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Review

The Rio Grande Rise: Current Knowledge and Future Frontiers for Deep-Sea Science, Mineral Resources and Governance

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Abstract

The Rio Grande Rise (RGR) is the largest oceanic plateau in the South Atlantic and represents a key natural laboratory for understanding oceanic plateau formation, deep-sea circulation, ecosystem functioning, and ferromanganese crust development. This study presents a critical synthesis of current scientific knowledge on the RGR, integrating geological, geophysical, oceanographic, biological, and geochemical evidence published over the last two decades. Geophysical data reveal a complex tectono-magmatic evolution involving Late Cretaceous plume-related volcanism, crustal thickening, rifting, and subsequent subsidence. The structural framework of the plateau is dominated by the Cruzeiro do Sul Rift, which plays a central role in controlling sedimentation, magmatism, and seawater circulation. Oceanographic studies demonstrate that the interaction between the southern branch of the South Equatorial Current and the complex topography of the RGR generates intense internal tides and bottom currents, strongly influencing sediment transport and benthic habitats. Biological investigations indicate that the RGR hosts diverse deep-sea communities, including sponge grounds, cold-water corals, and associated fauna, whose distribution is tightly linked to geomorphology and hydrodynamics. Ferromanganese crusts occurring on the plateau preserve valuable geochemical records of oceanographic and redox conditions, although their spatial distribution, thickness, and metal budgets remain incompletely constrained. Despite major advances, significant knowledge gaps persist regarding crustal structure, sedimentary evolution, ecosystem functioning, and mineral formation processes. This review highlights these uncertainties and outlines research priorities necessary to improve understanding of oceanic plateaus and deep-sea systems in the South Atlantic.

Keywords: Rio Grande Rise; deep-sea mining; ferromanganese crusts; ocean governance; South Atlantic; critical minerals; biodiversity conservation; continental shelf

1. Introduction

The Rio Grande Rise (RGR) is the largest oceanic plateau in the South Atlantic and represents a unique natural laboratory for scientific investigation, environmental conservation, and the assessment of strategic mineral resources. Located between 28° and 34° S, the RGR stands out for its geological complexity, ecological richness, and geopolitical relevance (Figure 1) [1].

Scientific interest in the region dates to the pioneering international expeditions in the 1970s and 1980s, most notably the Deep-Sea Drilling Project (DSDP) Leg 72, which drilled Site 516 and revealed a nearly complete sedimentary sequence overlying Cretaceous-aged basalts [2–4]. These findings inaugurated a longstanding debate on the crustal nature of the RGR, whether oceanic or continental, and laid the foundation for subsequent tectono-magmatic and paleoceanographic models of the South Atlantic [5–7].

Since then, the RGR has attracted increasing attention from geoscientists, oceanographers, biologists, and policymakers. Research has revealed a complex tectono-magmatic history [8,9], a largely unexplored deep-sea biodiversity [10–13], and the occurrence of metal-rich ferromanganese crusts with global relevance for critical mineral supply [11,14–18]. At the same time, significant uncertainties persist regarding the governance and sustainability of potential deep-sea mining activities [1,19–21].

These advances, supported by new geological and geophysical datasets generated by international research initiatives in the South Atlantic, including surveys conducted within the framework of the EMERGE (Multidisciplinary Study of Emerging Strategic Minerals and Mining Risk Assessment in the Rio Grande Rise) project, have substantially expanded the available information on the region. This progress makes it necessary to integrate and critically assess the existing data to clarify current interpretations, identify remaining uncertainties, and provide a coherent scientific framework for understanding deep-sea geological processes, ocean circulation, and associated biogeochemical cycles at the Rio Grande Rise.

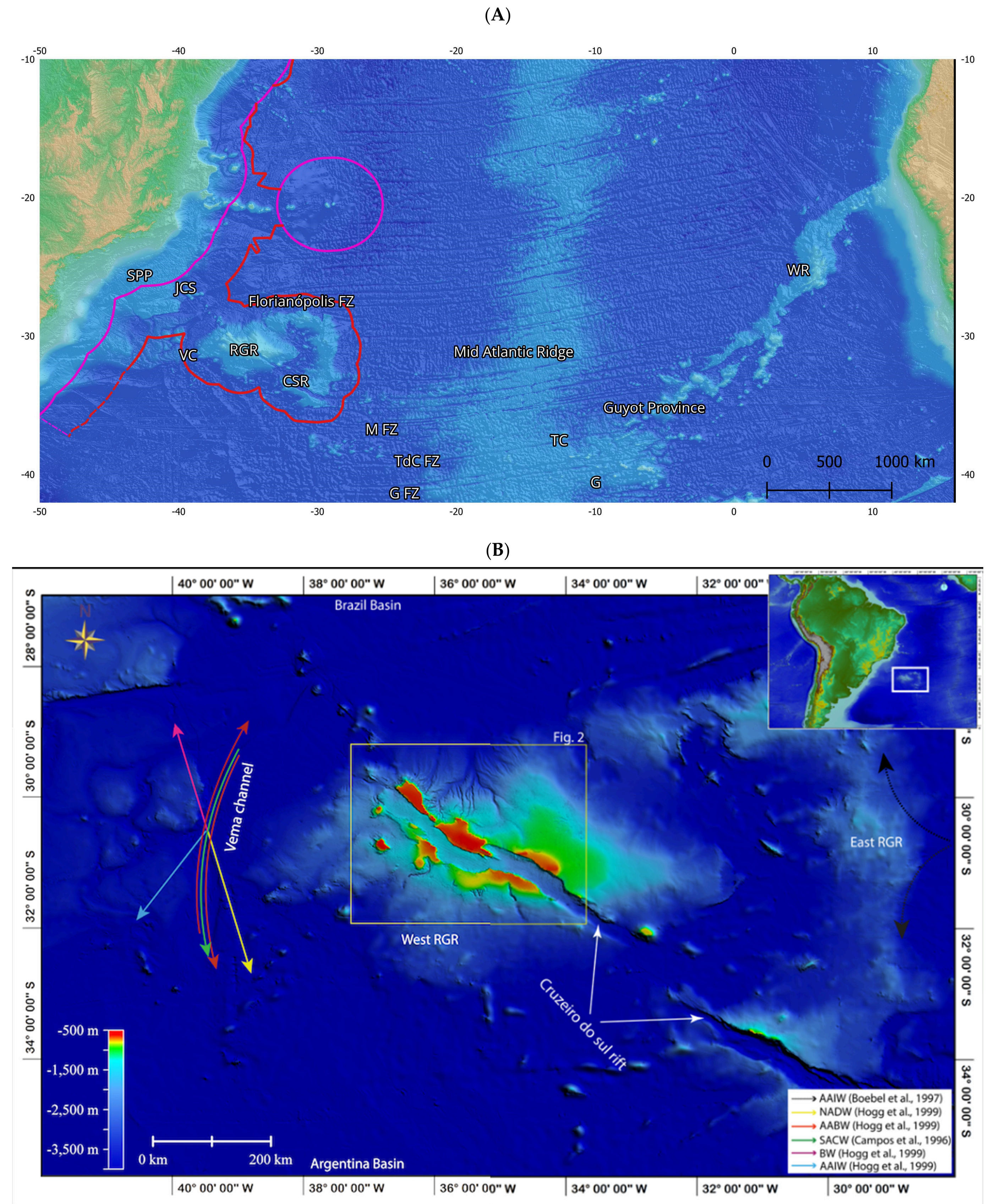

Figure 1. Regional setting and bathymetry of the Rio Grande Rise. (**A**)—Regional setting of the Rio Grande Rise in the South Atlantic, highlighting its position relative to the Brazilian continental margin, the Walvis Ridge, and major bathymetric domains. The Rio Grande Rise constitutes the most

extensive oceanic plateau in the South Atlantic and is a key target for integrated geological, biological, and mineral studies. JCS = Jean Charcot Seamounts; SPP = São Paulo plateau; TC = Tristan da Cunha; G = Gough; CSR = Cruzeiro do Sul Rift; MFZ = Meteor Fracture Zone; VC = Vema Channel; WR= Walvis Ridge. The purple line indicates the limit of the Exclusive Economic Zone (EEZ), and the red line indicates the limit of the continental shelf beyond 200 nautical miles claimed by Brazil but not yet approved. (**B**)—Shaded bathymetric map [22] around Rio Grande Rise showing the major geological features including Cruzeiro do Sul Rift, Vema Channel, Brazil basin, and Argentina basin. White rectangle highlights the study area displayed in further figures. The colored arrows show the main currents in the region [23–25].

This review provides a critical synthesis of the current scientific knowledge on the Rio Grande Rise, focusing on its geological and geophysical evolution, the influence of physical oceanographic processes on sedimentary and ecological patterns, the structure and functioning of deep-sea ecosystems, and the formation and geochemical characteristics of ferromanganese crusts. By integrating existing data, the study identifies major knowledge gaps and outlines key research directions relevant to future investigations of oceanic features and deep-sea environments and support informed decisions on conservation, mineral resources, and ocean governance.

2. Methodology

Methodological Approach

This study adopts a structured narrative review approach aimed at synthesizing multidisciplinary knowledge on the Rio Grande Rise. The review is based primarily on the peer-reviewed scientific literature, complemented by key expedition reports and publicly available datasets that have contributed substantially to the understanding of the region.

Given the heterogeneous and multidisciplinary nature of the available data and the fact that the research is conducted on the RGR remain spatially restricted and still is of an exploratory character, with no full environmental assessment having been presented, a narrative synthesis was considered more appropriate than a quantitative meta-analysis, as it allows the integration of geological, geophysical, biological, and oceanographic evidence within a coherent interpretative framework. Bibliographic searches were conducted using the Web of Science, Scopus, and Google Scholar databases, employing combinations of keywords such as “Rio Grande Rise”, “South Atlantic oceanic plateau”, “ferromanganese crusts”, “deep-sea biodiversity”, “oceanic plateaus”, and “South Atlantic tectonics”.

Priority was given to peer-reviewed publications published between 2000 and 2025, while earlier landmark studies, including those from DSDP Leg 72, were included to provide historical and geological context. Technical reports from recognized institutions and international research programs were also considered where relevant.

The selected literature was organized into four thematic domains: geological and geophysical evolution, physical oceanography and sedimentary dynamics, biodiversity and ecosystem structure, and ferromanganese crusts and geochemical processes. Within each domain, emphasis was placed on distinguishing observational evidence from interpretative models and on identifying unresolved questions, while avoiding extrapolations not supported by published data.

Despite significant advances in the understanding of the Rio Grande Rise, large portions of the plateau remain unsampled, and many interpretations are still based on sparse geophysical coverage or localized observations. As a result, spatial extrapolations involve inherent uncertainties, particularly with respect to crustal structure, sediment distribution, and the continuity of ferromanganese crusts. Consequently, several interpretations presented in this review should be regarded as provisional and subject to revision as new data becomes available. These limitations are explicitly acknowledged throughout the manuscript, and they underscore the need for additional high-resolution geophysical surveys, expanded sampling efforts, and integrated multidisciplinary investigations to refine current models and interpretations.

