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A global seamount classification to aid the scientific design of marine protected area networks

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ABSTRACT

Seamounts are prominent features of the world's seafloor, and are the target of deep-sea commercial fisheries, and of interest for minerals exploitation. They can host vulnerable benthic communities, which can be rapidly and severely impacted by human activities. There have been recent calls to establish networks of marine protected areas on the High Seas, including seamounts. However, there is little biological information on the benthic communities on seamounts, and this has limited the ability of scientists to inform managers about seamounts that should be protected as part of a network. In this paper we present a seamount classification based on "biologically meaningful" physical variables for which global-scale data are available. The approach involves the use of a general biogeographic classification for the bathyal depth zone (near-surface to 3500 m), and then uses four key environmental variables (overlying export production, summit depth, oxygen levels, and seamount proximity) to group seamounts with similar characteristics. This procedure is done in a simple hierarchical manner, which results in 194 seamount classes throughout the worlds oceans. The method was compared against a multivariate approach, and ground-truthed against octocoral data for the North Atlantic. We believe it gives biologically realistic groupings, in a transparent process that can be used to either directly select, or aid selection of, seamounts to be protected.

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1. Introduction

Seafloor ecosystems are increasingly impacted by human activities such as bottom fishing, oil drilling, waste disposal, and seafloor mining (e.g., Polunin et al., 2008; Smith et al., 2008). These activities, especially bottom trawling, can be highly destructive to seafloor ecosystems by depleting demersal fish populations, disrupting critical benthic habitat, and killing or damaging non-target species (e.g., Dayton et al., 2002; Gage et al., 2005). These human impacts threaten biodiversity and ecosystem function throughout the oceans, including the deep-sea areas beyond national jurisdiction (ABNJ) that constitute ~70% of the ocean floor. Thus, there is a need for large-scale management and conservation of deep-sea biodiversity and ecosystem function (e.g., Roberts, 2002; Clark et al., 2006; Smith et al., 2008). Because human impacts in the deep-sea are ecologically broad based (e.g., Koslow et al., 2000), conservation requires an ecosystem approach to management; i.e., the adverse affects of human activities on whole ecosystems must be managed considering the linkages between living and nonliving components, and the connectivity of marine populations (e.g., Probert, 1999). One component of an ecosystem approach to management is the use of networks of marine protected areas (MPAs) which exclude harmful human activities, facilitating the protection/restoration of biodiversity and ecosystem functions (PISCO, 2007). A substantial scientific literature now demonstrates that scientifically designed MPA networks can be highly effective tools for conserving biodiversity and ecosystem services (PISCO, 2007).

Ideally, the design of MPAs and MPA networks should follow four sequential steps: (1) Evaluation of conservation needs, (2) Definition of the objectives for establishing the MPAs, (3) Integration of information on the biological characteristics (e.g., life histories, dispersal patterns, species distributions) and habitat distribution of the managed ecosystem, and (4) Selection of suitable sites to serve as MPAs (Protected Areas, 2001). This general structure has many variations, especially with the consultation process, but typically remains strongly science-based (e.g., IUCN–WCPA, 2008; Gleason et al., 2010). Seamount systems have been highlighted as vulnerable to fishing by the United Nations

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General Assembly (resolutions 61/105, and 59/25) and subsequent actions by the Food and Agriculture Organisation of the UN has lead to the development of International Guidelines for the Management of deep-sea fisheries in the High Seas (e.g., FAO, 2008; FAO, 2009), conservation needs have been identified (e.g., Probert et al., 2007) scientific criteria recommended by bodies such as the Convention on Biological Diversity (e.g., CBDS, 2009) and underlying scientific objectives of an MPA system defined to preserve representative and unique marine habitats, as well as to preserve and conserve marine biodiversity, and ecosystem structure and function (e.g., Johnston and Santillo, 2004; George et al., 2007). Hence the stage is set for progress to stages 3 and 4.

In order to design such an MPA system it is necessary to first identify areas that contain, or can be predicted to contain, distinct habitats and/or communities. There are a number of means by which habitats/communities can be identified, but classification is among the most common methods used (Carpenter et al., 1999). In the marine environment, where there is frequently an absence of extensive, comparable, high quality biological community data, classification is performed using a number of environmental variables that define a combination of habitat characteristics that are likely to control the distribution and composition of pelagic and/or benthic communities. Such classifications already exist either for particular portions of the marine environment (e.g., deepwater, Greene et al., 1999); coastal waters (Zacharias and Roff, 2000), ecosystems (e.g., estuaries, Edgar et al., 2000), geographic regions (e.g., NW Atlantic shelf Valentine et al., 2005); NE Atlantic slope (Howell, 2010), and lately for the entire global seafloor (Harris and Whiteway, 2009). There are a variety of classification techniques available, but the two most popular methods are thematic or so-called *hierarchical* classification, and numerical or so-called *multivariate* classifications. Each of these two approaches has particular advantages and disadvantages. Multivariate classifications are generally bottom-up statistical grouping of multiple (usually) continuous variables, they are largely objective and are more likely to produce natural groupings (e.g., Snelder et al., 2007). However, they are relatively conceptually complicated and the process and output not so readily understood, plus there is no standard multivariate procedure. Despite their mathematical robustness, because they frequently produce a classification of a large number of groups they have not been widely adopted by environmental managers. On the other hand, hierarchical classifications are generally top-down sub-divisions of individual thematic layers (e.g., Roff et al., 2003). The divisions are subjectively made and thus there is the potential for identifying unnatural groupings. However, the hierarchical classifications are a very simple concept, there is essentially only one method, and the process and output readily understood. Thus this type of classification has been widely used to identify habitats (e.g., European Nature Information System (EUNIS) (Davies et al., 2004); Coastal and Marine Ecological Classification Standard (CMECS) (Madden et al., 2005)) and used for environmental management purposes (e.g., European Union Habitats and Species Directive (92/43/EEC). For habitat classifications to be particularly successful they need to be flexible, multi-scale and/or specific to a region and/or particular habitat type (e.g., Roff et al., 2003).

Seamounts and elevated summits of midocean ridges provide important habitats for a diverse array of species and communities adapted to lesser depths and harder substrate than the surrounding abyssal plain. They are habitats which can feature enhanced productivity and host aggregations of commercial fish species. Consequently they have become important for fisheries in the high seas (e.g., Gianni, 2004). Bottom trawling for deepwater species is widespread on seamounts throughout the world's oceans, with historic catches of at least 2 million tonnes (Clark et al., 2007), and annual catches of hundreds of thousands of tonnes (Watson et al., 2007). These fisheries include those for well-known species such as slender (pelagic) armorhead (*Pseudopentaceros wheeleri*), orange roughy (*Hoplostethus atlanticus*), and alfonsino (*Beryx splendens*). Although midwater trawling for pelagic species, and long-lining, is also common over seamounts, bottom trawling has received most attention because of the well-known impacts of such fishing on the benthic habitat and fauna (e.g., Koslow et al., 2001; Clark and Koslow, 2007; Clark and Rowden, 2009; Althaus et al., 2009). Seamounts are also attracting attention from mineral exploration companies for their cobalt-rich ferromanganese crusts and polymetallic sulphides (ISA, 2007). However, seamount communities are highly vulnerable to the effects of human activities (Clark et al., 2010) and have been identified as vulnerable marine ecosystems by the UNGA (2006). Consequently, there is increasing concern about their conservation (e.g., Probert et al., 2007). Because of limited biological data on seamounts offshore, it has been easy to delay action "until more is known" (e.g., Davies et al., 2007), yet there is an urgency to manage seamounts to ensure sustainability of fisheries and to protect benthic habitat (e.g., Alder and Wood, 2004; Rogers et al., 2008). Hence in this paper we outline the development of a hierarchical seamount classification methodology based on scientific principles and data that can inform subsequent discussions on designing an effective network of MPAs.

The overall goal of the study is to progress the design of seamount MPA networks in ABNJ, commonly referred to as "the High Seas". The specific objectives of the work were to design a hierarchical classification system for seamounts, to apply it to a global set of seamounts, to evaluate the performance by comparing with other classification methods, and with regional datasets of biological information. The results of this classification can then feed into subsequent detailed MPA design. National governance by individual countries apply within Exclusive Economic Zone areas. However, principles and methods considered for ABNJ could apply equally to features within EEZs.

2. Methods

2.1. Data

2.1.1. Seamount data selection

There are a number of definitions and applications of the term "seamount", ranging from the classical geological definition of discrete volcanic features with a vertical elevation from the surrounding seafloor of at least 1000 m, to more recent use of the term to encompass much smaller elevation features which are believed to function in a similar ecological way to larger features – the latter include knolls, pinnacles and hills where the elevation can be as low as 100 m (Pitcher, 2007). For many offshore areas, data on seamount location are only available from analysis of satellite altimetry (e.g., Wessel, 2001; Kitchingman and Lai, 2004) and these types of predictive analyses are thought to identify only large features, with an elevation of 1000–1500 m above the seafloor. Peaks of ridge systems confuse this definition when elevation to the seafloor off the sides of the ridge is large, but there is less elevation between the peaks along the ridge. Globally it is impractical to use datasets that identify a large number of seamounts with smaller elevations (200,000 + seamounts (Hillier and Watts, 2007)), and the position of these seamounts is often poorly defined (bathymetry derived from ship track data, including those prior to availability of GPS). Therefore for practical purposes the seamount dataset of Kitchingman and Lai (2004) was selected for use in this study. This dataset comprises the location of 14,287 large seamounts (rising 1500 m or more from the seafloor) estimated from analysis of 2 min resolution satellite altimetry data. Importantly, it includes estimates of the depth of the seamount at

