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Quantification and mapping of erosion in the Sergipe–Alagoas Basin using sonic logs and vitrinite reflectance data

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Abstract

Net erosion recorded in lithological columns of hundreds of wells from the proximal domain of the Sergipe–Alagoas Basin was quantified through palaeoburial indicators: transit time sonic logs (*DT*) and vitrinite reflectance profiles (*VRe*). The preferred determinations with *DT* logs of pelitic rocks compound a large database and are less subject to variations in sampling and laboratory procedures. The sonic log profiles of 485 wells have been used for the calculation of the net erosion grid, while just 60 VRe profiles have been used for this purpose. Net erosion varies typically from 100 to 700 m in the Sergipe Sub-basin to the south, probably as a result of isostatic compensation to the sedimentary loads of the post-rift stratigraphic sequences. The Alagoas Sub-basin to the north stands as the most eroded. The average net erosion in the Alagoas SB is around 750 m but reaches more than 1,200 m in the north. The main cause of the erosion of the syn-rift strata in the Alagoas SB is probably the long-time sub-aerial exposure of uplifted rift flanks. Late Albian tectonic inversion, focused on northern Alagoas SB, enhanced erosion as evidenced in seismic sections, especially those parallel to the coast.

KEYWORDS: Sergipe–Alagoas Basin; erosion; uplift; inversion tectonics; basin analysis.

INTRODUCTION

The Sergipe–Alagoas Basin is located next to the northern limit of the Eastern Brazilian Rifted Margin and, unusually, presents its proximal domain exposed along the coastal plain of the two northeast Brazil states that give its denomination. Displayed in an approximate N40E direction, this basin evolved as a passive margin from the Late Cretaceous to the Neogene following oblique rifting in the Early Cretaceous (Fig. 1). Its general direction is oblique to the prevailing NS direction of the South Atlantic Cretaceous Rift System to the south (Chang *et al.* 1991, Matos *et al.* 2021), the western counterpart of the rift system that led to the Brazil–Africa separation and to the South Atlantic Ocean opening during the Early Cretaceous. The WNW-ESE basin opening was imposed on the strong EW to SW-NE fabric of the Neoproterozoic Borborema Province (Delgado *et al.* 2003).

The processes that cause uplift and subsequent erosion in a sedimentary basin develop during periods of its history difficult to elucidate because of the obvious absence of a sedimentary record. Nevertheless, these processes need to be understood because they can strongly impact the development of petroleum systems. If, by one side, uplift may contribute to the development of oil and gas traps, by the other side, uplift can disturb the fluid retention of pre-existing accumulations (Doré *et al.* 2002a, 2002b). Wide erosive gaps bring uncertainties to petroleum system modeling, as the generation and expulsion peaks are controlled by the burial peak, and so, uplift may interrupt further maturation (Doré *et al.* 2002a, 2002b). The magnitude, age, and duration of an erosional episode also impact the prediction of compaction-dependent parameters of sediments, such as porosity, permeability, and thermal conductivity (Doré *et al.* 2002a, 2002b). In addition, the recognition of areas that have been uplifted can be crucial for the identification of favorable situations for unconventional plays of oil and shale gas, usually exposed near the oil or gas window on the surface or in the subsurface (Passey *et al.* 2010). Therefore, it is important to initially map the eroded packages in sedimentary basins and to consider

Supplementary material

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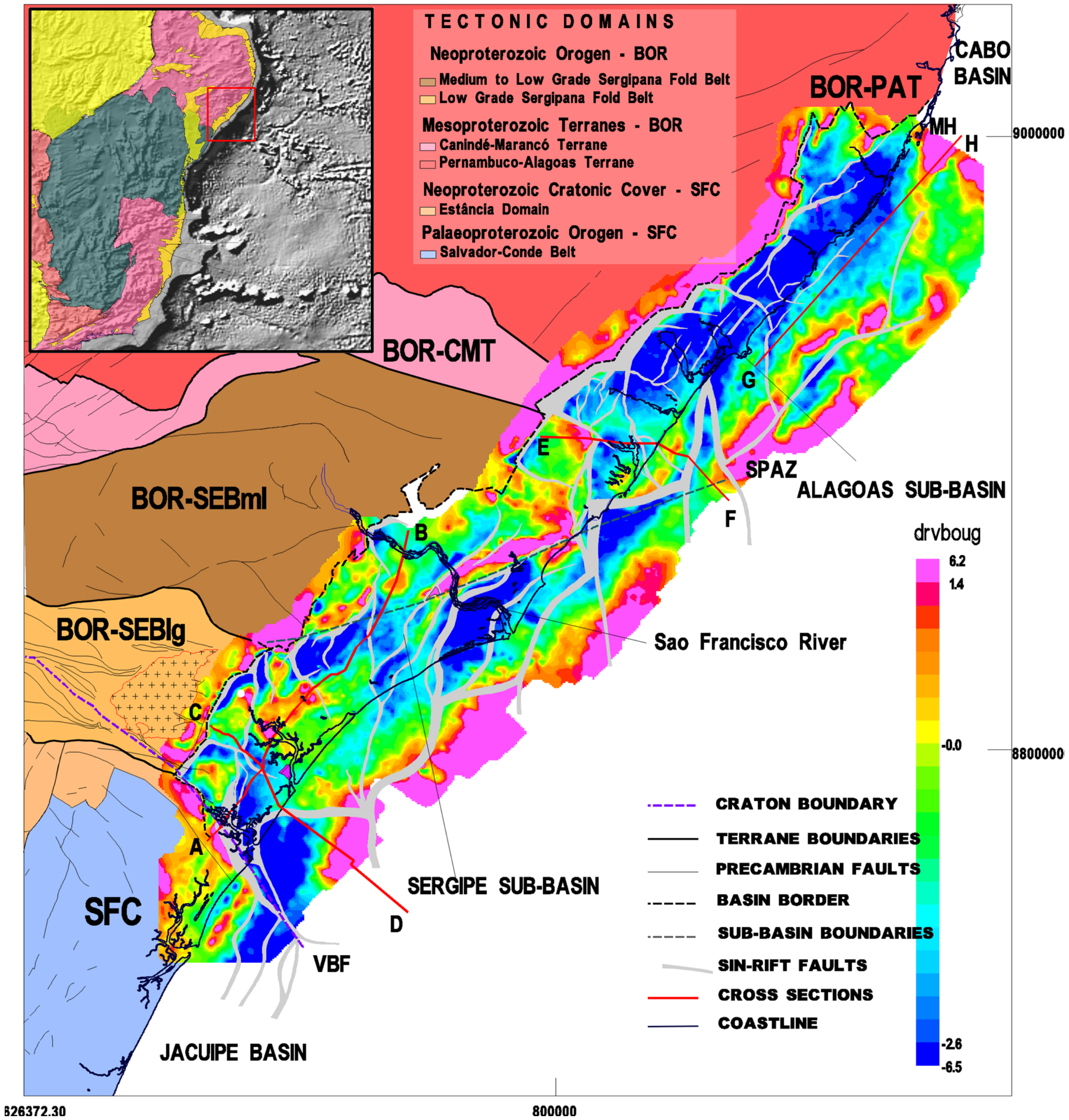

SCF: São Francisco Craton; BOR: Neoproterozoic Borborema Province; SFB: Sergipana Fold Belt; lg: low metamorphic grade; lmg: low to medium grade; CMT: Canindé-Marancó Terrane; PAT: Pernambuco-Alagoas Terrane; SPAZ: Siriri-Penedo Accommodation Zone, probable suture between the PAT and the SFB, both belong to the Borborema Province; VBF: Vaza Barris Fault limits the SFB and the CSF; MH: Maragogi High: limits Alagoas SB from Cabo Basin. Inset, Precambrian tectonic provinces and Phanerozoic sedimentary basins of East Brazil (Delgado *et al.* 2003), superimposed on elevation with free-air gravity anomaly shaded relief from satellite and onshore compilation (Sandwell and Smith 2009).

Figure 1. Map of the Sergipe-Alagoas Basin basement tectonic framework, modified from Lana (1985), superimposed on the map of the first derivative of the Bouguer gravity anomaly (drvboug), both composed with the map of the adjacent basement tectonic domains, based on Delgado *et al.* (2003). In red, locations of the geological and seismic sections discussed in the text. SCF: São Francisco Craton, BOR: Neoproterozoic Borborema Province, SFB Sergipana Fold Belt, lg: low metamorphic grade, lmg: low to medium grade; CMT: Canindé-Marancó Terrane; PAT: Pernambuco-Alagoas Terrane. SPAZ: Siriri-Penedo Accommodation Zone, probable suture between the PAT and the SFB, both belong to the Borborema Province. VBF: Vaza Barris Fault limits the SFB and the CSF. MH: Maragogi High: limits Alagoas SB from Cabo Basin. Inset, Precambrian tectonic provinces and Phanerozoic sedimentary basins of East Brazil (Delgado 2003), superimposed on elevation with free-air gravity anomaly shaded relief from satellite and onshore compilation (Sandwell and Smith 2009).

them further in the different basin modeling approaches (e.g., UK North Sea — Hillis *et al.* 1994, Argent *et al.* 1977; Alaska North Slope — Burns *et al.* 2005, among others).

The identification of overmature sedimentary columns, drilled by oil exploration wells, with vitrinite reflectance profiles (Dow 1977), or overcompacted ones with compressional wave transit time logs (sonic logs — Magara 1976, Issler 1992, Burns *et al.* 2005) allows the quantification of eroded packages. The erosion recorded by a maturation or compaction trend registered in a well can be quantified by comparison with a normal maturation or compaction trend, expressed by exponential mathematical functions (e.g. Dow 1977, Heasler & Kharitonova 1996). Net erosion, or apparent erosion, defined as the difference between the maximum burial reached by a geological marker and its present burial depth (BD) is the parameter that can be quantified with paleoburial indicators, e.g., sonic logs and vitrinite reflectance profiles, considering that a compaction contrast separated by an unconformity tend to be obscured by increasing reburial and compaction (Corcoran and Doré 2005). Therefore, net erosion is an underestimate of gross erosion where reburial occurs after an erosional period, in which situation, gross erosion (or total erosion) can only be appraised with additional geological information (Giles and Indrelid 1998). Nevertheless, the measured net erosion is an easily quantifiable parameter in wells and a starting point for regional evaluation of erosion and uplift, and its measurement with sonic logs and vitrinite reflectance profiles are valuable complementary tools for basin analysis quantitative studies.

Erosion estimates are measured in relation to the rock surface. Depths measured in a petroleum industry well are counted from the platform above the surface where the drilling equipment stands — measured depth (MD). However, for compaction studies, only the total rock sampled matters, the BD. Therefore, the height of the drilling platform is subtracted from the MD in onshore wells and water depth is also subtracted in offshore wells to determine the BD.

In this study, the eroded columns of 549 exploratory wells from the proximal domain of the Sergipe–Alagoas Basin were determined using compressional wave transit time logs (sonic, DT) and vitrinite reflectance logs from 257 wells, the main parameter for the evaluation of maturation of pelitic rocks used in oil exploration. The quantification in wells seeks the mapping of the net erosion along the basin through gridding techniques. Another important parameter for the study of erosion is the analysis of apatite fission tracks (AFT), which is not a routine methodology in the oil industry due to its costs and laboratory complexity, but it has been applied as a supplementary tool. AFT allows dating of cooling of samples, associated with uplift and erosion events. The results of the analysis of AFT of a pioneer survey of five wells of this basin will be presented in an article in preparation.

EVIDENCE OF REGIONAL EROSION IN THE SERGIPE–ALAGOAS BASIN

The Sergipe–Alagoas basin is a rifted margin that belongs to the Northern Albian Relay Zone of the Central Segment of the South Atlantic Cretaceous Rift System (Matos *et al.* 2021, Moulin *et al.* 2010). The Maragogipe High separates this basin from the Cabo basin to the north and the Vaza-Barris Fault separates it from the Jacuípe basin to the south (Lana 1985). The sedimentary infill starts with a pre-rift succession composed of a Permo-carboniferous package, up to 500 m thick, remnant of an intracratonic Palaeozoic basin, followed by an up to 300-m-thick succession of Jurassic red beds (Feijó 1994, Campos Neto *et al.* 2007). The rift phase was polyphasic, evolved from the Berriasian to the Aptian, that resulted in five mega sequences separated by unconformities, *latu sensu*. The syn-rift infill is highly variable onshore, from absent in some areas of Sergipe, in the south, to reaching more than 9,000 m in thickness in Alagoas to the north (Van der Ven *et al.* 1989). The Neocretaceous to Neogene post-rift succession is practically absent in Alagoas onshore, while it thickens from the Sergipe Sub-basin western border to offshore reaching up to 3,000 m (Fig. 2), punctuated by regional or global unconformities (Feijó 1994, Campos Neto *et al.* 2007).

The onshore Sergipe–Alagoas basin consists of a series of north-to-north-northeast trending, compartmented, rift blocks. The predominant fault direction is around N30E, but E-W to WNW-ESE transfer and relief faults are common (Lana 1985, Destro 1995). The border faults are discontinuous in the Sergipe sub-basin, while more continuous in Alagoas, interrupted by transfer faults (Figs. 1 and 3). The Neocomian to Early Albian rift kinematics is still controversial. Models of opening directions E-W, NW-SE, and NE-SW have been proposed over the years, generally considering direction changes during the rift phases. However, the rift tectonics could also be explained by the interplay of WNW-ESE kinematics imposed in a complex WSW-ENE basement fabric, through the oblique opening (Hamsi Jr. 2006). The WSW-ENE Siriri-Penedo Accommodation Zone (SPAZ) was probably the regional feature that controlled the obliquity of the rifting (Castro Jr. 1988).

