Marine Biodiversity Hub

National Environmental Science Programme

Geomorphological classification of reefs

- Draft Framework for an Australian Standard

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

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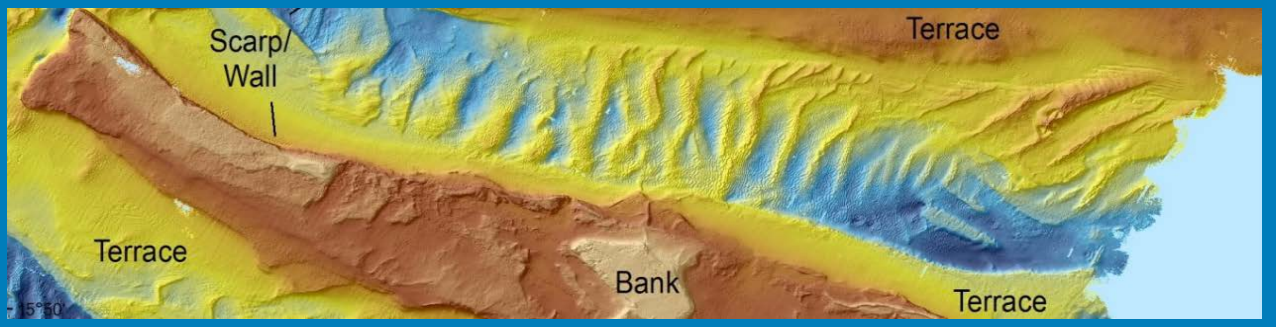

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Important Disclaimer

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EXECUTIVE SUMMARY

Reefs are recognised as seabed features that potentially support a diverse range of benthic and demersal biota and are recognised by the Australian Government as conservation values (i.e. Key Ecological Features) within marine bioregional plans. To support the ongoing monitoring and management of reef systems, the Marine Biodiversity Hub is undertaking a project to identify and collate all available mapping data for reefs on the continental shelf of Australia. This report presents a draft framework for describing the geomorphology of reefs based on the best available bathymetric data as the proposed standard for the classification of reefs in the Australian context. The classification incorporates a vocabulary of terms that describe reef origin, physical form (shape, relief, slope, rugosity) and substrate type (rock, unconsolidated, sediment texture). The broad environmental setting of a reef is also represented by categories of climatic region and shelf bathymetric zone. The classification is therefore intended for application to both rocky and biogenic reefs at the national scale, and links conceptually to the mapping of reef geomorphic features that forms part of the national benthic biogregionalisation (IMCRA). It is intended that the geomorphic classification presented here will be subsequently linked to a biological classification scheme for reef biota, thereby providing a comprehensive and integrated approach to the description of reef habitats.

1. INTRODUCTION

1.1 Background

Reef systems in the Commonwealth Marine Area have been identified as conservation values (i.e. Key Ecological Features - KEFs) within the Australian Government's Marine Bioregional Plans for their importance for biodiversity or ecosystem function and integrity (Commonwealth of Australia, 2012a-c, 2015). Reefs occur in all marine bioregions from the tropics to temperate areas and are represented by at least seven KEFs that intersect the continental shelf and a further four KEFs located off the shelf but which incorporate reef systems (see Appendix 1). Yet the distribution of reef features remains poorly documented. Existing maps of reef KEFs usually reflect where reefs have been incidentally mapped as part of unrelated surveys rather than as part of a targeted effort to build the inventory. Clearly, informed management of reef habitats and associated biota requires spatial data that provides for the description and monitoring of reef systems at the national scale.

Through the National Environmental Science Program (NESP), the Marine Biodiversity Hub has supported a one-year project that will identify and collate all available mapped seafloor reef data for the continental shelf of Australia. The project is part of the larger program 'Evaluating and Monitoring the Status of Marine Biodiversity Assets on the Continental Shelf' facilitated by the Hub. Project partners include the Institute for Marine and Antarctic Studies (IMAS) at 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). To facilitate the project, representatives from each partner institution/agency and stakeholders in the Marine Biodiversity Hub attended a workshop at IMAS in September 2015 to review available datasets and discuss approaches to data analysis and classification (see Lucieer et al., 2016).

A major output of this project will be a spatial map and geo-database accessible to the marine community of the mapped shelf reefs. This will be augmented with secondary products that will include the identification and assessment of spatial gaps in existing seafloor mapping datasets to help to inform setting national priorities for future survey work, including work planned to be undertaken by the Marine Biodiversity Hub. A third output will be the development of a geomorphological classification scheme for shelf reefs applicable for classification at multiple scales of data resolution (i.e. metres to tens of metres). This report delivers to that third output.

1.2 Importance of Reef Geomorphology

The geomorphology of physical structures on the seabed is known to influence the spatial patterns of benthic biodiversity and to influence the distribution of some demersal fish communities (e.g. McArthur et al., 2010, Rees et al., 2014). This is particularly the case for reefs, which provide a hard and stable substrate for sessile organisms and introduce topographic complexity to the seabed that promotes local-scale mixing by structures that can extend across tens of metres in elevation and thousands of square metres in planar area (e.g. Wolanski and Hamner, 1988; Hill et al., 2010). Reef geomorphology is highly varied as rock type (lithology) and age, water depth and

exposure to processes of erosion and sediment deposition can all influence the physical form of a reef. In turn, reef morphology will typically define the fine scale (decimetres to metres) distribution of epibenthic communities and demersal fishes (e.g., Roberts and Davis, 1996; Wedding et al., 2008). For example, a high relief reef with an irregular profile may support a different and more diverse community assemblage across its depth range than a low relief reef located across a narrow depth range (Monk et al., 2016). Similarly, reef form can strongly influence local scale circulation by redirecting currents and promoting turbulence. Documenting reef geomorphology is therefore an essential prerequisite to an informed understanding of observed patterns of biodiversity, for both benthic and demersal biota.

