Brazilian Marine Biodiversity

Paulo Yukio Gomes Sumida
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# Brazilian Deep-Sea Biodiversity

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# Brazilian Deep-Sea Biodiversity

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ISSN 2520-1077 ISSN 2520-1085 (electronic)
Brazilian Marine Biodiversity
ISBN 978-3-030-53221-5 ISBN 978-3-030-53222-2 (eBook)
https://doi.org/10.1007/978-3-030-53222-2



This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

# Chapter 8
# Living and Non-living Resources in Brazilian Deep Waters

**José Angel A. Perez, José Gustavo Natorf Abreu, André Oliveira de Souza Lima, Marcus Adonai Castro da Silva, Luis Henrique Polido de Souza, and Angelo Fraga Bernardino**

**Abstract** In Brazil, deep-sea marine environments extend over 3.5 million km$^2$, covering nearly 80% of Brazil's Economic Exclusive Zone (EEZ) in the southern tropical and subtropical Atlantic Ocean. Over this area, the exploitation of both living and non-living resources have gradually increased and supported by natural geological resources, scientific knowledge, geopolitics, economic interests, and technological development. Deep-sea fisheries developed between 2000 and 2008 in the slope areas off southeastern and southern Brazil, declining afterwards mostly because fish and shellfish stocks were shown to be little productive and little resilient. In contrast, large deep (200–2000 m) and ultra-deep (> 2000 m) oil and gas reservoirs were discovered off southeastern Brazil (Campos and Santos Basins) and were increasingly exploited by the national industry. In recent years, over 80% of Brazil's annual oil and gas production is extracted from these reservoirs, particularly from the so-called pre-salt layers. Deep-sea minerals off Brazil have long been mapped but the exploration and exploitation initiatives were incipient and focused on cobalt-rich ferromanganese crust deposits distributed in a large topographic feature known as Rio Grande Rise. Studies of the biotechnological potential of marine bacteria from the deep South Atlantic Ocean have focused mainly on hydrolytic enzymes and bioremediation. Their use in technological products in the next decade, however, still demands considerable technological development. A major concern, common to all deep-sea resources off Brazil, includes the effectiveness of the

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P. Y. G. Sumida et al. (eds.), *Brazilian Deep-Sea Biodiversity*, Brazilian Marine Biodiversity, https://doi.org/10.1007/978-3-030-53222-2_8

regulatory and management processes. Deficiencies, particularly regarding governance issues, have greatly hampered deep-sea fishing and may affect other activities as well. International management regimes, as required outside areas of national jurisdiction, are sometimes absent or need improvement to allow for the environmentally sustainable use of living and non-living deep-sea resources.

**Keywords** Brazilian EEZ · Fishing resources · Marine biotechnology · Pre-salt oil reservoirs · Deep sea mineral deposits · South Atlantic

## 8.1 Introduction

Deep-sea resources comprise mineral deposits, oil, gas, and biodiversity, either used as food or as biotechnological products, which can be extracted from deep marine environments beyond the continental shelf. In Brazil, these environments extend for over 3.5 million km$^2$, nearly 80% of the Economic Exclusive Zone (EEZ) surface area[1] (IBGE 2011). In the EEZ, the rights and obligations to study, exploit, and preserve have been secured since 1982 by the United Nations Convention of the Law of the Sea (UNCLOS, UNGA 1982). Most of this area is a seaward extension of the 8500-km-long continental margin bathed by the southern tropical and subtropical Atlantic Ocean (Fig. 8.1). In addition, areas surrounding oceanic islands (e.g. St. Peter's and Sr. Paul's Archipelago, Fernando de Noronha, Trindade) and, more recently, the Rio Grande Rise area are legal extensions to Brazil's EEZ.

This geographical situation has historically granted Brazil a wide access to deep-sea areas and its resources in the Southwest Atlantic. Nonetheless, the development of exploitation systems for both living and non-living resources has been gradual and determined by rich natural resources, increasing scientific knowledge, geopolitics, economic interests, and technological development. In the 1980s these elements converged in the development of the first oil extraction operations in the Campos Basin, 500–1600 m below the sea surface (Morais 2013). During the following decades, national research programs and commercial enterprises assessed further opportunities to exploit a number of deep-sea resources, also promoting studies to investigate the structure and functioning of ecosystems directly affected by deep ocean activities.

This chapter reviews the current knowledge on living and non-living deep-sea resources off the Brazilian coast, their exploration activities, and regulation or conservation initiatives. For convenience, we limit this analysis shoreward to the shelf break (200 m depth) and extend it offshore to areas 'beyond national jurisdiction', where the country has expressed interest in exploiting natural resources under UNCLOS regulations and other international agreements.

[1] These figures are estimates including the areas claimed in 2018 by Brazil to the UN Commission on the Limits of the Continental Shelf (e.g., the Rio Grande Rise area).

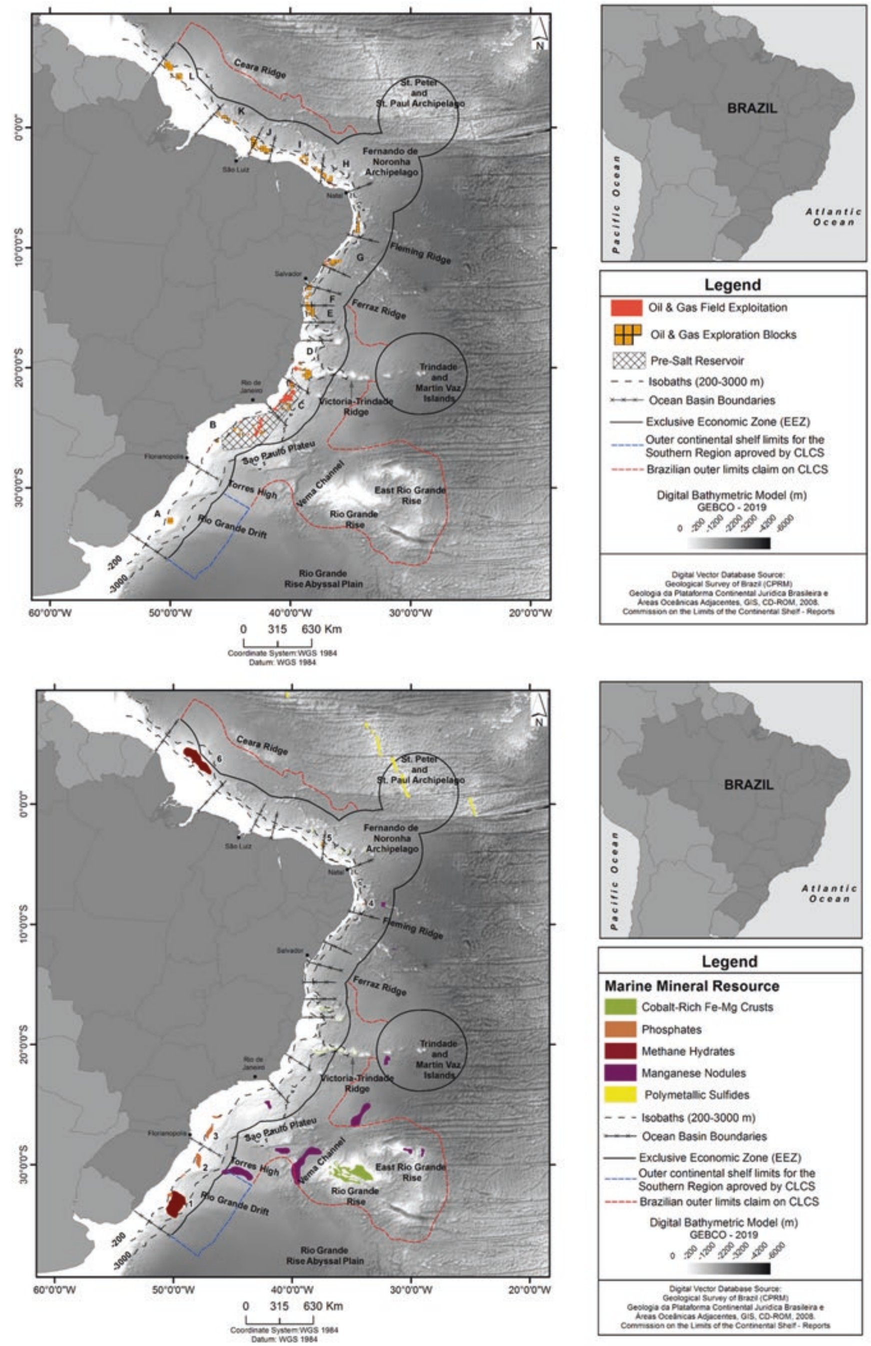


**Fig. 8.1** Bathymetric charts of Brazil's continental margin and adjacent Southwest Atlantic basin depicting the distribution of oil and gas fields (upper map) and marine mineral deposits (lower map) within the Brazilian Exclusive Economic Zone and International Waters. Sedimentary basins and geomorphological features are indicated: A. Pelotas, B. Santos, C. Campos, D. Espírito Santo, E. Jequitinhonha, F. Camamu-Almada, G. Sergipe-Alagoas, H. Potiguar, I. Ceará, J. Barreirinhas, K. Pará-Maranhão, L. Foz do Amazonas. 1. Rio Grande Cone, 2. Rio Grande Terrace, 3. Florianópolis Terrace, 4. Pernambuco Plateau, 5. Ceará Plateau, 6. Amazon submarine fan

### 8.1.1 Motivations to Exploit Deep-Sea Resources Off Brazil

The deep sea is generally remote and most unreceptive to human activities. It is also vast and poorly studied (Ramirez-Llodra et al. 2010 and chapters of this book). Valuable resources have been mapped and assessed in deep marine areas, but their economic exploitation tends to face large operational costs, which may reduce profitability. In general, these resources would necessarily be more productive and more valuable than those found in shallow waters or in terrestrial areas to be economically attractive.

