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FORMAÇÃO DE SHELF VALLEYS NA PLATAFORMA CONTINENTAL SUL DE PERNAMBUCO

Recife
2020

LUIS FELIPE DE MELO TASSINARI

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Dissertação apresentada ao Programa de Pós-Graduação em Oceanografia da Universidade Federal de Pernambuco, como um dos requisitos para a obtenção do título de Mestre em Oceanografia.

Área de concentração: Oceanografia Abiótica.

Orientadora: Prof.ª Dr.ª Tereza Cristina Medeiros de Araújo.

Coorientador: Prof. Dr. José Antônio Barbosa.

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"Às vezes a ciência é mais arte do que
ciência [...] Sou cientista; porque invento,
transformo, crio e destruo para viver, e
quando não gosto de algo no mundo, mudo".
Rick and Morty (2017).

RESUMO

Shelf Valleys (SV) representam vales escavados em plataforma a partir da erosão glacial e pela ocupação de sistemas fluviais durante eventos de queda do nível relativo do mar, sendo que a maior parte dos registros compreende o Pleistoceno. SV são feições geomorfológicas importantes para processos marinhos bióticos e abióticos, com pelo menos dez metros de profundidade e atingindo até 10 km de comprimento. Neste trabalho são apresentados novos dados sobre SV na região de plataforma média e profunda da bacia marginal de Pernambuco, NE, Brasil. A dissertação foi composta por dois artigos: o primeiro de cunho regional, cobriu cerca de 5.000 km^2, e o segundo focado em aspectos geomorfológicos e estruturais sobre uma área de 600 km^2. A abordagem da pesquisa incluiu a análise de dados de sísmica de reflexão providos pela indústria do petróleo, (seções 2D migradas em tempo, e magnetometria), que recobrem a região de interesse, e que foram úteis para a identificação e caracterização dos SV. Também foram utilizados dados de satélite, além de dados de batimetria obtidos por equipamento single Beam. O primeiro artigo traz o mapeamento de estruturas com formato de Canal (SV) em seções sísmicas, que foram comparadas e integradas usando imagens de satélite e levantamentos batimétricos. Foram mapeados então 14 SV, representando um aumento em mais de 70% do número de estruturas dessa natureza conhecidos na região. O mapeamento multi-data também permitiu estabelecer relação entre os rios atuais com a existência de incisões fluviais do Pleistoceno na plataforma continental. O segundo artigo tratou da integração entre os dados batimétricos, sísmicos e aeromagnéticos (arcabouço tectônico), o que permitiu a obtenção de informações sobre o processo de formação de alguns SV estudados. Foi possível estabelecer que os SV se formaram sobre falhas/fraturas formadas pelo processo de reativação/propagação de falhas do embasamento que se formaram originalmente durante o processo de abertura do Oceano Atlântico Sul Central. Também se comprovou que a geometria dos SV foi controlada pela relação entre os dois grupos de estruturas regionais que permitiram a abertura da bacia: zonas de cisalhamento Pré-Cambrianas e falhas de transferencia idade Cretácicas. O estudo aponta ainda, que a integração de dados de diferentes escalas de observação, incluindo dados regionais obtidos para a prospecção de hidrocarbonetos, podem ser utilizados para o mapeamento e a caracterização de SVs em plataformas continentais.

Palavras-chave: Shelf Valleys. Pleistoceno-Holoceno. Dados sísmicos regionais 2D. Bacia de Pernambuco. Plataformas continentais tropicais.

ABSTRACT

Shelf Valleys (SV) are formed by glacial erosion and by the occupation of fluvial system over continental shelves during events of sea-level fall, mainly during the Pleistocene. SV are channel-like structures with ten meters of depth into the continental shelf and at least 10 km in length. SV are important morphological features for biotic and non-biotic marine processes. In this work, new data on SV are presented in the middle and deep Shelf region of the Pernambuco marginal basin, NE, Brazil. Two articles conpounded the dissertation: the first of a regional nature, covering about 5,000 km^2, and the second is focused on geomorphological and structural aspects over an area of approximately 600 km^2. The research approach included the analysis of reflection seismic data provided by the petroleum industry (time-migrated 2D sections, and aeromagnetic surveys) covering the region of interest that were useful for the identification and characterization of the SV. Satellite data and bathymetry data obtained by single Beam equipment were also used. The first article brings the mapping of Channel-shaped (SV) structures into seismic sections, which were compared and integrated using satellite images and bathymetric surveys. This integration allowed the mapping of 14 SV, representing an increase of over 70% in the number of known structures of this nature in the region. The multi-date mapping also allowed establishing a relationship between the current rivers and the existence of Pleistocene fluvial incisions in the continental shelf. The second article dealt with the integration between bathymetric, seismic and aeromagnetic data (tectonic framework), which allowed obtaining information about the formation process of some studied SV. It was possible to establish that the VS formed on faults/fractures formed by the reactivation/propagation process of the basement faults that originally formed during the opening process of the Central South Atlantic Ocean. It was also proved that the geometry of the SV was controlled by the relationship between the two groups of regional structures that allowed the opening of the basin: Precambrian shear zones and Cretaceous transfer failures. The study suggests that integrating data from different observation scales, including regional data obtained for hydrocarbon prospecting, can be used for mapping and characterization of SVs on continental shelves.

Keyword: Shelf Valleys. Pleistocene-Holocene. 2D regional seismic data. Pernambuco Basin. Tropical continental shelves.

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1 INTRODUÇÃO

Uma plataforma continental é definida como "uma zona adjacente a um continente e que se estende da linha de baixa-mar a uma profundidade onde, normalmente, há um acentuado aumento de declividade em direção às profundezas oceânicas"(Iho, 2008).

De acordo com Harris e Whiteway (2011), shelf valleys são incisões feitas na plataforma continental com profundidades entre 10 e 120 metros. Em sua maioria são formados em grandes glaciações, quando o nível do mar cai drasticamente expondo a plataforma continental a ações de rios e drenagens (Dalrymple, 2006; Blum *et al.*, 2013).

Os levantamentos acerca dos processos atuais e pretéritos em plataformas continentais requerem a integração de conhecimentos de diferentes áreas, como por exemplo da Geologia, Geofísica e Oceanografia, visto que as diferentes informações são complementares por natureza (Boyer e Mari, 1997). A Geofísica desempenha um papel essencial em estudos offshore, através do uso de técnicas de obtenção de dados de forma indireta.

A Plataforma Continental de Pernambuco (PCPE) ainda é uma área da margem continental brasileira que apresenta poucos levantamentos geofísicos disponíveis para o mapeamento geomorfológico do fundo. Tal lacuna no conhecimento, acerca da geologia do arcabouço da região *offshore* desta região plataformal, representa uma oportunidade para realização de pesquisas voltadas para temas ainda não previamente tratados.

Investigações sobre o arcabouço geológico e sismoestratigráfico nessa região são evidentemente importantes, em um contexto de exploração econômica de recursos minerais e naturais na superfície e subsuperfície, bem como em um contexto de conservação. Portanto, um estudo mais aprofundado das feições presentes em sua plataforma continental, como por exemplo, a presença de *shelf Valleys* (SV), se faz necessário para o melhor entendimento de processos oceanográficos atuantes.

Embora a ocorrência de SVs seja mais comum em ambientes quase glaciais (Hambrey e Dowdeswell, 1994), elas também ocorrem em todos os continentes, nas margens continentais passivas e ativas (Harris *et al.*, 2014). A identificação e o mapeamento dos Shelf Valleys são de fundamental importância devido à influência direta nos processos oceanográficos / geológicos (Zhang e Lentz, 2017; 2018) e nos sistemas bióticos (Barrett *et al.*, 2010; Nichol *et al.*, 2013).

1.1 SHELF VALLEYS

Shelf valleys geralmente resultam de rios que passam a escavar a plataforma em resposta a uma queda no nível do mar. O vale formado por sistemas fluviais, que estendem seus canais em direção à bacia e se erodem em camadas subjacentes em resposta a uma queda relativa no nível do mar, e que permanecem expostos, não foram totalmente preenchidos em eventos transgressivos posteriores, são chamados de shelf valleys. Estas feições apresentam de 10 a 120 metros de profundidade (Harris e Whiteway, 2011; Harris *et al.*, 2014).

É importante ressaltar que, geralmente a medida que o nível do mar sobe, os sedimentos podem preencher totalmente os shelf valleys formando vales incisos, ou seja, formam corpos alongados alongados preenchidos com sedimentos, perpendiculares a costa (Harris *et al.*, 2005; Dalrymple, 2006; Blum *et al.*, 2013).

1.2 CONTEXTO GEOLÓGICO DA ÁREA

A área de estudo está localizada na Plataforma Continental Sul de Pernambuco, sendo está inserida no domínio da Bacia Pernambuco (Buarque *et al.*, 2017). O embasamento na região da quebra da plataforma é marcado por um alto estrutural posicionado de forma paralela a linha de costa, o Alto Maracatu. As principais estruturas que controlaram a evolução da Bacia de Pernambuco são as zonas de cisalhamento pré-cambrianas dúcteis, que possuem orientação principal NE-SW e E-W, na porção ao norte, e NW-SE na região mais ao sul da bacia (Buarque *et al.*, 2016; Correia Filho *et al.*, 2019).

Algumas zonas da plataforma continental interna e média, adjacentes à faixa costeira da bacia, estão sujeitas a descarga continental de pelo menos quatro rios (Capibaribe, Una, Ipojuca e Sirinhaém), com a presença de estuários e formação de canais de maré (Camargo *et al.*, 2015). Em períodos de regressão marinha, onde houve a exposição subaérea da plataforma continental, a rede hidrográfica expandiu sua área de drenagem continental, resultando na ação erosiva da região plataformal das bacias sedimentares marginais (Camargo *et al.*, 2015), como exemplificado pela presença de shelf valleys.

A cobertura sedimentar recente é dominada por sedimentos compostos por areia e cascalhos bioclasticos, principalmente constituídos de algas calcárias (Camargo, 2016). Essas características normalmente são encontradas em plataformas continentais tropicais, que apresentam escassez de sedimentos terrígenos (Manso *et al.*, 2003; Araújo *et al.*, 2004; Camargo *et al.*, 2015)

Nesta região, as irregularidades no relevo marinho estão relacionadas a ocorrências das seguintes feições topográficas: beachrocks, terraços, shelf valleys, ravinas e cânions submersos (Camargo, 2016; Goes *et al.*, 2019).

1.3 VARIAÇÕES DO NÍVEL DO MAR NA PCPE

Vários trabalhos têm tratado o registro da variação do nível relativo do mar durante o Holoceno. A proposta mais aceita é que a 1 milhão de anos, a profundidade do nível do mar era de 62 metros abaixo do nível atual (Lea *et al.*, 2002; Waelbroeck *et al.*, 2002), o que significa que a PCPE foi exposta a processos subaéreos. Vale a pena ressaltar que nos últimos 2,58 milhões de anos, o nível relativo do mar variou muito em todo o mundo, expondo e submergindo a PCPE, por exemplo. No entanto, estudos de variações dos níveis relativos do mar neste período que envolve o Quaternário, para esta região de estudo, ainda são escassos.

Por outro lado, modelos paleogeográficos produzidos a partir de uma escala de tempo mais recente, mostram que no último período de 120 mil anos, o nível do mar estava aproximadamente na mesma posição que atual (Camargo, 2016). Além disso, provavelmente, a plataforma nesta época apresentava as mesmas características atuais, faminta, rasa e quente. Há cerca de 80 mil anos uma regressão marinha levou a uma queda do nível relativo do mar que produziu um rebaixamento do nível relativo do mar cerca de 40 metros, ocasionando assim a exposição parcial da plataforma continental.

Após 25 mil anos o período de regressão marinha teve seu ápice e infere-se que o nível relativo do mar ficou abaixo da profundidade de 60 metros (Hanebuth *et al.*, 2003), o que, novamente, expôs completamente a PCPE aos processos erosivos subaéreos, assim. É possível que neste período, principalmente ocorreu a formação dos shelf valleys estudados por esta pesquisa, devido a ação das drenagens existentes neste período (Camargo, 2016).

De acordo com Cohen e Gibbard (2019) em sua tabela de correlação cronoestratigráfica global, foram muito bem definidas sete grandes períodos de regreção do nível do mar nos últimos 621 mil anos. Chamadas de terminações, que expuseram toda nossa plataforma continental e ocasionaram uma situação ótima para rios a erodirem, gerando assim os Shelf Valleys aqui estudados. A 7 terminações compiladas por Cohen e Gibbard (2019) são:

1- Terminação I a 14 000 anos
2- Terminação II a 130 000 anos
3- Terminação III a 243 000 anos

4- Terminação IV a 337 000 anos

5- Terminação V a 424 000 anos

6- Terminação VI a 533 000 anos

7- Terminação VII a 621 000 anos

Todas a terminações aqui mencionadas possuem uma periodicidade de aproximadamente 100 mil anos oque corrobora com a teoria proposta por Milankovitch (Schwarzacher, 1993) que devido a excentricidade orbital da Terra espera-se uma grande era glacial a cada 100 mil anos (Berger, 2013). Tal fato aumentaria exponencialmente o numero de períodos em que a plataforma continental de Pernambuco estaria esposta a erosão subaérea e consequente gênese ou retrabalhamento de shelf valleys ao longo da mesma.

1.4 GEOMORFOLOGIA DA PCPE

Alguns estudos locais descreveram as características geomorfológicas do relevo da área de estudo. Sendo encontrados beachrocks (Ferreira Jr et al., 2013), terraços, Shelf Valleys (Camargo et al., 2015) e pináculos locais (Goes et al., 2019). Lucatelli *et al.* (2019) demonstrou em um estudo regional em toda costa pernambucana através de processamento de dados batimétricos que a plataforma que continental é predominantemente plana, estreita e com baixo gradiente. O declive da plataforma possuí média inferior a 0,1°. As partes norte e sul da plataforma continental têm uma largura média de 38 km, enquanto a parte central é um pouco mais estreita, chegando a 33 km de largura. A borda da plataforma continental corre quase paralela à costa e onde o talude se inicia a uma profundidade de cerca de 60 a 65 m.

A plataforma continental pernambucana é um reflexo do baixo aporte sedimentar continental (Goes *et al.*, 2019) e tectonismo (Vital *et al.*, 2005), bem como da baixa taxa de erosão terrestre e sedimentação marinha (Manso *et al.*, 2003), ao passo que sua profundidade superficial é relacionada à ineficiência dos processos marinhos nos últimos períodos geológicos (Araújo *et al.*, 2004).

1.5 REFERENCIAL TEÓRICO GEOFÍSICO

Os resultados obtidos por levantamentos geofísicos permitem avaliar aspectos geológicos e geomorfológicos de subsuperfície em diferentes escalas, principalmente na aplicação a redução do risco exploratório de recursos minerais e de entendimento do tipo de fundo auxiliando na navegação, por exemplo (Harris e Whiteway, 2011; Picard *et al.*, 2018).

1.4.1 Batimetria monofeixe

A Batimetria monofeixe, ou Single Beam, é o método geofísico mais tradicional para medir a profundidade da coluna d’agua em oceanos, lagos, rios e etc. Ecobatimetros são os equipamentos utilizados para efetuar tal levantamento. Utilizando-se da emissão de sinais sonoros pontuais que percorrem a coluna d’agua atinge o fundo e retorna ao equipamento assim inferindo a profundidade no local abaixo do transdutor (Keen, 2017).