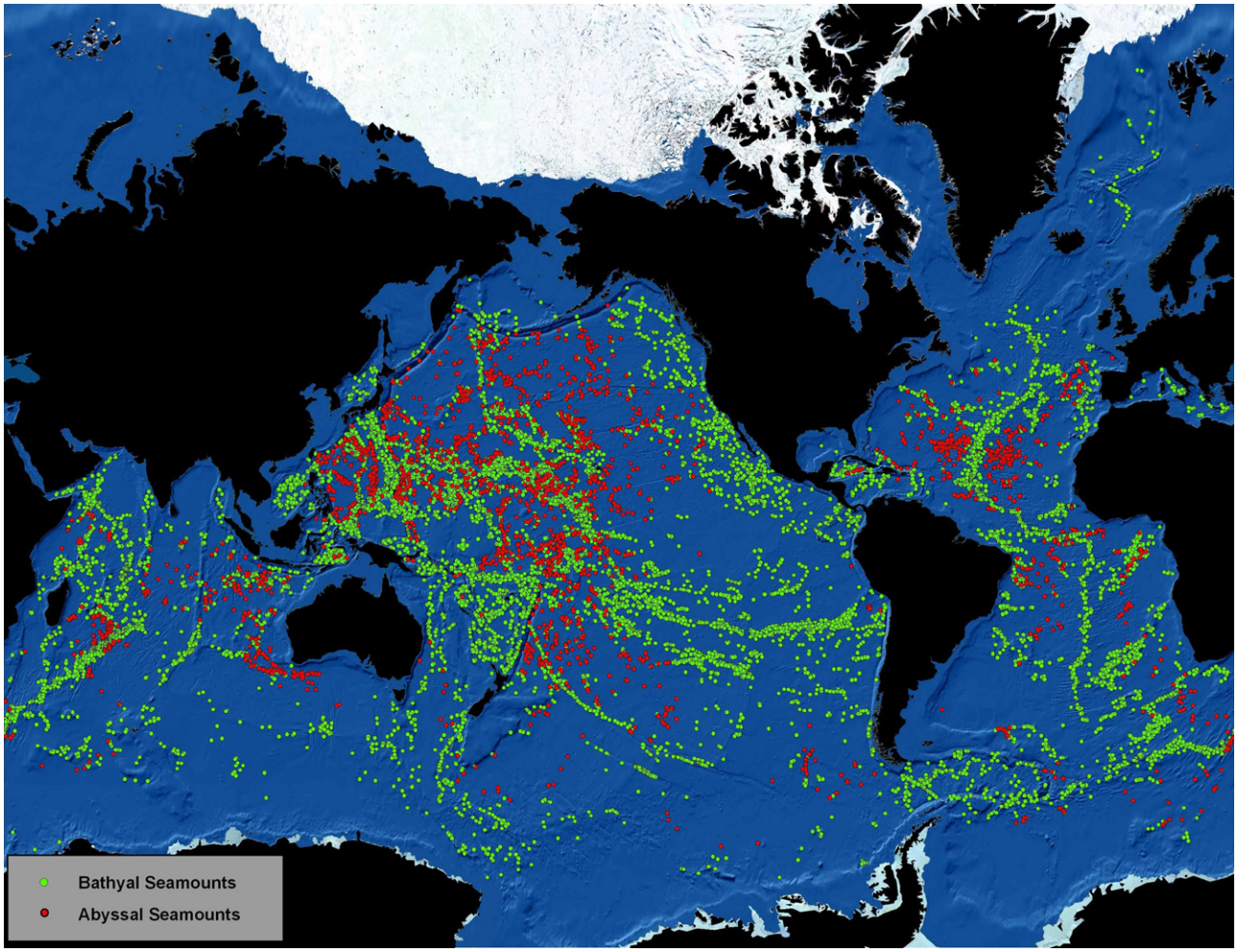

Fig. 1. The distribution of seamounts predicted by Kitchingman and Lai (2004) used in analyses (note this includes the abyssal depth seamounts, colour-coded).

its summit which makes it useful for biological application. However, it includes features that are estimated to rise near or to the sea surface (summits of <10 m water depth). These features (mostly atolls in the Pacific Ocean, see Allain et al., 2008) were removed from the dataset prior to analysis ($n = 1133$). Sixty-three seamounts could not be used as they lacked particular environmental data (see Section 2.1.4.1). The remaining dataset comprised 10,604 bathyal-depth seamounts (the main data used in analyses) and 2406 abyssal seamounts with summit depths greater than 3500 m (used in one of the analyses) (Fig. 1).

2.1.2. Areas for trial application of the classification

The aim was to apply the classification approach to all seamounts in the dataset to produce a global example of how the classification can be used as an aid to design marine protected area networks, and to several regions where: (1) additional seamount data were available to allow an evaluation of the relative performance of the hierarchical and multivariate classification approaches, and for where a previous seamount classification had already been produced; (2) expert knowledge and ground-truth data were available to evaluate whether the hierarchical classification results appeared sensible and hence whether the approach was valid; (3) an area of the seafloor that is already subject to a developing resource management strategy (for seabed mining) that includes proposed MPAs based on scientific criteria; (4) an area of the seafloor that is already subject to a developing resource management strategy (for fishing on seamounts) that includes MPAs proposed by stakeholders not based on scientific criteria.

2.1.2.1. New Zealand. Data are available for all the environmental variables proposed for use in the classification for about 1000 seamount features (in this case including knolls, hills and features with <1000 m elevation) (SEAMOUNT v2 database Rowden et al., 2008). A subset of these data ($n = 735$ which excluded seamounts with summits deeper than 3500 m) allows for a comparison of the results of both the hierarchical procedure and multivariate procedure using the same variables, to evaluate the use of a subjective hierarchical classification over an objective multivariate classification.

2.1.2.2. North Atlantic. The North Atlantic has extensive seamount features along the Mid-Atlantic Ridge (MAR) as well as more isolated seamounts and chains in both the western and northeastern areas of the Ocean. The area has been relatively well sampled and studied, and knowledge of the regional biogeography is better than for most oceans. This knowledge enables an evaluation of whether the simple hierarchical divisions fit with known biological distribution patterns. For the most part, information regarding the fauna of seamounts in the North Atlantic Ocean is restricted to one or a few groups sampled from a small number of seamounts located near to each other (e.g., harpacticoids from Great Meteor Seamount, polychaetes on eastern Atlantic seamounts). Over the

past several years, however, a concerted effort has been made to sample and identify the gorgonian octocorals from seamounts in both the eastern and western Atlantic (e.g., Grasshoff, 1981, 1985; Watling and Auster, 2005). These data have been collated and used here to examine the seamount classification pattern in the North Atlantic Ocean bathyal biogeographic province. In all, 84 species from 12 families were recorded from 19 seamounts.

2.1.2.3. Central-North Pacific. Seamounts in parts of the north Pacific have cobalt-rich crusts, which have potential for mining development. The International Seabed Authority (ISA) has solicited input from the scientific community on the biodiversity of these seamounts, and the development of appropriate measures to guide management if mining develops in the future. Classification of seamounts in the region of interest (known as the "Hein Box") would also link with proposed Reference Protection Sites in the Clarion–Clipperton Zone (CCZ) where manganese nodule mining is under the management auspices of the ISA. This latter proposal includes seamount sites, so will be included to evaluate the classification within the proposed Preservation Reference Areas ("Santuary Zones") (Anon, 2008). The analysis in this area includes abyssal-depth seamounts.

2.1.2.4. Southern Indian Ocean. At present there is no formal Regional Fisheries Management agency covering deepwater fishing activities in the Indian Ocean (tuna is managed, but not demersal species). The Southern Indian Ocean Deepwater Fisheries Association (SIODFA) has instituted several Benthic Protected Areas (BPAs) on seamounts of the Southwest Indian Ridge and 90 East Ridge. The selection of sites was based on agreement between fishing operators, and did not use a systematic scientific methodology (Shotton, 2006) and so comparison with the seamount classification approach will evaluate the distribution of existing closures against what might be required if scientific-based selection is ultimately undertaken.

2.1.3. Allocation of biogeographic region

Faunal composition varies throughout large areas of the worlds' oceans, for a variety of reasons including historical as well as present day processes. This variation should be recognised before any sub-division based solely on physical factors occurs. Biogeographic units can be used as a first cut to evaluate whether the area of interest (e.g., North Atlantic) is likely to be a single or multiple geographical entity. This initial division provides a large area (province) within which the fauna will generally be similar. We used the benthic province system recently developed as part of a general biogeographic classification of the ocean for UNESCO (2009). Most areas of the deep ocean have not yet been sampled, so this biogeographic classification (commonly known as the "GOODS" report) was based on a combination of environmental as well as biological factors.

The GOODS classification initially divided the ocean into 5 depth layers: 0–300 m, continental shelf; 300–800 m, upper bathyal; 800–3500 m, lower bathyal; 3500–6500 m, abyssal; >6500 m, hadal. Here we used primarily the biogeographic schemes for the lower bathyal, with the abyssal scheme used in one example. Since most of the potential impacts on seamounts will likely occur at depths less than 3500 m, only seamounts with summits at upper and lower bathyal depths were considered. The 14 provinces of the lower bathyal (Fig. 2) were based on general benthic faunal distribution analyses (e.g., the Russian results from Zezina (1997)), supplemented with oceanographic data such as temperature and salinity (see UNESCO, 2009). It is widely recognised that faunal change may occur within this zone (e.g., Carney et al., 1983), and

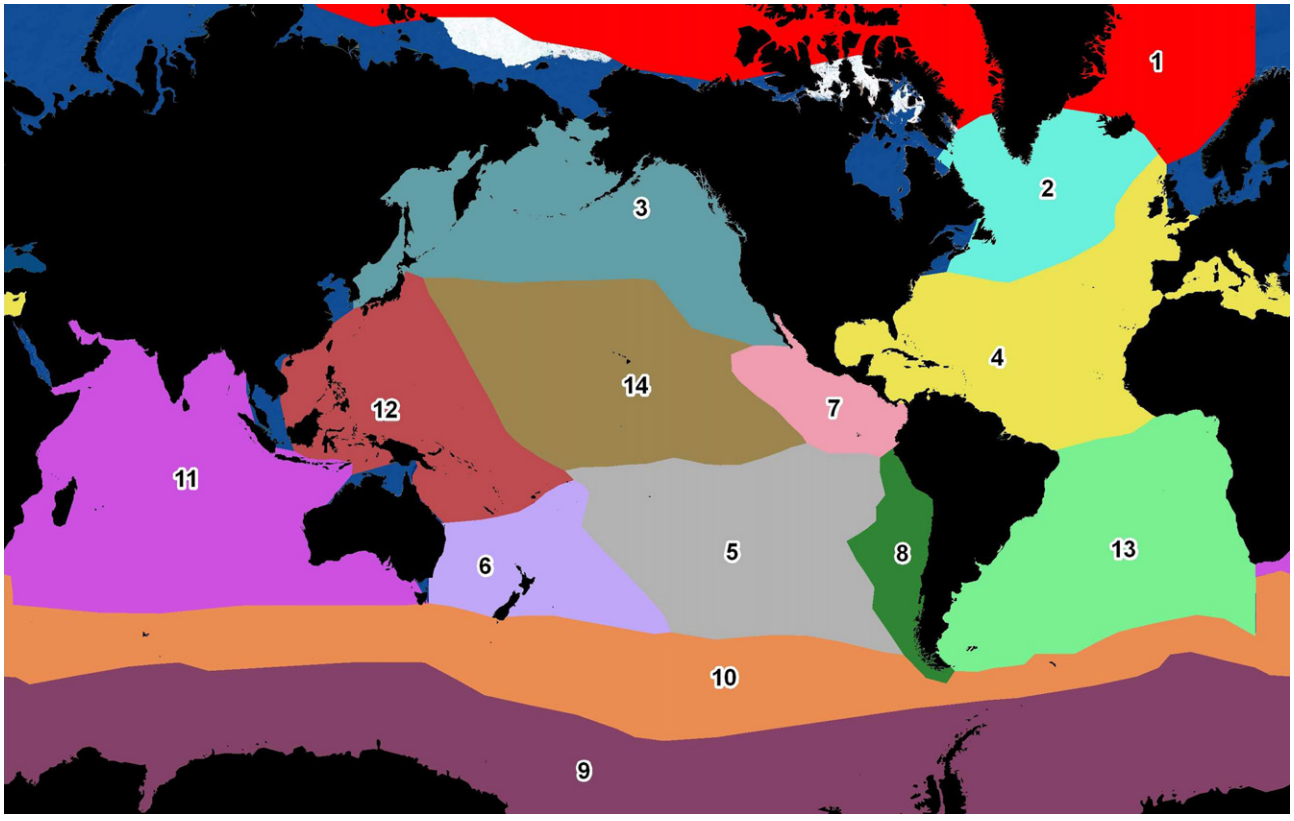

Fig. 2. Lower bathyal depth biogeographic provinces, from the GOODS report (UNESCO, 2009).

that human impacts, primarily in the form of fishing, will occur only in the upper part of this zone. As a result, for some analysis we have subdivided the zone into upper lower bathyal (800–1500 m) and lower lower bathyal (1501–3500 m) bands.