Notwithstanding, deep-sea activities have been established worldwide driven by motivations other than those purely economical, including (a) the need to secure access to potential deposits of raw materials, ever so demanded by new technological development (Hein et al. 2013), (b) the need to find alternatives to compensate for the depletion of continental and shallow water resources, and (c) strategic political interests. A combination of these motivations has historically driven the development of exploitation systems for deep-sea resources off Brazil.

In the 1960s, the Brazilian oil and gas company Petrobras started to focus its exploration activities on the deep seafloor, following experiences of other countries that have access to extensive sedimentary basins. Such a strategic decision followed a governmental policy towards attaining self-sufficiency in oil production and the expectations of finding oil reservoirs on the deep continental margin large enough to compensate for the general shortage of oil deposits on land (Milani et al. 2000; Morais 2013). These expectations were initially attained in the shallow water marine oil fields found in Campos Basin, which sustained increasing oil productions from 1973 to 1985, and stimulated, during the 1990s, new prospections and discoveries of even larger and deeper reservoirs.

In the same decade, the Brazilian 'industrial fishing' developed and expanded to exploit fish and shellfish stocks in the most productive continental shelf areas of northern, southeastern, and southern Brazilian coasts down to 100 m depths. In the following 20 years, fishing fleets increased and overcapitalized leading to important biomass reductions of their main pelagic and demersal resources, which provoked a process of diversification of fishing activities, targets, and areas (Perez et al. 2001). Among these activities, a substantial expansion of demersal fishing fleets towards the upper slope (200–500 m) took place from the late 1990s onwards, initially searching for profitable concentrations of traditional targets, but soon identifying new fishing resources (Perez et al. 2009). Technological limitations for deep-sea fishing operations were critical at this point and motivated the implementation of a governmental program based on chartering foreign fishing vessels to operate deeper and over valuable deep-sea resources (see below). While productivity was generally low, the high quality of the flesh of targeted fish species tended to raise their economic value, compensating for the higher costs of deep operations (Martínez-Musoles et al. 2016).

Substantial efforts have been exerted worldwide to map deep marine deposits, measure their mineral contents, develop extraction methods, and assess their ecological impacts (Hein et al. 2013). In Brazil, research initiatives have also been implemented since the 1960s (see below) to (a) map the EEZ seafloor and identify deposits with potential economic interest for the country including those occurring outside the Brazilian EEZ and, in this case, (b) to prepare for submission of exploration plans to the International Seabed Authority (ISA), an organization under UNCLOS created to regulate the access and rights to explore and exploit mineral resources in areas beyond national jurisdictions (or just the 'Area'). Motivations for these efforts have not been only economic or driven by the need for raw materials but also to ensure and expand the country's presence in the South Atlantic, particularly in those areas directly connected to the EEZ limits and those surrounding Brazil's oceanic islands (CGEE 2007).

### *8.1.2 Surveying for Deep-Sea Resources Off Brazil*

Prospecting for living and non-living marine resources off the Brazilian coast date back to the late 1960s and 1970s, when the Brazilian Navy, universities, and research institutes collaborated in the development of early exploratory marine studies. During this period, several fishing surveys were conducted, most of them as part of the 'Brazilian Program for Fisheries Research and Development (PDP)', which resulted from a bilateral agreement between the Brazilian Government and the United Nations Food and Agriculture Organization (FAO) in 1967 (see review in Haimovici et al., 2007). Another important initiative was the 'Exploration of Brazilian Continental Shelf Project (REMAC)', led by the Navy, Petrobras, and the Mineral Resources Research Company (later named Geological Survey of Brazil – CPRM). This initiative mapped the entire continental margin off Brazil between 1972 and 1978 collecting information on seafloor topography, sediments, and the location of potential mineral deposits, including oil (Zembruscki 1979). Efforts were mainly focused on continental shelf resources, but many initiatives conducted during this early period produced primary information on the environments and resources of deeper areas beyond the shelf break.

After the findings produced by the REMAC project, and stimulated by the discovery of the 'Garoupa' shallow water oil field in 1974, Petrobras continued its independent oil and gas survey program, reaching deep (500–2000 m) and ultra-deep areas (> 2000 m) in the 1990s and 2000s. Other living and non-living marine resources were studied mostly under the so-called National Policy for Marine Resources (PNRM), first established in 1980, and overseen by the newly created (1974) Interministerial Commission for Sea Resources (CIRM). Since 1982, CIRM has implemented the PNMR through 4-year 'Sectorial Plans for the Sea Resources' (PSRM).

In 1995–1997, during the implementation of the fourth PSRM, two programs were created with the objectives of describing and assessing the potential for exploitation of non-living[2] and living[3] resources within the Brazilian EEZ. Both programs were a response to the 1994 UNCLOS deliberations, which granted coastal states rights and responsibilities regarding the use of marine resources within their EEZ, and were intended to improve scientific knowledge particularly in the poorly described external limits of the continental margin. After nearly 10 years, REVIZEE came to an end having produced assessments of fishing resources down to 2000 m (Olavo et al. 2005, MMA 2006, Costa et al. 2007, Olavo et al. 2011 and others). REMPLAC is still active and has made efforts to assess phosphates, massive sulphide deposits, and cobalt-rich ferromanganese crusts and nodules along Brazil's continental margin and around oceanic islands (Martins 2009).

In 2009, CIRM created a new research program named PROAREA (Program for Prospection and Exploration of Mineral Resources of the International Seabed Area in the South and Equatorial Atlantic Ocean), following novel principles highlighted in the seventh PSRM, which demanded information to secure strategic political interests in both national waters and the high seas (CIRM 2009). PROAREA was objectively designed to increase scientific knowledge on deep South Atlantic geology and ecosystems, to a level that would permit Brazil (a) to elaborate and submit to the ISA proposals for deep-sea mineral exploration and, by doing so, (b) to increase the country's presence in the South Atlantic. From 2009 to 2013, a number of research cruises under PROAREA were carried out to prospect mineral deposits in the Rio Grande Rise area and the Mid-Atlantic Ridge. As a practical result, in 2015, the Geological Survey of Brazil (CPRM) signed with the ISA a contract for exploration of cobalt-rich ferromanganese crusts in the Rio Grande Rise, the first of this nature to be signed in the Atlantic Ocean.

Outside the umbrella of the PNRM, research initiatives contributed significantly to the understanding of deep-sea marine resources and ecosystems both within and outside Brazilian EEZ. Between 1999 and 2008, Brazilian fisheries authorities stimulated the development of deep-sea fishing by authorizing foreign vessels to operate off Brazil under chartering contracts with Brazilian companies. As part of the fishing companies' obligations, observers were kept on board during 100% of the operations and reported a variety of detailed fishing data (Perez et al. 2009). These data formed a robust empirical basis on fishing resources available on the slope and seamounts off Brazil, which sustained biomass assessments and further biological studies that are critical for establishing management plans (e.g. Perez et al. 2005; Dallagnolo et al. 2009; Sant'Ana and Perez 2016).

Furthermore, the environmental licensing process of offshore oil operations within Brazil's EEZ led to several regional assessments of deep-sea ecosystems. In the Campos Basin, Petrobras and an extensive collaboration of the scientific community carried out projects that described deep-sea habitats and continental margin biodiversity of an area encompassing the five largest oil fields (Lavrado and Brasil

[2] Evaluation of the Mineral Potential of the Brazilian Legal Continental Shelf – REMPLAC.

[3] Evaluation of the Sustainable Potential of Living Resources in the Exclusive Economic Zone – REVIZEE.

2010a, b; Costa et al. 2015; Cavalcanti et al. 2017; Martins et al. 2017; Lavrado et al. 2017a, b). Similar efforts have been taken on eastern and northeastern Brazil in areas targeted for offshore development (Marchioro et al. 2005; Bernardino et al. 2016, 2019). Considering that these fields have been responsible for nearly 80% of Brazil's oil and gas production, the referred research projects made a significant contribution to the construction of an environmental baseline in such a critical area.

Finally, it is worth mentioning international scientific initiatives focusing on the understanding of the South Atlantic deep ecosystems and biodiversity, with participation of Brazilian scientists. Under the 'Census of Marine Life' (CoML) initiative, projects like MAR ECO,[4] COMARGE,[5] and ChEss[6] produced valuable data for assessing perspectives of use and conservation of marine resources and ecosystems in the South Atlantic (Baker et al. 2010; Menot et al. 2010; Vecchione et al. 2010). The South Atlantic MAR ECO was led by Brazil and further produced information on deep biota including microbiological communities in the Rio Grande Rise, Mid-Atlantic Ridge and Walvis Ridge, and their potential for technological products (Perez et al. 2012). Similar studies were conducted in 2013, by a Brazil-Japan bilateral scientific agreement, which promoted the exploration of Brazil's continental margin (São Paulo Ridge and São Paulo Plateau) and oceanic areas including the Rio Grande Rise (Sumida et al. 2016; Fujikura et al. 2017; Montserrat et al. 2019). The latter area was also the target of a more recent Brazil-UK joint project called Marine E-tech[7] that promoted two oceanographic cruises (2018–2019) focused on understanding Fe-Mn deposit formation and environmental assessments for possible future mining activities on the RGR (Jovane et al. 2019).

### *8.1.3 Geological and Oceanographic Origin of Deep-Sea Resources Within Brazil's EEZ*

The geological expansion of the South Atlantic Ocean, as part of the continuous separation of the South American and African plates, provided some key elements to the understanding of the availability and potentialities of deep-sea resources off Brazil (Pérez-Díaz and Eagles 2017). During the Aptian period (~120 myr) the South Atlantic expansion was initiating with oceanic environments progressively expanding equatorward (Fig. 8.2). In this period, however, a topographic feature associated to the Rio Grande Fracture Zone elevated perpendicularly to the Mid-Atlantic Ridge, acting as a barrier to the northward marine circulation. In the Neo-Aptian (~112 myr), such a restriction contributed to the formation, to the north of this barrier, of a shallow water marine environment subject to dry climate conditions

[4] Patterns and Processes of the Ecosystems of the Northern Mid-Atlantic.

[5] Continental Margin Ecosystems.

[6] Biogeography of Deep-Water Chemosynthetic Ecosystems Project.

