MARINE ZONE MANAGEMENT AND THE EPBC ACT—HOW ENVIRONMENTAL MARINE GEOLOGICAL INFORMATION PROVIDES CERTAINTY FOR PETROLEUM EXPLORATION

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ABSTRACT

To protect the diversity of marine life in Australia's Exclusive Economic Zone (EEZ), the Federal Parliament has passed the Environmental Protection and Biodiversity Conservation (EPBC) Act 1999. The Act is being implemented through the design of a national representative system of marine protected areas (MPAs) that will place under protection a representative portion of Australia's EEZ by 2012. There have already been 13 MPAs nominated for the southeast region in 2006.

Limited biological data in Australia's EEZ has resulted in biophysical information compiled by Geoscience Australia being used as a proxy for seabed biodiversity in support of marine conservation planning. Information we use to characterise the seabed includes bathymetry, geomorphology, acoustic properties, sediment properties, and slope and sediment mobilisation due to waves and tides. To better characterise habitats on the Australian continental shelf, Geoscience Australia is creating seascape maps (similar to geological facies maps) that integrate these multiple layers of spatial data, and which are useful for the prediction of the distribution of biodiversity in Australia's EEZ. This information provides 100% spatial coverage based on objective, multivariate statistical methods and offers certainty for managers and stakeholders including the oil and gas industry, who are involved with designing Australia's national MPA system. Certainty for industries operating in the EEZ is enhanced by a reproducible, science-based approach for identifying conservation priorities and the classification of sea floor types within multiple use areas.

KEYWORDS

Seabed geomorpgology, multivariate analysis, seascapes, biodiversity, marine protected areas.

INTRODUCTION

Legislative framework for marine biodiversity conservation

In 1994, Australia ratified the United Nations Convention on Biological Diversity (CBD), and is therefore bound by its 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 marine protected areas (NRSMPA) as a part of implementing the Government's Oceans Policy (ANZECC, 1999). In particular, the EPBC Act promotes the conservation of biodiversity by providing protection for threatened species and ecological communities, migratory, marine and other protected species. The Act provides for the identification of key threatening processes, the protection of critical habitat, the preparation of management plans and issuing of conservation orders, and the regulation of wildlife import/export. The conservation of biodiversity in Australia's EEZ involves the development of regional marine plans followed by the design of MPAs in Commonwealth waters by the Department of Environment and Heritage (DEH), complementing those MPAs declared by State and Territory Governments within three nautical miles of the coastline. When completed, the Commonwealth and state MPA networks will together comprise the NRSMPA.

The regional marine planning process in Commonwealth waters is based on an ecosystems approach, which requires planning and management to be based on ecosystem boundaries rather than on political or jurisdictional boundaries. A critical step in the process was the recent development of a national bioregionalisation, which divides Australia's marine environment into unique bioregions, each characterised by endemic species and distinguishing ecological attributes (DEH, 2005). The national bioregionalisation complements the Interim Marine and Coastal Regionalisation of Australia (IMCRA V.3.3; Thackway and Cresswell, 1998) management framework by extending the system of bioregions beyond the continental shelf to cover all of Australia's EEZ.

To fully protect the biodiversity in a bioregion, MPAs must therefore be arranged in a network to maximise 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.

A key criterion for the design of the NRSMPA is that the MPA network must be comprehensive, adequate and representative (the CAR principle; ANZECC, 1999). In applying the CAR principle to the design of a national system of MPAs, comprehensive means that MPAs must contain the full range of ecosystems present on the seabed, recognised 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 NRSMPA is a co-operative venture between all State Governments and the Commonwealth Government. A substantial step forward for the NRSMPA was the nomination of a network of 13 MPAs for the southeast region in 2006. There are already over 200 MPAs in Australia and the goal is to establish a system of MPAs that will place under protection a comprehensive, adequate and representative portion of Australia's EEZ by 2012.

A key point of interest for users of the marine environment is that MPAs in Australia have a range of categories, from strictly no-take Sanctuary Zones to Multiple Use and Special Use Zones (Table 1). In the latter, Multiple Use and Special Use Zone categories, only some activities are restricted, related to bottom-trawl fishing operations. Activities such as oil and gas exploration and development are allowed within Multiple Use and Special Use Zones (Table 1). The composition of the NRSMPA will include multiple categories of MPAs such that the overall restrictions placed on oil and gas exploration and development will be minimised. For example, in the southeast region, only four of the 13 nominated MPAs contain areas that are zoned as Sanctuary Zones, where oil and gas exploration and development are excluded, and only one Sanctuary Zone is on the shelf (an area off southern Tasmania). The majority of the area within the nominated southeast MPAs is zoned as Multiple Use and Special Use Zones, which should have minimal impact upon oil and gas exploration or development.

Table 1. Categories of marine protected areas used by the Department of Environment and Heritage in the southeast planning region <http://www.deh.gov.au/coasts/mpa/southeast/index.html>. IUCN categories are from the World Conservation Union <http://www.iucn.org>.

DEH Cat.	Name	IUCN Cat.	Description
(i)	Sanctuary Zone	Ia	Scientific reference site—no extractive use.
(ii)	Benthic Sanctuary	Ia	Benthic environment from 500 metres below sea level to 100 below the seafloor—no extractive use. Pelagic fishing allowed in the area from the sea surface to 500 metres below sea level.
(iii)	Recreational Use Zone	II	Recreational activities allowed including recreational and charter fishing. No commercial extractive activities allowed.
(iv)	Multiple Use Zone	VI	Closed to demersal trawl, Danish seine, mesh netting, and scallop dredge methods of fishing. Other forms of commercial fishing allowed subject to conditions outlined in the management plan. Oil and gas exploration, development and associated activities and geosequestration of carbon are allowed.
(v)	Special Purpose Zone	VI	Closed to commercial fishing: allowable activities include recreational fishing, charter fishing, oil and gas exploration, development and associated activities and geosequestration of carbon.

Role of geoscience in the NRSMPA

To design a national representative system of MPAs to protect Australia's marine biodiversity, it would seem that a logical first step would be to produce a map showing the distribution of biodiversity in Australia's marine environment. The dilemma is that such a map does not exist and it is not possible at present to predict the spatial distribution of all marine life using the sparse biological information available. An alternative approach that is gaining acceptance is to use biophysical (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); in studies such as these, applications of spatially more complete, biophysical information have been employed to systematically map different habitats to support MPA design. This approach has already been adopted in Australia; due to the lack of sufficient biological data, the national marine bioregionalisation of Australia was designed primarily using physical surrogates, chiefly seabed geomorphology (DEH, 2005).

The combination of biophysical variables that define different habitats can be mapped if we know what variables to measure and over what spatial-temporal scales to map and measure them. The point is that communities will always exploit the availability of any given habitat, and although the species comprising that community will vary depending on biological factors (e.g. predator-prey relationships), the overall community types (as opposed to communities of specific species) are recognisable. Different species occupy the same ecological niche in different occurrences of the same habitat. Day and Roff (2000) conclude:

> 'It is possible to identify subtidal communities dominated by macrophytic algae in the Atlantic, Pacific and Arctic Oceans. In each geographical region, the species present and the species assemblages are different, but

the same types of communities with different species playing equivalent ecological roles are recognisable, irrespective of the specific geographical location.'

The scientific challenge in the application of biophysical data to predict biodiversity can be broken down into a series of questions.

1. What biophysical variables are the most useful surrogates for biodiversity?
2. How can multiple spatial data layers be integrated to make a single map of marine habitats?
3. How is this integrated map useful for designing MPAs?

In this paper, we present an overview of research undertaken at Geoscience Australia that addresses these questions. First we present some recent results related to the question of surrogacy from the Gulf of Carpentaria. Next a new seascape classification (Roff et al, 2003) of the southwest planning region is proposed that accounts for differences in benthic environments based on an integration of biophysical variables that have been measured or modelled. We then demonstrate how the spatial heterogeneity of seascapes suggests locations where conservation targets can be met while minimising the total area of MPAs required to achieve compliance with the CAR principle. Lastly, we discuss how the provision of reliable estimates on the distribution of biodiversity reduces risk for the petroleum industry.

WHAT BIOPHYSICAL VARIABLES ARE THE MOST USEFUL SURROGATES FOR BIODIVERSITY? A CASE STUDY FROM THE GULF OF CARPENTARIA

In May 2003, Geoscience Australia conducted a research voyage on the RV *Southern Surveyor* to the southeastern Gulf of Carpentaria.Combined physical and biological datasets were collected on this voyage, allowing detailed analysis of the relationships between the distribution of physical habitats and seabed communities. Sampling was targetted within distinct habitat types including coral reefs, relict bryozoan-mollusc (bryomol) reefs, submarine valleys, and shallow shelf and basin environments (Fig. 1).

At each site a range of samples was collected, including sediment grab samples for grain size and carbonate analysis, benthic biota from benthic sled samples and underwater video footage. Detailed bathymetry maps (e.g. Fig. 1) were also derived using a multibeam swath mapper, and water depth was obtained from the ship's echosounder. Model results were used to calculate values for sediment stability, including a measure of seabed exposure, which combines the frequency and magnitude of stress applied to the seabed (Hemer, 2006). The term exposure is used by ecologists with reference to the degree of wave and current energy to which a particular location is exposed (e.g. an exposed coastline is open to attack from ocean swell waves, versus a sheltered embayment that has less exposed shores). The benthic sled samples collected a total of 569 species during the voyage. These were tested against the range of physical variables to determine whether statistically meaningful relationships could be established which may allow better prediction of species distributions in this region (see Post et al, 2006).

