Environmental Features Relevant to Deep-Sea Mining along the Rio Grande Rise for the Implementation of Protected Areas

by

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Executive Summary

Deep-sea mining has been a rapidly expanding industry within the last couple of decades due to advancements in technology and increased economic feasibility. Mining is currently being explored in several locations within Areas Beyond National Jurisdiction around the world and mining activities may begin in the near future. Therefore, there is a high level of interest in developing effective mining regulations as soon as possible for these areas.

This creation of regulations is carried out by the International Seabed Authority which is the international regulatory body for deep-sea mining based on the United Nation Convention on the Law of the Sea. One emergent area of deep-sea mining exploration that the International Seabed Authority is tasked with managing is in the Rio Grande Rise off the Southeastern coast of Brazil. There are many unknowns regarding the ecology of this region and this makes it difficult for regulators to attempt to create protected areas from future mining activities that effectively preserve biodiversity.

To attempt to address this problem, within this study I focused on the following primary research questions:

1. How have regulations for the exploration of deep-sea mining been created for other minerals and regions in the past?
2. What environmental and non-mining human-use characteristics of the Rio Grande Rise must be considered when discussing regulations for mining in this region? Also, why are these characteristics important for understanding the ecology of the RGR?
3. How can we gain a better understanding of the habitats that exist along the Rio Grande Rise based on data that is presently available?

In the first part of this study, global environmental and human-use geospatial datasets were collected and mapped using ESRI ArcGIS for the Rio Grande Rise region. A literature review was then conducted to explore the significance of each dataset in explaining the ecology of the Rio Grande Rise and/or the designation of protected areas.

In the second part of this study, a seafloor biogeographic classification was carried out for the Rio Grande Rise region based on four environmental datasets that are known to be important in determining deep-sea species distributions and habitat heterogeneity.

These analyses represent a first-order approach at exploring the environmental conditions found within the Rio Grande Rise and the potential future impacts of mining. Therefore, this study provides valuable information that serves as a starting point for future investigations that will ultimately guide the regulatory process for deep-sea mining in this region.

Abstract

Interest in the extraction of mineral resources from the deep-sea has increased rapidly in the recent years due to technological advancements. Since 2001, the International Seabed Authority has granted over 25 exploration leases for deep-sea mining in oceanic Areas Beyond National Jurisdiction. These areas are often poorly studied and thus it is currently a challenge to develop effective regulations before mining activities commence. This study attempts to address this issue by exploring the environmental characteristics found in an emergent area of deep-sea mining exploration, the Rio Grande Rise (RGR) off the Southeastern coast of Brazil. This is accomplished through the compilation and mapping of environmental datasets for the RGR region as well as a biogeographic classification of the RGR seafloor based on several datasets that are known to influence deep-sea biodiversity. The goal of this study is to identify areas and features within this region that are important for regulators to consider as mining regulations and protected areas are developed in the near future.

Introduction

1.1 Deep-Sea Mining Background Information

1.1.1 Deep-Sea Mining/Mineral Resource Overview

The deep-sea (oceanic areas greater than 200 m in depth) is a little studied and poorly understood ecosystem (Ramirez-Llodra et al., 2011). Despite our lack of knowledge about deep-sea habitats, humans are beginning to use these habitats for their natural resources at increasing rates. One emergent example of this comes from the intent to undertake deep-sea mining (DSM) for mineral resources. While DSM has been discussed for many decades (SPC, 2013), it is now being enabled due to technological advancements in recent years (Wedding et al., 2015). Currently, DSM exploration is taking place in several locations in international waters as well as in the national waters of Papua New Guinea and Saudi Arabia. Regulations for resources in international waters are being developed by the United Nations regulatory body for DSM, the International Seabed Authority (ISA). The ISA faces a number of challenges due to the rapid expansion of DSM exploration and the lack of knowledge of the deep-sea habitats in which mining is being explored.

The main mineral types of mineral resources that are currently under consideration for deep-seafloor mining are ferromanganese cobalt-crusts, manganese nodules, and seafloor massive sulfide deposits. The technology used to extract these minerals is not yet fully developed but is being heavily researched so mining activities in some areas can begin within the next few years. This rapid development of technology means that the ISA must work quickly to develop comprehensive regulations before mining takes place in a region. In recent years, significant action has been taken to develop these regulations, as well as systems of protected areas set aside from mining activities, referred to as Areas of Particular Environmental Interest (APEI), for manganese nodule mining in the equatorial Pacific (Wedding et al., 2013) and seafloor massive sulfide deposit mining along the Mid-Atlantic Ridge (Morato et al., 2015). APEI design for cobalt-crust settings has yet to be considered, even though mining exploration has begun to take place for this resource along the Rio Grande Rise (RGR), off the southeastern coast of Brazil. This region is currently designated as in international waters, although in the future it may become part of the Brazilian Extended Continental Shelf Claim. The focus of this study is to compile existing, published knowledge of the environmental features found within the RGR region, as a first step to toward an environmental management plan for deep-sea mining in this area.

1.1.2 Legal Context of DSM

The ISA has legal power to regulate all aspects of DSM in the Area Beyond National Jurisdictions derived from the United Nations Convention on the Law of the Sea (UNCLOS). The ISA was implemented in 1994 to manage mineral resources as a "common heritage of mankind" and is tasked with ensuring that mining contractors use "best environmental practices" and the precautionary approach found in Principle 15 in the Rio Declaration of 1992 (UN, 1992). In 2001, the ISA created a system of regulations for the exploration for and extraction of polymetallic nodules and issued its first mining exploration lease. Since then, more than 25 exploration leases have been granted to contractors around the world and exploration regulations have been created for all three mineral resource types. Exploitation regulations for these resources are in development.

The main piece of legislation that pertains to DSM along the Rio Grande Rise is the ISA's decision relating to the "Regulations on Prospecting and Exploration for Cobalt-rich

Ferromanganese Crusts in the Area" (ISA, 2009). These regulations were enacted in 2012 and revised in 2013 and contain rules that countries must follow both before and after beginning mining in a certain area. This document also states that mining activities must be managed to avoid damaging certain marine habitats such as hydrothermal vents and deep-sea coral beds. (ISA, 2009). To fulfill the mandates of applying the precautionary approach and protecting vulnerable marine habitats, the ISA is creating Strategic Environmental Management Plans (SEMPs) that rely in part on networks of protected areas (APEI) before mining activities take place within a region. These SEMPs are developed through international workshops and are to take into consideration any environmental or social impacts that mining activities may have (ISA, 2015).

APEIs are to be placed around the outside of mining exploration areas with the purpose of conserving "the full range of habitat and communities" within a region to limit the potential loss of deep-sea biodiversity due to mining activities (Lodge et al., 2014., p. 68). To accomplish this, it has been proposed that APEIs protect "30 to 50% of the total management area" of the region and that they "should be large enough to maintain minimum viable population sizes for species potentially restricted to a sub-region" (Lodge et al., 2014, p. 68). These conservation goals give environmental managers clear guidelines with which they may assess the efficacy of any proposed APEI design within a region.

1.1.3 Past DSM APEI Case Studies

Although environmental management practices for cobalt-crust mining have only recently begun to be considered, there are some precedents set by the management of other types of DSM that can be informative in showing how the mandates of the ISA have been put into practice in the past. The most well-developed management guidelines for DSM are for the nodule mining in the Clarion-Clipperton Fracture Zone (CCZ) in the Eastern Pacific Ocean. Exploration for mining in this region has been underway since 2001 and now over 20% of the 6,000,000 km^2 management area of this region has been claimed by different companies and countries (Wedding et al., 2013). The proposal of a system of APEIs was not completed until 2013 and since a large portion of this area was already reserved, regulators had to place these areas around the outside of existing mining exploration claims (Wedding et al., 2013). These APEIs are now a part of the CCZ SEMP (ISA, 2008) and thus fulfill the ISA's mandate but may not may not be as effective as they could have been if they were developed before many exploration leases were handed out.

A more recent example of the development of mining regulation comes from the exploration of seafloor-massive sulfide mining along the northern Mid-Atlantic Ridge. Over the past two years, scientists have convened a series of workshops to explore mining in this region and develop recommendations for a Strategic Environmental Management Plan in the Atlantic (SEMPIA), with the goal of delineating protected areas before a large number of exploration claims are granted (Morato et al., 2015). The first SEMPIA workshop largely consisted of discussion of the collection of geospatial data that may be useful for exploring the ecology of the Atlantic basin seafloor and the potential impacts of mining in this region and the general concept for design of a network of protected areas (Morato et al., 2015). The following workshop in 2016 used these data to create a proposed system of APEIs that seeks to best preserve the biodiversity found along the Mid-Atlantic Ridge from the impact of future mining events (SEMPIA II, unpublished).

In the CCZ case study, APEIs were designed to be at least 200 km in length with a 100 km buffer zone to accommodate for the mean dispersal distance of deep-sea organisms (Gaines et al., 2010). This sets a useful standard when discussing the development of APEIs within the RGR region.

1.2 Rio Grande Rise Overview

1.2.1 Location and Physical Attributes

The area of interest of this study is the entire Rio Grande Rise (comprised of both Eastern and Western sections; Figure 1) and surrounding waters outside of national jurisdiction. The RGR is located ~1000 km off the coast of Brazil and is ~125 km from Brazil's extended continental shelf claim. The RGR has a topography that differs from surrounding oceanic crust and is not associated with earthquake activity; it is described as an aseismic ridge system (Camboa and Rabinowitz, 1984). The exact method of formation of the RGR is not known, but the Eastern and Western sections of the Rise formed at different times and have distinct morphologies (Camboa & Rabinowitz, 1984, Perez, 2015; Figure 1). Exploration lease blocks are located on the western Rise section. The western section of the Rise is approximately 1.5 times the size of Portugal (Perez, 2015) and comprises a large plateau at an average depth of approximately 2000 km with seamounts and steep slopes that may be the sites of extensive cobalt-crust deposits (Camboa & Rabinowitz, 1984).

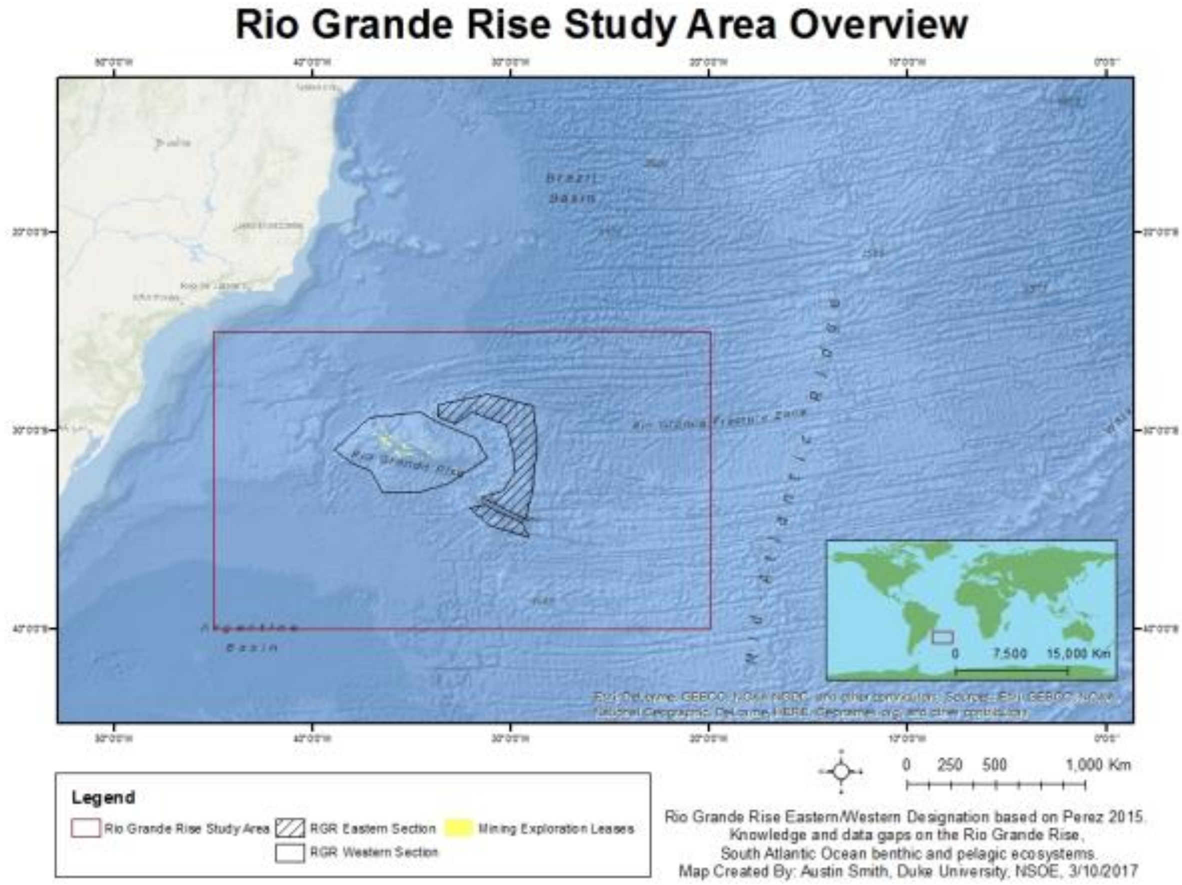


Figure 1: Rio Grande Rise Region Overview

1.2.2 Overview of Cobalt-Crust Deposits and Mining Exploration on RGR

Mineral exploration in this region began in 2015 when the International Seabed Authority (ISA) granted a 15-year exploration lease to the Companhia de Pesquisa de Recursos Minerais (CPRM) of Brazil (ISA, 2015). This exploration lease gave CPRM the right to freely explore an area of 3,000 square kilometers along the top of the Rio Grande Rise for the economic viability of harvesting cobalt-rich ferromanganese crusts there. Very little is currently known about the area and thus a regional environmental management plan that includes spatial management and networks of APEIs to protect the marine environment from the potential impacts of mining in the future is not yet developed. This study will explore a variety of environmental parameters for the

RGR region to provide more complete information on the ecosystems and ecology of the area to assist in future policy decisions regarding placement of APEIs.

