

**Influence of pre-salt alignments in post-Aptian magmatism in the Cabo Frio High and its surroundings, Santos and Campos basins, SE Brazil: An example of non-plume-related magmatism**

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**Abstract**

This study, based on interpretations of 2D and 3D seismic data, onshore satellite data, and offshore seismic mapping and well data, addresses the geological evolution of Late Cretaceous and Early Tertiary magmatism in the offshore Cabo Frio area, at the border between the Santos and Campos basins, SE Brazil. The analysis of the available data set suggests an alternative genesis for this magmatism, different from the classic mantle plume model. Seismic mapping of the main feeder dikes reveals a predominant SE-NW orientation, coincident with the alignment of the Cruzeiro do Sul deformation zone, in which the Cabo Frio High is included. This observation is coherent with the characteristics of the major onshore Precambrian strike-slip faults, which were reactivated during the Cenozoic. The largest offshore volumes of magmatic rocks occur intercalated in the sedimentary section and at the intersections of two fault alignments: a SE-NW, strike-slip fault trend and a SW-NE, normal fault trend, similar to the onshore alkaline bodies of the Poços de Caldas–Cabo Frio alignment. The possibly reactivated faults (mainly SE-NW transfer faults) could have cut through the whole lithosphere, reached the asthenosphere, and caused partial melting simply by pressure release.

**Resumo**

O estudo do magmatismo do Neocretáceo e Eoterciário na área *offshore* de Cabo Frio, situada no limite entre as bacias de Santos e de Campos, foi baseado na interpretação de dados sísmicos 2D e 3D processados com o auxílio da Técnica VA (volume de amplitudes), mapeamentos em terra e no mar e

dados de poços. Os dados sugerem interpretações para explicar a gênese desse magmatismo, as quais não levam em conta o modelo clássico de plumas mantélicas. O mapeamento dos principais diques alimentadores, em seções sísmicas de reflexão, revelou que eles têm direção predominante NW-SE, coincidente com o alinhamento da Zona de Deformação Cruzeiro do Sul, à qual pertence o Alto de Cabo Frio. Essa observação é coerente com as características das falhas de rejeito direcional mais importantes em terra, as quais são de idade Pré-Cambriana e sofreram reativação. Além disso, os volumes mais expressivos de rochas magmáticas, intercaladas na seção sedimentar, ocorrem próximos a áreas de interseção entre zonas de falhamentos de direção SE-NW (falhas de rejeito direcional) e SW-NE (falhas normais), assim como os maciços alcalinos pertencentes ao alinhamento Poços de Caldas–Cabo Frio. Esses dados sugerem que o magmatismo em questão não foi originado por plumas mantélicas, uma vez que as falhas reativadas (principalmente as falhas de rejeito direcional com orientação SE-NW) parecem ter rompido toda a litosfera, atingindo a astenosfera, onde causaram fusão parcial por simples alívio de pressão.

## **1. Introduction**

The purpose of this paper is to present a brief summary of what is presently known about post-Aptian magmatism in the area of the Cabo Frio High and its surroundings, as well as to provide new interpretations for its genesis. Aptian (125–112 My) is the time of deposition of the salt sequence in the area, which is shown in Fig. 1. The methodology for this work uses interpretations of 2D and 3D seismic data, correlated with well logs, and investigations of cuttings and cores of wells that drill magmatic rocks.

The mantle plume model is widely questioned. We present unpublished data that may provide new insights into that debate and enrich interpretations of the magmatism that occurs in southeast Brazil. Our data point to a non-plume origin for this magmatism.

## **2. Geologic setting**

The breakup of Pangaea in the Early Cretaceous led to the separation and drift of the South American and African continents. That event, called the Wealdenian Reactivation by Almeida (1967), created an

extensive system of intracontinental rifts. The maximum crustal extension was reached when the faults cut through the whole lithosphere, becoming conduits for basaltic lava flows, which formed one of the largest Phanerozoic volcanic provinces, the Paraná–Etendeka Province. Hawkesworth et al. (2000) determine that the climax of this volcanism happened between 133 and 125 My. Younger ages were obtained in tholeiitic dikes parallel to the current coast line. These dikes are parallel to Atlantic rifts that are currently under the marginal basins of Pelotas, Santos, Campos, and Espírito Santo, which probably contain basaltic rocks of similar ages at the time of largest mechanical subsidence in the area. A detailed study of the basaltic rocks of the rift phase in the Campos Basin was presented by Mizusaki (1986); in the proximal area of Santos Basin, they have been described by Fodor et al. (1983). The rifts gave rise to lacustrine depositional systems; the shales deposited during this phase are the main source rocks for oil and gas.

Strike-slip faults orthogonal to the rift propagation direction were responsible for jumps in the geographical positioning of the rifts. During a period of tectonic quiescence in the Aptian, marine ingression formed a large gulf with evaporite deposition. Afterward, during the evolution of the continental margin, vigorous salt tectonics formed salt windows, anticlines, and minibasins, creating favorable conditions for migration and the entrapment of oil and gas. The progressive drowning of the basins formed a wide carbonate platform in the Albian.

In the Late Cretaceous, a major siliciclastic inflow into the Santos Basin came from the uplifting of a proto-Serra do Mar Mountain Range that Almeida and Carneiro (1998) and Zalán (2004) locate in the area of the present-day continental shelf.

A tectonic event of great importance occurred in the Early Tertiary (Almeida and Carneiro, 1998). This event originated the Serra do Mar mountain complex and corresponded to a new pulse of magmatism, with ankaramitic flows in the Volta Redonda (Riccomini et al., 1983; Riccomini et al., 2004; Oreiro, 2004) and Itaboraí (Klein and Valença, 1984) basins, dated 48 My and 44 My, respectively. At the same time, intrusive and extrusive submarine magmatism occurred offshore. Extrusive magmatism was stronger on and around the Cabo Frio High. The climax of this magmatic event occurred at around 50 My (Rangel et al., 1990).

The Cenozoic rift basins of southern and southeastern Brazil all formed, according to Almeida and Carneiro (1998) and Zalán (2004), by a major tectonic event that began in the Paleocene. This event caused the reactivation of the main Precambrian shear zones of southeastern Brazil. This rift system comprises the Curitiba, São Paulo, Taubaté, Resende, and Volta Redonda basins (Amador and Castro, 1976; Almeida, 1976; Riccomini, 1989; Riccomini et al., 2004), as well as the São João Graben (Mohriak and Barros, 1990). The Itaboraí (Leinz, 1938; Beurlen and Sommer, 1954) and Macacu (Meis and Amador, 1977; Ferrari and Silva, 1997) basins are included in the Guanabara Graben (Ruellan, 1944; Almeida, 1976; Ferrari, 2001). The occurrence of Quaternary sediments in many of these basins indicates these reactivations are still in course. This event might have conditioned channelized features in the adjacent offshore basins. Moreira and Carminatti (2004) show, in an offshore area close to that studied herein, a complete slope-basin depositional system in which the channels have the same NW-SE direction of the tectonic alignments observed in the northern Santos Basin. During an eustatic rise, a mud system developed (Fig. 2), showing a chaotic seismofacies (which may be defined as the set of characteristics of the seismic reflections, including amplitudes, frequencies, and continuity). The chaotic seismofacies probably relates to earthquakes that occurred at the same time and/or just after the intrusive and mainly extrusive Early Tertiary magmatism.

### **3. Ages of magmatism**

Cordani (1970) presents 80 previously unpublished geochronologic analyses of rocks collected on many South Atlantic islands, using the K/Ar method. Cordani suggests occurrences of alkaline rocks in the southern and southeastern Brazilian shelf, where the alkaline massifs of São Sebastião, Montão do Trigo, Vitória, and Cabo Frio occur on nearshore islands. His hypothesis was reinforced by recent gravimetric and magnetometric data, according to the interpretation of Zalán and Oliveira (2005).

Almeida (1991) suggests that both the Brazilian volcanic islands and the seamounts of the Abrolhos volcanic complex/Vitória–Trindade fracture zone and the magmatic alignment of Poços de Caldas (82 Ma, Ar/Ar)–Cabo Frio (53 Ma, Ar/Ar) are located over extensive fracture zones, where the magma ascended during reactivations. However, several authors attribute such alignments to mantle

plumes and hotspots (e.g., Sadowsky and Dias Neto, 1981; Herz, 1987; Thompson et al., 1998; Szatmari et al., 2000; Cobbold et al., 2001; Assumpção et al., 2004; Thomaz Filho et al., 2005). In carefully analyzing the strike-slip faults inferred by Cobbold et al (2001), we conclude that the igneous bodies are placed at the intersections of the SE-NW–trending strike-slip faults with the SW-NE–trending normal ones.

Alves et al. (2005) analyze both normal and strike-slip faults along the Vitória–Trindade fracture zone and conclude that this zone acts as a conduit for the Trindade mantle plume. We agree that the faults shown by Alves et al. are deep structures that reach the asthenospheric mantle and cause partial melting by simple pressure release, as Foulger (2003) states: “Volcanism requires both a source of melt (apparently without exceptionally high temperatures) and extension of the Earth’s surface, to allow it to escape.”

The magmatism in offshore, SE Brasil has been studied by many authors (e. g. Rangel et al., 1990; Mizusaki and Mohriak, 1992; Rangel and Barros, 1994; Mohriak et al., 1995; Thomaz Filho and Rodrigues, 1999; Thomaz Filho et al., 2000; Mizusaki et al., 2002; Oreiro, 2002; Esteves and Rodrigues, 2003; Oreiro et al., 2003, 2004, 2005). In the onshore area, Valente (1997) pioneered the description of the geochemistry and petrography of the basaltic and alkaline dikes in the city of Rio de Janeiro. Valença (1980) offers a detailed petrogenetic study of the alkaline massifs located east of Guanabara Bay.

#### **4. Characteristics of the volcanic bodies in the study area**

The Early Tertiary (Paleocene and Eocene) magmatic rocks mainly arose from a central conduit system with volcanic edifices of conic form characterized by a chaotic seismofacies. The base of the volcanoes is marked by a single strong positive reflection, which comprised the seafloor at the time of formation of these volcanoes (Oreiro, 2002, Fig. 3). All wells previously drilled into these features in the Santos and Campos basins have sampled hyaloclastites and volcanoclastic rocks.

The dikes are easily identified in seismic data, where they reveal a set of strong, positive reflections with abrupt lateral terminations, discordant to the reflections related to the sedimentary strata into which they intruded. It is important to emphasize that subvertical dikes are rarely seen in conventional seismic data.

Seismic attributes help ease the visualization of subvertical dikes, in that they may be the most abundant feature in the areas of ample magmatic manifestations. For example, contrasts in acoustic impedance, expressed as root mean square (RMS) amplitude, can be used to identify changes in otherwise uniform seismic data. The RMS amplitudes can be extracted from any time window of the seismic data by the equation

$$X_{rms} = \sqrt{\frac{1}{n} \sum_{i=1}^n x_i^2},$$

where  $x_i$  represents the seismic amplitudes inside a given time window that comprises  $n$  samples. In this paper, all the seismic data are in time, and therefore, the RMS amplitude values are extracted from time windows defined both between chronostratigraphic units (isochrons) and encompassing some milliseconds (ms) above and below a given horizon (Fig. 4). Fig. 5 shows an example of a RMS amplitude map.