3. Scientific Results

3.1. Geology and Geophysics

The RGR is a series of large oceanic plateaus in the South Atlantic, located approximately 1000 km offshore southeastern Brazil, extending for nearly 1500 km and rising to ~3800 m above the surrounding abyssal plains (Figure 1). Together with the Walvis Ridge on the African margin, the RGR forms a prominent volcanic system traditionally linked to the Tristan–Gough mantle plume and the early phases of Gondwana breakup and South Atlantic opening during the Late Cretaceous [26,27]. The Tristan–Gough hotspot was active since 132 Ma (C34) and is related to Paraná–Etendeka continental flood basalts [28,29].

The Western Rio Grande Rise (WRGR) constitutes a distinctive geomorphological feature characterized by a broad plateau whose summit locally shoals to ~600 m water depth. The plateau reaches maximum dimensions of approximately 420 km (E–W) by 240 km (N–S). It is transected by the Cruzeiro do Sul Rift (CSR), oriented roughly N50W and exhibiting an average width of ~24 km. Recent geological surveys conducted by the Geological Survey of Brazil and the Oceanographic Institute of the University of São Paulo have significantly improved the understanding of the surface geology of the RGR [30,31]. Large portions of the plateau are covered by pelagic carbonates, red clays, and extensive ferromanganese (Fe–Mn) crusts, while volcanic rocks are locally exposed along the flanks and margins of the CSR [8,28,31–38]. This magmatism was closely associated with the formation of the Paraná–Etendeka Magmatic Province (LIP), constituting a key geological archive for understanding both the tectonic evolution and the paleoceanographic changes in the South Atlantic [5,39,40].

Flexural modeling based on gravity data suggests that the crust beneath the RGR reaches a thickness of up to ~30 km [41], while gravimetric inversions place the Moho at approximately 28 km [42] (Figure 2). These anomalous values have fueled the longstanding debate regarding the crustal nature of the RGR, with some authors proposing the presence of a microplate or a component of continental affinity beneath the plateau [43].

Recent integrated investigations along the Cruzeiro do Sul Rift have provided key insights into the tectonic framework of the WRGR. High-resolution multibeam bathymetry, side-scan sonar, magnetic surveys, and targeted dredging revealed basaltic rocks associated with Fe–Mn crusts, normal faulting, and well-defined magnetic lineaments [9]. These observations support the interpretation of an actively evolving rift system and underscore the tectonic importance of the CSR in the overall evolution of the RGR (Figure 3).

A significant advance in the reconstruction of the geological history of the RGR derives from the identification of extensive deposits of red clays formed by the chemical weathering of alkaline volcanic rocks under warm, humid conditions probably during the Eocene [38]. These deposits predate thermal subsidence and subsequent deepening of the plateau and provide robust evidence that parts of the WRGR were emergent or very shallow-water environments in the geological past.

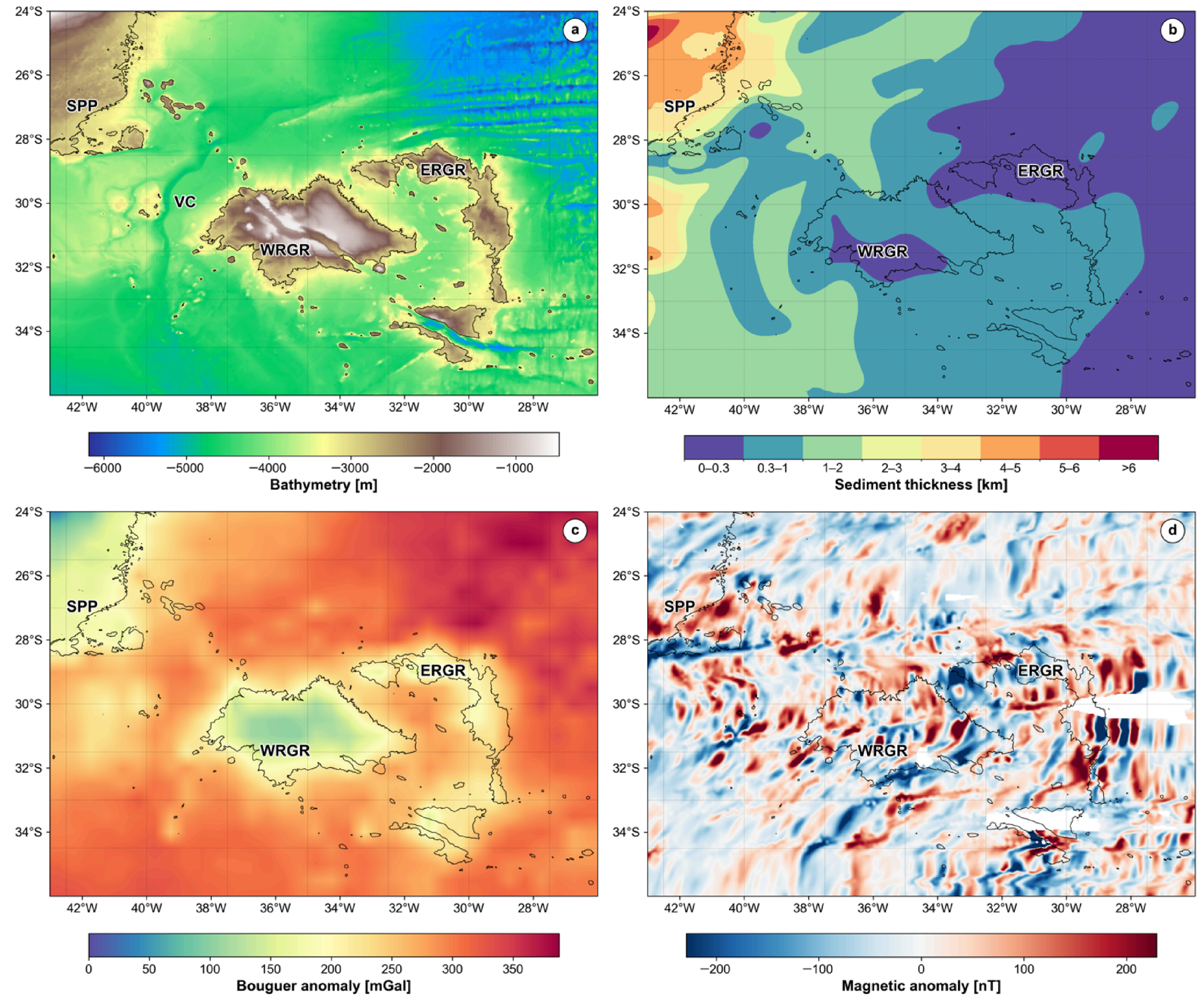

Figure 2. Regional geophysical maps of the South Atlantic margin highlighting the Rio Grande Rise region. (**a**) Bathymetry from the GEBCO 2025 grid. (**b**) Total sediment thickness, version 2 [44]. (**c**) Bouguer gravity anomaly derived from the Earth Gravitational Model EGM2008 [45]. (**d**) Magnetic anomaly from the EMAG2 global magnetic anomaly grid [46]. The São Paulo Plateau (SPP), West Rio Grande Rise (WRGR), East Rio Grande Rise (ERGR), and the Vema Channel (VC) are indicated. A −3000 m bathymetric contour is shown in all panels.

Several types of depressions have been mapped across the summit and flanks of the plateau, including prominent features interpreted as sinkholes, pockmarks, and mega-pockmarks [31,47]. Despite recent progress, uncertainties remain regarding the origin, timing, and evolution of these features, which may be linked to fluid migration, faulting, and diagenetic processes within the sedimentary cover.

Large areas of the WRGR summit are mantled by pelagic carbonates with thicknesses exceeding 40 m, as recovered in piston cores [37,48]. Strontium isotope ratios indicate that carbonate deposition began around ~7 Ma. These carbonates are often indurated and covered by Fe–Mn crusts [11,14,15,17]. Alternatively, thin layers of loose carbonates display bedforms and sedimentary structures shaped by bottom currents and tidal flows [34]. Fe–Mn crusts from the WRGR record two distinct growth generations. The older generation began forming between ~48 and 55 Ma and was later extensively modified by post-depositional alteration under suboxic conditions, resulting in phosphatization during the Miocene (ca. 20–6.8 Ma) [15,49]. Dredging operations have recovered pebbles of gabbro, granite, and pegmatite with ages ranging from ~400 to 2200 Ma, interpreted as potential evidence for a continental component in the basement of the RGR [50]. This hypothesis remains controversial and requires further verification through systematic geophysical surveys and deep drilling.

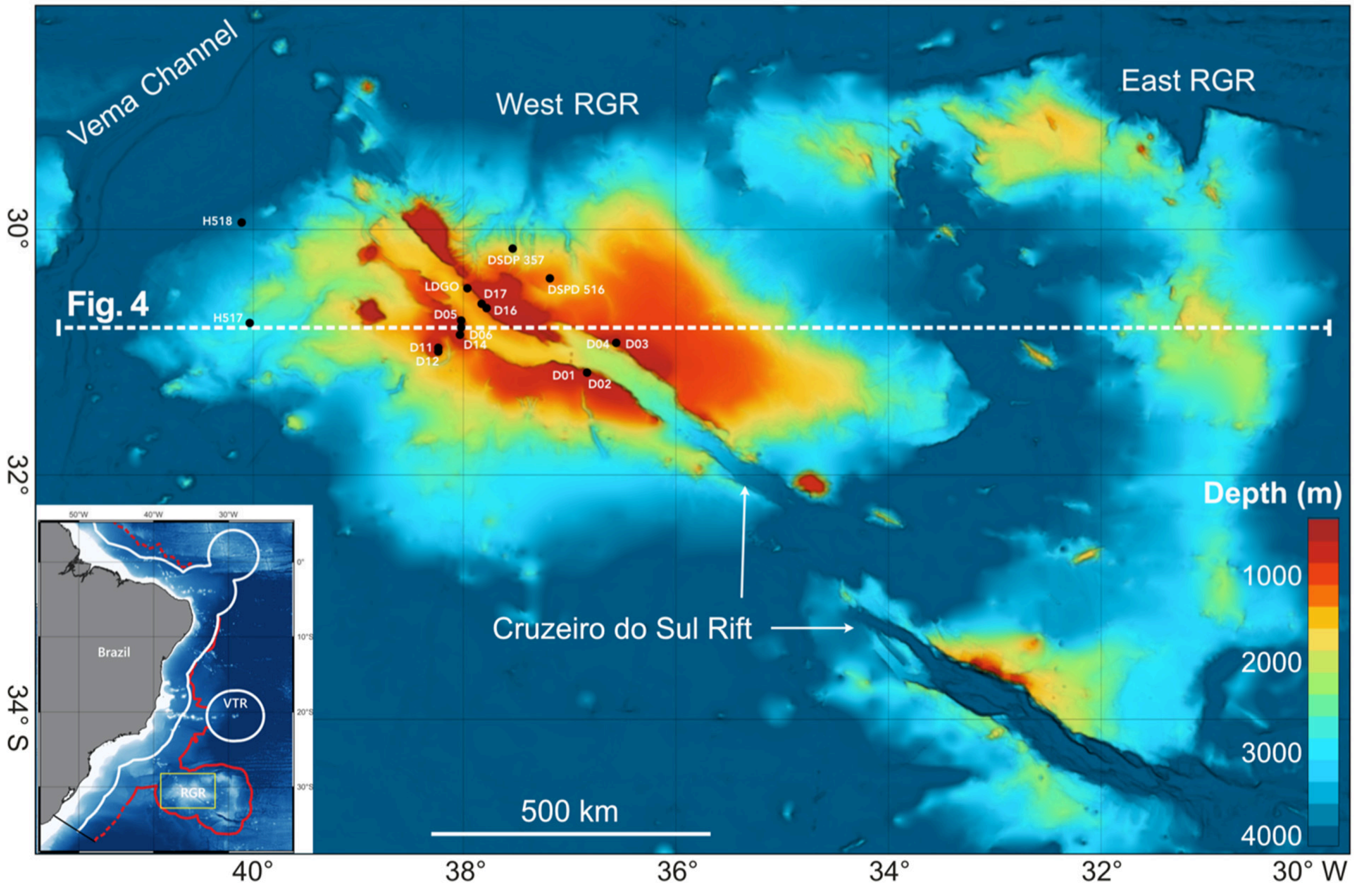

Figure 3. High-resolution bathymetry and tectonic framework of the Western Rio Grande Rise, showing the Cruzeiro do Sul Rift, major structural lineaments, and key sampling sites, including DSDP Hole 516F. The white dashed line refers to Figure 4. The complex morphology reflects the tectono-magmatic evolution of the Rise. In the small map, the white line indicates the limit of the Exclusive Economic Zone (EEZ), and the red line indicates the limit of the continental shelf beyond 200 nautical miles claimed by Brazil but not yet approved.

