UNIVERSIDADE FEDERAL FLUMINENSE
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DEPARTAMENTO DE GEOLOGIA E GEOFÍSICA

Tectonic Characterization of the Central Bransfield Strait Using Seismic Reflection Data

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Projeto Final do Curso de Graduação em Geofísica

Niterói – RJ, Brasil
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MATHEUS LIMA LEMOS DE OLIVEIRA

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Work presented to the Geophysics Bachelor Course of the Federal Fluminense University, as a requirement to obtain the degree of Bachelor in Geophysics.

Supervisor:
PhD. Arthur Ayres Neto - UFF

Co-supervisors:
PhD. Nicholas Hayman - UTIG
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ABSTRACT

The Project has as objective the study of the Central Bransfield Strait extensional evolution, localized in the Bransfield Strait, between the Antarctic Peninsula (AP) and the South Shetland Islands (SSI). The Bransfield Strait is a region where continental crust is in initial process of rifting, which still presents unsolved questions regarding its geologic evolution. The research motivation consists of the analysis and discussion of the geological processes involved in the basin formation, from the tectonic and seismic stratigraphic point of view. Thus, utilizing seismic reflection and bathymetry data, the project pursuits to contribute with the analysis of topics that are not completely solved regarding the geological evolution of the strait, for instance: the tectonics associated with the margins asymmetric spreading, the oceanic crust development in the region and the relationship between the sedimentary package found in the basin with the strait's extension. The research methods consist of an initial bibliographic review, the interpretation of processed seismic data and the discussion of results, comparing the progress of this work with studies concluded by other authors.

Keywords: Central Bransfield Strait; Antarctic Peninsula; Seismic Interpretation

RESUMO

O projeto tem como objetivo de estudar a evolução extensional da porção central do Estreito de Bransfield, localizada entre a Península Antártica (AP) e as Ilhas Shetland do Sul (SSI). O Estreito de Bransfield é uma região onde a crosta continental está em processo inicial de rifteamento, o qual ainda apresenta questões não respondidas quanto a sua evolução geológica. A motivação da pesquisa consiste na análise e na discussão dos processos geológicos envolvidos na formação da bacia, sob o ponto de vista tectônico e sismoestratigráfico. Desta forma, utilizando dados de sísmica de reflexão e dados de batimetria, o projeto busca contribuir na análise de alguns tópicos que ainda não estão completamente solucionados no estudo geológico do estreito, como por exemplo: a tectônica associada ao afastamento assimétrico da margem, o desenvolvimento da crosta oceânica na região, além da relação entre o pacote sedimentar encontrado na bacia com e o processo de extensão do estreito. A metodologia do trabalho conta com uma revisão bibliográfica inicial, com a interpretação de dados sísmicos processados, além da discussão dos resultados obtidos no trabalho, comparando-os com os estudos concluídos de outros autores.

Palavras-chave: Estreito de Bransfield; Península Antártica; Intepretação Sísmica

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LIST OF EQUATIONS

LIST OF ABBREVIATIONS

AP	Antarctic Peninsula
BSR	Bottom-Simulating Reflector
IUEM	Institut Universitaire Européen de la Mer
LDEO	Lamont Doherty Earth Observatory
SSI	South Shetland Islands
SST	South Shetland Trench
UTIG	University of Texas Institute for Geophysics

CONTENTS

1 INTRODUCTION

1.1 RESEARCH AREA

The Bransfield Strait is a back-arc basin in active extension, between the Antarctic Peninsula margin in SE, the South Shetland Islands in NW and the Scotia plate in the extreme NE. The strait is an elongated basin trending NE-SW and constituting an area of approximately 40,000 km^2. On figure 1, the main sectors are indicated by red dots. The Bridgeman and Deception volcanic islands identify geographic limits that define the area focused in this research, the Central Bransfield Basin.

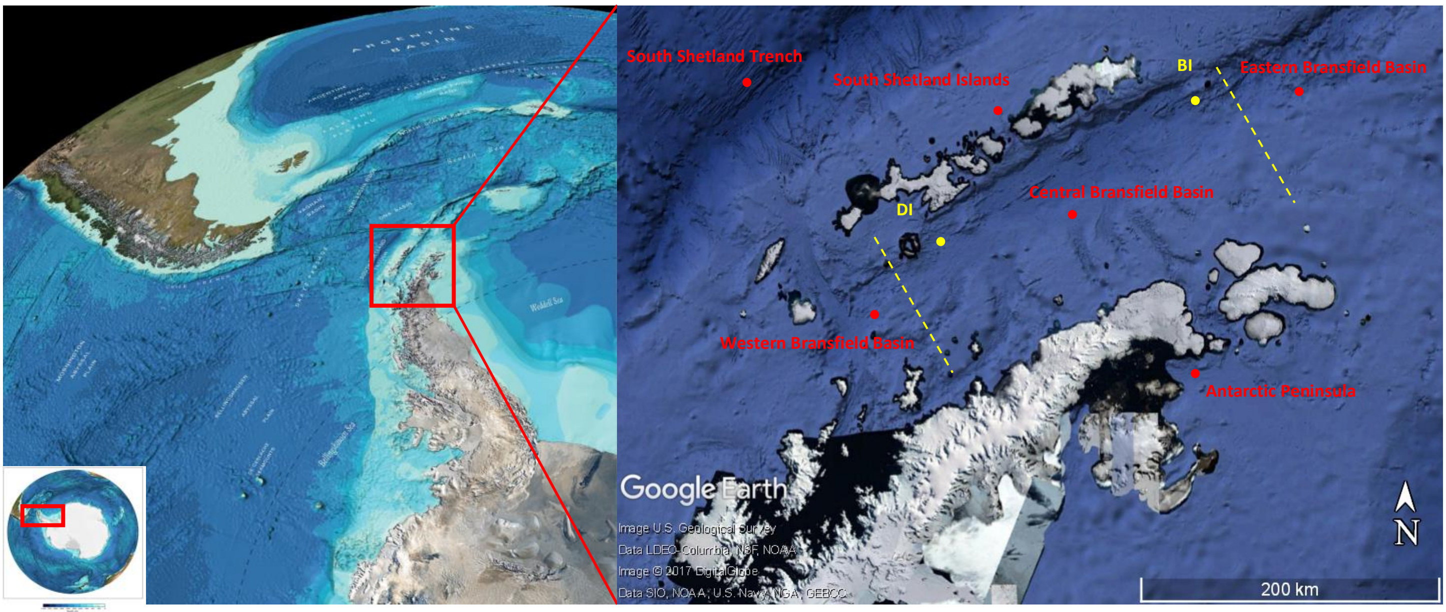

Figure 1. Location map. The two yellow dotted lines geographically delimitate the Central Bransfield Basin, between the Deception Island (DI) and Bridgeman Island (BI). Modified from General Bathymetric Chart of the Oceans and Google Earth.

1.2 OBJECTIVES

The main goal of this work is to understand and characterize the Central Bransfield Rift spreading, by studying the tectonic evolution in its margins and analyzing major signatures developed since the beginning of the rifting event, such as faulting, volcanic intrusions and sedimentary sequences. In order to conduce the research, multichannel seismic profiles and bathymetry data were used to interpret tectono-sedimentary phases and seafloor morphology. By integrating the data of previous researchers, this work intends to contribute to the understanding of the mechanisms affecting the extensional tectonism between the Antarctic Peninsula and the South Shetland Islands, also considering the hypothesis that active magmatism could be associated with the present rifting process in the region. The Bransfield Strait is known as an area of complex geological setting, due to the diversity of tectonic plate boundaries (passive, active and transformant) that formed its basins and developed the Antarctic Peninsula margins. As a motivation, the work will attempt to investigate extensional phases that can be observed in geophysical data mentioned before.

Some of the scientific questions to be discussed in this work are:

- What could be the nature of the tectonics that developed the asymmetric spreading of the margins?
- Could it be possible to associate the magmatic intrusions along the rift with its extensional faulting?
- Is it possible to characterize the sedimentation on the margins and relate them with tectono-sedimentary phases of extension?

1.3 Geologic Settings

1.3.1 Geomorphology of the Central Bransfield Strait

The Bransfield Strait is represented as an asymmetric basin elongated in the NE-SW direction (Figure 2). The strait approximated dimensions are 400 km long and 100 km wide, while the rift itself is 15 – 20 km wide (Lawver et al., 1995). The basin asymmetry is defined by a short (approximately 5 km wide) and steep (4.8º ~ 10.9º) South Shetland Islands margin and a long (approximately 60 km wide) and gentle (2.2º ~ 4.2º) Antarctic Peninsula margin (Bochu et al., 1994).

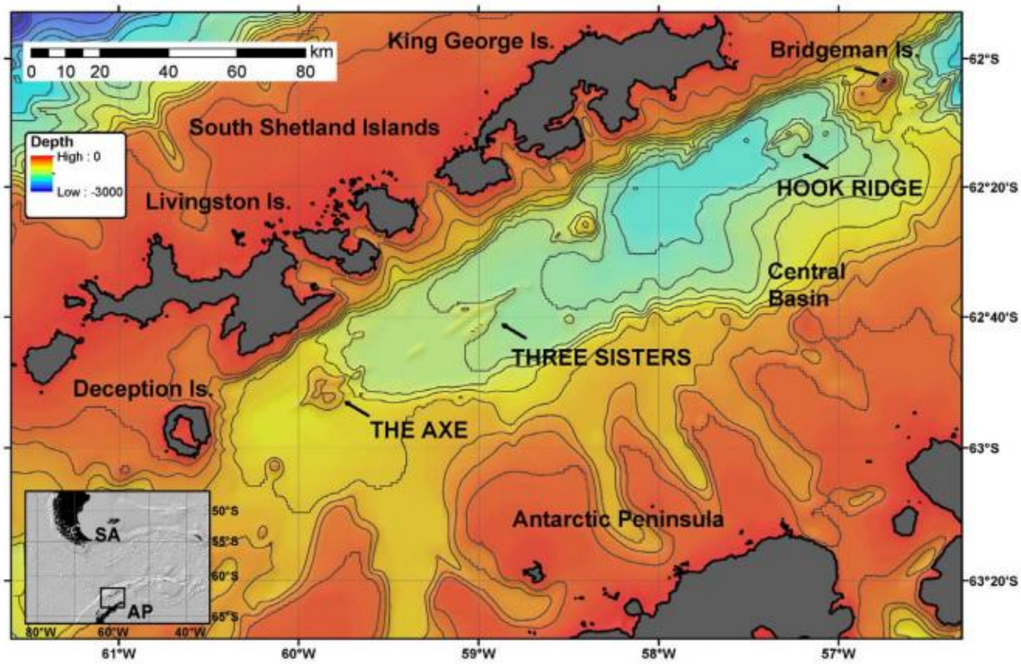

Figure 2. Bathymetric map of the strait. The NE-SW alignment of volcanic highs can be noticed, as well as the seafloor depth increasing towards the eastern basin sector. The arrows identify important volcanic elevations in the region. Source Aquilina et al. (2013).

The Bransfield Strait is generally divided into three basins: western, central and eastern (Lawver et al., 1995; Galindo-Zaldívar et al., 2006). At the western basin, southwest of the Deception Island, basement's mean depth is approximately 1000 meters. This portion encounters in its initial rifting stage although it is well distributed with intense normal faulting up to the seafloor. At the central basin, between

Deception Island and Bridgeman Island, basement depth measures up to 2000 meters. Lawver et al. (1995) observed in bathymetric maps that this basin is roughly 40 km wide and 200 km long. On the Antarctic Peninsula margin, the central basin has four large scale glacial throughs up to 250 meters deep, which carves the continental shelf basin ward (Imbo et al., 2003). Finally, the eastern basin, between Bridgeman Island and Clarence Island, presents maximum depth around 2740 meters, being 24 km wide and 120 km long.

In the Central Bransfield Basin, the main area of research of this work, volcanic edifices are found along a ENE-WSW trend in the seafloor (Figure 2). These volcanic plugs are younger than the rift, proposed by Lawver et al. (1995) to be Pleistocene formations. They constitute a central volcanic lineation, associated with the same extensional tectonics under development in the elongated strait (Gamboa and Maldonado, 1990; Keller and Fisk, 1992).

Barker and Austin (1998) studied the central basin by geographically subdividing it in three sectors: southwestern, central and northeastern, although these three sectors do not present physical structures that separate them into sub basins, such as a submarine high. This work studies the three sectors of the central Bransfield basin based on morphological, sedimentary and structural settings observed in the seismic and bathymetric data interpreted. The description of the data analyzed is presented in the results and discussion chapter of this text.

1.3.2 Antarctic Peninsula and South America breakup

During the early Jurassic (200 Ma), the Antarctic Peninsula formed a convergent margin with the South America in the supercontinent Gondwana (Barker 1982). The relative motion of the areas that turned to be the Antarctic Peninsula and the South America were reconstructed by Cunninghan et al. (1995), presenting the tectonic motions that fragmented these two regions into continental margins.

Since the last 84 Ma, Antarctic Peninsula and South America presented a common westward displacement relative to Africa, moving as a common block. During their separation from Africa, South America moved faster to the west than the Antarctic Peninsula. This setting caused these two areas to initiate a continental break up. The different relative velocity between the two continents lead to the development of a strike-slip faulting regime. Driven not only by an extensional displacement but also by distinct spreading velocities relative to the African plate, accelerated between 55-40 Ma, Antarctic and South America developed the Drake Passage and the Scotia Sea opening, connecting the Atlantic and the Pacific oceans by spreading both continental plates (Cunningham et al., 1995).

In addition to the east-west movement, Cunninghan et al. (1995) indicate that Antarctic Peninsula and South America started a north-south relative movement between them since 45 Ma. During this setting, the two continents developed a divergent regime, advancing the fragmentation between the two mentioned areas. Following the beginning of the north-south displacement, Antarctic Peninsula and South America drifted in a relative NW-SE direction, majorly dominated by the east-west transcurrent regime.

During the 40-20 Ma interval, north-south divergent movement between Antarctic Peninsula and South America increased in rate of expansion, until the stage when the two continents separated completely about 30 Ma (Cunninghan et al., 1995). Figure 3 presents motion reconstruction maps of the South America and Antarctic Peninsula, illustrating the dimension of the separation since 80 Ma.

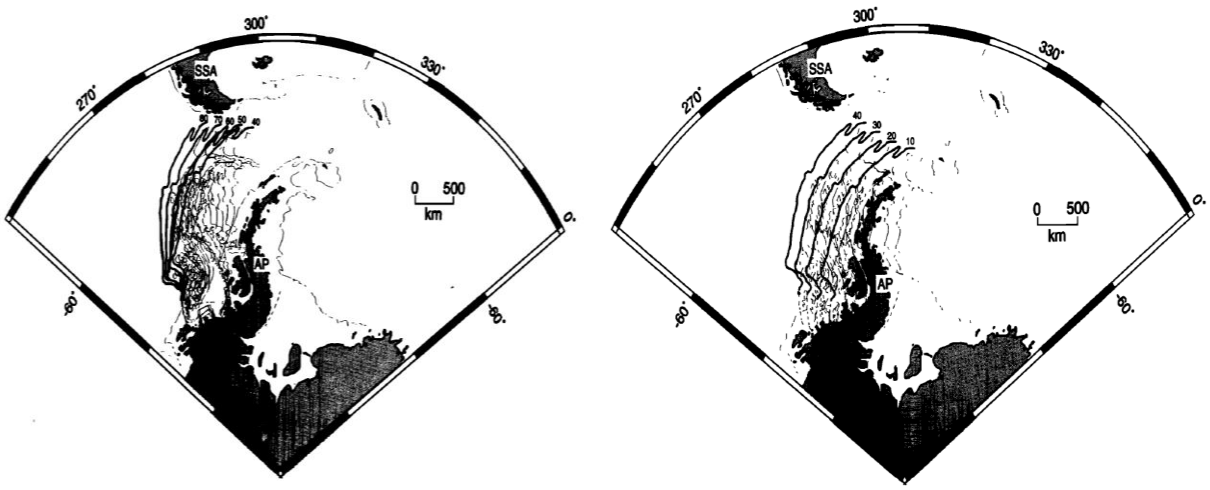

Figure 3. Reconstruction of the Antarctic Peninsula and the South America spreading between 80-10 Ma. The left figure demonstrates the east-west predominant relative movement between plates, while the right figure identifies an increase on the north-south movement component (Cunningham et al., 1995).

According to Cunningham et al. (1995), the proportion of crustal movement would be approximately 1320 km along the east-west strike-slip displacement and 490 km along north-south divergent displacement. In west Antarctic, fracture zones such as the Hero and the Shackleton Fracture zones (figure 4), are examples of inactive strike-slip faults formed during the NW-SE spreading of the Antarctic and the South America plates.