1.4.2 Sísmica de reflexão

O método geofísico de reflexão sísmica é capaz de delimitar diferentes litologias, a partir dos contrastes de impedância acústica. Quando um pulso sísmico incide sobre uma interface definida pelo contraste de impedâncias acústicas, uma fração da energia deste pulso é refletida de volta à superfície (Veeken, 2006). A quantidade de energia que é refletida ou, em outras palavras, a amplitude que retorna à superfície, é determinada pelo coeficiente de reflexão e podem ser calculadas pelas equações de Zoeppritz (Sheriff, 2002). Os geofones ou hidrofones então registram uma série de pulsos refletidos, que chegam com tempo de percurso determinados pela profundidade das interfaces e pelas velocidades de propagação da onda sísmica, em cada uma delas. Por fim, os dados de reflexão sísmica são exibidos como registros consistindo de inúmeros traços sísmicos (Gadallah e Fisher, 2009).

Reynolds (2011) aponta que o problema principal da sísmica de reflexão é a conversão dos dados medidos em tempo de percurso, para profundidade. Isso exige necessariamente informações a respeito das velocidades sísmicas em subsuperfície. Por essa razão, boa parte dos esforços realizados no processamento sísmico envolvem análises para um melhor entendimento desse parâmetro (Yilmaz, 1987; Yilmaz, 2001). Neste trabalho, o principal desafio será direcionado às etapas do processamento sísmico, como a análise de velocidades para a inversão, que permitem a conversão de dados sísmicos no domínio do tempo para o domínio do espaço obtendo-se noções de profundidade e posterior interpretação das feições de subsuperfície.

Essa técnica surgiu a partir da demanda gerada e impulsionada pela indústria petrolífera que possuía a necessidade de uma metodologia mais eficaz para interpretação de seções sísmicas, surgindo assim a Sismo estratigrafia (Payton, 1977). A mesma se desenvolveu como um método interdisciplinar, que reúne os processos autogênicos (gerados dentro do sistema) e halogênicos (gerados fora do sistema), em um modelo unificado para elucidar a arquitetura e evolução estratigráfica de bacias sedimentares (Miall e Postma, 1997; Miall, 2013).

1.4.3 Magnetometria

A magnetometria é uma técnica que utiliza a informação do campo magnético terrestre para a investigação das estruturas em subsuperfície considerando alterações na amplitude do campo magnético (CM) terrestre associadas à variação da concentração de minerais ferromagnéticos contidos nas rochas (Blakely, 1996).

A interpretação de dados magnéticos é muito utilizada no delineamento do arcabouço estrutural de bacias e, sobretudo, na exploração mineral (Blakely, 1996). O processamento desses dados permite ainda a estimativa de profundidade das fontes associadas a estas feições, mesmo que encobertas por uma camada sedimentar. Assim, tais técnicas constituem ferramentas importantes na construção de modelos geológico-geofísicos.

2 OBJETIVOS

Os objetivos consistem em um objetivo geral e quatro objetivos específicos descritos abaixo

2.1 OBJETIVO GERAL

O principal objetivo desta pesquisa é realizar uma integração de dados de superfície com dados de subsuperfície, para uma melhor compreensão da influência de estruturas de subsuperfície na formação de “shelf valleys” na região da plataforma continental sul de Pernambuco.

2.2 OBJETIVOS ESPECÍFICOS

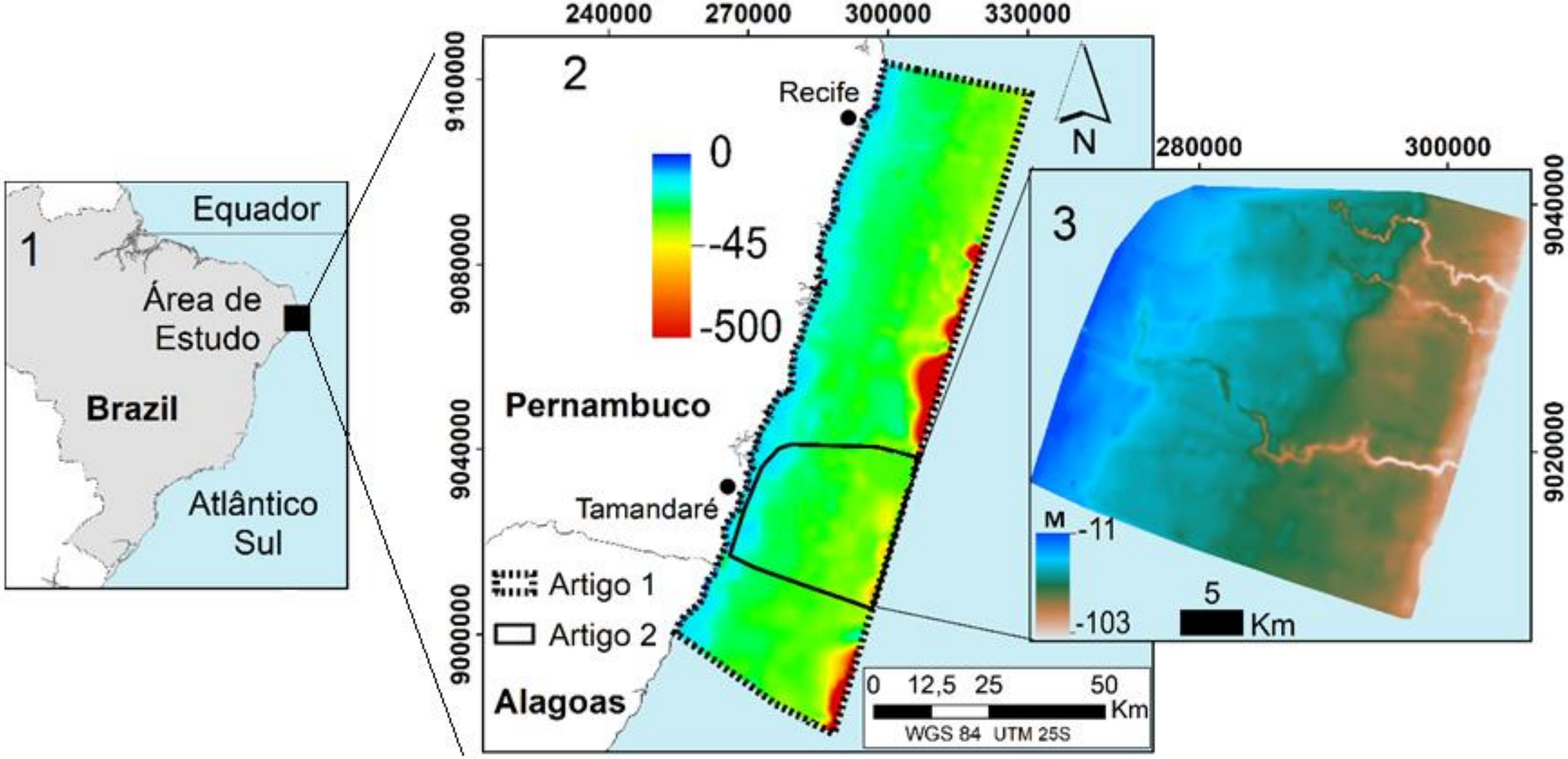
Os objetivos específicos consistem em:

- Caracterizar as feições geomórficas através de dados batimétricos existentes, bem como aqueles extraídos das seções sísmicas 2D.
- Investigar se há algum controle tectônico na formação dos shelf Valleys.
- Compreender como se deu a evolução dos mesmos durante o Quaternário.
- Investigar incisões ligadas a existência de Shelf Valleys na plataforma adjacente à Pernambuco.

3 ÁREA DE ESTUDO

A área do estudo em ambos artigos apresentados está inserida predominantemente na bacia de Pernambuco na PCPE (Fig. 1-1 Quadrado preto), envolvendo, as plataformas interna, média e externa, além da parte superior do talude continental. O primeiro artigo envolve uma área aproximada de 5,000 km² (Fig. 1-2 pontilhado), abrangendo do norte de Recife ao norte de Alagoas da linha do litoral até a quebra da plataforma. O segundo artigo foi focado na região sul de Pernambuco nas proximidades da cidade Tamandaré (Fig. 1 -3). Mostrando os três Shelf Valleys estudados neste artigo.

Figura 1) 1-Localização da área de estudo. 2) Detalhe da área de estudo nos domínios rasos da plataforma continental da Bacia de Pernambuco - Estado de Pernambuco (Fonte de dados batimétricos: Banco de dados GEBCO Weatherall *et al.* (2015). 3) Zoom na área de estudo do segundo artigo como dados batimétricos apresentando os três Shelf Valleys Mapeados.



Fonte: Tassinari 2020

4 ESTRUTURA DA DISSERTAÇÃO

Esta dissertação é composta de quatro capítulos, sendo o primeiro uma introdução com um breve referencial teórico, objetivos e área de estudo.

O segundo e terceiro capítulos correspondem aos resultados da mesma, sendo apresentados na forma de dois artigos independentes.

O quarto capitulo refere-se às considerações finais da dissertação.

5 RESULTADOS

Os artigos resultados são: Artigo I: "***Integrated Geophysical tools for characterization and mapping of Quaternary shelf valleys in the continental shelf of Pernambuco Basin, NE Brazil***". Este capítulo foi submetido para e está formatado de acordo com as normas do periódico "***Marine Geology***" ISSN: 0025-3227

Este capítulo trata da aplicação de um método baseado na integração de dados regionais, fornecidos por imagem de satélite (Landsat), levantamentos batimétricos (Single Beam) e seções sísmicas 2D (herdadas da indústria petrolífera), para mapear e caracterizar Shelf Valleys na plataforma continental da bacia de Pernambuco.

Artigo II: "***Neotectonics control on the Shelf Valleys formation in the Southern sector of continental shelf of Pernambuco- Brazil***". Este capítulo está formatado de acordo com as normas do periódico "***Regional Studies in Marine Science***" ISSN: 2352-4855

Este artigo visa verificar a existência de controle tectônico em três Shelf Valeys para os quais já existem dados batimétricos coletados. A metodologia adotada tratou da integração entre os dados batimétricos existentes, dados sísmicos e aeromagnéticos, com o objetivo de construir um melhor entendimento sobre o processo de formação destes.

5.1 INTEGRATED GEOPHYSICAL TOOLS FOR CHARACTERIZATION AND MAPPING OF QUATERNARY SHELF VALLEYS IN THE CONTINENTAL SHELF OF PERNAMBUCO BASIN, NE BRAZIL

Highlights

- Integration of seismic and non-seismic data used for the mapping of Quaternary shelf valleys
- The method allowed to identify 14 complete and 6 possible parts of Shelf Valleys formed during the last Neogene sea-level fluctuation
- It can be extrapolated that the valleys are being excavated since the Middle Miocene.
- The integration allowed to find the connection between Modernrivers and the Shelf Valleys

Abstract

Shelf valleys (SV) are formed by glacial erosion and by the occupation of fluvial systems over continental shelves during events of sea-level fall, mainly during the Pleistocene. SV are channel-like structures with 10 (ten) meters of depth into the continental shelf and at least 10km in length. SV are important morphological features for biotic and non-biotic marine processes. This paper presents a method based on integrating regional data, provided by satellite imagery (Landsat), bathymetric surveys, and regional 2D seismic sections, to map and characterize shelf valleys. The applied method uses oil-industry legacy datasets (2D seismic reflection surveys), available for the Brazilian continental shelf, to help the mapping of shallow marine morphological features. Therefore, re-utilizing legacy data for new information. The study area is in the offshore portion of the Pernambuco marginal basin, NE Brazil. The study area has approximately 5,000 km^2; although the water depth in this region varied from 0 to -500m, the SV mapping was limited to the shelf break depth in the region (approximately -65m). The mapping of Channel-like structures was compared and integrated using satellite images, bathymetric and seismic surveys. The interpretation of seismic data allowed the identification of incision structures, which remained, unfilled, or partially filled, during recent times. Integrating information on incision features found in subsurface data and mapped features on the seafloor showed a definite correlation which corroborated to the existence of Pleistocene-Recent fluvial incisions in the continental shelf. The correlation also allowed expansion of the identification to the parts of the study area not covered by detailed bathymetric data. The innovative method allowed the mapping of 14 shelf valleys (over 10 km in length) and 6 possible SV connections (less than 10 km in length). These numbers represent an increase on more than 70% of the mapped shelf valleys in the region, taking into consideration what other works and the international bathymetric database (GEBCO) previously identified. It showed that the method, based on the existent legacy seismic industry database, is affordable and reliable and could help to refine the mapping of these important structures. Therefore, aiding decision-makers optimizing management plans for the conservation of areas on the valleys nearby areas.

Keywords

Shelf Valleys, Pleistocene-Holocene, sea-level variations, regional 2D seismic data, Pernambuco Basin, tropical continental shelves

Introduction

Shelf Valleys (SV) represent incised valleys formed by the progradation of fluvial systems over the continental shelf, during periods of sea-level falls (regression) (Harris e Whiteway, 2011). These structures are frequently formed during the Pleistocene due to glacial-interglacial processes that driven to regressive events and consequent low stand periods, which directly affect continental shelves. SVs can be considered geomorphological features on the seafloor with a channel-like morphology (previous fluvial systems), which remained partially filled with sediments. They were drought and partially filled during the last transgression, caused by the interglacial onset (15.000 years BP) (Hanebuth *et al.*, 2003; Angulo *et al.*, 2006; Compton, 2011). In general, is accepted that SV present at least 10 km length and no more than 120 meters in depth (Harris *et al.*, 2014). Although the occurrence of SVs is more common in near glacial environments (Hambrey e Dowdeswell, 1994), they also occur in all continents, in passive and active continental margins (Fig. 1) (Harris *et al.*, 2014). The identification and mapping of Shelf Valleys are of fundamental importance because of the direct influence in oceanographic/geological processes (Zhang e Lentz, 2017; 2018), and in biotic systems (Barrett *et al.*, 2010; Nichol *et al.*, 2013).

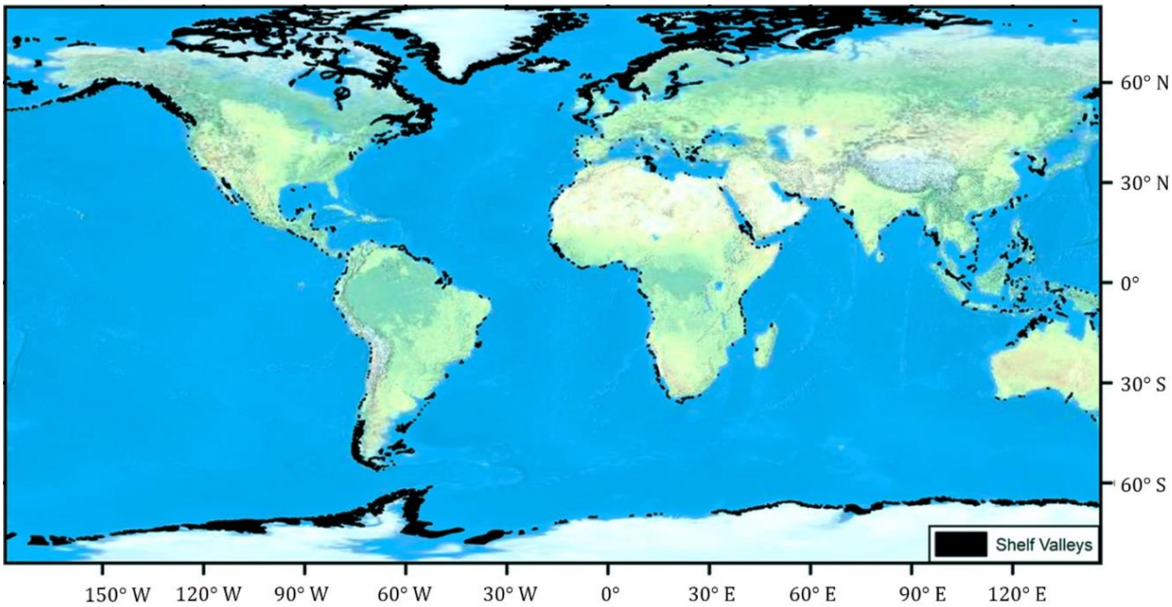


Figure 1 - Distribution of Shelf Valleys in continental shelves of the World. Shelf valleys data from Harris *et al.* (2014). Although there is an abundance in periglacial regions, occurrence in continental shelves in tropical areas are also common.