Cobalt-rich ferromanganese crusts form when iron and manganese oxides and various other metals precipitate out of seawater and accumulate on rocky slopes (SPC, 2013). This occurs widely throughout the ocean but the deposits which are economically viable for DSM tend to occur on steep slopes on the edges of seamounts between 600 to 7000 m in depth where rocky substrate is relatively free from other debris (SPC, 2013). The greatest accumulations of these crusts generally occur between 800 and 2500 m in areas where there is relatively high current flow (SPC, 2013). Economically viable cobalt crust deposits are uncommon in the Atlantic Ocean because the hydrothermal activity associated with most seamounts in this area dilutes the metals of economic interest (Hein et al., 1997). The RGR is a potential site for these deposits because it contains many seamounts (unassociated with hydrothermal activity) at the optimal depth range for economic viability.

If sufficient quantities of cobalt-rich crusts are found by CPRM along the Rio Grande Rise then CPRM may complete the exploration phase and apply for the right to begin mining activities. There are many unknowns about how this mining will take place, as the technology for harvesting cobalt-crusts has not been fully developed and most of the information coming from companies that are working on developing this technology is proprietary (SPC, 2013). Cobalt crust mining is likely to take place on steep slopes with rugged terrain and high current speeds (SPC, 2013). To overcome these obstacles, crust mining may be carried out by a bottom crawling with articulated cutting devices on the front (Figure 2; SPC, 2013).

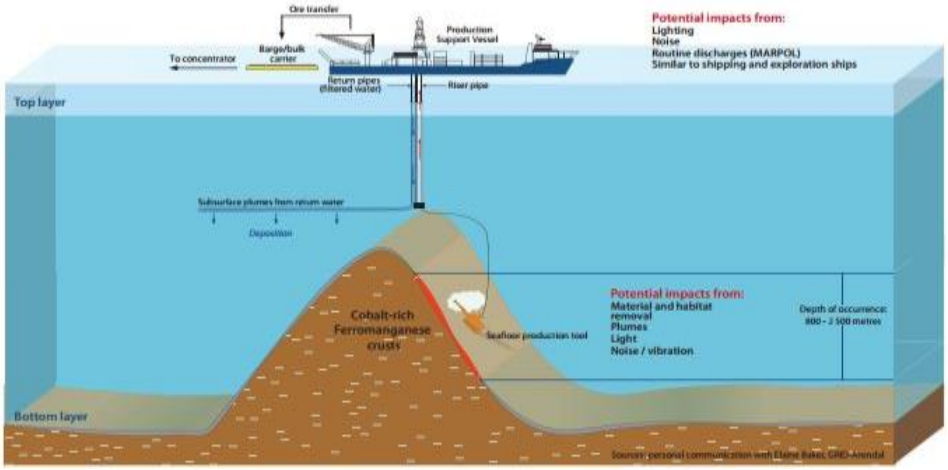


Figure 2: Potential Mining Scenario and Impacts Diagram (SPC,, 2013)

1.2.3 Potential Stakeholders of Mining

Given that DSM technology and practices are not fully developed, it is impossible to say who all the stakeholders will be, but there are several parties that are involved in present and future DSM policy decisions. In general, and for the Rio Grande Rise, these include mining technology developers such as the Companhia de Pesquisa de Recursos Minerais (CPRM), governments who have applied for mining exploration leases or may do so in the future, and non-governmental organizations and scientists interested development of sustainable mining practices. CPRM is the Brazilian state geological research organization who holds the only mining exploration rights for the region. This group will have a very high level of interest in any policy decisions on the regulation of mining along the Rio Grande Rise. As a fully-state sponsored institution, CPRM is also likely to be involved in development and review of recommendations for environmental management plans developed by the International Seabed Authority.

1.3 Introduction of “Proxy or Surrogate” Approach to Explaining Biology

1.3.1 Surrogate Parameters of Biodiversity and Ecosystem Function

Since many deep-sea environments are poorly studied and lack high-resolution data on biodiversity and other ecological parameters that are key to design of protected areas in shallow marine systems, “proxy” or “surrogate” dataset approaches are commonly used to as indicators of these ecological parameters (Watling et al., 2013). These “proxy” datasets are often used to distinguish distinct areas of seafloor and infer a first-order level of habitat heterogeneity. Proxy datasets (Depth, Salinity, Dissolved Oxygen, and POC Flux) were used to create a global model of seafloor biogeographic provinces in a recent study by Watling et al. (2013). Following the example of Watling et al. (2013) as well as Harris and Whiteway (2009), four proxy datasets (Depth, POC Flux, temperature, seafloor slope) were chosen to conduct a biogeographic classification exclusively for the Rio Grande Rise seafloor based on expected importance in determining regional biodiversity and data availability. The rationale and sources for the four data sets used in this study is included in Table 1. The parameters are ranked according to their expected level of importance in an analysis of the ecology of the Rio Grande Rise area.

Table 1: Parameters Known to be Important in Deep-Sea Biodiversity and Ecosystem Function and Included in Seafloor Classification

Dataset	Source	Reason	Citations
Depth	Weatherall et al., 2014	Deep-sea species diversity generally shows a unimodal distribution of decreasing diversity with increasing depth. This decrease can be especially strong for animals with large body sizes. Genetic diversity in some populations has also been shown to decrease with depth.	Etter et al., 2005, Rex et al., 2006, McClain amd Rex, 2015
POC Flux	Henson et al., 2012	Both quality and quantity of export productivity is suggested to be a primary driver of deep-sea biodiversity. Food availability is thought to be the major factor constraining species diversity in low productivity areas.	Smith et al., 1997, Levin et al., 2001, Woolley et al., 2016
Seafloor Temperature	Boyer et al., 2005	Like with depth, deep-sea species show a unimodal distribution of decreasing diversity with decreasing temperature. Temperature is only important in affecting biodiversity at very high or low levels though.	Yasuhara and Danovaro, 2014
Seafloor Slope	Slope derived from Weatherall et al., 2014	Morphology impacts ecosystem function on the regional level and biodiversity on smaller spatial scales. Greater diversity in seafloor morphology tends to lead to greater species diversity. Also hard bottom seafloor types tend to support high biodiversity levels.	Dunn and Halpin, 2009, Zeppilli et al., 2016

1.3.2 Other Parameters that may be Important for Protected Area Designation

In addition to the parameters highlighted above, potential human uses other than mining in the region, as well as other environmental datasets that further explain differences in seafloor terrain and biology throughout this area may be useful (Table 2). Selection of these datasets was mainly based on availability of published spatial datasets but was also assisted by the example of datasets included in the SEMPIA II (unpublished) workshop report.

Table 2: Additional Parameters to be Considered for Rio Grande Rise Deep-Sea Mining Regulation

Data Type	Data Source	Reason	Citations
Morphological Data			
Optimal Cobalt Crust Formation Locations	Derived from Weatherall et al., 2014 Bathymetry based on SPC, 2013	Identifies potential areas of interest for future mining activities.	SPC, 2013
Seamount Locations	Yesson et al., 2012	These may be important sites for mineral extraction. Also, unique environmental conditions surrounding individual seamounts can lead to significant differences in biology among seamounts within a region.	Yesson et al., 2012, SPC, 2013
Geological Data			
Substratum Type	Dutkiewicz et al., 2015	Sediment size and origin can be directly related to habitat availability for a number of deep-sea species	Etter and Grasle, 1992
Sediment Thickness	Whittaker et al., 2013	This may be indicative of seafloor water flow patterns and is related to the presence of cobalt-rich crusts	SPC, 2013
Biological Data			
Cold-Water Framework-Forming Coral Predicted Habitat	Davies and Guinotte, 2011	Cold-water corals provide structure that serves as a habitat for many deep-sea species. This habitat could be damaged in the immediate vicinity of mining activities.	Freiwald et al., 2004, Davies and Guinotte, 2011
Cold Water Octocoral Predicted Habitat	Yesson et al., 2012	Cold-water corals provide structure that serves as a habitat for many deep-sea species. This habitat could be damaged in the immediate vicinity of mining activities.	Freiwald et al., 2004, Yesson et al., 2012
Ecological or Biological Significant Area (EBSA) Locations	Bax et al., 2015	EBSAs identify known areas of high biodiversity and/or key habitat for rare species in the open ocean. Also, can be useful in highlighting areas of unique environmental conditions.	UN CBD, 2012
Global Open Ocean and Deep-seabed (GOODS) Biogeographic Provinces	Watling et al., 2013	This provides a biogeographic classification of the Rio Grande Rise seafloor based on many ecological, physical, geological, and human use parameters. This allows for the exploration of distinct areas within the RGR and is useful for comparison for the classification carried out in this study.	UNESCO, 2009
Physical Data			
Seafloor Dissolved Oxygen	Garcia et al. 2006	The presence of hypoxic conditions can be an important limiting factor for benthic species distributions.	Diaz and Rosenberg, 1995, Rogers, 2000
Non-Mining Human Uses			
Bottom Fisheries Locations	Bensch et al., 2009	Bottom fisheries can often be very destructive to seafloor habitats due to topographic alterations. This may have a strong cumulative effect if deep-sea mining occurs in the immediate vicinity of fishing activities.	Bensch et al., 2009, Pusceddu et al., 2014
Shipping Lanes	Halpern et al., 2008	The presence of high shipping traffic may lead to increased seafloor pollution and habitat degradation.	Ramirez-Llorda et al., 2011
Submarine Cables	Cablemap.info, 2016	Areas with submarine cables could be disrupted by future mining activities.	Ramirez-Llorda et al., 2011

Methods

2.1 Analysis of Environmental Datasets Relevant to DSM in the RGR

2.1.1 Definition of Study Area

The RGR consists of distinct Eastern and Western sections that are each approximately 150,000 km^2 in area and separated ~ 200 km from each other (Figure 1). The Western section of the RGR contains several seamounts that are being explored for ferromanganese cobalt-crust potential by CPRM; other seamounts located near the Western section (ranging ! 500-1000 km distant) may be explored for cobalt crust potential in the future. To encompass the Eastern and Western sections of the RGR and its surrounding features, a rectangular study area was defined with the coordinate ranges: 20° to 40° West and 25° to 40° South. This area is approximately 2,500 km long and 1,500 km wide and includes some portions of the Brazilian exclusive economic zone and extended continental shelf claims. This area was chosen because it allowed for exploration of environmental features surrounding both the small-scale mining exploration lease areas along the RGR (each approximately 50-100 km in length) as well as seamounts and other large-scale features that are located nearby the RGR.

2.1.2 Spatial Analysis of Datasets

Thirteen global datasets considered important in determining deep-sea biodiversity and ecosystem function (Tables 1 and 2) as well as 3 non-mining, human-use datasets (Table 2), were mapped in relation to mining exploration leases along the Rio Grande Rise using ESRI ArcGIS. When relevant, basis statistics (mean, standard deviation, range, etc.) were calculated for the entire RGR study area. A literature review was conducted for each dataset to document the importance of these data in defining a system of protected areas within this region.

2.2 Classification of Seabed Regions of the Rio Grande Rise

2.2.1 Classification Methods and Validation

To explore habitat heterogeneity within the RGR, seafloor areas were classified based on multivariate analysis of four biological and physical parameters that serve as proxies for ecosystem biodiversity and function. Datasets used in habitat classification were: Depth, POC Flux, Seafloor Temperature, and Seafloor Slope (Table 1). Each dataset was clipped to the defined RGR study area, converted to a cell size of 0.05 using the Resample tool in ArcGIS to standardize the data, and rescaled to a range of 0 to 100 using the ArcGIS Raster Calculator tool to ensure that the classification tool weighted each parameter equally. These steps follow those described in Harris and Whiteway (2009) and are necessary as each of the parameters used have different cell sizes and scales that would result in the inaccurate identification of clusters during the classification process if the data were not standardized**.** the classification procedures outlined in studies by Harris and Whiteway (2009) and Whiteway et al. (2007).

After formatting the datasets, an unsupervised classification was run using the ArcGIS ISOCluster Unsupervised Classification Tool. Default values for minimum class size (20) and sample interval (10) were used, but the classification was run iteratively for number of class values ranging from 5 to 20. This allowed for independent analysis of the clustering results of each iteration to ensure that the classes identified best represented real-world habitat regions. Optimal class size was determined by examining dendrograms of classification signatures, with best representation of differentiated classes determined based on maximum isolation of branches and minimum differences in between-class distance (Van Sickle, 1997).

