Applications of Geophysical Information to the Design of a Representative System of Marine Protected Areas in Southeastern Australia

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Abstract

Management of the marine environment in Australia's Exclusive Economic Zone (EEZ) is addressed by an Oceans Policy *that was put forward by the government in 1998. The policy is being implemented through Regional Marine Plans (RMPs), including the development of a network of representative Marine Protected Areas (MPAs). The southeast region of Australia has been the first part of the EEZ to undergo regional marine planning (in 2003) and MPA development processes are currently in progress.*

Abiotic geoscience information has been used extensively to provide crucial supporting information to characterize habitats and bioregions in order to inform managers of the diversity of major ecosystems which may be represented in MPAs. In the southeast region, eleven "Broad Areas Of Interest" (BAOI) were first identified to help focus attention on areas that contain the greatest diversity of geomorphological features and where an MPA could contribute the most to biodiversity conservation objectives. These areas are then "sampled" to provide a candidate MPA that is comprehensive, adequate and representative of bioregions, features, habitats and linked systems across the shelf, slope and abyssal plain. Areas outside a BAOI may also be considered for sampling. The objective is to design an MPA network that meets biodiversity conservation objectives while minimizing socio-economic impacts. For this reason, the specifications are applied through stakeholder consultation, supported by a scientific reference panel. So far, options for two candidate MPAs covering more than 40,000 square kilometres (the Murray and the Zeehan) have been identified.

An interpreted map of 21 categories of different seafloor geomorphic features was developed as a proxy for habitats in the deep-water, continental slope and abyssal areas to support the selection of BAOI. Subsequent to the design of the eleven BAOI and the two candidate MPAs, the geomorphic feature map was extended onto the shelf. Also, on the continental shelf, a "seascape" map was produced using multivariate analysis, incorporating environmental variables.

Geographic Information System (GIS) analysis shows that the 11 BAOIs capture a representative subset of the geomorphic features and seascapes that occur within the southeast region. The two candidate MPAs represent a subset of key geomorphological features and bioregions found within the larger BAOI. The more recent information on seascapes now reveals that some of the seascapes were not sampled. Although the ecological significance of "seascapes" is still to be determined, they indicate a spatial heterogeneity in habitat types that may be of interest to MPA design. This experience has demonstrated that GIS analysis of abiotic data is a valuable and complementary tool for designing representative MPAs.

Résumé

La gestion de l'environnement marin de la Zone économique exclusive (ZEE) de l'Australie est réglementée par une politique des océans qui a été mise de l'avant par le gouvernement en 1998. La politique est mise en oeuvre par l'entremise de plans marins régionaux, qui comprennent le développement d'un réseau de Zones de protection marine (ZPM) représentatives. La région du sud-est de l'Australie a été la première partie de la ZEE à être soumise à une planification marine régionale (en 2003) et à des processus de développement de ZPM qui progressent actuellement.

L'information abiotique géoscientifique est utilisée de façon étendue afin de fournir l'information de soutien cruciale à la caractérisation des habitats et des biorégions et pour informer les gestionnaires de la diversité des écosystèmes importants qui peuvent être représentés dans les ZPM. Dans la région du sud-est, onze "grandes zones d'intérêt" (GZI) ont d'abord été définies en vue d'attirer l'attention sur les zones qui contiennent la plus grande diversité en termes de caractéristiques géomorphologiques et où les ZPM pourraient contribuer aux objectifs de conservation qui visent une plus grande biodiversité. Ces zones sont ensuite "échantillonnées" afin d'obtenir une ZPM complète, adéquate et représentative des biorégions, des caractéristiques, des habitats et des systèmes associés sur toute la plate-forme, la pente et la plaine abyssale. Les secteurs à l'extérieur des GZI peuvent aussi être considérées pour l'échantillonnage. L'objectif est de concevoir un réseau de ZPM qui répond aux objectifs de conservation de la biodiversité tout en minimisant les impacts socio-économiques. C'est pourquoi les spécifications sont appliquées par l'entremise de la consultation d'intervenants appuyée par un panel de référence scientifique. Jusqu'à maintenant, des options pour deux ZPM potentielles qui couvrent plus de 40,000 kilomètres carrés (Murray et Zeehan) ont été définies.

Une carte d'interprétation qui comprend 21 catégories de différentes caractéristiques géomorphiques du fond marin a été élaborée pour présenter des données indirectes sur les habitats des eaux profondes, du talus continental et des zones abyssales, en soutien à la sélection des GZI. À la suite de la définition des onze GZI et des deux ZPM potentielles, la carte des caractéristiques géomorphiques a été étendue à la plate-forme. De plus, sur la plate-forme continentale, une carte de "paysage marin" a été produite à partir d'une analyse à variables multiples, qui comprend les variables environnementales.

L'analyse SIG montre que les onze GZI donnent un sous-ensemble représentatif des caractéristiques géomorphiques et des paysages sous-marins présents dans la région du sud-est. Les deux ZPM potentielles représentent un sous-ensemble de caractéristiques géomorphologiques principales et des biorégions qui se trouvent à l'intérieur d'une plus grande GZI. Les renseignements plus récents sur les paysages marins révèlent maintenant que certains de ces paysages marins n'ont pas été échantillonnés. Même si l'importance écologique des "paysages marins" reste à déterminer, ils semblent indiquer une hétérogénéité spatiale dans les types d'habitats qui peuvent être d'intérêt dans le cadre de la conception des ZPM. Cette expérience a permis de montrer que l'analyse SIG des données abiotiques est un outil important et complémentaire dans la conception de ZPM représentatives.

INTRODUCTION

In 1994, Australia ratified the United Nations Convention on Biological Diversity (CBD), and is therefore bound by the Articles and associated Obligations. Article 8 of the Convention requires Parties to establish Marine Protected Areas (MPAs) for the conservation and sustainable use of threatened species, habitats, living marine resources and ecological processes (de Fontaubert *et al.*, 1996). To meet its obligations under the Convention, the Australian government has confirmed its commitment to create a national representative system of MPAs as a part of implementing the Government's *Oceans Policy* (ANZECC, 1999).

Throughout the regional marine planning process, an ecosystem-based approach to ocean management has been adopted. This requires planning and management to be based on ecosystem boundaries rather than on political or jurisdictional boundaries. To fully protect the biodiversity in a region, MPAs must therefore be arranged in a *network* to maximize the protection of: 1) ecosystems; 2) ecosystem processes; and 3) ecosystem linkages/connectivity. Several authors have argued that any procedure adopted for the selection of MPA networks must provide for the inclusion of ecosystem aspects (*e.g.*, Vanderklift and Ward, 2000). For example, Roberts *et al.* (2003a) list a number of ecological criteria on which MPAs should be selected, including biogeographic representation, habitat representation and heterogeneity, endemism, connectivity, and vulnerable life stages.

Principles applied by Australia to the selection of MPAs reflect this focus on different aspects of the ecosystem; these include the precautionary principle[1] and that MPAs must be comprehensive, adequate and representative (the CAR principle; ANZECC, 1999). In applying the CAR principle to the design of a national MPA network, "comprehensive" means that MPAs must sample the full range of ecosystems, recognized at an appropriate scale, within and across each bioregion. The MPA network will be "adequate" if it has the required level of reservation to ensure the conservation of ecological viability and integrity of populations, species and communities. This includes replication of ecosystems as essential insurance against loss or damage caused by either natural events or anthropogenic activities outside the control of managers. Finally, the MPA network should contain examples of habitats that are "representative", which means that those marine areas that are selected for inclusion in MPAs should reasonably reflect the biotic diversity of the marine ecosystems from which they derive (ANZECC, 1999).

The development of a national "representative" system of MPAs in southeastern Australia commenced in 2002 in association with regional marine planning implemented by the National Oceans Office (which is now part of the Australian Government's Department of Environment and Heritage, DEH). A key output of the regional marine planning process was the creation of a bioregionalization for the southeast region, which, in turn, was used to help select "Broad Areas Of Interest (BAOI)" for potential MPA sites. Biological data were found to be scarce or absent in many instances, and most of the spatial information used to create the bioregionalization, and to later select BAOI, was based on abiotic, geophysical datasets that were assumed to be proxies for habitats and key ecosystem processes (*e.g.*, Roff and Taylor, 2000).

In this paper, the scientific processes of constructing the bioregionalization and then selecting BAOI for possible MPA candidates in southeastern Australia are reviewed. Emphasis is placed on the role of geoscience in these procedures along with a critical assessment of the BAOI and MPAs, in terms of the extent to which they conform with the CAR principle. Finally, a new "seascape" classification (Roff *et al.*, 2003) of the continental shelf is proposed that accounts for differences in habitats based on physical variables that have been measured or modelled for the region.

Geography and Geology of the Southeast Region

The region of southeastern Australia is defined as the seabed and oceans within Australia's Exclusive Economic Zone (EEZ) located between (and including) waters off southern New South Wales (NSW) and the Lacepede Shelf of South Australia, including Bass Strait and the waters around Tasmania (NOO, 2002; Figure 1). This area covers about 1.1 million km^2 and extends over 9° of latitude (37° to 46°S) in a mostly temperate climate regime (NOO, 2002). It includes territory, partly in the waters adjacent to New South Wales and South Australia, plus all the ocean territory of Victoria and surrounding Tasmania.

The shelf is narrow along the southern, eastern and western coasts of Tasmania and adjacent to New South Wales, with a broad shelf formed by Bass Strait and the Lacepede Shelf adjacent to South Australia (Figure 1). The shelf is locally as narrow as 10 km, adjacent to Cape Pillar and South West Cape. A dominant feature of the southeast shelf area is Bass Strait, which forms a shallow seaway between the Australian mainland and Tasmania. It is approximately 250 km wide with an average depth of 60 m (Jennings, 1958). In the centre of the Strait is the Bass Basin, a shallow depression, which occupies an area of about 66,000 km^2. It is approximately 120 km wide and has a maximum depth of 83 m near its geographic centre. Palaeozoic basement granite ridges occur on the eastern and western margins of the basin (Von der Borch, 1967; Von der Borch *et al.*, 1970). In the east, they form the Bassian Rise, a shallow sill having a water depth of approximately 55 m, whilst islands associated with this rise have a maximum elevation of 760 m. The southwestern margin, the King Island Rise, also has a water depth of approximately 55 m, and forms a strait between King Island and Tasmania. The northwest margin includes the Otway Depression, and close to the mainland it reaches a maximum sill depth of about 67 m.

Malikides *et al.* (1988) estimated that approximately 30,000 km^2 of Bass Strait is covered by large subtidal dunes (Figure 2). Dunes located to the north of Flinders Island average 7 m in height and 415 m in wavelength, composed of 42-92% carbonate, and a trend of decreasing carbonate content with decreasing grain size. The tidal and wave energy dictates that fine-grained sediment is transported away from the high-energy rim surrounding the basin and it is deposited in the deep, low-energy, central region of Bass Basin (Fandry, 1983; Harris, 1994; Harris and Coleman, 1998). The deposition of fine-grained, mainly calcareous material in the Bass Basin is in contrast to the open Otway and Gippsland sand-dominated shelves, where the rate of carbonate production is probably similar to Bass Basin, but the fine material is winnowed by tidal currents and waves, leaving only a sandy lag deposit (Blom and Alsop, 1988; James *et al.*, 1992; Lavering, 1994; Black and Oldman, 1999).

During Pleistocene sea level lowstands, the Bass Basin was enclosed by raised sills and sea level fluctuations have given rise to a number of periods when the basin existed as a lake or marine embayment. This occurred from 60,000 to 26,000 years BP and during the last glacial maximum (18,000 years BP), when the basin was completely isolated and a brackish lake was formed (Blom and Alsop, 1988; Harris, 2003). Sea level rise during the postglacial transgression flooded the basin, forming a marine embayment from 11,800 to 8700 years BP and the basin rim was completely flooded by about 8000 years BP, at which point Bass Strait was formed and Tasmania became a separate island.

The southeast continental margin evolved during the Cretaceous, when seafloor spreading became active around 82 Ma in the Tasman Sea and the Southern Ocean (Weissel and Hayes, 1977; Royer and Rollet, 1997; Exon *et al.*, 1997). The margin exhibits a slope angle typically ranging from 2 to 12°, but gradients are much steeper locally, up to 30° (Jenkins and Keene, 1992). The slope is bounded to the east by the East Tasman Saddle and Plateau and on the south by the South Tasman Rise (Exon *et al.*, 1997).

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[1] The precautionary principle applied to MPAs means that lack of scientific certainty about the correct size, location or number of MPAs should not prevent MPAs or MPA networks from being declared.

