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# Atolls of the world: A reappraisal from an optical remote sensing and global mapping perspective

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**Abstract :**

The Millennium Coral Reef Mapping Project (MCRMP) aimed to map coral reefs worldwide at geomorphological thematic scales using Landsat satellite images at 30 m spatial resolution. The 5-level hierarchical classification scheme implemented by MCRMP identified at Level 2 'Atolls' as one of the main types of coral reef complexes. In this review, the qualitative criteria used by MCRMP to identify atolls are presented. Then, we report on the global census of atolls, from which a consistent geomorphologic GIS database is provided. A total of 598 atolls are identified and mapped. The quantitative database provides surface areas for all geomorphologic units at Level 4 and 5 of the MCRMP classification scheme. It allows further work on atoll and coral reef classifications, regionally and globally, in order to identify geomorphic trends and outliers. It is also a convenient database to use in multivariate analyses with ancillary biodiversity, fishery, socio-economic or climate data.

**Highlights**

► Atolls are one of main type of coral reefs systems. ► Their global inventory have remained imperfect to date. ► An updated checklist of atolls worldwide is inferred from Landsat imagery. ► The protocol of the Millennium Coral Reef Mapping Project is used. ► 598 atolls are mapped with a 5-level hierarchical classification scheme.

**Keywords** : Remote sensing, Landsat, Millennium Coral Reef Mapping Project, Lagoon, Coral reef geomorphology

## Introduction

According to Woodroffe and Biribo (2011) in the Encyclopedia of Modern Coral Reefs (Hopley et al. 2011) '*atolls are annular mid-ocean reefs; the reef rim supports isolated, or near-continuous, reef islands composed of unlithified or poorly consolidated sand or gravel, and encloses a central lagoon*.' This recent definition of an atoll defines in a simple way one of the main emblematic types of coral reef formations using qualitative topological, sedimentological and geomorphological criteria. It highlights that the notion of the presence of a rim and a central lagoon are important. However, the same authors quickly emphasized in their encyclopedia entry that '*it is … difficult to settle on an unambiguous definition of what constitutes an atoll*' as they briefly review a series of checklist and definition attempted from Darwin (1842) to Wiens (1962). The definition of an atoll is even blurrier when other criteria related to the geological setting and genesis process of the reef at stake come into play, or when a number of atoll sub-types are listed (such as ocean atoll, shelf atoll, slope atoll, bank atoll, raised atoll, pseudo-atoll, etc.). The introduction of these sub-types and the variety of definition are clearly the consequences of views bounded by a narrow set of configurations (Stoddart 1978), which tend to favor local criteria and the multiplication of definitions before a more general, inclusive, and useful one can be proposed. Even the notion that atolls are necessarily mid-ocean systems is challenged by the designation of several broadly ring-shaped shelf reefs as atolls, as for instance in Belize (Gischler 2011), but also elsewhere as in Indonesia (Tomascik et al. 1997). The geological history of these continental features, which can be named as shelf reef platforms, radically depart from the mid-ocean features used to define atolls in the early pioneering coral reef geology work.

To our knowledge, besides Darwin (1842) who first established a list and map of atolls distribution, two publications have previously listed the atolls of the world. First, Bryan (1953) listed 409 atolls without extensive explanations on which criteria were used besides historical knowledge and usages. Second, Goldberg (2016) elaborated on this first checklist to provide a much needed revision, reaching 439 atolls. Goldberg (2016) enhanced the consistency of the criteria used to consider or not reef sites as atolls, using maps, and also satellite imagery and Space Shuttle or International Space Station photographs which were unavailable to Bryan (1953). Goldberg (2016) also acknowledged that certainly more entries will be added to his checklist when more observational data could be included. In addition, Goldberg (2016) also provided a useful web based interface (http://maps.fiu.edu/gis/goldberg/atolls, accessed March 2023) that was convenient to visualize atolls locations with satellite imagery. Nevertheless, despite the welcome update and more robust definitions, this was not completely satisfactory as there were in particular obvious cases of atolls missing in the list (e.g., several of the Entrecasteaux Reefs in the north of New Caledonia, or the large Eastern Fields in the south of Papua New Guinea), or atolls that did not seem like atolls as they did not fulfill some of the basic criteria in the aforementioned Woodroffe and Bribo (2011) definition. However, , in a new coming book, Goldberg and Rankey (2024) updated the 2016 list with 37 more atolls (Goldberg, pers. com.).