To enable the consistent description of reef habitat types, a standard classification of reef geomorphology is required. This report presents a framework for documenting the geomorphology of reefs as the proposed standard for the classification of reef types in the Australian context. The classification incorporates a vocabulary of terms that describe reef origin, physical form (shape, relief, slope, rugosity) and substrate type (rock, unconsolidated, sediment texture). Additionally, the broad environmental setting of a reef is represented by categories of climatic region and shelf bathymetric zone. It is intended that the geomorphic classification presented here will be linked to a biological classification scheme for reef biota such as the CATAMI scheme (CATAMI Technical Working Group, 2013), thereby providing a comprehensive and integrated approach to the description of reef habitats.

2. REEF GEOMORPHOLOGY CLASSIFICATION

2.1 Background

The reef geomorphology classification scheme and vocabulary proposed here draws largely upon the Coastal and Marine Ecological Classification Standard (CMECS) developed in the United States and published by the Federal Geographic Data Committee (FGDC, 2012). The CMECS scheme is among a number of marine habitat classification schemes that provide a framework and standard terms for a range of marine and coastal environmental parameters; and are reviewed in a separate Marine Biodiversity Hub report from the 2015 project workshop (Lucieer et al. 2016). The primary component from the CMECS scheme used here is the suite of geomorphic terms that comprise the geoform types and substrate type, with the former derived from the earlier scheme presented by Greene et al. (2007). The geoform component in CMECS is extensive and includes 137 types of depositional, erosional, tectonic, volcanic and glacial geomorphic features (includes level 1 and 2 geoforms as defined in CMECS). Among these, geoforms that relate to reefs in the Australian context constitute a small subset of 10 types and are adopted here as geofeatures (with the addition of the pinnacle geofeature not in CMECS). The definitions for these reef geofeatures as presented in the CMECS manual (FGDC, 2012) are applied here, but with minor revision in some instances (i.e. to remove reference to US examples). It is also noted that some geofeature terms are replicated in the International Hydrographic Organisation list of undersea feature names (IHO, 2013) and that the definitions used here are consistent with the IHO scheme (see section 2.4.4).

2.2 Link to Bioregionalisation (IMCRA)

The reef geomorphology classification scheme presented here builds on the benthic bioregionalisation of the Australian exclusive economic zone developed as part of the Integrated Marine and Coastal Regionalisation of Australia (IMCRA 4.0; www.environment.gov.au/node/18075). The benthic bioregionalisation includes a classification of seabed geomorphology that defines and maps geomorphic features on the Australian continental margin at a scale of 1:5 million using the 250 m national bathymetry grid (Heap and Harris, 2008). Reefs are one of the 21 geomorphic feature types mapped for the benthic bioregionalisation, where (and following the IHO, 2001) they are defined as ‘Rock lying at or near the sea surface that may constitute a hazard to surface navigation’ (Heap and Harris, 2008). In order to represent the key physical properties of reefs that may influence biodiversity, the scheme proposed here allows for the refinement of the benthic bioregionalisation by including geomorphic feature types that describe reef morphology at finer spatial scales (e.g. ridge, terrace, bank). Incorporating these additional feature types also allows a reef to be mapped as a composite of multiple geomorphic features, not previously achieved by the national scale mapping. As such, the geofeature terms used here all fall under the reef geomorphic feature of the benthic bioregionalisation, and form a subset of Level 3 (Geomorphological Units) within the overall hierarchical framework for classifying biodiversity at the continental scale (see Last et al., 2010).

2.3 Scope and Structure

The classification of seabed physical features presented here is limited to reefs, specifically reef morphology and composition. Additional contextual variables are included that allow for the general environmental setting of a reef to be included in the set of parameters that describe a particular reef. Following the CMECS scheme, the terms used here are scale independent, with emphasis on properties such as the relative dimensions of a reef so that feature types can be applied at a range of spatial scales and need not be constrained by the spatial resolution of a data set. The scheme is also non-hierarchical in structure, allowing for flexible application of any number, or combination, of categories to describe a reef, where the appropriate information is available.

In the following section, a systematic description of categories proposed to describe reef physical form and composition is presented. This includes definitions and descriptions of each term in the vocabulary, with examples.

2.4 Classification Categories

A suite of seven categories are proposed against which the geomorphology of a reef can be described and classified (Figure 2.4.1). These include: Reef Origin; Climatic Region; Shelf Zone; Geofeature; Relief; Slope; Rugosity and; Substrate. The Substrate category is divided into a number of sub-categories as optional descriptors of seabed composition. The utility of these categories for supporting the understanding of reef biodiversity are presented in Table 2.4.1. Each category requires a particular type of data to enable its application to the description of a reef. As a minimum, locational information (latitude and longitude) and water depth observed along a continuous profile of seabed are required to identify the presence of a reef and to describe its form in general terms. Where additional information is available on reef morphology and composition, a reef can be classified across the seven categories and additional substrate sub-categories but only if it has been mapped in its entirety to high spatial resolution (i.e. metres) using acoustic devices such as multibeam echo-sounder or LiDAR, and directly sampled to determine its composition and geological origin.

Figure 2.4.1: Reef geomorphology classification scheme

Table 2.4.1: Reef classification categories and their utility for understanding patterns of marine biodiversity associated with reefs

Category	Utility
1. Reef Origin	Establishes the formative process for the existence of a reef, including geological, abiotic (biogenic) or anthropogenic origins. This information may also describe the geological age of a reef.
2. Ocean Climate Zone	Describes the broad oceanographic and productivity setting for a reef that will limit the likely range of biota present on that reef.
3. Shelf Bathymetric Zone	Describes the broad water depth range and position on the continental shelf that a reef is situated within as an indicator of potential interaction with ocean currents and waves.
4. Geofeature	Describes the three-dimensional morphology (shape) of a reef as a first order indicator of the bathymetric expression, relative dimensions and structural complexity of a reef.
5. Relief	Describes the relative elevation of a reef above the surrounding seabed measured at the perimeter as an indicator of depth range and potential interaction with ocean currents and waves.
5.1. Slope	Describes the relative gradient of a reef across its full extent as an indicator of potential interaction with ocean currents and waves and of the stability of the reef.
6. Rugosity	Describes the relative roughness of a reef surface as an indicator of fine scale (metres to tens of metres) structural complexity of a reef as benthic habitat.
7. Substrate Type	Establishes the general composition of a reef as an indicator of its structural stability as a benthic habitat (e.g. bedrock substrate will provide greater stability than an unconsolidated boulder ridge).
7.1. Rock Lithology	Establishes the geological composition of a reef as an indicator of structural character of the reef as it influences the complexity of the reef surface (related to relief, rugosity and slope).
7.2. Rock Texture	Describes the size class of reefs comprised of discrete clasts (individually or as a field) as an indicator of fine scale (metres) structural complexity of the reef as benthic habitat.