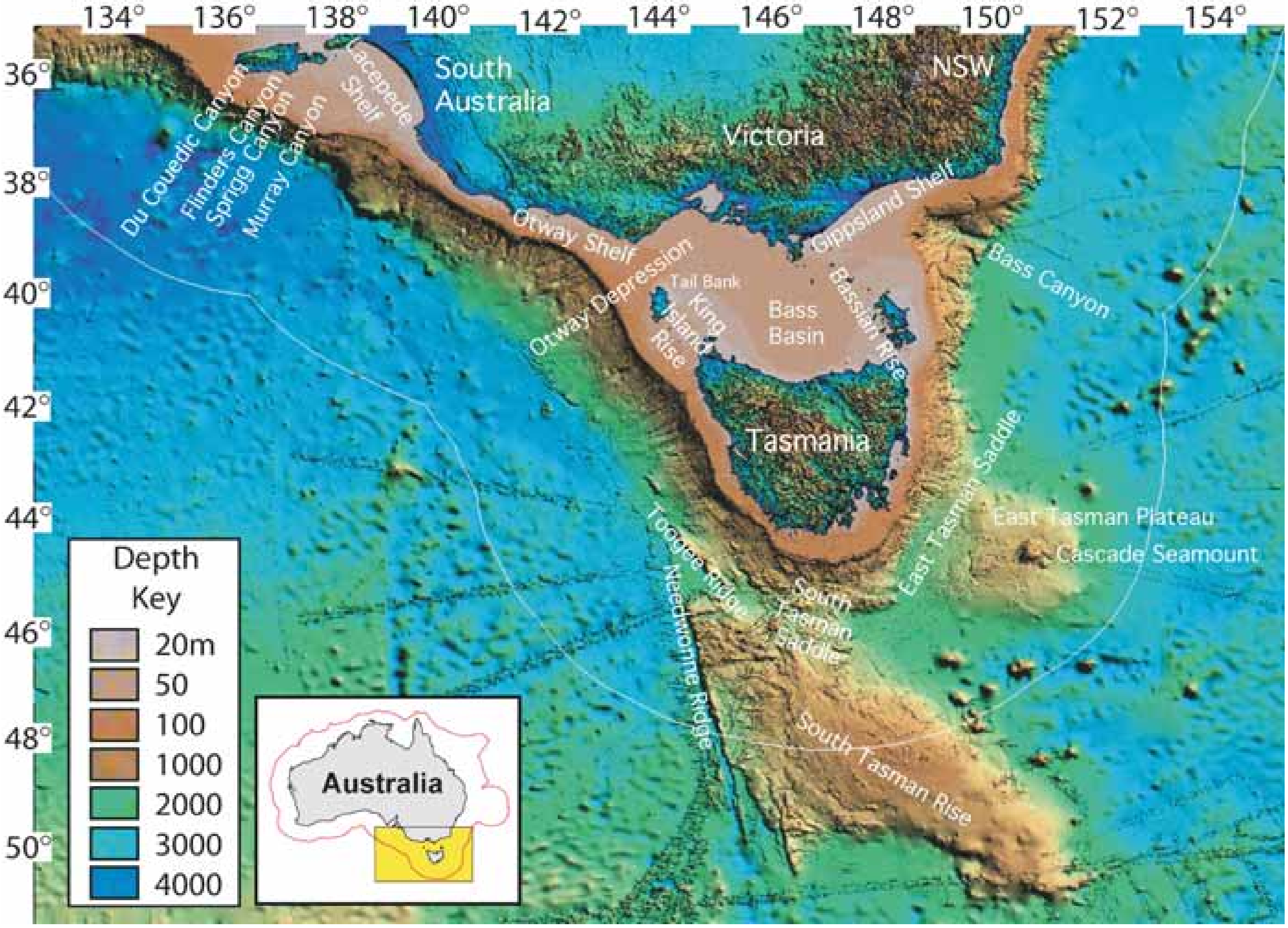

Figure 1. *Map of the southeast region of Australia showing location of the study area.*

These ocean plateaux are fragments of continental crust derived as a product of Gondwana rifting. On the southeast Australian margin, the continental slope is cut by numerous submarine canyons, notably the Bass Canyon, located on the eastern side of Bass Strait (Conolly, 1968; Hill *et al.*, 1998), and the Murray Canyon (Gingele *et al.*, 2004; Hill *et al.*, 2005; Figure 1). On the southern slope of New South Wales, Jenkins and Keene (1992) reviewed seismic data and identified numerous submarine slope failure structures up to 400 m thick and 25 km in downslope length.

Procedure for Selecting Candidate MPAs

The identification of candidate MPAs in southeastern Australia was based on a broad assessment of the biodiversity and ecosystem processes occurring in the region (NOO, 2002), followed by consultation with stakeholders to find solutions that achieved biodiversity conservation objectives while minimizing adverse socio-economic impacts. The steps in the MPA design process that required scientific input were as follows:

Step 1. Identify an agreed hierarchical framework which provides a context for mapping biological diversity at different spatial scales.

Step 2. Assemble the available biological and abiotic datasets into a computer Geographic Information System (GIS) and derive maps from the integration and analysis of the data layers.

Step 3. Interpret and synthesise the available spatial information to derive a "bioregionalization".

Step 4. Apply algorithms and expert judgement to nominate representative BAOI (focus areas for candidate MPAs).

Step 5. Provide scientific advice and information as required by stakeholders and environmental managers during the process to design candidate MPAs.

Step 5 involved helping to provide context for the BAOI located on the continental shelf and will be discussed below; a new evaluation of some GIS data layers was carried out to derive "seascape" maps that convey more detailed information about habitats and ecological processes than was previously available.

Step 1. Identify an Agreed Hierarchical Framework

The ecosystem-based approach to planning uses natural regions as planning units, but natural regions need to be identified on a range of hierarchically-nested scales for different planning and management purposes (see chapter Classification Schemes, this volume).

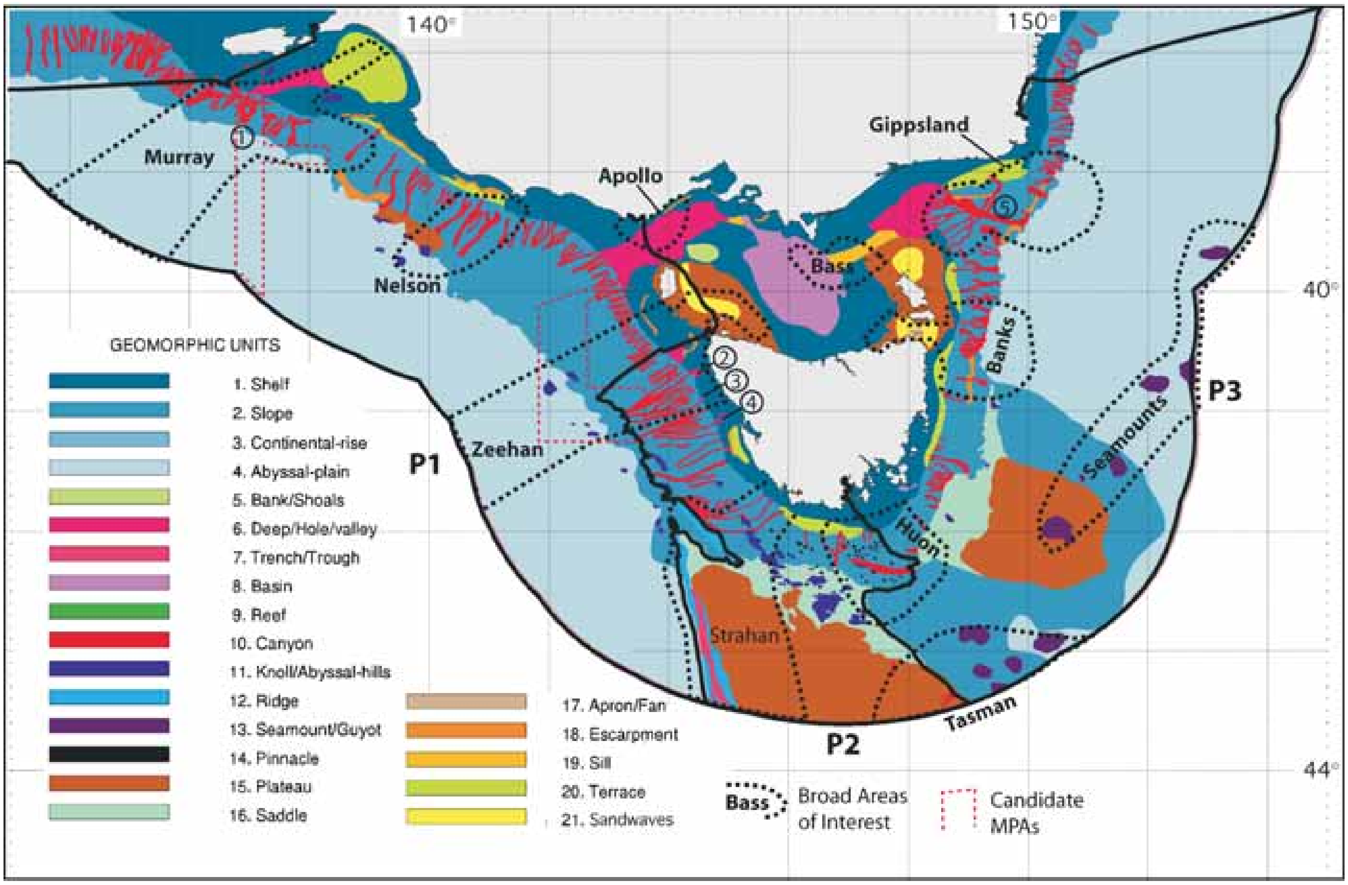

Figure 2. *Geomorphic features of the southeast region, showing the locations of BAOI, candidate marine protected areas and province boundaries. The provinces are numbered from west to east P1, P2 and P3. Circled numbers indicate the locations of submarine canyons having heads that extend onto the continental shelf; these include (1) Murray Canyon, (2, 3 and 4) un-named canyons offshore from western Tasmania and (5) Bass Canyon. Continental rise and submarine aprons and fans were not identified in the southeast region.*

The properties used to distinguish different hierarchical levels in natural systems are themselves continuously varying functions; thus, sharp, unequivocal boundaries are the exception rather than the rule. Alan and Starr (1982) observe that within any hierarchy, "discrete levels need to be recognized as convenience, not truth". Nevertheless, in most systems there are real discontinuities that can be recognized, and these have prompted the development of a number of classification schemes for different purposes (*e.g.*, Greene *et al.*, 1994, 1995, 1999; Davies and Moss, 1999; Roff and Taylor, 2000; Vanderklift and Ward, 2000). Hierarchical classification systems can be modified when missing components are identified and a good hierarchical classification system must have predictive power in terms of describing the relationship between habitats and communities. A hierarchical classification system is essential for the selection of representative or distinctive habitats (Roff and Taylor, 2000).

In the case of southeastern Australia, a nested hierarchy was adopted for a benthic classification scheme (Butler *et al.*, 2002), of which the four highest levels are relevant to the present discussion:

Level 1 Provinces: Broad-scale biogeographic units. Evolutionary biogeography is the key process at this level as reflected by the presence of regions of endemism. Provinces are typically of the order of ~1000 km in extent.

Level 2 Biomes: Comprised of neritic and oceanic zones divided by the continental shelf break. The neritic zone has three primary benthic biomes (estuarine, coastal marine, and shelf), whereas the oceanic zone consists of two primary benthic biomes (continental slope and abyssal). Sub-biomes may also be recognized based on distinct variations in the composition of biota. Biomes are nested within provincial units and are typically several 100s of km or more in extent.

Level 3 Geomorphological Units: Areas characterized by similar geomorphology. These may include (on the continental shelf) fields of sand waves, rocky outcrops, incised valleys, flat muddy seabeds, *etc.*, and (on the slope and at abyssal depths) submarine canyons, seamounts, oceanic ridges and troughs, *etc.* Such units may typically be about 100 km in extent.

Level 4 Biotopes: Defined on the bases of substrate type (rocky, sediment-covered or a mixture), with associated suites/collections of floral and faunal communities, modified by hydrological variables such as wave exposure, turbidity, and current speed.

The hierarchy had several other levels below level 4, and also a pelagic hierarchy was developed (Butler *et al.*, 2002), but these were not used in the present study. The Level 3 geomorphological units are considered as surrogates for specific assemblages of biota, based on numerous cases published in the literature. At broad spatial scales, or in cases where only sparse datasets exist, a number of workers advocate the use of abiotic (*i.e.*, geologic and oceanographic) indicators of benthic habitats and ecosystems as proxies for biological communities and species diversity (*e.g.*, Hockey and Branch, 1997; Roff and Taylor, 2000; Banks and Skilleter, 2002; Roberts *et al.*, 2003a, b); it follows that applications of spatially more complete, abiotic information should be employed to systematically map different habitats to support MPA design. Indeed, Greene *et al.* (1995, 1999) have devised a benthic marine habitat classification scheme that is strongly dependant upon seabed geology, whilst in Canada, Roff and Taylor (2000) and Zacharias and Roff (2000, 2001) used primarily bottom physiography and oceanographic information in their hierarchical geophysical approach to classify and map marine environments.

Step 2. Assemble Datasets into a GIS and derive Map Products

The collation of datasets into a computer-based (ARC/ESRI) GIS provided regional datasets about the broad pattern of biodiversity for MPA design. The datasets compiled included oceanographic information (temperature, salinity, nutrients, dissolved oxygen, currents), biological information (demersal fish and invertebrates) and analysis of satellite imagery (surface ocean) for primary productivity. A separate analysis of other important ecosystem processes in the region (*e.g.*, upwelling and primary productivity) was carried out (Butler *et al.*, 2002). A key product was the creation of a new bathymetry grid (250 m grid size) and derived products (geomorphic features, slope, drainage, *etc.*) that will be described in more detail below. The bathymetry grid provided a foundation upon which all other data layers could be "draped". Other geological information available included seabed sediment properties (for the continental shelf only), location of sedimentary basins, major fault systems, age of ocean crust and sediment thickness. In addition, a study of sediment mobilization on the continental shelf due to swell waves and tides was carried out (Porter-Smith *et al.*, 2004).

Step 3. Interpret and Synthesise Information to derive a Bioregionalization

A "bioregionalization" is defined here as a map depicting the boundaries of areas represented by each level in a hierarchical classification of habitat types (Provinces, Biomes, Geomorphological Units, *etc.*). This definition follows logically from the observation that identifying and mapping ecosystem variety is dependant upon them being viewed as nested within a hierarchy of spatial and temporal scales (*e.g.*, Greene *et al.*, 1994, 1995, 1999; Holling, 1992; Langton *et al.*, 1995; Garcia-Charton and Perez-Ruzafa, 1999; Poiani *et al.*, 2000; Roff and Taylor, 2000).

In deriving a bioregionalization for Australia's southeast region, the identification of (Level 1) Provinces and slope biomes was based primarily of demersal fish data (Butler *et al.*, 2002). The fish database contained information on presence and abundance of each species in neighbouring regions, as well as their presence, abundance and depth-distribution within the southeast region, for fish occurring deeper than 150 m. An expert workshop chose fish species that were informative in suggesting biological patterns reflecting biogeographic and evolutionary history, for use at Level 1, and small area spatial patterns for use at Level 2. Distributions of fish species were recorded as "strings" along the 500 m depth contour. For the analyses, the string was partitioned into smaller segments of about one degree latitude length (about 120 km) into which tabulations of species occurrences were maintained. The similarity or difference between adjacent string segments was measured using the Jaccard statistic, which identified boundaries between different provinces (Butler *et al.*, 2002). All of the work outlined above was carried out by government-funded, science-provider agencies that reported to a Southeast Regional Marine Planning Working Group (SERMPWG) comprised of representatives from stakeholder groups and government environmental managers.

Geomorphic features were mapped on the shelf, slope and abyssal plain (defined by the shelf break and the base of slope). Individual features were then aggregated into larger, Level 3 Geomorphological Units. In some cases, a single large feature would also be classed as a "unit" but generally the units were comprised of a number of smaller, individual features. The geomorphic mapping procedure was largely based on expert judgement and interpretation (Harris *et al.*, 2005).