2.1.4. Selection of physical variables and associated categories

It is recognised that a wide range of environmental factors can influence benthic biodiversity, but that a small number of key variables contain adequate information to draw inferences about patterns in species composition and distribution. We initially considered eight factors that are widely recognised as being important for seamount biodiversity (see Clark et al., 2010): substrate type, seamount size/shape (e.g., guyot/conical seamount), seamount elevation, summit depth, overlying water mass, dissolved oxygen level, volcanic activity (i.e., likelihood of having hydrothermal vent fauna), connectivity (proximity to adjacent seamounts, and whether isolated, in a chain etc).

In principle, a habitat classification scheme should include as many important factors as possible, but with seamounts in the High Seas availability of data is an issue, especially on a global scale. For example, it is well known that substrate type is a useful proxy for a combination of hydrographic and physical variables that can determine benthic faunal composition (see review by Howell (2010)), but global data are not available, and even at a regional level data are sparse or patchy. The simplicity of the scheme was also a consideration as we felt it needs to be readily understood and easy to apply for management purposes. Hence the list was reduced to focus on those variables which were felt to be the most biologically relevant driving factors, and for which global-scale data were available.

2.1.4.1. Export productivity. In most areas of the ocean, the benthos below about 200 m relies upon the deposition of organic matter to the seafloor from the upper layers of the water column (e.g., Levin et al., 2001). However, this is not easy to measure, and often surface production, calculated from chlorophyll *a* estimates from satellite data (e.g., Johnson et al., 2007) is used as a starting point for estimating how much food material is delivered to the sea floor in various regions of the ocean. The major problem with these kinds of estimates is that it is difficult to determine what fraction of surface production actually reaches the sea floor. Yool et al. (2007, 2009) recently developed a model to estimate the amount of organic carbon that, on average, is likely to be exported from the surface, and so will be available as food to organisms on the sea floor. This model provides a useful starting point for understanding export flux of organic matter in different parts of the ocean. We used the output from this model at a 200 m horizon to assign relative values of export flux of particulate organic carbon (hereafter termed organic matter flux) over a seamount. This depth was chosen to reflect changes occurring distant enough from the surface to reflect variable sinking characteristics in different regions. We identified ranges which we thought reflected the broad patterns of known production in parts of the ocean where processes are reasonably well understood (e.g., high levels downstream of upwelled nutrients, under strong surface currents, and oceanographic convergence zones).

Three categories of the export flux of particulate organic carbon were selected:

- "Low", <1 mol m^{-2} d^{-1}
- "Medium", 1 to <5 mol m^{-2} d^{-1}
- "High", ≥ 5 mol m^{-2} d^{-1}

2.1.4.2. Summit depth. Species occurrence and benthic assemblage composition is widely recognised to change with water depth (e.g., Carney et al., 1983; Gage and Tyler, 1991).

Three representative depth intervals were selected:

0–200 m – This depth band reflects the protrusion of the seamount summit into the photic zone and the particular community likely to develop at these shallow depths.
201–800 m – This depth band takes into account the distribution of vertically migrating animals (the scattering layer), and the impact of these on the benthic fauna that exists on the seamount summit at these depths. The 800 m depth limit was based on the upper bathyal split made by Zezina (1997).
801–3500 m – This is the depth band covered in the GOODS report as the lower bathyal biogeographic zone, and was based on a global evaluation of brachiopods by Zezina (1997). There is regional variation with depth in this band, and where such information is available it should be used to subdivide this broad range. For example, in temperate waters of the South Pacific Ocean and southern Indian Ocean there is a faunal change at around 1500 m (e.g., Althaus et al., 2009) where reef-building scleractinean corals become rare, in contrast to dominating the epifauna in shallower parts of the zone. Such a sub-division has been applied in our analysis of the Indian Ocean seamounts.

The full data available from Kitchingman and Lai (2004) includes seamounts with summit depths greater than 3500 m. These depths correspond to the abyssal zone where faunal composition is known to differ from the lower bathyal (UNESCO, 2009). In the CCZ region, abyssal seamounts are important, and so were included for that analysis. The deep seamounts should ideally be classified according to their abyssal biogeographic province from the GOODs report, but to simplify the analysis, we applied the same lower bathyal biogeographic boundaries as for shallower seamounts.

These depth bands apply to the seamount summit. The flanks will have common depths between the divisions. However, summit processes are different from those operating on seamount flanks or near the base (e.g., greater isolation, current intensification and interception of vertical migrators) and summits are likely to harbour a different biota (e.g., Baco, 2007). Although seamount fauna may be similar at the same depth on the flanks, varying summit depths will likely mean overall seamount biodiversity differs, and protection of representative fauna needs to consider such dissimilarity. Bottom fishing operations also typically start on the summit of a seamount, even if they extend down the flanks, and so summit areas receive a disproportionate amount of disturbance. Hence it is important to capture the summit depth in the classification.

2.1.4.3. Dissolved oxygen. Oxygen level in the water is important in determining species composition, and has been shown to influence the fauna on seamounts (Wishner et al., 1990). Very strong oxygen minima in areas of the northern Indian Ocean and northern and eastern Pacific are associated with different benthic fauna, and dissolved oxygen levels are related to water mass characteristics and consumption–decomposition processes (Levin et al., 1991). Oxygen levels at the depth of the seamount summit were obtained from the World Ocean Atlas.

Oxygen was divided into two categories based on studies of benthic zonation in the oxygen minimum zone (Levin, 2003):

- $\leq$ 1.0 ml/l – This value is the recognised level for defining the Oxygen Minimum Zone (OMZ)
- $>$ 1.0 ml/l – Above the OMZ level, oxygen is not felt to be limiting for most benthic invertebrates.

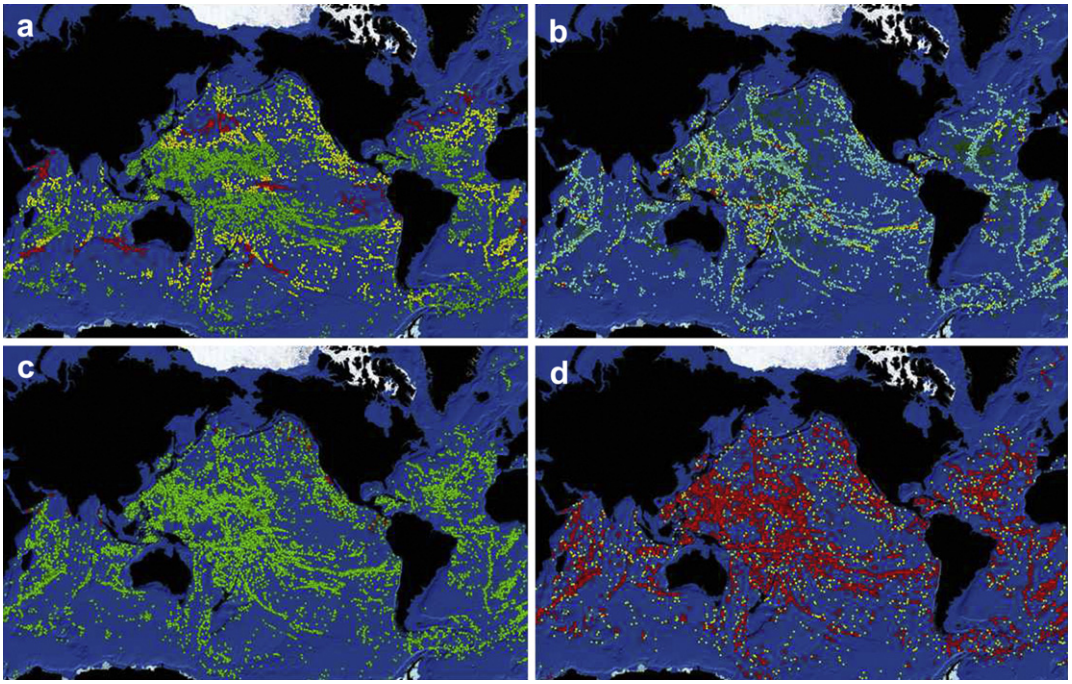

Fig. 3. The global seamount dataset, showing the distribution of values of the environmental variables used in the classification: (a) organic matter flux (red = high, yellow = medium, green = low) (b) summit depth (red = photic, yellow = upper bathyal, blue = lower bathyal, green = abyssal) (c) dissolved oxygen (red = OMZ, green = oxic) (d) proximity (red = close, yellow = distant).

2.1.4.4. Proximity. Connectivity between seamounts is important. Because seamounts are the main source of shallower habitats in oceans where the seafloor is primarily at abyssal depths, faunal assemblages that occur shallower than the deep-sea floor need to find and colonise seamounts, island slopes, or ridge peaks/highs. The dispersal capabilities of benthic invertebrates are not well known, but several papers have reviewed existing knowledge inshore. Kinlan and Gaines (2003) examined the likely dispersal distances of a number of shallow-water faunal groups in relation to the connectivity between reserves and found that, although mean dispersal distances ranged from a few metres to hundreds of kilometres, most invertebrate taxa were able to disperse less than 100 km. Few studies are based on seamounts, or on deep-sea fauna in general. There is genetic evidence of octocoral dispersal along the Hawaiian seamount chain being limited to between 100 and 200 km (Baco and Shank, 2005). However, for some corals there appears to be no genetic separation over large-scale ocean basins (Smith et al., 2004), and for other invertebrate taxa with non-planktotrophic larvae there is separation on smaller scales (e.g., Samadi et al., 2006). It is recognised that larval dispersal capability is highly variable between taxa and between regions depending on current flow and direction. However, such complexity is difficult to deal with in the high seas where information on current flow at depth is poorly known, and information on the reproductive nature of many faunal groups, and early life history characteristics (e.g., distribution in water column, duration of larval stages) are uncertain. We therefore decided that a separation distance of greater than 100 km constituted an isolated seamount compared with one that has neighbours 100 km or less away, especially if in a cluster or chain. The distance of 100 km is a subjective compromise which may tend to be conservative/precautionary for many taxa, but that is more appropriate for conservation purposes than defining too large a distance.

Two categories were applied to this variable:

" Close" proximity – ≤100 km between a seamount and its nearest neighbour

" Distant" proximity – >100 km between seamounts

The global distribution of the grouped values for each of these variables by seamount is shown in Fig. 3.

2.2. Data analysis

2.2.1. Application of the hierarchical classification approach

The first step in the hierarchical approach is to identify biogeographic provinces in an area of interest. Then, within each biogeographic province, the seamounts are sorted into groups based on the four physical factors in the order of:

Export productivity
Summit depth
Dissolved oxygen
Proximity

The order of these factors reflects a sequence identifying potential species richness and abundance of a community (export production), its composition (depth and oxygen) and its "uniqueness" (proximity). One of the factors influencing this order was the conservation importance of cold-water corals in discussions of vulnerable marine ecosystems (e.g., UNGA, 2006), and the amount of production reaching the seamount summit is likely to affect whether extensive thickets and reefs can form. However, the factors, order, and divisions within the variables could be altered depending upon the level of regional knowledge, but the intention here is to represent a workable global classification system. In practice, the order of the factors does not affect the number of classes, or their composition, but simply the order in which they are grouped together-all seamounts in a biogeographic province that are low in production, in the shallow depth band, with high oxygen, and are close together are identified in the same class irrespective of the order of selection.

