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Geodiversity and biodiversity: an integrated analysis as a basis for the sustainable exploitation of the mineral resources of the Albardão Continental Shelf, Pelotas Sedimentary Basin, RS, Brazil

PAULO H. MATTOS[1*], CARLOS R. A. TAGLIANI[1], RAPHAEL M. PINOTTI[2], JOÃO L. NICOLODI[1], LAURO J. CALLIARI[1], TIAGO B. R. GANDRA[3] & WASHINGTON L. S. FERREIRA[4]

[1] *Laboratório de Oceanografia Geológica, Universidade Federal do Rio Grande (FURG), CP 474, CEP 96201–900 Rio Grande, Brazil;*
[2] *Laboratório de Ecologia de Invertebrados Bentônicos, Universidade Federal do Rio Grande (FURG), CP 474, CEP 96201–900 Rio Grande, Brazil;*
[3] *Instituto Federal de Educação, Ciência e Tecnologia do Rio Grande do Sul – IFRS, Brazil;*
[4] *Laboratório de Gerenciamento Costeiro, Universidade Federal do Rio Grande (FURG), CP 474, CEP 96201–900 Rio Grande, Brazil*

*Corresponding author: mattos.paulo@gmail.com

Abstract: Seabed compartmentalization for classification purposes can be achieved in different ways and at varied scales depending on the purpose, methods employed and data availability. The aim of this study was to identify the environmental fragility of the Albardão Continental Shelf and its spatial variation, confronting the result with the spots of the existing mineral resources and assessing the potential of environmental conflict resulting from the integrated analysis, specially regards the occurrence of endemic and threatened benthic fauna. Despite the high potential for mineral exploration, the Albardão area presents some environmental fragility due to the presence of endemic and endangered benthic species, as well as the presence of submerged features, such as beach rock outcrops and linear sandy ridges with high ecosystem potential, providing shelter, food and favor reproductive aggregations to fish assemblages. The conflict maps produced in the present work are a good reference to give the initial support necessary to decision makers and is already an advance to the marine management process that must be continually updated, revised and improved.

Key words: Benthic fauna; endangered species; marine spatial planning; conservation; mining.

Resumo: Geodiversidade e biodiversidade: análise integrada como subsídio à explotação sustentável dos recursos minerais da Plataforma Continental do Albardão, Bacia Sedimentar de Pelotas, RS, Brasil. A compartimentalização do leito marinho para fins de classificação pode ser feita de diferentes maneiras e em escalas variadas dependendo do objetivo, métodos empregados e disponibilidade de dados. O objetivo deste estudo foi identificar a fragilidade ambiental da Plataforma Continental do Albardão e sua variação espacial, confrontando o resultado com os locais dos recursos minerais existentes e avaliando o potencial de conflito ambiental resultante de análise integrada, especialmente em relação à ocorrência de espécies bentônicas endêmicas e ameaçadas. Apesar do alto potencial de exploração mineral, a região do Albardão apresenta certa fragilidade ambiental, devido à presença de fauna bentônica endêmica e ameaçada de extinção, bem como à presença de feições submersas, como parcéis e bancos arenosos lineares com alto potencial ecossistêmico, os quais fornecem abrigo, alimento e favorecem as agregações reprodutivas para peixes ósseos e elasmobrânquios. Os mapas de conflito produzidos no presente trabalho são uma boa referência para dar o apoio inicial necessário aos tomadores de decisão e podem ser considerados um

avanço ao processo de gestão marinha que deve ser continuamente atualizado, revisado e melhorado.

Palavras-chave: Fauna bentônica; espécies ameaçadas de extinção; planejamento espacial marinho; conservação; mineração.

Introduction

The multiple interests in the marine and coastal areas have been fostering an increasing number of activities, some of them conflicting and counteracting exploitation and conservation agendas. These conflicts tend to weaken the ability of ocean environments to provide the many ecosystem functions, goods and services. Studies around the world have analyzed the relationship between coastal mining and the sustainable management of the marine environment, as well as possible impacts on biota (Earney 1990, Hilton 1994, Newell *et al*. 1998, Hitchcock & Bell 2004, Kim & Lim 2009).

However, some human uses of these environments are rising at levels that challenges our ability to plan them from a sectoral approach, requiring a more integrated and proactive method to planning and management of these uses and activities (IOPTF 2009). Most countries have already developed zoning of the marine space for various human activities such as maritime transport, oil and gas exploration, mining, renewable energy development, offshore aquaculture, and waste disposal. An example of this is the seabed mineral exploitation, which, if carried out in an unplanned manner, can cause serious damage to the upper layers of the sea floor, especially in the first centimeters, where most benthic fauna live (Earney 1990).