In 2002, the Millennium Coral Reef Mapping Project (MCRMP) was launched, funded by NASA, to enhance the mapping of the coral reef of the world using a detailed globally valid hierarchical geomorphological typology (Andréfouët et al. 2006). It took two years of literature search and preliminary mapping trials to freeze a first 5-level hierarchical typology, which was subsequently revised twice. Since 2012, the typology is stable and includes about 800 types of geomorphological units at the finest level of description (Andréfouët and Bionaz 2021). MCRMP baseline data were multispectral Landsat 7 satellite images at 30 meter resolution. In the early 2000s when MCRMP was launched, the scientific and management priorities were still to achieve a basic inventory of coral reef surface areas, and this was the main objective of the MCRMP project (Andréfouët and Bionaz 2021). When products became available, the detailed hierarchical typology made it possible to achieve worldwide scientific and management applications at different levels of description that could be tailored to different user needs (Gairin and Andréfouët 2020, Andréfouët and Bionaz 2021). Atolls were specifically included in the typology as one of the main coral reef geomorphological types, along with barrier or fringing reefs for instance.

To classify a reef site as an Atoll, the MCRMP used a number of criteria that had to be inferred only from Landsat images. While literature could provide additional information not visible on images, the majority of the sites did not have any scientific monographs to guide and complement the image-based interpretations. For instance, while the presence of small emerged land can be readily identified on multispectral imagery with near-infra red band (as available with Landsat), images alone do not inform immediately of the altitude of that land (except when shadows are visible) or the composition of its soils (carbonate or other origins). To label consistently a reef as an atoll, a number of MCRMP image-based criteria had to be met. These are both topological and geomorphological criteria. MCRMP geomorphological criteria are all present-day, or rather late Holocene age, criteria (although local atoll features may be older than Holocene in some cases). As such, and unlike some of the previous definitions, there are no criteria based on geological genesis processes, and the criteria can be globally applied.

In 2020, not all potential atolls of the world were mapped by MCRMP, although it seems that only a few were missing (based on Goldberg 2016). However, we took advantage of various COVID quarantine and lockdown periods while in New Caledonia to complete the census and reassess the check-list, also using Landsat 8 images that became available starting in 2014 in greater abundance and quality than the 1999-2003 SLC-OFF Landsat 7 images.

The objectives of this study is to present the MCRMP criteria used to identify and label atolls worldwide in order to provide a new coherent census from a global mapping project perspective. The result is a new listing of 598 atolls. While the criteria used to identify and label atolls are qualitative, the mapping work provides estimates of surface areas for all the atoll geomorphological classes of the MCRMP classification scheme. An online repository completes this study and provides an easy-to-use numerical databases in the form of GIS and Excel files for which we discuss potential applications. Indeed, this new quantitative database can be used by different users (scientists, managers, media) to allow further work on atoll and coral reef classifications, regionally and globally. Users can identify geomorphic trends and outliers, and can objectively include or not, at will, certain types of reef systems identified as atolls by MCRMP but that may not be perceived as true atolls in other projects due to some specificities (e.g., totally submerged rim, no deep lagoon, continental origins, etc) or due to criteria not taken into account by MCRMP (e.g., when considering traditional names). Finally, the database can be combined with ancillary biodiversity, fishery, socio-economic or climate data for a variety of analysis relevant for key topics such as conservation, biogeography, climate forcing, or food security (Andréfouët and Bionaz 2021).

## Material and Methods

### *MCRMP definitions and criteria*

The MCRMP project used a number of criteria to label polygons representing geomorphological units mapped by manual digitization of satellite imagery (Andréfouët et al. 2006). To label a reef complex (i.e., a suite of polygons) as an 'Atoll', the following criteria were used.

