1 An Appraisal of the Extent and Geomorphological Diversity of the Coral Reefs of the United Kingdom Dependent Territories

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Introduction

The 14 Dependent Territories governed by the United Kingdom (UK) Foreign and Commonwealth Office include in alphabetic order Anguilla, Ascension Island and Tristan da Cunha, British Antarctic Territory, Bermuda, British Indian Ocean Territory, British Virgin Islands, Cayman Islands, Falkland Islands, Gibraltar, Montserrat, Pitcairn Island, St Helena, South Georgia and South Sandwich Islands, Sovereign Base Areas on Cyprus and the Turks and Caicos Islands (Fig. 1.1). UK governance responsibilities for these territories include the strengthening of democracy, environmental protection, improvement of public services and law enforcement (Oldfield and Sheppard 1997)

Seven of these territories incorporate substantial reef systems, including Anguilla, Bermuda, the British Indian Ocean Territory (also known as the Chagos Islands), the British Virgin Islands, the Cayman Islands, the Pitcairn Islands and the Turks and Caicos Islands. These territories are composed of small remote islands that support a disproportionately large area of reefs, lagoons and associated marine biodiversity. The total reef area inside the Dependent Territories mapped by the Millennium Mapping Project is 4,712 km^2, which makes the UK approximately the twelfth reef nation of the World.

At the global scale, current estimates of national and regional reef areas derive from a variety of sources including marine charts and maps derived from remote sensing satellite images. They provide estimates that vary widely in accuracy. Basic information (reef or non-reef) on the location, extent and geomorphological nature of reefs systems has been compiled in the *World Atlas of Coral Reefs* published by the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC, Spalding et al. 2001). This atlas provided a global overview of reef distribution, however, the level of detail was largely determined by the variable availability and specification (scale, accuracy, precision) of marine charts across different reef regions. As a consequence, the inventory was often inconsistent from one area to another (Wabnitz et al. 2010). Other areas have since benefited from specific high resolution mapping projects that have provided accurate estimates of reef areas, itemized in different categories that follow a predefined typology of reef types and habitats (for instance, for Hawaii see Rohmann et al. 2005).

Starting in 2004, a global inventory of reef geomorphological diversity and units has produced consistent maps of reef areas worldwide. The data source is made of Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images, completed by occasional Landsat 5 and Aster satellite images. The project, named Millennium Coral Reef Mapping Project (MCRMP) has produced GIS files for many different parts of the world, as well as selected electronic atlases produced for non-GIS users. These regional atlases include Islands of the Central and Western Indian Ocean (Andréfouët et al. 2009b), Papua New Guinea (Andréfouët et al. 2006b) and the French Territories (Andréfouët et al. 2008). Other projects have distributed degraded (both in spatial and thematic resolutions) versions of the MCRMP products, for the Caribbean (Burke et al. 2004) and globally (Burke et al. 2010). The principles used to design the MCRMP typology, as well as the main hierarchical structure are described elsewhere (Andréfouët et al. 2006a; Andréfouët 2011). The typology and products have proved to be relevant in various contexts: for instance, we can cite geological appraisals (Andréfouët et al. 2009a), conservation planning (Green et al. 2009; Dalleau et al. 2010; Allnutt et al. 2012), fisheries and food security (Bell et al. 2009) and enhancement of the inventories of

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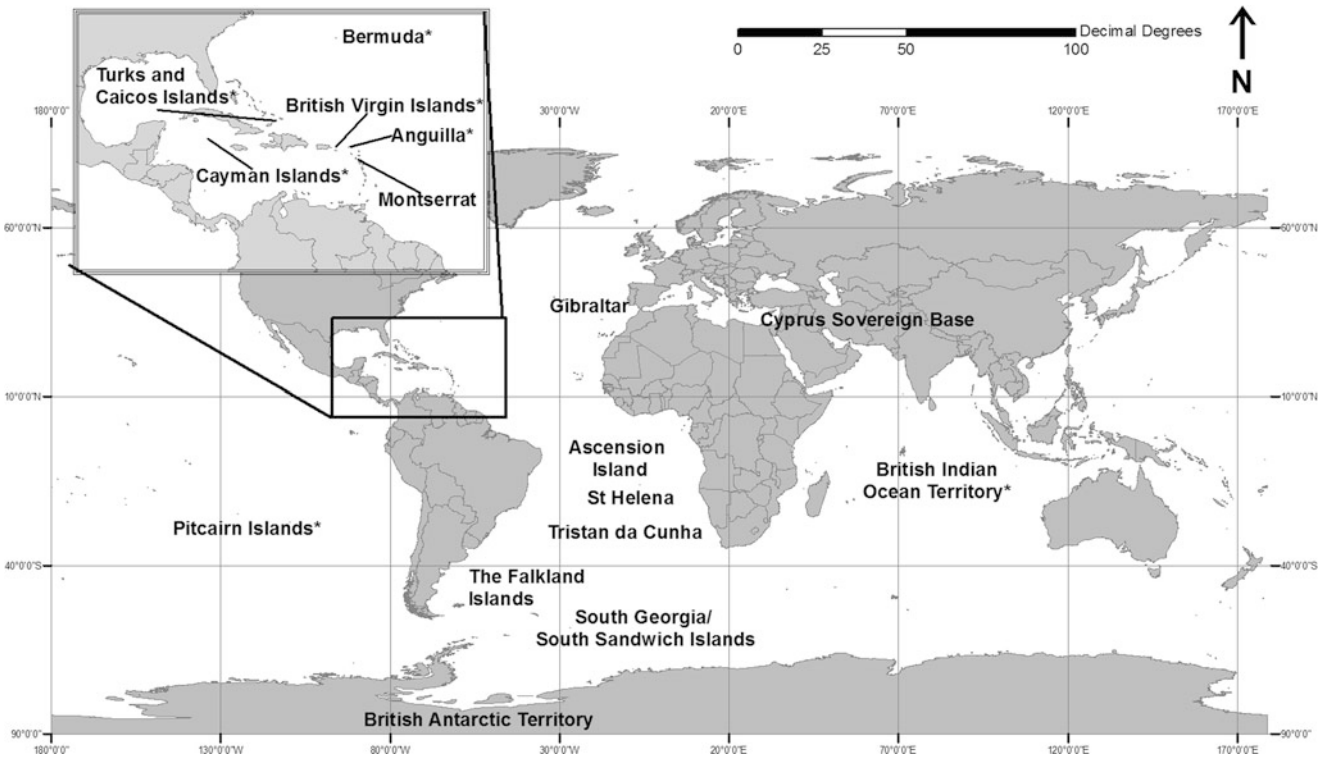