Category	Utility
7.2.1. Percent Cover	Describes the relative continuity of clasts across the seabed as an indicator of benthic habitat continuity (measured as a percentage of the reef surface area).
7.3. Sediment Texture	Describes the sediment size class covering a reef surface as an indicator of the potential for the reef to be buried by mobile sediment and therefore potentially modified as a benthic habitat.
7.3.1. Percent Cover	Describes the relative continuity of sediment covering a reef surface as an indicator of the extent to which the reef is buried and therefore potentially modified as a benthic habitat (measured as a percentage of the reef surface area).

2.5 Classification Vocabulary

Each of the seven classification categories comprises a set of terms that define the options for describing a reef against that category. This set of terms is the **proposed classification vocabulary** for the reef geomorphic classification scheme, the definitions for which are listed below.

2.5.1 Reef Origin

Anthropogenic	Human-made underwater structures, built to promote aggregations of marine life. Includes shipwrecks.
Biogenic	Solid, massive structures which are created by accumulations of organisms, usually rising from the seabed, or at least clearly forming a substantial, discrete community or habitat which is very different from the surrounding seabed. The structure of the reef may be composed almost entirely of the reef building organism and its tubes or shells, or it may to some degree be composed of sediments, stones and shells bound together by the organisms.
Lithic	Formed by non-biogenic substrata, including rock of sedimentary, metamorphic and igneous origin.
Indeterminate	The reef origin could not be determined based on the existing information

2.5.2 Ocean Climate Zone (after IMCRA 4.0; Heap et al. 2005)

Tropical	The zone extending north from the Tropic of Capricorn at 23.5^{o} S, characterised by warm to very warm ocean temperatures (>25^{o} C), generally nutrient poor (oligotrophic) and influenced by strong tidal currents, monsoonal shifts in wind direction and storm activity.
Sub-tropical	Located generally between ~25^{o} and 40^{o} latitude with seasonally variable ocean temperatures (~18 – 25^{o} C) and influenced by extra-tropical storms, poleward flowing boundary currents and associated eddy circulation.

Temperate - warm	Located along the southern margin of Australia from Cape Leeuwin to Kangaroo Island and on the eastern margin from Moreton Bay to Sydney. Mild to warm ocean temperatures (~15-20^{o} C), nutrient rich and highly productive, influenced seasonally by extratropical and mid-latitude storms and currents that promote upwelling.
Temperate - cool	Located in the ocean surrounding Tasmania. Cool ocean temperatures (~10-15^{o}C), nutrient rich and highly productive, influenced by southern ocean storms that promote localised upwelling.
Polar	Located at latitudes greater than 60^{o} with cold ocean temperatures (<10^{o} C) and high productivity due to plankton but with seasonal sea ice cover.

2.5.3 Shelf Zone

Intertidal	The area fringing the shoreline that is emergent at low tide and submerged at high tide
Inner Shelf	The shallower part of the continental shelf, typically **0 to 30 m** water depth
Mid Shelf	The part between the inner shelf and outer shelf, typically **30 – 60 m** water depth
Outer Shelf	The deeper part of the continental shelf extending to the shelf break, typically **60 – 200 m** water depth

2.5.4 Geofeature

Modified from geoforms in CMECS (FGDC, 2012), and where replicated in the International Hydrographic Organisation list of undersea feature comparative definitions are provided.

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. (IHO definition: “an elevation of the seafloor, at depths generally less than 200 m…”).
Channel	A linear or sinuous depression on an otherwise flat surface
Depression	A low lying area surrounded by higher ground and with no outlet or opening (i.e. closed)
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.
Ledge	A level to near-level planar surface bound on one or more sides by a slope and with a significantly greater length than width (e.g. length to width ratio of 10). Commonly formed along bedding planes in sedimentary rock that are exposed at the seabed.
Mound	A low, rounded protuberance, typically isolated. Dimensions in metres and generally smaller than a knob.
Pinnacle	A high tower or spire-shaped pillar of rock or coral, isolated or on the crest of a summit (IHO definition: “A spire shaped pillar either isolated or at the summit of a larger feature”).
Platform	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. (IHO definition: “An elongated elevation of varying complexity, size and gradient”)

Scarp	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.
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 (IHO definition: “A flat or gently sloping region, generally long and narrow bounded along one edge by a steeper descending slope and along the other by a steeper ascending slope”).
Indeterminate	The reef type could not be determined based on the existing information

2.5.5 Relief

Modified from ’Elevation Profile’ in FGDC (2012). Relief is calculated as the elevation range within a defined area relative to the length or diameter of that area, e.g., for a circular area with a diameter of 10 metres and an elevation range of 5 metres, the relief = 50% (medium).

Low	1% to 20%
Medium	20% to 50%
High	≥ 50%
Indeterminate	The relief of the reef relative to the surrounding seabed could not be determined based on the existing information

2.5.6 Slope

After Greene et al. (2007). Slope is calculated as the averaged slope gradient within the reef perimeter.

Flat	0 to < 5 degrees
Gently sloping	5 to < 30 degrees
Steeply sloping	30 to < 60 degrees
Vertical	60 to < 90 degrees
Overhang	≥ 90 degrees
Indeterminate	The slope angle of the reef surface could not be determined based on the existing information

2.5.7 Rugosity

After Greene et al. (2007). Rugosity is calculated as the ratio of the surface area to the planar area**;** e.g. 180 m^2 surface area across 100 m^2 planar area, the rugosity = 1.8.

