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Geoelectric Subsurface Characterization in the Emerged Portion of the Barra Falsa Channel using the Ground Conductivity Meter (LIN-EM), Bojuru, RS, Brazil

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Abstract

Geophysical investigation in the coastal region of the emerged portion of Barra Falsa, Bojuru, RS, Brazil, provided valuable information about the depositional evolution and paleoenvironmental changes that occurred during the Quaternary period. The combination of electromagnetic surveys, analysis of stratigraphic wells, 3.5 kHz reflection seismic and previous geological data allowed for a comprehensive characterization of sedimentary environments associated with sea-level fluctuations. Electromagnetic surveys using the LIN-EM method with the Geonics EM34™ system revealed different conductivity responses in the subsurface, which could be interpreted in relation to depositional events. Five depth intervals were identified and related to specific events, such as the closure of the Barra Falsa channel, estuarine infilling, and channel drowning during marine transgressions. Furthermore, the comparison of the results of electromagnetic surveys with data from stratigraphic wells allowed calibration of indirect data. This multidisciplinary approach highlights the importance of integrating geophysical and geological techniques to reconstruct coastal environment evolution over time. This study provides a detailed insight into paleoenvironmental and depositional changes on the coast of Bojuru, demonstrating how these techniques can significantly contribute to future research and the sustainable management of coastal areas. The knowledge gained here is essential for understanding the dynamics of coastal zones and the influences of sea-level variations in the Southern region of Brazil.

Key words: Coastal Evolution, Sea-level fluctuations, Stratigraphy, Paleochannels, LIN-EM Method.

Resumen

La investigación geofísica en la región costera de la porción emergida de Barra Falsa, Bojuru, RS, Brasil, proporcionó información valiosa sobre la evolución deposicional y los cambios paleoambientales que ocurrieron durante el período Cuaternario. La combinación de estudios electromagnéticos, análisis de pozos estratigráficos, sísmica de reflexión de 3.5 kHz y datos geológicos previos permitió una caracterización integral de los entornos sedimentarios asociados con las fluctuaciones del nivel del mar. Los estudios electromagnéticos utilizando el método LIN-EM con el sistema Geonics EM34™ revelaron diferentes respuestas de conductividad en el subsuelo, que pudieron interpretarse en relación con eventos deposicionales. Se identificaron cinco intervalos de profundidad y se relacionaron con eventos específicos, como el cierre del canal Barra Falsa, el relleno estuarino y el ahogamiento del canal durante las transgresiones marinas. Además, la comparación de los resultados de los estudios electromagnéticos con los datos de pozos estratigráficos permitió la calibración de datos indirectos. Este enfoque multidisciplinario destaca la importancia de integrar técnicas geofísicas y geológicas para reconstruir la evolución del entorno costero a lo largo del tiempo. Este estudio proporciona una visión detallada de los cambios paleoambientales y deposicionales en la costa de Bojuru, demostrando cómo estas técnicas pueden contribuir significativamente a investigaciones futuras y a la gestión sostenible de áreas costeras. El conocimiento adquirido aquí es esencial para comprender la dinámica de las zonas costeras y las influencias de las variaciones del nivel del mar en la región del sur de Brasil.

Palabras clave: Evolución Costera, Fluctuaciones del nivel del mar, Estratigrafía, Paleocanales, Método LIN-EM.

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1. Introduction

Coastal fluvial incision due to the relative sea-level fall has been demonstrated by various authors (Talling, 1998; Blum & Törnqvist, 2000), as well as on the coastal plain, and platform in the South of Brazil (Abreu & Calliari, 2005; Weschenfelder *et al.*, 2014; Barboza *et al.*, 2021). Previous studies suggest that the geological framework of barrier islands plays a significant role in the evolution of coastal environments, including pre-existing structures such as paleochannels and transgressive sedimentary features (Kraft *et al.*, 1982; Belknap & Kraft, 1985; Evans *et al.*, 1985; Riggs *et al.*, 1995; Short, 2010). At the scale of the coastal plain, the geological framework influences the structure of the coastal plain, which can include paleoinlet valleys and channels (Belknap & Kraft, 1985; Demarest & Leatherman, 1985; Colman & Gagliano, 1964; Frazier, 1967; Otvos & Giardino, 2004; Twichell *et al.*, 2013; Miselis *et al.*, 2014).

Several barrier island systems on passive continental margins are based on morpho-stratigraphic features from the Pleistocene, such as incised river valleys (Schupp *et al.*, 2006), inlet channels (FitzGerald *et al.*, 2012), and relic transgressive features (Houser, 2012).

Geological framework studies related to beach environments have been conducted through direct observation and beach profiling or through a combination of geophysical, remote sensing, and geological methods (Jol *et al.*, 1996; Hansen *et al.*, 2021). It is suggested that, despite vibracoring providing cost-effective point information in unconsolidated sediments along coastal barriers, this method has limited penetration depth.

The Ground Penetration Radar (GPR) method has been used to infer the dynamic trends of stratigraphic sequences with centimeter-scale resolution along profiles extending for tens of kilometers (Bennet *et al.*, 2008; Garrison *et al.*, 2010; Mallinson *et al.*, 2010; Ribolini *et al.*, 2021; Barboza *et al.*, 2021). While GPR is one of the most employed tools for mapping subsurface structures, it has limitations when encountering groundwater with hydrochemical characteristics of brackish or saline quality due to the attenuation of electromagnetic wave energy corresponding to the GPR signal, with severe compromise in the depth of investigation and data quality, often resulting in uninterpretable data. Other low frequency electromagnetic methods provide information at much greater depths than GPR, owing to the frequency range they operate within, such as Transient Aerial Electromagnetic (TEM-AEM) and Frequency Aerial Helicopter-borne Electromagnetic (HEM), Terrestrial Electromagnetic methods in the Time Domain: (TEM) and Frequency Domain: Horizontal Loop Electromagnetic (HLEM), Controlled Source Audiomegnetotellurics (CSAMT), Audiomegnetotellurics (AMT), Magnetotellurics (MT) and Low Induction Number Electromagnetic (LIN-EM) (McNeill, 1990). Additionally, these methods can map conductive regions in the subsurface.

In the vast coastal plain adjacent to the Patos Lagoon and the adjacent continental shelf, the position of these past dissection systems is still uncertain and controversial, with significant implications for current models of the geological and palaeogeographical evolution of the coastal plain in Rio Grande do Sul. The characterization of paleodrainage systems, compared to current drainage systems, has the potential to contribute to landscape reconstruction studies.

A multidisciplinary approach, integrating data from multiple sources, as for example GPR and Aerial Photos (Costas *et al.*, 2006) and GPR and sediments and foraminifera data collected from vibracores (Mallinson *et al.*, 2010), is important in studying coastal evolutionary events, including the possible influence of factors such as sea-level fluctuations, climatic variations, and tectonism. Coastal dissection systems have implications for current stratigraphic, evolutionary, and prospective models. The results obtained will provide new insights into the geological evolution of the coastal region of Southern Brazil and analogous systems.

The application of LIN-Electromagnetic method can be used to study the geological evolution of incised valleys and channels, as well as architectural elements in coastal environments. The results are integrated with previous studies using 3.5 kHz reflection seismic method within the Patos Lagoon. This improves our understanding of the current geological structure of the coastal plain in Rio Grande do Sul.

This study represents integrated research with a proposed focus on the thematic line of characterizing coastal sedimentary environments. Its objective is to characterize the quaternary depositional features, in terms of geoelectric subsurface characterization, in the emerged part of the Barra Falsa channel, Bojuru, Rio Grande do Sul, using the Ground Conductivity Meter (LIN-EM) electromagnetic method for subsurface geoelectric characterization.

The approach of electromagnetic (EM) geophysical method can be employed to investigate the geological evolution of incised valleys and channels, as well as associated architectural elements of coastal plains in coastal environments. Gourry *et al.* (2003) conducted a geophysical campaign with the aim of confirming the position of previously identified alluvial bodies to identify paleochannels. The principle of the methods used is based on discriminating between distinct types of deposits by their resistivity value contrasts (Zalasiewicz *et al.*, 1985). For example, silts and clays are more conductive than sands, and likewise, clayey materials may have different resistivities depending on their composition (Gourry *et al.*, 2003).