The first order of compartmentalization of this basin is configured by the delimitation of the Sergipe and Alagoas sub-basins by the SPAZ (Castro Jr. 1988). The first derivative of the Bouguer gravity anomaly map mimics the basement depth map (Lana 1985, Van der Ven *et al.* 1989), displaying the syn-rift structural blocks of the basin (Fig. 1). The SPAZ articulates a set of NNW-striking faults, which results in an *en echelon* pattern of grabens to the southeast, in the Sergipe SB, separated from the shallow basement domain to the northwest, in the Alagoas SB context. This accommodation zone apparently extends from the Sergipe basin border to the Maceio-Ascension Fracture Zone in the oceanic portion according to the aeromagnetometric maps (Hamsi Jr. 2006, Vasconcelos *et al.* 2019). The first derivative of the Bouguer gravity anomaly loses resolution offshore due to the strong signal of the elevation of the crust-mantle boundary (Moho discontinuity). The SPAZ is probably controlled by the suture between the Mesoproterozoic Pernambuco-Alagoas Terrane of the Borborema Province and the Paleoproterozoic São Francisco Craton, which roots the Neoproterozoic Sergipana Fold Belt of the Borborema Province (D'el-Rey Silva 1995).

The focus of this study is the onshore and shallow waters region where the rifted margin underwent low lithospheric thinning, corresponding to the proximal domain of both sub-basins in the sense proposed by Mohn *et al.* (2012). The proximal domains of the Alagoas and Sergipe sub-basins suffered different subsidence and uplift histories, probably because they developed over lithospheres with different thicknesses in the pre-rift and corresponding distinct crustal terranes. The receiver function survey suggests that the crust of the Sergipana Fold belt, basement of the Sergipe SB, is a little thinner than the crust of the Pernambuco-Alagoas Terrain, basement of the Alagoas SB, around 35 and 37 km, respectively (Fianco *et al.* 2019). The corresponding lithosphere thickness must be proportionally different due to isostasy.

The concept of sub-basins adopted to the Sergipe–Alagoas Basin considers the preservation of distinct sedimentary piles, not to original distinct depocenters. The contrast between the preserved regional columns in the two sub-basins is well represented in the 1994 versions of the stratigraphic charts (Feijó 1994), whose main assumption was the synthetic representation of a typical cross-section from the border to deep waters across each sub-basin. (Fig. 2). The southern Sergipe SB registers a complete passive margin evolution, while the northern Alagoas SB presents an aborted Early Cretaceous rift along the coastal plain and shelf (Feijó 1994). Stratigraphic packages of varying ages are exposed along the proximal domain of each sub-basin in incomplete and discontinuous columns, although the Sergipe succession is more complete.

Uplifted and eroded stratigraphic packages are truncated by regional unconformities. Several regional unconformities control the sedimentary infill of the two sub-basins, but only three of them were considered significant for this study by limiting measurable eroded sedimentary columns in regional scale, which occur distinctly in the two sub-basins (Campos Neto *et al.* 2007): the Pre-Neoalagoas Unconformity (PNAU), the Sub-Calumbi Unconformity (SCU), and the Pre-Barreiras Unconformity (PBU). This nomenclature follows the stratigraphic charts published in 2007, which differently seek to represent the widest range of the depositional sequences in the sub-basins (Campos Neto *et al.* 2007).

Sergipe Sub-basin

Stratigraphic column is the term used here to assign an informal sedimentary succession affected by the same erosional event, instead of the common use of "section" as an informal stratigraphic package. The term "section" is avoided to not be confused with the use of "section" as a bidimensional and vertical geological object. Three distinct stratigraphic columns are affected by erosion in different regions of the Sergipe SB. The Eocretaceous to pre-rift (Ki) sedimentary package is equivalent to the Coruripe and Perucaba Groups and comprises three syn-rift sequences plus two pre-rift sequences that occur in a complex situation, truncated by the PNAU (Campos Neto *et al.* 2007). The Alagoas Stage is a local choronostratigraphic unit that grossly corresponds to the Aptian (Fig. 2). This sub-basin is characterized by the presence of a prominent structural high in its central position (Meister and Aurich 1972), the Aracaju High (Fig. 3), surrounded by two pre-Alagoas rift depocenters, reactivated from Late Aptian to Early Albian (Koutsoukos *et al.* 1993). The main oil accumulations of this basin are concentrated in this high, where the Carmópolis Oil field prevails, the first supergiant discovered in Brazil, in production since 1963.

The PNAU sub-outcrop geological map reveals increasingly older stratigraphic units in the direction of the nucleus of the Aracaju High (Fig. 3). This map has been constructed using cuttings and core samples data, integrated with seismic interpretation. Medium to low metamorphic grade Schists and Phyllites of the Macururé Group, prevalent to the north, have been identified in the basement of the Aracaju High, instead of the expected low-grade metasediments of the Vaza Barris Group, which occur to the south of the São Miguel do Aleixo Fault in the basement to the West (Fig. 3). In the Sergipe SB, the minimum depositional hiatus related to the PNAU is significant, between 135 and 118 M.a., with the total absence of the basal Eoalagoas package, corresponding to the Maceió Formation, which reaches more than 2,000 m in the Alagoas Sub-basin (Feijó 1994). The Neoalagoas Muribeca Fm occurs in angular unconformity above syn and pre-rift sequences onshore Sergipe Sub-basin over the PNAU (Fig. 4), cutting down to the basement of the Sergipana Fold Belt in the center of the Aracaju High.

Along the western basin border, the "mid-Cretaceous" sedimentary package (Km) is exposed, comprising the Albian to Turonian packages of the Marine-Carbonatic Megasequence (Chang *et al.* 1991), Sergipe Group, plus the Neoaptian Muribeca Fm, developed above the PNAU (Fig. 5). The rift phase in this sub-basin, promoted by lithospheric extension and thinning, probably lasted until Early Albian, as recorded by the fan deltas of the Angico Member, lower Riachuelo Fm (Koutsoukos *et al.* 1993). This pile is exposed in some places, but in other places, it is truncated by the Late Oligocene PBU, while, in other places, it is truncated by the Campanian SCU (Fig. 4). To the east of the basin border, still onshore, the Neocretaceous column (Ks) appears, composed predominantly of shales of the Calumbi Fm (Fig. 5). This sedimentary package can occur either exposed, or partially eroded, truncated by the PBU or even by the Cretaceous-Paleogene unconformity (KPU) in shallow waters. Toward offshore, the infill of the Sergipe Sub-basin (Figs. 2 and 5) records the complete evolution of a passive margin through marine, post-rift, sedimentation from the Late Cretaceous to the Present, Piaçabuçu Group. The post-rift succession is punctuated by regional unconformities, common in the Brazilian Eastern margin, some of them of probable global character (Chang *et al.* 1991), which are better represented in the most recent stratigraphic chart (Campos Neto *et al.* 2007). The Paleogene sedimentary pile thickens offshore toward deep waters, outside the scope of this study.

Alagoas Sub-basin

Northward the SPAZ, the predominantly Eocretaceous (Ki), syn-rift, sedimentary infill is preserved in erosional truncation under the PBU (Fig. 6). Such a package can reach up to 9,000 m in the North of Alagoas and, for the practical purpose of net erosion determinations, it includes the Palaeozoic to Mesozoic pre-rift succession, which barely reaches 400 m. The Barreiras Fm is represented as Plio-Pleistocene in the most recent published stratigraphic charts of these sub-basins (Feijó 1994, Campos Neto *et al.* 2007). However, its age has been re-evaluated as Early Miocene (Fig. 2), based on micropaleontological, geochronological, and sedimentological data

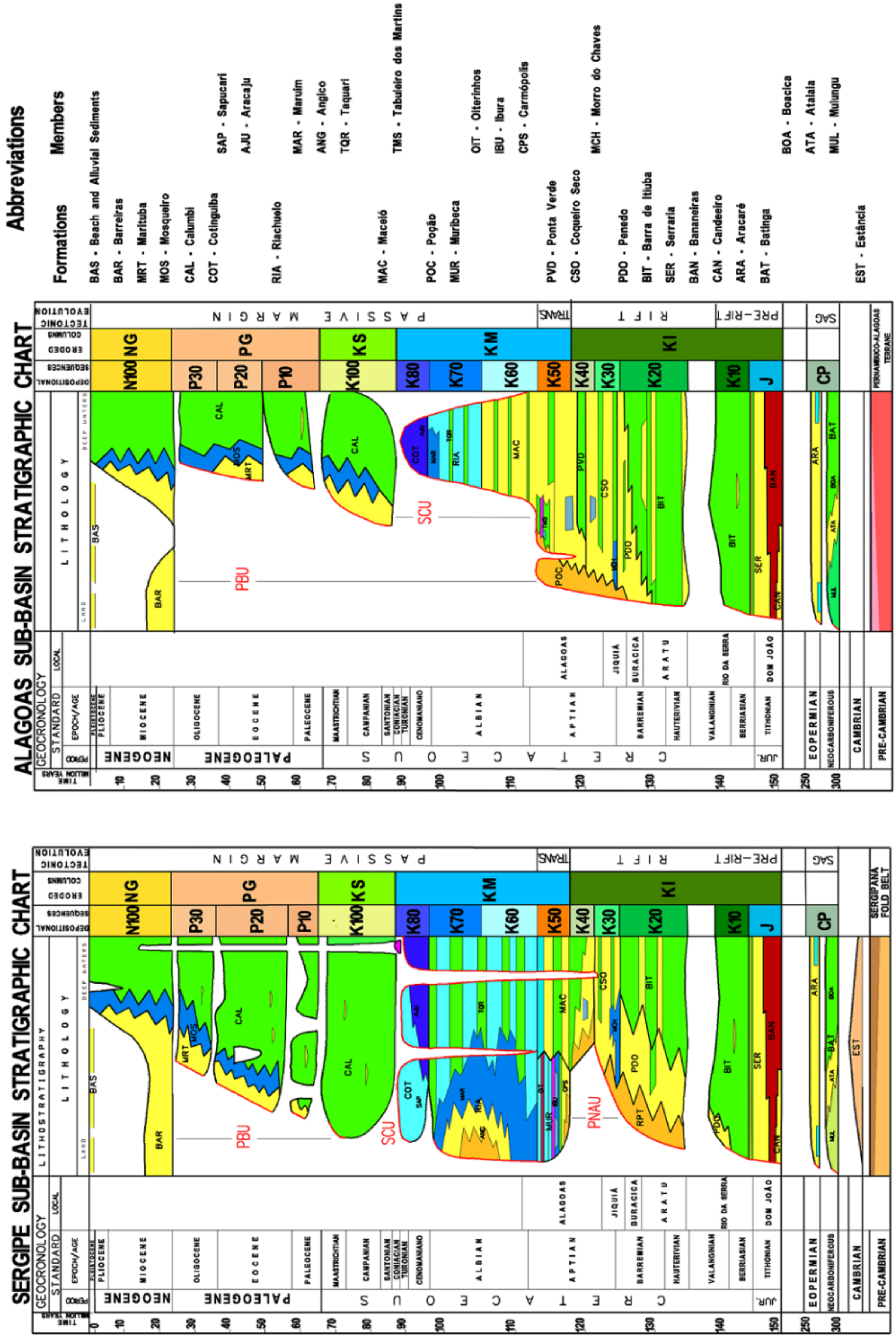

Figure 2. Stratigraphic charts of the Sergipe and Alagoas sub-basins proposed in 1994 that clearly display the main depositional hiatus of the proximal domains. In these modified versions, the Barreiras Fm. is repositioned in the Early Miocene, according to more recent data (Arai 2006, Rossetti *et al.* 2013). The Pre-Neoalagoas Unconformity (PNAU) at the base of the Muribeca Fm. is highlighted in the modified Sergipe Sub-basin chart, to the left. The Pre-Barreiras Unconformity (PBU), which separates this formation from the syn-rift, Eocretaceous units, is highlighted in the Alagoas Sub-basin chart, to the right.

