). The food-chain is based on chemosynthesis, where nutrients are proven from hydrocarbons supplied by cold seeps, hydrothermal vents, and ocean upwellings (Roberts, 2001; Roberts and Aharon, 1994; Zhou and Pratt, 2019). Thus, the deep-water carbonate mounds/mud mounds/reefs and bioherms are intrinsically found at/or near leaking faults, gas chimneys, pockmarks, authigenic carbonate, and HRDZs (Hovland and Judd, 1988; Rodriguez-Martinez et al., 2011).

The mounds in the seismic profiles L06 and L07 (Figs 9 and 10, respectively) are very similar to the mounds described by Hovland et al. (1994b), although on the Barreirinhas Basin they reach water depths superior to 2.5 km. Nevertheless, carbonate mounds, including those composed of biological communities, were reported in water depths greater than 3 km (Hovland, 2008; Lo Iacono et al., 2018). Other possibility for the mounds are the gas hydrates mounds or pingoes. Those features are also mobilized by hydrocarbon seepage and faults, and associated with gas chimneys, pockmarks, BSRs, authigenic carbonates, and deep reefs (Roberts, 2001; Chapman et al., 2004; Macelloni et al., 2013). On seismic sections, gas hydrate mounds are small protuberances with less than 50 m high and tens to hundreds of meters wide, characterized by fainted or lack of

internal reflections, blanking zones, or weak chaotic facies (Somoza et al., 2014; Zhang et al., 2021). On the northeastern edge of the Storegga slide scarp, Nyegga site, Norway, Hovland and Svensen (2006) characterized small hydrate mounds on the continental slope, associated with BSR, pockmarks, vertical pipes, gas hydrates, and authigenic carbonate. Serié et al. (2012) described gas hydrate mounds associated with salt structures, BSRs, and deep-water reefs on the Kwanza Basin, Angola. The mounds in Figures 9 and 10 are much bigger than the reported gas hydrate mounds and have continuous internal reflections in the greater part of the structure. However, other mounds across the basin fit with the description of size and seismic facies of gas hydrate mounds (Figs. 4c and 5c).

Mud diapirs and volcanoes are also similar to carbonate mounds. Examples are found in Makran accretionary prism (Pakistan) and Offshore Trinidad (Deville, 2009). The mounds reach hundreds to thousands of meters long, and tens to hundreds of meters high (Martinelli and Judd, 2004), similar to the mounds in Figures 9 and 10. Although mud volcanism is typical of compressional settings that give tectonic loading and seismic activity as driving mechanisms (Chiu et al., 2006; Chen et al., 2014), overpressure due to rapid sedimentation and high sedimentation rates are capable of inducing mud diapirism in a non-compressional context (Dimitrov, 2002). Nevertheless, the mounds in the Barreirinhas Basin are unlikely to be related to mud volcanism, because the major conduit generates pull-up effect only within the structure, with incipient or no deformation of the adjacent strata. Meanwhile, mud diapirs induce uplifting of the overburden, forming high-angle brittle faults, radially arranged fractures, and onlap terminations on both flanks of the diapir (Chiu et al., 2006; Chen et al., 2014; Zhang et al., 2018; Zhang et al., 2020; Zhong et al., 2021). Based on these aspects, it is more plausible that the aforementioned mounds are related to gas chimneys and faults feeding carbonate mounds.

5.2 Comparisons Between Barreirinhas Basin and Other Correlated Basins

In the context of the tectono-stratigraphic evolution of the Equatorial Atlantic, the Barreirinhas, Ivory Coast, and Tano basins constituted a conjugate margin, sharing genetic processes and similarities (Basile et al., 1993, 2005; Soares et al., 2007; Antobreh et al., 2009). Because of this, good perspectives are expected to find hydrocarbon reservoirs on the Brazilian counterpart (Oliveira et al., 2008, 2012; Davison et al., 2016; Pellegrini & Ribeiro, 2018; Wang et al., 2018; Montenegro et al., 2020; Conti and Oliva, 2021). Well drilling and geochemical surveys indicated the presence of light hydrocarbons and source

rocks (Noguti, 1964; Azevedo, 1987; Corrêa & Truckenbrodt, 1988; Zalán, 2015; Davison et al., 2016; Pellegrini & Ribeiro, 2018; Conte and Oliva, 2021; Conti and Oliva, 2021). Based on this, Figure 12 presents a generalized correlation about source and reservoir rocks within the Barreirinhas, Ivory Coast, and Tano basins in the Cretaceous. Reservoir rocks of the Barreirinhas Basin are not shown because no proven reserves were found yet, although potential siliciclastic reservoirs were identified with good permo-porosity (Ferreira, 2013).

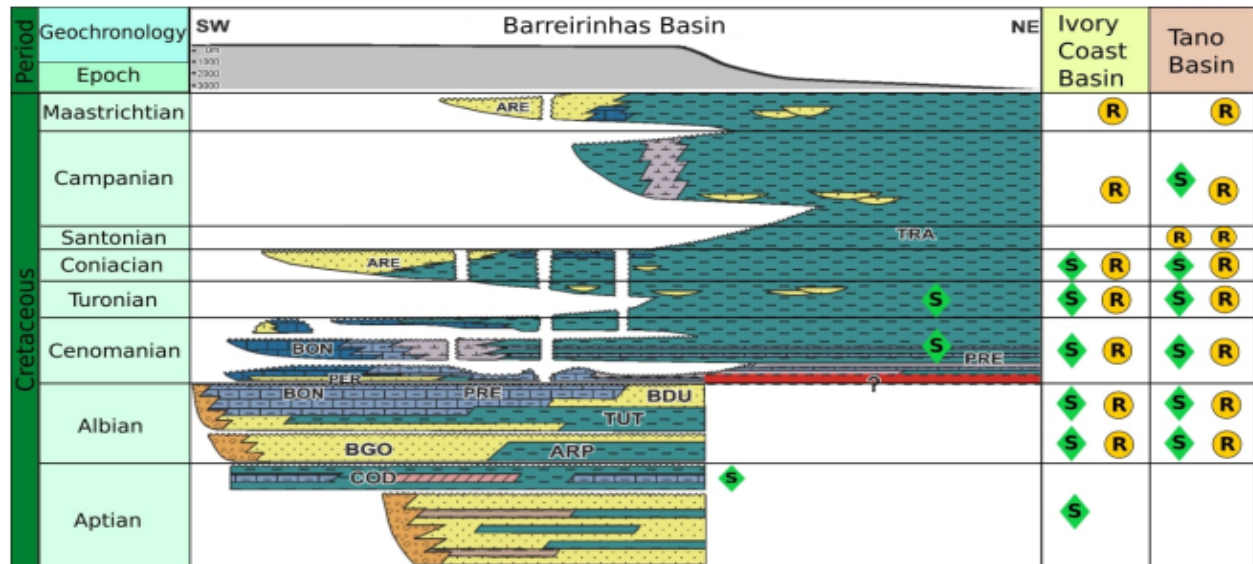


Fig. 12. Comparison between Barreirinhas, Ivory Coast, and Tano basins, showing the correlation of source (S) and reservoir (R) rocks. Stratigraphic chart of the Cretaceous modified from Trosdorf Junior et al. (2007). Compiled information from Noguti (1964), Azevedo (1987), MacGregor et al. (2003), Brownfield and Charpentier (2006), Dailly et al. (2013), Davison et al. (2016), Tetteh (2016), Pellegrini & Ribeiro (2018). Lithology legend and formation names are shown in Fig. 2.

The black shales of the Barreirinhas Basin are within the Preguiças and Travosas Formations (Fig. 2), but the most important source rock belong to the Aptian Codó Formation, in which organic matter content range from 3% to 24% with thickness greater than 80 m (Azevedo, 1987; Ferreira, 2013). Black shales (Cenomanian to Turonian) enriched in organic matter and formed in the global event of oceanic anoxia, are present in the three basins (Noguti, 1964; Brownfield and Charpentier, 2006; Tari, 2006; Bempong et al., 2019; Kelly and Doust, 2016). In all data of this study, the cold seeps and leaking conduits occur over the Turonian, suggesting that the three source rocks may be actively contributing to fluid migration. Comparing the Albian source rocks (Fig. 12), it is plausible that before the complete separation of South America-West Africa conjugate margins

occurred in the final of the syn-rift stage (102 Ma) (Basile et al., 1993; Soares et al., 2007), it should have Albian source rocks in the Barreirinhas Basin. Dark gray shales from the Albian Tutóia Formation (Canárias Group) were formed in deltaic environment, similar to the Albian black shales from Foxtrot, Espoir, Lion, and Tano fields formed in fluvial, deltaic to shallow-marine environments (Mattick, 1982; Corrêa & Truckenbrodt, 1988; Morrison et al., 2000; MacGregor et al., 2003; Mohriak, 2003; Júnior et al., 2008). Otherwise, sandstone and turbidite reservoirs of these fields may be similar to sedimentary units of the Albian Canárias Group of the Barreirinhas Basin.

Several Cenomanian to Maastrichtian exploration fields (Panthere, Gazelle, Paon, Belier, Ibex, Lion, Tweneboa, Enyenra, Ntomme, Teak, Odum) were discovered in the Ivory Coast and Tano basins (Mattick, 1982; Morrison et al., 2000; Basile et al., 2005; Brownfield and Charpentier, 2006; Tari, 2006; Jianping et al., 2010; Tetteh, 2016). The most important is the giant Jubilee field (Cenomanian to Turonian), formed by stacking turbidites filling lower-slope amalgamated channels and fan systems (Dailly et al., 2013; Sills and Agyapong, 2012; Tetteh, 2016). In the eastern sector of the Barreirinhas Basin, some areas of the lower-slope and continental rise have many resemblances with the Jubilee field. Canyon systems and deep channels provide most of the sediments in these deep domains. Many large pockmarks, HRDZs, leaking faults, gas chimneys, and BSRs indicates an active hydrocarbon migration (Figs. 6 and 8). The Travosas Formation has great thickness in this area and is characterized by very thick packages of turbidites with good indicatives of petroleum in geochemical analyses (Ferreira, 2013; Conti and Oliva, 2021).

The Pará-Maranhão Basin (Fig. 1a) is also similar to the Barreirinhas Basin. Shales from the Caju Group (TOC 1-2%, up to 5%) and Travossas Formation (TOC 0.5-1.7%) can generate source rocks, and potential reservoirs would be found into sandstones layers of the Canárias Group, turbidites (porosities ~ 20%) of the Travosas Formation, and carbonates of the Ilha de Santana Formation (Cui et al., 2014; Zalán, 2015; Nascimento et al., 2019). Moreover, the gravitational gliding system is also present in the Pará-Maranhão Basin and is prone to develop both reservoirs and structural traps in the distal fold and thrust belt (Cui et al., 2014; Zalán, 2015; Nascimento et al., 2019). Zalán (2015) identified strong bright spots near to a structural high situated upon the exhumed mantle and buried below igneous intrusions. Many similarities in the tectono-depositional settings were found in both basins by the above authors and in this study, including the hydrocarbon prospects associated with gravitational cells and those occurring in the vicinity of igneous intrusions. In addition, the Travosas Formation hosts the possible source rocks in both basins and the

reservoirs occur within the Canárias Group, Travosas Formation, and Ilha de Santana Formation.

6. CONCLUSION

The Brazilian Equatorial Margin (BEM) comprises a unique segment of complex geological history, inherited from the opening of the Equatorial Atlantic. Recently, the BEM gained special notoriety as a new exploratory frontier because important hydrocarbon reserves were found in both West Africa-South America conjugate margins. The Barreirinhas Basin occupies the central portion of the BEM and has counterparts with the oil and gas producers in Ivory Coast and Tano basins. Nevertheless, no relevant reserves were identified on the Barreirinhas Basin yet, moreover because of scarce studies regarding the petroleum systems, particularly on deep-waters.

A comprehensive study was carried out based on conventional 2D seismic on the offshore Barreirinhas Basin, applying seismic attributes to reduce exploratory risks by optimizing the conventional seismic lines. The results comprise the identification of several shallow-strata hydrocarbon leakage/seepage structures associated with hydrocarbon migration, including leaking faults, gas chimneys, pockmarks, hydrocarbon-derived diagenetic zone (HRDZ), bottom simulating reflectors (BSR), and deep-water mounds. The systematic mapping of these structures and analyses of their respective structural-stratigraphic controls suggest the establishment of four main interesting targets in the Barreirinhas basin:

1) gravitational gliding system in the western sector, in which the extensional domain is controlled by extensional faults, negative flower structures, faults bordering the shelf break, and gas chimneys that controls the migration of hydrocarbons, producing HRDZs, pockmarks, and BSR disruption. The distal compressional domain has decollements, faults, and folds controlling gas chimneys, deep-water mounds, and pockmarks.

2) neighboring areas of the igneous intrusion, with gas chimneys, faults, pockmarks, and bright spots.

3) the eastern sector of the transition between the lower-slope and continental rise, with BSRs, pockmarks, gas chimneys, and leaking faults associated with meandering channels and marginal levees.

4) central and northern sectors of continental rise and the abyssal plain, which have several deep-water mounds, some enormous, source by faults and large gas chimneys.

Previous geochemical analyses, allied with the presence of cold seeps and established chronostratigraphic horizons, suggest that the Preguiças (Cenomanian-Turonian) and Travosas (Turonian-Oligocene) formations can be the hydrocarbons source to cold seep formation. Comparisons between the Barreirinhas Basin and other basins with correlated

tectono-stratigraphic evolution, show that there is a potential active petroleum system in this basin. New source rocks may be present in the Albian Canárias Group and Albian-Turonian Caju Group, and the reservoirs rocks may occur in the Canárias Group (Albian), Travosas Formation (Turonian-Oligocene), and Ilha de Santana Formation (Turonian-Oligocene).

The shared geological history of the conjugate margin, coupled with the cold seep prospects, suggests promising hydrocarbon accumulations within the offshore Barreirinhas Basin in the BEM central sector. Geochemical surveys are necessary to certify and map possible hydrocarbon reservoirs. Drilling, well logging, and 2D and 3D high resolution seismic are fundamental to better comprehension about tectonics, magmatism, sedimentation, and oil and gas resources. The intrusions, pockmarks, BSRs, HRDZs, and deep-water mounds can be better studied through sampling, geochemical analyses, and ROVs and AUVs expeditions. Likewise, the Barreirinhas Basin can be a vast field to the petroleum industry and scientific research, with the latter especially focusing on the deep-water mounds, endowed with a great potential for the geobiology.

AUTHOR STATEMENT

Guilherme Martins Delabrida: Conceptualization, Investigation, Methodology, Visualization, Writing - Original Draft. Moab Praxedes Gomes: Supervision, Investigation, Validation, Conceptualization, Writing - Review and Editing. José Paulo de Melo Goulart: Data Curation, Methodology, Visualization, Data Interpretation. Diógenes Custódio de Oliveira: Data Curation, Methodology, Visualization, Data Interpretation. David Lopes de Castro: Project Administration, Resources, Funding Acquisition, Investigation, Validation, Writing - Review and Editing.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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6. FINAL REMARKS

The Brazilian Equatorial Margin (BEM) comprises a unique segment of complex geological history, inherited from the opening of the Equatorial Atlantic. Recently, the BEM gained special notoriety as a new exploratory frontier because important hydrocarbon reserves were found in both West Africa-South America conjugate margins. The Barreirinhas Basin occupies the central portion of the BEM and have counterparts with the oil and gas producers Ivory Coast and Tano basins. Nevertheless, no relevant reserves were identified on the Barreirinhas Basin yet, moreover due to the poor study in respect to the petroleum systems, particularly on deep-waters.

Investigation was made through conventional 2D seismic on the offshore Barreirinhas Basin, with additional use of seismic attributes, including RMS amplitude, instantaneous amplitude, instantaneous frequency, and chaos. These seismic attributes are extensively used in the petroleum industry to reduce exploratory risks by optimizing the conventional seismic lines. The results comprise the identification of cold seeps associated with hydrocarbon migration, including leaking faults, gas chimneys, pockmarks, hydrocarbon-derived diagenetic zone (HRDZ), bottom simulating reflectors (BSR), and deep-water mounds. Mapping of the identified structures and analyses of their respective structural-stratigraphic controls suggested the establishment of four main interesting targets:

1) gravitational gliding system in the western sector, in which the extensional domain is controlled by extensional faults, negative flower structures, faults bordering the shelf break, and gas chimneys that controls the migration of hydrocarbons, producing HRDZs, pockmarks, and BSR disruption. The distal compressional domain has decollements, faults, and folds controlling gas chimneys, deep-water mounds, and pockmarks.

2) neighboring areas of the igneous intrusion, with gas chimneys, faults, pockmarks, and bright spots.

3) the eastern sector of the transition between the lower-slope and continental rise, with BSRs, pockmarks, gas chimneys, and leaking faults associated with meandering channels and marginal levees.

4) central and northern sectors of the continental rise and the abyssal plain, which have several deep-water mounds, some enormous, sourced by faults and large gas chimneys.

Previous geochemical analyses, allied with the presence of cold seeps and established chronostratigraphic horizons, suggest that the Codó (Aptian), Preguiças (Cenomanian-

Turonian), and Travosas (Turonian-Oligocene) formations can be the source of the hydrocarbons to cold seep formation. Comparisons between the Barreirinhas Basin and other basins with correlated tectono-stratigraphic evolution show that there is a potential active petroleum system in this basin. New source rocks may be present in the Albian Canárias Group and Albian-Turonian Caju Group, and the reservoir rocks may occur in the Canárias Group (Albian), Travosas Formation (Turonian-Oligocene), and Ilha de Santana Formation (Turonian-Oligocene).

The shared geological history of the conjugate margin, coupled with the cold seep prospects, suggests promising hydrocarbon accumulations within the offshore Barreirinhas Basin in the BEM central sector. Geochemical surveys are necessary to certify and map possible hydrocarbon reservoirs. Drilling, well logging, and 2D and 3D high resolution seismic are fundamental to better comprehension about tectonics, magmatism, sedimentation, and oil and gas resources. The intrusions, pockmarks, BSRs, HRDZs, and deep-water mounds can be better studied through sampling, geochemical analyses, and ROVs and AUVs expeditions. Likewise, the Barreirinhas Basin can be a vast field to the petroleum industry and scientific research, with the latter especially focusing on the deep-water mounds, endowed with great potential for the geobiology.