Biophysical relationships in the Gulf of Carpentaria

Statistical analysis using the PRIMER-E software revealed that the distribution of the seabed biota in this region was most strongly correlated to a combination of physical variables: the sediment composition (mud and gravel content), seabed exposure, seabed morphology and water depth (Fig. 2; see Post et al, 2006 for further details). The plots in Figure 2 indicate that the distribution of each physical variable in relation to the benthic biota is distinct for each variable. No single variable is able to adequately represent the species distributions; however, by combining these variables, the benthic habitats in this region can be effectively characterised (Fig. 3; Table 2).

In a conceptual transect of the southeastern Gulf (Fig. 3), the inner shelf zone is characterised by shallow depths (15–30 m) with moderate seabed exposure and sandy, low-carbonate sediments (Fig. 3). The fauna in this inner shelf zone are dominated by mobile organisms (predominantly prawns and sea urchins) with relatively low diversity. The basin environment is also dominated by mobile fauna (predominantly polychaetes) with medium diversity, and due to the deeper water depths (51–65 m) has low to moderate seabed exposure with muddy sand sediments. The bryomol reef and valley environments lie at depths intermediate between the shelf and basin zones (25–39 m and 37–42 m respectively), and have a gravelly sand substrate with very high seabed exposure (maximum values). Seabed exposure is particularly high across the valley area as this system acts as a conduit for bottom currents. The fauna associated with these two zones are composed of equal abundances of attaching and mobile faunas, with the bryomol reef dominated by brittlestars, hydrozoans and bryozoans, and the valley faunas by bryozoans, crinoids and brittlestars.

The modern coral reef environment is divided into three distinct zones, each with a moderate to high seabed exposure (Fig. 3). The talus slope is sandy with high carbonate content, and the presence of ripples indicates strong bottom currents. These characteristics are associated with low faunal diversity dominated by solitary anemones. The reef margin, by contrast, is composed of muddy sand sediments, reflecting the relatively low energy of this area. These features have produced high faunal diversity with crinoids and sponges dominating the community. The reef platform is distinct from these other two zones in the higher energy and harder substrates, with relatively high gravel content. Faunas on the reef platform show high diversity, with an abundance of ascidians and octocorals.

HOW ARE SPECIES RELATED TO PHYSICAL FACTORS?

There are various mechanisms by which the physical factors identified in this study may be associated with

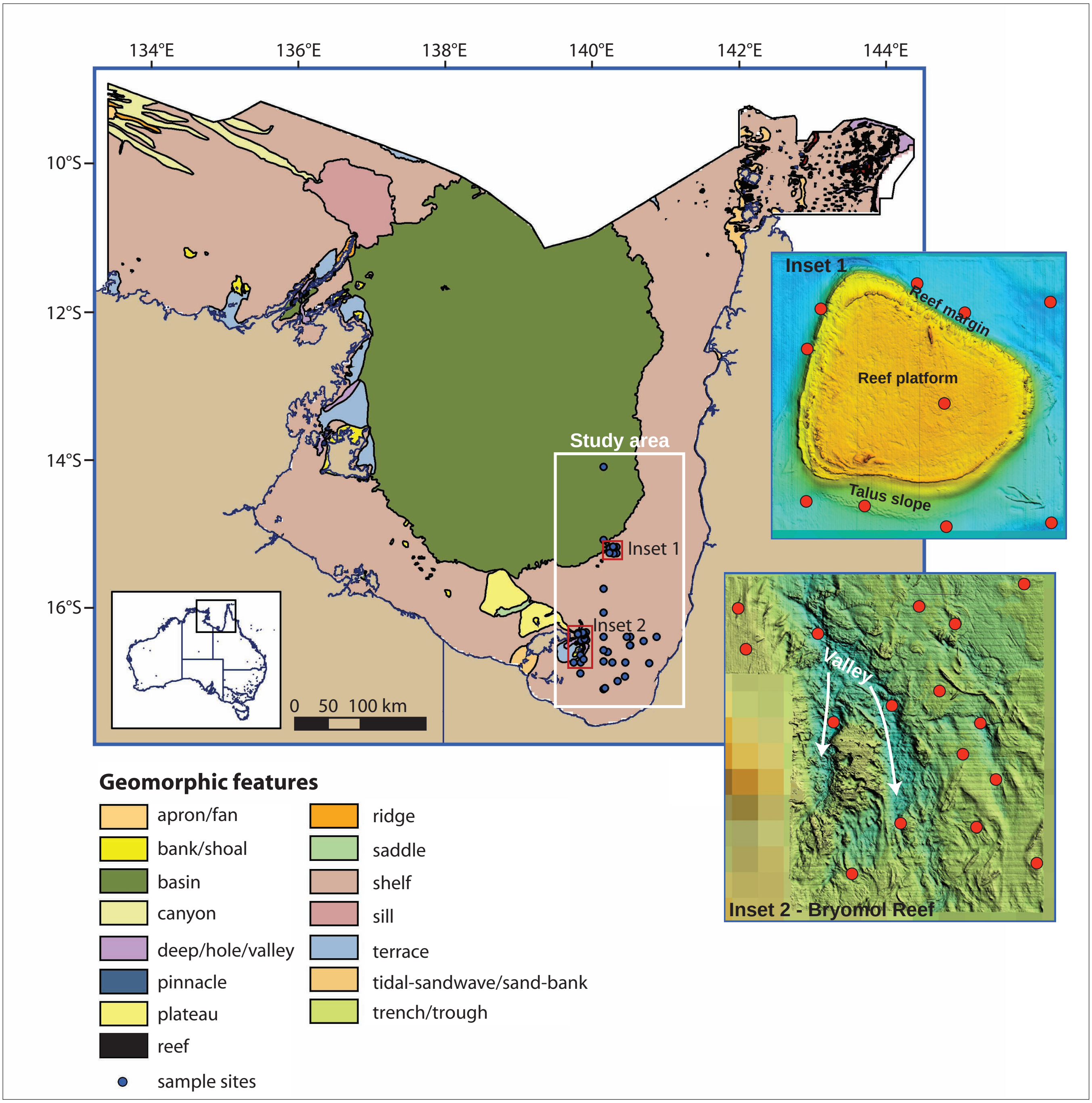


Figure 1. Geomorphic features in the Gulf of Carpentaria region (from Harris et al, 2005), showing the location of the study area in the southeastern gulf. The insets show sample sites superimposed over multibeam bathymetry images which reveal details of the geomorphic features.

the types of organisms present. The different substrates sampled in this study indicate that each substrate provides a habitat for different types of organisms. Areas with sandy substrates, such as the shelf and basin areas, are dominated by mobile deposit feeders and infauna, while gravelly areas, such as on the reef platform and bryomol reef areas, contain high proportions of suspension feeders. Mobile organisms and infauna require soft substrates in which they can burrow and forage for food (Jumars, 1993), explaining their high abundance on sandy substrates. Suspension feeders require strong anchor points to attach to, so the gravelly and hard substrates of the reef environments provide these organisms with a competitive advantage over mobile feeders and infauna.

The seabed exposure describes the stability of the seabed environment in terms of the degree to which current and wave energy is able to disturb and mobilise bottom sediments, which in turn has implications for the nature of the community dynamics. In areas with low frequency and low magnitude sediment disturbance, competition between organisms is enhanced, which tends to suppress diversity; in this way the exposure index and amount of seabed disturbance is related to the character of the benthic communities (Connell, 1978). The relatively low overall species diversity in the shelf and basin areas in this study is most likely associated with the lower seabed disturbance in these environments (where disturbance is low to moderate). In areas of very high frequency and magnitude of disturbance, diversity is also suppressed since frequent disturbance reduces reproductive success and the ability of the community to mature or be recolonised prior to the next disturbance event (Connell, 1978). An area of frequent and intense disturbance in this study occurs on the talus slope adjacent to the main patch reef, which is characterised by active sedimentation. The species diversity on this slope is substantially lower than is found at the surrounding reef sites where sediment input is much lower. This comparison suggests that areas of lower sediment input and lower disturbance (such as on the reefs) support a larger variety of faunas compared to disturbed areas (such as the talus slope) where species diversity is suppressed. The degree of disturbance also reflects current flows, and these can be essential in supplying nutrients and other food sources, which is particularly important for suspension feeders.

Water depth primarily reflects changes in light intensity, temperature, oxygen, salinity and energy (Murray, 1991). These factors have a significant impact on the species composition, and in this study depth is the main factor associated with distinct communities that occur between the shelf and basin environments.

Knowing the shape of the sea floor, or the geomorphology, provides an additional layer of information regarding the processes and features of the environment, including features such as the slope, the sea floor hardness/softness and processes such as current flow. By mapping the geomorphic features we are able to extrapolate our knowledge of the environment away from areas where we have sampled. For example, we can assume that all reef environments will have hard substrates which support suspension feeders, deep valleys will typically provide conduits for current flow which may provide important food sources to the benthic fauna, and basin environments will generally have relatively low energy and muddier sediments which provide a habitat for burrowing organisms and deposit feeders.

APPLYING PHYSICAL RELATIONSHIPS FOR MARINE PLANNING

The biophysical relationships established in this study of the southeastern Gulf of Carpentaria can be applied to understand and map the distribution and types of physical habitats in this region, and therefore to predict the diversity and distribution of marine benthic organisms across the broader region of the Gulf. Based on our knowledge of the relationship between the physical parameters and the benthic communities we can have confidence that the physical habitats, mapped based on biophysical datasets, describe environments that support distinct biological communities.

