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EVOLUÇÃO E GEOMORFOLOGIA DO CÂNION DO SÃO FRANCISCO E DO TALUDE ADJACENTE, COM BASE EM DADOS DE BATIMETRIA MULTIFEIXE

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Orientador: Prof. Dr. José Maria Landim Dominguez

Dissertação de Mestrado apresentada ao Programa de Pesquisa e Pós-Graduação em Geologia do Instituto de Geociências da Universidade Federal da Bahia como requisito parcial à obtenção do Título de Mestre em Geologia, Área de Concentração: Geologia Marinha, Costeira e Sedimentar.

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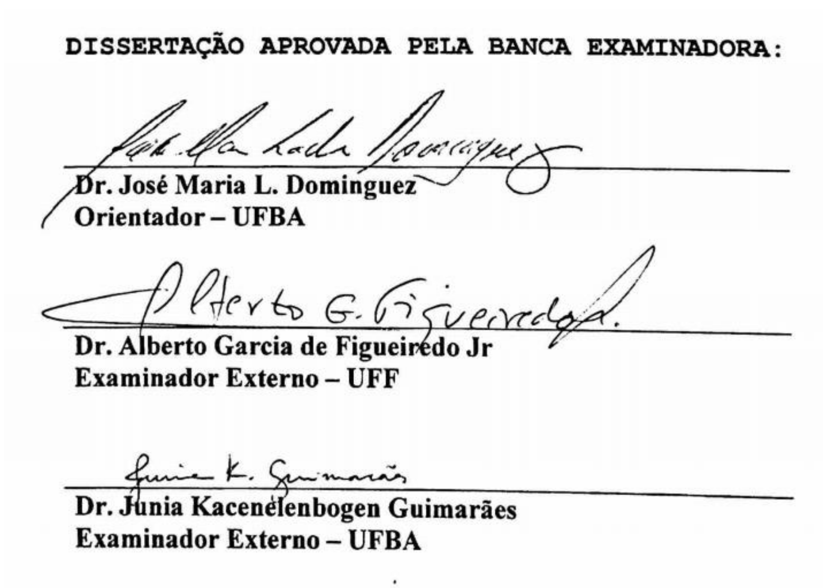

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“...você faz parte desse caminho...”

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RESUMO

Cânions submarinos são encontrados nas margens continentais de todo o mundo, e atuam como principais condutos de sedimentos para o oceano profundo. A sua origem é atribuída a muitas causas, com destaque para movimentos de massa, variações do nível do mar e correntes de turbidez. Apenas 2,6 % desses vales exibem direta conexão com sistema fluvial, e a maioria deles estão em margens ativas. O Cânion do São Francisco (CSF), localizado na região nordeste do Brasil, está diretamente associado ao delta homônimo. A clinoforma deltaica prograda atualmente sobre a cabeceira do cânion. Neste trabalho é apresentado uma caracterização detalhada do Cânion do São Francisco (CSF) e do talude adjacente, com base em dados de batimetria multifeixe coletados na região. Dados de sísmica 3D na cabeceira do cânion foram utilizados, ajudando a entender a formação e evolução do cânion, além de sua ligação com o rio São Francisco, que aparentemente ocorre independentemente do momento de nível do mar. Diversas estruturas foram mapeadas na região: sete cânions principais, sendo o maior o do São Francisco; um paleocânion do CSF; canais tributários; ravinas; *cut-offs*; desmoronamenots; *mounds* e *pockmarks*. A porção superior do CSF possui a maior declividade e é retilíneo. O segmento médio apresenta uma geometria sinuosa, com muitos *cutoffs*, além de terraços e diques marginais bordejando o talvegue do cânion. O cânion moderno do São Francisco está implantado sobre antigos cânions já preenchidos e representa um episódio de re-incisão, talvez associado a abaixamento do nível do mar desde o nível de mar alto do Mioceno Médio, ou no momento em que o rio São Francisco passou a desaguar na região. A agradação/progradação carbonática na plataforma externa ajudou na criação de depressão ao redor da cabeceira do cânion, que por sua vez é importante para canalização de sedimento para o vale. Os demais cânions vizinhos ao CSF formaram-se e se desenvolveram a partir de processos de instabilidade e deslizamentos no talude e exibem diferentes estágios de erosão regressiva, com a maioria deles confinados no talude. O CSF é o que apresenta a menor declividade média e o único cânion sinuoso, devido sua relação com um sistema fluvial. O paleocânion exibe similaridades morfológicas com o cânion atual (sinuosidade e declividade) e está situado a sul do cânion ativo. Sua existência aponta para uma mudança no canal principal por um processo de avulsão. Os *pockmarks* e *mounds* interpretados como estruturas de escape de gás e recifes de água profunda respectivamente, se concentram principalmente na porção nordeste da região de estudo. As correntes de contorno que atuam na região aparentam controlar desenvolvimento e distribuição dos *mounds* e *pockmarks*, como também na maturidade dos cânions submarinos no talude continental.

Palavras-chave: Batimetria multifeixe; Cânions submarinos; Talude continental; variação do nível do mar.

ABSTRACT

Submarine canyons are found on continental margins worldwide and they act as the main conductor of sediments to the deep ocean. The origin of these features is attributed to many causes, especially mass movements, changes in sea level and turbidity currents. Only 2.6% of these valleys exhibit a direct connection with fluvial systems and most of them are found in active margins .The São Francisco canyon (SFC), located in the northeastern region of Brazil, is directly associated with its homonymous delta. Currently the deltaic clinoform progrades over the canyon head. In this work we present the results of a multibeam bathymetric survey conducted in the region in May of 2011. 3D seismic data from the canyon head was utilized helping in the understanding of formation, evolution and link between the SFC and the São Francisco River. This link appears to happen regardless of the sea level moment. Several structures have been mapped: seven major canyons, the biggest one SFC; one paleocanyon of the SFC (SFPC); tributary channels; gullies; cutoffs; landslides; mounds and pockmarks. The upper segment of the SFC has the highest slope and rectilinear geometry. The middle segment has a meandering geometry with multiple cutoffs and displays several terraces and levees bordering the thalweg of the canyon. The modern São Francisco canyon is formed above an ancient canyon filled and represents a re-incision episode, perhaps associated with the lowering of sea level from the last high sea level of the middle Miocene, or with moment in which the São Francisco River began to flow into this region. The carbonate aggradation/proggradation of the outer shelf helped on the creation of a bathymetric low around the canyon head, which is important to the sediment funneling to the valley. The other canyons, next to the SFC, were formed by processes of instability and landslides on continental slope and exhibit different stages of regressive erosion, where most of them are confined on continental slope. The SFC is the one with the lowest average values of slope and is the unique sinuous canyon due its relationship with major fluvial system. The SFPC displays morphological similarities with the current canyon (sinuosity and slope) and is located southwards of the active canyon. Its existence leads to a change in the main channel by an avulsion process. The pockmarks and mounds that were interpreted as gas escape and deep water reefs respectively are concentrated mainly in the northeast portion of the study area. The contour current operating on the region appears to control the development and distribution of mounds and pockmarks and also the maturity of submarine canyons present on continental slope.

Keywords: Multibeam bathymetry; Submarine canyons; Continental slope; Sea level change.

SUMÁRIO

CAPÍTULO 1
INTRODUÇÃO GERAL

Introdução Geral

Cânions submarinos são feições geomorfológicas presentes nas margens continentais de todo o mundo (Harris and Whiteway, 2011). Eles atuam como principal conduto para transporte de materiais da plataforma continental para o oceano profundo (Shepard, 1972; Gardner 1989), e mais recentemente tem sido destacado o seu papel como *hot-spots* de biodiversidade marinha (De Leo et al., 2010; Cunha et al., 2011). O avanço tecnológico recente de sondas acústicas como batimetria multi-feixe e perfiladores de sub-fundo, ROVs e AUVs resultaram em uma explosão de trabalhos sobre cânions submarinos, com um grande nível de detalhe (Kolla et al., 2001; Babonneau et al., 2002; Schwenk et al., 2003; Popescu et al., 2004; Mitchell, 2005; Antobreh and Krastel, 2006; Lastras et al., 2007; Arzola et al., 2008; Porter-Smith et al., 2012; Gómez-Ballesteros., 2014; Jobe et al., 2015).

Francis P. Shepard, um dos precursores do estudo dessas feições (Shepard, 1936, 1963, 1972; 1981; Shepard and Dill, 1966), destacou os movimentos de massa, variações do nível do mar e ação de correntes de turbidez como principais fatores geradores dessas estruturas submarinas. Com o tempo, outras estruturas foram identificadas associadas a cânions submarinos e taludes continentais (Arzola et al., 2008; Deptuck et al., 2007; Greene et al., 2002; McAdoo et al., 2000), tais como desmoronamentos, terraços, ravinas, *pockmarks* e chaminés, e mesmo comunidades recifais de águas profundas (Dewangan et al., 2010; Somoza et al., 2014; Pilcher and Argent, 2007). Esse maior detalhamento da margem continental tem dado suporte a diversos ramos de atividades *offshore*, tais como a indústria de petróleo, operações navais e engenharia (Jobe et al 2011; Stow and Mayall, 2000; Posamentier, 2003; McAdoo et al., 2000; Piper, 2005; Porter-Smith et al., 2012).

Existe ainda uma considerável escassez de dados de qualidade sobre estas feições em várias regiões do mundo como o Brasil, ainda que o mesmo possua uma das mais extensas margens continentais. No Brasil, estes estudos estão restritos à região da bacia sedimentar de Campos, sudeste do Brasil, importante área produtora de petróleo (Viana et al., 1998; Almeida and Kowsmann, 2015) e à região do Cânion do Amazonas (Pirmez and Flood, 1995; Pirmez and Imran, 2003). Mais recentemente, Almeida et al., (2015), apresentaram uma caracterização detalhada dos cânions submarinos da bacia sedimentar Potiguar, situada na margem equatorial brasileira.

Segundo Harris and Whiteway, (2011) apenas 2,6 % dos cânions submarinos do mundo são identos na plataforma continental com direta relação a um sistema fluvial, e desses, apenas 22% estão em margens passivas. Defronte a um dos rios mais importantes da América Sul, O Cânion do São Francisco se apresenta como um cânion bastante inserido na plataforma continental e apresenta uma clara relação com o rio São Francisco. Esse cânion, entretanto nunca foi estudado detalhadamente. Até então os únicos trabalhos disponíveis sobre este cânion são os de Summerhayes et al., (1976) e Cainelli (1994) que apresentaram apenas caracterizações gerais da região com base em perfis batimétricos e linhas sísmicas 2D industriais. Mais recentemente Oliveira Jr et al. (2017) e Kowsmann et al. (2017) apresentaram uma caracterização do talude continental da margem leste do Brasil, abrangendo também o Cânion do São Francisco, baseando-se em dados batimétricos principalmente oriundos de dados de sísmica industrial adquiridos na região por industrias de petróleo.

A região de estudo encontra-se na divisa entre os estados de Sergipe e Alagoas, na margem continental leste do Brasil, sobre a bacia sedimentar de Sergipe-Alagoas. Mais especificamente, o foco do estudo será dado ao Cânion do São Francisco e o talude adjacente (Figura 1).

O talude continental da região é cortado por muitos cânions submarinos, classificados como imaturos (Cainelli, 1994). Apenas dois grandes cânions destacam-se na região: o do São

Francisco e o de Japaratuba, ambos considerados modernos por terem expressão na batimetria atual (Cainelli, 1994; Summerhayes et al., 1976). A plataforma continental da região é estreita, variando de 20 a 40 km de largura, possui baixa declividade, e é rasa, com a quebra ocorrendo em torno de 30 e 50 m (Cainelli, 1994; Dominguez, 1996). A sedimentação na plataforma continental à NE da desembocadura do rio São Francisco é dominantemente carbonática. Já a SW, areias siliclásticas predominam na plataforma interna média e sedimentos carbonáticos estão presentes apenas na plataforma externa. Ao redor da cabeceira do Cânion do São Francisco, lama é o sedimento predominante (Cainelli, 1994). Atualmente, a clinoforma deltaica do São Francisco começa a soterrar a cabeceira do cânion (Figura 1).

O rio São Francisco é a principal fonte de sedimento para a região, com extensão de 2863 km, e uma área da bacia hidrográfica de 641 000 km². Sua vazão média antes da construção de barragens era de 2 943 m³/s (Souza & Knoppers, 2003; Medeiros et al., 2007; Bandeira et al., 2008). O rio construiu durante o Quaternário um delta dominado por ondas que apresenta uma área de 800 km² (Figura 1b). Ao longo da linha de costa, a deriva litorânea é predominante para sudoeste, direção esta também preferencial para dispersão da pluma fluvial na plataforma continental (Bandeira et al., 2008).

a)

b)

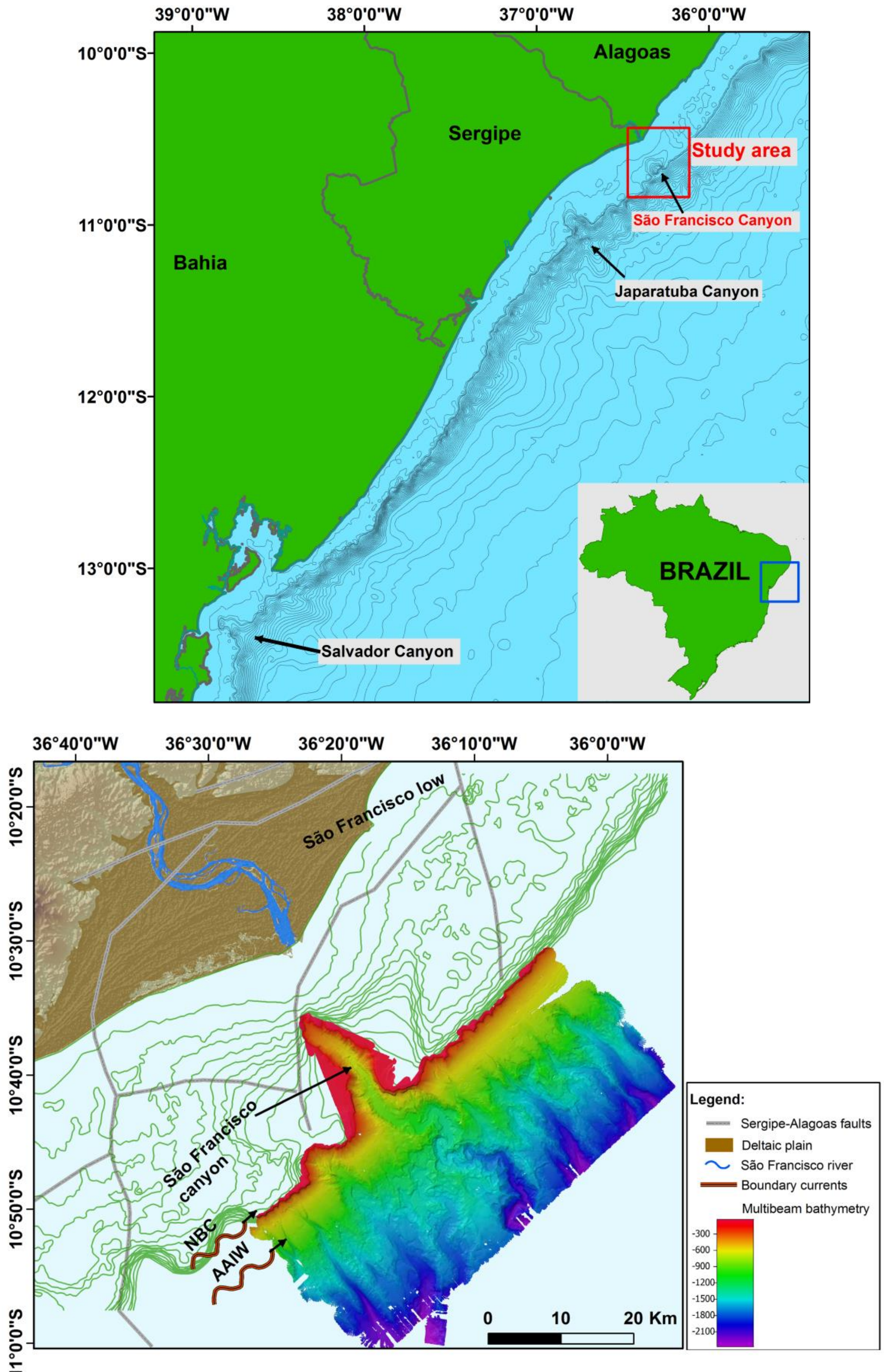

Figura 1 - a) Localização da área de estudo b) Area de estudo representada pela batimetria multifeixe; Principais falhas da bacia de Sergipe-Alagoas (adaptado de Souza-Lima, 2002); Correntes que bordejam a plataforma externa e talude superior também são indicadas na figura: CNB (Corrente Norte do Brasil) e AAIW (Antarctic Intermediate Water).

Neste trabalho, apresentamos a primeira caracterização detalhada do cânion do São Francisco (CSF) e talude adjacente, situado na margem leste brasileira, e associado ao delta do rio São Francisco, amplamente citado na literatura internacional como exemplo paradigmático de delta dominado ou influenciado por ondas (Dominguez, 1996; Howell et al., 2008). Além da caracterização baseada em levantamento com batimetria multifeixe, são discutidos, com base na geomorfologia submarina, os principais processos atuantes na região e a evolução recente do cânion. Apresenta-se também como objetivo entender e discutir o fator que faz com que o CSF se mantenha inserido na plataforma, mesmo em momento de nível de mar alto, e sua direta relação com o rio São Francisco, fator pouco existente no mundo, principalmente em regiões de margem passiva.

Essa dissertação subdivide-se em três capítulos:

Capítulo 1: Introdução Geral sobre o trabalho com uma breve revisão teórica, localização da área de estudo, contextualização do problema e objetivos;

Capítulo 2 – Apresentação do artigo, intitulado “*A shelf Incising river-connected submarine canyon in a passive margin: the case of the São Francisco (eastern Brazil)*”, a ser submetido;

Capítulo 3 – Apresentação das principais conclusões do trabalho.

Referências

Almeida, A.G., Kowsmann, R.O., 2015. Geomorfologia do talude continental e do platô de São Paulo. Geologia e Geomorfologia. p. 33–66.

Almeida, N.M., Vital, H., Gomes, M.P., 2015. Morphology of submarine canyons along the continental margin of the Potiguar Basin, NE Brazil. Marine and Petroleum Geology 68, 307–324.

Antobreh, A.A., Krastel, S., 2006. Morphology, seismic characteristics and development of Cap Timiris Canyon, offshore Mauritania: A newly discovered canyon preserved-off a major arid climatic region. Marine and Petroleum Geology 23, 37–59.

Arzola, R.G., Wynn, R.B., Lastras, G., Masson, D.G., Weaver, P.P.E., 2008. Sedimentary features and processes in the Nazaré and Setúbal submarine canyons, west Iberian margin. Marine Geology 250, 64–88.

Babonneau, N., Savoye, B., Cremer, M., Klein, B., 2002. Morphology and architecture of the present canyon and channel system of the Zaire deep-sea fan. Marine and Petroleum Geology 19, 445–467.

Bandeira, J.V., Enrique, O., Acosta, C., 2008. Long-term morphological impacts on the coastline of Sergipe State, Brazil, caused by the construction of dams in the São Francisco River Basin. Area 1–16.

Cainelli, C., 1994. Shelf processes and canyon/channel evolution controlling turbidite systems: examples from the Sergipe-Alagoas Basin, Brazil. GCSSEPM Foundation 15th Annual Research Conference. 39–50.

Cunha, M.R., Paterson, G.L.J., Amaro, T., Blackbird, S., de Stigter, H.C., Ferreira, C., Glover, A., Hilário, A., Kiriakoulakis, K., Neal, L., Ravara, A., Rodrigues, C.F., Tiago, Á., Billett, D.S.M.,

2011. Biodiversity of macrofaunal assemblages from three Portuguese submarine canyons (NE Atlantic). Deep-Sea Research Part II: Topical Studies in Oceanography 58, 2433–2447.

De Leo, F.C., Smith, C.R., Rowden, A.A., Bowden, D.A., Clark, M.R., 2010. Submarine canyons: hotspots of benthic biomass and productivity in the deep sea. Proceedings of the Royal Society B: Biological Sciences 277, 2783–2792.