The study area (Fig. 2) is in the Northeastern Brazilian continental shelf and it is part of the offshore Pernambuco Basin domains. The study area presents 5,000 km^2, the depth varied mostly from 0 to -60 meters with deeper areas after the shelf break. The study focuses the inner, middle, outer continental shelf and the Shelf break. Due to low spatial resolution, no SVs can be detected in geomorphological maps using the available GEBCO database, such as the global map of oceans compiled by Harris et al. (2014). (Fig. 2). Neither on other regional bathymetric surveys available such as the Brazilian Navy nautical maps. However, Camargo *et al.* (2015) mapped one SV on the study area which will be discussed later.

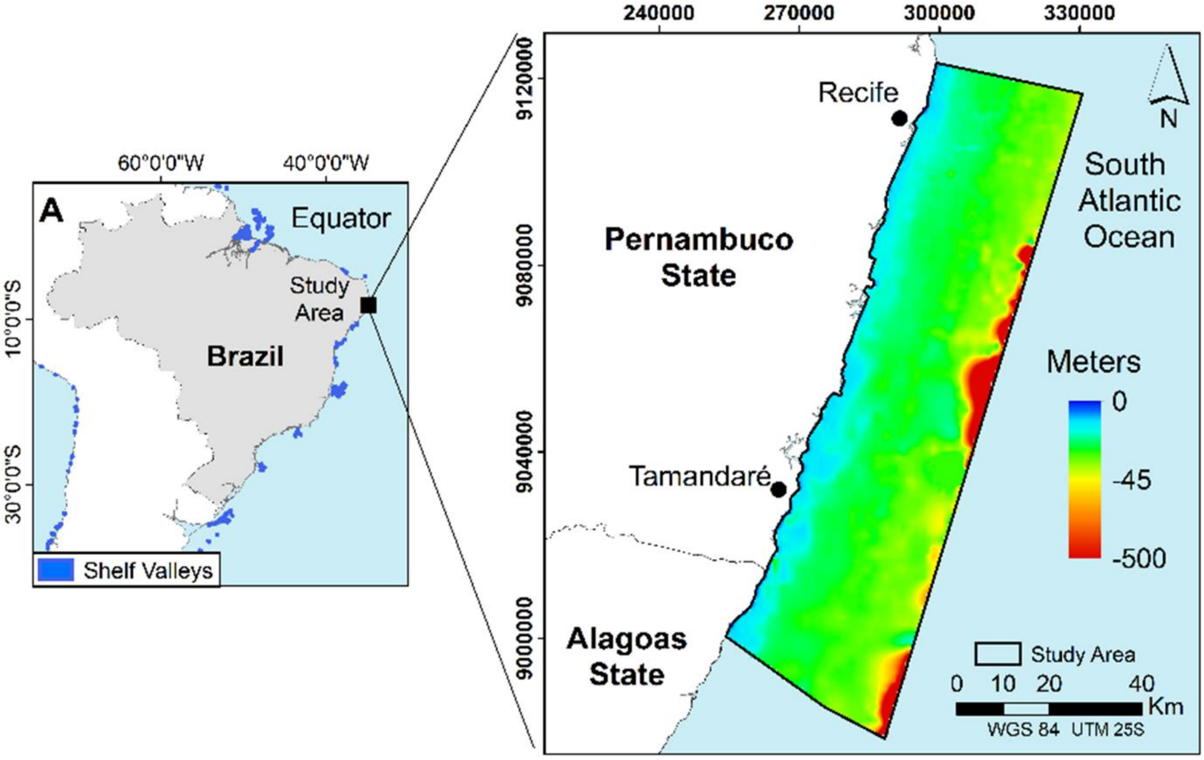


Figure 2 - A) Detail of SV mapped by Harris *et al.* (2014) in the Brazilian Atlantic margin (blue areas). The black square shows the location of the study area, which covered mostly a region from the littoral line to the shelf break. B) Detail of study area in the shallow domains of the continental shelf of Pernambuco Basin - Pernambuco State. Bathymetric data source: GEBCO Database (Weatherall *et al.*, 2015)

According to Kempf (1970), Manso *et al.* (2003), and Araújo *et al.* (2004), the present-day sediments that cover the study area are composed of biogenic carbonatic grains. Araújo *et al.* (2004) show that the Pernambuco Basin continental shelf has an average width of 33,28 kilometers to the shelf break, with an average depth of 60 meters to start the continental slope. Consequently, the continental shelf on the study area has a slope, of 0,18 % (for every 100 meters the continental shelf sinks 18 centimeters). With warm high-salinity waters this area represents a present-day sediment-starved tropical continental shelf (Manso *et al.*, 2003; Araújo *et al.*, 2004).

The relative Sea level was 62 meters below the present-day position one million years ago (Lea et al., 2002; Waelbroeck et al., 2002). This means that the study area was exposed to subaerial erosion, being below Sea level during this period. About 110,000 years ago the Sea level reached a maximum low and it was again positioned 60 meters below the present-day (Hanebuth *et al.*, 2003), so the study area was completely exposed to subaerial erosive processes, controlled by the pro-gradation of fluvial systems, which probably influenced the formation/rejuvenation of shelf valleys.

There is a lack of data for the study area, of normally applied methods to mapping underwater geomorphic features like SVs, such as multi-Beam and single Beam bathymetry or even shallow seismic reflection surveys (Picard *et al.*, 2018). Thus, the main objective of this study was to integrate bathymetric data that covers a small portion of the study area, with satellite imagery, to validate interpretation from regional 2D seismic sections (oil-industry legacy), mapping SVs in the continental shelf of Pernambuco Basin. The deep seismic sections seeking for the identification of shallow features associated with SVs, and the interpretation allowed to corroborate the incisions associated with the SVs in the recent deposits. The method represents an alternative approach to the identification and characterization of SVs in the Brazilian continental shelf.

Regional setting

The main structures that controlled the evolution of the Pernambuco Basin are the ductile pre-Cambrian shear zones, which have a main NE-SW and E-W orientation, in the northern portion, and NW-SE in the most southern region of the basin (Buarque *et al.*, 2017). Transfer faults formed during the rift show an NW-SE trend, and normal faults associated with the rift process shows an N-S and NNW-SSE trend. The coastal basin is bounded to the South by the Maragogi-Barreiros High, and to the north by the Pernambuco Shear Zone (Buarque *et al.*, 2017). The proximal region of the offshore domains of Pernambuco Basin is characterized by an elongated basement outer high which is positioned parallel to the coastline, trending almost N-S, named Maracatu High (Buarque *et al.*, 2016). The main drainage basins in the emerged adjacent area being formed within the coastal basin; they represent small fluvial basins which drainage systems were controlled by tectonic features (Bezerra *et al.*, 2014).

The present-day sedimentary cover of the continental shelf composition is of carbonatic grains of biogenic origin mainly consisting of calcareous algae remains (Manso *et al.*, 2003; Araújo *et al.*, 2004). These features are usually found in tropical continental shelves with a small input of terrigenous sediments (Meek et al. 2003; Camargo et al., 2015). Few studies had previously described geomorphologic features in surface relief of study area: Beachrocks (Ferreira Jr *et al.*, 2013), terraces, shelf valley (Camargo *et al.*, 2015), and local pinnacles (Goes *et al.*, 2019).

Materials and Methods

The basis of this methodology is to integrate different kinds of geophysical methods to map Shelf valleys (Fig. 3). However, on this work the detection of SVs has as the main method the interpretation of 2D seismic sections, to infer incisions caused by ancient rivers on the continental shelf. The secondary methods used to support the seismic interpretation were single-Beam bathymetry and Landsat imagery to check if the mapped seafloor morphology is a candidate to be an SV. The integration showing coincident areas with the incisions observed on the seismic sections will be the final criteria to map the SV (Fig. 3). Additionally, a hydrogeographic analysis was performed to check the main rivers basins in the study area. These steps enabled the verification of the relation of present-day main rivers and estuaries with possible mapped shelf valleys.

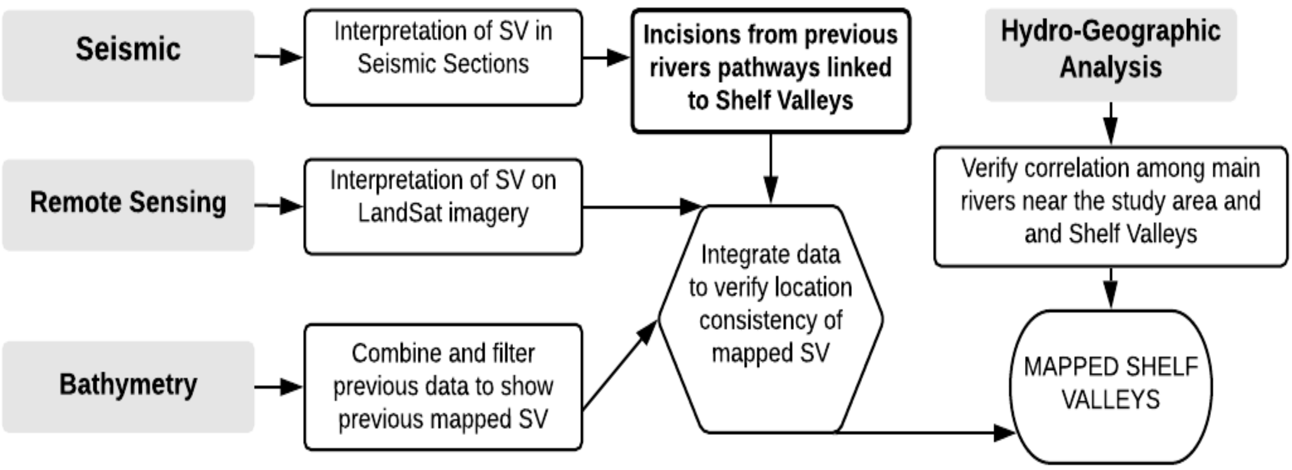


Figure 3 - Workflow with the methodology applied to the mapping and characterization of Shelf Valleys in the continental shelf of Pernambuco Basin.

As shown in the flowchart (Fig. 3) this work has four different steps based on the distinct data used. First, the interpretation of seismic data was the leading method to locate incisions excavated by preterit rivers on the continental shelf, as it is the broadest direct active method covering the whole study area. Second, single Beam bathymetry data available for part of the study area were used to constrain the identification and characterization of the structures in the seafloor

The third step was the use of remote sensing data, more specifically, satellite imagery. Landsat-8 OLI imagery was used to visualize channel-like features in the continent shelf and thus, locate possible shelf valleys in the study area. At last, an analysis of the main river basins was used to link with the SV formation. As shown in Figure 3, integrating all data in this work (Fig. 4) must reduce uncertainties intrinsic to the evidence provided by each type of data.

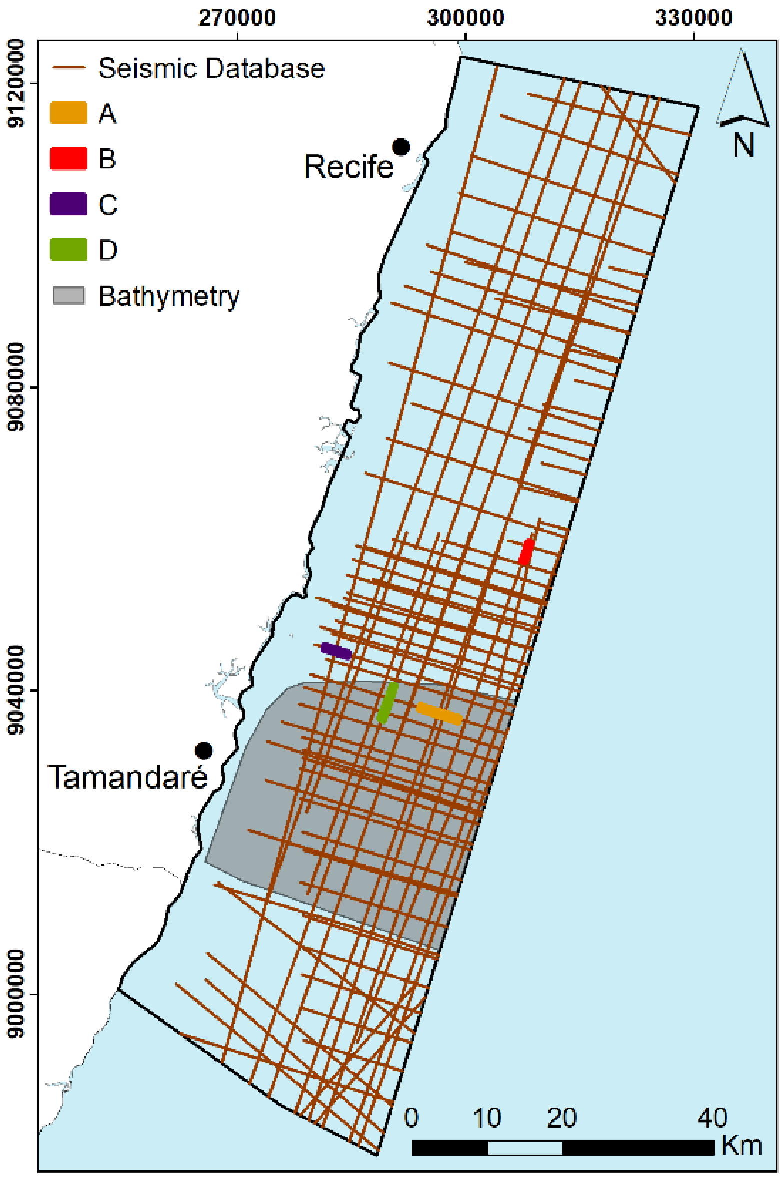


Figure 4 - Map of the studied area showing the location of the 2D seismic sections (brown lines). A; B; C; D are some examples of the incisions found in seismic sections that will be discussed later. The Bathymetric survey area in shown in gray and the Landsat image covers the whole area.

This approach allowed the confirmation that partially filled valleys observed in the seismic sections are linked to the channel-like structures mapped in the seafloor in the continental shelf by the other methods (Fig. 3). At last, the previously mapped incisions will have its origin confirmed by comparing the relationship between the mapped features and the position and concentration of large rivers/estuaries on the littoral region. All integrated data (Fig. 4) was used to generate maps with the WGS 84 projection system and UTM 25S coordinates.

Seismic Dataset

The seismic reflection dataset included 96 2D multichannel sections time-migrated (TWT). These seismic sections are legacy data prospected in the 80s and 90s decades by the oil-industry (Fig. 4), and the data provided by the National exploration and production repository (BDEP), from the National Agency for Petroleum Natural Gas and Biofuels (ANP). The interpretation was performed using Opendtect software provided by DGBS. The interpretation process focused on the first set of reflectors regarding the Recent to Quaternary sediment cover over the continental shelf seeking incisions such as in Figure 5. This interpretation process was performed on the entire seismic dataset (Fig. 4).

A comparison between stratigraphic data from Sergipe-Alagoas Basin with stratigraphic succession in Pernambuco Basin was used to define the age of the first important reflector below the seafloor surface. The age was possibly related to the Middle Miocene unconformity (MMU), based on the comparison of stratigraphy of Cenozoic deposits in Sergipe-Alagoas Basin (Fig. 5) (Neto *et al.*, 2007).