The concept of geodiversity emerged at the end of the 1990s, as a tool applied to the management of protected areas, due to the need for a term encompassing the abiotic elements of the natural environment (Brilha 2002, Serrano & Ruiz Flaño 2007, Gray 2008, Panizza 2009). According to Silva *et al*. (2008a), the application of geodiversity studies geared to territorial planning would function as an indicator of the skills and restrictions of the use of the physical environment of an area, as well as the impacts arising from its geologically inappropriate use. In the marine realm, this theme is rarely approached, with applications restricted to emersed portions of the oceanic islands or to coastal environments (Nunes *et al*. 2007, Felton 2010, Brooks *et al*. 2011, Gordon & Barron 2011, Rovere *et al*. 2011, Brooks *et al*. 2012, Kaskela *et al*. 2012).

In Brazil, the concept developed almost simultaneously with the international initiatives, with a focus geared to the characterization and quantification of geological heritage (Silva *et al*. 2008b). However, the initiatives to zoning the seabed to recognize its geodiversity are incipient in the literature (Maia & Castro 2015), which becomes an obstacle in the establishment of conceptual models derived from an integrated analysis.

According to Roff & Taylor (2000), one of the seabed data integration strategies is associated with the recognition of marine landscape units, which consist of the classification of a marine system compartment where interactions between different abiotic variables (sedimentology) and biotic (benthic fauna) provide a particular support for the establishment of landscape classes, which may be ecologically correlated to biotopes or habitats (Roff *et al*. 2003, Galparsoro *et al*. 2012). At Brazilian Southern Continental Shelf (BSCS) the benthic fauna deserves special attention, due to the presence of endemic species, such as the sea pansie *Renilla tentaculata* (Zamponi *et al.* 1997) and also large aggregations of echinoderms such as the sand dollar *Encope emarginata* and the starfish *Astropecten cingulatus*, this latter an endangered species (Machado *et al*. 2008), overlapping with deposits of sand and biodetritic gravel and generating potential conflicts between exploitation and preservation.

Benthic communities present an important ecological role in the trophic structure of marine systems, especially in terms of energy flow and nutrient cycling, being characterized as the intermediate link between the primary producers/consumers and the higher trophic levels (Coll *et al*. 2009, Nascimento *et al*. 2012). Mapping biologically and ecologically important areas, such as BSCS, together with their associated human uses and policies, has been emphasized as an important first step to supply a general framework and strategic tools for the sustainable development of this realm by combining an optimized use with a sustained ecosystem of high quality (Crowder & Norse 2008, Katsanevakis *et al.* 2011).

Marine Spatial Planning (MSP) is a practical way to create and establish a more rational organization of the use of marine space and the

interactions between its uses, to balance demands for development with the need to protect marine ecosystems, and to achieve social and economic objectives in an open and planned way (Ehler & Douvere 2009).

Several countries have been carrying out projects involving marine and coastal spatial planning. Some good examples including the establishment of the Protected Marine Area (MPA) of the Australian Great Barrier Reef and its management actions as precursors in the regulation of the marine space uses (Day 2002). Also, the territorial organization of the Belgium Sea, with the definition of different scenarios (Douvere *et al*. 2007) and an important stepping for effective MSP with the assessment of all marine biotopes in terms of goods and services provided and their sensitivity to human activities around Europe (Salomidi *et al*. 2012).

Specifically in the Brazilian case, the shared use of the marine environment in a planned and organized way is a challenge. In addition to dealing with the dimensions of the national territory, this planning process presupposes the involvement and participation of the different sectors that operate in the marine and coastal areas (MMA 2018). The discussion on this theme has started with the "International Seminar on Marine Spatial Planning, organized in 2014 by the Brazilian Environment Ministry and the support of UNESCO. Currently, the process is under discussion in the framework of the Interministerial Commission for the Sea Resources (CIRM) which, supported by several governmental institutions and the society, is preparing the scope for the first MSP in the country.

With the purpose of subsidizing solutions to these conflicts and suggesting management strategies appropriate for the maintenance of ecosystem functions and the establishment of Marine Spatial Planning, this study aims to identify natural fragility in the region of Albardão (Pelotas Basin), according to the potential of mineral exploration in the area, through an integrated analysis between the local geodiversity and the bioecological and socioeconomic components.