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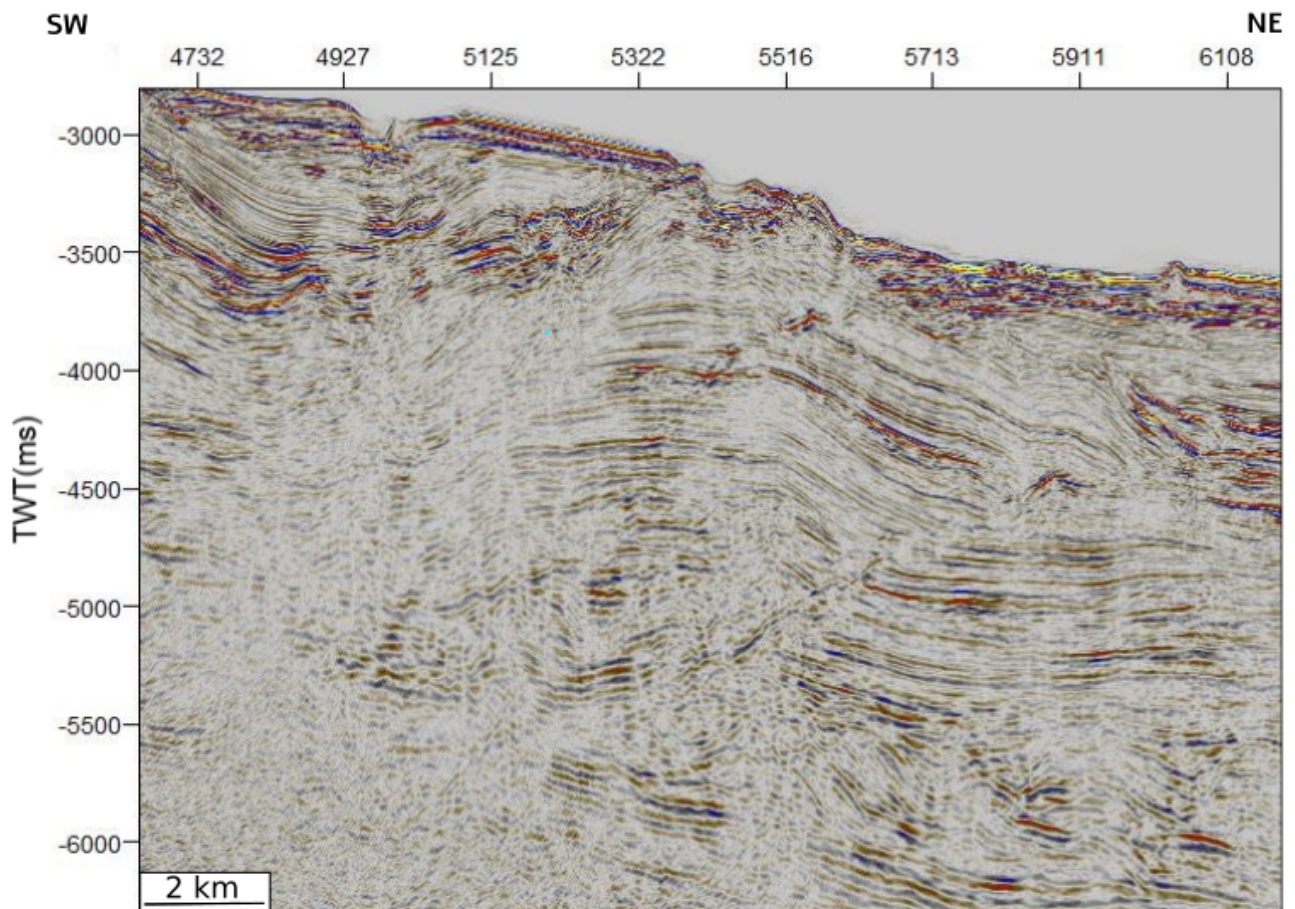
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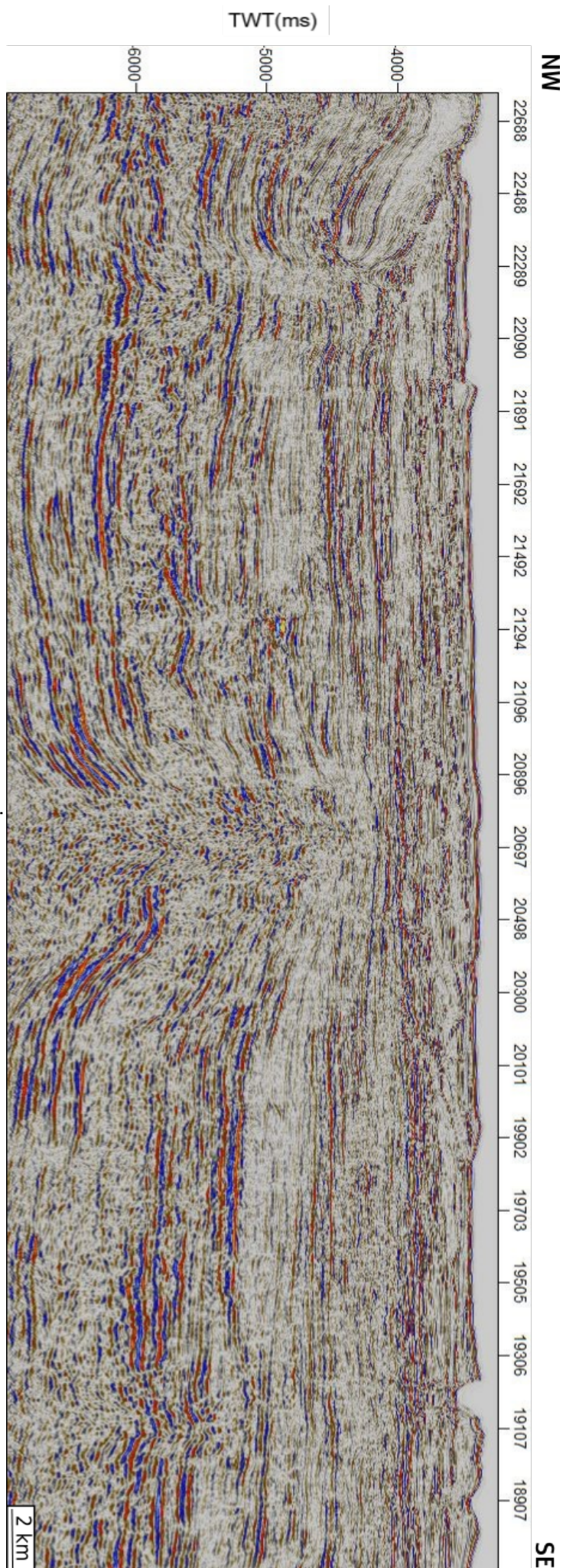
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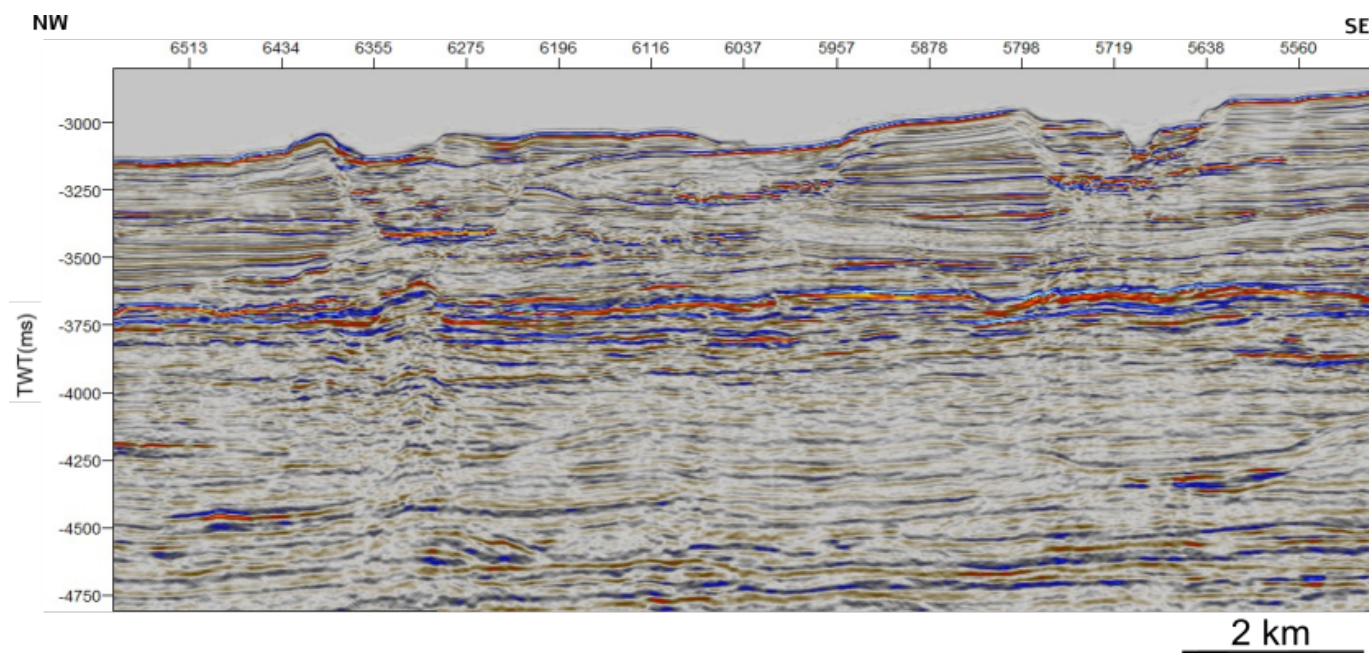
APPENDIX



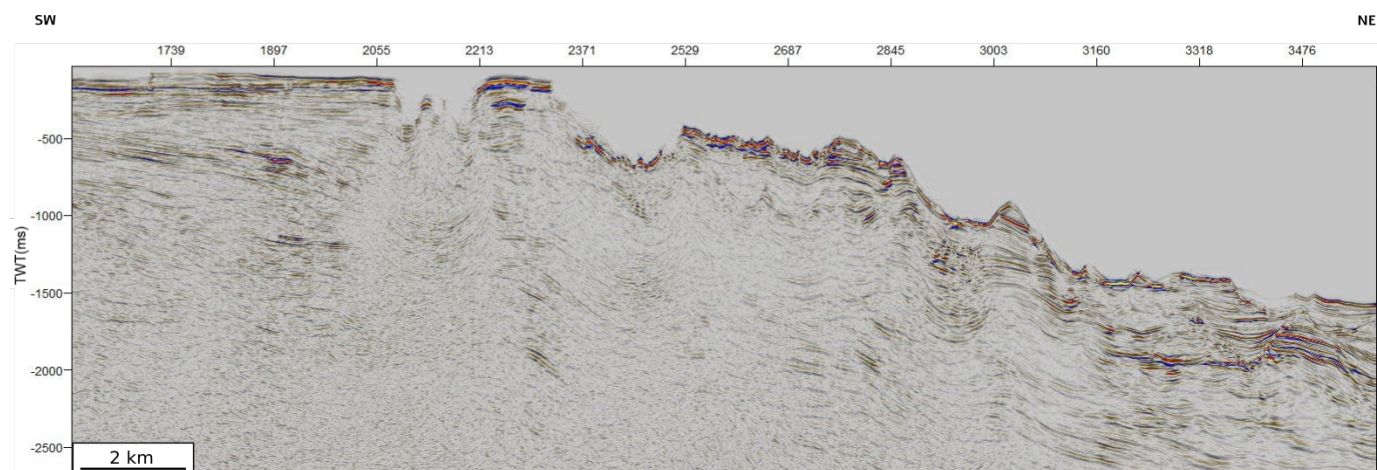
Appendix 1 Seismic section.



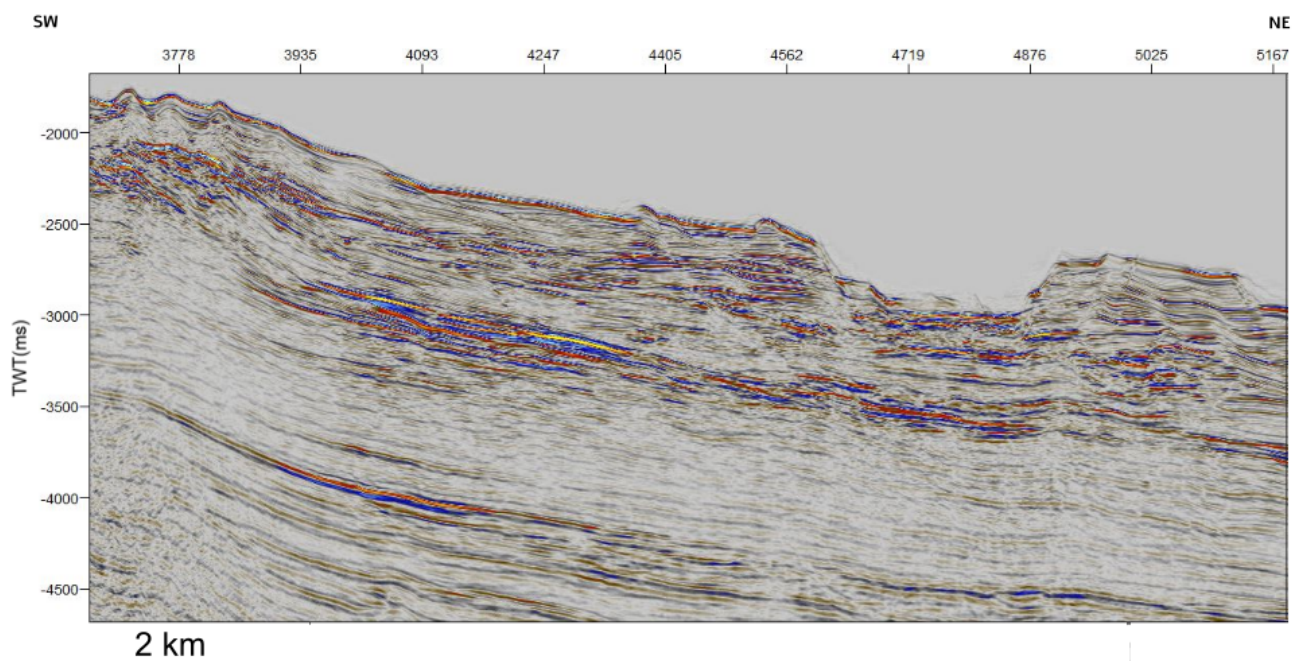
Appendix 2 Seismic section.