First, the reef complex had to be a MCRMP Level 2 reef. MCRMP Level 1 separates Oceanic from Continental reefs based on topological criteria rather than geological setting. Then the MCRMP Level 2 classes represent the first order of geomorphological reef organization, under which Level 3 and Level 4 classes add details. In other words, atolls are never included within another overarching larger reef complex. In practice, this means for instance that a Maldivian faro, hence a circular reef looking like an atoll but hierarchically at Level 3 within the lagoon of a Level 2 Atoll cannot be an atoll itself (Figure 1). Similarly, an annular reef with a central lagoon present on the barrier reef of an island or within a large barrier shelf system cannot be an atoll (Figure 1). With this criteria, all the large individual reefs present at a secondary level of organization, even circular with a rim and with an inner lagoon, are not classified as atolls. Should this criteria be relaxed, then several thousands of Level 3 'atolls' should be included in a revised atoll check list.

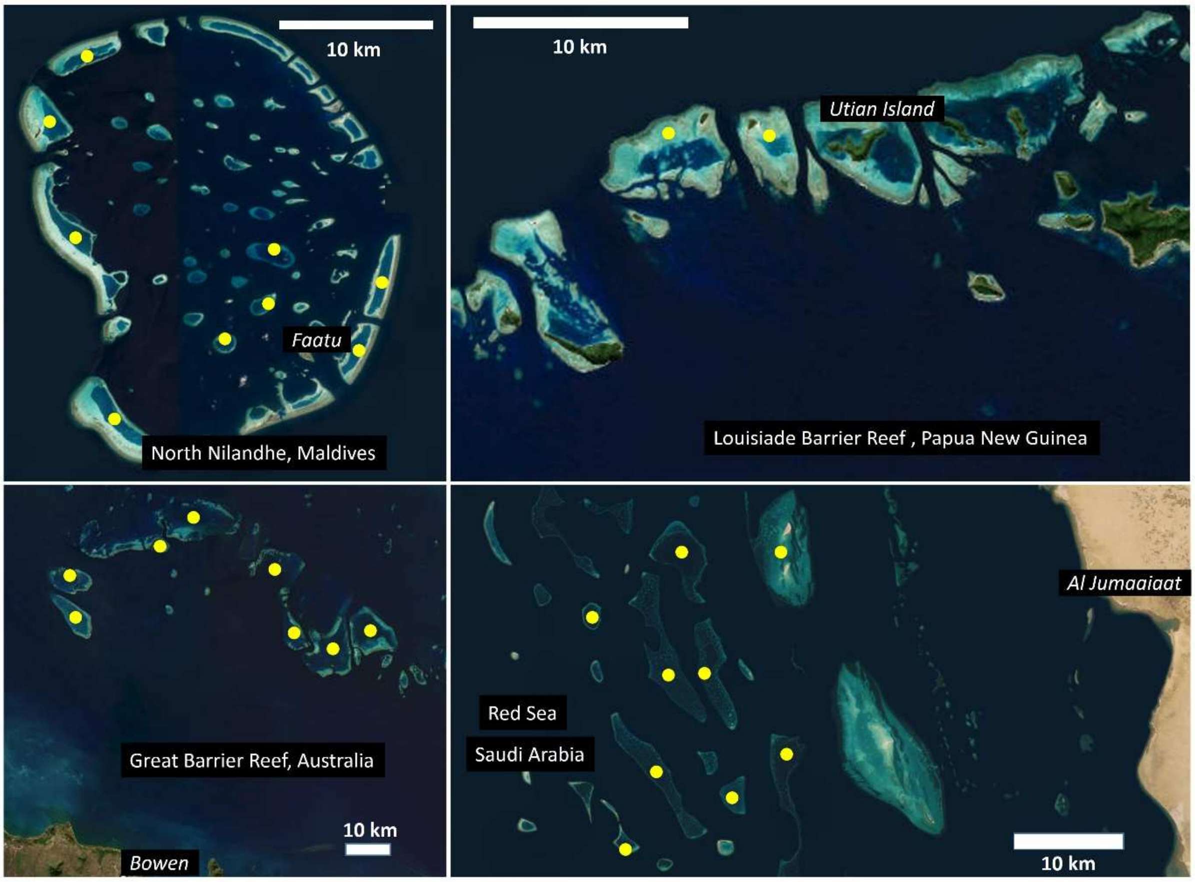


Figure 1: Yellow dots highlight some examples of reefs with an inner lagoon that are not atolls according to MCRMP criteria because they are part of larger ensembles. Not all possible yellow dots are shown for better visibility of the background images. Upper-Left: the North Nilandhe Atoll in Maldives as a whole is an atoll according to MCRMP, but the numerous inner individual rim and lagoon patch reefs are not considered as Atolls. These individual reefs with an inner sub-lagoon are actually called *faro*. Upper right image of the Louisiade Barrier Reef (Papua New Guinea) shows several atoll-likes individual reefs that are actually part of a segment of a barrier reef. Lower left: segment of the Great Barrier Reef shelf with large atoll-like structures. Lower right: Segment of the Saudi Arabia coastline with numerous individual atoll-like structures that are aligned parallel to the shore and part of what is rather characterized by MCRMP as multiple barrier reef complexes. (Background images : © Landsat/USGS).

For the second key criteria used to define an atoll by MCRMP, a reef site, either continental or oceanic (at Level 1), had to show the presence of a shallow or deep lagoon, even small compared to the rest of the reef complex. This lagoon had to be entirely or partially bounded by an optically visible rim. That rim can be emerged (vegetated or not), intertidal, subtidal (few meters deep with details visible) or 'drowned'. 