Study area: The study area comprises a part of the Continental Shelf adjacent to the Albardão Lighthouse (CSA) located in the southern portion of the Pelotas Sedimentary Basin (Fig. 1) between 32°88' / 33°74'S and 51°41' / 52°20'W. Climatologically, the region corresponds to a hot-temperate (Cfa - mesothermic) transition zone, due to the influence of the South - West Atlantic

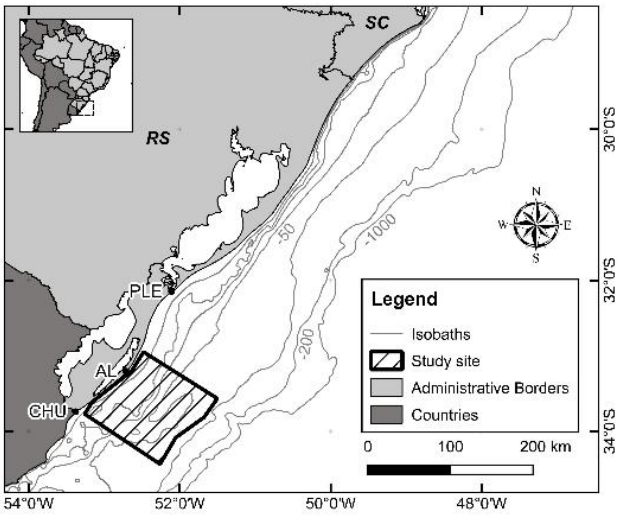

Figure 1. Location and boundaries of the study area within the Pelotas Basin area, southwestern Atlantic. **PLE**: Patos Lagoon estuary; **AL**: Albardão lighthouse; **CHU**: Chuí creek.

Subtropical Convergence (Semenov & Berman 1977).

In relation to the geomorphological characteristics, CSA presents very peculiar morphology and sedimentology, such as the presence of linear sand ridges, some of them associated with beach rocks outcrops (sand and shell fragments cemented by calcium carbonate), which comprises a limestone resource (Figueiredo Jr. 1975, Corrêa 1983), as well as a sandy belt that constitutes a past expression of an extensive sandy coastal plain at a recessive sea level (Corrêa 1987). It is also possible to observe the presence of paleochannels located in the southern limit of the inner and middle shelf, respectively delimited by the depths of 50 and 100m and also identified from the textural and mineralogical characteristics during the "Geocosta Sul I Expedition" carried out by the Laboratory of Geological Oceanography at the Federal University of Rio Grande - LOG/FURG (Abreu & Callliari 2005).

The substrate type is the main factor that influences the distribution and abundance of the macrobenthic fauna (Gray & Fisher 1981, McLusky & McIntyre 1988, Capítoli & Bemvenuti 2004), since the environments with a greater variety of bank types tend to present greater diversity of species (Fresi *et al*. 1983). This region is also a significant part of the nurseries for regional populations of 19 elasmobranchs species, seven of them critically endangered (Vooren & Klippel 2005).

Methods

Due to the availability of an extensive database on the Continental Shelf of the Rio Grande do Sul state, the compilation of abiotic, biotic and socioeconomic information from the Albardão region was use, generating a unique database, as well as an integrated analysis that could to subsidize actions related to Marine Spatial Planning. The sedimentology data was obtained from the Center of Coastal and Oceanic Geology Studies/Federal University of Rio Grande do Sul (CECO/UFRGS) and the Laboratory of Geological Oceanography/Federal University of Rio Grande (LOG/FURG). Data on the occurrence of mineral resources (heavy minerals and limestone) was gathered from the Brazilian Geological Survey Agency (CPRM), bathymetric data was collected by the Laboratory of Applied Hydroacoustics and benthic data was collected by the Laboratory of Macrobenthic Ecology, both at the Federal University of Rio Grande (FURG).

After reviewing and formatting the available information, these secondary data formed a digital database in the 2.14 Quantum GIS software, in which the respective thematic maps were created. These maps were analyze in an integrated way in the software Idrisi Selva® through multicriteria analysis.

The environmental fragility map was generated taking in to account five vulnerability factors: 1- sediment classification (gravel, very coarse sand, coarse sand, medium sand, fine sand, very fine sand, very course silt, coarse silt, medium silt, fine silt, very fine silt and mud), 2- submerged features (sandy ridges and beach rock outcrops/parcels), 3 - abundance of benthic fauna, 4 - benthic endemicity and 5 - endangered benthic species. Each factor was standardized for a continuous scale of vulnerability values (degree of exposure to hazard x responsiveness), defining the boundary between the most vulnerable and the least vulnerable through a relative or fuzzy concept (Tagliani 2003).