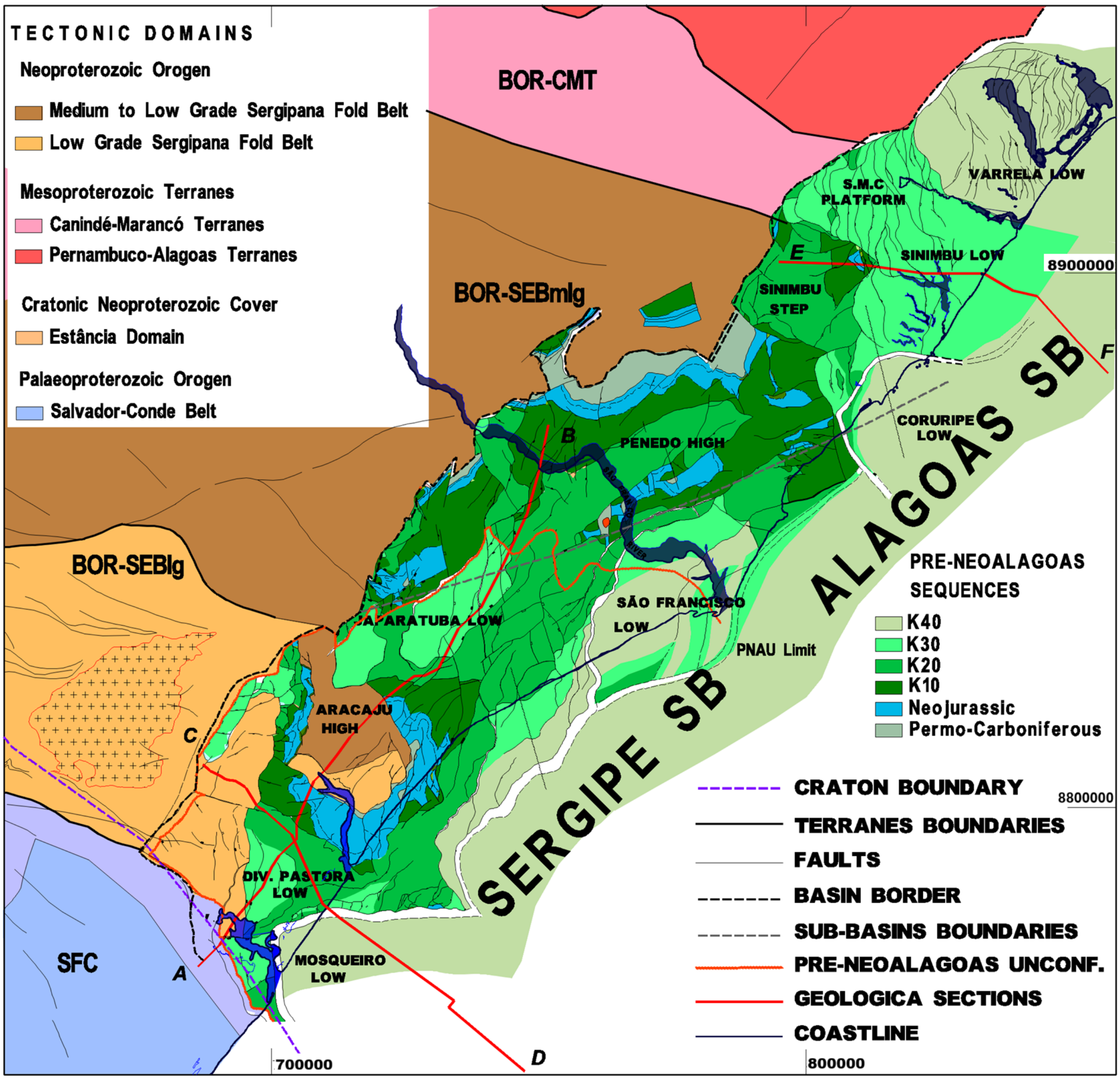

Figure 3. Sub-outcrop geological map of the Pre-Neoalagoas Unconformity (PNAU) in the Sergipe Sub-basin and sub-outcrop the Pre-Barreiras Unconformity in the Alagoas Sub-basin, with locations of the geological sections discussed in the text. Composed with the basement tectonic domains map, based on Delgado *et al.* (2003). Abbreviations as in Fig. 1. Colours of pre-Neoalagoas sequences as in the stratigraphic charts of Fig. 2.

(Arai 2006, Lima 2008, Rossetti *et al.* 2013). Therefore, the corresponding depositional hiatus related to this unconformity can reach almost 90 M.a.

The unconformity (PBU) between the Eomiocene Barreiras Fm and the Barremian to Eoaptian K10 to K40 sequences indicates erosion of rift shoulders in the Late Aptian–Early Albian time interval, after the last rifting pulse (Fig. 6). Unfortunately, a regional structural map in depth of the basement is still not available for this sub-basin, but well and seismic data show that the basement becomes deeper from the Penedo High in the south to the Varrela Low in the north, as suggested by the sub-crop map of the PBU in the Alagoas SB (Fig. 3). The deepening of the basement from southwest to northeast is interrupted by WNW-ESE transfer faults. The sub-crop map of the PBU is represented in this sub-basin, instead of the PNAU, due to the absence or difficult identification of the Neoalagoas sequences, correlated to the Muribeca Fm. However, well data indicate that these units are present offshore and in the north part of the sub-basin onshore. In shallow waters, and probably also in deep waters, the Eocretaceous syn-rift package prevails in this SB, ranging from 5,000 to 9,000 m, with a thin post-rift cover, Albian to Neogene, which thickens southward, toward offshore Sergipe Sub-basin (Feijó 1994).

In addition to the stratal evidence, the vitrine reflectance profiles (VR) from most of the wells of this sub-basin present overmaturation. Low-rank vitrinite precursor presents reflectivity between 0.18% and 0.2% at the depositional surface (Dow 1977). In many wells of the Alagoas SB, vitrinite reflectance values much greater than that interval are commonly projected at the surface from VR profiles, which suggests erosion of the shallower column (Fig. 6). The VR patterns of this SB basin are further discussed in Section 3.1. This behavior is conspicuous in the Alagoas Sub-basin, but it is also locally identified in the Sergipe SB and its mapping is one of the motivations of this study.

Objectives

While the Alagoas Sub-basin looks like an aborted rift in the proximal domain, where the syn-rift sequences are variably eroded under a wide depositional hiatus, the proximal Sergipe Sub-basin displays an important pre-Aptian doming (Meister and Aurich 1972), which tectonic evolution is unclear. One of the most important questions about the evolution of this basin is whether the Aracaju High in the Sergipe SB has been present since the beginning of the rift phase or if it has been activated in the Late Aptian, promoting the erosion of the pre-Neoalagoas package. In comparison with the Alagoas SB, it is not clear whether the preservation of younger packages to the north is due to differential subsidence or to different magnitudes of post-rift erosion.

The context of the proximal domain of this rifted margin, subject to inherent evolutionary processes, such as thermal subsidence and isostatic compensation to post-rift sedimentary loads, must be considered. These issues are here initially addressed through the quantification of erosion recorded in the lithological columns of wells drilled for oil and gas exploration, with widely available palaeoburial indicators: geophysical sonic logs and vitrinite reflectance data. The statistical analysis and mapping of the net erosion allows discussion of the processes involved in the uplift histories.

NET EROSION MEASUREMENTS WITH PALEOBURIAL INDICATORS

Vitrinite reflectance profiles

Methodology for Calculating Net Erosion Using Vitrinite Reflectance Data

Vitrinite is a type of organic maceral from higher plants whose reflectance to transmitted light is proportional to temperature and heating time, and it is considered the most reliable thermal maturity index used in petroleum exploration, despite sampling and measurements problems (Tissot and Welte 1984, Sweeney and Burnham 1990, Hackley *et al.* 2015). Its maturity rank is based on coal studies. Preparation of cuttings or core samples in specialized laboratories is necessary to enrich the vitrinite fragments from pelitic rock samples to be identified and quantified in petrographic thin sections by trained specialists.

Breaks in vitrine reflectance trends and VR greater than 0.2% extrapolated at the burial surface suggest net erosion and have been proposed as indicators for the calculation of eroded packages since the 70s (Dow 1977). However, a contrast of trends above and below an unconformity tends to decrease with the burial of a younger sedimentary column, making it difficult to identify erosion in an intermediate position of a drilled sedimentary column. Therefore, the methodology is more relevant to shallow erosions. In the original paper where the methodology for calculating erosion with VR profiles was proposed, for example, 32 samples were presented from an approximate 5,000-m-deep well, an average of one sample every 160 drilled meters (Dow 1977). Such detailed sampling is not common in the exploratory activity of mature basins,

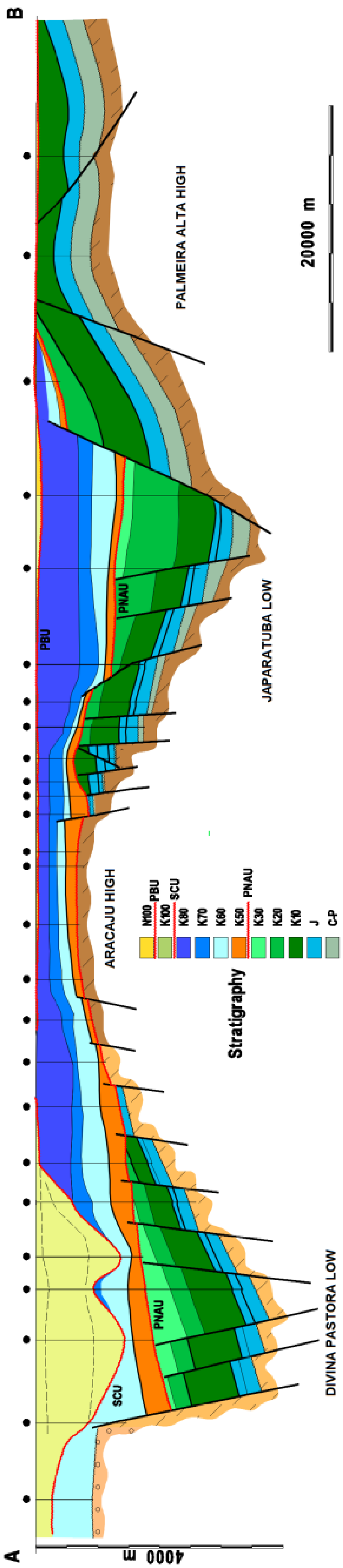

Figure 4. Geologic cross-section A-B, southwest to northeast direction along the Sergipe Sub-basin. Its SW end is at the Itaporanga High, then it crosses the Divina Pastora Low, the Aracaju High, the Japaratuba Low and finishes at the Palmeira Alta High. Location in Figs. 1 and 3. The Aracaju High is the main oil migration focalization megastructure of the Sergipe Sub-basin, flanked by the Divina Pastora low to the left, and the Japaratuba low to the right. Colours of the Pre-Neoalagoas sequences and basement domains according to the stratigraphic charts presented in Fig. 2 (Feijó 1994). Approximate vertical exaggeration 1:5.

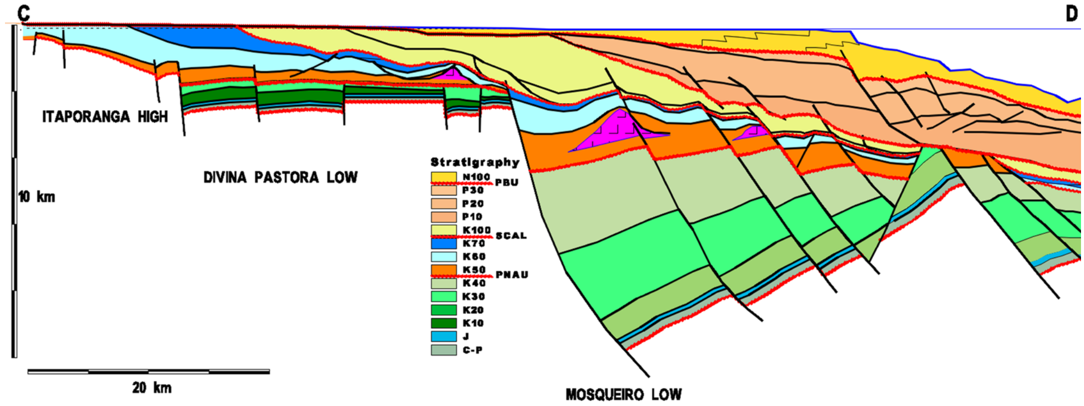

Figure 5. Geological dip cross-section C-D in the Sergipe Sub-basin, crossing the Itaporanga High, the Divina Pastora Low, onshore, and reaching the Mosqueiro Low in shallow waters. Location in figures 1 and 3. This cross-section shows the truncation of Senonian strata of the Calumbi Fm., Cenomanian-Turonian strata of the Cotinguiba Fm and Albian strata of the Riachuelo Fm. by the surface or locally by the Pre-Barreiras Unconformity. Colours of depositional sequences and basement domains according to the stratigraphic charts presented in Fig. 2. Approximate vertical exaggeration of 1:2.