'Drowned', within the limit of detection provided by Landsat images, means there is a rim detectable in very clear waters up to down to 40 meters maximum, and therefore only an outline is generally visible, without details. Atoll lagoons can therefore range from completely isolated from the ocean by an emerged rim (sometimes resulting in brackish or hypersaline lagoons) to very oceanic if the rim is largely subtidal or drowned. Rims and lagoons can thus span a wide range of exposure to oceanic forcing. Without the presence of lagoon clearly entirely or partially surrounded by a rim, a Level 2 reef site would be classified as a Bank. Uplifted atolls, hence without lagoons, are labeled as 'Uplifted Atolls' in the MCRMP typology, but are not included here in this check-list. As such, Nauru, , Niue, Makatea, Lifou and many others platforms which were once 'atolls' in their distant geological past are not listed here as atolls due to their lack of present-day lagoons (Nauru has a small brackish landlocked lake, named the Buada lagoon, but it is not a lagoon). Similarly, reef complexes that have seen their lagoons dry out, even recently, are not listed here as atolls. This includes for instance the small Tikei, Aki-Aki, Nukutavake or Tepoto Nord despite that they are all part of the largest atoll-only archipelago of the world (Tuamotu Archipelago in French Polynesia), but many other examples can be found elsewhere. The exclusion of these types of reef complexes is a major difference with Goldberg (2016)'s atoll check-list.

The two aforementioned topological and geomorphological criteria are the most important and could be inferred from Landsat images alone. Conversely, some criteria previously used in the literature were not considered by MCRMP, such as past name usages, or absence of some high lands. In general, for past name usages, MCRMP tried to follow the Stoddart (1978) reef terminology principles, and avoid as much as possible radical redefinitions that could conflict with past usages. However, using blindly traditional names can be often misleading, as they were often not based on any clear criteria or knowledge of underwater features. For instance, Chinchorro Bank or Turneffe Atoll in Mexico and Belize respectively should be classified as Bank and Atoll respectively based on their usual names. But they are fairly similar and both meet the MCRMP criteria to be labelled as atolls. Similarly, previously used labels to name a reef system such as 'shoal, 'cay', 'bank', 'reef', 'island' or '*pulau*' (island in Indonesian) are, among others, typically poor predictors of their final MCRMP labels. Pseudo-atolls, or almost-atolls, are two terms sometimes used in the reef geomorphological terminology when a central high island is surrounded by a vast lagoon itself bordered by a barrier reef. In the MCRMP classification, there are no pseudo or almost atolls. Instead, the reef complexes previously referred in some papers as pseudo or almost-atolls (e.g., Bora-Bora, Aitutaki, Gambier, Chuuk, etc.) are simply considered as Islands by MCRMP.