The technique used for multicriteria evaluation was the Weighted Linear Combination (WLC), in which the standardized continuous factors were combine by means of a weighted average, and the result is a continuous mapping of vulnerability. One of the advantages of the method is the possibility of assigning weights of different importance to each of the factors in the aggregation process, allowing retaining all the variability of the continuous data, besides the possibility of compensation among the factors (Eastman 1997). The assignment of weights to the criteria, or valuation, is the quantification of the relative importance of each of them in the decision process. The attribution of weights was performed through the Hierarchical Analysis Process (AHP), using Saaty's paired comparison scale (Saaty 2008).

Through Saaty's method, the factors are compared two by two in terms of their relative importance against the objective of the analysis (Table 1). After all possible combinations, the module calculates the set of weights and a consistency ratio, which indicates possible inconsistencies that might have raised during the paired comparison process (Fig. 2).

Each element of the matrix showed in Figure 2 indicates how much the factor of the left column is more important than the corresponding factor in the upper row. The assignment of weights is perform by comparing each of the factors listed in the first column with each of them in the upper row. For example, the factor 3 (Threatened species) was considered to be strongly more important than the factor 1 (Grain size), while the factor 5 (Beach rocks) was assigned to be moderately more important than the factor 1 (Grain size). The comparison of importance should always keep the focus of what is being analyze, i.e., an assessment of the natural fragility of the environment assuming an anthropic intervention.

The multicriteria evaluation proceeds to multiply each factor considered by its corresponding weight, which are added up, and then the sum is divided by the number of factors. As the weighted average is calculated for each pixel, the resulting image is a measure of the natural fragility of the environment ranging from 0 to 1.

Subsequently, attractiveness maps were drawn up for the exploitation of mineral resources (heavy minerals, limestone and sand for civil construction), all standardized in the same way as the previous ones, showing differentiated levels of attractiveness for these factors. Afterwards, through cross-tabulation (CROSSTAB), the fragility map was merged with the attractiveness maps, thus determining different degrees of potential conflicts of use.

Table I. Saaty's paired comparison scale.

1/9	1/7	1/5	1/3	1	3	5	7	9
Extremely important	Very strongly important	Strongly important	Moderately important	Equally important	Moderately important	Strongly important	Very strongly important	Extremely important
Less important				**More important**				

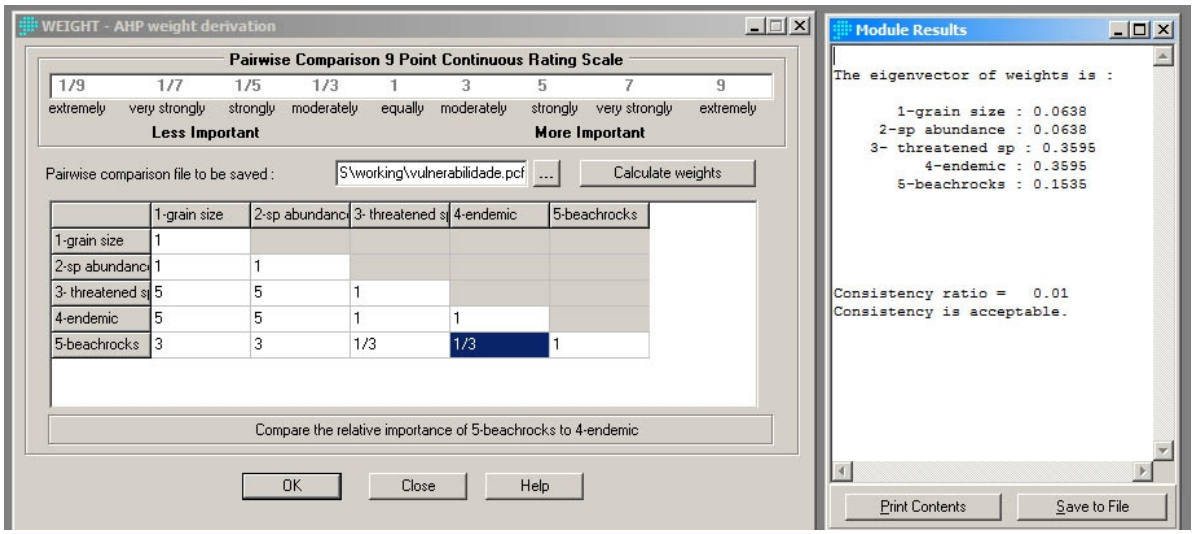

Figure 2. Pairwise comparison and relative weights on vulnerability analyses.