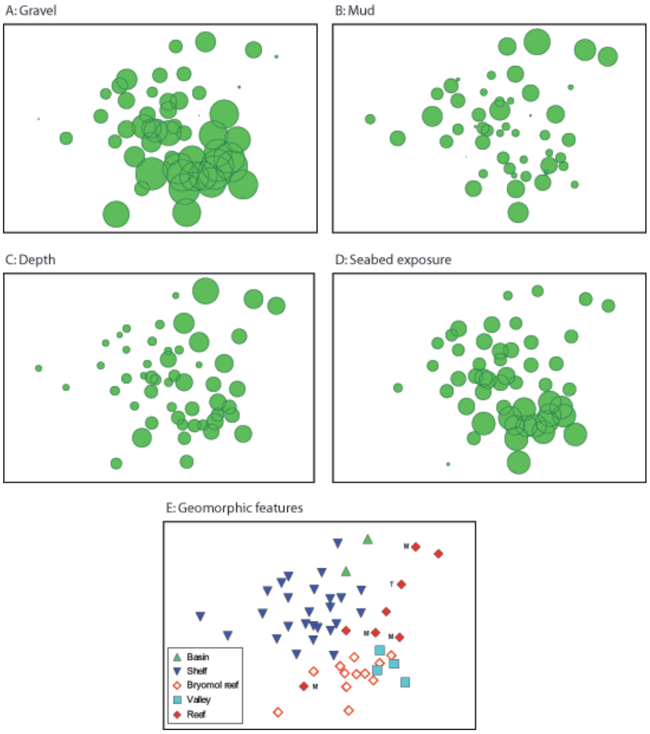


Figure 2. Non-metric, multi-dimensional scale (MDS) plots (stress value 0.23) with the distribution of sites based on the Bray-Curtis similarity matrix of the taxa. There are no units on the axes because this is a 2D representation of multi-dimensional data, hence the associations between points are shown by relative distance between points and the clustering of groups of points. The stress value depicts how well the multi-dimensional data plot in 2D space, with better representations indicated by lower stress values. A) percent gravel; B) percent mud; C) water depth; D) the seabed exposure; and E) geomorphic features. For the bubbles in Figures A-D, larger bubbles reflect higher values for the variable shown, e.g. for water depth, there is a trend of increasing depth towards the right-hand side of the faunal distribution. The distribution of the geomorphic features is also distinct across the species distributions. For the reef areas, the talus slope site (T) and reef margin sites (M) are also shown.

HOW CAN MULTIPLE SPATIAL DATA LAYERS BE INTEGRATED TO MAKE A SINGLE MAP OF MARINE HABITATS? A CASE STUDY FROM SOUTHWESTERN AUSTRALIA

Identification of useful data sets

The design of an MPA network to conserve biodiversity will be optimal if it is based on an understanding of habitat and ecosystem distributions and functions. Map-

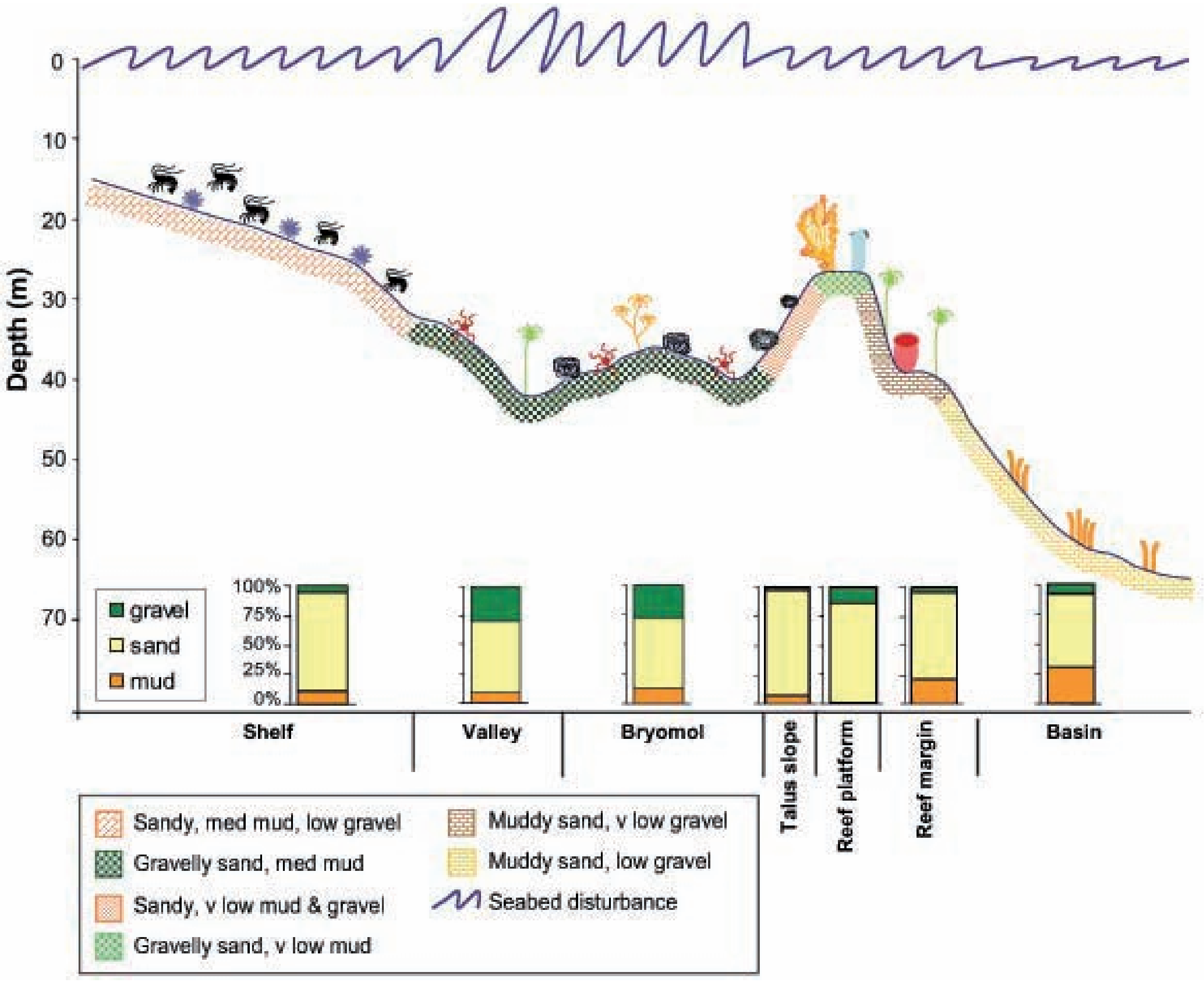


Figure 3. Relationship between physical properties and benthic biota in the southern Gulf of Carpentaria. For a full description of the key benthic biota (and definition of symbols) refer to Table 2.

ping the physical parameters that define habitats and environmental disturbance regimes (Pickett and White, 1985) is a useful starting place for managers to identify and characterise bioregions. The concept of disturbance regimes derives from landscape ecology, where (for example) the frequency and intensity of forest fires determines what kind of forest cover occurs in a particular area. Some examples of processes in the ocean that might be compared with forest fire regimes on land include: mass wasting events and slumping on the continental slope, storm events on the shelf where waves and currents are able to mobilise bottom sediments and dislodge benthic plants and animals, and flood events where freshwater plumes extend seawards from the coast causing drastic changes in ocean salinity. In each case, the disturbance event disturbs (or kills) benthic animals, which creates opportunities for new colonisers.

In the ocean, the heterogeneity of sediment types, gradients in productivity (food supply) and hydrodynamic regimes

Table 2. Characteristics of different benthic habitats and associated faunas in the southern Gulf of Carpentaria.

Morphology	Average depth (m)	Seabed exposure	Grain size	Dominant Fauna
Shelf	14–35	Mod	Sandy	Prawns Sea Urchins
Valley	37–43	Max	Sandy gravel	Bryozoans Brittlestars Crinoids
Bryomol reef	27–36	Max	Sandy gravel	Brittlestars Hydrozoans Bryozoans
Talus slope	38–43	Mod-High	Sandy	Anemones
Reef platform	27	Mod-High	Sandy gravel	Ascidians Octocorals
Reef margin	48–49	Mod-High	Sandy mud	Crinoids Sponges
Basin	51–65	Low-Mod	Sandy mud	Polychaetes

appear to correlate with and exert control over the diversity of deepsea habitats and species. The traditional global approach to zoogeography recognises, for example, that the dispersal of a species in ocean basins over geological time spans is influenced by the age of the ocean basin, deep ocean currents (as both barriers and means of dispersal), geomorphology and by water mass structure (Gage, 2004). Our study of the Gulf of Carpentaria demonstrates that depth, disturbance and grain size are useful predictors of diversity in benthic communities. Therefore, mapping of one or more of these biophysical attributes can be expected to be useful in helping to characterise different bioregions and to guide the design of MPA networks.

Deciding on which biophysical data sets to use for habitat mapping is a trade-off between the relevance of a variable to mapping habitats and its spatial coverage. Variables may be highly relevant but have poor spatial coverage (e.g. maps of species richness) or be of little relevance but have excellent spatial coverage (e.g. palaeomagnetic signature of ocean crust). In our analysis of the southwest planning region we selected the following variables to characterise benthic habitats: depth, seabed slope, geomorphic classification, seabed sediment properties, bottom water temperature and surface primary productivity.

Bathymetry and geomorphology

Geoscience Australia has collated existing digital bathymetric information and constructed a national bathymetric model having a grid size of 250 m (Webster and Petkovic, 2005). Based on this new bathymetric model, and with reference to published studies, Harris et al (2005) derived a map of sea floor geomorphic features covering the Australian EEZ. This information was recently reviewed and updated by Richardson et al (2005) for the southwest planning area. It is beyond the scope of this paper to review all of this information, but Figure 4 summarises the complex geomorphic composition of the southwest planning area.

In addition to geomorphology (Fig. 4) and depth (Fig. 5A), the slope of the seabed was determined from the 250 m bathymetric grid (Fig. 5B). Seabed slope was determined using ER Mappers slope filter function, with a filter span of 3 x 3 grid cells (750 x 750 m).