Another seismic attribute we use is the volume of amplitudes (VA). This method, developed by Bulhões (1999) and improved by Bulhões and Amorim (2005), allows for a better seismic visualization of volcanic systems, as well as sedimentary sequences in general. The equations used to obtain the VA attribute are shown in Fig 4. This attribute, represented by an appropriate black-and-white color pattern, can provide images that reinforce structural and stratigraphic features contained in seismic data, such as unconformities, faults, fractures, and different seismofacies. In this context, subvertical volcanic dikes appear as interruptions in the continuity of the horizontal or relatively gently dipping reflections. The VA attribute with  $-90^\circ$  of phase rotation makes conventional seismic sections resemble actual vertical outcropping planes, which may be useful in mapping, because this attribute seems to enhance seismic contrasts and enable a better visualization of geological features in seismic data.

Beneath each of the volcanic edifices, identified by their conic geometry and chaotic internal seismofacies, is a group of continuous, subvertical features that may represent fracture or fault zones, either filled or not by magmatic rocks. These features may represent feeder dikes of the volcanic and intrusive structures in the sedimentary section and the acoustic basement (Fig. 6).

Some feeder dikes are inclined and can be visible in conventional seismic sections, mainly in 3D surveys and marginal basins in which there was active post-salt magmatism.

The sills are more difficult to visualize in seismic sections; according to Pedro Victor Zalán (pers. comm., 2005), the feature shown in Fig. 7 is a sill intruded into unconsolidated sediments deposited at shallow depths. These water-saturated sediments may cause cooling and contraction of the central portion of the magmatic body, creating a feature similar to the classic circular to hexagonal geometry of a mud crack.

Finally, thicker magmatic bodies can appear in seismic sections as packages with well-defined tops and poorly defined bases, as well as low seismic amplitudes in their inner part. In the case of the well shown in Figs. 8 and 9, in its last 300 m, a homogeneous body of holocrystalline dolerite is sampled (Souza et al., 2001). This body may be either a shallow intrusion, comprising the magmatic reservoir of the volcano 2 km north of the well, or a set of submarine lava flows that erupted in a short time interval. This characterization may explain the absence of intercalated siliciclastic sediments. Figs. 8 and 9 show the position of the volcano in relation to the well, poorly defined in Fig. 8 but clearly visible in Fig. 9 (processed with VA technique with phase rotation of 90°, see Fig. 4). Fig. 9 shows a subvertical dike below the center of the volcanic edifice V2 that probably corresponds to the conduit that transported the magma from its reservoir, at uncertain depth, to the seafloor at the time of volcano formation. In the normal seismic section of Fig. 8, the feeder dikes are mostly invisible. However, the top and the base of the magmatic body are well marked by strong positive reflectors, defining a relatively homogeneous, low amplitude zone.

##### **5. Genetic model for the post-Aptian magmatism in the area**

The detailed information provided by the three-dimensional seismic survey between the Santos and Campos basins reveals the presence of dikes, sills, lava flows, and volcanic edifices at several chronostratigraphic levels, from the Albian to the Middle Eocene. Such features are aligned with SE-NW faults and fractures, interpreted here as subvertical feeder dikes. For example, Fig. 10 shows a concentration of ring dikes intruded into the Campanian sequence along a NW alignment observed in a time slice corresponding to the level of the pre-salt sediments.

Some dikes observed in the Santonian and Campanian sections have a “boomerang” form in seismic profiles. These dikes are expressed by strong amplitude anomalies in a window corresponding to the Campanian isochron RMS amplitude map (Fig. 11).

SE-NW strike-slip fault and fracture zones have been observed in practically all areas of the Campos and Santos basins, as well as in adjacent continental areas. Such features have acted as transfer zones since the formation of these basins and were reactivated during periods of major tectonic activity in the Late Cretaceous and Tertiary. Szatmari and Mohriak (1995) correlate major tectonic pulses of the Andean orogeny with magmatic phases in the post-salt section of the Santos and Campos basins.

Igneous activity is widespread in the Late Cretaceous and Eocene in the SW Campos Basin, as can be deduced from the RMS amplitude maps extracted from the seismic horizons windows corresponding to the tops of Maastrichtian and Santonian. The main source of magmatism is not the Cabo Frio High. Practically all volcanic edifices and intrusive bodies have their own corresponding subvertical feeder dikes, which are visible in the VA attribute sections. Strong evidence, based on seismic and well data, indicates that the greatest thickness of magmatic rocks coincides with intersections of NE fault zones with NW ones (Fig. 12). All volcanic edifices found in the SW portion of the Campos Basin are aligned along both SW-NE and SE-NW trends, parallel to the direction of the main fault zones (Fig. 12).

Some faults, mainly those of larger offsets, seem to displace the salt base. The evolution of these SW-NE faults is synsedimentary, and they displace the Late Cretaceous magmatic section, but they do not seem directly related to the genesis of this section. The fault heaves at the salt base are visible in some of the normal faults with NW-SE directional component, whose seismic signatures are flower structures. The directional component of such faults displaces the pre-salt, Late Cretaceous, and Tertiary sedimentary depocenters, as well as the SW-NE alignments of the salt diapirs (Fig. 13). The branches of these faults tend to converge inside the seismic basement in a single trace that can be mapped to the limit of the vertical seismic resolution (Fig. 14).

The SE-NW faults and fractures in this work represent the main conduits of post-Aptian magmatism. It is very important to note that magmatic bodies of different ages are superposed in the

area. The cuttings and cores of well B (Fig. 7, after Oreiro, 2002) reveal the presence of Eocene hyaloclastites and basalts, together with Santonian dolerite dikes that cut through the Cenomanian section. In the SW extreme of Campos Basin, the heights of the volcanic edifices reach hundreds of meters (Rangel and Barros, 1994).

On the basis of this evidence, we can infer that post-salt magmatism is more abundant where the occurrence of pre-salt faults is more frequent; this claim is also valid for the adjacent continental alkaline magmatism, represented by massive bodies generally placed at the intersection of SE-NW and SW-NE fault zones. This hypothesis is corroborated by the analysis of satellite images from NASA. Moreover, some alkaline intrusive bodies have their longer axis oriented NW, such as the Tinguá and Itatiaia massifs. Fig. 15 shows that the Tinguá body has, in plan, a grossly rectangular shape (10 km × 6.6 km) with limits marked by N45E and N45W alignments. The Passa-Quatro–Itatiaia intrusive bodies form a complex structure displaced by a well-marked fault zone (Bueno, 2000). This fault zone also displaces the crest lines of the Serra da Mantiqueira Mountain Range and creates deep talwegs for the recent drainage in the region (Fig 16). The fault zone can be traced from the Mantiqueira Mountain Range to the shoreline, as first described by Almeida (2001) as “the Funil Transfer Zone” (Figs. 15 and 16). Most post-Aptian magmatic features, observed in seismic sections and maps, in the offshore area have a generally SE-NW orientation (Figs. 11 and 12). Therefore, we posit that the main magmatic control in the marginal basins of SE Brazil and their adjacent continental areas is the reactivation of SE-NW, deep strike-slip fault zones and their intersections with SW-NE reactivated normal fault zones. This information supports the interpretation of Almeida (1991).

The petrographic characteristics of the igneous rocks in the offshore areas close to the Cabo Frio High (SW of Campos Basin, NE of Santos Basin), according to the data analyzed (Szatmari et al., 2003), show that it is basaltic magmatism. Most of the well samples analyzed in the area indicate that the Late Cretaceous basaltic rocks are tholeiitic, which supports our inference that the strike-slip faults that were the conduits for the magma reached the asthenosphere.

An alternative to the classic plume model is the model defined by Cañón-Tapia and Walker (2004), shown in Fig. 17. Melting of a mantle portion begins in a low velocity zone (LVZ), where the interconnectivity among the mineral grains allows for the eventual formation of a vertical conduit

entirely contained in the melting zone. When that conduit reaches the critical height, which depends on the density and lithostatic pressure of the overlying rocks, the magma ascends vertically, feeding itself from the supply of melted rock from the LVZ. If the amount of melted rock is great enough, the magma eventually can reach the surface. Thus, a volcanic edifice will form if the minimum regional stress is horizontal. If the amount of melted rock is not enough to allow the magma to reach the surface, the process will be aborted and form vertical dikes when  $\sigma_3$  is horizontal and sills when  $\sigma_3$  is vertical. Any other combination of stresses will produce dikes with different dip angles. A third situation, in which the amount of interconnected magma is not enough to sustain the pressure in the open conduit, is shown in Fig. 18. Cañón-Tapia and Walker (2004) conclude that it is possible to explain most of the volcanic features around the world by analyzing the degree of interconnectivity in the melting zone and the regional stress field. They mention that many authors define the magma chamber as mush columns from the melting zone. In our point of view, this theory is more suitable to explain the genesis of magmatism than the mantle plume in the study area.

According to Anderson (2000), the asthenosphere is chemically heterogeneous, and its long wavelength temperature variations in relation to its average temperature are  $\pm 200^\circ\text{C}$ . Such variations include temperature excesses that have been attributed to mantle plumes (Anderson, 2000, 2001). Moreover, because a large portion of the upper mantle is near its melting point, the criteria for dike intrusion are as follows: (1) the minimum compressional stress of the lithosphere should be horizontal and (2) the buoyancy of the melted material should overcome the active stress inside the plate. Anderson and Natland (2005) argue that the effects of pressure on the properties of the materials are not considered in experiments or computational simulations of mantle plumes. Their conclusion accords with our opinion that magmatic events may occur without an associated mantle plume.

We also note the difference between the interpretations of Anderson (2001) and Cañón Tapia and Walker (2004). The former assert that crustal movements play an important role in the mantle fusion, with partial asthenospheric melting produced by reactivations of older fault zones, and thus cause pressure relief. Cañón Tapia and Walker instead infer that the magma can create its own pathway when there is partial melting of a mantle area in which the spaces among the mineral grains

allow magma ascension, provided that the hydrostatic pressure of the magma overcomes the lithostatic pressure of the overlying rocks and that the regional  $\sigma_1$  is mainly horizontal.

Almeida's (1991) hypothesis states that a change in the pole of rotation between the South American and African plates occurred from 80 My and was responsible for deep faulting in the crust. These faults could have reached the asthenospheric mantle and caused partial melting by pressure release. Similar processes during Santonian/Campanian and Paleocene/Eocene times could explain the overlap of igneous rocks in the Cabo Frio area (Fig. 7), as is proposed in the general model of Anderson (2001).

Recent petrologic studies in plutonic and volcanic rocks of the Serra do Mar igneous province point to a non-plume origin for this magmatism (Brotzu et al, 2005).

Klein (1993) asserts that the intrusive and extrusive alkaline rocks of the Mendanha Massif (Fig. 15) were emplaced along a N80°E alignment, reactivated during Cretaceous–Tertiary periods. He concludes that this alignment was the pathway for the magma ascent.

The volcanic activities in the North Sea show some similarities with those of the SE Brazilian “passive” margin, despite their different ages of formation. There, Foulger and Anderson (2005) and Gernigon et al. (2006) propose a non-plume origin for Iceland and Vøring Basin magmatism, respectively.

Finally, Fairhead and Wilson (2005) provide a detailed study of deformation processes in the South Atlantic Ocean using high-resolution satellite data. They suggest that faults parallel to the motion of the South American plate and orientated NW are most susceptible to reactivation at both micro and macro scales. They also argue that the Rio Grande rise probably suffered dextral shear and extension. The feature they call the Rio Grande rise is the same as the Cruzeiro do Sul deformation zone (CSDZ) described by Souza (1991) (Fig. 19). We interpret the Cabo Frio High as the landward continuation of the CSDZ. Thus, the interpretation of Fairhead and Wilson (2005) is in agreement with the general conclusion presented here, namely, that the intensification of magmatic events on and around the Cabo Frio High was caused by the reactivation of SE-NW strike-slip zones that can be mapped by 3D and 2D data.