Geomorphic features were identified using the 250 m spatial resolution bathymetry maps with reference to previously published geological studies (Hill *et al.*, 1995, 1998; Hill and More, 2001; Exon *et al.*, 1997; and Bernardel *et al.*, 2000). A scale of 1:5,000,000 was selected, together with a 10 km minimum length scale, for the geomorphic features to be mapped. Geomorphic features that are smaller than 10 km in length were either aggregated into larger features (*e.g.*, a field of sand waves) or were ignored. This scale is constrained by the pixel size of the grid (*i.e.*, 40 pixels x 250 m = 10 km) and is consistent with the smoothing carried out for contour mapping (smoothed over 2250 m).

The vertical spacing of contours was set for 5 m on the shelf (0–500 m) and at 100 m for greater depths. Contour maps were supplemented by false-colour, azimuth-illuminated, bathymetric images, generated by assigning a gradational colour value to each (un-smoothed) depth pixel. These false-colour images were generated separately for the shelf and for the entire margin. The false colour images were useful for detecting some smaller, low-relief features that might be overlooked on a contour map.

Terms and nomenclature used to describe geomorphic features of the seabed are based on definitions endorsed by the International Hydrographic Organisation (IHO, 2001). Twenty-one separate categories of geomorphic feature (Table 1), extracted from the 53 types given by IHO (2001), were used by grouping similar geomorphic features into single categories (*e.g.*, "bank" and "shoal" are number 5; "deep", "hole" and "valley" are number 6; *etc.*) to reduce the amount of time required to classify features. A category for sand waves (subaqueous dunes of Ashley, 1990) and sand banks (number 21; Table 1) was also added because these are considered as important geomorphic features on the Australian continental shelf.

Table 1. List of geomorphic features mapped in Australia's southeast Exclusive Economic Zone. Definitions are from IHO (2001), except for sand waves and sand banks, which are defined in Ashley (1990)

No.	Name	Definition
1	Shelf	Zone adjacent to a continent (or around an island) and extending from the low water line to a depth at which there is usually a marked increase of slope towards oceanic depths.
2	Slope	Slope seaward from the shelf edge to the upper edge of a continental rise or the point where there is a general reduction in slope.
3	Rise	Gentle slope rising from the oceanic depths toward the foot of a continental slope.
4	Abyssal Plain	Extensive, flat, gently sloping or nearly level region at abyssal depths.
5	Bank	Elevation over which the depth of water is relatively shallow but normally sufficient for safe surface navigation.
	Shoal	Offshore hazard to surface navigation that is composed of unconsolidated material.
6	Basin	Depression, characteristically in the deep seafloor, more or less equidimensional in plan and of variable extent.
7	Canyon	A relatively narrow, deep depression with steep sides, the bottom of which generally has a continuous slope, developed characteristically on some continental slopes.
8	Deep	In oceanography, an obsolete term which was generally restricted to depths greater than 6000 m.
	Hole	Local depression, often steep sided, of the seafloor.
	Valley	Relatively shallow, wide depression, the bottom of which usually has a continuous gradient. This term is generally not used for features that have canyon-like characteristics for a significant portion of their extent.
9	Escarpment	Elongated and comparatively steep slope separating gently sloping areas.
10	Knoll	Relatively small isolated elevation of a rounded shape.
	Abyssal Hills	Tract, on occasion extensive, of low (100–500 m) elevations on the deep sea floor.
	Hill	Small isolated elevation.
	Mountains	Large and complex grouping of ridges and seamounts.
	Peak	Prominent elevation either pointed or of a very limited extent across the summit.
11	Pinnacle	High tower or spire-shaped pillar of rock or coral, alone or cresting a summit. It may extend above the surface of the water. It may or may not be a hazard to surface navigation.
12	Plateau	Flat or nearly flat area of considerable extent, dropping off abruptly on one or more sides.
13	Reef	Rock lying at or near the sea surface that may constitute a hazard to surface navigation.
14	Ridge	(a) Long, narrow elevation with steep sides. (b) Long, narrow elevation often separating ocean basins. (c) Linked major mid-oceanic mountain systems of global extent.
15	Saddle	Broad pass, resembling in shape a riding saddle, in a ridge or between contiguous seamounts.
16	Apron	Gently dipping featureless surface, underlain primarily by sediment, at the base of any steeper slope.
	Fan	Relatively smooth, fan-like, depositional feature normally sloping away from the outer termination of a canyon or canyon system.
17	Seamount	Large isolated elevation, greater than 1000 m in relief above the seafloor, characteristically of conical form.
	Guyot	Seamount having a comparatively smooth flat top.
18	Sill	Seafloor barrier of relatively shallow depth restricting water movement between basins.
19	Terrace	Relatively flat horizontal or gently inclined surface, sometimes long and narrow, which is bounded by a steeper ascending slope on one side and by a steeper descending slope on the opposite side.
20	Trench	Long narrow, characteristically very deep and asymmetrical depression of the seafloor, with relatively steep sides.
	Trough	Long depression of the seafloor characteristically flat bottomed and steep-sided and normally shallower than a trench.
21	Sand wave	Wave-like bed form made of sand on the seafloor.
	Sand Bank	Submerged bank of sand formed by tidal currents that may be exposed at low tide.

Features listed in Table 1 were identified on contour, drainage analysis (Butler *et al.*, 2002) and false-colour maps, and then drawn by hand onto transparent compilation maps. The separate polygons were digitized and stored as ARC/GIS shape files. The resulting map of geomorphic features (Figure 2) became a fundamentally important dataset for the derivation of the bioregionalization (Figure 3). The southeast region has 3 Provinces and 9 Biomes and 39 geomorphological units. The bioregionalization was approved by the SERMPWG (Butler *et al.*, 2002; NOO, 2002) and published by the National Oceans Office as part of the Southeast Regional Marine Plan (NOO, 2004).

The bioregionalization accepted by the National Oceans Office did not include the continental shelf because there already exists an earlier shelf bioregionalization for Australia (the Interim Marine and Coastal Regionalization for Australia, IMCRA; Thackway and Cresswell, 1998). The IMCRA, as endorsed by ANZECC (1999), is actively used by the State and Territory governments to assist MPA planning in State waters. Thus, the two schemes (IMCRA plus the new deep-water bioregionalization), derived at different times and based on different datasets, were used together to guide in the design of candidate marine protected areas (Figure 3). Although the map of geomorphic features (Figure 2) includes features on the continental shelf, IMCRA bioregions (considered here to be equal to Level 3 Geomorphological Units) were used to guide MPA planning on the shelf.

Step 4. Apply Algorithms and Expert Judgement to Nominate Representative Broad Areas Of Interest

Broad Areas Of Interest were identified through a combination of scientific modelling and expert opinion and the exchange of stakeholder ideas and information. Identification criteria developed with stakeholders for application within a broad, deep, offshore marine region were also used to guide the process of choosing the BAOI (L. Wilks, DEH, pers. comm., 2005). Scientific advice was provided by scientists from the CSIRO, Geoscience Australia and the Museum of Victoria.

Conceptually, there are a number of important decisions that have to be made before an MPA network can be designed. How many protected areas are required? Where should they be placed? How large should they be? (*e.g.*, Ray, 1999). For the southeast region, DEH provided a set of specifications to help address these questions (EA, 2003). Broadly summarized, these specifications are as follows: The reserve design system will include areas that represent a sample of the full range of bioregions in the southeastern region. Candidate areas may extend over several bioregions, *e.g.*, across latitudinal or cross-shelf ranges. They should be large enough to ensure adequate representation of an example of marine biodiversity at all ecosystem levels, and they should avoid fragmentation as well as edge effects resulting from use of adjacent areas. Candidate areas should include atypical/unique areas or areas

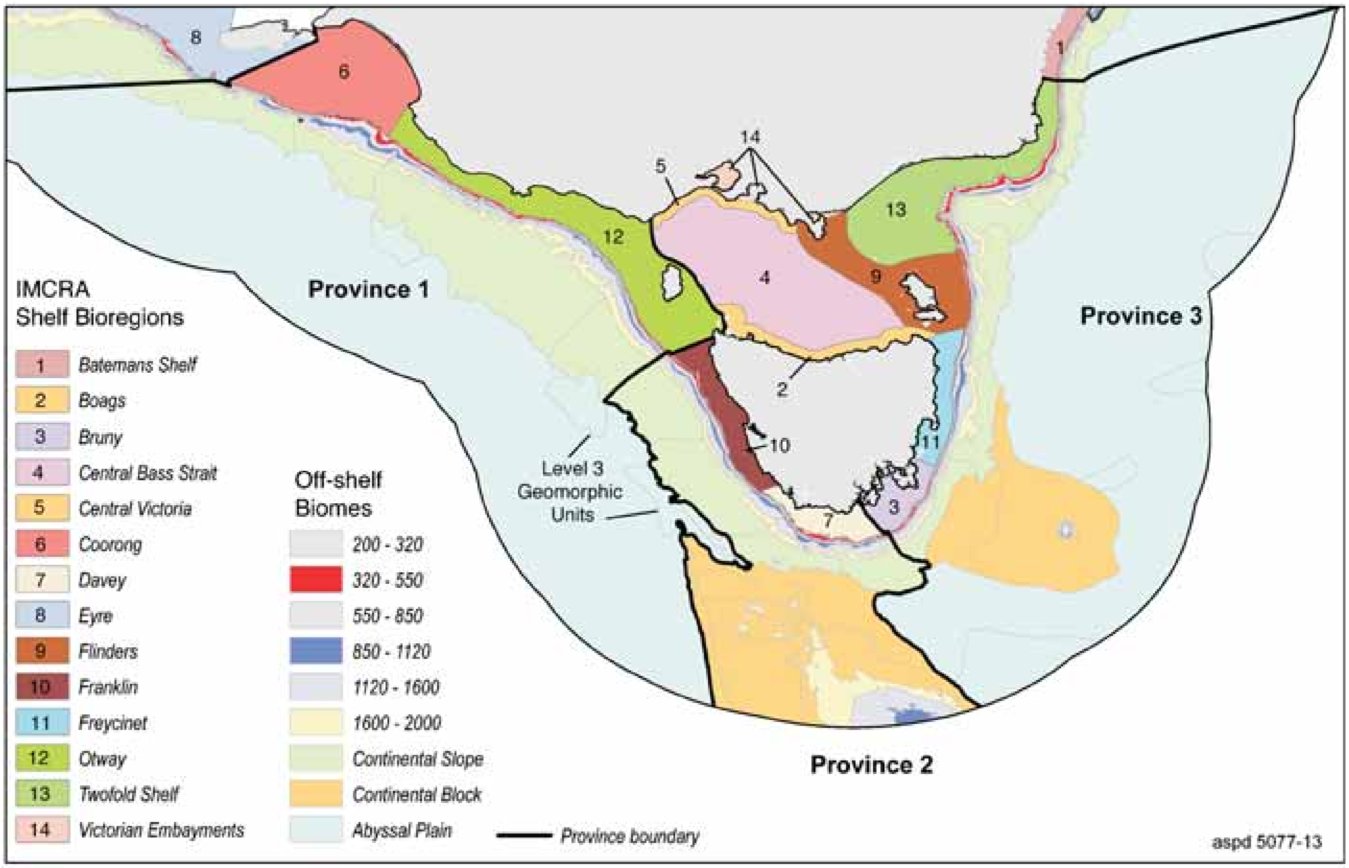

Figure 3. *Bioregionalization of the southeast region located offshore of the shelf break (NOO, 2002) and IMCRA mesoscale bioregions on the continental shelf (Thackway and Cresswell, 1998). Only 11 IMCRA bioregions overlap with the study area because the Bateman's Shelf and Eyre bioregions lie outside the southeast region and the Victorian Embayments bioregion is located in coastal waters not included in this study.*

known for high productivity (*e.g.*, geographical features, ecosystems, species, breeding/spawning areas) and include the whole of a biophysical feature/place to conserve the integrity of the biological unit. They should minimize conflict with users and have simple boundaries for cost-effective compliance and enforcement.

Furthermore, a set of system-wide objectives was also provided. These put forward that a viable system of MPAs should incorporate a small number of large reserves rather than a large number of small reserves to avoid fragmentation and ineffective management. The MPAs should take into consideration what is known about migration patterns, currents and connectivity among ecosystems as well as existing Commonwealth and State MPAs and other conservation tools such as species management (EA, 2003). The Department of Environment and Heritage specified that the MPAs would be managed as a range of International Union for the Conservation of Nature and Natural Resources (IUCN) categories, from strict nature reserves to managed resource protected areas, where these are compatible with the objectives of the reserve. There was no target size set for MPAs (*i.e.*, some percentage of the total area) but it was agreed that every bioregion and broad geomorphic feature be included within broad areas of interest within each of the three provinces.

A spatial analysis of the bioregionalization (Figure 3) was carried out using software called MARXAN[2] (Possingham *et al.*, 2000) that can accommodate a broad range of input data, including abiotic, biological and socio-economic data. MARXAN employs a spatial analysis technique called "simulated annealing" that selects two random MPA networks and compares the results; at each step, the "best" solution is kept and another randomly-selected network is compared; "best" is defined in terms of the greatest amount of diversity being enclosed within the smallest area. MARXAN has been used in Australia to design MPA networks in the Great Barrier Reef Marine Park (*e.g.*, Lewis *et al.*, 2003) and has also been used successfully in the USA and in Canada (Leslie *et al.*, 2003).

Locations that were repeatedly nominated by MARXAN as high-priority sites for conservation were enclosed within eleven hand-drawn polygons, BAOI that spanned Commonwealth waters on the shelf and in deep-water areas outside the continental shelf. MARXAN modelling artifacts were removed and other known ecosystem characteristics were included to ensure the BAOI comprehensively covered the variety of known features in the region (L. Wilks, DEH, pers. comm., 2005) The BAOI spanned the three main provinces in the region and included a range of shelf, slope and abyssal biomes, IMCRA bioregions on the shelf as well as a range of geomorphic units/features off the shelf. One BAOI included mostly seamount features in the Tasman Sea and another captured the geomorphic features of the South Tasman Rise; another two BAOI were chosen on the continental shelf in Bass Strait (Figure 2).

The Apollo, Murray and Nelson BAOI occur wholly in Province 1. The Bass, Banks, Gippsland and Seamounts BAOI occur wholly in Province 3. In contrast, the Strahan, Huon, Zeehan and Tasman BAOI occur mostly in Province 2, but have some overlap with Provinces 1 and 3 (Figure 2). A brief description of each BAOI, with their relevance to stakeholders and special conservation features, is provided in Table 2.