SEABED SEDIMENTS

Seabed sediment texture and composition are key variables that influence the composition and abundance of benthic marine biota (e.g. Snelgrove and Butman,

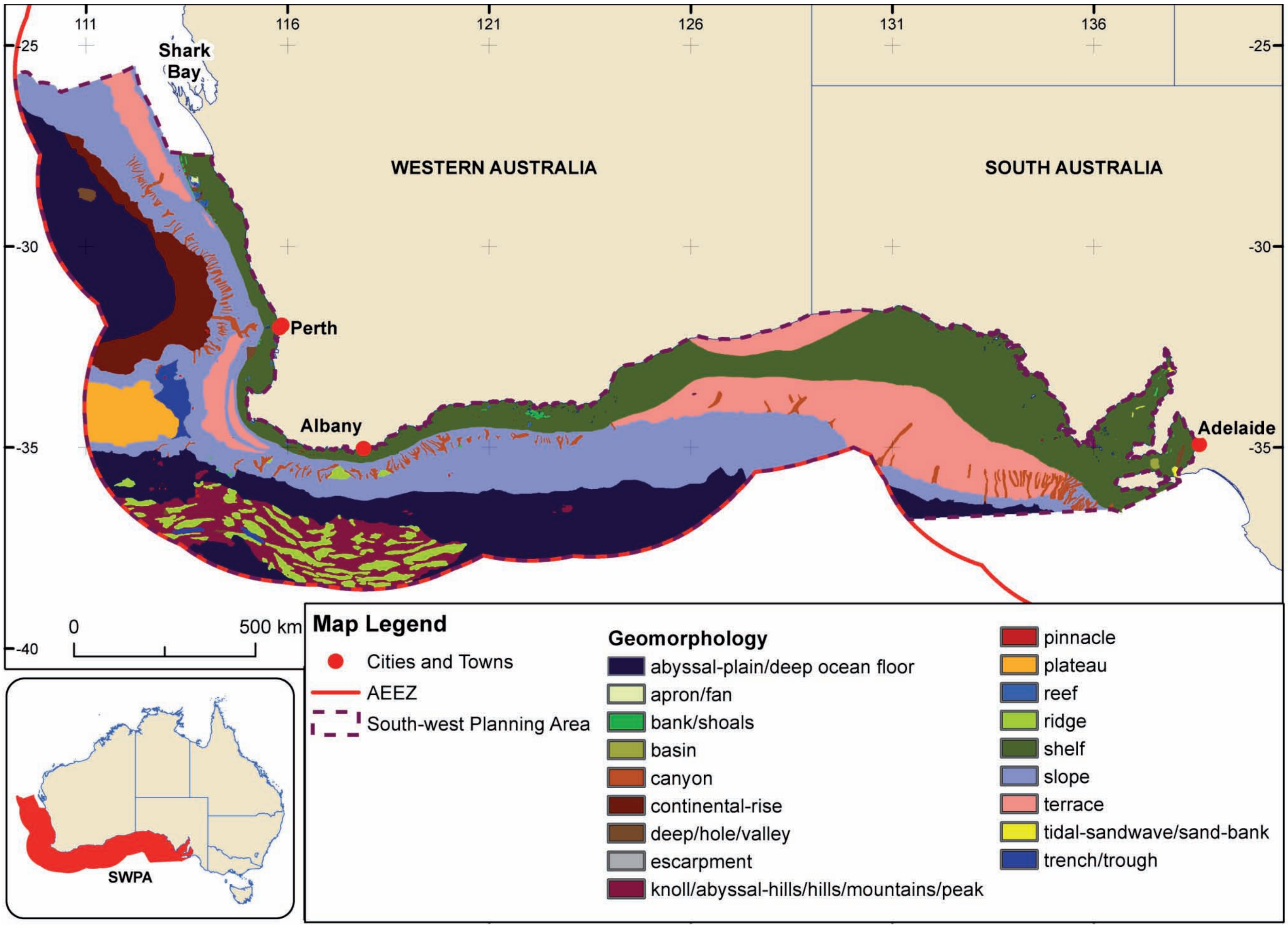


Figure 4. Geomorphic features of the southwest planning region (from Harris et al, 2005).

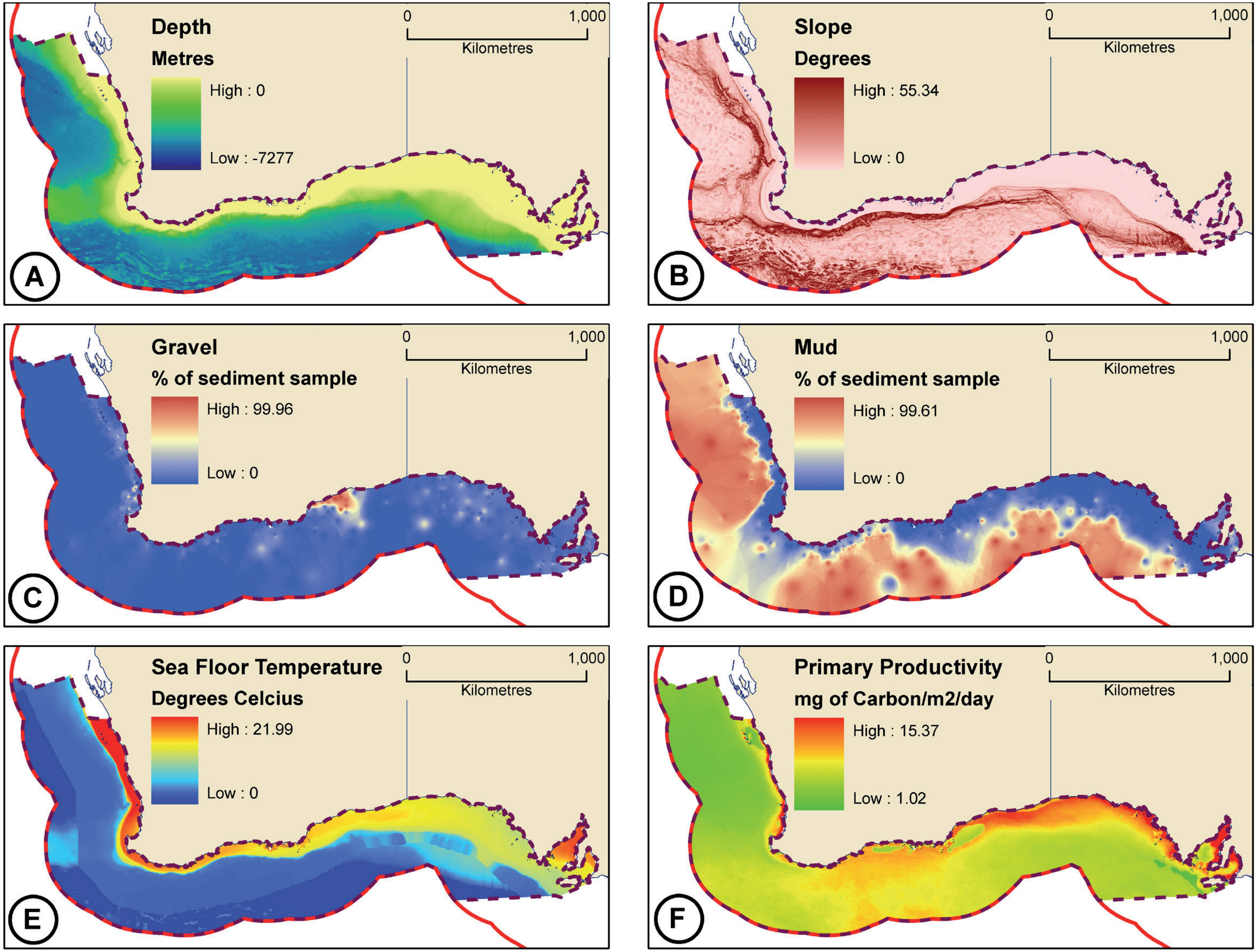


Figure 5. Maps of six input parameters used in this study to define seascapes for the southwest planing region: (A) bathymetry; (B) slope; (C) percent gravel; (D) percent mud; (E) seafloor temperature; and (F) surface ocean primary productivity.

1994; Orpin and Kostylev, 2006; Post et al, 2006). Texture (mean grain size) and composition (gravel, sand, mud and carbonate content) data have been generated for more than 1,000 sediment samples in the southwest planning area to improve the available quantitative data for this relatively data-poor region to support the derivation of the seascapes. Before these analyses were completed, the entire southwest planning area contained quantitative texture and composition data from only 90 locations. The addition of a significant number of data points increases the degree to which the spatial variability in the sediment properties can be captured with the available data.

To provide 100% coverage for the derivation of the seascapes, the sediment properties from the point data must be interpolated across the seabed (Figs 5C and D). The distance that each of the properties can be interpolated while capturing the spatial variability depends on the environment. Preliminary results for the southwest planning area indicate that the sediment properties must be interpolated over different distances for the shelf, slope, and abyssal plain/deep ocean floor, with 40 km being the greatest distance possible for interpolation on the abyssal plain/deep ocean floor. By contrast sediment properties on the shelf and slope vary over shorter distances ranging from several hundred metres on the shelf to several kilometres on the slope. The variability in sediment properties on the shelf reflects both the highly dynamic nature of this environment (with ocean currents having a significant influence on the size and composition of the individual grains) and the input of terrigenous sediment from the land. On the slope, the variability in sediment properties reflects the relative diversity of geomorphic features and environments. The spatial variability in submarine canyons is relatively high because of the different types of environments that occur in them, namely: flank, floor, and interfluve. Each of these environments is acted upon by a different combination of hydrodynamic and sedimentary processes that culminates in distinctive sediment properties. Because we know the spatial variability of sediment properties between different geomorphic features, such as submarine canyons, they can be used as a guide to help determine the degree to which the sediment properties can be interpolated in areas where detailed data are lacking.