1.3.3 Bransfield Strait

Localized in the Antarctic Peninsula continental shelf, the Bransfield Strait was set after the separation between the Antarctic Peninsula and the South America was well developed. The basin was originated from the subduction of the former Phoenix Plate beneath the Antarctic Plate, in the South Shetland Trench (Barker et al., 1998). The compressive tectonic developed the South Shetland Islands arc and the Bransfield Strait back-arc basin (Figure 4).

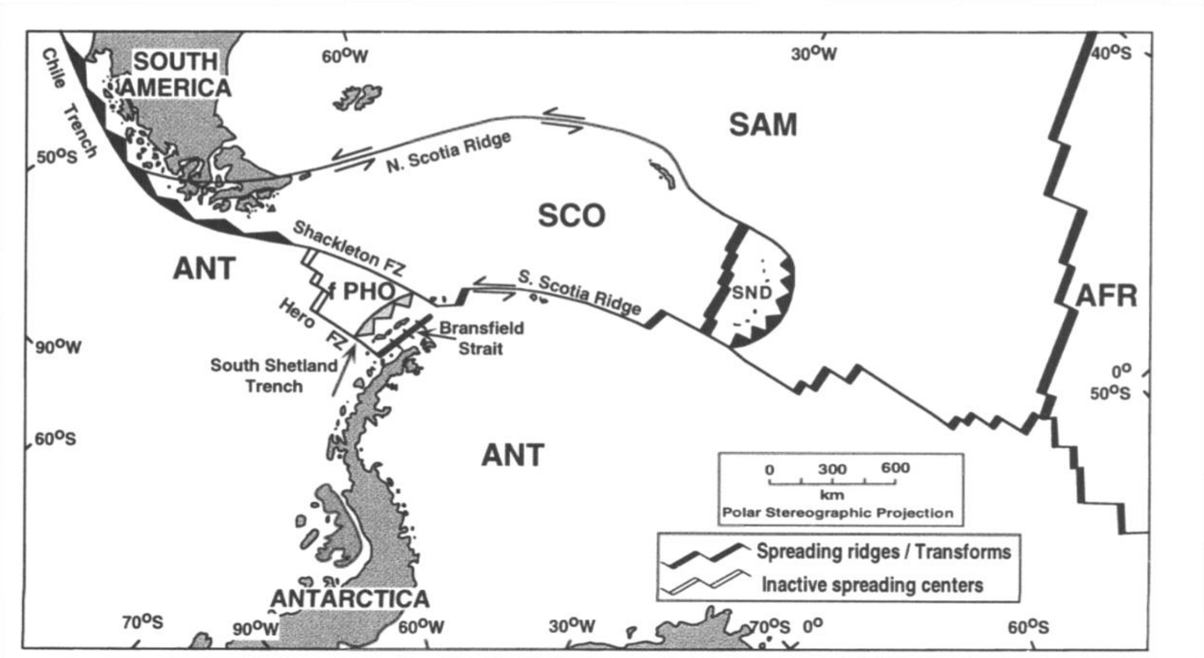

Figure 4. Regional tectonic setting of the Bransfield Strait. ANT = Antarctic Plate; f PHO = Former Phoenix Plate; SCO = Scotia Plate; SND = Sandwich Plate; SAM = South America Plate; AFR = Africa Plate. Source: Lawver et al., 1995.

The Phoenix Plate (Figure 5) is now extinct due to its subduction at the South Shetland Trench and consequent accretion beneath the Antarctic Plate. As the former Phoenix Plate was consumed by the subduction in the Antarctic Plate convergent margin, the Antarctic-Phoenix inactive spreading center initiated its collision with the submarine trench, from the Hero Fracture Zone towards the Shackleton Fracture Zone.

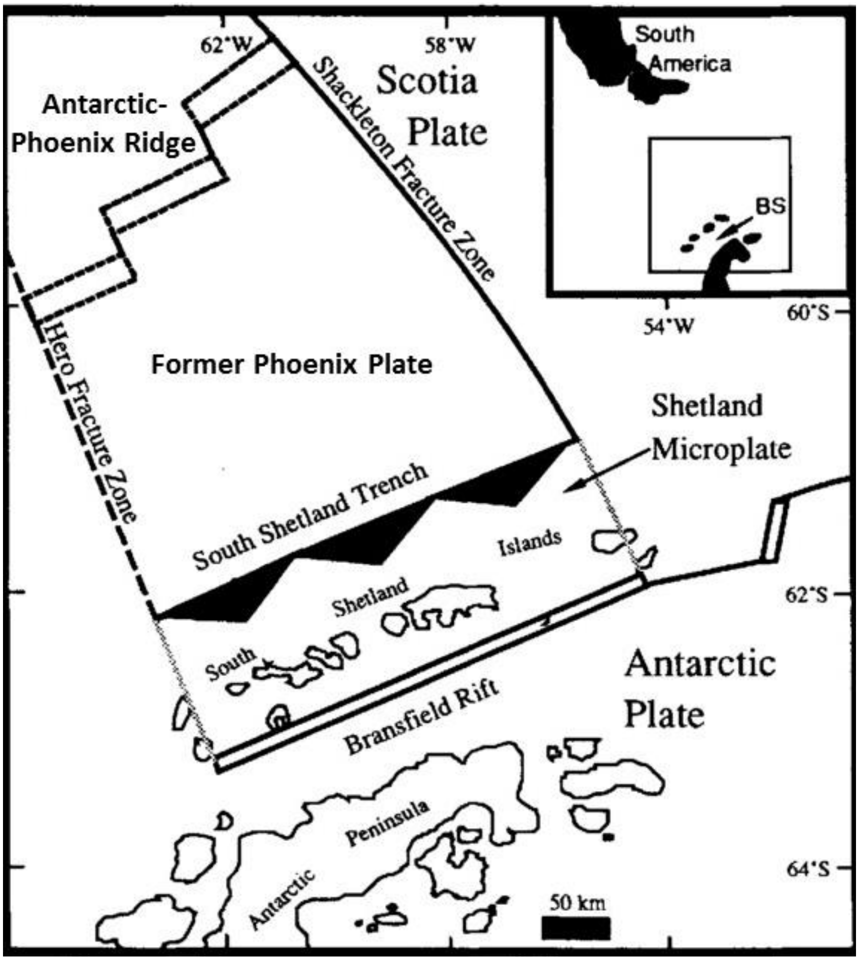

Figure 5. Tectonic setting of the former Phoenix Plate. BS = Bransfield Strait. Modified from Keller and Fisk, 1992.

Barker et al. (1998) affirm that collisions between the Antarctic-Phoenix ridge crest and the continental trench stopped the subduction of the former Phoenix Plate. Successions of ridge-trench collisions are related in ages ranging between 54-45 Ma, SW of the Heezen Fracture Zone, to 3.1-3.5 Ma, SW of the Hero Fracture Zone (Barker et al., 1998). The portion of plate observed NE of the Hero Fracture zone, SW of the Shackleton Fracture Zone and NW of the South Shetland Islands is the last remnant of the Phoenix Plate, also known as the Aluk Plate.

At present time, the Phoenix Plate is considered part of the Antarctic Plate due to a probable interruption in the subduction movement. Meanwhile Barker et al. (1998) believe that the former Phoenix Plate subduction has already been interrupted. However, Solari et al. (2008) suggest that the plate still undergoes subduction. This is evidenced by earthquakes found at large depth (55 km), which is considered by Pelayo and Wiens (1989) to be associated with the slow Phoenix Plate subduction. Altogether, it is common sense that the Phoenix Plate subduction is completely or nearly inactive. Moreover, it was also strongly proved that the Phoenix Plate subduction under the Antarctic plate is the main factor responsible for triggering the active Bransfield Strait extension (Barker et al., 1998; Galindo-Zaldívar et al., 2006). Besides the inactive or nearly active compressive movement, it is also considered that the transforming boundary between the Antarctic and the Scotia plates might be influencing the extension of the Bransfield Strait by a transtensive movement of sinistral faults (Galindo-Zaldívar et al., 2006).

1.3.4 Extensional mechanisms for the Bransfield Strait expansion

Different extensional mechanisms are attributed by several authors to explain what drives the strait expansion. One possible mechanism that started the Bransfield Strait extension was the rollback caused by the Phoenix Plate beneath the Antarctic Plate, considered to have initiated around 4 Ma, when the collisions of the Phoenix-Antarctic ridge crest with the trench stopped the subduction (Barker et al., 1998; Pelayo and Wiens, 1989; Galindo-Zaldívar et al., 2006). The trench rollback led the South Shetland Islands to migrate oceanward (NW) and caused the Bransfield Strait to extend in the same direction (Figure 6). The extension advance is evidenced by the onset of large normal faults in the South Shetland Islands and the Antarctic Peninsula margins, together with volcanic plugs found at the strait seafloor. Thus, the Bransfield Strait opening is widely suggested to be younger than 4 Ma, given the interpretation that its extension started as a result of the interruption of the plate subduction (Barker et al., 1998).

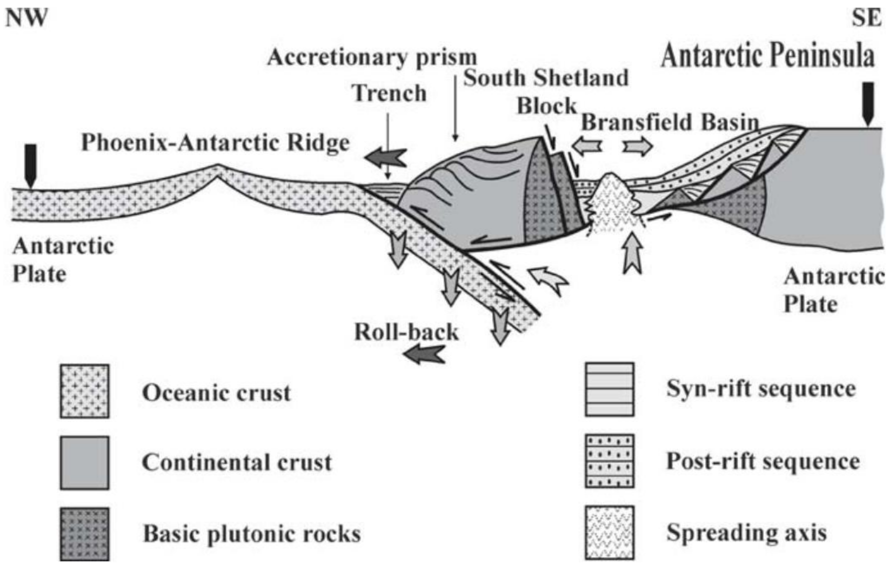

Figure 6. Tectonic sketch interpretation for the tectonic mechanism associated with the Bransfield Strait opening. Taken from Galindo-Zaldívar et al. (2006)

Similarly, others believe that the Bransfield Strait spreading is also in part influenced by the transformant tectonics at the Antarctic-Scotia plate boundary (Galindo-Zaldívar et al., 1996; Galindo-Zaldívar et al., 2006; González-Casado et al., 2000). The transformant movement is mentioned to have originated at the eastern section of the strait, in which the basin encounters an active transcurrent zone within the South Scotia Ridge. Such movement is produced by the plate boundary motion, resulting in transtensive sinistral faults in the Antarctic Plate, that extends the basin and develops the normal NE-SW faults observed at the margins (Galindo-Zaldívar et al., 1996).

Both mechanisms of extension cited previously have an impact on the initiation of the basin extension, although a substantial number of researchers attribute the rollback as the most influent. It must be considered that the asymmetric physiography of the margins and the varied opening rates along the NE-SW direction of the basin could be a combined effect of the transtensive extension occurring at the Antarctic-Scotia plate boundary and the rollback tension originated from the Phoenix-Antarctic plates convergence.

1.4 The seismic reflection method

Seismic reflection is a geophysical method used to investigate geological layers and structures present beneath the surface. This method is based on the propagation of acoustic energy, produced naturally by earthquakes or artificially by mechanical sources. Such seismic energy travels along layers in the interior of the Earth and is recorded by geophysical devices at the surface.

Among different methods, seismic is the most applied geophysical technique for investigation of sedimentary basins and geological deposits, due to its good accuracy, resolution and penetration (Telford et al., 1990). Seismic survey can be summarized as the generation of seismic waves, controlled by sources, and the record of travel times, associated with the seismic energy registered by a receiver. When surveying is on course, source and receivers are aligned in a straight line in the same surface, according to a pre-determined geometry that efficiently covers part of the geology beneath the surface. Thus, acquiring travel times for seismic pulses generated by a source, seismic wave paths can be calculated based on velocity of sonic waves traveling in each interface (Telford et al., 1990).

In this work, the seismic method is vital for detecting tectonic structures and sedimentary packages formed since the origin of the Bransfield Basin, contributing for a concrete analysis of the rift extension. Thus, using seismic data acquired from geophysical surveys at the Bransfield Strait, it was possible to determine regional subsurface structures reflected on physical properties of the rocks (Kearey et al., 2002).

1.4.1 Marine seismic surveying

For marine seismic surveying, sources (example: boomers, air guns, sparkers) and hydrophones are towed on the water surface by a boat. Seismic waves sent by sources travel through layers in subsurface, reflect in the opposite direction and return to the surface, where hydrophones register their arrival (figure 7).

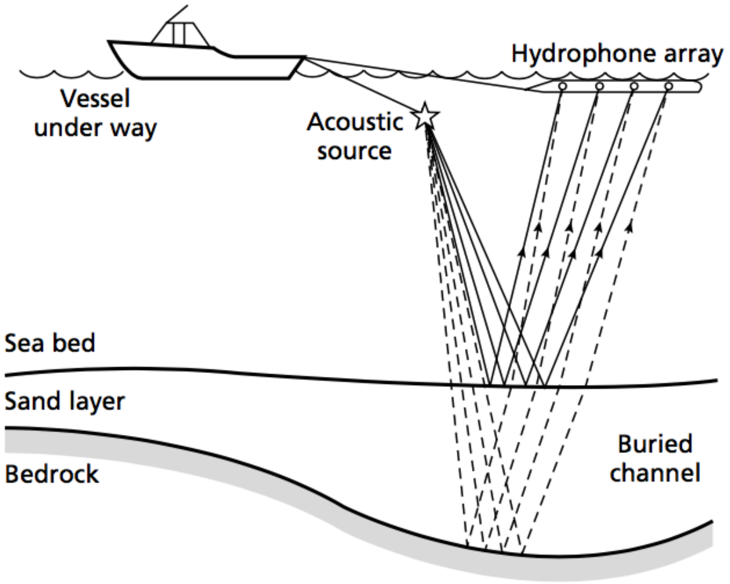

Figure 7. An example of a marine seismic reflection survey. key et al., 2002.

1.4.2 Seismic waves propagation

The propagation of a seismic pulse is determined by physical properties of a rock. The seismic velocity of a wave is linked to elastic properties of the medium in which it travels, in special, to density. When a wave encounters an interface between two rocks that contain distinct physical properties, the energy of the seismic pulse is converted into a reflection towards the initial rock and refraction towards the following rock (figure 8). In addition, the energy amplitude transmitted depends on the rock density (based on its grain's matrix), on the wave velocity in a rock and the angle of incidence of the ray path (Kearey et al., 2002).

During seismic acquisition, artificial seismic waves created by controlled sources travel through the subsurface, transmitting energy into the layers. The energy propagates in front waves towards the interior of the Earth, reflecting and refracting when it interacts with boundaries between different geological strata. For the seismic reflection method, geophones and hydrophones are used to record the reflected waves, analyzing the arrival time for different seismic pulses shot by the source.

Hence, the acoustic impedance (equation 1) is the physical property that relates the transmitted energy amplitude and the characteristics a rock. The acoustic impedance of a rock is defined by the product of its density (ρ) and the wave velocity (v) (Kearey et al., 2002). Also, the reflection coefficient (equation 2) measures the ratio of amplitude between reflected and refracted energy propagated when a seismic wave interacts with rocks that presents contrasting acoustic impedances (Zoeppritz, 1919, apud Kearey et al., 2002).

$$Z = \rho v$$

Equation 1. Acoustic impedance.

$$R = \frac{A_1}{A_0} = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

Equation 2. Acoustic reflection.