A schematic of this hierarchy is given in Fig. 4. The biogeographic province has been identified, and seamounts within that province

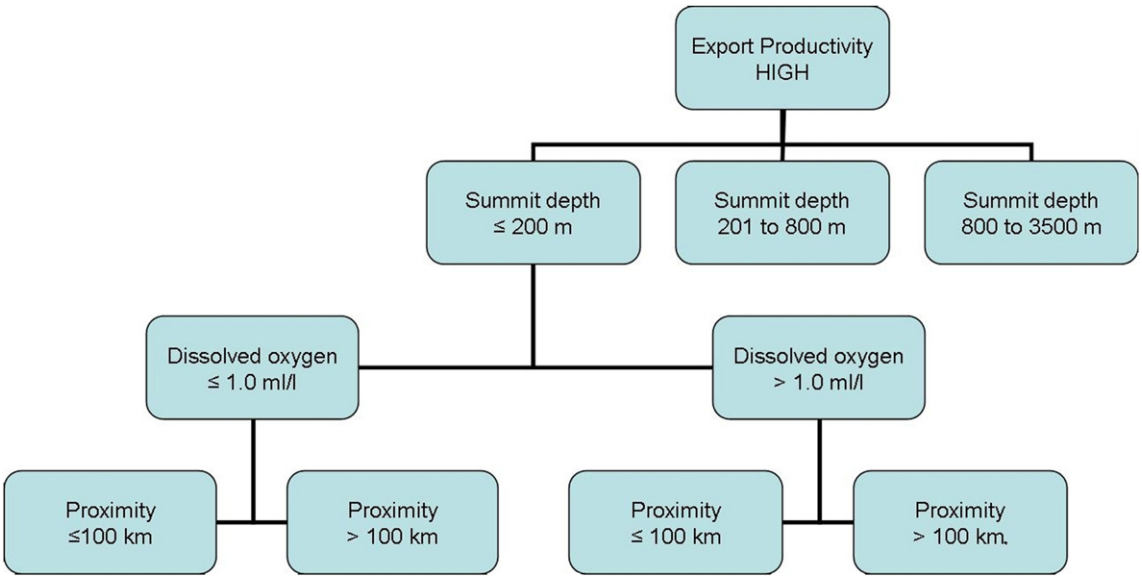

Fig. 4. Organisation chart of the hierarchical structure showing divisions within a biogeographic province for a high level of organic matter flux (the splits are repeated for medium and low organic matter flux values).

are progressively split into separate groups. Illustrated is a "High" value of export production (so similar divisions under "Medium" and "Low" production are not shown) which is then split by three depth bands, each depth band by two levels of dissolved oxygen, and they in turn are divided by the two categories of proximity.

This classification procedure can produce up to 36 classes of seamounts, but in many areas of the ocean some classes will not occur. For example, in the North Atlantic Ocean, dissolved oxygen levels are consistently above the OMZ level, and so the maximum number of classes is 24.

2.2.2. Application of the multivariate classification approach

The multivariate classification analysis was undertaken using the statistical software package PRIMER v6 (Clarke and Gorley, 2006; Clarke and Warwick, 2001 – and see references within for following routines). Before analysis, *continuous* data for each of the four variables were examined, using pairwise "draftman plots", for conformity to continuous, univariate, normal behaviour (the ideal), and the extent of correlation with each of the other variables. No variables required transformation and correlation coefficients between variables did not exceed 0.90, and thus all data were retained for analysis. Since variables were measured in different units and on different scales it was essential to either normalise data for each variable or use a distance metric, such as the Gower metric, that has inherent range standardisation. Each variable then has the tendency to contribute equally to the subsequent distance matrix. The variable biogeographic province was categorical, so for the analysis categories were treated as dummy variables (i.e., 0/1 variable for each province). A similarity matrix for all variables for the New Zealand region seamounts was then calculated using the Gower distance metric. A group average hierarchical classification procedure was performed on this similarity matrix using the program CLUSTER, and distinct groups or classes of seamounts were identified using the SIMPROF test. The latter procedure tests for the presence and statistical significance of structure (or "natural groups") in data by computing a similarity profile (by ranking the similarity matrix) and then comparing this profile to mean randomly generated similarity profiles. Distinct classes were deemed those with a similarity profile significantly different from the mean random profile at the 1% significance level. To determine the relationship between the resulting multivariate classification and the hierarchical classification, a RELATE test was performed. This test compared the underlying similarity matrix of the multivariate classification with a model similarity matrix for the hierarchical classification. The latter was generated by first creating a file where the variable hierarchical class is categorical (0/1 variable for each class), from which a similarity matrix was calculated using the Sorensen index (i.e., where a seamount's membership of a particular hierarchical class will be measured as either 100% or 0%). The test calculated a rank Spearman correlation coefficient (and significance) between the two similarity matrices.

2.2.3. Regional ground truth analysis

A presence–absence similarity matrix of octocoral species by seamount for the North Atlantic seamounts was analysed using routines in the statistical software package PRIMER v6 (see above for references and more detail). The resemblance index used was Sorensen's, and the similarity among the seamount octocoral fauna was determined by group averaging hierarchical cluster analysis using CLUSTER. Distinct groups of seamount octocoral fauna were identified using the routine SIMPROF.

2.2.4. Seamount MPA selection examples

The hierarchical classification allocates seamounts into groups we believe are likely to have different faunal assemblages. This information can then be used in more detailed discussions or combined with other data sets to inform MPA selection. However, in offshore areas especially there may be little other information. In such a case, the classification can stand alone as the basis for selecting seamounts for protection. We give two examples to illustrate this, for the southern Indian Ocean, and global oceans in ABNJ. A random selection is made taking 40% of seamounts in each class, within the area of interest (SIODFA area "of competence", and ABNJ). We use 40% based on the general conservation guidelines of protecting 30–50% of available habitat to prevent loss of biodiversity (e.g., Botsford et al., 2001; Airame et al., 2003), but note that percentage area targets vary, with 10% of "each of the world's ecological areas" accepted as part of The Convention on Biological Diversity to develop representative networks of MPAs (Decision VII/28 and VII/30) (CBD, 2004), while 20–30% of each marine habitat was recommended by the World

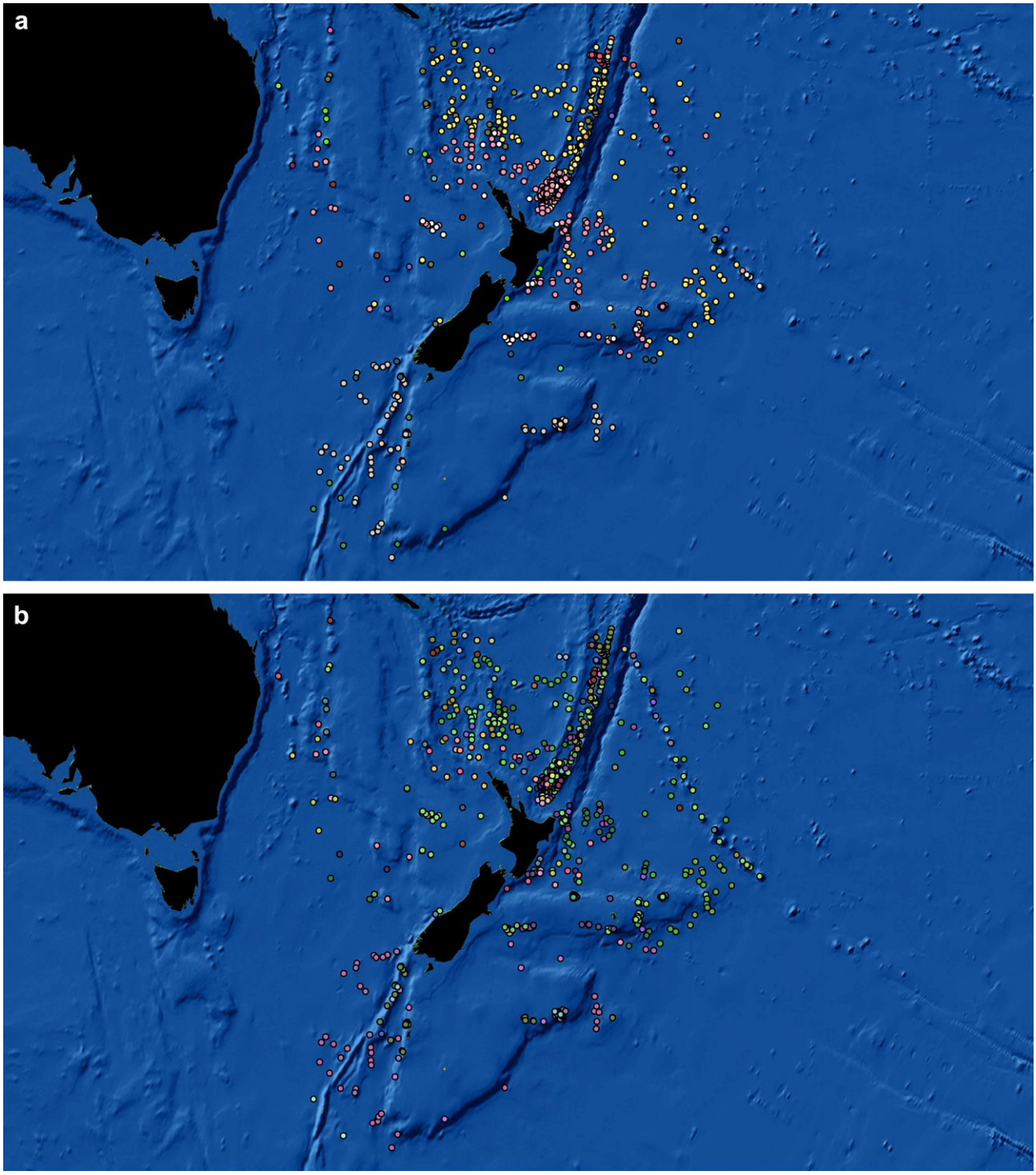

Fig. 5. Seamount classification in the New Zealand region using (a) the hierarchical method, and (b) a multivariate analysis.

Parks Congress in 2003 (Anon, 2003). Where a class within the area had only one seamount, it was selected for inclusion.