Bottom water temperature and primary productivity

Mean bottom water temperature and ocean surface primary productivity were derived from the National Bioregionalisation of Australia (DEH, 2005). The annual mean temperature of the water at the bottom of the ocean was derived from the CSIRO Atlas of Regional Seas (CARS). This data has a grid spacing of 2 km resolution on the continental shelf and slope and 0.1° (11.1 km) resolution for the rest of the EEZ (Fig. 5E). Monthly means for primary production for January, April, July and October (based on MODIS data from 1997–2004) were averaged into a single annual average at a spatial resolution of 0.01° (1.1 km; see Fig. 5F).

DERIVATION OF SEASCAPES

The procedure adopted here was inspired by the shelf habitat classification applied in eastern Canada by Roff et al (2003). These workers used ArcGIS to undertake a supervised classification, overlaying several spatial data layers to create seascape maps. The seascapes represent spatial areas having similar physical properties. In this approach, each input variable is analysed individually, and divided into meaningful classes. The variables are then overlayed (Day and Roff, 2000) and new classes are named for the combinations of each variable they are comprised. For example Roff et al, 2003 merged previously classified variables including physiography, wave and current regime, bed roughness and sediment type to create a map showing where combinations of these variables occur—a seascape map.

In this study, the classification method used is ER-Mapper's unsupervised ISOclass algorithm. The objective of this methodology is to allow the natural statistical breaks in each dataset to direct where the breaks between classes should occur. All variables are classified together, and given equal weighting, to yield a range of statistically different classes. Using the unsupervised method, the definition of any class does not depend on subjective judgement, thus limiting any introduced bias in the creation of separate classes. Geoscience Australia has used this approach previously to generate seascapes for the southeast planning region (Harris, in press) and in support of the national bioregionalisation for Australia (DEH, 2005).

In the southwest planning region, the variables used are: (1) water depth, (2) slope, (3) gravel content, (4) mud content, (5) sea floor temperature, and (6) primary productivity (see Fig. 5). The six data layers were converted to a standard 0.01 degree (~1.1 km) grid obtained by interpolation of existing data. 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 algorithm was allowed to reach a point where 100% of the classes were unchanged from one iteration to the next, which resulted in a range of from three to 15 possible classes. The optimum number of classes was chosen based on the distance ratio which is the average of the mean distance of each class member to its class mean. Where no definitive result was obtained using the distance ratio method, the Calinski-Harabasz pseudo F-statistic (Orpin and Kostylev, 2006) method was employed. In this study, 10 classes were chosen as the optimal number of classes, because at this point the mean average distance between class centre points appears to reach a local minimum (Fig. 6).

Having allowed the statistical distribution of data to define the number and spatial distribution of seascape classes, the question arises: what do these classes represent? To answer this question, a class-means graph was created which shows the mean value of each variable comprising each class (Fig. 7). The extreme (high and low) mean values can be used as descriptors for each class. For example, in comparison with other seascape classes, seascape 1 is characterised by large depths, cold water and high mud content, whilst seascape 4 is characterised by large depths, cold mud associated with low primary productivity. In this way, meaningful descriptive names can be derived for each of the 10 seascapes.

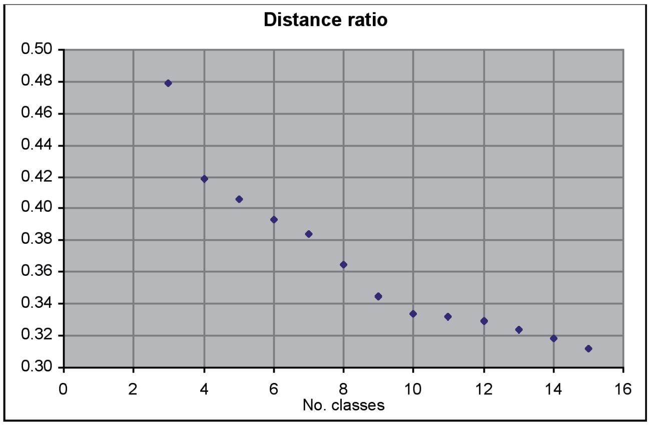


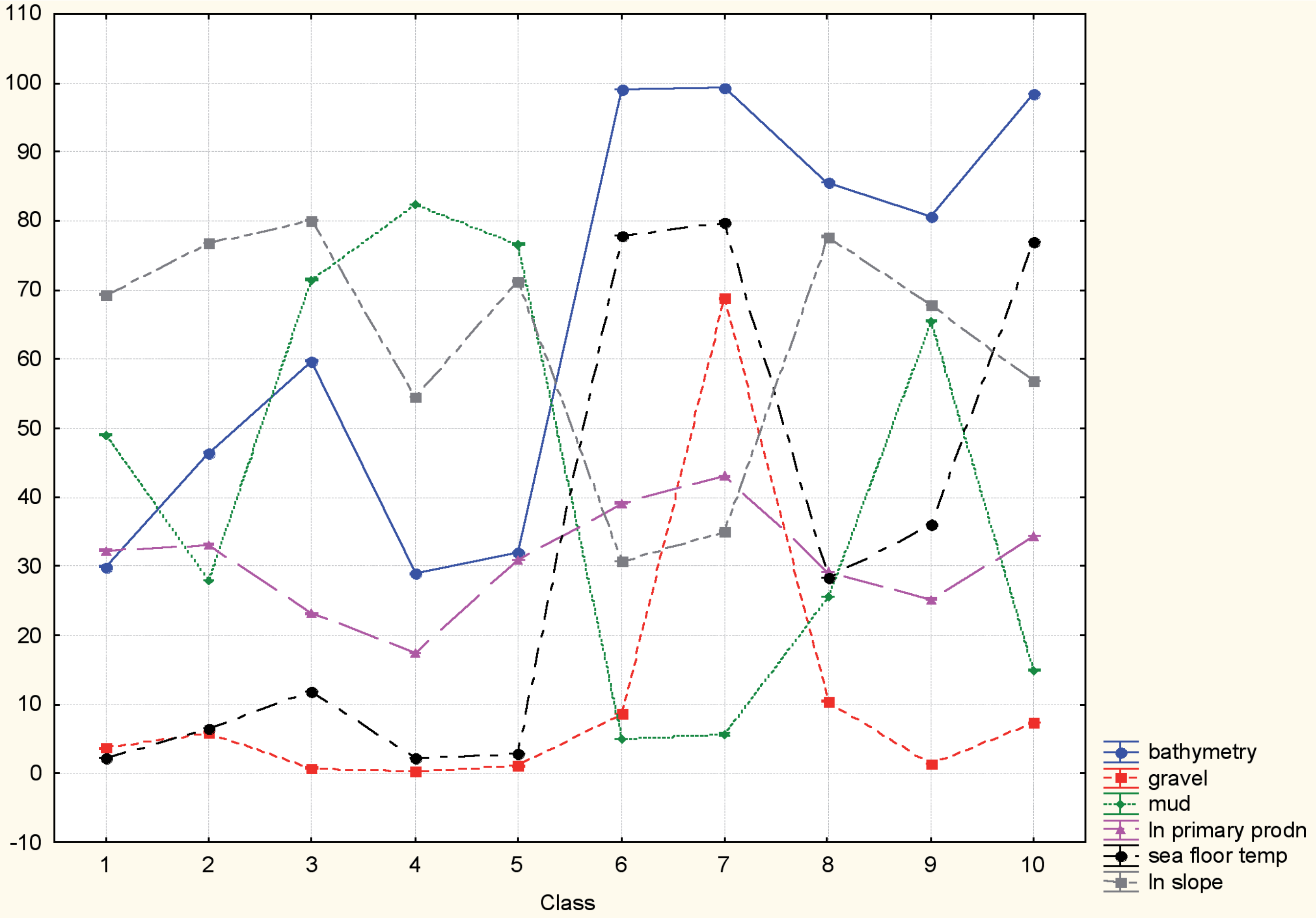
Figure 6. Distance ratio graph of the southwest planning region for classifications three through to 15. The graph shows how the local minimum indicates why 10 classes were chosen.

The spatial distribution of seascapes (Fig. 8) demonstrates a close correlation to the national marine bioregionalisation (DEH, 2005). Shelf provinces are closely associated with the spatial distributions of seascapes 6, 7 and 10, for example (Fig. 8). This result is not surprising since the national benthic bioregionalisation was based on essentially the same data sets (apart from sediment size data). The seascapes exhibit much more variety in the off-shelf regions, where the combination of classes 2, 3, 8 and 9 correspond with the slope biome, whereas seascapes 1, 4 and 5 correspond with the abyssal biome. The complex spatial character of the seascapes provides valuable information on the composition of the different provinces found in the southwest planning area.

HOW ARE SEASCAPES USEFUL FOR DESIGNING MPAS?

To identify areas where the most seascape diversity occurs, and where the most geomorphic diversity occurs, a focal variety analysis of the data was undertaken in ArcInfo (ESRI Inc.; Roff et al, 2003). The focal variety tool 'determines the number of unique values (or the variety) for each cell loca-

Figure 7 (below). Plot of mean values for parameters defining the composition of each of 10 seascapes mapped in the southwest planning area (see map in Fig. 8).