[7] Marine ferromanganese deposits: a major resource of E-tech elements.

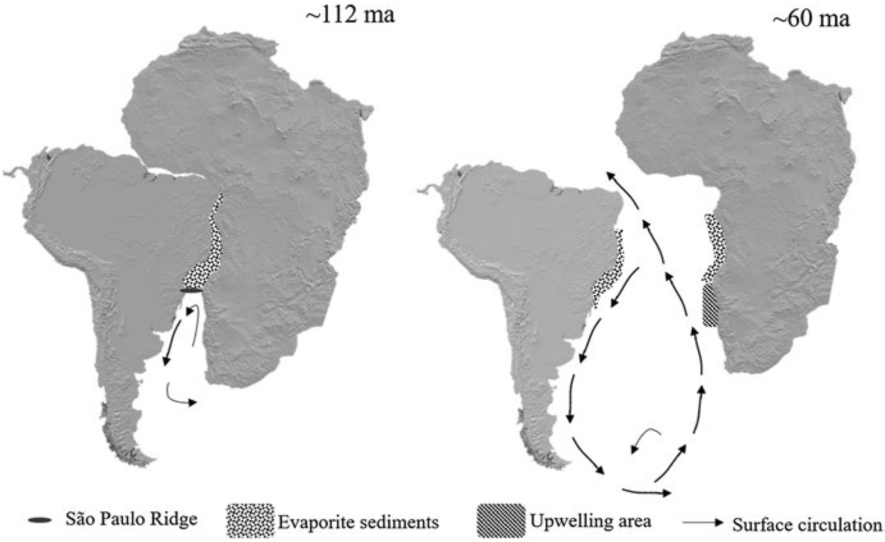


**Fig. 8.2** Schematic view of the South Atlantic expansion in the Neo-Aptian (~112 myr) and Maastrichtian periods (~60 myr), indicating the evaporitic deposition period and the likely reconstruction of surface circulation patterns and the SE Atlantic upwelling area (after Parrish and Curtis 1982; Angel 2003; Dias 2005; Pérez-Díaz and Eagles 2017)

that allowed the deposition of a thick layer of evaporite deposits (Mohriak 2003; Bizzi et al. 2003; Pérez-Díaz and Eagles 2017). As the distance between African and South American plates increased, marine circulation was established allowing for the enhanced deposition of deep marine sediments on both East and West continental margins. In the South American margin, this linear topographic feature is known as the São Paulo Ridge, and the evaporite and deep-sea sediments compose the São Paulo Plateau (Dias 2005; Alberoni et al. 2019). The evaporite layers, up to 2000 m thick in the São Paulo Plateau, have been associated with the formation of important pre-salt oil and gas deposits that today sustain the bulk of the offshore oil and gas industry in Brazil (Mohriak 2003; Bizzi et al. 2003).

Current patterns of oceanic wind-driven circulation and associated biophysical processes were also progressively established during the expansion of the South Atlantic (Pérez-Díaz and Eagles 2017). According to Parrish and Curtis (1982), the South Atlantic subtropical gyre and upwelling zones off the coast of West Africa appeared 70–60 million years ago, as a result of processes associated with climate-related wind fields and constraints of the basin morphology (Fig. 8.2). In that sense, the oceanic oligotrophic conditions that predominate in today's subtropical gyre could have been established back in the late Cretaceous, long influencing POC (particulate organic Carbon) flux and deep-sea life in the Brazilian continental margin and adjacent Southwest Atlantic basin. Primary productivity levels in surface waters overlaying the slope areas off Brazil have been historically limited, which also explains the generally low benthic biomass (Brandini 1990; Capítoli and Bemvenutti

2006; Smith et al. 2008a). In fact, using POC flux models, Wei et al. (2010) have predicted that such biomass should be significantly lower than that observed in the Southeast Atlantic margin, where the seafloor is under the influence of major coastal upwelling systems (Fig. 8.2).

Notwithstanding the apparent energy limitation, general descriptions of oceanographic conditions at the shelf-break and slope off southeastern and southern Brazil suggest a highly dynamic environment, which derives from the southward geostrophic flow of the Brazil current and its interactions with the continental margin topography. The Brazil current originates at approximately 10°S, as a southward flowing branch of the South Equatorial Current. Initially a shallow current formed by tropical waters, it flows southward over the shelf break and becomes faster, thicker, and deeper (0–750 m) at approximately 20°S, where it incorporates contributions of the South Atlantic Central Waters. South of 25°S the Brazil current overlays deep water currents (Antarctic Intermediate Water and North Atlantic Deep Water) that also flow southwards, influencing the slope region down to 3000 m (Castro et al. 2006). Along this path, meanders and eddies are frequently produced in association with along-shelf topography, which are known to induce shelf break upwellings (Campos et al. 2000; Palma et al. 2008). These tend to enhance subsurface primary productivity that locally exceeds levels recorded over shelf and coastal areas (Brandini 1990; Acha et al. 2004). Such biophysical processes may be relevant to sustain concentrations of slope predator fish and shellfish off southeastern and southern Brazil, which have been elemental to the development of deep-sea fishing activities (see below).

## 8.2 Living Resources

### *8.2.1 Fish and Shellfish*

The development of the deep-sea fisheries in Brazil started in 2000, driven by the offshore expansion of the national trawl fleet and operations of foreign fishing vessels authorized to fish in Brazilian waters under chartering contracts. In this process, upper bathyal depths (200–1000 m) were explored and profitable finfish and shellfish resources were identified and commercially exploited. Foreign fishing vessel activities introduced the use of deep-sea fishing methods in Brazil's EEZ, as well as international market opportunities. Their fishing operations, along with those of the national fleet, also led to an unprecedented impact on previously undisturbed areas of the Brazilian continental margin (see review in Perez et al. 2009).

Fishing activities of the foreign fleet extended widely along the Brazilian continental margin, from areas off the northern border with French Guiana (4–5° N) to the southern border with Uruguay (34°S), including seamount fishing off northeastern (Ceará Plateau and Fernando de Noronha Chain, 3–5°S) and southeastern (Vitória-Trindade Chain, 20°S) Brazil. However, 96% of over 32,000 fishing hauls conducted by the various fleets between 2000 and 2007 concentrated south of 18°S,

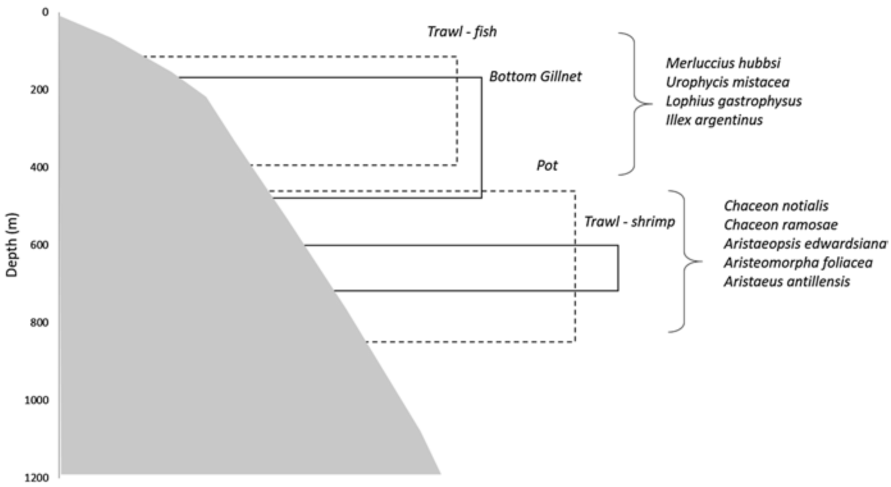


**Fig. 8.3** Schematic view of the bathymetric distribution of fishing resources and methods in the continental margin off Southeastern and Southern Brazil

and particularly in the southeastern sector of Brazilian coast (23–30°S) (Perez et al. 2009). Fishing operations, using different methods and targeting different species, were distributed in distinctive bathymetric zones along the slope (Fig. 8.3).

In 2000–2002, bottom gillnet fishing operations concentrated on the upper bathyal depths (250–500 m) in search for profitable catches of the monkfish (*Lophius gastrophysus*). This species was also a component of the catches of foreign trawlers that operated in the same depth strata, but whose main targets were the argentine-hake (*Merluccius hubbsi*) and other slope species, including the argentine short-fin squid (*Illex argentinus*) and the codling (*Urophycis mystacea*). Pot fishing for deep-sea crabs (family *Geryonidae*) was carried out between 1999 and 2005 in two distinct areas off southern Brazil. The southernmost one (south of 33°S) explored concentrations of the red crab *Chaceon notialis* between 200 to 900 m depths. This stock straddles the border with Uruguay, where it was also exploited by Uruguayan vessels. To the north, between 27° and 30°S, pot fishing operations aimed at the royal crab *Chaceon ramosae* (Fig. 8.4a) between 500 and 900 m depths. By the end of 2002, a new foreign trawl fleet entered the southeastern areas, this time targeting extremely valuable concentrations of three deep-sea shrimp species: *Aristaeopsis edwardsiana* (scarlet shrimp, Fig. 8.4b), *Aristaeomorpha foliacea* (giant red shrimp), and *Aristeus antillensis* (alistado shrimp). These trawlers operated down to 1100 m, but commercial catches were limited to a narrow bathymetric band between 700 to 750 m depths. They concentrated between 24 and 26°S, but after 2005, there were expansions to southern (south of 26°S) and northern (19–20°S) areas, the latter also including fishing operations at the Besnard seamount, a component of the Vitória-Trindade Chain (Dallagnolo et al. 2009). By 2008 this fishery also came to an end, terminating the foreign deep-sea fishing episode in Brazil (see review in Perez et al. 2009).