Results and Discussion

From the compilation of the sediment data available in the different databases it was possible to create a grain size distribution map (Fig. 3a), which shows the predominance of sandy bottoms to up 100 m. This pattern is interrupted by muddy bottoms related to the paleochannel of the Rio de La Plata during lower sea level periods (Corrêa 1996). These results, with a greater level of detail due to the large amount of data compiled, complement the study made by Martins et al. (1999) in the same area, which identified deposits predominantly formed by sands of medium to fine granulometry, with variable amounts of heavy minerals and shell fragments.

The occurrence of well-selected sediments is an indicative of reworking in highly energetic environments. The standardization of this factor (Fig. 3b) considered that the distribution of the benthic fauna is related to the different types of sediment present in the region, some of them with a high economic interest, such as sand and gravel, and some areas with the presence of soft bottom like a fine-grained or muddy sediments, a typical habitat for Nematodes and Copepods (Heip *et al.* 1985). Another factor considered important in the definition of the environmental vulnerability of the area was the presence of hard bottoms of beach rocks and submerged sandy ridges (Fig. 4a). These submerged features, like the Hermenegildo Parcel, further south, and the Albardão ridges further north, are large-three-dimensional consolidated substrates with high ecosystem potential by providing shelter, food and favoring reproductive aggregations of bone and elasmobranch fishes (Vooren & Klippel 2005).

Close to these features, there are generally abundant populations of benthic invertebrates that serve as food items of trophically superior organisms, such as the hermit crabs *Loxopagurus loxochelis*, which are present in the coastal portion of the CSA and are considered important items in the diet of the loggerhead sea turtle, *Caretta caretta* (Bugoni *et al*. 2003). Capitoli & Bemvenuti (2004, 2006) also reported the occurrence of echinoderms and characterized the zoobentonic community in the CSA, highlighting the relevance of the classes Echinoidea (*E. marginata*) and Asteroidea (*Astropecten sp.*) in this region of the Atlantic Ocean. Due to this ecosystemic importance, it was decided to consider as a vulnerability factor only the criterion of proximity of these submerged features, establishing that the lower the distance, the greater the vulnerability (Fig. 4b).

The resulting map of the integrated analysis between the variables mentioned above is a reflection of the relative importance of each factor in defining the environmental vulnerability, according

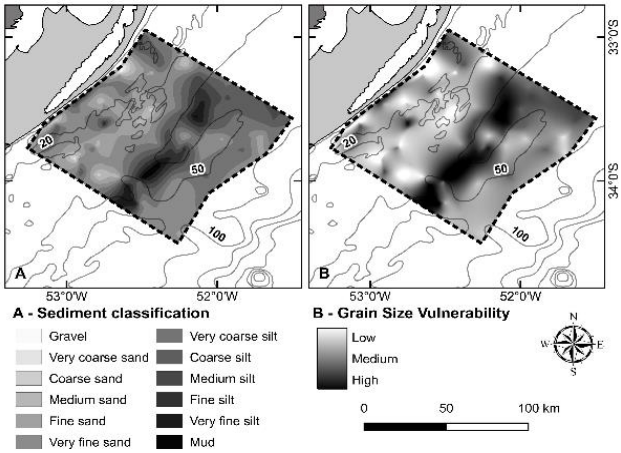

Figure 3. Sediment classification map (A) and Grain size vulnerability in the study area (B).

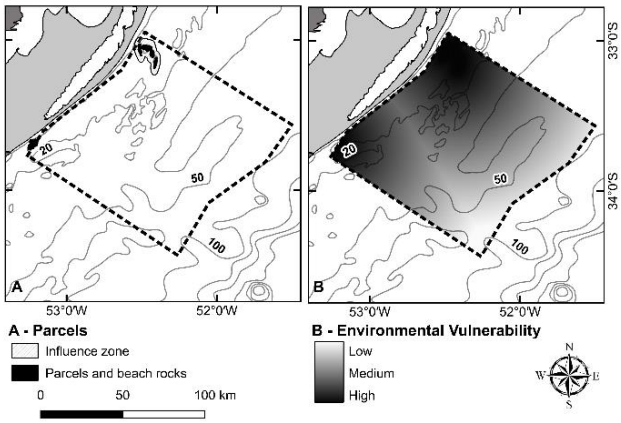

Figure 4. Location of sandy shoals and beach rocks (A) and standardized environmental vulnerability map (B).

to the importance weights attributed to each factor during the paired comparison, as well as due to the availability of the data used in the study (Fig. 5). However, this map provides extremely important information to characterize the natural fragility of this region against certain economic activities, in this case, exploitation of mineral resources.