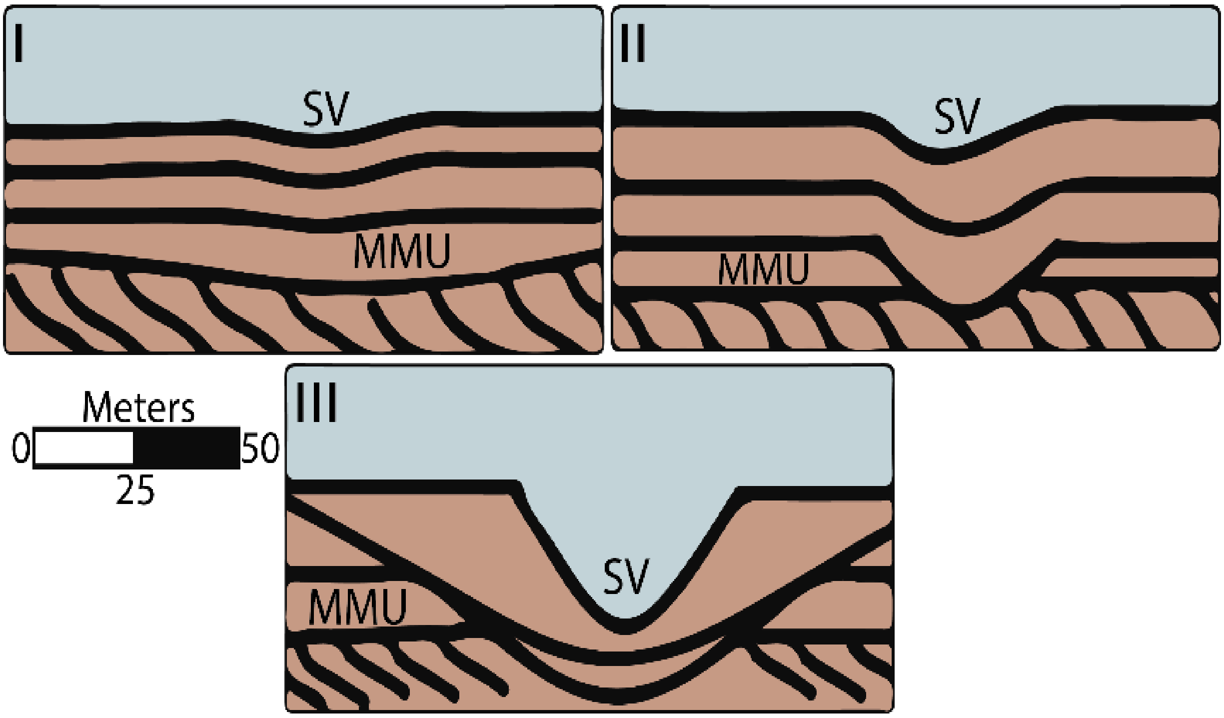


Figure 5 – Illustrations of different kinds of incisions interpreted as Shelf Valleys on the seismic sections. I) Small incision almost filled with sediments with the erosion of the MMU (in general found near the coastline). II) Most common kind of incisions found, partially filled with sediments and with erosion of the MMU. III) A deep incision that eroded the MMU with less sediment filling.

Bathymetric Processing

The bathymetric data (Fig. 4) belongs to the Bathymetric Database from the Laboratory of Geological Oceanography (LABOGEO, UFPE). This dataset contains 81 000 points on the study area, and the map used was obtained through minimum curvature gridding method (Swain, 1976; Smith e Wessel, 1990) with the cell size of 100 meters. The data were filtered using upward continuation (Blakely, 1996), 50 meters to cut off high amplitude spikes. The bathymetric data is a compilation of different single Beam surveys that generated grid spikes due to the navigation undergone by different boats, therefore the application of this filter was needed to smooth the final grid product and put the valleys in evidence.

Landsat Imagery processing

Remote sensing techniques are often more cost effective in surveying vast and remote areas for surface features interpretation and structure analyzes. However, for the recognition of shallow seafloor relief structures in satellite images, it is necessary ideal conditions such as the clean water conditions with no sediments in suspension. Thus, with some conditions, the detection of structures are possible with appropriate processing (Hedley *et al.*, 2016).

Landsat 8 OLI image (June 20, 2015) acquired through Earth Explorer Database (USGS) was used in this study. The image is considered of medium spatial resolution (30 meters/pixel) and was able to cover the entire study area. This study followed the first steps suggested by Silveira et al. (submitted) to apply Landsat-8 scenes to map paleochannels, which can be summarized by: Applying atmospheric correction using ATCOR module in ERDAS software, by using the metadata of the original Landsat image as input (Liang *et al.*, 2001). The following processing steps consisted of masking out land and clouds and a removal of sun glint (Hedley et al., 2005), which was necessary due to the sun reflex hitting water waves (Hedley *et al.*, 2005). The analysis of the processed image shows channel-like structures on the seafloor, that could be visualize in relative detail.

Hydro Geographical Analysis

The action of fluvial systems pro-grading overexposed continental shelves, during periods of sea-level fall, represents a mechanism of shelf valleys formation (Dalrymple, 2006; Conti e Furtado, 2009; Blum *et al.*, 2013; Gomes *et al.*, 2016). Thus, this research looked for a simple investigation of the main rivers in the adjacent coastal basin of the study area. The data on the drainage basins and the main present-day rivers was acquired from the Pernambuco State Environmental Agency (CPRH). Only the rivers with a drainage basin larger than 900 km² and a length of over 100 km, which mouths are in the study area, were chosen. It was expected that the origin of SVs is related to the largest river basins locations, or in the regions where more rivers mouths are concentrated. Hence, the spatial correlation as possible evidence of the origin of mapped SVs.

Results

Four examples of mapped incisions related to SV are in figure 6. The Middle Miocene unconformity affected by the incisions suggests posterior erosional events in the SV area (Pleistocene to Holocene) eroded also deposits formed below this horizon (Fig. 5). The interpretation of seismic data also shows that the valleys are partially filled, maybe by successive events of sediment deposition caused by the last transgressive-regressive processes (Fig. 5).

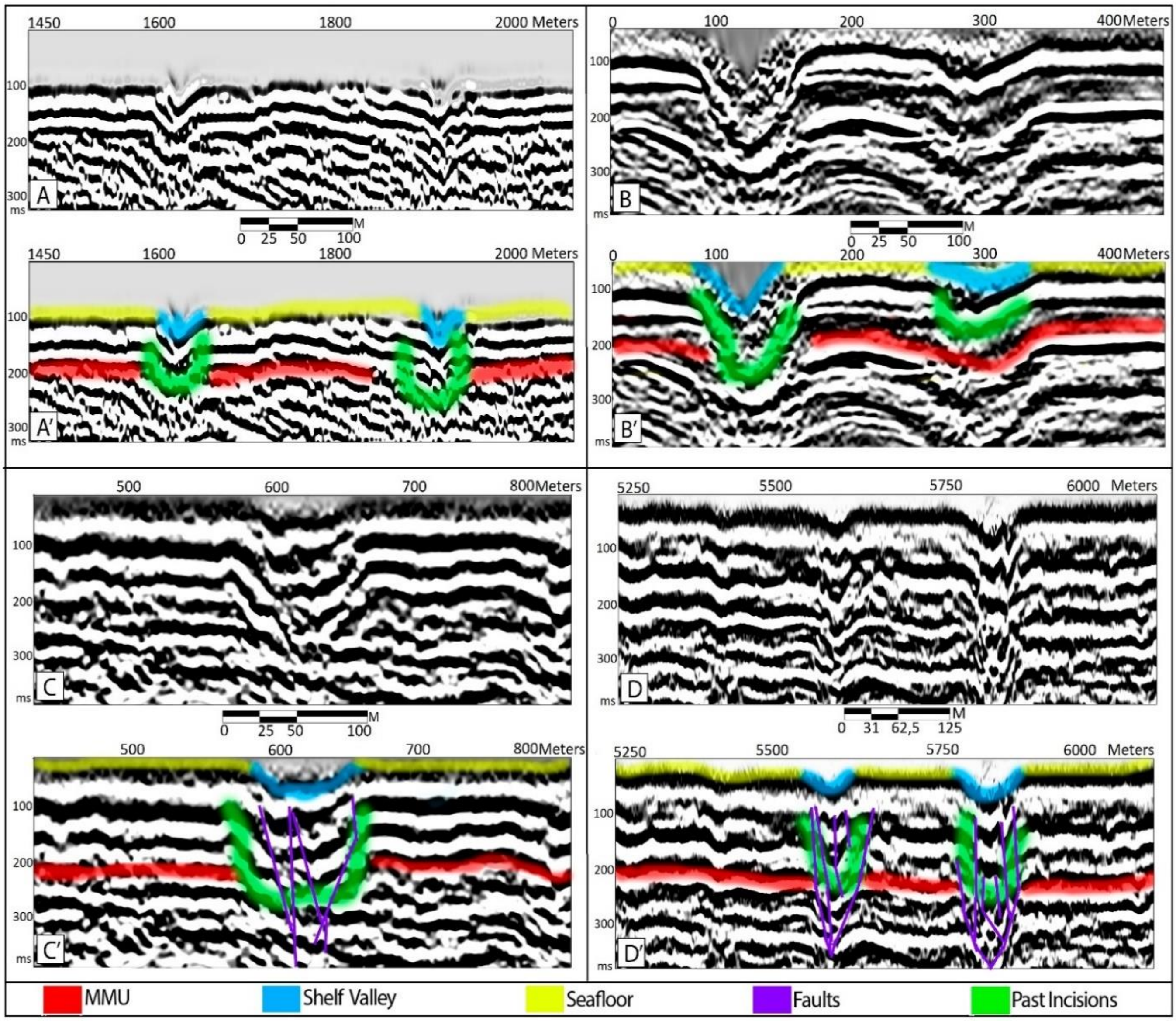


Figure 6 - Examples of incisions in the seafloor, identified in the seismic sections located over the continental shelf (Fig. 4). Yellow horizon - seafloor, red horizon - Middle Miocene unconformity? Blue lines - incisions, orange lines - faults. A) Two incisions on the seafloor that are partially filled, in the Southeastern part of the study area. B) Detail of two incisions in the center part of the study area. The incision shown in the left affected deposits older than the Middle Miocene horizon; C) Incision found in the center part of the study area. The channel was formed over vertical faults forming a negative flower; D) two incisions formed over faults in the *southeastern part of the study area.*

The 270 mapped incisions found on the seismic sections are on the Fig. 7. The mapping of the locals where the incisions were found (Fig. 4; Fig 5) in the seismic sections showed a very good pattern, with the points forming alignments with NW-SE, NE-SW, and almost N-S trends, which shows an important correlation with the structural framework of the basin. In addition, most alignments formed by the incision sites appear to have a strong correlation with rivers mouths in the coastal zone, which are evidently controlled by the tectonics of the basin too (Fig. 6).

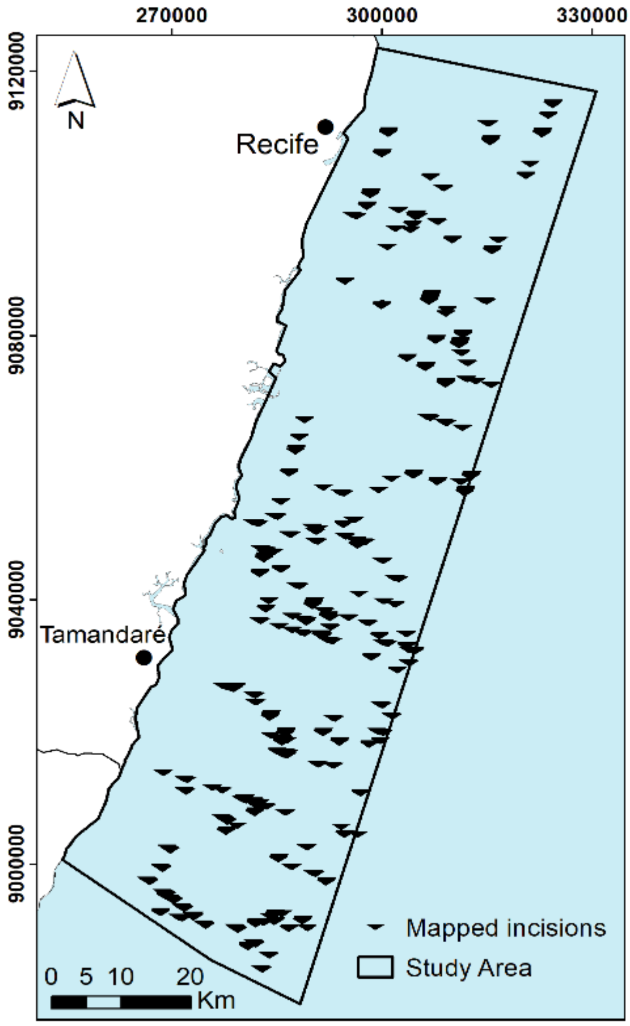


Figure 7- Map of the study area showing the location of incisions interpreted in the seismic sections.

Camargo *et al.* (2015) studied the characteristics of an occurrence of a shelf valley in the same region. Moreover, this study led to a detailed bathymetric survey campaign on the area and; consequently, the identification of the other two Shelf Valleys using bathymetric data the north (Fig. 8). The generated grid was integrated into this study with the main objective of verifying the correlation between the incisions found in the seismic data and the shelf valleys previously mapped.

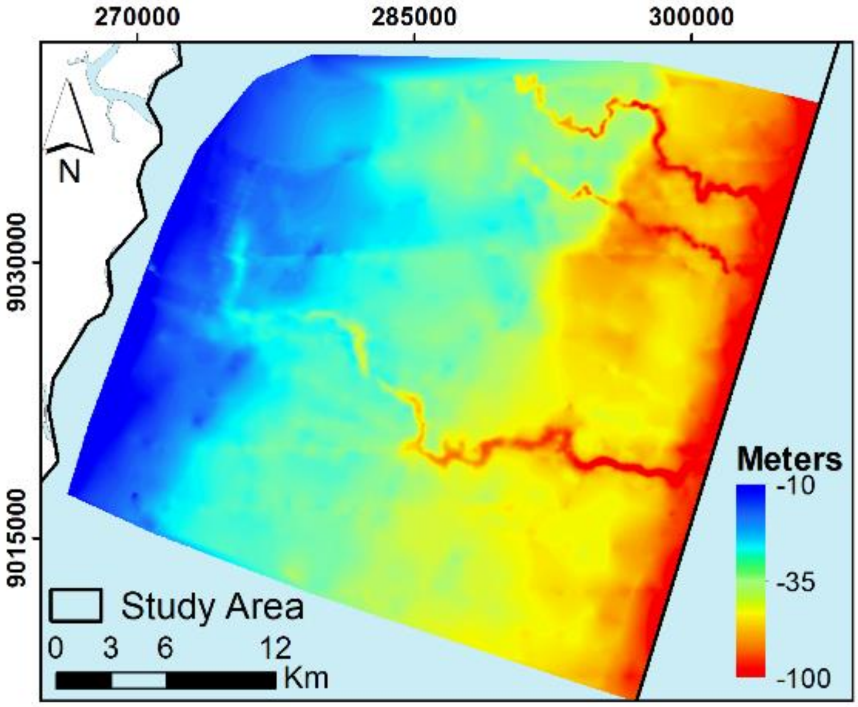


Figure 8: Combined Bathymetric survey on the study area showing three shelf valleys. The mapped one by Camargo et al. (2015) is the one in the south

A Landsat Image was used as a separate method to identify features in the shallow zone of the continental shelf as shelf valleys. The imagery cover for the study area was extracted and processed for the identification of seafloor structures. The composition used results from the bands 1, 3 and 4, merged.

The processing result in Figure 9, with the image for the total study area, and details. The information provided by this method was important, once the three shelf valleys identified in the bathymetric data by Camargo et al (2015) in the southwestern part of the study area, are clearly visible in the southwestern part of the image shown in Figure 8A. Various other channel-like features are visible crossing the continental shelf, as shown by Silveira et al (submitted) with a main NW-SE trend in the central and north part of the study area.