Step 5. Provide Scientific Advice and Information as required by Stakeholders and Environmental Managers to Design Candidate MPAs

Having identified 11 BAOI in the southeast region, environmental managers require information about them to be provided in a synthesized form, to explain their significance to the community, and to make progress to eventually derive candidate MPAs. The most important question to ask, in terms of adherence to the CAR principles, is: To what extent do the 11 BAOI reflect the diversity of habitats in the southeast region? To answer this question a simple analysis using ARC/GIS has been carried out to quantify the spatial distribution of geomorphic features (habitats): a) within the whole of the southeast region; b) within each of the 11 BAOI; and c) within each province.

The overall distribution pattern of cumulative surface areas of geomorphic features occurring in the southeast region is similar to cumulative surface areas of geomorphic features occurring in the combined 11 BAOI (Figure 4). This implies that, collectively, BAOI may be considered as containing a comprehensive and representative subset of the geomorphic features occurring in the southeast region.

The diversity of the types of features within BAOI (Table 3) illustrates that they are not all equal: the Apollo BAOI has only 3 feature types, Bass has 4, Seamounts 4, Strahan 6, Huon 7, Murray

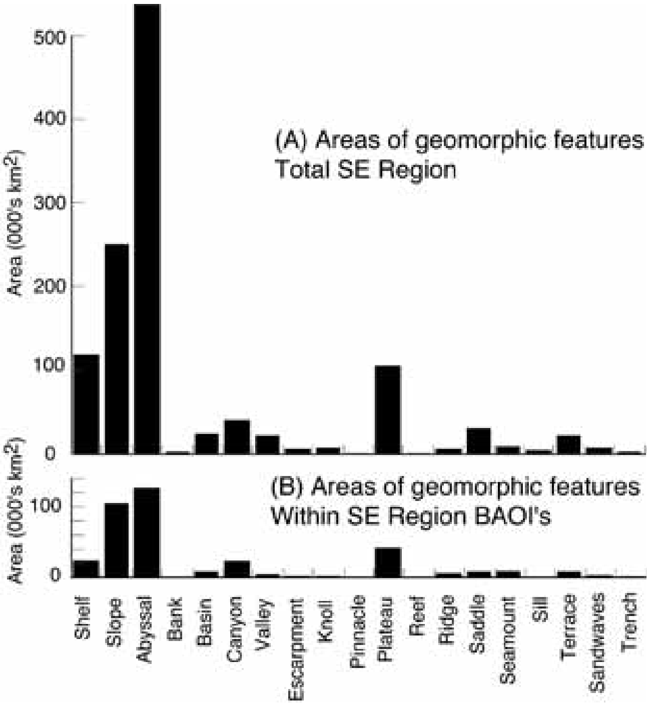

Figure 4. *Histogram showing (A) the cumulative surface areas of geomorphic features in the entire southeast region, and (B) contained within all 11 BAOI. Numerical values are listed in Table 3.*

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[2] Further information about MARXAN is available on the web at this URL: http://www.ecology.uq.edu.au/?page=20882

Table 2. List of 11 BAOI and descriptions of their major biological and physical features (where known), together with conservation values. See also DEH webpage: http://www.deh.gov.au/coasts/mpa/southeast/index.html

1. APOLLO – 4921 km^2. Located wholly on the continental shelf in Bass Strait, and consists of only the shelf, valley and escarpment geomorphic features. Includes zone of faunal overlap from Tasmanian and Bassian provinces. Diverse infaunal biota, predominantly crustaceans, polychaetes and molluscs. This BAOI is the smallest.

2. BANKS – 23,898 km^2. The shelf area includes a tidally-scoured channel (Banks Strait) and mobile sand waves, tidal current ridges, and current-scoured rocky seabed. There are numerous rocky reefs along the coastline. The area includes a shelf–abyss transition and the slope contains numerous, deeply-incised submarine canyons, spaced about 16 km apart, interspersed with a slope having no canyons.

3. BASS – 6013 km^2. This BAOI is adjacent to a state-declared MPA in Victoria around Wilson's Promontory and Tasmanian MPAs around the Kent Group of islands. Bass Basin was the site of a lake during the Pleistocene ice age. Conservation values include high fish and plant species richness.

4. GIPPSLAND – 33,644 km^2. This area is notable for containing one of Australia's most significant petroleum production areas and major shipping channels. It contains a shelf–abyss transition and is influenced by the warm waters of the south-flowing East Australia Current. A major submarine canyon complex (Bass Canyon) is located on the slope within this BAOI. Fisheries are important above the 600 m water depth.

5. HUON – 24,791 km^2. This BAOI is dominated by a "saddle" geomorphic feature, and includes a shelf–abyss transition. The continental slope here has no submarine canyons but does overlap an MPA over a group of pinnacles on the slope where Orange Roughy are protected. Contains several abyssal hills and peaks and a few seamounts. There is believed to be a large component of endemic species in this BAOI.

6. MURRAY – 76,170 km^2. Includes a shelf–abyss transition and is the largest BAOI. Barrier coast with nearshore-offshore gradient, traversed by Murray canyons, broad Lacepede Shelf-platform extending offshore from Murray River mouth. Flora and fauna typical of transitional warm to cool temperate waters. Continental slope, extensively incised by submarine canyons spaced 14 to 17 km apart, interspersed with slope having no canyons. Area of high-order predator foraging and breeding grounds (penguin, seal, whale, shark).

7. NELSON – 18,542 km^2. Narrow shelf area, extends from shelf to abyssal plain. Water typified by localized, regular, seasonally-cold, nutrient-rich coastal upwellings. High, deep-water wave energy attenuated by steep offshore–nearshore gradient. Extensively incised with submarine canyons spaced about every 15 km.

8. SEAMOUNTS – 41,258 km^2. As the name suggests, this BAOI is dominated by 6 large seamounts that cover an area of about 5200 km^2 notably the Cascade Seamount, which is 67 km in diameter at its base. The potential exists for endemicity at a level of "groups of seamounts" or even at a level of individual seamounts which are as yet not studied.

9. TASMAN – 54,885 km^2. Dome of South Tasman Rise contains submarine canyons spaced about 30 km apart, numerous seamounts and continental blocks. Plateau has 3 demersal-fish sub-biomes.

10. STRAHAN – 27,847 km^2. Narrow shelf off southwest Tasmania, exposed to large swell waves. Steep continental slope, extensively incised with submarine canyons spaced about 14 km apart. Region of South Tasman Rise has extensive plateau areas with ridges, swales and troughs >2000 m deep. Conservation values include seal and seabird breeding grounds.

11. ZEEHAN – 69,273 km^2. Extends from shelf into abyssal plain. Area of high coast-shelf-offshore exchange, transition in fish diversity. Tidal currents with tide–wave interaction, continental slope extensively incised by submarine canyons about every 7 km. Includes fisheries for Blue Grenadier, crab, Ling (trap and line), rock lobster and scallop grounds. There are existing petroleum industry lease areas and current petroleum industry gazettal areas. Conservation values include links between canyons, ocean currents, upwelling processes and flows through Bass Strait. Complex shelf seafloor in tidal passages are likely associated with complex habitat structure and diverse flora and fauna. Provide areas for high-order predator foraging and Blue Grenadier spawning.

8, Nelson 8, Zeehan 9, Gippsland 9, Banks 10 and Tasman 12. This is an important distinction to make because although the BAOI capture the full diversity of features occurring in the region, the diversity included within individual BAOI varies.

The surface areas of geomorphic features occurring within each province illustrates differences in geomorphic makeup between provinces (Figure 5). Province 1 is dominated by abyssal plains, which comprise over half of the overall area. Aside from the shelf and slope, canyons and terraces cover the largest area. Province 2 is dominated by the large plateau forming the South Tasman Rise and it is the only province containing pinnacle or trench features. Province 3 has large areas of abyssal plain but also contains plateaux saddles, basins and sand waves; seamounts are found only in Province 3.

In general, the BAOI reflect the composition of the provinces in which they occur (Figure 5). Some geomorphic features occur in

Table 3. List of occurrences of different geomorphic features (see Table 1) and their cumulative surface areas within each BAOI of the southeast region. The names of BAOI are shown on Figure 2

	TOTAL		Apollo		Banks		Bass		Gippsland		Huon		Murray		Nelson		Seamounts		Strahan		Tasman		Zeehan	
Feature	#	km^2	#	km^2	#	km^2	#	km^2	#	km^2	#	km^2	#	km^2	#	km^2	#	km^2	#	km^2	#	km^2	#	km^2
1 Shelf	46	117647	4	1528	3	2879	3	1681	3	1818	1	3619	5	4665	2	839					1	834	1	7543
2 Slope	40	249901			4	6913	19	?	?	11832	7	14288	4	14740	1	9211	1	6511	1	11730	11	9739	3	20368
3 Rise	NOT FOUND IN SOUTHEAST REGION																							
4 Abyssal	3	538426			1	8080			1	9797			1	46106	1	2925	1	23337	2	2750	1	4308	1	28910
5 Bank	3	1348											**2**	**95**										
6 Basin	6	24136			1	77	1	2857													3	5172		
7 Canyon	131	40193			3	1984			9	5364	8	1842	11	4438	9	2820			2	269	2	2121	25	4584
8 Valley	7	21010	1	3304					1	1392			1	2698									2	685
9 Escarpment	16	5875	1	89	2	433			4	788			1	762	3	130							2	428
10 Knoll	41	7228							1	70	3	281			3	517					4	836	6	838
11 Pinnacle	46	732									**35**	**495**											**1**	**25**
12 Plateau	6	105857			4	1857	1	125	2	98					1	1532	1	6189	1	8749	1	19231	3	388
13 Reef	1	4																						
14 Ridge	5	5840																			**5**	**5844**		
15 Saddle	2	30442			1	90					2	3207							1	525	2	4610		
16 Fan	NOT FOUND IN SOUTHEAST REGION																							
17 Seamount	11	9052															6	5220	5	3779				
18 Sill	2	2790					**1**	**1350**																
19 Terrace	8	22469			2	1208			1	2485	1	1059	1	2735	1	568					1	78		
20 Trench	2	2082																			**2**	**2087**		
21 Sand wave	5	7512	**1**	**1097**																			**1**	**2034**
TOTAL	381	1192500	6	4921	22	23898	6	6013	41	33644	57	24791	26	76170	21	18542	9	41258	6	27847	34	54885	44	69273

Bold numbers refer to features that occur in only one (Irreplacibility = 1) or two (Irreplacibility = 2) BAOI in the region. The “TOTAL” column refers to the occurrence of features in the southeast region.

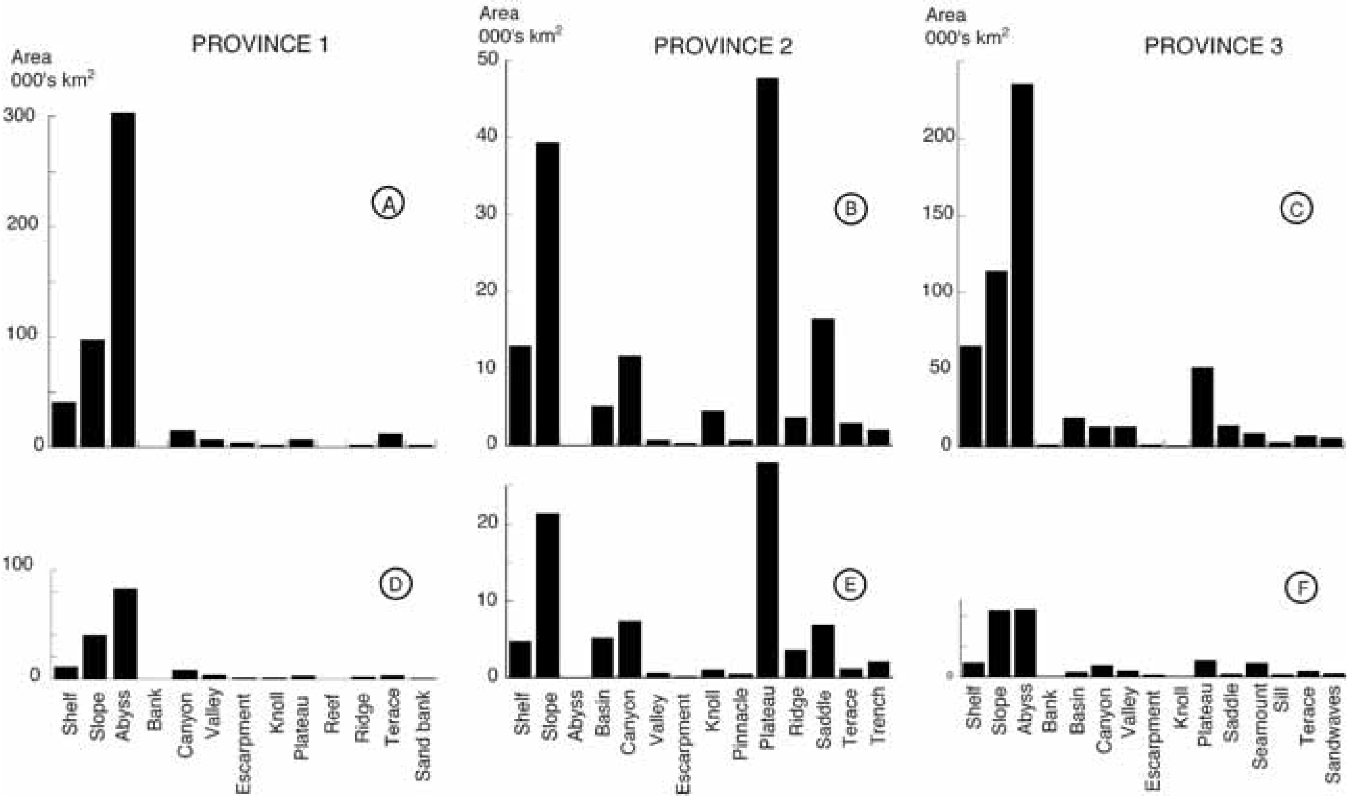

Figure 5. *Histograms showing the cumulative surface areas of geomorphic features in: (A) Province 1; (B) Province 2; (C) Province 3; and within the BAOI in (D) Province 1; (E) Province 2; and (F) Province 3.*

only a few locations, *e.g.*, pinnacles and ridges are only found off southern Tasmania (in Province 2) and consequently they are represented in only one or two BAOI (Table 3). These features have a high degree of "irreplacibility" (*e.g.*, Ferrier *et al.*, 2000), which means they are unique and must be included in the BAOI and MPAs that overlap the areas where they occur if they are to be included in the MPA network at all.