After the analyses of the aspects related to the vulnerability of the Albardão region, the economic attractiveness aspects were examined, with special attention to the mineral resources. Among the mineral resources of socio-economic value of the Brazilian Continental Shelf, the commercial extraction of aggregates (mainly in the form of sands and gravels) is a priority due to the importance in the recovery of eroded beaches or to constitute an important input for the construction industry, landfills, road coverings and land distribution, while the finer, clearer, essentially quartzous sands have Corrêa *et al*. (2008), on the other hand, analyzed the sources of heavy minerals as well as their superficial

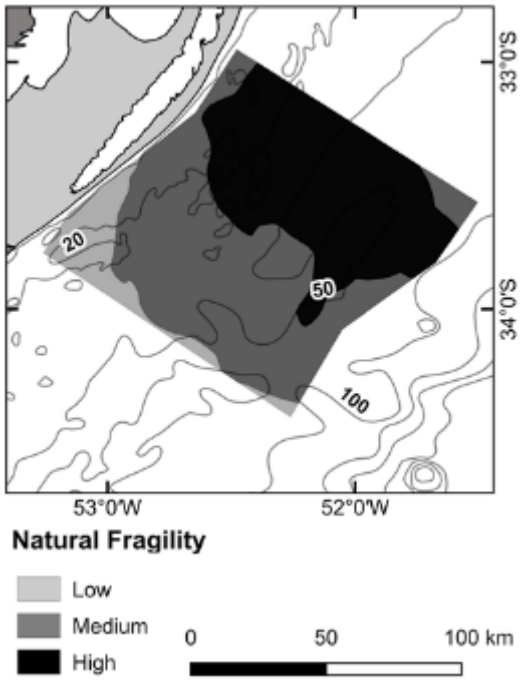

Figure 5. Natural fragility of the study area due to the presence of endemic and endangered benthic fauna.

distribution on the South Brazilian-Uruguayan Continental Shelf. According to these authors there are indications of heavy minerals in CSA, such as Ilmenite, Rutile and Zircon, which was also estimated by CPRM (Fig. 6b), besides the presence of energy resources (oil and gas) offshore. their direct use in the construction industry (Horn Filho 2003, Souza *et al*. 2007c).

The bioclastic limestone deposits (fragments of shells and echinoderms) of the Rio Grande do Sul Continental Shelf are linked to old high energy coastal lines, mainly those related to the Albardão regions, the subject of this work, and Parcel do Carpinteiro (further north), and may represent an economic potential in the order of $1x10^9$ tons (Corrêa 1983). Calliari & Klein (1992) also identified large biodetritic deposits associated with the coastal zone south of the Albardão, in the order of $2x10^6$ tons (Fig. 6a).

According to Souza *et al* (2009), the volume and potential of the sands and gravels present in the Continental Shelf exceed the value of any other non-living resource, except oil and gas. Among the possible impacts that the extraction of this kind of resources can generate in the marine environment are the increase of turbidity in the seawater, expressive accumulation of mud and destruction of geohabitats that are important to the benthic fauna (Trhush *et al*. 2002).