## 6. Conclusions

Post-salt magmatic events in the study area resulted from the reactivation of deep fault zones, many of which had been created by the breakup of the Pangaea supercontinent. The accurate mapping of magmatic sections in the area, using 2D and 3D conventional seismic data and some of their attributes, such as the VA technique, shows that the dikes and volcanic edifices formed at various ages in Late Cretaceous and Early Tertiary times and frequently overlap along SW-NE and SE-NW fault and fracture zones formed by accommodation to the movements of the South American plate. At the intersections of these two fault systems, the magmatic sections become wider and thicker, reaching thicknesses of 500 m or more.

The reactivation of deep fault zones seems to be the main cause of partial melting of portions of the asthenosphere by pressure release. The magma generated by this process rises in subvertical columns and sheets and reaches the surface, forming volcanic edifices, or intrudes the sediments. Therefore, we strongly believe in a non-plume origin for the magmatism in the study area and its surroundings.

#### **Acknowledgments**

The authors acknowledge Petrobras S. A. for granting permission to publish this paper. We are grateful to Carlos Lopo Varela and Valéria Lopes dos Santos, who first revised this paper, and to João Batista Françolin for providing the images in Figs. 15 and 16. We also thank Mario Ernesto Macedo Alves and his coworkers for their help in preparing some of the figures, as well Bianca de Miranda Fernandez for Fig. 12. Special gratitude is due to Renato Darros de Matos, Marta Mantovani, and Luis Otávio Aguiar Oliveira for their useful criticisms of the manuscript.

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### **Figure captions**

Fig. 1. Map of gravimetric anomalies from satellite altimetry, showing the location of 3D seismic survey (smaller black rectangle) and its surroundings (larger black rectangle). Some regional structural interpretations are also shown, such as the direction of great strike-slip (transfer) faults (modified from Cobbold et al., 2001; Thomaz Filho et al., 2005), the Jean Charcot Submarine Mounds (JS, lower right), and the alkaline massifs of southern Brazil (white). The interpretation of the transfer

faults is also based on regional seismic mapping in the northern Santos Basin. The satellite altimetry map is from <http://ucsd/topex/edu> (after Sandwell and Smith, 1997).

Fig. 2. Seismic section in time located in the northern Santos Basin. The black arrow points to a Middle Eocene chaotic seismofacies, considered to result from earthquake activity. The lower left contains a time structural map of the top of the Lower–Middle Eocene. The canyons (C) are parallel to the direction of the feeder dikes shown in Fig. 10. (after Moreira and Carminatti, 2004).

Fig. 3. Comparison of seismofacies defined in offshore Hawaii by Leslie et al. (2002) and seismostratigraphic aspects of the magmatic section in Cabo Frio. In the upper left, seismofacies A is interpreted to correspond to proximal slumps originating from volcanic edifices; seismofacies B to distal slumps; and seismofacies C to volcanoclastic turbidites. The upper right shows a seismic section (A) and its interpretation (B). The actual seafloor is composed of lava flows, and the chaotic seismofacies represents intercalations between older lava flows and volcanoclastic sediments originating from nearby volcanic cones. The lower panel shows a 2D seismic section from the Cabo Frio area, in which it is clear that the seismofacies situated near the cones is similar to seismofacies A defined by Leslie et al. (2002), which indicates both were formed by slumping. The strong positive reflections, adjacent to the cones, compose the seismic signature of older lava flows that comprised the seafloor at the time of formation of the volcanic edifices. The plane-parallel seismofacies over the magmatic section in the Cabo Frio area is composed of epiclastic sediments unrelated to the post-salt magmatic pulses.

Fig. 4. Equations of the volume of amplitudes (VA) technique. (1) Root mean square (RMS), (2) inverse Hilbert's Transform with  $-90^\circ$  phase rotation, (3) weighting window of the elementary seismic bed (ESB). The ESB is the thinner bedrock layer (M) that can be detected by the seismic method and the key element for weighting and computing the seismic data with VA. This technique is a post-stack seismic processing. Equation (2) makes the seismic section resemble a vertical outcropping surface (Fig. 9) by enhancing seismic contrasts, which allows better visualization of geological features such as channels, faults fractures, and volcanic bodies (after Bulhões and Amorim, 2005).

Fig. 5. Root mean square (RMS) amplitude map extracted from a 3D seismic volume with a 24 ms time window centered at the top of Cretaceous (1). The map shows that the seismic signature of a channelized lava flow is a strong positive reflection (black) (2). The strong reflection corresponds to a light gray channelized feature in (1). The amplitude scale (1) shows values on the right side varying from 0 to n (RMS amplitudes) and on the left side from 127 to -128; standard amplitude values for seismic lines displayed in 8 bits. See Fig. 4.

Fig. 6. (A) Strike seismic section in time through the study area, processed with the VA technique (see Fig. 4). Dike swarms and other near-vertical structures can be seen as subvertical interruptions of the continuous reflections (in white). (B) Zoom of A showing ring dikes with feeder dikes (subvertical black lines, 1), interpreted as the conduits for magma ascent.

Fig. 7. Seismic section in time showing a sill, named Victoria Regia structure by Pedro Victor Zalán (pers. comm., 2005). EH, Eocene hyaloclastite section; EB, Eocenic basalt lava flow; SD, Santonian dike intruded into Cenomanian sediments.

Fig. 8. Conventional seismic section showing the signature of magmatic features in the area. Note the volcanic edifice (V1) has a feeder dike that appears like a rotated “Y” and branches from a synsedimentary fault related to halokinesis. In its last 300 m, the well drilled a section of compact dolerite. The K/T unconformity, based on palaeontological data, seems to comprise older lava flows over which the volcanic edifices were built.

Fig. 9. Same section as in Fig. 8, processed with the VA technique (phase rotation of 90°, Fig. 4) (Bulhões and Amorim, 2005). This type of processing makes the seismic section resemble an outcropping surface and thus reveals that the volcanic edifice, named V2, has a vertical feeder dike that can be easily traced down to the lower limit of resolution of the seismic section. The fault plane to the left is partially filled with magmatic rocks that are linked to volcanic edifice (V1).

Fig. 10. (A) Root mean square (RMS) amplitude map extracted from the isochron of the Campanian interval. Some dikes are aligned in the same direction as the pre-rift alignment, which corresponds to a small portion of the big fault zone shown in the Fig. 5. To the left, the feeder dikes for the Tertiary volcanic edifices appear as straight lines trending N30W. (B) Time slice at the level of the pre-salt

sequence (4484 ms) showing an alignment with N30W direction, a boundary between a near circular structure (on left) and a chaotic seismofacies (on right). It also correlates with a zone of concentration of ring dikes in the much higher Campanian sequence (A). See Fig. 5 for an explanation of the amplitude scales.

Fig. 11. The same map as in Fig. 10, with two representative seismic sections, showing the ring dikes with a “boomerang” form in 2D seismic profiles. The seismic sections were processed with the VA technique with phase rotation of  $90^\circ$  (Fig. 4), so that the volcanic edifices (V) and the ring dikes (D) become prominent, with associated feeder dikes (FD). In the seismic sections, (1) top of the Paleocene; (2) K/T boundary; (3) top of the Santonian; (4) top of the salt; (5) base of the salt, and (6) Lower K acoustic basement. See Fig. 5 for an explanation of the amplitude scales.

Fig. 12. (A) 3D time structural map of the top of the Early Tertiary volcanic section in the area (Geoprobe™ processed image). (B) Map enhancing some important features; (F1) SW-NE Cabo Frio fault zone (Szatmari et al., 1996); (F2) SE-NW faults. The volcanic edifices are aligned on the borders of the two fault zone systems. On the intersections of the two fault systems, the volcanic edifices became more abundant and larger. They eventually coalesce, forming clusters (1). The directions of these edifices coincide with the main fault zones (Figs. 5 and 10). Almost all volcanic edifices have their conic geometry preserved; therefore, they were not exposed to subaerial erosion (Oreiro, 2002). (B) Seismic section (AA') showing that the volcanic edifices are on and over the K/T unconformity. Similarly, in the seismic section BB' (C), the cones were built over older lava flows on the K/T unconformity, as defined by palaeontological data.

Fig. 13. (A) Root mean square (RMS) amplitude map from the isochron of the salt; (B) seismic section, processed with the VA technique with a phase rotation of  $90^\circ$  (see Fig. 4, after Bulhões and Amorim, 2005), (1) top of the Paleocene, (2) K/T boundary, (3) top of the Santonian, (4) top of the salt, (5) base of the salt, and (6) Lower K magmatic basement; other intrusive and extrusive features marked with (I) and (E), respectively; (C) zoom of (B) that emphasizes the lopolith-shaped structure (L) and ring dike (RD), probably of Santonian age, lying above two salt domes (S) and concordant with the minibasin located between the domes. L has a feeder dike (FD) that cuts the pre-salt sequence. The same alignment (AL) present in Fig. 10 is located near a basement high (H) controlled

by faults that could have been of extensional character at the time of the basin formation and were reactivated as strike-slip faults during the Cenozoic tectonic episodes. See Fig. 5 for an explanation of the amplitude scales.

Fig. 14. Seismic section showing a flower structure with a set of normal faults with SE-NW strike-slip offsets in the SW Cabo Frio High. Offsets are defined by regional seismic interpretation. This figure shows a small portion of the big SE-NW fault zone in Fig. 10. See Fig. 5 for an explanation of the amplitude scales.