Deptuck, M.E., Sylvester, Z., Pirmez, C., O'Byrne, C., 2007. Migration–aggradation history and 3-D seismic geomorphology of submarine channels in the Pleistocene Benin-major Canyon, western Niger Delta slope. Marine and Petroleum Geology 24, 406–433.

Dewangan, P., Ramprasad, T., Ramana, M. V., Mazumdar, A., Desa, M., Badesab, F.K., 2010. Seabed morphology and gas venting features in the continental slope region of Krishna-Godavari basin, Bay of Bengal: Implications in gas-hydrate exploration. Marine and Petroleum Geology 27, 1628–1641.

Dominguez, J.M.L., 1996. The Sao Francisco strandplain: a paradigm for wave-dominated deltas? Geological Society, London, Special Publications 117, 217–231.

Gardner, W.D., 1989. Baltimore Canyon as a modern conduit of sediment to the deep sea. Deep Sea Research Part A, Oceanographic Research Papers 36, 323–358.

Gómez-Ballesteros, M., Druet, M., Muñoz, A., Arrese, B., Rivera, J., Sánchez, F., Cristobo, J., Parra, S., García-Alegre, A., González-Pola, C., Gallastegui, J., Acosta, J., 2014. Geomorphology of the Avilés Canyon System, Cantabrian Sea (Bay of Biscay) María. Deep-Sea Research Part II: Topical Studies in Oceanography 106, 99–117.

Greene, H.G., Maher, N.M., Paull, C.K., 2002. Physiography of the Monterey Bay National Marine Sanctuary and implications about continental margin development. Marine Geology 181, 55–82.

Harris, P.T., Whiteway, T., 2011. Global distribution of large submarine canyons: Geomorphic differences between active and passive continental margins. Marine Geology 285, 69–86.

Howell, J.A., Skorstad, A., MacDonald, A., Fordham, A., Flint, S., Fjellvoll, B., Manzocchi, T., 2008. Sedimentological parameterization of shallow-marine reservoirs. Petroleum Geoscience 14, 17–34.

Jobe, Z.R., Lowe, D.R., Uchytil, S.J., 2011. Two fundamentally different types of submarine canyons along the continental margin of Equatorial Guinea. Marine and Petroleum Geology 28, 843–860.

Jobe, Z.R., Sylvester, N., Parker, A.O., Howes, N., Slowey, N., Pirmez, C., 2015. Rapid adjustment of submarine channel architecture to changes in sediment supply. J Journal of Sedimentary Research 85, 729–753.

Kolla, V., Bourges, P., Urruty, J.-M., Safa, P., 2001. Tertiary sinuous channels architecture. Am. AAPG Bulletin 85, 1373–1405.

Lastras, G., Canals, M., Urgeles, R., Amblas, D., Ivanov, M., Droz, L., Dennielou, B., Fabrés, J., Schoolmeester, T., Akhmetzhanov, A., Orange, D., García-García, A., 2007. A walk down the Cap de Creus canyon, Northwestern Mediterranean Sea: Recent processes inferred from morphology and sediment bedforms. Marine Geology 246, 176–192.

McAdoo, B.G., Pratson, L.F., Orange, D.L., 2000. Submarine landslide geomorphology, US continental slope. Marine Geology 169, 103–136.

Medeiros, P.R.P., Knoppers, B., Júnior, R.C.S., 2007. Aporte Fluvial E Dispersão De Matéria Particulada Em Suspensão Na Zona Costeira Do Rio São Francisco (Se/Al). Geochimica 21, 212 – 231.

Mitchell, N.C., 2005. Interpreting long-profiles of canyons in the USA Atlantic continental slope. Marine Geology 214, 75–99.

Oliveira Jr et al. (2017) e Kowsmann et al. (2017) – Sergipe Alagoas

Pilcher, R., Argent, J., 2007. Mega-pockmarks and linear pockmark trains on the West African continental margin. Marine Geology 244, 15–32.

Piper, D.J.W., 2005. Late Cenozoic evolution of the continental margin of eastern Canada. Norwegian Journal of Geology 85, 305–318.

Pirmez, C., Flood, R.D., 1995. Morphology and structure of Amazon Channel. Proceeding Ocean Drill. Proceeding of the Ocean Drilling Program, Initial Reports 155, 23–45.

Pirmez, C., Imran, J., 2003. Reconstruction of turbidity currents in Amazon Channel. Marine and Petroleum Geology 20, 823–849.

Popescu, I., Lericolais, G., Panin, N., Normand, A., Dinu, C., Le Drezen, E., 2004. The Danube submarine canyon (Black Sea): morphology and sedimentary processes. Marine Geology 206, 249–265.

Porter-Smith, R., Lyne, V.D., Kloser, R.J., Lucieer, V.L., 2012. Catchment-based classification of Australia's continental slope canyons. Marine Geology 303-306, 183–192.

Posamentier, H.W., 2003. Depositional elements associated with a basin floor channel-levee system: case study from the Gulf of Mexico. Marine and Petroleum Geology 20, 677–690.

Schwenk, T., Spieß, V., Hübscher, C., Breitzke, M., 2003. Frequent channel avulsions within the active channel-levee system of the middle Bengal Fan - An exceptional channel-levee development derived from Parasound and Hydrosweep data. Deep-Sea Research Part II: Topical Studies in Oceanography 50, 1023–1045.

Shepard, F.P., 1936. The underlying causes of submarine canyons. Natl. Acad. Sci. Natl. Res. Council Pub. 22, 496–502.

Shepard, F.P., 1963. Submarine Geology. Harper & Row, New York, NY.

Shepard, F.P., Dill, R.F., 1966. Submarine Canyons and Other Sea Valleys. Rand McNally, Chicago, IL.

Shepard, F.P., 1972. Submarine canyons. Earth-Science Reviews 8, 1–12.

Shepard, F.P., 1981. Submarine canyons: multiple causes and long-time persistence. AAPG Bulletin 65, 1062–1077.

Somoza, L., Ercilla, G., Urgorri, V., León, R., Medialdea, T., Paredes, M., Gonzalez, F.J., Nombela, M. A., 2014. Detection and mapping of cold-water coral mounds and living Lophelia reefs in the Galicia Bank, Atlantic NW Iberia margin. Marine Geology 349, 73–90.

Souza, W.F.L., Knoppers, B., 2003. Fluxos de água e sedimentos a costa leste do Brasil: relações entre a tipologia e as pressões antrópicas. Geochimica Brasiliensis 17, 57-74.

Stow, D. a V, Mayall, M., 2000. Deep-water sedimentary systems: New models for the 21st century. Marine and Petroleum Geology 17, 125–135.

Summerhayes, C.P., Fainsten, R., Ellis, J.P., 1976. Continental margin off Sergipe and Alagoas, northeastern Brazil: a reconnaissance geophysical study of morphology and structure. Marine Geology 20, 345-361.

Viana, a. R., Faugeres, J.C., Kowsmann, R.O., Lima, J. a. M., Caddah, L.F.G., Rizzo, J.G., 1998. Hydrology, morphology and sedimentology of the Campos continental margin, offshore Brazil. Sedimentary Geology 115, 133–157.

CAPÍTULO 2
ARTIGO

CONFIRMAÇÃO DE SUBMISSÃO DO ARTIGO

MARINE GEOLOGY

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A shelf Incising river-connected submarine canyon in a passive margin: the case of the São Francisco (eastern Brazil)

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Abstract

Submarine canyons are found on continental margins worldwide and they act as the main conductor of sediments to the deep ocean. Only 2.6% of them exhibit direct connection with fluvial systems, as does the São Francisco canyon (SFC). In this work we provide a detailed morphological characterization of the São Francisco canyon based on multibeam survey and integrate this information with 3D seismic records from the canyon head in order to investigate the reasons for the continuous connectivity between canyon-river in the São Francisco area. Several structures have been mapped: seven major canyons, the biggest one SFC; one paleocanyon of the SFC (SFPC); tributary channels; gullies; cutoffs; landslides; mounds and pockmarks. The modern São Francisco canyon is formed above an ancient canyon filled and represents a re-incision episode, perhaps associated with the lowering of sea level from the last high sea level of the middle Miocene, or with moment in which the São Francisco River began to flow into this region. The carbonate aggradation/proggradation of the outer shelf helped on the creation of a bathymetric low around the canyon head, which is important to the sediment funneling to the valley. The other canyons, next to the SFC, were formed by processes of instability and landslides on continental slope and exhibit different stages of regressive erosion. The SFC is the one with the lowest average values of slope and is the unique sinuous canyon due its relationship with major fluvial system. The SFPC displays morphological similarities with the current canyon (sinuosity and slope), and its existence leads to a change in the main channel by an avulsion process. The pockmarks and mounds were interpreted as gas escape and deep water reefs respectively. They are concentrated mainly in the northeast portion of the study area. The contour current on the region appears to control the development and distribution of mounds and pockmarks and also the maturity of submarine canyons present on continental slope.

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O ARTIGO:

A shelf Incising river-connected submarine canyon in a passive margin: the case of the São Francisco (eastern Brazil)

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ABSTRACT

Submarine canyons are found on continental margins worldwide and they act as the main conductor of sediments to the deep ocean. Only 2.6% of them exhibit direct connection with fluvial systems, as does the São Francisco canyon (SFC). In this work we provide a detailed morphological characterization of the São Francisco canyon based on multibeam survey and integrate this information with 3D seismic records from the canyon head in order to investigate the reasons for the continuous connectivity between canyon-river in the São Francisco area. Several structures have been mapped: seven major canyons, the biggest one SFC; one paleocanyon of the SFC (SFPC); tributary channels; gullies; cutoffs; landslides; mounds and pockmarks. The modern São Francisco canyon is formed above an ancient canyon filled and represents a re-incision episode, perhaps associated with the lowering of sea level from the last high sea level of the middle Miocene, or with moment in which the São Francisco River began to flow into this region. The carbonate aggradation/proggradation of the outer shelf helped on the creation of a bathymetric low around the canyon head, which is important to the sediment funneling to the valley. The other canyons, next to the SFC, were formed by processes of instability and landslides on continental slope and exhibit different stages of regressive erosion. The SFC is the one with the lowest average values of slope and is the unique sinuous canyon due its relationship with major fluvial system. The SFPC displays morphological similarities with the current canyon (sinuosity and slope), and its existence leads to a change in the main channel by an avulsion process. The pockmarks and mounds were interpreted as gas escape and deep water reefs respectively. They are concentrated mainly in the northeast portion of the study area. The contour current on the region appears to control the development and distribution of mounds and pockmarks and also the maturity of submarine canyons present on continental slope.

Keywords: Multibeam bathymetry; Submarine canyons; Continental slope; Sea level change.

1. Introduction

Because submarine canyons act as the main duct for the transportation of material from the continental shelf to the deep ocean, especially during lowstands (Shepard, 1972; Gardner 1989), their study is important to answer fundamental questions related to sediment transfer from continents to the ocean basins (Liu and Leen 2004; Sweet and Blum, 2016). During sea-level highstands most canyons located in passive margins are believed to be inactive since connection between river systems and shoreline sediment sources is severed (Damuth and Kumar, 1975; Babonneau et al., 2002; Sweet and Blum, 2016).

Canyons have also been considered as hotspots of biodiversity (De Leo et al., 2010; Cunha et al., 2011), inductors of upwelling (Sobarzo et al., 2001; Sobarzo and Djurfeldt, 2004), and are also known as hazardous areas due to inherent geotechnical instabilities (Piper et al., 1999; Migeon et al., 2011; Su et al., 2012).

Although all major modern deltas present some association with submarine canyons (Petters, 1984; Popescu et al., 2004; Gamberi and Marani, 2008; Mahar and Zaigham, 2013; Clift et al., 2014), canyons incising the continental shelf and exhibiting a direct connection with fluvial systems represent only 2.6% of the mapped canyons in the world (Type I river-associated and shelf incising - Harris and Whiteway, 2011). Most of this type of canyon is found in active margins, with only 22% of them occurring in passive ones. Harris and Whiteway (2011) hypothesized that this behavior results from the fact that shelves on active continental margins tend to be narrower than in passive margins. The association with steeper catchments because of proximity with orogenic mountain belts implies that shelf valleys will be more deeply incised and therefore less likely to be infilled during highstands (Fagherazzi et al., 2004; Walsh and Nittrouer, 2009).

According to Harris and Whiteway (2011) in Brazil (a passive margin), only 03 canyons significantly indent the continental shelf (Salvador Canyon, Japaratuba Canyon and Amazon Canyon) (Figure 1). Although not mentioned in Harris and Whiteway (2011) review as indenting the shelf the São Francisco, this is the only canyon in the entire Brazilian continental margin that significantly indents the shelf and is directly connected to a delta. The Holocene clinoform of this wave-dominated delta presently reaches the homonymous canyon head (Dominguez, 1996) (Figure 1). All other major rivers in Brazil, including the Amazon, that have constructed Holocene deltas, do not show nowadays, a direct connection with a submarine canyon.

Although in the last decade a large body of literature has been published on various aspects of modern submarine canyons worldwide (Kolla et al., 2001; Popescu et al., 2004; Mitchell, 2005; Antobreh and Krastel, 2006; Lastras et al., 2007; Arzola et al., 2008; Lastras et al., 2011; Porter-Smith et al., 2012; Gómez-Ballesteros et al., 2014), the western South Atlantic is still a large blank in global compilations, due to a lack of data. For the São Francisco canyon the only work widely available to a broad audience is Summerhayes et al. (1976). Very recently Oliveira Jr et al. (2017) and Kowsmann et al. (2017) presented a geomorphological characterization of a stretch of approximately 37,760 km^2 of the continental slope off eastern Brazil, including the São Francisco canyon area. This characterization was based mostly on a compilation of bathymetric data from 3-D seismic surveys carried out by oil companies in the area.

Our aim in this paper is to provide a detailed morphological characterization of the upper portion of the São Francisco canyon based on a recent multibeam survey and integrate this information with 3D seismic records from the canyon head in order to investigate the possible reasons for the continuous direct connectivity canyon-river in the São Francisco area, which apparently occurs irrespective of sea-level position.

2. Material and methods

Bathymetric data was collected by the Brazilian Navy hydrographic ship Sirius in May 2011. The surveyed area was 1579.633 km^2, encompassing the region between the isobaths of 40 m and 2390 m. Survey was performed using a Kongsberg EM 302 Simrad multibeam echo sounder at an operational frequency of 30 kHz. Sounding lines were parallel to isobaths, using an angle of 150° for the scanning range. Space between sounding transects varied due to the width of the scanning range (3.5 times the depth of the water column). Initial data gathering and processing were performed using SIS® and CARIS HIPS® software, respectively. The resolution of the bathymetric grid produced was 10 m. The software Fledermaus® was used to process backscatter data, to interpret and individualize morphological features, and to determine various morphometric parameters (e.g. slope, length, aspect, etc).

Finally, 3D seismic records of the canyon head, provided by the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP) were used. These records were interpreted using the software OpendTect 5.0®. The maps that illustrate the present study were produced in ArcGis®.

3. Geological and oceanographic setting

3.1 Sergipe-Alagoas Sedimentary Basin

The study area is located at the eastern Brazilian continental margin, within the context of the Sergipe-Alagoas Sedimentary Basin (Figure 1). This basin resulted from the separation between South America and Africa during the late Jurassic and early Cretaceous, and presents a well-defined stratigraphic framework comprised by pre-rift, rift, and passive margin mega-sequences (Souza-Lima, 2002). The structural framework of this basin includes faults oriented according to N-S, E-W, and NE-SW directions, which formed during the rifting phase and originated tectonic sub-compartments (Figure 1). The depocenter known as the São Francisco Low, where the São Francisco River delta was more recently built upon, is among the most relevant sub-compartments of this basin.

Several immature submarine canyons which do not reach the shelf break incise the dominantly concave continental slope of the region (Cainelli, 1994). The two most relevant canyons in this area are the São Francisco and the Japaratuba canyons, both of which were considered modern due to their expression in current bathymetry (Summerhayes *et al*., 1976; Cainelli, 1994) (Figure 1). Previous authors considered both of these canyons inactive (Summerhayes et al., 1976). More recently Fontes et al. (2017) have suggested based on ^{14}C box core datings that the SFC was active at least until 2 ka.

The São Francisco Canyon (SFC) developed at the top of the Oligocene-Quaternary depositional sequence of the Piaçabuçu Formation and it is associated with an expressive submarine fan at further depth (Cainelli, 1994; Oliveira Jr et al., 2017). The Piaçabuçu Formation is composed by the Calumbi and Marituba members, with ages ranging from Tertiary to Quaternary (Cainelli, 1994). The Marituba member is comprised mostly by carbonate sediments and in some intervals by mixed siliciclastic-carbonate sediments, whereas the Calumbi member is made up basically by gravity flow deposits (Cainelli, 1992). Cainelli (1994) have also reported the existence of Miocene canyons showing coinciding paths with the modern SFC. So far, a precise age for inception of the modern canyon has not been stablished. During the late Tertiary the continental shelf experienced a significant carbonate aggradation, resulting in increased steepness of the slope (Cainelli, 1994).

3.2 The São Francisco River, the Continental Shelf and Slope

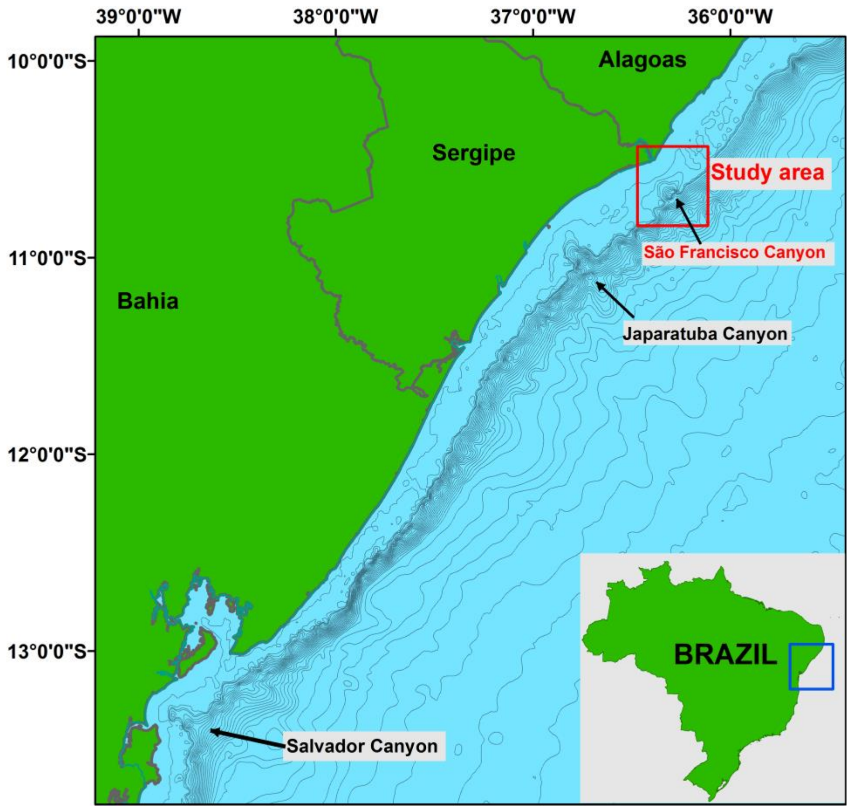
The São Francisco River is the main source of sediments to the region. Measuring 2,863 km in length and with a watershed of 641,000 km^2, the mean flow rate of this river, before the construction of dams, was 2,943 m^3s^{-1} (Souza & Knoppers, 2003; Medeiros et al., 2007; Bandeira et al., 2008). During the Quaternary, the São Francisco River built a wave-dominated delta measuring 800 km^2 (Figure 1).

The continental shelf of this region is narrow (between 20 and 40 km in width), and very shallow, with the shelf break starting approximately between the isobaths of 50 m and 70 m (Cainelli, 1994; Dominguez, 1996; Fontes et al., 2017). In front of the São Francisco a bathymetric depression is present in the shelf exhibiting sharp lateral boundaries whose origin is attributed to late Miocene tectonic activity (Santos et al., 2018). Inside this depression the São Francisco has built an extensive muddy clinoform which presently reaches the head of the canyon (Figure 1). Carbonate acumulation, mainly incrusting coralline algae, dominates on the middle outer shelf (de Araújo, 2018). The aforementioned depression helps funneling river borne and carbonate sediments to the modern canyon head.

