Marine Biodiversity Hub

National Environmental Science Programme

Identification and collation of Australia's shelf mapping datasets and development of a national geomorphological classification scheme for reef systems

Phase 1 Workshop Report

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Project D3 - Evaluating and monitoring the status of marine biodiversity assets on the continental shelf

Milestone 3 – Research Plan v1 (2015)

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Important Disclaimer

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EXECUTIVE SUMMARY

Rocky reefs form an important habitat on the continental shelf and are subject to disproportionate fishing pressure given the high productivity of this habitat relative to adjacent sandy seabed. Despite this, little is known of the extent and nature of these systems beyond their value to the fishing industry. This project collates all known mapping data from government and industry (including data acquired during CERF and NERP Hubs) to provide an updated map of this key habitat around Australia, and will identify critical gaps in this knowledge to be filled by targeted surveys. This will significantly improve the knowledge of these environmental assets within state waters and the Commonwealth Marine Area, improve our understanding of assets in marine protected areas and inform environmental assessment of proposed activities and developments required by environmental legislation. Collated information also contributes to development of a blueprint for monitoring key ecological features of the Commonwealth Marine Area. A geomorphological classification system is also being developed for these reefs, and associated cross-shelf habitats with the aim of it being accepted and adopted nationally, and it is being tested and refined for biological applicability. This milestone report documents the major outcomes of a national workshop intended to identify existing shelf-reef datasets, key stakeholders and develop a pathway to sharing our current data holdings nationally, and identifying priority knowledge gaps to prioritise future research projects in this space. It also documents workshop outcomes focussed on developing a nationally accepted classification for cross-shelf reef systems and associated habitats, and progress made subsequently in refining a scheme suitable for Australian conditions and agencies.

1. INTRODUCTION

The Marine Biodiversity Hub has supported a one-year project that will identify, and where possible collate, all known mapped seafloor rocky reef data on the continental shelf from around the nation. Currently this knowledge is very limited, particularly outside of state waters yet it is urgently needed to underpin spatial management of shelf systems. Rocky reefs systems have been identified as a Key Ecological Features (KEFs) in the Australian Government's Marine Bioregional Plans, yet the distribution of many of these shelf reefs remains poorly known, and current maps of these KEFs usually reflect where they have been incidentally mapped as part of unrelated surveys rather than as part of a targeted inventory.

Phase one of the project 'D3 Evaluating and monitoring the status of marine biodiversity assets on the continental shelf' is to identify 'shelf reef key ecological features'. The project is a partnership between the National Environmental Science Program (NESP) stakeholders the University of Tasmania, Geoscience Australia, CSIRO, NSW Department of Primary Industries, NSW Office of Environment and Heritage, the University of Western Australia and the Australian Institute of Marine Science (AIMS).

This research is part of the larger project 'Evaluating and Monitoring the Status of Marine Biodiversity Assets on the Continental Shelf' facilitated by the NESP Marine Biodiversity Hub. It brings together a wide range of stakeholders involved in marine spatial management. The project team plans to encourage the development of facilities to share data that is of national interest and be able to handle this data to respond to management needs and if possible identify priority gaps that can be addressed by future mapping surveys. In addition to collating all existing spatial data on rocky reef habitats on the continental shelf, we also aim to map biological attributes related to reef ecosystems in regional focus areas. Ideally, this project will be the initiation of a longer-term collaboration between stakeholders from universities, research agencies, government and industry. The map of shelf reef habitats can be used to inform the understanding of the distributions of marine habitats, faunal assemblages and vulnerabilities of these sites that will empower decision making in key regions.

A major output of this project will be a spatial map and also a spatial geo-database accessible to the marine community of the mapped shelf reefs. This will be augmented with secondary products that will include the identification of the most critical gaps in our current seafloor mapping datasets which help to inform national priorities for future survey work, including work planned to be undertaken by the Hub. A third output will be the development of a geomorphological classification scheme for shelf rocky reefs applicable for classification at multiple scales of data resolution. This report outlines the development of a framework to achieve the first steps in this project- identifying available datasets and classification of seabed data to capture reef habitat, as well as discussing a mechanism for prioritising studies aimed at filling the most pressing knowledge gaps.

In this first milestone report we will detail the outcomes of the project Workshop held on the 24th and 25th September 2015. The goal of the workshop was to scope out a path as to how we will deliver a spatial map of the distribution, extent and structure of shelf reef KEFs throughout Australian waters that is based on a nationally standardised classification scheme. The workshop was attended by twenty seven stakeholders and a clear path for moving into the second period of this project was established.

1.1 Workshop Outcomes

The workshop agenda (Appendix A) outlines the topics covered in the discussion over the two day meeting. The first day focused on the sources of data that stakeholders around Australia have access and custodianship over and what types of data would be useful for identifying reef features on the shelf. We heard from a number of representatives from leading institutions around Australia who presented the types, scale and coverage of marine reef data within their state or region. The attendees for the workshop ranged from government, university, industry and consultants. Based on the individuals experience we were able to get a broad overview of the nature of data available within the Australian marine jurisdiction (Figure 1).

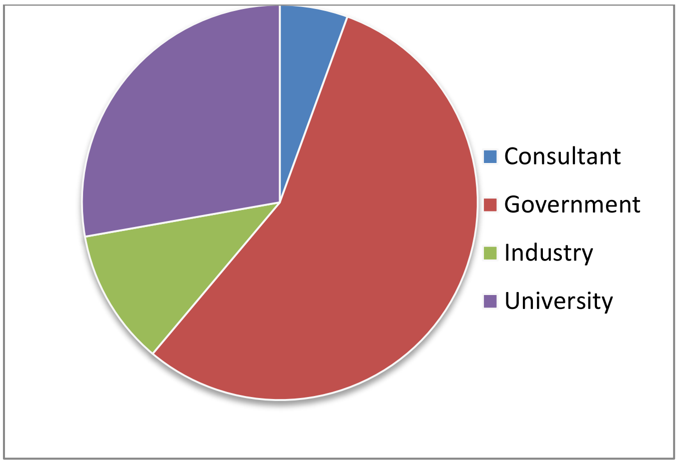

Figure 1. Distribution of participants by sector.

1.1.1 Key Ecological Features (KEFs) and the relationship to reef.

The introduction on the first day of the workshop provided the foundation for the discussions to follow as to the need for developing a spatial database on the distribution of reef ecosystems around the nation. Key ecological features are the parts of the marine ecosystem that are considered to be of importance for a marine region's biodiversity or ecosystem function and integrity.

Key ecological features (KEFs) are required to meet one or more of the following criteria:

1. a species, group of species, or a community with a regionally important ecological role (e.g. a predator, prey that affects a large biomass or number of other marine species);

2. a species, group of species, or a community that is nationally or regionally important for biodiversity;

3. an area or habitat that is nationally or regionally important for:

a) enhanced or high productivity (such as predictable upwellings - an upwelling occurs when cold nutrient-rich waters from the bottom of the ocean rise to the surface);

b) aggregations of marine life (such as feeding, resting, breeding or nursery areas);

c) biodiversity and endemism (species which only occur in a specific area); or

4. a unique seafloor feature, with known or presumed ecological properties of regional significance.

High biological value has been identified as the foundation of making a Key Ecological Feature, in the sense that it is the biological features that make the reefs important to the Departments planning initiative. The workshop highlighted the data sources that were available within the waters of each state. This will be discussed in Section 2.

1.1.2 A framework for spatial data analysis

To set the spatial boundary for this project there was an initial discussion on the framework for the spatial data management. It was agreed that the data would be collected within a spatial region of the coastline (0 m water depth) to the shelf break (on average 200 m water depth). The 200 m depth contour was calculated from the Geoscience Australia 50 m bathymetry grid. The 0 m contour was taken from the 1:25000 Australian coastline represented by the Mean High Water Mark (Figure 2).

Figure 2. The continental shelf as defined by the D3 project and the focus region for this analysis. The red line indicates the 200 m contour which delineates the exterior boundary of the data collation.

The Marine National Facility has conducted much of is investigations in national waters either just on the shelf break itself or just outside of the 200m contour (Figure 3). Large areas of seabed on the shelf have not been mapped and little is known about the characteristics of this seabed outside of coarse satellite altimeter measurements underlying modelled bathymetric data. This D3 project will highlight the gaps where future marine surveys can be prioritised to ensure that we maximise the investment in marine surveying around the nation.

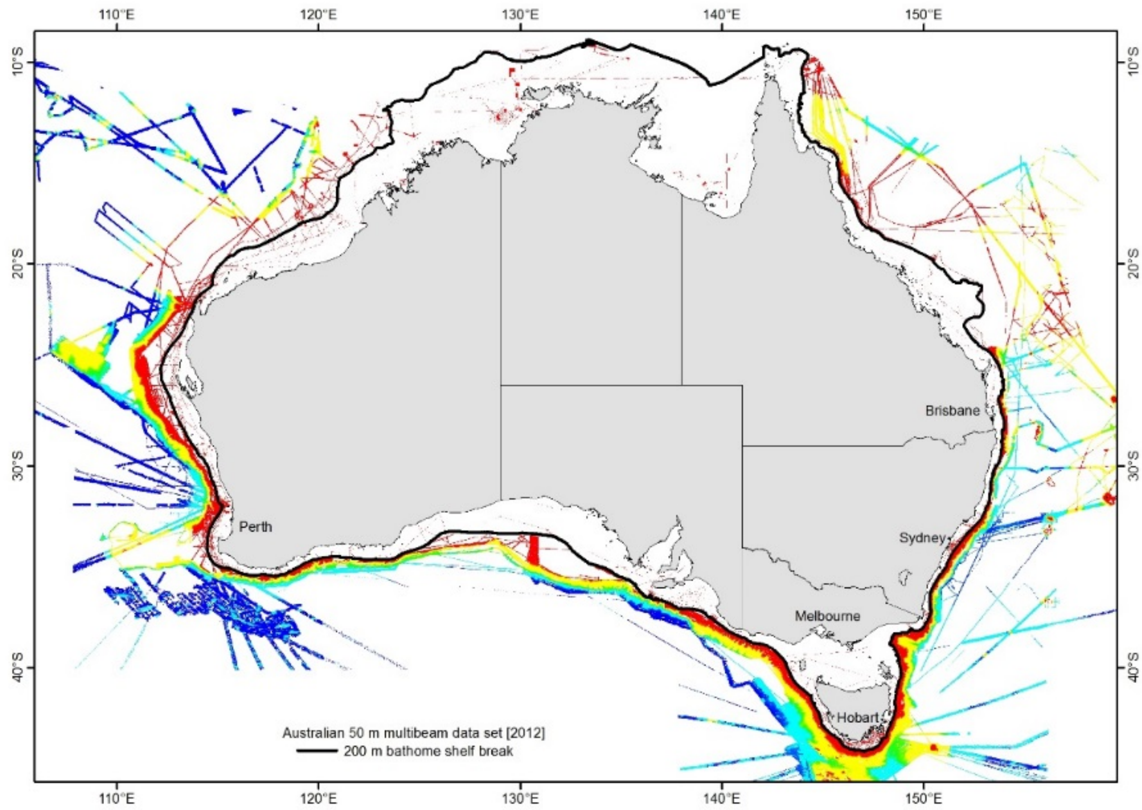

Figure 3. A map of CSIRO multibeam coverage around Australia. The black line indicates the approximate shelf break at the 200 m depth contour. Note the significant lack of coverage on the continental shelf itself.

Of particular importance to this research project is not only existing spatial data on reef systems but also the overlap between this spatial data and the distribution and extent of conservation values, such as Key Ecological Features (KEFs), that include reef as an important element of the value or feature. We refer to a number of reports that have been completed (Falkner et al. 2009, Dambacher et al. 2012, Hayes et al. 2015) regarding the identification of KEFs by the Australian Government. The identification of KEFs was informed by advice from scientists about the ecological processes and characteristics of Australia's marine bioregions. The locations of KEFs are important as they are used by proponents and regulators to inform environmental assessments and approvals of proposed activities in Australia's Commonwealth Marine Area. The Department of Environment (DoE) has recently (November 2015) generated a data record (ISO 19115 https://data.gov.au/dataset/marine-key-ecological-features) to provide access to spatial information on KEFs.

The KEFs that include reef as an important element of their character can be divided into three spatial categories a) tropical, b) sub-tropical, and c) temperate groupings and include; (i) Ashmore and Cartier Island and surrounding Commonwealth waters; (ii) Mermaid Reef and Commonwealth waters surrounding Rowley Shoals; (iii) Plateau and saddle North West of the Wellesley islands; (iv) the Reefs, Cays and herbivorous fishes of the Marion Plateau; (v) the reefs, cays and herbivorous fishes of the Queensland Plateau; (vi) the Seringapatam Reef and Commonwealth waters in the Scott Reef complex; (viii) the submerged coral reefs of the Gulf of Carpentaria; (viii) Commonwealth marine environment surrounding the

Houtman- Abrolhos Islands; (ix) the Elizabeth and Middleton Reefs; (x) the Commonwealth marine environment surrounding the Recherche Archipelago; (xi) the Commonwealth marine environment within and adjacent to the west-coast inshore lagoons; (xii) the rocky reefs and hard substrate of the south east marine region; and (xiii) the shelf rocky reefs of the temperate East region.

In order to create a spatial representation of KEFs for each Marine Region, DoE have interpreted the best available spatial information and applied their best judgement on how to spatially represent reef features based on scientific advice provided. In some areas, the limited spatial coverage of the data available to the Department has led to misrepresentation of these important features. An example, shown in Figure 4, is for the shelf reef off coastal NSW.

A major goal of this project will be to collate and assimilate all spatial data available around the nation into one database that the Department will be able to access to inform their management policy of these important habitats. Day 1 of the workshop showcased the data sets that have been collected by targeted field surveys within each state and territory of Australia. A number of key individuals representing a variety of government and academic institutions were invited to present the data available within their regions (see Appendix B for list of presenters). Available and relevant reef spatial data for the Australian shelf reef jurisdiction will be discussed in the following section.

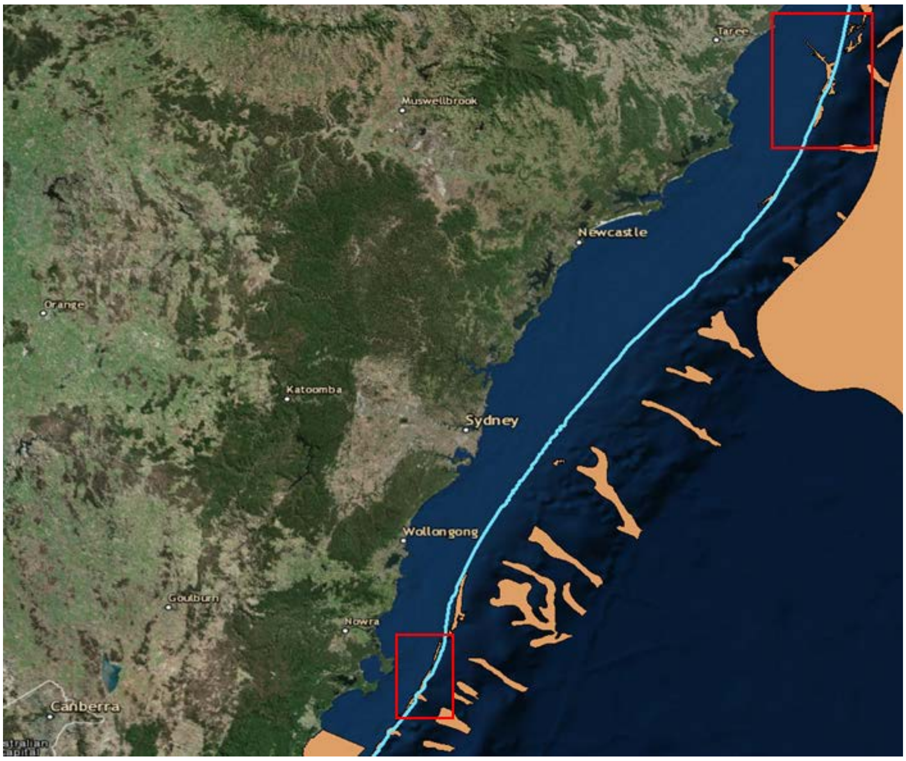

Figure 4. Shelf reef (blue line indicates 200 m depth) on the central NSW coast where the existing shelf reef key ecological feature (KEF) is mapped in Google Earth in orange. The highlighted box shows where reef has been incidentally mapped as part of slope mapping, but is not a product of targeted mapping or comprehensive mapping/knowledge so may be misleading if interpreted incorrectly.

2. AUSTRALIAN REEF DATASETS IN NATIONAL CUSTODIANSHIP

To establish the spatial data model for the D3 project we first needed to scope the potential sources of national marine habitat data holdings. From the workshop discussions, we were able to identify a number of key data sources, listed in Figure 5. With representatives present from each of these sectors, we were able to have an informed discussion about the potential for data access and the value of these data to meet the needs and objectives of the project.

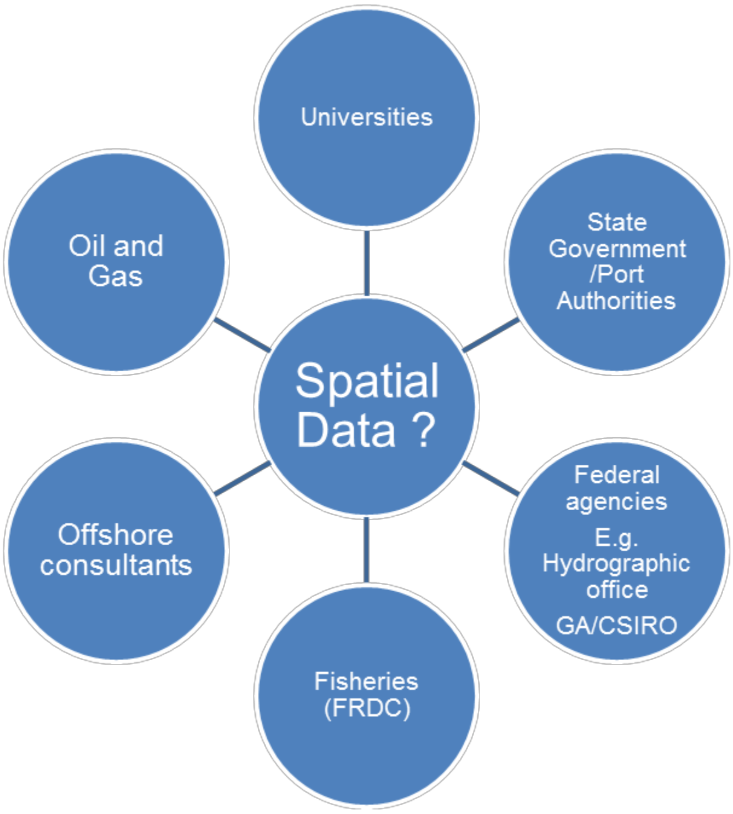

Figure 5. Data sources of spatial information for building a national understanding of the distribution of shelf reef habitats.

The workshop discussion covered a number of potential issues that may arise when attempting to source these data for the D3 project. These issues include- a) the availability of access to the data and custodianship, b) licencing of data products c) potential costs associated with access c) temporal and spatial resolution of the data that the custodians may be willing to provide, d) the format of the data (if it is raw data or derived spatial products) and e) if metadata is available for the spatial data product- as reporting on the origin, processing etc which is important to the integrity and QA/QC of the projects spatial database. The first datasets that we aim to collate includes the nationwide spatial data sets that are held by the Australian Hydrographic office, the CSIRO and Geoscience Australia.

2.1.1 Australian Hydrographic Office (AHO) S57 data

The Australian Hydrographic Service (formerly known as the Royal Australian Navy Hydrographic Service) is the Australian Commonwealth Government agency responsible for providing hydrographic services that meet Australia's obligations under the SOLAS (Safety of Life at Sea) convention and the national interest; enabling safe navigation, maritime trade and supporting protection of the marine environment. Hydrographic services provided by the AHS include the mapping and surveying of undersea terrain and irregularities on and under the water's surface (known collectively as hydrography), the provision of nautical charts and other publications, such as tide tables and Notices to Mariners. Over 400 paper charts are produced by the AHS, with the conversion of these to electronic navigational chart format completed in 2011. The Australian Hydrographic Office, through a memorandum of understanding with CSIRO has made the nation’s S-57 charts available to this project.

The IHO S-57 format is a vector interchange format used for maritime charts. It was developed by the International Hydrographic Organisation (IHO). For the nation there are over 800 separate charts containing information on a variety of features that are relevant to this project. Each S57 file has multiple layers and each layer has several levels of information. The attributes of these layers include survey coverage on continental shelf, comprehensive hydrographic chart data, fish havens, fisheries zones, fishing grounds, seabed area, individual soundings, underwater or awashed rocks and unsurveyed areas. Whilst these spatial data do not directly map reef area on the continental shelf, they are an invaluable resource for extrapolating or interpreting seafloor data representing hard bottom.

Due to the extensive national coverage of these data, they will be used as the foundation data set in regions where little or no data exists to augment our knowledge of reef habitat. The sounding points that can be extracted from this data set can be used in subsequent analysis to generate a fine scale bathymetric map for the nation at a resolution presently unavailable. Through the analysis of this fine scale bathymetric map we hope to be able to extract areas of potential reef habitat. Figure 6 shows the national data coverage surveyed by the Australian Hydrographic Service.