Ferromanganese crusts on the WRGR have also been the subject of detailed mineralogical, geochemical, and magnetic studies [51–53]. Comparisons between phosphatized and non-phosphatized crusts reveal significant differences in chemical composition, mineral phases, and magnetic properties, reflecting variations in redox conditions, phosphate and carbonate cycling, and mineral growth rates. These characteristics provide valuable insights into past oceanographic conditions and the economic potential of the deposits [17,53].

Subsurface knowledge of the WRGR is still primarily constrained by a single deep borehole, DSDP Hole 516F, drilled through ~1270 m of sediment below ~1313 m of water column and reaching the basaltic basement at ~2600 m. The transitional basalts are enriched tholeiitic rocks (E-MORB-type) dated at ~82–88 Ma, consistent with regional magnetic anomalies. The overlying sedimentary succession, dominated by pelagic carbonates, represents one of the most complete records of the Cretaceous to Cenozoic in the South Atlantic, including a notable increase in pelagic sedimentation during the middle Eocene and the presence of volcanogenic turbidites dated at ~47 Ma [2,37,39,54]. These volcanic features on the WRGR present some analogies with the Eocene magmatic episode recognized in the Cabo Frio region, between the norther Santos and southern Campos basins [55–57].

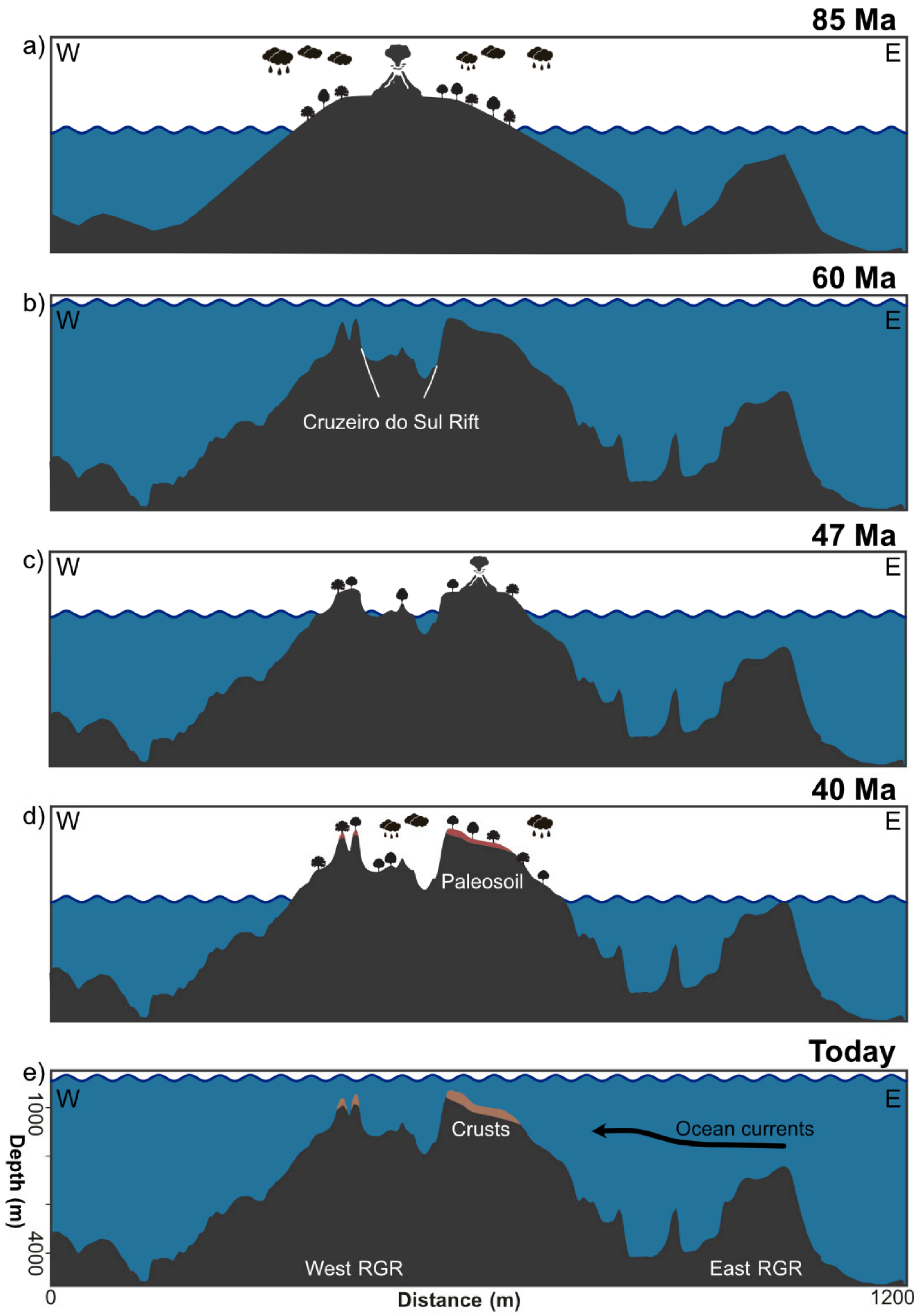

Figure 4. Conceptual model for the tectono-magmatic and sedimentary evolution of the Rio Grande Rise from the Cretaceous to the present, integrating the formation of hotspot magmatism, onset of tectonic rifting, partial emersion during the Eocene, and subsequent subsidence: (**a**) volcanic outpouring of oceanic crust; (**b**) extensional forces caused intense rifting and formation of the Cruzeiro do Sul Rift; (**c**) the uplift of significant seamounts that were subaerially exposed, and volcanogenic material; (**d**) alteration of volcanic rocks and formation of tropical paleosoil; (**e**) subsidence and formation polymetallic crusts.

High-resolution mapping has revealed the complex morphology of the RGR, including the WRGR plateau, the Cruzeiro do Sul Rift, the Florianópolis Fracture Zone, and the Jean

Charcot Seamounts. This mapping highlights strong contrasts in substrate type, Fe–Mn crusts, bioclastic sands, and fine sediments [31].

Despite significant advances, major knowledge gaps persist. The DSDP 516F borehole remains the only subsurface reference, and the coverage of seismic and magnetic data is insufficient to discriminate between oceanic and continental crust conclusively [2]. Marine magnetic coverage is particularly sparse, and existing global magnetic anomaly maps are dominated by low-frequency modeled fields, limiting their resolving power for the RGR [50].

The RGR lies within a domain of high magnetic and gravity anomalies, bounded by the Florianópolis Fracture Zone to the north and the Meteor Fracture Zone (35.5S) to the south. This geophysical pattern bears some similarities to that of Iceland, albeit within a distinct geotectonic and chronological context. The C34 Chron (~84 Ma) is associated with a pronounced negative magnetic anomaly crossing the RGR. In contrast, the characteristic stripped ("zebra") pattern of seafloor spreading anomalies is weakly developed and mainly observed east of C34.

Reprocessing of legacy seismic lines and correlation with existing borehole data have already enabled preliminary seismic–stratigraphic interpretations and the identification of tectonic and volcanic–sedimentary stages in the evolution of the RGR [58].

In the evolutionary model, five events were identified (Figure 4):

(a) Volcanic outpouring of oceanic crust caused by the Tristan–Gough hotspot, contemporaneous with the Paraná–Etendeka Large Igneous Province, would have given rise to the WRGR (Figure 4a; [28,29]);
(b) Uplift of the central part of the WRGR, extensional forces caused intense rifting and formation of the Cruzeiro do Sul Rift (CSR) extensional pulse which have been active from the Maastrichtian to the middle/upper Eocene, then, covered by pelagic sedimentation occurring over the volcanics of the WRGR and ERGR (Figure 4b; [6,58–60]);
(c) Plate accommodation and oceanic opening movements generated a second intense magmatism phase in the Eocene, which caused the uplift of significant seamounts that were subaerially exposed, while the active grabens were filled with volcanogenic material (Figure 4c; [8,28,35,36,38]);
(d) Mounds were formed within the sedimentary package and erosional truncation, providing evidence that part of the WRGR was exposed above sea level. Subsequently, the WRGR cooled and submerged, with fault analysis suggesting a period of little tectonic activity (Figure 4d; [37,39,48,54,58]);
(e) Formation of a dense system of sub-vertical normal faults (Eocene to Recent), classified as polygonal faults, which may be related to fluid upwelling and the formation of pockmarks (approximately 500 m in diameter); one hypothesis is that gas or hydrothermal groundwater vents occur at the base of the sedimentary package, as revealed by the presence of sub-vertical zones of seismic signal loss and thermal anomalies (Figure 4e; [9,31]).

There are similarities between the seismic facies of the stratigraphic units interpreted from the seismic lines of the western portion of the RGR and those from the Brazilian continental margin; other tectono-depositional similarities occur between the Brazilian continental margin and the RGR, such as the presence of Eocene volcanic seamounts along the sedimentary package in both regions.

Samples of alkaline volcanic rocks collected in recent dredging operations were subjected to petrographic analysis, elemental geochemistry, U–Pb zircon dating and Sr–Nd–Pb isotopic geochemistry [8]. Petrographic, mineralogical, and isotopic data indicate that these alkaline magmas evolved within a complex transcrustal magmatic system, involving multiple events of magma recharge and fractional crystallization. The isotopic signatures

(Sr–Nd–Pb) observed are consistent with Tristan-type enriched mantle sources, suggesting a genetic link to other volcanic provinces from the Walvis Ridge and Guyot Province.