A number of features that are found on the continental shelf (banks, sills, valleys and sand waves/sand banks) are poorly represented. This is because the shelf portion of the map of geomorphic features (Figure 2) was not available at the time the BAOI were identified – only the IMCRA bioregions were used. Rocky reefs are known to occur along the coast and at some offshore locations (Edgar *et al.*, 1997). Even though no rocky reefs were included in any of the BAOI (Table 3), they are already part of an MPA in Tasmanian state waters (NOO, 2004). A large, shallow bank, covering 1243 km^2 in western Bass Strait, was not included in any BAOI. However, two smaller banks cover 95 km^2 on the shelf about 10 km east of Kangaroo Island and part (26.5 km^2) of one of these was included in the Murray BAOI. There are two sills in the southeast region covering 2790 km^2 in Bass Strait (Figure 2) and the Bass BAOI includes 1350 km^2 of one of them (Table 3). Sand waves are included in two BAOI and shelf valleys are included in 4 BAOI.

Overall, some off-shelf features (ridges and pinnacles) and on-shelf features (banks, sills and sand waves) are found in only a few locations and they are included in only one or two BAOI. The low frequency of occurrence and representation of these features should be considered for designing any future candidate MPAs. In spite of the fact that geomorphic features occurring on the shelf were not included in the derivation of BAOI, all of them are represented to a certain extent.

Derivation of Shelf Seascapes

Although the IMCRA bioregions located in the southeast region are based on the best information that was available at the time (Thackway and Cresswell, 1998), new geophysical datasets were compiled for the southeast regional marine plan (NOO, 2002). These datasets provide the basis for a new spatial analysis of the continental shelf to identify differences between habitats that could be considered in assessing the 11 BAOI with respect to the guiding CAR principle.

The procedure adopted here was inspired by the shelf classification applied in eastern Canada by Roff *et al.* (2003). These workers used ARC/GIS to overlay several spatial data layers to create "seascape" maps. The seascapes represent spatial areas having similar physical properties. In this approach, a decision must be made as to how many habitats are defined by the available list of variables (*e.g.*, Roff *et al.* (2003) used physiography, wave and current regime, bed roughness and sediment type).

In the southeast region, the variables used are: 1) water depth, 2) surface sediment carbonate content, 3) gravel content, 4) mud content, 5) mean grain size, 6) geomorphic units, 7) percent time of threshold exceedence due to waves; and 8) percent time of threshold exceedence due to tidal currents (Heap *et al.*, 2005). The percent time of threshold exceedence was based on modelling (Harris *et al.*, 2000; Porter-Smith *et al.*, 2004) and is an estimate of the amount of time that surface swell waves or tidal currents are capable of mobilizing the surface sediment mean grain size at a specific location. Surface sediment data was not available for the far western section of the southeast region and so the Murray BAOI was not included in the seascape analysis.

The 8 data layers were converted to a standard 0.01 degree (~1.1 km) grid obtained by interpolating the existing data onto the finer grid as required. Each variable was scaled so that its range, within the final classification region, was 0 to 100. This ensured that each variable had equal weight in the classification process. The classification method used was ER-Mapper's unsupervised isoclass algorithm. One initial class was used because it was not necessary to start with more classes. Other parameters were left at their default values. Classifications were run until the algorithm reached a point where 100% of the classes were unchanged from one iteration to the next. However, in some cases, the algorithm did not reach the 100% unchanged point and had to be terminated manually. Nine classes appears to be optimal number for the southeast region, because this is a point where the mean average distance between class centre points appears to reach a minimum. See Heap *et al.* (2005) for full documentation of the seascape derivation outlined above.

GIS Analysis of Seascapes

The IMCRA bioregions and seascape maps produced here represent different levels within a hierarchical structure. IMCRA bioregions are roughly equivalent in size to the Level 3 Geomorphological Units defined in the southeast bioregionalization, whereas seascapes provide information on the heterogeneity of benthic environments at a finer scale (*i.e.*, variability *within* the larger IMCRA units). Seascapes are thus comparable to level 4 biotopes in the classification of Butler *et al.* (2002), except that there is no biological information associated with them (only physical environmental data).

To assess whether the broad areas of interest and candidate MPAs are truly comprehensive, adequate and representative, information is needed at an appropriately fine scale. There are 8 BAOI[3] that overlap with shelf seascapes (Figure 6), but there are only 11 IMCRA bioregions in the southeast region (Figure 3). This means that each BAOI includes at most 3 IMCRA bioregions. In contrast, even though there are only 9 seascape types, these are distributed spatially over 1359 different polygons (occurrences) in the southeast region (Table 4). The 8 BAOI that overlap with the shelf contain an average of 46 seascape polygons and only one (Tasman) has less than 20 (Table 4).

Having defined nine seascapes in the southeast region (Figure 6), the question is: To what extent do the BAOI reflect the overall cumulative surface areas of seascapes occurring in the southeast region? To answer this question, a simple analysis using ARC/GIS has been carried out to quantify the spatial distribution of seascapes: a) within the whole of the southeast region; b) within each of the BAOI; and b) within each Province.

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[3] The Murray BAOI does not include any shelf areas where seascapes were mapped and the Seamounts and Tasman BAOI do not include any shelf areas. Hence only 8 BAOI coincide with the shelf seascapes.

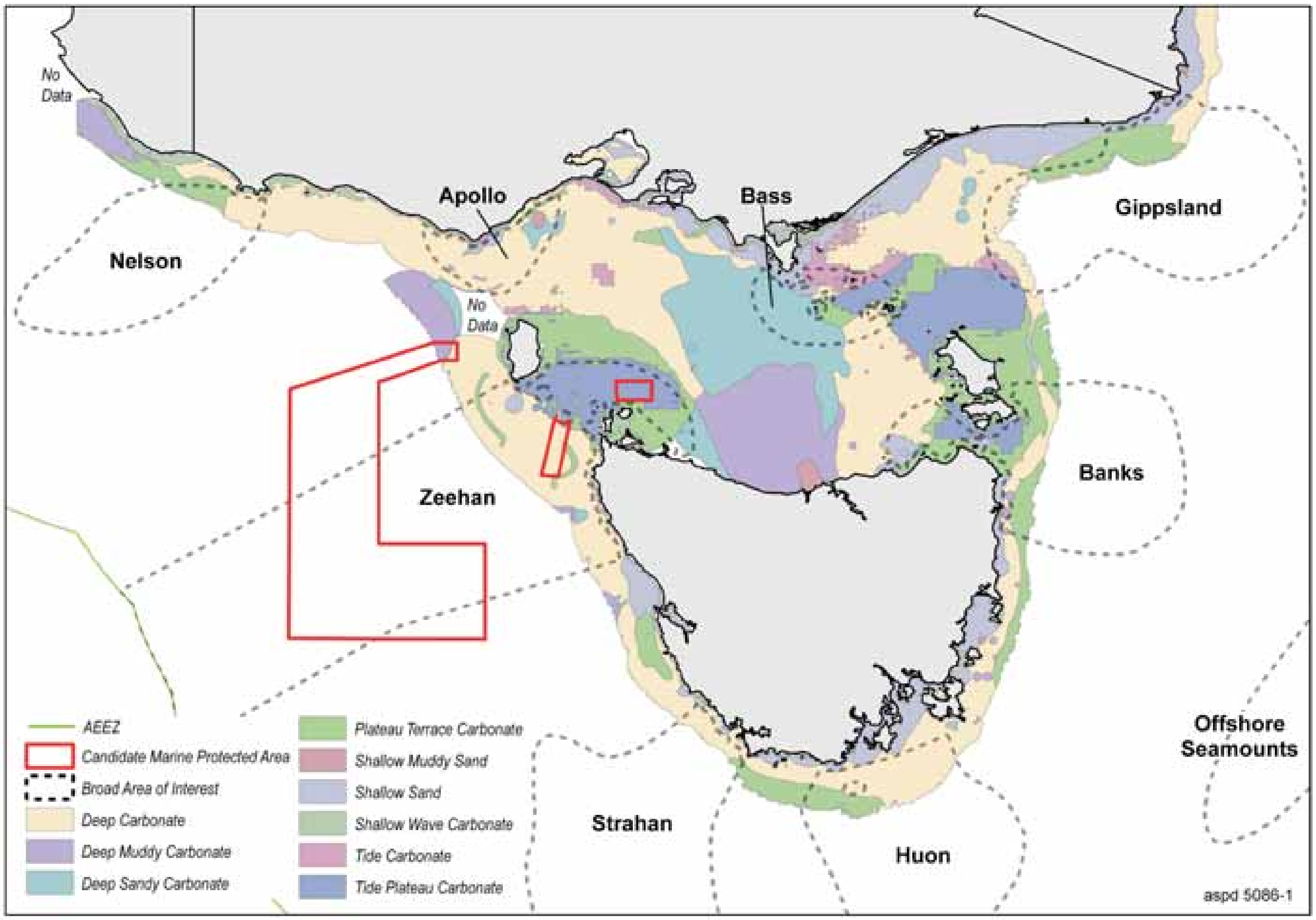

Figure 6. *Map of the seascapes of the southeast region showing the locations of BAOI and candidate MPAs.*

Table 4. List of occurrences of different seascapes and their cumulative surface areas within each BAOI of the southeast region. The names of BAOI are shown on Figure 2

	Apollo		Banks		Bass		Gippsland		Huon		Nelson		Tasman		Zeehan		SE Region
Seascape Name	No.	km^2	No.	km^2	No.	km^2	No.	km^2	No.	km^2	No.	km^2	No.	km^2	No.	km^2	km^2
1. Deep carbonate	16	4665	14	2353	18	876	22	2952	19	3746	20	922	1	875	7	8552	79,210
2. Deep muddy carb	1	2	7	71	0	0	6	37	0	0	0	0	0	0	5	119	14,424
3. Deep sandy carb	1	373	0	0	2	2820	17	81	8	49	0	0	2	1	13	431	16,788
4. Plateau terrace carb	1	95	11	3092	12	579	8	2542	2	1042	2	705	1	72	24	1582	26,390
5. Shallow muddy sand	1	137	3	4	0	0	0	0	0	0	0	0	0	0	0	0	725
6. Shallow sand	8	271	10	550	0	0	1	462	3	13	0	0	2	11	2	207	17,627
7. Shallow wave carb	not found in any BAOI																4085
8. Tide carbonate	7	36	1	31	15	722	16	245	0	0	0	0	0	0	9	36	4126
9. Tide plateau carb	0	0	7	1017	11	898	2	91	0	0	0	0	0	0	16	4416	14,982
TOTAL	35	5579	53	7118	59	5895	72	6410	32	4850	22	1627	6	959	88	16868	

The results show that the overall distribution pattern of cumulative surface areas of seascapes occurring in the southeast region is not well reflected in the cumulative surface areas of seascapes occurring in the combined BAOI (Figure 7). There are two major discrepancies and several minor ones. First, the Shallow-Wave-Carbonate seascape, which has a cumulative area of 4085 km^2 in the southeast region (Table 4), was not contained in any BAOI. This seascape is confined to locations close to the coastline, and since the BAOI tended not to include coastal areas, this seascape is not represented.

Second, only 303 km^2 of the Deep-Muddy-Carbonate seascape was included in BAOI, even though this seascape extends over an area of 14,424 km^2 in the southeast region (Table 4). The Deep-Muddy-Carbonate seascape occurs mostly in the central Bass Strait area, but it was not included because the Bass BAOI does not

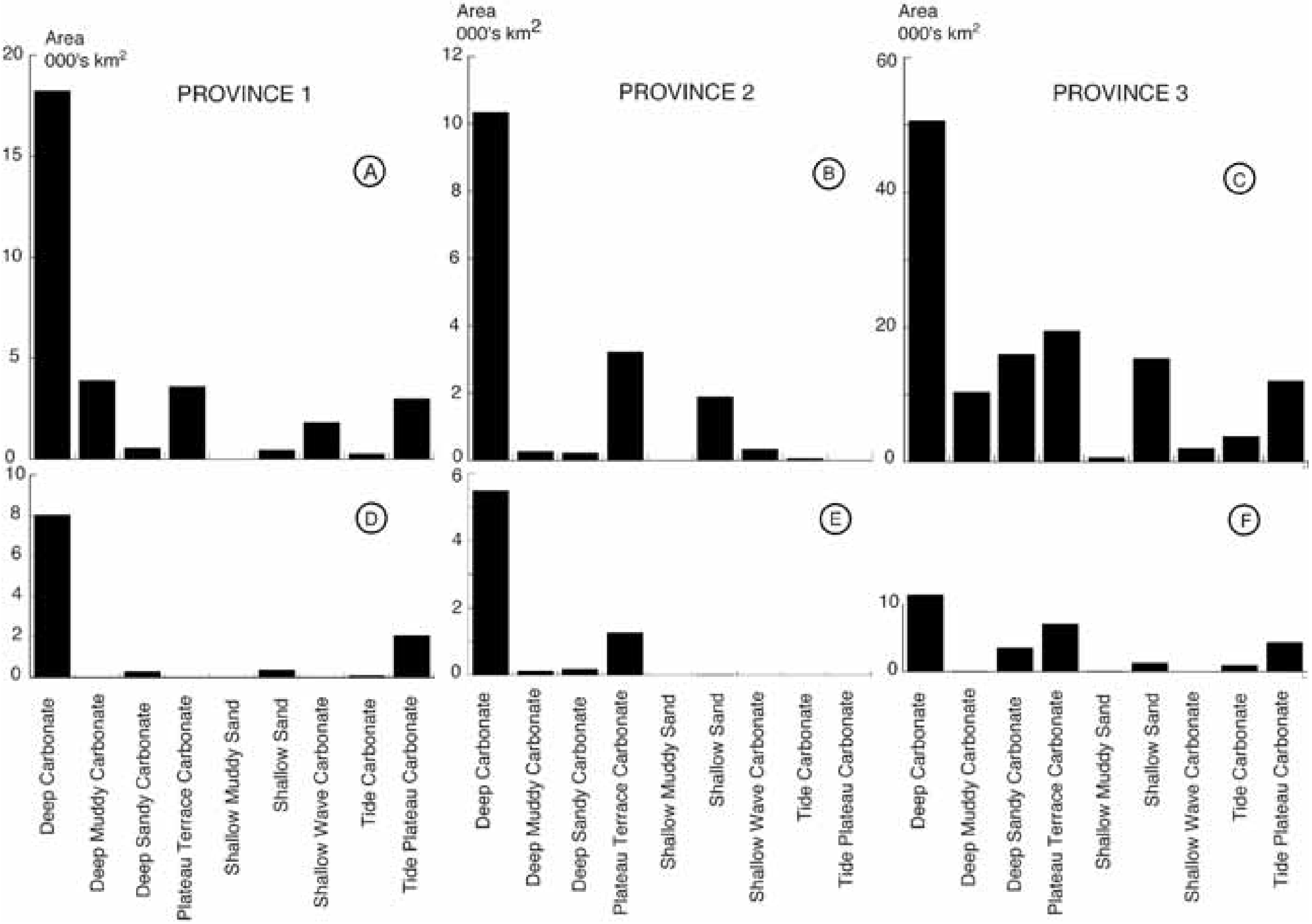

Figure 7. *Histograms showing the cumulative surface areas of seascapes in: (A) Province 1; (B) Province 2; (C) Province 3; and within the BAOI in (D) Province 1; (E) Province 2; and (F) Province 3.*

extend far enough southwards into the deepest parts of Bass Strait (Figure 6).