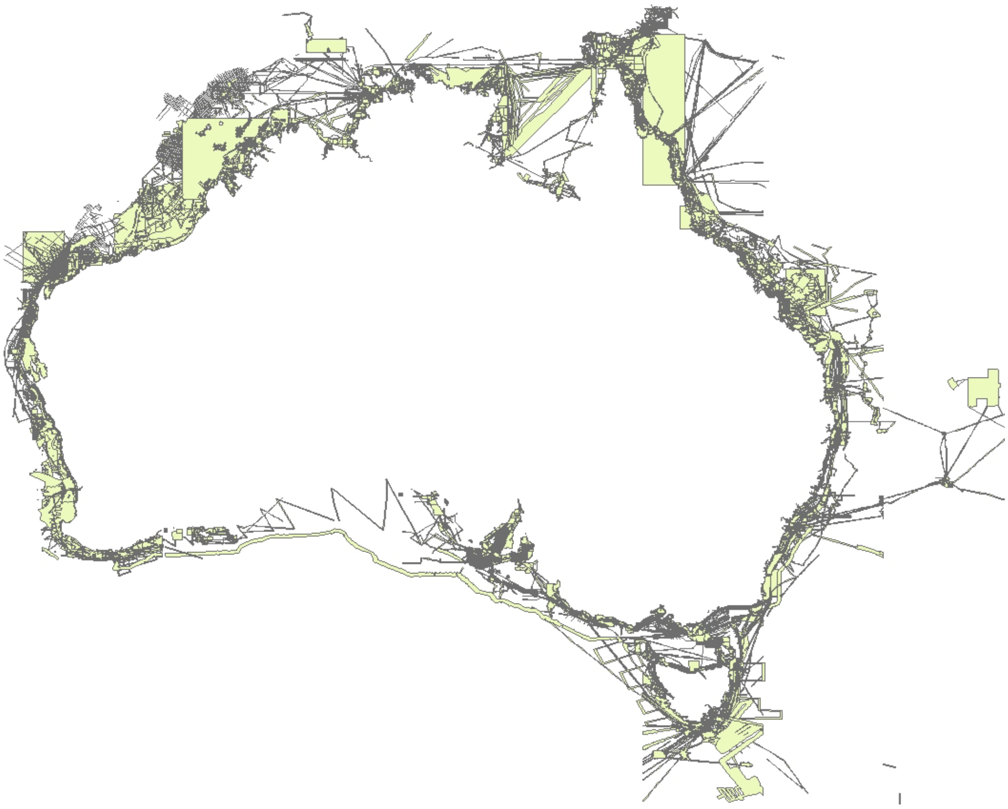

Figure 6. Australian Hydrographic Service data holding for seafloor survey [data extraction July 2015].

Although it is a complex vector format, IH) S57's main purpose is to convey hydrographical information as opposed to a strictly spatial vector format normally encountered in a geographical information system (GIS). Therefore, when converting from a S57 format to a shapefile some artistic licence should be expected. Additionally, several hydrographic charts overlap, thereby complicating the extraction of reefs features to a single layered shapefile.

(a) (b) (c)

Figure 7. a) S57 vector format depicting a reef with other all other available data layers. b) S57 vector format depicting a reef outline. c) S57 vector format converted to a shapefile.

The spatial location (x, y) of an S57 underwater feature is very accurate and therefore this data has great potential to confirm and compare reef locations on the continental shelf with composite data sources (Figure 7). The data holdings of the Australian Hydrographic Office include a range of data types from historical depth soundings through to modern multibeam sonar surveys. Whilst Figure 6 illustrates the extensive national coverage of these combined datasets, it does not illustrate the extent in individual areas where particular data holdings (individual surveys) occur. Ideally, if this project was to be as effective as possible, this information would be identified and ultimately be available as a national facility from which reef systems and other cross shelf habitats can be identified at multiple spatial scales. We are actively discussing with the AHO about if and how that may be practically achieved.

2.1.2 CSIRO

CSIRO, through the Marine National Facility (MNF), operates Australia's only blue water research vessel, which is tasked according to Australian science priorities. For 10 years the now-retired MNF research vessel *Southern Surveyor* undertook an extensive and incremental bathymetry and backscatter multibeam data acquisition program in conjunction with its other scientific activities.

Figure 8 shows multibeam bathymetry data held by CSIRO around the Australian coastal margin. Multibeam data held by CSIRO in depths less than 200 m are primarily derived from a Kongsberg EM300 multibeam echosounder mounted on RV *Southern Surveyor*, and were primarily acquired as subsequent transit lines during normal operations. A small number of near-coastal surveys acquired from a variety of vessels with a Kongsberg EM2040c portable multibeam echosounder are also available in localised areas of interest which usually incorporate reefs. Traditionally CSIRO focused on the 200 m – 1200 m depth range; consequently, shelf data are sparser than those of the upper slope.

CSIRO are collating these data holdings to derive bathymetry products to identify areas of reef habitat. These data holdings can be found at: http://www.marine.csiro.au/geoserver/index.html

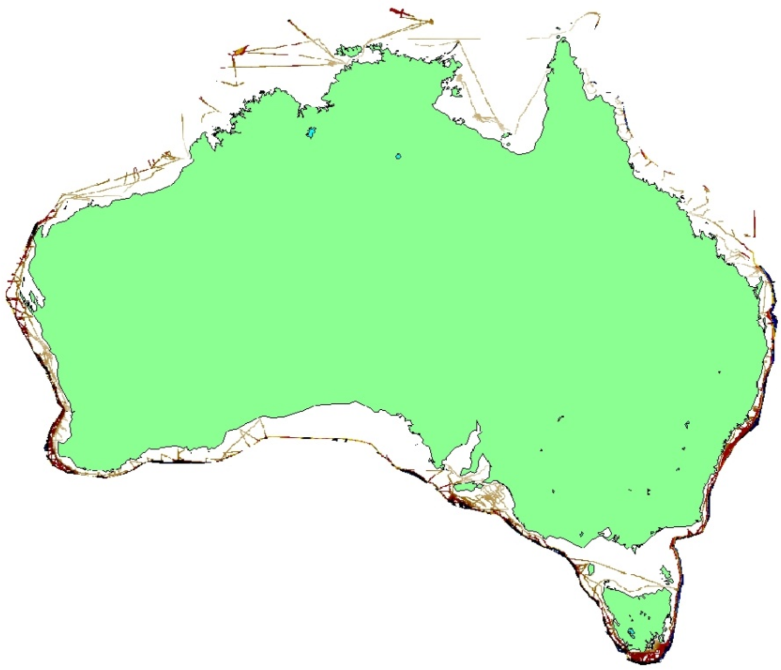

Figure 8. CSIRO data holding in < 200 m water for seafloor survey [data extraction December 2015].

2.1.3 Geoscience Australia

Geoscience Australia holds several national-scale datasets that may prove useful to reef mapping and classification. The 2009 bathymetry grid of Australia covers the entire Australian EEZ. In 2012, Geoscience Australia published its collection of multibeam bathymetry grids. This dataset contains all multibeam data (as tiles) held by Geoscience Australia as at August 2012 which has been gridded to 50 m spatial resolution. In addition, not collated in this 2012 product, Geoscience Australia has also acquired several additional multibeam datasets from surveys on the North and North-west shelf (e.g., Oceanic Shoals CMR, Joseph Bonaparte Gulf, Leveque Shelf and Carnarvon Shelf) and Tasmanian shelf, including the Flinders, Freycinet, and Huon CMRs).

The 'geomorphic features layer' of the Australian margin (Figure 9) was generated from analysis of a relief model of the seabed produced from the 2005 version of the national bathymetry dataset (Heap 2008). Twenty one feature types identified in this layer include several reef features. However, the reef features identified on the shelf are very limited in extent. Geoscience Australia also holds a complete collection of Landsat datasets, which may be useful for the reef mapping and classification.

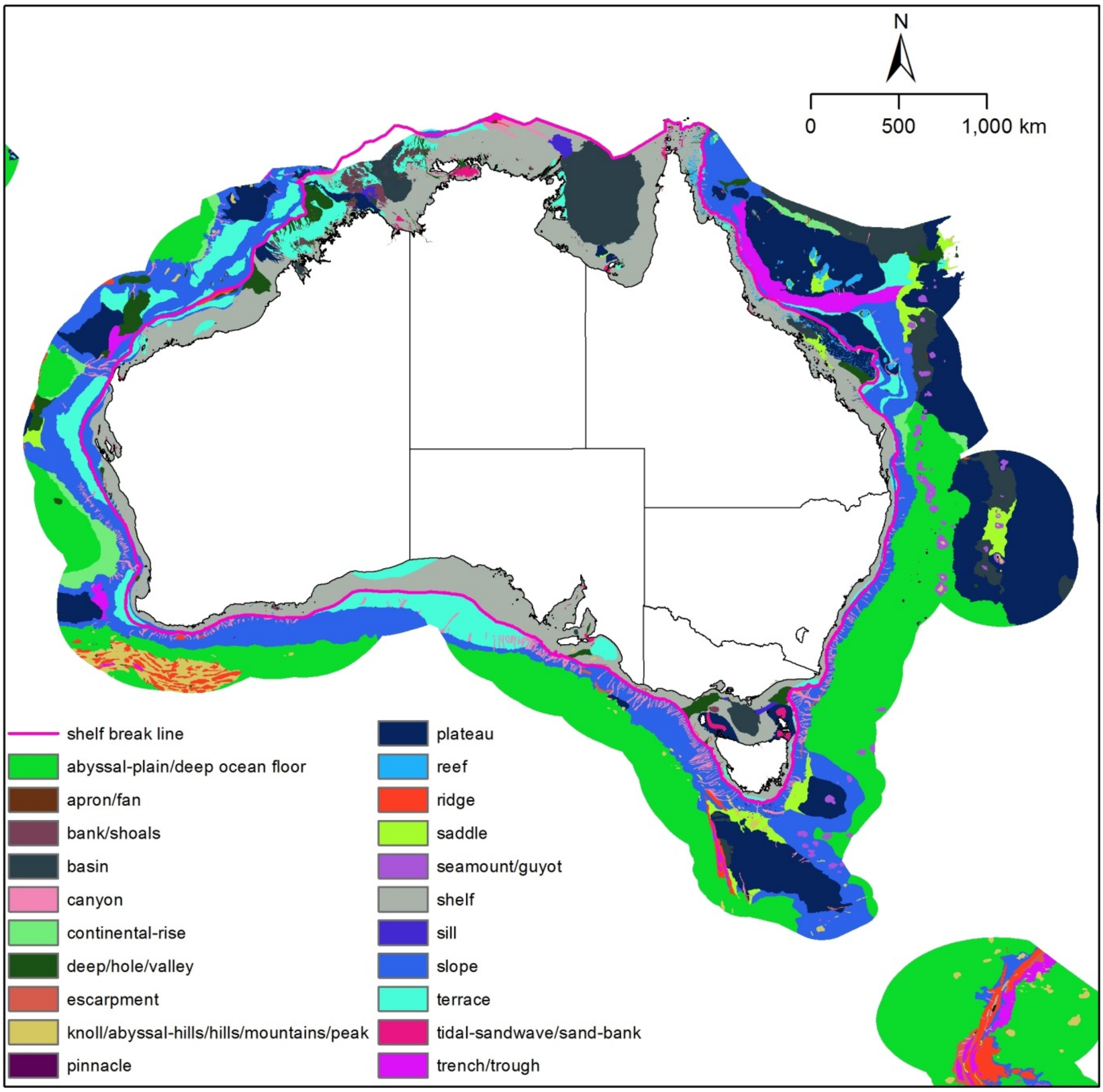

Figure 9. Geomorphic Feature Layer (Heap and Harris 2008).

2.1.4 State-based and other data holdings

The workshop discussion was able to highlight the significant contribution of state-based mapping programs, those at Universities and a number of other continental shelf reef data sources that may be available to the project. While the State-based datasets are the most significant holdings due to their high degree of validation due to being targeted habitat mapping projects, there are a number of other sources that have valuable holdings, including the Oil and Gas industry (Industry-Government Environmental Meta-database – IGEM), offshore consultants (e.g. Chris Jenkins) and ports authorities (e.g. Darwin Harbour). IGEM is a being facilitated by the industry body APPEA and contributors to this database include

Woodside, Chevron, Inpex, Murphy Oil Australia, PTTEP, Quadrant Energy (formally Apache), Santos and Shell Australia. The database is being developed and operated by the Western Australian Marine Science Institution (WAMSI). Table 1 describes an example of key benthic mapping data holdings that may be available to this project.

Table 1. An example of data holdings identified from other Australian data portals and databases with workshop representative listed.

Benthic Mapping Data Holdings	Data set title	Custodian/ Contact
Department of Environment NSW	Near shore sub tidal reef database Marine Habitats 2002 Marine Ocean Ecosystems 2002	Alan Jordan Peter Davies Tim Ingleton
University of Tasmania	SeaMap Tasmania Marine Habitat Mapping series 2000-2009 Commonwealth Environment Research Funding (CERF) South East Region Habitat Mapping National Environmental Research Program (NERP) Commonwealth MPAs Habitat Mapping	Vanessa Lucieer Neville Barrett
Parks Victoria	Multibeam bathymetry of the Victorian coastline Future Coasts Program- Lidar bathymetry of the Victorian coastline	Steffan Howe
Deakin University	NHT, Deakin and Parks Victoria funded state wide multibeam surveys Bonney Canyons survey	Daniel Ierodiaconou
The University of Western Australia	Coastal multibeam data in selected regions	Jessica Meeuwig
James Cook University	Great Barrier Reef Bathymetric data set [10 m, 50 m and 100 m resolution].	Thomas Bridge
	AUSLIG data sets with individual reef sites identified	Robin Beaman/ GBRMPA

2.2 State-based major holdings

In this section, we provide a summary of the survey data that are available to the project within each state.

2.2.1 Queensland

Representatives from the Queensland Government were not able to attend the workshop; however, representatives from the Australian Institute for Marine Science (AIMS) were present and indicated the nature of data holdings for this region. Where possible, all identified datasets will be collated to contribute to this project, and that has been facilitated via existing projects in Queensland that have been actively collating such cross-shelf data in recent years. The Queensland coastline and its associated EEZ to 200 m depth is dominated by major sub-tropical embayments in the south, the Great Barrier Reef at tropical latitudes and the Coral Sea beyond its continental shelf to the east. Its coastline also extends into the more turbid environments of the Torres Strait and Gulf of Carpentaria. Compared to many other regions of the Australian EEZ to these depths, this area has been relatively well studied, yet much of the area remains inadequately mapped using modern methods. There is a critical lack of information about the location and extent of deep-water ecosystems and seabed habitats for about a third of the Great Barrier Reef World Heritage Area that lies deeper than 200 m. In addition, much of the inter-reef seabed shallower than 100 m on the Great Barrier Reef shelf, and many of the shallow coral reefs themselves, have never been adequately mapped.

There are on-going efforts to resolve these information gaps. Project 3DGBR began in 2009 with the aim to collate all existing mapping data in an effort to develop a new high-resolution depth model for the GBR and adjoining Coral Sea (http://www.deepreef.org/projects/48-depth-model-gbr.html). This project aimed to collate bathymetric data collected from surveys using multibeam and single beam echo sounder data, satellite derived bathymetry data and airborne LIDAR. The project area is >3 million km^2, stretching from the Torres Strait to northern New South Wales and offshore into PNG, Solomon Islands and New Caledonia waters. The new 3D bathymetry model, called the gbr100 grid, accurately maps land elevation and ocean depths across this area using a grid pixel size of about 100 m resolution. Version 3 of the gbr100 grid and a range of media are available for download from the Deepreef Explorer website (http://www.deepreef.org/bathymetry/65-3dgbr-bathy.html) (Figure 10. Example of submerged reefs from Hydrographer's passage from Deepreef.org.), with a mirror copy also available on the e-Atlas website (http://eatlas.org.au/data/uuid/200aba6b-6fb6-443e-b84b-86b0bbdb53ac). Version 4 of the gbr100 grid is currently being validated and will be available in 2016, including a peer-reviewed publication.

These high-resolution maps can be coupled with areas of extensive biological surveying and monitoring of water quality, fish and benthic communities in reef and inter-reef habitats. Sampling of the biodiversity associated with deeper reef habitats has recently been receiving increased attention. Benthic imagery in depths from 15-150 m has been collected using an

Autonomous Underwater Vehicle (AUV) from 2007-2015. AUV surveys have been conducted over a large latitudinal range, from Lizard Island (14°) to the southern boundary of the Great Barrier Reef (24°S). Surveys have not been repeated through time, but can provide broad-scale information on benthic community composition. Information on the diversity of hard and soft corals on the shelf-edge in mesophotic depths has been gained through dredge sampling on the Southern Surveyor. AUV data have been combined with geophysical data derived from the GBR100 grid to create spatial predictions of the extent of mesophotic reef habitat in the GBRWHA (Figure 11).

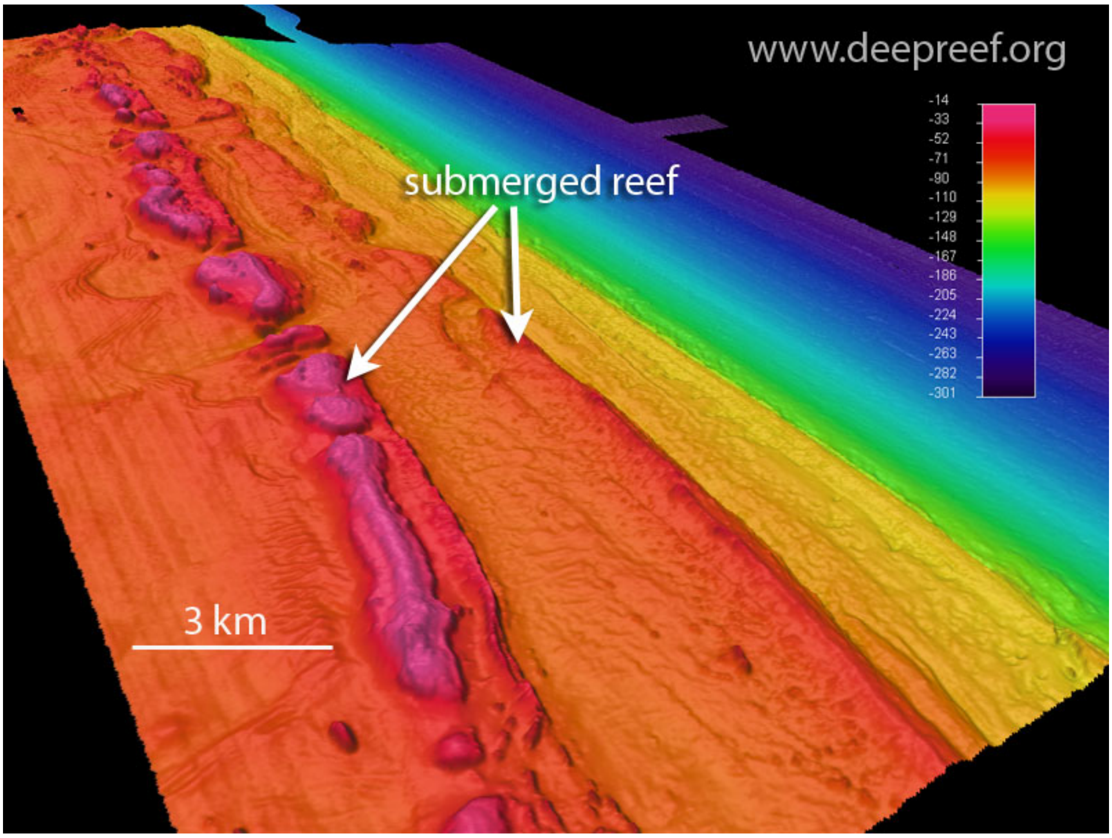

Figure 10. Example of submerged reefs from Hydrographer's passage from Deepreef.org.