Very Low	1.0 to < 1.25
Low	1.25 to < 1.50
Moderate	1.50 to < 1.75
High	1.75 to < 2.00
Very High	≥ 2.00
Indeterminate	The rugosity ratio between the reef's surface area and its planar area could not be determined based on the existing information

2.5.8 Substrate

Rock	Consolidated earth material (e.g. bedrock)
Unconsolidated Hard	A loose deposit of rock clasts (e.g. drowned boulder ridge)
Unconsolidated Soft	A loose deposit of sediment comprising mud, sand or gravel
Indeterminate	The substrate covering the reef surface could not be determined based on the existing information

2.5.9 Rock Lithology

Sedimentary	Formed by the deposition and subsequent cementation of grains of siliciclastic or bioclastic materials
Igneous	Formed through the cooling and solidification of magma or lava
Metamorphic	Formed from the transformation (metamorphism) of existing rock types by heat and pressure
Indeterminate	The rock lithology of the reef could not be determined based on the existing information

2.5.10 Rock Texture

After FGDC (2012)

Pavement	A level area (surface) of exposed rock
Megaclast (field)	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
Boulder (field)	Boulder has a size of 256 to < 4,096 (millimetres); or -8 to < -12 (phi)
Cobble (field)	Cobble has a size of 64 to < 256 (millimetres) or -6 to < -8 (phi)
Pebble (field)	Pebble has a size of 4 to < 64 (millimetres) or -1 to < -6 (phi)
Indeterminate	The texture of the rock that covers the reef surface could not be determined based on the existing information

2.5.11 Sediment Texture

After Folk (1954)

Gravel	>=80% gravel content
Muddy Gravel	30%-80% gravel content; sand to mud ratio <= 1
Muddy Sandy Gravel	30%-80% gravel content; 9 > sand to mud ratio > 1
Sandy Gravel	30%-80% gravel content; sand to mud ratio >= 9
Gravelly Mud	5%-30% gravel content; sand to mud ratio <= 1
Gravelly Muddy Sand	5%-30% gravel content; 9 > sand to mud ratio > 1
Gravelly Sand	5%-30% gravel content; sand to mud ratio >= 9
Sand	< 5% gravel content; sand to mud ratio >= 9
Muddy Sand	< 5% gravel content; 9 > sand to mud ratio > 1
Sandy Mud	< 5% gravel content; 1 > sand to mud ratio >= 1/9
Mud	< 5% gravel content; sand to mud ratio < 1/9
Indeterminate	The texture of the sediment that covers the reef could not be determined based on the existing information

2.5.12 Percent Cover

After FGDC (2012)

Trace	< 1%
Sparse	1 to < 30%
Moderate	30 to < 70%
Dense	70 to < 90%
Complete	90 to 100%
Indeterminate	The relative percent cover of each of the substrate components over the reef surface could not be determined based on the existing information

2.6 Examples of Reef Geofeatures

Representative examples of reef geofeatures are shown in the following Figures, including application of the range of classification categories and measured values specific to those features. These examples show the flexibility of a 'flat' (i.e. non-hierarchical) scheme, whereby any number of categories (or tags) may be used to describe a reef, depending on the information available. In many instances, a reef will be a composite of multiple geofeatures as shown in the examples below. The classification of such composite reefs can be achieved by simple tagging of each geofeature, or extend to delineation of polygons (not shown) for each geofeature to provide spatial statistics (e.g. surface area and dimensions).