Wave-generated longshore drift flows predominantly southwestwards, which is also the preferential direction for fluvial plume dispersion over the continental shelf (Bandeira et al., 2008, Bittencourt et al., 2002). Circulation on the upper continental slope is influenced by the North Brazil Current and the South Atlantic Central Water (SACW) between 100 and 500 m in depth, flowing northwards. At greater depths (between 500 and 1400 m), the Antarctic Intermediate Water (AAIW) is also present and flows northwards (Stramma and Schott, 1999; Stramma and England, 1999).

The slope at the study area extends from approximately 70 m to 3000 m deep and exhibits a concave profile, incised by numerous canyons. The SFC submarine fan is a well-developed sedimentation system that starts at the SFC head and extends to the foot of the continental slope rise (Oliveira Jr et al., 2017).

a)



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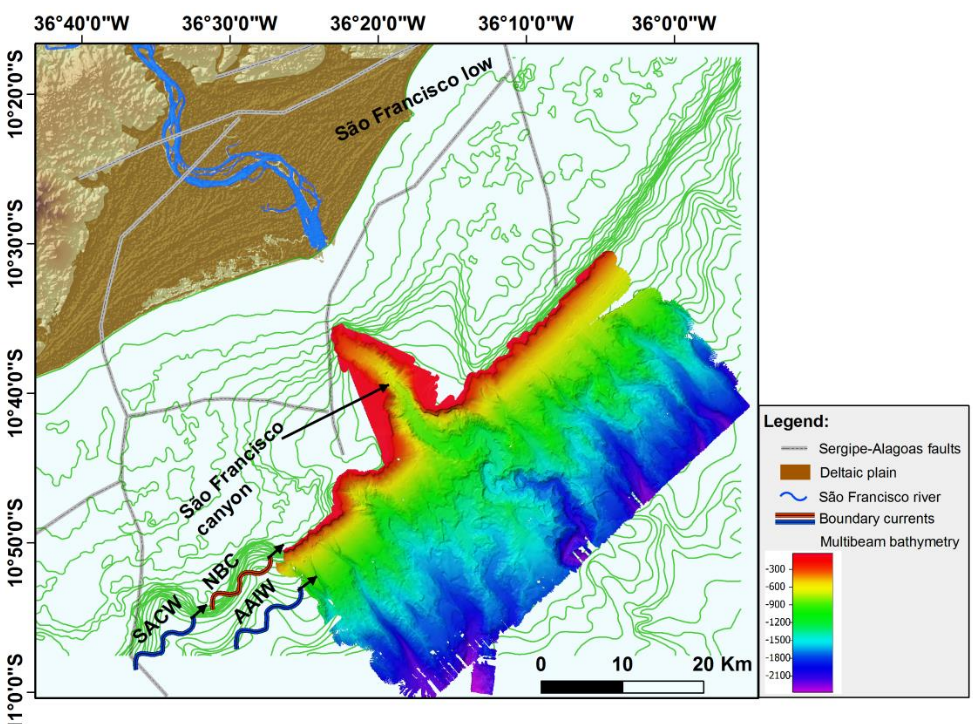


Figura 1 - a) Study area. b) Multibeam bathymetry; Sergipe-Alagoas Basin main faults (modified from Souza-Lima, 2002); Boundary currents on continental shelf and upper slope. NBC (North Brazil Current), SACW (South Atlantic Central Water) and AAIW (Antarctic Intermediate Water).

4. Results

Several canyons, C1, C2, C3, C4, C5, C6, and the São Francisco Canyon (SFC) were mapped, besides the São Francisco Paleo Canyon (SFPC), tributary channels, ravines, landslides, mounds and pockmarks (Figure 2).

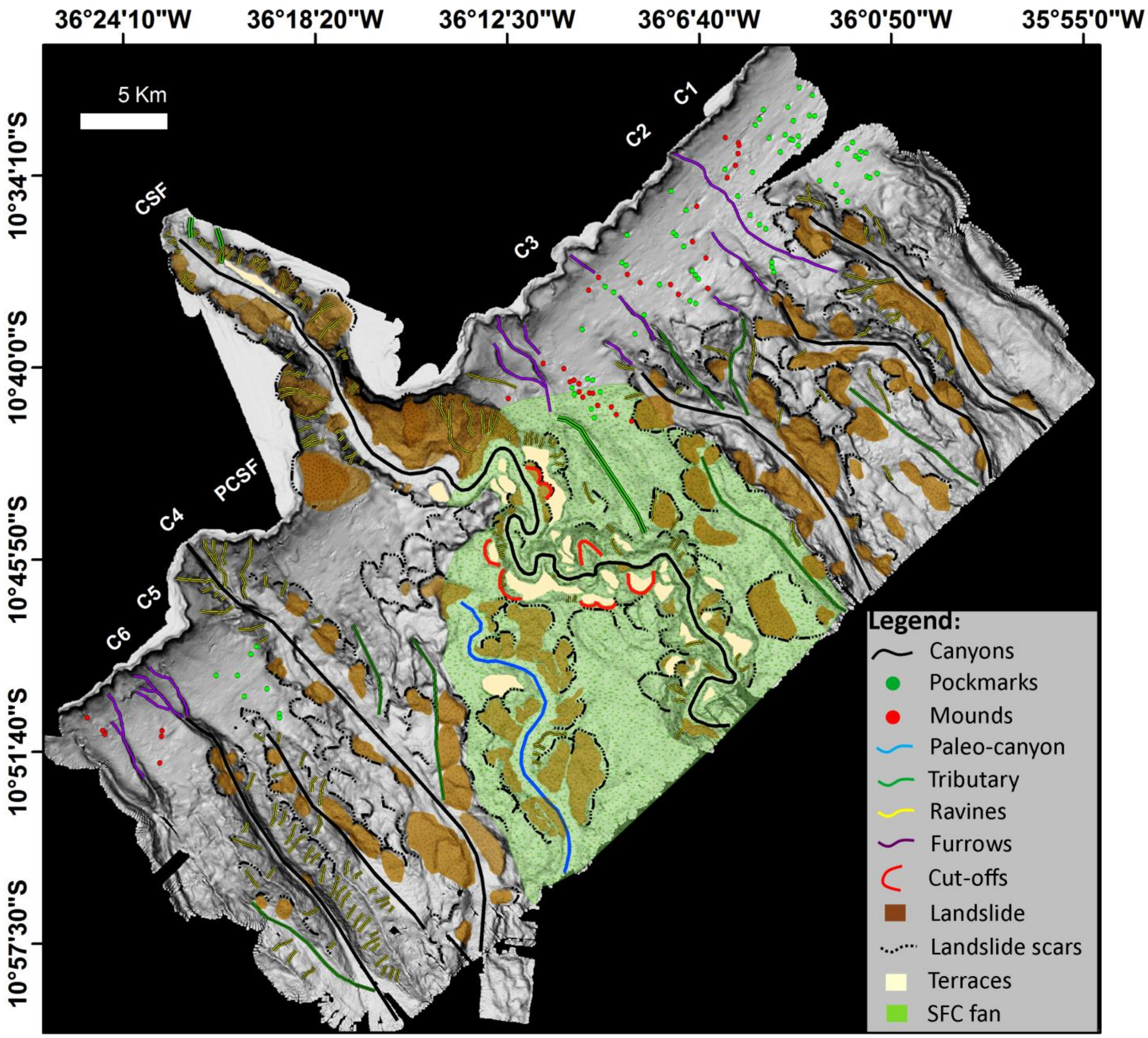


Figura 2 - Seafloor features, mapped in the study area. The position SFC fan mapped was taken from Kowsmann et al. (2017).

4.1 Canyons

According to Harris and Whiteway, (2011) classification, the submarine canyons are of three types: Type I – indents the continental shelf and exhibits a clear relationship with a fluvial system (SFC); Type II – only the head indents the shelf, and does not present a direct relationship with a fluvial system (C4); and Type III – confined to the continental slope (C1, C2, C3, C5, and C6) (Figures 1 and 4).

Figure 3 shows three longitudinal profiles of the continental slope, illustrating the main features of the mapped canyons (Figures 3A and 3B). Longitudinal profile 1, from the upper portion of the slope, indicates that this region presents a more depositional character. Only two major incisions are observed, which corresponded to canyon C4, whose head reaches the continental shelf, and to SFC, which indents the continental shelf for approximately 15 km (Figure 1). In addition, small furrows occur concentrated at the southwestern portion of the study area. The surface of the continental slope is convex and the interfluve that separates C4 from SFC is flat and wide (about 1 km) (Figure 3B).

In longitudinal profile 2, located at the mid portion of the continental slope, the seafloor is intensely cut (approximately 65% of the area) by the mapped canyons, which are separated by steep interfluves (ranging from 3°, between C4 and the SFPC, to 11°, between C5 and C6). However, the interfluves separating the canyons located northeast of the SFC and the SFC itself are clearly shallower (aprox. 200m) than those located southwestward. The SFPC is clearly visible and its thalweg is located at a considerably shallower depth when compared to the SFC and the other canyons identified (Figure 3B). The upper portion of the SF submarine fan is also clearly visible in this mid profile.

In longitudinal profile 3, located at the most distal portion of the study area, nearly all canyons are represented, including the SFPC and tributary channels. However, interfluves are less pronounced when compared to profile 2. Canyons located northeastwards of the SFC still present a more pronounced relief then those located southwestwards, but not so much pronounced as in profile 2. The shallowest interfluves, which are also the widest (aprox. 400 m), bordering the SFC and the SFPC, are part of the São Francisco submarine fan (Figure 3B).

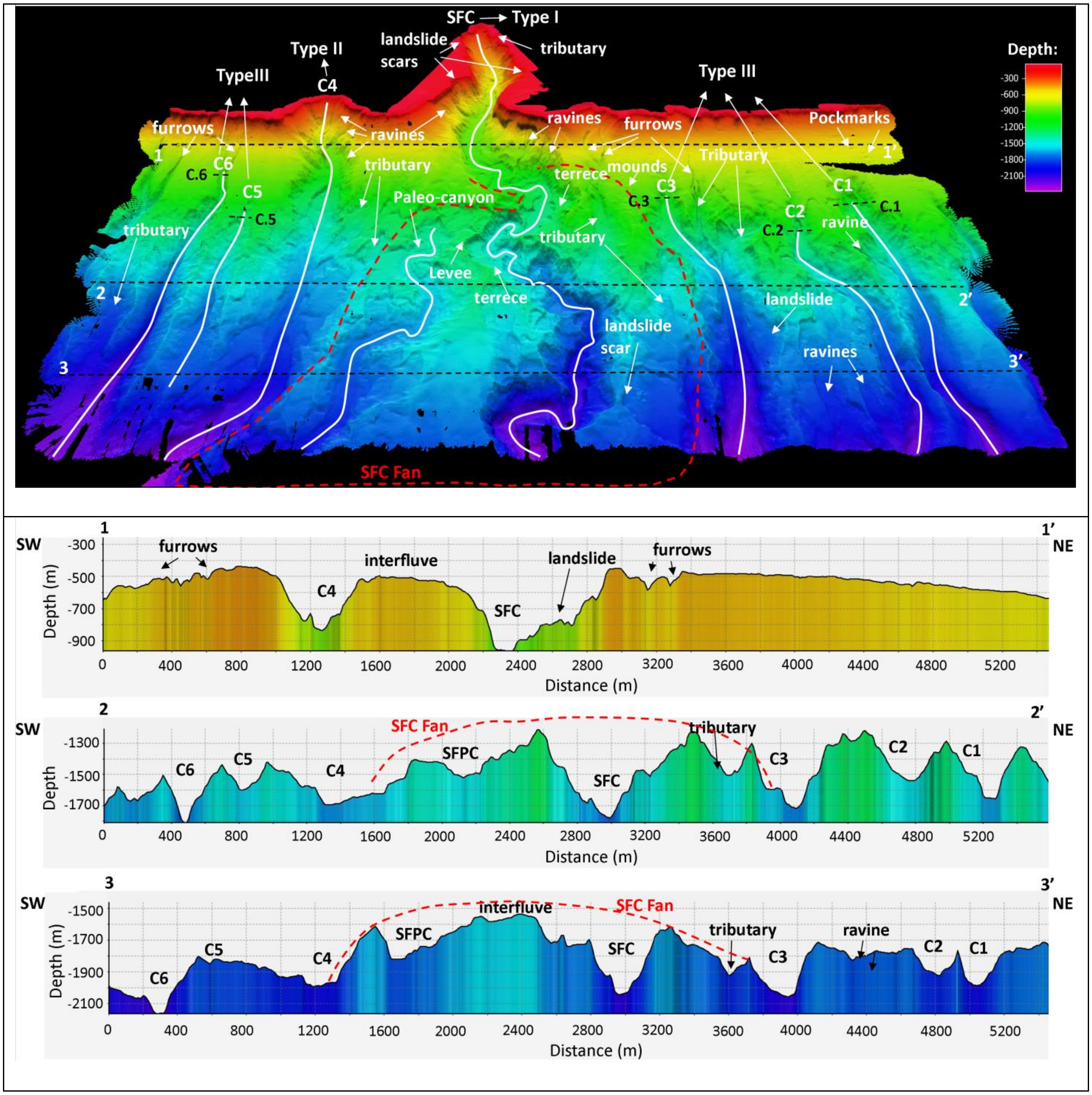


Figura 3 - a) 3D rendering of the imaged area. b) Bathymetric profiles (vertical exaggeration of 9.3) performed longitudinally in relation to the continental slope, oriented according to a SW-NE direction.

Figure 4 illustrates the longitudinal profiles of the thalwegs of the mapped canyons. The longitudinal profiles of canyons C1, C2, C3, C4, C5, and C6 present a concave up geometry and very similar slopes (between 3.3° and 4°). These profiles were approximately coincident, except for C4, which indents the shelf break and is steeper, with slope values as high as 11° (Figure 4).

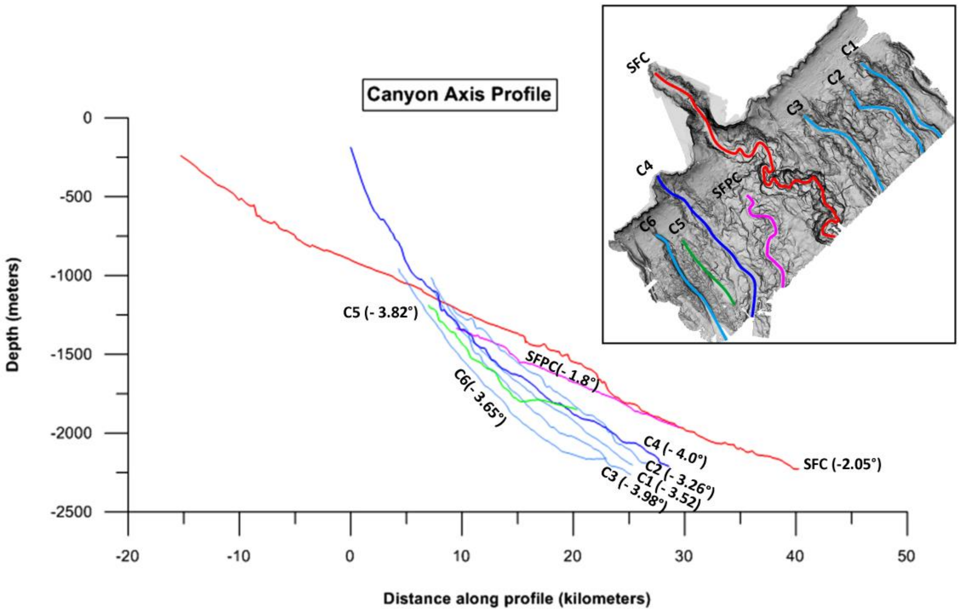


Figura 4 - Profiles performed along the thalwegs of canyons and of a paleo-channel/distributary (SFPC). The zero of the x-axis indicates the position of the current continental shelf break. The various colors used for the profiles are the same as the canyons of the 3D rendering of Figure 3A.

The longitudinal profiles of the SFC and of the SFPC show significantly lower slope values (2.05° and 1.80°, respectively). This slope difference results from the fact that the head of the SFC indents the continental shelf upslope, and also because these two channels have developed on the São Francisco submarine fan. A pronounced knickpoint is present in the SFC longitudinal profile (Figures 4 and 5). The longer SFC thalweg derives from its meandering character and greater shelf indentation (Figure 4).

Tabela 1 - Main characteristics of the canyons identified in the present study, including the SFPC: type of canyon, total length of the thalweg, maximum and minimum widths of the thalweg, maximum and minimum depths of the channel, mean slope, and sinuosity.

	Type	Thalweg length (km)	Thalweg width Max.(m)	Thalweg width Min.(m)	Channel depths Max.(m)	Channel depths Min.(m)	Mean slope	Sinuosity
C1	III	~ 17,92	~ 700	~ 200	~ 2200	~ 1030	-3,52°	1
C2	III	~ 17,62	~ 400	~ 100	~ 2200	~ 1060	-3,26°	1,1
C3	III	~ 18	~ 1000	~ 70	~ 2290	~ 1090	-3,59°	1
SFC	I	~ 55,6	~ 1000	~ 60	~ 2260	~ 130	-2,05°	1,4
C4	II	~ 28,58	~ 700	~ 100	~ 2265	~ 120	-3,99°	1
C5	III	~ 13,35	~ 350	~ 80	~ 1190	~ 1790	-3,82°	1
C6	III	~ 18,68	~ 600	~ 60	~ 2220	~ 980	-3,65°	1
SFPC	–	~ 20,02	~ 1100	~ 400	~ 1980	~ 1340	-1,80°	1,2

4.2 The São Francisco Canyon (SFC)

The SFC is the longest and most incised canyon of the study area, measuring 56 km in length in the imaged area and a maximum incision (between the interfluve and the thalweg) of 900 to 1000 m (Figure 5b,c). It is the only canyon that deeply indents the continental shelf and is directly connected to the SF river mouth located only 10 km away from the canyon head. The deltaic clinoform of the São Francisco River apparently feeds the canyon head nowadays as indicated by the geometry of the isobaths (Figure 1). In the imaged area, the deepest portion reached by the canyon thalweg is 2260 m (Figure 1).

4.2.1 Sinuosity and Slope

SFC sinuosity ratio was calculated as 1.4 (Table 1). The canyon is straighter at the portion where it indents the continental shelf (upper canyon – sinuosity of 1.11) and starts meandering at a depth of 1000 m (sinuosity of 1.58) where it intersects the continental slope in the region (Figure 5a).

The mean slope along the entire SFC (-2.05°), which was found to present an inverse relationship with sinuosity. The slope is steeper at the canyon head (-2.44°). This value decreases to -1.87° on the continental slope. However, there is a 2-km long stretch located at a depth between 1,600 and 1,750 m where the slope reaches values as high as 6° due to the presence of a knickpoint (Figure 5b).

4.2.2 Channel geometry

Cross-section profiles of the SFC generally present a “U”-shaped geometry (Figure 5c). The most pronounced relief is observed at the intersection between the canyon and the continental slope (Figure 5c - profile b) where it reaches more than 800 m, with asymmetric walls presenting slope values between 13° and 23°. Profile “a” at the head of the canyon, shows a minimum relief of 180 m (Figure 5c – profile a).

In profiles located downslope from the shelf break (mid canyon), where the canyon meanders, the depth difference between the thalweg and the edge of the canyon wall is approximately 450 m, with lateral walls exhibiting slope values of approximately 7° to 11° and with the presence of well-defined lateral terraces (Figure 5c – profiles c, d, e)). In profiles d and e, located downstream of the main knickpoint, the thalweg is more carved and narrower. In profile d, in particular, the width of the thalweg is only 60 m, whereas in the upper canyon it reaches up to 1000m.