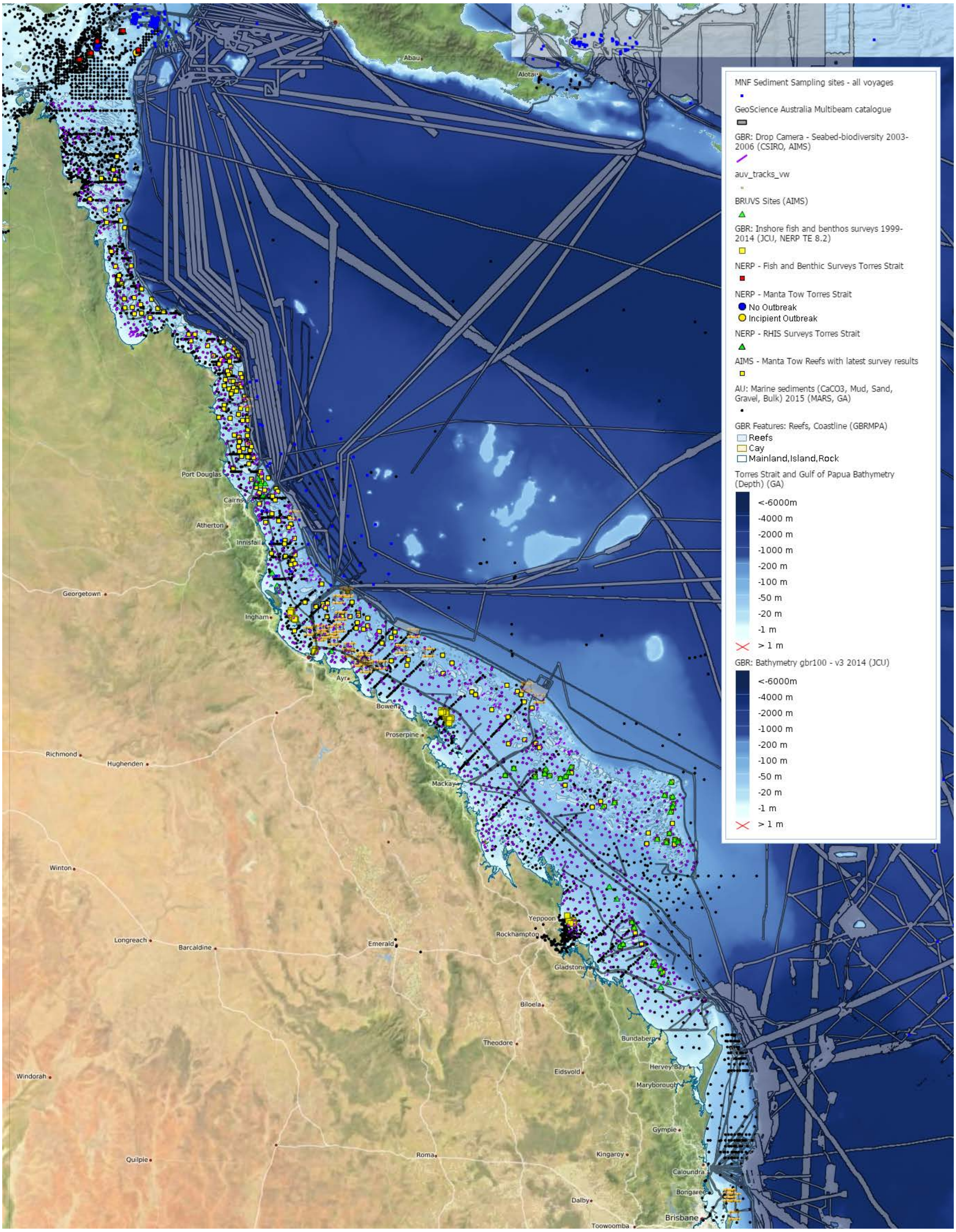

Figure 11. Map of data housed by the e-Atlas relevant habitat classification and associated biodiversity on the GBR (http://goo.gl/Qx9aeZ)

2.2.2 Victoria

The state of Victoria has led a number of initiatives to fill important knowledge gaps focussed on benthic habitats along its 2500 km of coast. This includes over 1500km^2 of multibeam sonar data collected with georeferenced ground truthing information (towed video with USBL positioning). In addition over 4000km^2 of bathymetric LiDAR data were acquired by Fugro LADS Corporation Pty Ltd in 2007 via the former Victorian Department of Sustainability and Environment (DSE now DELWP) as part of the Future Coasts Program for storm surge modelling. This dataset provides seafloor data for the majority of the Victorian coasts to depths of approximately 25 metres which is currently being used for as variety of habitat mapping initiatives (Zavalas 2014, Young et al. 2015) and fisheries assessment (Jalali et al. 2015). Deakin University, together with Australian Marine Ecology and Fathom Pacific have been contracted by the Victorian State Government (DELWP) to collate these and other marine mapping data sources (i.e. extracted from aerial imagery, ports multibeam) to collate and archive existing habitat mapping data in an agreed hierarchical classification scheme. This will include mapping products (i.e. raster/ polygon habitat maps) and ground-truth products from towed (over 100 linear km) and BRUV (>700 drops) Figure 12.

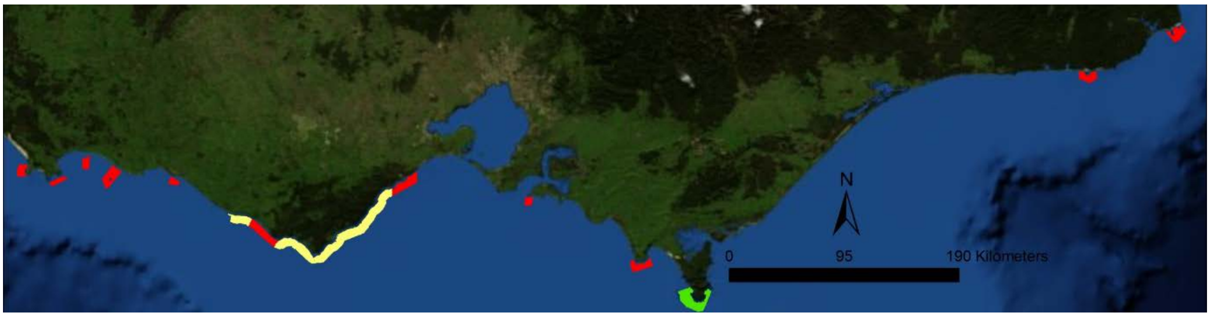

Figure 12. Image showing multibeam sonar data collection specifically for habitat mapping in Victorian coastal waters. Red- Marine National Parks (N=6) and state waters of interest (2005-2007) collected as part of the Victorian Habitat Mapping Project.

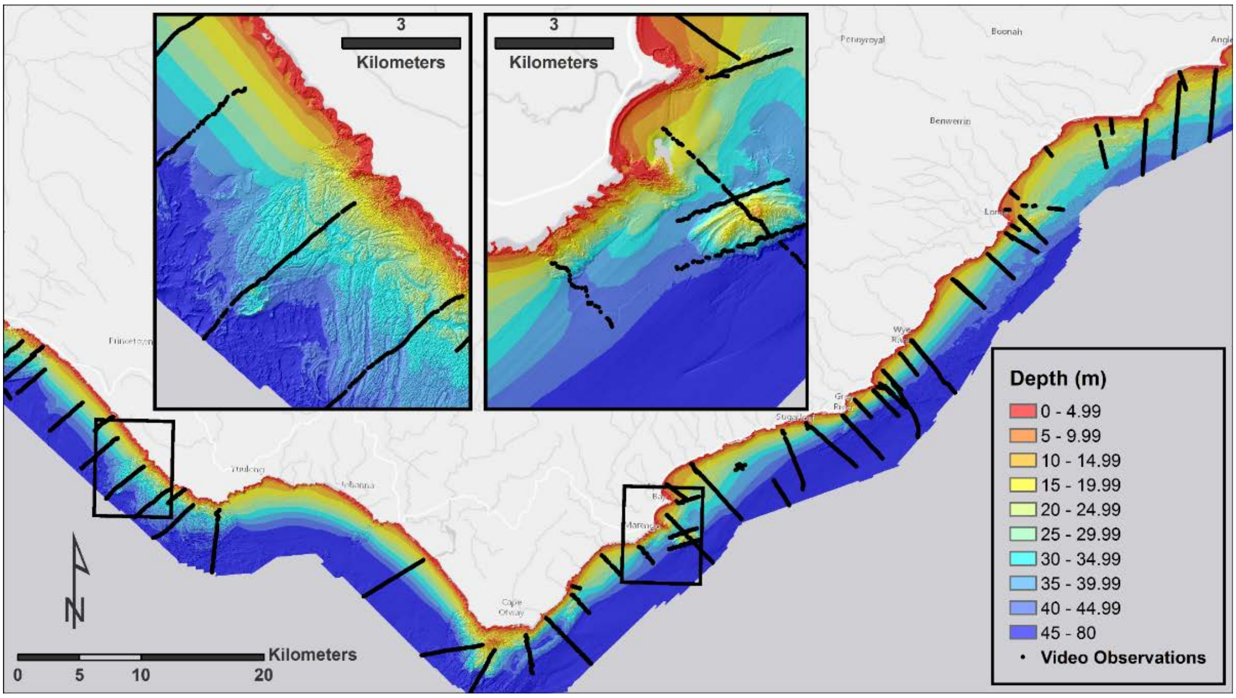

Figure 13. Extensive towed video available from habitat mapping initiatives along the Victorian coastline which have already been used to map Ecklonia forests.

2.2.3 New South Wales

The coastline of New South Wales is approximately 2,137 km long, with a state water area of 8,802 km^2 (http://www.ga.gov.au/scientific-topics/national-location-information/dimensions/area-of-australia-states-and-territories) and a total shelf area of approximately 38,000km^2. NSW has 184 estuaries that include drowned river valleys, bar built estuaries and Intermittently Closed and Open Lakes and Lagoons (ICOLLS).

NSW has had an ongoing program of bathymetric surveying since 1970's. To date 95 of the NSW estuaries have some bathymetric data. Most of this data has been collected using single beam surveys. There is also targeted older single beam bathymetric data from some inshore areas. Since 2005 the NSW government has sponsored a habitat mapping program which has focused on digitising habitat types from aerial photography and from targeted high resolution sidescan or multibeam surveys. Physical habitats have been classified by substrate type (reef or sand). The marine seabed habitat classification has been described in (Jordan et al. 2010)http://www.environment.nsw.gov.au/research/SeabedHabMap.htm and has been compiled as a 1:25000 seabed habitat map series. Targeted towed underwater video surveys have been completed at a number of sites throughout New South Wales to characterise the type of biota. This information has revealed broad patterns of biological assemblages and has formed the basis of the depth classification of subtidal reefs into shallow (0-20m), intermediate (20-60 m) and deep (> 60 m). Within estuaries, habitats are classified by dominant biological assemblages (Jordan et al. 2010).

The NSW seabed habitat-mapping program is ongoing and at the time of writing some 1900 km^2 of State Waters have been mapped using multibeam techniques. A further 550 km^2 of nearshore shallow habitats have been classified from best available aerial photography. The habitat maps are used for marine conservation planning, as an input to the Oil Spill Response Atlas and for Monitoring Evaluation and reporting of environmental condition in the marine environment.

In addition to seabed habitat mapping work 16 sites within the Batemans, Port Stephens Great Lakes and Solitary Islands Marine Parks have been targeted for ongoing repeat surveys using the IMOS/University of Sydney Autonomous Underwater Vehicle. Imagery from these surveys are subject to ongoing analysis to detect changes associated with marine conservation strategies and are available online at https://auv.aodn.org.au/auv/ .

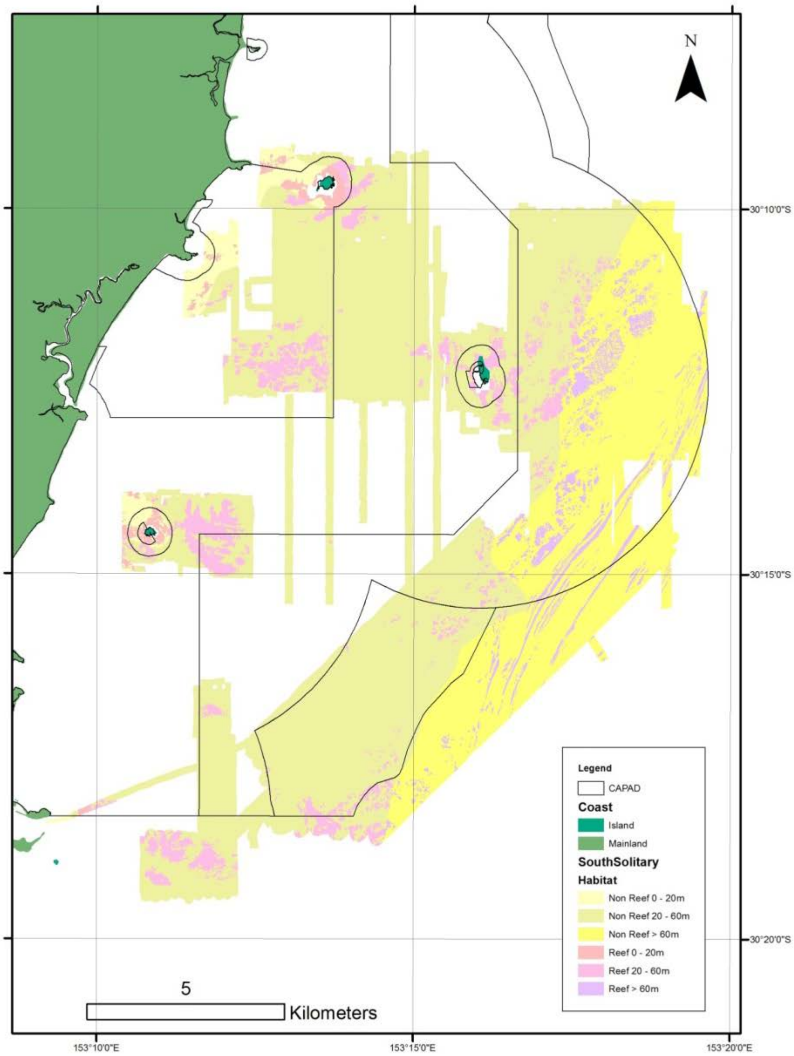

Figure 14. Focus site for New South Wales the Solitary Islands Marine Park.

2.2.4 South Australia

South Australia's (SA) has over 5,716 km of coastline, with approximately 60,282km^2 of area within state waters. Almost half of SA's state waters lie within its two sheltered gulfs. The majority of the benthic mapping carried out in SA to date has focussed on nearshore environments, and in large part been carried out within the gulfs and sheltered bays.

Early seabed mapping began in the 70's and was focussed on geological features although a mix of biological assemblages were often included (e.g. Shepherd and Sprigg (1976)). During the 1990's a broad scale national benthic mapping program was digitised using satellite imagery at a 1:100,000 scale and covered approximately 30% of SA state waters. In the early 2000's a variety of desktop mapping was carried out in localised areas from aerial imagery within the states two gulfs and in bays on Kangaroo Island (for a summary see https://data.environment.sa.gov.au/NRM-Report-Cards/_layouts/15/WopiFrame.aspx?sourcedoc=/NRM-Report-Cards/Documents/Are-the-extent-and-condition-of-our-seagrass-improving-additional-information.pdf&action=default&DefaultItemOpen=1) .

In 2005 the Department of Environment, Water and Natural Resources (DEWNR) began a benthic mapping program for shallow subtidal marine habitats (mostly above 20 m depth), initially within the gulfs and followed later by surveys in the bays of the west coast and shallow waters in the south east (Figure 15). The program was based on the digitisation of physical features visible in aerial imagery and a substantial amount of ground truthing using towed underwater video. Seabed maps were compiled at 1:10000 and 1:5000 resolution with habitats classified by the dominant biological assemblages including a range of reef characteristic types (see DEH project (2009), for an example of the classification scheme). Between 2005 and 2009 this program mapped approximately 10,158 km2 of seabed, 17% of state-waters, including 1372 km^2 of reef habitat (approximately 13% of the shallow, sub-tidal mapped habitats).

A number of other agencies within the state government in SA have also contributed to mapping of seabed habitats in state waters. Primary Industries and Regions SA (PIRSA) carried out multiple mapping and habitat assessment studies linked to fisheries and aquaculture across the state mostly using towed video. The Environment Protection Authority (EPA) collects similar information as part of its ongoing monitoring program. This point video data could provide information about the location of reef habitat but little spatial/area information

DEWNR also has an ongoing mapping program to support its marine parks program. This program has two focusses, the first is a rapid "benthic inventory mapping" method using towed video over broad scale sampling grids (maximum 1km^2 spacing), with the aim of gaining rapid insight into large expanses of previously unmapped seafloor within marine park sanctuary zones. Information collected in this way is mapped into reef, sand and seagrass classes and is used to guide monitoring and more detailed mapping using full cover techniques.

The second part of the program is more targeted and based on high resolution sidescan and multibeam survey techniques, again using targeted towed video surveys to characterise the seabed. Ongoing swath mapping focusses on priority marine park areas (in particular in sanctuary zones), however, to date surveys have covered a variety of areas and habitat types state wide (inside and outside of marine parks) and have covered approximately 225 km^2 in 22 locations. Of the areas covered using swath techniques, the majority have a significant proportion of reef habitat. This information is currently being compiled into a statewide layer, with associated digitised information from aerial photography to produce a classified habitat layer.

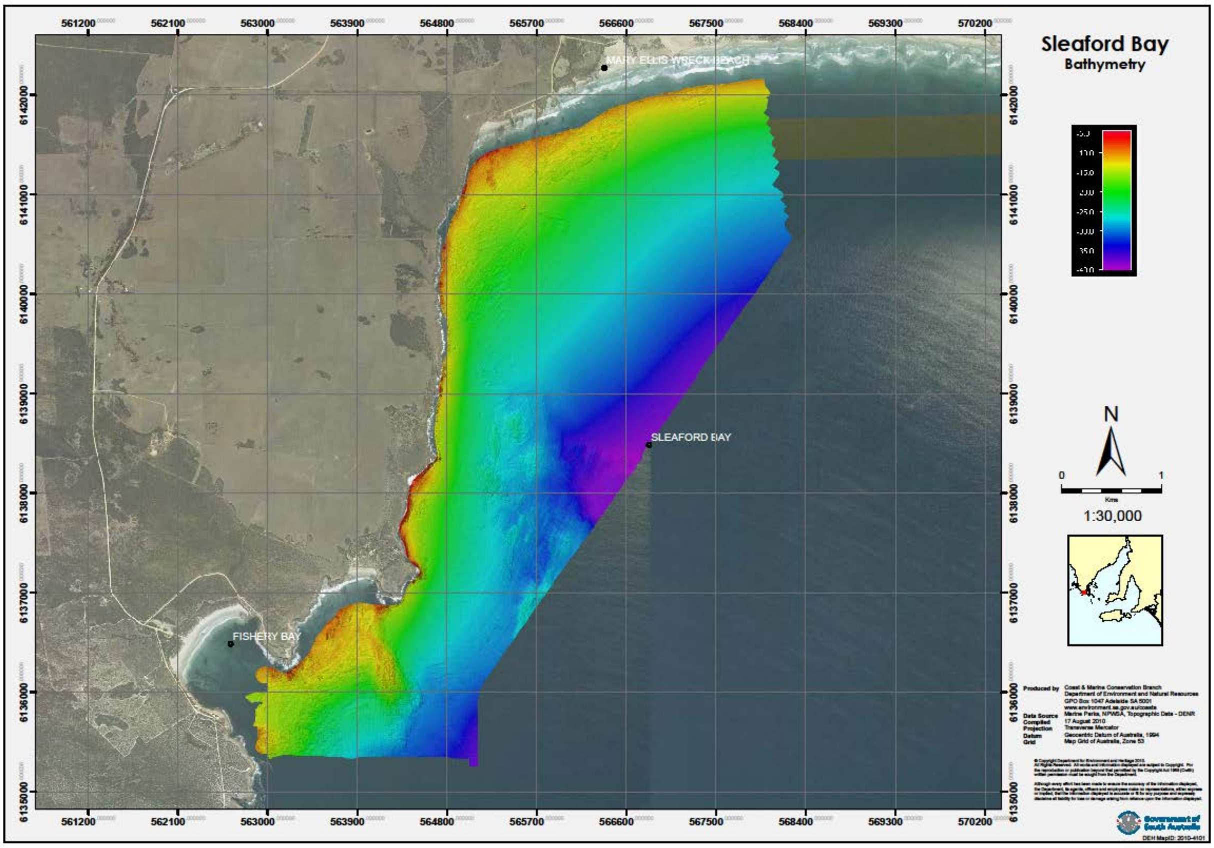

Figure 15. Swath sonar bathymetry for Sleaford Bay on southern Eyre Peninsula

2.2.5 Tasmania

The Tasmanian coastline, with its offshore islands, has a total length of 4882 km. This distance reflects the amount of seabed within its state jurisdiction. It is the fifth longest coastline following Western Australian, Queensland, the Northern Territory and South Australia (ref Geoscience Australia http://www.ga.gov.au/scientific-topics/national-location-information/dimensions/border-lengths). Initial marine mapping in Tasmania focussed on conservation planning with NHT funding, and was based on field surveys using single beam sonars, towed video and digitised aerial photography. Subsequent to completion of the first bioregion-wide mapping program in Australia (the Bruny Bioregion), a project called SeaMap Tasmania was instigated by the University of Tasmania and was funded through National Resource Management (NRM). This project continued the bioregional focus, and mapped 593.90 km^2 of the coastal seabed from the high water mark to the 40 m contour over a period from 2000-2009 (http://seamap.imas.utas.edu.au/) (Figure 16). The aim of SeaMap Tasmania project was to collect and collate data in support of the management of Tasmanian marine resources. Over this nine year period seabed habitat distribution in both estuarine and marine waters was collated into a single Geographic Information System data base. This data base extends from Whale Head in the states south east to the Woolnorth Point in the North West including selected harbours and ports on the west coast, and areas in Bass

Strait. This data was collected through a variety of survey methods which include photographic, acoustic (single beam, multibeam and sidescan sonar), biological and sediment sampling. In the past ten years this information has assisted in a wide range of coastal research and planning issues including marine protected area development, environmental impact modelling and assessment, fisheries assessments, marine farm planning, localised coastal development, State of Environment (SoE) reporting and pollution and oil spill response.

In addition, detailed multibeam sonar surveys have been undertaken in Tasmanian shelf waters through CERF and NERP Marine Biodiversity Hub projects, including coastal waters of the Tasman Peninsula Freycinet Peninsula Figure 17Figure 17)(including Freycinet CMR), Flinders CMR, Huon CMR and Tasman Fracture CMR. While not comprehensive in many of these areas, the mapping illustrates the range of typical cross shelf habitats in each region, and the extent that they are represented in the CMRs.