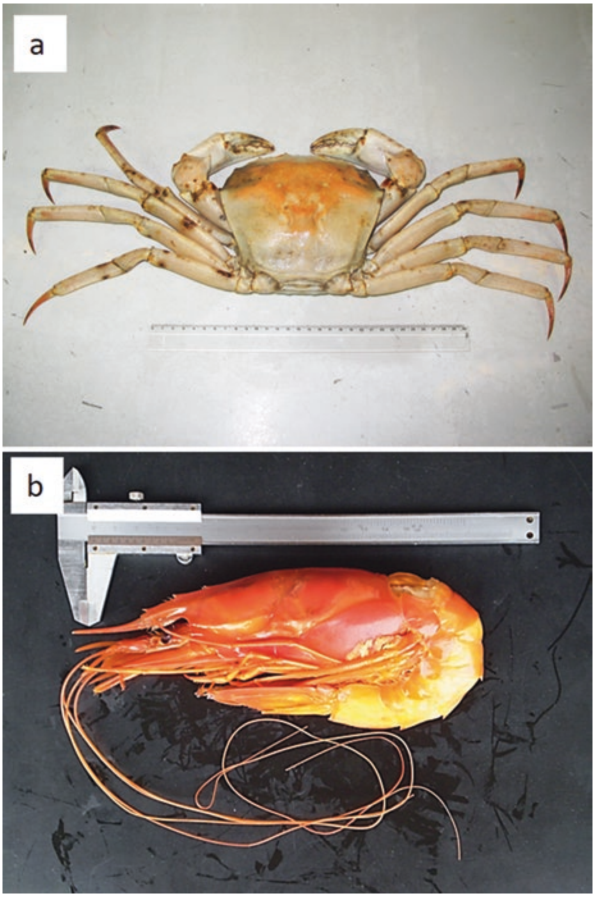


**Fig. 8.4** Deep-sea resources exploited off Brazilian coast. (**a**) Royal crab (*Chaceon ramosae*), (**b**) scarlet shrimp (*Aristaeopsis edwardsiana*). (Photos by Jose Angel A. Perez)

Deep-sea fishing, after the exit of the international fleet, continued through the operations of technologically adapted national bottom gillnet and pot vessels (e.g. Pio et al. 2016) but, most importantly, by national trawlers that increased their operations in the upper slope off southeastern and southern Brazil. Dias and Perez (2016) investigated the process of formation of this fleet that gradually adapted, both operationally and economically, to thrive year-round exclusively on catches of slope concentrations of the argentine hake, codling, and monkfish. Between 2007 and 2009, this fleet included 37 trawlers of slope 'specialist' skippers (sensu Branch et al. 2006). These, however, shared slope fishing areas with over 180 trawlers of 'generalist' skippers that operated opportunistically over the entire continental shelf and slope for a variety of resources.

Most slope fishing resources identified off Brazil underwent a 'boom and bust' exploitation pattern, commonly reported in deep-sea fishing developments worldwide (Norse et al. 2012). The period between 2000 and 2006 concentrated the bulk of catches reported along nearly 12 years of slope fishing development (total landings ~87,655 t, Fig. 8.5). Peaks were recorded in 2001 (monkfish, 7064 t), 2002 (argentine hake, 3709 t, codling, 7847 t, royal crab, 1252 t, argentine shortfin squid, 2600 t), 2003 (red crab, 1378 t), and 2005 (scarlet shrimp, 183 t, giant red shrimp, 43 t, alistado shrimp, 16 t). Trawling by national vessels continued the exploitation of the main slope fish targets from 2005 onwards landing, until 2011, relatively stable annual catches of monkfish and argentine hake (mean landings 2573 t and 1893 t, respectively). In the case of codling, annual catches exhibited an increasing trend until 2009, stabilizing thereafter (Fig. 8.5). Over 80% of the total royal and red crabs reported catches were landed between 2001 and 2006. The latter has been exploited by a single national pot vessel since 2010. Deep-sea shrimps sustained very limited but valuable catches which extended until 2008.

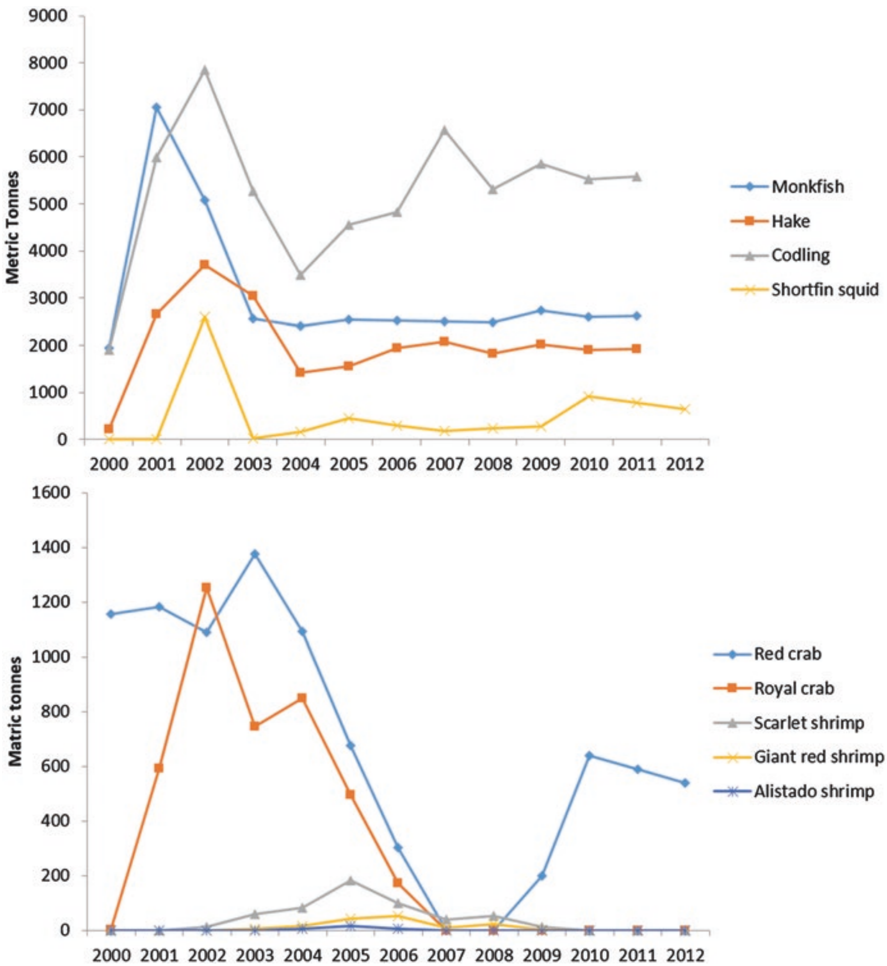


**Fig. 8.5** Landings of demersal fish and shellfish species caught in slope areas off Brazil from 2000 to 2012

Biomass dynamics assessments and maximum sustainable yield (MSY) estimates were available during the main exploitation period for most slope stocks targeted off Brazil (Table 8.1) (Perez et al. 2009). Important biomass reductions and overfishing scenarios were characterized for monkfish, argentine hake, codling, scarlet shrimp, and royal crab. By 2009 these stocks were regarded as fully exploited or overexploited (Table 8.1). These scenarios, in association with fluctuations in the international markets and changes in the national fishing policies, provoked the termination of the deep-sea fishing development program around 2008. Deep-sea crustaceans have been scarcely exploited or not exploited ever since. Slope fish exploitation, however, has persisted through a process adaptation of traditional demersal fishing methods (trawls and gillnets). Their catches have been relatively stable under or near MSY levels, except for the codling whose catches have greatly exceeded the estimated MSY.

The development of deep-sea fishing activities has produced an increasing spatial footprint whose effects may have extended beyond the overfishing scenarios. Slope trawlers, for example, have extended their operations over nearly 11% of the available and previously untouched slope area off southern and southeastern Brazil between 2003 and 2011. Within this footprint, trawling tended to concentrate in limited areas that were 'swept' 1 to 6 times during this period, burning 46.4 million litres of diesel and releasing to the atmosphere 125.2 thousand tons of $CO_2$ (Port et al. 2016a, b).

Bottom gillnets set to catch monkfish in 2001–2002 produced the unwanted mortality of 101 species of elasmobranchs, teleosts, crustaceans, marine birds, marine turtles, and cetaceans, most of them discarded at sea (Perez and Wahrlich 2005). The royal crab and a group of spider crabs (family Majidae) were also abundant in

**Table 8.1** Main finfish and shellfish species exploited in deep areas of the Brazilian continental margin. Biomass estimates refer to the period 2002–2006. Ov, over exploited; Fe, fully exploited; Un, unknown; MSY, maximum sustainable yield. After Perez et al. (2009)

| Species | Estimated biomass (t) | MSY (t/year) | Stock status 2009 | Mean catch (t) (after 2008) |
|---|---|---|---|---|
| Teleosts | | | | |
| *Lophius gastrophysus* | 62,776 | 2500–2000 | Ov | 2600 |
| *Merluccius hubbsi* | 21,934 | 2100–2200 | Fe/Ov | 1915 |
| *Urophycis mystacea* | 12,446 | 1182 | Fe/Ov | 5572 |
| Crustaceans | | | | |
| *Chaceon notialis* | 17,118 | 1027 | Fe | 0 |
| *Chaceon ramosae* | 11,634 | 593 | Fe/Ov | 357 |
| *Aristaeopsis edwardsiana* | 865 | 60 | Ov | 17 |
| *Aristaeomorpha foliacea* | 87 | 13–17 | Un | 6 |
| *Aristeus antillensis* | 50 | 9–11 | Un | <1 |
| Mollusks | | | | |
| *Illex argentinus* | Un | Un | Un | 552 |

the catches as well as the argentine hake, the codling, the beard fish (*Polimixia lowei*), the angel shark (*Squatina argentina*), and various skates. Visintin and Perez (2016), using a productivity–susceptibility risk analysis (PSA), estimated that over 80% of individuals captured non-intentionally by this fishery belonged to biologically vulnerable species, including four skates (genera *Dipturus*, *Atlantorraja,* and *Torpedo*) and five sharks (genera *Squalus*, *Squatina*, *Hexanchias*, *Echinorhinus,* and *Sphyrna*). A similar analysis assessed the retained catch of national slope trawlers revealing that 70% of individuals landed by this fishery were highly vulnerable to fishing mortality (Visintin 2015). These organisms belonged to eight species including some of those previously mentioned and the extremely vulnerable pink cusk-eel (*Genypterus brasiliensis*). Trawlers fishing for the deep-sea shrimps produced relatively abundant discards containing 108 species that included 72 fish, 19 crustaceans, and 10 cephalopod species (Perez et al. 2013). Because these were the deepest trawl fishing operations off Brazil, the affected megafauna included deep pelagic (e.g. family Neoscopelidae) and benthopelagic (e.g. families Macrouridae, Acropomatidae, Ophidiidae, Moridae, Ogcocephalidae, Etmopteridae) species also likely vulnerable to fishing mortality.