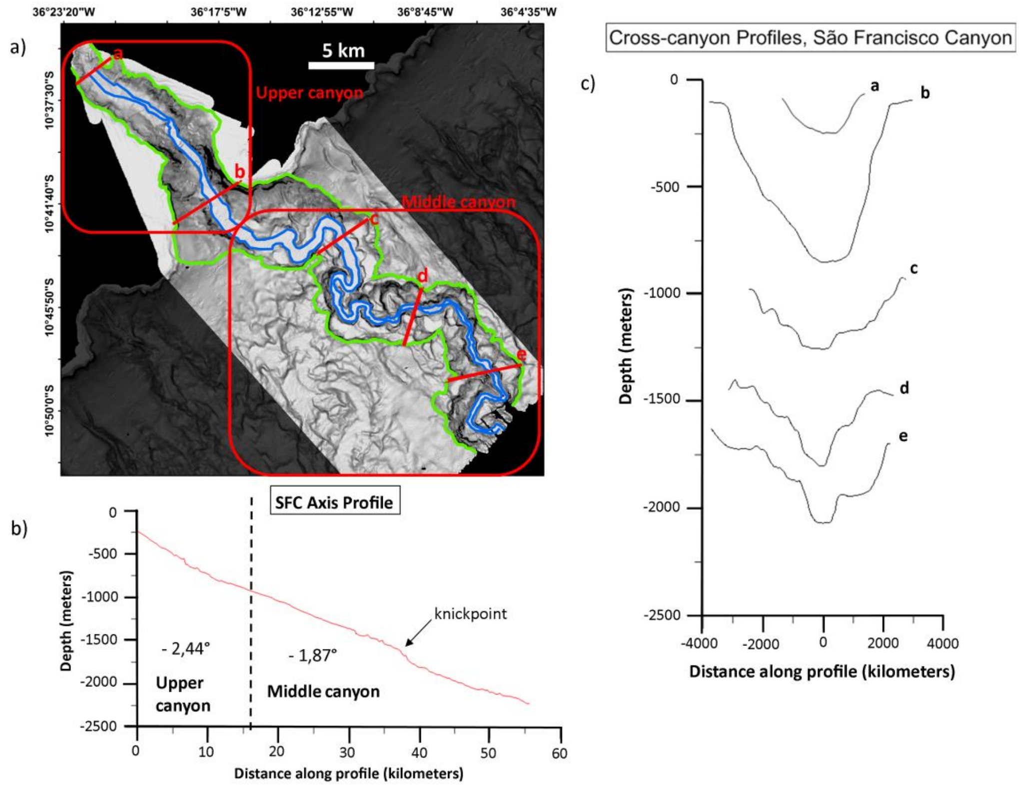


Figura 5 - São Francisco Canyon and cross-section profiles to the general orientation of the valley. Lateral limits of the current thalweg are represented in blue. Outer limits of the canyon are represented in green. The Figure also shows a longitudinal profile along the thalweg of the SFC.

4.2.3 Slides

Slides affecting the walls of the canyon and their respective depositional lobes are mainly concentrated at the head, where the canyon carves into the continental shelf (Figures 2 and 6). Slide scars with diameters larger than 2 km occurs mainly on the southwestern wall of the canyon (Figure 6). The largest depositional lobe related to a slide is located at the limit between the upper and mid portions of the canyon (Figure 7, Figure 3 – profile 1).

The rest of the canyon located downslope, shows only a few depositional lobes of considerably reduced dimensions. However, numerous slide scars are present, with no direct association with depositional lobes (disintegrative landslides) (McAdoo *et al.*, 2000) (Figures 6 and 7).

4.2.4 Ravines and tributary channels

A total of 97 ravines were mapped along the SFC, ranging between 0.3 and 3.2 km in length, and between 30 and 150 m in relief. The highest concentration of ravines was observed at the canyon head. Several ravines were related to landslide scars, especially affecting the wall of the northeastern portion of the canyon, which is the steepest. At the mid-section of the canyon, these ravines were concentrated in the region closest to the shelf break.

The two most expressive ravines at the head of the canyon (1.3 and 2 km in length and 100 m in relief) where considered to be tributary channels of the SFC. In the mid-section of the canyon only one tributary was observed, measuring 7.8 km in length and up to 300 m in relief. This tributary is fed by ravines that are connected to the shelf break (Figures 2, 6 and 7).

4.2.5 Terraces

A total of 28 internal lateral terraces were mapped for the SFC. The sole terrace located at the canyon head also have the lowest relief (15 m). The remaining terraces, located in the mid sector, present varying heights in relation to the canyon thalweg. The most expressive ones are positioned approximately 100 m above the canyon floor. However numerous terraces positioned between 170 and 230 m are present. The highest terraces, 320 to 400m, are present in those portions of the canyon showing the lowest slope values in the longitudinal profile (Figures 6 and 7).

4.2.6 Levees and cut-offs

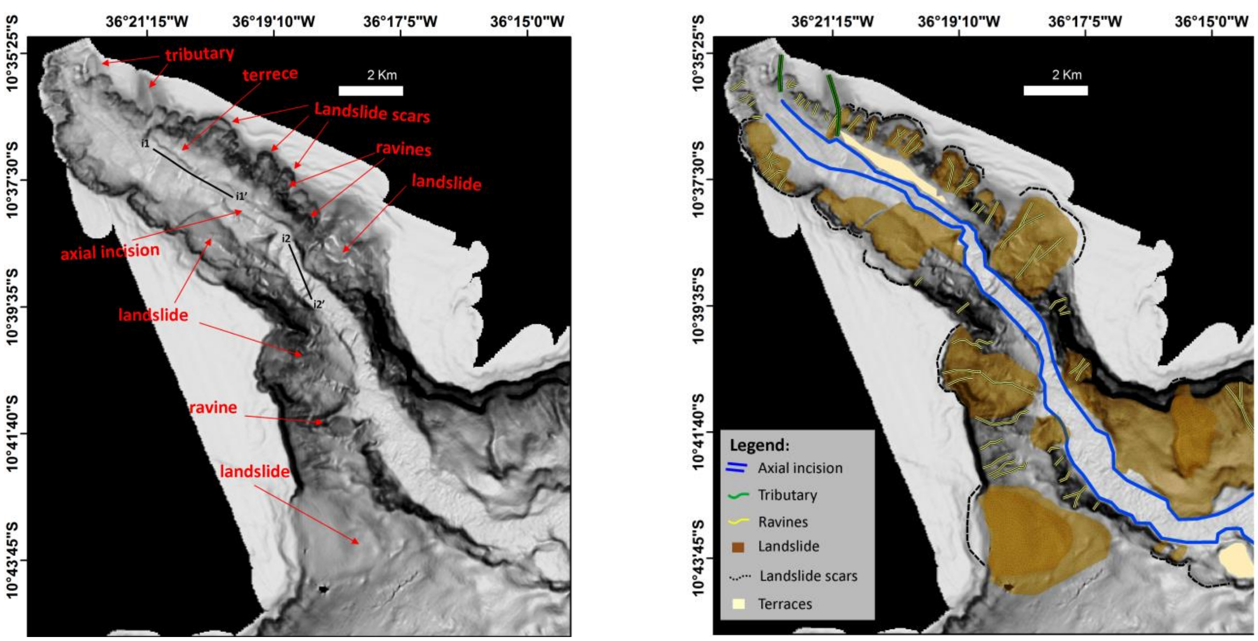
Levees, up to 20 m height, are found along the external margins of the SFC, especially at its mid portions. Within the SFC, levees up to 5 m high are also found associated with the innermost terraces, especially in the canyon stretch located immediately downslope from the canyon head (Figure 7).

Many of the levees are related to cut-off concave margins (Figure 7). A total of eight of these structures (cut-offs) were mapped and measure between 900 and 1700 m in diameter. The most expressive knickpoint found in the canyon is associated with the formation of one of these cut-offs, which was abandoned after the levee was breached (Figure 7).

4.2.7 Bed forms on the canyon floor

In the upper canyon floor it is common the presence of crescent shaped bed forms oriented perpendicular to the canyon axis. Their heights vary from 1m to 5 m approximately, and their wave length is about 100-200 m. Their steeper slopes point either up canyon or down canyon (Figure 6.b). Similar bed forms have been described in the literature and interpreted as crescentic bedform deposits (Hage et al., 2018). The presence of such bedforms indicates that sediment transport, at least in the upper canyon floor is still active today.

a)



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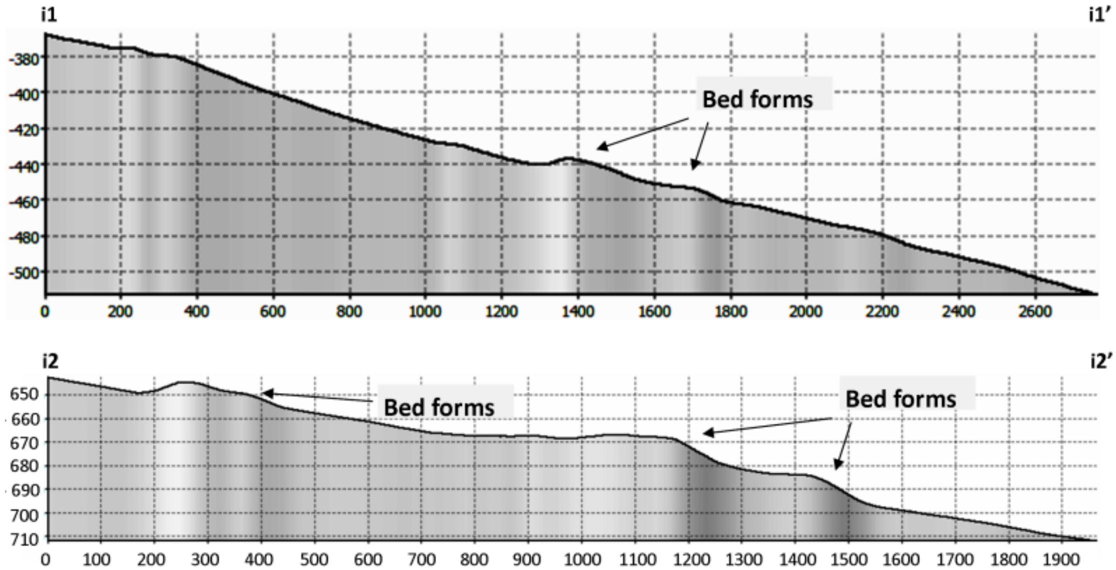


Figura 6 – a) Sector of the SFC where it indents the continental shelf. b) Bed forms on the canyon thalweg.

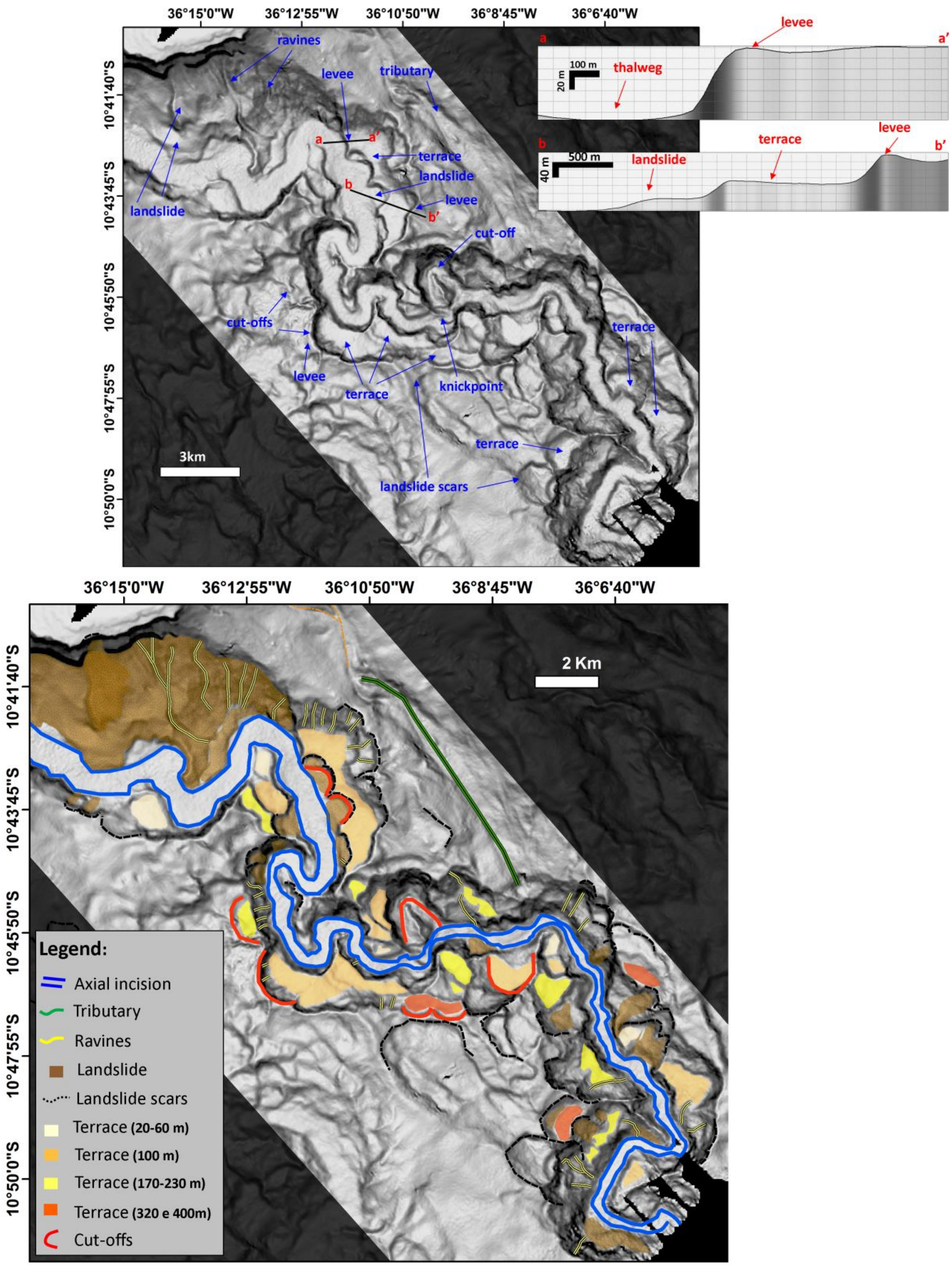


Figura 7 - Main features mapped in the mid portion of the SFC.

4.3 Paleo-canyon (or paleo-distributary) of the SFC

The São Francisco Paleo-canyon (SFPC) at our study area measures approximately 20 km in length and begins at a depth of approximately 1300 m, stretching down to 1970 m in depth in the imaged area (Table 1, Figures 3 and 8).

The SFPC is oriented NNW-SSE and have a sinuosity ratio of 1.2. Its mean slope (1.8°) is similar to that observed for the mid portion of the SFC. The “U”-shaped cross-section geometry of the SFPC is maintained along its entire length. The flat canyon floor shows a mean width of 700 m. Height difference between the thalweg and interfluves ranged between 60 and 200 m, and the lateral walls have slope values of approximately 8°, suggesting that the paleo canyon is much less carved than the active one (SFC) or has experienced significant infill since its abandonment. Some levees bordering the outer walls of the SFC show evidences of overflow deposits extending up to the SFPC, suggesting contribution to its infill (Figure 8).

Slide scars and associated depositional lobes are found along the entire length of the SFPC, obliterating canyon floor lateral terraces (Figure 2). Levees border the outer walls of the SFPC, and show reliefs ranging between 20 and 40 m, and are concentrated mainly on the southwestern margin of this feature. A 40 m high levee is present on the proximal portion of the SFPC, near its intersection with the SFC (Figure 8).

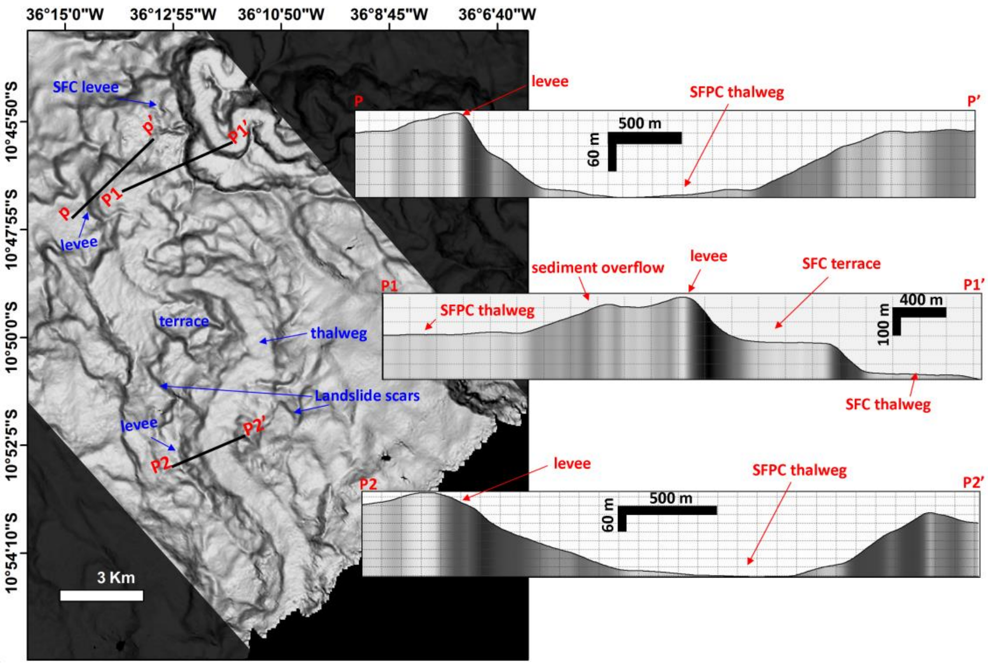


Figura 8 - São Francisco Paleo-canyon/distributary. The three bathymetric profiles illustrate the features discussed in the text.

4.4 Remaining Canyons (C1, C2, C3, C4, C5, and C6)

All remaining canyons mapped are nearly straight (sinuosity value of approximately 1). The largest one (C4), is 28.6 km long, followed by canyons C6, C3, C2, and C1, which presented similar lengths, ranging between 17.6 and 18.7 km. Canyon C5 was the shortest mapped (13.35 km) (Figure 4) (Table 1).

Canyon C4 is the only connected to the continental shelf at a depth of approximately 100 m), but is not linked with a fluvial system (Type II canyon). Its head is well developed and semicircular, measuring 6 km in diameter and 9 km in perimeter. The cross-section geometry of the head is “V”-shaped, with 520-m high surrounding walls and mean slope values ranging between 11.7° and 10.3° (Figure 9). At its most distal portion, the orientation of C4 canyon veers from NW-SE to N-S, when it encounters the SFPC (Figure 2).

Canyons C1, C2, C3, C5, and C6 are confined within the continental slope (Type III canyon). Their heads are located approximately between 850 and 1200 m in depth. They all have “V”-shaped heads, with narrow thalwegs (approximately 100 m). Canyon C1 shows the most developed and carved head (300 m of level difference between the thalweg and interfluves), and also exhibits slide scars. The C2, C3, C5, and C6 canyon heads have reliefs varying between 100 and 200 m (Figure 9).

The erosive nature and “V”-shaped geometry that dominates the proximal portion of all these canyons are replaced downslope by a “U” shaped geometry (Figure 3). Slide scars, ravines and tributary channels are also found in all of these canyons.