Fig. 1.1 Location of the UK Dependent Territories. *Asterisk* denotes reef territories

specific habitats such a seagrass beds (Wabnitz et al. 2008) or seamounts (Allain et al. 2008). Ongoing applications include connectivity and vulnerability to climate change assessments.

This chapter uses MCRMP products to conduct a geomorphological appraisal of the reef systems of the UK Dependent Territories with the following three objectives:

1. To identify where the coral reefs of the Dependent Territories are,
2. To generate a consistent and accurate measurement of reef areas, and
3. To delineate the morphological zones associated with these reef systems.

Methods

From a geomorphic perspective, coral reefs are three-dimensional structures that have evolved over geological timescales according to local sea level variations, subsidence, tectonics, hydrodynamic and climate forcing, and dominant living community types. They range in area from 1 to 100 km^2 in extent (Hopley 2011). As a result, reefs display a myriad of shapes and structures at a scale that can be resolved by high spatial resolution (1–30 m) optical spaceborne sensors down to a water depth of about 40 m in very clear waters. Typical depth penetration limit is around 20–30 m.

The UK Dependent Territories assessment was carried out using GIS layers generated as part of the Millennium Coral Reef Mapping Project (MCRCP). High resolution Landsat 7 ETM+ satellite images of coral reefs were interpreted using segmentation and photo-interpretation techniques to delineate regions belonging to different morphometric groups within a globally applicable typology of 800 classes (Andréfouët et al. 2006a). A reef "typology" refers to the definition of categories of reef objects according to a series of characteristics relevant for a given purpose (Andréfouët 2011).

The MCRCP hierarchical typology employs five hierarchical levels (Andréfouët et al. 2009a):

- Level 1: discriminates between oceanic and continental reefs;
- Level 2: discriminates the main reef complexes. Atolls, banks, uplifted atolls and islands can be either oceanic or continental. Then, the continental patch reefs, barrier reefs, fringing reefs and marginal structures are defined.

- Level 3: discriminates further details within each of the Level 2 blocks that are too numerous to cite here, but include for instance barrier, fringing and patch reefs of islands (either oceanic or continental), as well as different categories of these types: outer barrier, coastal barrier, multiple barrier, faro barrier, etc.; or lagoon exposed fringing, ocean-exposed fringing, etc.
- Level 4: defines the geomorphological units discernable on Landsat imagery within each of the previous blocks, including forereef, reef flat, pass, sedimentary terraces, enclosed lagoon, reef island, etc.
- Level 5: combines categories for Levels 1–4 to provide a final typology of 800 classes worldwide, although any single reef complex is likely to include between 1 and 20 classes at most. A level 5 label is thus the concatenation of the Levels 1–4. For instance a "Oceanic"/"Island"/"Coastal Barrier Reef"/"Reef Flat" makes a Level 5 description. Each combination is unique.

This appraisal was primarily conducted at Level 3 of the typological hierarchy, which provided an optimal simple, yet detailed level to facilitate comparison between the different territories.

In addition to the various geomorphologic attributes, each of the MCRCP polygon shapefiles has an associated "Reef" attribute that denoted whether the geomorphic unit supports significant coral communities (with a 1 value assigned to reefs and 0 assigned to non-reefs). For instance, the Level 4 classes "forereef", "reef flat", "subtidal reef flat", "pass", "pinnacle", etc. are considered as Reef, whereas terrace (i.e., sedimentary areas), lagoon, etc. are not considered part of the coral reef *per se*. To calculate the overall reef areas in the present assessment, we considered all polygons with a Reef attribute of value 1, for which the geometry calculator was employed to calculate the area, followed by the summary statistics tool to sum the areas of all the reef polygons.