This study aims to characterize, by subsurface geoelectrical distribution means, the superficial part of the Quaternary depositional features in the emerged part of the Barra Falsa channel, Bojuru, Rio Grande do Sul, using the Ground Conductivity Meter (LIN-EM) electromagnetic method.

2. Geological Background of the Study Area

The coastal region of Rio Grande do Sul (Andrade *et al.*, 1983; Asmus, 1983; Asmus & Porto, 1972; Asmus & Paim, 1986; Butler, 1970) has been studied with relatively few geophysical investigations, leading to many uncertainties related to the structural framework associated with Lagoon/barrier systems that are important within coastal depositional systems from the perspectives of geological stratigraphic recording (especially in relation to the Tertiary period), coastal evolution, sedimentation, including basement depth, lithological and structural contacts between the coastal plain and the Paraná Basin (Celmins, 1957; Dias *et al.*, 1994; Fontana, 1996; Rosa, 2007).

Extensive studies have focused on the coastal region of Rio Grande do Sul, addressing geological mapping (Horn *et al.*, 1984; Villwock *et al.*, 1986; Toldo Jr. *et al.*, 1991; Villwock & Tomazelli, 1995; Tomazelli & Villwock, 2000).

The geological evolution of the coastal zone in Southern Brazil was controlled by sea-level variations during the Pleistocene and Holocene periods (Corrêa, 1986, 1996; Dillenburg *et al.*, 2004; Martins *et al.*, 1996; Tomazelli & Villwock, 2000; Villwock & Tomazelli, 1995; Villwock *et al.*, 1986). Four lagoon-barrier depositional systems related to transgressive-regressive events during the Quaternary period have been recognized in the coastal plain of Rio Grande do Sul by Tomazelli & Villwock (2000).

Several architectural elements of the coastal sedimentary prism have been identified in seismic records of the coastal plain of Rio Grande do Sul (RS) and the adjacent continental shelf. Coastal fluvial incisions, due to sea-level fall, have been demonstrated by various authors (Talling, 1998; Blum & Törnqvist, 2000), as well as on the coastal plain and continental shelf of Southern Brazil (Abreu & Calliari, 2005; Weschenfelder *et al.*, 2014; Barboza *et al.*, 2021). In the coastal plain of Rio Grande do Sul, the incision and filling of coastal valleys and channels have been related to multiple events of sea-level rise and fall during the Quaternary period (Weschenfelder *et al.*, 2006, 2008a, 2008b, 2010a, 2014). Coastal plain incisions can extend towards the continental shelf and the shelf edge (Martins *et al.*, 1996; Corrêa *et al.*, 2007; Weschenfelder *et al.*, 2014; Weschenfelder & Corrêa, 2018; Barboza *et al.*, 2021).

Recently, significant paleodrainage systems have been identified in high-resolution seismic records within the Patos Lagoon (Weschenfelder *et al.* 2008A, 2008b, 2010a, 2010b, 2014, 2016) and on the adjacent continental shelf (Abreu & Calliari, 2005; Weschenfelder & Corrêa, 2018).

Figure 1 provides a visual representation of the study area's location and the layout of key surveying activities, where the so-called 'Barra Falsa' channel occurs and is addressed hereafter. The figure includes the following elements:

(a) 3.5 kHz Seismic Profile (A'-A"): This part of the figure shows a seismic profile (marine geophysical survey) labeled as A'-A".Seismic profiles are used to study the subsurface geological features and sediment layers. The profile helps researchers understand the subsurface geological structure. The 3.5 kHz Seismic Profile shown in the figure 1 specifically indicates the occurrence of the Barra Falsa Channel at the emerged part of the coast (adapted from Weschenfelder *et al.*, 2014).

(b) Position of the Electromagnetic Profile (B'-B"): This section of the figure represents the position of an electromagnetic (EM) survey profile labeled as B'-B", which is distinct from the seismic profile. Electromagnetic surveys, as described in the text, are used to investigate subsurface conductivity properties. The EM profile provides information about the electrical conductivity of the subsurface materials, which can be valuable for understanding geological and sedimentological characteristics.

(c) Stratigraphic Well B2: The figure also shows the location of a stratigraphic well labeled as B2 consisting of fine sand, silt and clay (according to Weschenfelder *et al.*, 2008b).

(d) Stratigraphic Well B0: The figure also shows the location of a stratigraphic well labeled as BO consisting of fine sand, silt and clay (according to Weschenfelder *et al.*, 2014).

(e) Overall, this figure provides an overview of the study area, highlighting the various survey methods and data collection points used in the research related to the coastal zone of Rio Grande do Sul.

3. Materials and Methods

This study is based on the application of terrestrial Electromagnetic (EM) method with the aim of enhancing our understanding of architectural elements associated with coastal evolution in the Barra Falsa channel region in Bojuru, RS. The application of EM method complements the study, primarily based on the analysis of 3.5 kHz Reflection Seismic profiles obtained in the Patos Lagoon. This study focused on the identification and mapping of the drainage network that dissected the study area. In addition to the seismic profiles (3.5 kHz), data from drilling samples and established knowledge about the geological environments of this coastal region of Rio Grande do Sul were used.

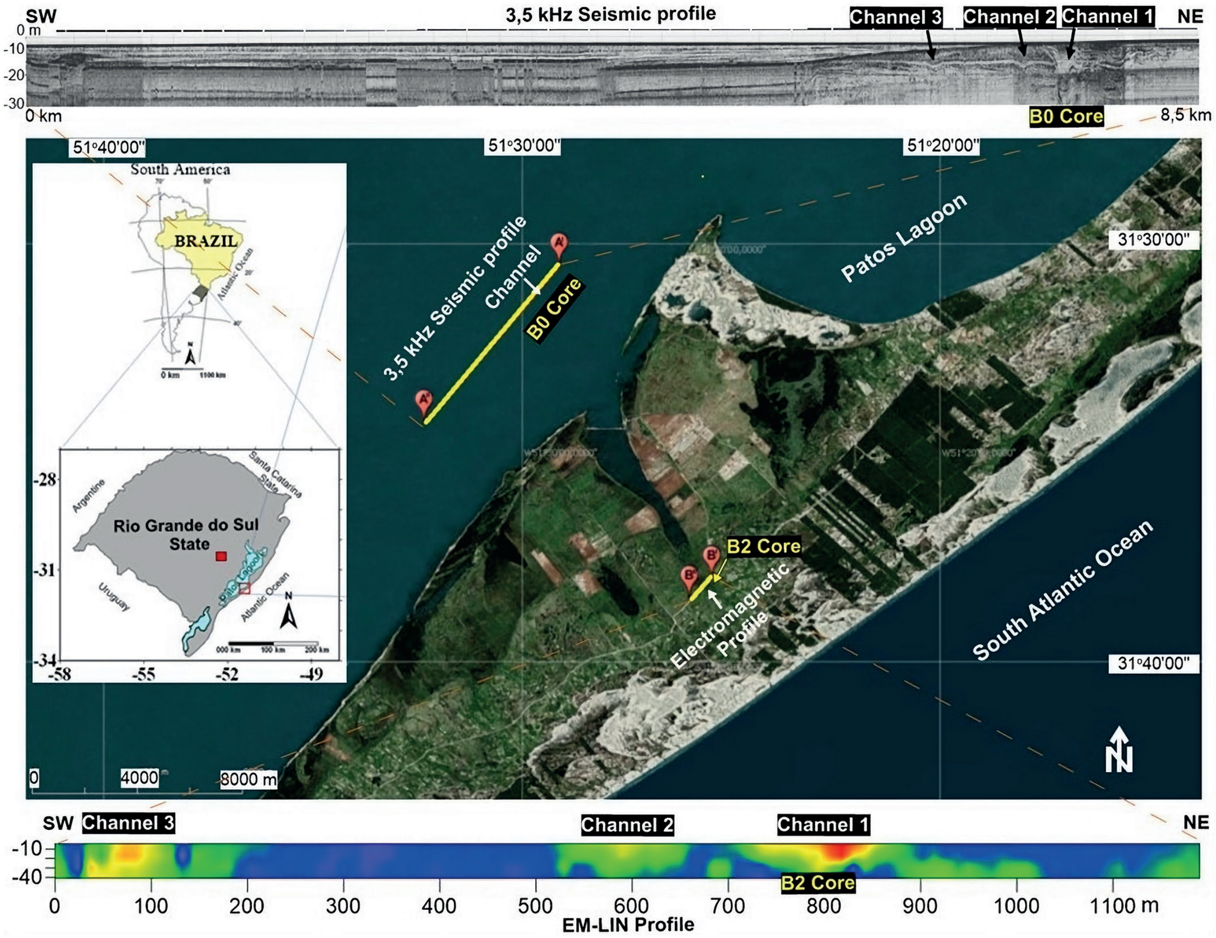

Figure 1. Location and situation of the Study Area in the Coastal Zone of Rio Grande do Sul, with a 3.5 kHz Seismic Profile (A'-A") and the Position of the Electromagnetic Profile (B'-B") and Stratigraphic Well B2. (Image: Google, 2011).