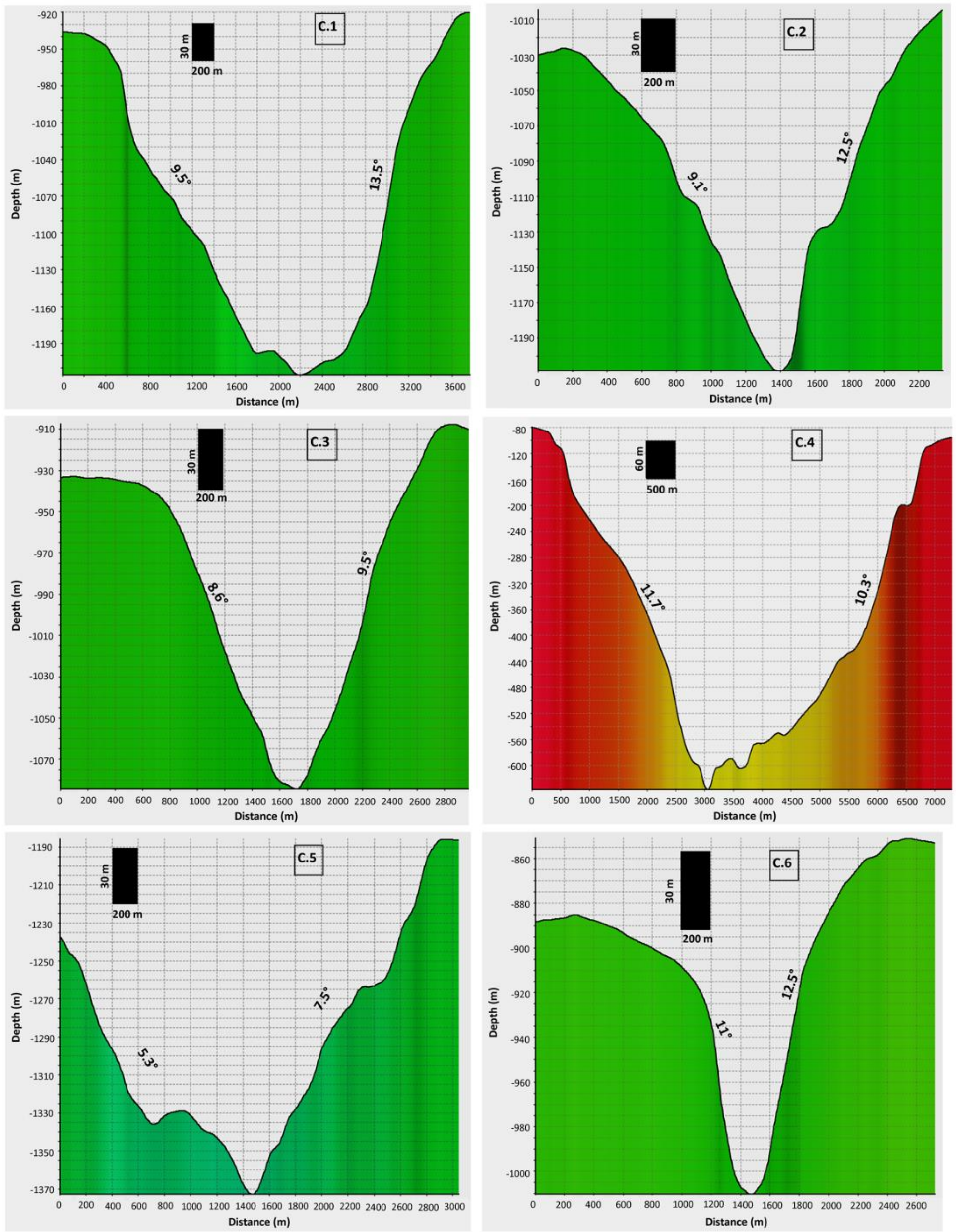


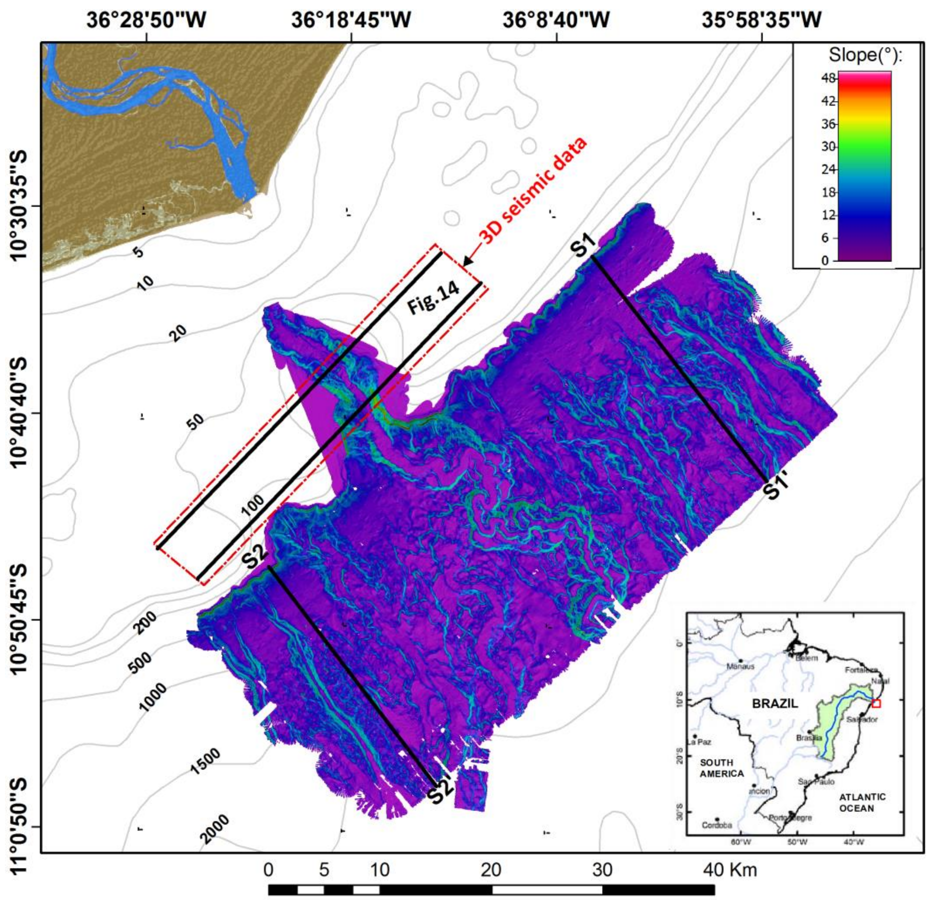
Figura 9 - Cross-section profiles of the heads of canyons C1, C2, C3, C4, C5, and C6. Profile location is shown in Figure 3. The colors of each image refer to the various depths, indicated in the legends of the multibeam bathymetry (Figure 1 and Figure 3, for example).

4.5 Continental Slope

The continental slope in the imaged area dips approximately 5°. However, values as high as 50° are found near the shelf break. In general, the continental slope southwesternwards of the SFC is steeper than northeasternwards. The upper portion of the continental slope extends down to approximately 600 m in depth at the southwestern portion, while at the northeastern portion it ends at 400 m (Figure 10).

Profile S1-S1' (northeastern portion) exhibits a mixed geometry. While the upper continental slope presents a concave geometry, the remaining of the profile has a convex upward shape (Figure 10). However, Profile S2-S2' (southwestern portion) shows a continuous concave geometry, and the canyons reach the edge of the continental shelf (Figures 1 and 10).

a)



b)

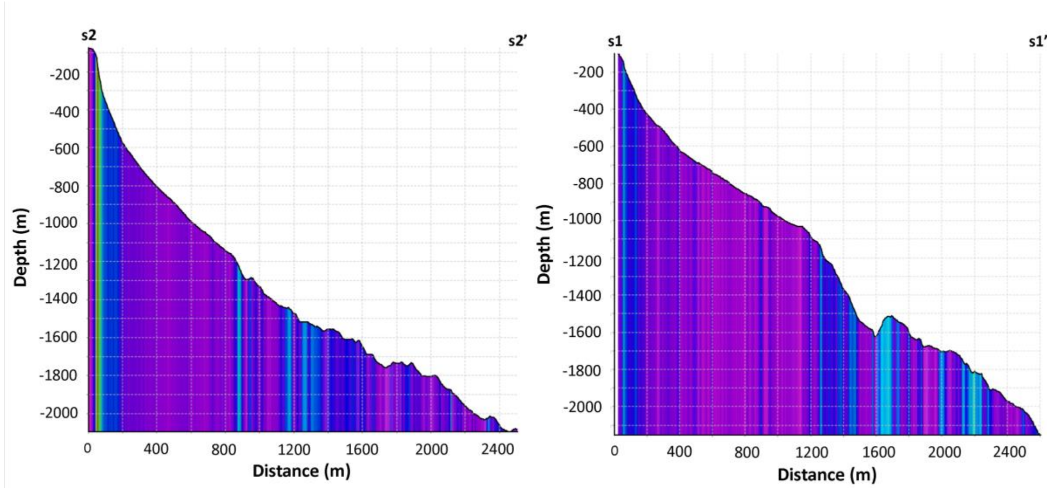


Figura 10 – a) Slope map of the study area. b) Longitudinal profiles of the continental slope illustrating slope variations. The position of the seismic profile of Figures 14 is also indicated in the image.

4.5.1 Other features on the continental slope

4.5.1.1 Slides

Submarine slide lobes and related scars are especially abundant on the continental slope, associated with canyon walls. More than 200 of the features were mapped, varying from approximately 500 m to 4 km of diameter. These features are also more abundant in the northeastern half of the study area (Figure 2).

4.5.1.2 Pockmarks and mounds

A total of 73 pockmarks and 36 mounds were mapped on the upper slope between 200 and 1000 m in depth. These features were particularly more abundant in the northeastern portion of the study area (Figures 2 and 11).

Mounds measured between 5 and 40 m in height and just over 200 m in diameter (Figures 12A and 12B). In relation to the surface of the continental slope, pockmarks measured between 15 and 20 m in depth with diameters ranging from 20 m, at the bottom, to 500 m at the sea floor (Figure 12C). Many of these structures were aligned, suggesting probable structural control (Cathles *et al*., 2010; Somoza *et al*., 2014), since some of these alignments represent extensions of canyons, tributaries, and ravines, especially at the northeastern portion of the area (Figure 2).

Scour marks are associated with these mounds and pockmarks especially on the upper continental slope. These scour marks indicate a preferential direction of bottom currents towards NE (Figure 11), which is in agreement with the flow direction of the North Brazil Current and the AAIW (Stramma and Schott, 1999; Stramma and England, 1999). High backscatter is also observed associated to these mounds, suggesting the presence of hard substrate (e.g. Figure 13b).

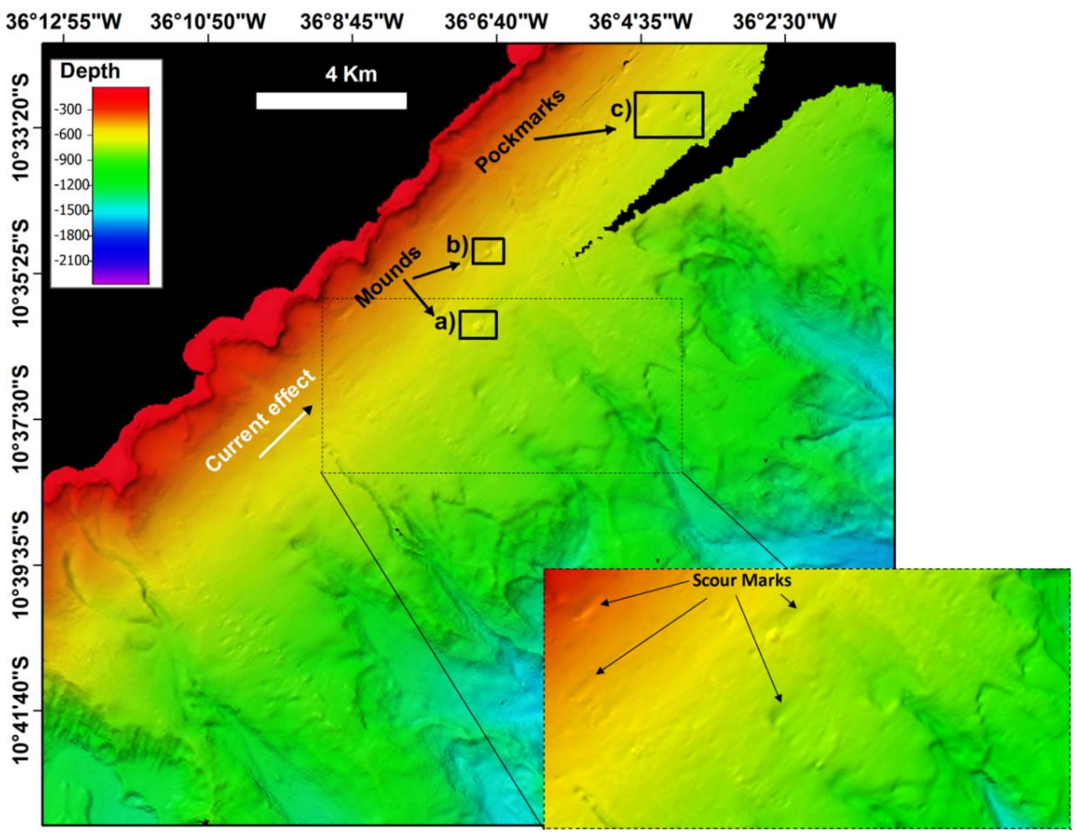


Figura 11 - Bathymetry of the northeastern area of the SFC, indicating mounds, pockmarks and the preferential movement direction of boundary currents. Note scour marks in the surroundings of these features.

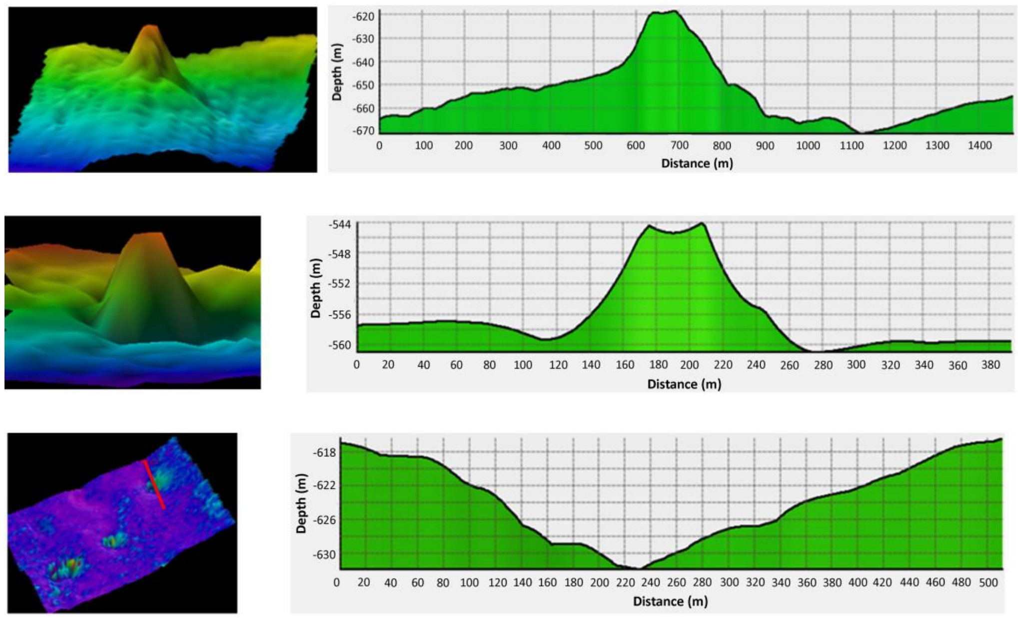


Figura 12 - Bathymetry detail of features identified as mounds (A and B) and pockmarks (C).

4.6 Backscatter

The low uniform backscatter values in most of the studied area (Figure 13) suggest the dominance of fine-grained sediments. High values are present, however, in areas close to the shelf edge, suggesting supply of coarse-grained carbonate grains from the shelf region.

Along the SFC, fine-grained sediments are apparently dominant. However, in the area around the canyon head, backscatter values are high, in association with landslides originating from the shelf. The canyon floor and walls in the region deeper than 1500 m, and downslope of the most important knickpoint also show high backscatter values. (Figure 13).

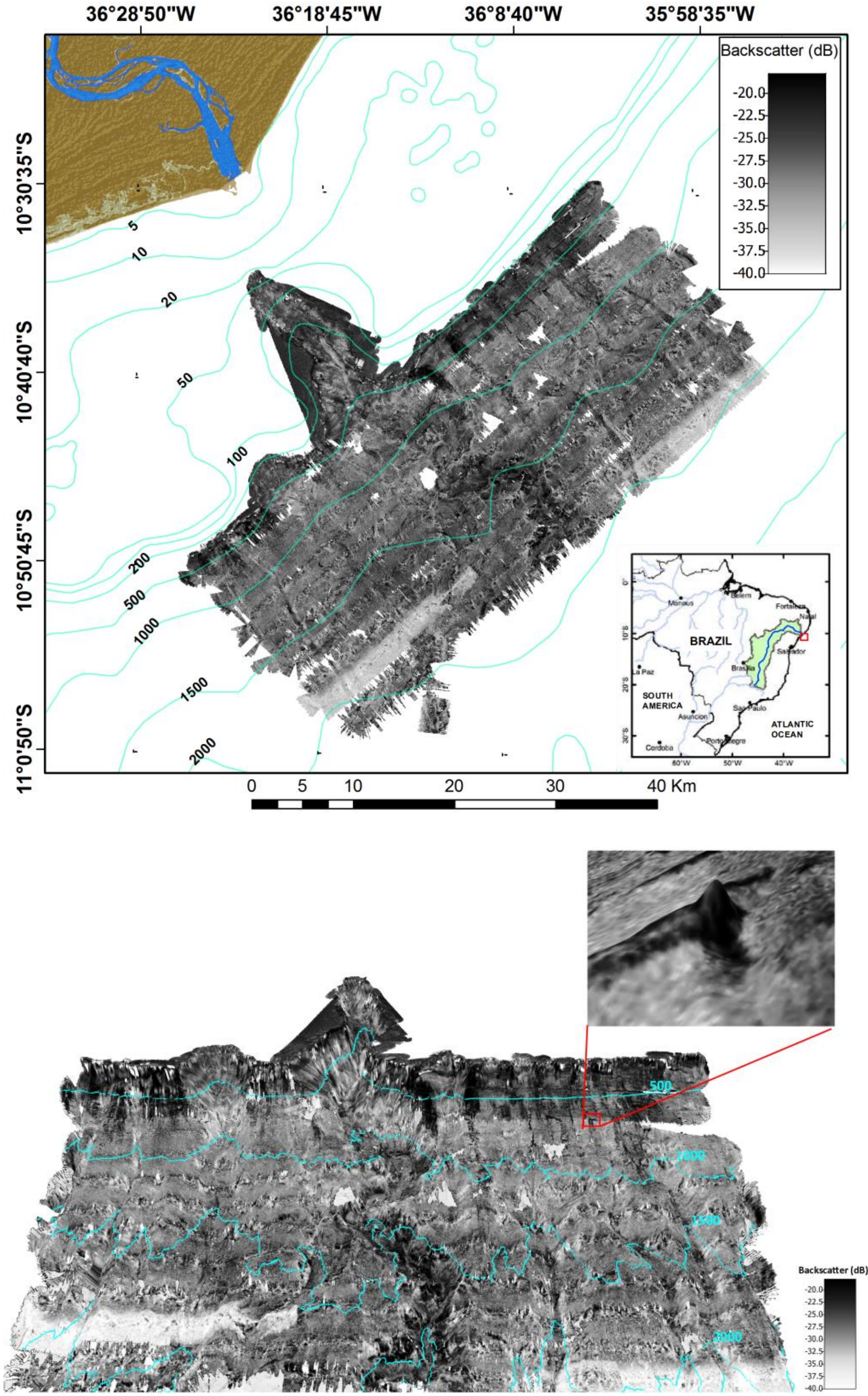


Figura 13 - a) Backscatter map of the imaged region, in planform. b) 3D rendering, highlighting the mound showed in Figure 12A.

4.7 3D Seismic

Castro (1989) (His figure 23) and Cainelli (1992), based on the integration of stratigraphic wells and 2D seismic lines placed the unconformity marking the boundary Eocene-Oligocene at approximately 0.5-1.0 sec (TWTT). We used this criteria to place this same boundary in our the 3D seismic records, setting a lower temporal boundary to the analysis that follows (Figure 14).

It can be clearly seen that the modern SFC was incised over an already infilled older-canyon, apparently of Eocene age, and located right below the Eocene-Oligocene transition (Figure 14). Above this unconformity, 05 stratigraphic units were identified, from bottom to top:

Unit 1: this unit extends along the entire seismic record. It is characterized by flat high amplitude reflectors particularly in those portions closer to the present day shoreline (Figure 14 a). The shallow Eocene valley precursor of the SFC is almost completely infilled by this unit.