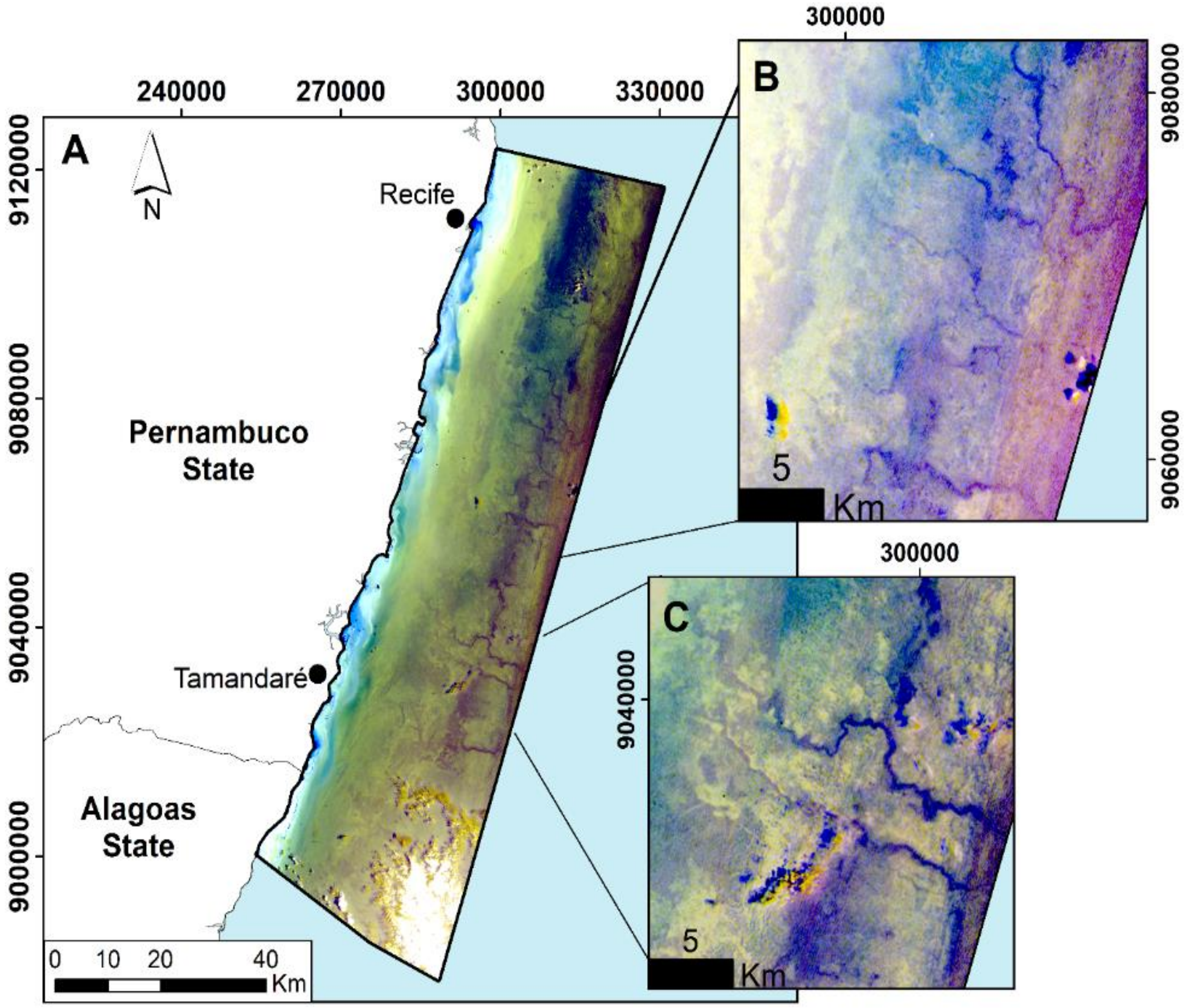


Figure 9 - A) image crop from a Landsat scene that covers the study region processed for the bands 1, 2 and 4. This composition allowed to identify channel-like structures that occur in the shallow continental shelf. B) Detail of the image showing elongated branching features in the seafloor trending most NW-SE. C) detail of the southern part of the image showing channel-like structures with the same form and size of the bathymetric data (Fig. 7).

This investigation also collected information about rivers with a basin area greater than 900 km² and basin perimeter longer than 100 km on the adjacent coastal zone of the study area (Fig 10). Detailed information on each river's area and perimeter is shown in table 1.

Table 1: The main river name of the basin in the adjacent coastal zone of the study area, and the area of fluvial drainage basins (Cprh, 2018).

River	Area (Km²)	Perimeter (Km)
Capibaribe	7 500	721
Una	6 700	673
Ipojuca	3 500	861
Jaboatão	1 000	195
Sirinhaém	2 080	380

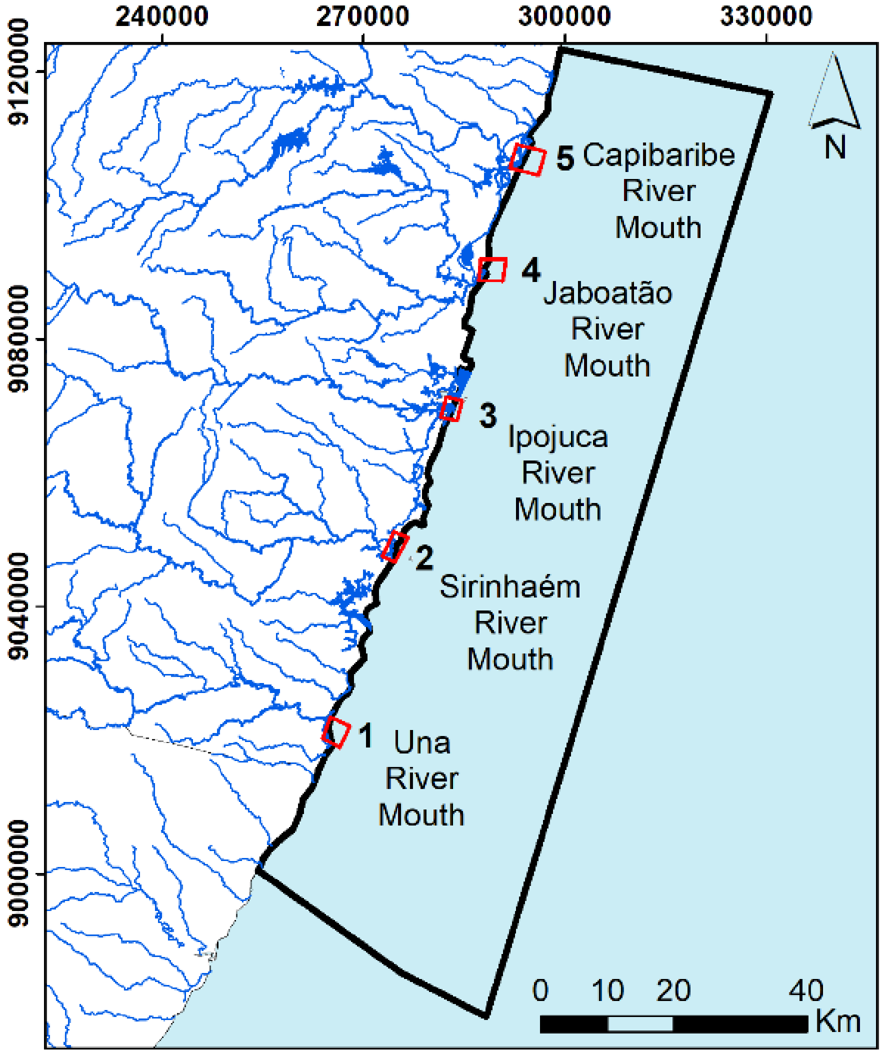


Figure 10 - Location of rivers/estuaries, which presented a higher potential to generate Shelf Valleys on the continental shelf of the Study Area.

The objective of this observation of present-day rivers in the coastal zone is to look for a direct correlation between these rivers and the location of shelf valleys identified by the integrated data used in this research. The potential those rivers present for the creation of shelf valleys, during the progradation of fluvial systems over the exposed continental shelf, caused by the Sea level fall events, are a factor have to be considered in the identification of these structures (Fig. 7). The data show five major rivers, which have the main trend for the main channel, which was NW-SE. These rivers locate over main transfer faults and shear zones that were active during the rift process that formed this marginal basin.

Discussion

The analysis of the integrated data showed a correlation between the location of incisions in the seafloor interpreted in the 2D seismic sections, the channel-like structures observed in the bathymetric data (Camargo et al., 2015), and in the processed Landsat image (Fig. 11). The visual correlation inclusive allows suggesting the structures are almost filled by sediments in the proximal region of the continental shelf, where the structures are less prominent in the seafloor (Fig. 11). This implies that the input of sediments caused a differential filling of the shelf valleys. The filling was more effective in the proximal region, and it is better exposed in the middle and distal regions. Another factor that can be responsible for that fact is the height of the vertical incision, which can be higher in the distal region because of physiography and the past continental shelf gradient (Camargo *et al.*, 2015).

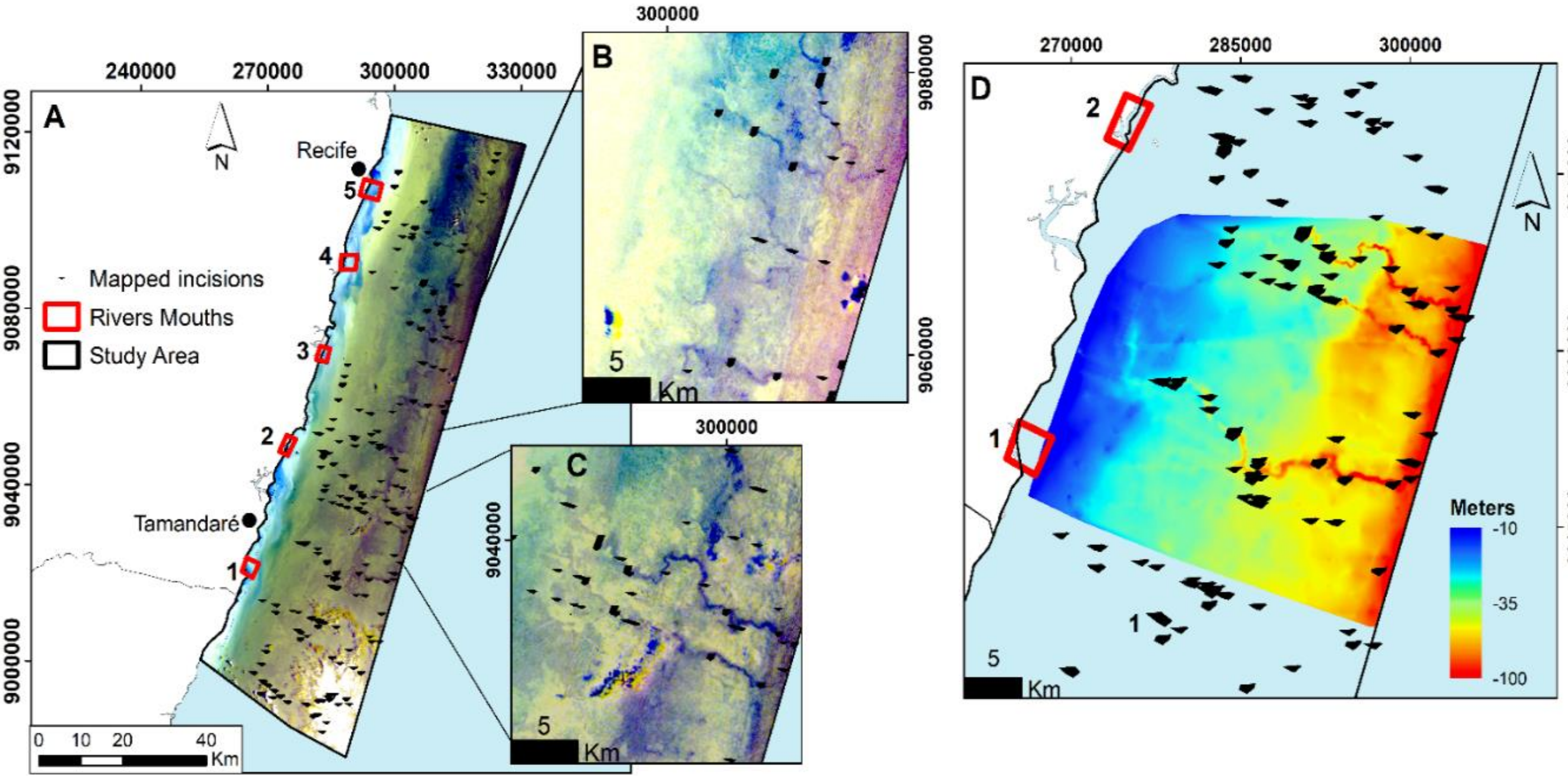


Figure 11: Data integration to interpret the SV. A) Integrated image using Landsat data with the mapped incisions as a top layer and the chosen river mouths areas. B) A detailed portion in an area without bathymetric data. C) Zoom in the area with detailed bathymetric data and Landsat imagery with the mapped incisions. D) Bathymetry showing the correlations of Shelf Valleys and its continuity on the mapped incisions and two river mouths in the area.

As shown in the examples used to illustrate the process of mapping of seafloor incisions the seismic section, 270 incisions were found in the seismic sections dataset (Fig. 5 and Fig.6). Some identified channels/incisions were formed over the propagation of faults that affected Cenozoic strata. These faults probably were created by tectonic reactivation of old structures in the continental shelf (Fig 6) (Bezerra *et al.*, 2014), but these structures were not addressed by this work.

In addition, the observation of the relation between the mapped shelf valleys and the main present-day rivers, hydro geographical analysis, in the coastal zone show a clear relation (red polygons on the littoral zone – fig 11). Some branching of the shelf valleys, which show abrupt changing of channel direction, are clearly caused by the capture of these channels by another family of structures that possibly affected Cenozoic deposits. The secondary trends, that caused a variation in the channels' directions, are N-S, NNE-SSW. The main trend, observed for the main rivers in the adjacent coastal area and for the shelf valleys in the continental shelf is NW-SE.

The relation between the mapped shelf valleys, by the integration of all data, and the hydro geographical data also show that the river size has an influence in the formation of the shelf valleys in the continental shelf. The smaller river system, the Jaboatão River basin is linked to fewer shelf valleys in the continental shelf than the other rivers, which are greater in extension and in the drainage basin area in the present-day (Fig. 12). This suggests that the effect of these rivers kept some correlation between the hydraulic potential in the past, and the hydraulic potential represented in the Holocene.