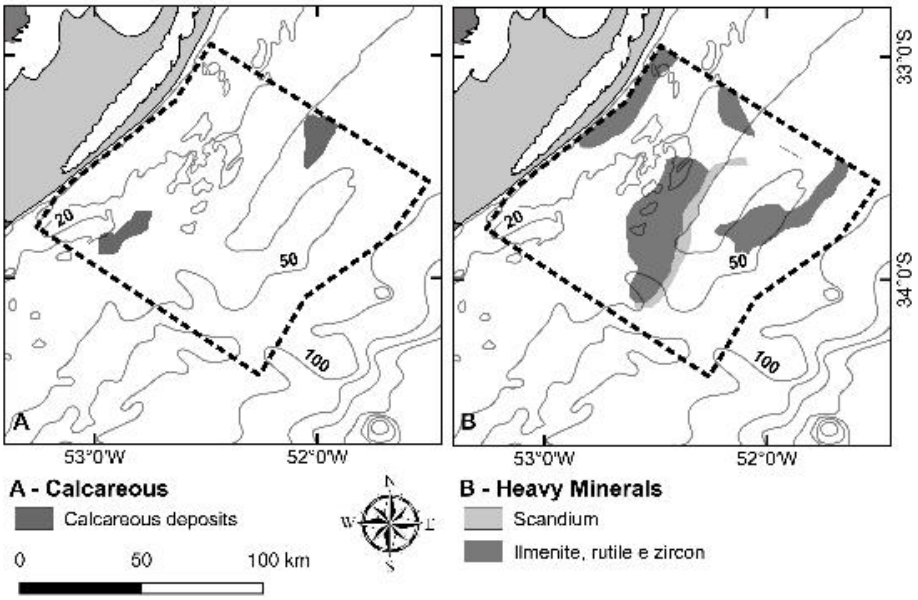

Figure 6. Location of the deposits of bioclastic limestone (a) and heavy minerals (b) in the Albardão Region. Source: CPRM.

Due to this occurrence, mainly in shallower areas, the results produced in this work shows that some regions presents a high potential of conflict, much due to its overlapping with the occurrences of benthic fauna. However, in most of the area, the conflict potential was consider as medium to low (Fig. 7). According to Vellinga (1989), the impact of sand dredging must be analyzed in terms of circulation of the Continental Shelf as well as in other economic and conservation issues, like fishing and local benthic fauna.

This caution between exploitation and environmental preservation is common in other countries. For example, in the United Kingdom, where dredging is regulated and confined to specific areas of concessions (Earney 1990) and also in the United States, where this kind of activity is regulated by major government agencies, such as the United States Geological Survey (USGS) and Coastal Engineering Research Center (CERC) (Souza & Neto 2007a).

In relation to the biodetritic limestone, the main areas of occurrence of this resource are restricted by two points, the first being further north and away from the coast and the second to the south of the study area and near the coastal region. Limestone is important in many sectors, especially industry (construction and metallurgy) and agriculture (soil amendments and mineral supplementation of poultry feed), but a future exploitation of this resource in the study area should be carried out in a cautious way, due to the environmental fragility and the conflict potential identified in the present study.

As for a possible exploitation of heavy minerals in the open sea, initially identified by Villwock *et al* (1977), which estimated reserves of around $112x10^3$ tons, this would depend on some factors, such as exploration cost, obtaining permits for mining, meeting environmental requirements, technology and transportation costs (Souza & Martins 2007). It is important to mention that, except for oil and gas, whose production assumes a more important economic role, development of mining activity tend to become stronger as a result of public ecological consciousness (Santana 1999). In order to clarify all results reached, Figure 7 shows a synthesis of all analyses made, through the crossing of natural fragility, marine mineral resources and potential conflict maps.

Conclusion

Based on the data collected and the analyzes performed by the present study we concluded there is a urgent need to establish a Marine Spatial Planning in Southern of Brazilian Continental Shelf, especially at Albardão region. It is possible through an efficient organization of socio-economic activities, in this case, the exploitation of mineral and energy resources, to avoid possible conflicts of interest (exploitation vs. conservation) and so to occur in a sustainable way.

In the CSA, there are important submerged mineral deposits whose eventual exploitation could

