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High-Resolution Sub-Bottom and Magnetometer Data From Southeastern Brazilian Coast

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INTRODUCTION

Sub-bottom profilers are used across shallow and deep oceanic waters with several applications, such as sea-level studies (e.g., Bastos et al., 2010; Koša, 2015; Aquino da Silva et al., 2016; Yoo et al., 2016), sedimentation process (e.g., Miller et al., 2013; Alves and de Mahiques, 2019), gas seeps (e.g., Benites et al., 2015; Michel et al., 2017), geomorphology (e.g., Jobe et al., 2011; Gomes et al., 2016), and others. Marine magnetometer data have also been used for most various studies, as archeological (Boyce et al., 2004), environmental (Boyce et al., 2001), engineering (Yu et al., 2007), and geological, mainly for mineral exploration (Dehler and Potter, 2002) and academic purposes (Müller et al., 1997). Combining both techniques enhances considerably the possibilities of geological and oceanographic interpretation, as multi-data surveys in marine environments allow complementary studies (e.g., Kadima et al., 2011; Demir et al., 2012).

The Boqueirão Strait in the northern coast of São Paulo (Southeast Brazil) connects two semi-enclosed bays, allowing water exchange between them (Mahiques and Souza, 1999). Despite its importance to the oceanographic evolution of the region, it has still been poorly studied. Therefore, this new dataset will contribute to future comprehension of the geologic and oceanographic evolution.

DATA COLLECTION

Location and Date

New seismic and magnetometer data were acquired on the region of the Boqueirão Strait during a cruise between November 26 and 30, 2018, onboard R/V Veliger II from Instituto Oceanográfico of Universidade de São Paulo. This 35-m-deep strait is located between 23°31′ S/45°06′ W and 23°32′ S/45°04′ W and is a unique region that separates the shallow areas of Flamengo Bay and the Toninhas Bay on the city of Ubatuba, northern coast of São Paulo State, Brazil (**Figure 1**). The strait also separates the continent from the Anchieta Island, a touristic destiny whose main beaches are located on Palmas Bay (**Figure 1**). The strait was probably formed from an ancient drainage system developed during the Quaternary in the Brazilian coast (Almeida, 1964), and, in fact, Mahiques and Souza (1999) found seismic and sediment evidences of regressive and transgressive surfaces in the area.

The Ubatuba region is characterized by the proximity of the Serra do Mar from the shore (**Figure 1**). The input of terrigenous sediments into the bay is mostly controlled by rainfall, resulting in fine sediments rich in organic matter (Mahiques, 1995). Sediments reaching the Flamengo Bay are characterized by a clockwise transport system. These sediments are reworked by the water that enters the bay from the western sector (Mahiques and Souza, 1999). On the Boqueirão area,

circulation is mostly due to SW–NE wind and wave currents that, with appropriate cold fronts influence, can reach up to 0.80 m/s (Tessler, 1988; Mahiques and Souza, 1999).

Seismic Data Collection

High-resolution single-channel seismic data were acquired using a SIG Sparker ELC-1200L coupled to an Energos 300J power supply, operating at 250J with a signature source-frequency of 0.9 kHz and 3.4 ms vertical resolution. Acquisition was performed at a constant vessel speed of 3.5 knots and, for decreasing the effect of vessel noise, the source used a 25-m layback. For data recording, a 4.7-m length SIG Streamer was used, with a single-channel formed by eight hydrophones coupled to a pre-amplifier to increase signal–noise rate. In order to minimize the effect of the vessel's noise on the hydrophones, the streamer used a 35-m layback, therefore spaced 10 m from the seismic source. Both the layback lengths for source and streamer were defined after a testing and calibration period prior to acquisition, in which different lengths were applied and noise decrease was read in the online data view of the acquisition software. More than 30 km of seismic data were collected in the datum WGS84 and UTM 23S projection, in a total coverage of circa 1.6 km^2 (**Figure 1**).