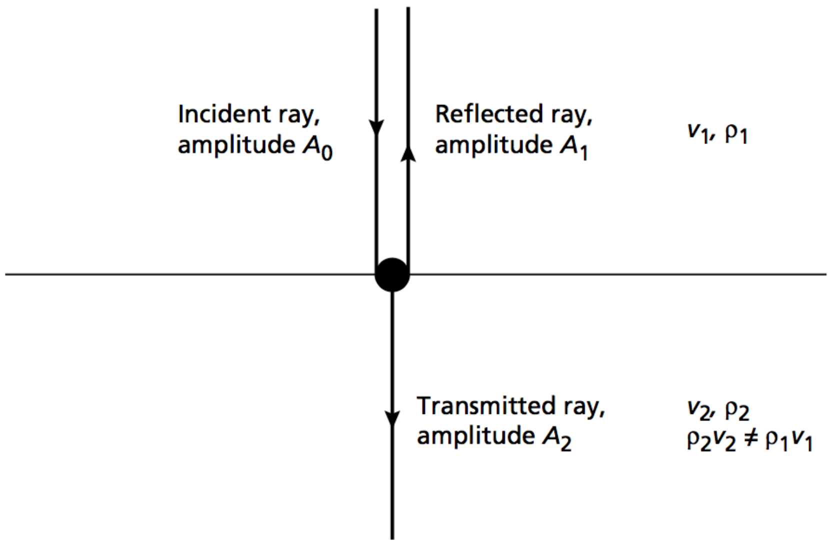

Figure 8. Propagation of rays associated with a normally incident ray on an interface with contrasting acoustic impedance. Kearey et al., 2002.

Conversely, each rock contain an acoustic impedance that defines the acoustic properties of a traveling wave. Although, when an incident wave is transmitted through layers with highly contrasting impedance, the amount of reflected energy is higher than the energy refracted. This results in stronger signal recorded by the sensors at the surface. Finally, these reflections can be observed at the seismic record. The seismic reflector represents a boundary between rocks with contrasting physical properties, and each reflective event observed in a seismic section is associated with a geological layer.

2 METHODS

This work focuses on interpreting and analyzing seismic and bathymetry data to characterize the extensional tectonic occurring in the Central Bransfield Strait. Therefore, 10 multichannel seismic lines, obtained in 1991 by the LDEO and the UTIG on the R/V Maurice Ewing expedition EW 9101 project, were used.

The seismic lines were loaded on the interpreting software Kingdom, where seismic interfaces associated with the basin extension history were mapped, such as the basement width and depth, volcanic mounds, faults and sedimentary packages.

The bathymetry was loaded on the mapping software Surfer, which plotted the data and produced contour maps where seafloor morphology, volcanic lineation and margins' steepness were interpreted.

3 RESULTS AND DISCUSSIONS

Seismic interpretations are presented in this section divided in the following topics: 1) Margin extension and fault association, 2) Distribution of volcanic formations, 3) Central Bransfield Basin bathymetry, 4) Analysis of sedimentary sequences and 5) Stratigraphic sequences related with the basin extension.

3.1 Margin extension and fault association

The results were grouped into 3 sectors with respect to the major characteristics of basin extension and fault distribution observed in 10 seismic profiles crossing the basin (Figure 9). The eastern sector comprehends the seismic lines AP-2, AP-3, AP-4 and AP-05. The central sector comprehends the seismic lines AP-6, AP-7 and AP-8. Finally, the western sector comprehends the seismic lines AP-9, AP-10 and AP-11.

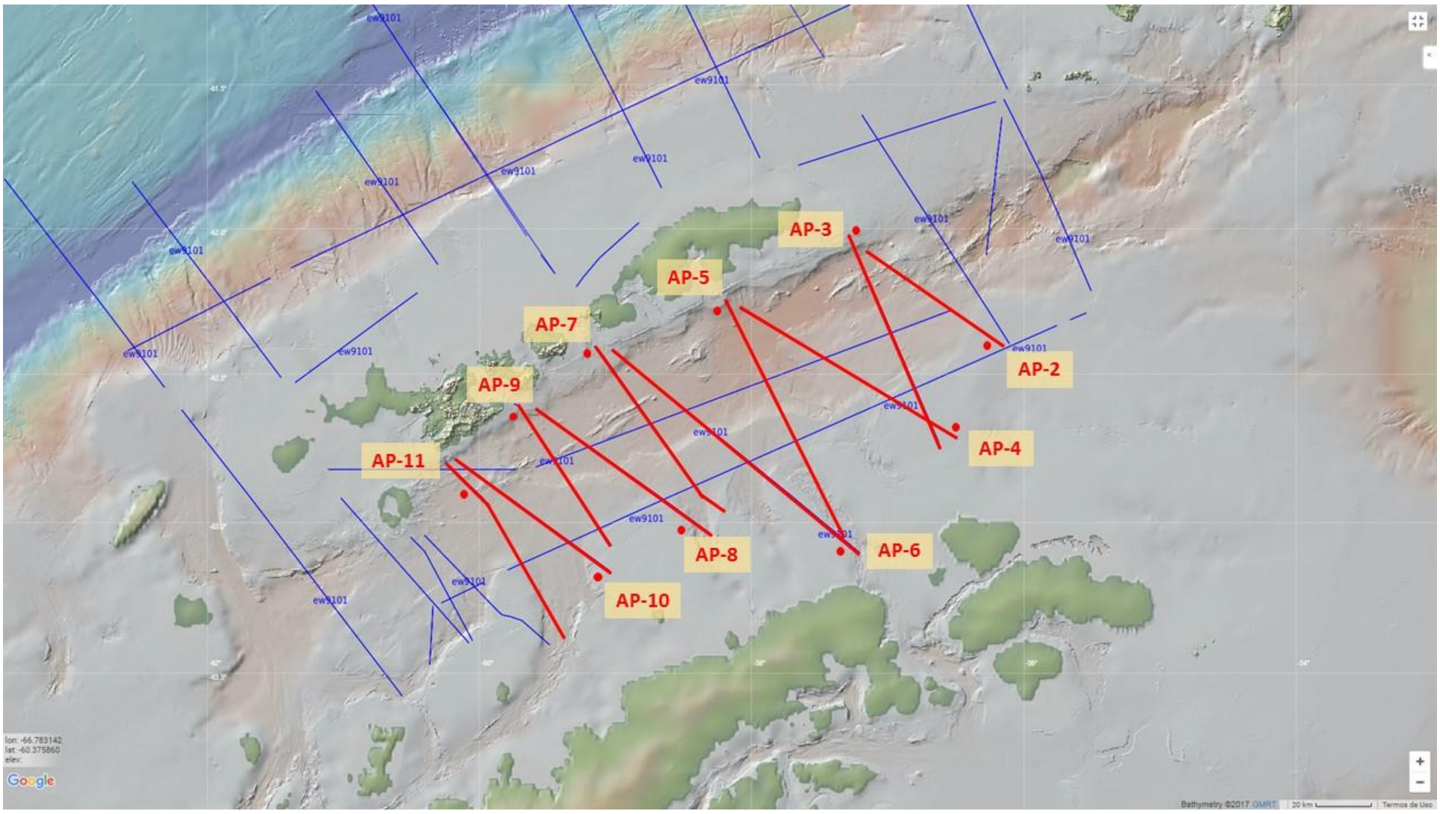

Figure 9. Bathymetric map with the seismic survey acquired during the EW9101 expedition. Seismic lines analyzed in this work are highlighted in red. Map obtained from the Lamont-Doherty Earth Observatory – Marine Geoscience Data System portal.

Seismic profiles of the Central Bransfield Basin suggest that the main style of tectonic faults present are normal (Figure 10), with a NW-SE trend. These fault structures are observed in seismic profiles along all sectors of the Central Bransfield Basin and their differences in size and depth suggests that a non-uniform opening event is active in the strait. The distribution of faults is greater over the Antarctic Peninsula margin than in the South Shetland Islands margin, suggesting that the extension is asymmetric and that spreading could be more advanced over the Antarctic Peninsula margin.

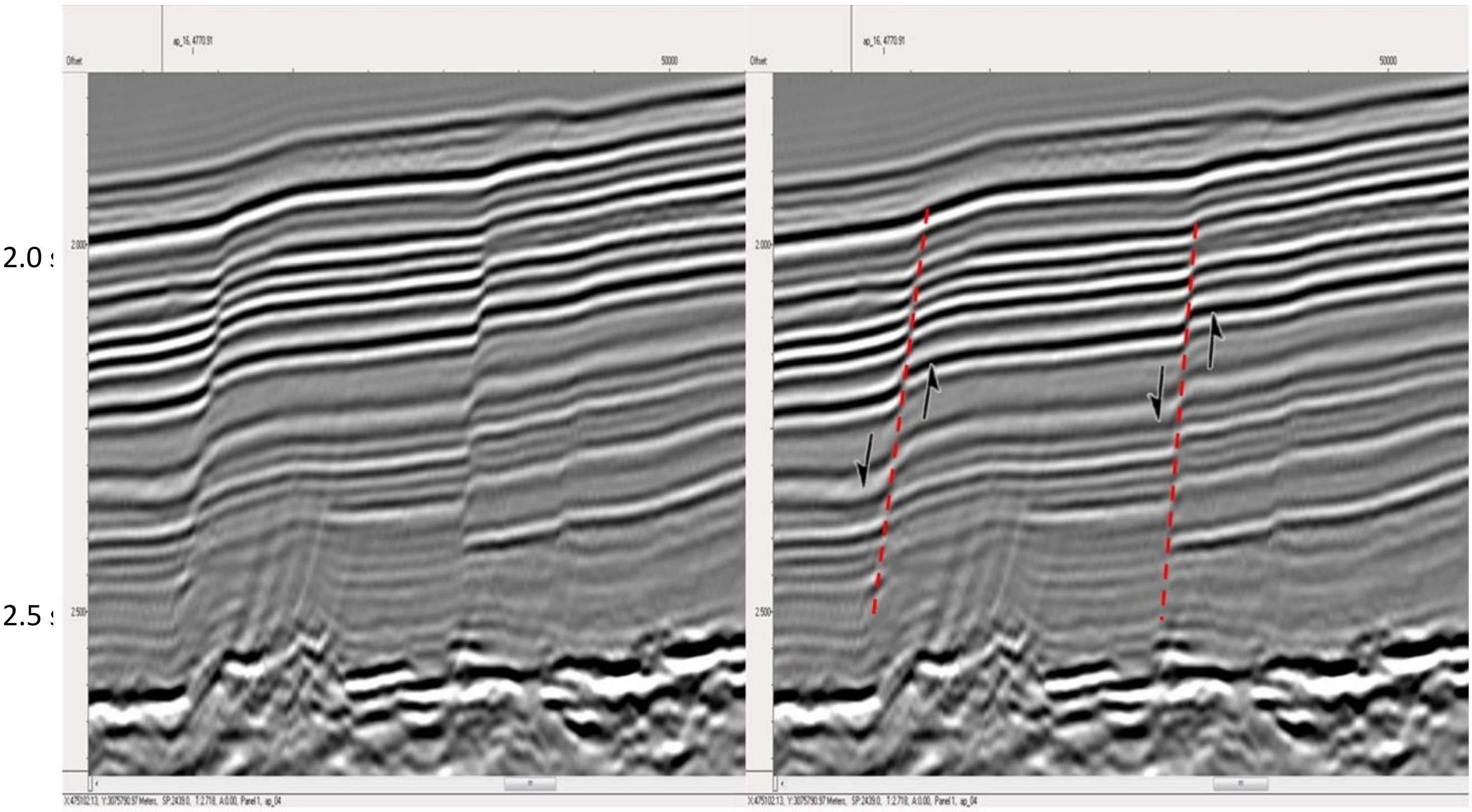

Figure 10. Example of normal faults observed on profile AP-04. The red dotted lines are interpretations of the faults, while the black arrows represent the movement between the faulted blocks.

3.1.1 Eastern sector

The eastern sector is geographically close to the Bridgeman Island volcanic formation. Extensions between the Antarctic Peninsula and the South Shetland Island margins are the largest observed in the central strait and measures between 50-60 km wide. Seafloor depths across the central axis of the eastern sector were determined using bathymetry in correlation with seismic data. Depths observed around the active center of extension measures between 1800-2000 meters approximately.

The extension is tectonically dominated by normal faults. Seismic lines AP-03 (Figure 11) and AP-04 (Figure 12) show examples of these faults distributions on both margins, with length between 1.2 and 0.6 seconds TWT. On both profiles, normal faults extend the crust and conduce magmatic intrusions towards the basement and the sedimentary column. Furthermore, seaward dipping reflectors can be pointed out in the figures to show that the accommodation of sedimentary rocks is advancing towards the center of extension of the basin. Faulting occur in greater quantity along the wide Antarctic Peninsula margin, in which large sedimentary packages are intensely deformed by recent faulting, than in the narrower South Shetland Islands margin. The superior number of faults, as well as their lengths suggest that the Antarctic Peninsula was more distended by the extension than the South Shetland Islands margin.

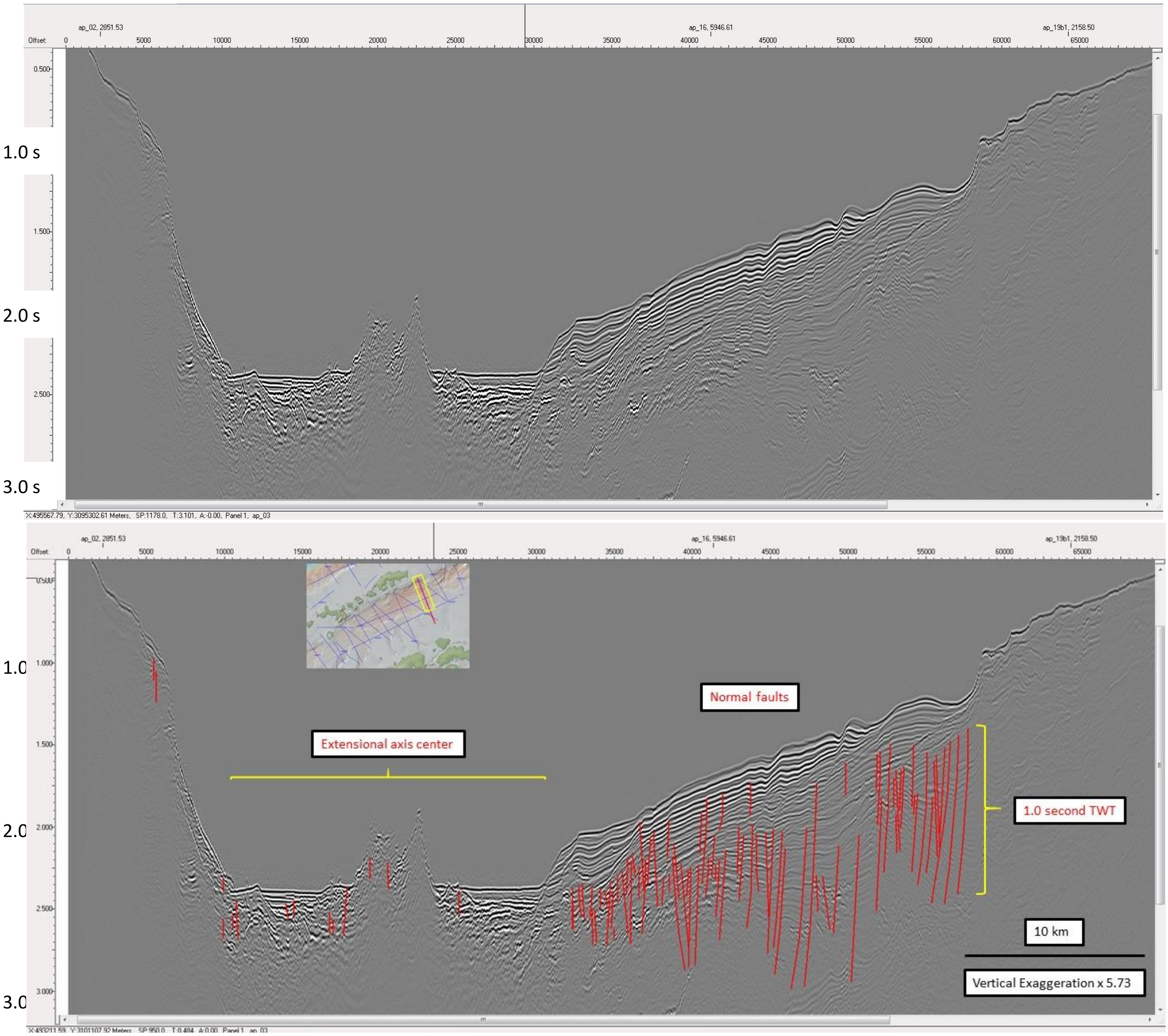

Figure 11. Seismic line AP-03 in the eastern sector of the Central Bransfield Basin.