Listing the BAOI in terms of the diversity of the seascapes they contain illustrates that not all BAOI are equal: the Nelson BAOI has only 2 seascape types, Huon 4, Tasman 4, Bass 5, Apollo 7, Zeehan 7, Gippsland 7 and Banks 7.

The cumulative surface areas of seascapes occurring within each province illustrates differences in distribution patterns between provinces (Figure 6). In all provinces, the Deep-Carbonate seascape covers the greatest area but other than this similarity, the surface areas of seascapes is different in each province. In Province 1, the Deep-Muddy-Carbonate, Plateau-Terrace-Carbonate and Tide-Plateau-Carbonate seascapes each cover more than 3000 km^2. Province 2 is dominated by the Plateau-Terrace-Carbonate and Shallow-Sand seascapes, and unlike, provinces 1 and 3, there is very little Tide-Plateau-Carbonate facies. Province 3 has large areas of Tide-Plateau-Carbonate, which is associated with the areas of sand waves (Figures 2, 6 and 7). The Shallow-Muddy-Sand seascape is found only in Province 3.

Generally, the seascapes are poorly represented among the 8 (shelf) BAOI. Four out of eight seascapes that occur in Province 1 are not represented within the BAOI (Figure 7). The ratios are four out of seven for Province 2 and six out of nine for Province 3.

The "Adequacy" of the Broad Areas of Interest

The guiding CAR principles of comprehensiveness, adequacy and representativeness provide a basis on which to judge the BAOI described in this study. Once a specific criteria has been nominated (*i.e.*, geomorphic feature content, or seascape content), it is relatively simple to assess whether or not a BAOI is comprehensive or representative with respect to a given area using GIS analysis as outlined above; a given feature or seascape either occurs in a BAOI or it does not. The question of adequacy is more difficult to answer because it requires information as to what is the minimum fraction of a habitat that must be protected for an MPA to be sustainable. Although the figure of 20% is frequently cited (*e.g.*, Beck and Odaya, 2001), it should be noted that the size, shape and spacing between adjacent MPAs are also important determinants of adequacy. Using a simple percentage target fails to account for threats to biodiversity values, management effectiveness within reserves and complementary management of areas outside of reserves (Kriwoken, 1996). A variety of assessment tools (other than percentage targets) will be used by a Scientific Peer Review Panel to evaluate the network of MPAs against CAR principles.

Nevertheless, from the perspective of seascapes and geomorphic features, some comment as to the adequacy of the 11 BAOI can be made based on the relative proportion of surface areas. It seems reasonable that an MPA scheme that grossly under-represents a particular seascape or geomorphic feature type should be scrutinized more closely than one that has a "reasonable" representation (taken here to be >20%). There are some points of concern (Tables 5 and 6) in that amongst geomorphic features, no rocky reefs and only 1.9% of bank features in the southeast region are contained in the BAOI; all other features are represented in the BAOI by more that 20%. With respect to seascapes, none of the Shallow-Wave-Carbonate, only 2.1% of Deep-Muddy-Carbonate and only 11.73% of Shallow-Sand seascapes are contained in the BAOI (Table 6). All other seascapes are represented by more than 20% (Table 6).

The lack of rocky reef geomorphic features and Shallow-Wave-Carbonate seascapes in the BAOI is an expected outcome, because these are primarily coastal in nature (Edgar *et al.*, 1997) and it was never the intention of the BAOI to represent coastal biomes. The poor representation of bank features and the Deep-Muddy-Carbonate seascape can be explained because these are both located on the continental shelf, where only the IMCRA bioregions were used to guide in the selection of the BAOI. However, the analysis of the data suggests these habitats exist and are under-represented within the BAOI. The 11.73% of Shallow-Sand seascape contained in the BAOI will need further examination to ensure that this is an adequate amount.

Table 5. List of geomorphic features and the percentage of area included in BAOI and candidate MPAs as a fraction of provinces 1, 2 and 3, plus (in column 6) the percentage of area included in all BAOI as a fraction of the whole southeast region

Feature	BAOI/P1 Area%	MPA/P1 Area%	BAOI/P2 Area%	BAOI/P3 Area%	All BAOI Area%
Shelf	27.97	6.735	37.03	14.11	20.30
Slope	41.13	20.48	54.28	38.16	41.86
Abyss	27.10	7.10		18.65	23.44
Bank	28.19			0	1.93
Basin			100	15.48	33.59
Canyon	54.75	16.50	63.02	58.23	58.27
Valley	50.86	6.22	78.19	29.43	22.73
Escarpment	30.48	5.813	46.45	76.59	43.25
Knoll	55.30	34.67	25.49	18.05	35.17
Pinnacle			71.03		71.04
Plateau	44.88	1.669	58.78	20.70	39.40
Reef				0	0
Ridge			100		100
Saddle			41.61	11.53	27.70
Seamount				99.04	99.42
Sill				48.38	48.39
Terrace	25.81	0	38.59	54.97	36.20
Trench			100		100
Sand waves	39.53	19.83		42.60	41.68

Note that only two candidate MPAs have been selected for Province 1 (*i.e.*, there will eventually be other MPAs nominated for Province 1). A blank cell indicates that the respective geomorphic feature does not occur in that Province, whereas a zero value indicates that the respective geomorphic feature does occur in that province but not in any BAOI (or MPA)

The representation of geomorphic features by BAOI on a provincial basis has a higher occurrence of areas falling below 20% (Table 5). In particular, BAOI in Province 3 contain only 14% of the shelf, 15% of basin, 18% of knoll and 11.5 % of saddle features (Table 5). BAOI in the other two provinces are more adequate in terms of the percentage area of geomorphic features that they contain, which is over 25% for all feature types.

GIS Analysis of Candidate Marine Protected Areas

Two candidate MPAs for the Murray and Zeehan BAOI (Figure 2) have been identified based on the specifications for sampling these areas and through consultation with stakeholders (NOO, 2004). These areas may be subject to further refinement and will be evaluated as part of a system by a Scientific Peer Review Panel, once the remaining candidate MPAs have been identified.

The final step in the MPA design procedure is to apply the specification to each of the BAOI to ensure key bioregions and features are sampled. While the BAOI are a starting point, areas outside the BAOI may also be considered where they achieve the same biodiversity objective with less adverse socio-economic impacts. The role of science is to provide advice and feedback to the stakeholder groups and to environmental managers (in this case DEH) about the comprehensiveness, adequacy and representativeness of the candidate MPAs. A specific question that can be answered by GIS analysis is: To what extent does the MPA reflect the overall cumulative surface areas of habitats occurring in the BAOI?

Assessment of Candidate MPAs in relation to Geomorphic Features and Seascapes

A comparison of the cumulative surface areas of geomorphic features occurring in the Murray candidate MPAs with the BAOI (Figure 8) indicates that none of the 2735 km^2 of terrace features in the Murray BAOI (Table 3) is included in the MPA. The terrace in question is located on the Lacepede Shelf (James *et al.*, 1992;

Table 6. List of seascapes and the percentage of area included in BAOI

Seascape Name	% Area
Deep carbonate	34.46
Deep muddy carbonate	2.10
Deep sandy carbonate	22.39
Plateau terrace carbonate	48.52
Shallow muddy sand	20.00
Shallow sand	11.73
Shallow wave carboante	0.00
Tide carbonate	26.76
Tide plateau carbonate	49.67

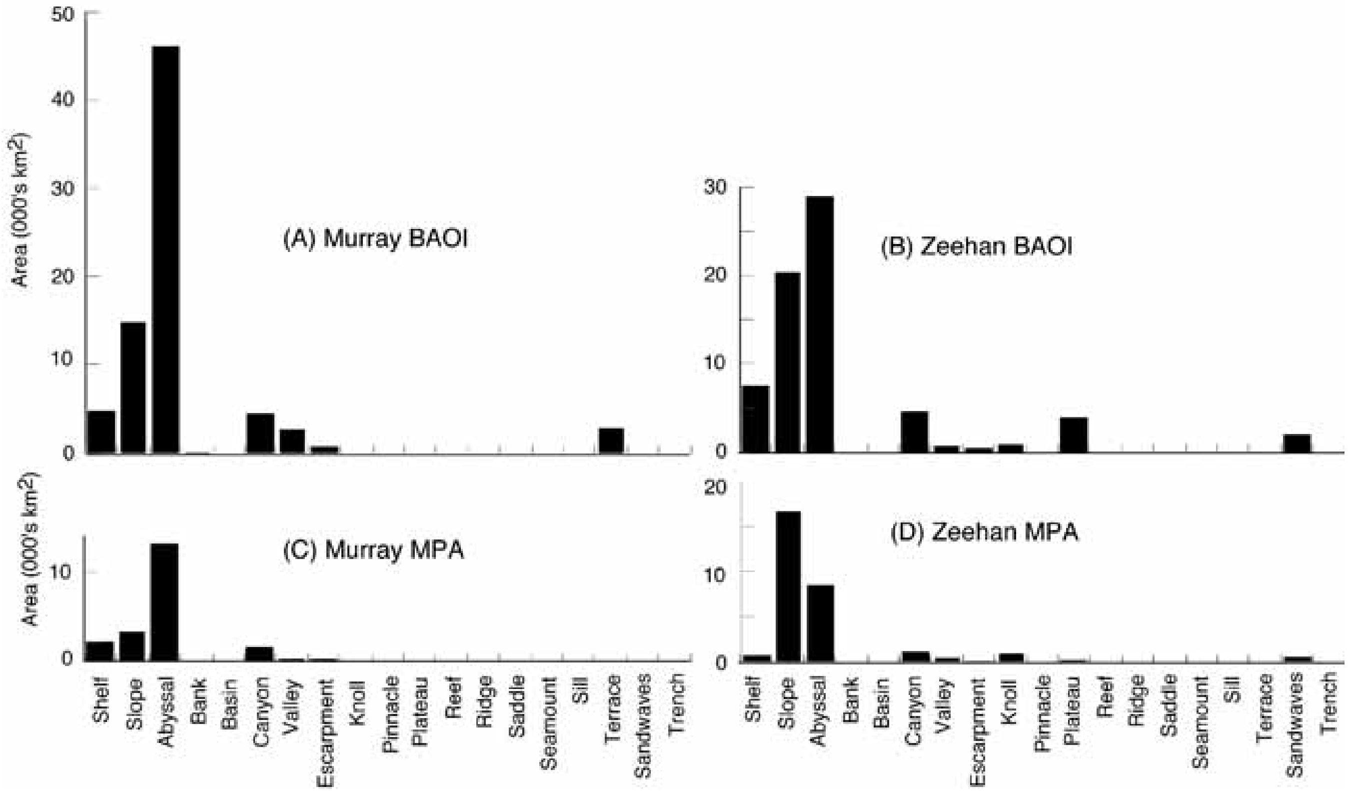

Figure 8. *Histograms showing the cumulative surface areas of geomorphic features in: (A) Murray BAOI; (B) Zeehan BAOI; (C) Murray candidate MPA; and (D) Zeehan candidate MPA.*

Figure 1). This terrace feature is wholly contained within the Coorong IMCRA bioregion (Figures 2 and 3). Although the other geomorphic features are represented by adequate proportions in the Murray candidate MPA compared with the Murray BAOI (*i.e.*, greater than 20%; Figure 8), the absence of terrace features in the candidate MPA is not consistent with the CAR principles.

For the Zeehan candidate MPA, although most geomorphic features are represented by adequate (>20%) proportions, the areas of shelf, plateau and escarpment are much reduced in the candidate MPA versus the BAOI. The shelf area is 7543 km^2 in the Zeehan BAOI compared with 607 km^2 in the candidate MPA; the area of Plateau is 3881 km^2 in the BAOI compared with 111 km^2 in the candidate MPA; and the area of escarpment is 428 km^2 in the BAOI compared with 30 km^2 in the candidate MPA. These represent percentages of only 8.05%, 2.86% and 7.01%, respectively. Therefore, the adequacy of these areas, as being sufficient to fully capture the biodiversity associated with the three habitat types, warrants further scrutiny.

A comparison of seascape areas contained in the Zeehan BAOI with those contained in the candidate MPA (Figure 9) illustrates a significant decrease in both the number of seascapes represented and their cumulative surface areas. Whereas the BAOI contained 7 seascapes, the candidate MPA contains only 3 (Deep-Carbonate, Deep-Muddy-Carbonate and Tide-Plateau-Carbonate). The Murray BAOI and candidate MPA fall outside of the shelf region where seascapes were mapped.

DISCUSSION

The results of the GIS analyses carried out in support of the south-east region MPA selection process has clearly demonstrated the value and utility of geophysical datasets. The geomorphic features map has proven to be particularly useful, given its strong association with habitats and 100% spatial coverage in the region. The seascapes map provides detailed information about physical processes and parameters on the shelf that supplements the much more broadscale IMCRA bioregions. Geographic Information Systems analysis using geomorphic features and seascapes defined here enables a quantitative and unambiguous assessment of the BAOI and candidate MPAs in relation to their CAR. Such an assessment would not be possible using the existing biological datasets on their own because of their patchy coverage and inconsistent collection methods across the region. But there are other reasons why the use of geophysical-based habitat maps may be preferable to using biological sampling techniques in the design of representative MPA candidates.