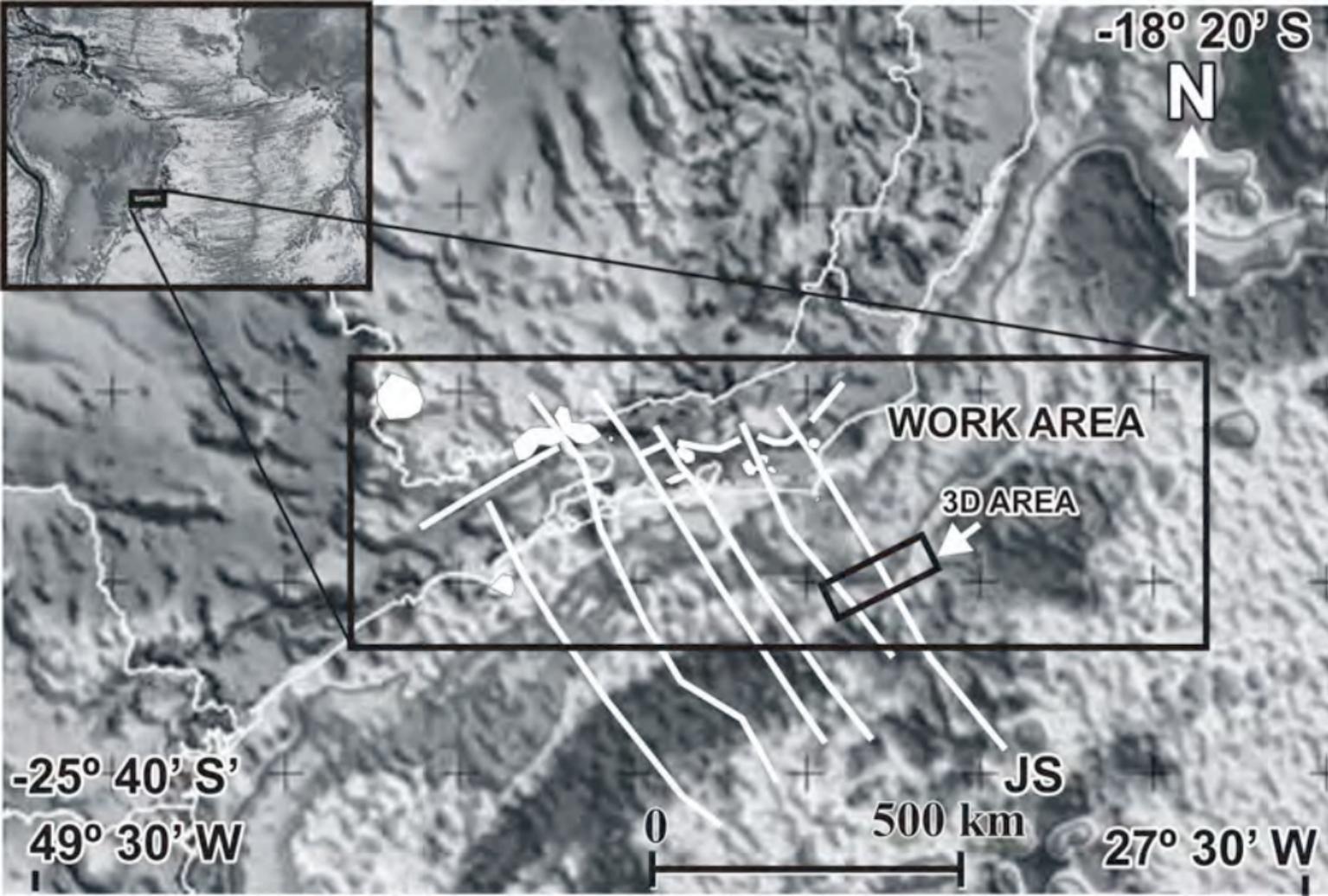
Fig. 15. Shuttle Radar Topographic Mission (SRTM) mosaic of part of southeastern Brazil showing near circular alkaline bodies (in white): 1, Poços de Caldas; 2, Ponte Nova; 3, Passa Quatro; 4, Itatiaia; 5, Morro Redondo; 6, Marapicu; 7, Mendanha; 8, Tinguá; 9, Soarinho; 10, Tanguá; 11, Rio Bonito; 12, Ilha de Cabo Frio and 13, Morro de São João. Also in white are linear old Precambrian shear zones reactivated in the Cenozoic as normal faults, forming the Continental Rift of southeastern Brazil (Almeida, 1976; Riccomini, 1989; Riccomini et al., 2004; Zalán, 2004; Zalán and Oliveira, 2005). Some of the proposed structures of this continental rift are as follows: A, Taubaté Basin; B, Resende Basin; C, Volta Redonda Graben; D, Guanabara Graben; and E, Barra de São João Graben. The transfer zones we interpret are shown as black alignments. F and VR are the Funil (Almeida, 2001) and Volta Redonda (Valeriano and Heilbron, 1993) transfer zones, respectively. The black square onshore and black rectangle offshore show the areas of Fig. 16 and the mapped 3D survey, respectively. The dashed line offshore shows the boundary between the Santos and the Campos basins. The STRM data come NASA and are integrated and processed by the geologist João Batista França.

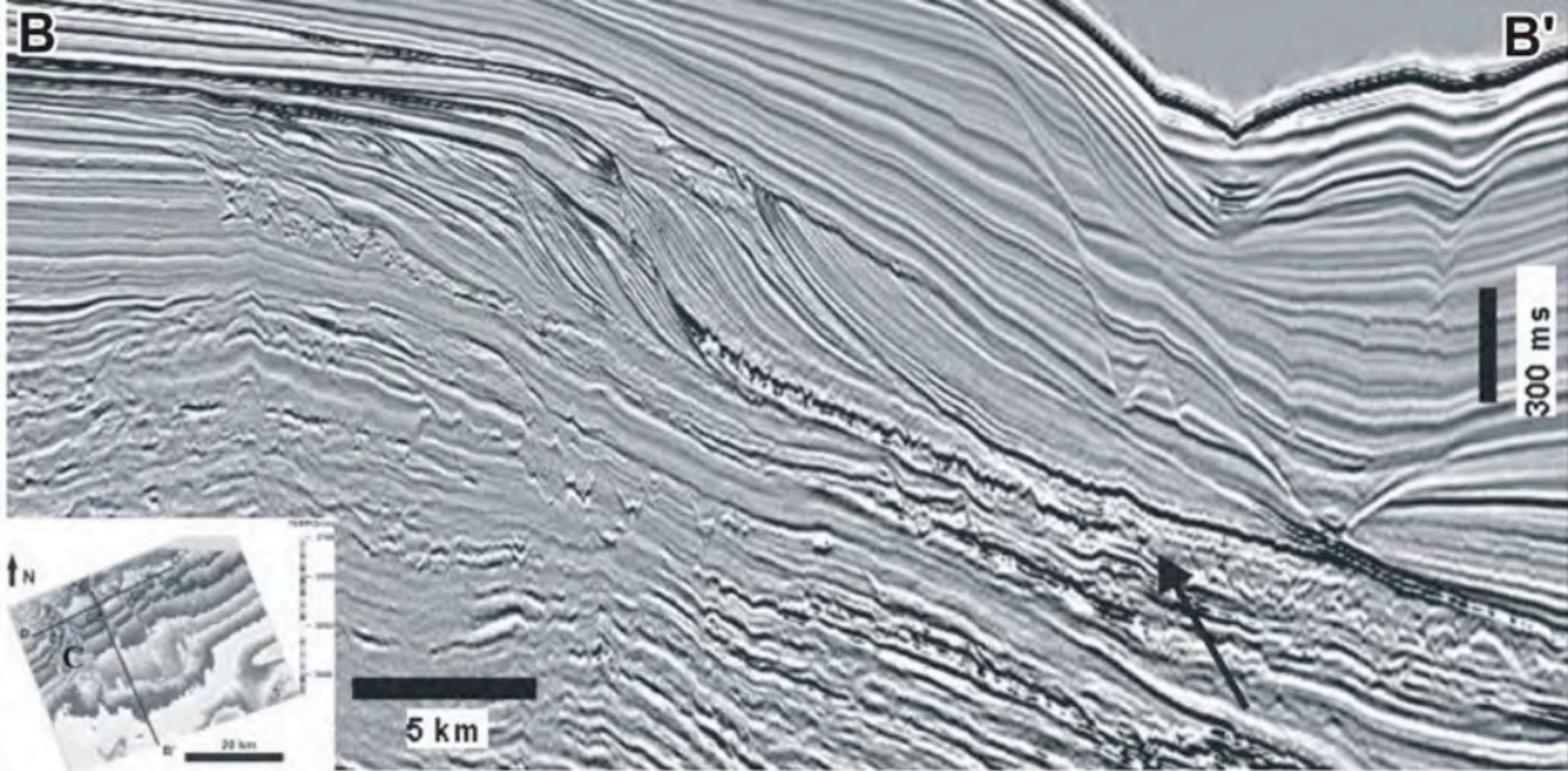
Fig. 16. Close-up of the Itatiaia and Passa Quatro massifs and their faulted late Proterozoic country rocks. Note horse-tail structure (HT) at the southeast corner of the Passa Quatro intrusion, which may reflect rotation caused by the effect on the hot alkaline massif of the associated NNW-trending dextral strike-slip fault. F1 is after Bueno (2000). F2 lies along the continuation of a major transfer zone defined by Almeida (2001). PCL, Precambrian lineaments. The dashed contour marks the near-circular alkaline bodies; the dotted line marks the outcrop zone of alkaline rocks in the Itatiaia Massif.

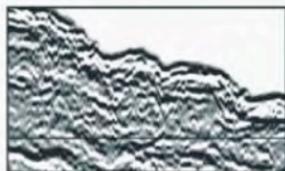
Fig. 17. Diagrams showing the evolution of the melt network during hydraulic fracturing. (A) Time immediately before a narrow channel (curved line in black) reaches the critical height to initiate fracturing. (B) Melt that flowed from the LVZ collected by the opening conduit, while producing a zone of melt exhaustion in its vicinity, shown by lighter shades of gray. (C) System in which the conduit is large enough to reach the surface and construct a volcanic edifice. The eruption stops when the melt network cannot supply the conduit with enough melt to sustain the pressure on the dike, even if there is enough melt available in the LVZ. The vertical arrows in (A) and (C) indicate the origin of the next fracturing event. The insets in (A) and (B) show the effects of a well-interconnected network of melt (left of conduit) and a limited degree of interconnectivity (right of conduit). In (C), the black square is the approximate extent of our study area. Modified after Canon-Tapia and Walker, 2004.

Fig. 18. Schematic evolution of a volcanic system from just before the end of the gestation period. Gray-scale conduits are active or very recent; black conduits mark older events in which magma has solidified. The zones in light gray in the LVZ are filled with melted rock. (A) Melting zone within the LVZ begins to form, (B) leading to the formation of a mush column. (C) The amount of interconnected magma is not enough to keep the pressure in the mush column, regardless of the regional stress orientation; however, if the supply of melt continues, a region of partial melting will form at lower depths. Its influence on the regional stress may result in hydraulic fracturing directions that could deviate considerably from the vertical. Note that scheme E is very similar to the VA seismic sections of our study area (F), where FD, feeder dikes; RD, ring dikes; and V, volcanic edifice. Modified after Canon-Tapia and Walker, 2004.

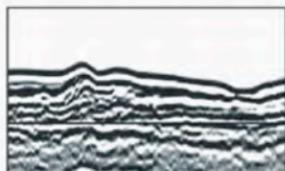
Fig. 19. Image of free air gravimetry (left) and the interpretation of Fairhead and Wilson (2005, right). (1) Cruzeiro do Sul deformation zone (Souza, 1991), (2) Vitória–Trindade fracture zone, (3) Abrolhos volcanic complex, and (4) Rio Grande rise. The small rectangle is the study area. The strike-slip displacement is secondary in comparison to the lateral extension that created a collapsed zone that constitutes the Cruzeiro do Sul deformation zone.







Seismofacie A

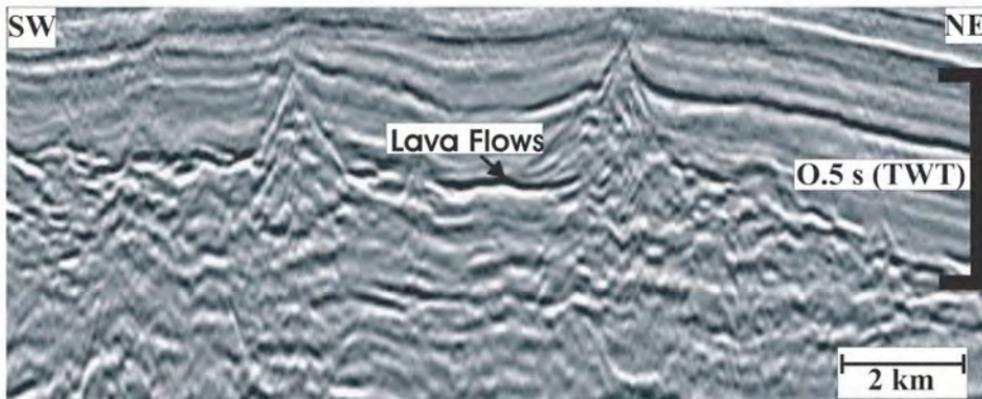
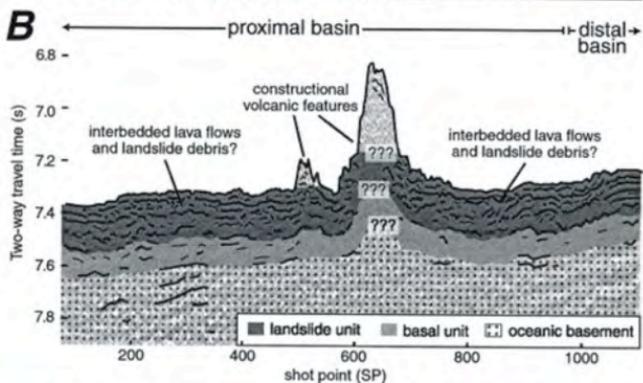
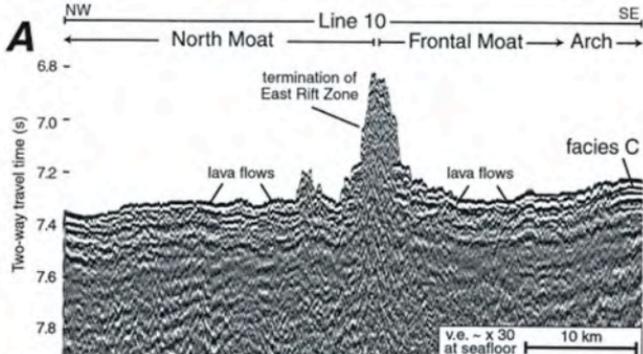