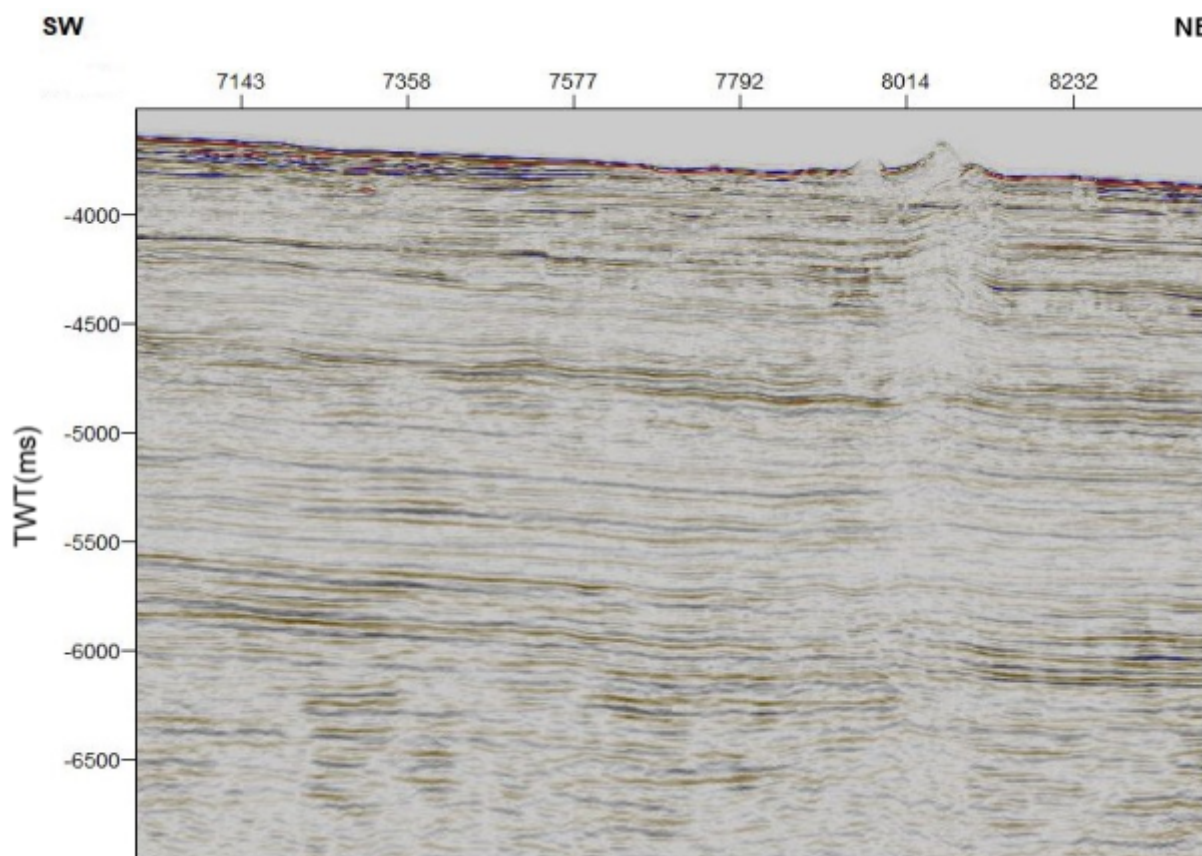
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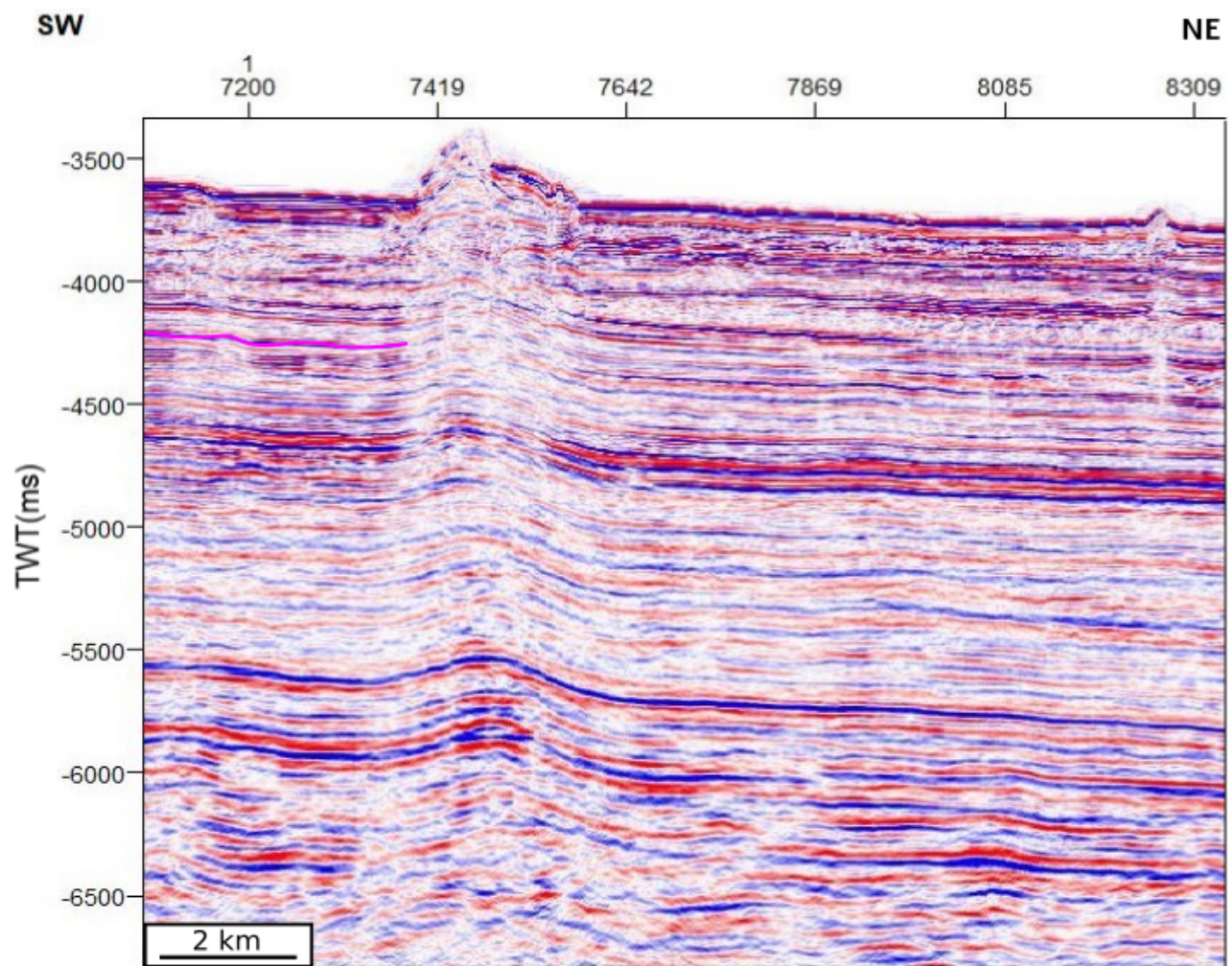
Appendix 4 Seismic section.



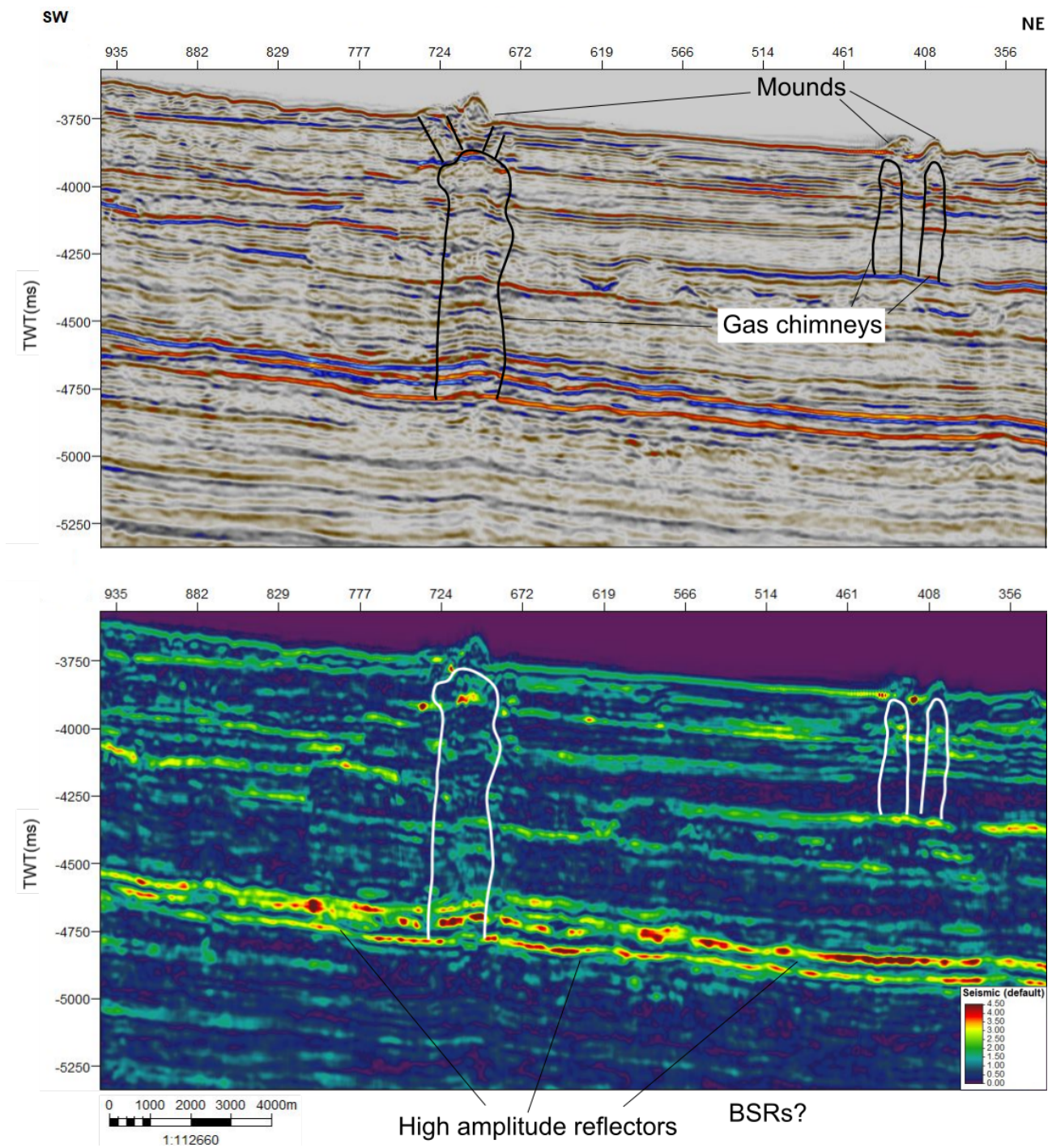
Appendix 5 Seismic section.



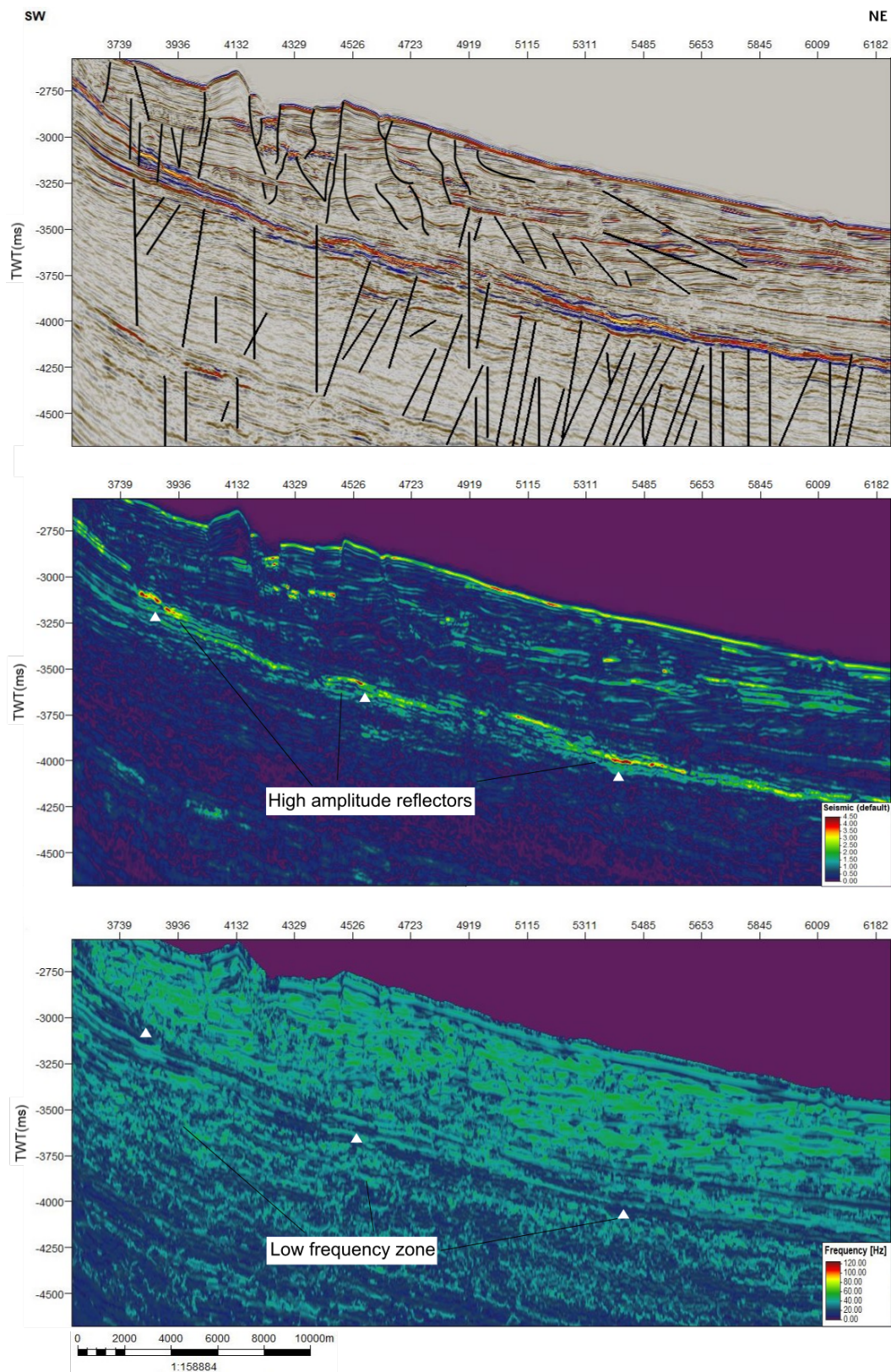
Appendix 6 Seismic section.



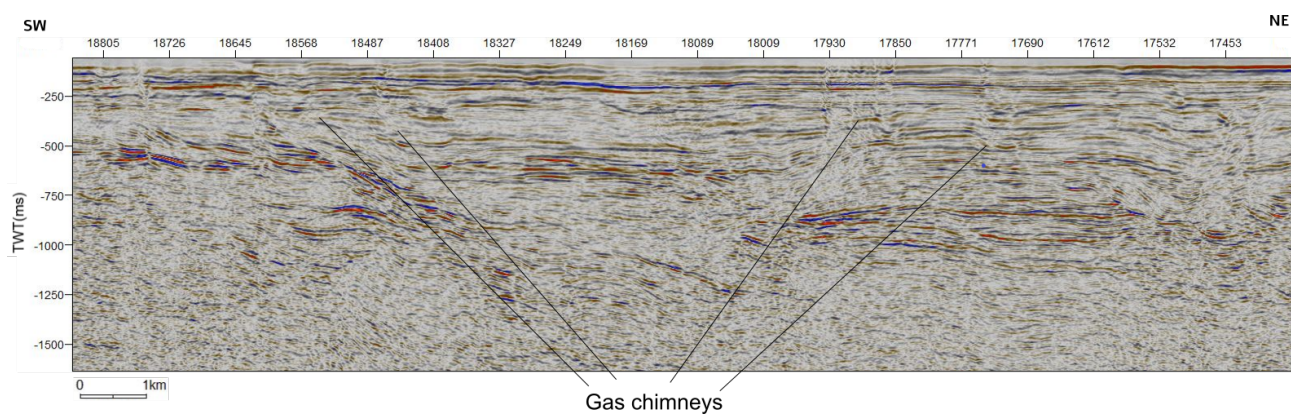
Appendix 7 Seismic section.



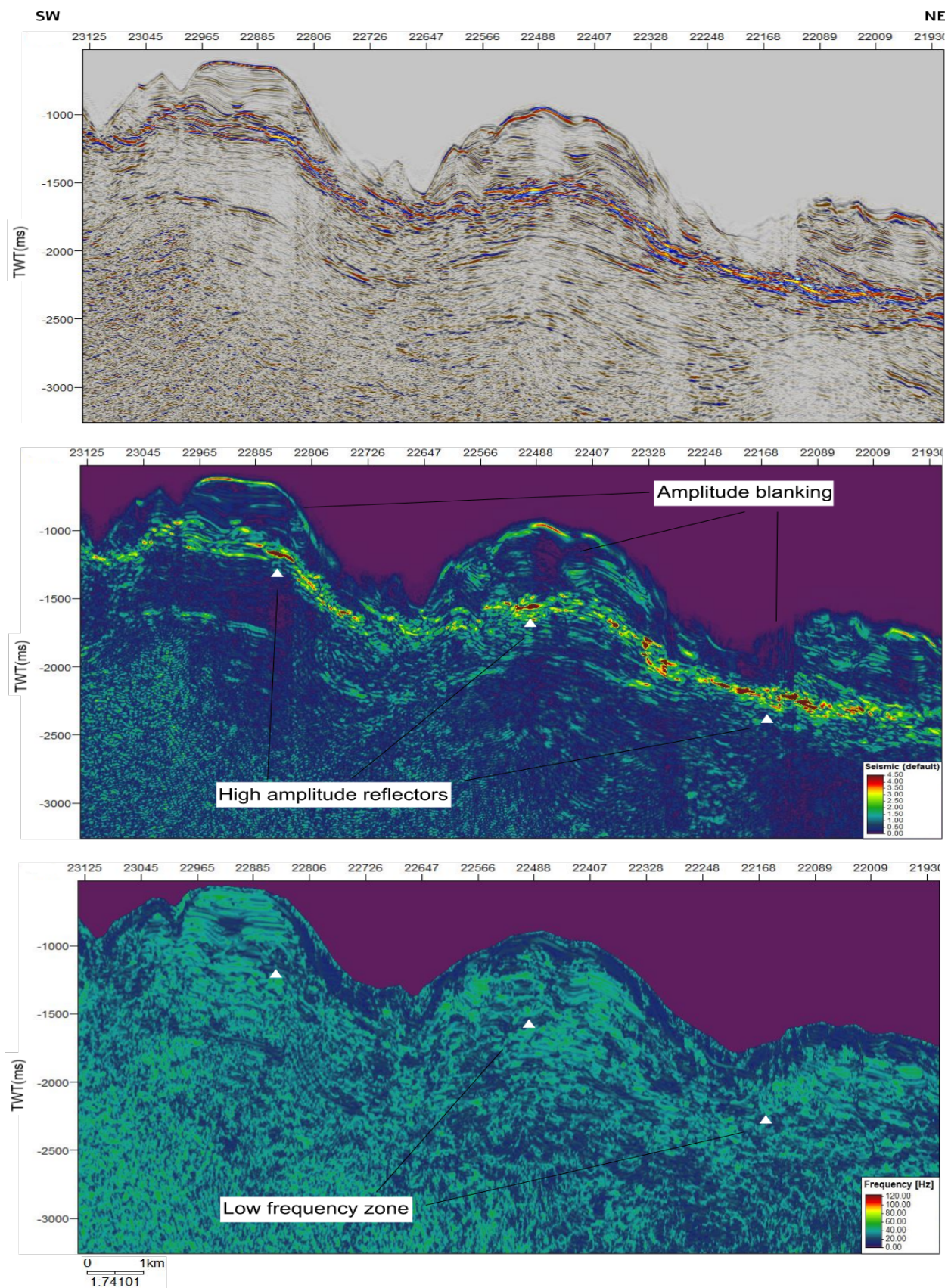
Appendix 8 Seismic section and instantaneous amplitude.