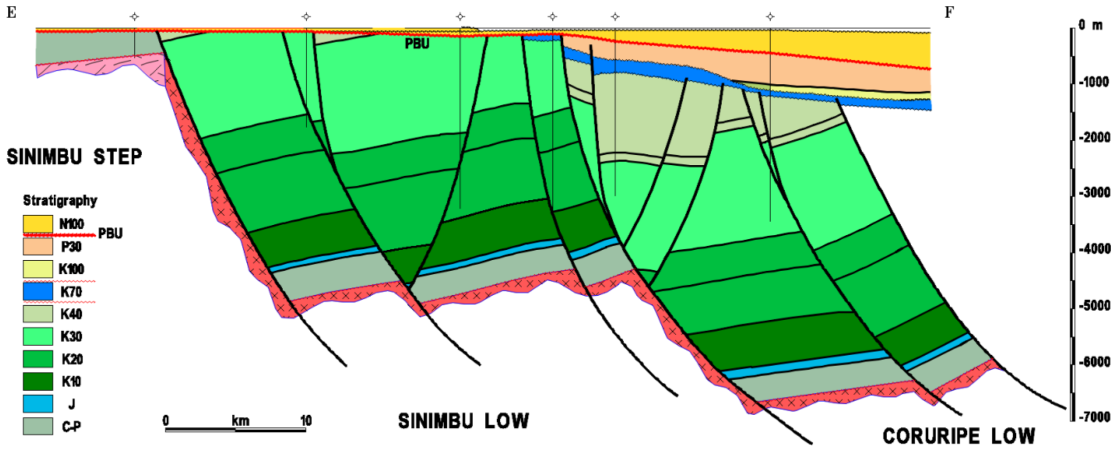

Figure 6. Geological cross-section E-F in the Alagoas Sub-basin, crossing the Sinimbu Step, the Sinimbu Low, onshore, and reaching the Coruripe Low, in shallow waters. Location in Figs. 1 and 3. This section shows the truncation of the Ponta Verde and Coqueiro Seco formations by the Pre-Barreiras Unconformity in rotated blocks. Colours of depositional sequences and basement domains according to the stratigraphic charts presented in Fig. 2. Approximate vertical exaggeration of 1:4.

being generally limited to 5–10 points along an exploratory well of the Sergipe–Alagoas Basin, an average of one sample every 500 m; thus, many wells have only up to three samples. The database available for this basin, mostly assembled by Petrobras, is based on mean Ro measurements by sample and composed mostly of cuttings data. Some data are Ro equivalent from spore fluorescence or coloration index from vitrinite poor samples. The historical database of the basin was composed of analysis from various laboratories besides the laboratory from CENPES, the Petrobras research center, which may bring interlaboratory inconsistencies. The origin and type of VR data were not taken into consideration in this study.

The quantification of erosion using functions of equivalent VR profiles (VRe) fitted to VR well data has been necessary for 1D petroleum system models for this basin carried out by the authors, particularly for onshore Alagoas wells (Fig. 7), whose profiles commonly extrapolate to VRe greater than 0.2% at burial surface (Fig. 8A and 9A–9E). This situation suggests that the vitrinites of the sampled sedimentary column were subjected to deeper and warmer depths in the past and subsequently exhumed and cooled following erosion of the shallower strata. As an example, the geohistory of the 1-BSM-1-AL well (Fig. 7A) was performed with GENEX software (Beicip-Franlab 1989), considering the erosion of the Eocretaceous package of 800 m, as determined from the sonic log. The VRe profile suggests still greater net erosion (Fig. 7B), but as it will be discussed later, the sonic estimate was preferred due to better sampling of the interval. Compaction parameters obtained from the basin database were applied to the burial history, and a lithospheric thinning factor (Beta) of 1.33, determined by tectonic subsidence curve fitting, was applied to the thermal modeling.

Net erosion measurements of 257 wells using vitrinite reflectance profiles were carried out with the determination of the constants *a* and *b* of the linear relationship between the equivalent vitrinite reflectance profile, *VRe*, and the BD, *BD* (Fig. 8A) (Eq. 1):

$$VRe = a * BD + b \quad (1)$$

Net erosion of the shallow portions of the sedimentary columns could then be determined by calculating the extrapolated

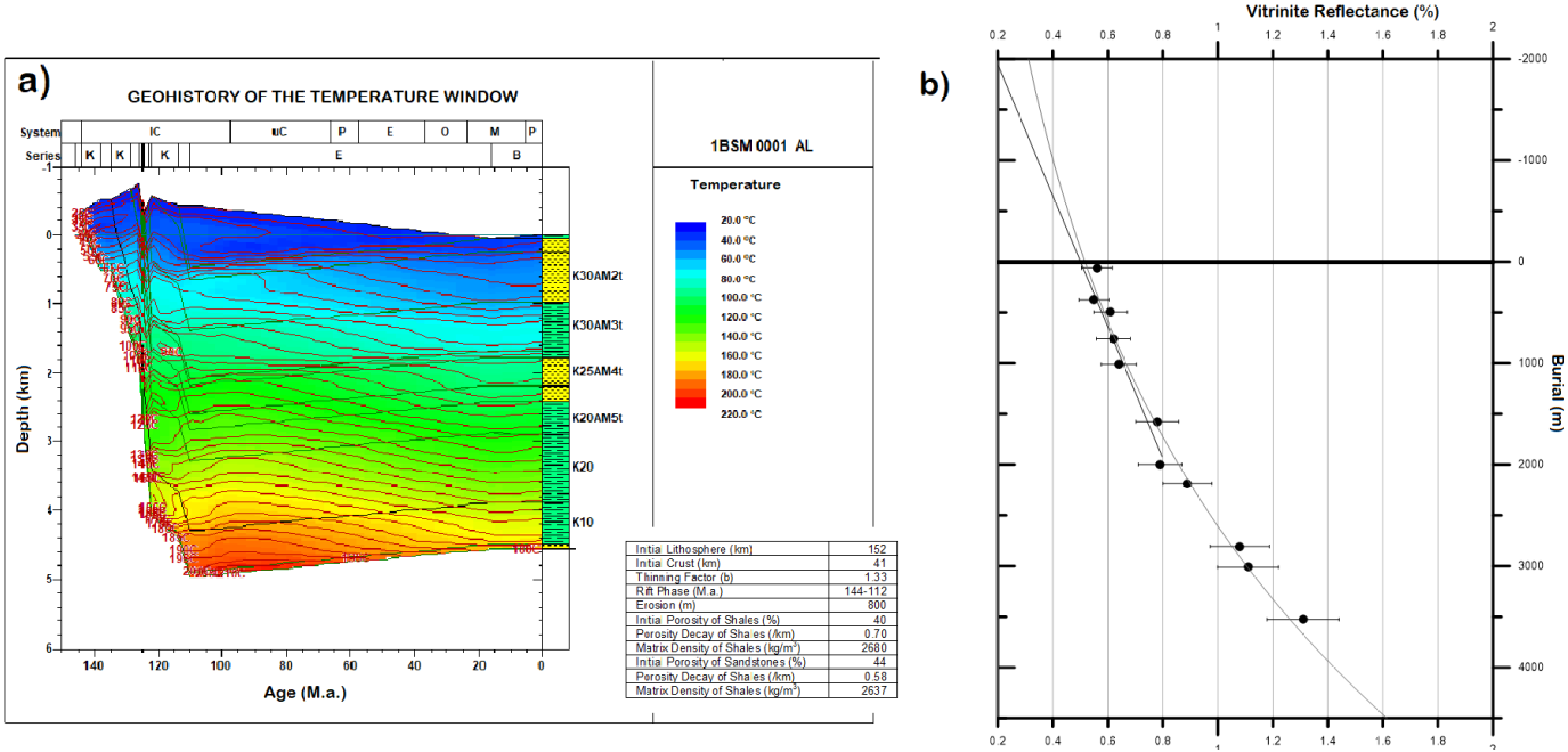

Figure 7. (A) Geohistory and temperature window diagram of well 1-BSM-1-AL, located in the coast of the Alagoas Sub-basin (Fig. 1), calculated with Genex-1D, using erosion from 110 to 18 M.a. Modelling parameters are presented in the inserted table. (B) Considered net eroded column of 1800 m, measured by linear relationship fit to VR data down to 0.7%. If an exponential relationship is adopted, the apparent erosion would be greater than 3,000 m. Well location in Fig. 13.

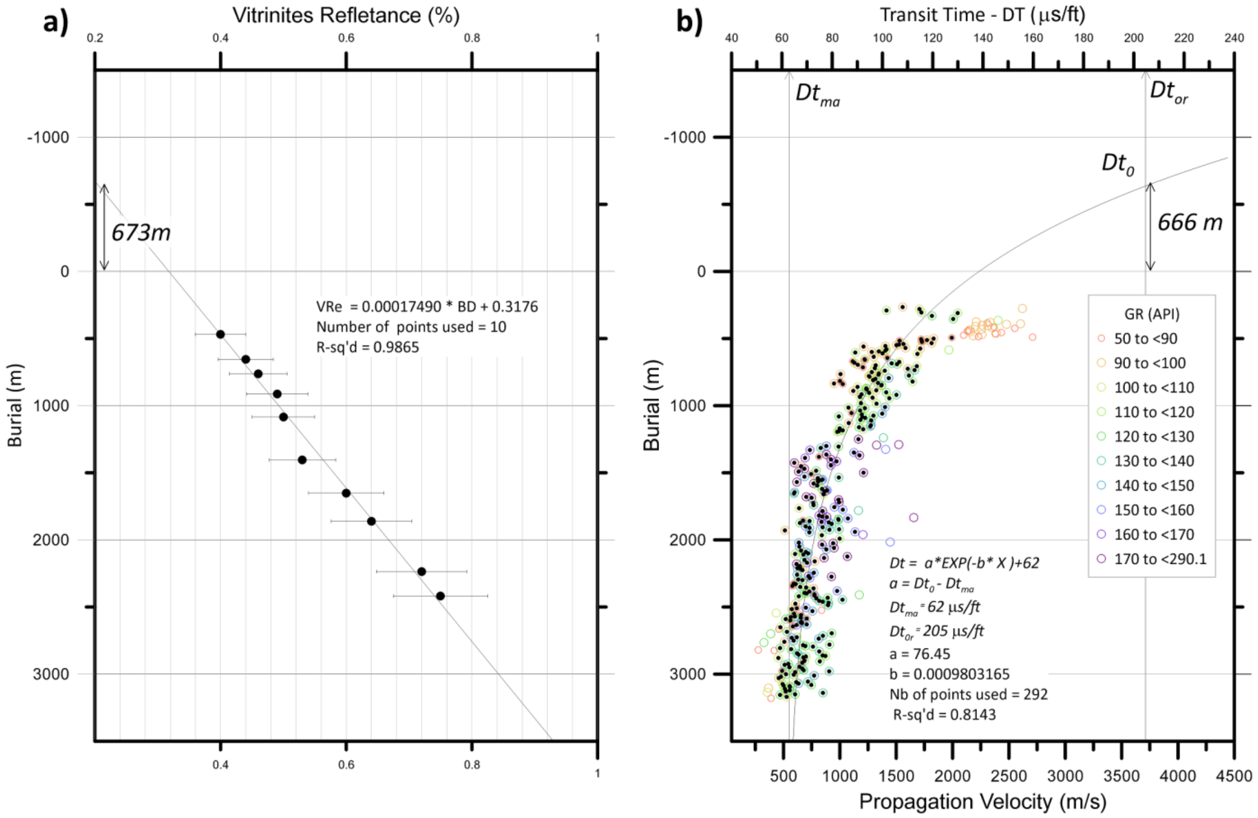

Figure 8. (A) Vitrinites reflectance profile and (B) sonic log of well 1-FH-2-AL from Alagoas Sub-basin, illustrating the determination of apparent erosion with each methodology. The main parameters are presented in the respective diagram. The estimates for this well are practically coincident. Well locations in Fig. 13.

elevation (negative in the burial axis) that corresponds to 0.2% of *VRe*, from the linear Eq. 2:

$$NE\_VR = -\frac{(b-0{,}2)}{a} \quad (2)$$

The calculations were performed with the software Grapher® from Golden Software, v14 to v20. Linear variation of *VRe* with burial was assumed from 0.2 at the surface to 0.85%, instead of the popular exponential relationship (Dow 1977), because most of the wells from this basin that sampled maturation greater than 0.7% of VRe present the bilinear pattern identified in a global survey (Suggate 1998, Nielsen *et al.* 2017), with inflections around 0.7–1.0% (Figs. 9A, 9B and 9E). Erosion estimates with the linear equation tend to be lower than estimates with the exponential equation (Fig. 7B), so the adopted approach is conservative.

Classification of net erosion determinations with vitrinite reflectance profiles

Despite the high variability in the basin, net eroded columns estimated with VRe profiles of neighbor wells are consistent in specific structural contexts. As an example, erosion of 820 m of a Ki stratigraphic column was estimated with well 1-SMC-2-AL data in the São Miguel dos Campos Platform (Fig. 9A), onshore Alagoas SB, a tectonic compartment with many wells with more than 500 m of erosion. Conversely, a small net erosion estimate of 152 m has been calculated for the Ks column of the well 6-ALS-36-AL in the São Francisco Low, shallow waters in the transition between Alagoas and Sergipe sub-basins (Fig. 9B). This estimate is within the error margin for null erosion, considering the scattering of points. Similarly, close to null erosion was estimated for well 1-SES-63 in shallow waters Sergipe (Fig. 9C).

Most of the wells that have reached greater than 0.7% VRe maturation in well-defined profiles seem to corroborate the bilinear pattern with a "knee" between 0.7% and 1.0% VR (Suggate 1998). For example, a net erosion of 831 m was estimated for 3-FGT-4-AL (Figure 9d), while a net erosion of 965 m was estimated for 1-LD-1-AL (Fig. 9E). However, a few wells from the basin that reached VR higher than 1.0% present instead of linear trends (Fig. 9F).

Still, remarkable problems in the VR database draw attention. Some wells too close to each other present quite distinct VRe profiles, suggesting unrealistic different eroded columns. For example, wells 1-TM-1-AL and 6-TM-54-AL, located just 2 km apart, onshore Alagoas Sub-basin (Fig. 10A), display a larger than 1,000 m difference in net erosion estimates. The first seems to be incorrect as it extrapolates 0.2% VRe in negative BD. Commonly identified distinct trends of two or more wells from the same cluster suggest poor repeatability of VR data. Particularly, the lack of sampling above 1,000 burials makes the net erosion estimate of some wells inaccurate. As an example, the VRe profile of well 1-ALS-11 from Eocretaceous samples below 1,500 m BD, under the devoid of vitrinites Neocretaceous to Paleogene interval, extrapolates in the range from -400 to 100 m BD at 0.2% VRe (Fig. 10B).