3. Results

3.1. Comparison of classification methods (New Zealand seamounts)

The hierarchical classification of seamounts in the New Zealand region produced 22 classes in total, with 614 seamounts being distributed among 15 classes in biogeographic province 6 (northern and central parts of the region), 109 seamounts in 6 classes in province 10 (southern area), and 1 class with a single seamount in province 12 (extreme north western edge of region) (Fig. 5(a)). The majority (>70%) of seamounts in province 6 were in two classes (41% and 32%), and 66% of seamounts in province 10 were in one class. The multivariate classification produced a total of 57 seamount groups or classes, with seamounts distributed among 49 classes in province 6, 8 classes in province 10, and 1 class in province 12 (Fig. 5(b)). One class in province 6 had a large number of

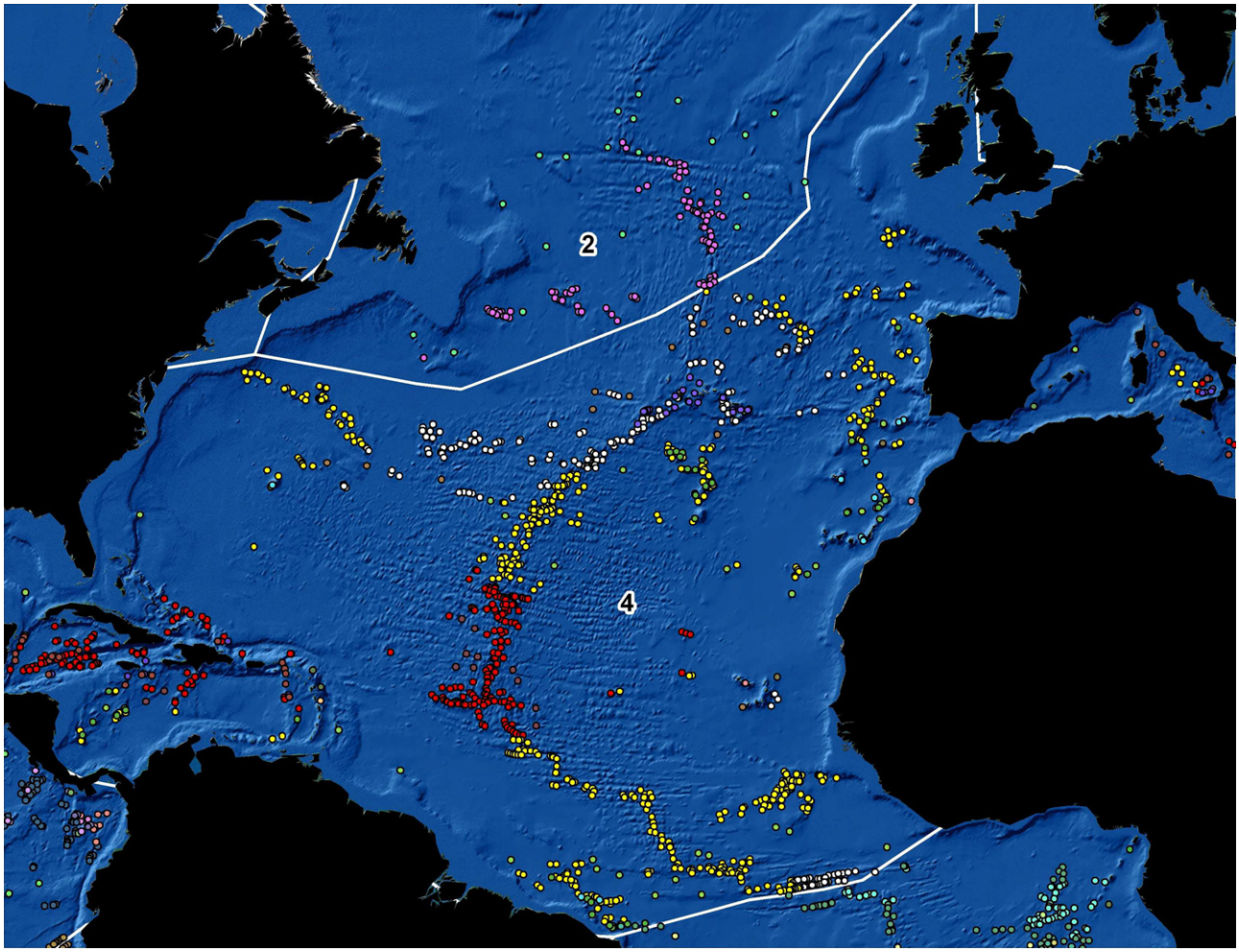

Fig. 6. Hierarchical seamount classification in the North Atlantic region.

seamounts (n = 146 or 24% of seamounts in the province). The majority (63%) of seamounts in province 10 were distributed more or less equally among 2 multivariate classes, In comparison to the hierarchical classification the number of classes produced by the multivariate classification was very different for province 6, similar for province 10, and the same for province 12. The distribution of the number of seamounts within classes, for provinces 6 and 10, was different between classification types. The formal RELATE test of the closeness of the two classification procedures revealed a relatively weak, though significant, correlation of $\rho = 0.476$ (0.1%). A visual comparison of the spatial distribution of seamount classes for the two classification types reveals that for province 10 there is a relatively high degree of spatial concordance among the classes, the major difference being the finer spatial scale division in the multivariate classification of the larger hierarchical classes. This pattern is particularly evident for the largest class (light pink) to the southwest and southeast of New Zealand. A similar finer spatial scale sub-division of classes by the multivariate classification is also apparent for seamounts in province 6. The pattern is particularly evident for seamounts associated with the Colville and Kermadec Ridges to the north-northeast of New Zealand.

3.2. Ground truthing for a reasonably well-known area (North Atlantic seamounts)

Within the North Atlantic region (Provinces 2 and 4), there are 1197 seamounts grouped into 19 classes (Fig. 6). The primary distinguishing feature for these seamount classes is organic matter flux and proximity. Seamounts of the New England chain (yellow) are similar to those of the central region of the Mid-Atlantic Ridge (MAR), being characterised by lower bathyal depths, medium organic matter flux, and close proximity. There is a second widespread grouping in the northern section, with high organic matter flux (grey), and a smaller cluster of shallower seamounts further north (dark green). There is a transition southwards along the MAR where organic matter flux becomes low in a band from the Caribbean right across the Atlantic (red).

Cluster analysis of the octocoral data from North Atlantic seamounts suggests that seamounts can be divided into two distinct groups on the basis of their fauna: one encompassing the New England and Corner Rise groups to the west of the MAR, and one encompassing a seamount on the ridge and seamounts to the east. This generally reflects the broader pattern documented earlier by Watling and Auster (2005). It also matches well the hierarchical classification, with the New England-Corner Rise seamounts showing as yellow and grey, and the sampled seamounts in the eastern Atlantic being in the classes displayed as mid-green. Overall, this gives substantial confidence that the hierarchical classes are biologically realistic.

3.3. Overall global seamount classification

The hierarchical classification method was applied to the global seamount dataset for the bathyal zone (abyssal seamounts with

Table 1
Number of classes and number of seamounts per province based on the hierarchical classification method.

Province	No. of classes	No. of seamounts
1	5	42
2	2	103
3	19	501
4	17	1094
5	11	1204
6	17	526
7	13	362
8	14	234
9	11	381
10	15	861
11	20	1201
12	16	1811
13	16	808
14	18	1476
Total 14	194	10,604

summit depths greater than 3500 m were excluded). The classification divided the 14 provinces into 194 seamount classes, with a total number of 10,604 seamounts (Table 1). Most provinces have between 10 and 20 classes, the exception being provinces 1 and 2 which are the Arctic and northern North Atlantic. The seamounts in these provinces are similar in depth (all with summits in a single group between 800 and 3500 m), all are above the OMZ, and most are medium organic matter flux. All the other provinces have seamounts spanning a wider depth range, and consequently more classes.

The seamount classes generally contain clusters or chains of seamounts (Fig. 7). For example, seamounts on the MAR often fall within similar classes along latitudinal bands, where values of organic matter flux are similar. Exceptions include individual seamounts at unusual depths which may fall into separate and scattered classes within the region. A similar pattern occurs with seamounts of major seamount chains in the Pacific (e.g., Louisville, Hawaiian and Emperor seamount chains) which exhibit broad-scale affinities, with occasional individual seamount differences. Prominent clusters also occur in the western-North Pacific Ocean (provinces 12 (mid-green) and 14 (yellow)) which are characterised by low organic matter flux, lower bathyal summit depth, oxic conditions, and close proximity.

The number of seamounts in each class varies between provinces (Fig. 8). Many classes within a province have a small number of seamounts, with a few classes having large numbers. Although provinces 3–14 all have 11–20 classes, three classes in each province account for between 72% and 89% of the total number of seamounts in each province. All provinces have several classes with only one or two seamount members.

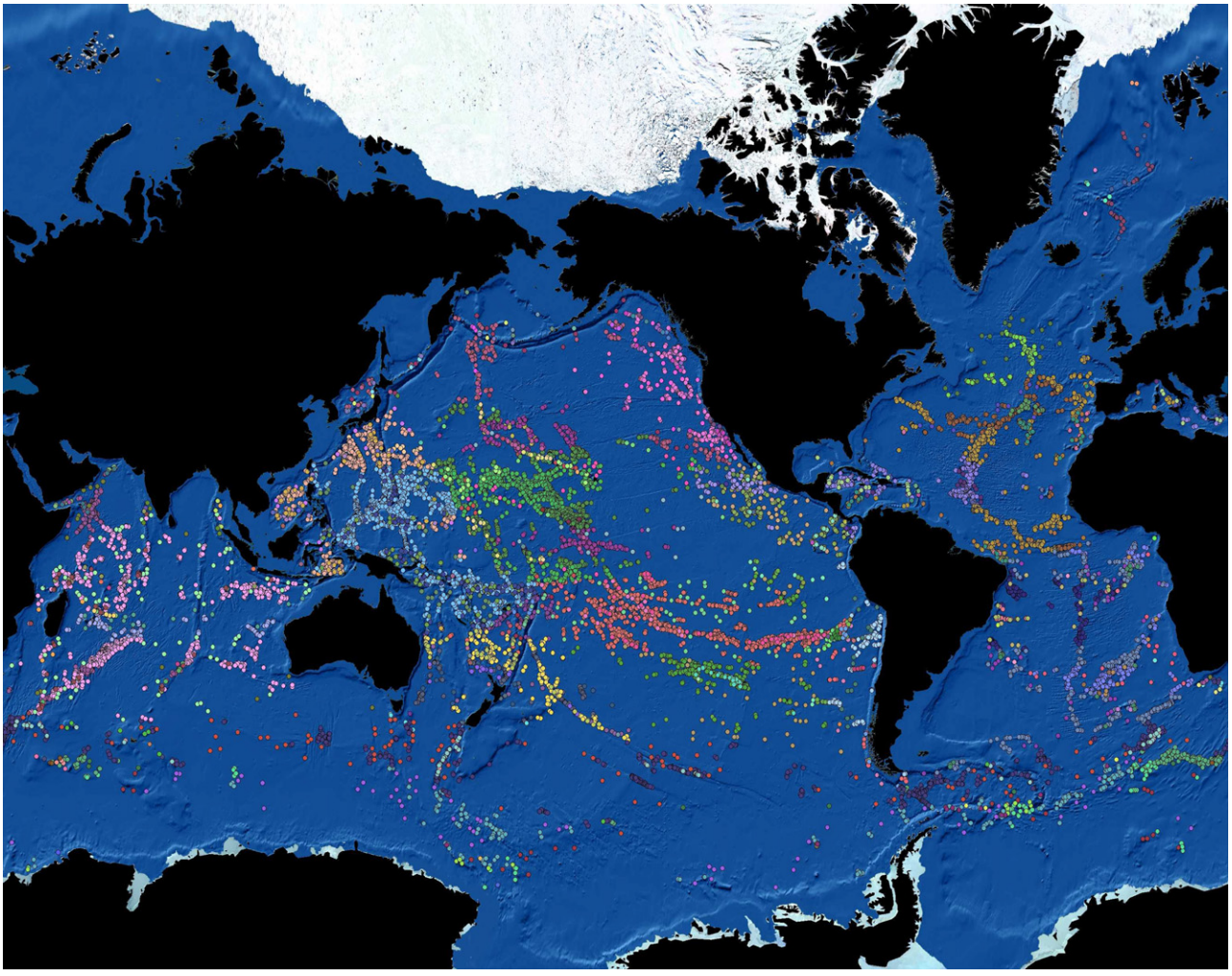

Fig. 7. The global seamount classification, showing the 11,000 bathyal depth seamounts divided into 194 classes.