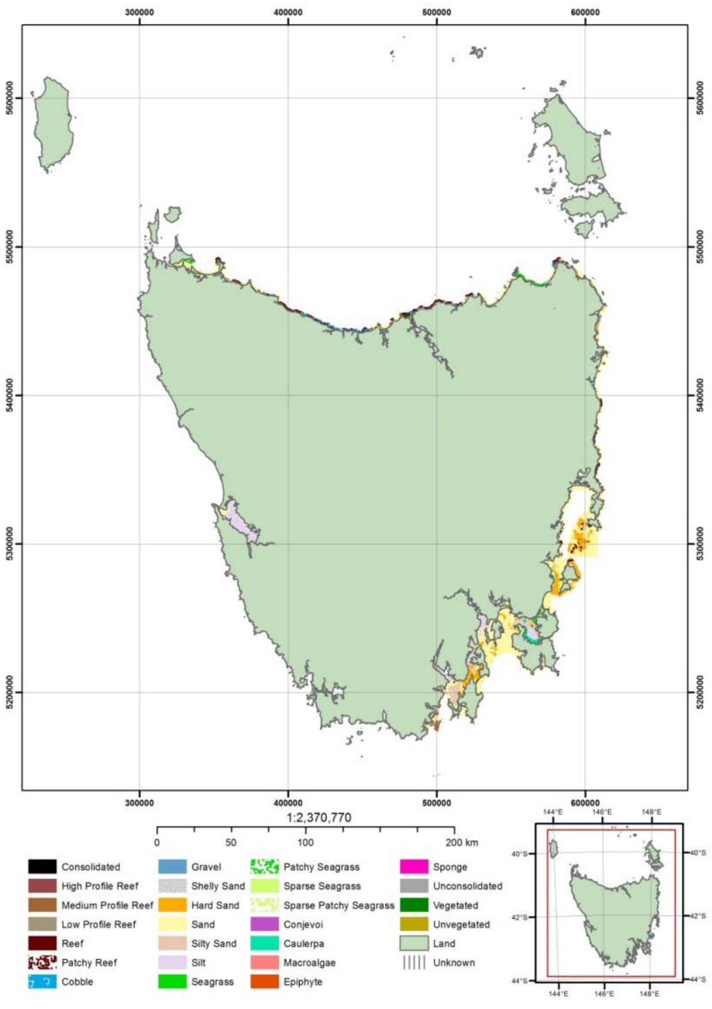

Figure 16. The extent of the Seamap Tasmania surveys conducted between 2000 and 2009 by the University of Tasmania.

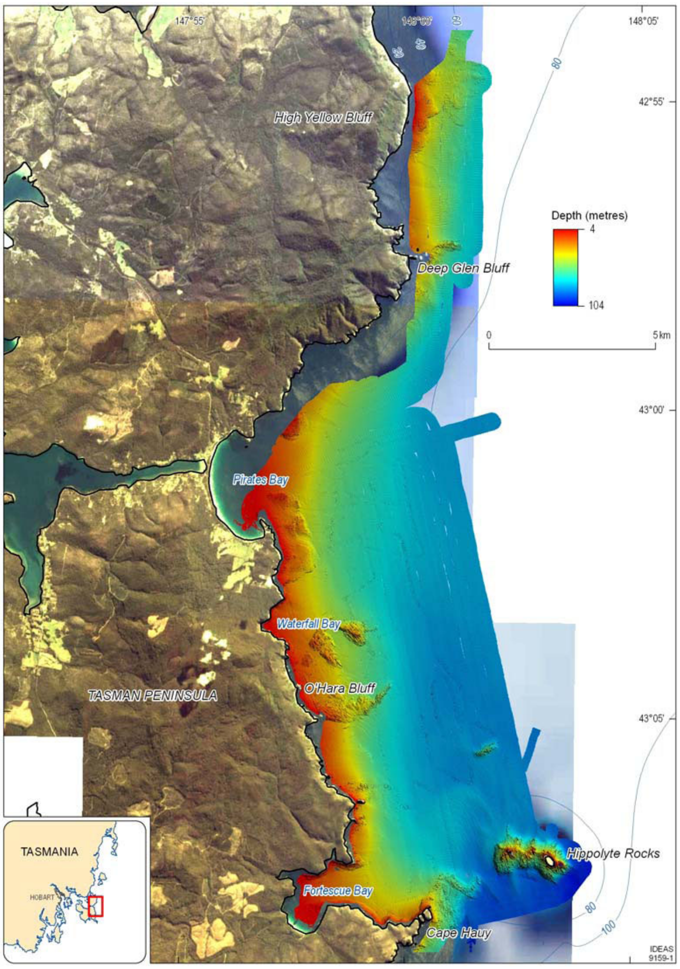

Figure 17. Multibeam sonar bathymetric map of south eastern Tasmania between High Yellow Bluff and Cape Hauy.

2.2.6 Western Australia

Western Australia's coastline is approximately 20,781 km long and with state waters area of 115,740 km^2, surpassed nationally only by Queensland (http://www.ga.gov.au/scientific-topics/national-location-information/dimensions/area-of-australia-states-and-territories). Its marine environment extends from the tropics in the northern Indian Ocean through to the temperate ecosystems of the Southern Ocean. A major feature of the Western Australian shelf is the ancient shoreline that provides rocky substrate paralleling the modern coast. Additionally, the State's offshore islands also cover some 7,892 km of coastline. Reflecting these attributes, rocky reefs play a major ecological role within the State.

There are a number of sources for data on rocky reefs in Western Australia. These include work undertaken through the Natural Heritage Trust funded Marine Futures program that generated high quality multibeam data for eight representative locations in the State's southwest (Figure 18). Each of these locations varied between 100 and 200 km2 in area, and between 10 and 120 m water depth; a total of approximately 1500 km2 was surveyed. Fish and benthic surveys were also associated with each multibeam survey, including the collection of towed video of the seabed.

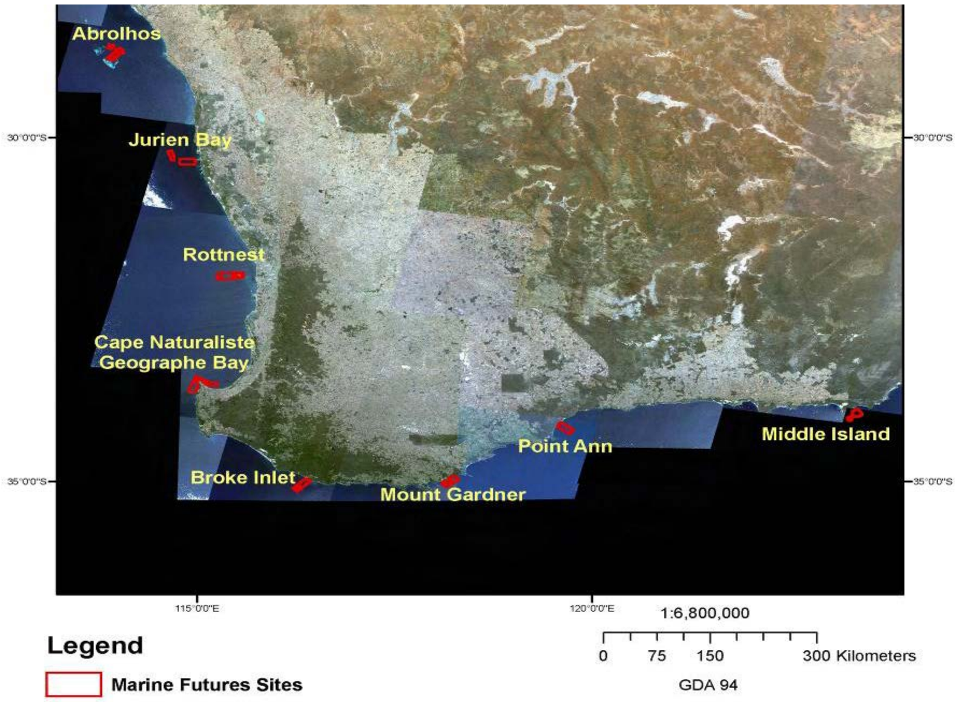

Figure 18. Locations of multibeam data collection along the south western Australian coastline.

Apparent from the multibeam data was the presence of ancient submerged coastlines that now form rocky reefs along the coast (Figure 19). Amidst extensive flats of mobile sediments, these rocky structures support the development of communities of sessile invertebrates such as sponges, and support high diversity and abundance of fishes relative to sediment habitats.

Habitat data on shelf rocky reefs has also been generated by mapping exercises undertaken through the Marine Biodiversity Hub (http://www.nespmarine.edu.au/system/files/Carnarvon%20shelf%20poster_web.pdf) and through the activities of the offshore oil and gas sector. In the latter case, multibeam data collection and benthic habitat mapping can be undertaken as a part of (1) exploration surveys, (2) environmental impact assessments, or infrastructure development (i.e. pipelines). There is a wealth of data held by the sector and discussions are currently underway to make those data available to the NESP Marine Biodiversity Hub.

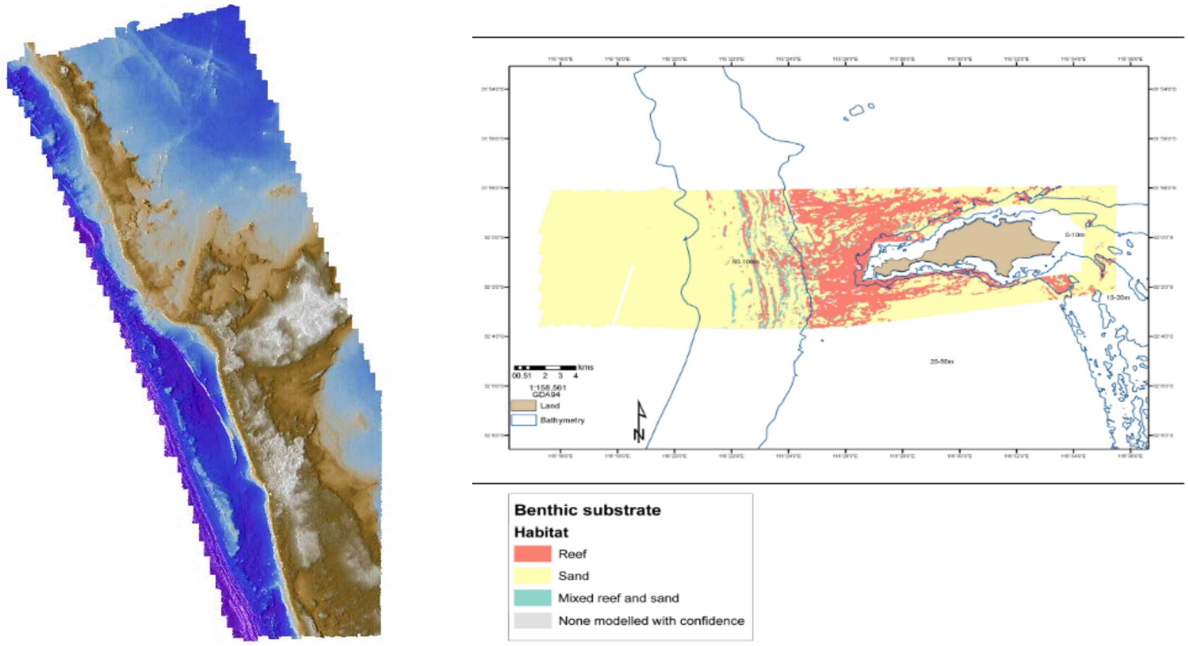

Figure 19. Habitat map for Rottnest Island indicating presence of offshore reef structures.

2.2.7 Northern Territory

The Northern Territory coastline is unique in Australia. At nearly 11,000 km in length, the coastline and adjacent marine environment is remote, sparsely populated and occupies a region of the world with relatively low anthropogenic activity (Halpern 2008). The marine ecosystems are considered relatively healthy and intact with high diversity of habitats and species. The offshore waters comprise of nearly 525,000 km^2 of a relatively shallow shelf having significant heterogeneity in the types of habitat, particularly on the outer Arafura and Sahul Shelves (Heap et al. 2010)

The scientific information on the Territory's reefs is at most modest. The collection of data is predominately driven by the need to establish baseline information to inform sustainable management of marine resources (pelagic and benthic fisheries, oil and gas, shipping), risk assessments of development applications (e.g. oil and gas, port infrastructure development, aquaculture) and conservation planning (Commonwealth Marine Reserves program, habitat use by EPBC Act listed species.

Reefal habitats are known to occur throughout Northern Territory (NT) coastal waters (e.g. Pellew Islands, Groote Eylandt, Wessel Islands, Cobourg Peninsula, Vernon Islands, Bynoe Harbour and Port Keats). Examples of reefal habitats on the shelf include the Bonaparte Gulf (e.g. oceanic reefs, shoals west of Melville Island) and Arafura Sea (e.g. Crocodile Islands, shoals north of the Goulburn Islands). The location of most reefs has been derived from charts, with some near-shore reefs also highlighted in the recreational fishing guide 'Northern Australian Fish Finder '(Flynn M. and Green 2013). However, there are large spatial data gaps that hamper broad-scale assessment of most areas.

Historically, opportunistic sampling of reefs using benthic trawls and diver observations /collections were used to create taxonomic lists and to determine biodiversity values for reef benthic communities in NT coastal and near shore waters. The Museum and Arts Gallery of the Northern Territory (MAGNT) holds much of these data which are centred on Darwin Harbour Vernon Islands, Bynoe Harbour (e.g. Wolstenholme et al. (1997), Hooper et al. (2002)) and Port Essington (Cobourg Peninsula). These data are available through the Atlas of Living Australia portal.

In 2004, the National Oceans Office contracted Australian Institute of Marine Science (AIMS) to describe the spatial variability of coral reef biodiversity across NT waters (Veron 2004, Veron et al. 2004) and Geoscience Australia (GA) to synthesise the geology (including identification of relict and modern reefal structures (Heap et al. 2004) as part the regional marine planning process for the Norther Planning Area. These studies concluded that reefs are diverse and species composition shows affinities to both western and eastern Australian reef habitats; and the Gulf of Carpentaria has potentially a number of submerged reefs and platforms along the 30-40 m depth contour line.

Further, the NT Department of Primary Industries and Fisheries, in collaboration with AIMS, have described a number of reefs across Arnhem Land as part of identifying brood stock and grow out sites for the farming of sponges in regional Northern Territory (Sellers et al. 2004). They conducted a survey of sponge diversity and abundance in waters adjacent at seven localities (20 sites). They used towed video to characterise the benthos and collected sponge specimens at selected sites.

Postgraduate students from Charles Darwin University have studied selected reefal sites in detail (community structure) in Darwin Harbour (Fern 1995) and broadly (giant clams and associated habitat) across northern and eastern Arnhem Land (Penny pers comm).

Seabed mapping of NT offshore and shelf waters using high resolution multibeam sonar is limited (Figure 21). Geoscience Australia and AIMS have undertaken collaborative surveys in targeted areas of the Gulf of Carpentaria (Harris et al. 2004), Bonaparte Gulf and Timor Sea (Anderson 2011, Heap and Harris 2011, Przeslawski 2011, Nicholas 2015)and Arafura sea (Logan et al. 2006). Through sampling and observation from underwater video, these surveys have collected baseline information about broad community and habitat types, including reefs, as well as develop species inventories within the specific survey areas. Initial assessments of these data show that reefs and shoals in the Bonaparte Gulf and Timor Sea are significant biodiversity hotspots for sponges and provide important structural complexity and habitat for other fauna (Przeslawski R et al. 2014, Przeslawski et al. 2015).

Building on the methodologies established by GA and AIMS, the Department of Land Resource Management (DLRM, NTG) partnered with GA and AIMS in 2013 to deliver the INPEX Environmental Offset program 'Mapping Marine and Estuarine Benthic Habitats in Darwin and Bynoe Harbours'. The collaborative project will deliver high quality data on the spatial distribution of physical and benthic community habitats in the Darwin-Bynoe region (2250 km^2). The 4 year mapping program will be completed by June 2018. The project consists of seabed mapping using multibeam sonar, sediment sampling (grainsize, sediment chemistry, carbon and oxygen fluxes, development of hydrodynamic/wave/sediment transport models to derive current strength, bottom stress, kinetic energy and sediment mobility parameters. The benthic communities will be characterised using towed video and still photography. Geospatial analysis techniques will be used to generate products that predict patterns of seabed substrate type and associated benthic communities, including for reef habitats. To date, data have been collected for Darwin Harbour. Mapping in Bynoe Harbour will start in 2016.

The Department of Primary Industry and Fisheries has recently closed five areas between Port Keats, Darwin and around the Tiwi Islands to address concerns for the unstainable harvest of selected reef fish. These reef fish protection areas range in size from 91 to 482 km^2 totalling 1854 km^2. Selected areas within and outside these areas are being mapped using a WASSP multibeam sonar. These maps will help identify sites for monitoring fish abundance using acoustic surveys, and deploying BRUVS to characterise fish reef fish communities Figure 20. Mapping coverage on the NT shelf, showing areas mapped in high resolution using multibeam sonar (A to G) and sites where reef is known to exist from charts but remain poorly documented. (Figure 20).

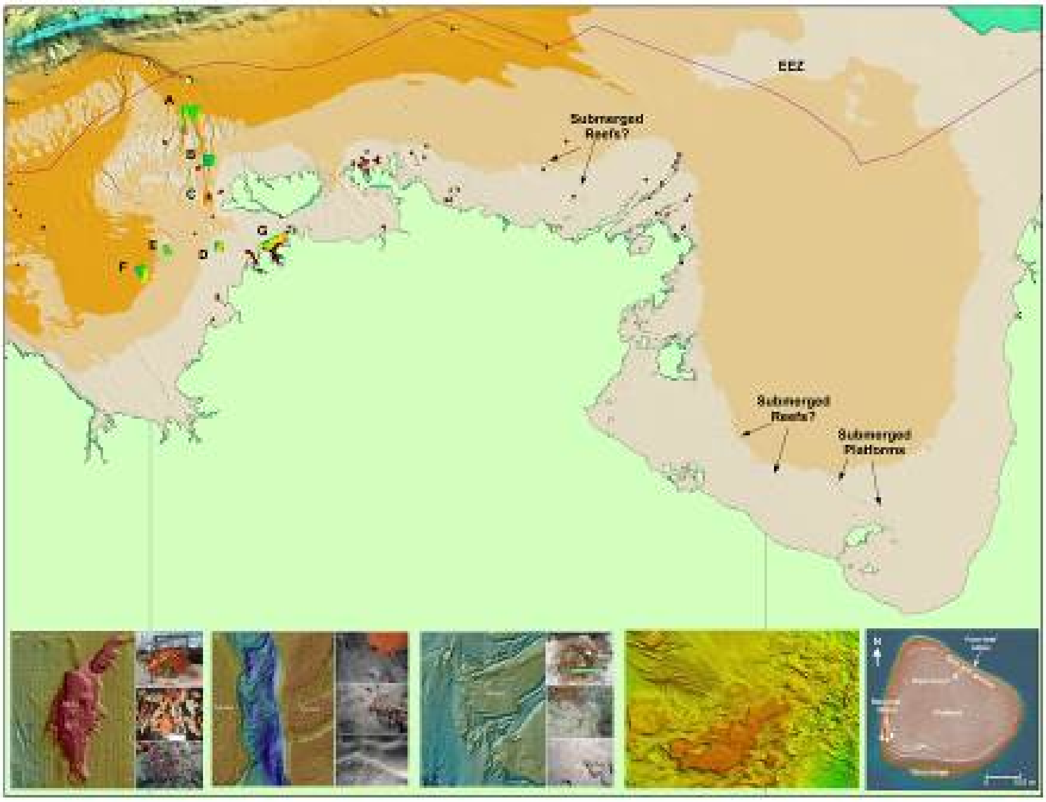

Figure 20. Mapping coverage on the NT shelf, showing areas mapped in high resolution using multibeam sonar (A to G) and sites where reef is known to exist from charts but remain poorly documented.

3. A PATHWAY TO INTEGRATING AND VISUALISING EXISTING DATA SOURCES TO DEVELOP AN UPDATED MAP OF SHELF REEF DISTRIBUTION.

Survey and monitoring programs are needed to identify both the physical and biological value of shelf habitats. Such programs need to have a common approach to reporting of outputs that are consistent at a national scale for State of Environment (SoE) understanding and reporting. In this section, we will review a method for the integration of both geomorphological and physical data to create a national reef map. We will address the classification system that will be adapted for this project. We will also identify a pathway to synthesise both the physical and biological data into one classification for the regional focus sites. This will be reported in Milestone 9 'Report on collation of available biological and habitat inventory data for Commonwealth shelf waters and associated model development'.

3.1 What types of data can we extract reef information from?

There are a number of different spatial data sources that reef data can be extracted. In this project we are keen to explore all types of data holdings that may lead us to generate a complete spatial product of reefs on the continental shelf. These sources include biological data, acoustic data and fisheries data. Some of this data may already exist as a reef spatial product or may need to be processed to extract the required data. Figure 21 demonstrates that classification and processing procedures we will be required to refine the reef spatial data product, due to the potential of it being sourced from a variety of mapping applications, which are likely to have used different approaches to generate the data.