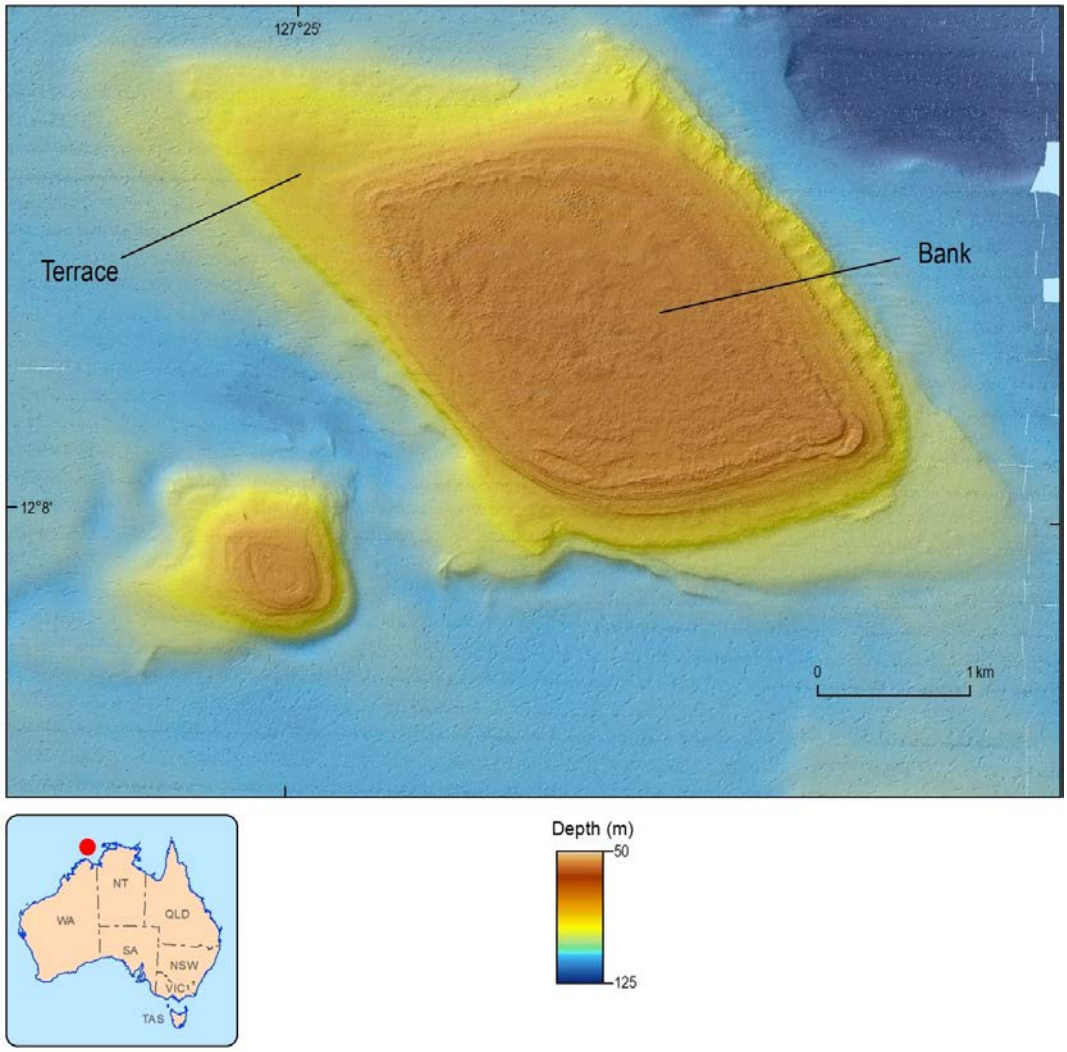

Figure 2.6.1: Multibeam sonar image of a composite bank and terrace geofeature that forms part of the Pinnacles of the Bonaparte Basin, a Key Ecological Feature in the North-west Marine Region. This geofeature also lies within the Oceanic Shoals Commonwealth Marine Reserve.

Origin	Climate Region	Shelf Zone	Geofeature	Relief	Slope	Rugosity	Substrate	Rock Lithology
Biogenic	Tropical	Outer Shelf	Bank	Low to Medium[1]	Flat[2]	Very Low[3]	Rock	Indet
Biogenic	Tropical	Outer Shelf	Terrace	Low	Flat	Very Low	Rock	Indet

Notes:
1. Bank relief measured as: 0.5-3m elevation range / 6m diameter circular area = 8-50%
2. Bank slope measured as: 1.8^{o}
3. Bank rugosity measured within a polygon (not shown) as:: 6224303m^2/6217631m^2 = 1.001

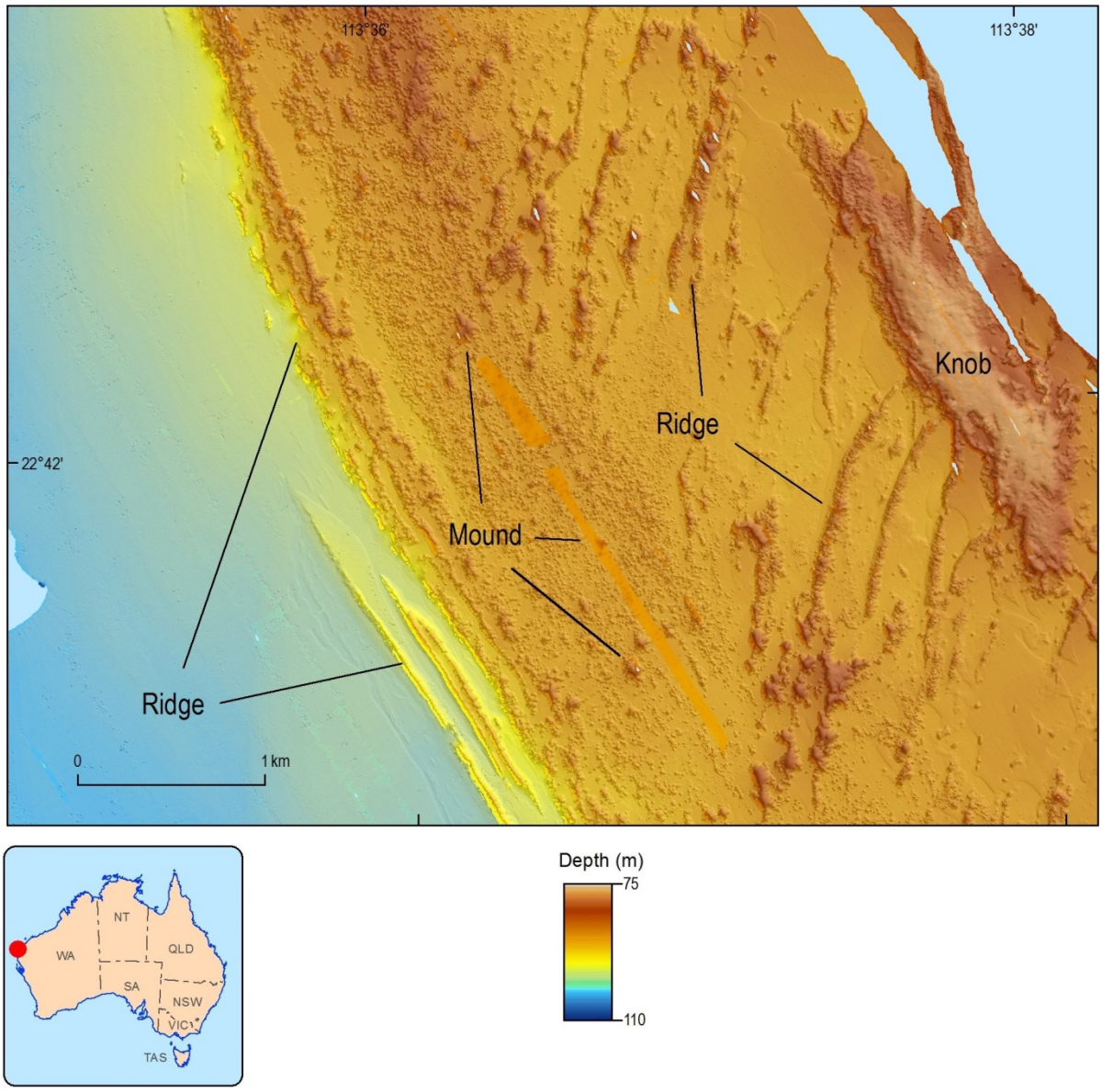

Figure 2.6.2: Multibeam sonar image of ridge and mound geofeatures forming a reef system that lies inshore of the Commonwealth waters adjacent to Ningaloo Reef, a Key Ecological Feature in the North-west Marine Region.