Knowledge of the ecological significance of different physical environments in the ocean is limited and we will probably never truly understand all of the bio-physio-chemical interactions that they support. Therefore, mapping biodiversity using biological data is just as much an approximation as the use of geophysical data.

Benthic habitats are not fixed in space or time, but rather they are constantly evolving. For example, all marine life found on con-

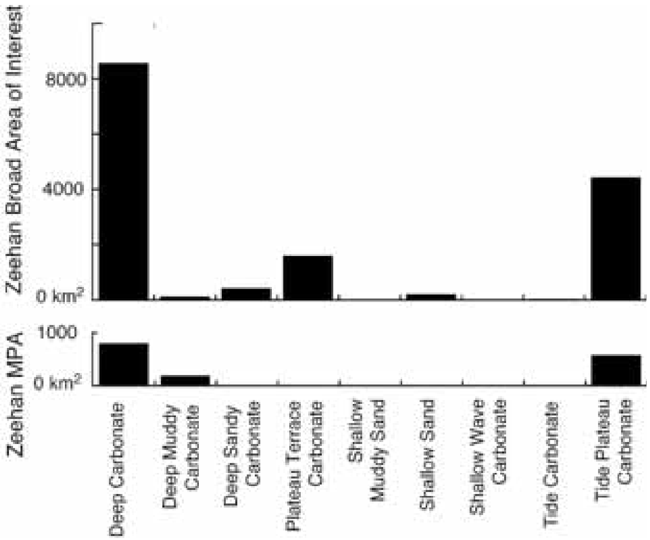

Figure 9. *Histograms showing the cumulative surface areas of seascapes in the Zeehan BAOI (upper) and Zeehan candidate MPA (lower).*

tinental shelves today arrived in the past 10,000 years or less, after the last ice age, and in the case of many communities the colonization process is ongoing. Natural processes like storms, tsunamis or turbidity flows may destroy all life in a given habitat that is later recolonized. Therefore, mapping biodiversity using only biological data might be biased against species that are late to colonize (or are colonizing) a specific habitat.

In the case of severely degraded areas, where human impacts have been significant, the original benthic communities may no longer exist; the assessment of such areas using only biological sampling will yield a biased result. A "snapshot" survey of the biota present in a given area at any moment in time will not capture the temporal variability and will invariably yield a biased result, in terms of the actual (or potential) benthic communities that an area may support.

The natural diversity of geological features has been termed *geodiversity* by some geologists, and the conservation of such diversity can be included as a criterion for the selection of reserves (Gray, 2004). This concept is not unfamiliar to conservationists, because many iconic terrestrial parks are defined on the basis of a prominent physical feature (*e.g.*, the Grand Canyon in the USA or Uluru in Australia) and similarly some marine protected areas are defined by the presence of a particular reef, island or rocky promontory. However, biological aspects of habitats are emphasized by most government agencies and nature conservation organizations and in many cases, there is little, if any, acknowledgment of the geological aspects of habitats (Gray, 2004).

From a precautionary perspective, therefore, it is more valid to use the available information to identify and protect all of the physical variability that occurs between different habitats in an area, that may or may not host a particular species or community, than it is to map actual biodiversity using species richness or assemblages. This has been called a *potential habitats* (Gary Greene, pers. comm., 2005) mapping approach and it is comparable to the geophysical approach advocated by Zacharius and Roff (2000, 2001) and Roff *et al.* (2003). In this approach, biological data are used to inform what physical parameters are most important for habitat characterization, or are the best surrogates for mapping habitats, rather than for attempting to directly map the diversity of species, communities or habitats.

Significance of "Special" Geomorphic Features: Seamounts and Canyons

Conceptually, the habitat mapping approach based on geomorphic features, as proposed by Greene *et al.* (1999) and used in this study, has the added advantage that there already exists detailed ecological models associated with many geomorphically-defined habitats. As noted by Roff *et al.* (2003), marine ecology textbooks are commonly organized into chapters having broad habitat types as titles (*e.g.*, estuaries, rocky shores, *etc.*). Of particular significance to deep-sea habitats are the studies of the ecology of seamounts and submarine canyons; these are "special" geomorphic features, known to support unique biological communities that are comparatively well documented in the literature.

Seamounts project above the abyssal plain and cause currents to be deflected around and over them. Some may rise to a depth where their tops are within the photic zone, but most commonly their summits are well below this depth. These conditions give rise to diverse communities of sessile organisms that take advantage of the rocky substrate and enhanced current flow which carries food to them. Seamounts are isolated habitats that have evolved slowly over millions of years and they support communities having a high degree of endemism (Rogers, 1994; Tyler, 1995). For example, 40–51% of the species found at the Nasca/Saa-y-Gomez chain off western South America (Parin *et al.*, 1997) and 29–34% of those from seamounts in the Coral and Tasman Seas were new to science (Richer de Forges *et al.*, 2000). These properties make seamounts of special ecological significance and explain why 99.42% of seamounts in the southeast region were included in BAOI (Table 5).

Ecologically, there may be no significant difference between seamounts and some other seabed features that have prominent vertical relief, such as knolls, ridges, pinnacles or escarpments. These features all have locally-steep slopes with rocky outcrop and the habitats might also be similar among them. The acceleration of currents over such features is a function of their height in relation to the depth of water, as well as to their orientation with respect to the current. The isolated nature of seamounts, which plays a role in the evolution of endemic species (*e.g.*, Rogers, 1994), is not represented by ridges or escarpments, but knolls and pinnacles do have this factor in common with seamounts.

Submarine canyons are incised into the continental slope by the repeated erosive effects of density currents and sediment slumping over thousands to millions of years. Canyons generally have steep sides, often eroded into lithified strata that provides hardground habitat for sessile organisms. The canyon head (*i.e.*, the shallow end of the canyon) may intrude landward across the shelf, often joining with major land drainage systems. Alternatively, canyons may be wholly confined to the continental slope. Oceanographically, canyons may affect local upwelling patterns and enhanced productivity. Pelagic fisheries and cetacean feeding grounds are commonly located at the heads of submarine canyons (Hooker *et al.*, 1999). For these reasons, 58.27% of canyons and 22.73% of shelf valleys occurring in the southeast region were included in the BAOI (Table 5).

Submarine canyons that extend across the continental shelf and approach the coast are known to intercept organic-matter-rich-sediments being transported along the inner shelf zone; examples are the Scripps and Monterey canyons in California (Shepard, 1963) and the "No Ground" channel incised into the Ganges-Brahmaputra Delta (Kuehl *et al.*, 1997). This process causes organic-rich material to be supplied to the head of Scripps Canyon, for example, and transported down-slope, where it provides nourishment to feed a diverse and abundant macrofauna (Vetter and Dayton, 1999). Canyons that do not have a significant landward extension presumably would not intercept littoral sediments and would not be expected to contain such a rich fauna. Applying the precautionary principle suggests, therefore, that shelf systems having landward extensions should be distinguished from those that do not. It follows that the representation of the two canyon types should ideally be recognized separately within the MPA design process, and that grouping all canyon types into a single category misses important ecological differences.

In the southeast region, there are 131 separate canyon systems (Table 3) but only 5 of these have landward extensions that intrude onto the shelf (Figure 2). Three of the 5 shelf-intruding canyons are located off western Tasmania within the Zeehan BAOI. The other two are Bass Canyon at the eastern side of Bass Strait, and the Murray Canyon located south of Kangaroo Island (Figure 2). The Murray Canyon (Hill *et al.*, 2005) is included in the Murray candidate MPA and the Zeehan candidate MPA includes the deep, foot of slope portions of two of the shelf-intruding canyons (Figure 2). Thus in the southeast region, this important distinction between submarine canyon types has been taken into account in the selection of BAOI and candidate MPAs.

Information Requirements for Ocean Management: Shelf vs. Slope-abyss

In many cases, knowledge of the geomorphology of the habitat is adequate at a broad scale (*e.g.*, Level 2), but it is not specific enough to provide a useful habitat classification at lower levels in the hierarchy (*e.g.*, Level 4). Combinations of biotic and other abiotic information are needed to subdivide broad areas that would otherwise be classified as a single habitat on a geomorphic basis. For example, continental shelves can appear as broad, geomorphically featureless plains (*e.g.*, Figure 2), but they actually contain many different habitats that can only be differentiated based on other physical variables such as wave energy, ocean bottom temperature, intertidal exposure, depth of sunlight penetration, tidal and ocean current strength, turbidity and mobilization of bed sediments to name a few (*e.g.*, Kostylev *et al.*, 2001; Roff *et al.*, 2003; Porter-Smith *et al.*, 2004). The seascape analysis carried out here is an attempt to account for these differences between habitat types and their spatial variability (see Figures 6 and 7).

Human uses and impacts in the marine environment are focused on the coastal and shelf biomes, and therefore the selection of MPAs here is the most complicated (and some might argue the most urgent). Resource extraction and other human uses are frequently confined to localized areas, where the loss of access may have extreme economic consequences. The result is that small areas (1 to 10 km) are sampled for inclusion in MPAs (*e.g.*, note the two small areas on the shelf included in the Zeehan candidate MPA; Figure 6) and therefore the data required for MPA design should be ideally compiled at an appropriately fine spatial scale. By comparison, the slope and abyssal environments are utilized by humans to a much lesser extent. The MPAs here can be much larger and the data required for their selection can be compiled at a spatial scale that is generally coarser than for the shelf and coastal biomes.

The conclusion from the above discussion is that, generally, managers will require relatively fine-scaled spatial data (Level 4 Biotopes or finer) for selecting MPAs within coastal and shelf biomes. On the slope and in abyssal environments, habitat information at the scale of Level 3 Geomorphological Units (*cf.* the Mega- or Meso-habitats of Greene *et al.*, 1999) will probably be sufficient for MPA selection. Thus different methods for spatial habitat mapping will need to be applied to the different biomes, to better inform the design of MPAs.

CONCLUSIONS

The creation of a new bioregionalization and the selection of a representative system of marine protected areas on the southeastern section of Australia's EEZ has relied upon geoscience information throughout the process. Biological and bathymetric information defined boundaries at the highest levels (Provinces and Biomes) of the bioregionalization but lower levels (Geomorphological Units) were defined on the basis of geomorphic interpretations of existing bathymetric data. A set of 11 BAOI was chosen for MPA consideration based on the new slope–abyss bioregionalization, together with the previous IMCRA bioregions on the shelf.

An assessment was carried out using geomorphic features and new information on shelf seascapes to test the extent to which the BAOI were comprehensive, adequate and representative. The BAOI do capture a representative subset of the geomorphic features that occur within the southeast region. However, the shelf seascapes contained within the BAOI capture only a portion of those occurring within the southeast region. The two MPAs, furthermore, do not contain all of the geomorphic feature types and seascapes found within the larger BAOI. Since the BAOI and MPAs were designed without the shelf geomorphic features or seascapes being included, this is not a surprising outcome. However, the analysis carried out here does indicate that a review of the remaining BAOI would be warranted prior to any decisions being made regarding candidate MPAs.

The adequacy of the BAOI was assessed based on the percentage area of geomorphic features contained in the BAOI compared with that within provinces and within the southeast region overall. The overall representation of geomorphic features by BAOI was generally >20% of total surface area, but on a provincial basis several feature types had less that 20% representation (Table 5). In particular, BAOI in Province 3 shelf, basin, knoll and saddle features are under-represented (Table 5). BAOI in the other two provinces contained over 25% for all feature types.

Two ecologically important geomorphic features, seamounts and submarine canyons, are well represented in the BAOI (99% and 58% of total surface area is included, respectively). Five submarine canyons in the southeast region extend onto the continental shelf and are of potentially high ecological significance compared with other canyons. All five of these canyons were included within BAOI and have been at least partially included in the two candidate MPAs.

This experience has demonstrated that spatial GIS analysis of abiotic data is a valuable tool throughout the process of MPA network design and stakeholder consultation. Mapping abiotic, potential habitats is particularly useful for identifying MPA candidates on the scale of continental margins. Whereas the ecology of many types of seafloor geomorphic feature has been described in the literature, the same is not true for “seascapes” derived from multivariate analysis. Further research is needed into integrating physical and biological datasets to gain a better understanding of surrogacy relationships and the amount of control that different physical variables exert over the occurrence of biota in different environments.

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REFERENCES

Airame, S., Dugan, J.E., Lafferty, K., Leslie, H., McArdle, D., and Warner, R.R., 2003, Applying ecological criteria to marine reserve design: a case study from the California Channel Islands: Ecological Applications, v. 13, p. S170-S184.

Allen, T.F.H., and Starr, T.B., 1982. Hierarchy - Perspectives for Ecological Complexity: University of Chicago Press, Chicago, 287 p.

ANZECC, 1999, Australian and New Zealand Environment and Conservation Council: Task Force on Marine Protected Areas. Strategic plan of action for the national representative system of marine protected areas: a guide for action by Australian Government: Environment Australia for ANZECC, Canberra, 80 p.

Ashley, G.M., 1990, Classification of large-scale subaqueous bedforms: a new look at an old problem: Journal of Sedimentary Petrology., v. 60, p. 160-172.

Banks, S.A., and Skilleter, G.A., 2002, Mapping intertidal habitats and an evaluation of their conservation status in Queensland, Australia: Ocean and Coastal Management, v. 45, no. 8, p. 485-509.

Beck, M.W., and Odaya, M., 2001, Ecoregional planning in marine environments: identifying priority sites for conservation in the northern Gulf of Mexico: Aquatic Conservation: Marine and Freshwater Ecosystems, v. 11, p. 235-242.

Bernardel, G., Alcock, M., Petkovic, P., Thomas, S., and Levinson, M., 2000, Seafloor mapping of the South-east Region and adjacent waters - AUSTREA-2 cruise report: south-east of Tasmania and southern Macquarie Ridge: AGSO, Record 2000/46, 75 p.

Black, K.P., and Oldman, J.W., 1999, Wave mechanisms responsible for grain sorting and non-uniform ripple distribution across two moderate-energy, sandy continental shelves: Marine Geology, v. 162, p. 121-132.

Blom, W.M., and Alsop, D.B., 1988, Carbonate mud sedimentation on a temperate shelf: Bass Basin, southeast Australia: Sedimentary Geology, v, 60, p. 269-280.

Butler, A., Harris, P.T., Lyne, V., Heap, A., Passlow, V.L., and Smith, R.N.P., 2002, An interim, draft bioregionalisation for the continental slope and deeper waters of the South-East Marine Region of Australia: Report to the National Oceans Office, Geoscience Australia and CSIRO, Hobart, 35 p.