Some examples from previous reef mapping projects include:

- Very high resolution, Multispectral imageries including IKONOS (Knudby et al. 2011) and QuickBird (Mishra et al. 2006, Kendall et al. 2012) ; shallow water only (< 30 m water depth)
- Airborne Hyperspectral data (Lesser and Mobley 2007, Mishra et al. 2007);-shallow water only (<20 m water depth)
- Combination of air photography, multispectral and hyperspectral data (Wedding et al. 2008);-shallow water only
- Multibeam bathymetry (Dartnell and Gardner 2004, Harris et al. 2004, Roberts et al. 2005, Beaman et al. 2008, Lucieer et al. 2013, Huang et al. 2014).
- Lidar bathymetry (Chust 2008, Zavalas et al. 2014)-shallow water only
- Multibeam backscatter (Cochrane and Lafferty 2002, Erdey-Heydorn 2008, Huang et al. 2013, Lucieer 2013, Lucieer et al. 2013, Huang et al. 2014); and
- Sidescan backscatter (Kendall et al. 2005, Degraer et al. 2008, Lucieer 2008)
- Fisheries data (Williams et al. 2009)- on untrawlable grounds may indicate seabed with high degrees of rugosity or reef.

These data sets are shown as examples in Figure 22. In some instances, the data may be point samples (without any spatial representation of reef boundary's) through to high-resolution three-dimensional data sets with fully complemented biological data.

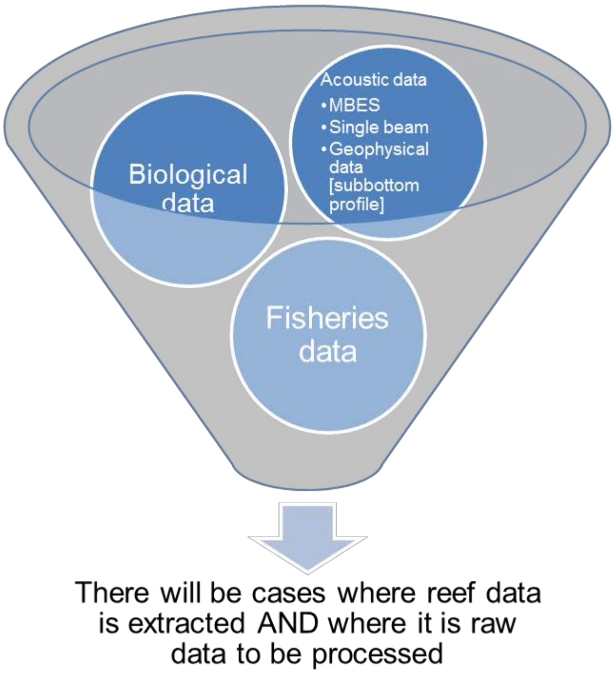

Figure 21. We will be required to generate approaches to consolidate all available spatial data to generate a synthesised output data product.

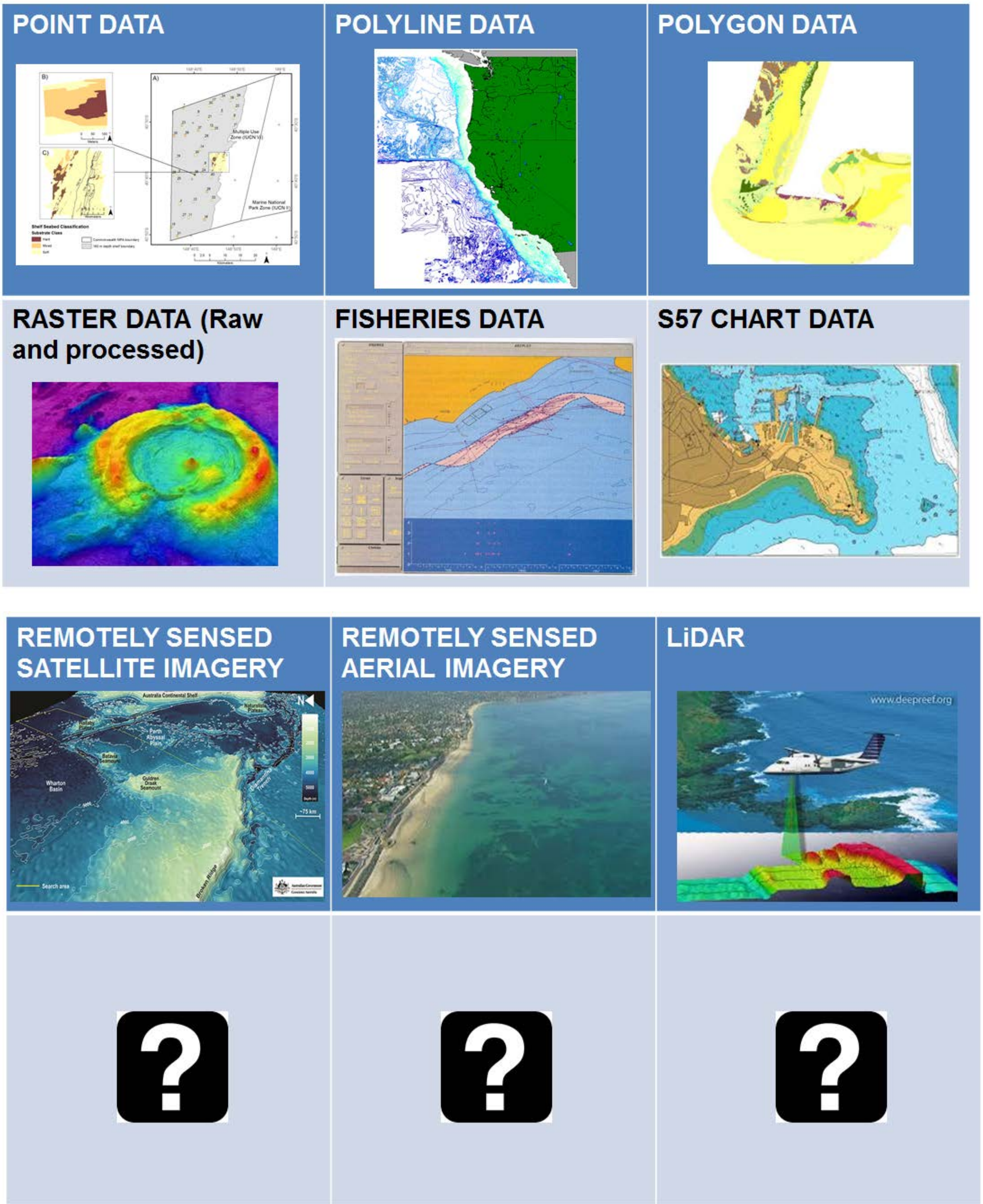

Figure 22. Examples of datasets that reef information may be able to be extracted from. These data range from very high spatial resolution with high degrees of spatial accuracy to broad scale data that will generalise the spatial boundaries of the reefs

3.1.1 Reef mapping techniques

Sub tidal rock reefs are composed of rocks or carbonate material that is always submerged. The can be found in both shallow and deep water across the shelf. Reefs provide an essential solid foundation which many plants and animals need to survive. Shallow reefs can support extensive marine plant communities forming kelp forests whereas deeper reefs can support a large diversity of sponges and marine invertebrates.

Over recent years there have been significant technological developments that have made mapping reef systems possible over large areas of the continental shelf. The latest remote sensing technologies such as acoustics allow measurements of depth and intensity of the backscatter energy to estimate the seafloor hardness and roughness over large areas (Lucieer and Jordan 2007, Brown et al. 2011, Lucieer et al. 2013). There are a number of airborne and vessel based techniques that are currently used to map bathymetry and seafloor roughness and hardness, and these are often combined with data from existing aerial photos and broad scale depth soundings to profile information on reef systems at different resolutions. Bathymetry data can be used to construct seabed digital terrain models (DTM) from which seabed morphology can be identified and mapped. In addition, many secondary terrain variables such as slope gradient, topographic relief can be derived from bathymetry data for the better mapping of seabed geology, morphology and substrate types (Lundblad et al. 2006, Wilson et al. 2007). Reefs can be identified from bathymetry data and terrain variables as they are often have higher topographic relief than surrounding flat seabed (Dartnell and Gardner 2004, Zieger et al. 2009, Huang et al. 2014). Bathymetry data can be derived from different sources including satellite altimetry (Smith and Sandwell, 1997), multibeam eco-sounder (De Moustier and Matsumoto, 1993), bathymetric sidescan sonar (De Moustier and Matsumoto, 1993), bathymetric Lidar(Costa et al., 2009), and optical remotely sensed data (Mishra et al., 2007; Fearns et al., 2011). Acoustic backscatter data are mainly obtained from either multibeam eco-sounder (De Moustier and Matsumoto, 1993) or sidescan sonar (Searle et al., 1990). For optical remote sensing, the suitable data for bathymetry estimation and substrate mapping include air photography, moderate and high resolution multispectral imagery, and hyperspectral imagery. It should be noted that Lidar and optical remotely sensed data are only applicable for the coastal areas with clear and shallow waters, due to rapid attenuation of light in water. Multibeam and sidescan sonars can operate in a much larger depth range, from a few metres to a few thousands metres.

The backscatter intensity is largely controlled by three seabed physical properties: the acoustic impedance contrast (often called “hardness”), apparent interface roughness (relative to acoustic frequency) and volume inhomogeneity (Jackson 1996, Ferrini and Flood 2006). Rocky reefs, due to its much stronger hardness than soft sediment, normally incurs stronger backscatter return, which can be easily differentiated from sediments on backscatter data (Lucieer 2008, Huang et al. 2013, Huang et al. 2014). Similarly, substrates would have different spectral signatures on optical remotely sensed data. This warrants the use of optical remotely sensed data such as hyperspectral imagery for the classification of coral reef and other substrate types (Mishra et al. 2007).

To translate the reef data into reef information we need to examine appropriate methods to do so. Reefs can be mapped manually or automatically. Automatic mapping approaches often can be further divided into unsupervised, supervised and hybrid techniques. Visual interpretation relies on the experience and knowledge of the domain experts. The manual mapping techniques such as on-screen digitising are often supported by GIS and 3-D visualisation environments. Despite its subjectivity, the manual method is still popular for reef identification and mapping (e.g., Harris et al. (2004), Kendall et al. (2005), Roberts et al. (2005), Beaman et al. (2008), Wedding and Friedlander (2008), Kendall et al. (2012)). As an example, this is the approach currently adopted for mapping in NSW state waters, with digitised polygons (reef outlines) being the primary processed data product from the raw mapping data.

Unsupervised classification is a data-driven approach without involving ground truth samples and expert knowledge. This approach is an iterative process that eventually assigns a data point into a class, with the aim to maximise inter-class variances while minimise within-class variances. Reefs have been mapped through unsupervised methods such as ISODATA (e.g.,Mishra et al. (2006), Mishra et al. (2007)). Supervised mapping methods require training samples. A supervised learning algorithm analyses the patterns of the training data and produces an inferred function to separate the data into classes. The model developed in such a way can be used to make predictions at unseen data points. Reefs can be separated from other substrate types using traditional supervised algorithms such as Maximum Likelihood Classifier and Minimum Euclidean Distance Classifier (e.g., Lesser and Mobley (2007), Chust (2008), Erdey-Heydorn (2008), Knudby et al. (2011). More recently, advanced non-parametric algorithms such as classification trees, neural networks, and K-Nearest Neighbour have been used for reefs mapping (e.g., Huang (2013), Lucieer et al. (2013), Huang (2014), Zavalas et al. (2014)). In addition, rule-based classification techniques, used alone or in combination with other classification techniques (i.e., hybrid method), have also been used for reefs mapping (e.g., Dartnell and Gardner (2004), Lucieer and Pederson (2008), Lucieer and Lucieer (2009).

The workshop discussed the range of data available from stakeholders and ways of integrating this data into a tool for visualising all the available datasets to readily identify where cross-shelf reef systems were known, and their nature and extent where this is known. Given the complexity of the differing data sources this is a significant challenge but remains a key focus of activities within this project during 2016. Associated with this is the development of capacity and protocols to add datasets to a national database structure, regardless of their nature, including raw multibeam data, gridded products from multibeam surveys (xyz point data), polylines, polygons etc. This remains a significant challenge, and its uptake will vary depending on state/institutional willingness to contribute data at various levels but we aim to have the necessary infrastructure in place to facilitate storage of such datasets where agencies are willing. The workshop heard that significant shelf-based multibeam survey datasets may have been erased by one national agency due to an incapacity to hold such large datasets, and ideally a national facility could be established to ensure such valuable data was able to be retained in the future.

4. REEF CLASSIFICATION

Mapping and classification are a means to collect information and group it into meaningful and consistent categories that can be used for a variety of purposes. In the marine environment, mapping and classification is recognised as an essential tool for management and conservation, and with increasing use and exploitation of the marine environment for recreational and commercial industries it is clear that effective management will be key to ensure marine resources are sustained into the future.

4.1 Key questions to ask when adopting or designing a reef classification scheme

As noted in Edmunds and Flynn (2015) there is presently no comprehensive marine habitat classification scheme for Australia. Of the nationally adopted classifications schemes the habitats that are identified are usually broad habitat features and substratum types (e.g., reviews by Ball et al. (2006), Mount and Bricher (2008)). At the workshop we discussed the need to develop a nationally applicable and accepted scheme for classifying cross shelf habitats (that specifically focus on rocky reef systems) based on geomorphology and mappable physical and biological processes that in turn may structure the distribution of biodiversity. These discussions focussed on the overall need, as well as schemes adopted internationally in this space as well as being developed locally for Victorian State waters. A range of presentations reviewed existing schemes and potential ways of adopting and refining such schemes for Australian needs and conditions. This was followed by a one day specialist meeting to make progress on potential schemes, and to test the extent that they may meet regional variation and needs. The aim of the workshop, and the project in general was to develop a working scheme and test it in some case study areas for suitability. While the scheme itself can ultimately be applied from local to national scales at varying levels of complexity, it is not a planned outcome of this project itself, as retrofitting existing mapping data with such a scheme is a significant task in itself, and in many cases, requires substantial additional data that is not currently available in most areas.

The initial intent and purpose of any mapping survey will dictate the attributes that are labelled onto the spatial classes that are identified. As broad scale surveys for mapping the seafloor are generally the first phase of exploring a marine area, the initial classes that are selected usually represent what can be mapped using remote sensing technologies and summarises the knowledge of a marine area into dominant classes. Table 3 indicates that the purpose of a mapping survey will define the habitat scale and objectives of a classification scheme. The objective is then representative of a particular information type.

So while the finer levels of a classification scheme will not be applied to outputs from the D3 project, the first phase of the D3 shelf reef mapping project will produce a ‘summary of knowledge’ Level 1 (Table 2) classification around the nation. At this level the classification of the seafloor will be dominated by broad geomorphic features which can be identified on the seafloor as potential reef habitats. As a more refined example of how this scheme could apply when there is sufficient knowledge, the second phase of the project will then move to Level 3 (Table 2) where indicative distributions of regional scale habitats showing biological details will be presented for regional focus sites (as explained in section 2.3). The purposes of the mapping initiative distributions will influence how we structure the geo database in terms of classification, detail, data types, implied accuracies etc.

Table 2. The purposes of establishing a national habitat classification scheme for Australia.

Scope	Objective	Information type
1. Summary of knowledge	Provide a summary of knowledge at a nation level for spatial policy	Broad distribution patterns of major ecosystem components
2. Overview of habitat knowledge	Show distribution of major habitat types that are relevant to policy (e.g. reefs, seagrass, mangroves)	Characteristic habitat distribution patterns (GIS layers) and summary statistics
3. Indicative distribution map of habitats	Provide a regional spatial inventory relevant to local context for site selection and management of physiographic units	Moderately detailed map of habitat distribution
4. Reliable habitat distribution map	Provide baseline distributional data/boundary determination for site specific management	Information on the extent and composition of habitats
5. Monitoring baseline	Provide a baseline for critical condition monitoring	Robust data on distribution, boundaries and composition of key habitats [Statistical baseline data/ requires repeat surveys of habitat composition.

D3 Shelf Reefs Mapping Primary Goals in Phase 1

When choosing to adopt or develop a marine habitat/geomorphology classification scheme there are a number of higher level objectives that need to be addressed to ensure that the classification is suitable for the aims of the project.

4.2 Objectives of a classification scheme

Classification has application beyond reef environments
Although this study is primarily focussed on rocky reef environments, it should be flexible to allow for the inclusion of other geomorphic structures at a later date. This would enable not only the management of one particular feature, but a holistic strategy for all seabed features.

Classification is methodical and structured
The classification scheme should be well-structured and have easy navigation through the framework allowing a methodical decision-tree based delineation of various reef/seabed morphologies. At each level there should be feature descriptions and to aid the correct classification and decision.

Classification is readily coded for efficient spatial analysis
Characteristics of the recommended schemes include that they are well-structured, and employ coding to represent each choice in the hierarchy so that a feature would have its typology recorded. Advantages of this includes facilitating easier and rapid analysis in a GIS (Greene et al. 2008). Allotting coding representing a reefs features typology is advantageous for environmental managers as it relays information of a feature in a concise manner.

Able to maximise the availability of data (don't dumb down just to fit a "scheme").
The amount of data on continental shelf reefs is varied, therefore the framework must accommodate this as it would be unrealistic to have complete data at all levels. Accuracy of survey methodology and techniques become more sophisticated over time and some areas will always be more surveyed than others. A good classification scheme should allow the available information about a reef feature to be categorised within the framework to be captured and not made redundant because there is no information or data above and below in the hierarchy. In simple terms, a reef can be 'tagged' with just one descriptor if all that is known is that descriptor (e.g. depth), rather than the whole reef being labelled as "unknown" if no other information in a hierarchy is available (such as "pavement").

Provide the potential for inter-and intra- reef analysis and description where data is available
A classification scheme should have capacity (based on the availability of data) to go down to a fine spatial resolution thereby allowing not only analysis between rocky reefs, but the variability within a reef.

4.3 What classification schemes have been adopted internationally?

There are approximately 14 international hierarchical schemes for characterising marine habitats (Greene et al. 2008). A direct comparison between schemes can be difficult (Figure 23) as many classification schemes were developed for specific habitat types, different data collection methods and conflicting terminology, making the compatibility and transference between classification schemes problematic (Lund and Wilbur 2007, Greene et al. 2008, Harris and Baker 2012). There have been several reviews of hierarchical classification schemes (Lund and Wilbur 2007, Greene et al. 2008, Harris and Baker 2012). In a major report, Lund and Wilbur (2007) reviewed several hierarchical schemes for a classification feasibility study for coastal and marine environments in Massachusetts, Massachusetts Office of Coastal Zone Management, Boston. They produced a list of appropriate schemes according to various criteria. This report, schemes examined by it, and produced subsequently were reviewed by researchers associated with this project (UTas and GA) and the state of Victoria prior to the workshop and their benefits/suitability for incorporation into an Australian scheme was discussed at the workshop. A review of this literature and how it was used to inform the final classification scheme we propose for Australia will be included in our final report of the geomorphological classification.

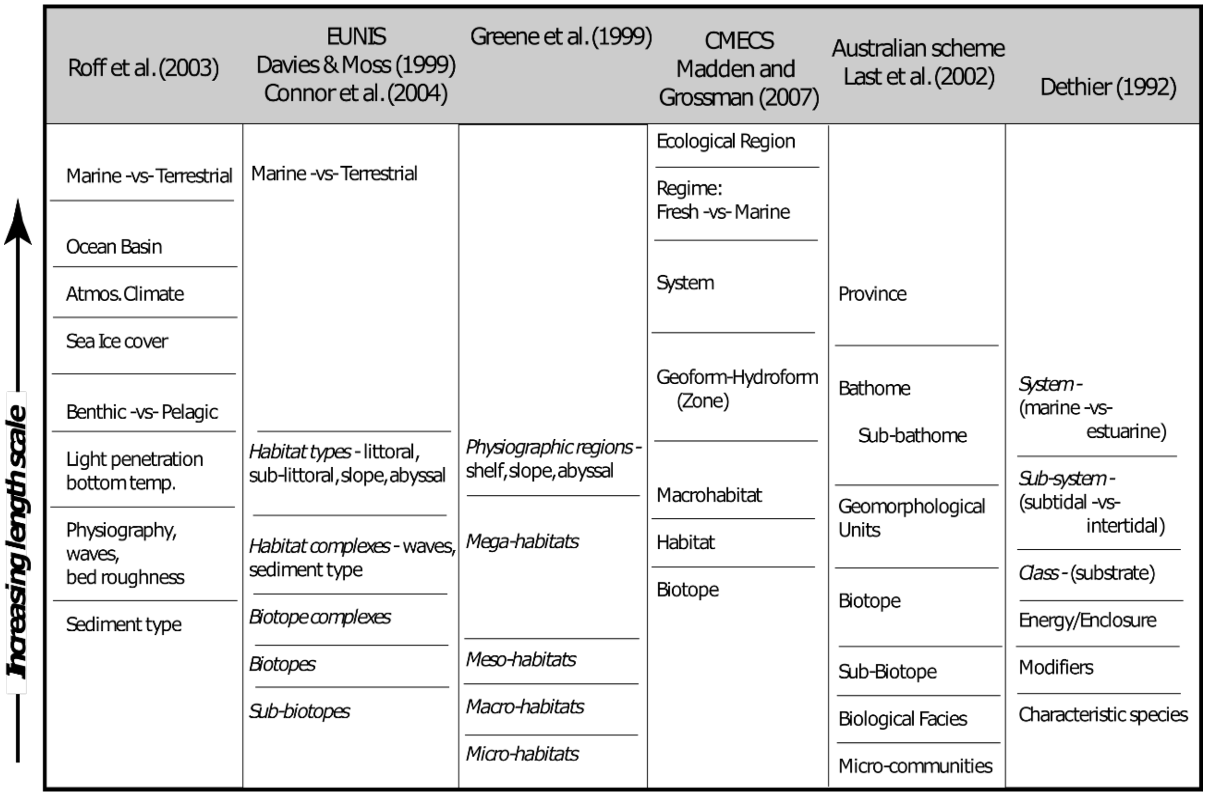

Figure 23. Comparison, on the basis of length scale, of the hierarchical schemes (Reprinted from Harris and Baker (2012) Seafloor Geomorphology as Benthic Habitat: GeoHab Atlas of seafloor geomorphic features and benthic habitats).