3.1 Application of Electromagnetic Methods in Coastal Studies

In terms of electromagnetic methods applied in coastal evolution studies, there are still few geophysical methods used. Several electromagnetic (EM) methods can be applied to coastal environmental such as Transient Aerial Electromagnetic (TEM-AEM) (Auken *et al.*, 2009; Viezzoli *et al.*, 2008; Vrbancich, 2009; Christensen & Halkjaer, 2014); and Frequency Aerial Electromagnetic Helicopter-borne (HEM) (Steuer *et al.*, 2009; Siemon *et al.*, 2009); Terrestrial Electromagnetic methods in the Time Domain: Transient Electromagnetic (TEM) (Meju *et al.*, 1999; El-Kaliouby and Abdalla, 2015) and in Frequency Domain: Horizontal Loop Electromagnetic (HLEM), Controlled Source Audiomagnetotellurics (CSAMT), Audiomagnetotellurics (AMT), Magnetotellurics (MT) (Tezkan, 1999) and Low Induction Number Electromagnetic (LIN-EM) (McNeill, 1990; Ruppel *et al.*, 2000; Paine *et al.*, 2004; Seijmonsbergen *et al.*, 2004; Lima *et al.*, 2019) (Figure 2; Table 1). Electromagnetic methods were developed to map the geoelectric distribution in the subsurface and, therefore, interpret sedimentological, lithological, and hydrogeological properties based on the geoelectric characteristics of subsurface structures.

One methodology used to describe the relationship between electrical conductivity values versus depth is the use of mathematical inversion techniques (Santos, 2004; Santos *et al.*, 2010; Wait, 1958). Guérin *et al.* (1996) showed that 1D modeling is valid if the depth of the bodies is of the same order of magnitude as the spacing between the transmitting and receiving coils. Usually, resistivity or conductivity maps are interpreted only qualitatively in applied prospecting. When additional information is required about depth or resistivity of existing features, various electrical soundings are performed in locations where (a) the structure is considered near to a 1D situation; (b) the interpretation is relevant to describe underlying features. In fact, true 1D conditions are never encountered, and an interpretation based on a 3D model (Tabbagh, 1985) would be very costly in terms of budget, acquisition time, and computational processing.

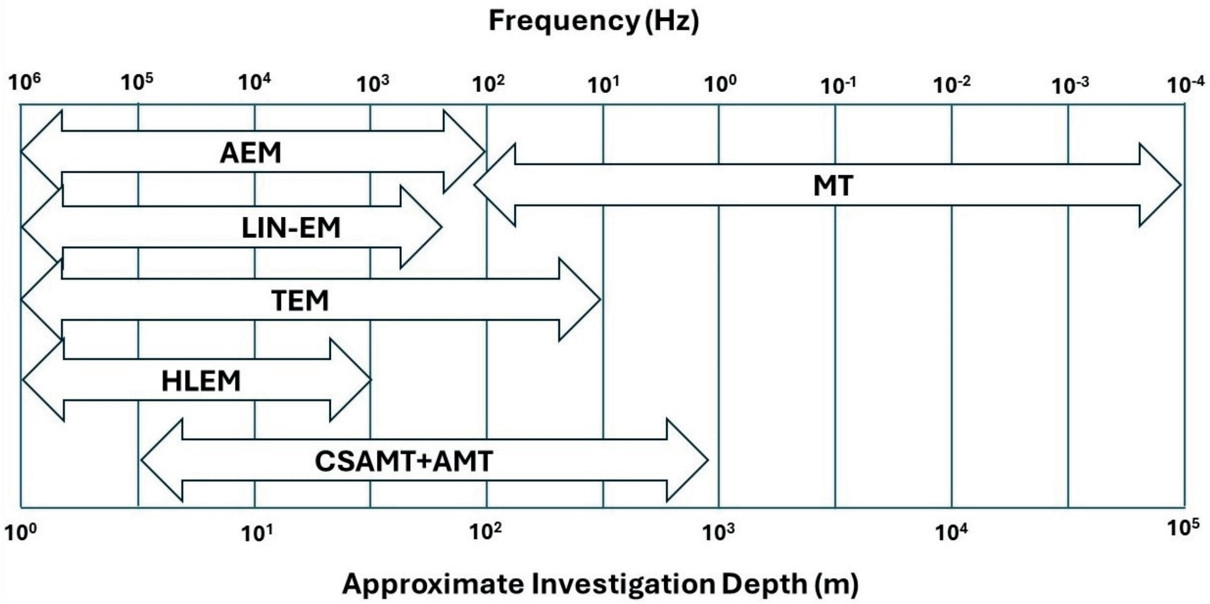

Figure 2. Frequency and approximate investigation depth of some Electromagnetic Methods.

Table 1. Main characteristics of Electromagnetic Methods (adapted from Tezkan, 1999; Meju, 2002).

Method	Advantages	Source of excitation	Investigation targets
LIN-EM	Can probe multiple depths simultaneously, not affected by salinity, inexpensive, can cover large areas rapidly, shallow depths (up to 60 m).	Active / Magnetic Dipole	Stratigraphy, structure, saltwater intrusion, paleochannel, mineralization, lineaments, faults, regional conductivity distribution.
AEM	Can probe multiple depths simultaneously, not affected by salinity, expensive, can cover large areas rapidly.	Active / Magnetic Dipole	Lineaments, faults, shallow aquifers, shallow saltwater intrusions, karst features, mineralization, regional. conductivity distribution
HLEM	Can cover large areas rapidly, investigate shallow depths (up to 60 m).	Active / Magnetic Dipole	Lineaments, faults, shallow saltwater intrusions, karst features, mineralization.
CSAMT/			
AMT	Capable of detecting features missed by seismic, can cover larger survey areas.	Active+ Passive / Plane Wave	Deep structure, stratigraphy, karst features, freshwater-saltwater interface, intrusive bodies, shallow intrusive.
TEM	Investigate deep depths (depth > 100 m).		
	Active / Magnetic Dipole	Deep structure, stratigraphy, deep aquifers karst features, freshwater-saltwater interface, mineralization, shallow intrusive.	
MT	Investigate very deep depths.	Passive / Plane Wave	Deep structure, deep regional aquifers, basement architecture, faults, lineaments, intrusive bodies, deep intrusive, conductivity distribution.

However, lateral changes are often smooth, allowing the application of an approximate 1D inversion process. This can enhance the knowledge of subsurface structure by transforming apparent resistivity (or conductivity) variations into a more significant parameter such as the thickness or conductivity of a given layer (Guérin *et al.*, 1996).

Different terrestrial electromagnetic survey methods have been developed. Some of these methods employ multi-frequency EM systems for deep investigation in a fixed set, with only the frequencies varying, while a specific method was developed for parametric surveys, meaning it uses a single-frequency system considering low induction number condition (LIN-EM), varying the distance between the transmitter and receiver coils to investigate different depths. According to McNeill (1996), this method offers a significant advantage over multi-frequency systems.