Reef extent will clearly depend on the definition used: the "Reef" definition used here was largely consistent and compatible with a classical definition of coral reefs. For instance, it was compatible with the definition that state that coral reefs are "physical structure which has been built up and continues to grow over decadal time scales, as a result of the accumulation of calcium carbonate laid down by hermatypic corals and other organisms" (Spalding et al. 2001). Other definitions as provided by *The Encyclopedia of Modern Coral Reefs* elaborate further on the geomorphological components of coral reefs, including coral tracts (large areas of indefinite extent) and massive structures (in basal area and thickness and wave resistance) (Done 2011). These definitions were also consistent with the MCRMP definition.

Results

The reef systems of the Dependent Territories included 19 Level 3 reef classes, covering a total reef area of 4,712 km^2 (this figure relates to the areas that were identified as Reef only, as explained above). These included reef areas from atolls, barrier, banks, fringing and patch categories (Table 1.1).

If we compare the MCRCP estimates with Spalding et al. (2001), it can be seen from Fig. 1.3 that in many cases (5 out of 7 nations), the UNEP-WCMC study delineated more extensive reef areas than the MCRMP. The differences are significant in several instances (reaching 139% in the case of the British Virgin Islands). Similar discrepancies have been reported elsewhere (Andréfouët et al. 2006b; Wabnitz et al. 2010), illustrating the inherent variability associated with the different mapping approaches.

Discussion: Characteristics of Each Territory

For each Territory, we provide the Level 1 and Level 2 MCRMP label, and some information from the literature combined with the new inventory at Level 3 (Fig. 1.2).

Turks and Caicos (*Oceanic/Island*)

The limestone islands of the Turks and Caicos Islands group stretch across the northern extent of the relatively small Turks Bank and the much larger Caicos Bank (area 3,933 km^2). The margins of these banks slope down to a deeper shelf structure at a depth of 20–30 m that descends into oceanic water exceeding 4 km depth (Sullivan et al. 1994). Across the northern shore of the Caicos Islands is a coastal barrier reef complex with exposed fringing reefs on the oceanward aspect. Geologically, the subaerial islands that have developed in the Turks and Caicos Islands (area 924 km^2) consist of oolithic limestone sediments, with eolianite hills that have developed on the windward shores reaching up to 75 m above sea-level and karst limestone cliffs (Wanless and Dravis 1989). Of the overall typology, the Turks and Caicos Islands consisted of 11 different classes, with the shelf terrace occupying 60% of the mapped shallow platform.

Anguilla (*Oceanic/Island*)

Anguilla is a low coralline island (area 192 km^2), which has developed on a volcanic base, as part of the Lesser Antilles arc, which stretches 800 km across the eastern margin of

Table 1.1 A morphometric summary of the reef areas of the Dependent Territories (N.B. The right hand side column quotes % cover of the five most dominant geomorphic classes and therefore does not sum to 100%)

Territory	Area mapped/km^2	Reef area/km^2	# classes	Five dominant level 3 classes
Anguilla	2,537	43	7	*Shelf slope* (89%) *Main land* (8%) *Ocean exposed fringing* (2%) *Shelf terrace* (1%) *Bank lagoon* (0.4%)
Bermuda	733	340	7	*Island lagoon* (34%) *Outer Barrier complex* (32%) *Ocean exposed fringing* (13%) *Intra-lagoon patch reef complex* (11%) *Main land* (8%)
British Indian Ocean Territory	15,639	2,859	10	*Drowned atoll* (77%) *Atoll lagoon* (15%) *Atoll rim* (4%) *Drowned Bank* (3%) *Bank lagoon* (1%)
British Virgin Islands	4,500	138	9	*Shelf slope* (91%) *Lagoon exposed fringing* (3.5%) *Outer barrier reef complex* (2.8%) *Intra-lagoon patch reef complex* (1%) *Shelf patch reef complex* (0.8%)
Cayman Islands	471	471	9	*Main Land* (56%) *Island lagoon* (16%) *Coastal Barrier reef complex* (7%) *Ocean exposed fringing* (6%) *Shelf terrace* (5%)
Turks and Caicos Islands	6,885	822	11	*Shelf terrace* (60%) *Main land* (14%) *Shelf slope* (12%) *Shelf structure* (8%) *Coastal barrier reef complex* (3%)
Pitcairn Islands	89	39	9	*Main land* (52%) *Shelf slope* (20%) *Bank barrier* (10%) *Atoll rim* (7%) *Ocean exposed fringing* (7%)

the Caribbean Sea (Stein et al. 1982). The total area of reef systems mapped for Anguilla was 2,537 km^2 comprised of submerged banks and terraces, a shelf slope and fringing reefs. The fringing reefs have developed along the north and south coast of the island together with a number of offshore cays that support smaller reef platforms. The dominant morphological feature mapped for Anguilla was the submarine shelf shared with St Martin to the southeast, which occupied 89% of the area of the reef system. Along the northern extent of this Bank are exposed linear segments of fringing reef along the shelf edge. This 17 km-long reef along the southeast coast is considered to be one of the most important unbroken reefs in the eastern Caribbean (Putney 1982).