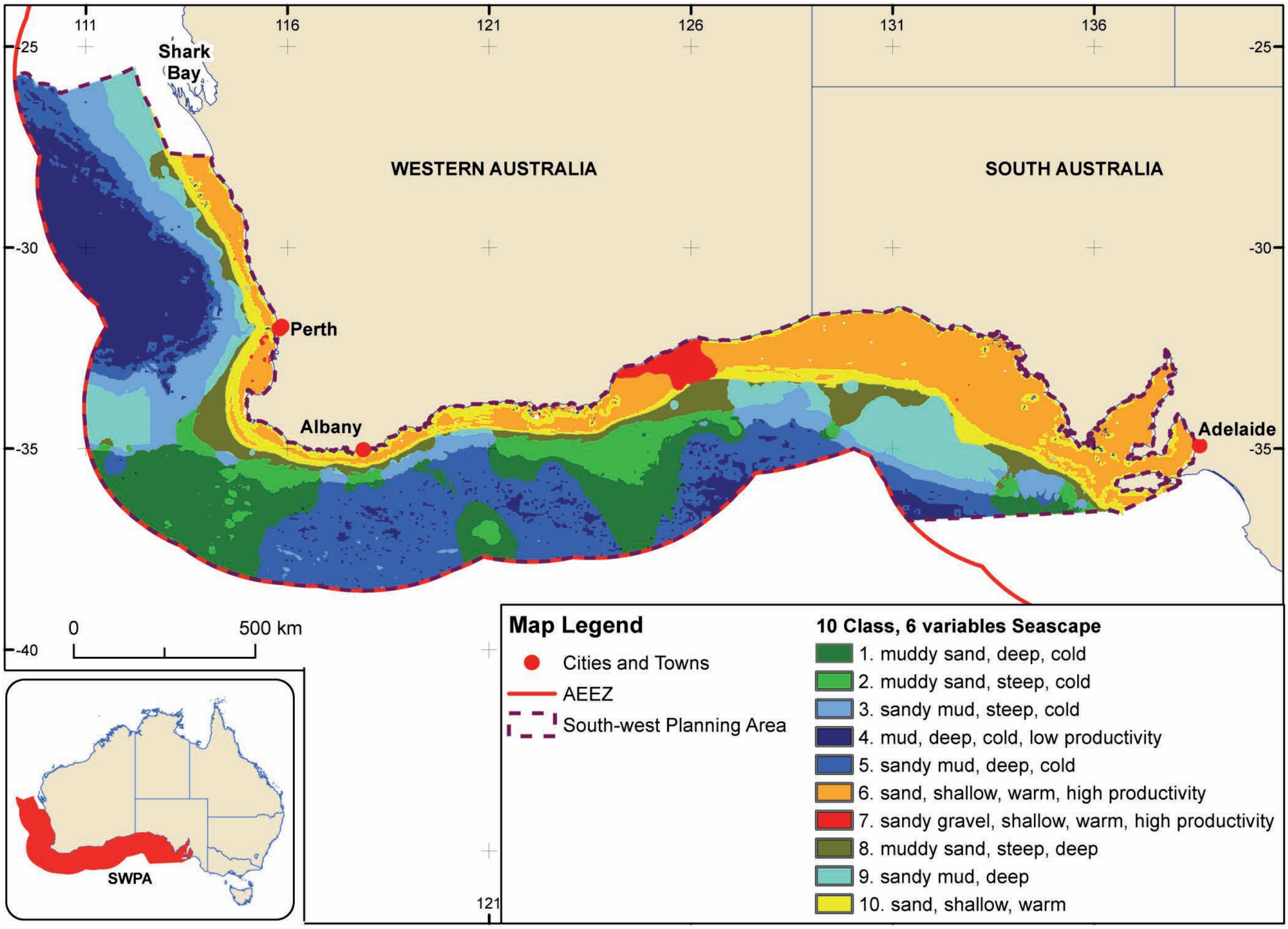


Figure 8. Seascape classification of the south west planning area (defined based on mean values for parameters shown in Figs 5 and 7).

tion on an input raster within a specified neighbourhood and sends it to the corresponding cell location on the output raster' (ArcGIS Desktop Help, ESRI, 2006).

The user determines the neighbourhood that will be investigated for each cell. The neighbourhood is defined by shape (circle or rectangle) and by distance from centroid, or number of cells. For each cell the focal variety program will calculate how many different values are in the surrounding specified neighbourhood and give the cell the value representing the number of different values it finds.

The focal variety analysis was carried out separately for the seascapes map (Fig. 9) and for the geomorphic features map (Fig. 10). Interestingly, hotspots of heterogeneity are located in similar areas in both maps, along the shelf break, foot of slope and over the Naturaliste Plateau. Very high heterogeneity is indicated for the Abrolhos Reefs, Perth Canyon region and shelf areas off Albany (Figs 9 and 10). The sum of the seascape and geomorphic focal variety maps (Fig. 11) provides a synthesis of the two separate analyses.

Given that combined seascapes and geomorphology focal variety analysis (Fig. 11) are representative to a first approximation of the diversity of benthic habitats, it can also be considered to be a representation of benthic biodiversity. This has direct applications in designing and cross-validating the NRSMPA, which has a goal of conserving marine biodiversity within each of the provincial bioregions located in each planning region. The hotspots of habitat heterogeneity (Fig. 11) immediately suggest themselves within bioregions as candidates for MPAs, where conserving the maximum biodiversity can be achieved in the smallest possible area (see also Roff and Taylor, 2000).

It is important to emphasise that the seascapes approach is not a replacement for direct sampling and mapping of biodiversity. Areas suggested as biodiversity hotspots based on surrogates (Fig. 11) need to be validated by field surveys. Seascapes and physical surrogates for biodiversity are a useful, complementary means of identifying locations where biodiversity conservation can be optimised within MPAs, to augment and fill in the gaps where other biological data sources provide little or no coverage.

ESTIMATES OF THE DISTRIBUTION OF BIODIVERSITY INCREASES CERTAINTY FOR THE PETROLEUM INDUSTRY

From the perspective of the oil and gas industry, the NRSMPA increases risk and uncertainty because of the

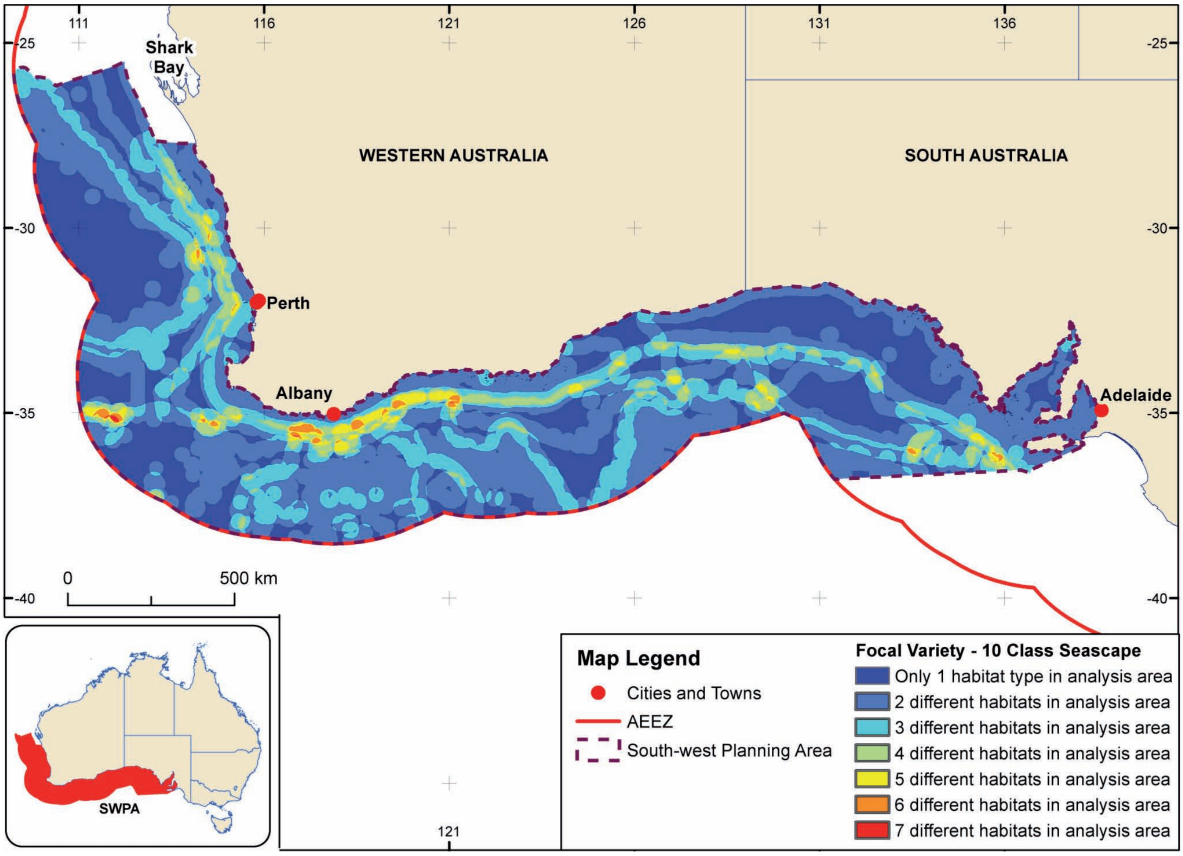


Figure 9. Focal variety analysis of the 10 seascape classes defined for the south-west planning area (shown in Fig. 8).