The continuity of alkaline magmatism from the WRGR toward the Brazilian margin is suggested by the alignment of the Jean Charcot Seamounts, which remain poorly sampled and represent a priority target for future geological investigations. The presence of clasts of Precambrian crystalline rocks of diverse ages was reported by [9]. Dredging carried out by the Oceanographic Institute of the Universidade de São Paulo in subsequent missions recovered new samples of crystalline rocks and two samples of sedimentary rocks of Paleozoic age (inferred from the age of detrital zircons). Those crystalline and sedimentary rocks found on the plateau summit remain one of the most enigmatic observations. Their rounded morphology, stratigraphic setting, and lack of thermal overprinting argue against an origin as xenoliths transported by Eocene magmatism. In contrast, explanations such as dropstones derived from glacial transport are conflicting with regional ocean circulation patterns. Another option could be that these samples are ballast stones discarded by transcontinental navigations during the slave trade between the 14th and 19th centuries. In this context, estimating the age of clast deposition based on the thickness of Fe–Mn oxide coatings has been proposed as a promising approach.

The confirmation or dismissal of a continental component within the basement of the WRGR remains a question of significant scientific and strategic relevance that can be resolved only with a new deep stratigraphic borehole.

3.2. Physical Oceanography of the Rio Grande Rise

Research on the physical oceanography of the Western Rio Grande Rise (WRGR) has focused on the interaction between large-scale circulation, internal tides, and interactions with complex topography, which together generate a distinctive hydrodynamic regime in the southwestern Atlantic (Figure 5). Regional circulation is primarily controlled by the southern branch of the South Equatorial Current (SEC) at approximately 30°S (sSEC30) [61], which extends from the surface to depths of about 2500 m and exhibits a core between roughly 287 and 570 m water depth (Figure 5).

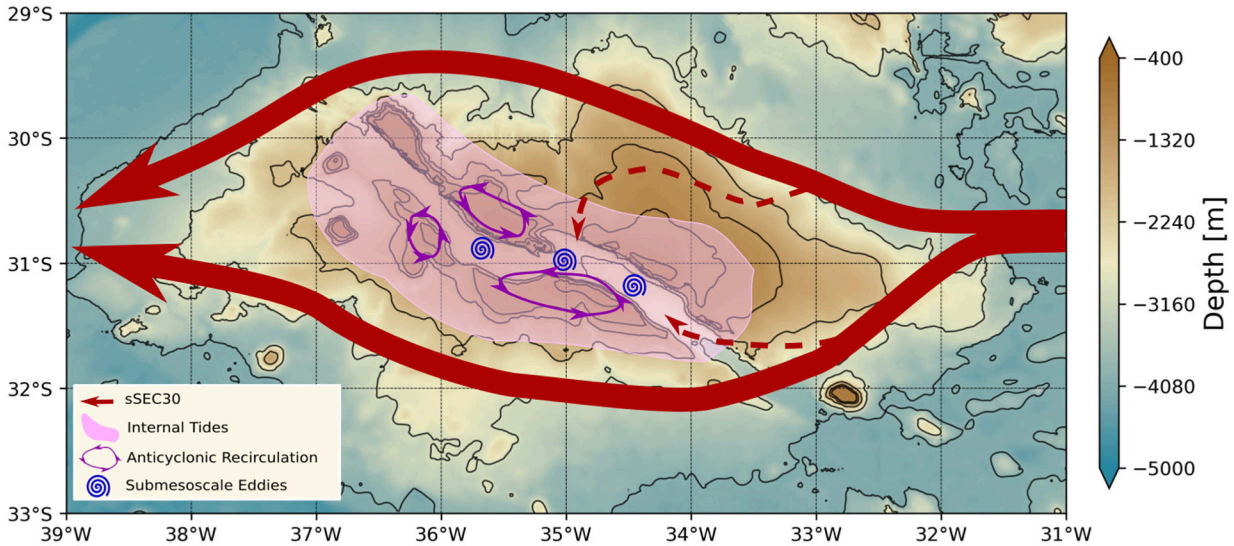

Figure 5. Schematic representation of the main oceanographic processes affecting the Western Rio Grande Rise, including the interaction between the southern branch of the South Equatorial Current (sSEC30), internal tide generation on the Cruzeiro do Sul Rift slopes, and topographic control on circulation and sediment dynamics (modified from [62]). Solid red arrows represent the main branches of the sSEC30, while dashed red arrows indicate secondary branches that can enter the CSR.

Modeling studies indicate that the sSEC30 does not display a well-defined annual transport cycle [61]. When this current impinges on the WRGR, it bifurcates, flowing around the Rise and strongly modulating local circulation patterns [61,62]. This interaction between mean flow and topography plays a central role in shaping the hydrodynamic environment of the plateau.

At the regional scale, the WRGR has been identified as one of the main hotspots of internal tide generation in the southwestern Atlantic [62]. The semidiurnal M2 tidal constituent dominates hydrodynamic variability, with current amplitudes reaching ~0.3 m·s^{-1}. The baroclinic (internal tide) component is intensified near the seafloor. Internal tides are generated mainly along the steep flanks of the Cruzeiro do Sul Rift, where barotropic tidal energy is converted into internal tidal beams that propagate both upward and downward (Figure 6; [62]).

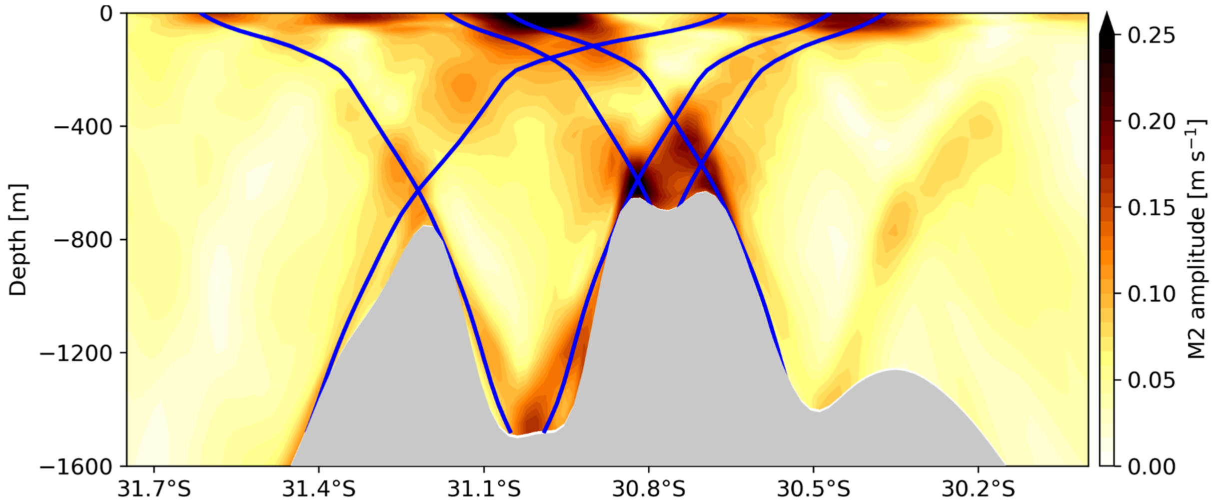

Figure 6. M2 tidal velocity amplitude with the M2 tidal beams (characteristic paths, blue lines). This transect is located along the 35.28○W meridian at the WRGR. From [62].

The interaction between internal tides, the mean flow associated with the sSEC30, and the abrupt topography of the WRGR produces a persistent anticyclonic circulation around the main topographic highs. This circulation is driven by tidal rectification and the Taylor effect, and is primarily confined to depths between ~500 and 1500 m. In addition, tidal rectification generates an intensified near-bottom mean flow, with velocities reaching ~0.2 m·s^{-1}. Detailed analyses of the upper ~1600 m of the water column further elucidate the tight coupling between hydrodynamics, topography, and sedimentary processes on the WRGR.

Overall, the WRGR constitutes an oceanographic system in which barotropic and baroclinic tides, submesoscale eddies, the sSEC30, and sedimentary processes interact strongly with complex topography, generating intricate patterns of circulation and mass transport. Future research priorities include the detailed quantification of interactions between the sSEC30 and the major topographic features of the WRGR, as well as the characterization of submesoscale processes, such as the formation, evolution, and decay of eddies. Improved understanding of sediment transport, resuspension, and dispersal is also essential to assess how bottom currents shape sedimentary architecture and influence the exposure, erosion, and burial of ferromanganese crusts, with direct implications for benthic ecosystems and biogeochemical cycles in the southwestern Atlantic.

3.3. Biodiversity and Ecosystem Dynamics

The euphotic zone (0–200 m) over the RGR is occupied by the warm and saline Tropical Water of the South Atlantic Subtropical Gyre [63], characterized by low nutrient concentrations and, hence, low primary productivity [64,65]. The injection of new nutrients from deeper layers into the phytoplankton community is restricted due to permanent stratification and physical stability of the upper water column. Pico- and nanophytoplankton initiate the energy and matter flux of the pelagic ecosystem through predominantly regenerated production (sensu [66]), especially by the cyanobacteria *Prochlorococcus* and *Synechococcus* [64], atmospheric nitrogen fixation [67], and transfer of dissolved organic matter to higher trophic levels via biological pump. In addition, most of the particulate organic matter produced by the phytoplankton in the euphotic zone is remineralized in the microbial loop by heterotrophic prokaryotes [68,69], particularly by the heterotrophic bacteria *Oceanospirillales* (Gammaproteobacteria) and *SAR11* (Alphaproteobacteria) [64]. A small fraction of the particulate organic carbon from primary producers is exported to deeper waters [70], as the primary source of energy in and below the meso- and bathypelagic zones. Nevertheless, the rise erases the ocean floor from ca. 4000 m to depths shallower than 1000 m and the steep bathymetric gradient surrounding the rise associated with internal waves promote the uplift of adjacent isopycnals favoring topographic upwelling, which is typical of seamounts and plateaus [71,72]. This may bring new nutrients to the lower half of the euphotic zone enhancing biological activity and deep-sea particle export [73]. Dissolved metals in the water column adsorb onto particulate organic material [74] and are also taken up by microorganisms [75], which, when exported vertically, represents an important step in the formation of marine mineral resources [74,76].

The RGR has garnered significant interest due to the discovery of strategic ferromanganese deposits. Research in the region is critical not only for elucidating its unique ecosystems but also for informing responsible ocean stewardship. Recent research has revealed that these ferromanganese crusts of the RGR function not only as mineral resources but also as complex microhabitats [10–12]. Marine microbiology studies demonstrate that these crusts host specialized microbial communities playing key roles in biogeochemical cycles, including ammonia-oxidizing archaea (e.g., *Candidatus Nitrosopumilus*), nitrite-oxidizing bacteria (*Nitrospirae*), methanotrophs, and metal-reducing microorganisms, such as *Betaproteobacteriales* and *Pseudomonadales.* These studies have detected a high number of unclassified and unknown prokaryotic DNA sequences [10,11,13], indicating a large proportion of unknown microbial species and hidden functions in the RGR seawater, sediment, and crusts. Furthermore, scientists have shown that microbial diversity at the Rio Grande Rise (RGR) clusters into distinct groups according to microhabitat—specifically sediments, crusts, and geochemistry [11]. This highlights a strong coupling between microbial processes and crust formation compared with Pacific and other places in Atlantic Oceans [10,11,13].

The RGR is a large oceanic plateau that stands out from the surrounding abyssal plains like an oasis in the desert. Shallower sectors of the Rise, typically between ~600 and 1000 m, host a benthic fauna comparable to that of seamounts, with increased concentrations of organisms along escarpments and steep slopes where stronger currents enhance food supply (Figure 7). Suspension feeders, such as sponges and cold-water corals, are particularly abundant at these settings [77,78].