In studies of coastal regions, with the goal of characterizing the subsurface geological framework and coastal plain morphology, where direct subsurface observation using techniques, such as drilling cores has limitations in terms of depth and resolution, geophysical methods have been used. Among these methods, can mention the seismic method (Emery, 1969; Simms *et al.*, 2006); Ground Penetration Radar electromagnetic method (Leatherman, 1987; Jol *et al.*, 1996; Heteren *et al.*, 1998; Neal & Robets, 2000; Buynevich & Fitzgerald, 2003); shallow geophysics Slingram method, electromagnetic method in the frequency domain (Seijmonsbergen *et al.*, 2004); and Remote Sensing method (Hansen *et al.*, 2021).

Originally, this Swedish term referred to a "horizontal-loop" method (Keller & Frischnecht, 1966), but it is now commonly referred to as "two-loop" methods where one transmitting and one receiving coil are operated independently in the frequency domain, regardless of their relative orientations. A general nomenclature system has been proposed for different coil configurations for terrestrial instruments (Frischknecht *et al.*, 1991). In the work of Thiesson *et al.* (2011), the use of vertical configurations for Slingram devices was researched both theoretically and practically. In their studies, vertical devices with the same coil spacing had a slightly lower investigation depth than horizontal devices. However, the apparent magnetic susceptibility maps corresponding to vertical devices exhibited less anisotropy than horizontal devices. Practical cases studied showed that the vertical configuration provided results in good agreement with classical measurements. This can provide complementary information, particularly for shallow features (Thiesson, *et al.*, 2011). A general nomenclature system was recently proposed for different coil configurations for land-based instruments (Frischknecht *et al.*, 1991). Electromagnetic methods are more suitable for use because they allow subsurface characterization in a shorter time frame compared to traditional geological investigation techniques and/or other geophysical methods (Weymer *et al.*, 2015). However, these methods are underutilized due to a lack of understanding by non-geophysicists (George & Woodgate, 2002).

Most electromagnetic methods applied in coastal environments have been used for brine intrusion studies, for example: Fitterman & Stewart (1986); Fitterman & Deszcz-Pan (1998); Duque *et al.* (2008); Wiederhold *et al.* (2010); Maia & Lima (2003); Lima & Maia (2004); Lima & Ulugergerli (2005); Time-Domain Airborne Electromagnetic method (Vrbancich, 2009; Delefortrie *et al.*, 2014). However, few authors have used terrestrial electromagnetic methods to study subsurface geology and hydrogeology (Paine *et al.*, 2004; Seijmonsbergen *et al.*, 2004), and to study coastal barrier island geological evolution (Lopes *et al.*, 2013; Lima *et al.*, 2019). For these studies, electromagnetic survey profiles are oriented both orthogonally (Paine *et al.*, 2004) and longitudinally (Seijmonsbergen *et al.*, 2004; Lima *et al.*, 2019) to the shoreline. Pine *et al.* (2004) used the Geonics EM38^{TM} system to measure apparent conductivity values at an approximate investigation depth of 0.8 m (horizontal dipole mode) and 1.5 m (vertical dipole mode) with a station spacing of 20 m. The aim of the study was to evaluate if the integrated use of electromagnetic and LIDAR data improves the accuracy and resolution of coastal wetland mapping. In the longitudinal direction to the shoreline, Seijmonsbergen *et al.* (2004) used the Geonics EM34^{TM} system oriented in the horizontal dipole mode with a coil separation of 20 m and a station spacing of 20 m. This field configuration results in a theoretical investigation depth of approximately 15 m.

Gourry *et al.* (2003) used various geophysical methods, including electromagnetic walking profiles. This method used, were also able to identify paleochannels containing clays and peat, representing the only datable sediments that can be used to define a reliable stratigraphic and chronological architecture. As a result of the work, Gourry *et al.* (2003) obtained the resistivity contrasts that could were attributed to lithological changes and geological variations. Therefore, the conductive cover corresponded to recent flood deposits, and the conductive material of the paleochannel was estimated using 1D inversion of electromagnetic data. The main results obtained were the delineation of paleochannels and sedimentary bodies deposited at different evolutive periods.

The application of the Frequency Domain Electromagnetic (FDEM) method for 60 m maximum theorical depth investigation, known as the Ground Conductivity Meter (LIN-EM) (McNeill, 1980), is indicated for mineral and groundwater prospecting in crystalline media (Lima, 2007; Lima *et al.*, 2009), as well as for saline intrusion problems in coastal aquifers (McNeill, 1990; Maia & Lima, 2003; Lima & Maia, 2004; Lima & Ulugergerli, 2005).

Previous studies conducted in the same area using the same geophysical investigation method (Lopes *et al.*, 2013), in which data were collected along two profiles near and orthogonal to the shoreline, inferred, from cross-sections of apparent conductivity along the profiles, the depths of features related to Holocene Barrier deposits (IV) and Pleistocene Barrier (III) and Lagoonal III, in the evolution of coastal dynamics and local geology.

3.2 Electromagnetic Ground Conductivity Meter (LIN-EM) method.

The field gelophysical survey employed the Geonics EM34™ system model 3XL system. The method applied is based on the principle of electromagnetic induction treated in the frequency domain. Considering two circular coils, with the first designated as the transmitter coil and the second as the receiver coil, an alternating current is applied to the transmitter coil. These two coils are maintained at a predetermined distance and are positioned on the surface in two distinct configurations: (1) both aligned in a vertical plane in the same manner, referred to as the Horizontal Dipole; and (2) both placed horizontally, referred to as the Vertical Dipole. This method is known as Ground Conductivity Meter (FDEM-GCM), as well as Low-Induction Number Electromagnetic (LIN-EM). The alternating current applied to the transmitter coil generates a time-varying magnetic field, which induces various small eddy currents that penetrate the subsurface. These eddy currents induce a secondary magnetic field, denoted as *Hs*, which is detected along with the primary magnetic field, denoted as *Hp*, by the receiver coil. The Ground Conductivity Meter method employs portable equipment carried by two individuals to directly measure subsurface conductivity. In general, the secondary magnetic field is a function that includes the spacing (s) between the coils, the operating frequency (f), and the soil conductivity (σ). The quantity measured by the receiver coil is the ratio between the *Hs* field, considering the coils positioned over a semi-homogeneous subsurface with conductivity σ, and the *Hp* field considering both coils in free space. Under certain boundary conditions, i. e. where it is assumed the main assumptions: (a) The transmitter frequency is sufficiently low that we can ignore the influence of self and mutual inductance in any ground current flow (the instruments operate at low frequencies of less than 15 kHz); (b) The instrument is operated at zero elevation (ground surface); (c) A magnetic permeability of free space ($\mu_0 = 4\pi \times 10^{-7}\,\mathrm{Hm}^{-1}$, SI units); (d) Asymptotic approximation of Maxwell's equations (McNeill and Bosnar, 1999; Selepeng, 2016). And it is assumed that the induction number B is much less than 1 (the condition B « 1 is technically known as "operation at low values of induction number") (McNeill and Bosnar, 1999), the expressions for the field ratios, for both vertical and horizontal dipole configurations, can be simplified to a single expression (equation 1):

$$\left(\frac{H_s}{H_p}\right)_V \simeq \left(\frac{H_s}{H_p}\right)_H \simeq \frac{\mathrm{i}B^2}{2} = \frac{i\omega\mu_0\sigma s^2}{4} \tag{1}$$

where,

H_s= secondary magnetic field
H_p = primary magnetic field
V = vertical mode
H = horizontal mode
$i = \sqrt{-1}$
B is the induction number
ω = 2πf
μ_0 = permeability of free space
σ = conductivity
s = spacing between the transmitter and receiver coils

When B is much less than 1, as defined in terms of the skin depth (δ), (equation 2):

$$\delta = \sqrt{\frac{2}{\omega\mu_0\sigma}} \tag{2}$$

where,

B is the induction number.
ω = 2πf
μ_0 = permeability of free space
σ = conductivity

Thus, instrument readings are expressed in terms of apparent conductivity (σ_a), as defined by (McNeil, 1980; Parasnis, 1986), (equation 3):

$$\sigma_a = \frac{4}{\omega\mu_0 s^2}\left(\frac{H_s}{H_p}\right) \tag{3}$$

where,

σ_a = apparent conductivity
ω = 2πf
μ_0 = permeability of free space
s = spacing between the transmitter and receiver coils
H_s = secondary magnetic field
H_p = primary magnetic field

4. Results and Discussions

4.1 Analysis of Electromagnetic Data

The positions of the paleochannels align with the bathymetric data of Patos Lagoon and the Atlantic Ocean, which supports the data from the 3.5 kHz reflection seismic data (Figure 3).