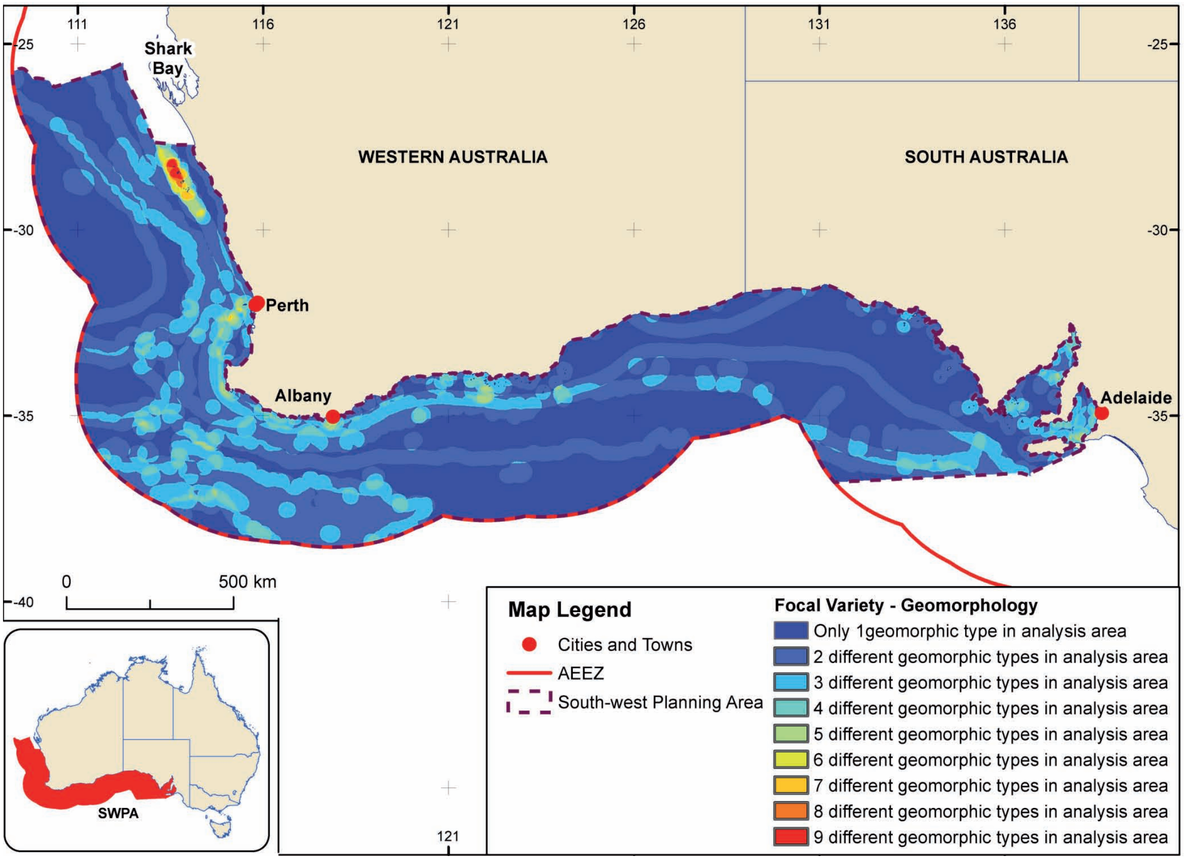


Figure 10. Focal variety analysis of the geomorphic features in the south-west planning area (shown in Fig. 4).

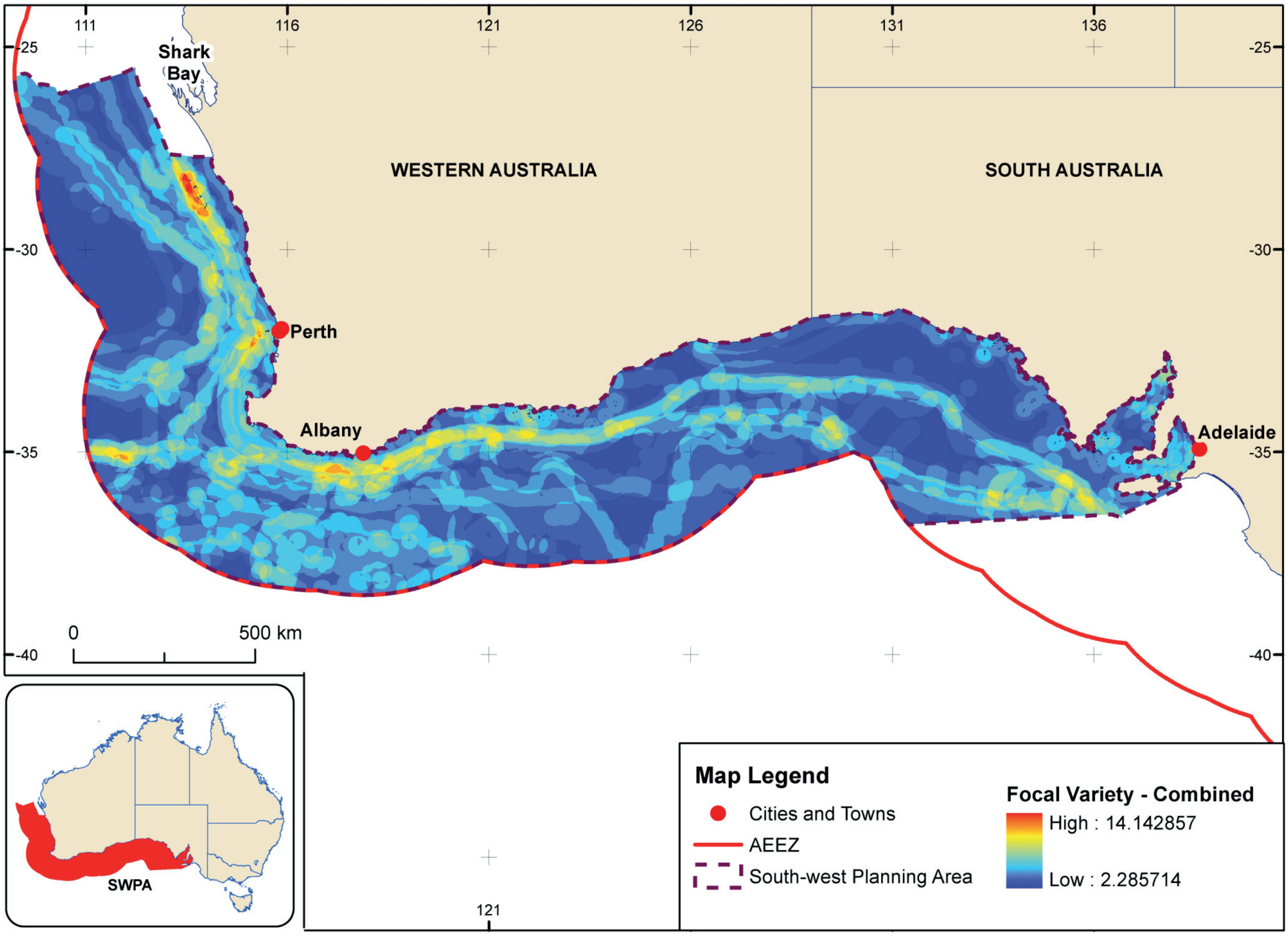


Figure 11. Combination of the focal variety analyses of the geomorphology and seascape classification of the southwest planning area, created through addition of the two datasets (shown in Figs 9 and 10).

possible loss of access to potentially prospective areas. Where understanding is poor and information is scarce, conservation managers are forced to respond by seeking the inclusion of larger areas within MPAs to offset the lack of certainty that all habitats and biodiversity assets have been protected. In this way, the lack of information is a major impediment to both the conservation of critical habitat and the development of secure offshore oil and gas resources.

The procedures outlined above for the derivation of seascapes in Australia's EEZ provide an unbiassed, independent methodology for assessing the spatial variability in benthic habitats and characterisation of the benthic environment in terms of a set of quantified parameters. Our approach provides 100% spatial coverage so that all areas are classified. Furthermore, we have suggested an objective method for analysing seascapes and geomorphic feature maps to provide a synthesis map, which we suggest is a first approximation of benthic biodiversity (at least in terms of habitats). We suggest that such an analytical approach removes potential sources of bias and subjectivity and therefore provides a higher degree of confidence in the final product and hence more certainty in the outcome for stakeholders in the MPA design process. For example, any proposed MPA scheme can easily be assessed by using a geographic information system (GIS) to ascertain if the seascapes and geomorphic features occurring in a given region are comprehensive, adequate and representative (see analysis of the southeast region by Harris, in press).

Just as conservationists will appreciate that not all regions of sea floor are of direct or equal interest to the oil and gas industry, the oil and gas industry will appreciate that not all areas of sea floor have the same value for conservation. We can represent these differences of relative interest, for conservation value and of the oil and gas industry, in terms of the geomorphic features map (Fig. 4; Table 3). Sea floor areas containing potential hydrocarbon deposits that are of interest to the oil and gas industry are related to a range of factors other than geomorphology. However, the areas contained in petroleum leases in Australia are (in descending order of percentage of the area of features within leases) shelf valleys, terraces, banks/shoals, escarpments, canyons, sills, continental slope, pinnacles, shelf, basins, sandwaves, and so on (see Table 3); generally these features must also coincide with thick deposits in sedimentary basins to be prospective for

Table 3. Area of geomorphic features in Australia's marine environment (after Harris et al, 2005) in relation to areas within petroleum leases. The features are listed in decreasing order of percentage of areas in petroleum leases (e.g. 35.9% of shelf valleys are in petroleum lease areas, etc.). The total area for Australia relates to the continent of Australia including Tasmania but excluding offshore island territories. For comparison, the land area of Australia is 7,686,734 km^2.

Feature	Area in Australia (km^2)	Area in petroleum leases (km^2)	Percentage area in petroleum leases
valley	164,035	58,815	35.9
terrace	550,716	151,307	27.5
bank/shoals	50,308	12,975	25.8
escarpment	7,018	1,779	25.4
canyon	104,161	24,820	23.8
sill	17,351	3,097	17.8
slope	1,275,516	148,689	11.7
pinnacle	4,675	469	10.0
shelf	1,237,078	118,268	9.56
basin	483,932	37,225	7.69
sandwave	12,935	855	6.62
trench/trough	123,403	5,783	4.69
plateau	1,238,064	55,149	4.45
apron/fan	6,611	168	2.55
reef	47,892	637	1.33
ridge	57,747	194	0.34
saddle	114,173	0	0
seamount	49,566	0	0
continental-rise	100,891	0	0
abyssal-plain floor	1,408,357	0	0
TOTAL	**7,166,800**	**620,230**	**8.65**

hydrocarbons. By comparison, the abyssal plain, abyssal hills, saddles and seamounts have little, if any, potential for containing hydrocarbons and are of low interest (Table 3 and Fig. 12).