One of the most striking biological features of the RGR is the presence of extensive gardens formed by the glass sponge *Sarostegia oculata*, often associated with the zoantharian *Thoracactis topsenti* [79,80]. Together, these organisms form branching, coral-like structures that create complex three-dimensional habitats supporting a wide range of invertebrates and fishes. In contrast, broad plateau areas typically host sparser fauna, and sediment accumulation supports infaunal communities. Diverse demersal fishes, including eels, oreos, and other deep-sea taxa inhabit these habitats.

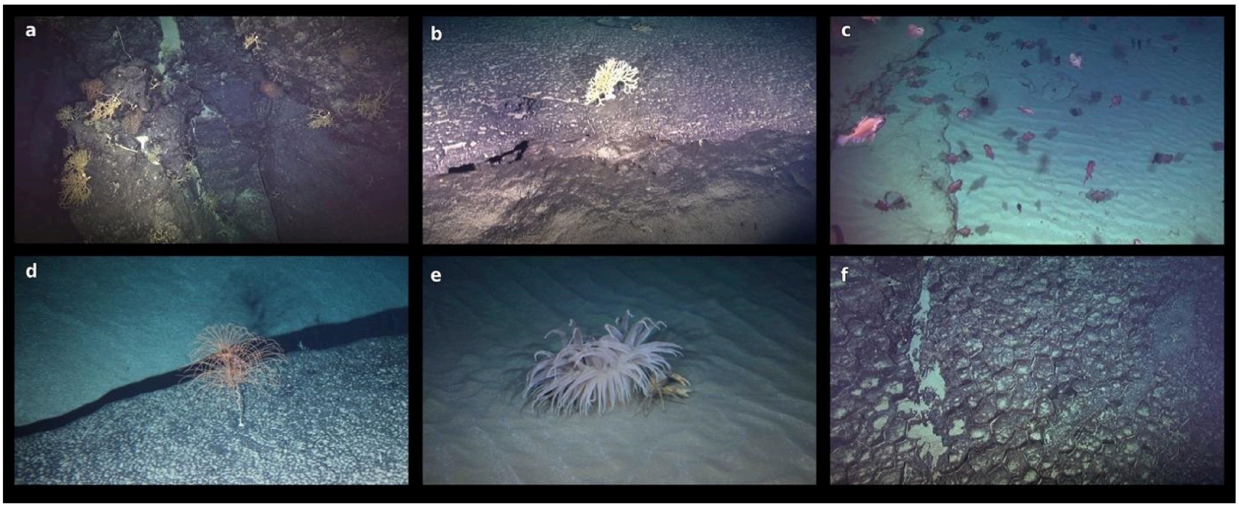

Figure 7. (**a**). Rift wall, populated by suspension-feeders *Sarostegia oculata* and *Iridogorgia* sp. (**b**). A single *S. oculata* on the top of Fe–Mn crust pavement, right on the edge of the rift. (**c**). Shoal of Oreosoma cf. atlanticus found on the plateau of RGR. (**d**). *Iridogorgia* sp. on Fe–Mn crust. (**e**). Chaceon sanctaehelenae under a sea anemone (Actiniaria). (**f**). Columnar basalt formations, indicating the area was above sea level in the past.

High-resolution benthic habitat mapping further reveals a strong geomorphological control on biological distribution demonstrating that benthic faunal assemblages vary systematically with geomorphology and substrate, reinforcing the intrinsic link between geodiversity and biodiversity on the RGR [12,31]. Plateaus, peaks, escarpments, and valleys feature distinct substrates—from ferromanganese crusts and bioclastic sands to fine sediments—each supporting unique faunal assemblages in relation to hydrodynamics. Exposed hard substrates sustain dense communities of sessile fauna like cold-water corals and sponges, while soft sediments harbor diverse infaunal communities.

Long-term monitoring initiated in 1998 and conducted by the Oceanographic Museum of Univali in the State of Santa Catarina, Brazil, has demonstrated the geostrategic and ecological importance of the RGR as a breeding, nursery, and migratory area for several species of commercial and conservation interest [81,82]. Since the 1990s, the RGR has attracted pelagic longline fisheries operating from southern Brazil and Uruguay, as well as distant-water fishing vessels. Systematic monitoring of fishing landings and onboard activities revealed two main areas of fishing concentration: one along the outer continental slope within Brazil's Exclusive Economic Zone, and another over the central oceanic banks of the RGR [83,84].

The long-term program was created to monitor the longline fleet using the American pelagic longline, targeting swordfish (*Xiphias gladius*), tuna (*Thunnus* spp.), and blue shark (*Prionace glauca*) in the RGR area [85]. Between 1999 and 2010, an average of 15.8 hauls per trip and 1117 hooks per haul was recorded. During this period, 12 species from 7 families and 4 orders of Elasmobranchii were recorded, including rare species such as the Antarctic sleeper shark *Somniosus antarcticus* and the cookiecutter shark *Isistius plutodus*. In addition, other 32 species from 14 families and 6 orders of Actinopterygii were also recorded, many new to the region [84]. Furthermore, over one thousand sea turtles were registered at the RGR area, most of them loggerheads (*Caretta caretta*—979 individuals). Leatherback turtles were recorded in smaller numbers (27; *Dermochelys coriacea*), while three hybrids from loggerhead and most likely with hawksbill turtles (*Eretmochelys imbricata*) were also found. All records were made based on incidental capture [86].

Surveys of seabird taxonomic diversity recorded 23 species within the order Procellariiformes [87]. The assemblage included several species considered rare or of limited occurrence in the southwestern Atlantic, notably the southern royal albatross (*Diomedea epomophora*), the northern royal albatross (*Diomedea sanfordi*), the shy albatross (*Thalassarche cauta*), the sooty albatross (*Phoebetria fusca*), the blue petrel (*Halobaena caerulea*), and the white-faced storm petrel (*Pelagodroma marina*). Furthermore, the surveys documented a significant range extension for the region with the first recorded observation of the white-headed petrel (*Pterodroma lessoni*) [87]. Sightings confirmed the presence of multiple cetaceans, including the Bryde's whale (*Balaenoptera edeni*), the sperm whale (*Physeter macrocephalus*), the long-beaked common dolphin (*Delphinus capensis*), the spotted dolphin (*Stenella attenuata*), the southern right whale dolphin (*Lissodelphis peronii*), and the long-finned pilot whale (*Globicephala melas*), as well as an incidental capture of a Risso's dolphin (*Grampus griseus*). Furthermore, indirect evidence suggested the presence of *Orcinus orca* [85].

The research further identified the area as the primary breeding and/or rearing ground for the porbeagle shark (*Lamna nasus*) in the South Atlantic, based on the capture of a high abundance of neonates and small juveniles. Recently, a large number of organisms from diverse zoological groups have been discovered, some of which had not yet been described, including a new species of sea urchin, *Araeosoma* (*Echinothuriidae, Echinoidea*) [88], and a crustacean, *Pasiphaea* (*Pasiphaeidae*, *Pleocyemata*) [89]. Despite these findings, data on the region's most basal vertebrate groups remain critically limited [82].

Despite growing knowledge, major uncertainties remain regarding new micro and macro species, species connectivity, population dynamics, and ecosystem functions and resilience, particularly in relation to local physical process and long-term environmental change. Following future accurate studies, the RGR might be defined as a biodiversity hotspot: "areas featuring exceptional concentrations of endemic species and experiencing exceptional loss of habitat" [90].

3.4. Present-Day Governance

The RGR occupies a central position in contemporary debates on deep-sea governance and the environmental implications of marine mineral extraction [1,12,91]. A new concept for use of the Ocean resource is emerging worldwide: the "Blue Economy" as the sustainable use of ocean and aquatic resources for economic growth, improved livelihoods, and human well-being, while preserving the health of ecosystems. It aims to balance economic development with environmental preservation, encompassing sectors such as fishing, tourism, renewable energy and maritime transport. On one hand, the RGR represents a strategic frontier for Brazil within the framework of the "Blue Amazon" (Amazonia Azul), offering potential access to critical mineral resources of global significance [12,92–94]. On the other hand, its fragile and poorly understood ecosystems demand precaution, interdisciplinary research, and robust institutional frameworks [91,95,96].

These challenges demand urgent responses, but also offer significant opportunities for advancing scientific knowledge and developing technologies linked to both the exploration of strategic mineral resources and the protection of fragile and poorly understood ecosystems [91,97–100]. Deepwater mining, although not yet implemented on a commercial scale, is considered a critical frontier for the energy transition, due to the growing demand for minerals such as cobalt, nickel, and rare earths [91,101–103].

The Geological Survey of Brazil (SGB, once called CPRM (Companhia de Pesquisa de Recursos Minerais)), sponsored by the Brazilian government, signed 52 ferromanganese crust exploration contracts with the International Seabed Authority (ISA) between 2014 and 2018, but subsequently opted to concentrate efforts on the claim for extension of the continental shelf [1,104–106]. Since 2018, the Brazilian claim for the inclusion of the RGR within the Extended Continental Shelf (ECS) is being evaluated by the Commission on the Limits of the Continental Shelf (CLCS), a body of the United Nations Convention on the

Law of the Sea (UNCLOS) [105,107]. This claim to extend Brazilian sovereign rights over the seabed beyond the 200 nautical mile limit, based on scientific evidence, considers that the Rise is a natural extension of its land territory.

While the RGR was previously considered to be situated within areas administered by the ISA as part of the "common heritage of mankind," the Brazil's submission for an ECS under the UNCLOS [1,21,105,107–110] has led to a more complex legal and institutional setting for the region.

First of all, in the international sphere we can observe, for example, that interactions between the ECS and Marine Protected Areas (MPAs) in areas beyond national jurisdiction (ABNJ) illustrate potential conflicts between resources rights and conservation goals [111], even though no MPA currently exists in the RGR. Secondly, the absence of a comprehensive national legal framework governing marine mineral exploration and exploitation remains an important institutional gap [105,108,112,113]. This regulatory situation may limit Brazil's strategic position and constrain long-term planning [105,112,114]. Finally, the interaction between international and national levels deserves particular attention: as ISA continues to develop its Mining Code to regulate activities beyond national jurisdiction, greater alignment between domestic legislation and international standards will be increasingly important [115–117].

4. Discussion

4.1. Governance and Socio-Environmental Impacts

The RGR presents critical governance challenges at the intersection of deep-sea mining, biodiversity conservation, and national and international law [1,91,118]. The region's legal status is in transition, from a contract signed between the ISA and the SGB to a Brazilian claim of an extended continental shelf before the CLCS. This shift introduces legal complexities that must be addressed under both national and international law [105,107,119].

Brazil lacks comprehensive domestic legislation governing marine mineral extraction, creating regulatory uncertainty that hampers strategic planning [105,112,118]. This gap contrasts with the ISA's advancing Mining Code and highlights the urgent need for legal harmonization between national and international standards [47,117,119]. At the same time, interactions among international regimes can create conflicts between the outer limits of the continental shelf beyond 200 nautical miles claim—in the case of the RGR—and the future establishment of MPAS under the Biodiversity Beyond National Jurisdiction (BBNJ) Agreement [111,120,121].