### *8.2.2 Biotechnological Products*

Biotechnology can be defined as the use of living beings or their products in commercial and industrial processes (Evans and Furlong 2003). Among the different types of living creatures that may be employed in biotechnology, microorganisms and bacteria in particular are key components of deep-sea ecosystems (Fang and Kato 2010; Gao et al. 2015; Zhang et al. 2016). In Brazil the prospection of biotechnological products from marine organisms, including those from the deep sea, has been another strategic initiative promoted by de PSRM under the BIOMAR[8] program since 2005 (CIRM 2009).

The diversity and prospection of deep-sea bacteria have been carried out by two approaches. The first one is based on the cultivation of microorganisms from the samples studied (culture-dependent approach); the second is based on the study of DNA and other molecules obtained directly from the samples (culture-independent approach) (Tringe and Rubin 2005). It is accepted that the latter is the best approach to access the majority of the components of the microbial communities, since most of the bacteria in marine samples are non-cultivable by traditional microbiology methods (Fuhrman and Hagström 2008). Nevertheless, the microbial cultures provide a more efficient way to study the physiology and may be essential to describe new bacteria species (Krieg 2001) and identify biotechnological uses of these organisms (Bhatnagara and Kim 2012). Finally, both approaches should be used in

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accessing the microbial diversity of a particular environment, since they may be complementary to each other in both the ecological and biotechnological contexts.

Culturable bacteria reported from culture-dependent studies in the deep South Atlantic are similar to those reported in other oceanic regions and belong to the phyla Proteobacteria, Bacteroidetes, Rhodothermaeota, Cyanobacteria, Firmicutes, and Actinobacteria (Schon et al. 2002; Berkenheger et al. 2003; Berkenheger and Fischer 2004; Wang et al. 2010; Odisi et al. 2012; da Silva et al. 2013; Li et al. 2014; Gao et al. 2015; Xu et al. 2016; Rigonato et al. 2016). These microorganisms were detected in samples of sediment (Odisi et al. 2012; da Silva et al. 2013; Gao et al. 2015; Xu et al. 2016), seawater (Schon et al. 2002; Wang et al. 2010; Rigonato et al. 2016), suspended organic aggregates (Berkenheger et al. 2003; Berkenheger and Fischer 2004), hydrothermal vents (Xu et al. 2016), and deep-sea animals (Deming et al. 1984), collected from the distinct regions of the South Atlantic including the Rio Grande Rise, the Equatorial, the mid-ocean ridge, and the Walvis Ridge regions.

In studies employing culture-independent techniques, the dominance of Proteobacteria in seawater of the deep Southeast Atlantic was also reported, which was represented mainly by Alphaproteobacteria, being *Alteromonas* as one of the most abundant genera. Other phyla included Cyanobacteria, Bacteroidetes, Verrucomicrobia, Acidobacteria, Actinobacteria, and Firmicutes (Friedline et al. 2012). In sediments collected from the Angola, Cape, and Guinea basins, Schauer et al. (2010) reported the dominance of the phylum Proteobacteria, including the classes Gammaproteobacteria and Deltaproteobacteria, and prominence of Acidobacteria. Other phyla detected include Chloroflexi, Bacteroidetes, and Planctomycetes.

The studies of the biotechnological potential of marine bacteria from the deep South Atlantic Ocean have focused mainly on hydrolytic enzymes and bioremediation. Enzymes are among the most prospected biomolecules from marine organism in general. Its application includes detergent supplementation (Nerurkar et al. 2013) and fuel production (Tan et al. 2010), for instance, and the interest in marine enzymes arises from their unusual properties including salinity, thermostability, and activity in high pressures (Debashish et al. 2005).

Lipases, i.e. enzymes that act on lipids, are the best studied enzymes in deep South Atlantic bacteria; these enzymes are produced by a wide range of marine bacteria, in agreement with its biological importance in the nutrition and the normal function of cells. Most of the marine bacteria with lipolytic activity were reported among the phyla Proteobacteria (class Gammaproteobacteria) and Firmicutes (class Bacilli) (Berkenheger et al. 2003; de Beer et al. 2006; Odisi et al. 2012). Important genera producing these enzymes include *Bacillus* and *Marinobacter*. Bacteria from sediments and suspended organic matter seems to be more lipolytic than those living free in the water (Berkenheger et al. 2003; Odisi et al. 2012), which may indicate the presence of polymeric and particulate organic matter in these microhabitats (Fenchel et al. 2012).

Other enzymes, such as cellulase, i.e. enzymes that act on cellulose, and amylase, i.e. those that act on starch, were also reported from bacteria isolated from the deep South Atlantic (Smith 1970; Berkenheger et al. 2003; Odisi et al. 2012; Lima et al. 2013). These bacteria were obtained from sediment samples of the Rio Grande Rise region (Odisi et al. 2012, Lima et al. 2013) and off the northeast coast of Brazil (Smith 1970), and from suspended organic matter of seawater collected at the South Equatorial region (Berkenheger et al. 2003).

Bioremediation is the use of organisms, mainly microorganisms, in the recovery of environments contaminated with oil, metals, and other toxic substances. Oil-degrading bacteria, with potential of bioremediation, have been isolated from deep waters of the equatorial and mid-ocean regions (Wang et al. 2010) and from the mid-ocean ridge sediments of the South Atlantic Ocean (Gao et al. 2015). Most of the isolated bacteria belong to the phylum Proteobacteria, with *Alcanivorax* and *Dietzia* being the most commonly reported genera from seawater and sediments, respectively.

Culture-independent approaches have also been used for the discovery of novel molecules with biotechnological potential (Fang et al. 2010; Leis et al. 2015; Ferrer et al. 2016). This is a promising approach for the biotechnological prospection of South Atlantic deep-sea microorganisms.

In general, recent initiatives to explore the deep sea off Brazil and in the South Atlantic, as previously mentioned, have provided opportunities for the prospection of microorganisms and molecules and their potential application in technological products and processes. Yet the country has benefitted little from these potentialities as the development of mechanisms of transformation, particularly in association with the industry, is still limited.

## 8.3 Non-living Resources

### *8.3.1 Oil and Gas*

The Brazilian continental margin has experienced a significant development of deep-sea oil exploration activities that were comparable to other productive areas such as the Gulf of Mexico and the North Sea. Petrobras has explored deep oil reservoirs for nearly 30 years, becoming a global player in offshore hydrocarbon production (Milani et al. 2000). A milestone in this exploration and exploitation process was the discovery of the giant 'Albacora' and 'Marlim' offshore oil fields, between 1984 and 1987, which represented not only an evidence of new frontiers for the oil industry but also a motivation for a subsequent technological leap, as required to improve oil extraction in deep and remote oceanic areas (Morais 2013). This leap involved significant investment in research programs designed to develop technological solutions for submarine systems including production outflow, production units, and their anchoring systems (Morais 2013).

Deep-sea post-salt deposits, found in areas deeper than 2000 m, are associated with ancient shales covered by deltaic progradations. In Campos Basin (Fig. 8.1), these turbiditic deposits contain oil reserves estimated in 12 billion barrels (Milani et al. 2000), being comparable to reserves found in other important deep-sea oil provinces of the world, such as those found off Congo, Niger, and Nile river deltas. The pre-salt oil fields are located along the Campos and Santos Basin (between 20° and 27°S), distributed within a marine area 800 km long, 200 km wide, and 5000–7000 m below the sea surface (Fig. 8.1). In this area, low-density oil reservoirs are found in a sequence of over 100 million years old sedimentary rocks, 3000–5000 m below the seafloor surface. These rocks are compressed below an extensive salt layer and are rich in organic matter originated in the continent and transported by river systems to troughs formed by the rifting process during the breakup of Gondwana (Morais 2013). Pre-salt oil and gas reservoirs comprise 30% of all Brazilian reserves, estimated (in 2014) in 16,183 billion barrels.