2.2.3 Classification Nomenclature

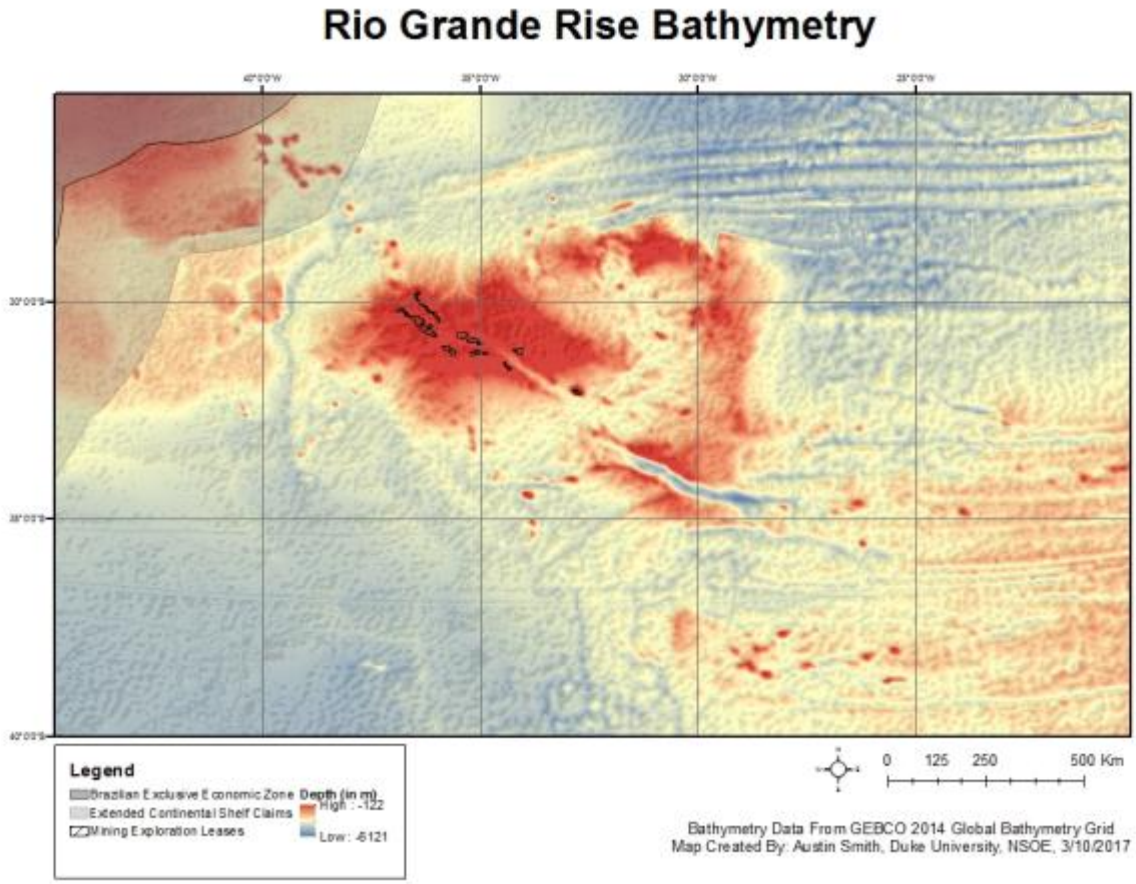
Descriptive statistics (mean, standard deviation, range) for the four environmental parameters were used to define descriptive labels for each class, with the depth classification as the first label in the descriptive string due to its importance in determining species distributions throughout the deep-sea (McClain and Rex, 2015). Classes containing the three highest or lowest mean values for any parameter were assigned to the descriptive label for that parameter. This classification scheme follows the example of Harris and Whiteway (2009).

Results

3.1 Environmental/Non-Mining Human Use Data for the RGR

3.1.1 Morphological Parameters

The Rio Grande Rise region encompasses depths from ~100m to ~6000m (Figure 3). The average depth of the entire study area is 4,920 meters while the average depth of the current mining exploration leases is only 960 meters. Mining exploration leases represent < 0.01% of (~3,175 km^2) of the approximately 3,750,000 km^2 RGR study area, but have more than a 5-fold range of depth values (i.e., 440 to 2430 m).



Bathymetry Data From GEBCO 2014 Global Bathymetry Grid
Map Created By: Austin Smith, Duke University, NSOE, 3/10/2017

Figure 3: Rio Grande Rise Bathymetry

Depth ranges in which cobalt crusts are most likely to be found (800 to 2500m; SPC, 2013) are abundant throughout the RGR study area (Figure 4). For the Western section of the Rio Grande Rise, where mining exploration leases are held, these leases comprise 0.02% of the total optimal crust formation area.

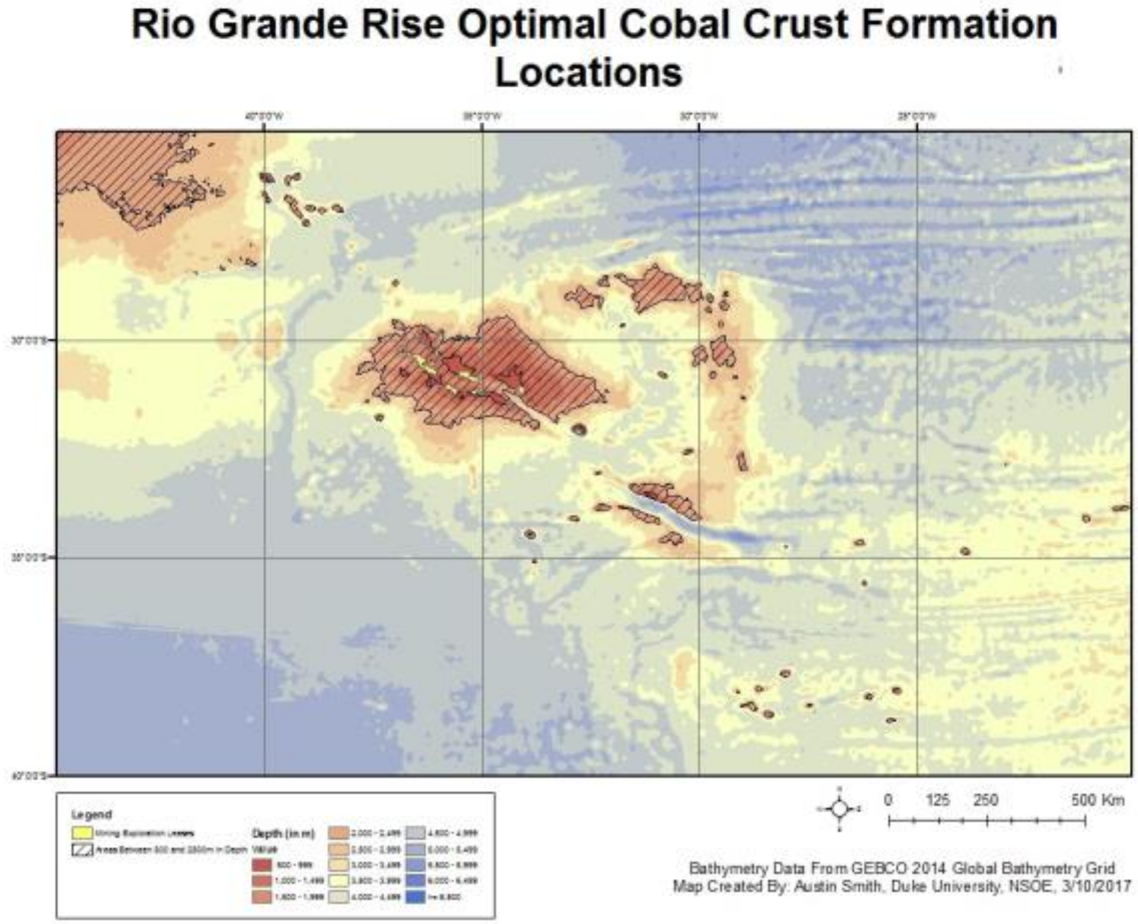
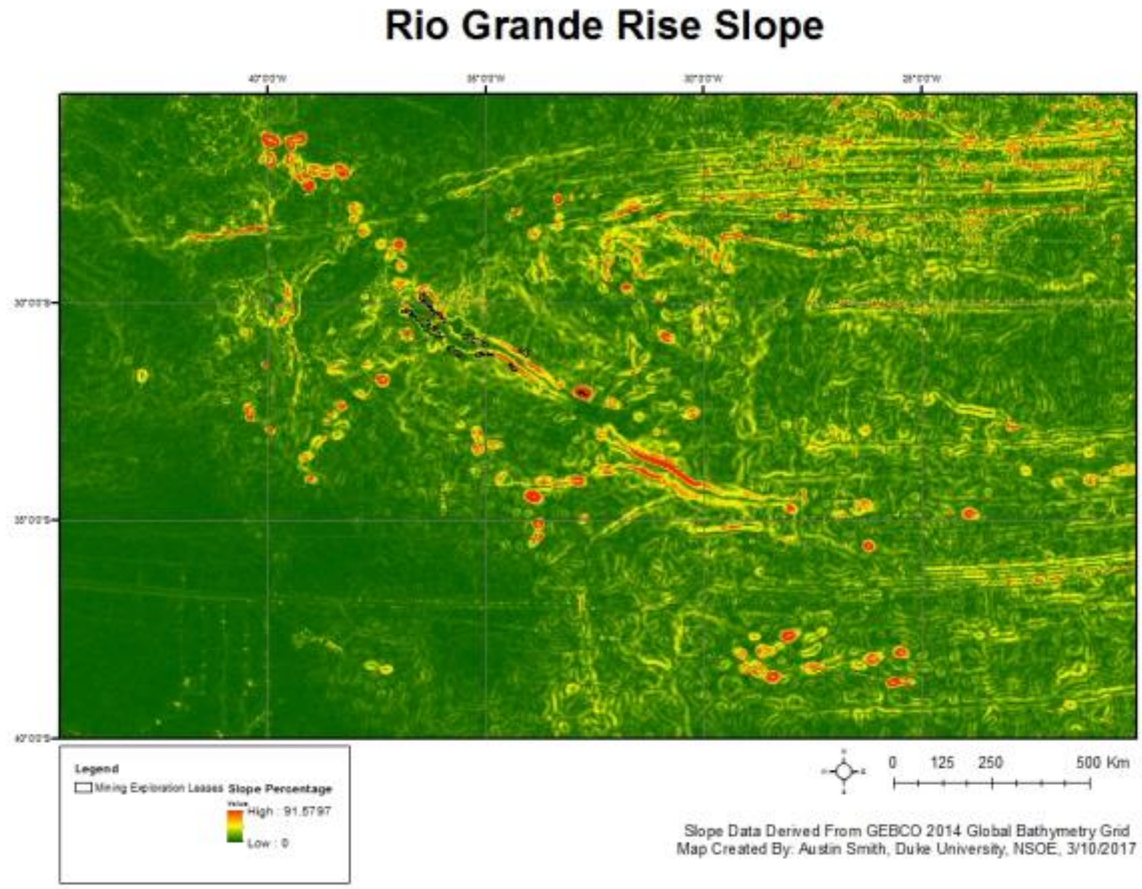


Figure 4: Optimal Cobalt Crust Formation Locations

In general, slope was low throughout the majority of the study area (mean % slope ~2.5; Figure 5). Even along the top of the western section of the Rise, mean % slope was only slightly higher (3.5). Greater topographic complexity occurs in association with seamounts off the rise and in the mining exploration lease areas, where mean % slope was 5.7.



Slope Data Derived From GEBCO 2014 Global Bathymetry Grid
Map Created By: Austin Smith, Duke University, NSOE, 3/10/2017

Figure 5: Rio Grande Rise Slope Percentage

More than 150 seamounts were identified across the study area. Summit depths range from 420 to 4265 m; seamount area ranged from 400 km^2 to 1160 km^2. The majority of these seamounts were identified in areas surrounding the Eastern and Western sections and only 2 seamounts were within or overlapping with exploration lease areas (Figure 6).