Unit 2: still shows parallel reflectors although with much less amplitude. Towards the top, this unit progressively acquires a progradational character (depicted in light blue in figure 14) from laterally sourced sediments, and accompanied by an increase of reflector amplitude. This unit increases in thickness seawards and laterally away from the canyon head. (Figure 14). This lateral increase in thickness reflecting greater accumulation rates apparently contributed to the initiation of the bathymetric “depression” that surrounds the SFC head nowadays.

Unit 3: infills the bathymetric “depression” mentioned above onlaping unit 2. Reflector amplitudes are less pronounced. Please note that the units 1, 2 and 3 do not extend inside de the SFC valley and area truncated by unit 4.

Unit 4: this unit has been described by Cainelli (1992) as a “younger than Miocene” canyon, which has been completely infilled. It truncates the previous units, and increases in width continent ward (Figures 14a and 15). In its inner, wider portion it is almost transparent with a few very low amplitude reflectors whereas in the outer portion chaotic reflectors dominate.

Unit 5: this is the topmost and thinnest unit mapped, corresponding to the present São Francisco delta and infills the subdued bathymetric depression that formed at the end of deposition of unit 2.

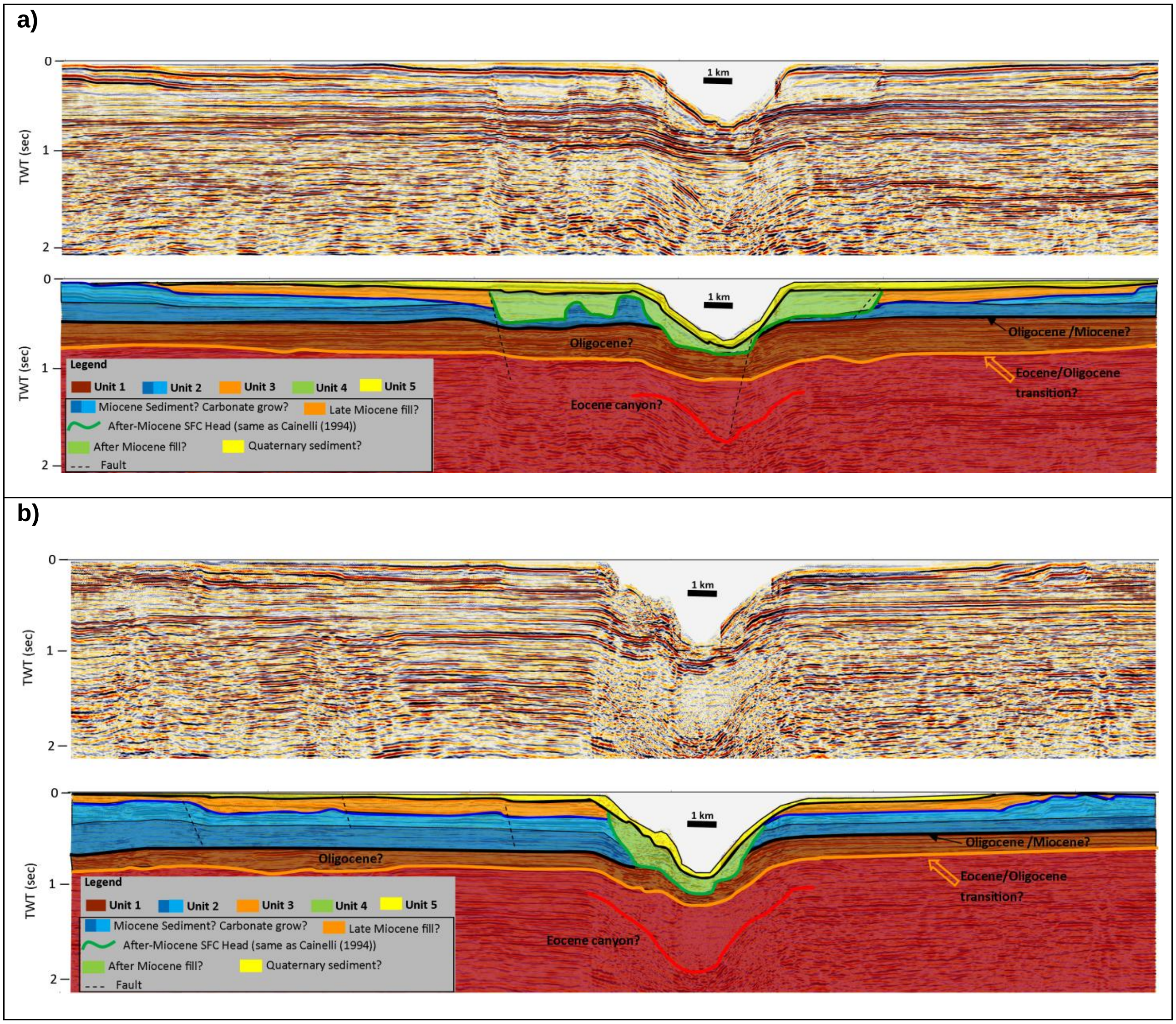
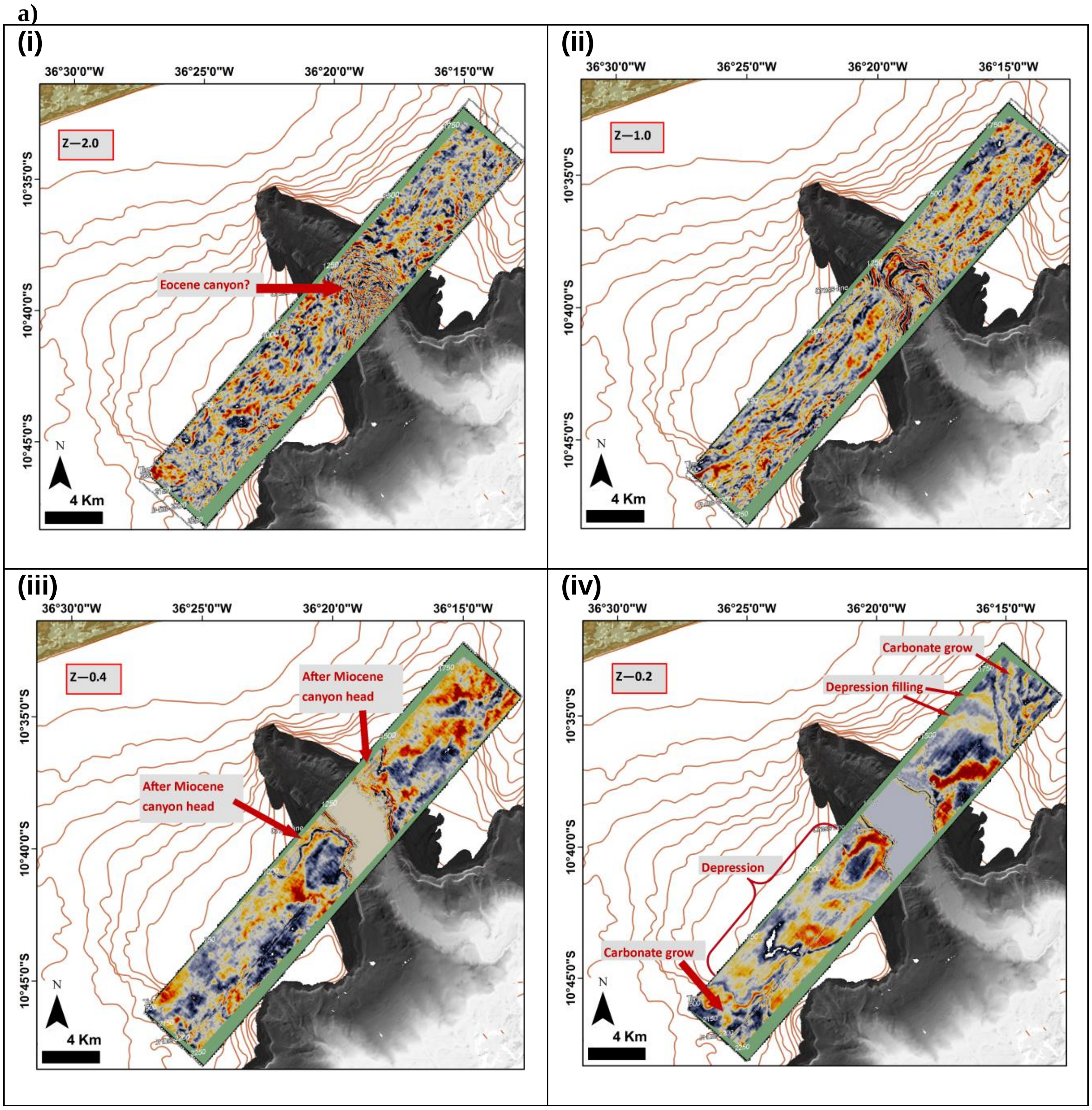


Figure 14 – Strike seismic profiles (inner line (a) and outer liner (b)) from the region of the head of the SFC, in the sector where it indents the continental shelf. The right position of the lines is seen in the Figure 10.

Seismic time slices from the Eocene-Oligocene boundary to the sea floor show the progressive enlargement of the canyon head from its Eocene precursor (Figure 15a). The so called "post-Miocene canyon" of Cainelli (1992) marks the moment in which the canyon head was widest, reaching almost 5 km in its most landward limit. Apart from this, the rest of the canyon head incising the shelf has maintained a fixed position since the beginning of the Oligocene (Figure 15b).

The time slices also show the progressive development of the bathymetric depression as a result of the lateral carbonate agradational build up, and its later axial infilling possibly by siliciclastic sediments.

a)



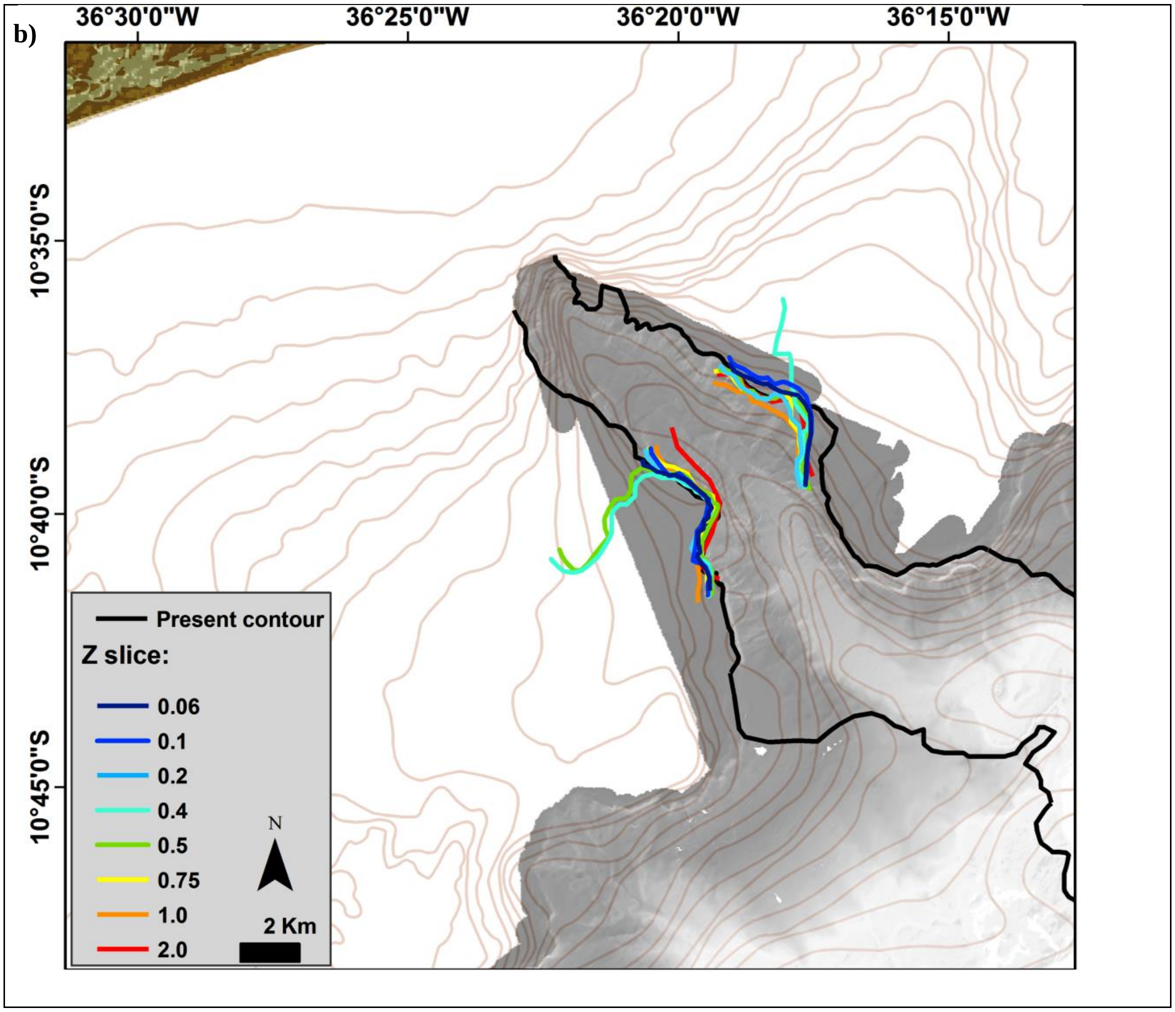


Figure 15 – a) Z-slices obtained from the 3D seismic survey showing the evolution of the ancestral/modern SFC through time. Z values are in miliseconds (TWT). B) Shows the position contour of each head margin through the time.

5. Discussion

5.1 Origin and evolution of the São Francisco Canyon

Two main processes act, either separatly or together, in the development of submarine canyons: i) erosion by turbiditic flows derived from fluvial systems; and ii) retrogressive erosion produced by sedimentary instability, associated with faults and landslides, in the region of the continental slope (Shepard, 1936; Shepard, 1981; Twichell and Roberts, 1982; Pratson et al., 1994; Pratson and Coakley, 1996; Harris and Whiteway, 2011; Green et al., 2007; Green and Uken, 2008; Mauffrey et al., 2017).

Nowadays the SFC besides indenting the shelf is also directly associated with a river system, which suggests a direct link between canyon inception and fluvial sediment supply. A number of factors may have contributed for the inception and evolution of the canyon and its associated submarine fan. Throughout most of the Tertiary, the continental margin of the Sergipe-Alagoas basin was characterized by a mixed siliciclastic-carbonate sedimentation (Cainelli, 1992). After the Eocene the margin experienced expressive progradation-agradation of the outer shelf carbonates which caused progressive steepening of the continental slope, which might also have contributed to an increase in gravitational instability of the slope sediments.

Along eastern Brazil the most important Neogene highstand deposits is the Barreiras Formation. This Formation has been deposited in a coastal setting associated with the early-mid-Miocene transgression that inundated the Brazil's continent seaboard (Rossetti et al., 2013). The drop in sea level afterwards might have had the effect of bringing the source of siliciclastic sediments closer to the shelf break. The increase in siliciclastic sediment supply might have had an inhibitory effect on carbonate development in the immediate vicinities of the São Francisco river mouth. As a result only in those portions away from the river plume, carbonate sedimentation/aggradation took place which in the end has favored development of the bathymetrical depression, whose remnants are still visible today. The creation of this bathymetric depression helped to funnel siliciclastics to the precursory SFC, which was almost completely buried during the Oligocene. This would tentatively place canyon inception sometime after the Miocene highstand. The so-called "post-Miocene canyon" of Cainelli (1994) would have formed during this time, and at least in its portion closer to the shoreline was later almost completely infilled (unit 4).

With the pronounced drop in eustatic sea level after the development of the NHIS, during the Pliocene bringing the average sea-level position to -40 to -60 m (Miller et al., 2005), most of the shelf remained exposed to subaerial conditions, and funneling of the São Francisco river sediments down canyon, resulted in its reactivation and development of the modern SFC, which agrees with the early suggestion of Cainelli (1994), of a Plio-Pleistocene age for the modern canyon. The hypothesis of sea level lowering as a major contributor to canyon shelf indentation has also been put forward to explain such features at the Ebro delta in the Mediterranean Sea (Mauffrey et al., 2017), in the Eastern South Atlantic Margin (Antobreh and Krastel, 2006), and at the Danube Canyon (Popescu et al., 2004).

The aspects mentioned above although important probably would not produce the same results if the continental shelf at the region were not narrow (Harris and Whiteway, 2011). Narrow shelves are known to favor the connection between river and canyon (Normark et al., 2009; Sweet and Blum, 2016), also favoring canyon maintenance in the long run.

The distance that separates the main river from the canyon is an important control to determine sediment delivery (Sweet and Blum, 2016). The smaller this distance the easier would be the sediment delivery. Narrow shelves favor the possibility that even during highstands continental sediments can be fed to canyon systems (Sweet and Blum, 2016).

Two other factors may have played a role in promoting/enhancing the shelf incision and connection between canyon and river.

The Miocene was a time globally characterized by an increase in continental erosion (Clift, 2010). At this period, the South American continent suffered modifications in its drainage network, which lead for instance to the development of the modern Amazon River (King, 1957; Figueiredo et al., 2009; Shephard and Muller, 2010). In relation to the São Francisco river, some authors have suggested the possibility that originally it emptied in northern Brazil (Figure. 10 in Grabert, 1968; Potter, 1997). Later the river has been captured by drainage originating in the eastern Brazil coast after South America – Africa separation. The São Francisco then started discharging at its present location, increasing sediment supply to the study area. This increased sediment supply would then favor inception of the canyon after the Miocene. The SFPC might date from that initial inception and its sinuosity, although not as pronounced as the SFC, might indicate that it remained active for an extended period of time (Peakall et al., 2000; Babonneau et al., 2002; Maier et al., 2013; Hansen et al., 2017). Since its abandonment, by avulsion, it has been progressive infilled by sediments from lateral wall slides and overflow from turbidity currents during the initial incising phases of the present SFC. The high degree of incision of the current SFC, possibly a result of the continued drop in eustatic sea level during the Plio-Pleistocene (see below) will probably preclude future canyon avulsions (Schwenk et al., 2003; Deptuck et al., 2007).

Finally neotectonics may also have played a role in the development of the bathymetric depression mentioned before, which helped to trap and funnel siliciclastic and carbonate sediments to the canyon. Recent research has suggested that delta development at the São Francisco have been affected by tectonic movement along existing faults both in the deltaic plain (Lima et al. 2014) and in the shelf area (Santos et al., 2018). Nevertheless no major fault so far has been mapped associated with the SFC (Oliveira et al., 2017).

Summing up the inception of the canyon and its direct linkage with the river appears to result from the action of two major factors acting in an originally narrow shelf: drop in sea level since the Miocene highstand and funneling of siliciclastic and carbonate sediments to the deep-sea resulting from the appearance of a bathymetric depression in the shelf in from of the river mouth. This bathymetric depression may have resulted from the combined interaction of neotectonics and differential accumulation rates between shelf carbonates and siliciclastics. Without such a funneling effect the connection between river and canyon probably would have taken place through a narrow incised channel.

5.2 Canyon-river connection x sea level changes

During Quaternary the mean sea level position was between 45 and 65 m below the current sea level (Lea et al., 2002; Blum and Hattier-Womack, 2009). The shelf of the area is one of the narrowest shelves on passive margins in the world, with the shelf break between 50 m and 70 m (Cainelli, 1994; Dominguez, 1996; Fontes et al., 2017). Therefore, during the most part of the last 1.8 million years, a large portion of the shelf was exposed favoring sub-aerial erosion on the shelf and the continued connection between the São Francisco river mouth and the head of the canyon. This has enhanced sediment transfer to the basin. These factors would help explaining the construction of a large submarine fan complex on the continental slope of the region (Cainelli, 1994; Oliveira Jr. et al., 2017). This aspect would also make this kind of canyon a potential producer of good hydrocarbon reservoirs (Jobe et al., 2011; Stow and Mayall, 2000; Dailly et al., 2002).

Canyon sinuosity, presence of knickpoints along the thalweg, and marginal terraces are also expressions of the linkage between river and canyon, and the effects of sea level changes, especially during lowstands (Piper, 2005; Arzola et al. 2008; Puga-Bernabéu, et al., 2011; Harris and Whiteway, 2011; Jobe *et al*., 2011; Posamentier, 2003). Terrace development in submarine canyons is a response to incision caused by increases in energy, deriving from continued canyon-river connection (Baztan et al., 2005).