In recent years, over 80% of Brazil's annual oil and gas production has been extracted from deep (200–2000 m) and ultra-deep (> 2000 m) oil fields (Fig. 8.6). These areas comprise nearly 10% of all Brazilian oil fields in a production phase and are located in Campos and Santos basins, where extraction of oil and gas is mostly from pre-salt reservoirs. In 2017, the most productive fields included 'Lula' (2200 m depth, 73,4500 barrels per day), 'Sapinhoá' (2140 m depth, 25,2200 barrels per day), and 'Jubarte' (1355 m depth, 12,1700 barrels per day). The offshore oil and gas production in Brazil's EEZ has expanded towards deeper sedimentary

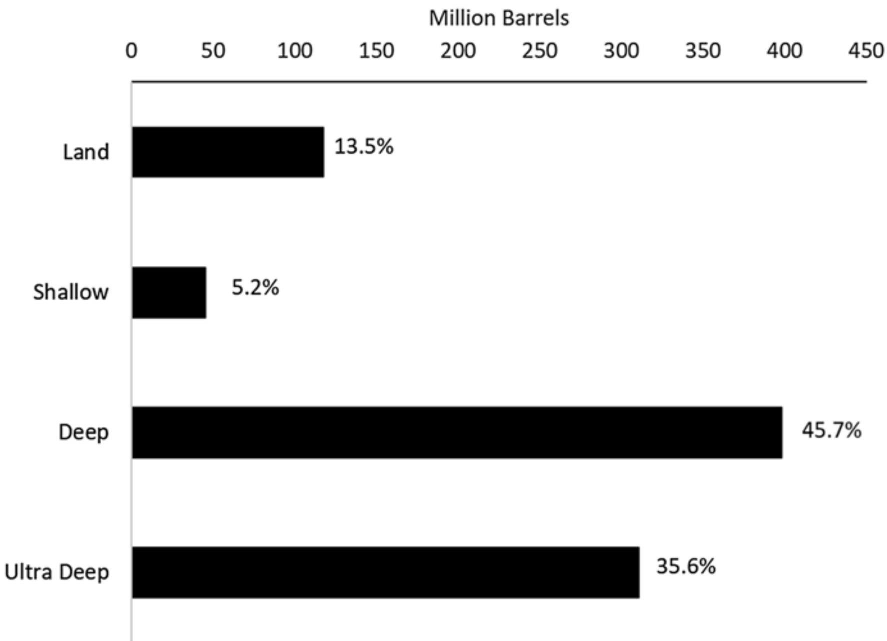


**Fig. 8.6** Total amount of oil extracted in Brazil between January and November of 2017 (million barrels) in land, shallow (0–200 m), deep (200–2000 m), and ultra-deep (> 2000 m) waters. Percentages indicate the relative contribution of each category to the total production. Data from the 'Brazilian National Agency of Petroleum, Natural Gas and Biofuels' – ANP (www.anp.gov.br)

basins in the equatorial and subtropical areas. New bidding rounds starting in 2017 are leasing hundreds of deep-sea offshore areas in the Amazon Basin, on the northeastern and southeastern margins (ANP 2017; Bernardino and Sumida 2017).

### *8.3.2 Phosphates*

Marine phosphate deposits tend to occur in authigenic sedimentary rocks (Notholt 1980; Slansky 1992) as a result of diagenetic processes (phosphogenesis) that take place in the sedimentary layers rich in organic matter mostly between 200 and 1500 m depth, under the effect of minimum oxygen zones, and low terrigenous sedimentation (Baturin 1982; Filippelli 2011). In addition, these deposits must have been reworked during the eustatic sea level oscillation, which occurred between the Triassic and the Quaternary periods, concentrating phosphorus in the seabed sediments (Glenn et al. 1994).

In general, phosphoric pentoxide ($P_2O_5$) is a minor component of marine authigenic sedimentary rocks. However, their concentration may raise above 18% in some rocks, which are known as 'phosphorites' (Trappe 1998, 2001). These deposits are often found in oceanic areas under the influence of permanent upwelling systems, which tend to occur in the western margin of most continents (Baturin and Bezrukov 1979; Baturin 1982) and on top of rises and seamounts in the deep sea (Glenn et al. 1994).

The Brazilian coast is located in the eastern side of the South American continent deprived of major permanent upwelling zones (Fig. 8.2). However, according to the global model of phosphogenesis proposed by Riggs and Sheldon (1990), natural conditions at the shelf break and on top of seamounts off Brazilian continental shelf tended to favour phosphogenesis and the formation of phosphorites during the transgression and regression of Lower to Middle Miocene (~25 to 10 MaBP), known as Episode II of phosphogenesis (Riggs and Sheldon 1990). In addition, along the Brazilian margin, there are small and seasonal upwelling events, from São Tomé Cape (20°S) to Santa Marta Grande Cape (28°S), determined by local wind-circulation patterns, which allow for moderate primary productivity enhancement (Acha et al. 2004) and which may have favoured modern phosphogenesis.

In the Brazilian EEZ, deposits of phosphorites have been recorded in the summit of Ceará Plateau (400 m depth, 3°S) and upper level of Pernambuco Plateau (700–1250 m, 8°S) (Millimann and Amaral 1974; Melo et al. 1978; Guazelli and Costa 1978; Menor et al. 1979; Schobbenhaus 1984; Lenoble et al. 1995; Santana 1999), in the Florianópolis Terrace (200–600 m, 28°S), and the Rio Grande Terrace (200–800 m, 30°S) (Abreu et al. 2014) (Fig. 8.1). Furthermore, backscattering and bathymetric data were used to map potential deposits in an extensive area between 200 and 1000 m depth from São Tomé Cape (20°S) to Chuí (34°S) (Pinho et al. 2011).

Phosphorites off Brazil were found to occur in different forms, including nodules with few centimetres in diameter, to plate-like crusts paving the seafloor (Fig. 8.7). They contain 0.2–27% of phosphoric pentoxide ($P_2O_5$), and in some rocks there are

**Fig. 8.7** Phosphate rocks dredged at the shelf-break off southern Brazil. (**a**) plate-like crusts, (**b**) nodules with few centimetres in diameter. (Photos by Luis H. P. de Souza. Scale = 15 cm)

significant contents of $Fe_2O_3$ (14%) and $TiO_2$ (1.7%) as well rare earth elements (REE) (Rocha et al. 1975; Lenoble et al. 1995). Recently, phosphate rocks were dredged by CPRM at depths between 700 and 1500 m on the Rio Grande Rise with high content of $P_2O_5$ (16.0 wt.%) and REE. These deposits represent the main substrate of Co-rich iron-manganese crusts (Cavalcanti et al. 2015).

Deposits found at the shelf break and upper slope, where $P_2O_5$ contents exceed 15%, can be regarded as potential mineral resources of the deep Brazilian continental margin, which are greatly demanded by the national agro-industry. In addition, phosphate rocks with a moderate to high contents of REE can be a likely source of raw materials needed for high-tech and green-tech development in the nearest future (Hein et al. 2016). Because available geochemical data is highly variable, a more precise delimitation of areas where phosphate mining can be economically viable is needed. CPRM has promoted and strongly supported these studies among the national scientific community in the context of the REMPLAC project.

### *8.3.3 Gas Hydrates*

Gas hydrates are methane molecules trapped inside ice crystalline structures. The combination of methane gas and frozen water is known as clathrate or methane hydrates. The origin of methane gas contained in hydrates is related to hydrocarbon reserves and the activity of bacteria on organic matter within the ocean floor, under high pressure and low temperature (<5 °C) (Clennell 2000; Grauls 2001). Gas hydrates are abundantly present in the frozen soil of polar and subpolar regions (e.g. permafrost), where they are formed a few metres below the soil surface, and in the deep ocean floor inside chilled layers of sediment that cover the lower slope and continental rise areas. Sediment layers that contain gas hydrates are generally found more than 500 m below the ocean surface and within the upper 100 m of the sedimentary package. In sedimentary areas of the Gulf of Mexico and the Niger River delta, they have been found in structures associated with gas escapement (Hovland et al. 1997). The so-called pockmarks are seafloor depressions formed by the dissolution of gas hydrate and its escape during glacial-interglacial cycles (Judd and Hovland 2007; Davy et al. 2010).

Gas hydrates are found in deep marine sediments of all continental margins and may comprise twice the volume of all known marine resources, including oil and gas (Clennell 2000). For that reason, they have been regarded as a future source of energy. Storing and using gas hydrates for that purpose, however, is still technologically difficult; one cubic metre of methane trapped in the clathrate structure will expand to 164 $m^3$ of gas when exposed to normal levels of pressure and temperature and can combust spontaneously. Moreover, methane is an important greenhouse gas and its usage may imply important environmental consequences related to global warming.

Gas hydrates have been reported off Brazil on the Amazon submarine fan and in the Rio Grande Cone on the Southwest Atlantic (Fig. 8.1, Maslin et al. 1998, Sad et al. 1998, Fontana and Mussumeci 1994, Giongo et al. 2016). Pockmarks with diameters as large as 230 m were also reported in association with salt diapirism and extensional faults that likely promote gas hydrate seepage in Santos Basin between 300 and 800 m (Sumida et al. 2004; Sharp and Badalini 2013; Schattner et al. 2016; Mahiques et al. 2017). Evidence of methane gas seepage were also recorded in sediment cores obtained inside a pockmark in the Pelotas Basin (Miller et al. 2015). Using seismic data, these authors also proposed the likely presence of gas hydrates in the Rio Grande Cone. In addition, chemosynthesis-based communities were found in the same area (Giongo et al. 2016).

These indications are little comprehensive and insufficient for any projection about the future use of these hydrates as sources of energy in Brazil. However, ongoing research projects are directing efforts and resources to understand the existence of large pockmark fields and their association with methane seepage off the coasts of São Paulo, Paraná, and Santa Catarina States (Schattner et al. 2016, Mahiques et al. 2017).

### *8.3.4 Metal-Rich Mineral Deposits*

Cobalt-rich ferromanganese crusts, polymetallic nodules, and seafloor massive sulphides are metallic mineral deposits found on deep oceanic basins and topographic features (e.g. seamounts and ridges) with potential for commercial exploitation in the future (Hein and Koschinsky 2013; Boschen et al. 2013). Seafloor massive sulphides (SMS) are formed by precipitation of sulfides and metals dissolved in 200–400 °C seawater expelled from hydrothermal vent systems (Boschen et al. 2013). The full process involves (a) percolation of deep seawater into the seafloor leading to (b) subsequent heating by geothermal activity with dissolution of metals and sulfides from surrounding rocks and (c) their precipitation when such fluids mix again with cold seawater. This precipitation can take place below or above the seafloor, in the latter case forming chimneys around the point of hydrothermal fluid flow (vent), which will eventually collapse and form mounds. SMS deposits have been found in areas of volcanic activity, particularly near the central axis of mid-ocean ridges and back-arc spreading systems, and can contain varying proportions of Cu, Zn, Al, as well as gold and silver (Boschen et al. 2013). These deposits have been little explored in the South Atlantic Ocean, yet they are likely to occur along the mid-Atlantic ridge including areas within Brazil's EEZ in the vicinity of St. Peter's and St. Paul's Archipelago (Fig. 8.1, CGEE 2007).