Finally, with the MCRMP criteria and data sources, several reef complexes with a rim and a lagoon are classified as atolls even if their rims are not totally composed of carbonate material. The presence of only carbonate sediments was an important criteria used in some of the previous atoll definitions (Woodroffe and Biribo 2011), and it is probably the consequences of the early Darwinian view of the oceanic genesis of an atoll, for which all remnants of volcanic or continental rocks have disappeared through subsidence under layers of carbonate sediments. This 'carbonate only' criteria may not be completely endorsed here, especially since it may be difficult to always obtain information on the nature of an island present on an atoll rim. For instance Clipperton Atoll (Charpy 2009), known for its 29m-high volcanic trachyandesite rock, remains here classified as an atoll despite this prominent non-carbonate high land. However, such exceptions are rare.

### *Atoll mapping and census*

Atolls were mapped worldwide between 2002 and 2012 by a team of three mappers using Landsat 7 images. Only one person (SA) validated each product for consistency sake. The final products were completed in 2020 using Landsat 8 satellite images (one mapper, SA). Generally, the Landsat 8 archive (2014-present) provided much more high quality images for any given site than the more restricted Landsat 7 image archive (1999-2003) due to the every-opportunity systematic acquisition strategy implemented by the Landsat 8 mission. For consistency sake, all the MCRMP Atolls and Banks mapped before 2012 were re-checked so that exactly the same criteria were used before a reef site was included in the present check-list.

With the MCRMP mapping protocol, each individual polygon of each reef complex has:

- A Level 1 attribute: to indicate if the polygon is Oceanic or Continental. An atoll can be either Oceanic or Continental.
- A Level 2 attribute: this indicates if the reef complexe is an Atoll, Uplifted Atoll, Bank, Island, Barrier, Fringing, Patch or Shelf reef complex.
- Level 3 attributes: this adds details to the Level 2 complex. For atolls, Level 3 specifies if the polygon is part of the Rim, Patch Reef, Lagoon, or Drowned Lagoon subdivisions. A drowned lagoon is defined as such if it is enclosed by a drowned rim
- Level 4 attributes: this adds details to Level 3 attributes, with specific geomorphological units that can be attached to Level 3 classes. For instance a Level 4 ‘reef flat’ can be specified to add details to a Level-3 Rim or Patch reef polygon, while a ‘Pass’ can add detail for the Rim. There are 36 possible Level-4 geomorphological attributes in total for atolls worldwide, including for land. Note however that most atolls have a much lower number of Level-4 classes (Figure 2).
- Level 5: this level actually concatenates all previous attributes into a unique code. Hence, a polygon with Level 1 to Level 4 attributes as ‘Oceanic /Atoll/ Rim/ Reef flat’ has a different Level 5 code than a ‘Continental/Atoll/Rim/Reef flat’ polygon. There are 73 possible Level 5 codes for all atolls worldwide (including Land codes). Note however that most atolls have a much lower number of Level 5 classes.

Examples of atolls mapped at Level 4 are provided Figure 2.