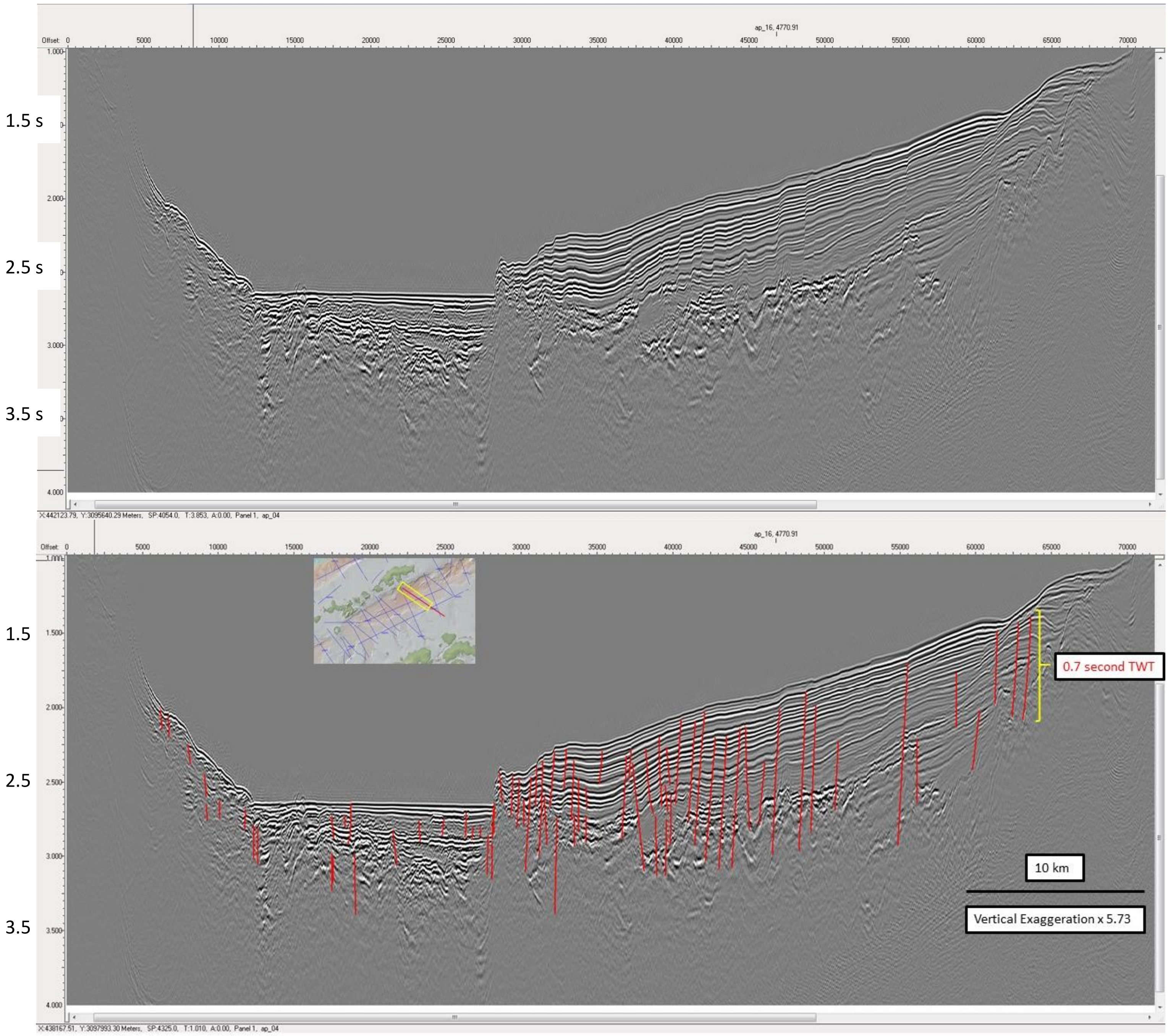

Figure 12. Seismic line AP-04 in the eastern sector of the Central Bransfield Basin.

3.1.2 Central sector

The central sector, compared to the eastern sector, is less developed in terms of tectonic extension and in the size of the faults. The distance between the Antarctic Peninsula and the South Shetland Island margins in this region is approximately 40-50 km. In respect to the basement subsidence, mean seafloor depth along the center of expansion range from 1300 to 1700 meters.

Seismic profile AP-06 (Figure 13), reveal a predominance of planar normal faults on both margins of the basin central sector, displaying lengths between 0.4 and 0.1 seconds TWT, where these faults seem steeper in dip compared to faults in the eastern sector. The central sector, likewise, presents normal faults that act as conduits for magmatic intrusions that reach shallow sedimentary rocks and, eventually, the seafloor.

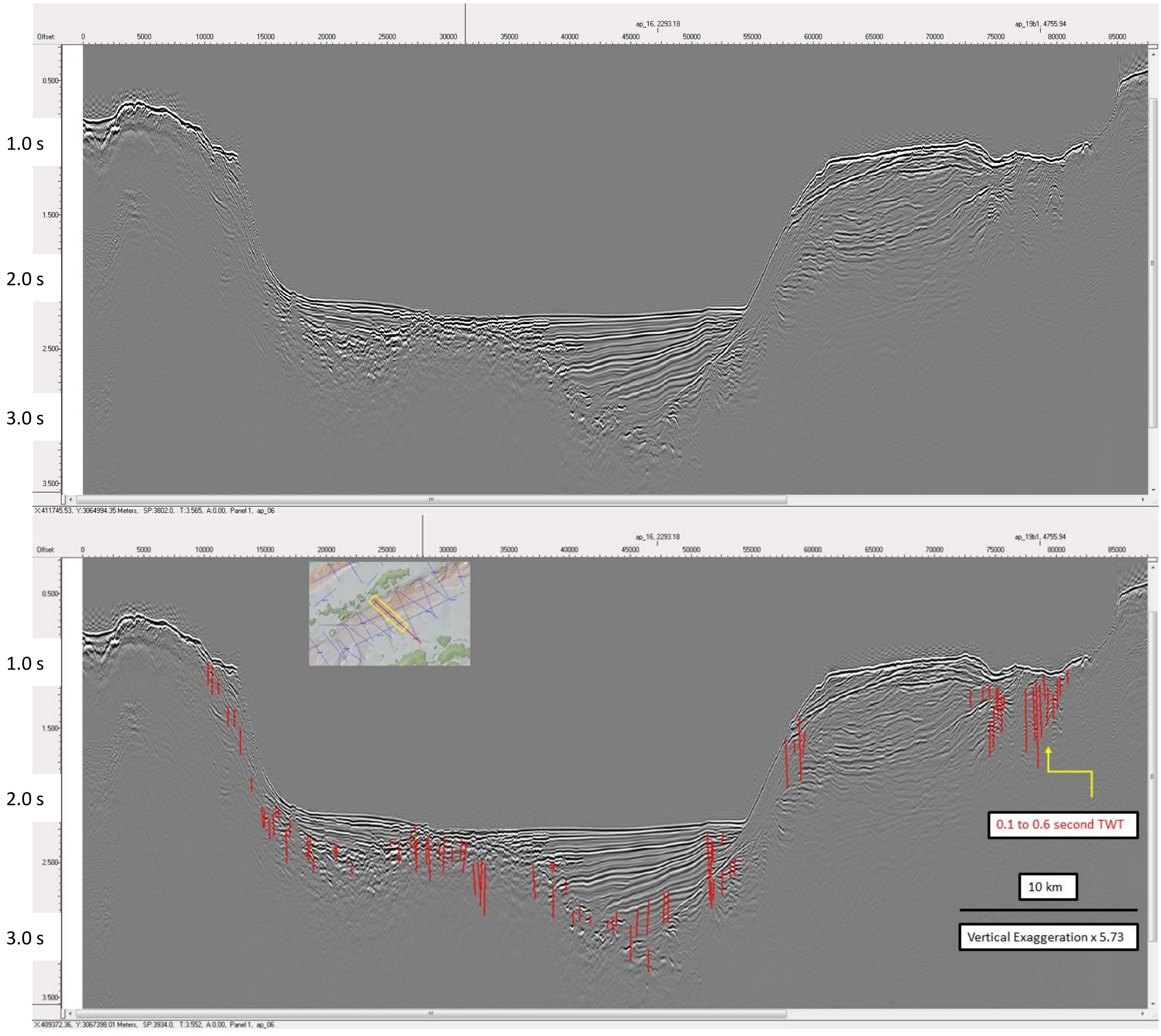

Figure 13. Seismic line AP-06 in the central sector of the Central Bransfield Basin.

3.1.3 Western sector

The western sector is identified by its geographical proximity to the Deception Island volcanic formation. From all sectors, this is the one in which tectonic extension is less advanced, although not inexistent. Distances between the South Shetland Islands and the Antarctic Peninsula continental slopes are roughly around 30-35 km. It is also the shallowest sector, with mean seafloor depth reaching values between 1000-1500 meters.

Seismic line AP-09 (Figure 14) illustrate that the tectonic regime deforms sedimentary layers with planar normal faults measuring from 0.6 to 0.4 second TWT in length. Tectonic deformations affect both margins in similar quantity and demonstrate lengths equal or slightly bigger than the faults seen in the central sector.

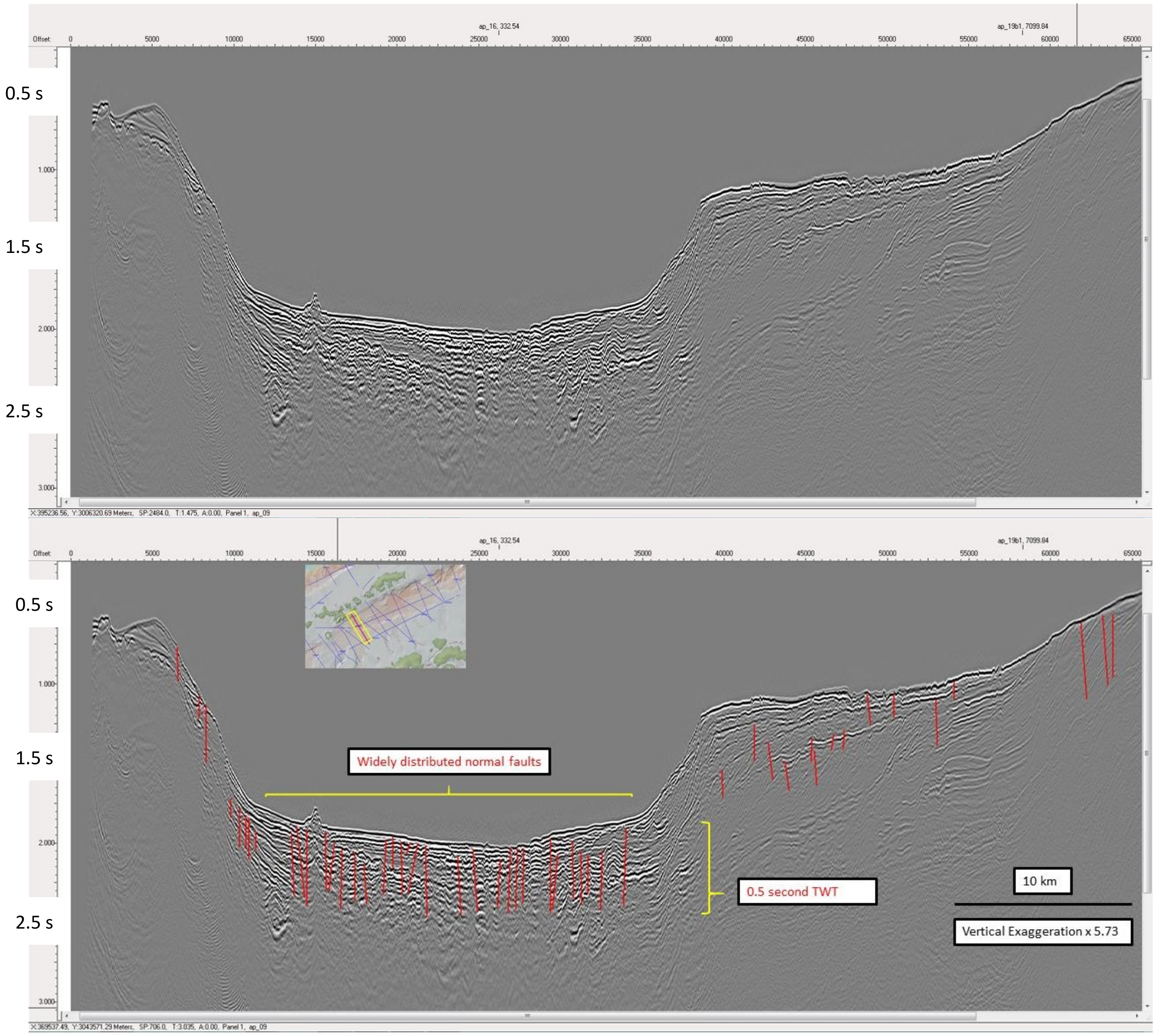

Figure 14. Seismic line AP-09 in the western basin sector of the Central Bransfield Basin.

To sum up, normal faults distend both the South Shetland Islands and the Antarctic Peninsula margins in all sector, although the quantity of faults vary when the 3 sectors are compared. Normal faults are more distributed at the Antarctic Peninsula margin, well correlated with large scale crust subsidence. Moreover, normal faults are observed in all seismic lines, varying in length in each sector, according to the seismic interpretation: greatest lengths are found in the eastern sector and smallest lengths are found in the western sector.

3.2 Distribution of volcanic formations

Characterized by a passive margin in initial formation, the Central Bransfield Strait continental crust is fragmented by faults that conduct magma from the mantle into the lithosphere towards superficial layers at the basin ridge. These magmatic flows are registered in seismic profiles and are interpreted as magmatic intrusions (sills) and extrusions (volcanic elevations).

3.2.1 Volcanic elevations

The primary aspect characterizing volcanic mounds in the Bransfield Strait is the linear WSW-ENE trend at seafloor surface. In the three sectors of the central basin, volcanic highs are oriented at a preferential direction sub-parallel to the strait's NE-SW orientation. Bathymetric data obtained from the ETOPO 1 database (Figure 15) contributed to check the distribution of volcanic structures along the axial ridge, assisting to measure the distances between them, as well as their elevations and their lateral dimensions.

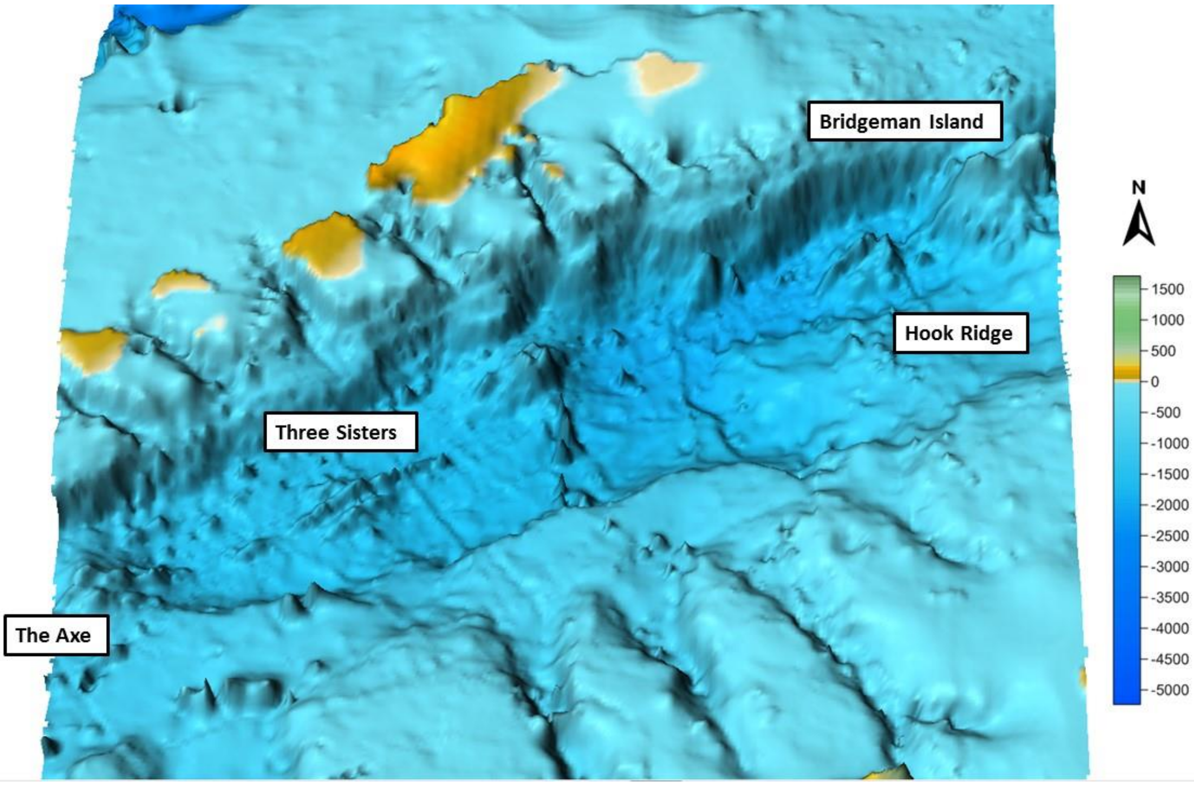

Figure 15. Bathymetry of the Central Bransfield Basin, identifying singular volcanic elevations on the seafloor. Volcanic highs are aligned in a WSW-ENE trend. Data obtained from the ETOPO 1 database.