The acquisition of seismic data was performed with the software Meridata MDCS 5.2, which controlled shot and recording settings. The source used a SEG capacitor bank of up to 300 J, which was triggered by MDCS software. Navigation was acquired with a DGPS system Hemisphere Atlas Link, which provides horizontal resolution up to 0.1 m and vertical precision of 0.2 m. Installation offsets were measured on the port.

Magnetometer Data Collection

A magnetometric survey was performed using a SeaSPY 2 magnetometer, from Marine Magnetics, simultaneous to the seismic survey. The SeaSPY has an Overhauser sensor that measures the intensity of the magnetic field vector, regardless of its direction. The resolution is 0.001 nT and the absolute accuracy is 0.1 nT. There is no heading error, temperature drift, or dead zone associated with the measurements.

The magnetometer layback was 30 m to avoid interferences from the vessel, along the same profiles presented in **Figure 1**, adding the maneuver path. The optimal tow-cable length has been defined to be 30 m after several surveys with the research vessel. Prior to acquisition, offsets for the magnetometer and GPS antenna were measured and applied to the acquisition software BOB. The sample rate was 1 Hz, resulting in 13,330 data points distant by 4 m along the profiles.

The diurnal magnetic anomaly was registered by a ground Overhauser magnetometer, a GSM-19 from GEM Systems, located at a shore-based magnetic station, on the Ubatuba base of the Instituto Oceanográfico of Universidade de São Paulo, 5 km apart from the survey area.

DATA DESCRIPTION

Seismic Dataset

After acquisition, seismic data were converted to SGY format (IEEE Float-32 bit) using Meridata REX software and applying the acquisition offsets. Therefore, all seismic data have precise position information (bytes 73 and 77) in WGS84/UTM 23S. Shotpoint (SP) information is located on byte 17. No filters, gain, or any other processing was applied to the data, except for the pre-amplifier on the streamer. Trace length varies between 100 and 150 ms, with sampling interval of 50 μs and positive seabed reflection. Details on the seismic data format are presented on **Table 1**.

Given the proximity of the Serra do Mar formation to the coast in this region, it is possible to interpret the acoustic basement (interpreted in red in **Figures 2A,B**) as the crystalline basement in most of the seismic sections. A detailed view of the survey area shows the basement outcrops near the continent (north) and the Anchieta Island (south). A seismic line N–S oriented (**Figure 2A**) indicates that the basement is much shallower in the southern sector, close to the Anchieta Island, and some sections clearly show the basement outcropping on the seafloor (**Figure 2B**), pointing to the connection between the continent and the island.

Above the basement reflector and the present seafloor multiple (mapped in green in **Figure 2A**), it is possible to notice important reflectors related to ancient oceanographic and possibly sea-level conditions. The "paleo-Boqueirão" represents an ancient configuration of the region, with morphological characteristics much similar to the present. On the flanks of this paleo-depression, a stabilization surface on the northern sector and a ravinement surface on the southern, as well as erosive truncation on the slope, point to structures produced by sea-level variations, as interpreted by Mahiques and Souza (1999).

Magnetometer Dataset

The abnormal spikes were removed from the collected dataset; thereafter, the diurnal magnetic correction was applied using shore-based magnetic station data. Besides the preprocessing described above, no filter or further corrections were applied to calculate the total magnetic field (**Figure 2C**). A NE trending formed by a series of dipoles is highlighted by the magnetic data. The pattern can be related to the basement structure, since the region is located in the Ribeira Belt, a neoproterozoic orogenic belt formed by the accretion of terranes in the NE trending (Heilbron and Machado, 2003).