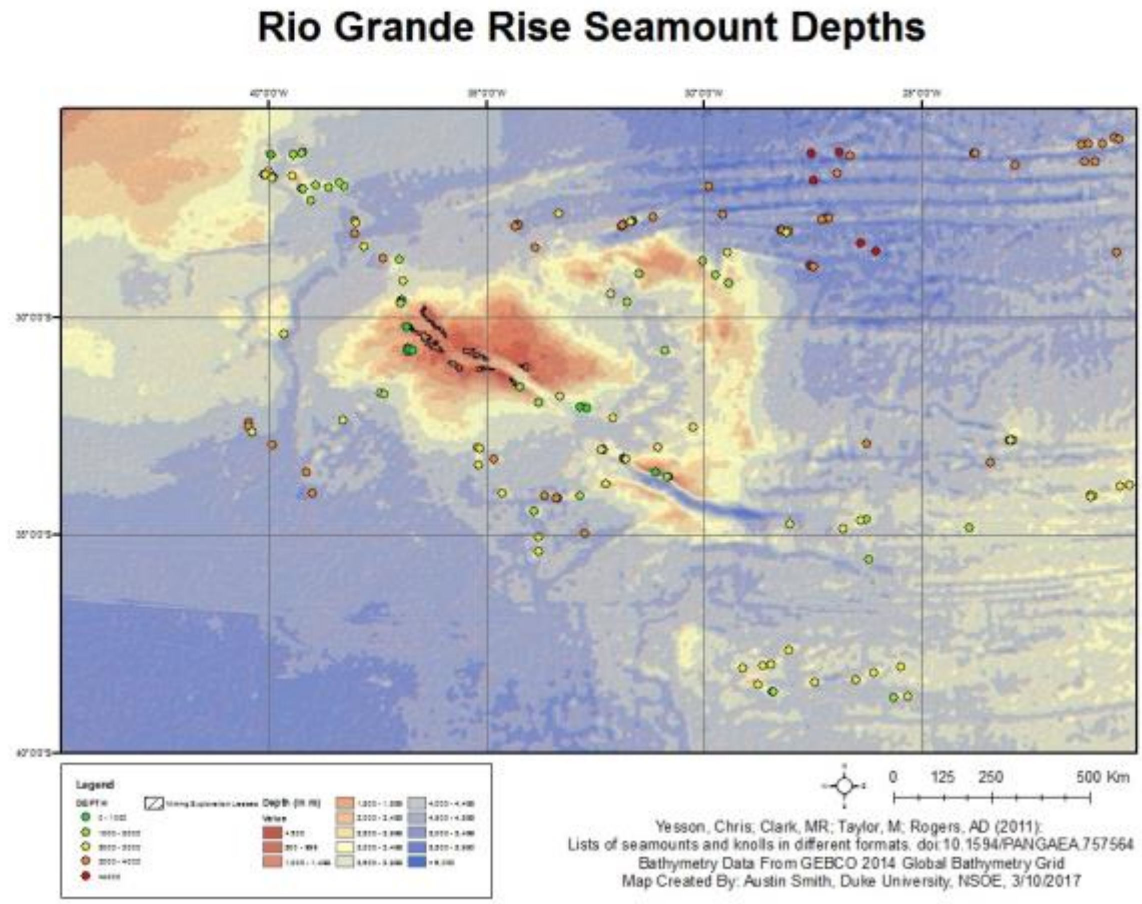
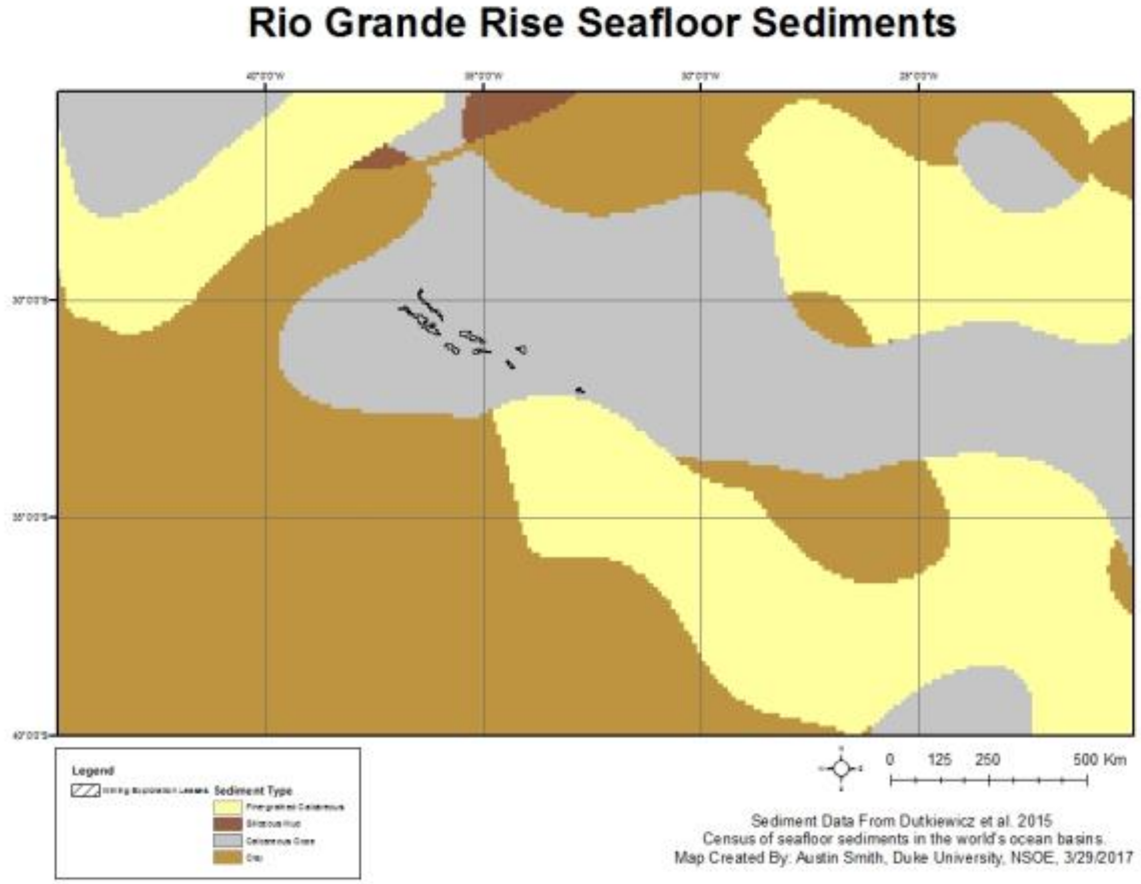


Figure 6: Rio Grande Rise Seamount Locations and Depths

3.1.2 Geological Parameters

Four different sediment types were detected throughout the study area (Figure 7). Of the total RGR study area, 27% is covered by biogenic sediment (Calcareous Ooze), 31% is covered by transitional sediments (Fine-grained Calcareous Sediment or Siliceous Mud), and 42% is covered by Siliciclastic sediment (clay), as defined by Dutkiewicz et al. (2015). In general, clay was the dominant sediment type in deep waters surrounding the Rise while the rise itself and within the exploration leases was predominantly calcareous ooze.

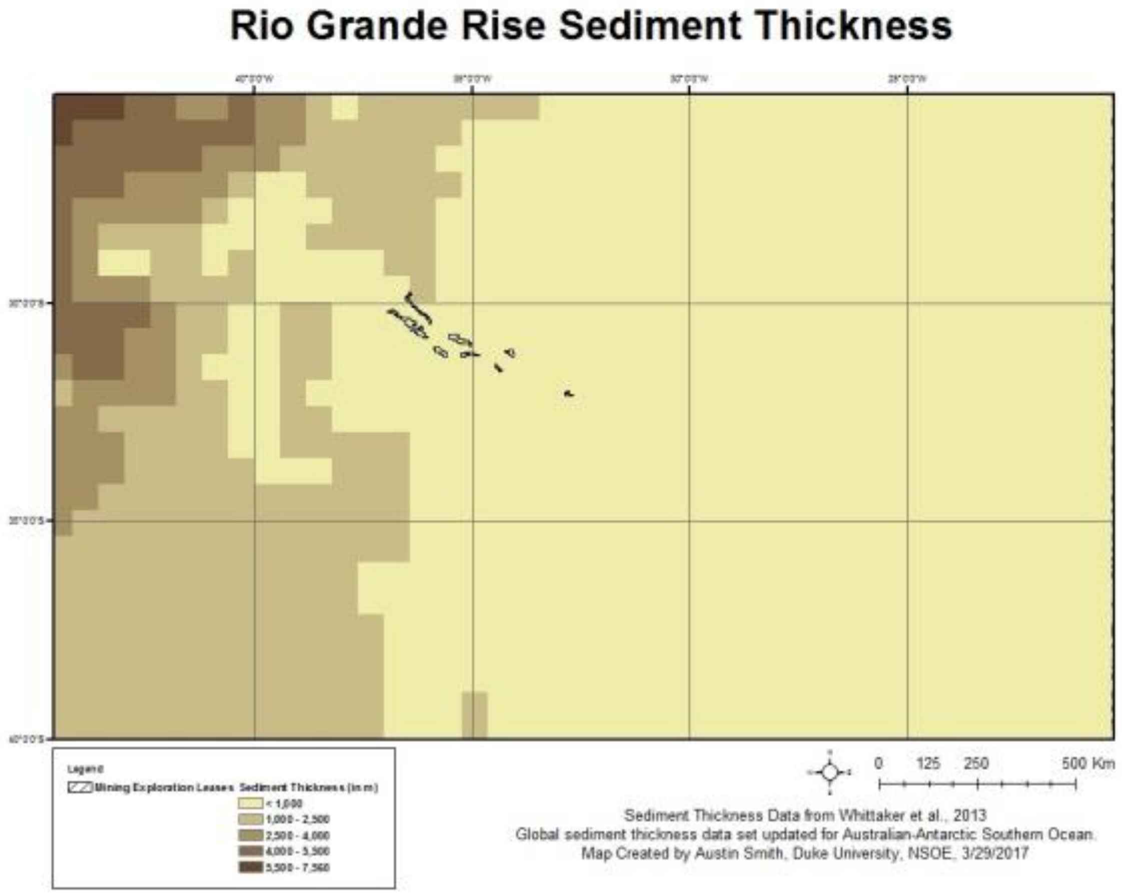


Rio Grande Rise Seafloor Sediments

Sediment Data From Dutkiewicz et al. 2015
Census of seafloor sediments in the world's ocean basins.
Map Created By: Austin Smith, Duke University, NSOE, 3/29/2017

Figure 7: Rio Grande Rise Substratum Type

Sediment thickness varied greatly across the study region, ranging from 78 to 7,560 meters. These values were much more homogenous within the mining exploration lease areas, where thickness is estimated to be 1000m or less. The main source of heterogeneity in sediment thickness within the study region is associated with nearshore areas northwest of the Rio Grande Rise (Figure 8). These values are only very coarsely estimated.



Sediment Thickness Data from Whittaker et al., 2013
Global sediment thickness data set updated for Australian-Antarctic Southern Ocean.
Map Created by Austin Smith, Duke University, NSOE, 3/29/2017

Figure 8: Rio Grande Rise Sediment Thickness

3.1.2 Biological Parameters

The Rio Grande Rise region is modeled to have a high degree of habitat suitability for a variety of cold-water coral species. Octocoral habitat suitability showed that nearly the entire rise is predicted to contain habitat suitable for at least one Octocoral suborder (Figure 9). Additionally, the majority western section of the Rise is predicted to support four or more Octocoral suborders. Exploration leases of W-RGR overlap with many areas of high Octocoral habitat suitability; the area of the leases is low compared to total area of predicted Octocoral habitat. For example, the mining exploration leases only overlap with only 0.0001% of the total area that is predicted to support 7 Octocoral suborders within the entire RGR region (Figure 10).

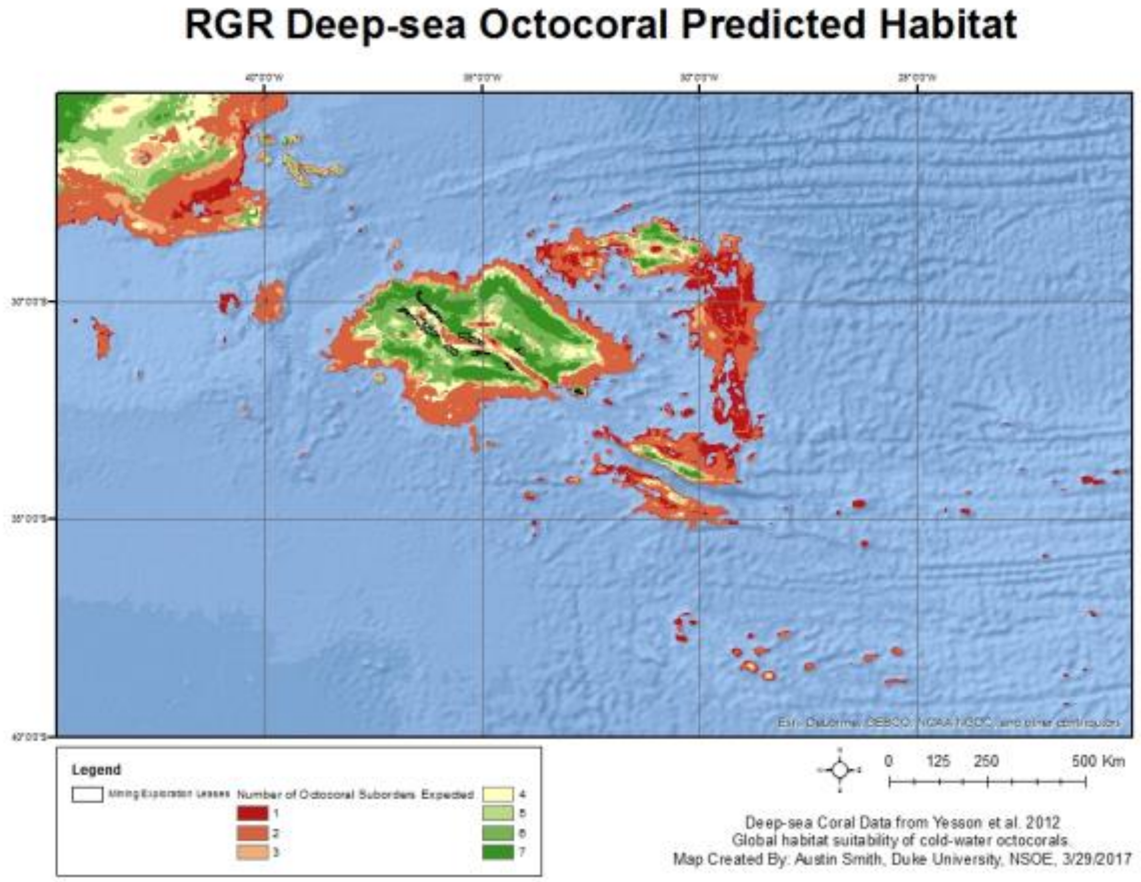


Figure 9: Cold-Water Octocoral Predicted Habitat

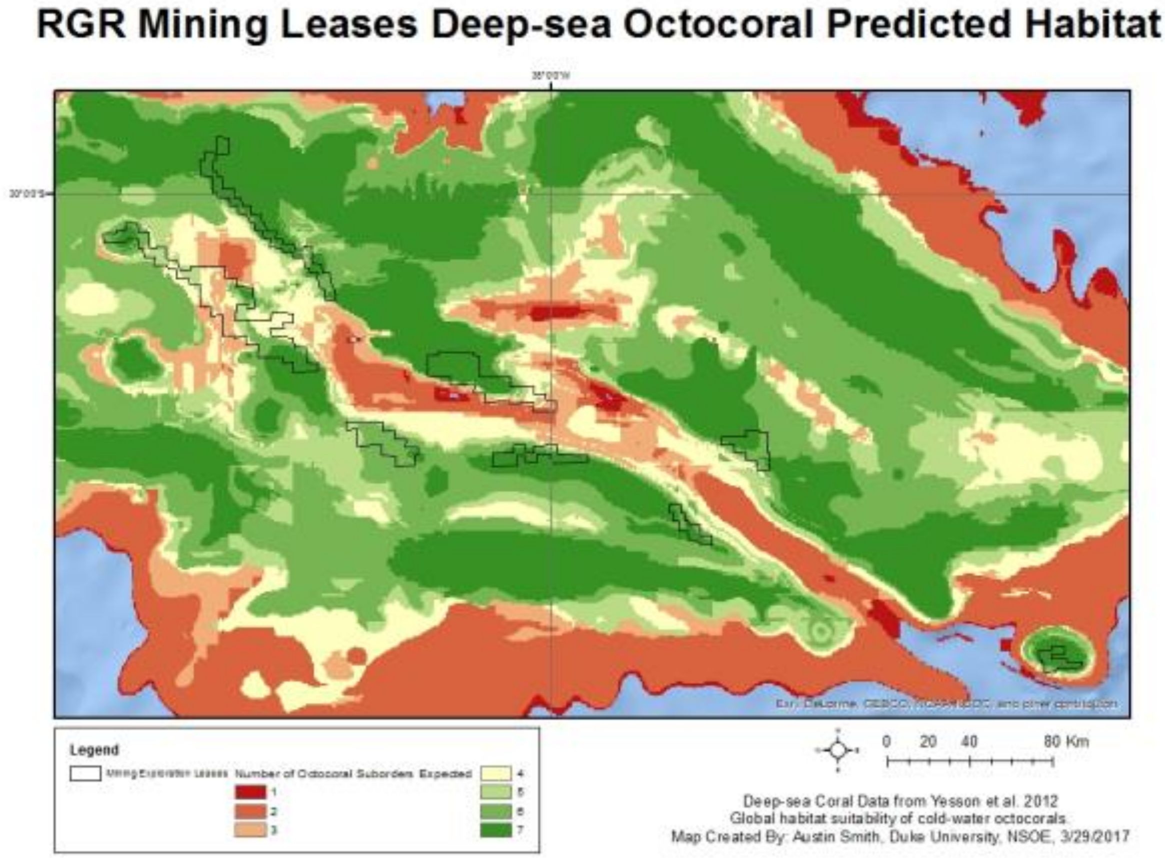


Figure 10: Cold-Water Octocoral Predicted Habitat within Western RGR

Framework-forming cold-water coral predicted habitat was also found to overlap with a large portion of the W-RGR and the exploration leases (Figure 11). As with Octocoral species though, this overlap accounted for only a minute portion of the total predicted habitat area.