The alignment of volcanic highs in the Central Bransfield Basin is comprehended between the Bridgeman Island and the Deception Island volcanoes, approximately 220 km apart. Volcanic mounds located between these volcanos are not evenly spaced, separated by 40 to 60 km along the basin`s axis. In addition, some volcanic signatures express lateral prolongation, as the example of the Three Sisters volcanic ridge complex. Mean altitudes for these highs in the eastern basin sector are in the order of 700 meters tall, while in the central and western sectors, these altitudes are around 600 and 200 meters, respectively.

Seismic profiles AP-03 in the eastern, AP-07 in the central and AP-11 in the western basin sectors reveal the presence of these extrusions at the axial strait (Figures 16, 17 and 18).

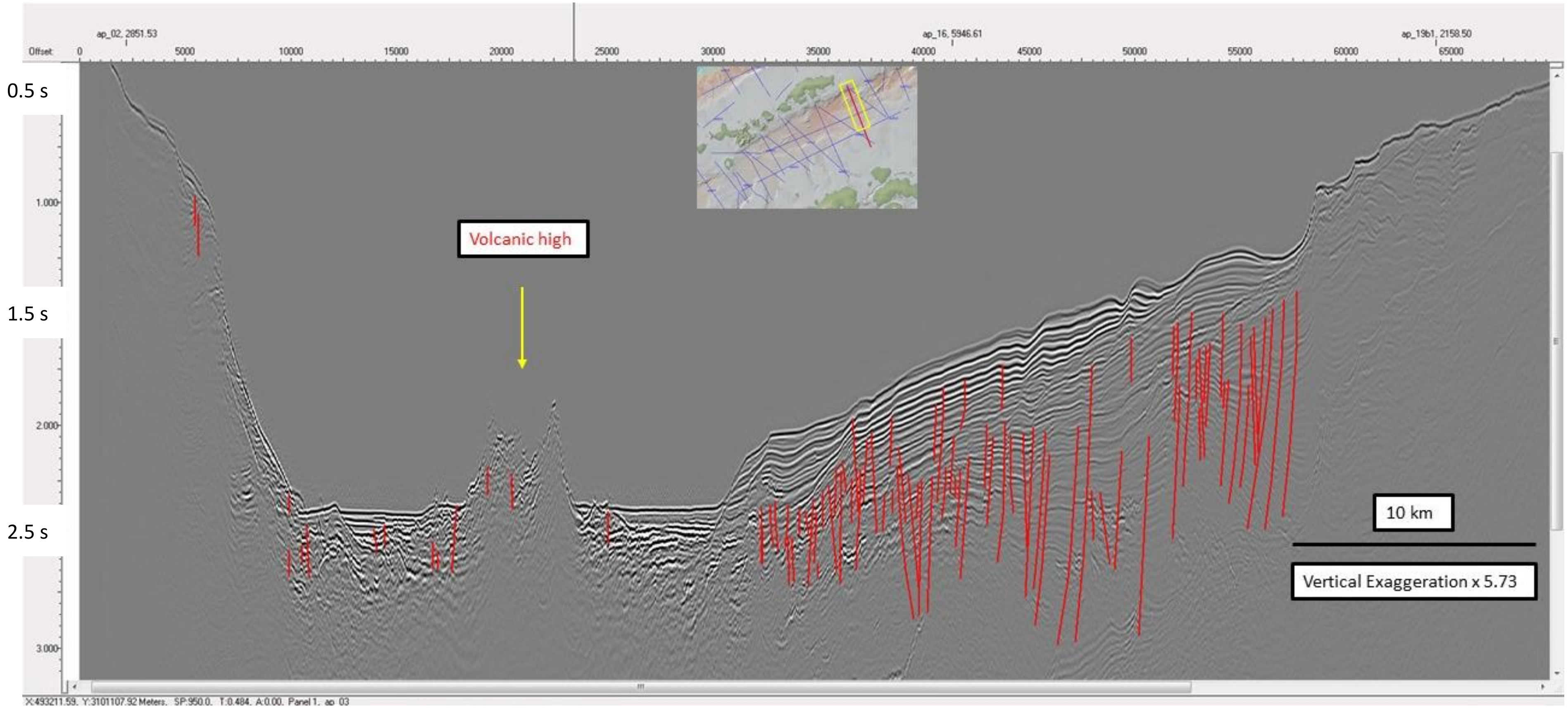

Figure 16. Seismic profile AP-03, identifying volcanic elevations in the eastern sector of the Central Bransfield Basin.

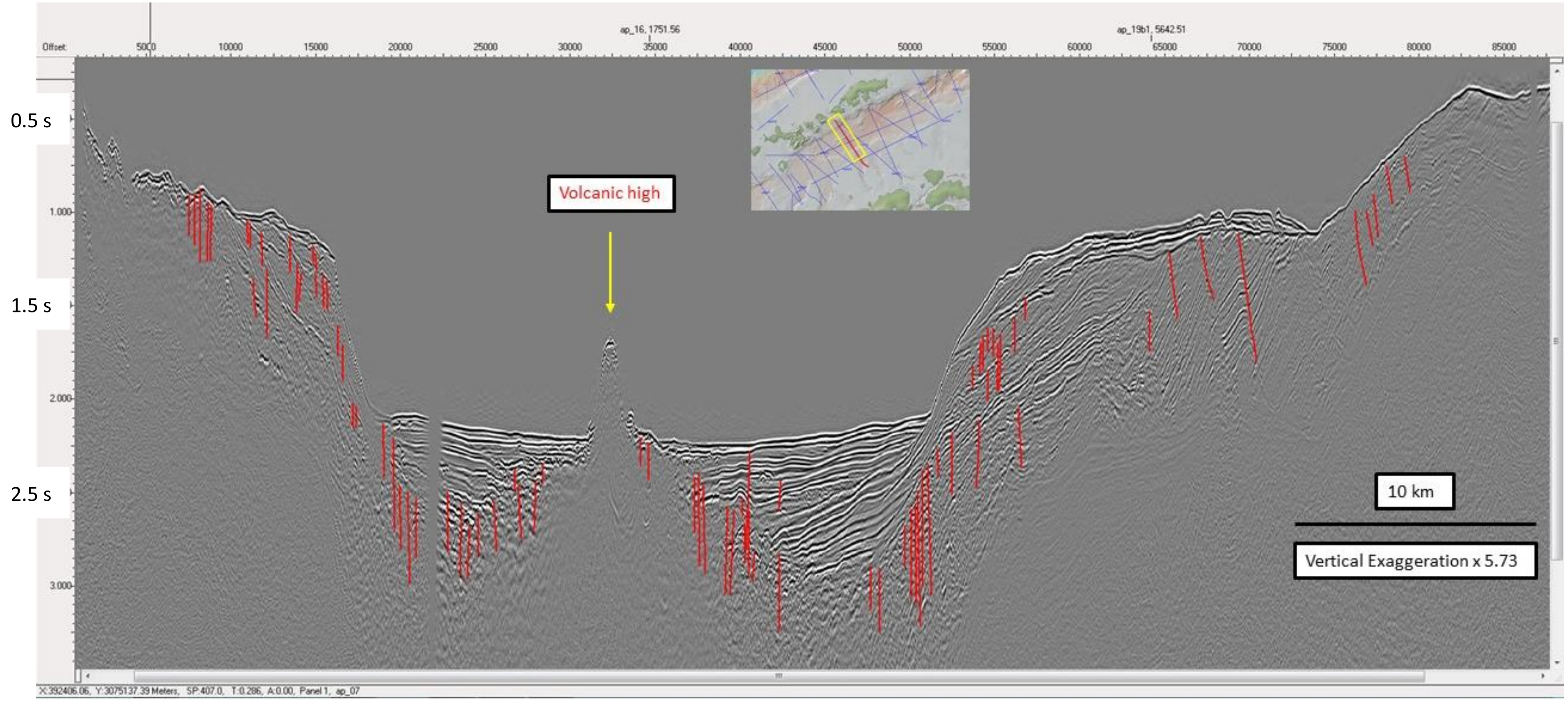

Figure 17. Seismic profile AP-07, identifying volcanic elevations in the central sector of the Central Bransfield Basin.

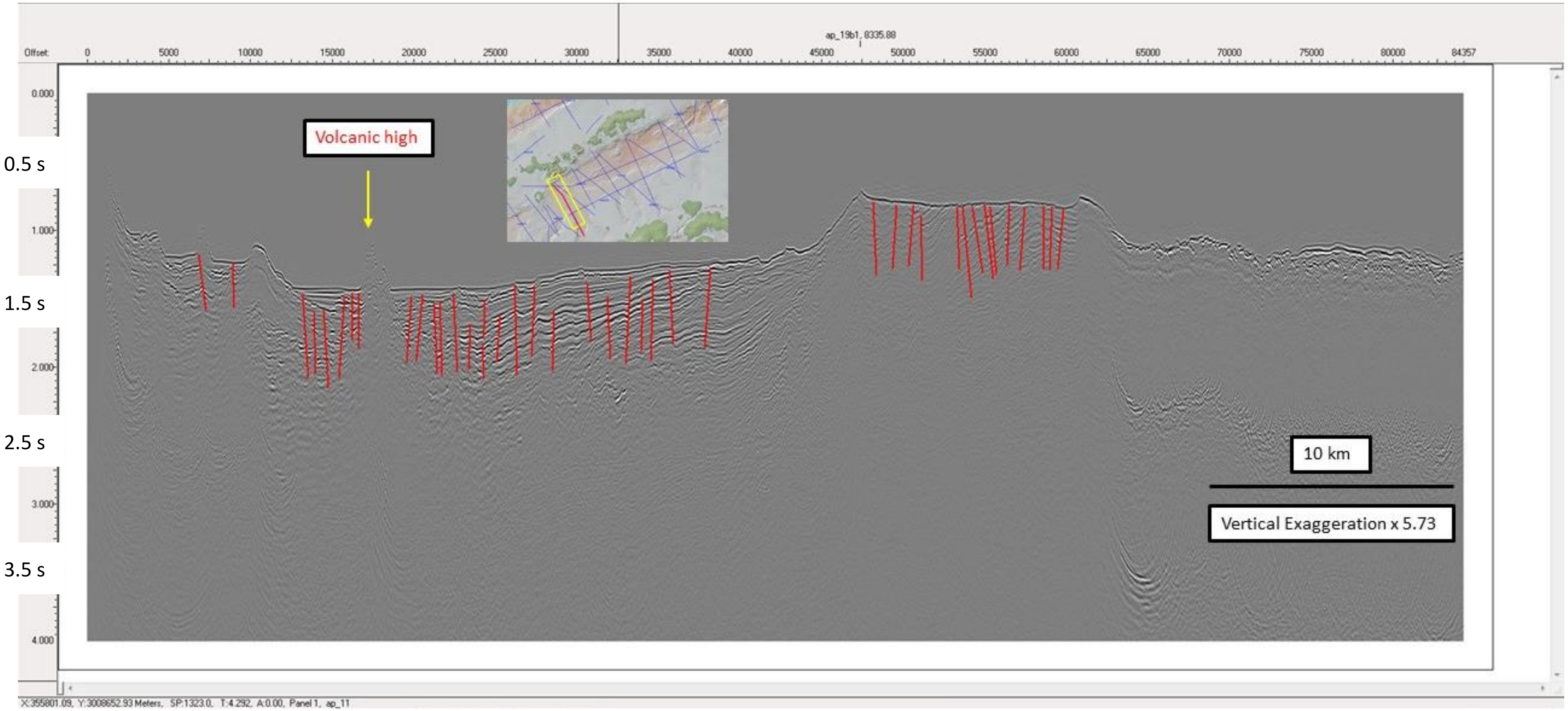

Figure 18. Seismic profile AP-11, identifying volcanic elevations in the western sector of the Central Bransfield Basin.

3.2.2 Magmatic intrusions

Seismic data suggest that intrusions occur in the submarine basement and in the sedimentary layers above it. Clearly predominant near the axial ridge, faults fracture the basement and the sedimentary column conducing magma from the upper asthenosphere towards the surface.

In the eastern basin sector, the seismic line AP-04 (Figure 19) shows a continental crust greatly deformed and interpolated by high amplitude intrusions in the fault planes. Conversely, such intrusions also fill in sedimentary layers to form continuous layers of strong reflective sills at 2.50 and 3.00 seconds TWT along the line (Offsets 10000 to 25000 and 30000 to 55000).

In the central basin sector, the seismic lines AP-06 (Figure 20) present magmatic intrusions that are not as continuous as the sills interpreted at the eastern basin sector, but smaller and more fragmented at the continental basement. Besides the magmatism occurring near the faults, modest sills are configured inside sedimentary layers. However, these sills have their occurrence geographically limited to the volcanic ridge area (Offsets 20000 to 40000; 2.50 seconds TWT).

Finally, in the western basin sector, the seismic line AP-09 (Figure 21) shows that intrusions appear as faulted reflectors of high amplitude. Different from the intrusions observed on the central sector, the ones in this area present larger lateral flow. Comparing all profiles in the western sector, it is possible to point out that the line AP-09 (in accordance with the central basin sector) does not contain a highly intruded and deformed basement, such as the profile AP-04 from the eastern sector for instance. The observation over the occurrence of intrusions in each sector of the Central Bransfield Basin is another fact that adds in the interpretation that basin is opening from NE to SW.

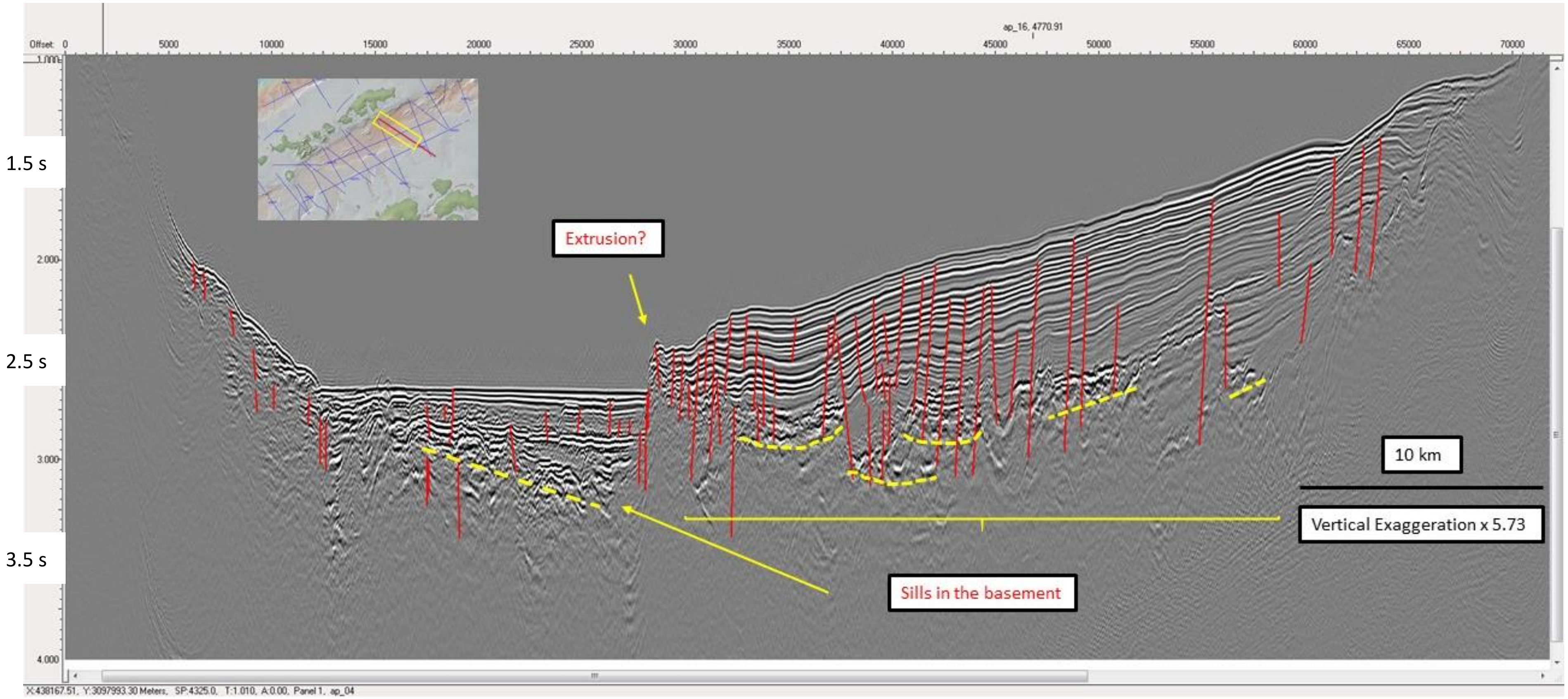

Figure 19. Seismic profile AP-04 showing intrusions in the basement. Some intrusions are interpreted as possible sills (yellow dotted lines), considering their strong lateral signature. A possible extrusive high isolate the sedimentary strata over the basin center.