Data Availability

The seismic and magnetometer data are available in the community at FigShare.com (doi: 10.6084/m9.figshare. 11861889). Seismic data are available in SGY format (see detailed description in **Table 1**). SGY files are named following their date: YYYYMMDD_HHMMSS. Magnetometer data are
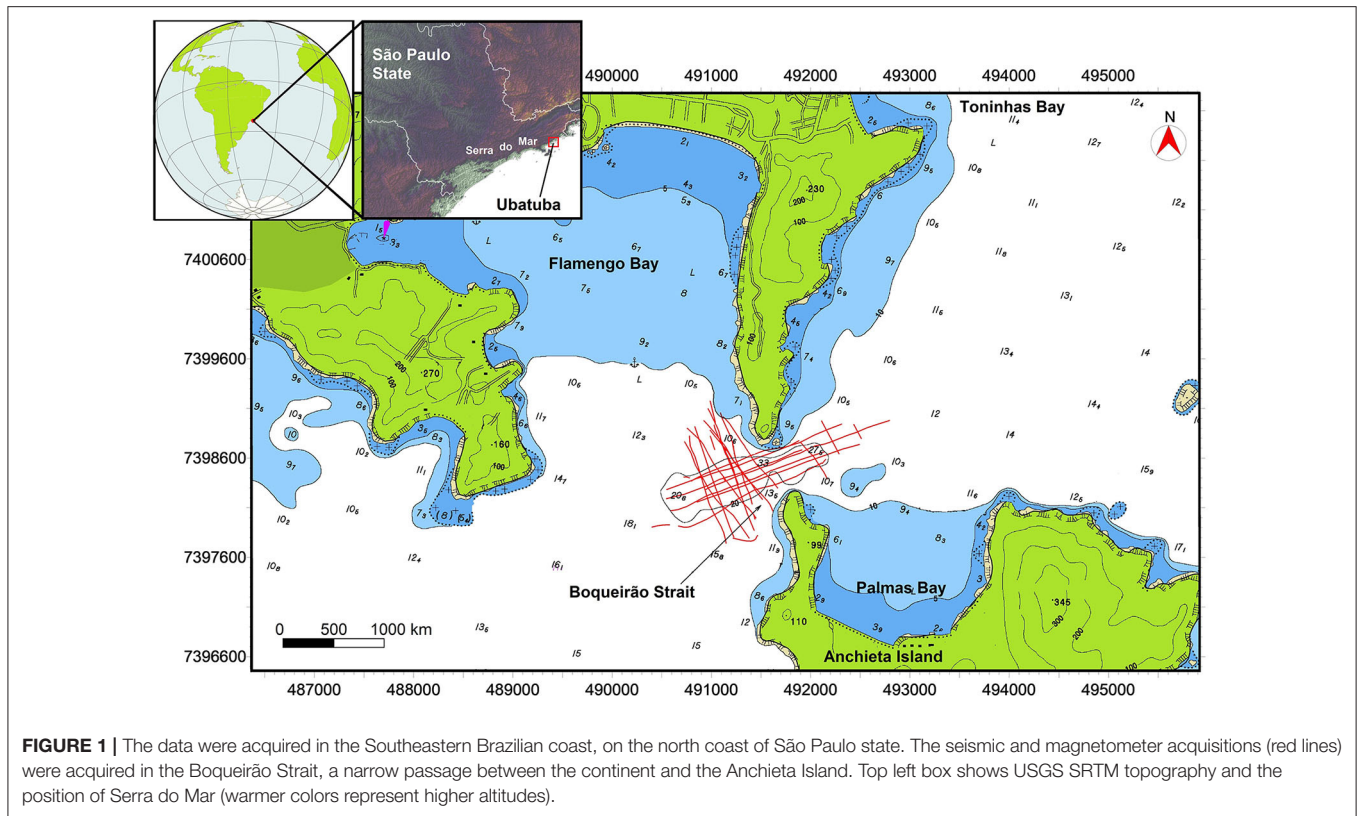
FIGURE 1 | The data were acquired in the Southeastern Brazilian coast, on the north coast of São Paulo state. The seismic and magnetometer acquisitions (red lines) were acquired in the Boqueirão Strait, a narrow passage between the continent and the Anchieta Island. Top left box shows USGS SRTM topography and the position of Serra do Mar (warmer colors represent higher altitudes).

TABLE 1 | Summary of SGY data information.