Some wells present too irregular distributions of VR samples that produce so poorly defined VRe trends, which also

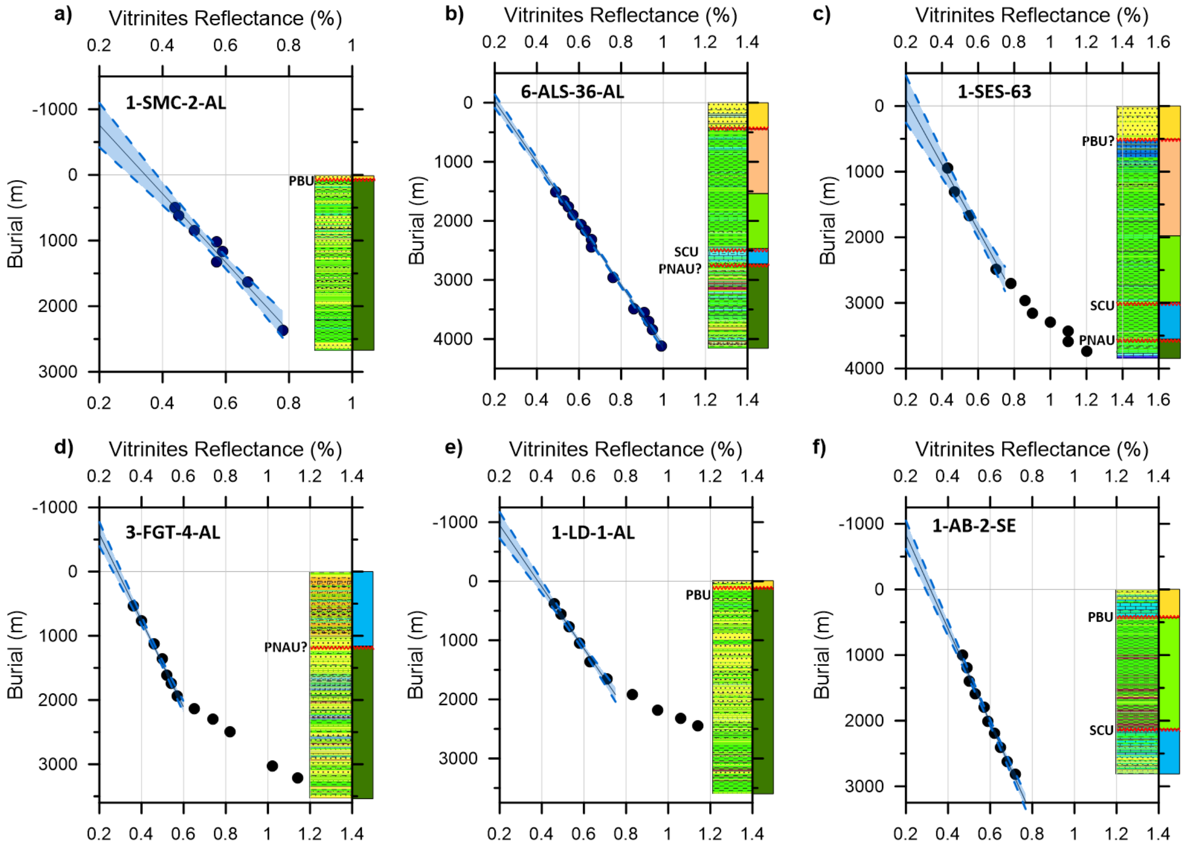

Figure 9. Examples of reliable vitrinite reflectance profiles with confidence intervals of 95% (calculated with Grapher v.19): (a) 1-SMC-2-AL, (b) 6-ALS-36-AL, (c) 1-SES-63, (d) 3-FGT-4-AL, (e) 1-LD-1-AL and (f) 1-AB-2-SE. Variable vertical scale. Corresponding lithotype columns and main stratigraphic columns on the right side of the plots, colours according to Fig. 2. Well locations in Fig. 13.

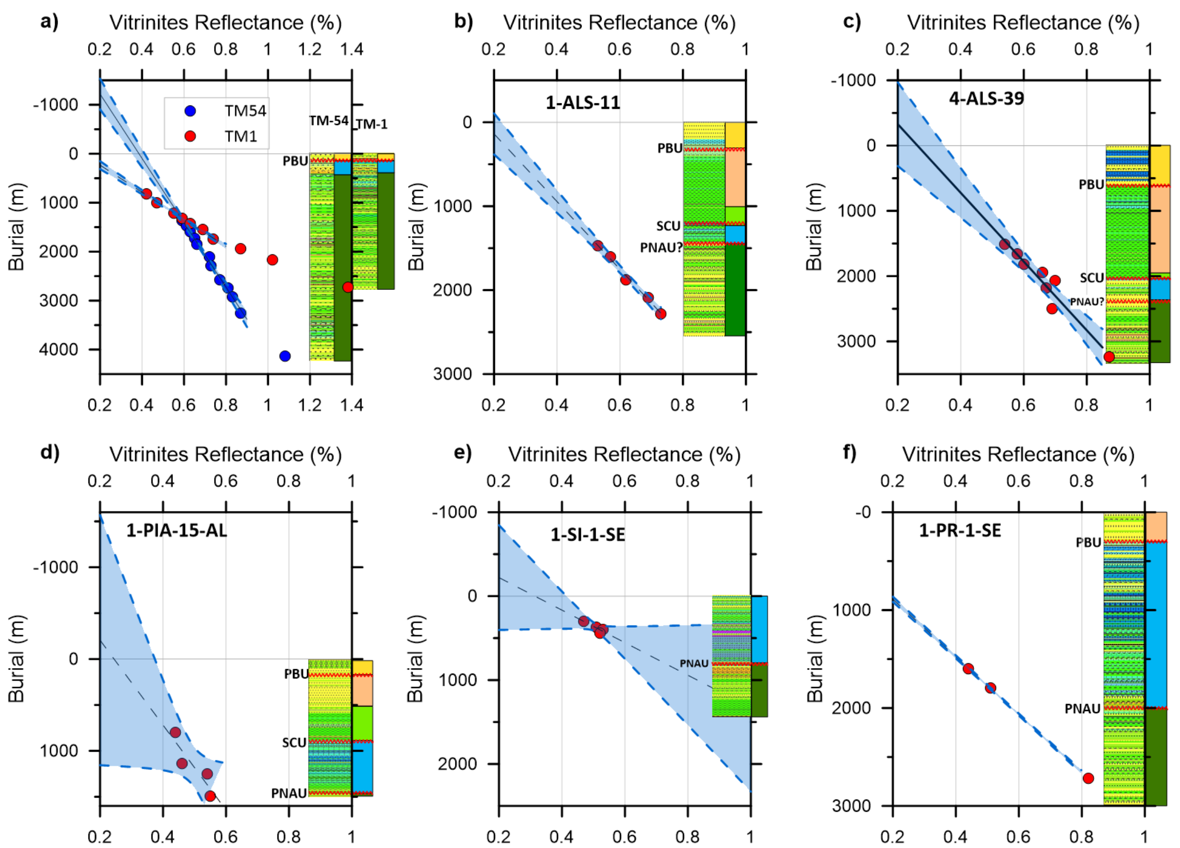

Figure 10. Examples of unreliable vitrinite reflectance profiles with confidence intervals of 95% (calculated with Grapher v.19): (a) 1-TM-1-AL and 6-TM-54-AL, (b) 1-ALS-11, (c) 4-ALS-39-AL, (d) 1-PIA-15-AL, (e) 1-SI-1-SE and (f) 1-PR-1-SE. Variable vertical scale. Corresponding lithotype columns and main stratigraphic columns on the right side of the plots, colours according to Fig. 2. Well locations in Fig. 13.

brings uncertainty to erosion calculations, as indicated by the confidence interval of the calculated fits (Figs. 9A, 9C and 10C). A considerable number of wells have less than five samples, which also results in unreliable trends (Figs. 10D–10F). Some of these also present scattered sampling (Fig. 10D), while others sample too thin columns, less than 500 m (Fig. 10E), and others present data that extrapolate the VRe trend to negative BD (Fig. 10F).

Therefore, the quality of VRe profiles is determined by: the shallower sampling, the scatter of VR data, the sampled interval, especially compared with total depth, the quantity of samples, as poor sampling can result in unreliable trends, and the extrapolation of the trend to negative BD at VR of 0.2%. Therefore, the vitrinite reflectance profiles have been classified into four quality ranks, whose detailed criteria and statistics are presented in the supplementary material:

- Wells with very poor sampling, less than five samples, very poor alignment, or too thin column sampled, whose trends were considered useless for erosion calculations, and those used in maturation studies should be considered with care (Fig. 10E): 76 (30%);
- Wells with more than two samples in abnormally immature trends that extrapolate to negative BD at 0.2% VR are considered unreliable for erosion calculations, which should be better revised (Figs. 10A (TM-1), 10B, 10F): 42 (16%);
- Wells with regularly defined VRe trends due to sampling of the shallow portion or minimum recovery and high correlation coefficients, which are useful for erosion calculations and for maturation calibration but should be subjected to revision whenever it is possible (Figs. 7B, 10C and 10F): 102 (40%);
- Wells with well-defined VRe trends due to good sampling of the shallow portion, good recovery, and high coefficients of determination, which are useful for erosion calculations and for maturation calibration (Figs. 7A, 7D, 7E and 8A): 37 (14%).

Therefore, only a fraction of the wells with vitrinite reflectance data could be used for erosion calculations with confidence. The vitrinite reflectance is an extremely important parameter for petroleum systems studies as the best organic maturity indicator. However, as it has been identified in several studies, VR data are subject to serious limitations due to sampling and laboratory factors that result in spurious variations (Burns *et al*. 2005, Corcoran and Doré 2005): low preservation of vitrinite in some pelitic samples, the cutting samples can represent reworked intervals of more mature strata, the cutting samples can be contaminated by collapsed pelitic fragments during drilling, and human factor in the preparation and identification of vitrinite macerals, which requires intense training and strict application of established practices (Hackley *et al*. 2015).

The Sergipe–Alagoas Basin vitrinite reflectance database is heterogeneous, created in the 70s, with some phases of revision. Part of the sampling has been analyzed in the Petrobras Research Centre (CENPES) laboratory, part was analyzed in other national and international laboratories, such as those acquired from wells drilled under risk contracts in the 1980s. As evidenced in reanalyses, there is low reproducibility of vitrinite reflectance determinations, commonly attributed to the paucity of the maceral in the samples. As an alternative to the sampling and human limitations of the vitrinite reflectance profiles, geophysical sonic logs have been preferred for measuring eroded columns in sedimentary basins.

Shale transit time logs

Methodology for calculating net erosion using sonic logs

Well logs of compressional wave propagation velocity (sonic) are widely available in petroleum exploration and have been acquired in the Sergipe–Alagoas Basin since the 60s, establishing a much larger database than VR data. Sonic profiles are usually expressed in transit time by foot (*Dt/ft*), the inverse of the propagation velocity, varying typically from 43.5 µs/ft in dolomite to 189 µs/ft or more in freshwater drilling mud, which correspond to the propagation velocities 7,010 and 1,613 m/s, respectively (Schlumberger 1991). Normally, the transit time of a given sedimentary lithotype decays exponentially with burial from the value at the depositional surface, Dt_0, to the matrix transit time, Dt_{ma}, due to the loss of porosity mainly by mechanical compaction, representing a potential paleolithostatic stress indicator (Giles and Indrelid 1998). Measurements in pelitic rocks (shales and siltstones) are preferred for erosion calculations, as these lithotypes are less susceptible to chemical compaction resulting from diagenesis, not directly related to burial (Magara 1976, Issler 1992).

After a series of methodologies have been proposed to quantify erosion using some variable that expresses shale porosity decay measured with sonic logs (Magara 1976, Issler 1992, Burns *et al*. 2005), it was established the approach developed in a study to measure post-Miocene erosion from well data of the intracratonic Bighorn Basin, USA (Heasler & Kharitonova 1996), which used the shale transit time itself, *Dt*. This approach is based on Eq. 3, in which *Dt* decays exponentially with BD from the measured or extrapolated surface transit time, Dt_0, toward the matrix transit time, Dt_{ma} (Fig. 8B):

$$Dt = (Dt_0 - Dt_{ma}) * e^{(-b*BD)} + Dt_{ma} \quad (3)$$

A more compacted sedimentary package than the normal pattern suggests erosion of a shallow interval. In this case, the transit time measured or extrapolated at the surface, *Dt(BD = 0)*, should be less than the expected under normal compaction, Dt_{0r}, in the range of 189–210 µs/ft. This methodology has been applied with variations to several geological contexts, such as the Neogene inversion of the Irish Sea failed rift (Ware and Turner 2002), the post-breakup Neogene rearrangement of the Northeast Atlantic margin, the post-Albian inversion of the Otway basin passive margin, southwest of Australia (Tassone *et al*. 2014a, 2014b), and the post-rift erosion of the continental rift Recôncavo Basin, Northeast Brazil (Coutinho 2008), among others.