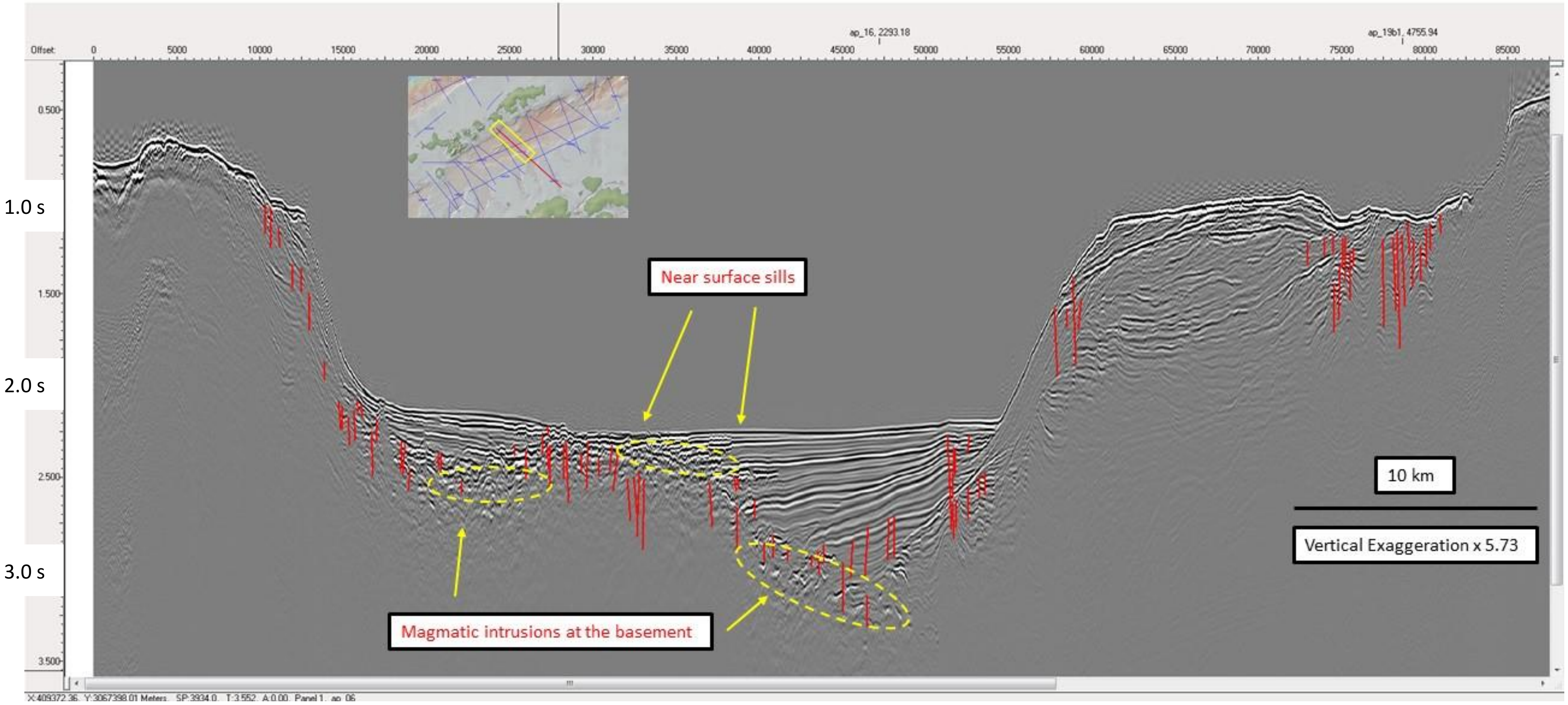

Figure 20. Seismic profile AP-06 which also shows intrusions in the basement. Possible sills are interpreted (yellow dotted circles) over the spreading center.

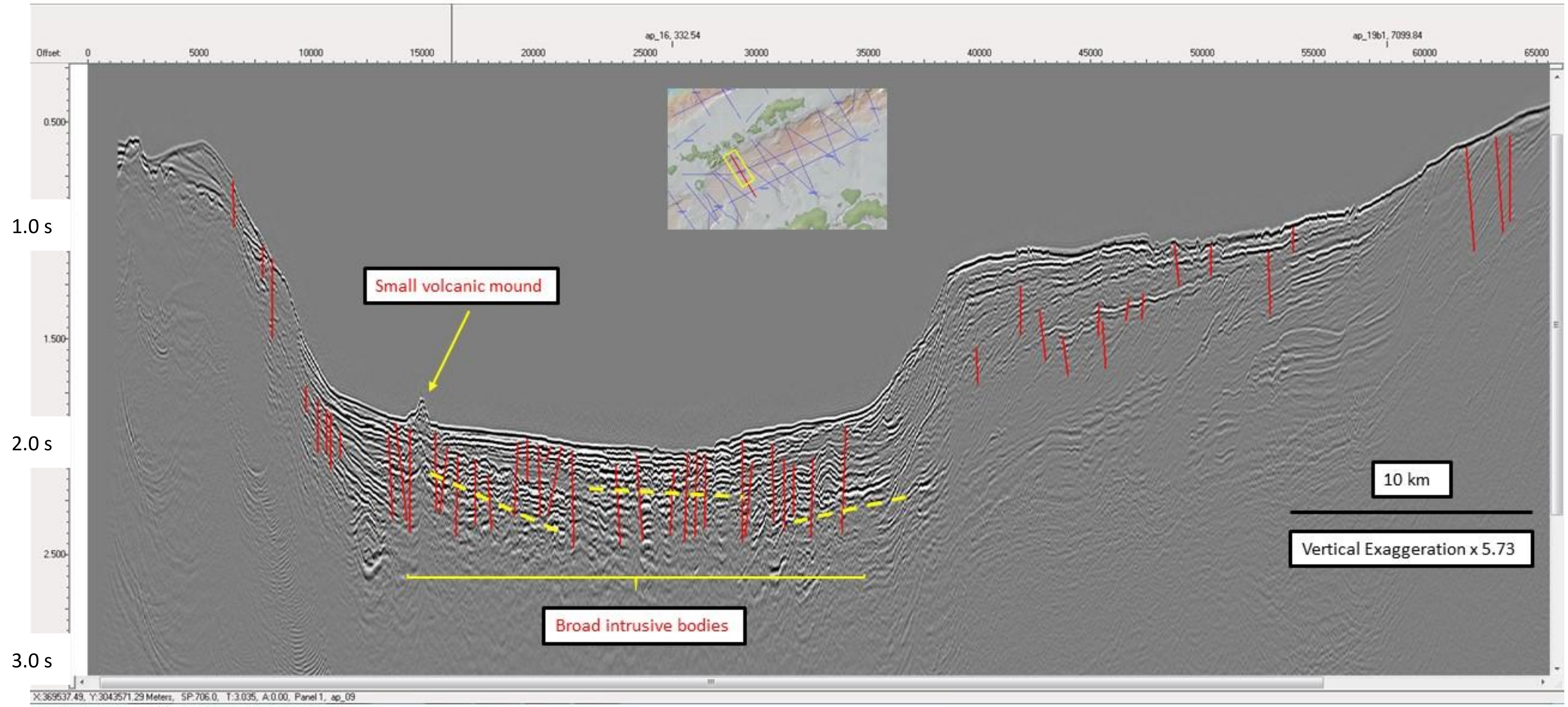

Figure 21. Seismic profile AP-09 identifying a volcanic elevation. Intrusions are interpreted (yellow dotted lines) over a broad area between the sedimentary column.

3.3 Central Bransfield Basin bathymetry

The study of submarine topography is essential to enhance interpretations over tectonic and volcanic structures present at the submarine terrain. In this work, bathymetry also assisted in measuring distances along and across the strait, as well as the dimensions of multiple volcanic structures. In such manner, this section describes the observations collected from analyzing the bathymetric data obtained from the ETOPO 1 database (National Oceanic and Atmospheric Administration – NOAA). This data was downloaded from the NOAA website and loaded using the software Surfer, allowing to create 2D and 3D visualizations of the submarine morphology of the Central Bransfield Basin (Figure 22).

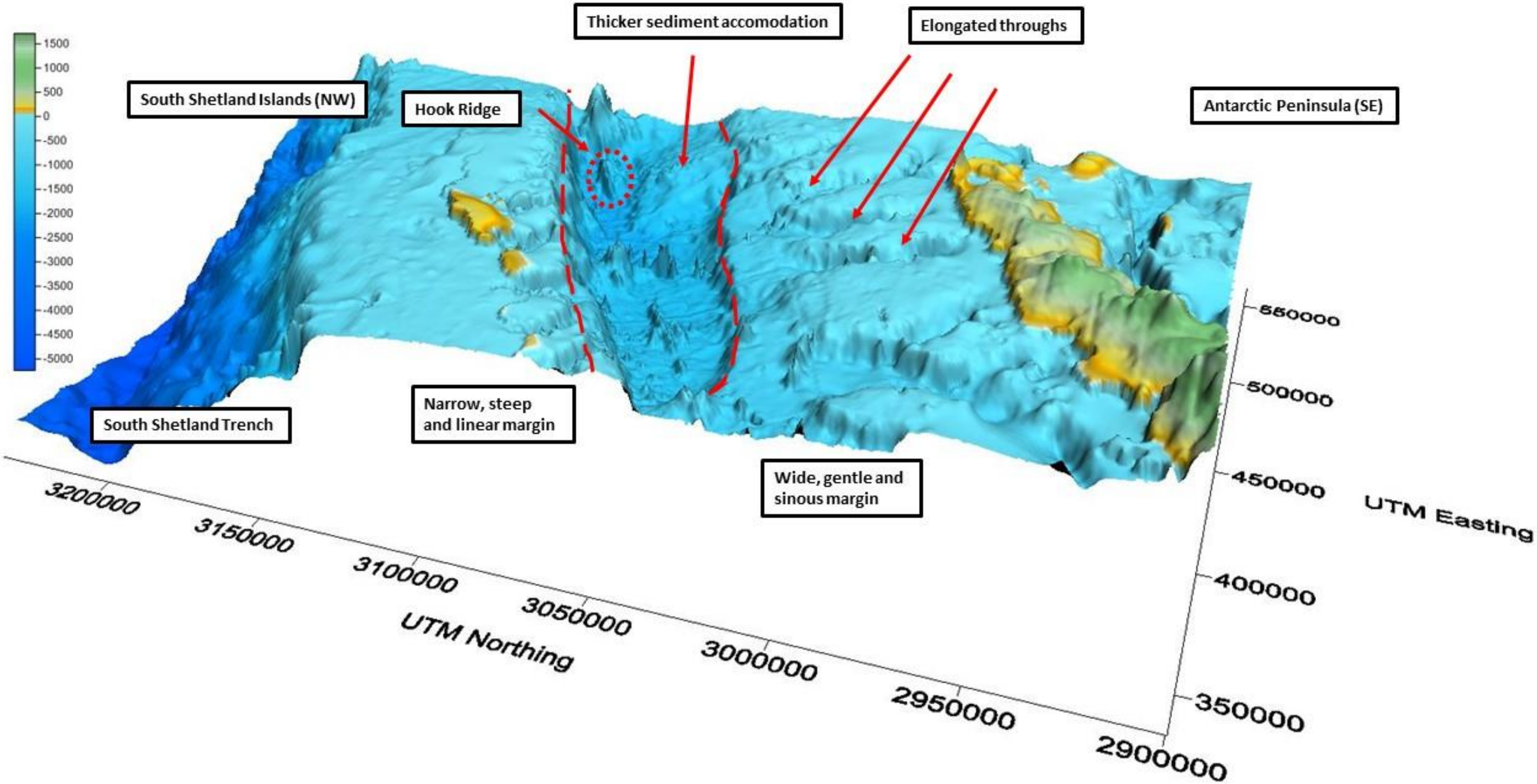

Figure 22. Bathymetry identifying the main morphological features along the Central Bransfield Strait. The red arrows identify important structures, such as elongated throughs and areas with large sediment accommodation. The dotted circle identifies the Hook Ridge volcano at the basin eastern sector, while the dotted lines indicate the continental slope linearity along the basin.

The bathymetry shows some features already observed on the seismic data, with the advantage of the tridimensional view. On the South Shetland Island margin, a narrow and steep continental slope characterizes a region poorly supplied of sediments and sculpted by abrupt troughs. The continental slope in this margin is approximately linear and is characterized by a constant degree in steepness along the basin sectors (Figure 22).

On the other hand, the Antarctic Peninsula continental slope is wide and gentle, but also sinuous, with changes in steepness towards the basin center. It is observed that the continental slope of the Antarctic Peninsula margin is gentler over the eastern sector, increasing in steepness towards the western sector (Figure 21). Moreover, the eastern sector of the Antarctic Peninsula margin accommodates thicker packages of sediment, which are possibly correlated with successive mass movement deposits. Those deposits shaped extensive and elongated throughs that carved the Antarctic Peninsula shelf. The sediments eroded from these throughs possibly have influence on the greater subsidence noticed on the eastern sector, due to the higher amount of weight received in comparison to the central and western sectors (Figure 22).

Seafloor in this basin is naturally deeper and wider around the eastern sector, whereas maximum depth is found around the Hook Ridge volcanic formation (Figure 22), approximately 2000 meters depth. The seafloor base slowly narrows and elevates towards the western sector, where mean seafloor is around 900 meters deep. In general, the seafloor is rugged in all sectors of the basin, due to varied sedimentation thicknesses, in addition to small to large scale volcanic mounds. A small portion where seafloor is less rough and more horizontal is found at the basin eastern sector, towards the southwestern base of the Hook Ridge formation.

The last element that highlights the strait morphology are the volcanic elevations, which present different orientations along the basin (Figure 23). The lineation 1 represents the WSW-ENE volcanic arc sub-parallel to the strait spreading axis and measuring approximately 191.9 Km. The lineation 2 represents another WSW-ENE arc, slightly divergent from the lineation 1, measuring approximately 107.8 Km. The lineation 3 represents a NNW-SSE arc, near perpendicular to the strait spreading axis, measuring approximately 37.2 Km. The lineation 4 represents a

NW-SE small arc at the continental margin, measuring approximately 20.1 Km. The lineation 5 represents another arc at the continental margin, with orientation trend E-E and measuring approximately 28 Km.

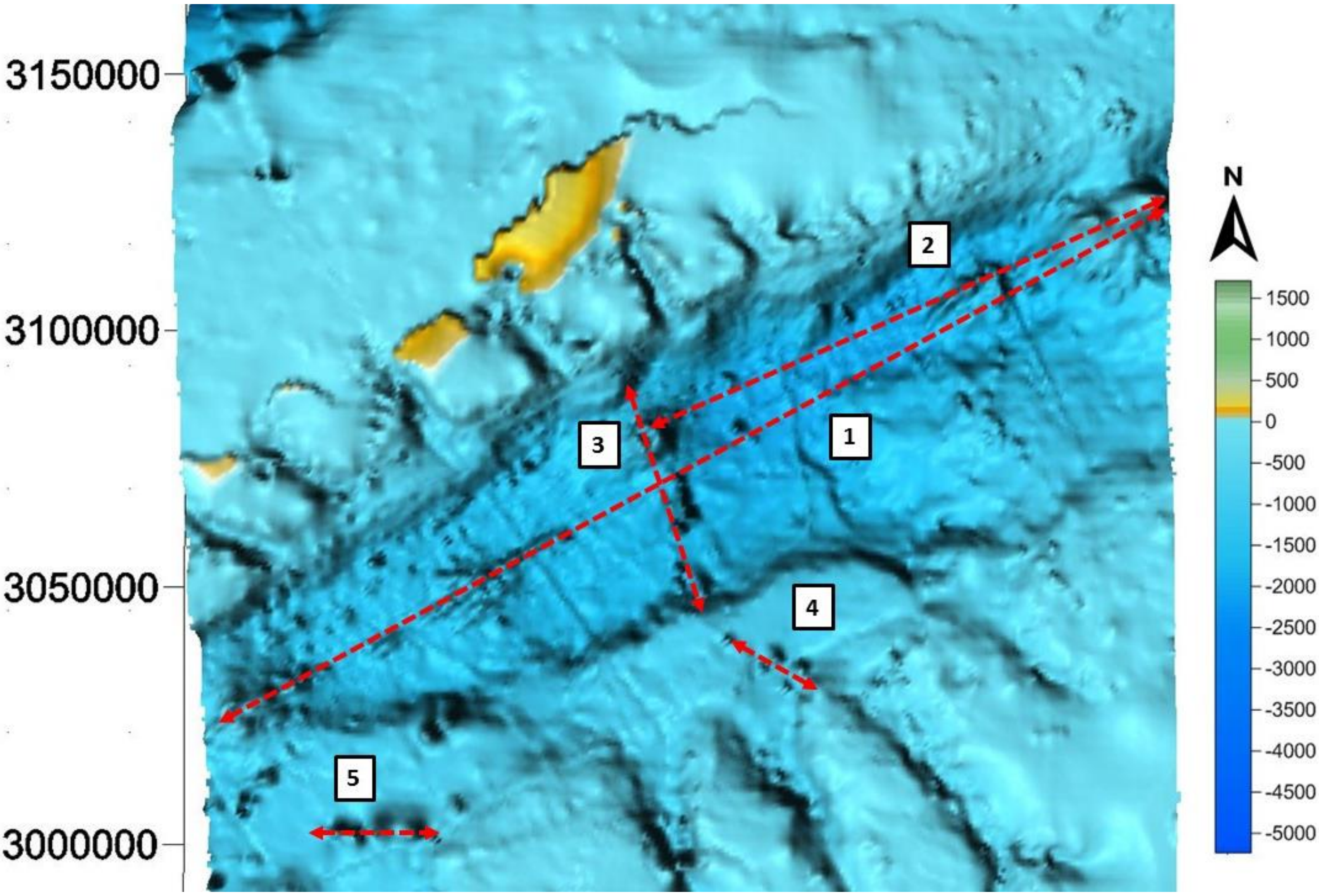

Figure 23. Bathymetry identifying different volcanic mounts orientations observed in the basin, represented by red dotted arrows. Lineation 1 trends WSE-ENE; Lineation 2 trends WSE-ENE; Lineation 3 trends NNW-SSE; Lineation 4 trends NW-SE; Lineation 5 trend E-W.