One of the most versatile and successful hierarchical schemes is the Coastal and Marine Systems of North America (CMECS) funded by NOAA. CMECS (Madden et al. 2005) can accommodate freshwater and marine components. It was initially developed for use in North America however, due to its flexibility and versatility; it is rapidly being adopted and altered by leading research agencies. North America has a highly variable range of climatic conditions. Many are similar to Australia however, due to the CMECS framework and the ease of including new features it allows Australian unique features to be included.

There has been much work done on hierarchical classification schemes in Australia (Butler et al. 2001, NOO 2004, Beaman et al. 2005, Heap and Harris 2008, Last et al. 2010, Huang et al. 2011) yet not one classification scheme has been adopted nationally. We propose in this project to work from the CMECS scheme and develop inclusions for our unique reef habitats and data sets.

Boundaries in the natural world particularly in the marine environment are rarely categorical (Harris and Baker 2012) and any boundaries are more likely to be fuzzy or transitionary (Lyne et al. 2009). However, for effectual environmental management it is necessary to impose boundaries as it gives structure for decision making. However, every level of a hierarchy should be rule-based on an understanding and conceptualisation of a natural process (Poiani et al. 2000).

The classification scheme that we adopt shall be well-structured and will use codes as is inherent in the CMECS system. The hierarchical structure of the CMECS scheme will allow for a methodical decision tree-based delineation of various reef features. At each level of classification there are descriptions to aid in categorisation. This classification codes have been developed for facilitating subsequent analysis using a GIS (Greene et al. 2008) enabling environmental managers make informed decisions from the constructed reef spatial geodatabase.

Not all reefs would be fully documented at every level of the classification structure. CMECS has the capacity to deal with lack of data and can accommodate a partial classification and missing information above and below the hierarchy. As schemes improve over time, it is necessary to reclassify past efforts. Through the CMEC decision-tree structure, and detailed descriptions, reclassification of previous classification efforts is possible and accommodates the re-classification of a reef feature from older and more redundant schemes and allows for the inclusion of other geomorphic feature in the future.

A notable advantage of CMECS is that it adheres to many international standards. For instance, the International Hydrographic Organisation's descriptors for sea bed substrate characteristics displayed on hydrographic charts and geological definitions including quantitative descriptions of consolidated materials and unconsolidated material. IHO standards – GA's seascapes were based on these standards. This makes reclassification possible. This has the advantage of international conformity. It is worth noting that current work done at Geoscience Australia on seascapes is a derivation of IHO standards and very closely aligned allowing for direct comparison.

By adopting CMECS it puts us on a common international standard but still having the flexibility and versatility to include features unique to Australia. Another advantage is that by having common standards with the international community, it enables a future capacity to compare and research not just regional but global variability. To test the CMECS classification scheme, part of a NSW reef system was reclassified in the workshop using CMECS standards and definitions as laid out in the manual and derived CMECS geoforms for Australian reefs and development of a classification. Through this exercise State agency experts familiar with the seabed variability of the region found that geoforms were able to be adequately classified, including small scale features down to 1m resolution, and were therefore a suitable fit to the classification needs of NSW agencies.

Subsequent to the workshop, and following the decision at the workshop that the best approach to move towards an Australian system with international comparability was to adopt and refine the CMECS scheme with a revised set of terms (vocabulary) and match it with an additional and suitable set of environmental attributes to move a geomorphological classification scheme further towards one additionally suitable for habitat classification and biodiversity description/prediction. Subsequent to the workshop a working group has continued discussions around developing a suitable adaptation of the CMECS scheme and matching environmental descriptors. The draft set of CMECS descriptors and modifications/additions to these is shown in Appendix C, and these will now form the basis of further revision over the next six months. This will include refinement and robust testing of the scheme by all interested agencies to ensure it meets their needs from the broadest to finest scale, and is likely to be adopted as a nationally accepted and utilised standard.

Figure 24 and Figure 25 provide an example of the CMECS classification scheme for physiographic setting to geoform type and the hierarchical workflow to move from substrate to subgroup.

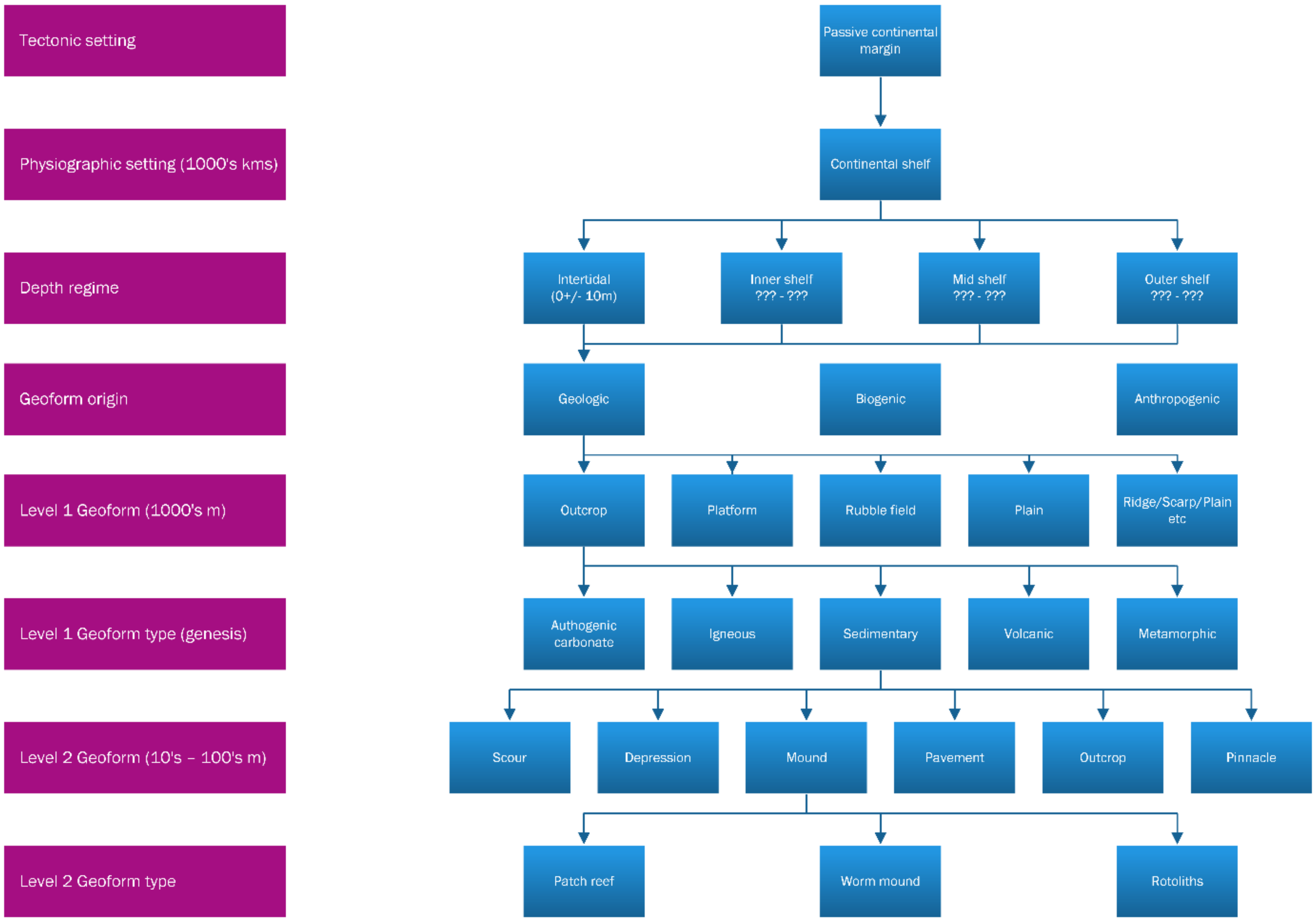

Figure 24. CMECS - Physiographic setting to Geoform type.

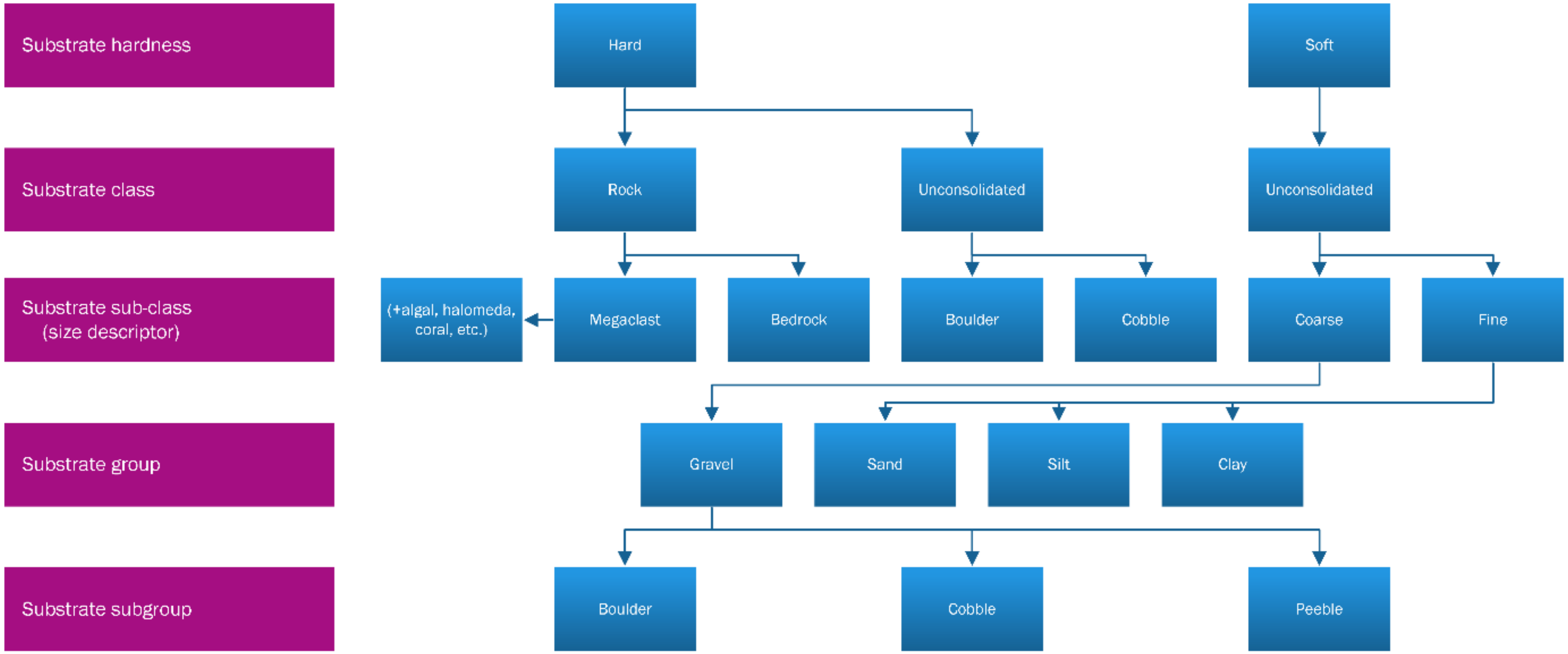

Figure 25. CMECS – Substrate to subgroup

As mentioned above, in addition to the geoform classification, additional environmental factors can play an important role in structuring the biological assemblages that may occupy these reefs. Hence mapping these additional features is important for transforming geoform classifications into habitat level classifications. Some of these have been explored recently by the Victorian government for refining classifications in state waters (Edmunds and Flynn 2015, Edmunds and Flynn 2015). These factors, and more, were discussed at the workshop with participants and several key environmental drivers have been subsequently refined for application within an Australian scheme, including descriptors of productivity and exposure to swells, waves and currents. A draft set of these environmental modifiers is presented here as Appendices D and E.

To further facilitate the range of details encapsulated in the hierarchical classification schemes where features can be numerically coded to the finest scheme level based on that hierarchy, an additional "tagging" approach can also be used for more specific attributes of reef classification, such as the presence of specific biological features. The "tagging" approach consists of defined vocabularies and terms (e.g., tags) that describe a range of geo-bio-physical characteristics of a reef. These vocabularies and terms can be arranged in a structured (e.g., flat table) or non-structured (hierarchical) form. So, there is considerable potential for capturing a variety of information in a flexible manner. For example, a reef can be classified and tagged as:

Location [lat:-42.896,lon:170.288 to lat:-43.839, lon: 170.389]
--Taxa [] (No biology items recorded)
Topography [terrace of bank on shelf]
Measurements [temperature:15.25°C]
Origin [non-biogenic]
Feature [bank on shelf]
Gear [grab; box core]
Partitioning the data into different categories would be achieved by querying for tags matching a defined set of conditions:
For example: Reef class 1 = geography[North OR North-west Commonwealth waters] AND origin[biogenic NOT rubble] AND feature[Shelf OR Slope] AND taxa[COUNTOF(coral)>1]

Note that no hierarchical order is required with this type of system. Splitting on location, for instance, can happen before or after a split on feature type or taxa. Adopting a tagged approach would also make it possible to work with varying levels of data resolution (including absent information). For example, it is possible to identify that Oceanic Shoals Patch 2 is contained within the North OR North-west Commonwealth waters (coarse split), whereas a query on fine-level location information would return a null answer if no matches were found. Using a tag-based design would also make it possible to superimpose multiple classification schemes over the same base collection of information (including hierarchical designs, if desired).

The first step in further developing such a scheme will be to build the vocabularies and terms that will be used as tags to describe reefs. Once a vocabulary is established we can explore/test a hierarchical design and/or a tagged design in terms of flexibility to deliver information effectively.

4.3.1 Vocabularies and Terms used to describe and adapt a classification scheme for Australian needs

Environmental variables are often used as surrogates for marine species distributions and biodiversity patterns (McArthur et al. 2010). These environmental variables can be grouped into three habitat quality factors: habitat heterogeneity, productivity and disturbance (Levin et al. 2001, Kostylev 2012). Our initial development on the vocabularies and terms for the reef classification is also based on these three habitat quality factors. To describe and classify habitat heterogeneity we have modified a range of terms used in the CMECS scheme to define geoforms (or geomorphic features) that best represent reefs and their physiographic setting. These terms are listed in Table 3: CMECS and modified CMECS definitions for the geoform, tectonic and physiographic terms, showing the CMECS definition and proposed modified definition. The revised definitions are intended to focus on the description of reef form and relative size; with no reference to absolute dimensions (examples from North America are also removed).

Additional terms that describe other environmental factors that may influence reef habitat heterogeneity include:

- Geographic location, water depth, water temperature, dissolved oxygen, salinity, turbidity, elevation profile, seabed rugosity, seabed slope, substrate hardness, substrate class, substrate descriptor, substrate percentage, light penetration, geomorphic element and morphometric feature. Definitions for these factors are provided in Appendix C.

Terms for reef productivity include:

- Primary productivity and organic matter in the water column and sediments (Appendix D).

Terms for reef disturbance include:

- Energy type and intensity, tidal range, potential exposure, storm impact and anthropogenic impact (Appendix E).

Together, these defined vocabularies and terms lay out the foundation for the design of a reef habitat classification scheme.

Table 3: CMECS and modified CMECS definitions for the geoform, tectonic and physiographic terms

Vocabulary	Term	CMECS Definition	Modified Definition
Geoform (Reef)		Geomorphic features that are elevated area above the surrounding seafloor, often with hard substrate	Geomorphic features that comprise an elevated area above the surrounding seafloor, commonly with hard substrate
	bank	An elevated area above the surrounding seafloor that rises near the surface. Banks generally are low-relief features, of modest-to substantial extent, that normally remain submerged. They may have a variety of shapes and may show signs of erosion resulting from exposure during periods of lower sea level. Banks tend to occur on the continental shelf. Banks differ from shoals in having greater size and temporal persistence. The Geoform Bank differs from the Coral Reef Zone modifier Bank based on its geologic origin.	An elevated area above the surrounding seafloor. Banks generally are low-relief features that normally remain submerged. They may have a variety of shapes. Banks differ from shoals in having greater size and temporal persistence. (The Geoform Bank differs from the Coral Reef Zone modifier Bank based on its geologic origin).
	knob	A rounded protuberance, usually prominent or isolated with steep sides; also including peaks or other projections from seamounts, or a groups of boulders, or other protruding areas of resistant rocks.	A rounded protuberance, usually prominent or isolated with steep sides. Includes peaks or other projections from seamounts, groups of boulders, or other protruding areas of resistant rocks.
	ledge	Bedding planes that are exposed (either on the surface or at depth) often form ledges that have a high habitat value and support colonizing plants and animals. Ledges often provide a more level surface than the bounding slopes. Ledges in the intertidal zone can form shelves or projections of rock (that are much longer	A narrow, level to near-level planar surface bound on one or more sides by a slope. Commonly formed along bedding planes in sedimentary rock that are exposed at the seabed.

Vocabulary	Term	CMECS Definition	Modified Definition
		than they are wide) on a rock wall or cliff face. They are formed along a coast by differential wave action on softer rocks and may be eroded by biological and chemical weathering.	
	mound/hummock	A low, rounded, natural hill of unspecified origin, which is generally less than 3 meters high	A low, rounded protuberance, typically isolated. Dimensions in metres and generally smaller than a knob.
	platform	Any level or nearly level surface, ranging in size from a terrace or bench to a plateau defined by slopes around its edges.	An elevated, level or nearly level surface bound by a descending slope on all sides.
	ridge	A long, narrow elevation, usually sharp crested with steep sides. Larger ridges can form an extended upland between valleys.	A long, narrow elevation, usually sharp crested with steep sides. Larger ridges can form an extended upland between valleys.
	scarp/wall	A relatively straight, cliff-like face or slope of considerable linear extent, which breaks up the general continuity of the land by separating surfaces lying at different levels (as along the margin of a plateau or mesa). The term wall can be applied to steep or vertical areas on the seaward or exposed side of a reef. Although hard corals may be present, walls in this setting are formed by geologic processes and are not the result of reef-building activities by corals. A wall may be vertical or terraced, and is often referred to as the "dropoff."	A relatively straight, cliff-like face or slope of considerable linear extent (hundreds to thousands of metres), which breaks up the general continuity of the seabed by separating surfaces lying at different levels (as along the margin of a plateau). It may be terraced. The term wall can be applied to steep or vertical areas on the seaward or exposed side of a reef.