British Virgin Islands (*Oceanic/ Island*)

The Virgin Islands constitute the eastern extremity of the Greater Antilles arc and, in administrative terms, the shallow shelf on which the Virgin Islands sit can be subdivided into the US Virgin islands in the lower south western portion of the shelf and the British Virgin Islands on the upper north eastern portion. There are 40 uplifted volcanic islands, small cays,

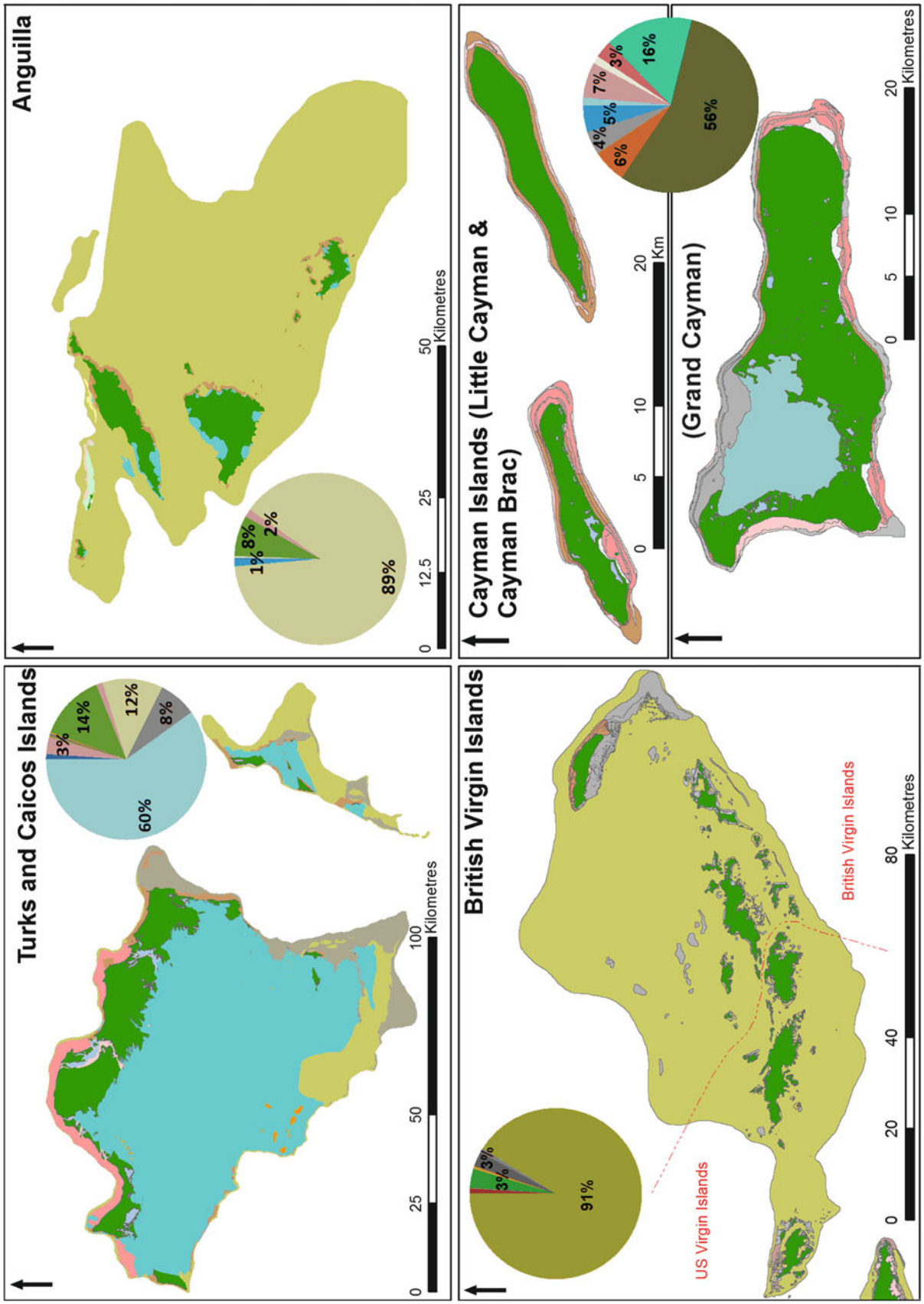

Fig. 1.2 Geomorphological maps of the reef systems of the UK Dependent Territories. Pie charts indicate % coverage of the geomorphic units for each territory (see key for units)