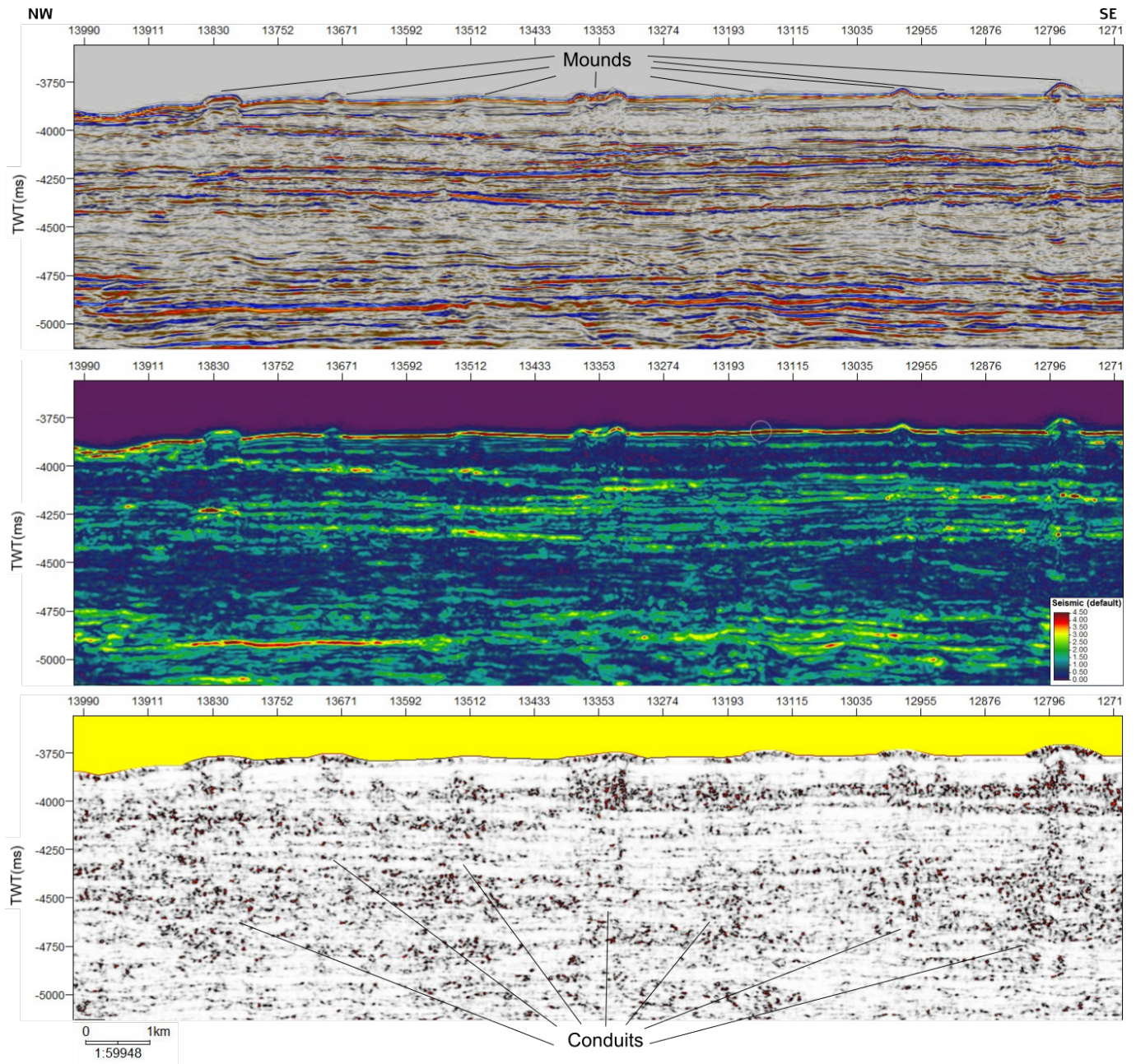
Appendix 9 Seismic section, instantaneous amplitude, and instantaneous frequency.



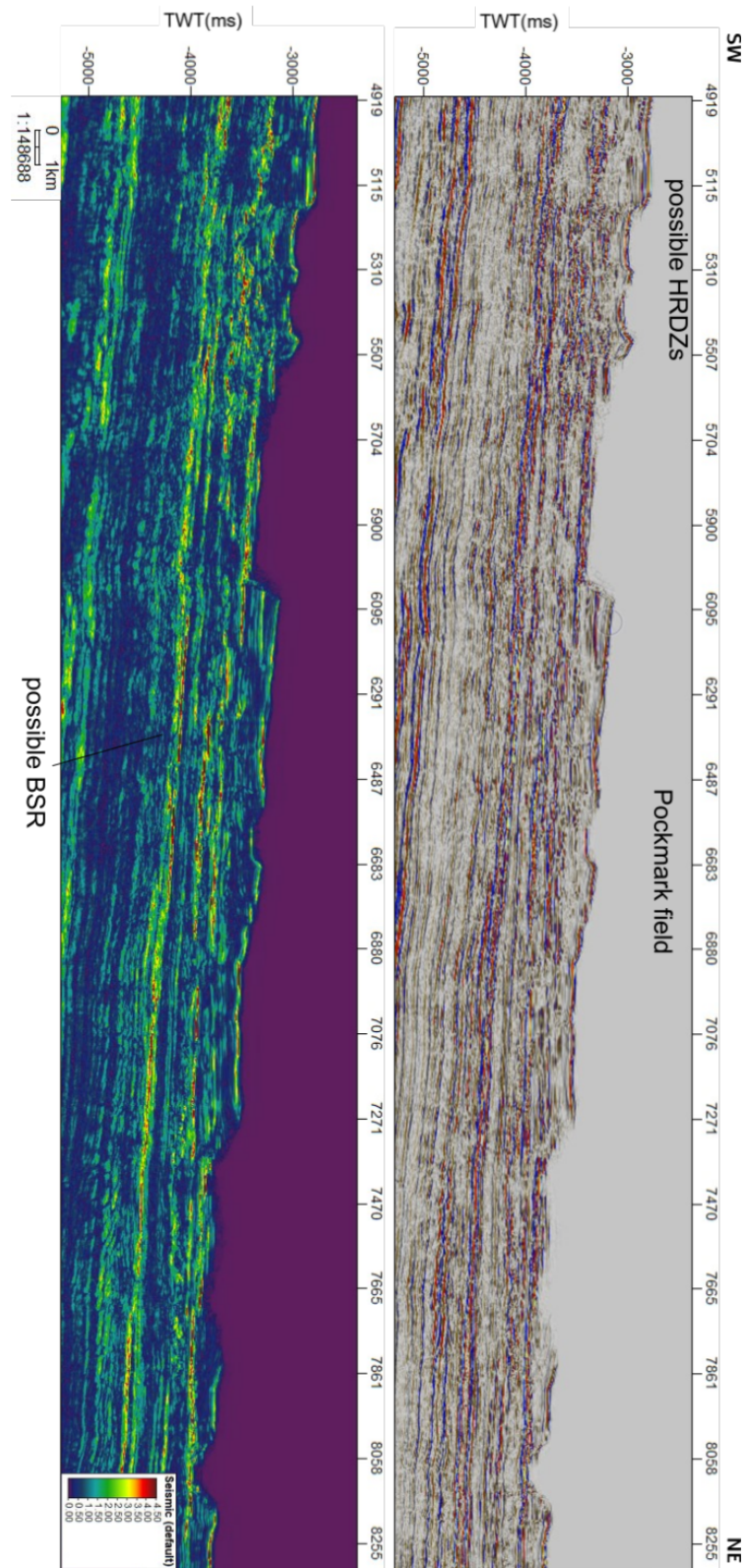
Appendix 10 Seismic section.



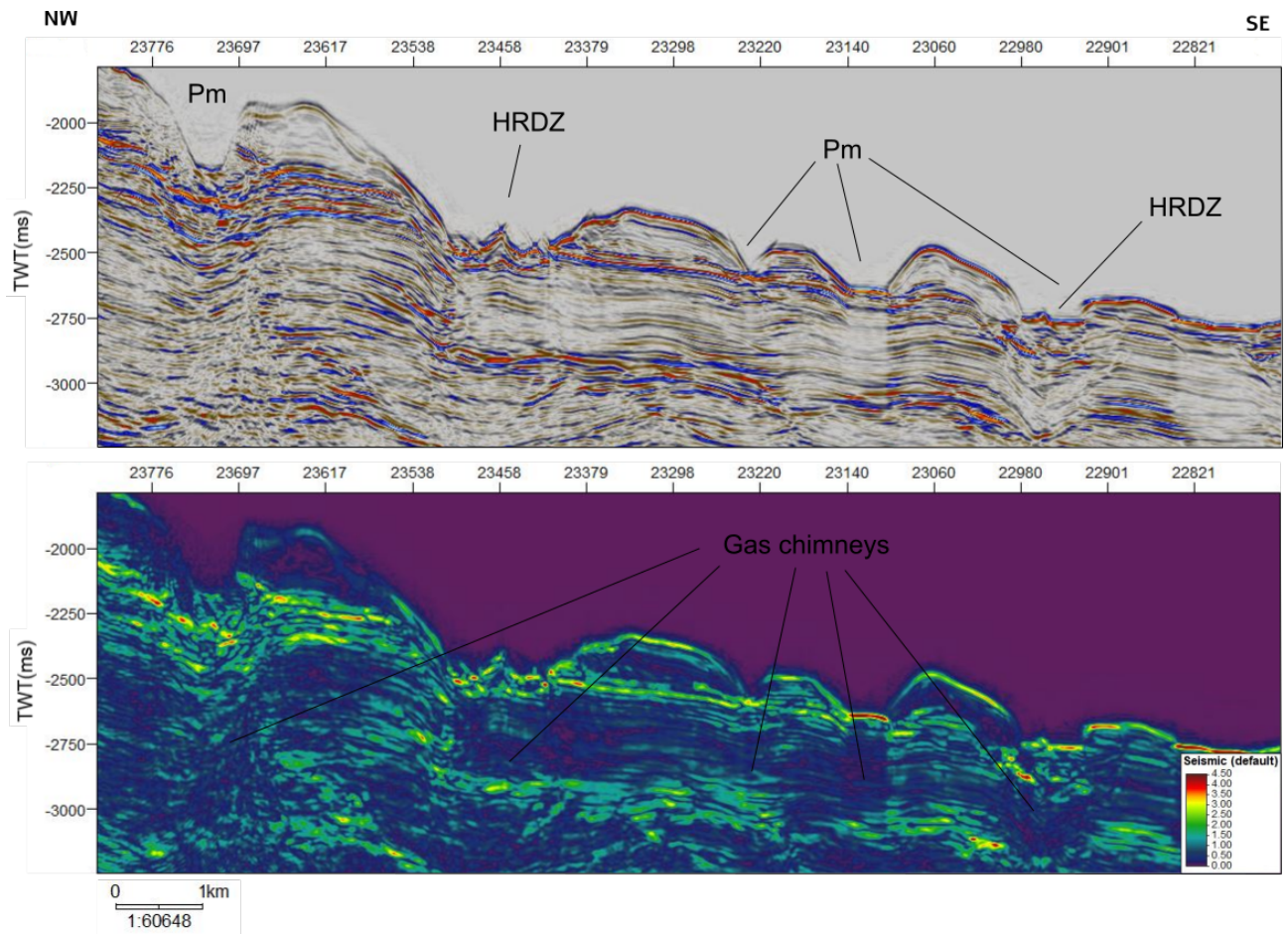
Appendix 11 Seismic section, instantaneous amplitude, and instantaneous frequency.



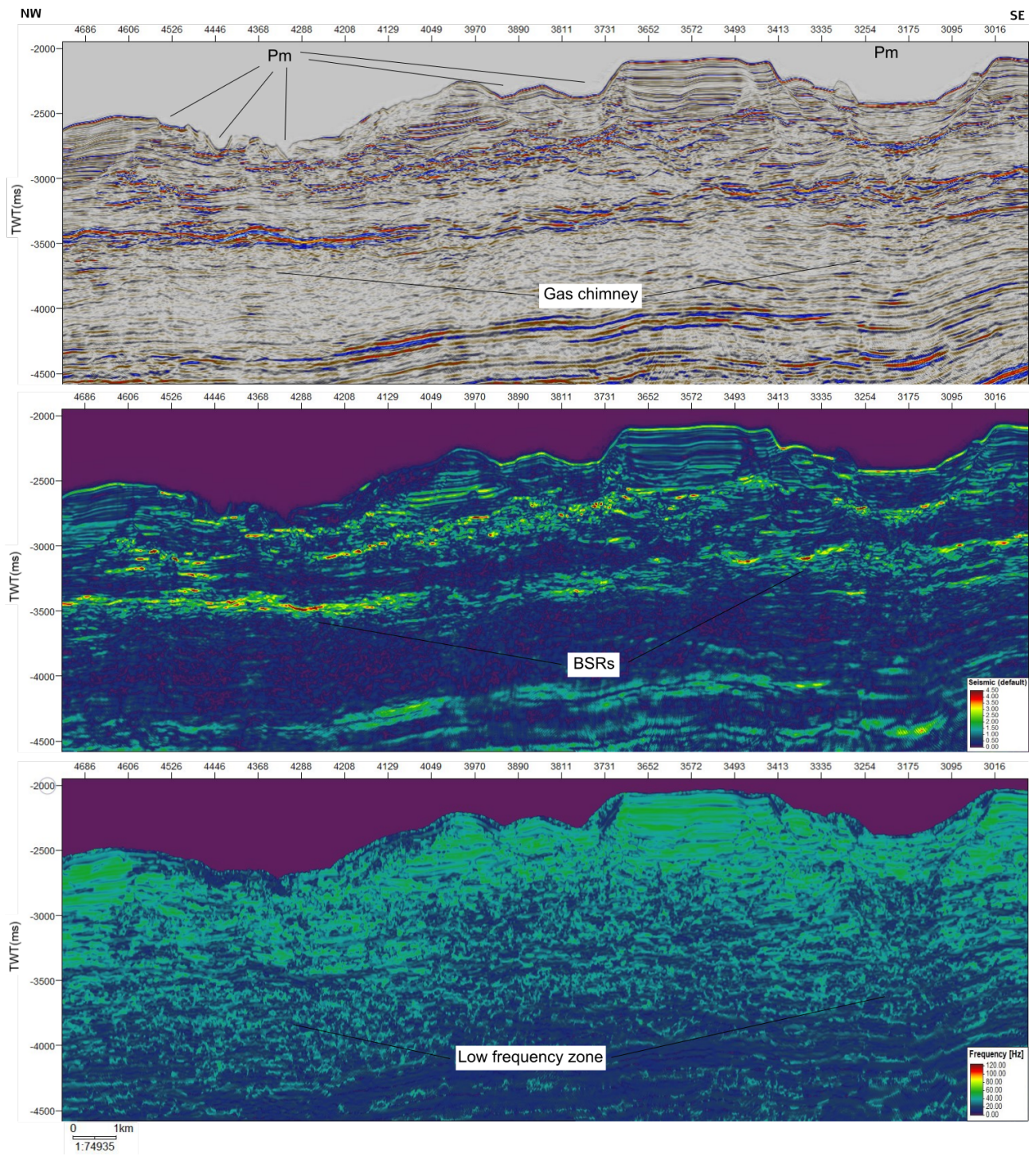
Appendix 12 Seismic section, instantaneous amplitude, and chaos.



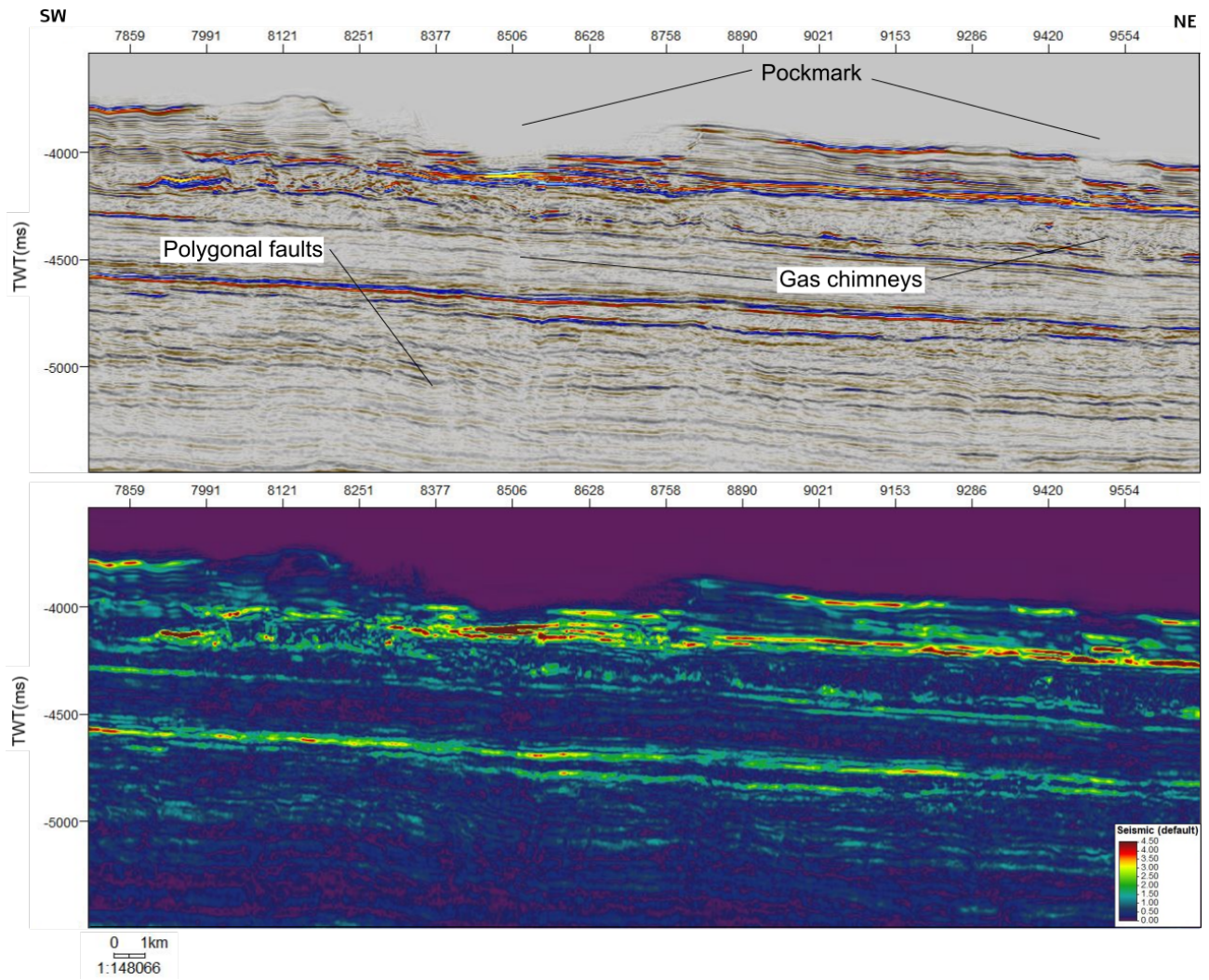
Appendix 13 Seismic section and instantaneous amplitude.