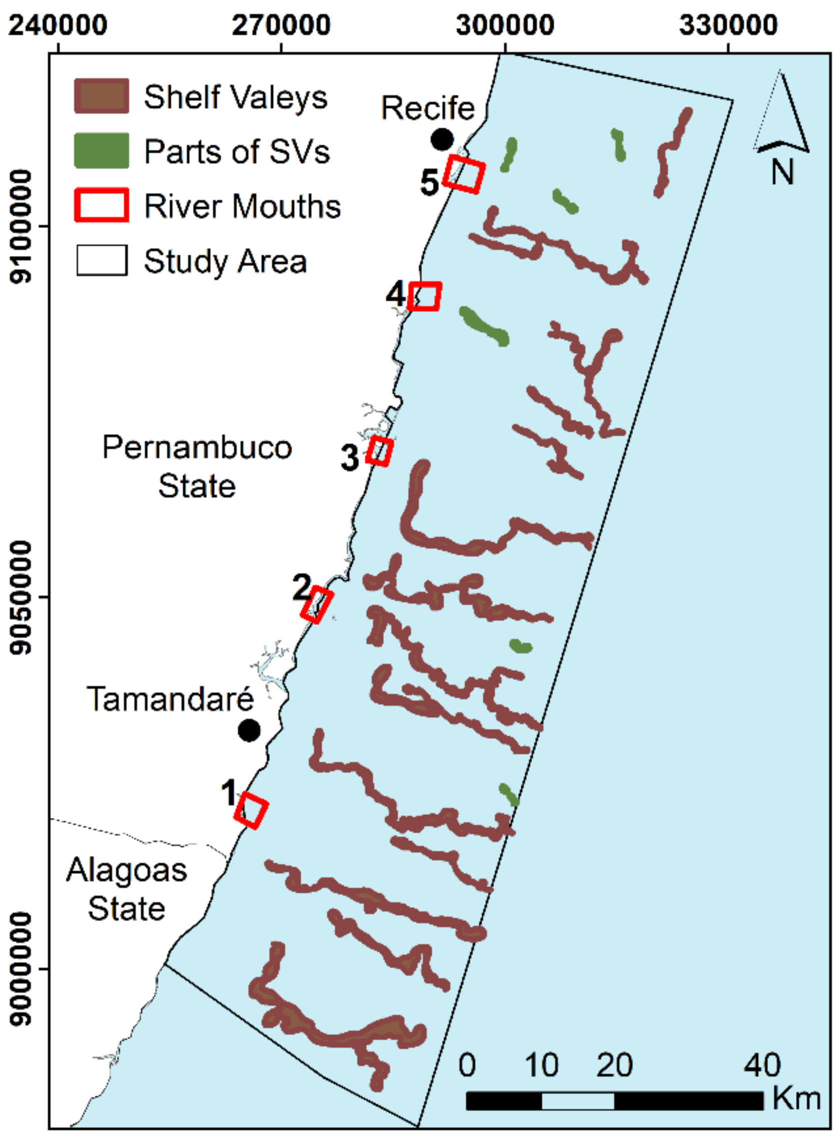


Figure 12 - The brown lines represent all the Mapped shelf valleys, with the information provided by the seismic data, bathymetric and remote sensing data. The green lines are part of Shelf Valleys with less than 10 km of extension. From 1 to 5 are the main rivers that might have excavated the Shelf Valleys on the continental shelf.

Conclusions

The methodology used to map shelf valleys, based on the interpretation and mapping of incisions in the seismic sections proved effective, as the mapped valleys on bathymetry and remote sensing imagery represent the same structures, seen in surface and subsurface.

The approach used, based on the integration of subsurface data, remote sensing, and surface information, allowed to identify 14 complete Shelf Valleys and 6 elongated depressions; which are possible meanders of Shelf Valleys on the continental shelf of

Pernambuco marginal basin. This information could complement the Gebco database, which has no information about these structures, and previous articles on the shallow marine characteristics of this area.

The Hydro Geographical analysis, which tried to correlate the most important rivers in the region and the shelf valleys, showed a very positive correlation between the present-day rivers and the structures in the continental shelf. The results also show that the channels are more exposed in the distal region of the continental shelf and that the strong tectonic control of the rivers in the adjacent coastal zone acted the same way during the formation of shelf valleys as the progradation of the fluvial systems during periods of sea-level fall and continental shelf exposure.

This approach, which represents a fast, low-cost alternative, to other sophisticated bathymetric survey-based methods, can be very effective for the mapping of such structures in shallow continental shelves, where conventional seismic data (legacy data) is available.

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5.2 NEOTECTONICS CONTROL ON THE SHELF VALLEYS FORMATION IN THE SOUTHERN SECTOR OF CONTINENTAL SHELF OF PERNAMBUCO- BRAZIL

Highlights

- Integration of geophysical data used for understanding Quaternary Shelf Valleys placement on the continental shelf of Pernambuco- Brazil
- The method allowed to identify shallow structures controlling the meanders directions of the Shelf Valleys
- It can be extrapolated that the valleys were being excavated since the Middle Miocene and the rivers flow (marine transgression) were captured by transfer faults.

Abstract

Shelf Valleys (SV) are incised valleys in periods of marine transgression by a preterit river flow; this study focus is to verify the existence of structural control on the placement of Shelf Valleys using Magnetometry and Seismic data. The study area is on the Northeastern Brazilian continental shelf placed on the Pernambuco basin covering an area of approximately 950 km^2 , from the inner shelf (-25 m) to the shelf break (-55 m). Because of a regular grid of preterit geophysical data from the Oil industry three SV were analyzed. At first was compiled and processed a bathymetric dataset to put in evidence the SV showing its format along the continental shelf. Several filters applied to the magnetic data to show magnetic lineaments related to shallow structures. Seismic sections were analyzed to find and map shallow (first 300ms) faults. At last, all the data were integrated showing a strong correlation between shallow structures and the SV placement and its meanders.

Keywords
Shelf Valleys, Seismic data, Marine Geomorphology, Tectonics.

Introduction

Shelf Valleys (SV) are incised valleys on the continental shelf formed by fluvial erosion, in periods of marine regression (Harris e Whiteway, 2011). In other words, SV are geomorphological features on the seafloor with the channel-like pathway partially filled with sediments, this characteristics can be assumed as a heritage of preterit rivers flowing on the exposed continental shelf. An SV has variable length and up to 120 meters in depth (Harris *et al.*, 2014). In consequence, only recent continental shelves with low to medium sediment intake preserved well developed SV, otherwise they will be filled by sedimentary deposits during the late marine transgressions or very they became very shallow to be detected as a SV.

The study area (Fig. 1) is located in the Northeastern Brazilian continental shelf (Fig. 1-A), and it belong to the Pernambuco marginal basin (Fig. 1-B). it covered an area of approximately 950 km² (Fig. 1-C), from the inner shelf to the shelf break zone where the bathymetric depth reached approximately 55 meters (Araújo *et al.*, 2004). The relative sea level in this region one million years ago was estimated in approximately 62 meters below the current level (Lea et al., 2002; Waelbroeck et al., 2002). That information means that the continental shelf was above sea level during this time. About 110,000 years ago the period of marine regression had its final apex and it is inferred that the relative sea level was below the depth of 60 meters (Hanebuth et al., 2003), which again exposed the study area to sub-aerial erosive processes, thus forming the present shelf valleys, because of the rivers in this period. Consequently, there are three Shelf Valleys in the study area that can be detected on satellite imagery (Fig. 1) Silveira *et al*. and Tassinari *et al.* (Submitted 2020).

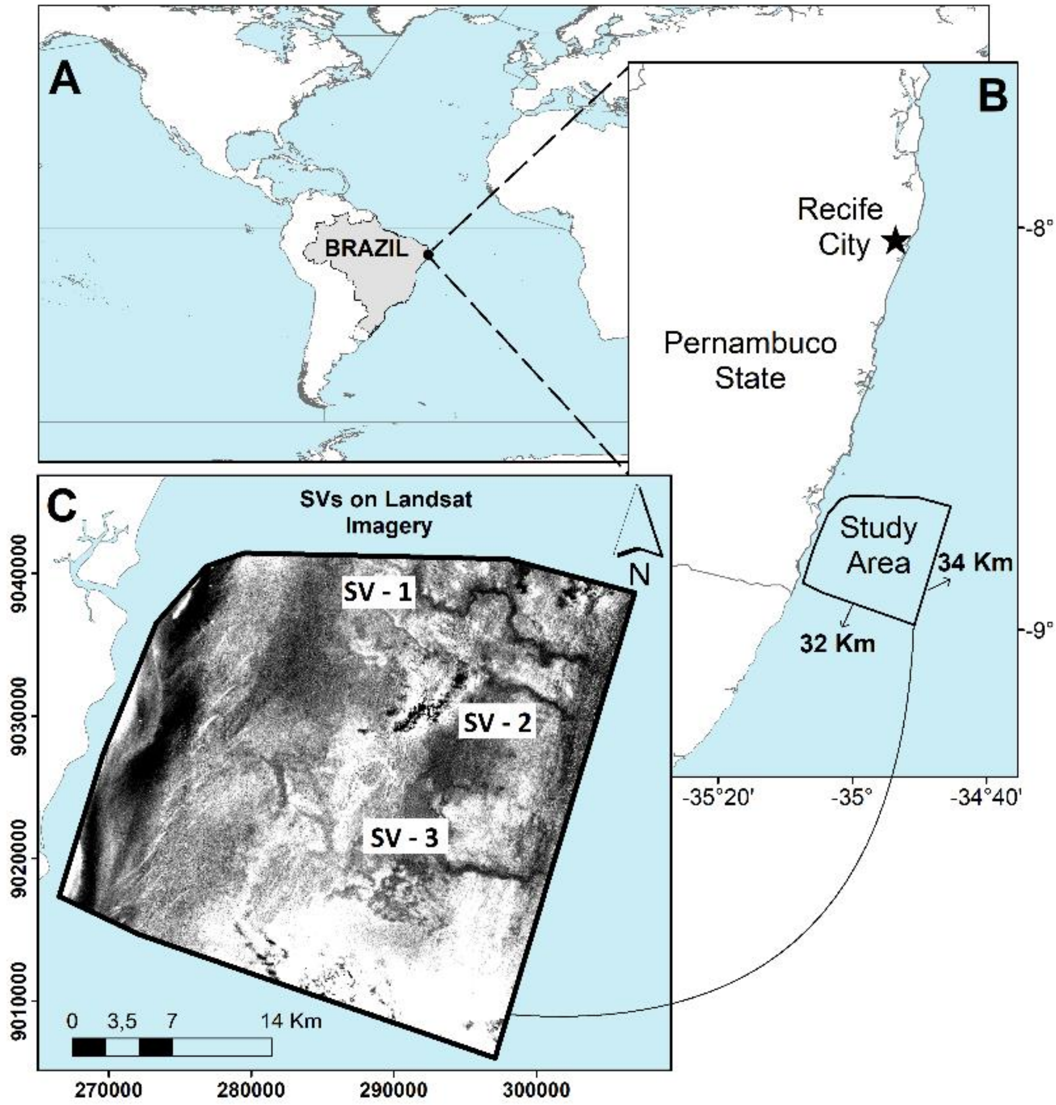

Fig 1: Location of study area A-) marginal area in the South American continent B) Study area on the continental margin of the Pernambuco Basin C) Study area showing three Shelf Valleys (SVs) on LANDSAT Satellite imagery.

Regional setting

According to Kempf (1970), Manso *et al.* (2003) and Araújo *et al.* (2004) the continental shelf of the study is covered with biogenic carbonatic sediments. The Shelf is shallow and presents a gentle gradient and warm high-salinity waters. Additionally, it is considered a sediment starved tropical continental shelf (Manso *et al.*, 2003; Araújo *et al.*, 2004).

The continental Shelf of Pernambuco Basin is dominated by a structural high that runs parallel to the coastline, the Maracatu High, which acted like an outer hinge. The main structures that controlled the evolution of the Pernambuco Basin are the ductile pre-Cambrian shear zones, which have a main NE-SW and E-W direction, in the northern portion of the Shelf, and transforming faults trending NW-SE in the southernmost region of the basin (Buarque et al., 2017). According to Correia Filho *et al.* (2019), the rift process also created normal faults trending N-S NNE-SSW in the onshore region of the basin.

The continental shelf sedimentary cover is composed of sand, gravel, and bio-clasts mainly comprising calcareous algae remains (Camargo, 2016). These features are usually found in tropical continental shelves with a shortage of terrigenous sediments (Meek et al. 2003; Camargo et al, 2015). The mainly geomorphic features in the study region are represented by Beachrocks, terraces, shelf valleys, ravines and submerged canyons (Camargo *et al.*, 2015; Goes *et al.*, 2019).

Methods

The aim of this work was the integration of data got with three geophysical methods (Fig. 2) Bathymetry, Seismic and Magnetometry to understand the origin and evolution of Shelf Valleys formed during the Quaternary in the Shelf of Pernambuco Basin. Specific techniques of modeling were applied for each dataset, which allowed an integrated interpretation about the geology of the region considering information about the sea floor surface from subsurface. The flowchart in Figure 2 shows the procedures adopted to process the data.

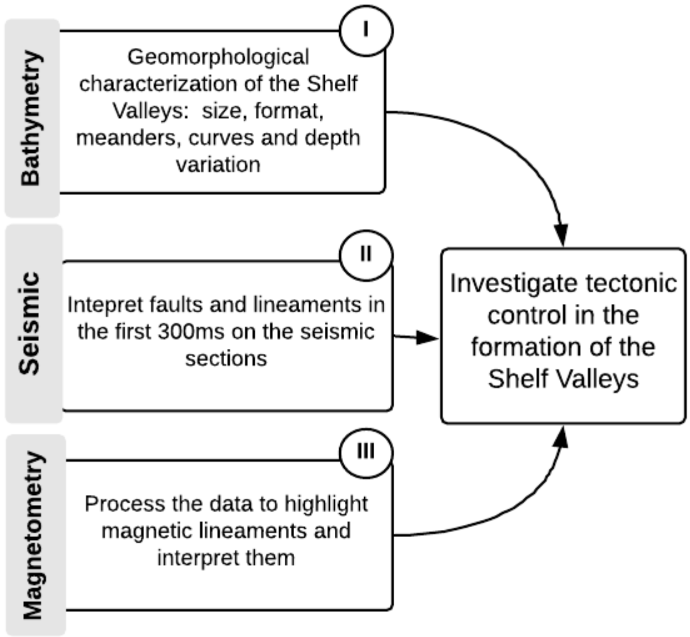

Figure 2: Flowchart of the three different steps applied to the gathered data, with the expected information of each used method, to investigate the origin and characteristics of Shelf Valleys in the study area.

Single Beam Bathymetric data that covers the study area, with dense sampling on the channels (Fig. 3 A), were grided using the minimum curvature method (Briggs, 1974) with a cell size of 25 meters. Because this bathymetric dataset is formed by different surveys collected by distinct boats in various atmospheric conditions, it was needed to apply a low pass filter (Upward continuation), to remove the high amplitude spikes due to the boats movement (Fig. 3B), and, achieve a smoothness appearance for the final grid and highlighting the SV .

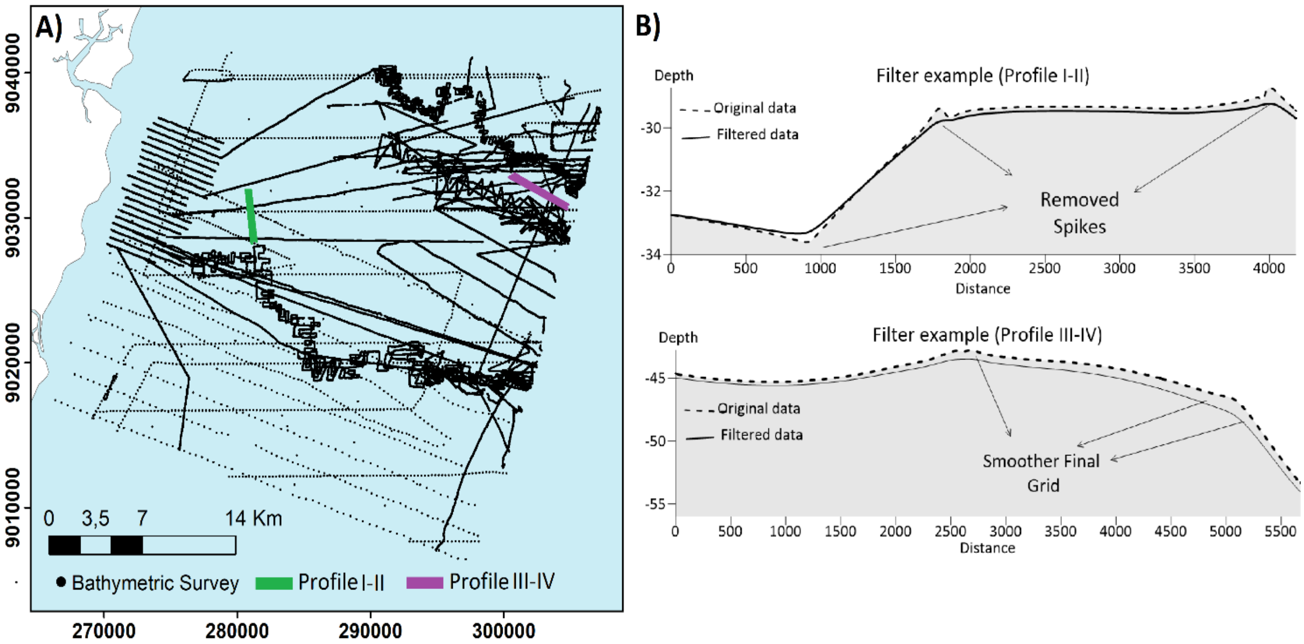

Figure 3: Compiled bathymetric dataset, built with different surveys, which covers the study area. A) Surveys paths (the green line and the purple line represents sections extracted from the interpolated grid. B) Example of bathymetric sections extracted from the grided survey, and the result of smoothness filter application, used to adjust the data, and to remove spike values. .