In the current study, the field geophysical survey consisted of three coincident and orthogonal traverse profiles with respect to the selected structures (inferred paleodrainages), covering a total distance of 2,100 meters.

The observed values of apparent conductivity (mS/m) for the horizontal dipole configuration with 10 m spacing between the transmitter and receiver coils represent readings at a theoretical investigation depth of 7.5 meters. These measured values show lower apparent conductivity results, which can be interpreted as shallower depths being correlated with more resistive sedimentary environments.

The curve corresponding to the survey using a 10 m vertical dipole configuration represents a theoretical investigation depth of 15 meters, sensitive to vertical variations, and presents higher apparent conductivity values, which correlate with more conductive environments.

The curve for the horizontal dipole arrangement with 20 m spacing between the coils represents a theoretical investigation depth of 15 meters, sensitive to lateral variations, and exhibits average apparent conductivity values.

The 20 m vertical dipole configuration represents a theoretical investigation depth of 30 meters. The results show moderate apparent conductivity values.

Analyzing the behavior of the curves of apparent conductivity (mS/m) versus distance (m) for all measurement configurations, three regions of abrupt variations in the observed values, indicating more conductive regions, are identified, characterizing areas associated with the occurrence of channels (Figure 4).

The results of data processing are presented as subsurface geoelectric distribution profiles along the geophysical profiles. Initially, cross-sections are constructed based on interpolated apparent conductivity values using the Kriging method, utilizing SURFER 9.0 software from Golden Software Inc.

The next step in data processing involved performing mathematical operations for 1-D inversions, where electrical

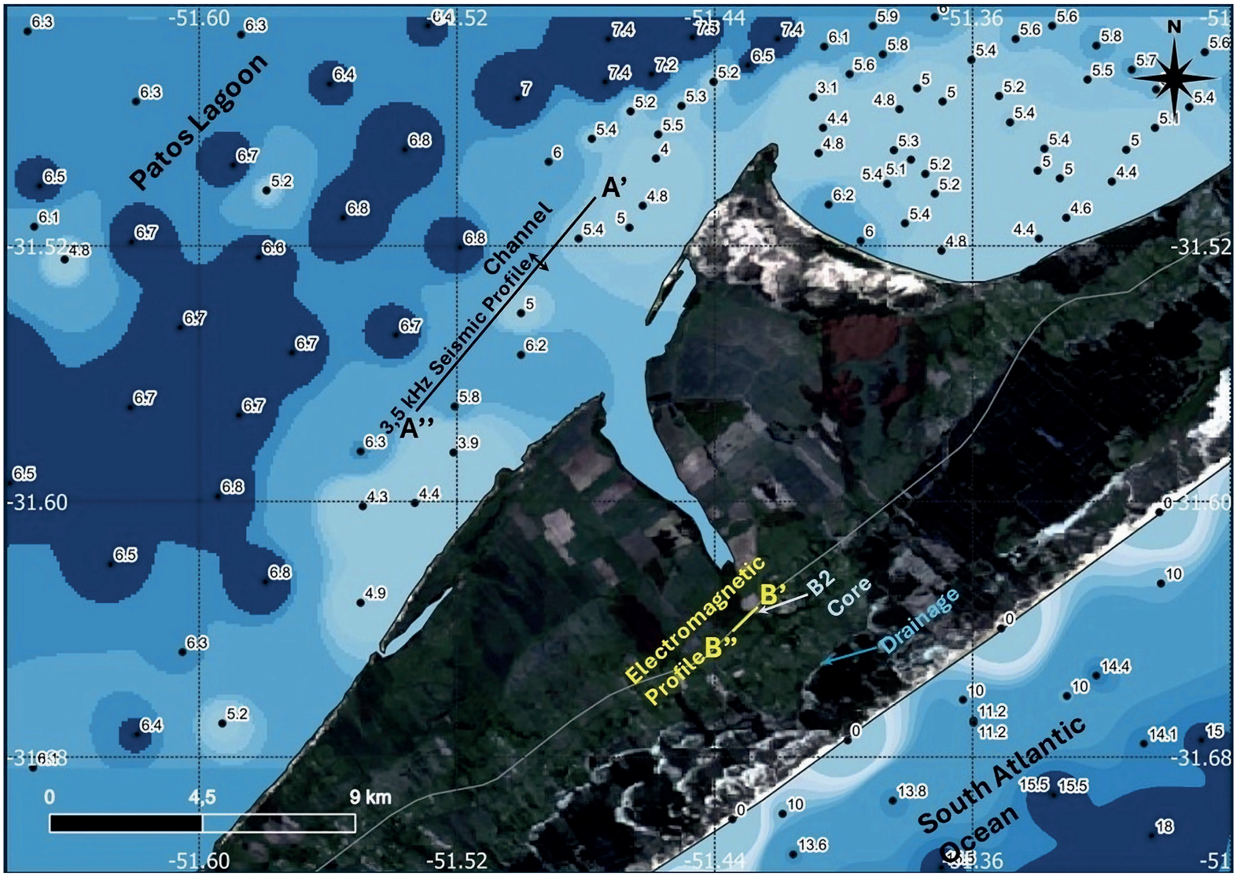

Figure 3. Study Area Showing the Position of 3.5 kHz Reflection Seismic Profiles (A'-A'') and Electromagnetic with Ground Conductivity Meter Profiles (B'-B'') and Bathymetric Points in Patos Lagoon, and Some Iso-bathymetric Lines of the South Atlantic Ocean. Source: Modified from the Centro de Hidrografia da Marinha (**https://www.marinha.mil.br/chm/dados-do-segnav-cartas-raster-347**) and Google (2011).

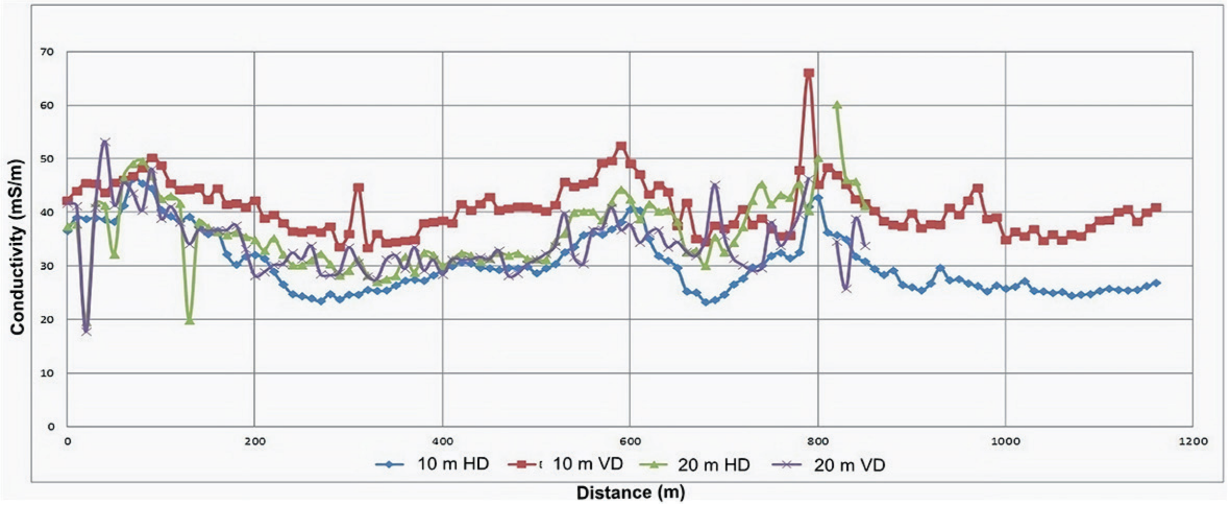

Figure 4. Electrical Conductivity data measured using 10 m HD (Horizontal Dipole), 10 m VD (Vertical Dipole), 20 m HD, and 20 m VD configurations, along with terrain data for Barra Falsa, Bojuru.

conductivity values were transformed into electrical resistivity values. For this purpose, a computational code (Lima *et al.*, 2009) based on formulas developed by McNeill (1980) and an inversion algorithm were used. The algorithm was a modified 1-D inversion with 2-D smoothing constraints between adjacent 1-D models (Santos, 2004).