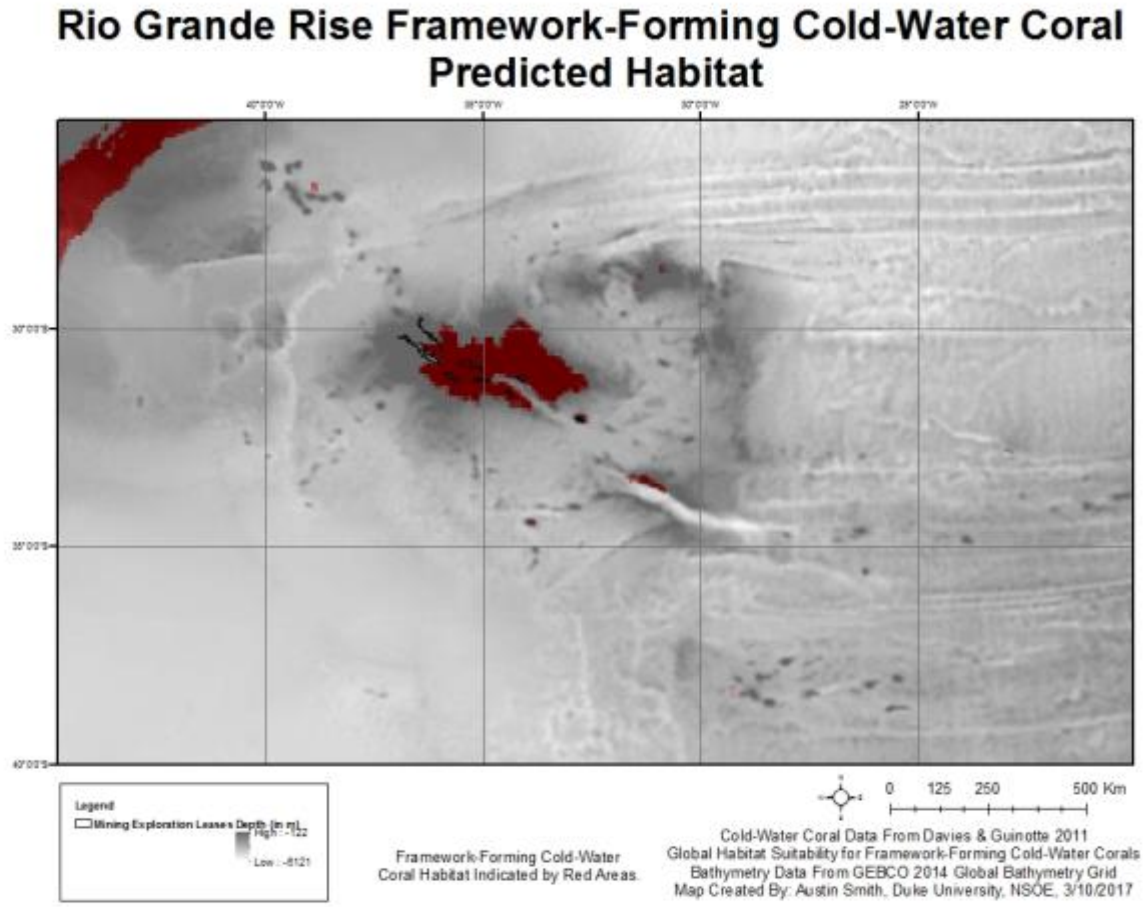
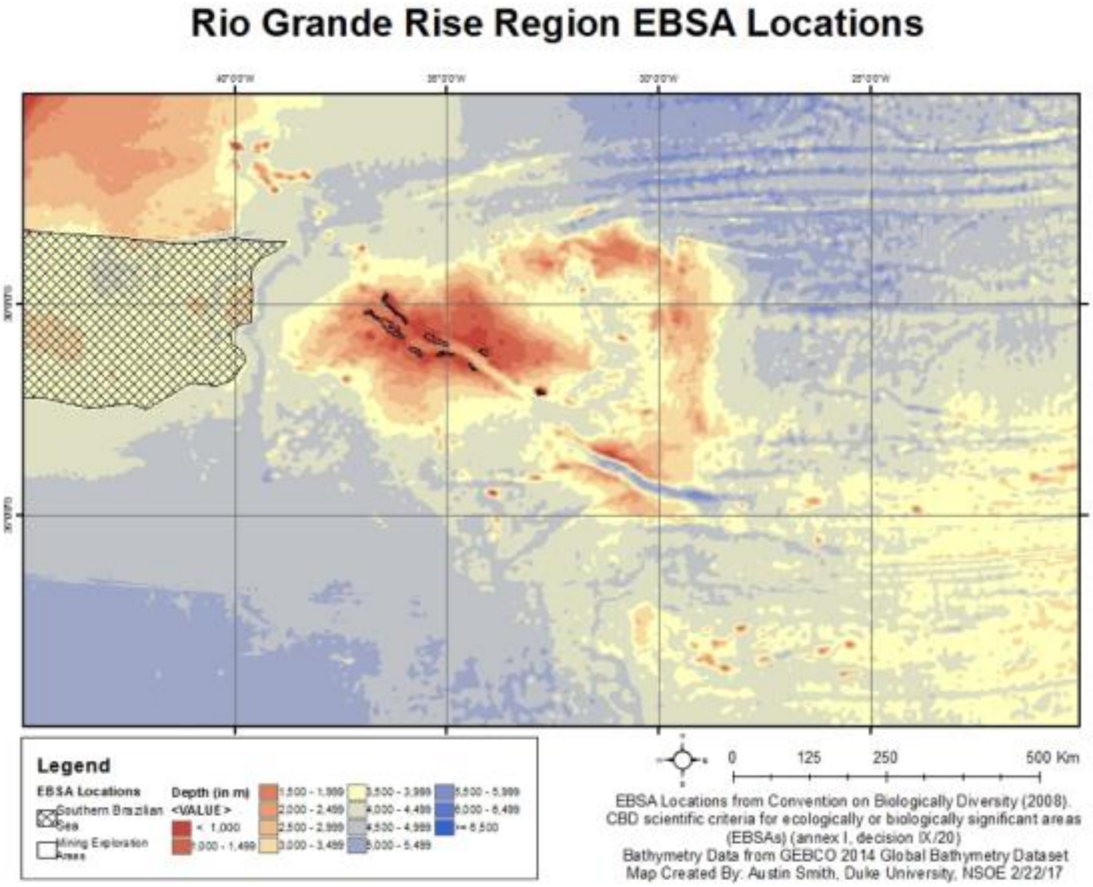


Figure 11: Cold-Water Framework-Forming Coral Predicted Habitat

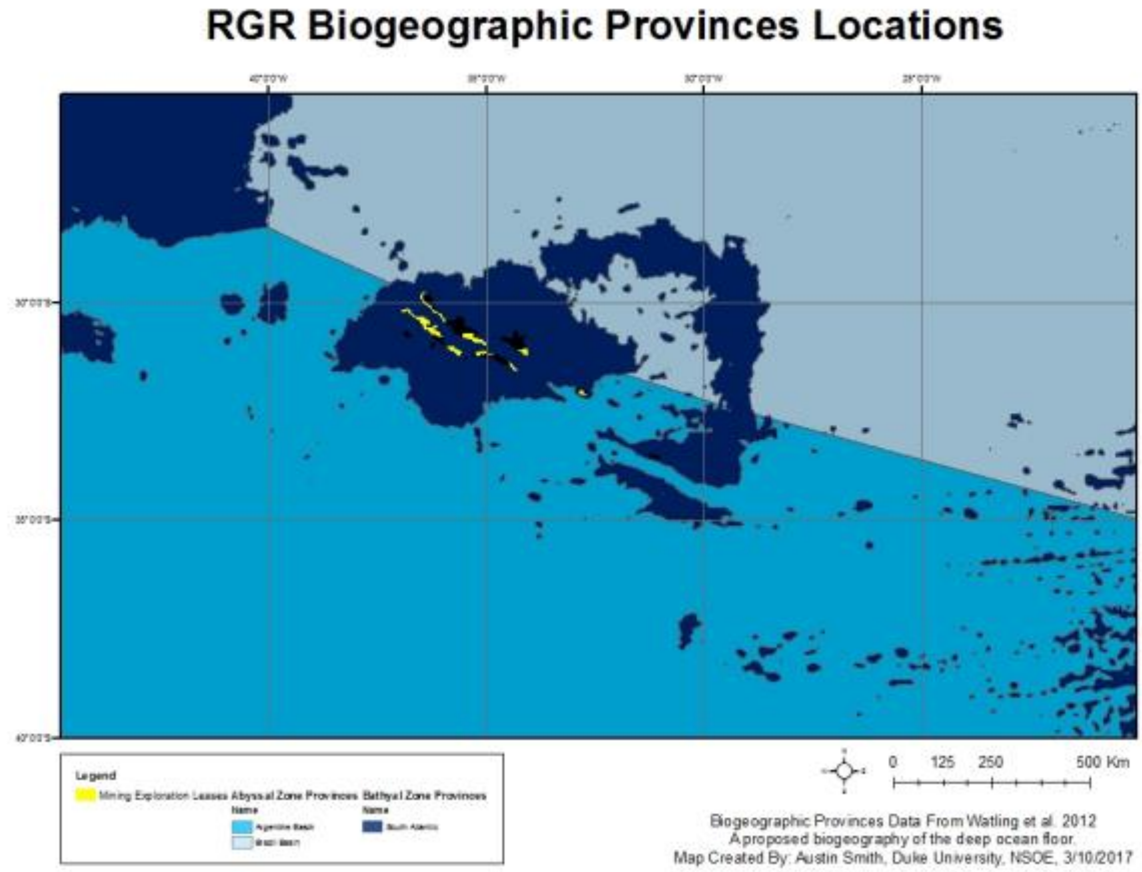
The Southern Brazilian Sea Ecologically or Biologically Significant Area (EBSA; CBD 2012) is located in western extreme of the RGR study area (Figure 12). This EBSA does not overlap with the existing exploration claims. It does comprise a high degree of bathymetric complexity, similar to that seen throughout the RGR region, with a depth range of 2,713 to 4,750 m.