Environmental concerns are acute given the RGR's slow-growing, long-lived ecosystems with limited resilience. Deep-sea mining impacts include: (1) irreversible habitat destruction and substrate removal [122,123]; (2) sediment plumes dispersing metals and contaminants over extensive areas [124,125]; and (3) anthropogenic noise propagating hundreds of kilometers through the SOFAR channel, disrupting marine species dependent on sound [126,127]. Metal toxicity and ecosystem resilience remain poorly understood due to limited access to deep-sea bioindicator species [122,128].

Brazil's alignment with the ISA's 2023 precautionary pause reflects growing recognition that a robust scientific baseline is essential before commercial decisions [21,129,130]. Socioeconomic dimensions add complexity, as multiple sectors—fisheries, mining and conservation—compete for ocean space, demanding ecosystem-based management approaches [20,131].

4.2. Mineral Resources and Economic Potential

The RGR has emerged as one of the most promising regions in the South Atlantic for marine mineral resources in relation to the CPRM–SGB contract. Nevertheless, publicly available information is scarce and focused on specific areas [14,15]. Scientific and economic interest is primarily focused on Fe–Mn crusts, with secondary attention to phosphate deposits, and, to a lesser extent, the potential occurrence of polymetallic nodules. These deposits result from the extremely slow accumulation of Fe and Mn oxides over millions of years, during which they incorporate metals of high strategic value, including cobalt, nickel, copper, lithium, tellurium, and rare earth elements, which are critical for the energy-transition technologies and high-tech industries [14,15,32,76]. Recent surveys demonstrate that Fe–Mn crusts on the RGR (Figure 8) exhibit exceptionally high enrichments in these elements, placing the region among the most metal-rich Fe–Mn crust provinces documented worldwide [17]. Furthermore, phosphorites are widely distributed on the seafloor of continental shelves and slopes along the western continental margins of the Pacific and Atlantic Oceans and are commonly associated with Fe–Mn mineralization, representing a potential source of phosphates, rare earth elements, and yttrium [14,132,133].

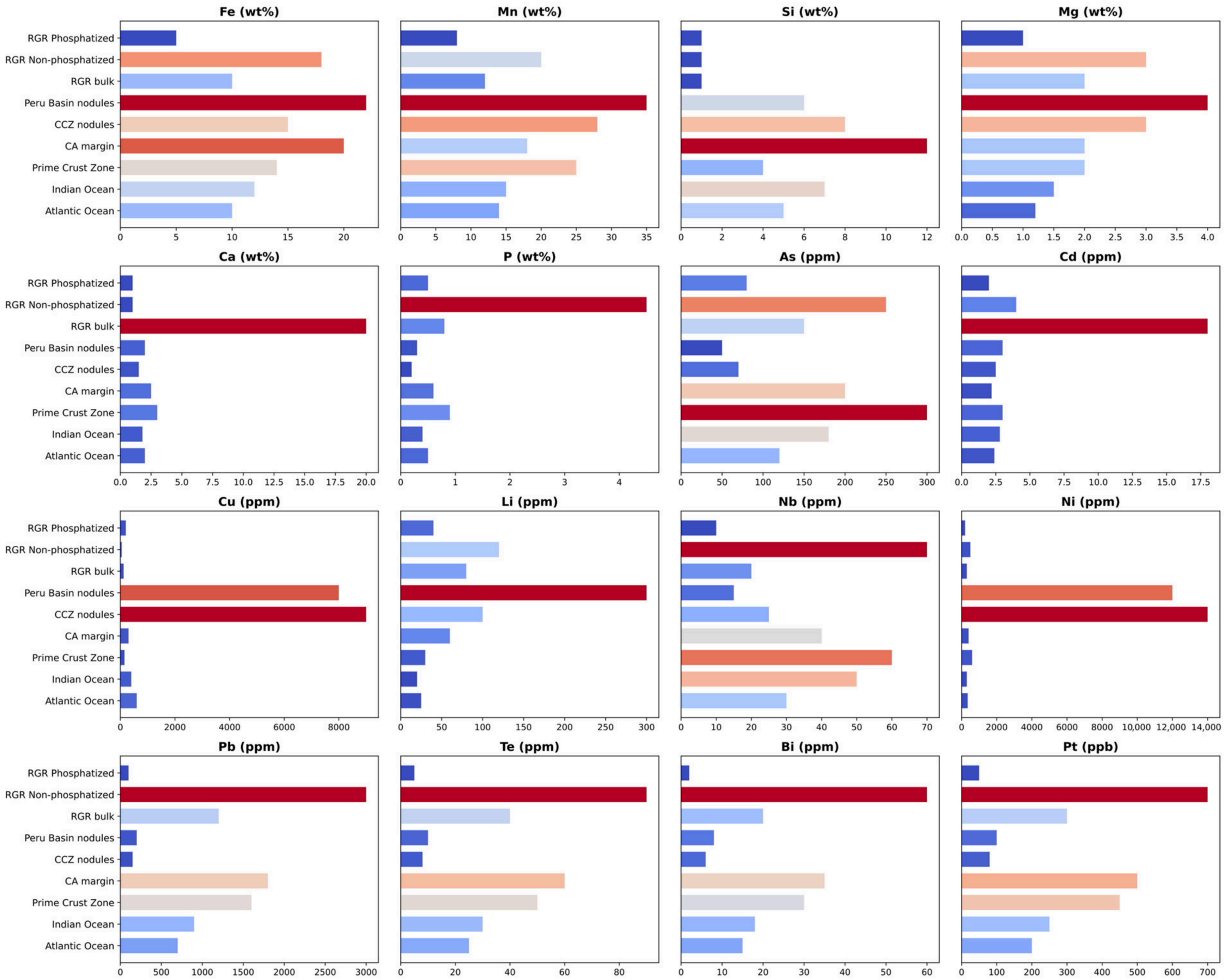

Figure 8. Chemical comparison of major global Fe-Mn polymetallic deposits. For the RGR, we include the bulk, non-phosphatized and phosphatized phases (modified from [15]). Bars with red (blue) tones means the major (minor) amount.

Ferromanganese crusts on the RGR consist of fine intergrowths of poorly crystalline Fe- and Mn-oxide minerals formed under variable oceanic biogeochemical conditions. As such, they preserve valuable records of past redox conditions, ocean circulation patterns, and biogeochemical processes, in addition to their economic significance [16,32,51,53]. Hydrogenetic precipitation under oxic conditions favors the formation of vernadite directly from seawater, whereas 10 Å manganates such as asbolane and lithiophorite precipitate from porewaters under suboxic conditions. Goethite commonly co-occurs and can form under both redox regimes [11]. These oxides exhibit strong and selective trace-metal uptake: lithiophorite and asbolane preferentially concentrate lithium, nickel, copper, and zinc, whereas vernadite concentrate cobalt, tellurium, and cerium [17,51].

Mineralogical analyses indicate the dominance of vernadite and 10 Å manganates, mineral phases with strong adsorption capacity for cobalt, tellurium, and rare-earth elements. Geochemical and magnetic studies also confirm the presence of two distinct growth phases: an older phosphatized layer formed during the Miocene (approximately 20–6.8 Ma) and a younger, non-phosphatized hydrogenetic layer that continues to grow today. These layers preserve valuable records of past redox conditions, ocean circulation, and biogeochemical processes, in addition to their economic significance when phosphatization usually imply remobilization and enrichment of metals (Ni, Cu, Pt, etc.) by early diagenesis [16,53].

Geochemical and magnetic studies indicate a clear depth-dependent variability in Fe–Mn crust composition across the RGR. At shallower depths (approximately 625–850 m), crusts typically display a two-layer architecture, consisting of a thick phosphatized layer formed during the Miocene (approximately 20–6.8 Ma) overlain by a thinner, non-phosphatized hydrogenetic layer that continues to accrete today. This Miocene phosphatization event is considered to be due to changes in redox conditions as consequence of the formation of an Oxygen Minimum Zone (OMZ) related to increase in primary productivity [16], resulted in the substitution and cementation of pelagic carbonates by carbonate fluorapatite, profoundly modifying mineralogical assemblages, bulk geochemical compositions, and magnetic properties of the crusts (Figure 9). In contrast, deeper-water crusts (approximately 1500–5000 m) are non-phosphatized because they remained below the Miocene OMZ; they are purely hydrogenetic and particularly enriched in cobalt, molybdenum, vanadium, and uranium, with peak enrichments typically occurring between 2000 and 4000 m water depth [14–16].

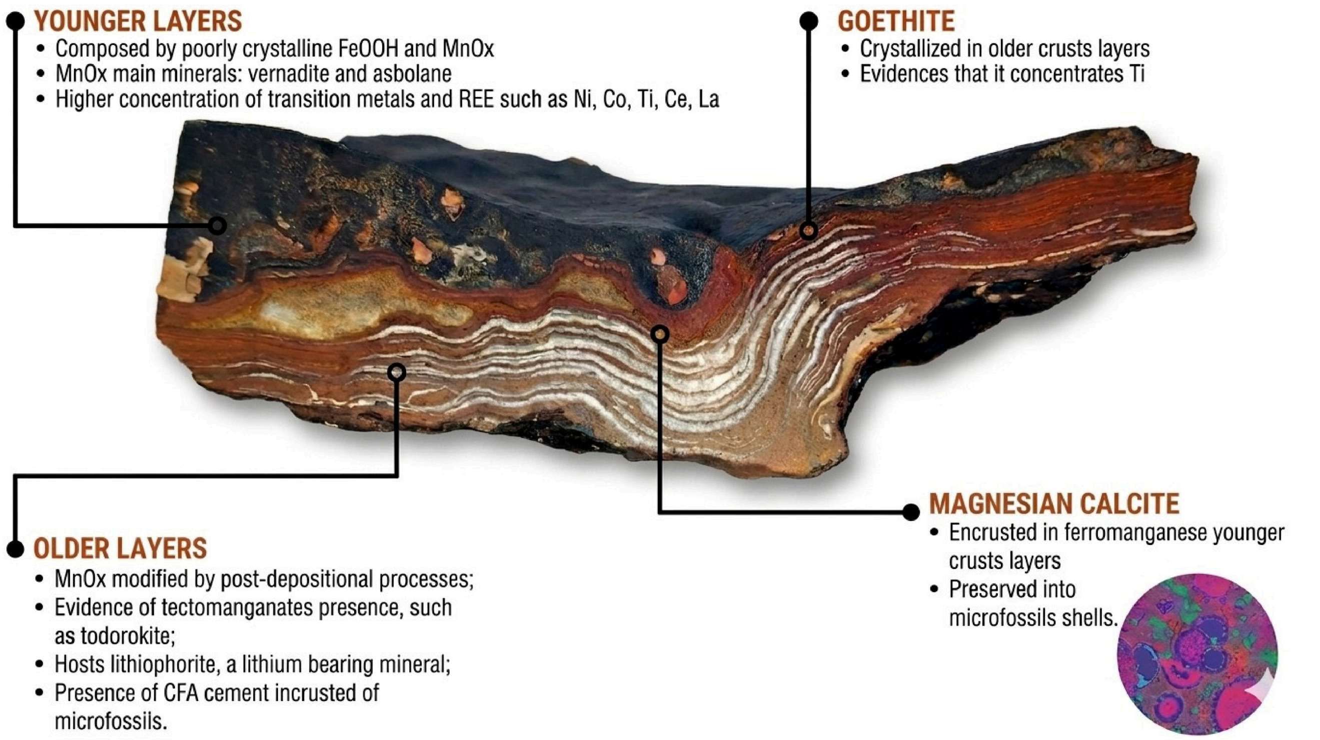

Figure 9. Characterization of a Fe–Mn crust sample from the RGR (modified from [17]).