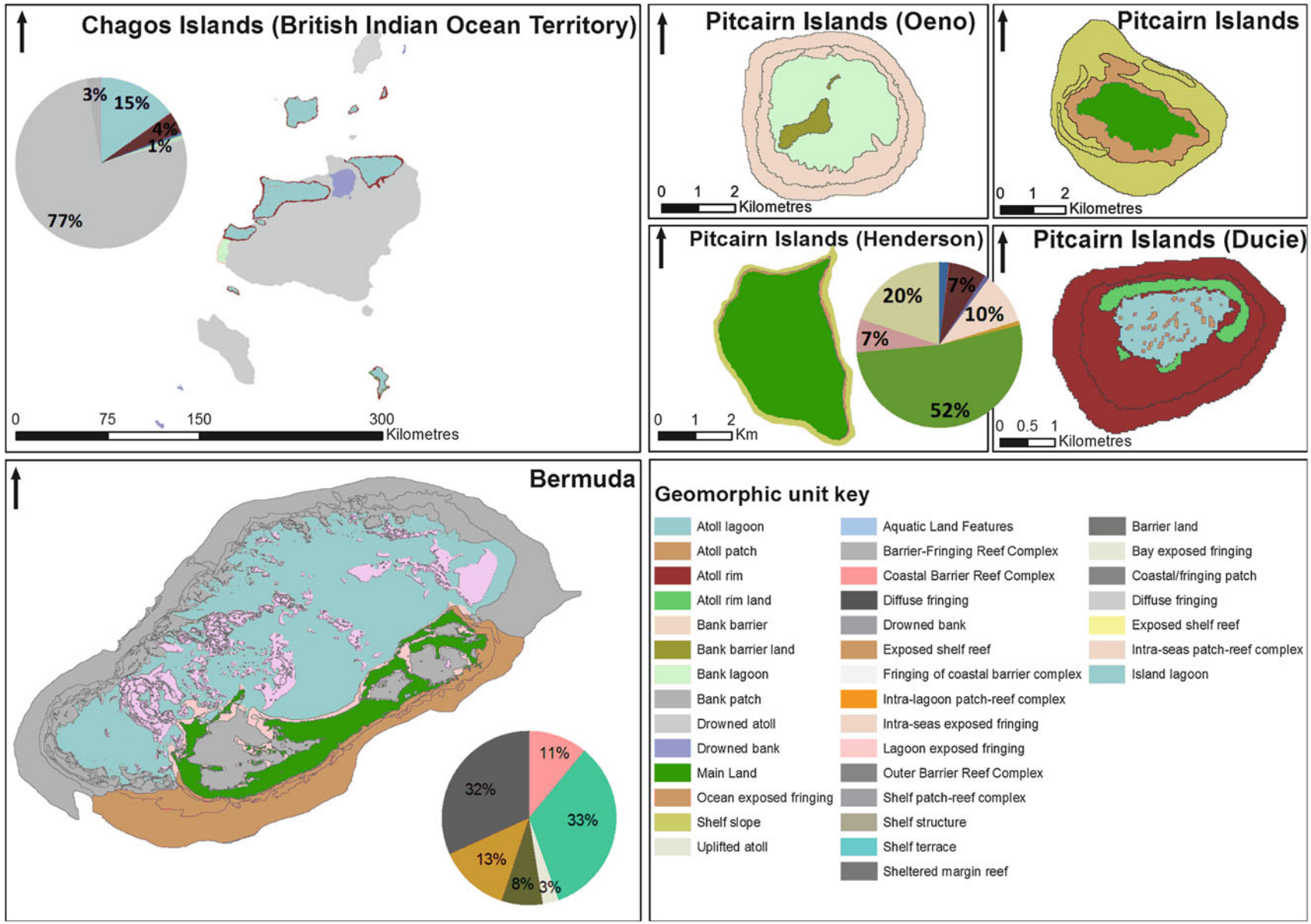

Fig. 1.2 (continued)