Conolly, R.J., 1968, Submarine canyons of the continental margin, East Bass Strait (Australia): Marine Geology, v. 6, p. 449-461.

Davies, C.E., and Moss, D., 1999, The EUNIS classification: ITE project T0809219: European Environment Agency, 124 p.

de Fontaubert, A.C., Downes, D.R., and Agardy, T., 1996, Biodiversity in the Seas: Implementing the Convention on Biological Diversity in Marine and Coastal Habitats: World Conservation Union (IUCN), Gland, Switzerland, 82 p.

EA, 2003, Australia’s South-east Marine Region: A User’s Guide to Identifying Candidiate Areas for a Regional Representative System of Marine Protetced Areas: Report Prepared by Environment Australia, CSIRO Marine Research and the National Oceans Office. Environment Australia, Canberra, 86 p. http://www.deh.gov.au/coasts/mpa/

Edgar, G.J., Moverley, J., Barrett, N.S., Peters, D., and Reed, C., 1997, The conservation-related benefits of a systematic marine biological sampling programme: the Tasmanian reef bioregionalisation as a case study: Biological Conservation, v. 79, no. 2-3, p. 227-240.

Exon, N.F., Berry, R.F., Crawford, A.J., and Hill, P.J., 1997, Geological evolution of the East Tasman Plateau, a continental fragment southeast of Tasmania: Australian Journal of Earth Science, v. 44, p. 597-608.

Fandry, C.B., 1983, Model for the three-dimensional structure of wind-driven and tidal circulation in Bass Strait: Australia Journal of Marine and Freshwater Research, v. 34, p. 121-141.

Ferrier, S., Pressey, R.L., and Barrett, T.W., 2000, A new predictor of the irreplaceability of areas for achieving a conservation goal, its application to real-world planning, and a research agenda for further refinements: Biological Conservation, v. 93, p. 303-325.

Garcia-Charton, J.A., and Perez-Ruzafa, A., 1999, Ecological heterogeneity and the evaluation of the effects of marine reserves: Fisheries Research, v. 42, p. 1-20.

Gingele, F.X., De Deckker, P., and Hillenbrand, C.-D., 2004, Late Quaternary terrigenous sediments from the Murray Canyons area, offshore South Australia and their implications for sea level change, palaeoclimate and palaeodrainage of the Murray-Darling basin: Marine Geology, v. 212, no. 1-4, p. 183-197.

Gray, M., 2004, Geodiversity - Valuing and Conserving Abiotic Nature: John Wiley & Sons, Chichester, U.K., 434 p.

Greene, H.G., Yoklavich, M.M., Barry, J.P., Orange, D.L., Sullivan, D.E., and Cailliet, G.M., 1994, Geology and related benthic habitats of Monterey canyon, central California: EOS transactions of the American Geophysical Union Supplement, v. 75, no. 3, p. 203.

Greene, H.G., Yoklavich, M.M., Sullivan, D., and Cailliet, G.M., 1995, A geophysical approach to classifying marine benthic habitats: Monterey Bay as a model, *in* ‘Applications of Side-Scan Sonar and Laser-Line Systems in Fisheries Research’: Alaska Department Fish and Game Special Publication No. 9, p. 15-30.

Greene, H.G., Yoklavich, M.M., Starr, R.M., O’Connell, V.M., Wakefield, W.W., Sullivan, D.E., McRea, J.E., and Cailliet, G.M., 1999, A classification scheme for deep seafloor habitats. Ocenaologica Acta, v. 22, no. 6, p. 663-678.

Harris, G., 2003, Changing sedimentary environments in Bass Basin, a cool water carbonate sink, late Pleistocene to Holocene: Unpublished M.Sc thesis, University of Sydney, Sydney, 193 p.

Harris, P.T., 1994, Comparison of tropical, carbonate and temperate, siliciclastic tidally dominated sedimentary deposits: examples from the Australian continental shelf: Australian Journal of Earth Science, v. 41, p. 241-254.

Harris, P.T., and Coleman, R., 1998, Estimating global shelf sediment mobility due to swell waves: Marine Geology, v. 150, p. 171-177.

Harris, P.T., Heap, A.D., Passlow, V., Sbaffi, L., Fellows, M., Porter-Smith, R., Buchanan, C., and Daniell, J., 2005, Geomorphic features of the continental margin of Australia: Report to the National Oceans Office on the production of a consistent, high-quality bathymetric data grid and definition and description of geomorphic units for part of Australia’s marine jurisdiction: Geoscience Australia, Record 2003/30, Canberra, 147 p.

Heap, A.D., Harris, P.T., Last, P., Lyne, V., Hinde, A., and Woods, M., 2005, Draft Benthic Bioregionalisation of Australia’s Exclusive Economic Zone: Geoscience Australia Report to the National Oceans Office: Geoscience Australia, Canberra ACT, 140 p.

Hill, P.J., De Deckker, P., and Exon, N.F., 2005, Geomorphology and evolution of the gigantic Murray canyons on the Australian southern margin. Australian Journal of Earth Science, v. 52, p. 117-136.

Hill, P.J., and Moore, A.M.G., 2001, Geological framework of the South Tasman Rise and East Tasman Plateau: Geoscience Australia, Record 2001/40, 29 p.

Hill, P.J., Exon, N.F., and Royer, J.-Y., 1995, Swath-mapping the Australian continental margin: results from offshore Tasmania: Exploration Geophysics, v. 26, p. 403-411.

Hill, P.J., Exon, N.F., Keene, J.B., and Smith, S.M., 1998, The continental margin of east Tasmania and Gippsland; structure and development using new multibeam sonar data, *in* Rajagopalan, S., and Pettifer, G., eds., ASEG 13th International geophysical conference and exhibition; conference papers: Blackwell Scientific Publications, Melbourne, p. 410-419.

Hockey, P.A.R., and Branch, G.M., 1997, Criteria, objectives and methodology for evaluating marine protected areas in South Africa: South African Journal of Marine Science, v. 18, p. 369-383.

Holling, C.S., 1992. Cross-scale morphology, geometry and dynamics of ecosystems: Ecological Monographs, v. 62, p. 447-502.

Hooker, S.K., Whitehead, H., and Gowans, S., 1999, Marine protected area design and the spatial and temporal distribution of cetaceans in a submarine canyon: Conservation Biology, v. 13, no. 3, p. 592-602.

IHO, 2001, Standardization of Undersea Feature Names: Guidelines Proposal form Terminology: International Hydrographic Organisation and International Oceanographic Commission, Monaco, 40 p., http://www.iho.shom.fr/publicat/free/files/B6efEd3.pdf

James, N.P., Bone, Y., Von Der Borch, C., and Gostin, V.A., 1992, Modern carbonate and terrigenous clastic sediments on a cool water, high energy, mid-latitude shelf: Lacepede, southern Australia: Sedimentology, v. 39, p. 877-903.

Jenkins, C.J., and Keene, J.B., 1992, Submarine slope failures of the southeast Australian continental slope: a thinly sedimented margin: Deep Sea Research, v. 39, no. 2, p. 121-136.

Jennings, J.N., 1958, The submarine topography of Bass Strait: Proceedings of the Royal Society of Victoria, v. 71, p. 49-71.

Kostylev, V.E., Todd, B.J., Fader, G.B.J., Courtney, R.C., Cameron, G.D.M., and Pickrill, R.A., 2001, Benthic habitat mapping on the Scotian Shelf based on multibeam bathymetry, surficial geology and sea floor photographs: Marine Ecology Progress Series, v. 219, p. 121.

Kriwoken, L.K., 1996,. Australian biodiversity and marine protected areas: Ocean and Coastal Management, v. 33, no. 1, p. 113-132.

Kuehl, S.A., Levy, B.M., Moore, W.S., and Allison, M.A., 1997, Subaqueous delta of the Ganges-Brahmaputra river system: Marine Geology, v. 144, p. 81-96.

Langton, R.W., Auster, P.J., and Schneider, D.C., 1995, A spatial and temporal perspective on research and management of groundfish in the northwest Atlantic: Reviews in Fisheries Science, v. 3, p. 201-229.

Lavering, I.H., 1994, Marine environments of southeast Australia (Gippsland shelf and Bass Strait) and the impact of offshore petroleum exploration and production activity: Marine Georesources and Geotechnology, v. 12, p. 201-226.

Leslie, H., Ruckelshaus, M., Ball, I.R., Andelman, S., and Possingham, H., 2003, Using siting algorithms in the design of marine reserve networks: Ecological Applications, v. 13, p. S185-S198.

Lewis, A., Slegers, S., Lowe, D., Muller, L., Fernandes, L., and Day, J., 2003, Use of spatial analysis and GIS techniques to re-zone the Great Barrier Reef Marine Park: Coastal GIS Workshop, 7-8 July, 2003, University of Wollongong, Australia, p. 1-12.

Malikides, M., Harris, P.T., Jenkins, C.J., and Keene, J.B., 1988, Carbonate sandwaves in Bass Strait: Australian Journal of Earth Science, v. 35, p. 303-311.

NOO, 2002, Ecosystems – Nature's diversity: The South-east Regional Marine Plan Assessment Reports: National Oceans Office, Hobart, Tasmania 214 p., http://www.oceans.gov.au/assessments_phase.jsp

NOO, 2004, South-east Regional Marine Plan: Implementing Australia's Oceans Policy in the South-east Marine Region: National Oceans Office, Hobart, Tasmania, 111 p., http://www.oceans.gov.au/se_implementation_plan.jsp

Parin, N.V., Mironov, A.N., and Nesis, K.N., 1997, Biology of the Nazca and Sala y Gomez submarine ridges: an outpost of the Indo-West Pacific fauna in the eastern Pacific Ocean: composition and distribution of the fauna, its communities and history: Advances in Marine Biology, v. 32, p. 145-252.

Poiani, K.A., Richter, B.D., Anderson, M.G., and Richter, H.E., 2000, Biodiversity conservation at multiple scales: functional sites, landscapes, and networks: Bioscience, v. 50, p. 133-146.

Porter-Smith, R., Harris, P.T., Anderson, O., Coleman, R., and Greenslade, D., 2004, Classification of the Australian continental shelf based on predicted sediment threshold exceedance due to tidal currents and swell waves: Marine Geology, v. 211, p. 1-20.

Possingham, H.P., Ball, I.R., and Andelman, S., 2000, Mathematical methods for identifying representative reserve networks, *in* Ferson, S., and Burgman, M., eds., Quantitative Methods for Conservation Biology: Springer-Verlag, New York, p. 291-305.

Ray, G.C., 1999, Coastal-marine protected areas: agonies of choice: Aquatic Conservation: Marine and Freshwater Ecosystems, v. 9, no. 6, p. 607-614.

Richer de Forges, B., Koslow, J.A., and Poore, G.C.B., 2000, Diversity and endemsism of the benthic seamount macrofauna in the southwest Pacific: Nature, v. 405, p. 944-947.

Roberts, C., Andelman, S., Branch, G., Bustamante, R., Castilla, J.C., Dugan, J., Halpern, B., Lafferty, K., Leslie, H., Lubchenco, J., McArdle, D., Possingham, H., Ruckelshaus, M., and Warner, R., 2003a: Application of ecological criteria in selecting marine reserves and developing reserve networks: Ecological Applications, v. 13, no. 1, p. 215-228.

Roberts, C., Andelman, S., Branch, G., Bustamante, R., Castilla, J.C., Dugan, J., Halpern, B., Lafferty, K., Leslie, H., Lubchenco, J., McArdle, D., Possingham, H., Ruckelshaus, M., and Warner, R., 2003b, Ecological criteria for evaluating candidate sites for marine reserves: Ecological Applications, v. 13, no. 1, p. 199-214.

Roff, J.C., and Taylor, M.E., 2000, National frameworks for marine conservation - a hierarchical geophysical approach: Aquatic Conservation: Marine and Freshwater Ecosystems, v. 10, p. 209-223.

Roff, J.C., Taylor, M.E., and Laughren, J., 2003, Geophysical approaches to the classification, delineation and monitoring of marine habitats and their communities: Aquatic Conservation: Marine and Freshwater Ecosystems, v. 13, no. 1, p. 77-90.

Rogers, A.D., 1994, The biology of seamounts: Advances in Marine Biology, v. 30, p. 305-350.

Royer, J.-Y., and Rollet, N., 1997, Plate-tectonic setting of the Tasmanian region: Australian Journal of Earth Science, v. 44, no. 5, p. 543-560.

Shepard, F.P., 1963, Submarine Geology: Harper & Row, New York, 557 p.

Thackway, R., and Cresswell, I.D., 1998, Interim Marine and Coastal Regionalisation for Australia: An ecosystem-based classification for marine and coastal environments, Environment Australia, Canberra, 114 p.

Tyler, P.A., 1995, Conditions for the existence of life at the deep sea floor: an update: Oceanography and Marine Biology Annual Review, v. 33, p. 221-244.

Vanderklift, M.A., and Ward, T.J., 2000, Using biological survey data when selecting marine protected areas: an operational framework and associated risks: Pacific Conservation Biology, v. 6, no. 2, p. 152-161.

Vetter, E.W., and Dayton, P.K., 1999, Organic enrichment by macrophyte detritus, and abundance patters of megafaunal populations in submarine canyons: Marine Ecology Progress Series, v. 186, p. 137-148.

Von Der Borch, C., 1967, Southern Australian submarine canyons: Marine Geology, v. 6, p. 267-279.

Von Der Borch, C.C., Conolly, J.R., and Dietz, R.S., 1970, Sedimentation and structure of the continental margin in the vacinity of the Otway Basin, Southern Australia: Marine Geology, v. 8, p. 59-83.

Ward, T.J., Vanderklift, M.A., Nicholls, A.O., and Kenchington, R.A., 1999, Selecting marine reserves using habitats and species assemblages as surrogates: Ecological Applications, v. 9, p. 691-698.

Weissel, J.K., and Hayes, D.G., 1977, Evolution of the Tasman Sea reappraisal: Earth and Planetary Science Letters, v. 36, p. 77-84.

Zacharias, M.A., and Roff, J.C., 2000, A hierarchical ecological approach to conserving marine biodiversity: Conservation Biology, v. 14, no. 5, p. 1327-1334.

Zacharias, M.A., and Roff, J.C., 2001, Zacharias and Roff vs. Salomon et al.: who adds more value to marine conservation efforts?: Conservation Biology, v. 15, no. 5, p. 1456-1458.