Based on the 1-D inversion results, cross-sections of subsurface geoelectric distribution were created using interpolated electrical resistivity values (Figure 5).

Incised valleys, their infilling channels, and related architectural elements are common aspects of Quaternary coastal stratigraphy (Anderson and Rodriguez, 2008; Blum *et al.*, 2013; Aliotta *et al.*, 2013) and are typically formed by fluvial incision of the continental shelf during sea-level lowstands (Nordfjord *et al.*, 2005).

Well-defined paleoincisions and related features have been identified in seismic profiles within the Patos Lagoon (Weschenfelder *et al.*, 2014). Channel-type paleoincisions are filled with seismic facies units that create negative reliefs in the underlying strata.

According to Weschenfelder *et al.* (2008b), the Barra Falsa incision was active during the last regressive event in the Late Pleistocene and was progressively filled with fluvial, estuarine, marine, and lagoonal sediments during the Holocene transgression. The Barra Falsa feature resulted from a connection (inlet) between the Patos Lagoon and the Atlantic Ocean, the closure of which is attributed to changes in sedimentation related to the maximum Holocene transgression and subsequent regression (Toldo *et al.*, 1991).

The paleochannels can reach a few hundred meters in width, and sedimentary infill can reach up to 20 meters in thickness (Figure 6).

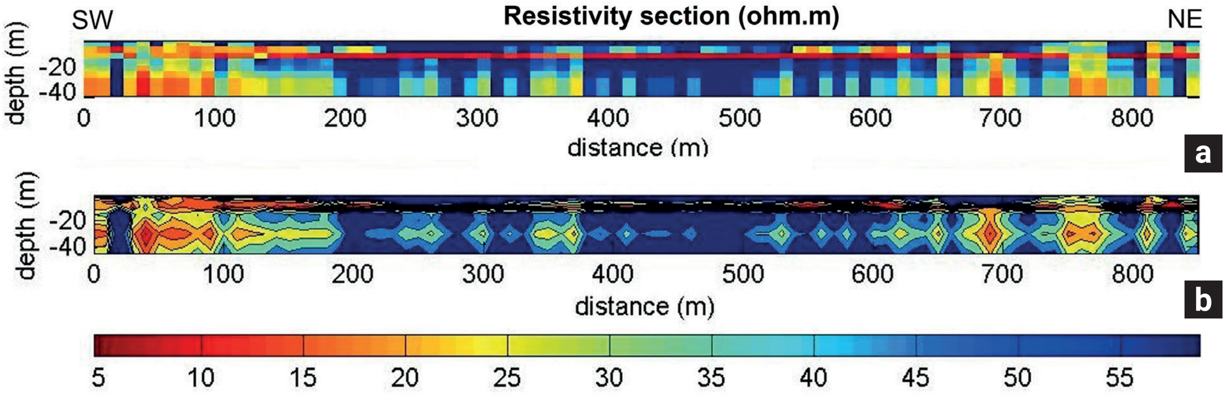

Figure 5. GeoelectricSections: (a) Electrical Resistivity Values Obtained by 1D Inversion; and (b) Interpolated Electrical Resistivity Values Obtained by 1D Inversion.

Analyzing the results obtained from electromagnetic surveys (LIN-EM), both in the resistivity sections (Figure 5a) and in the interpolated resistivity sections (Figure 5b) obtained by 1-D inversion, as well as in the apparent conductivity section (Figure 6a), a strong correlation is observed between the identification of paleochannels in seismic sections and the identification of conductive regions in the resistivity and geoelectric sections of apparent conductivity (Figures 5a, 6b). The seismic surfaces allowed the establishment of two distinct environments, non-contemporary and well-defined cutting and filling incision events, as well as three distinct sequences (S1, S2 and S3) (Figure 6c).

The reflectors from seismic data within Patos Lagoon in the vicinity of Barra Falsa made it possible to establish the relative succession of the oldest incisions S1 and S2 intersected by the reflectors of the youngest (limit sequence S2 and S3) (Weschenfelder *et al.*, 2014). A high correlation is observed with the architectural and lithological features observed in the reflection seismic sections conducted within the Patos Lagoon (Weschenfelder *et al.*, 2014; Santos-Fischer *et al.*, 2018).

The considerable number of incised valleys and channels that occur in the coastal plain (Weschenfelder *et al.*, 2014; 2016) and continental shelf (Corrêa, 1996; Martins *et al.*, 1996; Abreu and Calliari, 2005; Barboza *et al.*, 2021) is evidence that the coastal zone and platform of southern Brazil were deeply dissected during various regressive events in the Quaternary period. Prior to the subsequent submergence of the exposed coastal plain due to transgression, the platform surface was subaerial and subject to severe erosion and river incision. At the base, there are remnants of ancient channels. These are relict channels from when fluvial erosion processes reached greater depths because the source areas on the continent were higher. Over time, there was an equilibrium-seeking process, filling in other valleys due to lateral meandering of the Camaquã riverbed and the formation of a lagoon delta. Marine transgressive and regressive processes partially destroyed these old channels, leaving some remnants that were identified in electromagnetic surveys. These are a continuation of ancient channels of the Camaquã riverdelta in deltaic portions that were submerged by marine transgressions.

The width of the channels observed in the LIN-EM survey profile of figure 6 with 970 meters in length are approximately 176 meters (channel 1), 130 meters (channel 2) and 88 meters (channel 3). The first is located over the Barra Falsa channel, at 820 meters, where there is a stratigraphic well B2; the second channel is at 590 meters, and the third is located 75 meters from the beginning of the profile (SW). The first channel, in relation to the second, is separated by emerged strips of 60 meters, and the second, in relation to the third channel, is 425 meters away. These portions are characterized by high apparent conductivity ranging from 40 to 58 mS/m (low apparent resistivity). The interpreted channels corroborate with the current widths of the Camaquã riverdelta, which presents, from left (W) to right (E), the Barra Falsa channel, the Barra Funda channel, and the Barra Grande channel with widths of 78 meters, 140 meters, 98 meters,

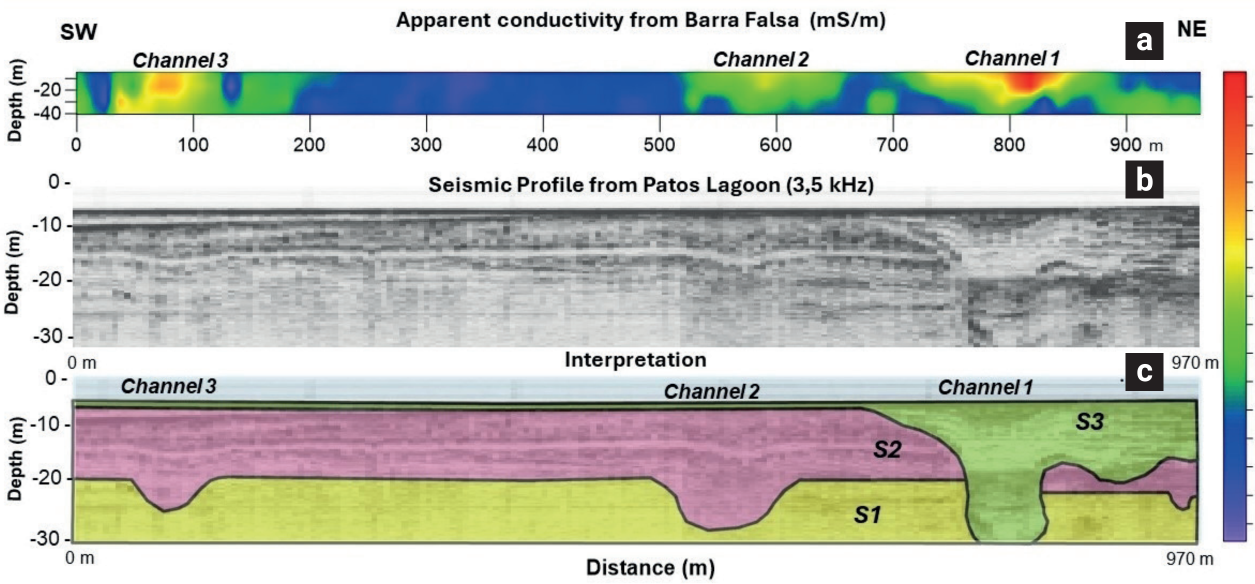

Figure 6. (a) l Section of Apparent Conductivity from the Electromagnetic Profile (LIN-EM) 20 m HD and 20 m VD configurations; b) Seismic profile of Patos Lagoon correlated with electromagnetic (EM-34) data from Barra Falsa (Weschenfelder *et al.*, 2014); and c) Sequence boundaries of seismic surfaces S1, S3 and S3 from oldest to youngest. Cutting and filling incision events and interpretation of channel architecture (adapted from Weschenfelder *et al.*, 2014).