Seismofacie B



Seismofacie C

1 km



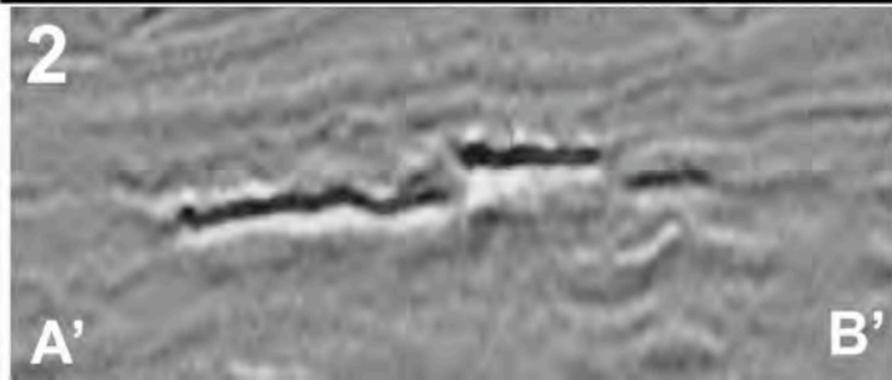
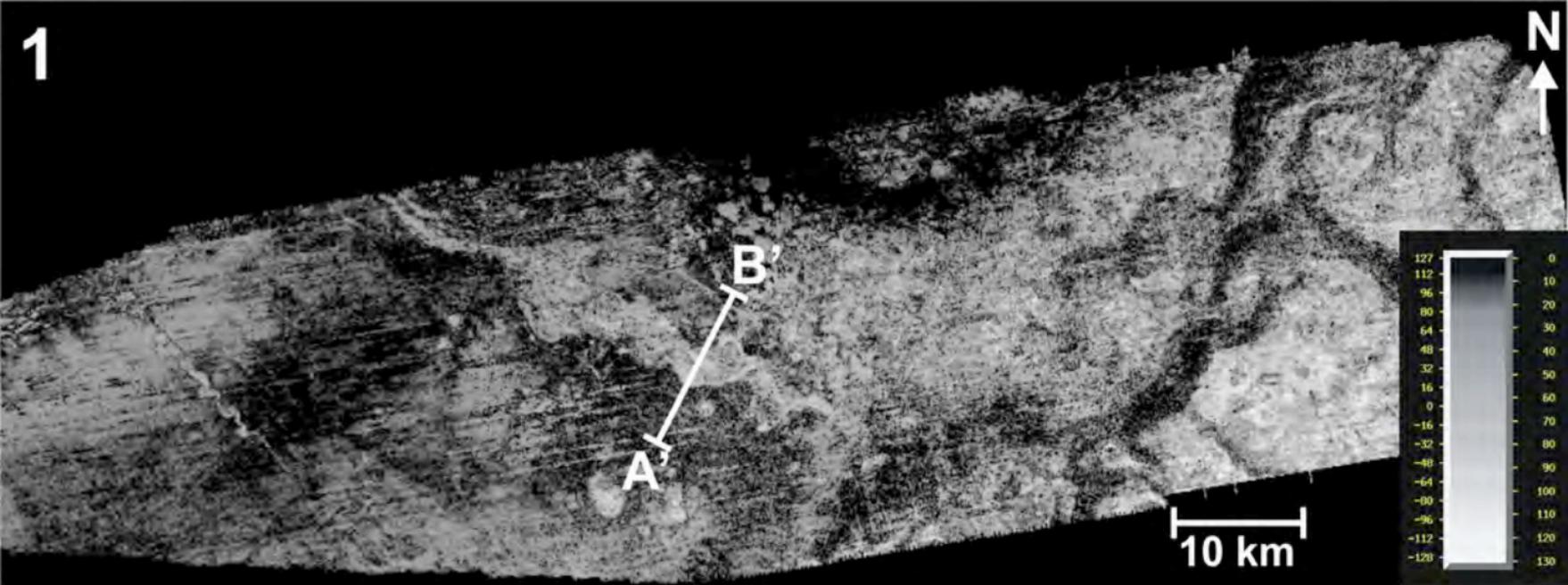
# VA Technique - Equations

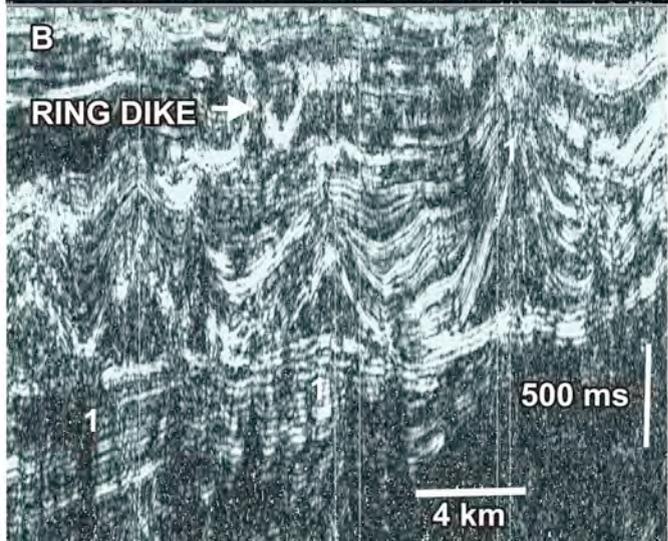
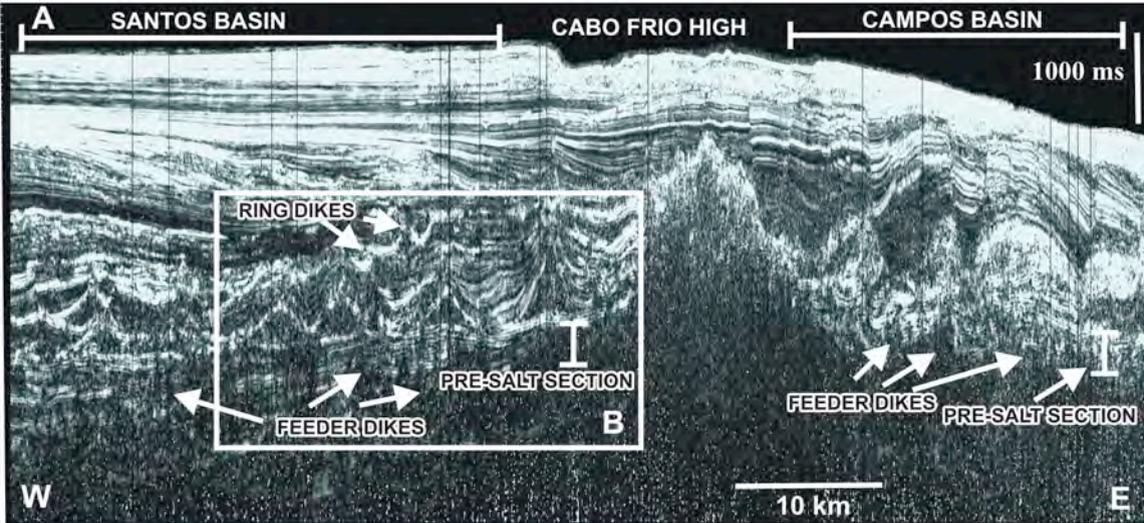
$$(1) \quad \bar{X}_{RMS_i} = \sqrt{\frac{\sum_{j=i-M/2}^{i+M/2} x_j^2}{M}}$$

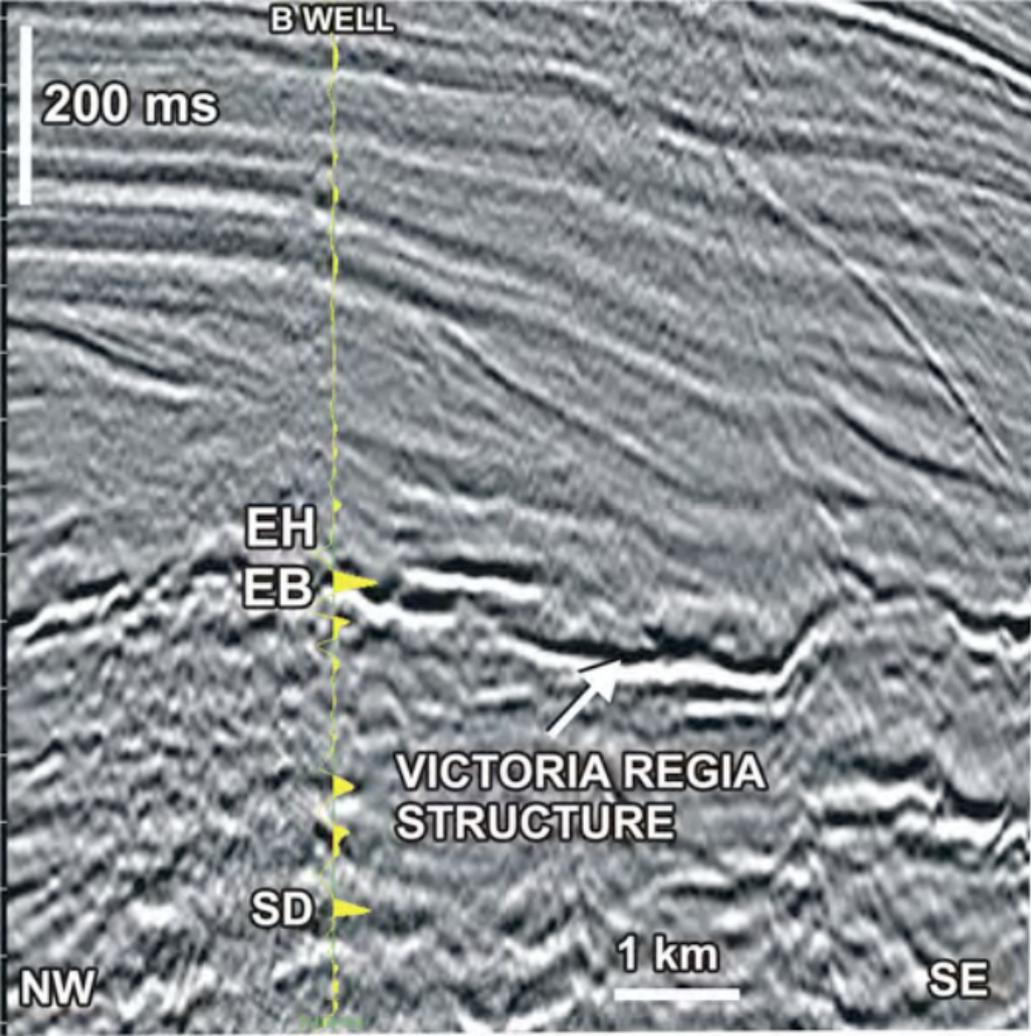
$$(2) \quad \bar{X}_{RMS_{-90^{\circ}_i}} = H^{-1} \left\{ \bar{X}_{RMS_i} \right\}$$