Geochemical studies indicate strong spatial variability in metal concentrations, suggesting that local hydrodynamic conditions, substrate exposure time, and oxygen availability play a key role in controlling crust growth rates and composition [11,16]. The contribution of microbial mediation to metal oxidation and precipitation is increasingly recognized but remains insufficiently quantified in the RGR context.

The chemical composition and distribution of Fe–Mn crusts on the RGR is complex and depends of a series of factors, including biological productivity (phosphatization/redox changes), oceanographic dynamics (accretion rates/selective enrichment), and the subbottom characteristics [14–16]. However, despite recent advances and geopolitical movements toward deep sea mining, the scientific knowledge on mineralogical composition and the spatial distribution of these crusts remains poorly constrained (Figure 10). The data available today are mainly demonstrating sample quality from specific locations, not a complete resource assessment. Critical parameters for mining evaluation are entirely absent: there is no available reconstruction of crust distribution area, average thickness, or consequent metal resources. Large-scale future research is fundamental to realistic resource assessment of the region. This knowledge gap highlights the need for further high-resolution mineralogical, geochemical, and geophysical investigations to fully assess the RGR's resource potential. Such efforts are essential not only for optimizing exploration strategies, but also for ensuring that any future mining activities are informed by robust scientific understanding and carefully balance economic interests with environmental sustainability.

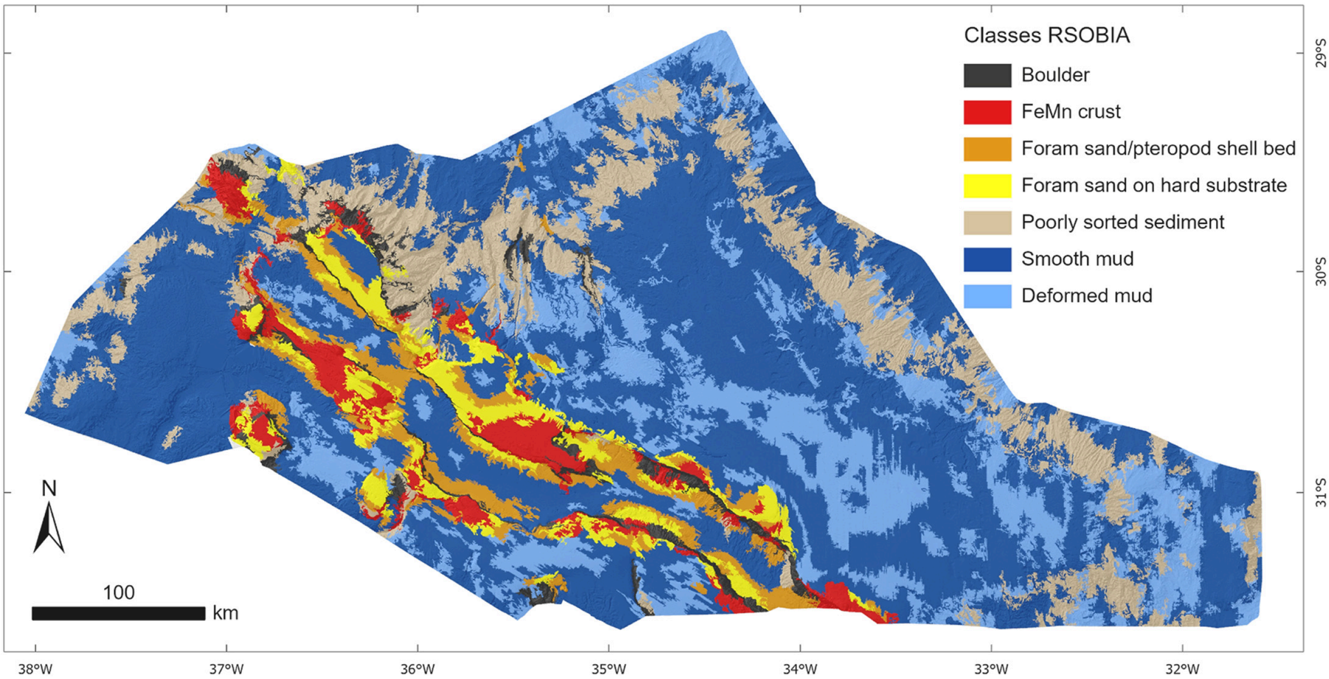

Figure 10. Ferromanganese crusts in the Western Rio Grande Rise using Benthic Terrain Model (BTM) and the Remote Sensing Object-Based Image Analysis (RSOBIA) [31].

A systematic multiphysical survey (e.g., reflection seismics, gravity, magnetic and electromagnetic surveys) covering the entire RGR (in different azimuth directions) and extending at least 25% beyond its inferred limits is therefore considered essential. Combined with gravimetric, bathymetric, and geological datasets, such a survey could provide critical constraints on the spatial extent of the RGR and its crustal nature. The use of Autonomous Underwater Vehicles (AUVs), Remotely Operated Vehicles (ROVs) or Deep-Towed Vehicles is fundamental to recover biological, geological and water samples and data from the water–sediment surface. Likewise, uncrewed aerial vehicles deployed from oceanographic vessels have been proposed as a feasible strategy for acquiring high-resolution airborne geophysical data over the rise.

4.3. Extraction Methods

From a technological perspective, the exploitation of Fe–Mn crusts remains challenging. Unlike polymetallic nodules, crusts are strongly lithified and firmly attached to the basaltic or sometimes sedimentary semiconsolidated substrates, requiring robust cutting technologies for recovery [134,135]. International test programs have explored deep-sea mining systems using floating production platforms, vertical riser systems, and seabed cutting tools [136]. Hydraulic lift systems, which utilize slurry pumps to circulate the liquid–solid mixture, are well-suited for shallow-water operations. Airlift systems, on the other hand, are suitable for greater depths. In an airlift system, compressed air is injected into the riser, reducing the density of the internal fluid column and thereby creating a pressure differential relative to the surrounding hydrostatic pressure. As a result, the air–liquid–solid mixture is driven upward through the riser. The high mechanical strength of Fe–Mn crusts and the environmental sensitivity of deep-sea ecosystems present significant technological and environmental challenges that must be addressed before any commercial exploitation can be contemplated [137,138].

There is still no established production system for crusts/nodules, but several arrangements have been proposed and tested. A typical system involves a floating platform, an ore lift riser to conduct multiphase flow, a water return pipeline, and a seafloor collection/cutting tool. For the RGR, the floating platform is essential, as the crusts are distributed on the top of the plateaus (~1000 m) and on the slopes up to ~4000 m, beyond the usual reach of fixed platforms (~350 m). The subsea system includes the riser (possibly with parallel lines for lift and water return), a flexible jumper connecting it to the bottom tool, and the cutting equipment. Future regulations will define whether the water returns to the bottom or if a closed circuit will be required. In terms of ore lift, hydraulic lift (two-phase flow) is suitable for shallower depths, while air-lift (three-phase) is recommended for deep water.

The Japan Oil, Gas and Metals National Corporation (JOGMEC) has already tested a prototype crust cutter in an ocean environment. The increased global demand for critical minerals, driven by decarbonization policies and the high-tech industry, reinforces the economic relevance of the South Atlantic. However, there are still significant uncertainties regarding the commercial viability of deep-sea mining, considering operational costs, environmental risks, and regulatory uncertainties [139].

4.4. Metallurgical Processing and Strategic Applications

The growing global demand for clean and highly efficient energy technologies has driven the search for critical elements, such as rare earth elements (REEs), yttrium, cobalt, and nickel, which are essential in the manufacture of permanent magnets, wind turbines, electric vehicles, photovoltaic panels, and low-energy LEDs. China's dominance in global REE production highlights a significant geopolitical and economic dependence [76,92,140,141]. In this context, the search for new sources of strategic metals has become a scientific and technological priority.

Although the average REE content in marine crusts is relatively low (~0.25%), their global reserves are comparable to those of large continental deposits such as Bayan Obo (China) and Mountain Pass (USA).

Despite the high economic potential of the RGR Fe–Mn crusts, their metallurgical processing still faces significant challenges [142,143]. Conventional methods used for REE extraction, such as acid calcination with concentrated H_2SO_4 (>93% by weight) at temperatures above 200 °C, require high energy consumption, are highly corrosive, and produce large volumes of waste [144]. In this context, it is essential to develop alternative hydrometallurgical routes, such as selective precipitation or hybrid approaches that integrate selective precipitation and solvent extraction, aiming at the efficient recovery of REEs and yttrium from the Fe–Mn crusts of the Rio Grande Rise to improve product yield, purity and environmental sustainability.

4.5. Viability of Deep-Sea Mining and Impacts of Crusts Exploitation from RGR

Ordinarily, to define the viability of deep-sea mining and crusts exploitation from RGR, we need to compare the economic feasibility of mining polymetallic manganese nodules and cobalt-rich ferromanganese crusts in a scenario of mutual exclusivity. However, metallurgy optimization and environmentally sustainable lixiviation are the main factors for this calculation; nevertheless, prices are not the only drivers. Assessing the viability of deep-sea mining involves multiple dimensions beyond economics. As [145] noted, legal, political, technological, and environmental issues are often more critical than economic factors alone. Importantly, societal perception and acceptance of deep-sea mining world-wide and at the Rio Grande Rise, which can have a fundamental role in successful development of the exploration and exploitation projects [146], are not taken into consideration in this calculation. Moreover, the perception of different groups on the consequences that deep-sea mining would cause are commonly viewed as highly complex and conflictual at the point of jeopardizing the entire blue economy. In order to unravel and debate these complex interactions, a complete and accurate environmental impact assessment with a view to precisely calculating and, consequently, minimizing the risks is needed. On the other side, a potential environmental mining disaster caused by deep sea mining would worsen the deep-sea mining perception, provoking the demise of the entire blue economy. Subsequently, massive and crucial scientific investments are urgent in order to precisely calculate the deep-sea environmental impacts (cumulative and synergetic) before undertaking any kind of deep-sea mining.

The exploitation of these resources involves the use of mineral-collecting robots on the seabed, surface ore processing, and the re-deposition of drainage water on the seabed (e.g., [128,147,148]). Ore extraction may cause pollution from noise, vibration, or light, and from sediment plumes or drainage water containing particles, contaminants, and nutrients (Figure 11) [96,98,148,149]. This will have significant negative environmental consequences, such as habitat destruction, crushing of animals by collectors, displacement of swimming animals to other locations; light, vibration, and sound can cause disorientation; and sediment clouds can damage filtration organs and induce toxic effects (metals) [123,148–151].

Greater proximity to the extraction site and longer duration of the activity increase the severity of these impacts on the affected ecosystems, with negative effects on biodiversity, productivity, carbon sequestration, and ecosystem services such as fishing or genetic resources [122,123,148,152].