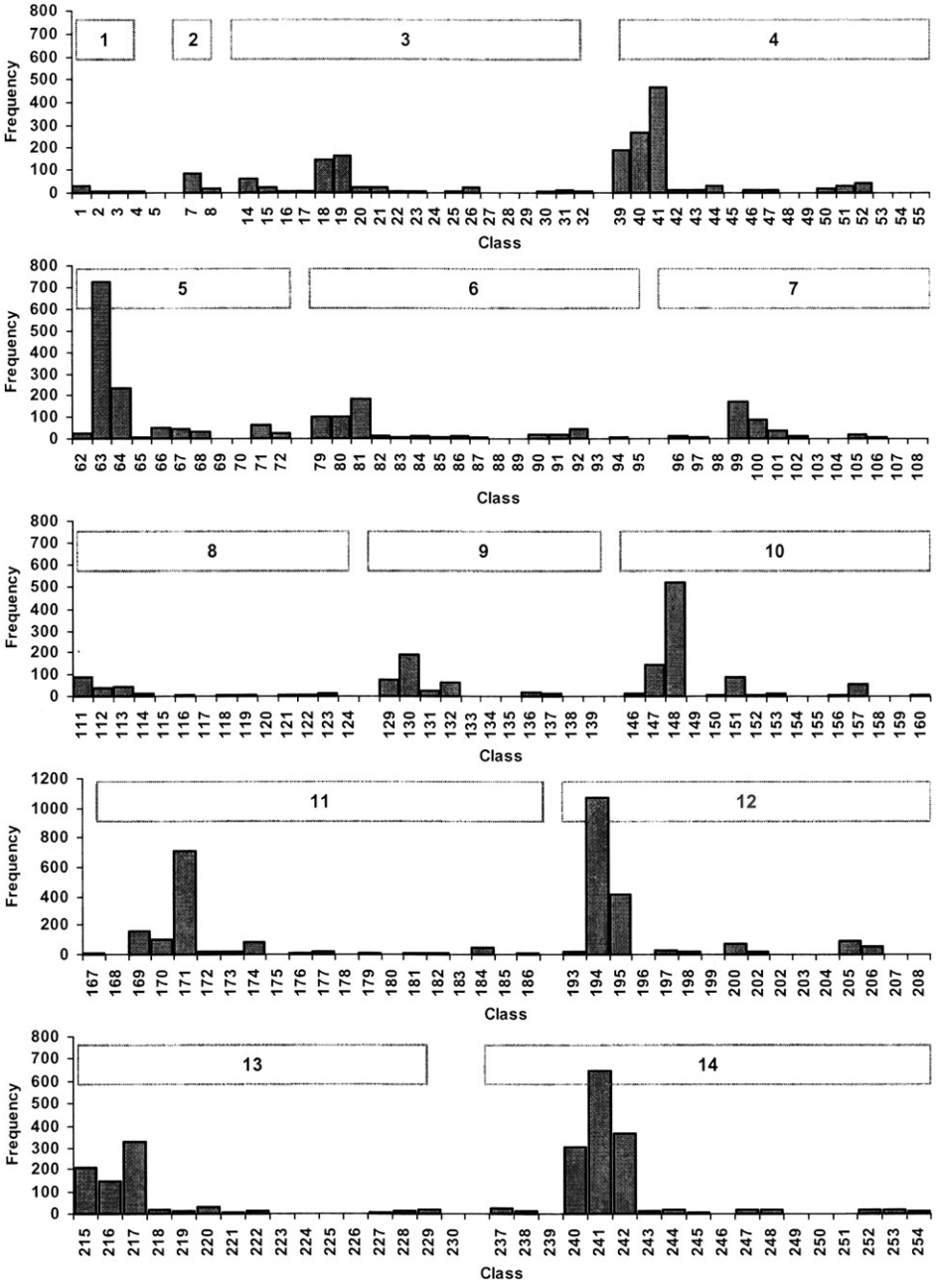

Fig. 8. Histograms of the frequency of seamounts by class within biogeographic province.

3.4. Application to area where a classification is already applied for other impact (mining), and faces potential fishing impact — the Clarion–Clipperton Zone, eastern Pacific Ocean

The general region of the CCZ includes provinces 3, 7 and 14 (see Fig. 2). The classification of bathyal seamounts created 35 classes (Fig. 9(a)) comprising 1020 seamounts. The seamounts tend to be geographically clustered, with most features in three classes, each with about 200 seamounts, at the western end of the region. The central area of the CCZ has a relatively low number of bathyaldepth seamounts.

The area for which manganese nodule resource licences have been issued (Fig. 9(b)) contains 364 bathyal seamounts in 25 classes, and 128 abyssal-depth seamounts in 9 classes. The majority of bathyal seamounts are lower bathyal depths, with only 3 and 4 seamounts in photic and upper abyssal depths respectively. The seamounts in the recommended "Sanctuary Zones" are mainly abyssal-depth features (18 seamounts). However, there are seven bathyal features from classes 240 (3), 242 (1), 243 (2), and 244 (1) that are included. These are thought to be deeper than current trawling depths, and so are unlikely to be the target of any fishing activity. However some of the seamounts to the northwest of the area are at fishable depths. There are no seamount classes that are unique to the immediate CCZ area.

3.5. Application to Southern Indian Ocean: to compare science-based Versus Industry BPAs

The global-scale plots can be hard to interpret on the more-regional level that is likely to be appropriate for management. The North Atlantic ground-truth example, and the CCZ above, give an indication of the number of classes that environmental

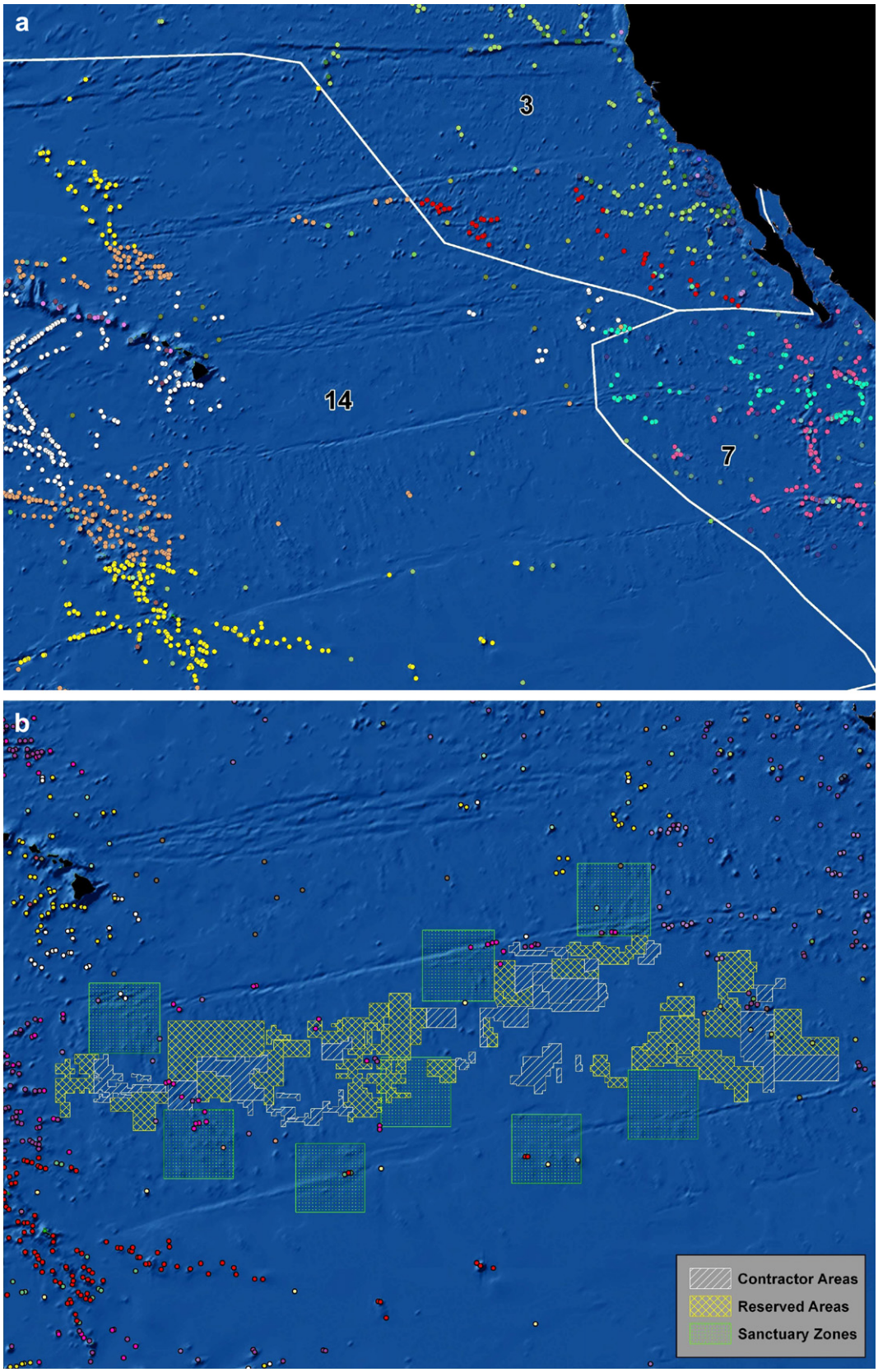

Fig. 9. (a) The eastern-central Pacific Ocean, showing the general area of the Clarion–Clipperton Zone (CCZ), and the bathyal seamount classification. (b) The CCZ area of prospecting licenses, proposed "Sanctuary Areas", and the hierarchical seamount classification of bathyal and abyssal seamounts combined.