Origin	Climate Region	Shelf Zone	Geofeature	Relief	Slope	Rugosity	Substrate	Rock Lithology
Biogenic	Sub-Tropical	Inner Shelf	Mound	Medium	Flat	Low	Rock	Indet.
Biogenic	Sub-Tropical	Inner Shelf	Ridge	Medium[1]	Gently slopping[2]	Very Low[3]	Rock	Indet.

Notes:
1. Ridge relief measured as: 3-6m elevation range / 18m diameter circular area = 16.7-33.3%
2. Ridge slope measured as: 12.4^{o}
3. Ridge rugosity measured within a polygon (not shown) as: 91332m^2/87873m^2=1.04

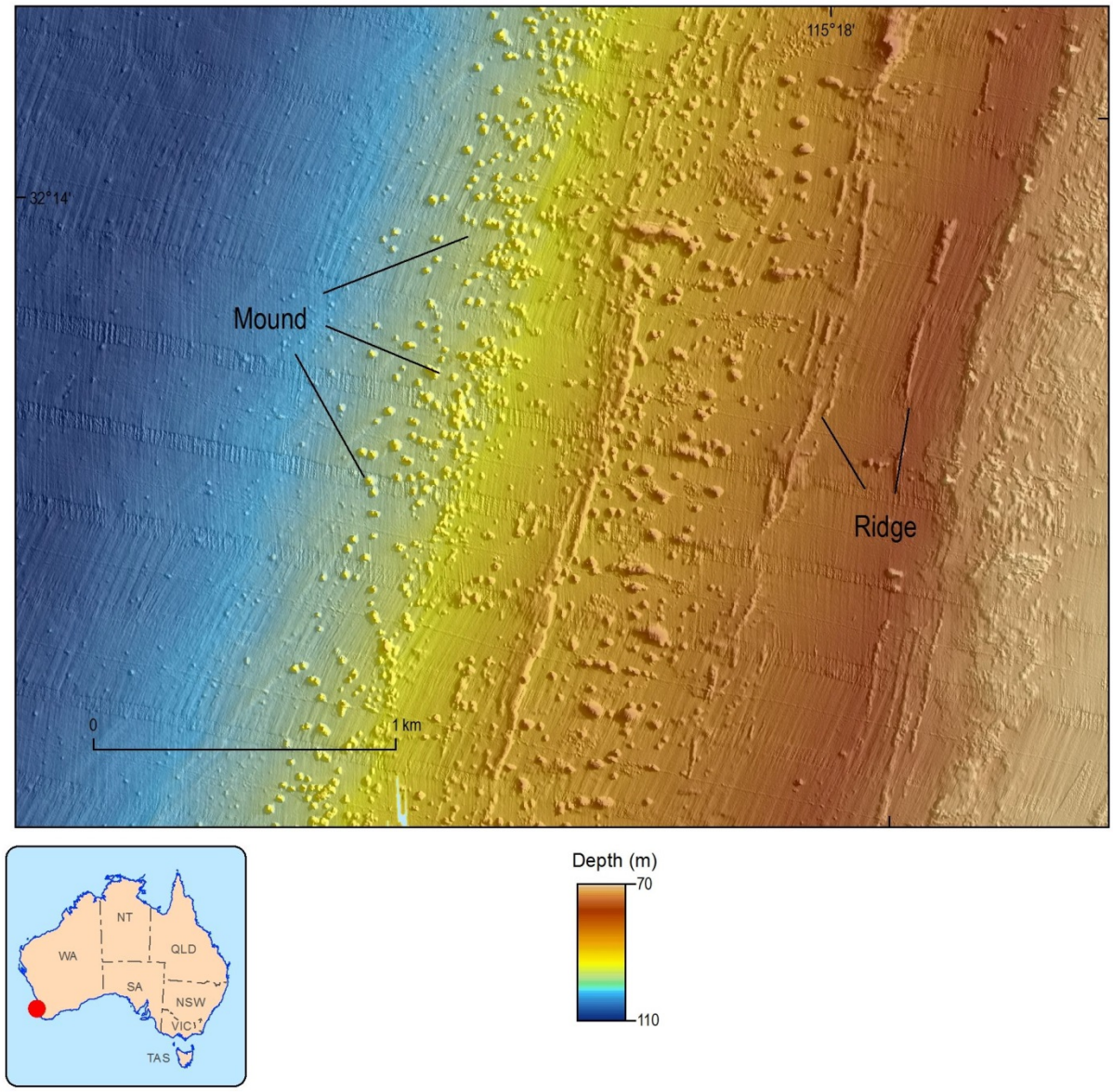

Figure 2.6.3: Multibeam sonar image of ridge and mound geofeatures within the Western Rock Lobster Key Ecological Feature in the South-west Marine Region.

Origin	Climate Region	Shelf Zone	Geofeature	Relief	Slope	Rugosity	Substrate	Rock Lithology
Biogenic	Sub-tropical	Outer Shelf	Mound	Medium-High[1]	Gently sloping[2]	Very Low[3]	Rock	Indet.
Biogenic	Sub-tropical	Outer Shelf	Ridge	Low-Medium[4]	Flat[5]	Very Low[6]	Rock	Indet.