Vocabulary	Term	CMECS Definition	Modified Definition
	terrace	Any long, narrow, relatively level or gently inclined surface, generally less broad than a plain, but broader than a ledge and bounded along one edge by a steeper descending slope and along the other by a steeper ascending slope. Terraces may border a valley floor or shoreline, and they can represent the former position of a flood plain, lake, or sea shore. Terraces may be created by erosion, wave action, uplift, currents, or any other process.	A relatively level or gently inclined surface defined along one edge by a steeper descending slope and along the other by a steeper ascending slope. Terraces may border a valley floor or shoreline, and they can represent the former position of a flood plain or shoreline.
	pinnacle	Any high tower or spire-shaped pillar of rock or coral, alone or cresting a summit	A high tower or spire-shaped pillar of rock or coral, isolated or on the crest of a summit.
Tectonic Setting		**Tectonics** is concerned with the processes which control the structure and properties of the Earth's crust, and its evolution through time.	**Tectonics** is concerned with the processes which control the structure and properties of the Earth's crust, and its evolution through time.
	passive continental margin	The transition between oceanic and continental crust that is not an active plate margin. This feature was constructed by sedimentation above an ancient rift, now marked by transitional crust. Major tectonic movement is broad, whereas regional vertical adjustment, Earthquakes, and volcanic activity are minor and local.	The transition between oceanic and continental crust that is not an active plate margin. Major tectonic movement is broad, whereas regional vertical adjustment, Earthquakes, and volcanic activity are minor and local.
Physiographic Setting			
	barrier reef	A long, narrow coral reef, roughly parallel to the shore and separated from it by a lagoon of considerable depth and width. This reef may enclose a volcanic island (either wholly or	A long, narrow coral reef, roughly parallel to the shore and separated from it by a lagoon. May enclose a volcanic island (either wholly or in part), or it may lie a great

Vocabulary	Term	CMECS Definition	Modified Definition
		in part), or it may lie a great distance from a continental coast (such as the Great Barrier Reef). Generally, barrier reefs follow the coasts for long distances—often with short interruptions that are called passes or channels. Three principle examples of this type of feature are Australia's Great Barrier Reef, the New Caledonia Barrier Reef, and the MesoAmerican Barrier Reef system—although similar features exist elsewhere.	distance from a continental coast (such as the Great Barrier Reef). Generally, barrier reefs follow the coasts for long distances (hundreds of km) but with short interruptions that are called passes or channels.
	bight	A broad bend or curve in a generally open coast. Examples include the South Atlantic Bight and the Southern California Bight. These are distinguished from Embayment/Bays by the shallower angle between the apex of the bight and the adjacent coasts, although the term Bay has been used to name these features (e.g., Bay of Campeche).	A broad bend or curve on a generally open coast. Distinguished from Embayment/Bays by the shallower angle between the apex of the bight and adjacent coast, although the term Bay has been used to name these features.
	continental island/shelf	That part of the continental margin that is between the shoreline and the continental slope (or a depth or 200 meters when there is no noticeable continental slope); it is characterized by its very gentle slope of 0.1°. Island shelves are analogous to the continental shelves, but surround islands.	That part of the continental margin that is between the shoreline and the continental slope (or a depth or 200 meters when there is no noticeable continental slope); it is characterized by its very gentle slope of 0.1°. Island shelves are analogous to the continental shelves, but surround islands.
	embayment/bay	A water body with some level of enclosure by land at different spatial scales. These can be wide, curving indentations in the	A water body with some degree of enclosure by land at different spatial scales. These can be wide, curving

Vocabulary	Term	CMECS Definition	Modified Definition
		coast, arms of the sea, or bodies of water almost surrounded by land. These features can be small—with considerable freshwater and terrestrial influence—or large and generally oceanic in character	indentations in the coast, arms of the sea, or bodies of water almost surrounded by land. These features can be small—with considerable freshwater and terrestrial influence—or large and generally oceanic in character
	fjord	A long, narrow, glacially eroded inlet or arm of the sea. They are often U-shaped, steep-walled, and deep. Because of their depth, they tend to have low surface-area-to-volume ratios. They have moderate watershed-to-water-area ratios and low-to-moderate riverine inputs. Fjords often have a geologic sill formation at the seaward end caused by glacial action. This morphology—combined with a low exchange of bottom waters with the ocean—can result in formation of hypoxic bottom waters.	A long, narrow, glacially eroded inlet or arm of the sea. They are often U-shaped, steep-walled, and deep. Because of their depth, they tend to have low surface-area-to-volume ratios. They have moderate watershed-to-water-area ratios and low-to-moderate riverine inputs. Fjords often have a geologic sill formation at the seaward end caused by glacial action.
	inland/enclosed sea	A large, water body almost completely surrounded by land. Salinities range from fresh through marine. The term inland is used to describe situations where the water body is connected to an adjacent large water body by a narrow strait, channel, canal, or river. Examples of this type of setting are the Mediterranean and Black Seas. The Great Lakes, due to their connectivity to the Atlantic Ocean via the St. Lawrence River also fall into this category.	A large, water body almost completely surrounded by land. Salinities range from fresh through marine. The term inland is used to describe situations where the water body is connected to an adjacent large water body by a narrow strait, channel, canal, or river.

Vocabulary	Term	CMECS Definition	Modified Definition
	shelf basin	Basins occurring on the continental shelf formed by offshore faulting activity.	Basins occurring on the continental shelf formed by offshore faulting activity.
	shelf break	The slope discontinuity (rapid change in gradient) of 3° or greater that occurs at the outer edge of the continental shelf. This boundary generally occurs at a depth between 100–200 meters and forms the boundary between the Marine Offshore and Oceanic Subsystems.	The slope discontinuity (rapid change in gradient) of 3° or greater that occurs at the outer edge of the continental shelf. This boundary generally occurs at a depth between 100–200 m.
	sound	(a) A relatively long, narrow waterway connecting two larger bodies of water (or two parts of the same water body), or an arm of the sea forming a channel between the mainland and an island (e.g., Puget Sound, WA). A sound is generally wider and more extensive than a strait. (b) A long, large, rather broad inlet of the ocean, which generally extends parallel to the coast (e.g., Long Island Sound, NY).	(a) A relatively long, narrow waterway connecting two larger bodies of water (or two parts of the same water body), or an arm of the sea forming a channel between the mainland and an island. A sound is generally wider and more extensive than a strait. (b) A long, large, broad inlet of the ocean, which generally extends parallel to the coast.
	submarine canyon	A general term for all linear, steep-sided valleys on the seafloor. These canyons can be associated with terrestrial or nearshore river inputs, such as in the Hudson or Mississippi canyons.	A linear, steep-sided valley on the seafloor. Can be associated with terrestrial or nearshore river inputs.

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4.3.2 Metadata for the reef classification database

Reef mapping studies generate considerable volumes of data; it is most important that sound data management practices are put in place to describe how the data were collected and processed and to describe how the resultant maps were developed. In this project we will need to rely on the metadata from each dataset used in the compilation of a composite reef data layer from benthic marine habitats. Metadata is the term used for the information that describes data. Poor data management can result in valuable data being lost (because it is not properly archived) or the data being passed to others without sufficient documentation to know the quality and possible limitations of the data. Each study typically includes data of many different types (remote sensing and ground truthing), some of which can be very large in volume (e.g. multibeam sonar data). Sound data management practices are therefore extremely important to track the data from the time they are collected, through the processing stages, and ultimately to when they are archived. We propose that the D3 Shelf Reef Project adopt the AODN metadata guidelines. This metadata complies with international metadata standards.

A metadata model for marine spatial data exists through the Australian Online Data Network (AODN). The AODN was formed through collaboration between six Australian Commonwealth Agencies with primary responsibility for marine data. Since its inception, the AODN has grown to encompass organisations and individual members of the Australian, New Zealand and Pacific marine research community. The Commonwealth agencies collaborating with the AODN include the Australian Institute of Marine Science, Geoscience Australia, the Royal Australian Navy, the Australian Bureau of Meteorology, CSIRO, the Australian Antarctic Division, the Integrated Marine Observing System. The AODN community contributors include the Environmental Protection Authority Victoria and the Institute for Marine and Antarctic Studies at the University of Tasmania.

As the major stakeholders to the Marine Biodiversity Hub being Geoscience Australia, CSIRO and the University of Tasmania we have established networks with the AODN. Therefore we propose that if data is to be loaded onto the AODN we adopt the metadata structure used in their data management system. The AODN metadata structure generates a catalogue from the metadata entry and a search tool. Data managers can use this tool to build a catalogue of datasets and to harvest metadata from AODN. Anyone interested in AODN data can use this catalogue, and its search functions, to find and preview datasets. The AODN metadata catalogue is an instance of GeoNetwork version 2.10.3. GeoNetwork version 2.10.3 is freely available and therefore addresses the goal of this project- to make the data products of this project easily available to the Australian Marine Community.

The url for the online AODN metadata catalogue is http://catalogue.aodn.org.au

4.3.3 Looking forward

In addition to collating the broad scale reef substrate data for around the nation, a second major goal of this project is to develop an appropriate geomorphological classification scheme for cross-shelf reefs and to provide suitable physical environmental modifiers such that this scheme also captures major biological patterns. Therefore, as the draft classification scheme is developed, we propose to validate major cross-shelf components on a regional basis with existing biological data, using several case studies that encapsulate typical reef habitats for each of these regions. It is only then that we are examining reef ‘habitat’ as opposed to ‘reef’ as a seafloor structure.

Mapping biological data over broad geographic areas is very time consuming and expensive (Hill et al. 2014). For the most part, this information does not exist at the scale of the national data sets. However, where state and local mapping projects have been completed regional biological data does exist in a spatial format. To be able to identify new and update the boundaries of existing key ecological features we must examine the biological data at a resolution that is relevant to the ecosystems of interest. For the project we therefore propose examining focus sites within each region where co-located biological data will be analysed to augment the reef mapping product.

We propose the use of two classification schemes (this is discussed further in Section 3). The first classification scheme will describe and characterise the geomorphic structure of the physical reef systems at the national scale. The second classification scheme will be applied to the regional area focus sites and include methods for tagging the biological data to reef structure.

The data from the regional area focus sites will specifically provide the shelf reef information necessary to highlight the utility of the geomorphological classification scheme at a local scale, it will also aid to (i) improve the management of marine biodiversity through an evaluation of the results of management interventions on shelf reefs; (ii) develop and apply methods for monitoring the status and trends of key marine species associated with reef habitats, (iii) build the knowledge base of key marine species and ecosystems associated with reefs in waters of the Australian continental shelf, particularly within CMRs, (iv) identify pressures on the marine environment, and understand their impact to better target policy and management actions , and (v) better understand issues that are common to the fishing industry and the environment including identifying solutions of mutual benefit.

Queensland: Areas of overlap between habitat mapping and biological sampling in Queensland offer a number of choices for focus sites for testing the habitat classification scheme that will emerge from this project. For example, northern and southern sites are available that would allow comparisons across steep physical and biodiversity gradients across both longitude and latitude and that could encompass a range of habitat types including hard reef, sandy/muddy bottoms, crossed with shallow and deep locations.

Victoria: Our focus area of interest will be the Cape Otway region encompassing over 800km2 from the 12 Apostles MNP in the west to Bells beach in the east where full coverage seabed mapping has been achieved combining bathymetric Lidar and MBES products to the 3nm state limit. There is also extensive towed video available from habitat mapping initiatives (see coverage of video observations Figure 13) which have already been used to map Ecklonia forests (Young et al. 2015)

New South Wales: The focus area in NSW Wales is located in the Solitary Islands Marine Park and adjacent Commonwealth Waters where multibeam surveys, towed video and AUV surveys all exist Figure 14. The area of interest lies between Coffs Harbour in the South and Groper Islet to the north and then toward the east for 6km. This area includes South Solitary Island and associated reefs. The focus area includes reefs which were studied in detail by the Marine Biodiversity Hub under the NERP program using multibeam towed video and the

(AUV). This focus area includes a variety of habitats from deep reefs to shallow island reefs, soft substrate and reefs of various geological provenances, including relict coastlines.

Tasmania: There are a number of sites where the seabed habitat mapping data is complemented with targeted habitat monitoring that examines changes in habitat extent and structure at a finer resolution over time (Hill et al. 2014). Therefore, these areas are likely focus sites for validation of the reef geomorphological classification scheme with associated biology in the Tasmanian region, with a particular focus in the south east region on the Tasman Peninsula (Figure 17) that was mapped by the Commonwealth Environmental Research Fund (CERF) Biodiversity Hub in 2008. In collaboration with Geoscience Australia an area of 117 km2 in the 8-90 m depth range was mapped using a multibeam system. This area incorporates 14.4km2 of reef and includes iconic areas such as Cape Huay and Pirates Bay. The morphology of the reefs in this area ranges from relatively subdued surfaces formed on sandstone to irregular dolerite and granite reefs. Low relief sandstone reefs are stepped in cross section and have an average slope of 2-3 degrees with flat areas that are partially sediment covered. From the SeaMap Tasmania project (2000-2009) and from the CERF and National Environmental Research Project (NERP) marine biodiversity hub research the seafloor data in this area is well augmented with fine scale biological data from surveys using divers, the Sirius Autonomous Underwater Vehicle (AUV) and reef monitoring surveys over a range of depths (Nichol et al. 2009). The reefs in this region are characteristic of reef systems in the south east region and will provide a good complement to the nation's reef characterisation project.

Western Australia: The current WA data holdings include a range of sampled areas where experimental studies undertaken as part of the Marine Futures program have provided extensive co-located multibeam mapping and biological datasets. These datasets offer the capability to readily assess the biological applicability of proposed reef habitat classification schemes within the study areas.

Northern Territory: Project D3 will use data holdings for reefs in NT offshore waters as one case study to test the proposed reef classification scheme. The focus area will include a number of areas mapped by multibeam sonar that form a transect across the NT shelf from shelf edge to Darwin Harbour. These areas include three locations on the shelf mapped by GA/AIMS in the Bonaparte Gulf and Darwin Harbour.

These areas are well suited for testing (1) the applicability of the proposed reef classification scheme and (2) data adequacy for describing benthic habitat in NT waters.

5. DISCUSSION

In the last decade there has been significant investment to collect seabed habitat data around the nation by each State and Territory. Government agencies, often in collaboration with university researchers, hold valuable data products that are of use for a variety of purposes in areas including marine management and resource assessment. However, whilst the level of interest in and need for these datasets has grown significantly over the last 4-5 years, access to them is often difficult. The datasets are scattered throughout numerous agencies and institutions Australia-wide, information is often limited and difficult to find, and the use of multiple datasets can be hindered by disparate data collection and inconsistent classification methods.

This D3 project will bring together data from a number of sources nationally, and the data will be made discoverable and accessible to potential users using a variety of interfaces. Projects like 'SeaMap Tasmania', 'RedMap' and 'Reef Life Survey' have now generated awareness of what is possible when spatial data are made publically available, and these highly valued data assets will facilitate cross disciplinary research and allow commercial values to be explored by the national marine community.

This project will extract and collate spatial data for benthic reef habitats on the continental shelf. It will build upon the National Intertidal/Subtidal Benthic Habitat Classification (Mount and Bricher 2008, Mount and Prahalad 2009) generating a nationally consistent classification scheme and allowing free public access to the data and data products (where permitted).

This report summarises the results of a national workshop to (1) update our knowledge of rocky reef distribution on the continental shelf, (2) compile this knowledge into a national storage facility where possible, (3) inform the identification and prioritisation of significant gaps in our knowledge of rocky reef distribution for guiding future mapping programs, and (4) develop a national accepted classification scheme for cross-shelf reef systems and associated shelf features. It also summarises work undertaken subsequent to the workshop to progress the project aims up until December 2015, particularly with respect to development of the classification scheme. The report lists a range of key datasets that have been identified and scoped to be utilised in this project where they can be made available by data owners. It also provides the basis from which we move forward in the period between January and June 2016 to complete the classification scheme, collate existing reef datasets, and undertake the gap analysis of priority areas to focus future mapping work on reef systems.

The workshop and a smaller planning workshop of research partners prior to the main workshop identified all the major known mapping datasets in Australian shelf waters and developed a collaborative framework for collating many of these in a way that effectively updates the current maps of reef systems available to the Commonwealth for planning and management of assets such as key ecological features and CMRs. Many research agencies/groups agreed to share mapping data and work on protocols that were effective for this information transfer, ranging from sharing of post-processed data products such as polygons of digitised reef outlines, through to full sets of raw data that allow future reprocessing of derived products. Over the next six months the most appropriate mechanisms for storing and displaying this collated data will be developed and refined to both produce a final mapping product (revised shelf reef KEF maps) and a national facility for storing and sharing shelf mapping data in its various forms that can then link to the AODN for ready access and *search-ability*.

The workshops initiated a national discussion on potential classification schemes for cross shelf reef and hard substrate geoforms and habitats, and there was broad agreement that the US CMECS scheme developed by NOAA seemed to provide an adequate framework on which an Australian scheme could be built and expanded upon to meet local requirements. A draft revision of this framework has subsequently been further developed by a working group arising from the workshop, including revised terminology and the addition of a set of appropriate environmental modifiers to the scheme to make it more applicable for describing habitat level variation in addition to variation in geomorphology. This framework will be further developed, tested and revised over the next six months by Hub partners and collaborating workshop participants, and in several case-study areas (outlined in section 4.3.3), the validity of this scheme for describing biological patterns across the major geomorphological classes within reef systems will be tested using partners existing biological and physical datasets.

Finally, the workshop discussed a gap analysis arising from the data collation and how to go about prioritising the major mapping needs once the full datasets had been collated. One significant point of agreement was that as very little of Australia's shelf had been mapped at all in Commonwealth waters, a key focus of gap filling should be on mapping representative reef habitats at regional to bioregional scales, with filling the largest spatial gaps with representative examples as an initial target. Further, that this should have a clear CMR focus, such that the mapped areas can then form the basis of an integrated monitoring program incorporating these into a national reference areas network for monitoring change through time in response to anthropogenic pressures, including climate change, and the effectiveness of measures such as CMRs in mitigating negative impacts.

6. CONCLUSION

This workshop report covers the progress made in the first five months of project D3 and is predominantly focused on the outcomes of our major stakeholder workshop, and the subsequent progress made towards the project goals. These goals include (1) identifying and collating existing datasets from as many stakeholders as possible to update the national knowledge of the distribution of rocky reefs within shelf waters, (2) to provide a national repository and distribution point for this data, (3) to identify priority gaps to guide future national mapping initiatives, and (4) to develop a nationally accepted classification scheme for describing shelf geoforms and suitable matching modifiers to allow this classification to define habitats that may be meaningful at a biological level. Progress to date has been substantial, with a broad range of datasets being identified and with holders of many of the most significant ones being both engaged with the project and willing to contribute this data at a range of levels of detail. Initial steps have also been made towards development of a database system to handle and display this data. The proposed classification scheme has been developed to the stage that it is ready to be tested and refined by key workshop participants in the 2017 New Year. While the main gap analysis requires completion of the nation-wide collation of existing data, it was very clear at the workshop that these gaps are geographically widespread and substantial and that many bioregions are completely unrepresented by shelf-based mapping. A consensus at the workshop was that new regional mapping be focussed around CMRs where possible to provide the necessary habitat knowledge needed to underpin a national network of reference areas for monitoring of biological change. With that in mind, a field program commenced in NSW to provide initial mapping within the Hunter CMR. This region of central NSW had very little shelf mapping outside of State waters, yet was known to be subject to significant anthropogenic pressures based on pressure data presented at the workshop.

APPENDIX A WORKSHOP AGENDA

Day 1 - Thursday 24 September 2015, 09:00-17:00 IMAS Waterfront Building

	Schedule
09.00 – 09:15	Welcome by Dr Neville Barrett.
09:15- 09:30	Introduction and scope of the D3 project : 'Evaluating and monitoring the status of marine biodiversity assets on the continental shelf- Phase 1-shelf reef key ecological features'
09:30 – 09:45	Brief introduction from all workshop participants [name, affiliation, interest in the project/ links to D3]
09:45- 11.00	CHAIR: Dr Neville Barrett 5 minute presentations by stakeholders and custodians of data: 1. Scott Nichol [Geoscience Australia] 2. Tara Martin [CSIRO] 3. Peter Davies [NSW 4. Steffan Howe [Parks Victoria] 5. Dan Ierodiaconou [Deakin University] 6. Jessica Meeuwig [Centre for Marine Futures WA] 7. Neil Smit [Northern Territory Department of Infrastructure, Planning and Environment 8. Thomas Bridge [James Cook University] 9. Julian Caley [AIMS] 10. Rick Smith [IMAS]
11.00 – 11.30	Morning tea break
11.30 – 13.00	CHAIR: Dr Vanessa Lucieer Discussion: Spatial data management for D3. What type of data might be useful to build a shared national understanding of the distribution of shelf reef habitats? What format might the data be in? How are we defining a reef? What exactly is a Key Ecological Feature (KEF)?

	Schedule
	How does scale and resolution of the data affect our goal? What issues are we going to come up against in accessing spatial data? Q: What is our spatial data goal? A: to be able to generate a multi-scale reef product for marine jurisdiction.
13.00 – 14.00	Lunch
14.00 – 15.00	CHAIR: Dr Neville Barrett Discussion: What are the priority knowledge gaps around the nation? 1. Commonwealth Marine Reserves 2. Key Ecological Feature management for reef systems 3. What explicitly does the Dept of Env want to know?
15.00 – 15.30	Afternoon tea break
15.30 – 17.00	CHAIR: Dr Tara Martin Presentation of potential classification schemes 1. Dr Rick Smith: Introduction of global classification schemes for reef systems 2. Dr Scott Nicol: A “straw man” shelf rocky reef scheme to facilitate discussion 3. Dr Matthew Edmunds (Australian Marine Ecology): Progress towards an integrated classification scheme for Victorian waters Discussion of a classification scheme that identifies the geomorphological drivers of biology. Explanation of breakout sessions for Day 2.
17.00 – 18.30	Drinks- The Brick Factory Salamanca Square
18.30	Dinner- Blue Eye Seafood R*estaurant [opposite IMAS building]*

Day 2 – Friday 25 September 2015, 09:00-15:30 CSIRO Waterfront Building

	Schedule
09.00 – 10.30	Arrive at CSIRO and sign in at the front desk. Break out session 1 and 2: Classification schemes. 1: Ecological classification [Cove room]- CHAIR Jessica Meeuwig / Vanessa Lucieer 2: Geomorphological classification [Wellington Room] CHAIRS-Scott Nichol and Rick Porter-Smith
10.30 – 11.00	Morning tea break [CSIRO Cafeteria]
11.00 – 13.00	Continuation of break-out sessions. Explore available datasets- how would we synthesise the existing data into a classification scheme?
13.00 – 13.45	Lunch [CSIRO Cafeteria]
13.45 – 15.00	CHAIR: Dr Neville Barrett Small group break out reporting to larger group. Formation of a working group to progress key areas over the duration of the project.
15.30	Afternoon tea break and close

APPENDIX B WORKSHOP ATTENDEES

Attendees at the D3 Workshop held in Hobart of the 24th and 25th of September 2015.