EBSA Locations from Convention on Biologically Diversity (2008). CBD scientific criteria for ecologically or biologically significant areas (EBSAs) (annex I, decision IX/20)
Bathymetry Data from GEBCO 2014 Global Bathymetry Dataset
Map Created By: Austin Smith, Duke University, NSOE 2/22/17

Figure 12: Rio Grande Rise EBSA Locations

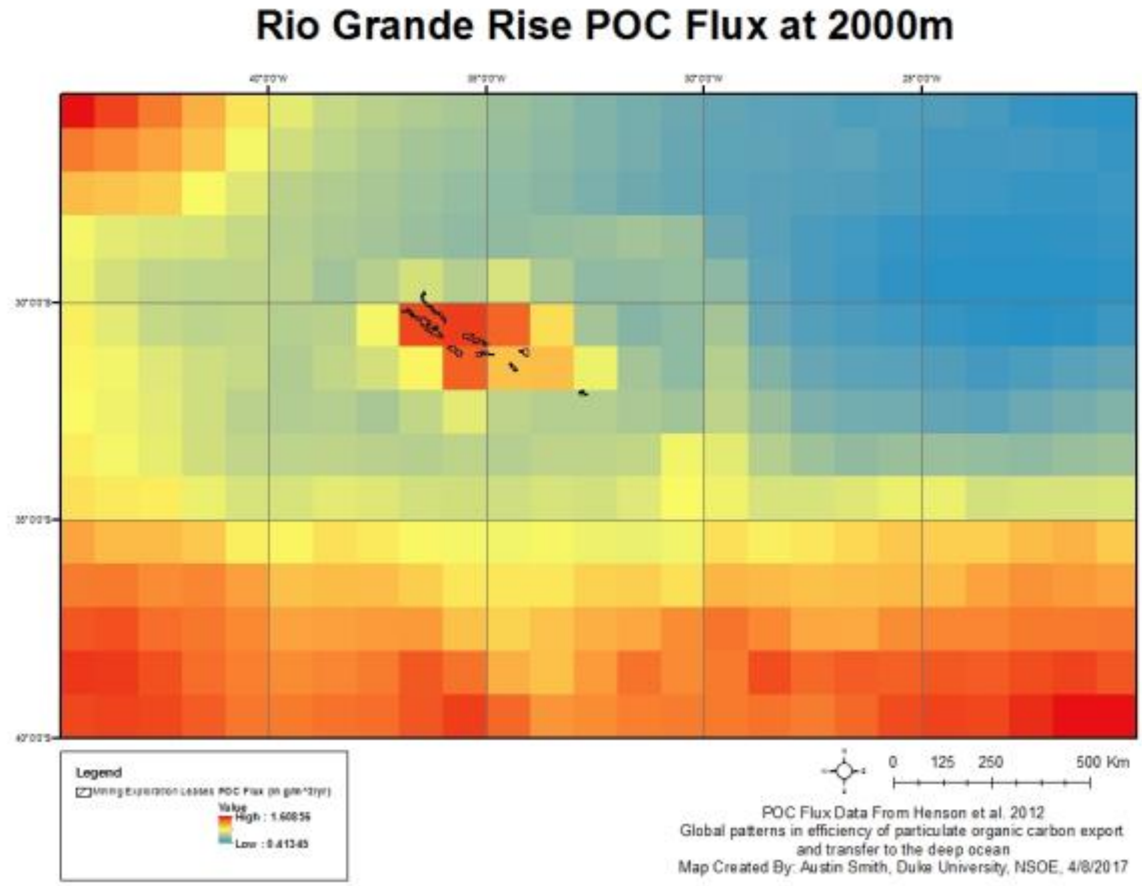
The Global Open Ocean Deep-sea (GOODS) biogeographic province dataset (Watling et al., 2012) indicates that there is a transition between northern (Brazilian Basin) and southern (Argentine Basin) abyssal provinces in the RGR study area (Figure 13). Shallower portions of the RGR study area, including the W-RGR and E-RGR (and all existing exploration blocks) belong to a single, South Atlantic, bathyal province.



Biogeographic Provinces Data From Watling et al. 2012
A proposed biogeography of the deep ocean floor.
Map Created By: Austin Smith, Duke University, NSOE, 3/10/2017

Figure 13: Rio Grande Rise Biogeographic Provinces

` Particulate Organic Carbon (POC) flux at 2000 meters within the Rio Grande Rise study area varied by a factor of four, between 0.41 and 1.61 g/m^2/year (Figure 14). High POC fluxes are associated with bathyal depths of the W- and E-RGR and NW section of the study area. They were also detected along the southern margin of the study area.

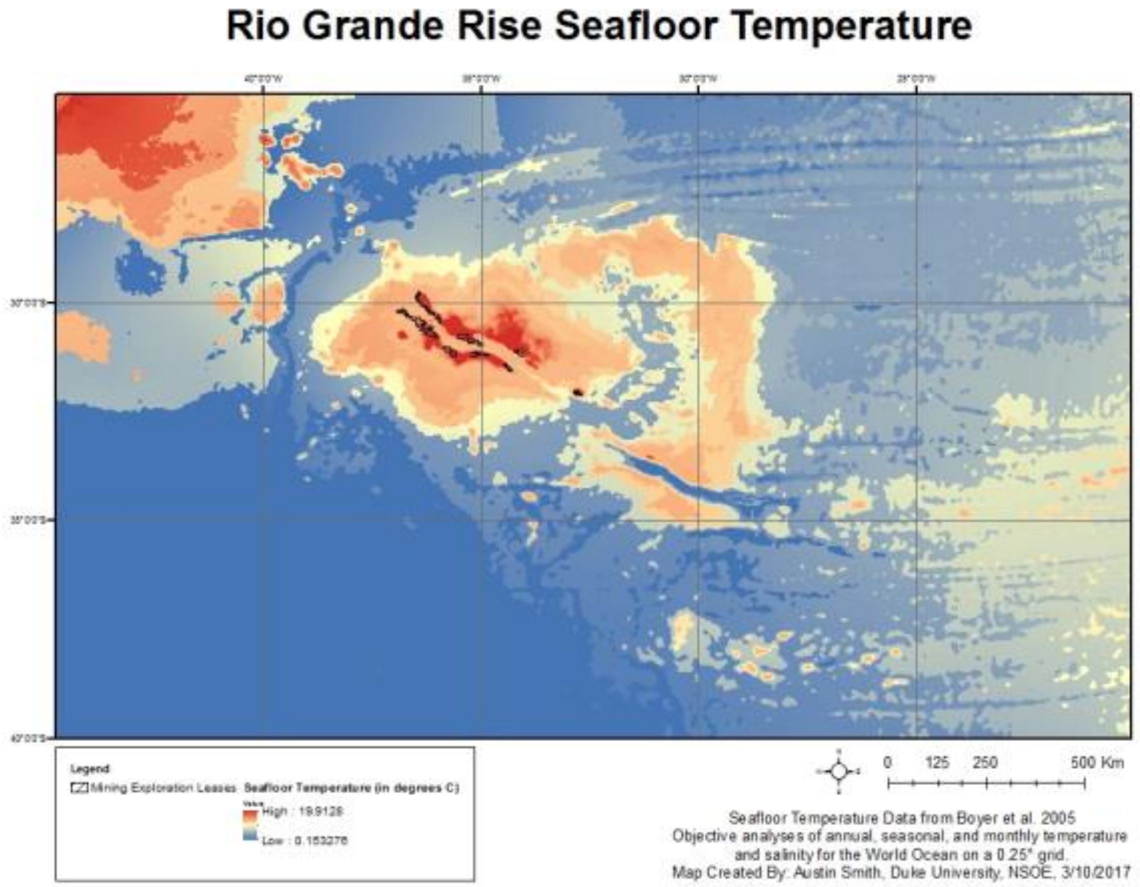


POC Flux Data From Henson et al. 2012
Global patterns in efficiency of particulate organic carbon export
and transfer to the deep ocean
Map Created By: Austin Smith, Duke University, NSOE, 4/8/2017

Figure 14: Rio Grande Rise Particulate Organic Carbon Flux at 2000 m

3.1.3 Physio-chemical Parameters

Seafloor temperatures in the RGR study area vary from nearly 0◦C to >19◦C (Figure 15). The temperature range was much narrower within the mining exploration lease areas, where temperature varied from 2.8◦C to 10.7◦C. This variation in temperature occurs over a small spatial area (exploration leases are approximately 50-100 km in length) and includes temperature values that fall within the ranges highlighted as important by Yasuhara and Danovaro (2014).

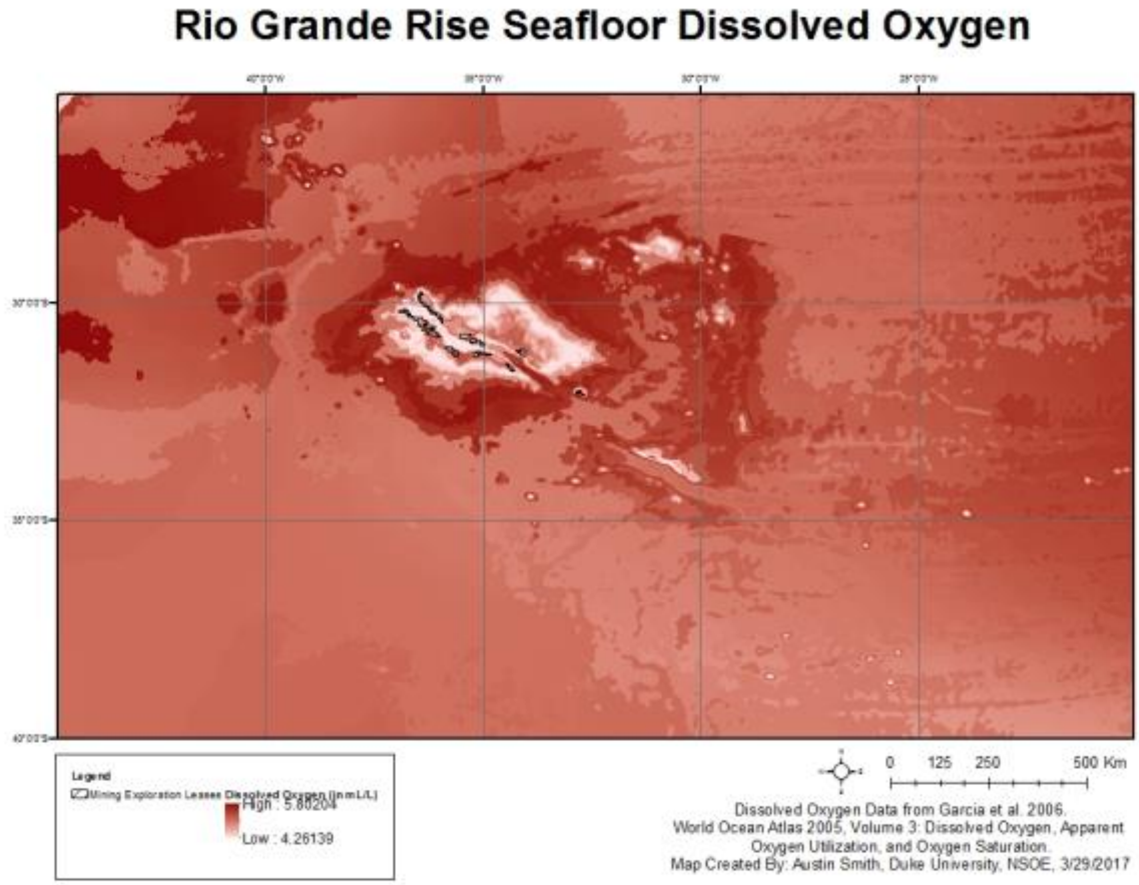


Rio Grande Rise Seafloor Temperature

Seafloor Temperature Data from Boyer et al. 2005
Objective analyses of annual, seasonal, and monthly temperature
and salinity for the World Ocean on a 0.25° grid.
Map Created By: Austin Smith, Duke University, NSOE, 3/10/2017

Figure 15: Rio Grande Rise Seafloor Temperature

Seafloor dissolved oxygen was saturated through the study area, ranging from ~ 4.3 and 5.8 mL/L, and lowest at the shallowest depths (Figure 16).



Dissolved Oxygen Data from Garcia et al. 2006.
World Ocean Atlas 2005, Volume 3: Dissolved Oxygen, Apparent Oxygen Utilization, and Oxygen Saturation.
Map Created By: Austin Smith, Duke University, NSOE, 3/29/2017

Figure 16: Rio Grande Rise Seafloor Dissolved Oxygen

3.1.5 Non-Mining Human Uses

No bottom fisheries as defined by the Bensch et al. (2009) were detected within 1,500 km of the Rio Grande Rise study (Figure 17).

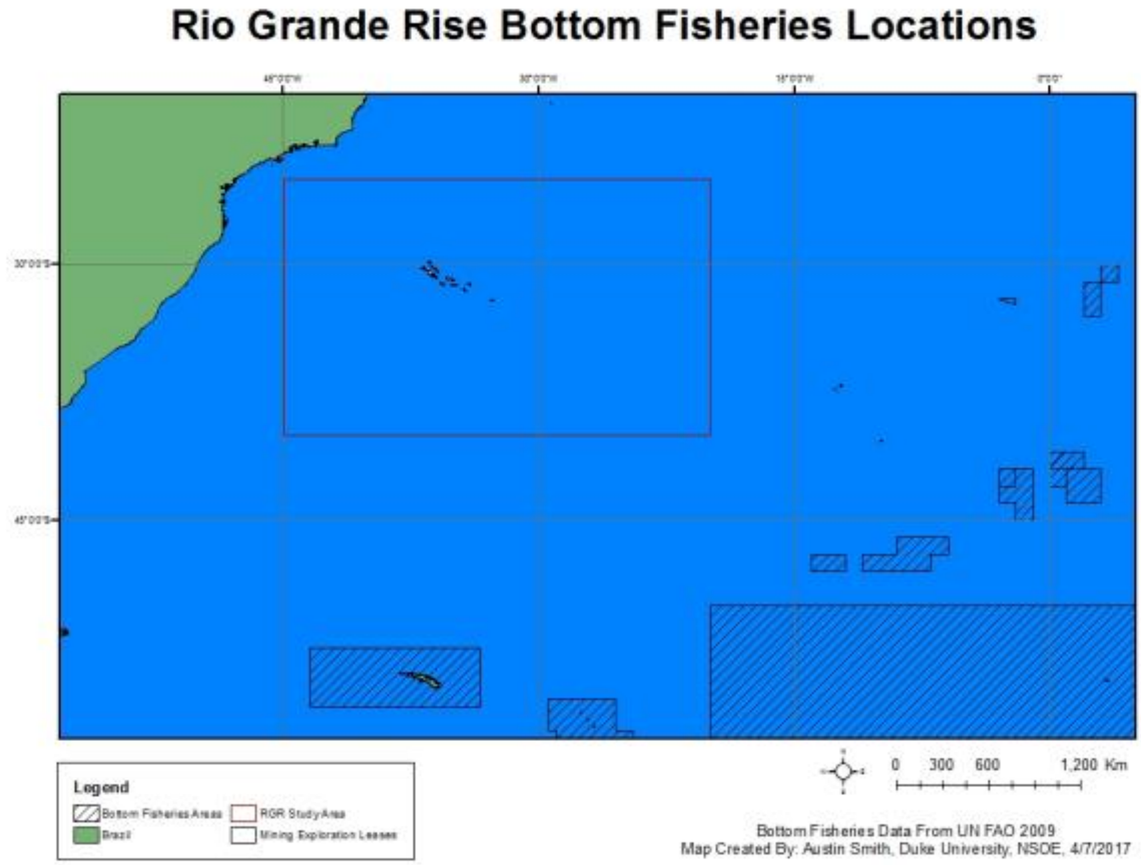


Figure 17: Rio Grande Rise Bottom Fisheries Locations

Only one submarine cable was found to run through the study area. This cable, “Atlantis-2”, is located approximately 300 km northwest of the Rio Grande Rise and runs along relatively shallow waters near the Brazilian coast (Figure 18).