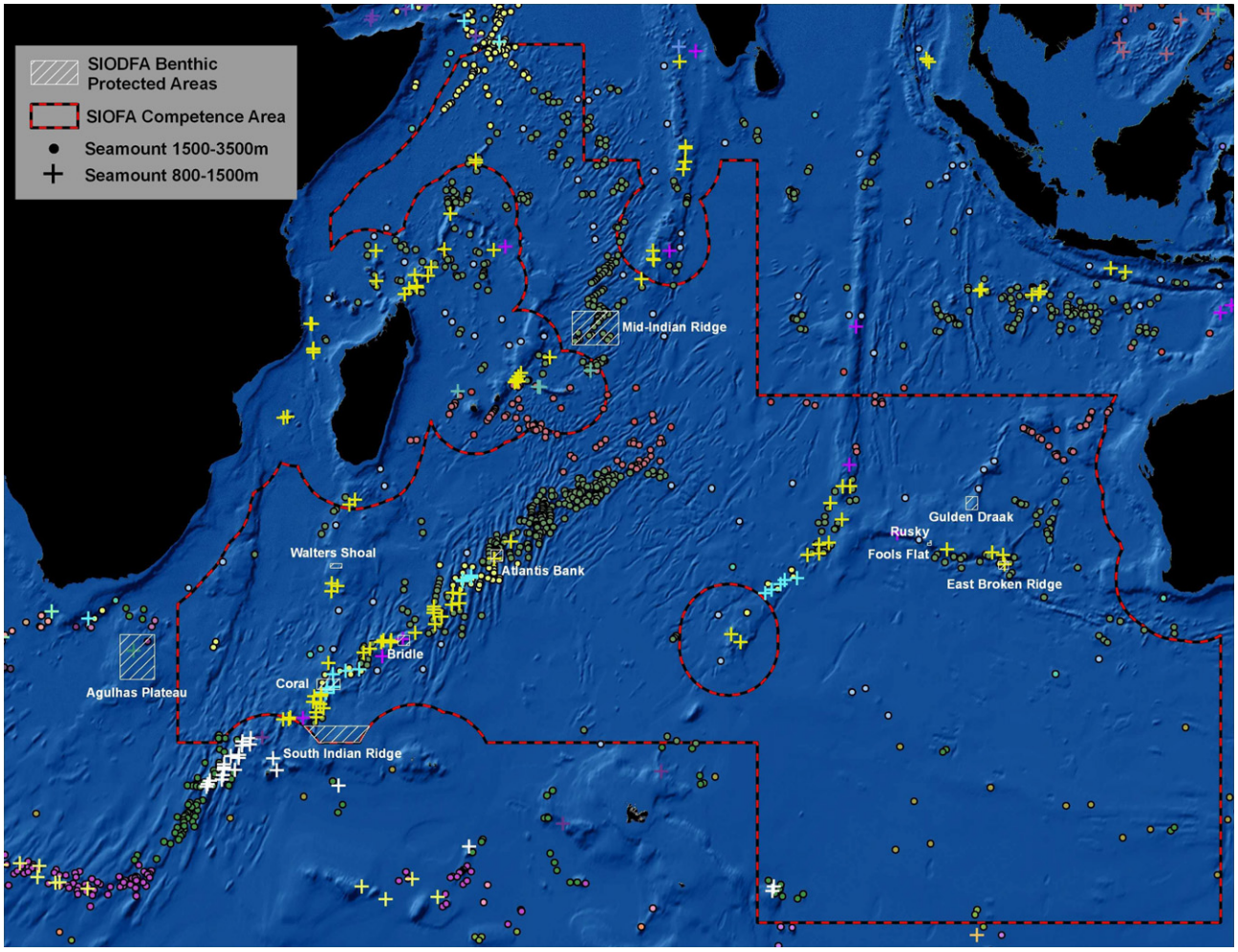

Fig. 10. The southern Indian Ocean, showing the hierarchical seamount classification (based on additional 800–1500 and 1500–3500 m summit depth split) within the area of Southern Indian Ocean Deepwater Fishers Association (SIODFA) "competence", and SIODFA Benthic Protected Areas.

managers may need to consider in the development of conservation plans. A further example is presented here, for the Southern Indian Ocean, which is a region currently being fished for deepwater species, yet for which limited biological knowledge is available to inform management. Within the Southern Indian Ocean the deepwater fishery is managed voluntarily by the Southern Indian Ocean Deepwater Fishery Association (SIODFA). This has defined an area "of competence" which covers a large proportion of the western and southern parts of the region (see Fig. 10). The SIODFA area was used for this analysis, and a further split in the Summit Depth variable was made, at 1500 m, to acknowledge the faunal changes as scleractinean coral communities become rare.

There are 688 bathyal seamounts in the SIODFA area, which are classified into 18 classes (Fig. 10). The majority of these seamounts are on the Southwest Indian Ridge, which extends from due south off South Africa northeastwards into the central Indian Ocean. This ridge also contains many of the 95 seamounts which have summit depths less than 1500 m, and are therefore potentially fishable (by trawling). These seamounts are members of 9 different classes, although 63 of these seamounts are in just two classes (Table 2).

SIODFA has designated several voluntary Benthic Protected Areas (BPAs) within the region (Allain et al., 2008). These BPAs contain 37 bathyal seamounts, of which 6 are "fishable", in 6 of our hierarchical classes (Table 2). The majority (over 80%) of the BPA seamounts are from one class (171) which is characterised by summit depths between 1500 m and 3500 m (mostly below fishable depths and where stony corals are likely to be rare), medium organic matter flux, oxic, and close proximity.

Under the hierarchical classification method, a total of 277 seamounts would be protected using a 40% random selection from each of the 18 classes (Fig. 11), including 39 at fishable depths in 8 classes (Table 2).

3.6. Example application to global selection of seamount MPAs

The application of the 40% random selection for ABNJ throughout the world's oceans is given in Fig. 12, which plots the distribution of 2221 seamounts which represent 110 seamount classes. Note that this selection protects a seamount if it is the only member of its class in a particular biogeographical province, as they could be biologically unique. The distribution of seamount classes and number of seamounts by biogeographic province is summarized in Table 3. The maximum number of seamount classes is 12, with relatively large numbers of seamounts being protected in Provinces 4 (North-Central Atlantic), 5 (central South Pacific), 10 (Subantarctic regions), 11 (Indian Ocean), 13 (South Atlantic) and 14 (central North Pacific).

Table 2
Number of seamounts per class in the SIODFA area of the southern Indian Ocean, comparing numbers of seamounts per class, numbers derived from a 40% random selection of seamounts using the hierarchical classification method, and the SIODFA Benthic Protected Areas (BPAs) seamounts (fishable depth classes (<1500 m) are in italics).

Seamount class	No. of seamounts		
	Hierarchical method	40% Selection	Industry BPAs
129	2	1	
148	13	5	
151	11	4	
157	1	1	
169	78	31	1
170	64	26	
171	382	153	30
172	4	2	
173	8	3	
174	31	12	
177	3	1	
182	4	2	1
184	13	5	
185	2	1	
186	2	1	
500	49	20	2
501	17	7	2
502	4	2	1
Total 18	688	277	37

4. Discussion

4.1. Comparison with multivariate classification

The hierarchical classification was designed to produce a limited number of classes in order to present a simple and readily appreciated scheme that could be easily adopted by environmental managers. As expected, the unconstrained multivariate classification produced more classes overall than the hierarchical classification when trialled using seamounts in the New Zealand region. Nonetheless, the correlation between the two types of classification was statistically significant, although it was not particularly strong. However, there was a degree of concordance between the spatial distributions of the seamount classes produced by the two types of classification. This result suggested to us that the multivariate classification represents, in effect, a finer spatial scale representation of the hierarchical classification, rather than a fundamentally different classification. The latter would be a concern and would have reduced our confidence in the efficacy of the hierarchical procedure. Thus it was with some confidence that we proceeded to apply the hierarchical classification more widely, and to examine its relevance in terms of representing the benthic communities likely to be found on seamounts. The second “test”, comparing the classification results with an analysis of octocoral communities in the North Atlantic, confirmed our confidence. The patterns in the North

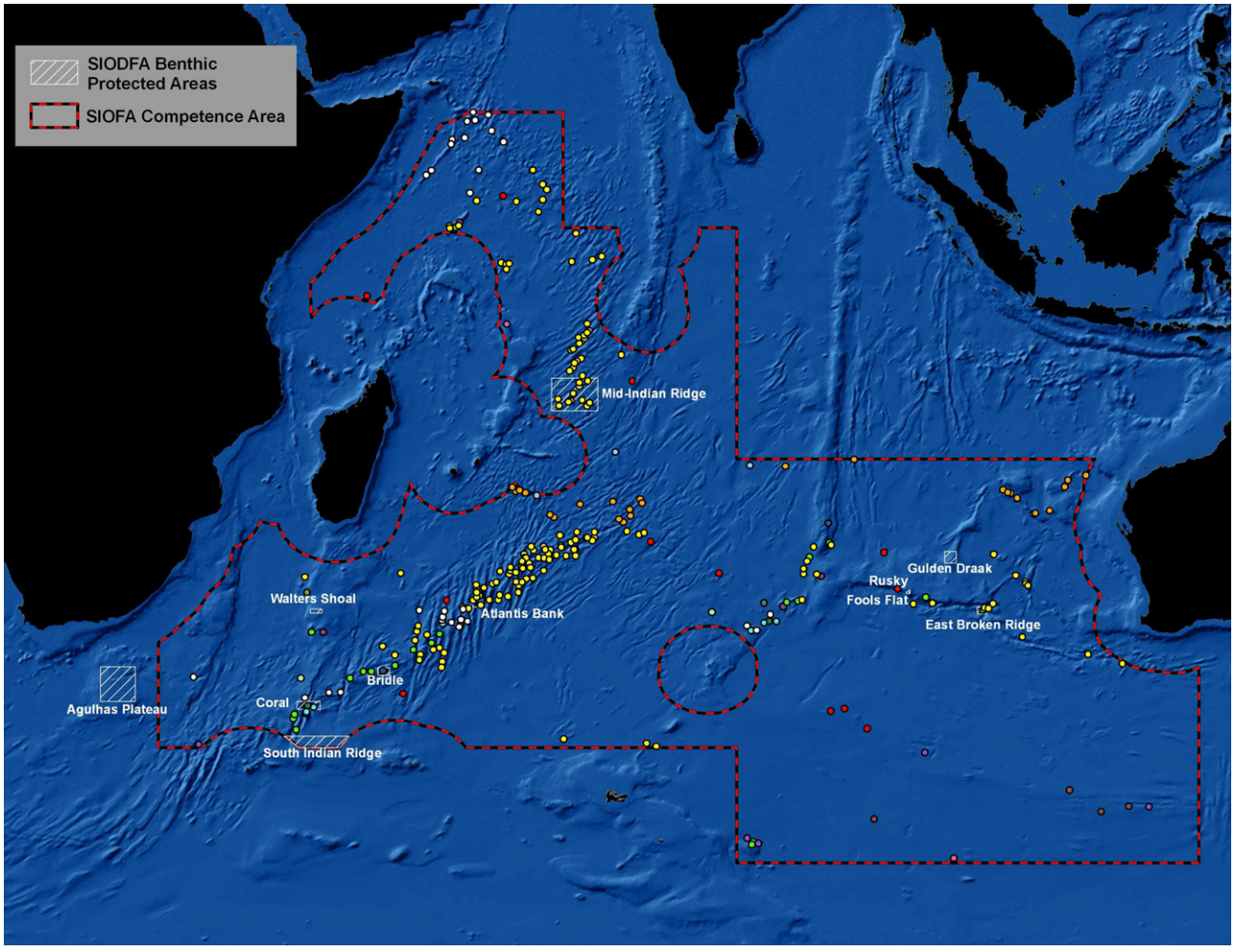

Fig. 11. The southern Indian Ocean, showing a random 40% selection of seamounts from the hierarchical seamount classification.