138 meters, 83 meters, 294 meters, 450 meters, and 163 meters, separated by emerged portions. This characterizes the existence of a deltaic system with distributaries that was drowned and infilled, reinforcing the idea of parallel river systems that cut through the barriers.

4.2 EM Analysis and B2 Well

Analyses of Apparent Conductivity data (mS/m) from the cross-section pseudo-section and 1D Inversion data expressed in resistivity (Ωm) from the cross-section resistivity section along the road orthogonal to the inferred incised paleochannels were performed. This road exhibits a slight altitude variation, which can be considered flat, with an elevation of approximately three meters above the B2 sampling well's mouth.

Based on this information, the analysis of apparent electrical conductivity values correlates with depth information that is three meters deeper than the values from the sampled well. Therefore, the subsurface geoelectric distribution is interpreted by correlating it with the results interpreted by Weschenfelder *et al.* (2008b) based on seismic correlations and result syntheses, and by Santos-Fischer *et al.* (2016) based on diatom assemblages from the Late Pleistocene to the Holocene (Figure 7).

The changing sea-level allowed for estuarine sand and mud-sand deposition in the B2 test well (Barra Falsa channel) in the interval from 25.5 to 21.45 meters. Beds (geological strata) of freshwater, marine, and brackish-marine origin are present, indicating a high marine influence on the system, which implies a marine-estuarine environment prior to 11,500- and 10,240-years BP (Santos-Fischer *et al.*, 2016).

Resistivity (Ωm)	**Apparent Conductivity (mS/m)**
The EM34 system does not detect shallower depths.	The EM34 system does n detect shallower depths.
23 a 38	40 a 48
23 a 38	50 a 66
15 -30	50 a 56
23 a 58	38 a 46

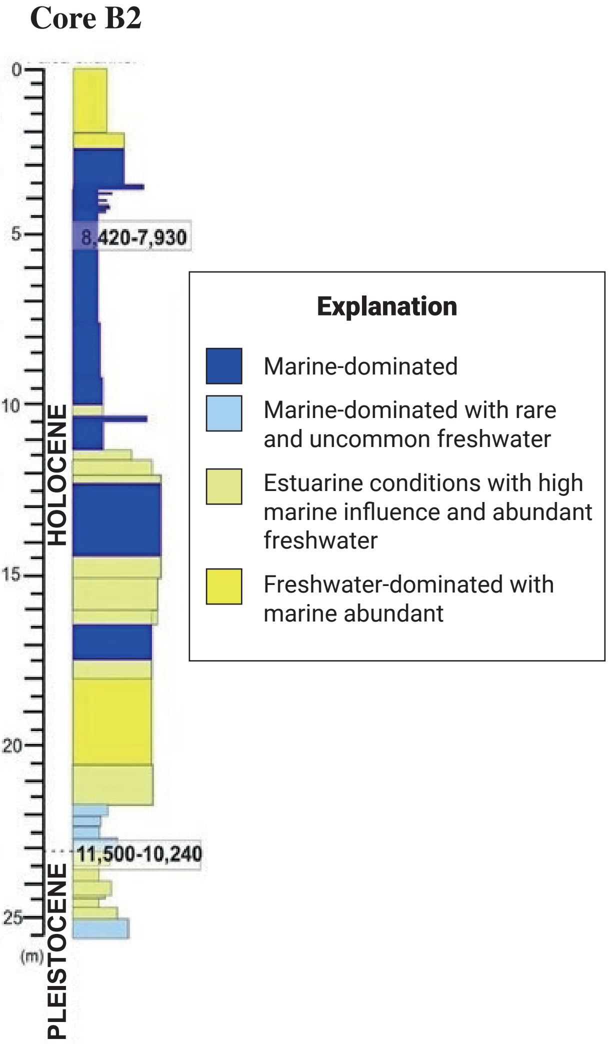

Figure 7. Stratigraphic well B2 in the extension of the Barra Falsa channel and respective past depositional environments with resistivity and apparent conductivity values, Bojuru, RS.

Changes in sedimentation within the Camaquã river channel and incised valley associated with the alternation between marine and estuarine deposition were observed. In the interval from 21.30 to 12 meters, estuarine deposition was partially interrupted. According to Santos-Fischer *et al.* (2016), only freshwater diatoms persisted in this sequence. Intermittent influxes of marine diatoms were also observed, which is related to successive openings and closures of the inlet until complete coastal submergence. An increase in fluvial influence was recorded in the interval from 11.45 to 10 meters and was more strongly associated with sand deposition.

Santos-Fischer *et al.* (2016) interpret the test well over the incised paleochannel, in the extension of the Barra Falsa channel, and conclude that the abrupt changes in sedimentation regimes are related to sedimentary depositions from marine to shallow estuarine environments. The marine sequences are characteristic of Mid-Holocene deposition associated with higher sea levels. The Holocene sequences are related to the openings and closures of the Barra Falsa channel. Santos-Fischer *et al.* (2016) subdivided the palaeoecological scenario of the southern coast of Brazil into four different depositional environments: (a) Predominantly Marine; (b) Predominantly Marine with rare or unusual freshwater occurrence; (c) Estuarine conditions with high marine influence and abundant freshwater; and (d) Predominantly Freshwater with abundant marine influence.

Figure 8 LIN-EM survey results with 10 m spacing between transmitting and receiving coils in both vertical and horizontal modes and 20 m spacing in both vertical and horizontal modes, highlighting the most conductive areas in red to yellow and yellow-green, covering theoretical investigation depths of 7.5, 15, and 30 meters, identifying the former channels parallel to the coast of Patos Lagoon and perpendicular to the Barra Falsa channel, in the Bojuru, RS region (Figures 5a, 5b, 8).

4.3 Geophysical Results Analysis

Analyzing the responses of geophysical measurements, initially, it was expected to obtain distinct and well-defined resistivity value ranges for the three different sedimentary environments. However, due to the complexity of depositional events in terms of characterizing the geoelectric distribution with close resistivity values, these intervals have some equal values. Nevertheless, it can be observed and emphasized that there are some characteristic responses:

For zone 1, where the fluvial influence predominates in terms of the sedimentary environment, the upper limit of the resistivity value range is above 30 Ωm up to 38 Ωm, which is in line with what is expected for environments with freshwater sediments, i.e., higher resistivity values.

For zone 2, where complete coastal submersion occurs, various resistivity values are observed, but it is noted that the lower limit of the resistivity value range shows minimum values of up to 15 Ωm, indicating agreement with more conductive resistivity values related to marine submersion.

For zone 3, related to the sedimentary environment with marine-estuarine characteristics, the geoelectric distribution range has medium resistivity values with lower limits of 18 Ωm and upper limits of 25 Ωm, which are compatible with an environment influenced by estuarine and marine waters.

In terms of the responses of geophysical measurements expressed in apparent conductivity values, the following observations can be made for the three different sedimentary environments:

For zone 1, where the fluvial influence predominates in the sedimentary environment, the lower limit of the apparent conductivity value range is smaller, with a lower limit of 30 mS/m, in line with what is expected for environments with freshwater sediments.

For zone 2, where complete coastal submersion occurs, there are various apparent conductivity values, but it is observed that the upper limit of the apparent conductivity value range shows higher values of up to 66 mS/m. This result indicates agreement with more conductive values related to the influence of marine submersion.