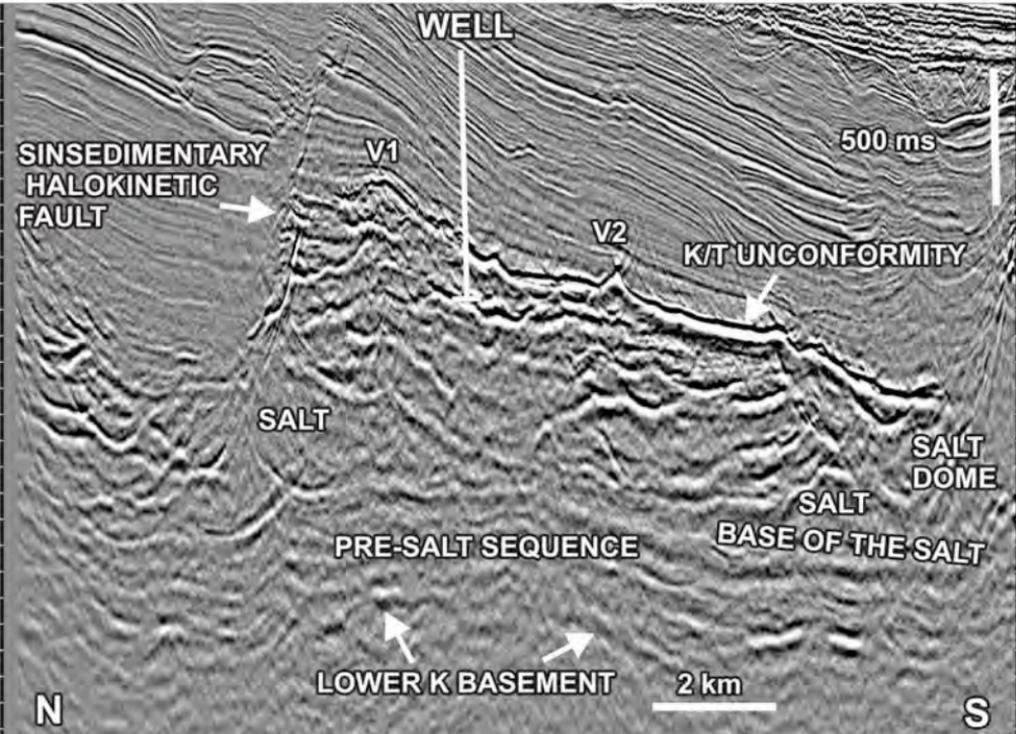
(3)  $M =$  Thickness of the elementary seismic bed

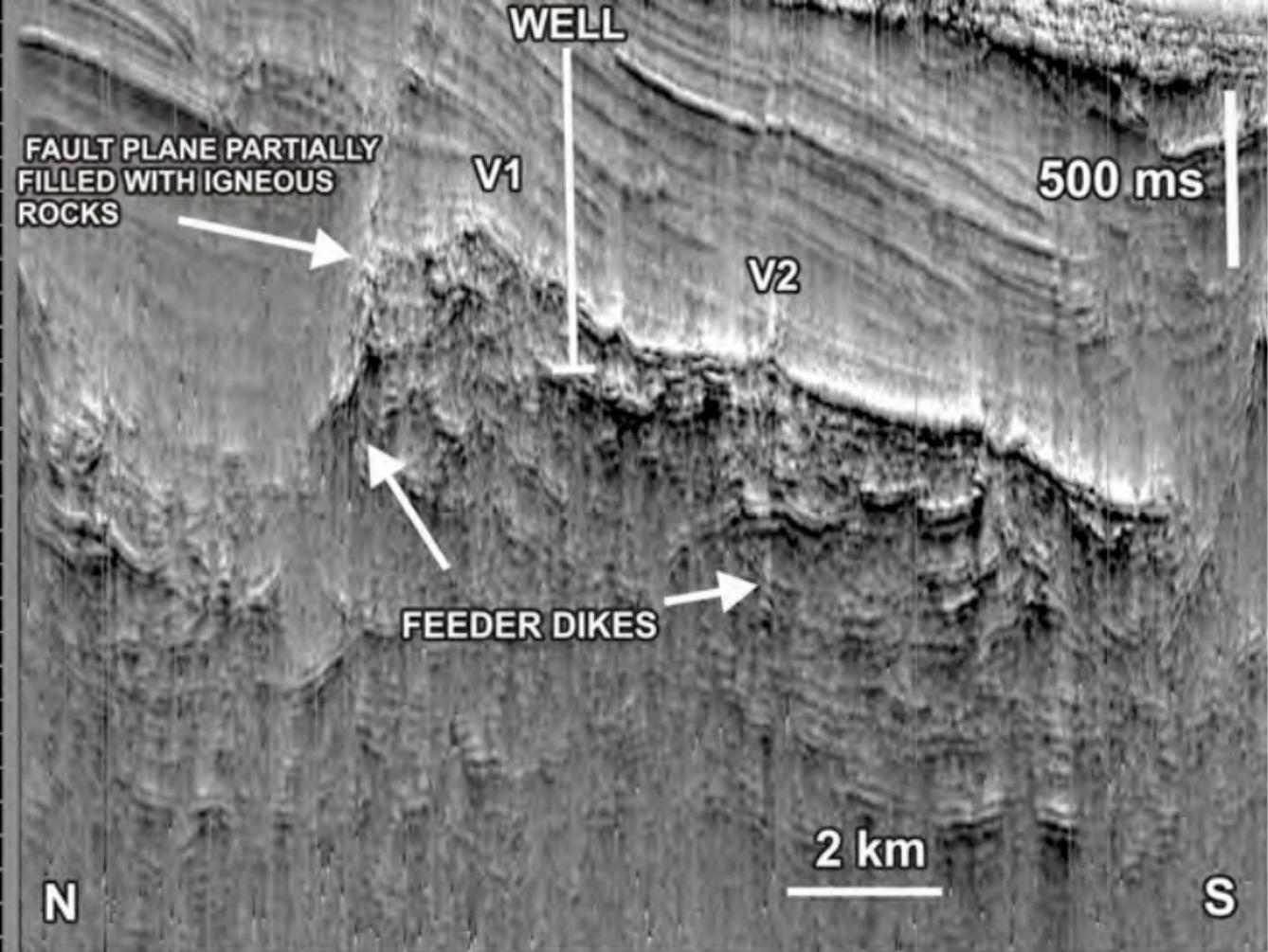


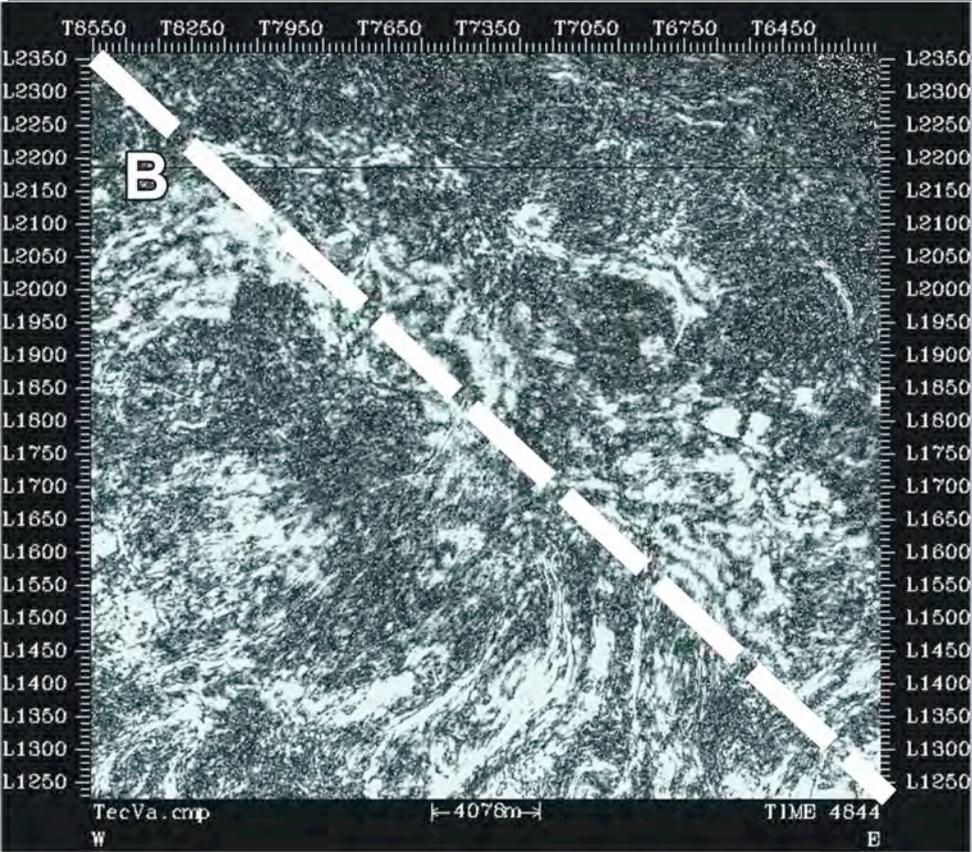
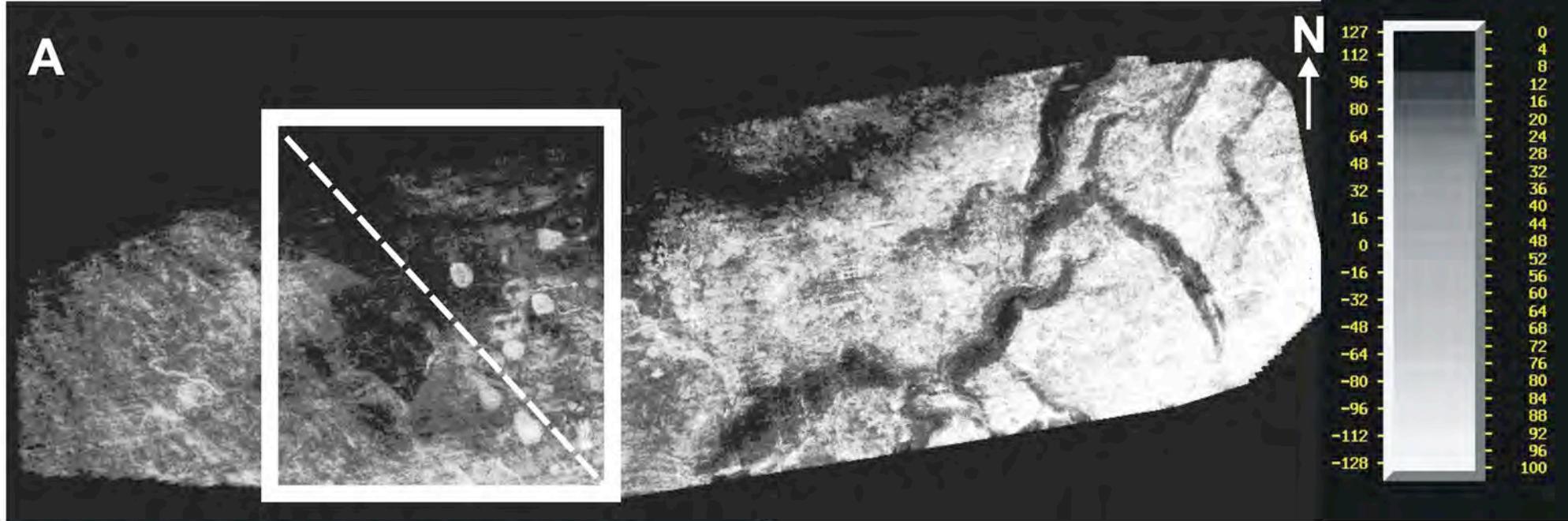