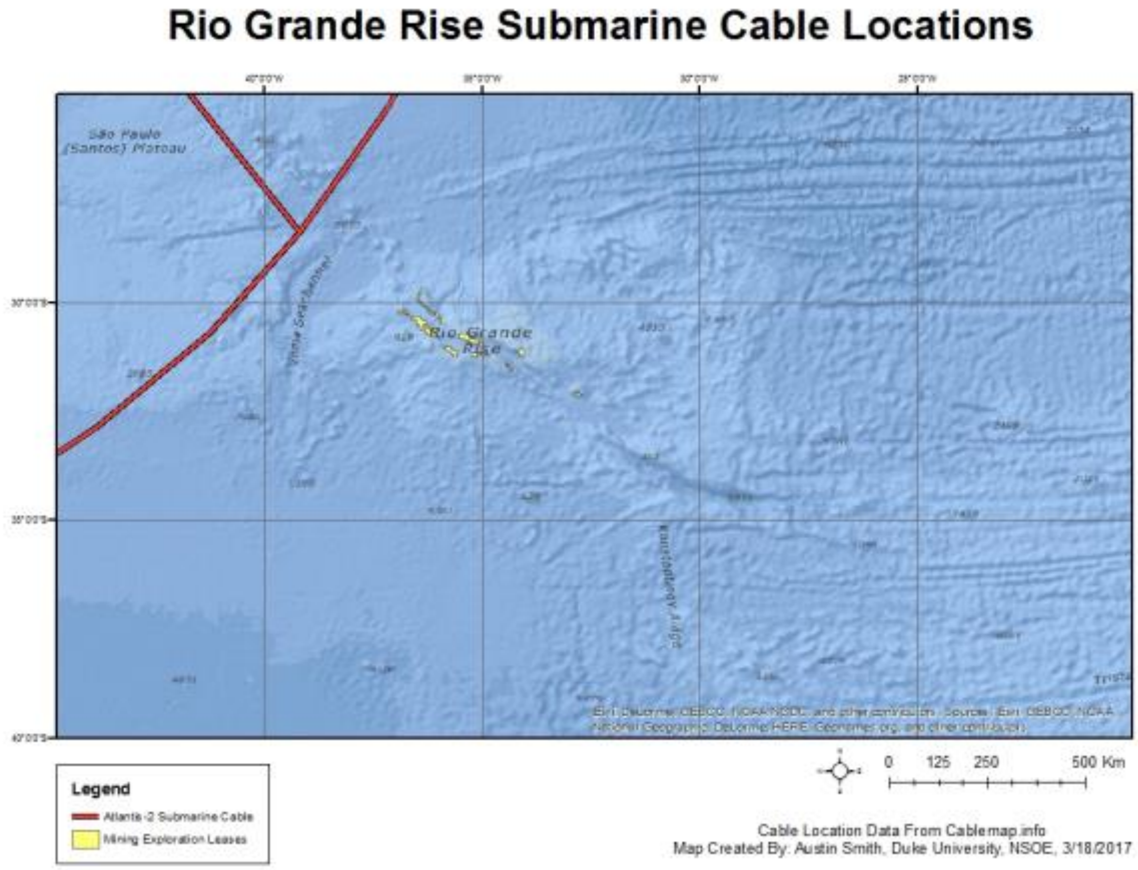


Figure 18: Rio Grande Rise Submarine Cable Locations

There is a high level of shipping activity in the Northern portion of the Rio Grande Rise region, with up to 189 ship tracks per year per 1 km^2 cell (Figure 19). Shipping intensity was much lower across the rise itself and the mining exploration leases, though. Shipping tracks only overlapped with one of the exploration lease blocks (5 to 6 ship tracks per year per 1 km^2) were found within this block.

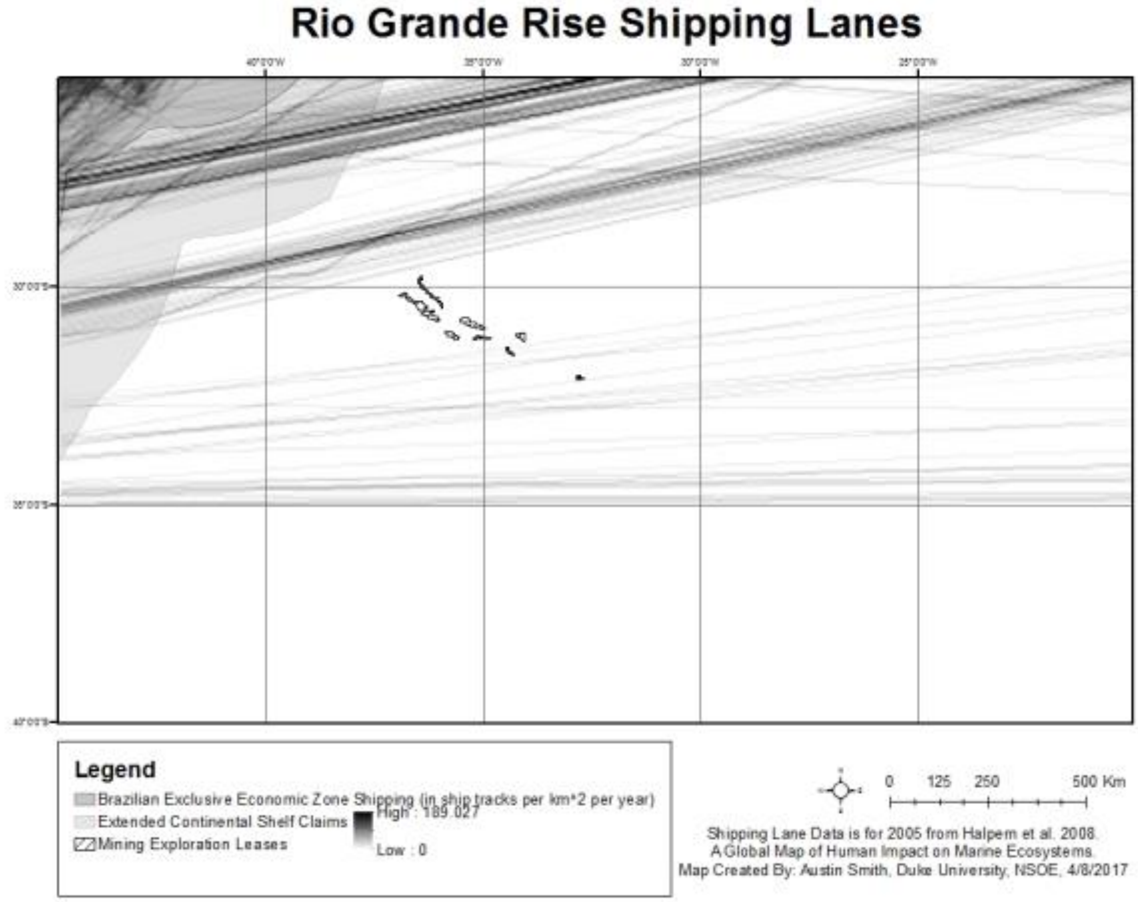


Figure 19: Rio Grande Rise Shipping Lanes

3.2 Seafloor Region Classification

A 9-class output was identified as the optimal class number, as this output was found to have the greatest average between-class distance and between-class distances were of a similar magnitude. In general, the classes identified were aggregated across the RGR study area (Figure 20). The W-RGR and its exploration lease blocks (with one exception) was almost uniformly “shallow, high POC, warm” (Figure 21); the E-RGR was predominantly “shallow, warm, steep slope”. The majority of isolated seamounts off of the Rise also shared the W-RGR classification (Figure 20). Table 3 provides a summary of the ranges of parameters used in this classification as well as biologically relevant ranges obtained through a literature review.