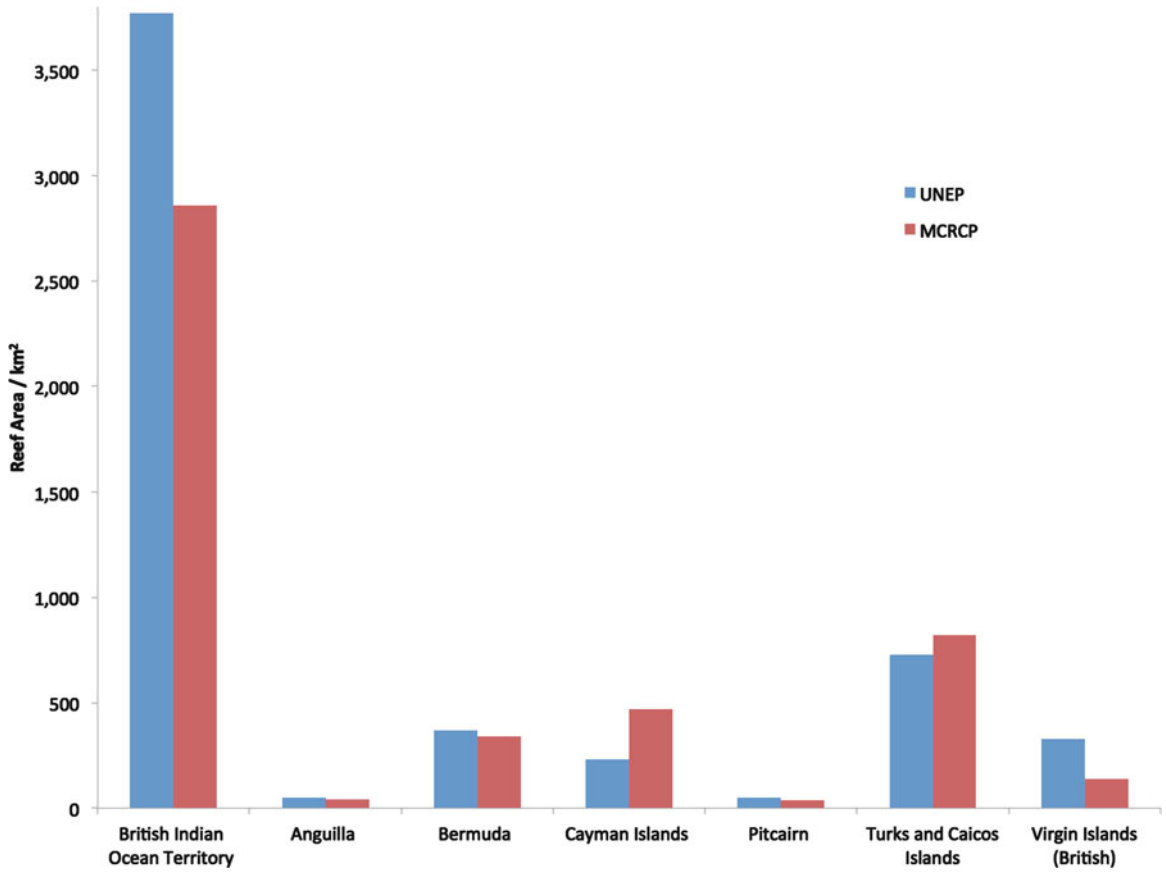

Fig. 1.3 Reef areas for each of the Dependent Territories compared between the previous reference (World atlas of coral reefs, Spalding et al. 2001, in *blue*) and the millennium coral reef Mapping project (*red*)

reef platforms and rocks in the group, the largest of which is Tortola (54 km^2). These rise from the Puerto Rican shelf, which sits at 65 m below sea level. The small shelf patch reef complex has largely developed within a matrix of volcanic uplift around the larger islands across the central shelf area. On the eastern windward side an outer barrier reef complex has developed in association with Anegada, a relatively flat emergent coral limestone platform (altitude 8 m) (Oldfield et al. 1999).

Cayman Islands (*Oceanic/Island*)

The flat, low lying Cayman Islands consist of three islands: Grand Cayman, Cayman Brac and Little Cayman, which sit at the western end of the Greater Antilles group. The islands sit along the Cayman Ridge, which forms the northern margin of the east–west aligned Oriente Transform Fault (Brunt and Davies 1994). The Cayman Islands have a collective land area of 261 km^2, which supports a series of terraced fringing and barrier reefs upon which spur and groove formations have developed that display considerable variability in structural form in relation to local wave power dynamics around the islands (Roberts 1974). A total reef area of 126 km^2 is supported by these islands in the form of an outer and coastal barrier reef complex, exposed fringing reef and shelf terrace.

British Indian Ocean Territory (*Oceanic/Island*)

The British Indian Ocean Territory lies at the southernmost extension of the north–south aligned Chagos-Laccadive Ridge and is composed of a limestone cap several 100 m thick that has developed over the hotspot that now lies under Reunion (Sheppard and Wells 1988; Parson and Evans 2005). The reef systems of the British Indian Ocean Territories are comprised of 2,859 km^2 reef area, which fall into ten classes related to the major morphological units (Andréfouët et al. 2009b). These include five atolls (The Great Chagos Bank

(the largest atoll structure in the world at 9,210 km^2), Diego Garcia, Egmont, Peros Banhos and Salomon). There is also an atoll whose islands disappeared and which became awash in the past 250 years (Blenheim), and many drowned banks of which Speakers Bank, Pitt Bank, Victory Bank and Centurion Bank are perhaps the best known. Each of the atolls has substantial lagoons, ranging in size from 11 to 940 km^2 with carbonate rims of varying degrees of subaerial exposure around their perimeter. All atolls and submerged banks appear to be actively growing reefs (Sheppard and Wells 1988).

Pitcairn Islands (*Oceanic/ Island*)

The Pitcairn group is comprised of four widely spaced atolls and islands in the South Pacific Ocean that fall along two geological structural lineations associated with hotspot activity of the clockwise-spreading Pacific plate (Spencer 1995). These four structures are Pitcairn Island (a volcanic island), Henderson Island (an uplifted atoll) and two small atolls, Oeno and Ducie. Collectively the islands can be classified into nine geomorphic units, dominated by emergent volcanic and reef islands, which represent 52% of the area mapped. Pitcairn is a volcanic island that rises 3.5 km from the seafloor with a peak that stands 347 m above sea level with continuous narrow fringing reef around it (Benton and Spencer 1995). The atoll of Henderson Island is a reef-capped volcano that was uplifted as a result of crustal loading by the adjacent Pitcairn volcano (Fosberg et al. 1983; Wells and Jenkins 1988), giving rise to several unique biodiversity characteristics for which Henderson has been designated a UNESCO World Heritage Site. Oeno atoll has a marked outer reef rim perimeter, with an island of area 0.7 km^2 that has developed at the centre of the lagoon. Ducie atoll (6 km^2) is the most easterly atoll of the Indo-Pacific reef province and the southern most atoll of the world, thought to be the surface expression of a field of seamounts (Spencer 1995).