In this study, exponential decay equations of shales transit time by BD, $Dt(BD)$, of 549 wells were fit using the tool of the software Grapher® from Golden Software, v14–v20, assuming as constants of Eq. 3, the shale matrix transit time, Dt_{ma}, and inverting for the difference between the specific Dt_0 and Dt_{ma} of the sampled trend and the exponential decay constant b, which represents the rate of compaction (Fig. 8B). The matrix transit time Dt_{ma} of 62 μs/ft is the average from the samples from deeper than 3,000 m BD well data of the Alagoas SB, generally highly compacted. The selected Dt_{ma} is close to the value estimated for other basins (Heasler & Kharitonova 1996, Ware and Turner 2002).

To decrease the original variability of the original sonic logs data, typically sampled at around 60 cm, the shale sonic logs have been resampled at every 5 m. In some works, clean sonic transit time well data sets have been obtained by averaging continuous 10–20-m intervals (e.g., Tassone *et al.* 2014a, 2014b). In this study instead, original data with minimal pre-processing were subjected to the numerical fit. Therefore, net erosion has been calculated for each well finding the extrapolated elevation (negative) that corresponds to the reference transit time, Dt_{0r}, of 205 μs/ft (1,487 m/s), expected at the surface for normal compaction, through the Eq. 4 (Fig. 8B):

$$NE\_Dt = -\frac{ln[(Dt_{0r} - Dt_{ma})/Dt_0]}{b} \quad (4)$$

The use of the typical freshwater mud transit time as Dt_{0r}, 189 μs/ft, as preferred by some authors (e.g., Heasler & Kharitonova 1996), would imply in slight underestimation of the net erosion, in the order of a few tens of meters.

An alternative approach for calculating erosion is the evaluation of a reference normal compaction "Supercurve" against which the sonic profiles are compared (Ware and Turner 2002, Coutinho 2008, Tassone *et al.* 2014a, 2014b). This "Supercurve" would be assumed as the standard burial pattern of the basin, ensured by comparison with a well-defined VRe profile (e.g., Coutinho 2008) or other criteria. This approach was not adopted in this study due to the difficulty of evaluating a "Supercurve" representative of this whole basin or even of each sub-basin. Furthermore, the transit time decay rate of Eq. 3, parameter b, was allowed to vary, which can represent facies or burial time differences.

Classification of net erosion determinations with sonic logs

Similarly to vitrinite reflectance data, net erosion calculations with sonic logs are sensitive to thickness sampled, shallower depth sampled, data scattering, sampling density, and presence of undercompacted intervals. Sedimentary columns logged with sonic over at least 1,250 m ensured the best regressions (Fig. 11 and Suppl. Mat.). This criterion has been relaxed to at least 470 m of the sampled interval to include shallow basement wells from the Sergipe SB with consistent compaction trends (Fig. 11C). The best results have also been achieved with wells logged from less than 800 m BD (Figs. 11A–11E), criterion relaxed to include wells with well-defined trends, logged with shallower depths from 800 to 1,250 m (Fig. 11F).

The sampling of pelite data in each well was based on the interpreted lithotypes from the composite logs stored in the Petrobras database. The following difficulties for identification of compaction trends of pelitic transit time with burial are highlighted:

- Intervals with enlarged borehole diameters may present spurious readings of the sonic log affected by drilling mud. The caliper log has been useful for interpreting compaction trends of *Dt* less affected by washouts in some wells (Figs. 11D, 12A and 12D). However, the caliper log is not regularly sensitive, and it was not available for all the wells analyzed;
- Interstratifications of shale with sandstone or limestone make the sonic profile noisy, which is not always accurately represented in the lithology column of the composite logs. Noisy profiles result in highly scattered trends. Coefficients of determination greater than 0.8 ensured the best trends, but larger than 0.7 coefficients have also been accepted. Outliers have been visually eliminated (Figs. 11 and 12). The gamma-ray profiles have been useful as an auxiliary tool to interpret the pelitic compaction trends in some wells (Figs. 12B and 12C);
- Undercompacted intervals occur in many wells, notably in the Neocretaceous to Paleogene package offshore Sergipe, which makes it difficult to define the compaction trends. Depending on the thickness of the undercompacted zone and the depth range affected, the normal compaction trend may be misinterpreted. Undercompacted intervals may be identified visually, sometimes with the support of gamma-ray or caliper profiles (Figs. 12D and 12E). Undercompaction of the shallower interval may be responsible for some extrapolated negative BDs determined for some wells. In these situations, inverted DT_0 is considerably greater than the assumed DT_{0r}, 205 μs/ft (Fig. 12E). Undercompaction and interstratification are also commonly observed in sin-rift packages, under Neocretaceous to Paleogene successions offshore Sergipe SB (Figs. 12A–12C and 12E).

The transit time logs have also been classified into four ranks of quality, considering the recovery of the shallower BD, the logged thickness, the presence of undercompacted intervals, the coefficients of determination, and the ratio of used points to the total, which measures the need of filtering spurious intervals and outliers. Detailed criteria and statistics are presented in the supplementary material.

- Wells with compaction profiles considered unreliable due to corrupted sonic profiles or with limited pelitic sampling, useless for erosion calculation: 71 (13%);
- Wells with unreliable compaction profiles that extrapolate to negative BD due to shallow undercompaction: 31 (6%);
- Wells with regularly defined compaction profiles, whose eroded column calculations have been considered consistent: 336 (61%);
- Wells with well-defined compaction profiles that allow good quality eroded column determinations: 111 (20%).

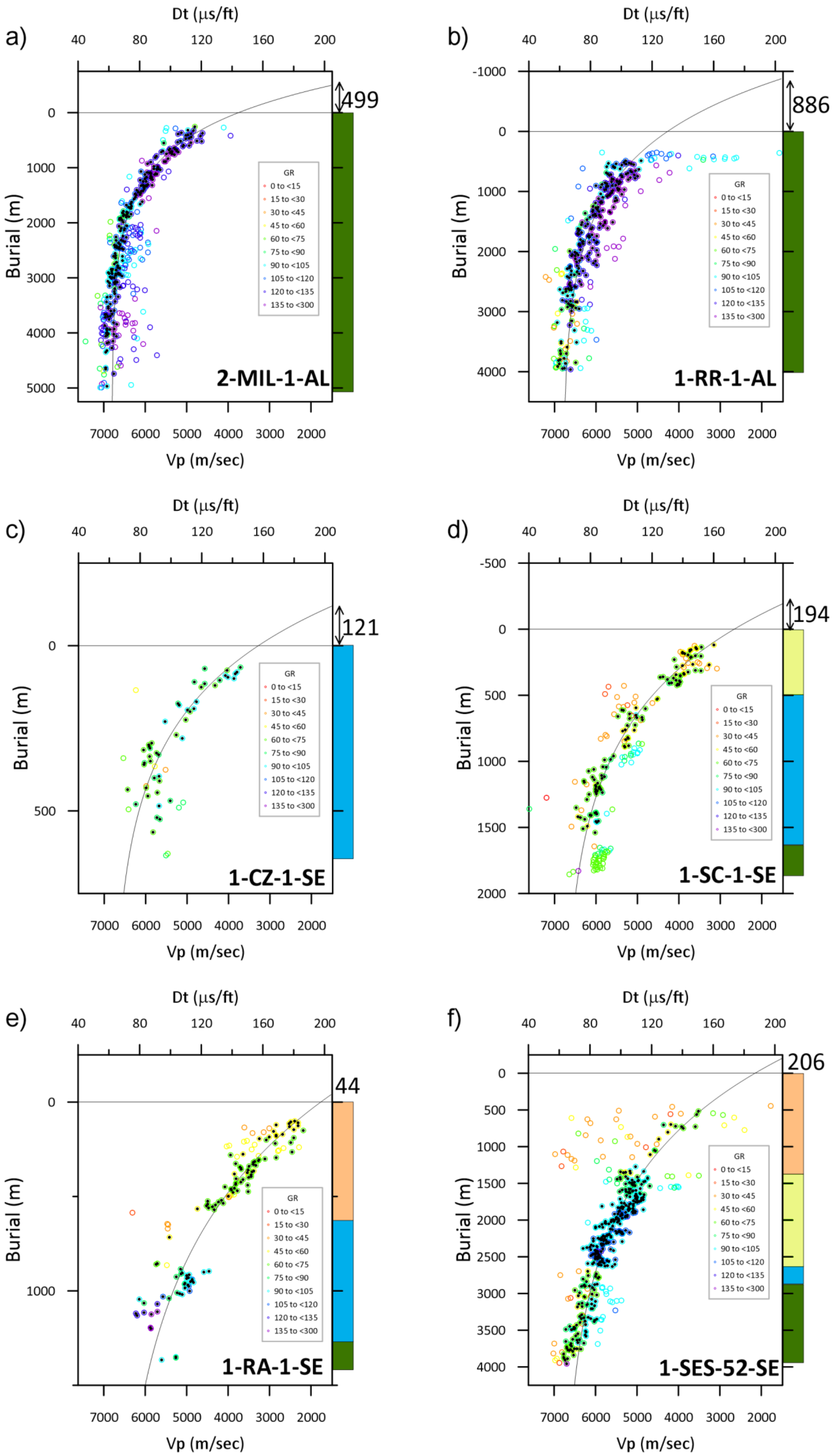

Figure 11. Examples of reliable compaction curves from sonic logs and numerical fits with the assumed exponential relationship, representing different regions of the basin: (a) 2-MIL-1-AL, (b) 1-RR-1-AL, (c) 1-CZ-1-SE, (d) 1-SC-1-SE, (e) 1-RA-1-SE and (f) 1-SES-52. Dt readings sampled at each 5 m are superposed by corresponding class scatter diagrams of Gamma Ray or Caliper logs for the exclusion of spurious intervals and outliers. Points with GR less than 50 °API were excluded. Variable vertical scale: Points with GR less than 50 °API must not correspond to pelitic rocks. Corresponding main stratigraphic columns on the right side of the plots, colours according to Fig. 2. Net erosion above the stratigraphic columns. Locations in Fig. 13.

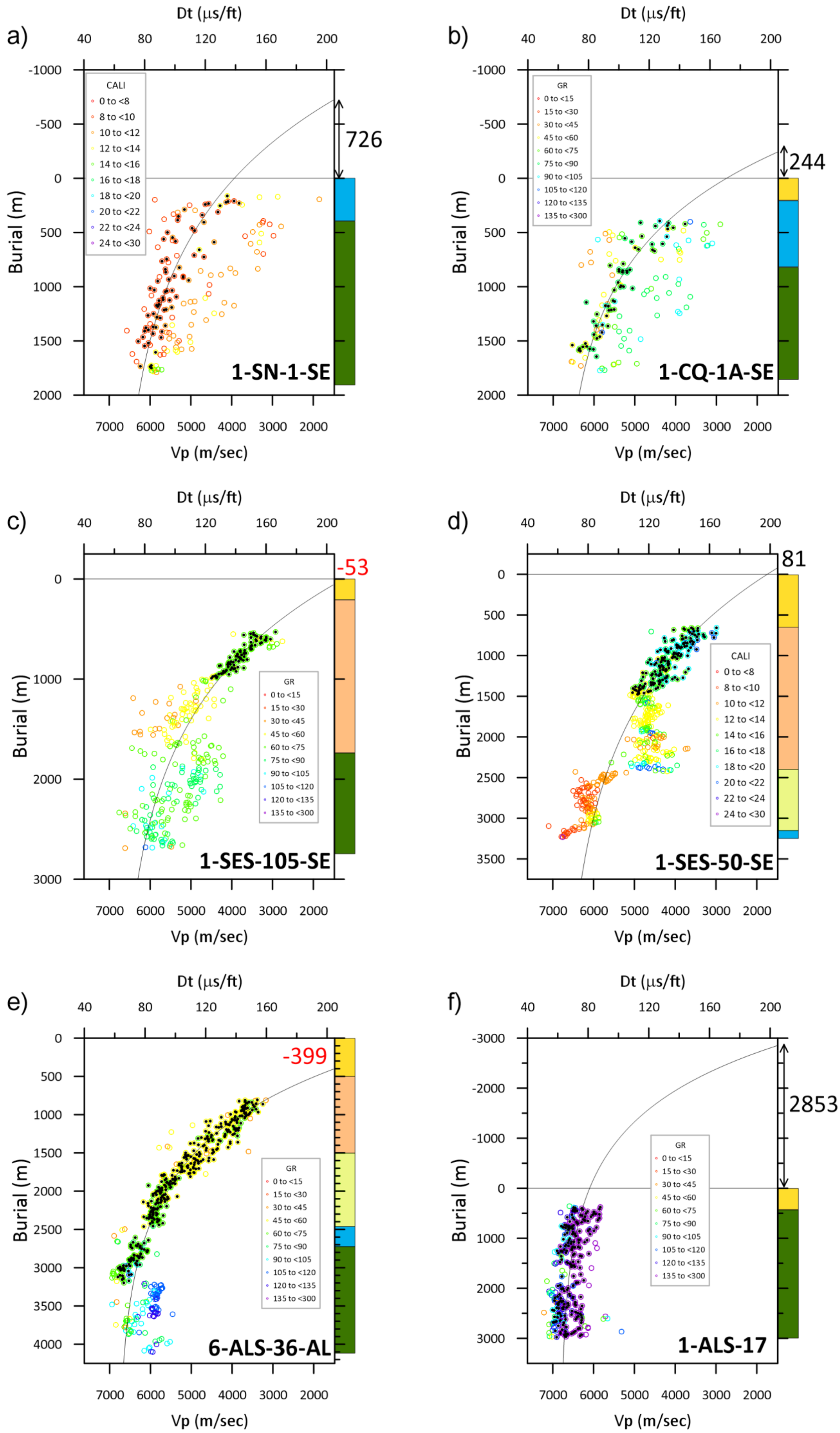

Figure 12. Examples of pitfalls in identifying compaction trends in sonic logs: (A) 1-SN-1-SE, (B) 1-CQ-1A-SE, (C) 1-SES-105, (D) 1-SES-50, (E) 6-ALS-36-SE and (F) 1-ALS-17. Dt readings sampled at each 5 m are superposed by corresponding class scatter diagrams of Gamma Ray or Caliper logs for the exclusion of spurious intervals and outliers. Points with GR less than 50 °API were excluded. Corresponding main stratigraphic columns on the right side of the plots, colours according to Fig. 2. Variable vertical scale: Net erosion above the stratigraphic columns. Locations in Fig. 13.