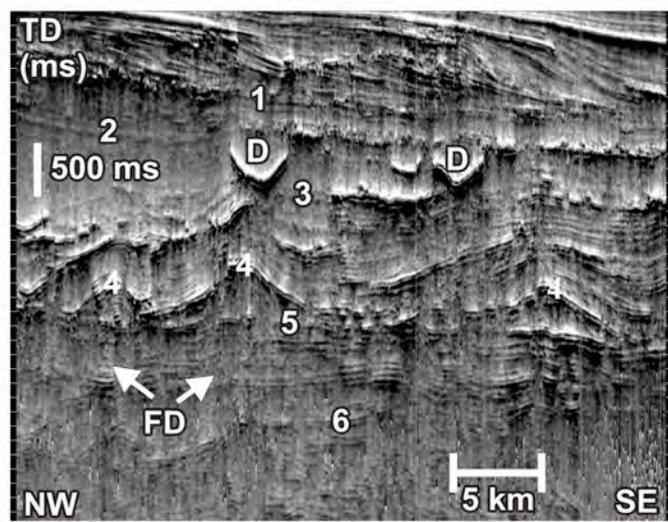
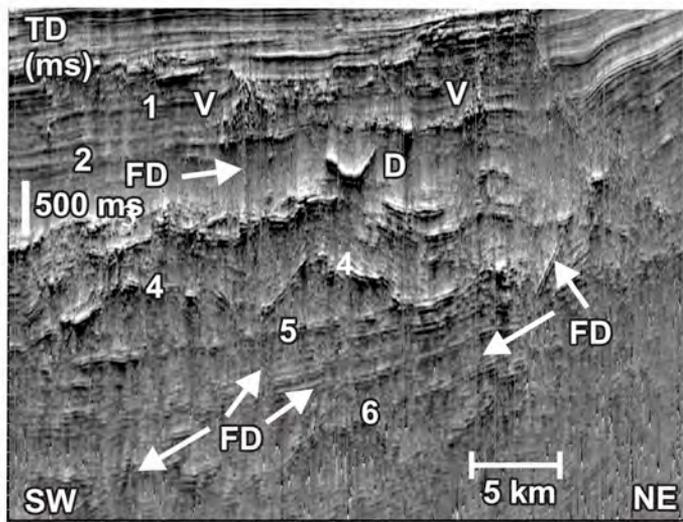
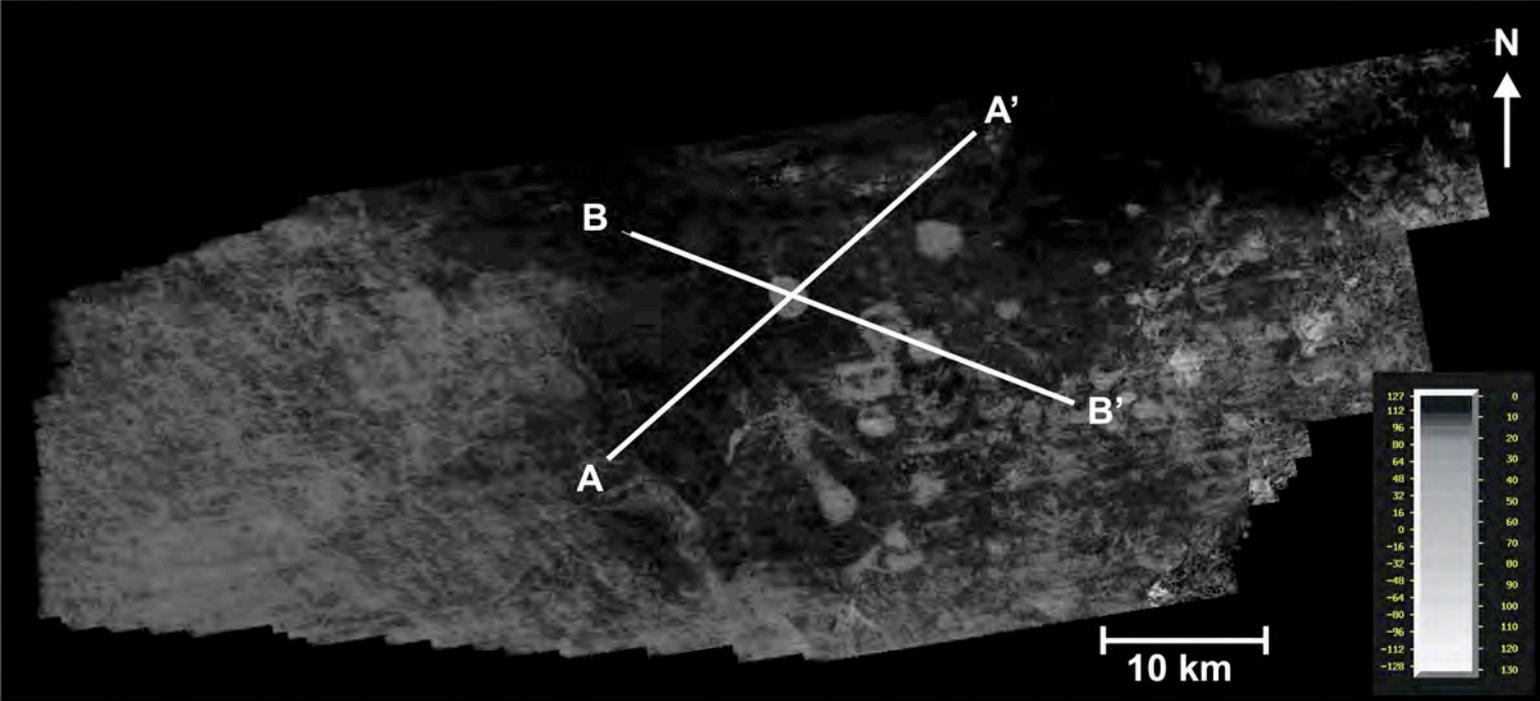


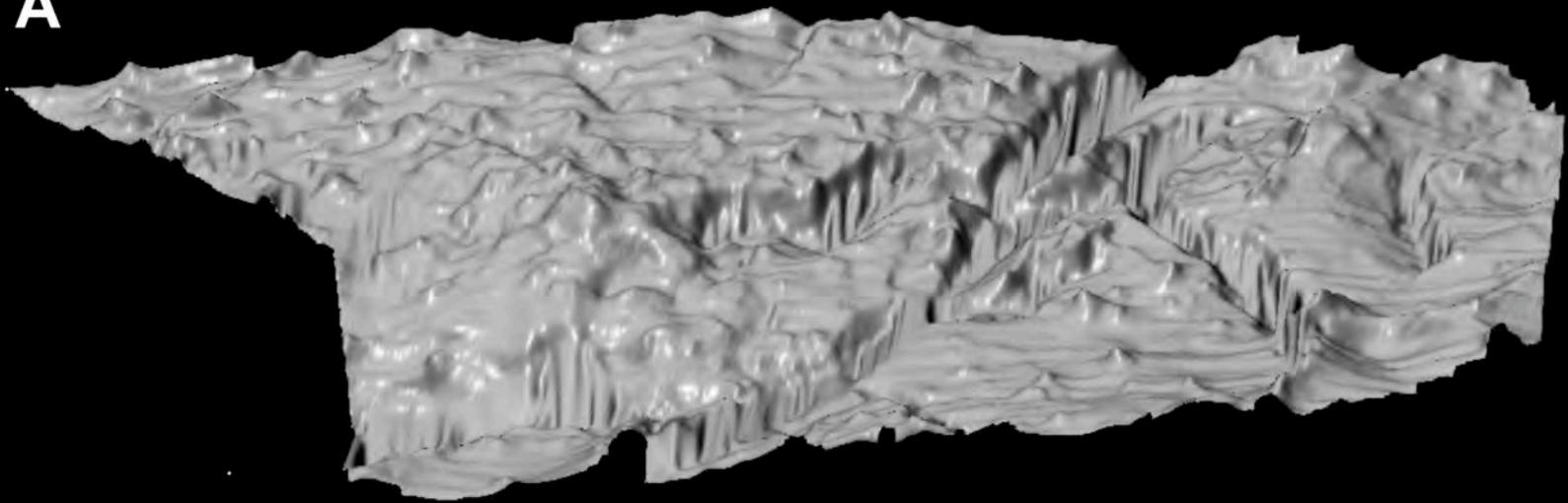
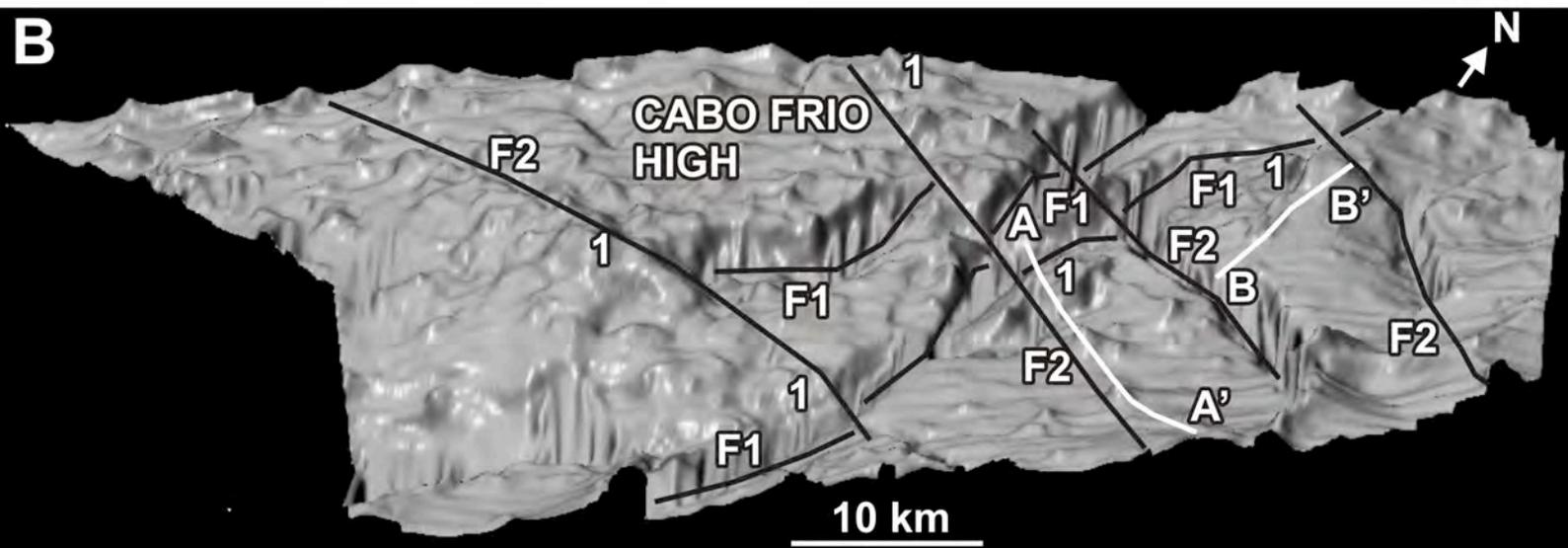