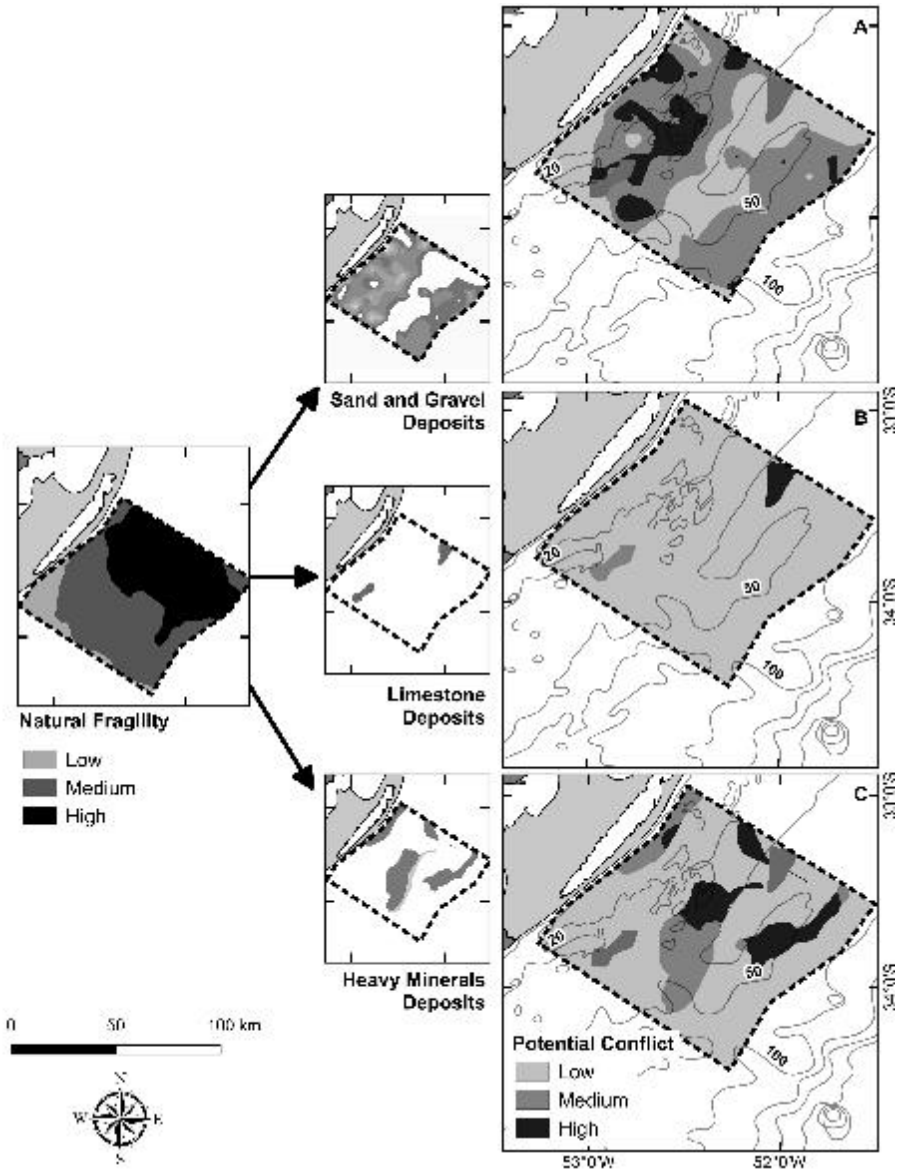

Figure 7. A synthesis of all analyses made showing the crossing between natural fragility, marine mineral resources and potential conflict maps.

cause significant environmental impacts. Although there is no option in searching other locational alternative, since mineral resources were accumulate by natural processes during regional geological evolution, its distribution is neither continuous nor homogeneous. The same mineral resources can be located in areas with different environmental characteristics or distinct environmental fragility, which leads to assume that its eventual exploitation can affect the area in a different way, causing greater or lesser impact.

In addition, the submerged features identified in the Albardão region are important breeding and feeding areas for marine fauna and, as such, should be protect as a way of maintaining ecosystem functions. The presence of endemic (*R. tentaculata*) and endangered (*A. cingulatus*) benthic species, as well as the submerged features, stands out the importance of maintenance the ecosystem services against human activities. The changes caused by anthropogenic effects around the world, without a marine planned, has degraded and destroyed the environments, leading many species, even entire communities, to extinction.

Although the spatial representation of the objective to be achieved is excellent, it should be seen only as a result of the available data that were used in the multicriteria evaluation. Of those five vulnerability factors used for the mapping of natural fragility in the study area, two of them endangered

species and endemic species presented only 4 and 5 records respectively, and these records were used for the respective vulnerability map. If there were a denser and complete sampling mesh, the results would certainly be closer to reality, greatly improving the quality of the final product.

Certainly, other variables should be consider in the analysis, such as preferential fishing sites, influence of marine currents, seasonal variations of temperature and salinity of the water column and its relation with nutrients available. Research initiatives are need to know the diversity of other taxa, especially top predators in areas subject to numerous environmental impacts such as the Pelotas Basin, whose exploratory potential (minerals and energy) tends to conflict with the management and preservation policies of species. Marine Spatial Planning is a multisector process to be achieve as soon as possible in response to society's growing demands for natural resources at sea, since decision-making is often carried out even without a minimum of technical criteria.

The conflict maps produced in the present work are a good reference to give the initial support necessary to decision makers and they are already an advance to the marine management process that must be continually updated, revised and improved.

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