Notes:
1. Mound relief measured as: 1.3-7.2m elevation range / 6m diameter circular area = 22-120%
2. Mound slope measured as: 22º
3. Mound rugosity measured within a polygon (not shown) as: 997m^2/832m^2 = 1.2
4. Ridge relief measured as: 0.3-2.1m elevation range / 6m diameter circular area = 3-35%
5. Ridge slope measured as: 4.7º
6. Ridge rugosity measured within a polygon (not shown) as: 3596m^2/3572m^2 = 1.007

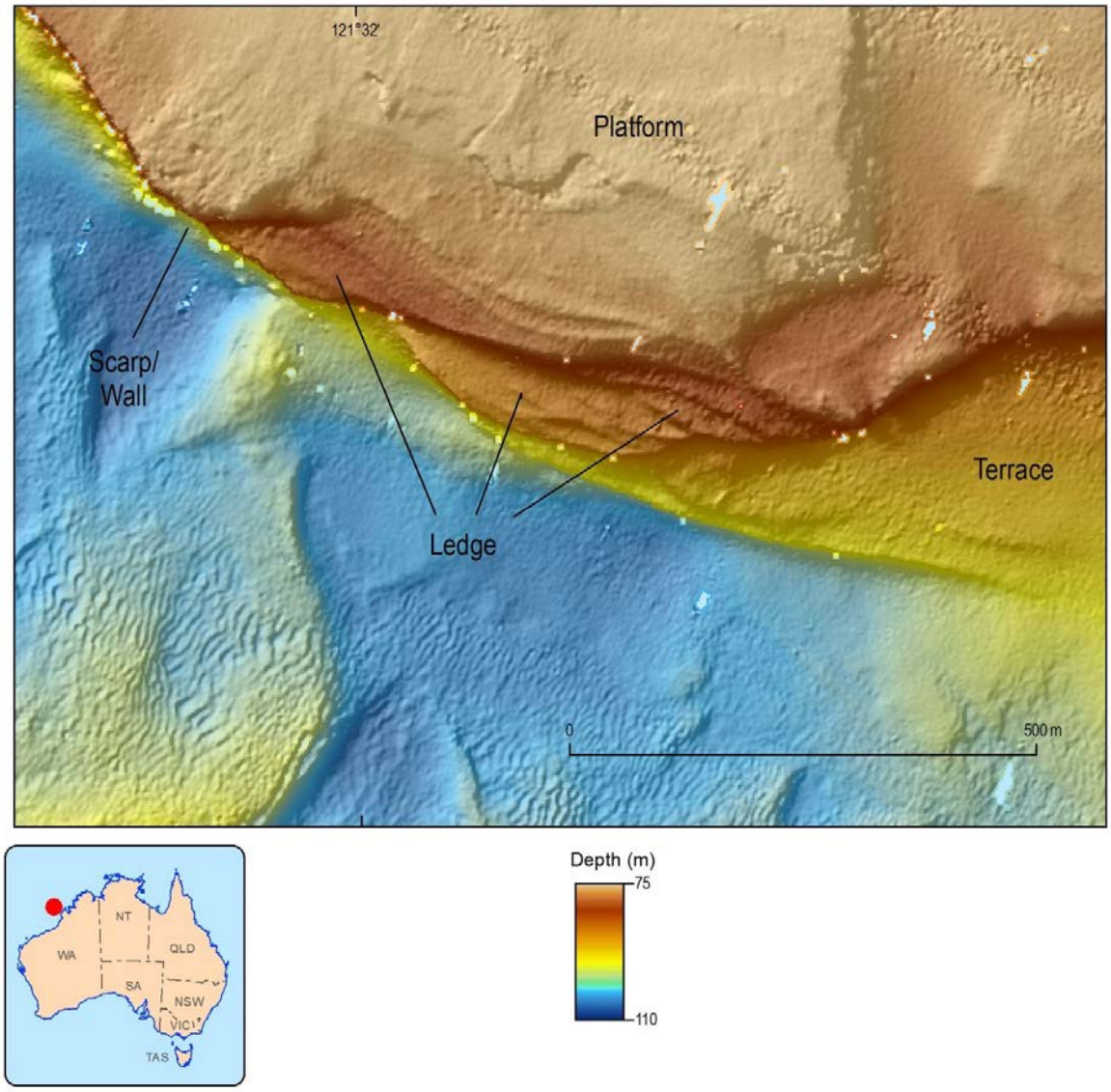

Figure 2.6.4: Multibeam sonar image of platform, terrace, ledge and scarp geofeatures on an outer shelf reef within the Kimberley Commonwealth Marine Reserve, North-west Marine Region.

Origin	Climate Region	Shelf Zone	Geofeature	Relief	Slope	Rugosity	Substrate	Rock Lithology
Biogenic	Tropical	Outer Shelf	Terrace	Low to Medium[1]	Flat[2]	Very Low[3]	Rock	Indet.
Biogenic	Tropical	Outer Shelf	Platform	Low	Flat	Moderate	Rock	Indet.
Biogenic	Tropical	Outer Shelf	Ledge	Low	Gently sloping	Low	Rock	Indet.
Biogenic	Tropical	Outer Shelf	Scarp	High	Vertical	Indet	Rock	Indet.

Notes:
1. Terrace relief measured as: 0.5-4m elevation range /12m diameter circular area = 4-33.3%
2. Terrace slope measured as: 1.1°
3. Terrace rugosity measured within a polygon (not shown) as: 1894280 m^2/189268 m^2 = 1.0008