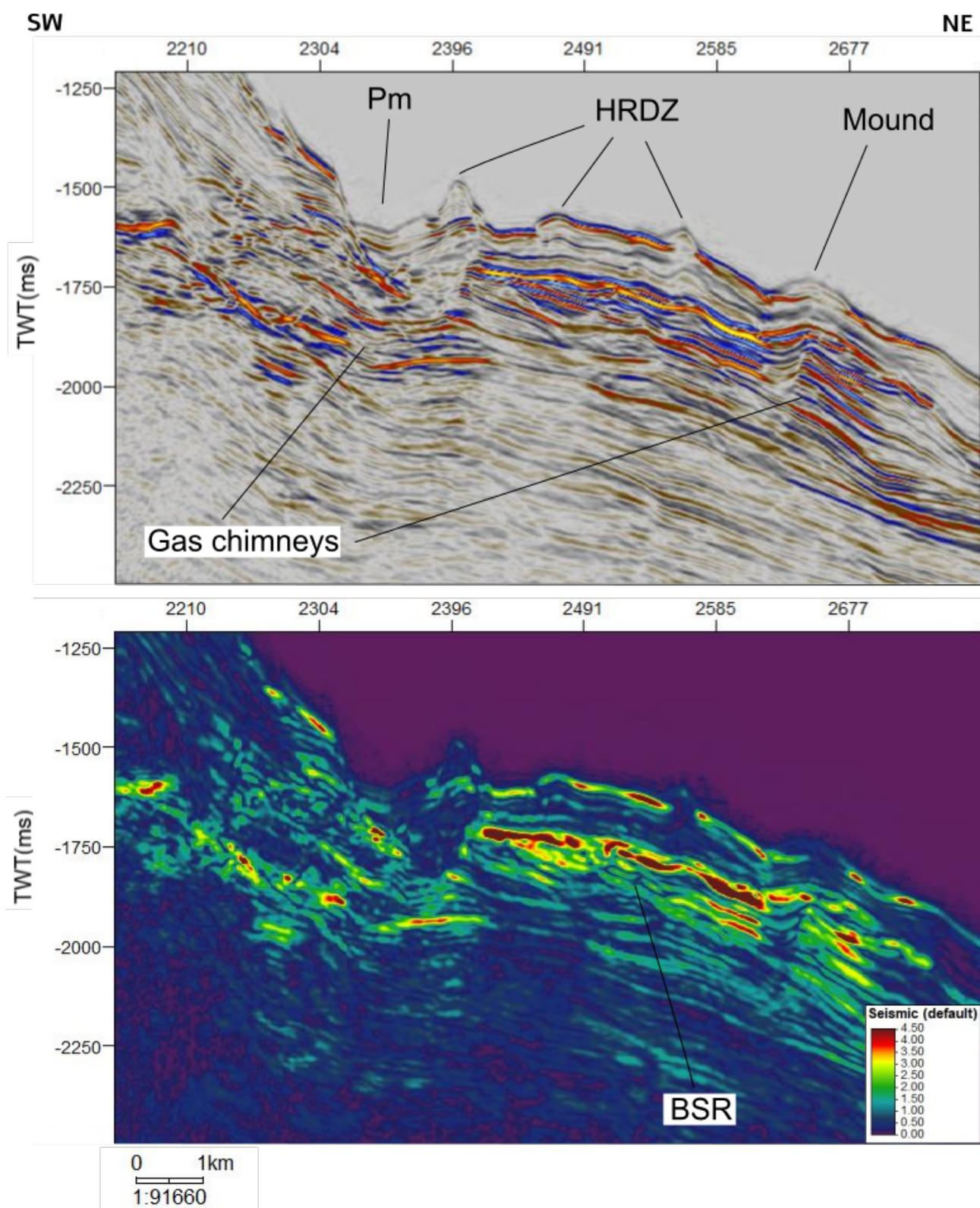
Appendix 14 Seismic section and instantaneous amplitude.



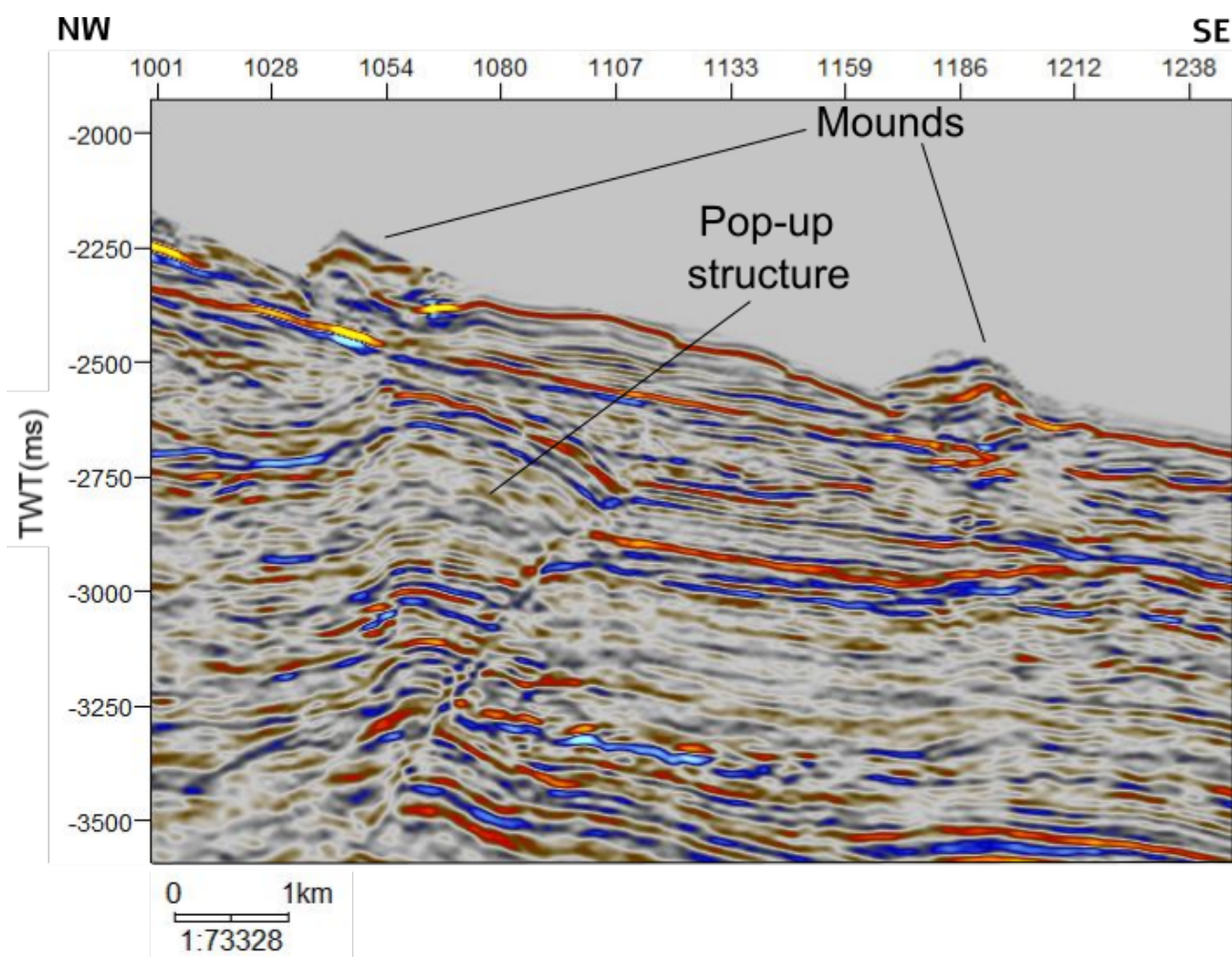
Appendix 15 Seismic section, instantaneous amplitude, and instantaneous frequency.



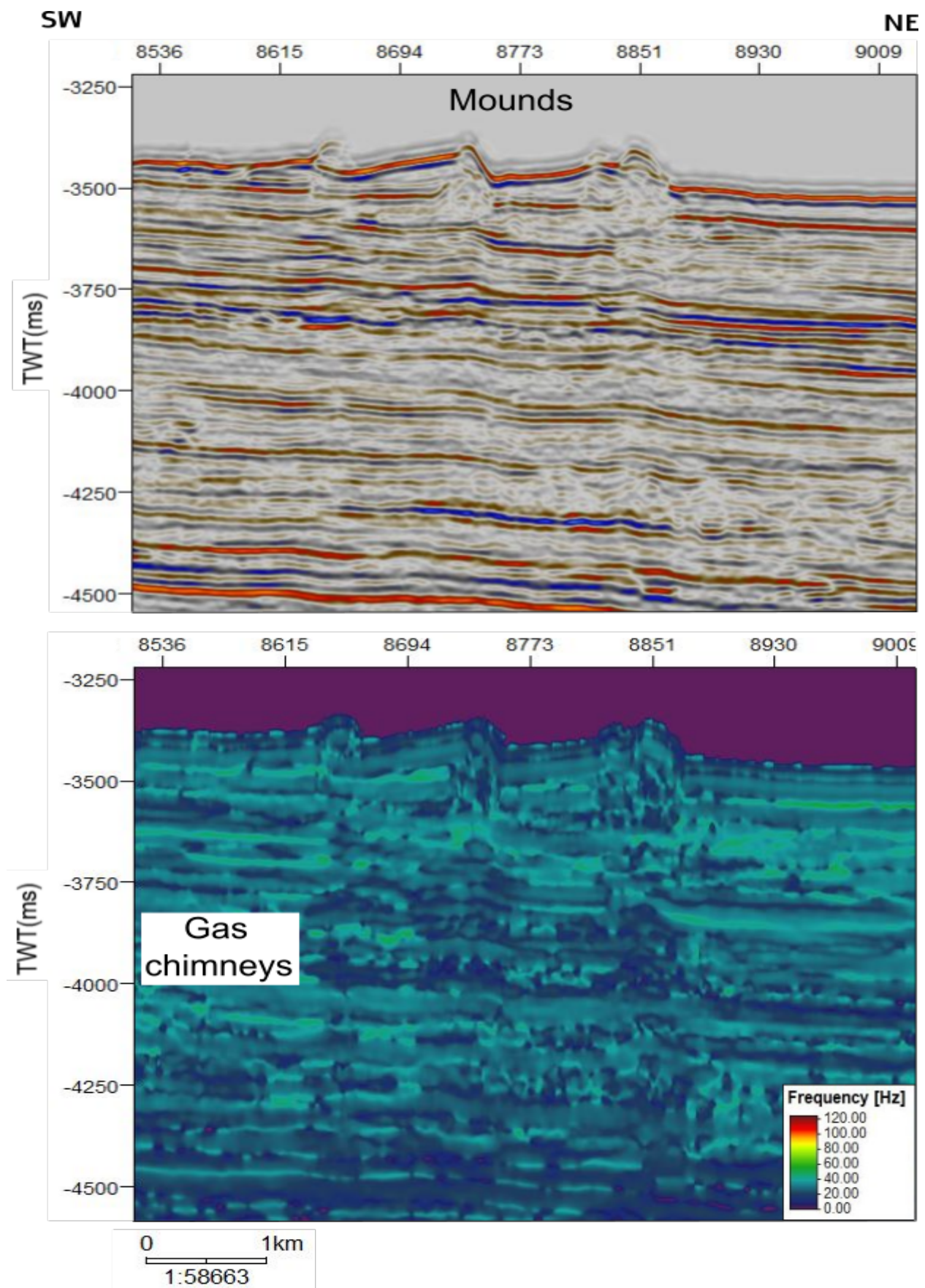
Appendix 16 Seismic section and instantaneous amplitude.



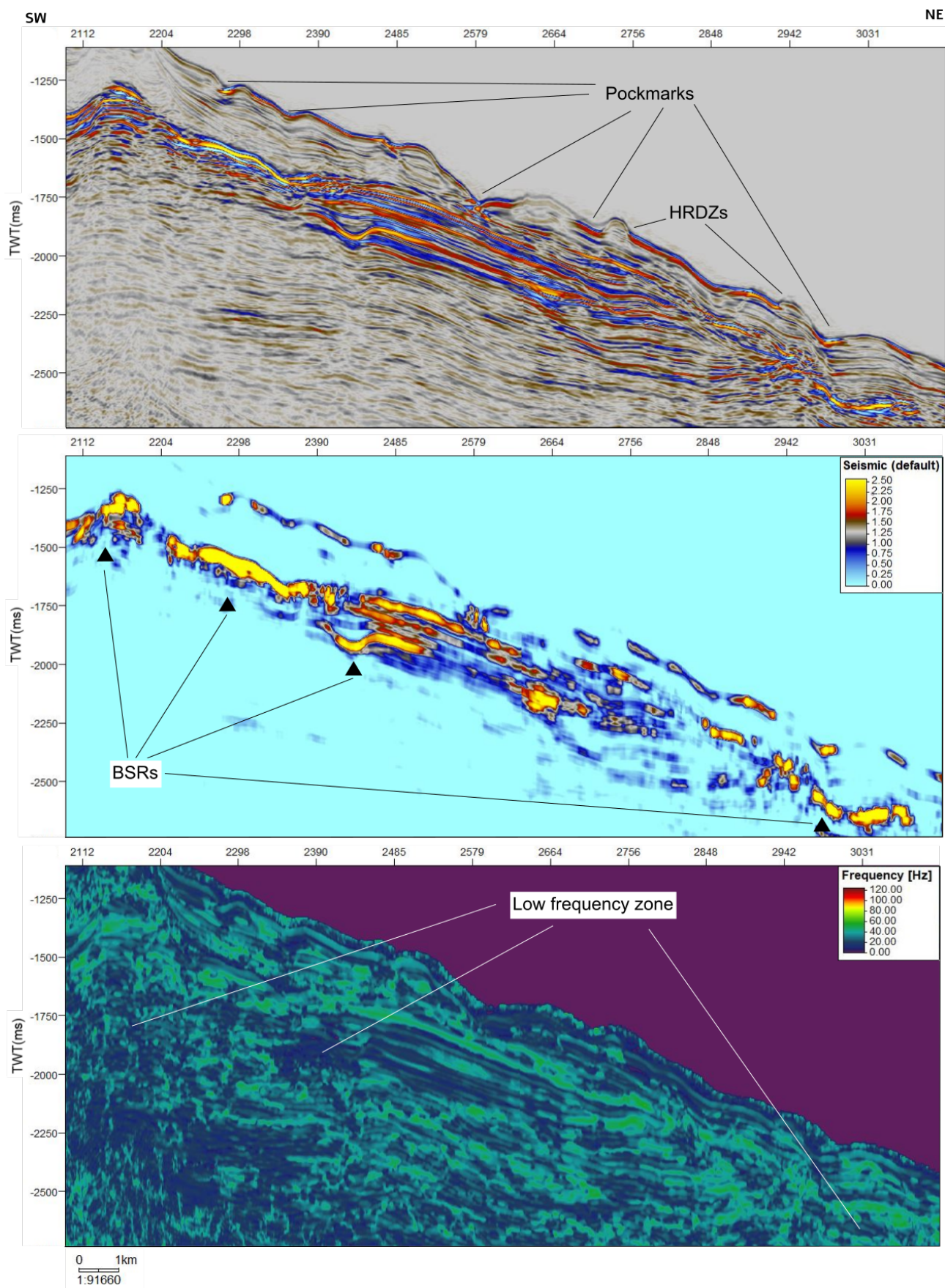
Appendix 17 Seismic section and instantaneous amplitude.



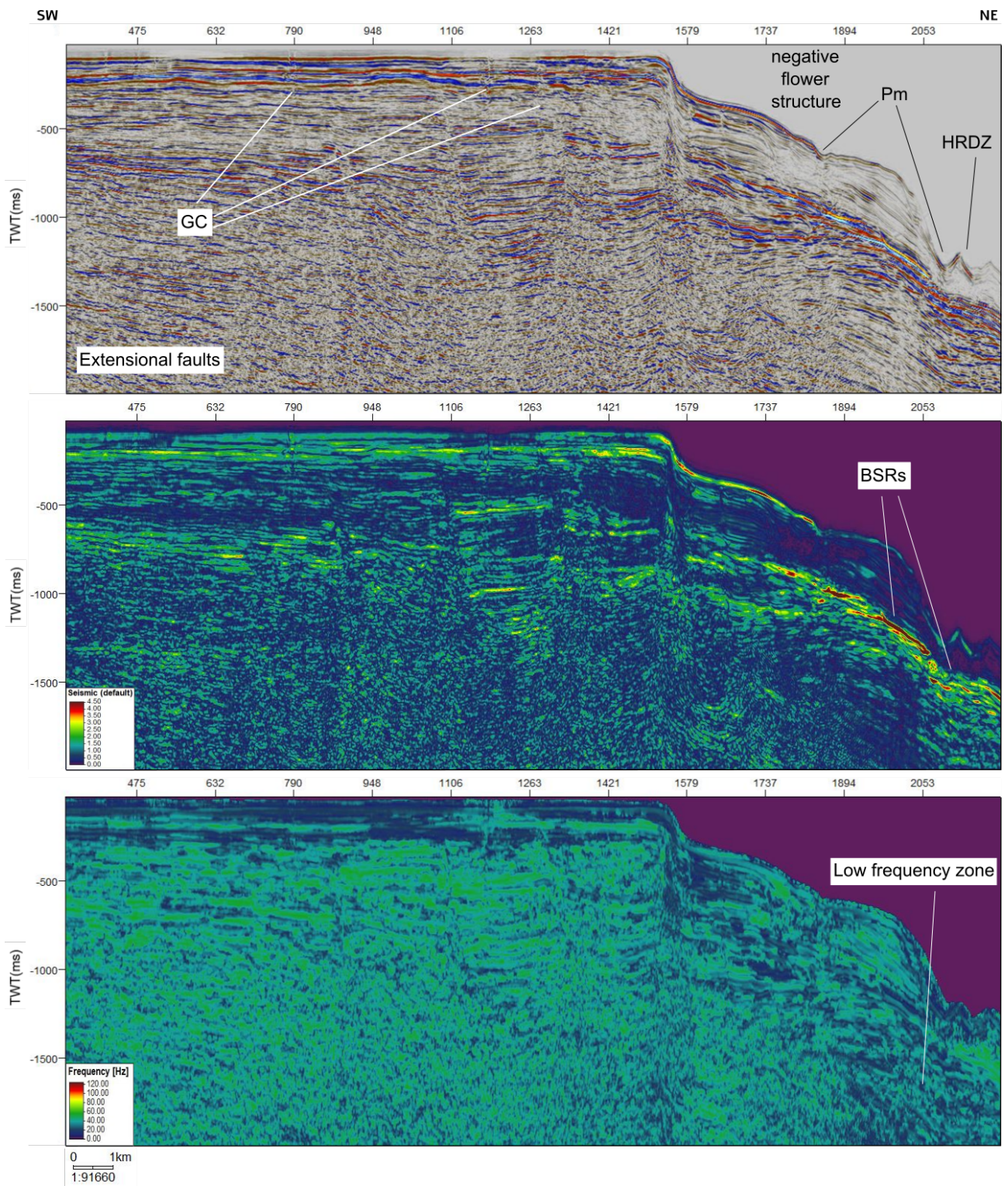
Appendix 18 Seismic section.