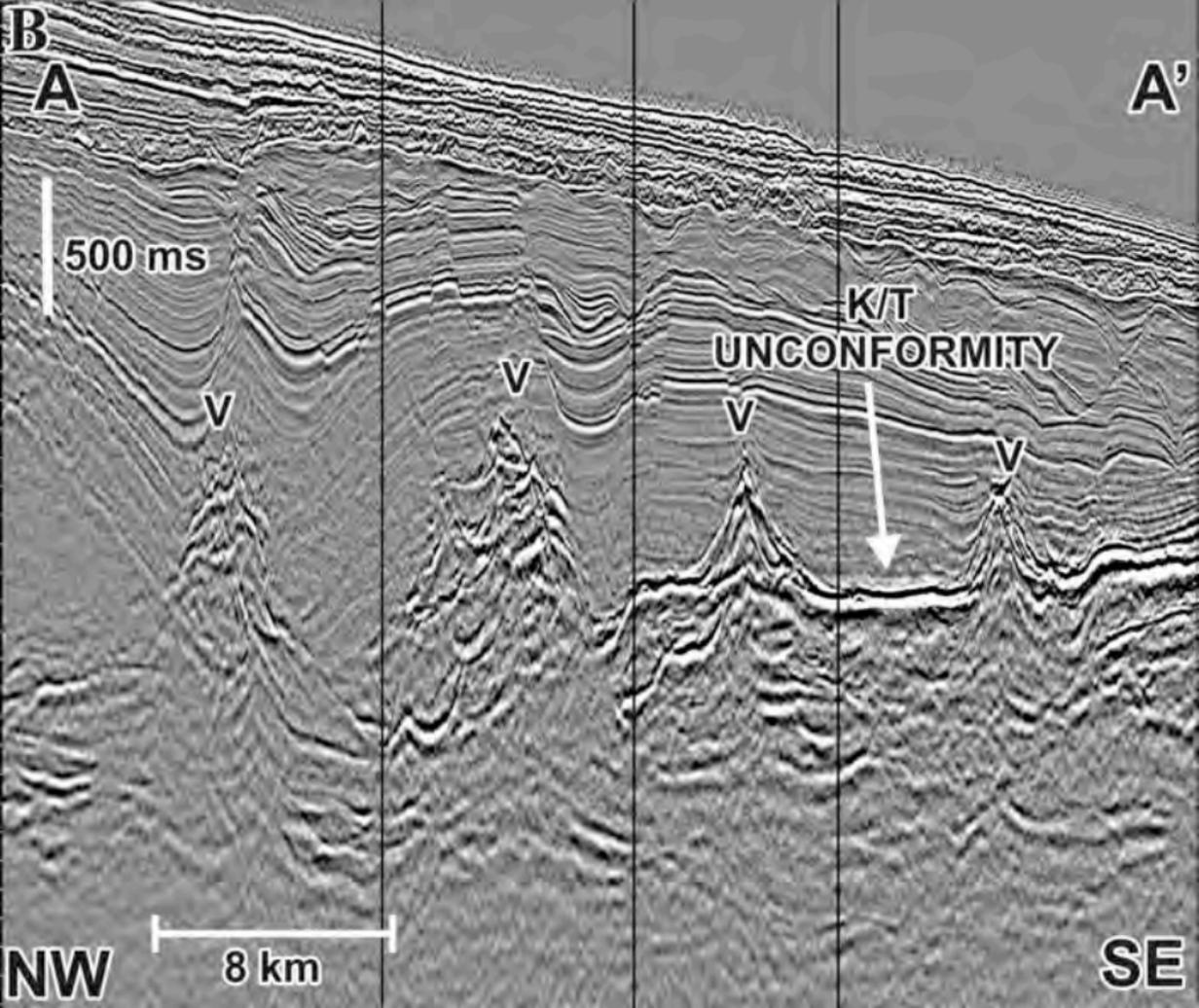


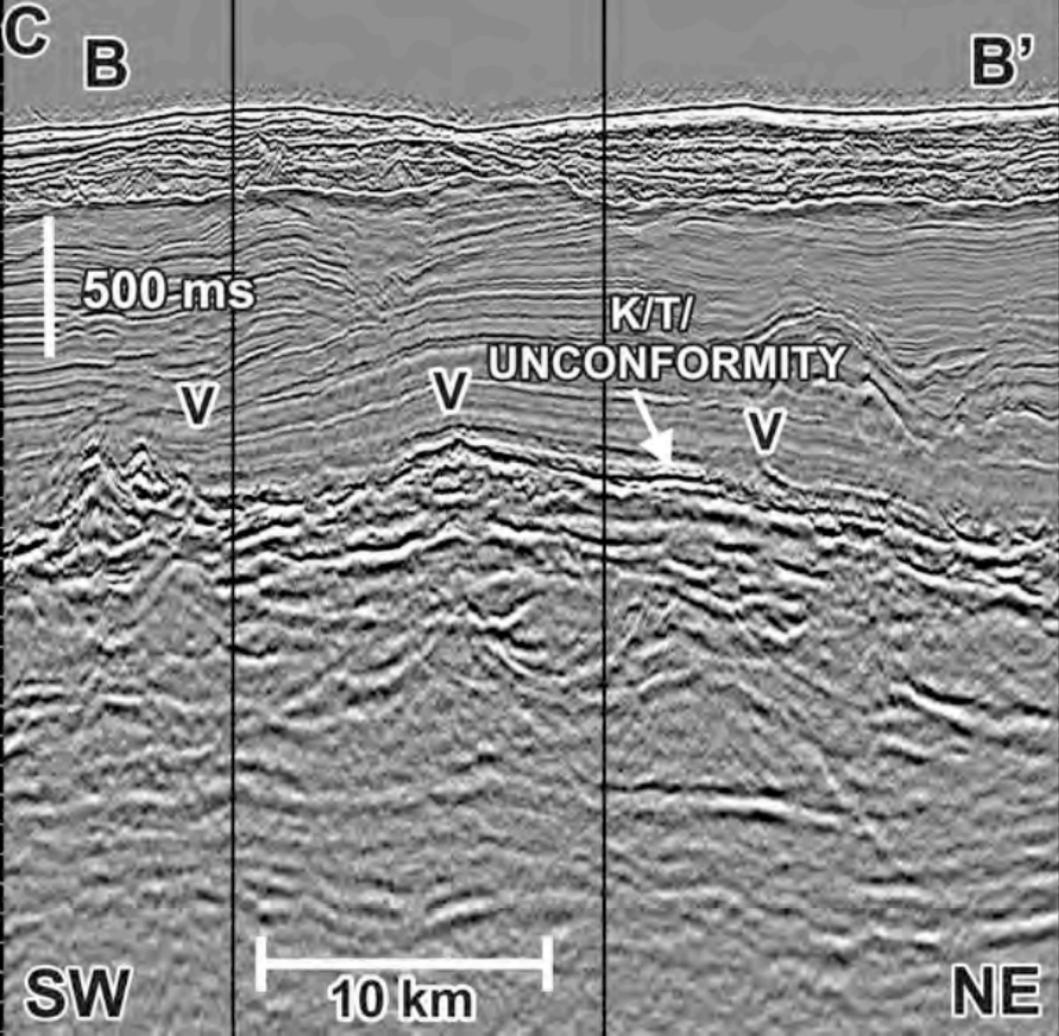


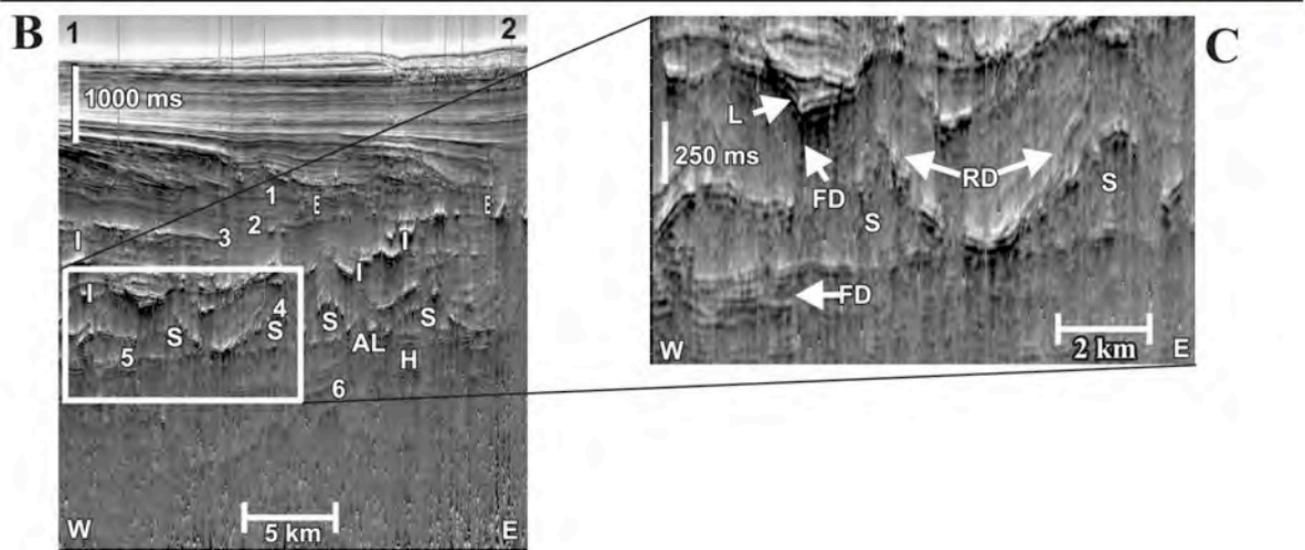
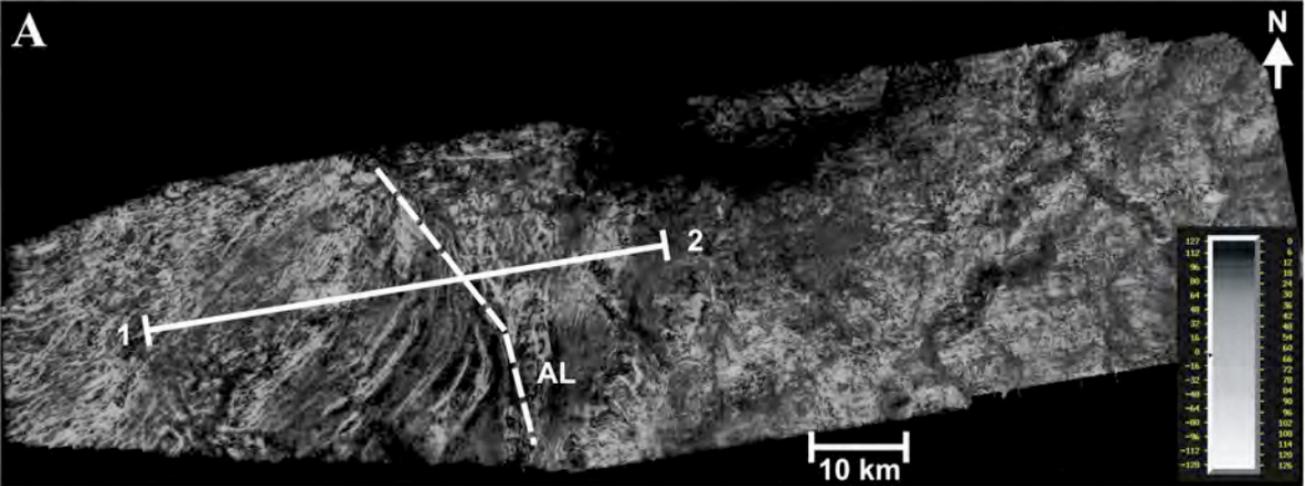




**A****B**







# CABO FRIO HIGH

500 ms

W

5 km

E