Bermuda (*Oceanic/Island*)

Bermuda is comprised of 150 isolated coral limestone islands in the Sargasso Sea, western Atlantic Ocean, that have formed along the rim of an extinct submarine volcano approximately 1,000 km east of the North Carolina on the continental USA coastline. The extinct volcano sits on top of the Bermuda Platform, a topographic high of the Bermuda Pedestal, a basement that lies in water depths around 75 m (Vacher and Rowe 1997). The land area (56 km^2) is predominantly comprised of a network of ten main islands that are joined by causeways. The extinct volcano rim surrounds a substantial island lagoon (246 km^2). The Bermuda reef system (total area 677 km^2) is formed by the most northerly coral reefs in the world, which form a large outer barrier reef structure that encompasses an island lagoon of area 246 km^2.

Further Refinements to the Reef Inventory

Figures 1.4 and 1.5 demonstrate the full detail (Level 5) contained in the MCRCP products for the Chagos Islands and Anguila. The additional level of detail is apparent from the number of classes represented at this level, which are 24 and 71 for the Chagos islands and Anguila respectively (as opposed to 10 and 22 at Level 3).

The identification of 4,712 km^2 of reef within the UK Dependent Territories was possible using a remote sensing dataset of the requisite accuracy, resolution, consistency and completeness for consistently delineating shallow reef morphological units. Such consistency is important for regions that span the Atlantic, Indian and Pacific Oceans yet fall under a common governance framework. All of the major (Level 2) morphological reef units identified in the MCRCP global typology including atolls, banks, uplifted atolls, islands, patch reefs barrier reefs, fringing reefs and marginal structures are represented in the UK Dependent Territories.

As satellite remote sensing images have become increasingly available at a resolution commensurate with reef landform morphological variability (1–100 km^2), morphometrics derived from them represent an important source of information for managing both global environmental change and anthropogenic influences on reefs. Assessment of reefs according to morphogenetic phenomena, such as tectonic activity, sea level rise, sediment and hydrodynamics, provides a fundamental basis on which ecological dynamics and the impacts of human activities can be superimposed and understood. To this end, this geomorphological assessment, generated for the first time from consistent images of the UK Dependent territories, presents a useful foundation for the incorporation of morphodynamic information into marine environmental management decisions and policies.

While this study draws on the best available data for the time being, this assessment could be further improved by combining higher specification remote sensing data and targeted ground referencing field campaigns in a coordinated manner across the UK Dependent Territories. This additional effort will allow mapping in greater detail fine geomorphological structures (e.g., spur and grooves, different types of reef flats) as well as biological assemblages and benthic cover.