Name format	DATE_TIME.sgy
Data format	SGY IEEE Float (32 bit)
Position	WGS84/UTM 23S
Gain	No
Filter	No
Pre-amplify	Applied on the streamer
Bytes for X/Y information	73/77
Byte for SP information	17
Trace length	100–150 ms
Sample interval	50 µs
Seafloor reflection	Positive

available on text file format (.XYZ), including navigation. Data also include the shapefile of the seismic acquisition survey.
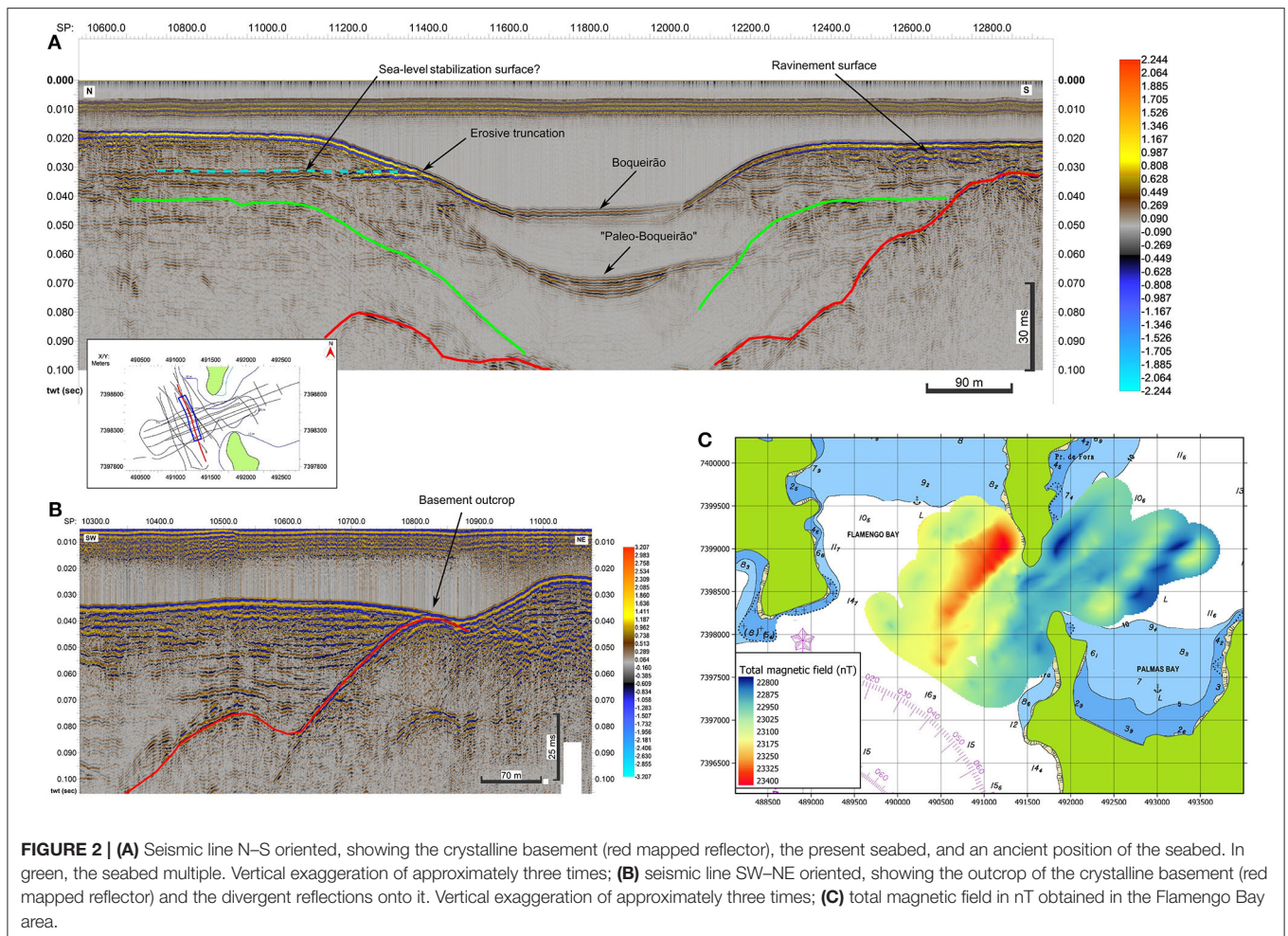
POSSIBLE APPLICATIONS