NET EROSION MAP AND DISCUSSION

The net erosion determined with sonic logs presents a low correlation with those calculated with the vitrinite reflectance profiles, as it has been observed in other basins where such a comparison was documented, for example, in the Irish Sea (Corcoran and Doré 2005) and in Alaska's North Slope (Burns *et al.* 2005). From the total of 549 wells analyzed with Dt or VR, 484 wells have been used for the gridding and statistics, focused on the proximal domain of the basin. Sonic log determinations have been generally preferred because they form a larger database, usually sample thick intervals, and are less subject to sampling and interlaboratory variations. Net erosions determined with VR of just 60 wells were considered better than the corresponding determinations with DT and were considered in the gridding and statistics.

The regional variation in net erosion along the Sergipe–Alagoas Basin is represented in maps of classified points and of the grid calculated by kriging in 2,500 m cells, performed with the Surfer ® Version 24 software (Figs. 13 and 14). The kriging was based on a Rational Quadratic variogram with the Nugget

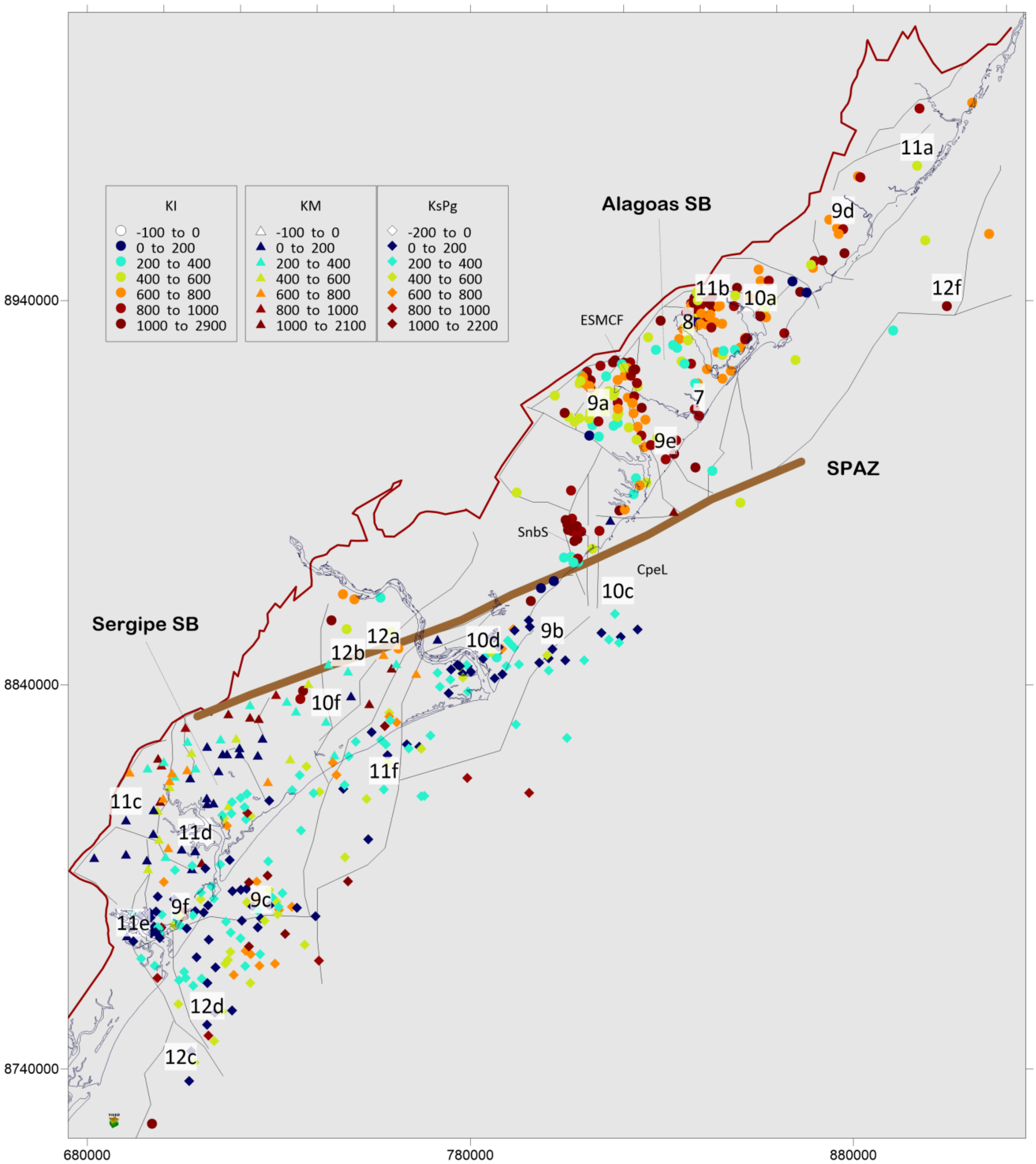

Figure 13. Net erosion map with determinations classified by intervals in the proximal domain of the Sergipe-Alagoas Basin with good to regular fits. Colour scale in meters. Circles correspond to measurements in Eocretaceous (Ki) columns, triangles correspond to measurements in the Aptian-Turonian columns (Km), and diamonds correspond to measurements in Neocretaceous to Paleogene columns (Ks-Pg). Results details in supplementary table. Superimposed on the basement tectonic framework map, modified from Lana (1985). Coordinates in UTM, Datum Sirgas 2000, MC39.

effect, an anisotropy ratio of 4.7 with an angle of 32° (SIRGAS 2000, Central Meridian 39W). Eocretaceous columns (Ki) prevail in the Alagoas SB (Figs. 11A, 11B and 13), while Neoaptian to Turonian columns (Km) prevail close to the Sergipe SB border (Figs. 11C, 11D and 13), Neocretaceous columns (Ks) predominate from the coastal region to shallow waters of Sergipe SB (Figs. 11F and 13), and Paleogene to Neogene columns (Pg) occur offshore Sergipe Sub-basin (Figs. 11E and 13).

Eroded thickness grids are important input data for basin modeling. For practical purposes, it should be more appropriate to consider the two sub-basins as distinct contexts, Alagoas SB with a predominance of erosion from the Ki columns and Sergipe SB with a predominance of erosion of the Km to Pg columns, with obviously different erosion histories. Also, for the purpose of basin modeling, the assessment of eroded thicknesses in well data is essential for the selection of wells to evaluate the representative normal compaction trends of the main sedimentary lithotypes: siliciclastic, pelite, and carbonate. Wells with mostly continuous sedimentation and minor erosion should be selected for the evaluation of standard compaction curves. The mapping of the net erosion from the best determinations of the Sergipe–Alagoas Basin highlights the main processes involved in syn and post-rift uplifts of the basin, as discussed below. Some typical processes of extensional basins and rifted margins may be linked

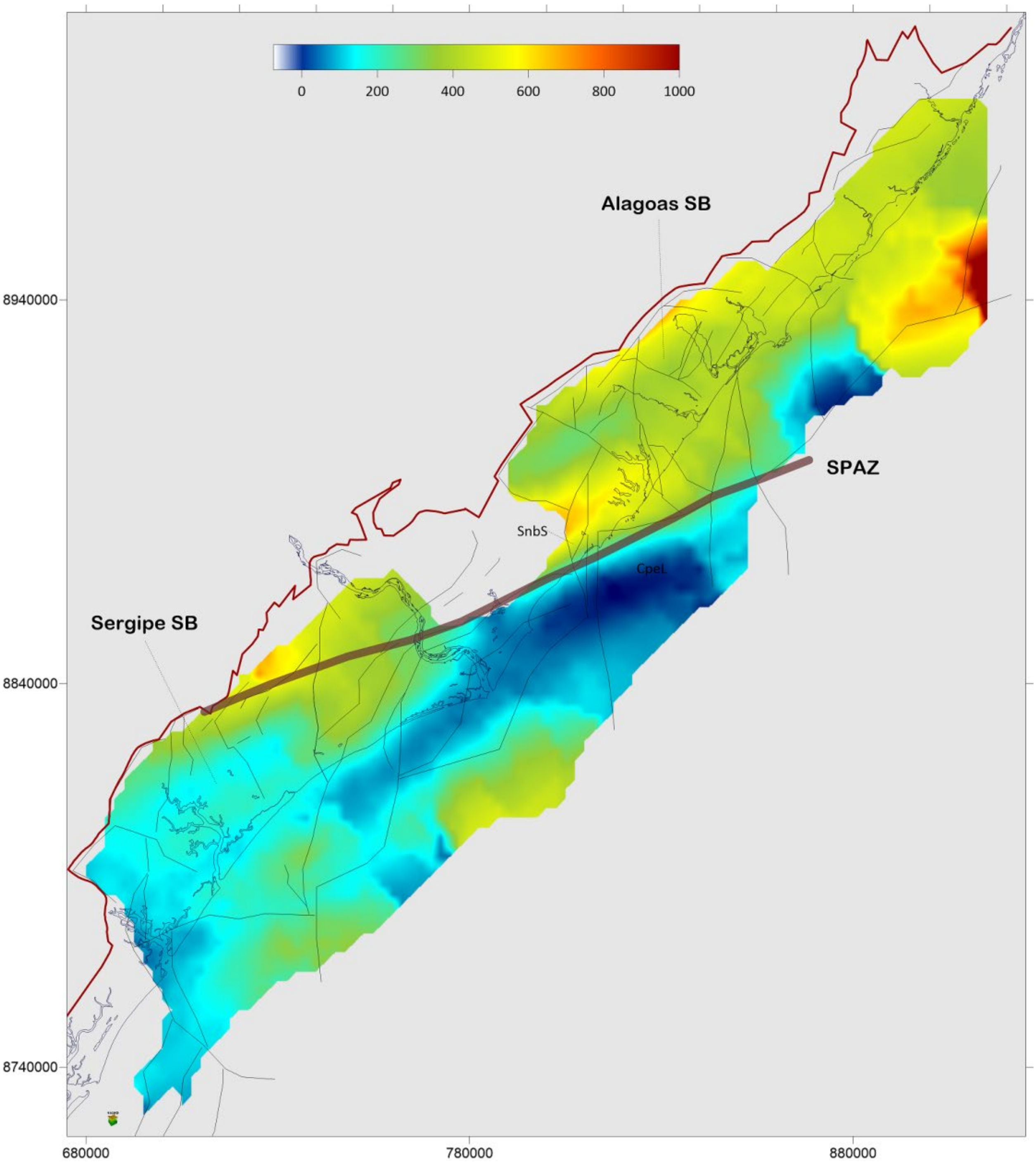

Figure 14. Net erosion grid map of the proximal domain of the Sergipe-Alagoas Basin. Colour scale in meters. Coordinates in UTM, Datum Sirgas 2000, MC39. Gridding details in the text.

to the erosions measured in the wells, but inversion tectonics could also be characterized.

Probably, due to its nature as an oblique rifted margin that encompasses two Precambrian terranes, this basin was subjected to distinct episodes of sub-aerial exposure and erosion in the two sub-basins. The basement of the Alagoas SB is the granitic Pernambuco-Alagoas Terrane, in contrast with the metasediments of the Sergipana Fold Belt, the basement of the Sergipe SB. While proximal Sergipe SB suffered continuous, still episodic, infill since the rift phase from the Early to Late Cretaceous, Alagoas SB stayed mostly exposed since the end of rifting in the Early Cretaceous.

Sergipe Sub-basin

A lower level of net erosion is measured in the Sergipe SB, according to the grid map and the histogram (Figs. 14 and 15). To the south of the SPAZ, this sub-basin presents the lowest net erosion, as the Neocretaceous to Paleogene sedimentary pile of the marine, post-rift, Calumbi Fm prevails (Fig. 15). The Aptian-Turonian pile (Km), sampled with wells located close to this sub-basin border, presents 400–800 m of eroded thickness. Some increase in net erosion is shown in the offshore limit of the map that can be related to channel incision or any tectonic process in this region and should be further investigated.

A Neoaptian Event was responsible for the domal configuration of the Aracaju High, with truncations of the pre-Neoaptian packages by the PNAU. However, it was not possible to evaluate the net erosion related to this event, due to the small columns of syn and pre-rift packages sampled by the wells that drilled below the PNAU. Moreover, the DT trends are not clearly configured, either by limited thickness or high scatter. Besides, several wells in these depocenters do not present a sonic log. The age and limits of eroded columns of this megastructure will be discussed further in an article in preparation based on apatite fission track data.

