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A multidisciplinary approach for studying deep-sea habitats in Santos Basin

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It is recognized that the deep ocean and underlying seafloor comprise the largest habitats on Earth, hosting a major part of our biosphere. Although the deep sea remains underexplored, recent studies indicated that the deep pelagic and benthic ecosystems harbor diverse organisms adapted to cold temperatures and high hydrostatic pressure (e.g., Gooday et al., 2020; Xiao et al., 2021; Feng et al., 2022). These organisms play an essential role in the ocean's biogeochemical cycles, thus supporting key global ecological processes, such as carbon sequestration driven by biological and microbial carbon pumps along the water column (Legendre et al., 2015) and methane oxidation in benthic cold seep habitats mediated by prokaryotic methanotrophs (Ruff et al., 2015). The high costs associated with the technical challenges in exploring the deep sea render studies difficult, resulting in the great majority of the deep ocean's biodiversity, chemistry, and geology remaining unknown (Da Ros et al., 2019).

Anthropogenic activities and global climate change have caused top-down (e.g., fisheries overexploitation) and bottom-up (e.g., eutrophication induced by nutrients released into coastal waters) impacts on several marine ecosystems (Da Ros et al., 2019). However, anthropogenic impacts in deep-sea ecosystems remain poorly understood. One major concern is that industries are moving rapidly toward exploiting deep-sea resources (e.g., mining activities), increasing the need for international laws to protect marine areas (Da Ros et al., 2019; Howell et al., 2020). Protection of deep-sea ecosystems might be the most challenging yet least standardized goal of global nature conservation (Danovaro et al., 2020).

The roadmap for the Ocean Decade recognizes the deep ocean as a frontier of science and discovery. It alludes to the advance in understanding of deep-sea ecosystems, their functions, vulnerabilities, and services to society (Howell et al., 2020). Several ongoing initiatives are suggesting standardized efforts to support the Ocean Decade and the United Nations Sustainable Development Goal 14 (life below water), focusing on conservation and monitoring of the deep sea which include, among others, the Deep-Ocean Stewardship Initiative (DOSI) and the International Network for Scientific Investigation of Deep-Sea Ecosystems (INDEEP) (Danovaro et al., 2020).

In the Santos Basin (southeastern Brazilian continental margin), various deep-sea geological features have been recently discovered,

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including pockmarks (de Mahiques et al., 2017; dos Santos et al., 2018; Schattner et al., 2018; Ramos et al., 2020) and giant carbonate mound complexes (Maly et al., 2019). Deep-sea pockmarks are depressions formed on the seafloor due to temporal fluid/gas seepage with a consequent bottom collapse (Ramos et al., 2020). The Santos Basin hosts thousands of pockmarks formed by salt tectonic activity on the subsurface. Along the upper slope of the Santos Basin, Maly et al. (2019) found the first megastructure of carbonate ridge for the Southwestern Atlantic, the Alpha Crucis Carbonate Ridge, an approximately 17×11 km wide ring-shaped feature, probably fed by fluids escaping from the subsurface through fractures generated by intense halokinesis (Schattner et al. 2018; Maly et al. 2019). Though acoustic data suggest the presence of gas chimneys and recent to sub-recent seepage activity (likely methane), this has not yet been confirmed by in-situ geochemistry analyses and description of chemosynthetic fauna. These geological features in the Santos Basin harbor poorly known biodiversity, likely supported by chemosynthesis. They are considered Vulnerable Marine Ecosystems because of their low recovery potential when disturbed (Maly et al., 2019). Thus, understanding their biodiversity and geochemistry is required to formulate and implement future conservation management strategies.

This Special Issue reports on multidisciplinary studies that aim to unveil the biodiversity, geology, and geochemistry of the Santos Basin's pelagic and benthic ecosystems associated with the geological features of pockmarks and carbonate mounds. These studies had the financial support of the R&D project Biology and Geochemistry of Oil and Gas Seepages, SW Atlantic (BIOIL), supported by Shell Brasil and the Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP).

The Special Issue comprises nine articles, of which eight originally address issues of chemistry, geology, and biodiversity along the Santos Basin slope and one relates to a method description focusing on detailing the oceanographic cruise procedures performed to develop the BIOIL project. The article Seep Hunting in the Santos Basin, Southwest Atlantic: Sampling Strategy and Employed Methods of the Multidisciplinary Cruise BIOIL 1, authored by Sumida and collaborators, covered this sampling procedures description and reported the methods to seek, map, and collect geological, chemical, and biological data from different deep-sea habitats in the Santos Basin continental slope. The authors detailed methods for the characterization of geomorphological features and the steps to characterize free-living prokaryotes, determine the chemosynthetic rates and heterotrophic microbial production, and study the fauna and their ecological and evolutionary links within and across ocean basins. The results from the cruise were presented separately in articles that comprise this Special Issue.

Trevisani and collaborators authored Chemical Characterization of Deep-Sea Corals from the Continental Slope of Santos Basin (southeastern Brazilian upper margin), which characterized the chemistry of deep-sea scleractinian coral skeletons collected in carbonate mounds and pockmark areas. The study revealed that the chemical composition in pockmark areas indicated an affinity to terrigenous and particulate materials input, with the region having more nutrients and anthropogenic material than other deep-sea regions. They suggest that the carbonate mounds can act as barriers for metals from land flows. The authors mention that they first assessed the potential of coral species for chemical characterization and the first inventory of stable metals and isotopes in the Southwest Atlantic.