Mahiques and Souza (1999) published the seismic stratigraphy of the Boqueirão Strait two decades ago. With the technological advances in seismic acquisition, these new data provide a better tool to enhance the studies on the region. The improvement of data is based on positioning technology

evolution, with the use of differential Global Positioning System (GPS), for example, as well as newer seismic source, recorder, and digital/analogic conversion tools. The seismic and paleobathymetry characteristics of this strait can provide important information to the Quaternary evolution of the southern coast of Brazil. With the support of other data such as cores and gravimetric data, more detailed research can be carried out in order to contribute to the still poor sea-level change studies on the region (Klein et al., 2005; Veiga, 2005; Angulo et al., 2006; Alves and de Mahiques, 2019).

This dataset can be used as a guide for sediment sampling. Recent studies question the actual sea-level curve applied to portions of São Paulo coast (Suguio and Martin, 1978; Angulo et al., 2006). Sediment cores would make it possible to date and correlate the seismic surfaces interpreted with sea-level changes during the Quaternary.

For studies focused on tectonics of passive margins, these datasets are oriented to guide data acquisitions in a more regional perspective. Many of the faults found on the seismic data show the same orientation observed on continental outcrops. Authors such as Almeida (1964) and Zalán and Oliveira (2005) offer a different perspective over the evolution of the rift systems found southeast of Brazil. Nonetheless, the lack of information over the continental shelf creates a gap of data between continental and deep marine deposits. This dataset was a first attempt to search for structures that relate tectonics with syndepositional sedimentation.

FIGURE 2 | **(A)** Seismic line N–S oriented, showing the crystalline basement (red mapped reflector), the present seabed, and an ancient position of the seabed. In green, the seabed multiple. Vertical exaggeration of approximately three times; **(B)** seismic line SW–NE oriented, showing the outcrop of the crystalline basement (red mapped reflector) and the divergent reflections onto it. Vertical exaggeration of approximately three times; **(C)** total magnetic field in nT obtained in the Flamengo Bay area.

The magnetic data can be used to distinguish geological structures on the area, as faults and basement features that may complement studies about the formation of the bay, identifying fragile zones and regional patterns.

The uncompleted magnetic anomalies limit the interpretation of the volume and depth of the magnetic sources. Since the anomalies are not completely outlined, the modeling of them is not conclusive.

Limitations

The limitation of this single-channel seismic data is related to the acquisition process in shallow water environments. In such environment and in addition to using a single-channel system, the multiple reflections are present and the removal is difficult (**Figure 2A**). Additionally, as a high-energy source (250 J) was used in order to reach the deepest areas of the basement, the shallowest regions have high-amplitude reflections and multiples.

Recording was maintained even during short crossing lines and owing to that, some seismic lines are very short. Nevertheless, all lines were kept in the dataset.

Finally, the most important limitation is that there are no new sediment cores in the area. Therefore, with this dataset alone, it is not possible to assign sedimentary information and/or ages to the reflectors.

FINAL REMARKS

The north coast of São Paulo state in Southeastern Brazil is a region of great importance due to its natural conservancy and environmental significance. It is fundamental to further develop studies in the regions, especially those related to its formation and evolution of this portion of the Brazilian Margin. Only with this information the scientific community will be able to provide evolution models for the area, better understanding the effects of sea-level and depositional changes during the Quaternary and Holocene. These kinds of studies will contribute to the development of climate change scenarios for coastal zones and aid government mitigatory policies. Therefore, this new geophysical dataset can aid researchers with those goals.

DATA AVAILABILITY STATEMENT

AUTHOR CONTRIBUTIONS

DA, EC, and DM were responsible for data collection and organization. DA was responsible for writing the manuscript. EC, DM, and RS were responsible for reviewing the manuscript. LJ coordinated the process. All authors contributed to the article and approved the submitted version.

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