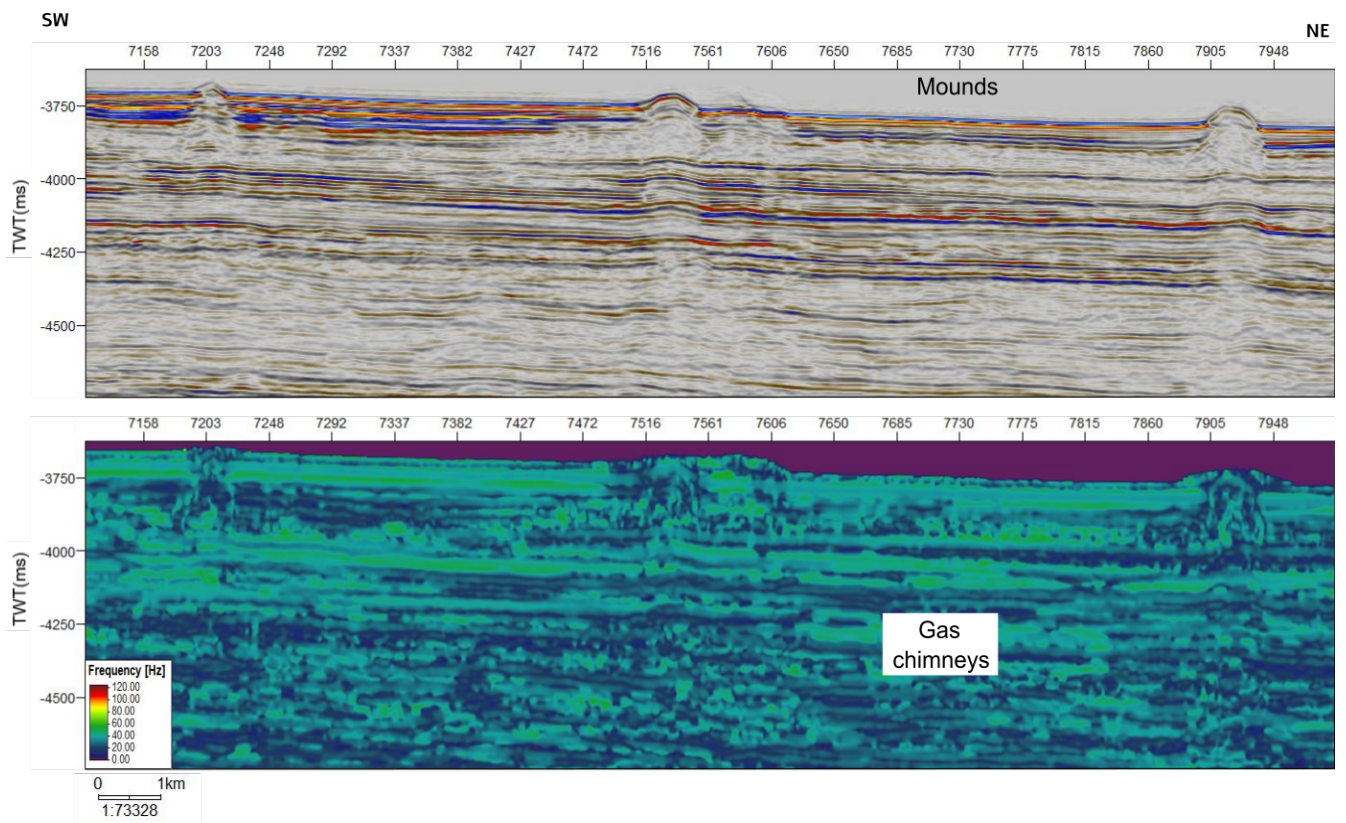
Appendix 19 Seismic section and instantaneous frequency.



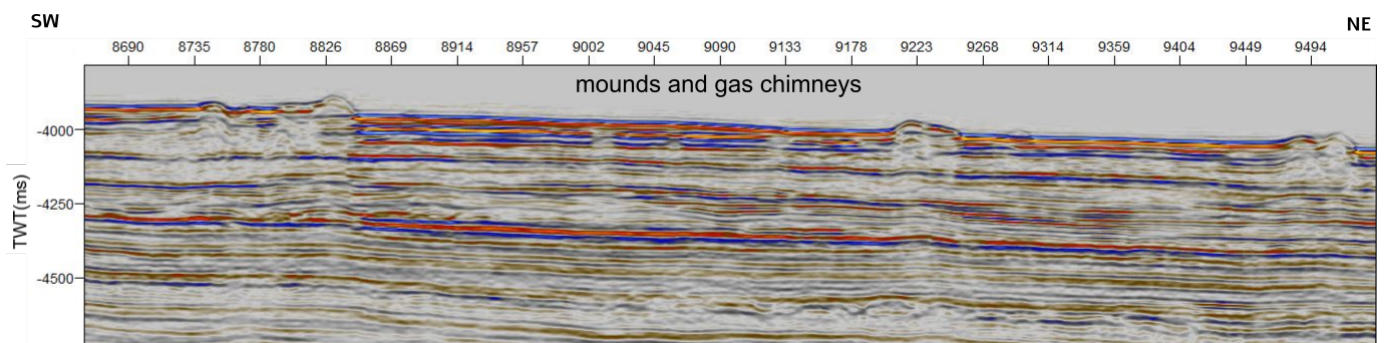
Appendix 20 Seismic section, RMS Amplitude, and instantaneous frequency.



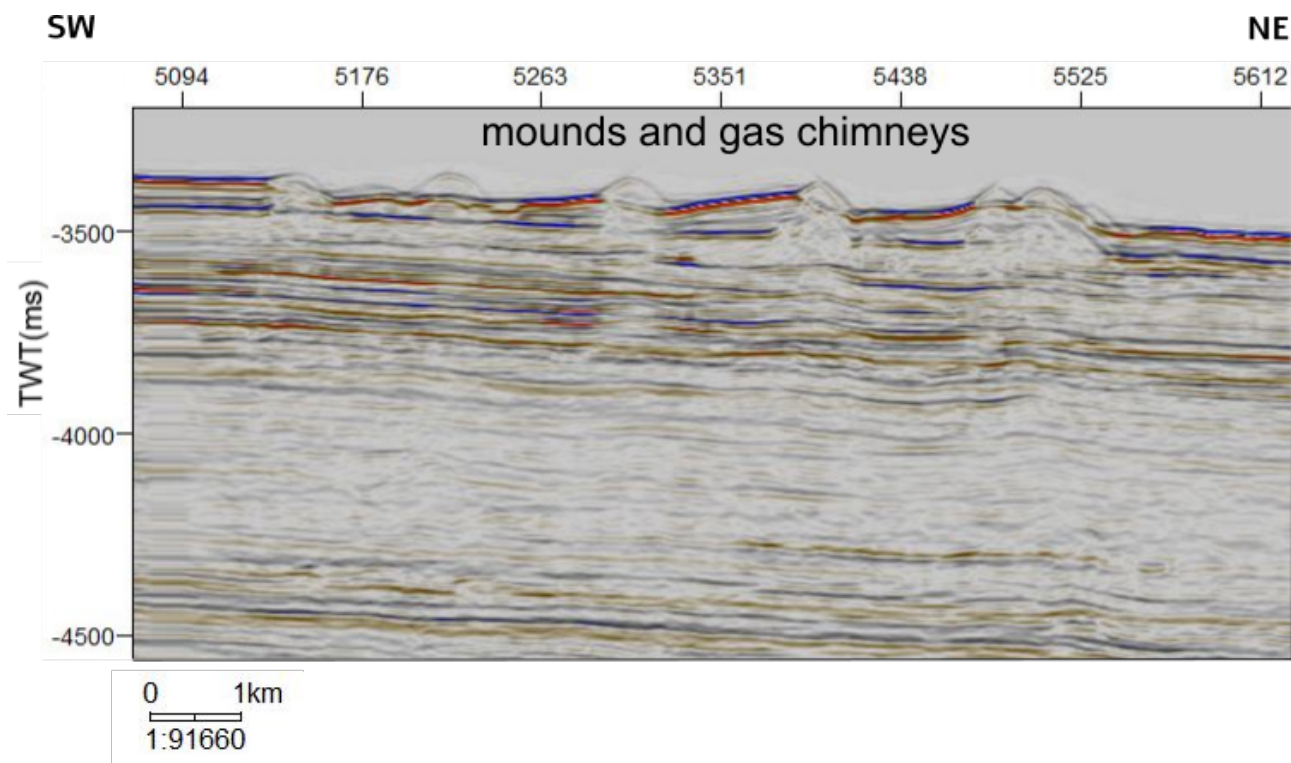
Appendix 21 Seismic section, instantaneous amplitude, and instantaneous frequency.



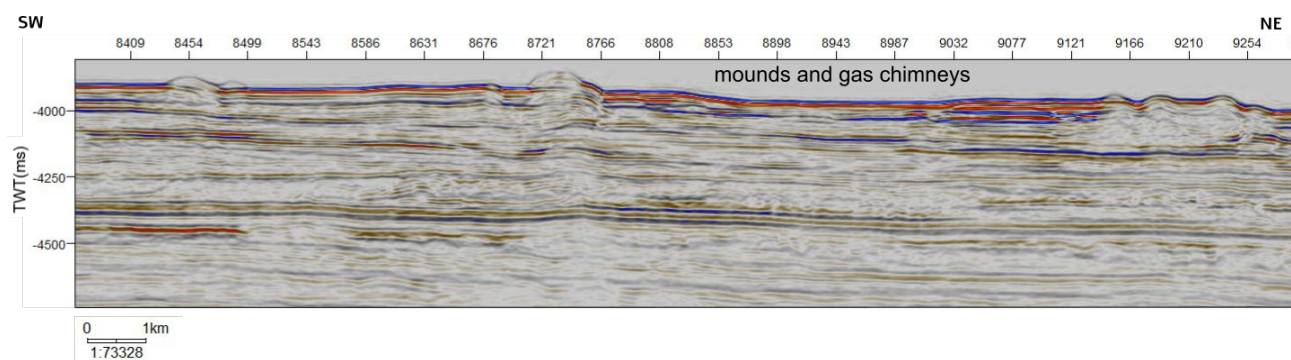
Appendix 22 Seismic section and instantaneous frequency.



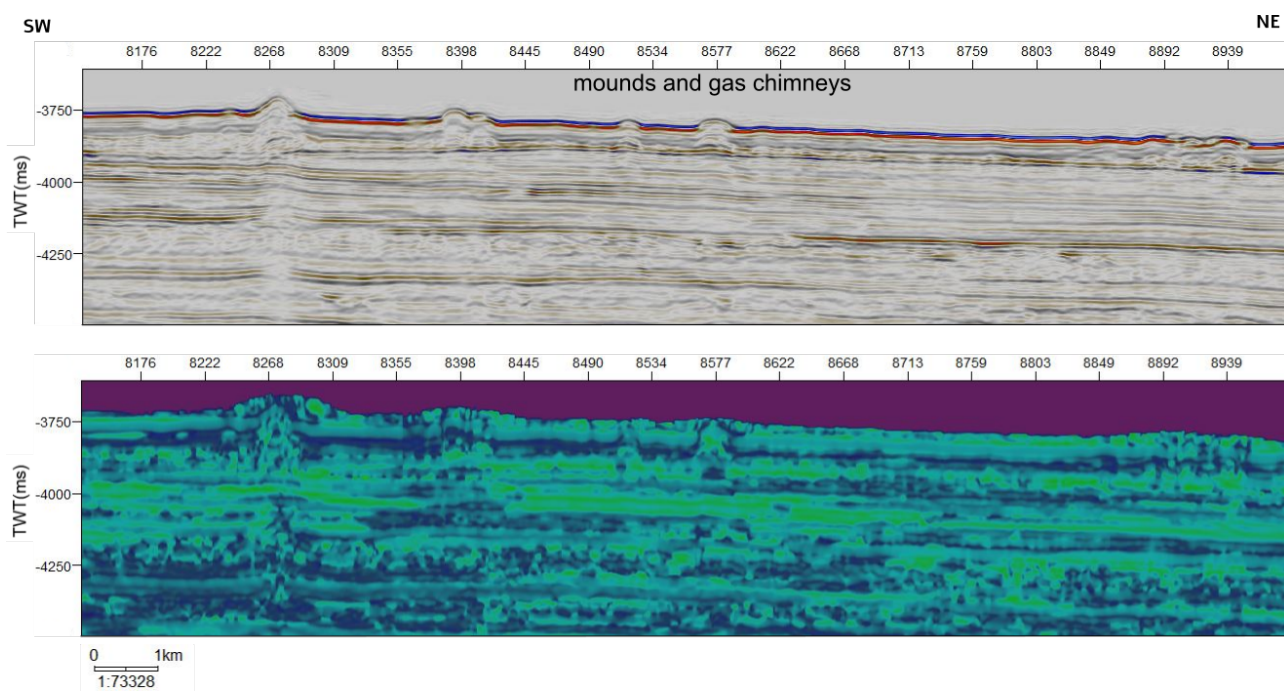
Appendix 23 Seismic section.



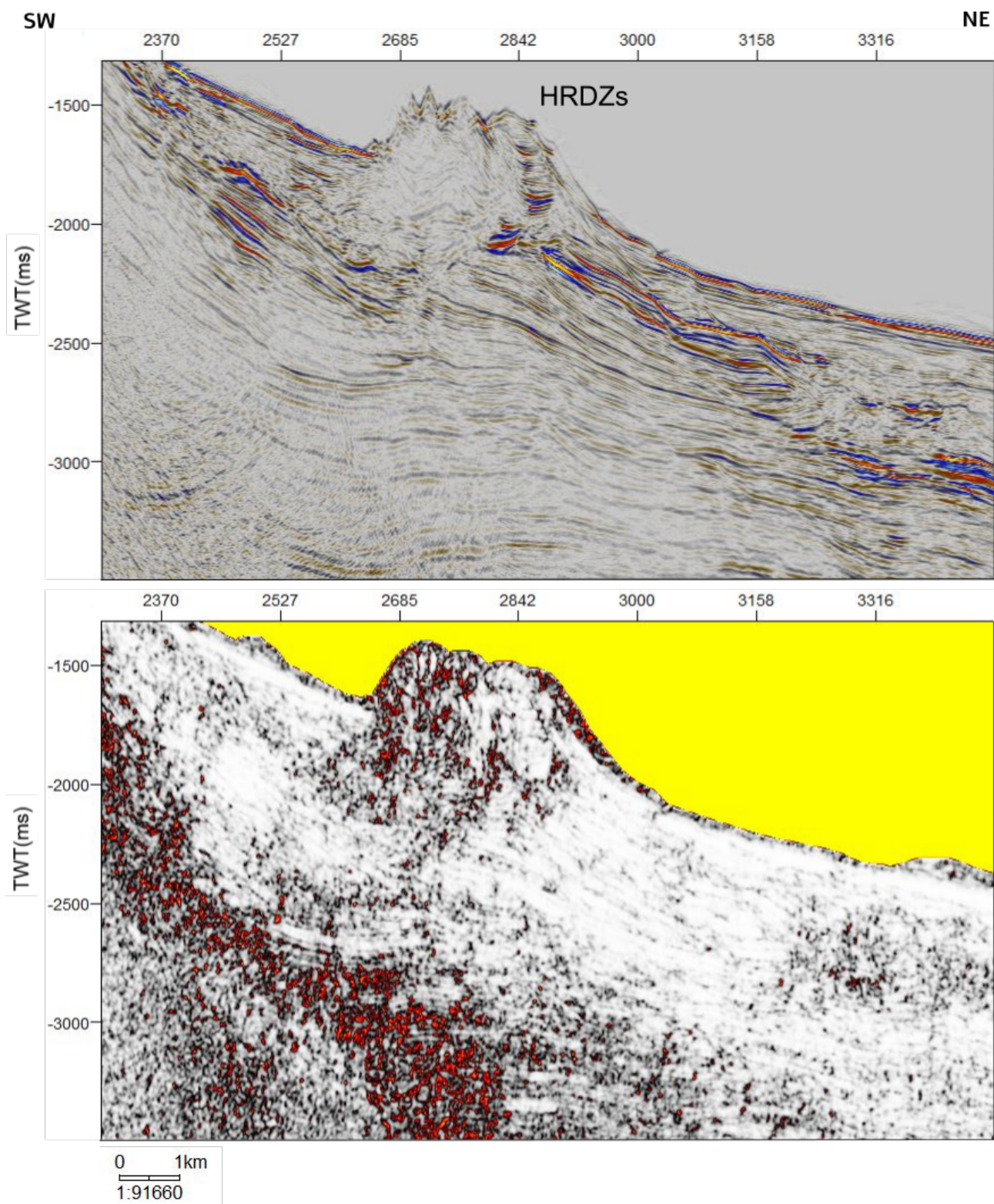
Appendix 24 Seismic section.