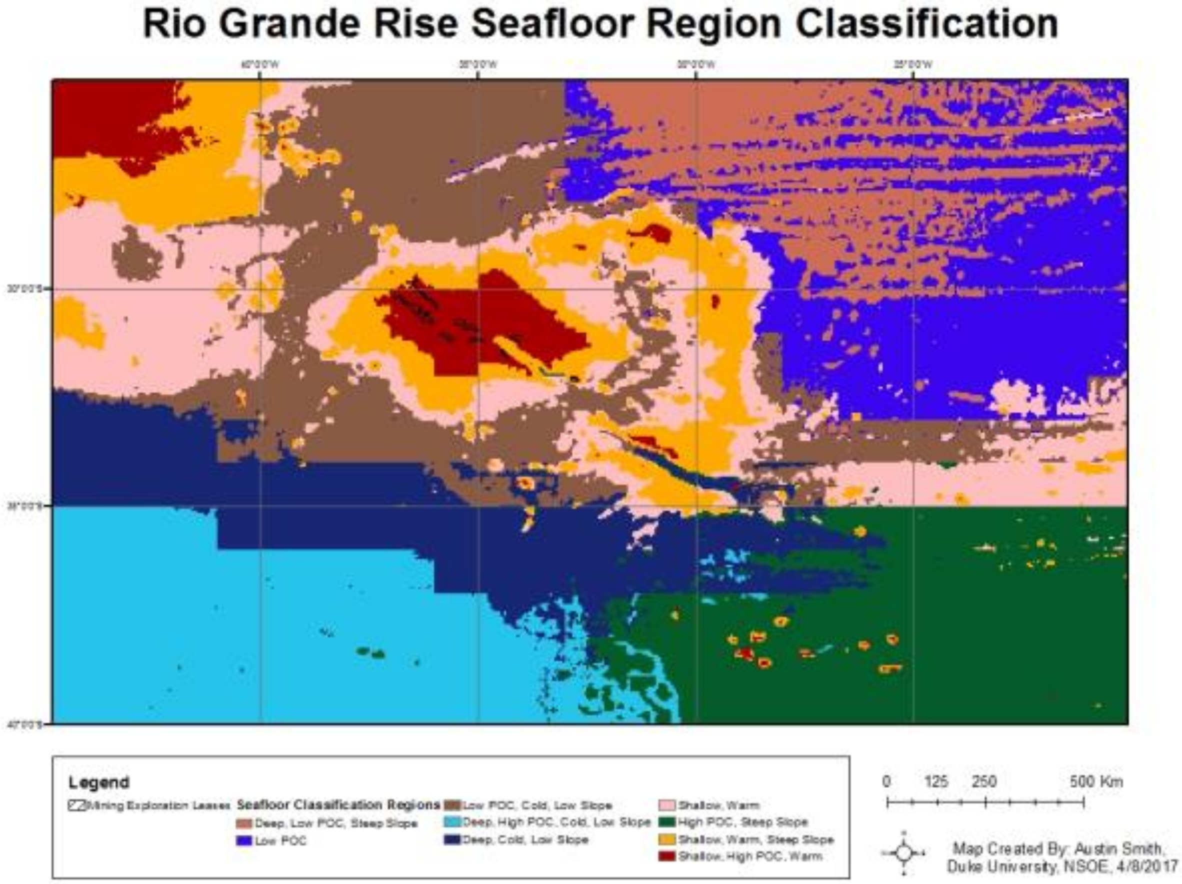


Figure 20: Rio Grande Rise Seafloor Region Classification

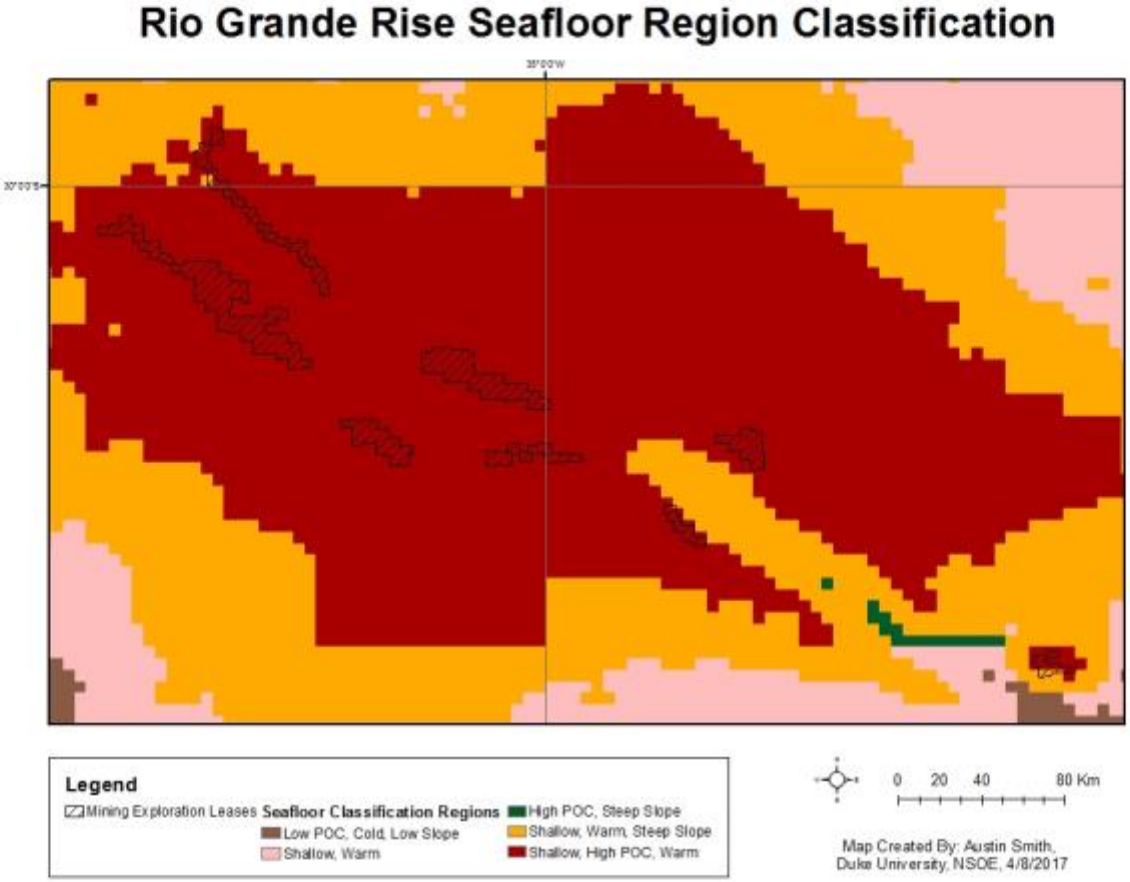


Figure 21: Seafloor Regions within Western RGR

Table 3: Seafloor Region Classification Parameters and Values Observed

Environmental Parameter	Data Source	Biologically Relevant Range	Range Observed in RGR
Depth	Weatherall et al., 2014	Biomass (gC/m^2) decreases between approximately 0.02-0.45/1km depth. Greatest changes in diversity/biomass with depth in the deep-sea occurs in heterogeneous bathyal region. (Rex et al., 2006)	122 - 6121 m and all mining exploration lease areas are in bathyal region.
POC Flux	Henson et al., 2012	No specific limiting range found but POC is cited as the primary driver of ecosystem function by many sources. (ex: McClain et al. 2012, Woolley et al., 2016) Also, study by Smith et al. (1997) suggests that microbial biodiversity increases by 0.015 ug C/cm^2 per mmol C/m^2 day of POC flux	0.41 - 1.61 mmol C/m^2 day
Seafloor Temperature	Boyer et al., 2005	Deep-sea biodiversity increases as temperature increases below 5 degrees C but decreases as temperature increases between approximately 10 to 15 degrees C. Temperature not likely important driver in between these values. (Yasuhara and Danovaro, 2014)	0.15 - 19.91 degrees C
Seafloor Morphology Parameters (Slope, Bathymetric Position Index, Rugosity, etc.)	Slope derived from Weatherall et al., 2014	No specific limiting range for biology but slope is one measurement of seafloor heterogeneity which has been shown to influence biodiversity and ecosystem function. (Zeppilli et al., 2016) Along with sediment thickness, slope may be important in determining species distributions (Snelgrove and Butman, 1995)	0 - 91.58% Slope

Discussion

4.1 Environmental/Non-Mining Human-Use Data

4.1.1 Morphological Parameters

Morphology is useful for predicting where deep-sea mining activities may take place within the RGR region in the future (SPC, 2013) as well as biomass and biodiversity patterns (McClain and Rex, 2015, Zeppilli et al., 2016). The high degree of variability in bathymetric and slope percentage measurements (Figures 3 and 5) across the current mining exploration leases suggests that mining activities within these areas may impact a wide variety of different species and habitat types over a small area. This is further supported by the finding that the mining leases all fall within the bathyal zone based on the classification carried out by Watling et al. (2012) (Figure 13). The bathyal zone contains key habitat for deep-sea macro fauna and megafauna and has been suggested to be much more important for species formation than the abyssal zone due to its relatively high level of genetic diversity and morphological heterogeneity (Rex et al., 2006, Etter et al., 2005). Despite the high level of localized impact suggested by these morphological parameters, it seems that there is sufficient space available within the RGR study area to place APEIs that have similar variability in bathymetry and slope to that seen within current mining lease areas. This is well represented in the finding that the current mining exploration leases occupy only a very small fraction of the total optimal cobalt crust formation locations (Figure 4).

The final morphological parameter measured, seamount location (Figure 6), is primarily useful in determining potential future locations of mining activity. Cobalt-crust mining exploration has generally been conducted on the sides of seamounts as these features generally have steep slopes and high current levels that allows for the deposition of crusts (SPC, 2013). Therefore, it was somewhat unexpected that very few of the mining exploration locations in the RGR region were identified as seamount areas. This may be due to the fact that current mining exploration in this region is focused on the slope of the Rise itself. Regardless, seamount location data will likely be useful in future assessments of APEI placement within the RGR region because of its productiveness of future mining exploration areas and mining impact on regional biodiversity (Yesson et al., 2012).

4.1.2 Geological Parameters

The calcareous ooze substratum type found along most of the top of the Rise is a type of biogenic sediment made up of loose grains that are organic in origin (Mazullo et al., 1990). The presence of biogenic sediments such as this likely indicates high nutrient levels near the surface in these areas (Dutkiewicz et al., 2015). This is supported by POC flux data (Figure 14) which also indicated the presence of high nutrient levels along the rise (Henson et al., 2012). The trends in nutrient levels suggested by these data will likely be informative in the future placement of APEIs in this region but It should be noted though that both these datasets contain global, low resolution data and thus can only very general observations of regional conditions can be drawn from them.

The relatively low sediment thickness value seen across the RGR (Figure 8) is somewhat expected as cobalt-rich ferromanganese crusts generally are found on steep slopes with little soft sediment cover (SPC, 2013). The variability that is seen within the western extreme of the RGR study area is likely due to sedimentary runoff from Brazil. The lack of variability in sediment thickness across the Rise itself means that that this parameter is unlikely to play a key role in the determination of APEI placement within this region.

4.1.3 Biological Parameters

Cold-Water Octocorals and Framework-Forming corals are known to provided key structure and habitat space for a variety of deep-sea species (Freiwald et al., 2004). Therefore, areas that are predicted to contain many coral species may support high biodiversity levels. The overlap of predicted habitat for both types of Cold-water coral with the mining exploration leases means that areas directly around future mining sites may experience significant loss of this habitat type. However, since exploration leases take up such a small portion of the total habitat that is potentially suitable for both types of coral there is likely enough area available within this region to create APEIs that effectively preserve regional biodiversity of corals. To accomplish this, future APEI designation should be carried out to preserve both the maximal total area of Cold-Water coral predicted habitat and areas that are expected to contain multiple coral species whenever possible.

The identification of Ecological or Biological Significant Areas (EBSAs) indicates areas that are biologically distinct as the current system of global marine EBSAs is determined based on a variety of environmental cirteria such as rarity of species and biological diversity and productivity levels (Bax et al., 2015). The Southern Brazilian Sea EBSA that overlaps with the RGR study area was specifically found to have high topographic and oceanographic complexity and is an important site biologically as it serves as a transition area between cooler Patagonian waters and tropical waters to the north (CBD, 2012). This is supported by evidence for the convergance of water masses in this area in what is known as the South Atlantic Subtropical

Convergance (Smythe-Wright, 1997). Based on this, the location of the Southern Brazilian Sea EBSA within the RGR region is a key consideration for APEI designation even though it does not directly overlap the Rise (Figure 12).

The deep-sea biogeographic classification scheme included in this analysis (Watling et al., 2012; Figure 13) allows for the further exploration distinct biogeographic zones within the RGR study area and provides a comparison for the seafloor classification carried out in this study. The division of the abyssal RGR region into “Brazilian” and “Argentine” basins in this classification further highlights the fact that the RGR region serves as a transition zone between cool Patagonian and warm tropical water masses (CBD, 2012, Smythe-Wright, 1997).This seems to suggest that the seafloor directly surrounding either side of the RGR may contain very different organisms and habitats than the other side. Converseley, the identical classification of all bathyal zones within the RGR region (Watling et al., 2012) supports what was found in the RGR seafloor classificaiton carried out here (Figures 20 and 21) and suggests homogeneity within these areas.

Particulate Organic Carbon Flux correlates strongly with benthic productivity and biodiversity (McClain et al., 2012 & Woolley et al., 2016) and therefore has been a key consideration for the placement of mining APEIs in other regions (Wedding et al., 2013, Van Dover, 2017, pers. comm.). The high POC flux levels at and around the mining exploration leases (Figure 14) suggest that these areas have the potential to support high biodiversity. However, the resolution of the POC flux data used in this study was very coarse thus it is difficult to come to more specific conclusions about the patterns observed in this data throughout the study area. Still, based on the importance of POC flux as highlighted by recent literature and the high degree of regional variation seen in this study this a key parameter for the future evaluation of deep-sea mining in the RGR region.

4.1.4 Physio-Chemical Parameters

The high degree of variation in seafloor temperature across both the mining exploration leases and the entire study area is likely due to the variation in depth seen throughout the study area (Figures 3 and 15). This variability suggests that temperature may be spatially limiting for some species within this region (Yashuhara and Danovaro, 2014). If this is the case, these species may be greatly reduced if mining activities take place over a large portion of their range. Yashuhara and Danovaro (2014) showed that temperature is especially important in determining species distributions at levels below 5 degrees Celcius and above 10 degrees Celcius and areas within these ranges should be taken into consideration when discussing future APEI placement within this region.

Seafloor dissolved oxygen is unlikely to have a similarly limiting effect on biology within the RGR region as the entire study area was found to be well above hypoxic levels (Rogers, 2000; Figure 16). This dataset should continue to be monitored for change in the future because of its potential improtance in determining biological distributions (Diaz & Rosenberg, 1995, Rogers, 2000) but at this time oxygen differences are negligible throughout the region. For this reason, this parameter was not included in the seafloor classification run in this study even though it was used in the example carried out by Harris and Whiteway (2009).

4.1.5 Non-Mining Human Uses

The three human use datasets explored appear relatively unlikely to be impacted by mining activities within the RGR in the near future. First, the absence of bottom fisheries sites within the RGR study area suggests that fishing pressure is likely low in the area. This does not mean that there is no fishing taking place at all, however, as the presence of fishing is noted in the “Southern Brazilian Sea” EBSA report (CBD, 2012). It is likely that the fishing pressures found within the RGR study area are not covered in the Bensch et al. (2009) dataset utilized in this study and therefore future studies should include a more comprehensive look at fishing activities in this region.

The other two datasets, shipping activity and submarine cables, also had very low overlap with the region explored. Some shipping activity was found over the current mining exploration leases but it does not appear to occur at a sufficient level to have a significant impact on these areas. It should be noted, though, that this data came from ship tracks in 2005 and there could be some change in the area since then (Halpern et al., 2008). Additionally, it does not appear that submarine cables will have to be a major consideration for regulators in the future as the only submarine cable found within this region, “Atlantis-2”, is not close to any current mining leases (cablemap.info).

4.2 Seafloor Region Classification

Given that the seafloor classification was based on four of the environmental datasets mapped in this study it is unsurprising that the results of this classification reflect the trends seen in these data across the RGR region (Figures 20). The aggregate nature of the classes identified suggests that while there may be significant variation across the study area local areas are similar to each other in general. This is illustrated by the homogenous classification of the W-RGR (Figure 21). The finding that depth and temperature had extreme values within this section in comparison to the rest of the study area suggests that these parameters may be critical in future APEI designation in this region as they have been in the APEI designation in previous mining case studies (Wedding et al., 2013, Van Dover, 2017, pers. comm., SEMPIA II, unpublished). POC flux was also found to have an extreme value in the main class of the W-RGR but was more homogenous throughout the mining lease areas and thus may not play such an important role in determining APEI placement in this region.

The seafloor classification discussed here certainly has important ramifications for future APEI designation but it should be noted that there is large amount of uncertainty in this classification. This uncertainty mainly comes from the use of global environmental datasets that are often low-resolution. Also, the validation of optimal class numbers using only the classification dendrograms may have resulted in greater uncertainty. For these reasons, this classification is useful for gaining a broad overview of where different clusters of environmental conditions occur within the RGR study area but is not intended to provide exact recommendations for the placement of APEIs in the region. This process must be completed in the future once a full-scale SEMP is created that incorporates the data presented here with further, up-to-date data that more fully explains the environmental conditions found in this region.

Conclusion

The recent granting of mining exploration leases by the ISA within the Rio Grande Rise region necessitates the exploration of the ecological and environmental features of this region since there are many unknowns about these features and how they may be impacted by mining activities in the near future. In addition, the ISA is required to create a Strategic Environmental Management Plan for this region that contains APEI designations before mining activities proceed and this process requires extensive knowledge regarding environmental and human-use parameters (ISA, 2015). This study serves as a first step approach at compiling and describing data that is likely relevant in this process. It is the goal of this study that the datasets and findings contained within are now able to be used in future discussions of DSM regulations in this region including the designation of protected areas.

Although a system of APEIs was not directly proposed in this study, the data utilized provide key information for the placement of these areas in the future. The general trend found in the environmental data for this region is that conditions are relatively homogenous across much of the top of the rise and especially within the current extent of mining exploration leases. There are some exceptions to this such as the high level of variation found in POC flux and seafloor temperature within mining exploration leases that may indicate that these parameters may play an important role in restricting the range of certain species within these areas (Levin et al. 2001, Yashuhara and Danovaro, 2014). Overall, though the majority of environmental and non-mining human-use data seems to indicate that if mining activities are restricted to the current exploration leases areas then mining impact will be relatively localized and minimal.

Despite this finding, it is important that environmental data such as that utilized in this study continue to be monitored in this region to ensure the effectiveness of protected areas in the future. The datasets used in this study were included based on previous DSM case studies (Wedding et al., 2013, Morato et al., 2015) and data availability and they do not necessarily constitute a comprehensive list of factors that may be impacted by mining or that may describe the ecology and physical attributes of the RGR region. Therefore, it is imperative that future studies continue to expand and modify the list of datasets utilized here as necessary and that high-resolution data be sought out whenever possible to ensure optimal accuracy. If these steps are taken than this study can serve as a useful first order approach of describing the environmental conditions found within the Rio Grande Rise region and assisting in the placement of protected areas from mining that effectively preserve the biodiversity of this region well into the future.

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