Polymetallic nodules typically occur between 3500 and 6500 m depth and over sediment-covered basins. They grow around a nucleus by precipitation of Fe and Mn oxides that originate from seawater, pore water, and a mixture of both (Hein et al. 2013). Seawater (hydrogenic process) is the main source of Co that concentrates in deposition areas defined by specific geomorphology and deep-water flux regimes (Palma and Pessanha 2000). Pore water (diagenetic process) is a source of other metals such as Ni and Cu. Nodule fields are extensive below areas of moderate to high primary productivity, high oxygen concentration, low sedimentation rate, high availability of nuclei, and usually below the calcite compensation depth (Hein et al. 2013). The most prominent known nodule field is located in central Pacific Ocean, an area known as Clarion Clipperton Zone (CCZ) where nearly 34 billion tons of nodules have been estimated, containing large amounts of Mn (7.5 billion tons), Ni (340 million tons), Cu (265 million tons), and Co (78 million tons) (Morgan 2000; Martins et al. 2006; Cavalcanti 2011). Other known fields are in central Indian Ocean, Peru basin (SE Pacific), and the Blake Plateau, (NE Atlantic) (Manhein 1972; Palma and Pessanha 2000; Cavalcanti 2011).

Polymetallic nodules were first recorded off Brazil in 1974, during the geological surveys conducted under the REMAC project. Nearly 150 kg of polymetallic nodules were sampled in the Pernambuco Plateau, northeastern Brazil, between 1750 and 2200 m depths (Fig. 8.1, Souza et al. 2009). The nuclei of these nodules were formed by phosphorites containing 28% of phosphorus, and the periphery contained Mn (20–30%), Fe (30%), Ni (0.2–1.4%), Co (0.6–1.55%), Cu (0.04–0.26%), Pb (0.08–0.53%) and Zn (0.12%) (Melo et al. 1978). Other areas of nodule occurrence near the Brazilian continental margin include the Vema Channel and the flanks of Vitória-Trindade Chain (Fig. 8.1, CGEE 2007).

Cobalt-rich ferromanganese crusts normally occur between 400 and 4000 m depth as pavements or as coatings on hard rock surfaces. Deposits are found on flanks and summits of isolated seamounts, oceanic rises and ridges, plateaus, and abyssal hills where the rocks have been swept clean of sediments for millions of years (Hein et al. 2000). Crusts may form from diagenetic, hydrogenetic, or hydrothermal processes (Roy 1992; Usui and Someya 1997). Crusts of higher economic interests are formed over the seafloor by precipitation and accretion of Fe and Mn oxides from cold seawater (hydrogenetic) and are probably influenced by bacterial biomineralization that increases trace metal concentrations including Co, Ni, Cu, Zn, Pt, Te, Ce, and Tl (Hein et al. 2000; Liao et al. 2011; Hein et al. 2013).

Hydrogenetic cobalt-rich ferromanganese crusts grow at rates of approximately 1 to 5 $mm.My^{-1}$. Crust growth is more effective in areas below the minimum oxygen zone where concentrations of dissolved Mn and associated metals are highest (Hein et al. 2013). The thickness of the crusts can vary from a few centimetres to 25 cm. Deposits may cover approximately 1.7% of ocean seafloor surface (6.3 million $km^2$) and are thickest between 800 and 2200 m depths in the Northwest Pacific, where seamounts date back to the Jurassic Period, the oldest recorded in the world ocean (Hein 2006; Cavalcanti 2011). In the Brazilian EEZ, cobalt-rich ferromanganese crusts were reported in the Pernambuco Plateau, northeastern Brazil, but the most significant deposits were found in the Rio Grande Rise (Fig. 8.1, Martins et al. 2006). Such a finding motivated the implementation of the PROAREA program (see above), which promoted prospecting operations of CPRM in the area, between 2009 and 2011, using both national and foreign research vessels. Seafloor mapping and geological sampling during these surveys allowed the description of areas of crust distribution and characterized plate-like and film-like crust pavements (Fig. 8.7) that frequently covered phosphate rocks as nuclei (Cavalcanti et al. 2015). Mean crust geochemical composition indicated the presence of MnO (26.7%), $Fe_2O_3$ (27.7%), Co (0.81%), Ni (0.37%), and other trace metals (Ba, Cu, Ce, $TiO_2$) (Cavalcanti et al. 2015).

Because the Rio Grande Rise was originally located in areas beyond national jurisdiction, these prospective studies were used for the elaboration of a 'Plan of Work' for crust exploration, submitted in 2013 to the ISA. In 2015, a fifteen-year contract was signed between Brazil's CPRM and the ISA, whereby new surveys were carried out in the Rio Grande Rise, improving knowledge on these deposits and their potential for exploitation, as well as on the associated benthic ecosystem, as required by the ISA regulations (see below). Substantial contributions to such knowledge have also derived from scientific surveys conducted under the E-tech project in 2018–2019 (Jovane et al. 2019).

After the development of the offshore oil and gas production, the exploration of cobalt-rich ferromanganese crusts in the Rio Grande Rise area represented a new milestone in the national process of developing means for exploitation of deep-sea non-living resources. The scientific results attained during exploration activities, combined with political interests, further motivated the Brazilian Government to include the Rio Grande Rise area in a proposal for extension of the limits of Brazilian EEZ submitted in 2018 to the UN Commission on the Limits of the Continental Shelf (Alberoni et al. 2019).

## 8.4 Sustainable Use and Conservation Issues

### *8.4.1 Fisheries Management*

In 1999, the management of underexploited or unexploited fisheries resources in Brazil was attributed to a specific management authority, outside the regular fishery administration regime established by the Ministry of the Environment. When the deep-sea fishery development initiated in 2000, most resources fell within this definition, being, since then, submitted to a less restrictive management regime. This management regime included an advisory committee composed of representatives of government authorities, fishers, and scientists, with the mandate to propose management measures for deep-sea fisheries and resources. A parallel scientific committee was also created to promote deep-sea fisheries data collection by observers on board fishing vessels, logbooks, and landings monitoring systems. Based on available data, this scientific committee assessed commercial stocks and proposed management options.

Between 2001 and 2008, the advisory committee effectively proposed timely management plans for the monkfish fishery, multi-species slope trawl, and red and royal crab fisheries (Perez et al. 2009). Their implementation, however, was generally slow, obstructed by ineffective governance, and therefore unable to prevent overfishing of most resources. After 2008, the advisory committee structure was deactivated and management of deep-sea resources was reincorporated into a regime common to all fishing resources, which involved a top-down decision process shared by fishing authorities of the Ministry of Environment and the recently created Ministry of Fisheries and Aquaculture. This ministry was extinct in 2015 leading to a period of uncertainty in the country's fishing management process. In 2019 this process concentrated again in a single agency linked to the Ministry of Agriculture and Livestock.

After nearly 10 years of the termination of the foreign fleet activity in slope areas, and in the absence of any new significant fishing activity in the area, recovery of deep-sea stocks such as deep-sea crabs and deep-sea shrimp is uncertain. Stocks of monkfish and other slope fishes however have remained under considerable fishing pressure exerted by trawlers and their management regime is currently unclear (Dias and Perez 2016).

Another legacy of the 2000–2008 deep-sea fishery management regime was the adoption of two 'no take' areas as spatial management measures in the monkfish and slope trawl fisheries management plans (Perez 2007). These zones were placed across the slope topographic profile, between 100 and 1000 m depth, off the states of Santa Catarina and Rio Grande do Sul (28° and 30°S) and off the state of São Paulo (23° and 25°S). Their design aimed at protecting the monkfish stock integrity and reducing the unintentional mortality of megafaunal species including sharks, cetaceans, wreckfish, and royal and spider crabs (Perez and Wahrlich 2005). Their adoption extended to other management plans in the area, but their enforcement has been inefficient due to the generally unstable governance of the fishing management regimes in Brazil (Perez et al. 2009).

### *8.4.2 Leasing of Offshore Oil and Gas Fields*

Activities involving exploration, development, and exploitation of oil and gas in the marine environment are conducted in Brazil through concession contracts obtained after a bidding process (Mariano and La Rovere 2007). Because such activities are capable of potentially causing pollution and habitat degradation (Cordes et al. 2016), contractors must submit their projects to an environmental licensing process carried out by the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA). Most activities related to drilling of wells for prospection of oil and gas reservoirs and production, either for research or commercial purposes, are regulated by specific legal instruments, whereas marine seismic surveys follow Brazil's general regulations for environmental licensing. Each of these activities requires environmental impact assessments (EIA) and specific licenses from IBAMA (Porto et al. 2007). These assessments must follow project-based guidelines issued by IBAMA after the project submission by the contractors. Licenses for installation of offshore structures are valid for up to 10 years, and all other activities, including seismic surveys, are licensed by IBAMA for periods compatible with the schedule of approved activities.

In general terms, IBAMA has demanded Petrobras and other oil companies operating in Campos and Santos Basin to conduct environmental studies that allow assessing the effects of seismic and other activities of the oil industry on vulnerable fauna and coastal fishing activities. Baseline studies on the deep-sea basins where oil and gas offshore activities take place have included extensive chemical, physical, biological, and ecological assessments (Lavrado and Brasil 2010b; Bernardino et al. 2016; Almeida and Kowsmann 2017; Lavrado et al. 2017a, b; Silveira et al. 2017). However, whereas these broad baseline studies have provided important environmental characterization of slope and abyssal areas within offshore oilfields, the occurrence of deep-sea vulnerable ecosystems, including cold-water coral reefs and cold seeps, has still been largely overlooked (Bernardino and Sumida 2017). For example, there is large evidence for the presence of deep-sea seeps (Sumida et al. 2004; Giongo et al. 2016; Fujikura et al. 2017; Mahiques et al. 2017), cold-water coral reefs and submarine canyons within offshore fields (Almada and Bernadino 2017; Bernardino et al. 2019). Yet areas offered on bidding rounds by the Brazilian Government (ANP) broadly overlap areas where these vulnerable ecosystems occur, a sign that existing baseline environmental assessments may have been completely disregarded (Almada and Bernadino 2017). In Campos Basin, for example, the offshore oil and gas leased blocks significantly overlap (>80% of ecosystem area) with cold-water coral reefs and submarine canyons. Furthermore, the expansion of the offshore industry in the 14th ANP biding rounds (2017–2019) have the potential to expand the overlap of leased areas with vulnerable deep-sea ecosystems to other basins in the northern, northeastern, and southern margins of Brazil's EEZ (Bernardino and Sumida 2017).