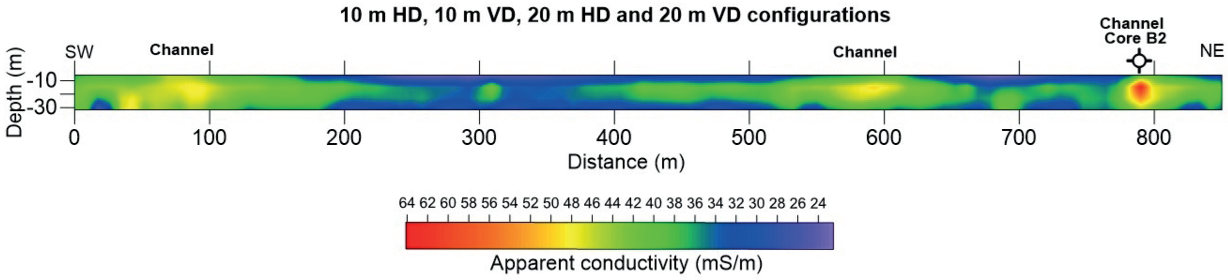

Figure 8. Geoelectric section with a length of 900 m of Apparent Conductivity from the electromagnetic (LIN-EM) profile with the 10 m HD, 10 m VD, 20 m HD, and 20 m VD configurations.

For zone 3, related to the sedimentary environment with marine-estuarine characteristics, the geoelectric distribution range has medium apparent conductivity values with lower limits of 38 Ωm and upper limits of 50 Ωm, which are compatible with an environment influenced by estuarine and marine waters (Table 2).

Weschenfelder *et al.* (2008b) divided the total depth of the B2 stratigraphic well into five depth interval ranges, relating them to various depositional events throughout coastal evolution. When observing the electromagnetic survey's response in terms of resistivity obtained through 1D inversion and correlating it with the different depth ranges of well B2, we can make the following assertions:

For depth range 1, there are no corresponding resistivity values because the Geonics EM34™ system used in this study, due to the frequency used in the transmitting coil, does not provide measurement readings for very shallow depths (0 - 7.5 m).

Regarding depth ranges 2 and 3, the calculated resistivity values represent average values (23 – 38 Ωm) and agree with sedimentary environments influenced by marine-estuarine conditions.

For depth range 4, which represents the maximum transgression event and drowning of the channel, more conductive values are observed at the lower end of the range, with resistivity values of up to 15 Ωm, consistent with more conductive values related to the influence of drowning by marine waters.

For depth range 5, more resistive values are observed at the upper end of the range, with resistivity values of up to 58 Ωm, consistent with more resistive values related to fluvial infilling and a phase of sea-level regression and lowering.

When examining the electromagnetic survey's response in terms of apparent conductivity for the five subdivided ranges of the B2 stratigraphic well, as described by Weschenfelder *et al.* (2008b), the following results obtained:

For depth range 1, there are no corresponding apparent conductivity values because the Geonics EM34™ system used in this LIN-EM survey does not provide measurement readings for very shallow depths (0 - 7.5 m).

In relation to depth range 2, the obtained apparent conductivity values represent average values of 40 - 48 mS/m and agree with sedimentary environments influenced by marine-estuarine conditions.

In depth range 3, where the sedimentary environment under marine-estuarine influence occurred during a transgressive phase with a higher sea level, more conductive values are observed at the upper end of the apparent conductivity range, reaching up to 66 mS/m.

For depth range 4, representing the maximum transgression event and drowning of the channel, more conductive values are observed, with a maximum apparent conductivity value of 56 mS/m.

For depth range 5, less conductive values are observed at the lower end of the range, with apparent conductivity of up to 38 mS/m, consistent with more resistive values related to fluvial infilling and a phase of sea-level regression and lowering (Table 3).

5. Conclusions

The integrated geophysical investigation presented in this study provided valuable information about the Quaternary depositional history and paleoenvironmental changes in the coastal zone in the emerged part of the Barra Falsa channel, Bojuru, RS, Brazil.

The integration of electromagnetic data, borehole sediment descriptions, and previous geological studies has allowed for the identification and characterization of different sedimentary environments associated with past sea-level fluctuations.

The electromagnetic surveys, conducted using the LIN-EM method, revealed distinct conductivity responses in the subsurface, which were interpreted in the context of sedimentary environments. Five depth ranges were identified and correlated with specific depositional events:

Table 2. Interpretation of Inverted Electromagnetic Data with Resistivity (Ωm) and Apparent Conductivity (mS/m) values versus depth (m) (sedimentary environments based on Santos-Fisher *et al.*, 2016).

Zone	Depth Interval (m)	Resistivity (Ω.m)	Apparent Conductivity (mS/m)	Sedimentary Environment
1	7,5 - 12	23 a 38	30 a 50	Fluvial influence. No marine taxon contributions were recorded
2	12 - 21	15 a 30	48 a 66	Complete coastal drowning
3	21 - 25	18 a 25	38 a 50	Marine-estuarine environment.

Table 3. Interpretation of 1D Inversion Electromagnetic Data Converted into Resistivity Values (Ωm) and Apparent Electrical Conductivity Values (mS/m) and versus Depth (m), sedimentary environments based on Weschenfelder *et al.* (2008b).

Zone	Depth Interval (m)	Resistivity (Ωm)	Apparent Conductivity (mS/m)	Sedimentary Environment
1	0 - 3,0	The EM34 system does not detect shallower depths.	The EM34 system does not detect shallower depths.	- Lagoonal environment establishment following sea level highstand - Lagoonal muds and fine sands deposition - Barra Falsa channel closure processes
2	3,0 - 7,5	23 a 38	40 a 48	- Channel filling by estuarine and marine clays during transgression maximum
3	7,5 - 12	23 a 38	50 a 66	- Channel filling by estuarine and marine muds during the transgressive to highstand sea level phase
4	12 - 23	15 -30	50 a 56	- Estuarine channel filling - Filling by transgressive sands - Channel drowning and filling during transgression
5	23 -25	23 a 58	38 a 46	- Fluvial channel complex fill - Lateral accreting fluvial facies - Channel avulsion and incision during regression and lowstand phase

- 0 - 3.0 m: The EM34 system did not detect shallower depths, but this range is associated with a lagoon environment followed by sea-level rise. It features lagoon mud and fine sand deposition, as well as the process of closing the Barra Falsa channel.
- 3.0 - 7.5 m: This interval represents the filling of the channel with marine and estuarine clays during the maximum transgression. The resistivity values range from 23 to 38 Ωm, while the apparent conductivity values range from 40 to 48 mS/m.
- 7.5 - 12 m: Within this range, the channel was filled with marine and estuarine mud during the transgressive phase at higher sea levels. Resistivity values vary from 23 to 38 Ωm, and apparent conductivity values range from 50 to 66 mS/m.
- 12 - 23 m: This depth interval corresponds to estuarine channel filling, filling with transgressive sands, and the drowning and filling of the channel during transgression. The resistivity values range from 15 to 30 Ωm, and apparent conductivity values range from 50 to 56 mS/m.
- 23 - 25,5 m: In this range, a complex fluvial channel filling process occurred, involving the accretion of lateral fluvial facies and incision and channel separation during the regression, and lowering phase. Resistivity values range from 23 to 58 Ωm, while apparent conductivity values range from 38 to 46 mS/m.

These interpretations align with the stratigraphic and paleoenvironmental information obtained from borehole B2 and provide a comprehensive understanding of the sedimentary history in the study area.

Furthermore, the results of the electromagnetic surveys demonstrate a strong correlation between the identified paleochannels in seismic sections and the conductive regions in the geoelectric sections, supporting the reliability of the geophysical data in delineating subsurface geological features.

Overall, this multidisciplinary approach combining geophysics, borehole analysis, and geological studies enhances our knowledge of the coastal evolution and paleoenvironments of the southern Brazilian coast, particularly in the Bojuru region. The findings contribute to a better understanding of the complex interplay between sea-level fluctuations and sedimentary processes in coastal environments and provide valuable data for future coastal management and research endeavors.

6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

7. Acknowledgments

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