This continued river-canyon connection, favored by an average position of sea level of -40 to -60m has other important implications for slope sedimentation. This situation would favor direct delivery of fine riverborne sediments northeastwards flowing contour currents hugging the upper slope. Corroborating evidences include:

(i) the apex of the submarine fan at the point where the canyon intercepts the slope is asymmetrical towards northeast (Figure 2);

(ii) canyon interfluves in the upper slope region, northeastwards of the SFC are shallower that those located southwestwards;

(iii) the upper continental slope southwestwards of the SFC is more dissected by submarine canyons. All canyons mapped, but for the SFC, were formed by the retrogressive erosion, with no directly association with a fluvial sedimentary source. Their development are related with instability processes and landslides on the continental slope (Pratson et al., 1994; Pratson and Coakley, 1996) and can exhibit different stages of maturity (initial, transitional, and mature) (Puga-Bernabéu, et al., 2011). The canyons located southwestwards from the SFC are more developed, with heads reaching (mature stage – C4) or nearly reaching the shelf break (C6 – transitional stage). On the other hand, all the canyons located northeastwards of the SFC (C1, C2 and C3) exhibit a transitional character, with their heads occurring at greater depths compared to those located southwestwards. Canyon wall morphology also indicates a northeastward transport with the southern walls exhibiting gentler slopes than the northern ones; and

(iv) scour marks associated with pockmarks and mounds indicate northeastward sediment transport on the upper slope. These scour marks are indicative of the action of intense currents (Cathles et al., 2010; Mol et al., 2011; Somoza et al., 2014). Mounds and pockmarks, which are more numerous northeastward of the SFC can be indicative of confined gas exudation (Hovland and Svensen, 2006; Cathles et al., 2010; Somoza et al., 2014), that would supposedly be favored by higher organic matter content associated with higher sedimentation rates at this region. Mounds could also represent deep-sea coral reefs, usually formed by *Lophelia pertusa* and *Madrepora oculata* (Roberts et al., 2003; Raddatz et al., 2014; Somoza et al., 2014), that occur in association with strong current intensity (Guinotte et al., 2006; Mol et al., 2011; Raddatz et al., 2014).

5.3 Recent activity of the SFC

The Last Glacial Maximum (LGM) is considered the last moment of high activity in submarine canyons in the world (Piper and Savoye 1993; Pratson et al., 1994; Weber et al., 1997; Prins et al., 2000; Popescu et al., 2001; Babonneau et al., 2002; Gervais et al., 2006; Ducassou et al., 2009; McHargue et al., 2011; Sweet and Blum, 2016). With sea level below 100 m during the LGM, there was a direct connection between the river mouth and the head of the canyon, and the delivery of sandier sediments to the canyon was certainly higher (Deptuck et al., 2007; Jobe et al., 2015; McHargue et al., 2011 Pratson and Coakley, 1996; Baztan et al., 2005; Oiwane et al; 2011). During such episodes axial incision and lateral terrace development is enhanced as described by Baztan et al. (2005) for the canyons of the Gulf of Lion in the Mediterranean during Quaternary lowstands.

Many submarine canyons around the world were considered inactive with the retreat of sedimentary sources during highstand periods (Damuth and Kumar, 1975; Babonneau et al., 2002; Antobreh and Krastel, 2006). However, some canyons are still considered active due to the proximity between the canyon head and the main river (Babonneau et al., 2002; Sweet and Blum, 2016), or the sedimentary input provided by continental shelves, even with no relationship with fluvial systems (Antobreh and Krastel, 2006; Arzola et al., 2008; Allin et al., 2016).

Summerhayes et al. (1976) considered that the SFC is currently inactive. Oliveira Jr. et al, (2017), also considers that most of the canyon is inactive, because of a flat floor without any axial incision. Box cores taken from the flat canyon floor in depths ranging from 2000 to 3000 m approximately, have shown a dominance of slump deposits infilling the canyon (Kowsmann et al., 2017). However these authors also reported a radiocarbon date of 2130 cal years BP for wood fragments in sandy sediments collected at 3045m depth at the canyon floor concluding for a “recent” transport activity in the distal portion of the canyon. Lemos Jr. (2017) have concluded based on the study of a piston-core collected at a depth of 1200m, that only 3.4m of sediment accumulated in the past 11000 years, most of which is also related to mass movements. However, at a depth of about 3.0m at that piston core, he described the presence of unequivocally fine-grained turbidite deposits dated from the early Holocene (11,180-10,900 cal years BP). At that time sea level was positioned approximately 60 m below the present level, which coincides with the end of the Younger Dryas period (Liu et al., 2004). This seems to be the last time a direct connection river-canyon existed. Presently the São Francisco sandy sediments are retained within the deltaic plain, forming regressive littoral sands typical of wave-dominated deltas (Dominguez, 1996). These sands are separated from the canyon head by a muddy deltaic clinoform, which progrades over the canyon head (Figure 1). This will increasingly supply fine-grained sediments to the canyon (Sweet and Blum, 2016), an assumption corroborated by Lemos Jr (2017) who reported radiocarbon dates of 400 yrs BP for the muddy sediments recovered from the upper 101 cm of the piston-core studied.

Moreover, the presence of a small axial incision (Figure 6a) at the canyon head incising the lateral mass movement deposits suggests active sediment transport at least in the portion of the canyon closer to the delta clinoform. The absence, in our multibeam records, of extensive lateral mass movements deposits infilling the canyon floor may also be an evidence of removal of these materials by turbidity currents (Twichell and Roberts, 1982), even if diluted. Also, the presence of crescentic bedforms at the canyon floor, especially on the upper canyon (Figure 6b), supports the hypothesis of modern sediment transport activity. These bedforms can be formed under super-critical flow conditions in turbidity currents and can migrate upslope (Hage et al., 2018).

Finally the high backscatter values found in portions of the canyon floor deeper than 1400m, might result from the presence of coarser sediments, transported to this region, either during Late Quaternary lowstands or during more recent high energy events, that reaches the deeper portions of the canyon. Shallower that this depth only fine grain sediments are found on the canyon floor, either sourced from the delta clinoform, or hemipelagic in nature.

A conceptual evolutionary model describing the SFC behavior and sediment transport at different moments of sea level is shown in Figure 16:

(i) During lowstands (UGM, for example), the shelf would be completely exposed, the river was directly connected to the canyon head, and riverborne sediments would be directly delivered to the canyon. At such moments, incision, terrace formation and levees would favorably develop.

(ii) Because of the narrow and shallow nature of the local continental shelf, even with sea level positioned between -40 to -60 m below the present level, which characterized the last 1Ma, the shelf was still completely exposed. We can assume that an active connection canyon-river existed most of the time during the Late Quaternary. The river would empty directly over the continental slope and a northeastwards preferential dispersal of the fine-grained sediments would occur promoted by contour currents. Several lines of evidence discussed above corroborate this interpretation.

(iii) Sea level rise that peaked at Late Quaternary highstands caused the entire shelf and river valley to be flooded and the link river-canyon was severed.

(iv) The Late Quaternary interglacials although brief (lasting ~10ka), lasted enough to allow the construction of highstand deltas and eventually the deltaic clinoform would reach the canyon head resulting in the reconnection of river-canyon system. At these highstands however, with the shelf entirely flooded, fine grained sediment dispersal would be directed southwestwards, by prevailing winds.

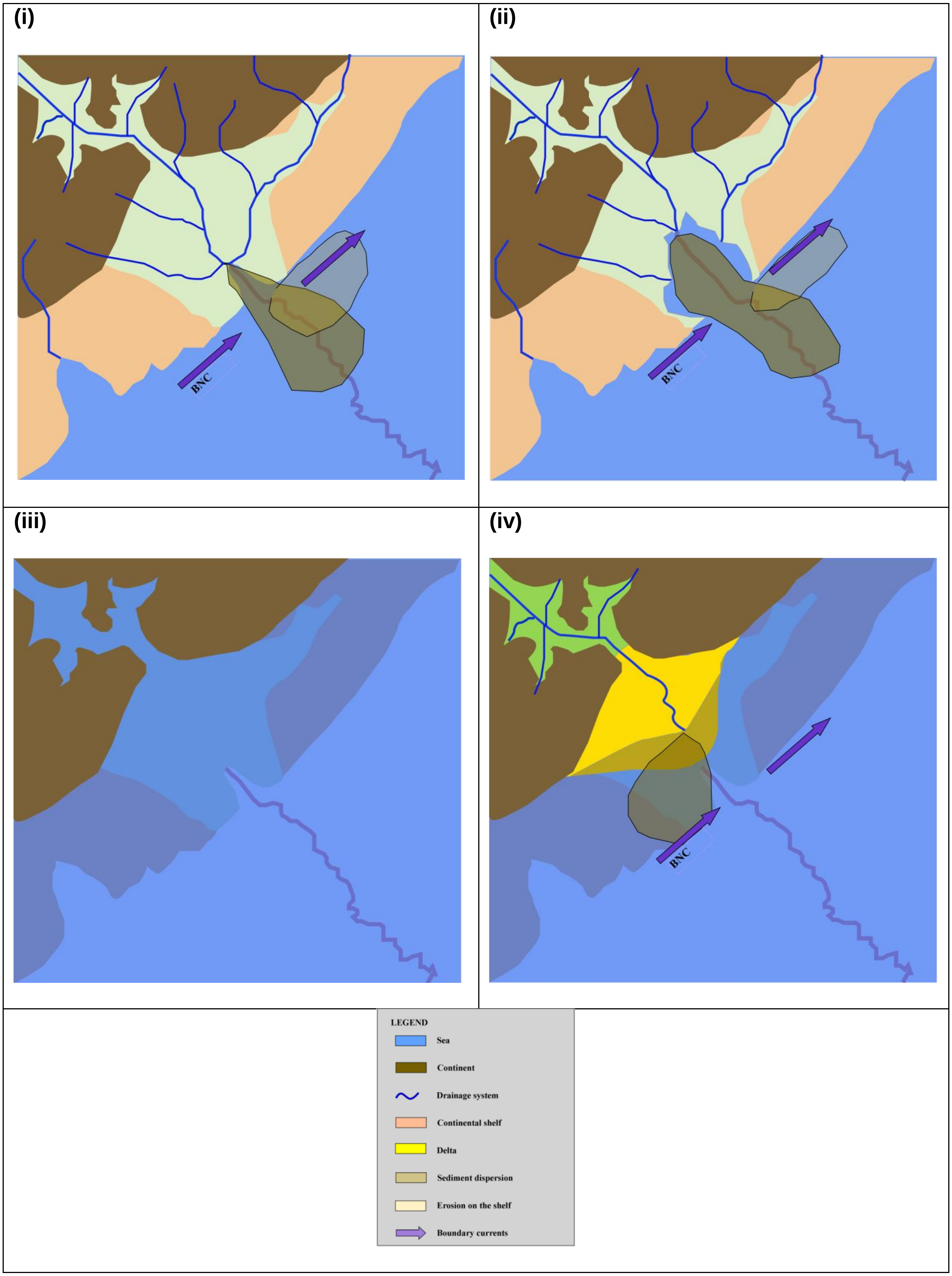


Figure 16 - Schematic connection evolution between SFR and SFC.

6. Conclusion

The present study presented the results of a multibeam bathymetry survey at the São Francisco Canyon and neighboring areas and its integration with 3D seismic data from the canyon head. Several types of submarine canyons, exhibiting various degrees of maturity, were mapped in the continental slope. The SFC is the only canyon at the Brazilian continental margin that deeply incises the shelf and at the same time is directly linked with a major river system. It also exhibits a high degree of meandering possibly due to this association.

The modern SFC was carved into a more ancient, already infilled precursor of Late Eocene age, representing a re-incision episode, possibly related to the eustatic sea-level fall since the Middle Miocene highstand. We hypothesize that the inception of the modern SFC took place during Late Miocene - Pliocene time. The aggradation of shelf-edge carbonates gave origin of a bathymetric depression around the canyon head, possibly enhanced by neotectonic fault reactivation. This bathymetric depression, still present today, helped trapping and funneling of riverborne sediments to the deep sea. This seems to be one of the most important factors inducing continued sediment connection between river-canyon and incision throughout the Quaternary, with development of several generations of lateral terraces and levees, characteristic of the SFC .

During most of the Quaternary the local shallow and narrow shelf has been exposed to subaerial conditions with the river emptying at or very close to the canyon head. Fine-grained riverborne sediment dispersion, specially during lower sea levels was controlled by boundary currents flowing northeastwards along the upper portion of the continental slope. This has caused marked morphological differences in the upper slope situated to northeast and to southeast of the SFC, affecting the degree of maturity of submarine canyons, distribution of mounds and pockmarks, and depth of canyon interfluves.

During highstands, with the shelf flooded, fine-grained river born sediments were transported dominantly southwestwards by the coastal flow generated by prevailing winds.

The presence of a small axial incision and crescentic bedforms on the upper canyon floor suggests that direct delivery of sediments to the canyon by the São Francisco deltaic muddy clinoform is taking place during the present highstand.

Reference

Allin, J.R., Hunt, J.E., Talling, P.J., Clare, M.A., Pope, E., Masson, D.G., 2016. Different frequencies and triggers of canyon filling and flushing events in Nazaré Canyon, offshore Portugal. Marine Geology 371, 89–105.

Antobreh, A.A., Krastel, S., 2006. Morphology, seismic characteristics and development of Cap Timiris Canyon, offshore Mauritania: A newly discovered canyon preserved-off a major arid climatic region. Marine and Petroleum Geology 23, 37–59.

Arzola, R.G., Wynn, R.B., Lastras, G., Masson, D.G., Weaver, P.P.E., 2008. Sedimentary features and processes in the Nazaré and Setúbal submarine canyons, west Iberian margin. Marine Geology 250, 64–88.

Babonneau, N., Savoye, B., Cremer, M., Klein, B., 2002. Morphology and architecture of the present canyon and channel system of the Zaire deep-sea fan. Marine and Petroleum Geology 19, 445–467.

Bandeira, J.V., Enrique, O., Acosta, C., 2008. Long-term morphological impacts on the coastline of Sergipe State, Brazil, caused by the construction of dams in the São Francisco River Basin. Area 1–16.

Baztan, J., Berné, S., Olivet, J.L., Rabineau, M., Aslanian, D., Gaudin, M., Réhault, J.P., Canals, M., 2005. Axial incision: The key to understand submarine canyon evolution (in the western Gulf of Lion). Marine and Petroleum Geology 22, 805–826.

Bittencourt, A.C.S.P., Martin, L., Dominguez, J.M.L., Silva, I.R., Sousa, D.L., 2002. A significant longshore transport divergence zone at the Northeastern Brazilian coast: implications on coastal Quaternary evolution. An. Acad. Bras. Cienc. 74, 505–518.

Blum, M.D., Hattier-Womack, J., 2009. Climate change, sea-level change, and fluvial sediment supply to deepwater depositional systems. External Controls on Deep-Water Depositional Systems. SEPM Special Publication 92, 15–40.

Cainelli, C., 1992. Sequence stratigraphy, canyons, and gravity mass flow deposits in the Piaçabuçu Formation, Sergipe-Alagoas Basin, Brazil. Doctoral thesis. The University of Texas at Austin, 233 p.

Cainelli, C., 1994. Shelf processes and canyon/channel evolution controlling turbidite systems: examples from the Sergipe-Alagoas Basin, Brazil. GCSSEPM Foundation 15th Annual Research Conference. 39–50.

Cathles, L.M., Su, Z., Chen, D., 2010. The physics of gas chimney and pockmark formation, with implications for assessment of seafloor hazards and gas sequestration. Marine and Petroleum Geology 27, 82–91.

Castro Jr, A.C.M.D., 1989. Structural evolution of the Sergipe-Alagoas Basin, Brazil. Doctoral dissertation, Rice University.

Clift, P.D., 2010. Enhanced global continental erosion and exhumation driven by Oligo-Miocene climate change. Geophysical Research Letters 37, 1–6.

Clift, P.D., Giosan, L., Henstock, T.J., Tabrez, A.R., 2014. Sediment storage and reworking on the shelf and in the Canyon of the Indus River-Fan System since the last glacial maximum. Basin Research 26, 183–202.

Cunha, M.R., Paterson, G.L.J., Amaro, T., Blackbird, S., de Stigter, H.C., Ferreira, C., Glover, A., Hilário, A., Kiriakoulakis, K., Neal, L., Ravara, A., Rodrigues, C.F., Tiago, Á., Billett, D.S.M., 2011. Biodiversity of macrofaunal assemblages from three Portuguese submarine canyons (NE Atlantic). Deep-Sea Research Part II: Topical Studies in Oceanography 58, 2433–2447.

Dailly, P., Lowry, P., Goh, K., Monson, G., 2002. Exploration and development of Ceiba Field, Rio Muni Basin, Southern Equatorial Guinea. The leading edge. 1140–1146.

Damuth, J.E., Kumar, N., 1975. Amazon cone: morphology,sediments, age, and growth pattern. Geological Society of America Bulletin 86, 863–878.

de Araújo, H. A. B., Dominguez, J. M. L., de Jesus Machado, A., & Rangel, A. G. D. A. N., 2018. Benthic foraminifera distribution in a deltaic clinoform (São Francisco Delta, eastern Brazil): A reference study. Journal of Marine Systems 186, 1-16.

De Leo, F.C., Smith, C.R., Rowden, A.A., Bowden, D.A., Clark, M.R., 2010. Submarine canyons: hotspots of benthic biomass and productivity in the deep sea. Proceedings of the Royal Society B: Biological Sciences 277, 2783–2792.

Deptuck, M.E., Sylvester, Z., Pirmez, C., O'Byrne, C., 2007. Migration–aggradation history and 3-D seismic geomorphology of submarine channels in the Pleistocene Benin-major Canyon, western Niger Delta slope. Marine and Petroleum Geology 24, 406–433.

Dominguez, J.M.L., 1996. The Sao Francisco strandplain: a paradigm for wave-dominated deltas? Geological Society, London, Special Publications 117, 217–231.

Ducassou, E., Migeon, S., Mulder, T., Murat, A., Capodondi, L., Bernasconi, S.M., and Mascle, J., 2009. Evolution of the Nile deep-sea turbidite system during the Late Quaternary: influence of climate change on fan sedimentation. Sedimentology 56, 2061–2090.

Fagherazzi, S., Howard, A.D., Wiberg, P.L., 2004. Modeling fluvial erosion and deposition on continental shelves during sea level cycles. Journal of Geophysical Research 109, 148-227.

Figueiredo, J., Hoorn, C., Ven, P. Van Der, Soares, E., 2009. Late Miocene onset of the Amazon River and the Amazon deep-sea fan: Evidence from the Foz do Amazonas Basin. Geology 37, 619-622.

Fontes, L.C. da S., Santos, J.R., Santos, L.A., Mendonça, J.B.S., Santos, M.S. dos, 2017. Geologia e Geomorfologia da Bacia de Sergipe-Alagoas. Editora Universidade Federal de Sergipe. pp. 25–96; 138-162.

Gamberi, F., Marani, M., 2008. Controls on Holocene deep-water sedimentation in the northern Gioia Basin, Tyrrhenian Sea. Sedimentology 55, 1889–1903.

Gardner, W.D., 1989. Baltimore Canyon as a modern conduit of sediment to the deep sea. Deep Sea Research Part A, Oceanographic Research Papers 36, 323–358.

Gervais, A., Mulder, T., Savoye,B., and Gonthier, E., 2006, Sediment distribution and evolution of sedimentary processes in a small sandy turbidite system (Golo system, Mediterranean Sea): implication for various geometries based on core framework. Geo- Marine Letters 26, 373–395.

Gómez-Ballesteros, M., Druet, M., Muñoz, A., Arrese, B., Rivera, J., Sánchez, F., Cristobo, J., Parra, S., García-Alegre, A., González-Pola, C., Gallastegui, J., Acosta, J., 2014. Geomorphology of the Avilés Canyon System, Cantabrian Sea (Bay of Biscay) María. Deep-Sea Research Part II: Topical Studies in Oceanography 106, 99–117.

Grabert, H., 1968. Postmesozoische entwässerung und oszillation am ostrande des Brasilianischen schildes. Geologische Rundschau, 58, 166-190.