Equally, in terms of biodiversity conservation, not all geomorphic features are of equal value. A major advantage of the habitat-mapping approach based on geomorphic features is that detailed ecological models already exist for many geomorphically defined habitats (Greene et al, 1999). So we already know that seamounts, deepsea vents, submarine canyons, shallow banks and rocky reefs (for example) are special geomorphic feature types, because they are spatially rare and are known to support unique biological communities that are comparatively well documented in the literature. In contrast, some features such as abyssal plains and abyssal hills are spatially common; others such as tidal sand banks and deep ocean trenches are less common spatially but are known to have relatively low biodiversity. Anthropogenic threats to biodiversity also vary among features, from the multiple threats faced by coral reef systems to few, if any, threats to abyssal communities. For these reasons, the map of sea floor geomorphology (Fig. 4) is a useful spatial representation of the diversity and distribution of benthic environments and communities that exist in the southwest planning area. It provides insights into the locations of habitats as well as their relative value as conservation assets (Fig. 12).

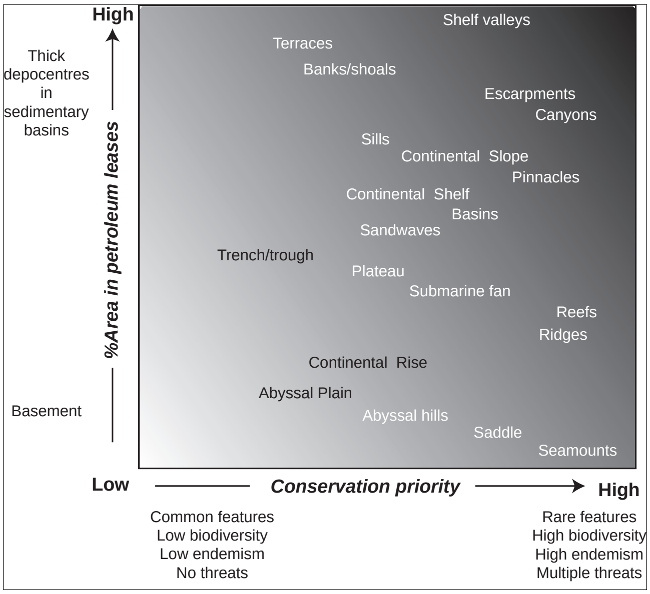


Figure 12. Matrix plot showing positions of geomorphic features relative to their conservation value (X-axis) in relation to oil and gas industry interest (Y-axis; Table 3). The interest by the oil and gas industry is based on the percentage area of geomorphic features located within petroleum leases (Table 3) and depends on the co-occurrence of sub-surface sedimentary basins. Some features having high conservation value correspond with shelf or slope environments (coral reefs, shelf valleys, rocky banks and shoals), whilst others are confined to abyssal regions (seamounts; ocean ridges). The design of MPAs coinciding with features occurring in the upper-right section of the plot are likely to be more controversial than those coinciding with the lower-left section of the plot. Such plots can be constructed for various sectoral interests (e.g. fisheries and tourism) to assist managers with understanding spatial relationships of different groups.

The plot of oil and gas industry interest in relation to conservation value (Fig. 12) illustrates that there are a range of features that are of much greater interest for one group than the other. For example, seamounts are of considerable value for conservation but of little interest for petroleum exploration. Where there is an overlap in interest for both groups (in the upper right hand corner of Fig. 12) the potential for contrasting views on management decisions can be expected. In this category are such features as banks, shoals and shelf valleys (for example). Nevertheless, certainty and confidence are improved because there already exists a map of seabed geomorphic features for the whole of the Australian EEZ (Harris et al, 2005).

CONCLUSIONS

We set out in this paper to answer three fundamental questions.

1. What biophysical variables are the most useful surrogates for marine biodiversity?

2. How can multiple spatial biophysical data layers be integrated to make a single map of marine habitats?
3. How is this single integrated map useful for designing a national system of representative MPAs?

To support management of the various uses of resources in the EEZ, including marine conservation and petroleum exploration and production, Geoscience Australia is conducting research into the surrogacy relationships between the occurrence of benthic biota and biophysical parameters. In this paper we presented recent results from the Gulf of Carpentaria, where our work has demonstrated that sediment size, seabed disturbance by waves and tides and water depth explain the occurrence of benthic biota in a significant proportion of sites. Although we expect that these relationships will apply to other areas in the gulf, and perhaps to much of northern Australia, we do not expect them to hold true in the deep ocean environments or perhaps in other (e.g. temperate) parts of Australia. Thus the answer to the first question is that the biophysical variables most useful for predicting biodiversity vary from one region to the next and it is not possible to define a single set of variables that explains biodiversity in all marine environments.

Having said that, previous published research has illustrated that variables including depth, seabed slope, sediment type, food supply and ocean temperature are correlated with the occurrence of different benthic communities in many locations. To answer the question of how to integrate these multiple data layers, we have used multivariate techniques to create seascape maps representative of the spatial diversity of benthic environments and habitat types. Our seascapes maps provide 100% spatial coverage and identify a subset of variables that define the key attributes of each seascape type.

Using GIS focal variety analysis techniques, a map of seascape heterogeneity has been created for the southwest planning area that we suggest is a first approximation of the distribution of benthic biodiversity. The answer to the third question, therefore, is that hotspots in maps of seascape heterogeneity may be considered as possible sites for the location of MPAs within different bioregions. The maps of geomorphic features and seascapes can also be use to validate whether any particular MPA network design conforms to the CAR principle. Thus maps of integrated biophysical parameters have application to MPA design and also provide a means of testing whether design criteria have been met.

In summary, our biophysical, seascapes-mapping approach provides a means of overcoming the huge, biodiversity information gap that otherwise exists for most of Australia's EEZ, and therefore provides a degree of increased certainty for managers and stakeholders. The examples outlined here, for surrogacy research in the Gulf of Carpentaria and seascapes analysis for the southwest planning area, are part of a larger program presently underway within Geoscience Australia that will have applications to all areas of Australia's EEZ in the years ahead.

ACKNOWLEDGEMENTS

Thanks to John Kennard, Tony Stephenson, Phil O'Brien (Geoscience Australia), Robert Batterham (Santos) and Dave Cockshell (PIRSA) for their helpful suggestions that improved the content of this paper. Published with permission of the executive director, Geoscience Australia.

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APPEA

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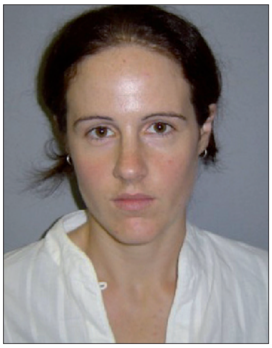
Peter Harris is leader of the Marine and Coastal Environment Group in Geoscience Australia. He completed a BSc in marine geology at the University of Washington (Seattle, USA) in 1981 and a PhD at the University of Wales, (Swansea, UK) in 1984. He has published over 70 research papers on the physical sedimentology and palaeoenvironments of estuaries, temperate and tropical carbonate shelves and the Antarctic. His group at Geoscience Australia has supported government initiatives in marine planning and the design of marine protected areas through the application of marine geological knowledge. Member: GSA, SEPM and AMSA.

Andrew Heap is project leader for the Seabed Mapping and Characterisation project at Geoscience Australia. His role is to direct research examining the inter-relationships between geoscience, oceanography and biology in the context of spatial modelling and process studies. Andrew received his PhD from James Cook University in 2000 and his research includes the geomorphic evolution of estuaries to spatial analysis of seabed habitats. Throughout his career Andrew has focussed on applications of marine geology to solving practical problems for government and industry.

Alix Post is a research scientist in Geoscience Australia's Seabed Mapping and Characterisation group. She graduated from the Australian National University in 1997 and received a PhD in Southern Ocean palaeoclimatology from the University of Tasmania in 2004. Alix joined GA as a graduate recruit in 2002, and has since spent most of time working in the Marine and Coastal Environment Group. Her present research is focussed on understanding seabed habitats in regions as diverse as tropical Australia to Antarctica.

Tanya Whiteway graduated from the Australian National University in 2000 with an Honours degree in Resource and Environmental Management. She worked for Ecowise Environmental as a GIS officer and GIS project manager for six years managing environmental GIS and catchment management projects and bathymetric surveys. Tanya recently joined Geoscience Australia and is now working on marine and coastal projects investigating spatial analysis of biophysical data to create seascape maps.



Anna Potter is a research scientist with the Petroleum and Marine Division (PMD) of Geoscience Australia. She gained a Bsc (Hons) in Earth Science from Deakin University, Melbourne, in 2004 where she worked on deepwater clastic palaeoenvironments and sedimentology. Her work at Geoscience Australia has included regolith assessment for risk research and hyperspectral mapping of gold and base metal mineral systems. She is now assessing the regional sedimentology of Australia's southwest margin for marine environmental planning.

Marita Bradshaw is group leader of Petroleum Prospectivity and Promotion at Geoscience Australia, responsible for the program of new data acquisition in frontier basins and the geotechnical component of the annual offshore acreage release. Marita's previous roles at Geoscience Australia and its predecessors over the last 20 years, have been focussed on the petroleum systems of Australia and the region. During 1996–7 she was on staff exchange with WMC Resources working with the International New Ventures team. Marita began her career in petroleum geology with ESSO Australia in 1981. She has a BSc (Hons) degree in Geomorphology from the University of Sydney and a PhD in evaporite and carbonate geology from the University of WA. Member: PESA and GSA.