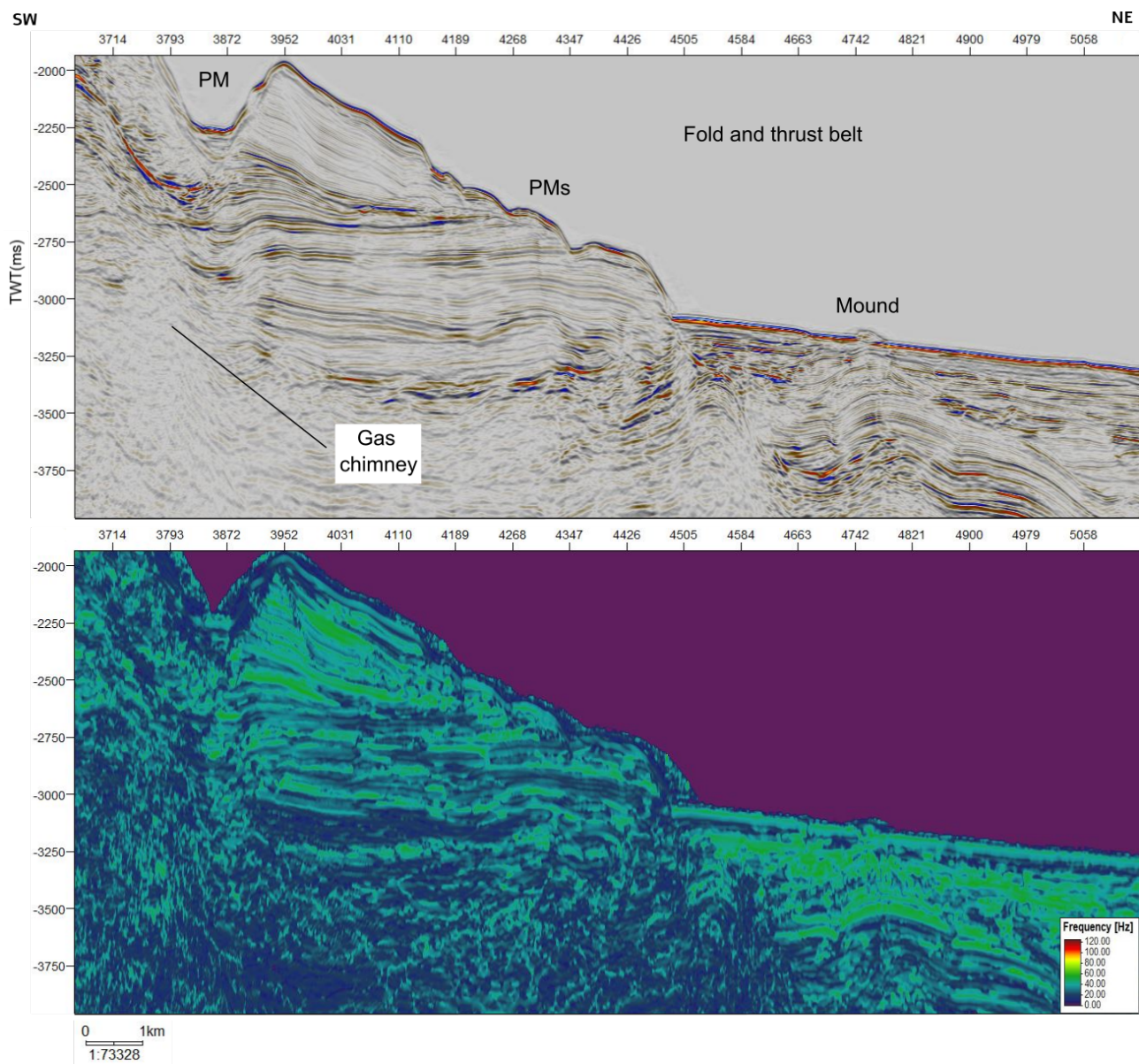
Appendix 25 Seismic section.



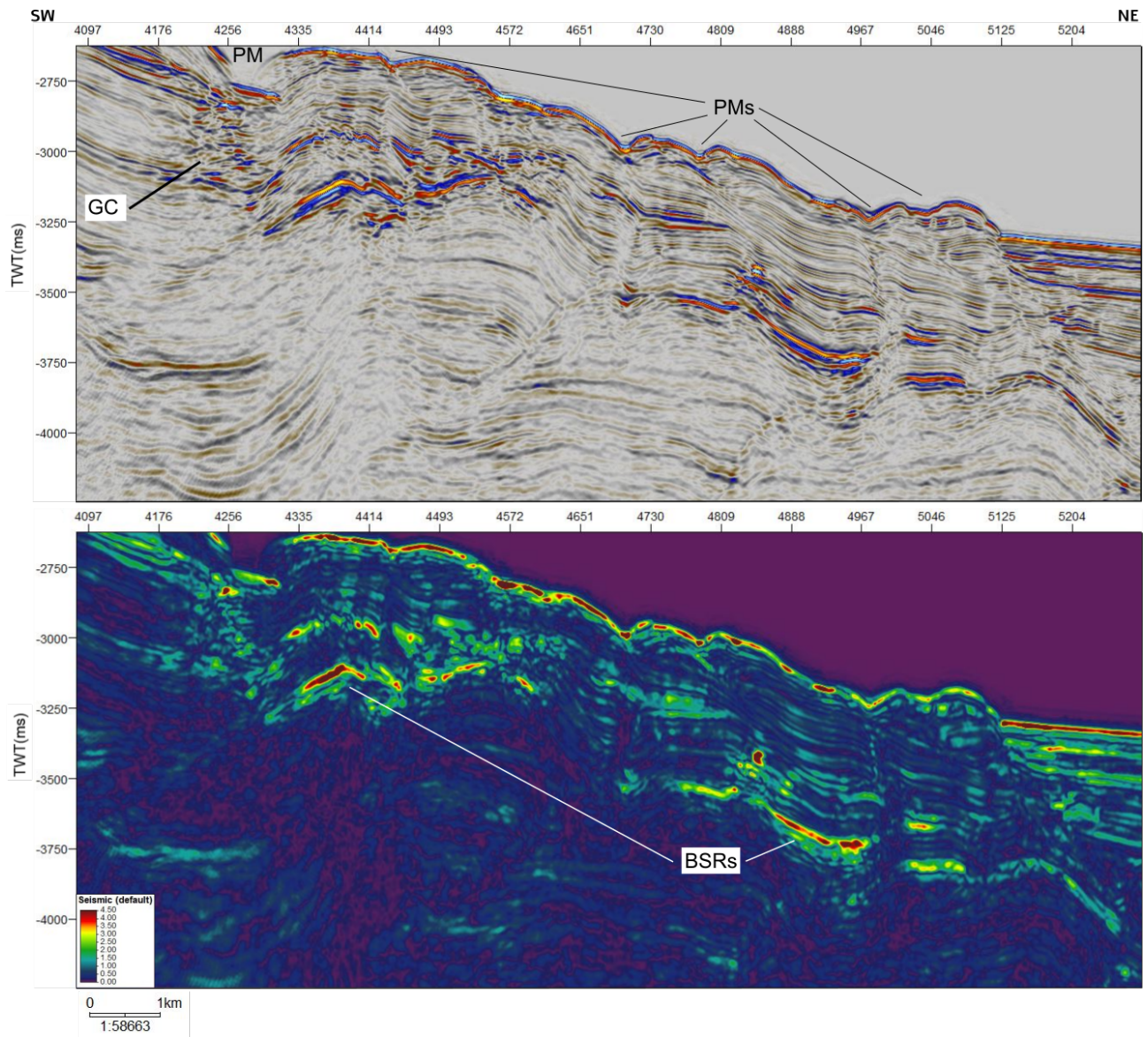
Appendix 26 Seismic section and instantaneous frequency.



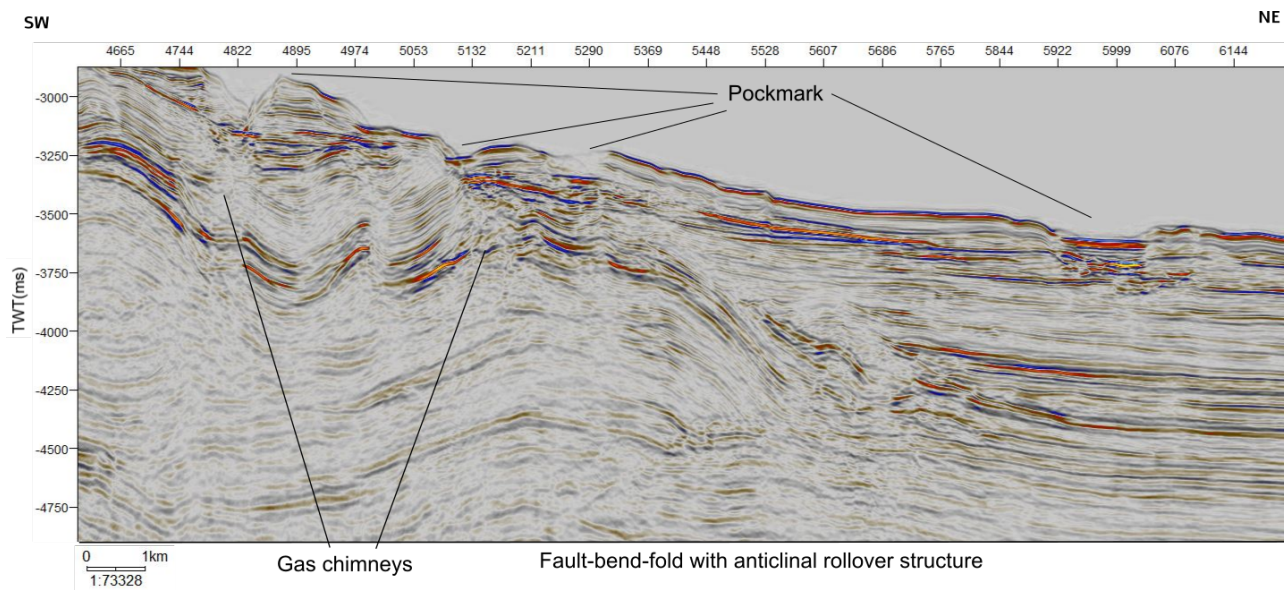
Appendix 27 Seismic section and chaos.



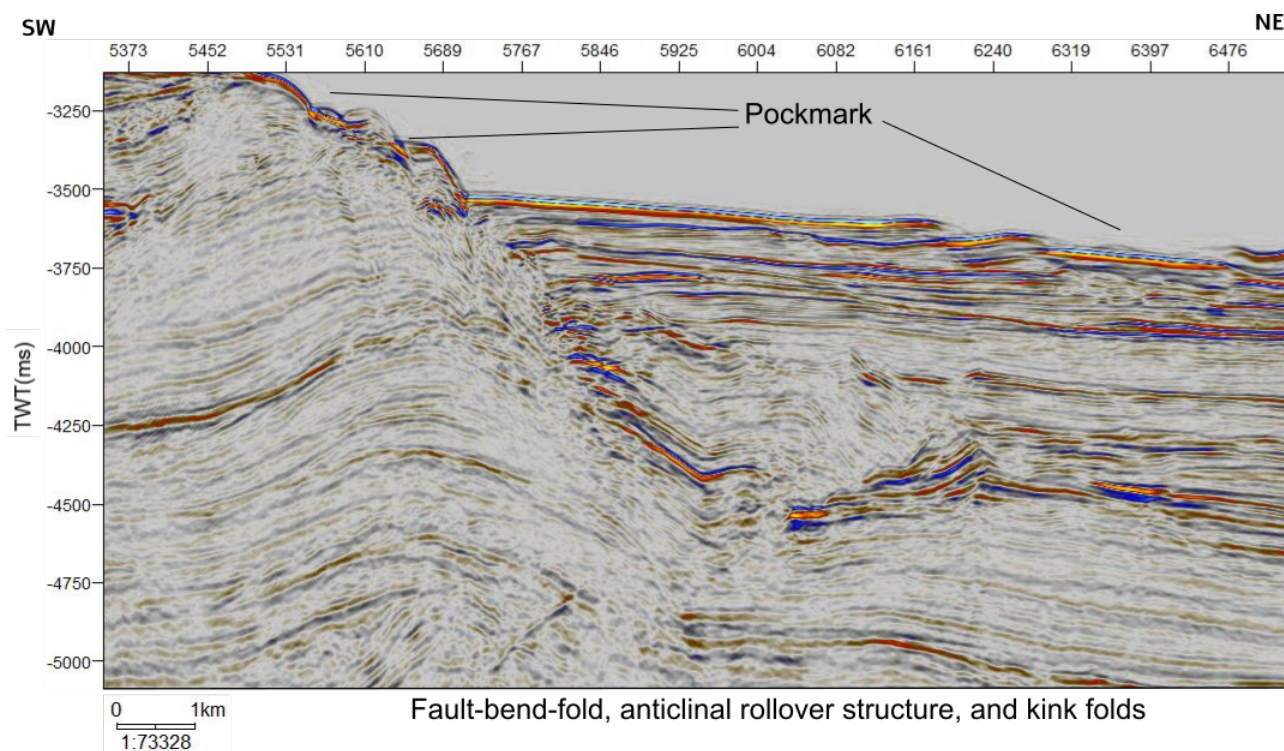
Appendix 28 Seismic section and instantaneous frequency.



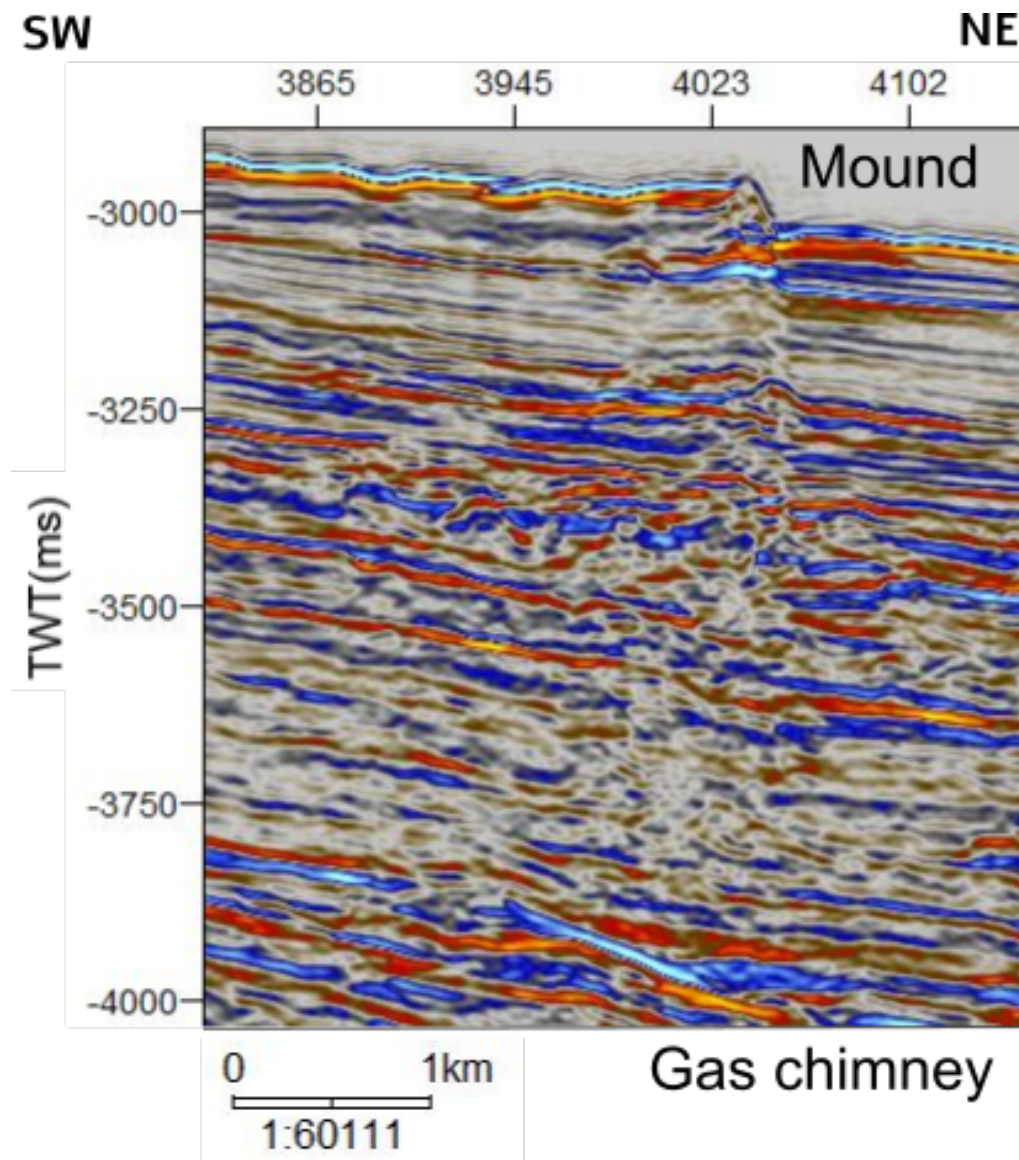
Appendix 29 Seismic section and instantaneous amplitude.