Three main vectors concentrate the concerns [91,99,124,152,153]:

1. Physical disturbance and habitat destruction—mechanical collectors of crusts and nodules cause irreversible removal of the substrate, burial of organisms, and loss of unique habitats [122,123,149].
2. Pollution by sediment plumes and drainage—the resuspension of fine particles can affect filter-feeding organisms and food webs, transporting metals and contaminants over long distances [122,124,125,149].
3. Anthropogenic noise—in general, sound propagates faster and with less attenuation in water than in air, thus giving sound the ability to reach great distances in the marine environment. In deep ocean regions (~1000 m), the SOFAR (Sound Fixing and Ranging) channel enhances the long-range propagation of low-frequency sound by minimizing attenuation, allowing noise from mining activities to propagate over

hundreds of kilometers [126,127,154,155]. Therefore, the noise produced by vessels, dredging, pumps, and excavation can impact marine ecosystems through the phenomenon of masking or by directly damaging marine species that depend on sound for communication, orientation, feeding, and reproduction [156]. Despite the growing threat posed by noise pollution in the deep sea, it is important to highlight the significant scarcity of data and the absence of standardized methodologies for characterizing reference noise levels and their cumulative effects, especially in the southern hemisphere [157–159].

The ecotoxicological dimension represents another critical challenge [122,124,128,148]. Little is known about the toxicity of metals released during the exploration of crusts and phosphorites [122,128,147]. One of the greatest challenges is obtaining bioindicator species at great depths, hindering studies on resilience and population maintenance [124,128].

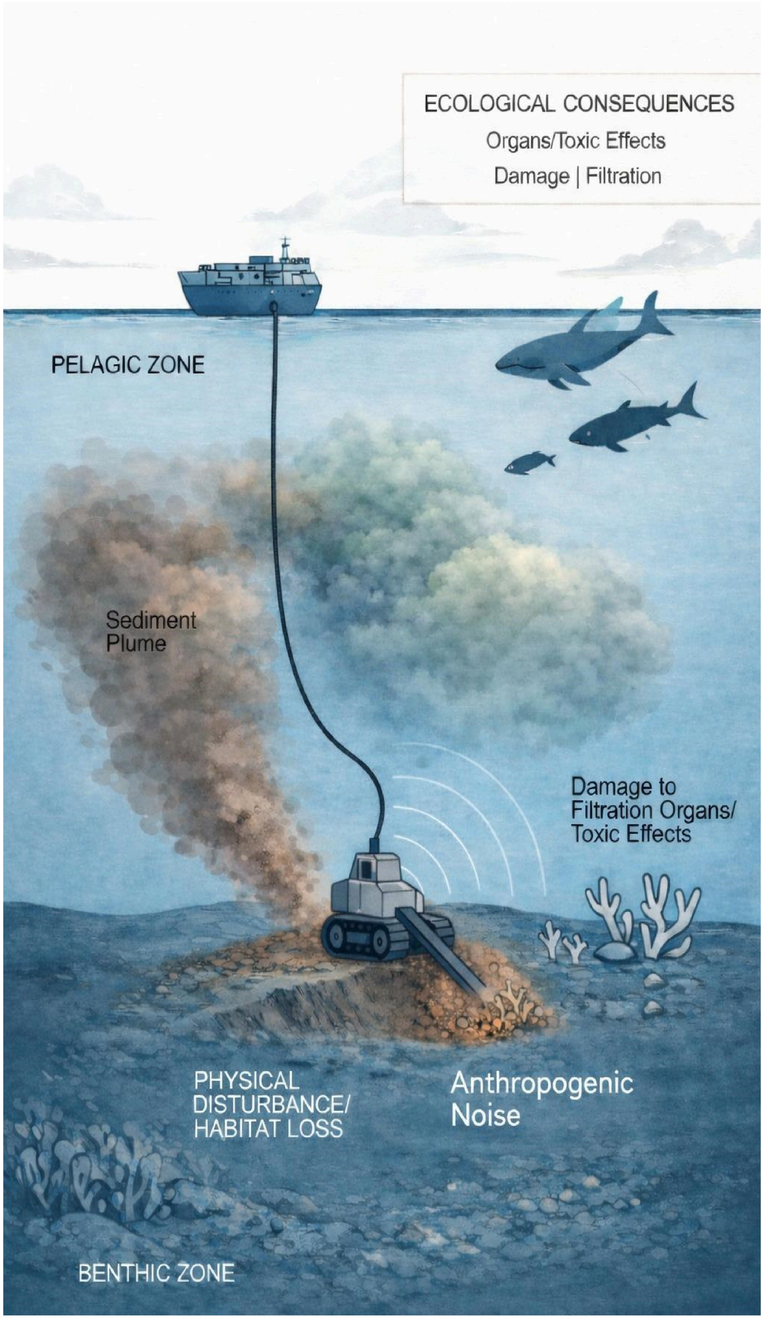

Figure 11. Scheme representing the impacts affecting the marine environment in relation to deep-sea mining operations.

4.6. Environmental and Socioeconomic Considerations—Future Prospectives

Although this review focuses primarily on the scientific understanding of the Rio Grande Rise, assessing its mineral resources necessarily requires consideration of environmental risks and economic feasibility. Ferromanganese crusts occur in ecosystems characterized by slow biological turnover and limited resilience to disturbance. Mechanical removal of crusts, sediment resuspension, and noise propagation may produce long-lasting ecological effects, particularly in habitats dominated by sessile fauna and long-lived organisms.

At the same time, the economic viability of crust exploitation remains uncertain. The extraction of strongly lithified ferromanganese crusts requires complex cutting technologies, vertical lifting systems, and metallurgical processes capable of efficiently recovering strategic elements such as cobalt, nickel, and rare earth elements. Operational costs, technological constraints, regulatory uncertainty, and environmental safeguards therefore represent critical factors influencing potential future exploitation. Consequently, robust environmental baselines, detailed resource assessments, and integrated cost–benefit analyses remain essential prerequisites for realistically evaluating any large-scale mining scenario in the Rio Grande Rise.

There is a pivotal need for more basic science before any commercial decision, because any miscalculation in the analysis of the impacts and cumulative impacts might jeopardize the entire risk assessment evaluation [129]. This effort indicates that international regulation is in transition, oscillating between economic interests and global environmental commitments [130,160,161].

Finally, the socioeconomic dimension cannot be dissociated from the debate [20,124]. The exploitation of the RGR involves the interests of different sectors: fishing, mining, conservation, and coastal communities [1,12,162]. The conflicts between large-scale longline fishing, already recorded in the region, and potential mining on the plateau illustrate how governance decisions must consider multiple uses of the sea, in line with Ecosystem-Based Management [20,131,163].

Deepwater mineral exploration should not be seen merely as an economic opportunity, but as an ethical and political test of the capacity of each country within its ECS and the international community to preserve humanity's common heritage without compromising the ecological integrity of the oceans [21,107,130,161,164–167].

Environmental concerns are particularly acute in the context of deep-sea mining. RGR ecosystems are characterized by slow-growing, long-lived organisms with low reproductive rates and extremely limited resilience to disturbance. Potential impacts include habitat destruction, sediment plumes, noise, light, and chemical contamination, all of which may have long-lasting or irreversible effects. Effective governance, therefore, requires the application of the precautionary principle, ecosystem-based management, and long-term environmental monitoring.

Institutions such as environmental agencies play a central role in ensuring that decision-making is informed by robust scientific evidence [168]. Strengthening institutional capacity, investing in environmental baseline studies, and fostering transparency and public engagement are essential components of responsible ocean governance.

However, crucial gaps remain: a thorough understanding of the relationships between deep-sea biodiversity and the formation of polymetallic deposits; a detailed assessment of potential conflicts that may arise between fishing activity and mineral exploration; and realistic analyses that consider the costs, benefits, and risks associated with deep-sea mining in the Rio Grande Rise.

Advances in high-resolution geophysical databases—seismic, magnetic, gravimetric and electromagnetic surveys—will be crucial for filling fundamental gaps, testing hypotheses about the continental crust, and elucidating the architecture of the Cruzeiro do Sul Rift, producing 4D models of tectono-magmatic evolution that will guide future surveys.

Stratigraphic surveys and multidisciplinary coring campaigns will establish precise chronologies of the RGR, from the Late Cretaceous to the Recent, calibrating events of volcanism, phosphatization, and emergence as an island. In parallel, in-depth research in deep-sea ecology and functional metagenomics will reveal essential metabolic functions of microbiomes associated with ferromanganese crusts and sediments, connecting invisible processes to the sustainability of ecosystem services and offering biomarkers for environmental monitoring.

The integration of high-resolution geomorphology, substrate, and fauna will allow the definition of zones of high ecological value and the construction of transparent criteria for exclusion, mitigation, and environmental compensation, consolidating a cartography of habitats and resources as a basis for marine spatial planning. Experimental tests on plumes, noise, and crust shear, conducted on controlled-impact platforms, will be fundamental to establishing quantifiable thresholds that guide real-time decisions. Ecotoxicology will advance in defining mobility and bioavailability limits for metals from a precautionary perspective.

Within this same framework, the economic and social evaluation of non-extraction, conservation, and mining scenarios should incorporate not only costs and revenues, but also the value of ecosystem services, economic viability and societal acceptability, allowing the construction of decision-making panels that support public policies. This scientific basis needs to be accompanied by a regulatory and operational framework capable of translating evidence into implementable rules under the United Nations Convention on the Law of the Sea (UNCLOS) and national law, providing an operational code for the deep sea aligned with international best practices.

To assess the objective economic viability of large-scale deep-sea mining, a detailed metallurgical study is also needed to optimize the extraction of each element from each type of crust. Furthermore, crust production cannot represent only a commodity for the country's economy; an effort must be made to utilize these elements in applied forms, with varying degrees of purity, to obtain concrete improvements through the energy transition.

Finally, the consolidation of a national critical mass will depend on the training of new generations of scientists and technicians. Field schools, international cooperation programs, fellowships, and open data platforms and protocols should train specialists in geosciences, biology, engineering, and social sciences, strengthening a national and international research network.

5. Conclusions and Perspectives

The Rio Grande Rise constitutes a key natural laboratory for investigating oceanic plateau formation, deep-sea ecosystem functioning, and the development of ferromanganese crust deposits. This review integrates multidisciplinary evidence accumulated over the last decades, providing a comprehensive synthesis of current knowledge on the geological evolution, oceanographic processes, biodiversity patterns, and mineral resources of the region.

The available data indicate that the Rio Grande Rise formed through a complex interaction of plume-related magmatism, crustal thickening, tectonic rifting, and subsequent subsidence associated with the opening of the South Atlantic. The plateau hosts extensive ferromanganese crust deposits enriched in strategic metals. At the same time, its complex geomorphology and hydrodynamic regime support diverse deep-sea ecosystems closely linked to substrate type and oceanographic conditions.

Despite significant advances, important uncertainties remain. Major knowledge gaps include the crustal nature and internal structure of the plateau, the spatial distribution and thickness of ferromanganese crusts, the total metal resource potential, and the ecological functioning and resilience of deep-sea communities. Additional uncertainties relate to the environmental consequences and economic feasibility of potential mineral exploitation, which remain poorly constrained due to limited geological sampling, sparse geophysical coverage, and incomplete ecological baseline data.

Addressing these uncertainties will require expanded geophysical surveys, new deep-drilling campaigns, systematic geological and biological sampling, and integrated multidisciplinary investigations that combine geology, oceanography, geochemistry, and ecology. Such efforts are essential to refine current interpretations and to improve the scientific basis for future assessments of environmental risks and mineral resource potential in the Rio Grande Rise.

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