3.4 – Analysis of sedimentary sequences

The seismic stratigraphic interpretation revealed that the Central Bransfield Strait is composed of two main sedimentary sequences above the acoustic basement, which can be correlated with two tectonic phases of the basin evolution. The lower sequence is identified as S1 and represents a syn-rift sequence, characterized by faulted and rotated blocks, in addition to intrusions, in general, over the active rifting zone. The upper sequence, identified as S2, represents a post-rift sequence, whereas layers are less faulted, more continuous and prograde basinward. The two interpreted sequences are divided by a larger unconformity, identified by U1.

On the profiles presented in this section, the basement is identified by the red reflector and represents the base of the syn-rift S1 sequence. The basement reflector varies in depth along the profiles and in some portions, it is impossible to be interpreted due to seismic noise. Thus, this horizon was interpreted as a solid line in regions where the basement could be better identified and as a dotted line in regions of uncertainty (Figures 24, 25, and 26).

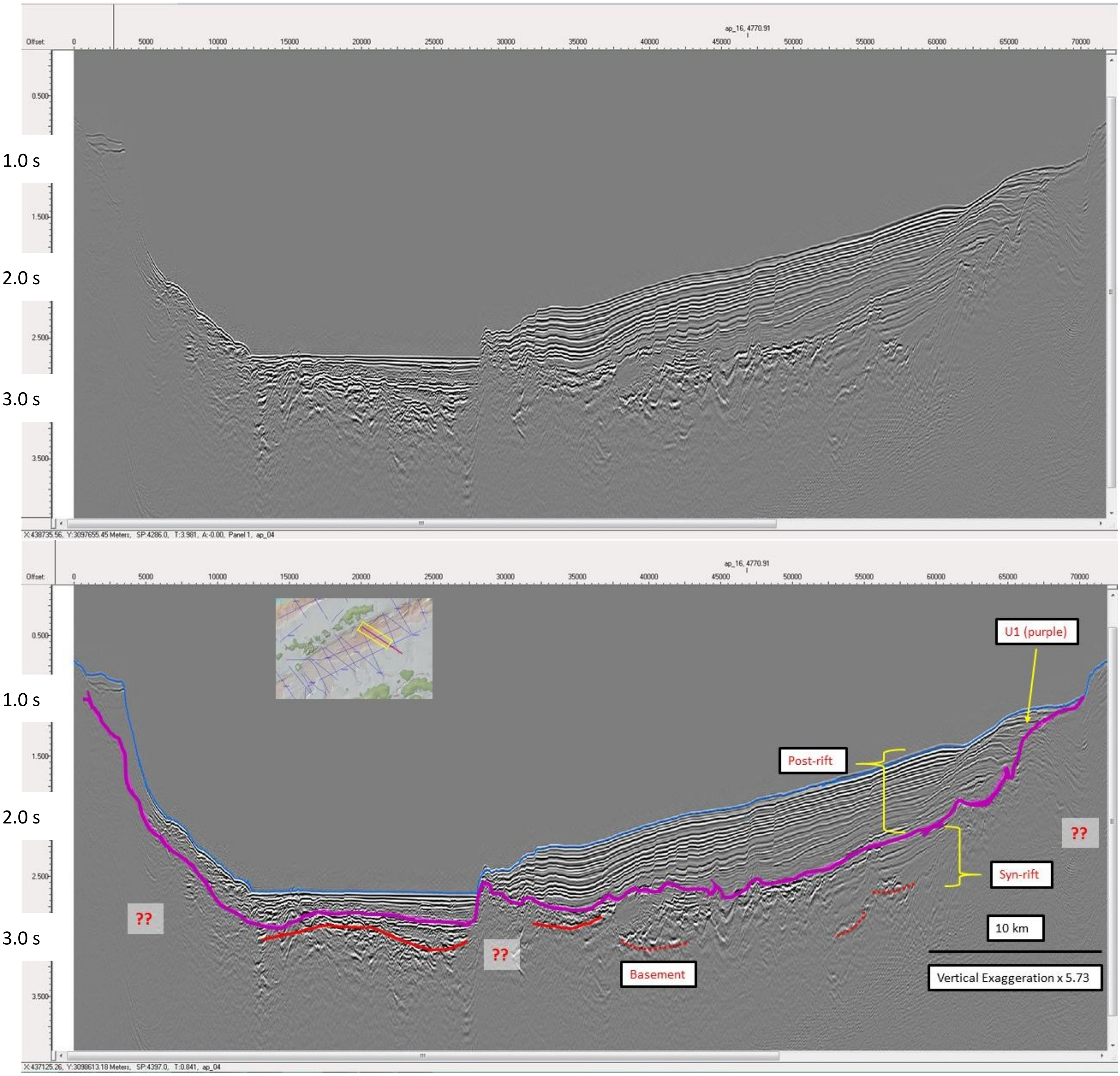

Figure 24. Sedimentary sequences interpretation for the line AP-04. The thick purple line represents the unconformity U1. The solid red lines are interpretations of the basement, while the red dotted lines are interpretations of possible segments of the basement. The interrogations in red represent the areas where the basement could not be observed.

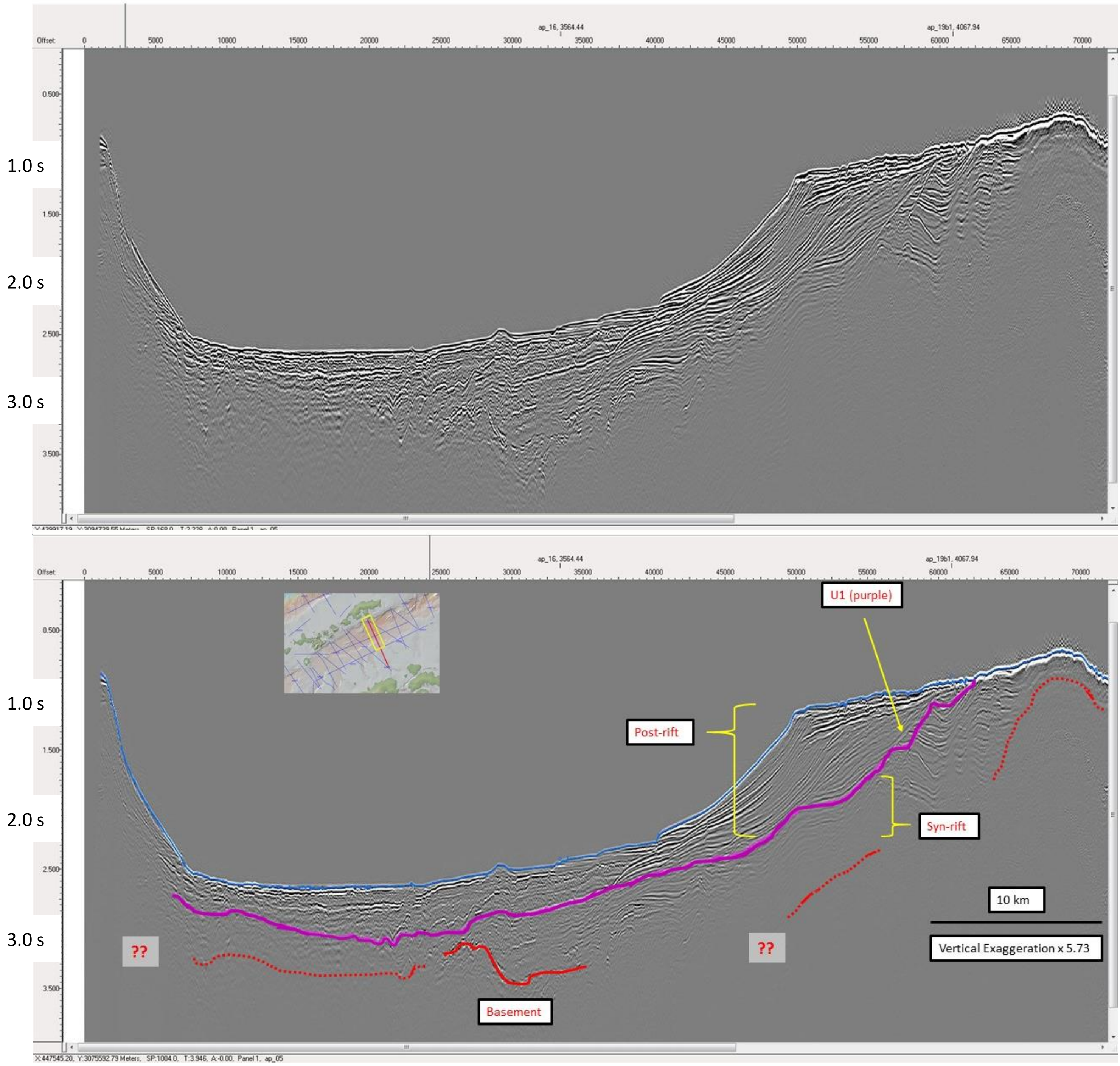

Figure 25. Sedimentary sequences interpretation for the line AP-05. The solid red lines are interpretations of the basement, while the red dotted lines are interpretations of possible segments of the basement. The interrogations in red represent the areas where the basement could not be observed.

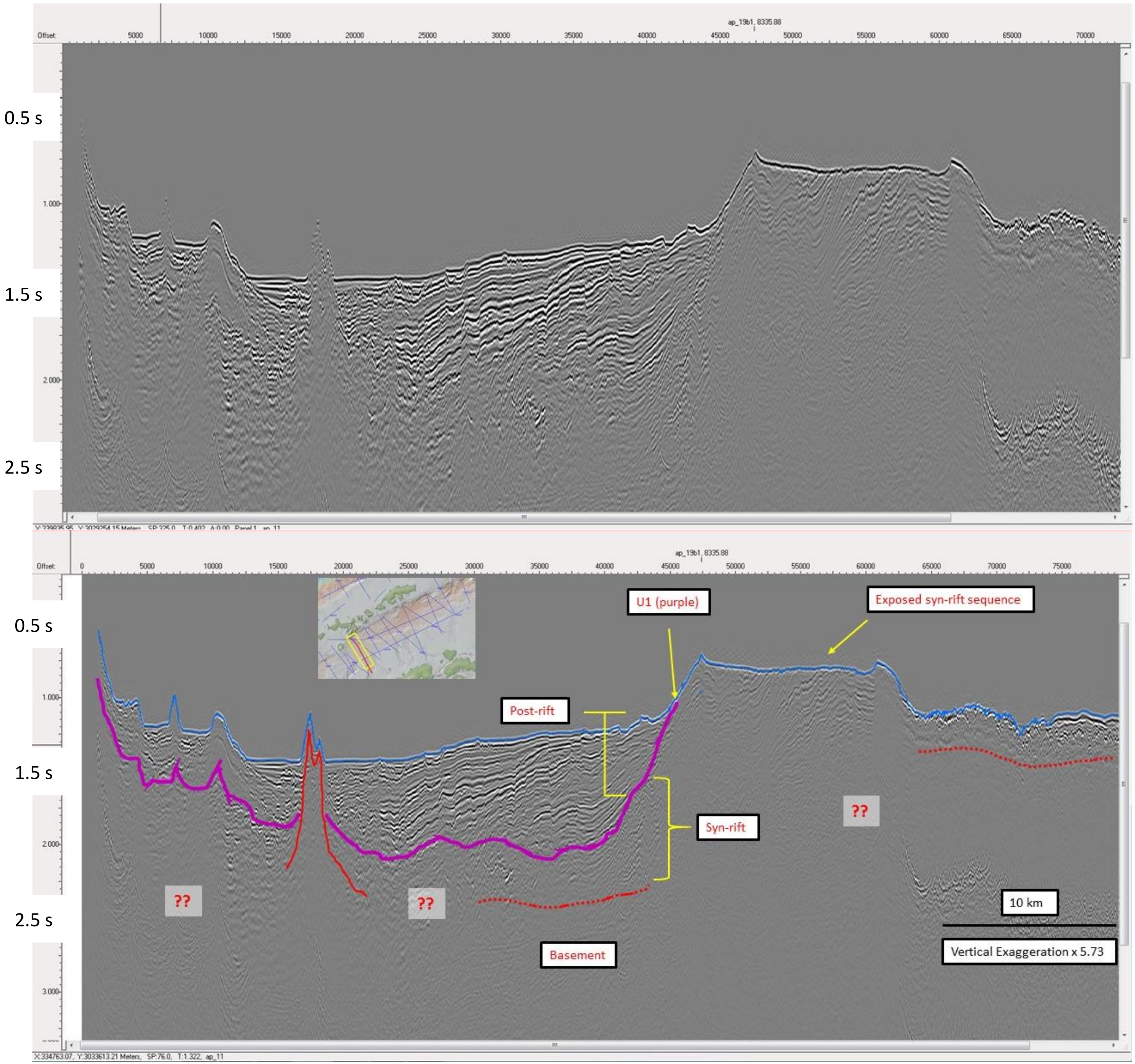

Figure 26. Sedimentary sequences interpretation for the line AP-11. The solid red lines are interpretations of the basement, while the red dotted lines are interpretations of possible segments of the basement. The interrogations in red represent the areas where the basement could not be observed.

The unconformity U1 is an erosional contact identified by the purple reflector, representing the top of the syn-rift sequence (S1). The S1 sequence is observed on seismic profiles intensely deformed by the normal faulting, reported on section 6.1, and indicates occurrence of extensional activity during opening the basin. This sequence normally outcrops at the surface, over the upper continental slope of the Antarctic Peninsula, projecting eroded surfaces at the seafloor (Figure 26).

Sequence S2, interpreted as a post-rift sequence, was deposited above the unconformity U1. This sedimentary package is identified by successive progradation of layers, increasing in thickness from the continental slopes toward the center of the basin. Internal erosional surfaces segment these prograding packages, suggesting that erosion and deposition of sediments may happen seasonally at the continental shelf, cutting through the continental slope and depositing at its base.

Based on the geological setting, on sedimentary sequences interpretations and on other authors (Lodolo et al., 2002; Takao, 2011), the Bransfield margin is a potential region for accumulation of gas hydrates. Gas hydrates form in areas of high pressure and low temperature, commonly found on outer continental margins and in permafrost (Sain, 2008). Thus, observing the 10 seismic profiles interpreted in this work, probable accumulations of gas hydrate were considered, evidenced by the presence of a BSR (Bottom-Simulating Reflector) near the Antarctic Peninsula margin. The BSR represents the base of a gas hydrate stability zone and marks an interface between sediments bearing gas hydrates above and sediments bearing free-gas underneath (Sain, 2008). As an example of possible gas hydrate accumulation, the seismic profile AP-03 depicts a reflector similar to a BSR common shape. The BSR is characterized as an anomalous faint reflection, parallel to the seafloor but with opposite polarity in amplitude, that crosses real reflectors on the seismic profile, similar to multiples reflections (Figures 27). In this seismic profile, the interpreted seafloor presents positive polarity in amplitude, while the BSR presents a negative polarity.