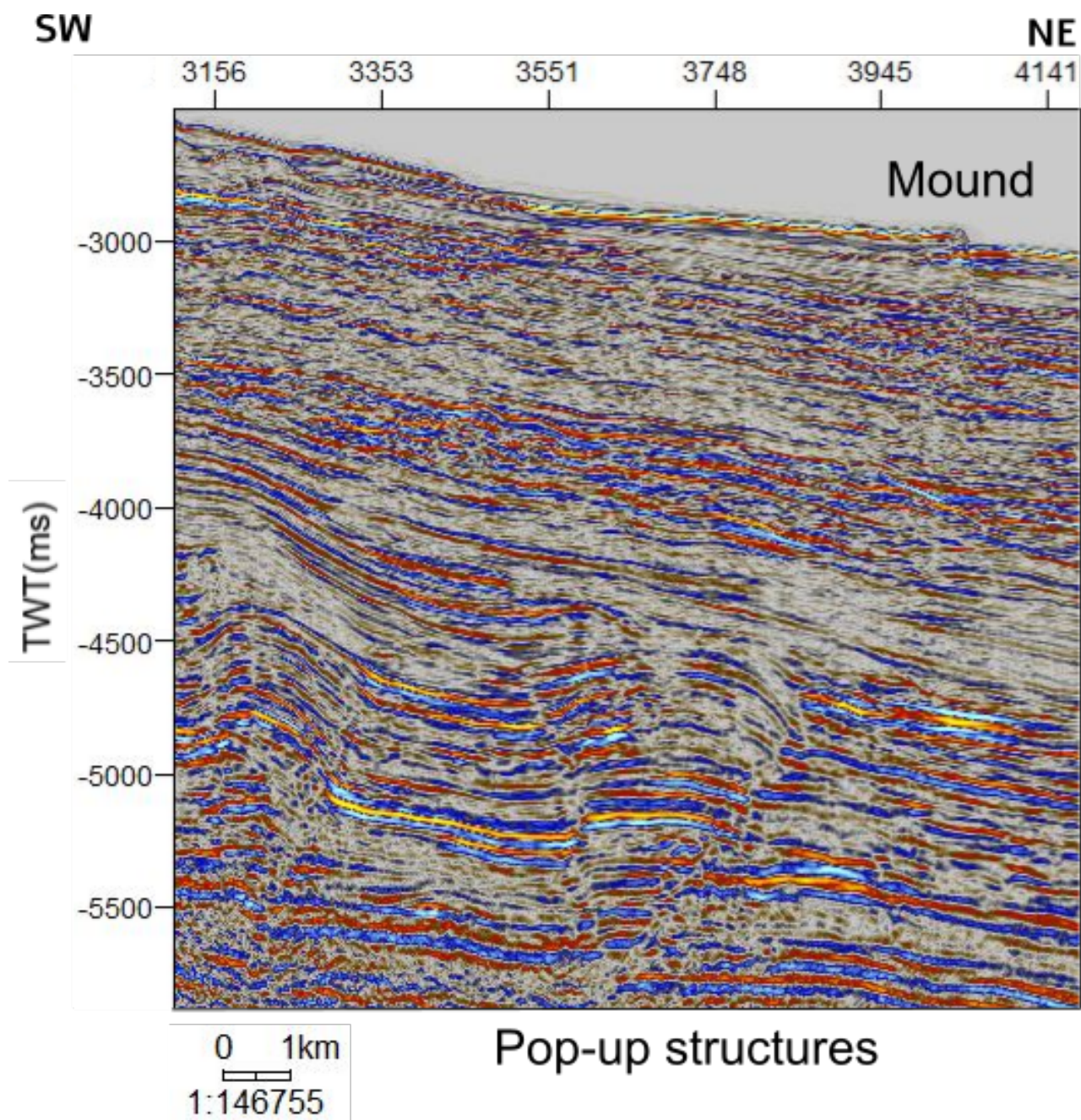
Appendix 30 Seismic section.



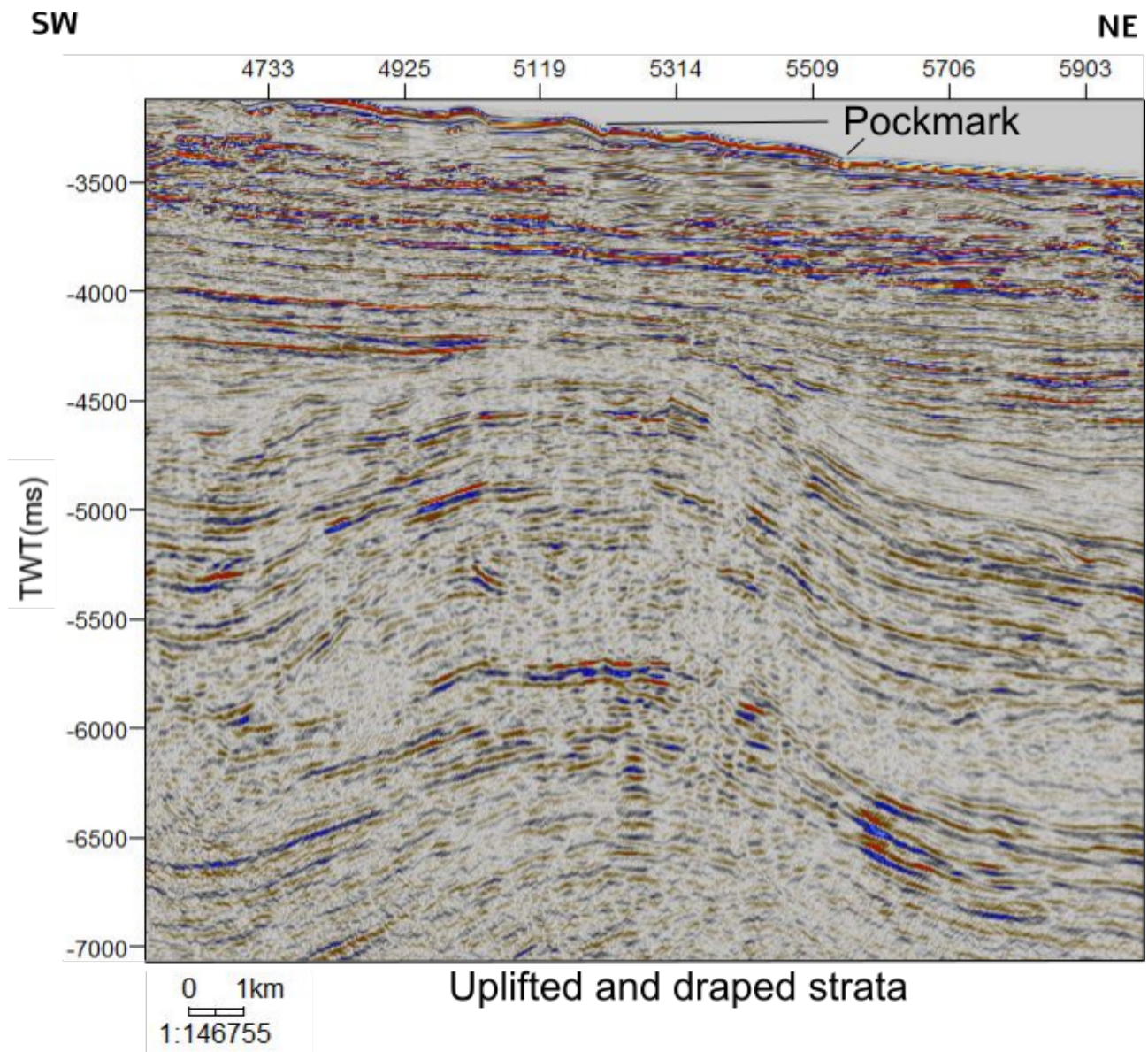
Appendix 31 Seismic section.



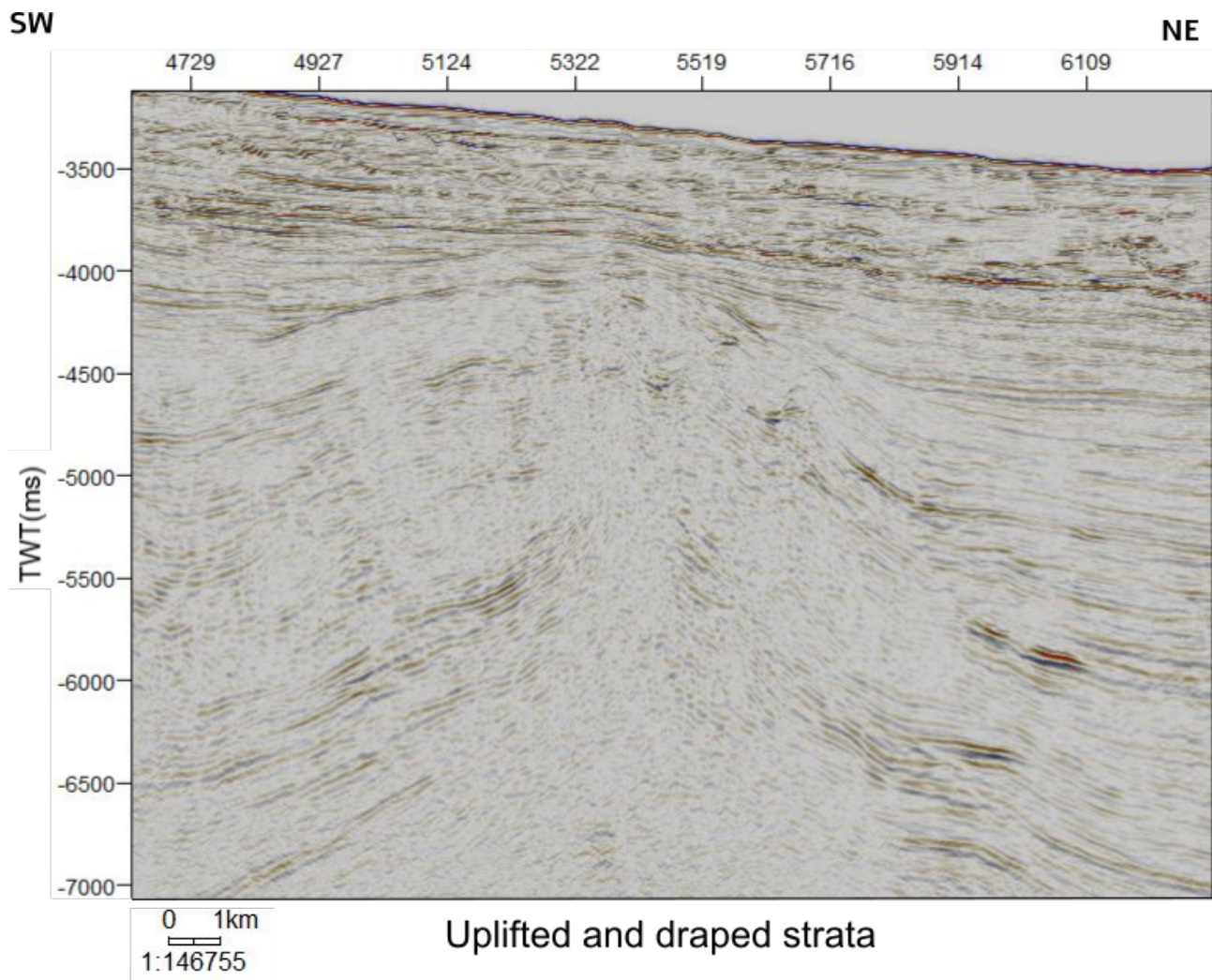
Appendix 32 Seismic section.



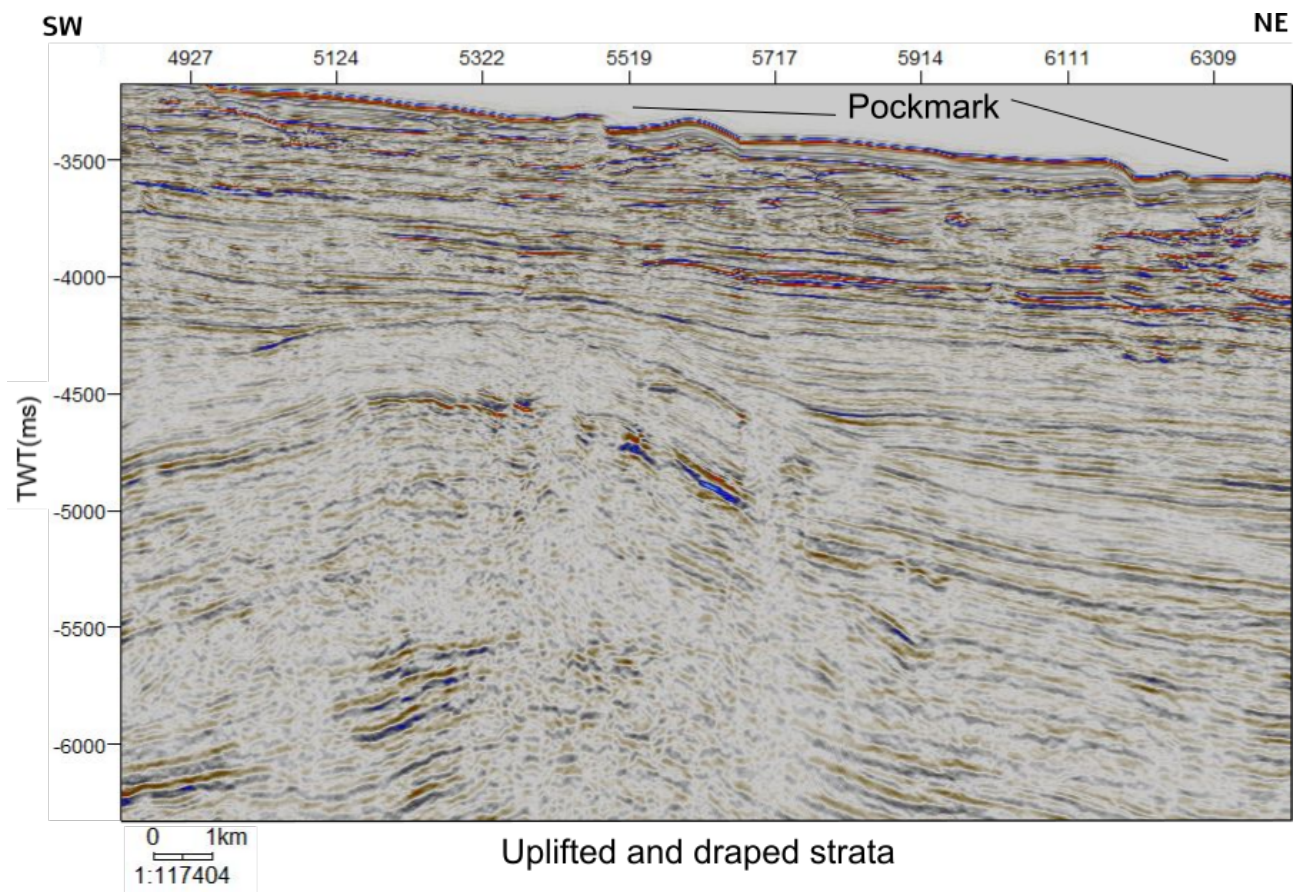
Appendix 33 Seismic section.



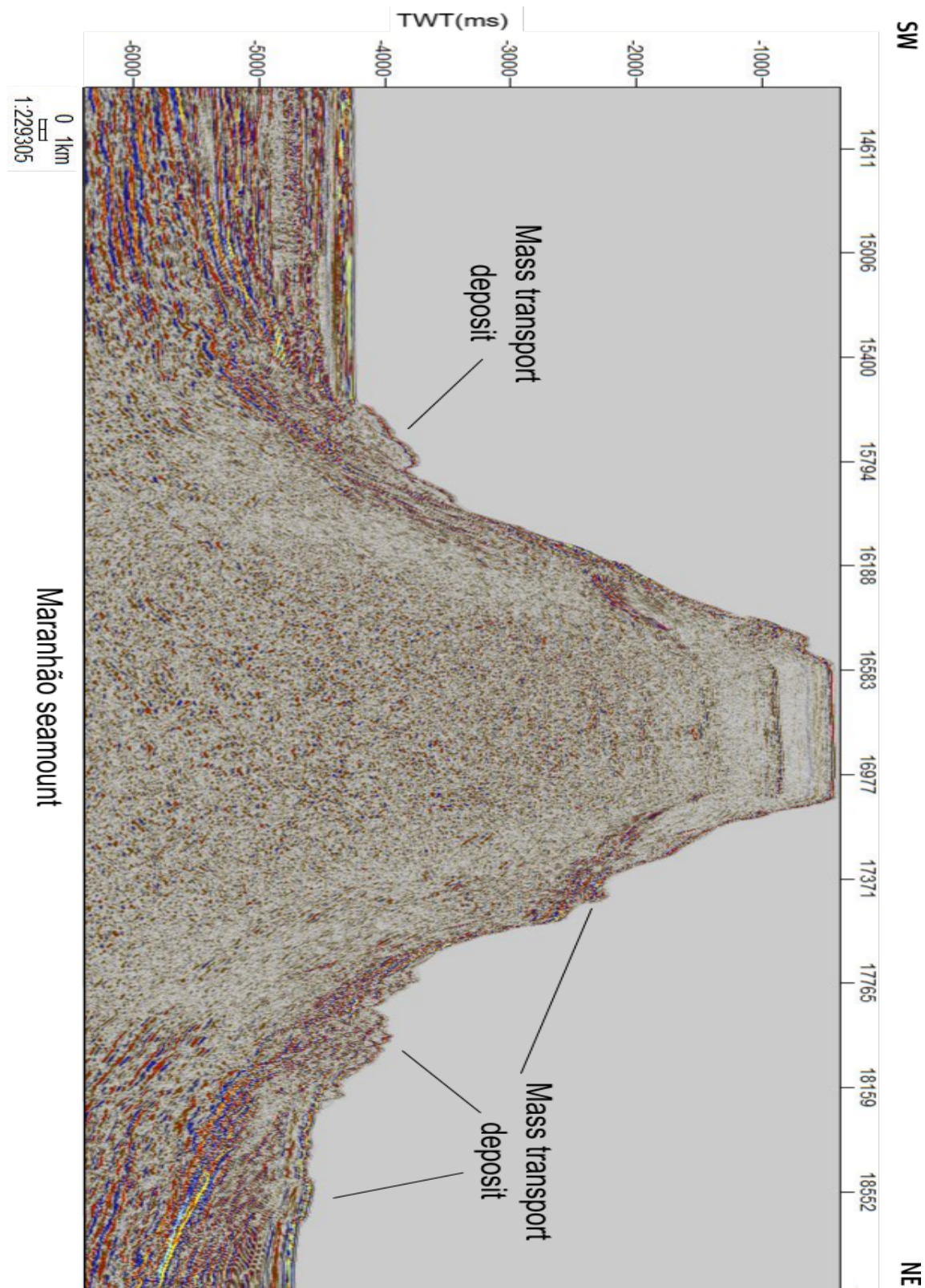
Appendix 34 Seismic section.



Appendix 35 Seismic section.



Appendix 36 Seismic section.



Appendix 37 Seismic section.