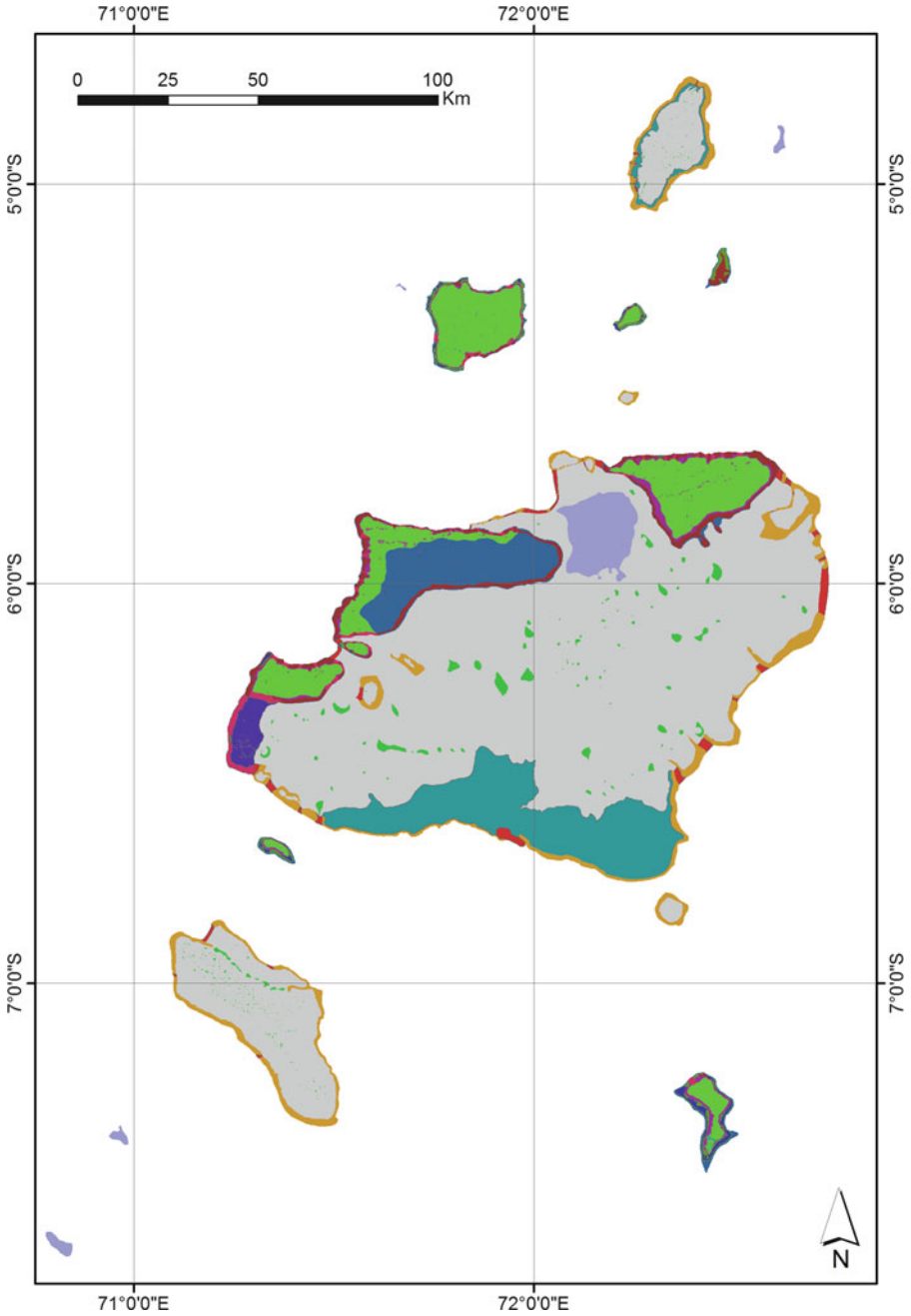

Fig. 1.4 The Chagos Islands (or British Indian Ocean Territory), illustrating the detail included at Level 5 in the MCRCP geomorphological map

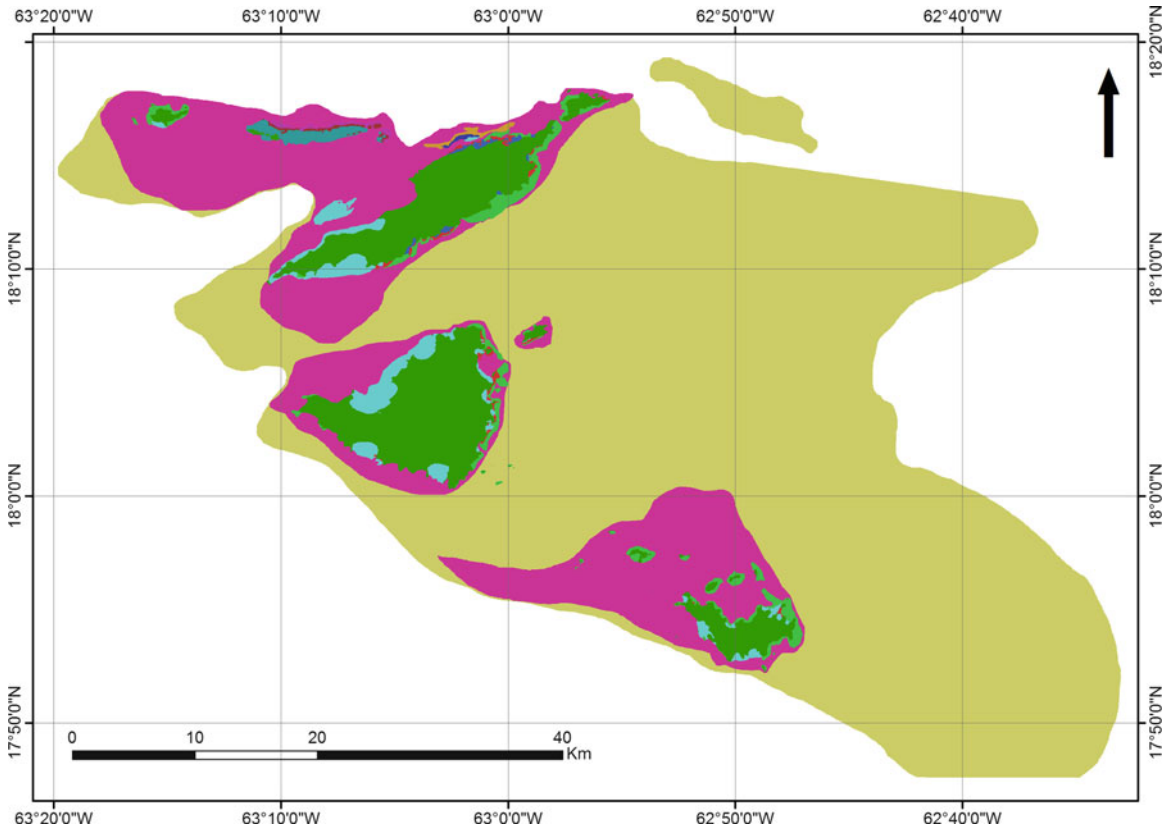

Fig. 1.5 Anguila, illustrating the detail included at Level 5 of the MCRCP Geomorphological map

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