Name		Email
1.	Steffan Howe	steffan.howe@parks.vic.gov.au
2.	Dave Miller	David.Miller2@sa.gov.au
3.	Kate Lee	kate.lee@dpi.nsw.gov.au
4.	Jessica Meeuwig	jessica.meeuwig@uwa.edu.au
5.	Carolyn Armstrong	Carolyn.Armstrong@environment.gov.au
6.	Tom Bridge	thomas.bridge@jcu.edu.au
7.	Julien Caley	J.Caley@aims.gov.au
8.	Alex Cowdery	a.cowdery@fugro.com
9.	Peter Davies	Peter.Davies@environment.nsw.gov.au
10.	Matt Edmunds	Matt@marine-ecology.com.au
11.	Lawrence Ferns	Lawrance.Ferns@delwp.vic.gov.au
12.	Adrian Flynn	adrian.flynn@fathompacific.com
13.	Daniel Ierodiaconou	daniel.ierodiaconou@deakin.edu.au
14.	Scott Nichol	scott.nichol@ga.gov.au
15.	Amanda Parr	Amanda.Parr@environment.gov.au
16.	Roland Pitcher	Roland.Pitcher@csiro.au
17.	Neil Smit	Neil.Smit@nt.gov.au
18.	Shaun Wilson	Shaun.Wilson@DPaW.wa.gov.au
19.	Neville Barrett	Neville.Barrett@utas.edu.au
20.	Emma Flukes	eflukes@utas.edu.au
21.	Keith Hayes	Keith.Hayes@csiro.au
22.	Paul Hedge	Paul.Hedge@csiro.au
23.	Vanessa Lucieer	Vanessa.Lucieer@utas.edu.au
24.	Tara Martin	T.Martin@csiro.au
25.	Roger Proctor	Roger.Proctor@utas.edu.au
26.	Rick Smith	r.smith@utas.edu.au
27.	Giulia Porro	Giulia.Porro@afma.gov.au

APPENDIX C VOCABULARIES AND TERMS FOR DEFINING REEF HETEROGENEITY

Vocabulary	Term	Definition	Definition Source	Datasets
Geoform - Reef		Geomorphic features that comprise an elevated area above the surrounding seafloor, commonly with hard substrate		bathymetric data, e.g., derived from multibeam, single beam, lidar, satellite altimetry, optical remotely sensed data, or a combination of above
	bank	An elevated area above the surrounding seafloor. Banks generally are low-relief features that normally remain submerged. They may have a variety of shapes. Banks differ from shoals in having greater size and temporal persistence. (The Geoform Bank differs from the Coral Reef Zone modifier Bank based on its geologic origin).	CMECS/modified	
	knob	A rounded protuberance, usually prominent or isolated with steep sides. Includes peaks or other projections from seamounts, groups of boulders, or other protruding areas of resistant rocks.	CMECS/modified	

Vocabulary	Term	Definition	Definition Source	Datasets
	ledge	A narrow, level to near-level planar surface bound on one or more sides by a slope. Commonly formed along bedding planes in sedimentary rock that are exposed at the seabed.	CMECS/modified	
	mound/hummock	A low, rounded protuberance, typically isolated. Dimensions in metres and generally smaller than a knob.	CMECS/modified	
	platform	An elevated, level or nearly level surface bound by a descending slope on all sides.	CMECS/modified	
	ridge	A long, narrow elevation, usually sharp crested with steep sides. Larger ridges can form an extended upland between valleys.	CMECS/modified	
	scarp/wall	A relatively straight, cliff-like face or slope of considerable linear extent (hundreds to thousands of metres), which breaks up the general continuity of the seabed by separating surfaces lying at different levels (as along the margin of a plateau). It may be terraced. The term wall can be applied to steep or vertical areas on the seaward or exposed side of a reef.	CMECS/modified	
	terrace	A relatively level or gently inclined surface defined along one edge by a steeper descending slope and along the other by a steeper ascending slope. Terraces may border a valley floor or shoreline, and they can represent the former position of a flood plain or shoreline.	CMECS/modified	

Vocabulary	Term	Definition	Definition Source	Datasets
	pinnacle	A high tower or spire-shaped pillar of rock or coral, isolated or on the crest of a summit.	IHO	
Tectonic		**Tectonics** is concerned with the processes which control the structure and properties of the Earth's crust, and its evolution through time.	WIKI	geological data
	passive continental margin	The transition between oceanic and continental crust that is not an active plate margin. Major tectonic movement is broad, whereas regional vertical adjustment, Earthquakes, and volcanic activity are minor and local.	CMECS/modified	
Physiographic				bathymetric/topographic data
	barrier reef	A long, narrow coral reef, roughly parallel to the shore and separated from it by a lagoon. May enclose a volcanic island (either wholly or in part), or it may lie a great distance from a continental coast (such as the Great Barrier Reef). Generally, barrier reefs follow the coasts for long distances (hundreds of km) but with short interruptions that are called passes or channels.	CMECS/modified	
	bight	A broad bend or curve on a generally open coast. Distinguished from Embayment/Bays by the shallower angle between the apex of the bight and adjacent coast, although the term Bay has been used to name these features.	CMECS/modified	

Vocabulary	Term	Definition	Definition Source	Datasets
	continental island/shelf	That part of the continental margin that is between the shoreline and the continental slope (or a depth or 200 meters when there is no noticeable continental slope); it is characterized by its very gentle slope of 0.1°. Island shelves are analogous to the continental shelves, but surround islands.	CMECS/unmodified	
	embayment/bay	A water body with some degree of enclosure by land at different spatial scales. These can be wide, curving indentations in the coast, arms of the sea, or bodies of water almost surrounded by land. These features can be small—with considerable freshwater and terrestrial influence—or large and generally oceanic in character	CMECS/modified	
	fjord	A long, narrow, glacially eroded inlet or arm of the sea. They are often U-shaped, steep-walled, and deep. Because of their depth, they tend to have low surface-area-to-volume ratios. They have moderate watershed-to-water-area ratios and low-to-moderate riverine inputs. Fjords often have a geologic sill formation at the seaward end caused by glacial action.	CMECS/modified	
	inland/enclosed sea	A large, water body almost completely surrounded by land. Salinities range from fresh through marine. The term inland is used to describe situations where the water body is connected to an adjacent large water body by a narrow strait, channel, canal, or river.	CMECS/modified	
	shelf basin	Basins occurring on the continental shelf formed by offshore faulting activity.	CMECS/unmodified	

Vocabulary	Term	Definition	Definition Source	Datasets
	shelf break	The slope discontinuity (rapid change in gradient) of 3° or greater that occurs at the outer edge of the continental shelf. This boundary generally occurs at a depth between 100–200 m.	CMECS/modified	
	sound	(a) A relatively long, narrow waterway connecting two larger bodies of water (or two parts of the same water body), or an arm of the sea forming a channel between the mainland and an island. A sound is generally wider and more extensive than a strait. (b) A long, large, broad inlet of the ocean, which generally extends parallel to the coast.	CMECS/modified	
	submarine canyon	A linear, steep-sided valley on the seafloor. Can be associated with terrestrial or nearshore river inputs.	CMECS/modified	
Geographic Location		geographic location or region of the reef		
	latitude/longitude	an exact or approximate lat and lon (e.g., 25.65 S/ 114.32 E)		GPS, data with location information
	North marine planning region		Australian marine planning region polygon data	Australian marine planning region polygon data
	East marine planning region		Australian marine planning region polygon data	Australian marine planning region polygon data
	South-east marine planning region		Australian marine planning region polygon data	Australian marine planning region polygon data
	South-west marine planning region		Australian marine planning region polygon data	Australian marine planning region polygon data

Vocabulary	Term	Definition	Definition Source	Datasets
	North-west marine planning region		Australian marine planning region polygon data	Australian marine planning region polygon data
Water Depth		water depth of the reef		bathymetric data
	minimum depth	water depth at the top of the reef		
	maximum depth	water depth at the base of the reef		
	intertidal	The area that is above water at low tide and under water at high tide		
	inner shelf	The shallower part of the continental shelf		
	mid shelf	The part between the inner shelf and outer shelf		
	outer shelf	The deeper part of the continental shelf		
Temperature		Sea surface temperature		modelled or measured SST
	minimum temperature	minimum annual SST above the reef		
	maximum temperature	maximum annual SST above the reef		
	mean temperature	mean annual SST above the reef		
	tropical zone	These zones are found in the areas of the trade winds and are characterized by dry conditions, persistent winds and high evaporation rates.	http://www.iupui.edu/~g115/mod09/lecture01.html	
	subtropical zone	Subtropical climates zones are found generally between 25 and 35 degrees latitude and characterised by light winds and low rainfall.		
	temperate zone	Located in the areas of the westerly winds, temperate zones are characterized by high rainfall and strong storms that may be extratropical cyclones.		

Vocabulary	Term	Definition	Definition Source	Datasets
	subpolar zone	Located at greater than 60 degrees latitude in each hemisphere, subpolar zones are characterized by low rainfall and cold temperatures. Sea ice forms in these areas during winter months, creating high salinity water beneath the ice. In summer months, ice melts creating a low salinity layer at the surface.		
	polar zone	Located near the polar regions of each hemisphere, the polar zone is characterized by low rainfall and light winds. Most of this zone is covered by ice all year and water temperatures below ice cover are near freezing.		
Dissolved Oxygen		The amount of oxygen that is dissolved (and hence available to sustain marine life) in water		modelled or measured dissolved oxygen data, such as from CARS datasets
	Anoxic	0 to < 0.1 (mg/L)	CMECS	
	Severely Hypoxic	0.1 to < 2 (mg/L)	CMECS	
	Hypoxic	2 to < 4 (mg/L)	CMECS	
	Oxic	4 to < 8 (mg/L)	CMECS	
	Highly Oxic	8 to < 12 (mg/L)	CMECS	
	Very Oxic	≥ 12 (mg/L)	CMECS	
Salinity		the saltiness or dissolved salt content of a body of water		modelled or measured salinity data, such as from CARS datasets
	Oligohaline	< 5 (Practical Salinity Scale)	CMECS	
	Mesohaline	5 to < 18 (Practical Salinity Scale)	CMECS	
	Lower Polyhaline	18 to < 25 (Practical Salinity Scale)	CMECS	
	Upper Polyhaline	25 to < 30 (Practical Salinity Scale)	CMECS	

Vocabulary	Term	Definition	Definition Source	Datasets
	Euhaline	30 to < 40 (Practical Salinity Scale)	CMECS	
	Hyperhaline	≥ 40 (Practical Salinity Scale)	CMECS	
Turbidity		a measure of the degree to which the water loses its transparency due to the presence of suspended particulates		modelled or measured turbidity data, such as secchi depth, euphotic depth, k490, etc.
	Extremely Turbid	< 1 (Secchi Depth in metre)	CMECS	
	Highly Turbid	1 to < 2 (Secchi Depth in metre)	CMECS	
	Moderately Turbid	2 to < 5 (Secchi Depth in metre)	CMECS	
	Clear	5 to < 20 (Secchi Depth in metre)	CMECS	
	Extremely Clear	≥ 20 (Secchi Depth in metre)	CMECS	
Elevation Profile		the maximum elevation of the reef relative to the surrounding seabed		bathymetric data
	Low	0.1 to < 2 (m)	CMECS	
	Medium	2 to < 5 (m)	CMECS	
	High	≥ 5 (m)	CMECS	
Rugosity		the ratio between the surface area and the planar area		bathymetric data
	Very Low	1.0 to < 1.25	Greene et al. 2007	
	Low	1.25 to < 1.50	Greene et al. 2007	
	Moderate	1.50 to < 1.75	Greene et al. 2007	
	High	1.75 to < 2.00	Greene et al. 2007	
	Very High	≥ 2.00	Greene et al. 2007	
Slope		the angle of the surface		bathymetric data

Vocabulary	Term	Definition	Definition Source	Datasets
	Flat	0 to < 5	Greene et al. 2007	
	Sloping	5 to < 30	Greene et al. 2007	
	Steeply Sloping	30 to < 60	Greene et al. 2007	
	Vertical	60 to < 90	Greene et al. 2007	
	Overhang	≥ 90	Greene et al. 2007	
Substrate hardness		the hardness (e.g., consolidated or unconsolidated) of the substrate		backscatter data, video data
	Hard	consolidated materials (e.g., bedrock, boulder)		
	Soft	unconsolidated materials (e.g., sediments)		
Substrate class		the type of materials that cover the seabed		backscatter data, bathymetric data, video data and sediment data
	bedrock	Substrate with mostly continuous formations of bedrock that cover the Geologic Substrate surface	CMECS	
	megaclast	Substrate where individual rocks—with particle sizes greater than or equal to 4.0 meters (4,096 millimetres) in any dimension—cover the Geologic Substrate surface	CMECS	
	boulder	256 to < 4,096 (millimetres); -8 to < -12 (phi)	CMECS (Table 7.1)	
	cobble	64 to < 256; -6 to < -8	CMECS (Table 7.1)	
	pebble	4 to < 64; -1 to < -6	CMECS (Table 7.1)	
	coarse sediment	sediment that comprises mainly coarse materials, including granules (2-4 mm), very coarse sand (1-2 mm), coarse sand (0.5 - 1 mm) and medium sand (0.25-0.5 mm)	Wentworth (1922)	

Vocabulary	Term	Definition	Definition Source	Datasets
	fine sediment	sediment that comprises mainly fine materials, including fine sand (0.125-0.5 mm), very fine sand (0.063-0.125 mm), silt (8-73 microns) and clay (<8 microns)	Wentworth (1922)	
Substrate descriptor		describes substrate origin and composition		backscatter data, bathymetric data, video data and sediment data
	Well-mixed	Different elements within a sample, observational unit, or reporting unit are well-mixed or poorly-sorted at the scale of the sample or unit. Well-mixed implies that elements or particles are completely and relatively evenly intermingled, e.g., Granule/Sand/Mud particles in an area with high bioturbation. This is one of several terms used in CMECS to describe unit variability. Note that CMECS does not use the equivalent geological term “Poorly-Sorted”, because the descriptor may be used to describe distributions of non-geological features (such as biological communities or Geoform Component structures).	CMECS	
	Patchy	Different elements within a sample, observational unit, or reporting unit are grouped into clusters or patches at the scale of the sample or unit. “Patchy” implies that clusters of elements or particles are arranged in a haphazard manner, as clusters of pebbles scattered on sand. This is one of several terms used in CMECS to describe unit variability.	CMECS	

Vocabulary	Term	Definition	Definition Source	Datasets
	Well-sorted	Different elements within a sample, observational unit, or reporting unit are separated into different areas at the scale of the sample or unit. Well-sorted implies that elements or particles are (or have been) separated and arranged in a non- haphazard manner, as an area of Coarse Sand adjacent to an area of Clay. This is one of several terms used in CMECS to describe unit variability.	CMECS	
	Volcaniclastic	Particles or substrates composed primarily of volcanic rock, crystals, glassy pumice, ash, or other volcanic products.	CMECS	
	Sulfidic	Substrate in which bacterial sulfate reduction is an important biogeochemical process; this generally occurs in anaerobic environments and is often identifiable by a very low reflectance black or blue colour.	CMECS	
	Siliciclastic	Particles or substrates composed primarily of silicate minerals e.g., quartz, sandstone, siltstone.	CMECS	
	carbonate	Particles or substrates composed mainly of carbonate minerals, e.g., limestone, dolostone.	CMECS	
Substrate percentage cover		the relative percent cover of each of the components of the substrate	CMECS	backscatter data, bathymetric data, video data and sediment data
	trace	< 1%	CMECS	
	sparse	1 to < 30%	CMECS	
	moderate	30 to < 70%	CMECS	
	dense	70 to < 90%	CMECS	
	complete	90 to 100%	CMECS	

Vocabulary	Term	Definition	Definition Source	Datasets
Light Penetration		amount of light in water column that is available to marine life		can be measured in-site, or can use surrogates such as water depth (bathymetric data) , euphotic depth, etc
	Aphotic	Region of the water column where no ambient light penetrates, no photosynthesis occurs, and animals cannot make use of visual cues based on even reduced levels of ambient light. In oceans, this zone typically lies below 500–1,000 meters of depth. In turbid estuaries, this zone may be very shallow.	CMECS	
	Dysphotic	Region of the water column, below the compensation depth, that receives less than 2% of the surface light; plants and algae cannot achieve positive photosynthetic production in this region, but some ambient light does penetrate such that animals can make use of visual cues based on reduced levels of ambient light.	CMECS	
	Photic - low insolation	Region of the water column where ambient light is 2 to 30% of surface light and phototrophic organisms can photosynthesize.	CMECS	
	Photic - moderate insolation	Region of the water column where ambient light is 30 to 70% of surface light and phototrophic organisms can photosynthesize.	CMECS	
	Photic - high insolation	Region of the water column where ambient light is 70 to 100% of surface light and phototrophic organisms can photosynthesize.	CMECS	

Vocabulary	Term	Definition	Definition Source	Datasets
Geomorphic element		describes the topographic positions or zones		bathymetric data
	Crest	Area high in the landscape, having positive plan and/or profile curvature	Speight 1990	
	Depression	Area low in the landscape, having negative plan and/or profile curvature	Speight 1990	
	Flat	areas having a slope < 3%	Speight 1990	
	Slope	Planar element with an average slope > 1%	Speight 1990	
Morphometric feature		describes fine-scale morphometric form	Wood 1996; Zieger et al. 2009	bathymetric data
	peak	Point that lies on a local convexity in all directions (all neighbours lower)	Wood 1996	
	ridge	Point that lies on a local convexity that is orthogonal to a line with no convexity/concavity	Wood 1996	
	plane	Points that do not lie on any surface concavity or convexity	Wood 1996	
	pit	Point that lies in a local concavity in all directions (all neighbours higher).	Wood 1996	
	channel	Point that lies in a local concavity that is orthogonal to a line with no concavity/convexity	Wood 1996	
	pass	Point that lies on a local convexity that is orthogonal to a local concavity	Wood 1996	

APPENDIX D VOCABULARIES AND TERMS FOR DEFINING REEF PRODUCTIVITY

Vocabulary	Term	Definition	Definition Source	Datasets
Water column primary productivity		is the rate at which energy is converted mainly by photosynthetic autotrophs to organic substances; water column primary productivity, in this case, is measured by chlorophyll a concentrations		modelled or measured sea surface chlorophyll a data
	Oligotrophic	Chlorophyll a Level (μg/L) < 0.1	Antoine et al. 1996	
	Mesotrophic	Chlorophyll a Level (μg/L) 0.1 to < 1	Antoine et al. 1996	
	Eutrophic	Chlorophyll a Level (μg/L) >=1	Antoine et al. 1996	
Water Particular Organic Matter		Material of plant or animal origin that is suspended in water, often measured as the amount of carbon		modelled or measured POC datasets
	hyperoligotrophic	< 20 mg/m3	Stramski et al. 2008	
	Oligotrophic	20 to 85 mg/m3		
	Mesotrophic	85 to 150 mg/m3		
	Eutrophic	>150 mg/m3		
Benthic CO2 flux (respiration)		the amount of CO2 released from a unit area of sediment over a specific time interval, during the decomposition of organic matter		
	hyper eutrophic	>137 mmol/m2/d	Eyre and Ferguson 2009	
	Eutrophic	91.3 to 137 mmol/m2/d		
	mesotrophic	45.6 to 91.3 mmol/m2/d		
	Oligotrophic	<45.6 mmol/m2/d		

Vocabulary	Term	Definition	Definition Source	Datasets
sediment organic carbon		the amount of organic carbon preserved within sediment		
	low	<0.5 mg OC/m2	Burdige 2006	
	typical	0.5 to 1.1 mg OC/m2		
	high	>1.1 mg OC/m2		

APPENDIX E VOCABULARIES AND TERMS FOR DEFINING REEF DISTURBANCE

Vocabulary	Term	Definition	Definition Source	Datasets
Energy type		Origin of the energy		modelled data, such as WAM
	Wind wave	Vertical and transverse oscillating surface water motion due to wind energy.	Dethier (1990) and Zacharias et al. (1998)	
	Tidal or gravitational wave	Periodic, horizontally oscillating water motion.	Dethier (1990) and Zacharias et al. (1998)	
Energy Intensity		Strength of energy, often measured as flux speed		Modelled data, such as GEOMACS; Bluelink reanalysis data
	Very Low Energy flux	Area experiences little current motion under most conditions.	CMECS	
	Low Energy flux	Area typically experiences very weak currents (0–1 knots).	CMECS	
	Moderate Energy flux	Area regularly experiences moderate tidal currents (> 1–3 knots).	CMECS	
	High Energy flux	Area regularly experiences strong currents (> 3 knots).	CMECS	
Tidal range		is the vertical difference between the high tide and the low tide		BOM
	Micro-tidal	< 2 m	Masselink and Short (1993)	
	Meso-tidal	2 to 4 m		
	Macro-tidal	> 4 m		
Exposure		how exposed or sheltered the area is to the wave or tide activities		Modelled data, such as GEOMACS, GIS analysis, or proxy like topographic Aspect
	very exposed	the area is very exposed to wave or tide activities		

Vocabulary	Term	Definition	Definition Source	Datasets
	exposed	the area is exposed to wave or tide activities		
	sheltered	the area is sheltered to wave or tide activities		
	very sheltered	the area is very sheltered to wave or tide activities		
Storm impact		the overall impact from storm events considering their frequency, duration and magnitude		Modelled data such as WAM, or BOM climate data
	High impact	area is highly impacted by storm events		
	Moderate impact	area is moderately impacted by storm events		
	low impact	area is not or lightly impacted by storm events		
Anthropogenic impact		the overall disturbance due to human activities including marine management practice, fishery activities, industry development and terrestrial inputs, etc		a range of environmental, biological and social datasets
	high	area has high anthropogenic disturbance		
	moderate	area has moderate anthropogenic disturbance		
	low	area has low anthropogenic disturbance		
	no	area has no anthropogenic disturbance, e.g., pristine area		

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