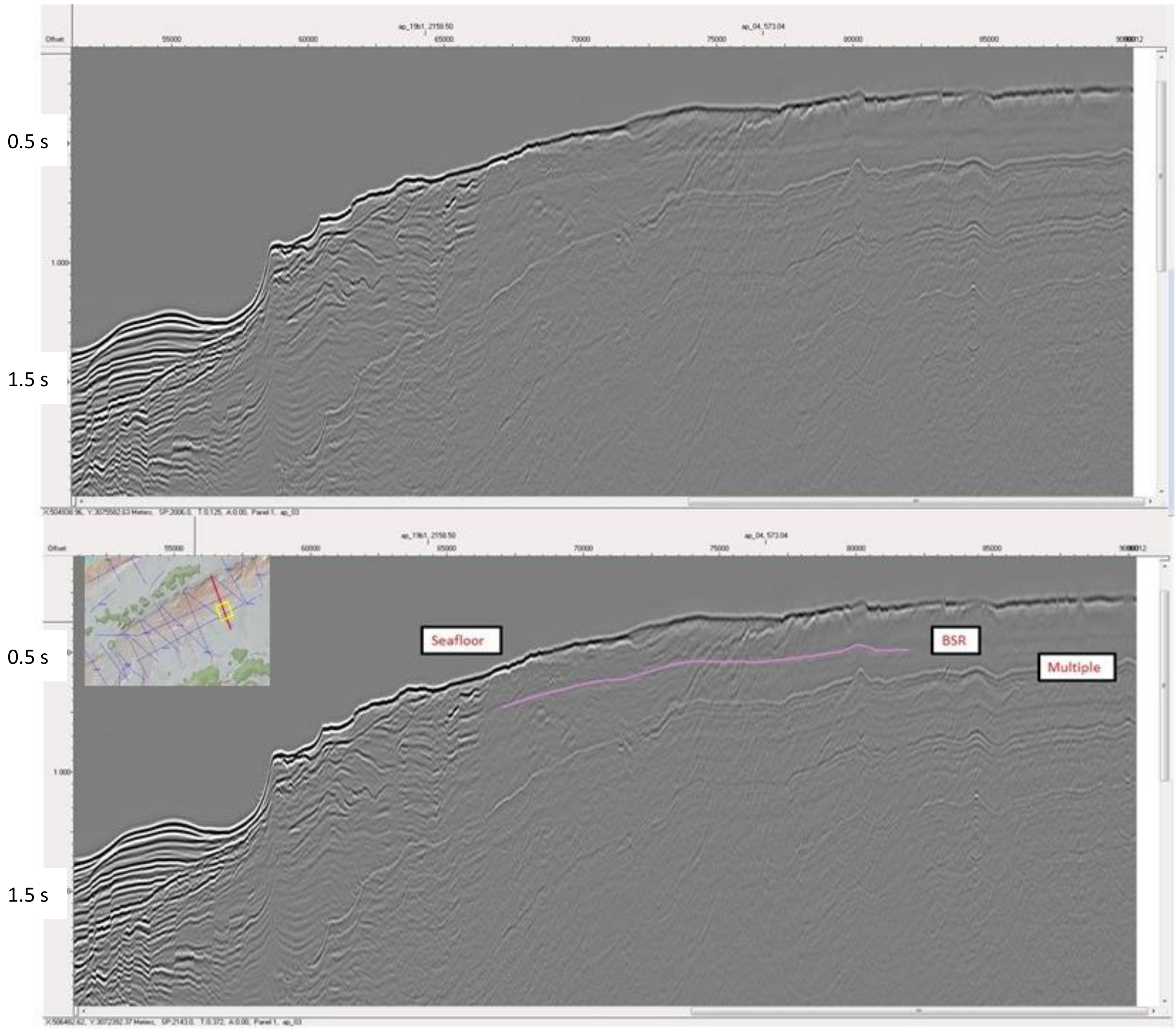

Figure 27. Possible Bottom-Simulating Reflector (BSR) observed at the Antarctic Peninsula margin. Seismic profile AP-03.

The figure 27 may represent a real example of BSR found on the Antarctic Peninsula margin, indicating its potential for accumulation of hydrocarbon reserves. In order to certify this possibility, an analysis of amplitudes between the seafloor and the BSR is presented on figure 28. It is expected that the amplitudes of the seafloor reflector and the amplitudes of the BSR be similar in shape, but with opposite polarity and different in module.

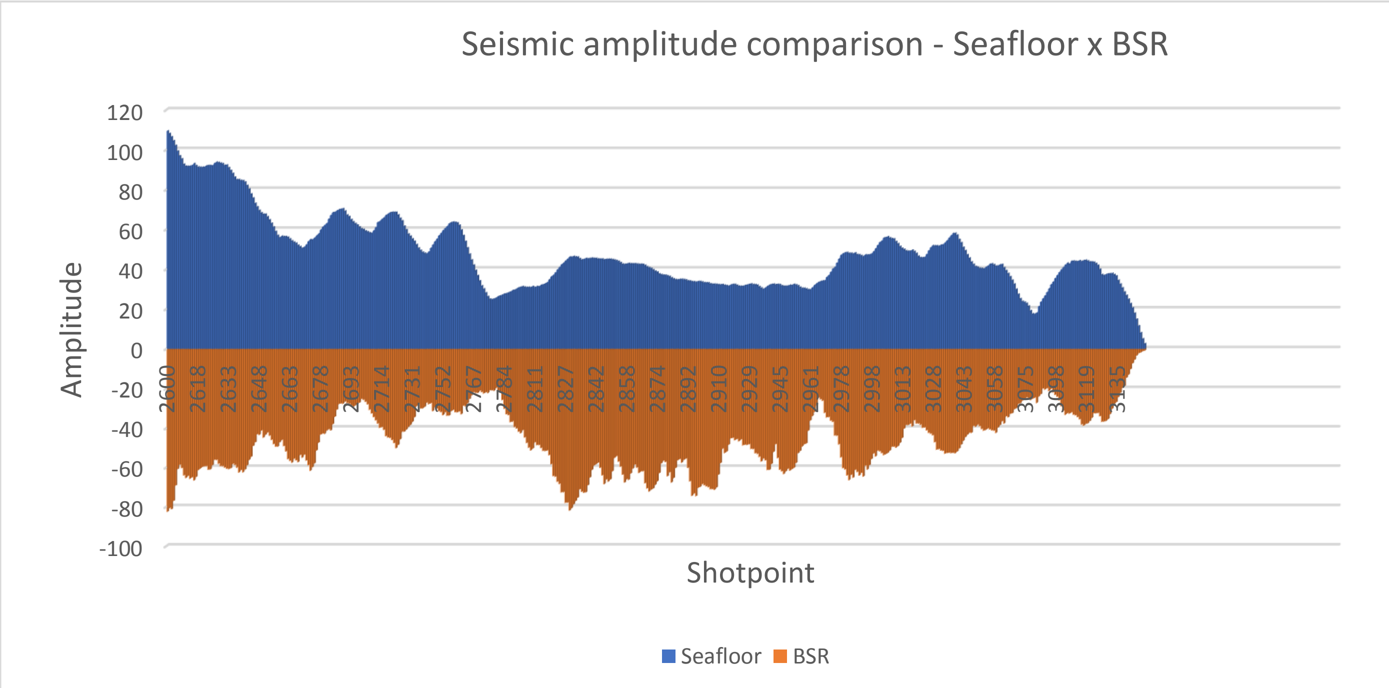

Figure 28. Comparison of seismic amplitudes between the seafloor and the BSR observed on seismic profile AP-03.

After comparing their amplitudes, it can be considered that the BSR pointed on line AP-03 at the Antarctic Peninsula margin identifies a real gas hydrate zone. This discovery is relevant because few studies discuss about the Bransfield Basin potential for hydrocarbon accumulations. Takao (2011) identifies real BSR over the South Shetland Islands margin, while this work suggests their presence over the Antarctic Peninsula margin of the Central Bransfield Basin. Thus, this work exhibit in seismic profiles and through the seismic amplitude comparisons strong evidences for gas hydrates accumulations.

In addition to possible hydrocarbon accumulations, the profile AP-06 (Figure 29) identifies a possible gas seep at the base of the continental slope. The seep would be associated with faults that conduce the gas toward the seafloor. On seismic reflection, this is observed as cone-shaped diffuse reflections overlying horizontal reflectors.

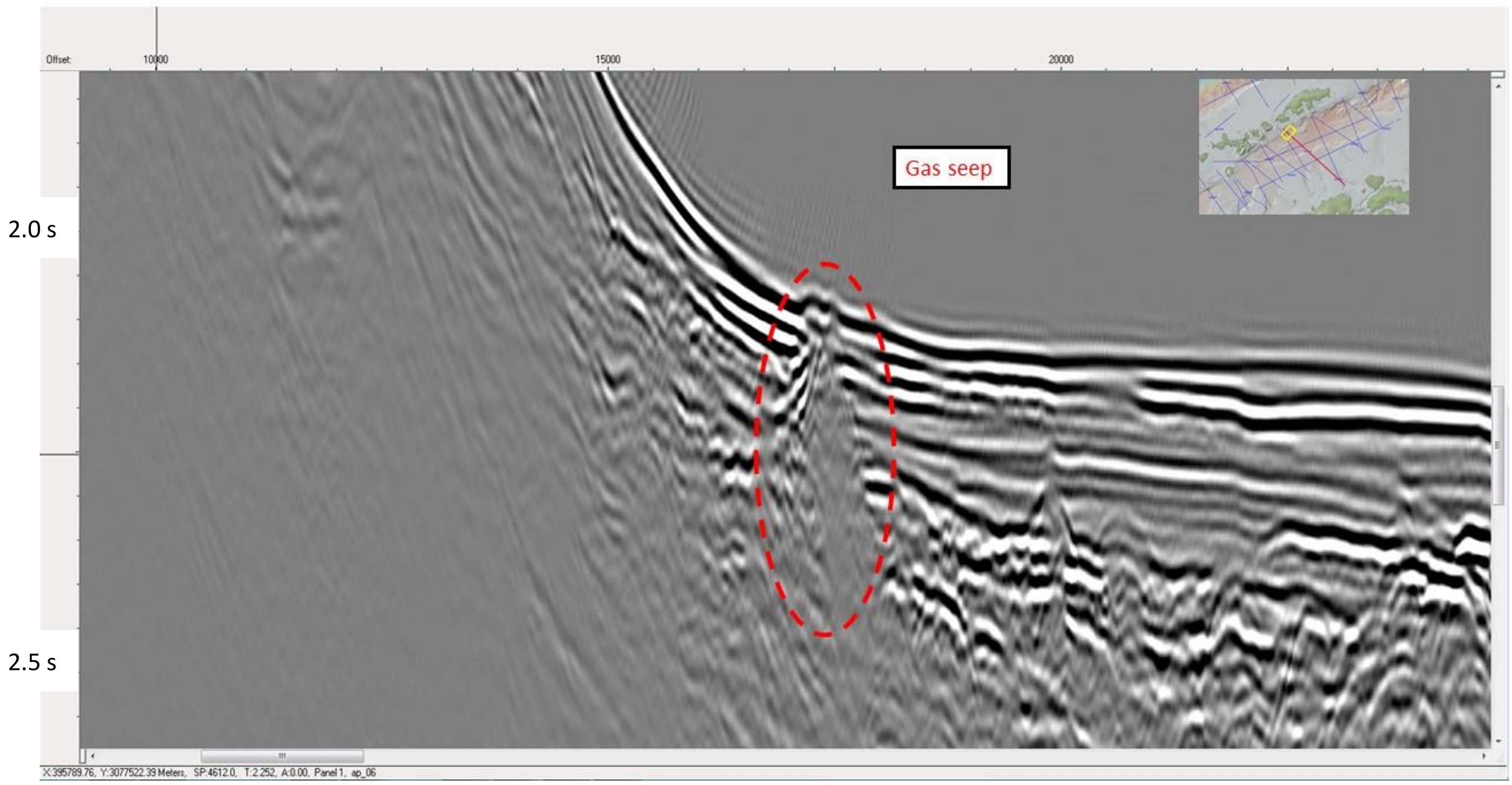

Figure 29. Possible gas seep observed at the continental slope base at the South Shetland Islands margin, identified by the red dotted circle. Seismic profile AP-06.

3.5 Stratigraphic sequences related with the basin extension

Chapter 3.4 describes the two main sedimentary sequences observed at the seismic stratigraphic analysis, that correspond to distinct phases in the strait opening evolution: the lower syn-rift and the upper post-rift. In the syn-rift phase, sedimentary deposits are found intensely deformed by faults developed during the initial rifting stage. The syn-rift sequence is made of eroded sediments transported by ice sheets, directly associated with glacial processes (Garcia et al., 2011; Magrani and Neto, 2014). The post-rift sequence is characterized by sedimentary packages originated from glacial processes, mass transport process and marine processes (Garcia et al., 2011; Gabriele, 2006). Different from the syn-rift sequence, the post-rift sequence is deformed by minor faults and shows an upward transition from glacial dominated deposits to open marine deposits (Garcia et al., 2011).

Interpretations of the post-rift sequence show internal regional erosions that slice the deposit towards the basin center, suggesting a cyclicity of sedimentary fluxes. According to Prieto et al. (1998) and García et al., (2008), erosional surfaces and their stratigraphic units, observed on chapter 3.4, are essentially controlled by cycles of glacial and interglacial periods. During glacial periods, ice sheets covered the continental shelf in a large extension and sedimentation was mainly associated with ice sheets transport. This process sculpted inner troughs throughout the mid slope platform, depositing prograding wedges towards the basin seafloor.

During interglacial periods, when ice sheets were retracted towards the upper continental shelf, sedimentation was defined by marine processes, such as hemipelagic deposition over all portions of the basin, and slide processes, such as turbidites at the base of the continental slope (Garcia et al., 2011). Moreover, contouritic processes, resulted from bottom current activity, formed stratified layers at the deep basin (Imbo et al., 2003). The interglacial deposits mentioned in the post-rift sequence show greater thicknesses over the deepest portion of the basin, such as at the basin seafloor and at the continental slope base, while these deposits show thinner thicknesses at the upper slope and at the continental shelf.

The stratigraphic transition of depositional environments is related to climatic changes at the Antarctic Peninsula that caused the advance and retraction of ice sheets, in addition to the onset of the Antarctic Circumpolar Current, activated after the Drake Passage opening, around 15 Ma (Gabriele, 2006). Since the Last Glacial Maximum around 14 to 15 Ka, deglaciation decreased the glacial transport in the Bransfield basin margins and lead to the formation of sedimentary deposits mainly associated with glacimarine processes, such as gravity fluxes and sea bottom currents.

In addition to climatic changes that influenced the development of the syn-rift sequence, as mentioned by Prieto et al. (1998) and Garcia et al. (2008), the weight of sedimentary loads also had an impact on accumulation of sediments over the Bransfield basin. The accommodation space for sediments depends on the continuous tectonic extension of the basin and on tectonic faults formed during this process. Thus, faults in the Central Bransfield Basin are set by horizontal extensional forces (rollback tension) and are activated or re-activated by the weight of sedimentary sequence that deposited on the margins during glacial and interglacial periods. The onset of faults and the increasing load of sediments influence on the steepness of the margin, which has a direct relation with the internal erosions observed in the seismic interpretation (for example the U1 unconformity) and with the turbidite deposits reported by Garcia et al. (2011).

4 CONCLUSIONS

In this work, the seismic reflection and the bathymetry were essential to map major characteristics of the Bransfield strait in order to understand the rifting processes extending the basin, relating them to the basin subsidence, to the margins physiography and to volcanic formations derived from the extensional tectonics.

In response to physiographic and tectonic structures interpreted on seismic lines and on bathymetry, the Central Bransfield Basin was studied in this work divided in three sectors (eastern, central and western), which show different stages of rifting. The eastern basin sector is characterized by presenting larger faults, greater seafloor subsidence and thicker sedimentary accumulations, confirming the assumption as the older of the three sectors. The interpretation also confirmed that the Bransfield Strait initially rifted in the NE region and is advancing towards its SW portion.

The interpretation of the seismic profiles highlighted two main sedimentary sequences (S1 and S2), related to distinct tectono-sedimentary phases of the strait. A regional unconformity U1 separates a lower syn-rift from an upper post-rift sequence. This regional unconformity marks the transition from a deposit mainly associated with glacial sedimentation processes to a deposit associated with glacio-marine sedimentation processes.

Moreover, potential accumulations of gas hydrates in sediments over the Antarctic Peninsula margin were observed. Among the interpreted lines, one potential of BSR was identified and its amplitude was analyzed in order to confirm the possibility of a real gas hydrate stability zone present in the Antarctic continental margin.

For future works, the tectonic structure of the rift could be better understood with the use of magnetic and or gravimetric data to better constrain the area of magmatism occurring under the spreading axis, added to intrusions noticed on along the margins. In addition, the reprocessing of seismic lines is interesting to attenuate seismic noise (ex.: multiples) and obtain better resolution in depth, specially towards the basement and possibly towards the Mohorovicic discontinuity. Finally, appropriate attention could be directed to identify and analyze other possible BSR and certify the Antarctic Peninsula potential for hydrocarbon accumulations.

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