The 2D seismic sections dataset represent surveys acquired with the seismic reflection method. All the studied sections represent multichannel time migrated surveys. The National Agency of Petroleum, Natural Gas and Biofuels (ANP) data repository (BDEP) provided this dataset. This data represent legacy database assimilated by different campaigns from the 70s to the 90s of the past century. Due the different quality grades of the seismic sections, the research applied different post-processing tools to improve the interpretation: gain filter, low frequency filters and hilbert transform attribute extraction. For all the seismic sections, in the Shelf, the study focused in the initial 500 ms of the surveys, which is the interval that possess the incision structures.

The aeromagnetic survey used for this research was provided by the BDEP-ANP (Exploration and Production Database from the Brazilian National Agency of Petroleum, Natural Gas and Biofuels). The *Platô de Pernambuco* survey was taken in 1988 with NW-SE-oriented flight lines with 3 km spacing, and flight height of 500 m. The aeromagnetic data were gridded using bidirectional techinique with a cell size of 2 km (Fig. 4). Additional processing was performed to get the residual magnetic anomaly map, which allowed evidencing the magnetic lineaments in the region (Fig. 4 TILTs and TDRs)

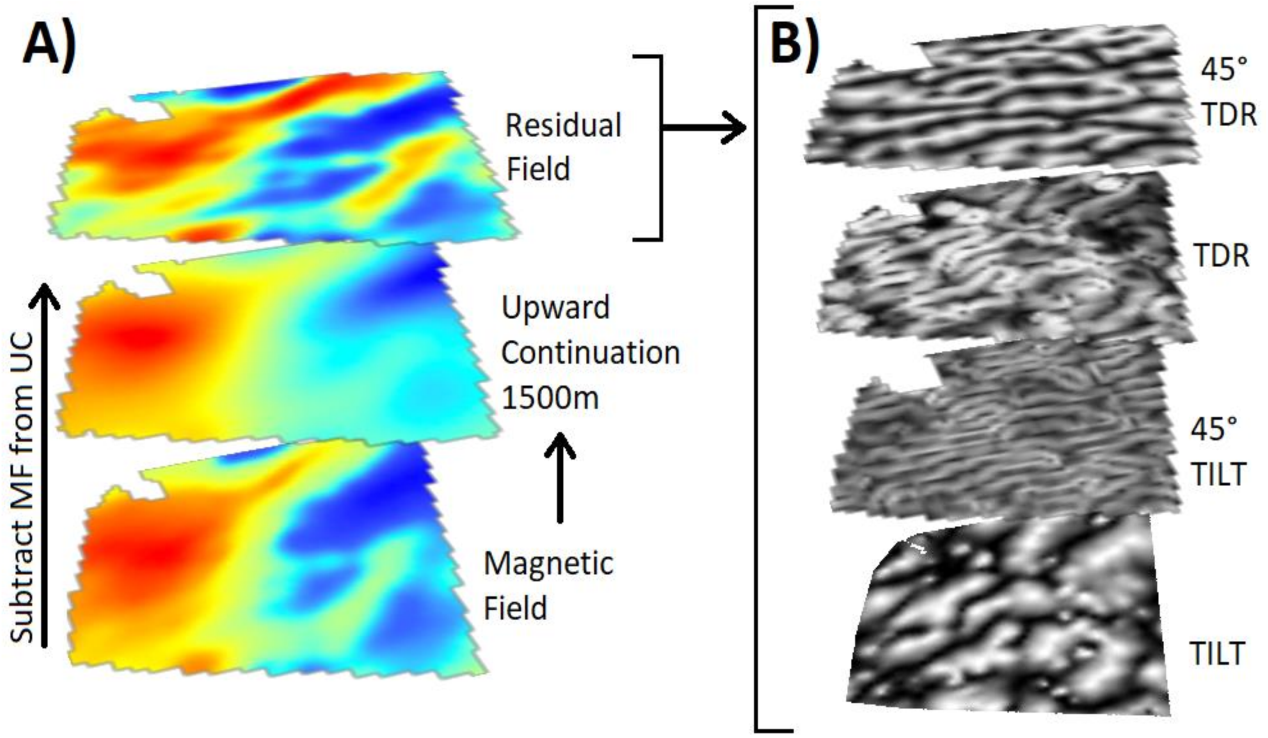

Figure 4: workflow of aeromagnetic data processing. A) magnetic anomaly field map, upward continuation map, and residual magnetic anomaly map. B) TILT map, 45° TILT map, TDR map and 45° TDR map.

The processing of the aeromagnetic data also included the application of Upward Continuation filter for 1500 m. This filter attenuates high frequency anomalies, and maintain those longer wavelength anomalies that may be associated with the presence of deep magnetic sources (Henderson e Zietz, 1949). The residual magnetic anomaly map was also extracted from the magnetic anomaly map. This map allowed the identification of shallower magnetic sources, without generating gains on noise. For the analysis of shallow structures within the basement of the Shelf was produced magnetic transformations trough the Verduzco *et al.* (2004) adapted method (Fig. 4-B),getting the TILT map and the horizontal derivative (TDR) from the residual field. Which allowed highlighting magnetic lineaments associated with high frequency magnetic sources.

Arcording to (Miller e Singh, 1994)the TILT method is based on the ratio between the vertical and horizontal derivatives from the magnetic anomaly field. The TILT angle varies between -90° and 90°, and the center of the magnetic source presents maximum values. Values equal to zero or near zero represents the limits of the source (Verduzco *et al.*, 2004) . The TILT modeling can help to reveal features that cannot be defined by other methods. The horizontal derivative of TILT can reveal shallower structures. That was important for the studied case, in which we were interested in understand the influence of basement structures in the location of shelf valleys. Using TILT method for modeling the aeromagnetic data also present the possibility of define the borders of magnetic bodies (magnetic lineaments) in various depths with better resolution (Ferreira *et al.*, 2011; Ferreira *et al.*, 2013).

Results

The bathymetric map of the study area (Fig. 5 –A) shows that the depths on the continental shelf varies from -25 meters, near the coastal area, to approximately -55 m at the Shelf break. The map showed the occurrence of three Shelf Valleys which crossed the shelf extension almost perpendicularly across the shelf break. It meanders of the exposed valleys are clear in the map. The map also showed some places where the direction of the valleys changed abruptly, almost 90°, forming regions where the capture of the drainage formed rectangular meanders (white dotted circles) (Fig. 5-A). Four profiles were plotted on the grided data showing the depth variation of the three valleys (Fig. 5-B).

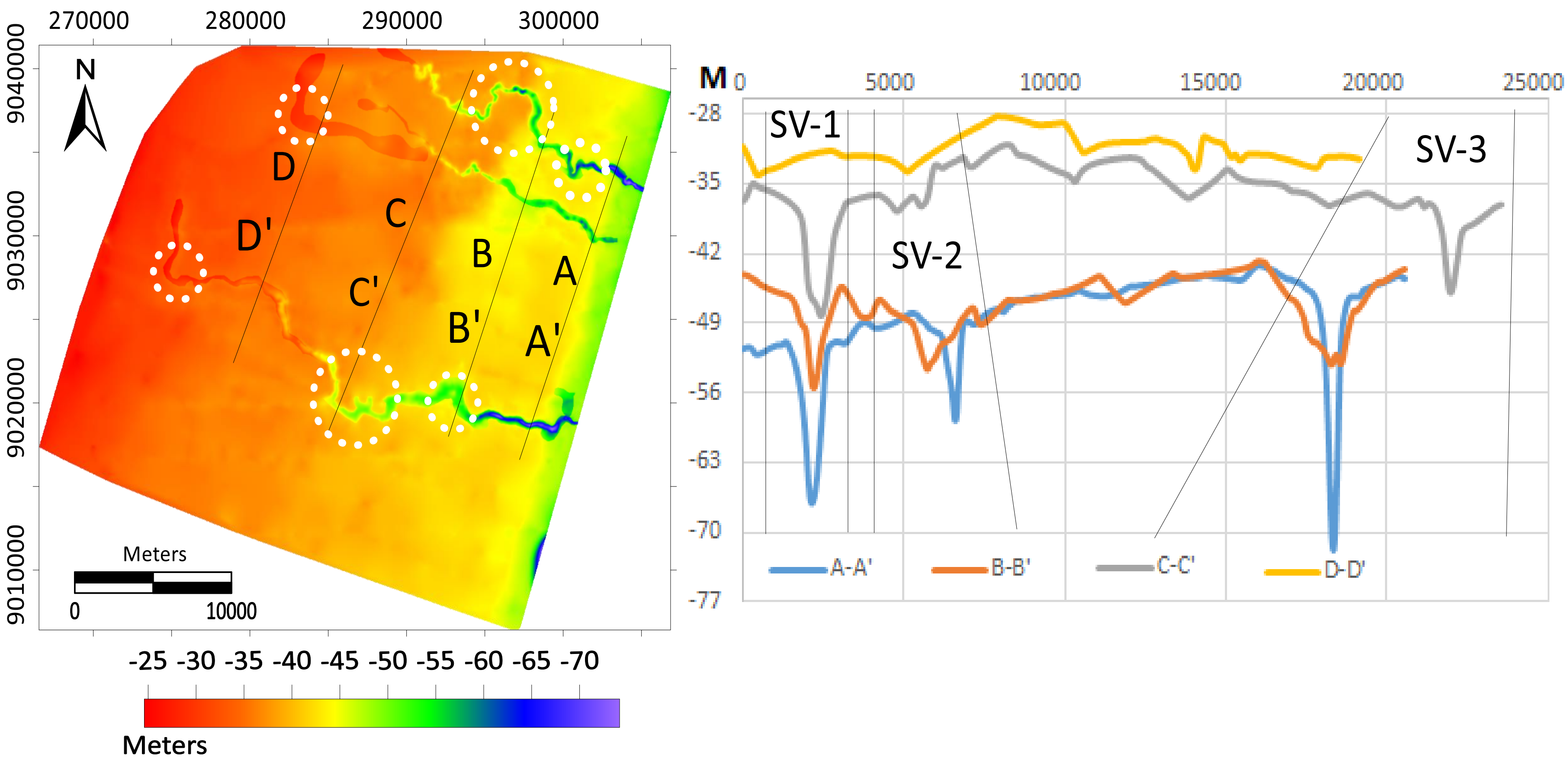

Figure 5: A) Bathymetric map of the study area showing the Three Shelf valleys with the main changes in the valleys directions highlighted by (dotted white circles). B) The profiles crossing the valleys show that the valleys depth increase from the proximal area to the coast (profile D-D') towards the shelf break (profile A-A').

The systematic analysis of the seismic sections allowed the interpretation of faults that crossed the sedimentary deposits that covered the Shelf (Fig. 6). Two examples of an interpreted seismic section can be found on the Figure 6 this procedure was undergone in all seismic lines to plot its location on a final map. The faults observed in the upper Cenozoic section that covers the Shelf possibly were generated by reactivation of rift faults of the basement of the basin (Correia Filho *et al.*, 2019). These structures possibly result from propagation of faults linked to the Pre-Cambrian shear zones and transfer faults, which are active during the rifting process that produced the basin opening. The interpreted faults on the Figure 6 are known as *Flower structures*, which are a strong evidence of Strike slip tectonics. Which suggest a component of current reactivation of the older structures that occur in the basement of the studied region. This structure affected the strata interpreted as the past incisions from the channels (that were filled) and the Middle Miocene unconformity.

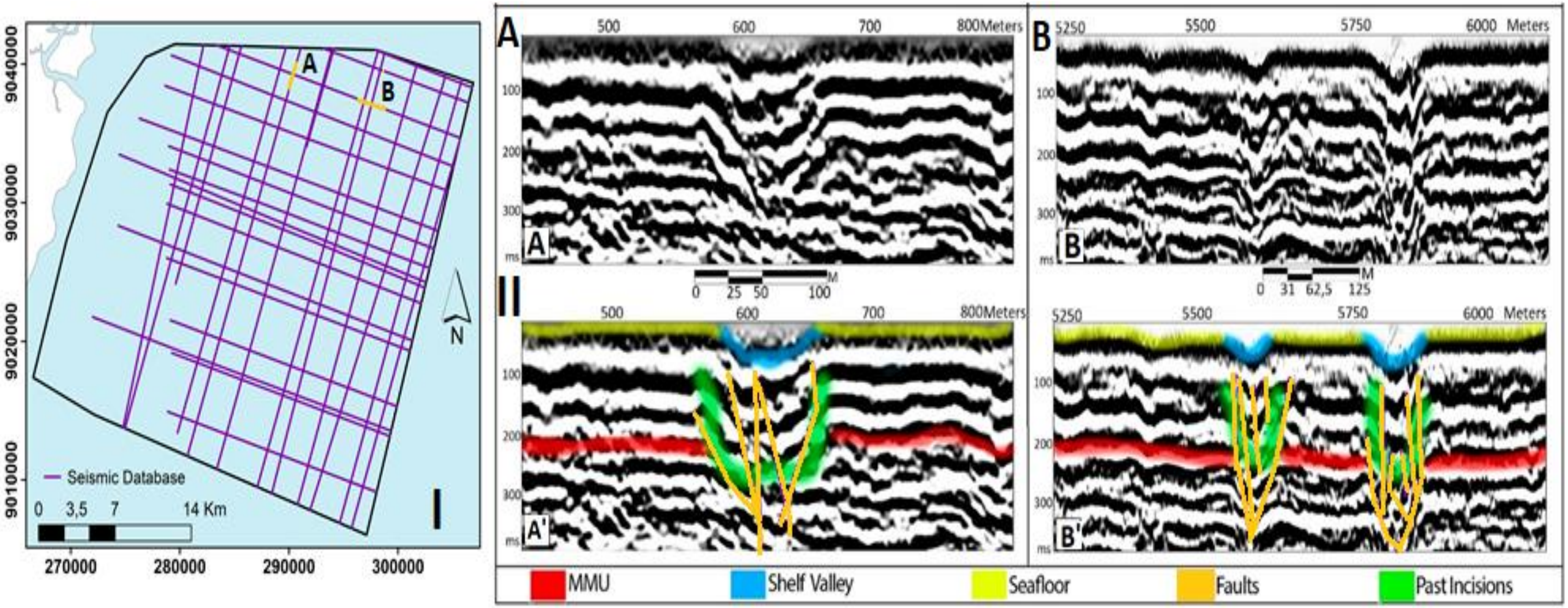

Figure 6: I) Seismic lines location plotted in purple A and B are two chosen examples to be shown. II) Two examples of the seismic section in the studied region A and B without interpretation A' and B' interpreted seismic sections. Yellow: Sea Floor. Blue: Modernincision of the Shelf Valley. Green: Past incisions of the Shelf Valleys. Red: Middle Miocene unconformity. Orange: Mapped Geological Faults, which controlled the location of the incisions. It was also observed that the present shelf valleys were positioned over other shelf valleys, which were buried by recent deposits.