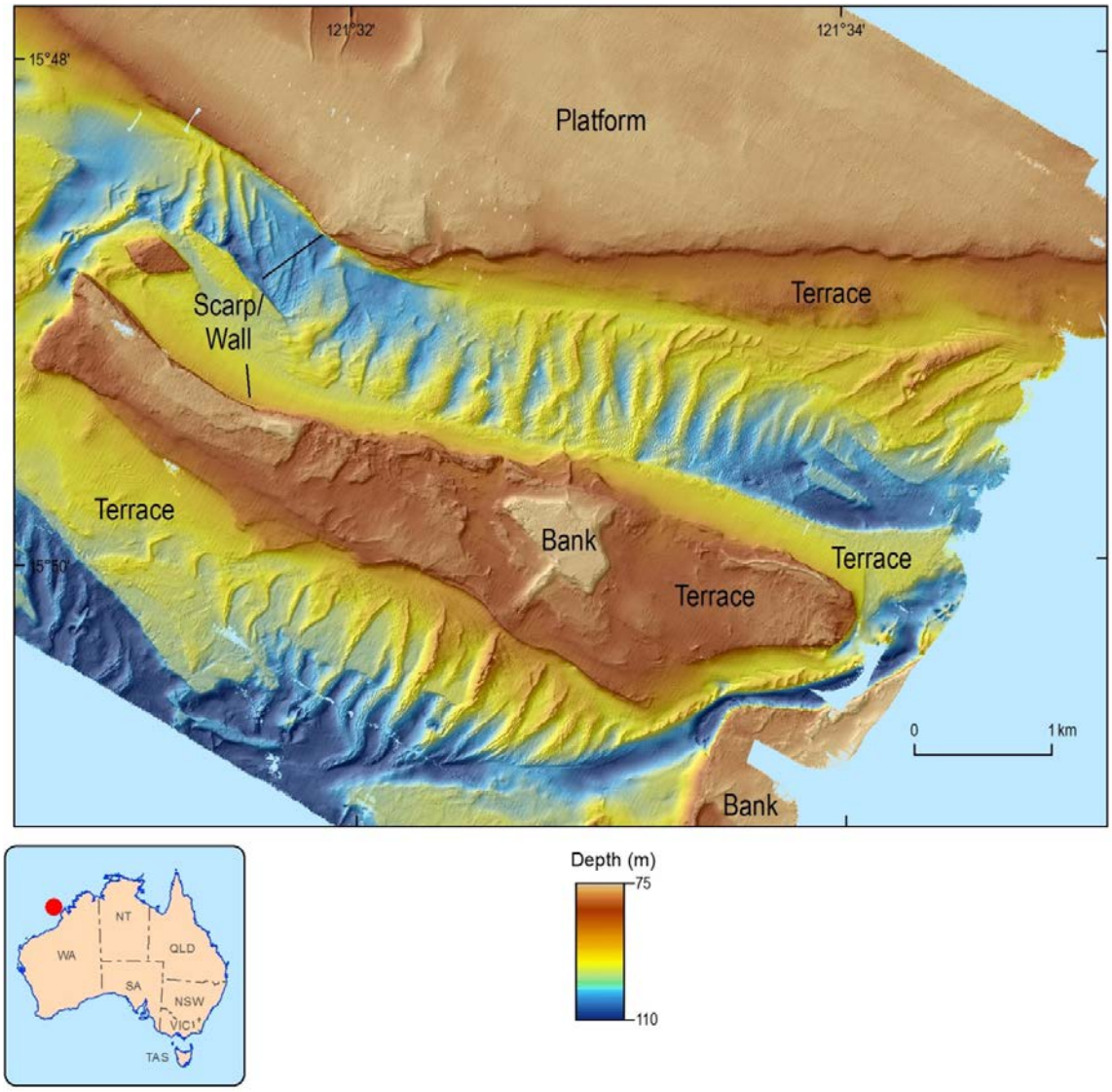

Figure 2.6.5: Multibeam sonar image of platform, terrace, bank and scarp geofeatures on an outer shelf reef within the Kimberley Commonwealth Marine Reserve, North-west Marine Region.

Origin	Climate Region	Shelf Zone	Geofeature	Relief	Slope	Rugosity	Substrate	Rock Lithology
Indeterminate	Tropical	Outer Shelf	Platform	Low to High[1]	Flat[2]	Very Low[3]	Rock	Indet.
Indeterminate	Tropical	Outer Shelf	Terrace	Low to Medium	Flat	Moderate	Rock	Indet.
Indeterminate	Tropical	Outer Shelf	Scarp	High	Vertical	Indet.	Rock	Indet.
Indeterminate	Tropical	Outer Shelf	Bank	Medium	Flat	Low	Rock	Indet.

Notes:
1. Relief measured as: 0.2-7m/12m = 1.7-58%
2. Slope measured as: 0.6º
3. Rugosity measured within a polygon (not shown) as: 28046687m^2/2803680m^2 = 1.0004

3. FUTURE WORK

The reef geomorphology classification scheme presented here allows for the standardised description of reef habitat heterogeneity across a range of spatial scales. It also provides a basis for interpreting the spatial distribution of reef types in the context of the geomorphic evolution of the continental shelf. For example, the interpretation of low profile ridges on the outer shelf as potentially relict (i.e. drowned) coastal features can be supported through the application of specific categories in the scheme (e.g. origin, shelf zone, substrate), where the appropriate information is available. The scheme also has the potential for extension to a habitat classification through the integration of additional environmental parameters that are known to influence marine biodiversity. Key factors are those that influence primary productivity and those that may drive temporal change (or disturbance) to a reef biological community. These are elements that will be addressed in ongoing work within the shelf reef assets project.

Finally, the scheme is intentionally designed not to be hierarchical in structure to allow for use of any number, or combination of, categories (or tags) to describe a reef. The utility of the tag approach lies in improved searchability of datasets when published online. In this context, development of an online resource to provide examples of classified reefs and summary information for end-users would facilitate uptake of the scheme.

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6. APPENDIX 1

Within the Commonwealth Marine Area, 54 Key Ecological Features (KEFs) have been identified, of which 32 have been modelled using qualitative methods to understand potential responses to human pressures (Hayes et al., 2015a,b). To guide the assessment of KEF condition, the Marine Biodiversity Hub developed a blueprint for monitoring KEFs (Hayes et al., 2015b). The blueprint proposes six functional groups of KEFs based on common biophysical features and processes, as follows: Canyons; Deep sea beds; Areas of enhanced productivity; Seamounts; Shelf reefs; and; Shelf sea beds. The shelf reef group comprises at least 11 KEFs listed below, but sub-divided here into KEFs that are located on the continental shelf and others that sit beyond the shelf break.

Shelf reef KEFs (following Hayes et al. 2015b):

- Ashmore and Cartier Island and surrounding Commonwealth waters
- Plateau and saddle north-west of the Wellesley Islands
- Submerged coral reefs of the Gulf of Carpentaria
- Commonwealth marine environment surrounding the Houtman-Abrolhos Islands
- Commonwealth marine environment surrounding the Recherche Archipelago
- Commonwealth marine environment within and adjacent to the west-coast inshore lagoons
- Shelf rocky reefs of the Temperate East region.

Off-shelf Reef KEFs:

- Mermaid Reef and Commonwealth waters surrounding Rowley Shoals
- Reefs, cays and herbivorous fishes of the Queensland Plateau
- Seringapatam Reef and Commonwealth waters in the Scott Reef complex
- Elizabeth and Middleton Reefs

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