Lourenço and collaborators also performed chemical characterization, focusing on measurements of organic matter in sediments associated with the pockmark area. They authored the article Characterization of the Organic Matter in Pockmark Areas of the Southwestern Atlantic Upper Slope, in which they measured hydrocarbons, sterols, long-chain alcohols, stable isotopes of carbon and nitrogen, total organic carbon, and total nitrogen. They found that all organic compound concentrations were low compared to active pockmarks in other oceans. They proposed three possibilities for this: that primary productivity might be the main source of organic matter in the sediment, not hydrocarbon-rich fluid; that a high abundance of methanotrophic organisms may promote the degradation and oxidation of hydrocarbons; and that these sites are inactive or have not been active in the recent past.

Santos and collaborators studied the geological processes involved in sedimentation over the Alpha Crucis Carbonate Ridge. They authored Sedimentation in the Adjacencies of a Southwestern Atlantic Giant Carbonate Ridge, in which they described the first multiproxy approach to investigate sediment covering the Alpha Crucis Carbonate Ridge and its adjacencies. The authors revealed differences in the radiocarbon aging and grain size data according to distinct regions of the mounds. For example, the top of the mound had a prevalence of sandy fractions, whereas muddy sediments dominated the adjacent areas. The proxies indicated biogenic sedimentation in the area and two primary terrigenous sources. The authors highlight that this is the first study to integrate grain size and geochemical characterization of the Alpha Crucis Carbonate Ridge.

Nakamura and collaborators authored Methane-related Community of a Carbonate-enriched Pockmark, Brazilian Southeastern Continental Slope, which examined the ecology of a methane-related microbial community in an inactive carbonate-enriched pockmark. After sediment core incubation with enriched CH_4 at local temperature (5°C), the authors reported microbial taxa found previously in marine bottom waters, carbonate crusts, active cold-seeps, and inactive pockmarks. These were related to aerobic methanotrophy, methylotrophy, aerobic and anaerobic non-methane hydrocarbon degradation, and fermentation. The authors highlight that this is the first survey of key microbial groups related to methane metabolism of a Brazilian deep-sea pockmark.

Bendia and collaborators described the archaeal diversity in seafloor and subseafloor carbonate-rich sediment. They authored First Description of Archaeal Communities in Carbonate-rich Seafloor and Subseafloor Sediments from the Southwestern Atlantic Slope, in which they revealed a high abundance of Nitrososphaeria in surface sediment. By contrast, they found several uncultivated anaerobic and poorly known Archaea in the subsurface, which comprised representatives of all supergroups (Asgard, TACK, DPANN, and Euryarchaeota). The authors argued that these Archaea are known to harbor diverse metabolic capabilities, including autotrophic and heterotrophic pathways such as acetogenesis, methylotrophy, and degradation of labile and recalcitrant organic compounds. They mentioned that this is the first description of archaeal communities in carbonate-rich sediment from the Southwest Atlantic, providing important new biodiversity knowledge of this vulnerable marine ecosystem.

Passos and collaborators authored Contribution of Chemoautotrophy and Heterotrophy to the Microbial Carbon Cycle in the Southwestern Atlantic Ocean, which revealed the dark carbon fixation (DCF) rates and heterotrophic microbial production (HMP) in pelagic and benthic ecosystems of the Santos Basin, where the authors found that DCF rates are relatively high, with sediment harboring higher rates than the water column. They suggest future studies to elucidate the environmental drivers of chemosynthesis in the Santos Basin, to be investigated. Chemosynthesis is an important ecological process of primary productivity that is crucial for understanding the carbon balance of the ocean.

Carrerette and collaborators investigated the macrofaunal composition and structure associated with deep-sea coral habitats and pockmark areas along the upper continental slope of the Santos Basin. They authored Macrobenthic Assemblages across Deep-sea Pockmarks and Carbonate Mounds at Santos Basin, SW Atlantic, where they describe finding a mosaic of benthic habitats and an association between macrobenthic fauna and geomorphology of the area, as well as with environmental variables such as substrate composition and water flux. They argued the importance of providing baseline information of macrobenthic fauna for future research, monitoring activities, and conservation strategies.

Bergamo and collaborators authored ABYSSAL Database: an Integrated WebGIS Platform for Deep-sea Information from the South Atlantic. They constructed the first online geodatabase of deep-sea information for the South Atlantic, encompassing biological, microbiological, geological, chemical, and physical data in a multidisciplinary repository. They call attention to the accessibility of the database by other researchers and explain how it will help disseminate deep-sea knowledge of the South Atlantic.

The collection of studies in the Special Issue of Biology and Geochemistry of Seabed Pockmark and Carbonate Mound Habitats on the Continental Slope of Santos Basin, Southwest Atlantic shows the importance of a multidisciplinary approach to oceanography studies, in order to better understand the functioning of these vulnerable marine ecosystems, which are in urgent need of viable conservation and effective management solutions.

AUTHOR CONTRIBUTIONS

A.G.B.; O.C.: Investigation; Writing – original draft; Writing – review & editing.

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