Green, A.N., Goff, J. a., Uken, R., 2007. Geomorphological evidence for upslope canyon-forming processes on the northern KwaZulu-Natal shelf, SW Indian Ocean, South Africa. Geo-Marine Letters 27, 399–409.

Green, A., Uken, R., 2008. Submarine landsliding and canyon evolution on the northern KwaZulu-Natal continental shelf, South Africa, SW Indian Ocean. Marine Geology 254, 152–170.

Guimarães, J.K., 2010. Evolução do delta do rio São Francisco - estratigrafia do Quaternário e relações morfodinâmicas. Doctoral thesis. Federal University of Bahia, 145 p.

Guinotte, J.M., Orr, J., Cairns, S., Freiwald, A., Morgan, L., George, R., 2006. Will human-induced changes in seawater chemistry alter the distribution of deep-sea scleractinian corals? Frontiers in Ecology and the Environment 4, 141–146.

Hansen, L., Janocko, M., Kane, I., Kneller, B., 2017. Submarine channel evolution , terrace development , and preservation of intra-channel thin-bedded turbidites: Mahin and Avon channels , offshore Nigeria. Marine Geology 383, 146–167.

Hage, S., Cartigny, M.J.B., Clare, M.A., Sumner, E.J., Vendettuoli, D., Clarke, J.E.H., Hubbard, S.M., Talling, P.J., Lintern, D.G., Stacey, C.D., Englert, R.G., Vardy, M.E., Hunt, J.E., Yokokawa, M., Parsons, D.R., Hizzett, J.L., Azpiroz-zabala, M., Vellinga, A.J., 2018. How to recognize crescentic bedforms formed by supercritical turbidity currents in the geologic record: Insights from active submarine channels. Geology 46, 563–566.

Harris, P.T., Whiteway, T., 2011. Global distribution of large submarine canyons: Geomorphic differences between active and passive continental margins. Marine Geology 285, 69–86;

Hovland, M., Svensen, H., 2006. Submarine pingoes: Indicators of shallow gas hydrates in a pockmark at Nyegga, Norwegian Sea. Marine Geology 228, 15–23.

Jobe, Z.R., Lowe, D.R., Uchytil, S.J., 2011. Two fundamentally different types of submarine canyons along the continental margin of Equatorial Guinea. Marine and Petroleum Geology 28, 843–860.

Jobe, Z.R., Sylvester, N., Parker, A.O., Howes, N., Slowey, N., Pirmez, C., 2015. Rapid adjustment of submarine channel architecture to changes in sediment supply. J Journal of Sedimentary Research 85, 729–753.

King, L.C., 1957. A geomorfologia do Brasil Oriental. Instituto Brasileiro de Geografia e Estatística, Conselho Nacional de Geografia.

Kolla, V., Bourges, P., Urruty, J.-M., Safa, P., 2001. Tertiary sinuous channels architecture. Am. AAPG Bulletin 85, 1373–1405.

Kowsmann, R.O., Oliveira Jr, E.A., Vicalvi, M.A., 2017. Geologia e Geomorfologia da Bacia de Sergipe-Alagoas. Editora Universidade Federal de Sergipe 164–195.

Lastras, G., Canals, M., Urgeles, R., Amblas, D., Ivanov, M., Droz, L., Dennielou, B., Fabrés, J., Schoolmeester, T., Akhmetzhanov, A., Orange, D., García-García, A., 2007. A walk down the Cap de Creus canyon, Northwestern Mediterranean Sea: Recent processes inferred from morphology and sediment bedforms. Marine Geology 246, 176–192.

Lastras, G., Canals, M., Amblas, D., Lavoie, C., Church, I., De Mol, B., Duran, R., Calafat, A.M., Hughes-Clarke, J.E., Smith, C.J., Heussner, S., 2011. Understanding sediment dynamics of two large submarine valleys from seafloor data: Blanes and La Fonera canyons, northwestern Mediterranean Sea. Marine Geology 280, 20–39.

Lea, D.W., Martin, P.A., Pak, D.K., Spero, H.J., 2002. Reconstructing a 350 ky history of sea level using planktonic Mg / Ca and oxygen isotope records from a Cocos Ridge core. Quaternary Science Reviews 21, 283–293.

Lemos Jr, I.C., 2017. Dinâmica sedimentar holocênica no Cânion do São Francisco (Nordeste, Brasil), com base no estudo de foraminíferos e na composição da matéria orgânica. Doctoral thesis. Federal University of Bahia, 88p.

Lima, C.C.U., Bezerra, F.H.R., Nogueira, F.C.C., Maia, R.P., Sousa, M.O.L., 2014. Tectonophysics Quaternary fault control on the coastal sedimentation and morphology of the São Francisco coastal plain, Brazil. Tectonophysics 633, 98–114.

Liu, J.P., Milliman, J.D., Gao, S., Cheng, P., 2004. Holocene development of the Yellow River ' s subaqueous delta , North Yellow Sea. Marine Geology 209, 45–67.

Liu, J.T., Leen, H., 2004. Sediment dynamics in a submarine canyon : a case of river – sea interaction. Marine Geology 207, 55–81.

Mahar, G.A., Zaigham, N.A., 2013. Identification of Temporal Shifting Trends of Submarine Indus Canyon, Pakistan. Journal of Water Resource and Protection 5, 520–528.

Maier, K.L., Fildani, A., Paull, C.K., Timothy, R., 2013. Deep-sea channel evolution and stratigraphic architecture from inception to abandonment from high-resolution Autonomous Underwater Vehicle surveys offshore central California. Sedimentology 60, 935–960.

Mauffrey, M.-A., Urgeles, R., Berné, S., Canning, J., 2017. Development of submarine canyons after the Mid-Pleistocene Transition on the Ebro margin, NW Mediterranean : The role of fluvial connections. Quaternary Science Reviews 158, 77–93.

McAdoo, B.G., Pratson, L.F., Orange, D.L., 2000. Submarine landslide geomorphology, US continental slope. Marine Geology 169, 103–136.

McHargue, T., Pyrcz, M.J., Sullivan, M.D., Clark, J.D., Fildani, a., Romans, B.W., Covault, J. a., Levy, M., Posamentier, H.W., Drinkwater, N.J., 2011. Architecture of turbidite channel systems on the continental slope: Patterns and predictions. Marine and Petroleum Geology 28, 728–743.

Medeiros, P.R.P., Knoppers, B., Júnior, R.C.S., 2007. Aporte Fluvial E Dispersão De Matéria Particulada Em Suspensão Na Zona Costeira Do Rio São Francisco (Se/Al). Geochimica 21, 212 – 231.

Migeon, S., Cattaneo, A., Hassoun, V., Larroque, C., Corradi, N., Fanucci, F., Dano, A., Lepinay, B.M. de, Sage, F., Gorini, C., 2011. Morphology, distribution and origin of recent submarine landslides of the Ligurian Margin (North-western Mediterranean): some insights into geohazard assessment. Marine Geophysical Research 32, 225–243.

Miller, K. G., Kominz, M. A., Browning, J. V., Wright, J. D., Mountain, G. S., Katz, M. E., Sugarman, P, J., Cramer, B.S., Christie-Blick, N., Pekar, S. F., 2005. The Phanerozoic record of global sea-level change. Science 310, 1293-1298.

Mitchell, N.C., 2005. Interpreting long-profiles of canyons in the USA Atlantic continental slope. Marine Geology 214, 75–99.

Mol, L. D, Van Rooij, D., Pirlet, H., Greinert, J., Frank, N., Quemmerais, F., Henriet, J.P., 2011. Cold-water coral habitats in the Penmarc'h and Guilvinec Canyons (Bay of Biscay): Deep-water versus shallow-water settings. Marine Geology 282, 40–52. Mota, A. de A., Grison, F., Kobiyam, M., 2013. Relação entre sinuosidade e índices topográficos na zona topográfica fluvial. Revista Geonorte 9, 42–60.

Normark, W.R., Piper, D.J.W., Romans, B.W., 2009. Submarine canyon and fan systems of the California Continental Borderland. Geol. Soc. Am. Spec. Pap. 454, 141–168.

Oliveira Jr, E.A., Kowsmann, R.O., Schreiner, S., Ferreira, E.T.I., 2017. Geologia e Geomorfologia da Bacia de Sergipe-Alagoas. Editora Universidade Federal de Sergipe. p.98–133.

Oiwane, H., Tonai, S., Kiyokawa, S., Nakamura, Y., Suganuma, Y., Tokuyama, H., 2011. Geomorphological development of the Goto Submarine Canyon, northeastern East China Sea. Marine Geology 288, 49–60.

Peakall, J., Mccaffrey, B., Kneller, B.E.N., 2000. A process model for the evolution, morphology, and architecture of sinuous submarine channels. Journal of Sedimentary Research 70, 434–448.

Petters, S.W., 1984. An ancient submarine canyon in the Oligocene-Miocene of the western Niger Delta. Sedimentology 31, 805–810.

Piper, D.J.W., Cochonat, P., Morrison, M.L., 1999. The sequence of events around the epicenter of the 1929 Grand Banks earthquake: Initiation of debris flows and turbidity currents inferred from sidescan sonar. Sedimentology 46, 79–97.

Piper, D.J.W., and Savoye, B., 1993. Process of late Quaternary turbidity current flow and deposition on the Var deep-sea fan, north-west Mediterranean Sea: Sedimentology 50, 557–582.

Piper, D.J.W., 2005. Late Cenozoic evolution of the continental margin of eastern Canada. Norwegian Journal of Geology 85, 305–318.

Popescu, I., Lericolais, G., Panin, N., Normand, A., Dinu, C., Le Drezen, E., 2004. The Danube submarine canyon (Black Sea): morphology and sedimentary processes. Marine Geology 206, 249–265.

Popescu, I., Lericolais, G., Panin, N., Wong, H.K., Droz, L., 2001. Late Quaternary channel avulsions on the Danube deep-sea fan, Black Sea. Marine Geology 179, 25–37.

Porter-Smith, R., Lyne, V.D., Kloser, R.J., Lucieer, V.L., 2012. Catchment-based classification of Australia's continental slope canyons. Marine Geology 303-306, 183–192.

Posamentier, H.W., 2003. Depositional elements associated with a basin floor channel-levee system: case study from the Gulf of Mexico. Marine and Petroleum Geology 20, 677–690.

Potter, P.E., 1997. The Mesozoic and Cenozoic paleodrainage of South America: a natural history. Journal of South American Earth Sciences 10, 331–344.

Pratson, L.F., Ryan, W.B.F., Mountain, G.S., Twichell, D.C., 1994. Submarine canyon initiation by downslope-eroding sediment flow: Evidence in late Cenozoic strata on the New Jersey continental slope. Geological Society of America Bulletin 106, 395–412.

Pratson, L.F., Coakley, B.J., 1996. A model for the headward erosion of submarine canyons induced by downslope-eroding sediment flows. Bulletin of the Geological Society of America 108, 225–234.

Prins, M.A., Postma, G., Cleveringa, J., Cramp, A., and Kenyon, N.H., 2000, Controls on terrigenous sediment supply to the Arabian Sea during the Quaternary: the Indus Fan. Marine Geology 169, 327–349.

Puga-Bernabéu, Á., Webster, J.M., Beaman, R.J., Guilbaud, V., 2011. Morphology and controls on the evolution of a mixed carbonate-siliciclastic submarine canyon system, Great Barrier Reef margin, north-eastern Australia. Marine Geology 289, 100–116.

Raddatz, J., Rüggeberg, A., Liebetrau, V., Foubert, A., Hathorne, E.C., Fietzke, J., Eisenhauer, A., Dullo, W.C., 2014. Environmental boundary conditions of cold-water coral mound growth over the last 3 million years in the Porcupine Seabight, Northeast Atlantic. Deep Sea Research Part II: Topical Studies in Oceanography 99, 227–236.

Roberts, J.M., Long, D., Wilson, J.B., Mortensen, P.B., Gage, J.D., 2003. The cold-water coral Lophelia pertusa (Scleractinia) and enigmatic seabed mounds along the north-east Atlantic margin: Are they related? Marine Pollution Bulletin 46, 7–20.

Rossetti, D.F., Bezerra, F.H.R., Dominguez, J.M.L., 2013. Earth-Science Reviews Late Oligocene – Miocene transgressions along the equatorial and eastern margins of Brazil. Earth Science Reviews 123, 87–112.

Santos, A.A., Dominguez, J.M.L., Dutra, A.C., 2018. Avaliação de controles estruturais na evolução do delta do rio São Francisco utilizando métodos geofísicos. Master thesis. Federal University of Bahia, 48p.

Schwenk, T., Spieß, V., Hübscher, C., Breitzke, M., 2003. Frequent channel avulsions within the active channel-levee system of the middle Bengal Fan - An exceptional channel-levee development derived from Parasound and Hydrosweep data. Deep-Sea Research Part II: Topical Studies in Oceanography 50, 1023–1045.

Shepard, F.P., 1936. The underlying causes of submarine canyons. Natl. Acad. Sci. Natl. Res. Council Pub. 22, 496–502.

Shepard, F.P., 1972. Submarine canyons. Earth-Science Reviews 8, 1–12.

Shepard, F.P., 1981. Submarine canyons: multiple causes and long-time persistence. AAPG Bulletin 65, 1062–1077.

Shephard, G.E., Muller, R.D., 2010. Miocene drainage reversal of the Amazon River driven by plate-mantle interaction. Nature Geoscience 3, 870–875.

Sobarzo, M., Figueroa, M., Djurfeldt, L., 2001. Upwelling of subsurface water into the rim of the Biobío submarine canyon as a response to surface winds. Continental Shelf Research 21, 279–299.

Sobarzo, M., Djurfeldt, L., 2004. Coastal upwelling process on a continental shelf limited by submarine canyons , Concepción , central Chile. Journal of Geophysical Research 109, 148-227.

Somoza, L., Ercilla, G., Urgorri, V., León, R., Medialdea, T., Paredes, M., Gonzalez, F.J., Nombela, M. A., 2014. Detection and mapping of cold-water coral mounds and living Lophelia reefs in the Galicia Bank, Atlantic NW Iberia margin. Marine Geology 349, 73–90.

Souza, W.F.L., Knoppers, B., 2003. Fluxos de água e sedimentos a costa leste do Brasil: relações entre a tipologia e as pressões antrópicas. Geochimica Brasiliensis 17, 57-74.

Souza-Lima, W., Andrade, E. de J., Bengtson, P., Galm, P.C., 2002. A bacia de Sergipe Alagoas, evolução geológica, estratigrafia e conteúdo fóssil. Fundação Paleontológica Phoenix, Aracaju, 34 pp.

Stow, D. a V, Mayall, M., 2000. Deep-water sedimentary systems: New models for the 21st century. Marine and Petroleum Geology 17, 125–135.

Stramma, L., England, M., 1999. On the water masses and mean circulation of the South Atlantic Ocean. Journal of Geophysical Research 104, 20863–20883.

Stramma, L., Schott, F., 1999. The mean flow field of the tropical Atlantic Ocean. Deep-Sea Research II 46, 279–303.

Su, C., Tseng, J., Hsu, H., Chiang, C., Yu, H., Lin, S., Liu, J.T., 2012. Records of submarine natural hazards off SW Taiwan. Geological Society, London, Special Publications 361, 41–60.

Summerhayes, C.P., Fainsten, R., Ellis, J.P., 1976. Continental margin off Sergipe and Alagoas, northeastern Brazil: a reconnaissance geophysical study of morphology and structure. Marine Geology 20, 345-361.

Sweet, M.L., Blum, M.D., 2016. Connections between fluvial to shallow marine environments and submarine canyons : Implications for sediment transfer to deep water. Journal of Sedimentary Research 86, 1147–1162.

Twichell, D.C., Roberts, D.G., 1982. Morphology, distribution, and development of submarine canyons on the United States Atlantic continental slope between Hudson arid Baltimore Canyons. Geology 10, 408–412.

Walsh, J.P. and Nittrouer, C.A., 2009. Understanding fine-grained river-sediment dispersal on continental margins. Marine Geology, 263, 34-45.

Weber, M.E., Wiedicke, M.H., KudrasS, H.R., Hubscher, C., and Erlenkeuser, H., 1997, Active growth of the Bengal Fan during sea-level rise and highstand. Geology 25, 315–318.

CAPÍTULO 3
CONCLUSÕES

Esse estudo apresentou resultados de dados de batimetria multifeixe coletados ao longo do Cânion do São Francisco (CSF) e talude adjacente e sua integração com dados de sísmica 3D na cabeceira do cânion. Diferentes tipos de cânions exibindo diferentes graus de maturidade foram mapeados na região. O CSF apresenta-se como único cânion na margem continental do Brasil que é profundamente inciso na plataforma e apresenta direta conexão com um sistema fluvial. Ele apresenta alto grau de meandramento possivelmente devido a essa relação. O CSF moderno foi escavado sobre cânion mais antigo, já preenchido, representando um episódio de reincisão, talvez associado com a queda do nível do mar desde os níveis de mar alto do Mioceno Médio. É hipotetizado que a incisão do CSF moderno se deu durante o final do Mioceno – Plioceno. A agradação/progradação da plataforma externa corbonática deu origem a depressão batimétrica ao redor da cabeceira do cânion, possivelmente realçado por reativações neotectônicas. Essa depressão ajudou a trapear e afunilar sedimentos fluviais para o oceano profundo, o que aparenta ser um dos fatores mais importantes induzindo a continua conexão e incisão durante o Quaternário, com a geração de diversos terraços e diques marginais. Durante a maior parte do Quaternário a plataforma estava exposta a condições subaéreas com o rio desaguando diretamente ou perto da cabeceira do cânion. Sedimentos fluviais mais finos eram controlados por correntes de contorno fluindo para nordeste ao longo da porção superior do talude continental. Esse processo gerou diferentes marcas morfológicas no talude superior nas porções a nordeste e sudoeste do CSF, afetando o grau de maturidade de cânions submarinos, distribuição de *mounds* e *pockmarcks* e profundidade dos interflúvios entre cânions. Durante momentos de nível de mar alto, com afogamento da plataforma, sedimentos fluviais finos são transportados principalmente para sudoeste pela corrente costeira gerada pelos ventos predominantes. A presença de uma pequena incisão axial e crescentes formas de leito na porção superior do cânion sugere um fornecimento direto de sedimentos para o cânion pela lamosa clinoforma deltaica que atualmente alcança a cabeceira do cânion, mesmo durante nível de mar alto.

ANEXO A
REGRAS DE FORMATAÇÃO DA REVISTA

REVISTA: MARINE GEOLOGY

PREPARATION
Formatting requirements
There are no strict formatting requirements but all manuscripts must contain the essential elements needed to convey your manuscript, for example Abstract, Keywords, Introduction, Materials and Methods, Results, Conclusions, Artwork and Tables with Captions.
If your article includes any Videos and/or other Supplementary material, this should be included in your initial submission for peer review purposes.
Divide the article into clearly defined sections. Please ensure the text of your paper is double-spaced this is an essential peer review requirement. Please ensure your paper has consecutive line numbering this is an essential peer review requirement.
Please ensure your paper includes page numbers this is an essential peer review requirement.

Reference style
All citations in the text should refer to:
1. Single author: the author's name (without initials, unless there is ambiguity) and the year of publication;
2. Two authors: both authors' names and the year of publication;
3. Three or more authors: first author's name followed by "et al." and the year of publication.
Citations may be made directly (or parenthetically). Groups of references should be listed first chronologically, then alphabetically.
List: References should be arranged first alphabetically and then further sorted chronologically if necessary. More than one reference from the same author(s) in the same year must be identified by the letters "a", "b", "c", etc., placed after the year of publication.
Examples:
Reference to a journal publication:
Van der Geer, J., Hanraads, J.A.J., Lupton, R.A., 2000. The art of writing a scientific article. Journal of Scientific Communication 163, 51-59.
Reference to a book:
Strunk Jr., W., White, E.B., 1979. The Elements of Style, third ed. Macmillan, New York.
Reference to a chapter in an edited book:
Mettam, G.R., Adams, L.B., 1999. How to prepare an electronic version of your article, in: Jones, B.S., Smith , R.Z. (Eds.), Introduction to the Electronic Age. E-Publishing Inc., New York, pp. 281-304.