### *8.4.3 Licensing Mineral Exploration*

The use of mineral deposits, either terrestrial or marine within Brazil's EEZ, require a two-stage authorization process that will result in research and mining permits, both issued by the Ministry of Mines and Energy (MME). This permit determines a period whereby applicants will assess the deposit qualitatively and quantitatively as well as the feasibility of its economical use. Results of these studies are then submitted in the form of a report to the National Mining Agency (ANM) who will decide on its approval and determine if the project can proceed to the second stage. The concession for mining permits will require a submission to ANM of a plan of economical use that will delimit precisely the exploitation area and the mining activities. If approved, DNMP will grant a mining concession for an undetermined period of time (Cavalcanti 2011).

Because mining activities potentially degrade the environment, deep-sea mining within the EEZ also requires an Environmental Impact Assessment (EIA), environmental licensing, and, eventually, a plan for recuperation of a degraded area. All permits are issued by IBAMA, but they are mandatory for mining concessions only, and not research activities. The EIA must be contained in an Environmental Impact Report whose approval by IBAMA determines whether the mining project can be granted an environmental license or not. Also, a plan for recuperation of degraded areas should be submitted and approved by IBAMA, whereby it is indicated how natural conditions will be restored once mining is ceased in the licensed area. Because deep-sea mining has not been attempted in the Brazilian jurisdictional waters, these are all regulations prescribed by law, but never put in practice in Brazil.

Outside the EEZ limits, Brazil's initiatives to explore deep-sea minerals are submitted to UNCLOS and regulations established by the ISA. Mining companies, sponsored by an UNCLOS member State, can apply for prospection, exploration, and exploitation permits in the area. Exploration permits have been requested in international areas and follow 'mining codes' developed for polymetallic nodules (ISBA 2013), Cobalt-rich ferromanganese crusts (ISBA 2012), and SMS (ISBA 2010). These regulations require applications to inform the size of exploration area, in the case of ferromanganese crusts formed by no more than 150 rectangular blocks with 20 $km^2$ surface (total of 3000 $km^2$). They must also contain a 'Plan of Work' for the first 5 years of activities describing an exploration program, with detailed oceanographic and environmental baseline studies that would enable an assessment of the potential environmental impacts of exploration activities. The plan must also provide a preliminary assessment of the possible impact of the proposed exploration activities on the marine environment and detail proposed actions for the prevention, reduction, and control of pollution and other hazards (ISBA 2012). The Plan of Work is reviewed by ISA's Legal and Technical Commission (LTC) who has the mandate to recommend its approval to ISA's Council and Assembly. After the contract is signed between the applicant and the ISA, the contractors must deliver annual reports and environmental data collected in the claim area to the ISA secretariat who will submit to the LTC for approval.

CPRM's Plan of Work for cobalt-rich ferromanganese crusts was recommended for approval by the LTC in February 2014 and approved by the Council and Assembly in July 2014. It includes the development of environmental baseline studies in the claim area on the Rio Grande Rise during the first 3 years (2016–2018) and geological exploration studies in the following 2-year period (2019–2020). In 2017–2018, CPRM submitted annual reports, informing results of exploration activities in claim area. In the context of the inclusion of this area in the extension of the Brazilian EEZ, the development of the referred 'Plan of Work' is currently uncertain. As part of Brazilian extended EEZ, any cobalt crust exploration/exploitation initiative in the Rio Grande Rise would normally follow national regulations, as previously described.

### *8.4.4 Ecosystem Conservation*

In 2007 the Brazilian Ministry of the Environment defined priority areas for conservation in the national territory and marine areas within national jurisdiction (MMA 2007). Extensive deep-sea areas were classified as 'insufficiently known', yet some deep regions were considered of 'extreme biological importance' both in the continental margin (e.g. Rio Grande Terrace and Rio Grande Cone) and the adjacent oceanic basin mostly around oceanic islands (e.g. St. Peter's and St. Paul's Archipelago, Fernando de Noronha, Trindade, Rocas Atoll) and seamounts (e.g. Vitória-Trindade Chain, Almirante Saldanha bank, Sirius, and others).

Beyond areas of national jurisdiction, a number of governmental initiatives have established procedures regarding conservation of deep-sea ecosystems all of them applicable to the Southwest Atlantic. Deep-sea fisheries in the high seas, for example, have been submitted to management recommendations that include criteria for identifying and protecting 'Vulnerable Marine Ecosystems (VMEs)', i.e. communities and organisms that when submitted to 'adverse impacts' would hardly recover (FAO 2016). These recommendations however have been mostly applied in regional fisheries organizations, non-existing in the SW Atlantic (Rogers and Gianni 2010). A similar concept was defined by the Convention on Biological Diversity (CBD) as 'Ecologically and Biologically Significant Areas' (EBSAs) to be used as starting points to the definition of marine protected areas in the high seas (Smith et al. 2008b; Wedding et al. 2013; Dunn et al. 2014). Four EBSAs proposed in the 'Wider Caribbean and Western Mid-Atlantic Region' encompass deep-sea areas off Brazil: (a) Banks Chain of Northern Brazil and Fernando de Noronha, (b) Abrolhos Bank and Vitória-Trindade Chain, (c) Southern Brazilian Sea, and (d) Atlantic Equatorial Fracture Zone and high productivity system (CBD 2014). The latter covers a large extension across the equatorial Atlantic including crests and trenches of the Romanche Fracture Zone and Saint Peter's and Saint Paul's Archipelago and its surrounding EEZ. This area was also considered an 'Area of Particular Environmental Interest - APEI' (sensu Lodge et al. 2014) in the process for designing a Strategic Environmental Management Plan (SEMP) for the northern Mid-Atlantic Ridge (Dunn et al. 2018). In 2018 a large marine-protected area was created around the Saint Peter's and Saint Paul's Archipelago aimed at preservation of '… the marine environment, water column and seamounts … ' (Brasil 2018).

Finally, in 2015 the United Nations General Assembly proposed the ongoing development of an international legally binding instrument under UNCLOS on the conservation and sustainable use of marine biological diversity in areas beyond national jurisdiction (ABNJ) (UNGA 2015). Focal points of this instrument include regulations regarding the access to marine genetic resources in the high seas (Druel et al. 2013), which will be applicable in the South Atlantic basin, where bioprospection initiatives have been carried out by Brazil (e.g. Odisi et al. 2012; Lima et al. 2013) and other countries.

## 8.5 Conclusions

The use of living and non-living resources of Brazilian deep waters and adjacent Southwest Atlantic basin has been guided by different motivations and subject to different levels of scientific knowledge on their occurrence, value, availability, and productivity potential (Table 8.2). It has also been limited by the existence and availability of technologies suitable for extraction and transformation into products, and a regulatory process that ensure sustainability, in a broad ecological sense.

Fisheries resources and oil and gas have been explored with extant technologies during the past decade or more. Deep-sea fishing requires a costly transformation of traditional fishing fleets, but stocks were shown to be little productive and little

**Table 8.2** Qualitative assessment of the use of deep-sea living resources in Brazil

| | Living | | Non-living | |
|---|---|---|---|---|
| | Fish and shellfish | Biotech products | Oil and gas | Mineral deposits |
| Main motivations to exploit | Economic | Economic | Economic | Economic |
| | Compensation for productivity loss of shallow water stocks | Scientific and technological development | Self-sufficiency in oil production | Geopolitical strategy |
| Knowledge on natural occurrence and availability | Mostly known | Insufficiently known | Mostly known | Insufficiently known |
| Known potential productivity | Low | Uncertain | High | Uncertain |
| Availability of technologies for exploitation and use | Available | Partially available | Mostly available | Mostly unavailable |
| Availability of regulations for sustainable use or to minimize environmental impacts | Mostly available (but little effective) | Unavailable | Available (but likely insufficient) | Mostly available (but effectiveness is uncertain) |
| Perspectives of use in the future | Unpromising (but possible in very small scale) | Uncertain but promising | Promising | Uncertain but promising |

resilient, sustaining only very small fisheries. Deep-sea oil and gas reserves, on the contrary, are estimated to be large and suitable for extraction. In part, such a contrast is historically associated with the genesis of the South Atlantic Ocean that favoured the formation of extensive oil deposits along sedimentary margins off Brazil, but also led to the formation of a nutrient-poor subtropical gyre that influences most of Brazil's continental margin and consequently sustains limited fish exploitable biomass, especially in deep areas. Both activities, however, leave clear footprints in the deep-sea environments, with impacts not fully dimensioned or prevented by environmental regulations.

On the other hand, biotechnological products and deep-sea minerals have been preliminarily prospected and their potential use in the next decade is uncertain. The former depends on microorganisms (or their DNA) extracted from the deep-sea environments at the cost of little (or none) environmental impacts. Yet the transformation of potentially useful molecules and genes into technological products still needs considerable development, although with promising results. Mining deep-sea minerals is still largely dependent on the availability of suitable technologies, and most of the countries' efforts have been focused on acquiring knowledge not only on the potential of deposits but also on environmental impacts by exploitation activities.

A major concern, common to all deep-sea resources off Brazil, includes the effectiveness of the regulatory and management processes. Deficiencies, particularly regarding governance issues, have greatly hampered deep-sea fishing and may affect other activities as well. International management regimes, as required outside areas of national jurisdiction, are sometimes absent, for example, in the case of demersal fisheries in the SW Atlantic that, unlike other regions, lack a regional management body. In other cases, regulations have been in place (e.g. ISA's mining codes), but probably need improvement to effectively protect sensible areas and their fragile biodiversity (Wedding et al. 2013).

**Acknowledgements** Authors are grateful to the Geological Survey of Brazil (CPRM) and the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP) for making available information essential for this review. The senior author is supported by CNPq – Ministry of Science, Technology, Innovation and Communication (process 310504/2016-3).

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