The total magnetic field map showed the occurrence of a normal magnetic dipole varying from 39 to -188 Nanotesla (nT) (Fig. 7-A). The upward continued magnetic field (Fig 7-B) showed a similar dipole, which values varied from 10 to -153 nT. Moreover, as expected the residual anomaly map (Fig. 7-C) started showing a response of shallower structures that can be related to filled faults from the rift process because of its orientation. The 45º degrees TDR filter map (Fig. 7-D), the default TDR filter map (Fig. 7-E) , the 45º degrees TILT filter map (Fig 7-F) and the default TILT filter map (Fig. 7 G) applied to enhance the visualization of magnetic lineaments on the study area and interpret the final map of the lineaments (Fig. 7-H).

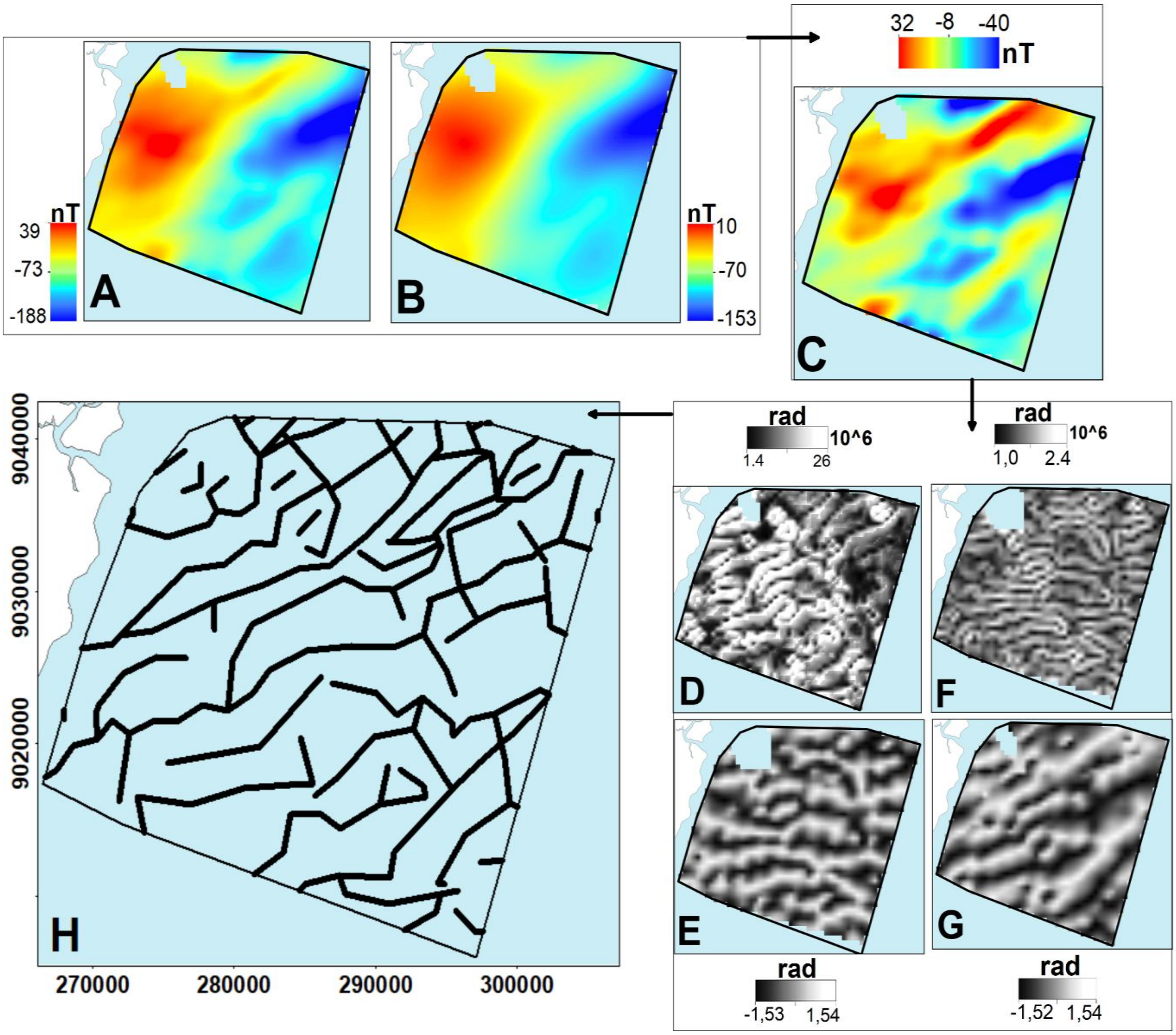

Figure 7: Integrated interpretation of the maps produced by the modeling of the aeromagnetic data. A) Total Magnetic anomaly map. B) Upward continuation map. C) Residual magnetic anomaly map. D) 45º degrees TDR filter map. E) Default TDR filter map. F) 45º degrees

TILT filter map. G) Default TILT filter map. H) Map of the main lineaments of the basement in the studied area based interpreting modeled aeromagnetic data.

Discussion

Based on the bathymetry map (Fig 5-A) it is not possible to define if the valleys were formed through different regimes of hydraulic flows because the gradient of depth of the valleys across the Shelf are similar and the gradient of the Shelf are similar in the studied region. However, the fact that the studied region represents a sediment-starved Shelf (Araújo *et al.*, 2004). This is clear because the valleys are more filled near the coast and deeper as closer to the Shelf Break that it gets. The low intake of sediments on the coast might been the same scenario on the past explaining why the shelf valleys, which result from erosion the river drainage that now is drowned in the present coastal zone, were not filled in the last sea level rise during the Holocene. The shelf valleys show a more prominent depth in the distal part of the Shelf, where the sediment input was less effective during the Holocene.

On the data integration (Fig. 8) with the format of the three SV, the magnetic lineaments and the point cloud of the detected faults and lineaments from the seismic can be seen a direct influence of faults and fractures on the SV-3 and SV-1 format. On the other hand, the SV-2 shows to be linear and probably captured and placed on a deeper fault.

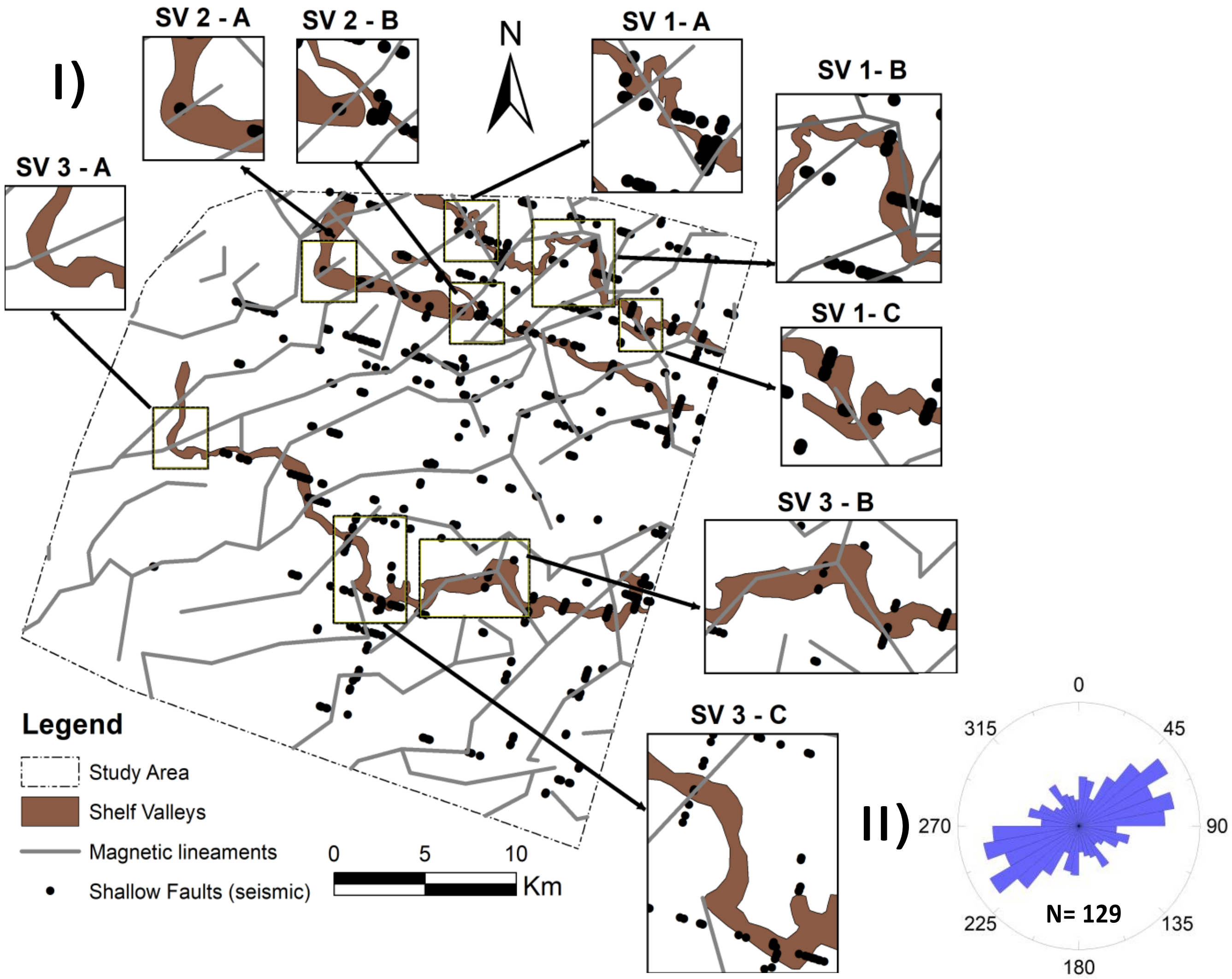

Figure 8: I) Data integration with the drawing of the shelf valleys from the filtered bathymetric grid, point cloud of the mapped faults on the seismic sections and the magnetic lineaments. II) Rosette diagram from the mapped magnetic lineaments showing the lineaments from the rift process being NE-SW and the transfer faults NW-SE.

Integration of bathymetry data, aeromagnetic data modeling and the position of faults in the Cenozoic strata over the Shelf, it was possible to define the influence of faults in the geometry of the channels. The SV-1 and SV-3. These valleys showed abrupt changes in the channel geometry which follow the direction of the main structures of the basement beneath the Shelf (Fig. 8). The SV-2 showed a more linear geometry, which could imply less influence of structures. All three channels are possibly seated over propagation of transfer faults of the basement, trending NW-SE (Fig.8). The abrupt changes in the geometry of channels, show meanders of rectangular forms, which could be caused by the capture of the drainage by faults trending N-S and NNE-SSW. A few changes show a E-W to ENE-WSW.

The main orientation of the channels possibly showed that the main structures formed by the Cenozoic reactivation of the basement were the transfer faults (NW-SE). And that, the secondary influence was created by faults formed by the reactivation of shear zones (NE-SW), and also normal faults, trending N-S and NNE-SSW.

Correia Filho *et al.* (2019) compiled on their work the main proposed models that explains the neotectonical reactivation events in passive margin basins. Among these theories, the chosen one for this area that explain the faults that controlled the arrangement of the Shelf Valleys is the reactivation of old structures related to the *Farfield* effect. This stress would have been applied by the Andes. This model says that the diving angle of the Nazca Plate, under subduction under the South American Plate, plays an important role in this context, because the larger this angle, the greater the regime of efforts directed to the Brazilian northeast). This arrangement suggests mastery of a transcurrent regime, with maximum compression E-W and extension N-S (Bezerra et al., 2014 (Marques et al., 2013; Folgueira et al., 2015).

Conclusions

The filter of the single Beam bathymetric data was successful to highlight the Shelf Valleys arrangement. Interpreting faults on the seismic section (direct method) integrated with the interpretation of the magnetic lineaments (indirect method) was effective to show a structural control on the Shelf Valleys.

The study of 2D seismic data showed that the coverage since the Middle Miocene covering the Shelf Valleys was affected by faults, high angle faults formed under transcurrent regime created from the reactivation of shear zones. Mainly on the channels, regions can be found exhibit negative and positive flower pattern structures. These faults associated with the magnetic lineaments suggests a process of reactivation of structures that affected deposits under the a current tectonical regime,

All the Three Shelf Valleys are arranged into shear zones whose main structural trend is NE-SW, and faults with structural trend NW-SE. The capture process of the preterit drainage on the exposed continental shelf has created Shelf Valleys with rectilinear patterns with abrupt changes of direction because of neotectonical control with almost perpendicular dominant directions.

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6 CONSIDERAÇÕES FINAIS

A abordagem utilizada nessa dissertação representa uma alternativa rápida e de baixo custo a outros sofisticados métodos de aquisição de dados batimétricos, e se mostrou muito eficaz para o mapeamento do tipo de estrutura aqui tratada em plataformas continentais rasas, onde estão disponíveis dados sísmicos convencionais (dados legados da indústria de petróleo).

A integração de dados de subsuperfície, sensoriamento remoto e informações de superfície, permitiu identificar 14 SV e 6 depressões alongadas, interpretadas aqui como possíveis meandros dos Shelf Valleys na plataforma continental da bacia marginal de Pernambuco. Essas informações podem complementar o banco de dados da GEBCO, que não possui informações sobre essas estruturas.

A análise hidrogeográfica permitiu correlacionar os rios mais importantes da região e os SV na plataforma, e foi possível com isso definir uma relação entre os rios atuais e as estruturas da plataforma continental. Os resultados também mostraram que os canais estão mais expostos na região distal da plataforma continental e que o forte controle tectônico exercido sobre os rios na zona costeira adjacente agiu da mesma maneira durante a formação dos Shelf Valleys.

A partir da integração de dados no segundo artigo, a morfologia dos três SV, o estudo de lineamentos magnéticos e o mapeamento de estruturas rúpteis de subsuperfície, detectadas a partir dos dados de sísmica de reflexão, permitiram concluir que existe uma influência direta de falhas e fraturas na formação dos SV-3 e SV- 1. Por outro lado, o SV-2 mostrou-se linear, provavelmente totalmente encaixado em uma falha, indicando que pode ser suscetível à influência dos processos tectônicos.

Os resultados deste trabalho permitem supor que o rio pretérito, que flui na plataforma continental exposta, seguiu o caminho menos energético, tendo seu curso sido controlado por falhas pré-existentes. Esse comportamento é evidente nas três partes ampliadas. O SV 3-A mostra uma parte em que o Sv faz uma curva aproximada de 90º e é coincidente com um lineamento magnético. O SV 3-B mostra um meandro do SV e uma curva coincidente com os lineamentos magnéticos e as fraturas mapeadas. O SV 3-C mostra um meandro de SV coincidente com lineamentos magnéticos e estruturas de falhas que foram interpretadas nos dados sísmicos

O SV-1 é mais profundo que o SV-2 e mais raso que o SV-3. Considerando interpretação utilizada para as feições observadas através dos dados batimétricos filtrados, propõe-se que o SV 1-A mostra um pequeno meandro Sv para o norte coincidente com dois lineamentos magnéticos e falhas. O SV 1-A mostra um meandro SV grande e os lineamentos magnéticos têm aproximadamente o mesmo formato do meandro. O SV 1-C mostra um meandro do SV para o sul coincidente com lineamentos magnéticos e fraturas mapeadas no dado sísmico

No caso do SV-2, o vale escavado não possui meandros e não há influência evidente de falhas e fraturas. O SV 2-A mostra uma porção em que o Sv faz uma curva aproximada de 90º e é coincidente com um lineamento magnético e fraturas identificadas no dado sísmico. O SV 2-B mostra uma interrupção do SV coincidente com o um lineamento magnético e fraturas.

O estudo de dados sísmicos 2D mostrou que a cobertura desde o Mioceno Médio que cobre os Shelf Valleys foi afetada por falhas, falhas de alto ângulo formadas sob regime transcorrente criado a partir da reativação de zonas de cisalhamento. Principalmente nos canais, pode-se encontrar regiões com estruturas de padrões flor negativos e positivos. Essas falhas associadas aos lineamentos magnéticos sugerem um processo de encaixe dos vales e reativação de estruturas que afetaram os depósitos sob o regime tectônico durante o Quaternário superior.

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