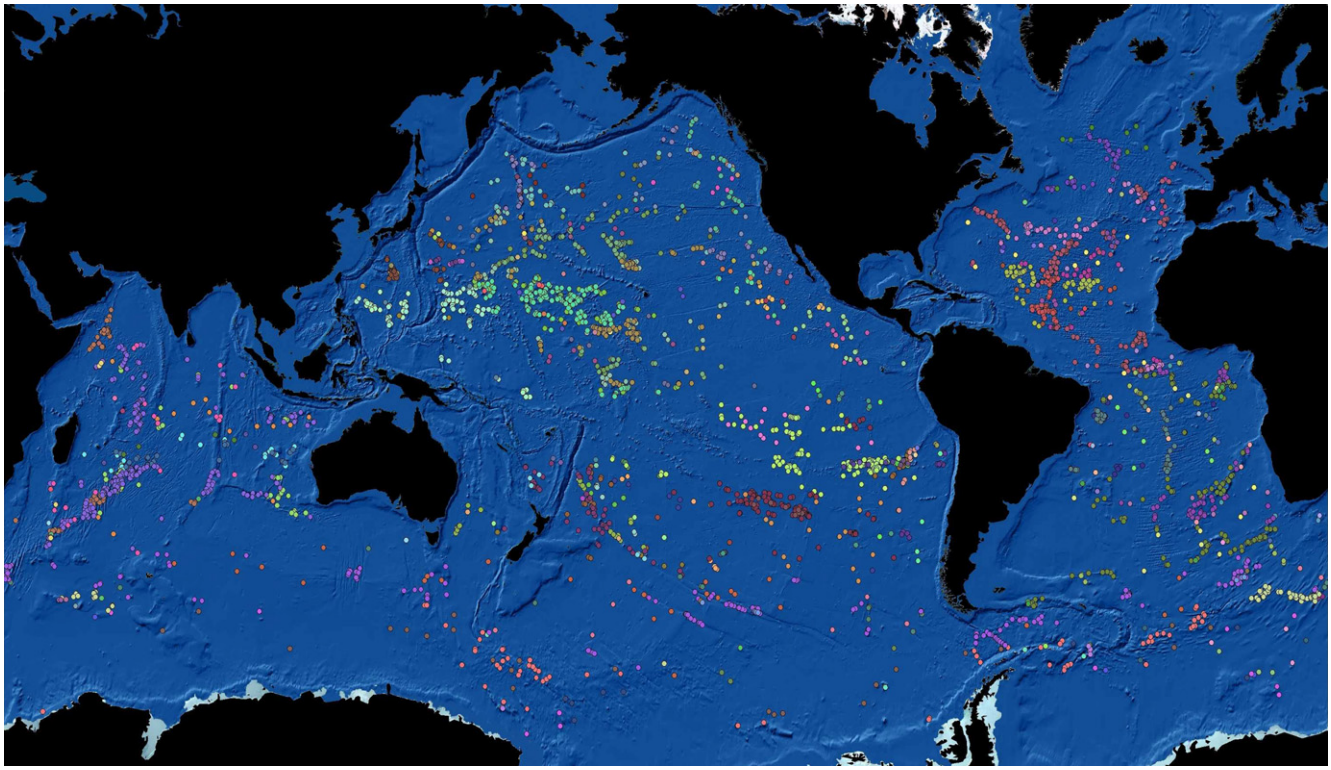

Fig. 12. The global seamount classification, showing a random 40% selection of seamounts from Areas Beyond National Jurisdiction.

Atlantic matched reasonably well, with the marked octocoral split between New England-Corner Rise seamounts and seamounts in the eastern Atlantic mirrored in the hierarchical classification.

4.2. Selection of variables

Biogeographic province is a key division in this system. We applied the most up-to-date benthic biogeography available (UNESCO, 2009). However, in this report, there was no classification of the upper bathyal zone, solely the lower bathyal. Hence we assume that the lower bathyal province structure is suitable also for lesser depths. Where seamounts occur deeper than the bathyal, an abyssal biogeography from the GOODS report can be applied, as we did for the CCZ. We acknowledge there can be some confounding of variables in this system, as we know that export production was already factored into Abyssal Province definition. If more detailed biogeography is known for a region, that could be used in place of the GOODS results.

A large number of variables have been used in classification systems to represent biological diversity, but typically these have included a combination of biogeography, depth, seabed features/geomorphology, substrate and biological assemblages (see review by Howell, 2010). The choice of factors, and divisions within them, have been dictated to an extent by our objective of developing a classification that can be applied globally, in data-poor situations. However, the hierarchical structure is able to be modified to incorporate regional-scale information. For example, depth is further subdivided in our treatment of the Southern Indian Ocean, where we know that faunal communities change at about 1500 m as stony corals become infrequent. Similar information in other regions can be examined to subdivide the depth range of 800–3500 m, which we acknowledge is very broad. Howell (2010) in her review of the Northeast Atlantic proposed depth divisions at 750 m, 1100 m, 1800 m, and 2700 m.

The values we have used for dividing the variables are not necessarily appropriate for all regions, or for all taxa. The OMZ division at 1 ml/l was based on studies on the Oman margin and other deep-sea oxygen-poor areas by Levin (2003). This value is likely to be reasonable for benthic invertebrates. However, recent work by Vaquer-Sunyer and Duarte (2009) investigating the effects of hypoxia in a number of coastal sites, noted sublethal effects at higher values, especially for bentho-pelagic fishes. Although the overall mean value from their study was 1.1 ml/l, there was variability between taxa. It is unclear what influence sublethal effects may have on the community as a whole, and also how their shallow-water results transfer to deeper habitats, but if certain taxa were of particular concern for conservation objectives then the OMZ value could be raised.

The physical classification is based on seamount summit depth. Physical variable values were selected as close as possible to that

Table 3
Number of classes and number of seamounts per province in ABNJ based on a random 40% selection of seamounts in each hierarchical classification class.

Province	No. of classes	No. of seamounts
1	1	6
2	2	41
3	8	95
4	7	272
5	9	269
6	9	86
7	5	50
8	9	49
9	9	124
10	11	258
11	11	309
12	6	89
13	12	256
14	11	317
Total 14	110	2221

depth. Elevation was initially recognised as an important consideration when a seamount spans a large depth range from the abyssal seafloor, versus a peak on a mid-ocean ridge. The greater the elevation, the wider the depth range, or habitat diversity, and hence potentially biodiversity. However, elevation and seamount size are difficult to estimate, and complicated when a seamount might be part of a ridge, where the boundary between the seamount and ridge is unclear. One solution to this problem of size and scale is to apply a standard area around the summit that would be considered the seamount extent. Based partly on the knowledge that dispersal of invertebrate taxa is often over small distances, we would recommend that any application of management to a seamount includes a 100 km buffer zone around it. That therefore provides coverage of biodiversity on the flanks, irrespective of whether the feature is an isolated seamount, ridge summit, and also whether it is large or tall. Therefore, the use of summit-associated parameters is appropriate, and this avoids the need for extensive depth-stratified data, that becomes complicated in terms of both data availability and its application for management.

4.3. Second tier information

Biological data should not be ignored in any MPA design process. However, given the paucity of good data offshore on seamounts, information on species composition is unlikely to be of great use in defining a classification of seamounts. However, such data can be applied after the initial physical classification, in a selection process that may identify important habitats (e.g., spawning grounds, nursery areas, hydrothermal vent communities) or vulnerable marine ecosystems (VME) such as coral reefs and sponge gardens (e.g., Hall-Spencer et al., 2009). Predictive modeling techniques may be applied to help aid identification of potential VME habitat (e.g., Clark et al., 2006; Davies et al., 2008; Tittensor et al., 2009).

Geological information could also be useful to consider. In the absence of specific biological information, recognising the presence of volcanic/hydrothermal activity may indicate there is a likelihood of vent fauna. The high levels of endemism associated with hydrothermal fields (e.g., Van Dover, 2000) imply that these should be protected if they are likely to host unique fauna, although the often short-life of vents, and the often low diversity associated with them, need to be considered in MPA design.

The known presence of bottom trawl fisheries could be included in the selection process as well. This is a negative selection criterion, where seamounts that have been extensively trawled would be excluded from selection, thereby focussing reserves on pristine areas, and not unnecessarily restricting fishing activities. Human threats are commonly incorporated into an MPA selection process, and this can work both ways to prevent damage to the habitat, and enhance fishery yields (e.g., Roberts et al., 2003).

4.4. Management application

The analysis presented here considers only seamounts. However, it is uncertain how independent seamount habitat and communities are from the surrounding environment (Clark et al., 2010). Harris and Whiteway (2009) examined a range of global biophysical data, and defined 11 seascapes. These are typically very large, spanning huge expanses of the world's ocean basins and ridges, and all contain seamounts. Although the classifications are entirely separate, combining our results for a specific habitat can nest within, and complement, a much broader-scale classification system (such as that of Harris and Whiteway (2009)), or multiple MPA-system proposals that address different habitats or regions of the world (see review by Corrigan and Kershaw (2008)).

The classification system presented here is intended to be part of an MPA selection process, not the end point for actual selection. Although biological representation would seem a fundamental foundation for MPA design, it is only one component, and political, social, economic, and management aspects also need to be considered. However, the work presented here is a starting point in a data-limited situation, where more formal approaches may be restricted by the amount of information Either a random selection process, or a post-classification second-tier approach are two options for moving forward within such a selection framework. The examples given globally and for the southern Indian Ocean used a 40% selection criterion. This number is often discussed and debated, but whatever percentage is chosen, a further consideration is whether selection of seamounts for protection should be a simple random sampling of each class. Isolated seamounts may have greater potential for endemism, and so a higher level of protection may be necessary for seamounts that are widely separated, or for classes with few seamounts. However, such considerations may occur at a regional level where environmental managers can use the classification as a first step in the MPA selection process.

Higher relative protection may also be warranted for seamount classes with few members. Faunal communities are likely to vary somewhat between seamounts with similar physical characteristics, and if only one or two in a class are protected this may not encompass the range of community variability, compared with the chances of this being captured where more seamounts in a larger class are selected.

A further consideration is protection of seamounts across the geographical distribution of the class. Random selection procedures may by chance select seamounts that are aggregated to an extent. Where nothing is known about the benthic fauna, there may be advantages in ensuring a geographical spread that will increase the chances of including any systematic trends in community structure, and also reduce the chances of missing seamounts near a provincial boundary, where there may be transitional fauna.

The hierarchical method presented here can also be used to evaluate the potential effectiveness of other conservation strategies. The CCZ comparison showed that the seamounts within the proposed "Sanctuary Zones" did not include all seamount classes in the immediate area, and so protection of seamounts over a wider area than just the CCZ was required to afford representative protection. Similarly, in the southern Indian Ocean, the number and "class" of seamount protected under the SIODFA BPA network was clearly inadequate. Most protected seamounts were in one class (which was too deep for trawling), and the total number of seamounts protected was comparatively low.

It is hoped that we will be able to make the data and classification methods available online as part of the Census of Marine Life programme on Seamounts ("CenSeam"). This will give environmental managers the ability to run the classification based on different divisions within the variables, and with different seamount data sets. We plan to link this through the SeamountsOnline portal (http://seamounts.sdsc.edu) and make the output from the global classification available as a KML file for use in Goggle Earth.

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