This sub-basin presents modest net erosions according to the preservation of younger sedimentary infill in its proximal domain, mainly the package deposited between the Alagoas and the Maastrichtian. The largest net erosion in this sub-basin affects mid-cretaceous columns (Km) close to the western basin border (Fig. 14). The process that most likely caused the regional exposure was the gradual doming at the flexural bulge resulting from the regional isostatic compensation to the sedimentary loads of the marine, post-rift, sedimentary sequences deposited offshore from Albian to the Present as shown in a dip cross-section from the Itaporanga High to the Mosqueiro Low (Fig. 5, section C–D in Figs. 1 and 3). Besides, channel incision seems to be the cause of localized erosion offshore.

Alagoas Sub-basin

The Alagoas Sub-basin, with prevailing Ki columns, stands as the most eroded region, with a strong localized anomaly in the north. The average net erosion measured in wells that sampled Eocretaceous columns (Ki) is around 750 m and can reach up to 1,250 m (Figs. 13–15), but two outliers exceed 2,000 m. Net erosion determinations do not seem to correlate with the deepening of the basement blocks from southwest to northeast. On the contrary, higher than 750 m net erosion estimates suggest local tectonic controls (Figs. 13 and 14): close to the western basin border, in the small north-south block between the Sinimbu Step and the Coruripe Low, and in the structural high around well 1-ALS-17 (Figs. 12F), in the northeast portion of shallow waters, also highlighted in the first derivative of the Bouguer gravity anomaly (Fig. 1), which will be discussed further in Section 4.2.3.

Rift shoulders of the last rift pulses

Part of the erosion measured in the Alagoas SB seems to correspond to truncations of flexural rift shoulders of faulted blocks (Weissel and Karner 1989), developed during the last rift phase in the Neoaptian, as suggested by the geologic cross-section presented above (Fig. 6). The development of these rift shoulders seems to be simultaneous with the deposition of the Eoalagoas Maceió Fm in the structural low blocks in shallow waters and to the north of the sub-basin, beyond the Varrela Low. Thus, net erosion could vary in a higher frequency than that sampled by the dense network of exploratory wells acquired in this basin. The analysis of net erosion could be performed in regional geological sections (Giles and Indrelid 1998), which are still scarce in this sub-basin.

Erosion of exposed syn-rift strata

During rifting time in this sub-basin, from Berriasian to Aptian, regional elevation was probably a few hundreds of meters above sea level. The thermal subsidence that followed the rift phase apparently was not sufficient to create accommodation space in the proximal domain, which is still emerging today, as suggested by the geohistory diagrams of wells from this region (Fig. 7A). The insufficient thermal subsidence for accommodation space creation in this region was due to small lithosphere thinning (Beta factor), less than 1.5, as has been similarly pointed out to explain the minor post-rift subsidence in the adjacent Reconcavo-Tucano-Jatoba Rift System (Magnavita *et al.* 1994). Increasing accommodation space was created in the region of shallow waters to the south until the Late Cretaceous, subject to larger lithosphere thinning. Therefore, uplifted syn-rift strata have been exposed to erosion in this region from the Albian until the Late Oligocene-Miocene transgression (Arai 2006, Lima 2008, Rossetti *et al.* 2013), according to the stratigraphic record.

Tectonic inversion in North Alagoas

Net erosion of the highly compacted column sampled by well 1-ALS-17 was determined as the extreme value of 2,853 m with the methodology applied to sonic log data, in an interval of 2,605 m, sampled from 375 m BD (Fig. 12F). Despite the reliable trend, the fit of the exponential equation for highly compacted, but scattered data, presents some inaccuracy, besides, the VR trend of this well is not reliable. Still, the clearly compacted column suggests high erosion. In contrast, there is clear seismic evidence of a tectonic inversion that affected the Neocomian to Aptian syn-rift package in shallow waters of the Northern Alagoas, which explains the erosion suggested by the 1-ALS-17 data. Such tectonic inversion is evident in the SSW-NNE striking GH seismic section, parallel to the coastline, 20 km northwest from 1-ALS-17 (Fig. 16, location in Fig. 1), which presents an inverted syn-rift depocenter as a broad anticline and the truncation of the syn-rift

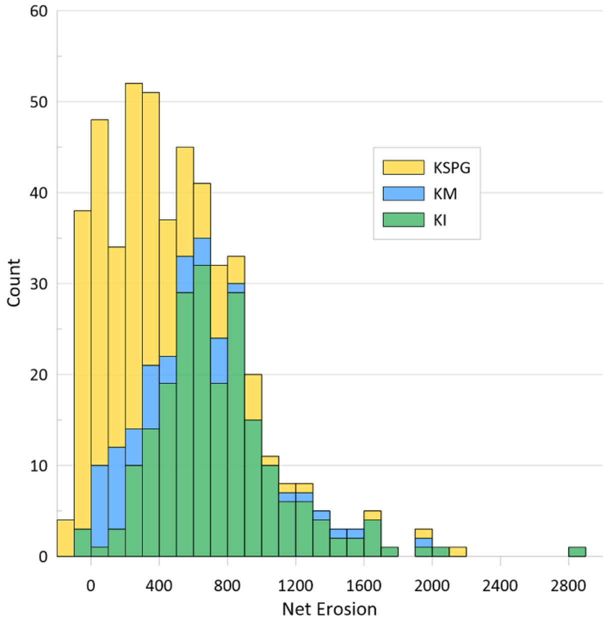

Figure 15. Histograms of net erosion determined with well data used in this study. In green, wells with predominance of Eocretaceous column, Ki. In blue, wells with predominance of Aptian-Turonian column, Km. In yellow, wells with predominance of Neocretaceous to Paleogene column, KsPg. In blank, sum of all stratigraphic intervals.

strata in its northern portion, corresponding to the Maragogi High. Therefore, the age of formation of this high, the boundary between the Sergipe–Alagoas and Cabo basins, seems to be late to post-rift, probably Early Albian.

The dip seismic section that crosses 1-ALS-17 does not present as good quality but still displays a mega anticline suggestive of compression. This inversion structure is high in the Bouguer derivative grid (Fig. 1) and has been previously interpreted as a local transpressional feature in a dominant sinistral transtensional system that controlled the initial rift phase in the Neocomian (Lana 1985, Szatmari and Milani 1999). However, this inversion clearly affects the whole sin-rift strata, up to the Neoaptian strata. It is possible that this tectonic inversion has affected the onshore region; however, this hypothesis has not been explored and it is far from being consensual among the Petrobras explorationists who worked in the area. This inversion is distinct and more compelling than the suggestive, but modest features, identified by Vasconcelos *et al.* (2019), related to reactivation of major regional shear zones, inherited from the basement, and interpreted as post-rift.

CONCLUSIONS

Net erosion measurements with sonic logs were preferred because they are less subject to sampling and laboratory mishandling and because sonic logs compound a larger database. Eroded columns of 484 wells from the proximal domain of the Sergipe–Alagoas Basin were determined by the numerical fit of the rate of decay (b) and of the transit time at surface (Dt_0) parameters of the exponential decay equation for a sonic log of pelitic columns, sampled every five meters. Sedimentary columns logged at least 1,250 m and that recovered the shallowest 800 m ensured the best regressions.

Just a fraction of the 257 wells with VR data, 60 wells, have been considered with reliable trends for erosion calculations. There is no geographic or stratigraphic control on the distribution of wells with better-quality VR logs. In general, these are wells with good linear alignment of VR profiles up to 0.7%, with coefficients of determination greater than 0.95, and with sampled columns more than 1,000 m thick. The VR database of this basin should be scrutinized and used with care.

The map of net erosion of the Sergipe–Alagoas Basin shows increasing values from a lower level of 250 m, prevailing to the south of the SPAZ, in the Sergipe SB, where predominates the Neocretaceous to Paleogene sedimentary pile (Ks-Pg). However, some wells that drilled these columns offshore show net erosion greater than 600 m, probably due to channel incision. The most likely process considered to have caused the uplift and erosion in the onshore portion of Sergipe SB is the continuous doming in the flexural bulge resulting from the isostatic compensation to the post-rift sedimentary loads offshore, from the Albian to Present marine sedimentary packages.

The Alagoas SB appears as the most eroded, especially toward the basin border, with a strong anomaly in the northeast shallow waters. In this sub-basin, average erosion around 750 m affected the Eocretaceous package and can reach up to 2,000 m locally. The syn-rift strata erosion seems to have followed the exposure of uplifted rift block flanks since the end of rifting, and probably, also enhanced by inversion tectonics. Post-rift thermal subsidence, apparently, was not enough to create accommodation space in the proximal domain, which is still emerging today. In this way, this region has remained subject to erosion since the last rift phase in the Late Aptian. Notably, in the shallow waters of northern Alagoas, seismic sections show impressive tectonic inversion features that affected the syn-rift package deposited from the Neocomian to Aptian, corroborated by the highly compacted sonic log trend of well 1-ALS-17. The tectonic inversion possibly affected the onshore region and may have contributed to the magnitude of the measured erosion, but its distribution and magnitude need to be further constrained.

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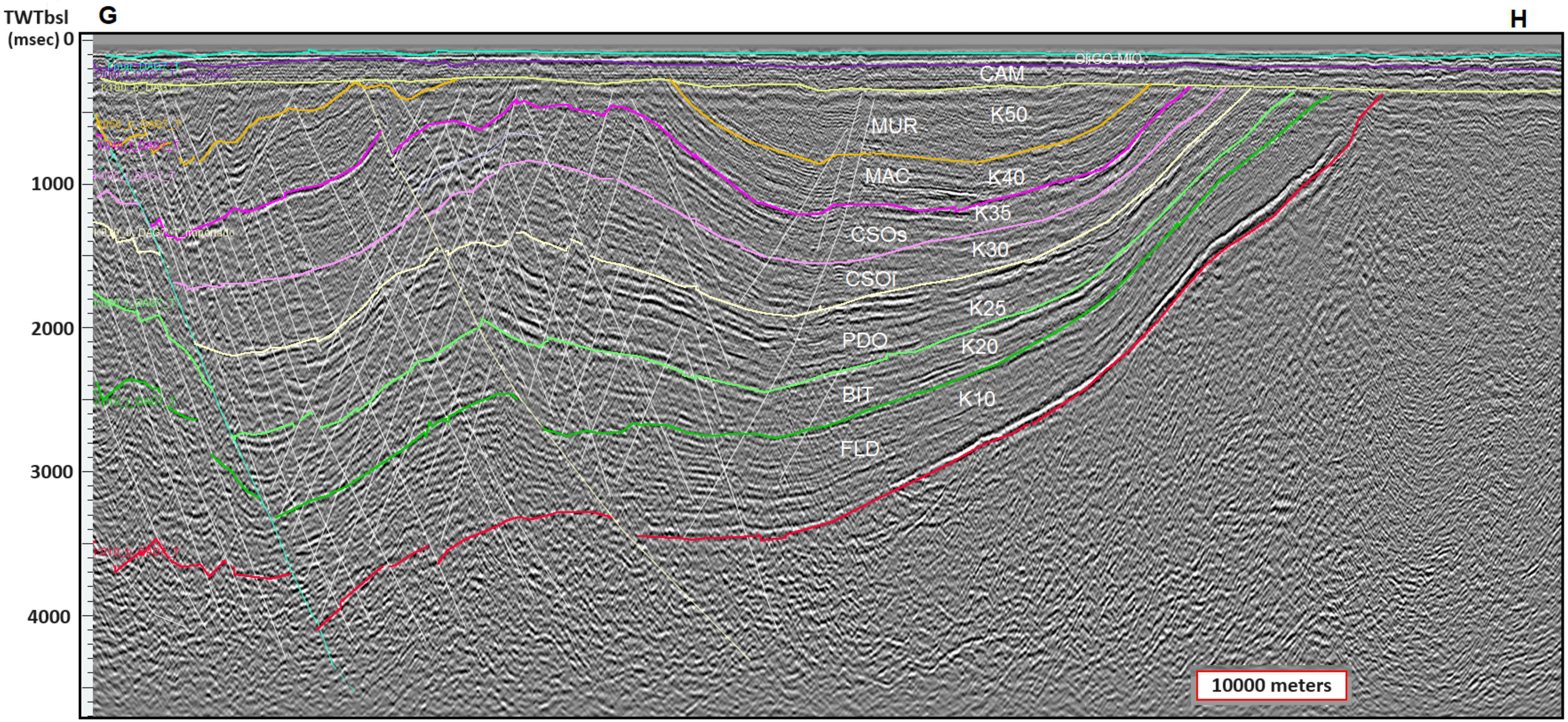

Figure 16. Double-time reflection seismic section southwest to northeast, parallel to the coast in shallow waters of north Alagoas, location in Fig. 1. Interpretations of the main limits of sin-rift sequences, truncated by an Oligocene surface, are presented. Depocenter inversion is shown on the left, to southwest, and impressive truncation of sin-rift strata, on the right, to northeast, which corresponds to the Maragogi High, boundary between the Sergipe-Alagoas and Cabo basins. This evidence suggests a tectonic inversion event that would have occurred between the end of the Aptian and the Oligocene.

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