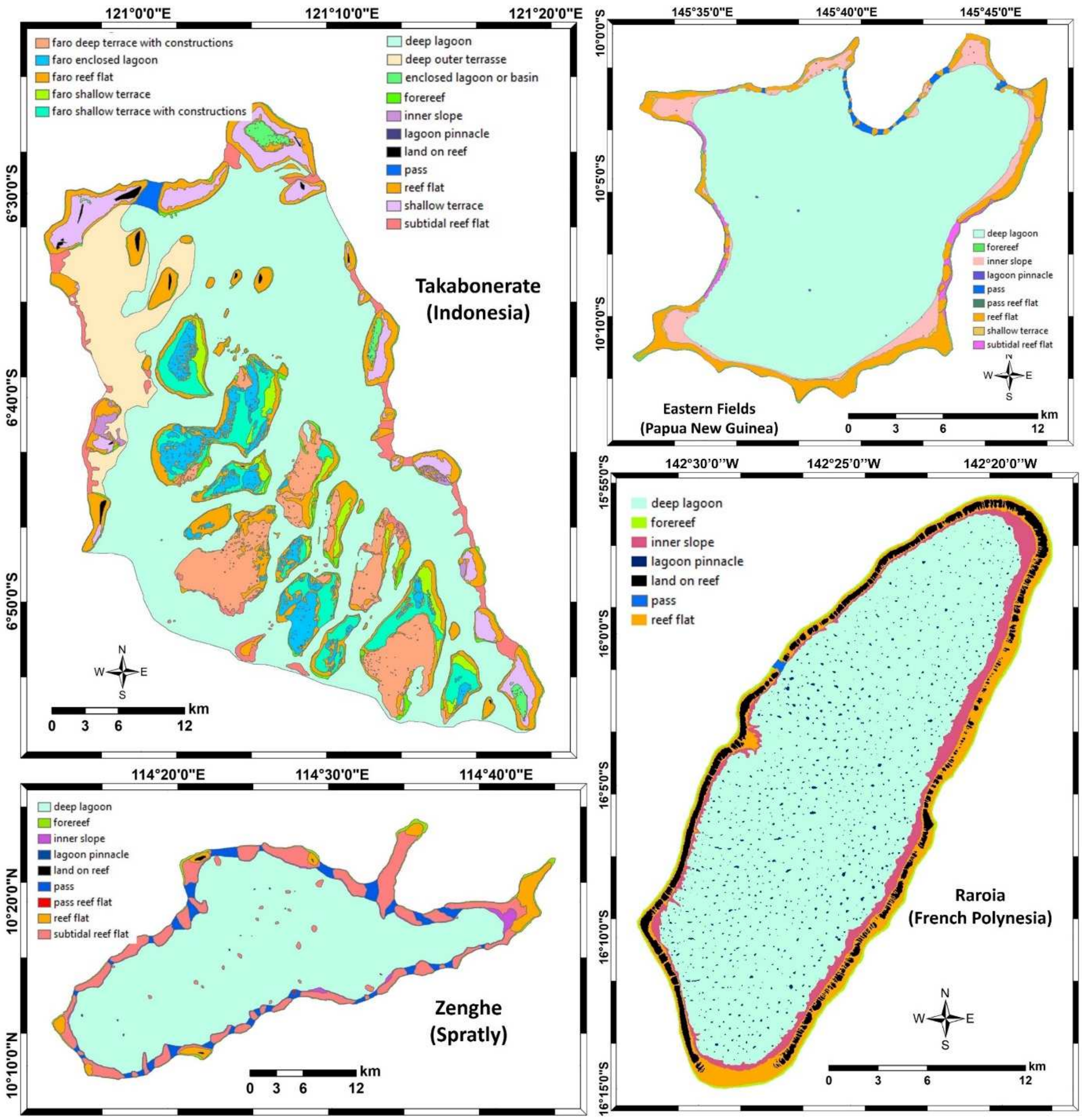


Figure 2: Examples of atoll mapped by MCRMP at Level 4.Upper-left: Takabonerate Atoll in Indonesia, a complex system with large patch reef ensembles in the main lagoon, themselves with their own lagoons (hence, the *faro* denominations). Upper-right: Eastern Fields in Papua New Guinea, a large landless atoll bounded by intertidal reef flats and with a handful of pinnacle in its lagoon. Lower right: Raroia Atoll in French Polynesia, a fairly closed atoll with almost continuous presence of land on the rim. Also the atoll with the highest number of coral pinnacles worldwide, with more than 1600 pinnacles (Andréfouët et al. 2020). Finally, lower left, the Zenghe Atoll in the Spratly archipelago, characterized by its subtidal rim and few intertidal reef flats. Because the map presented here are MCRMP Level 4 maps, Zenghe's reef flats for the rim or for the lagoon patch reefs appear with the same color. At Level 5, these two geomorphological units have a different codes and can be distinguished.

Morphometric statistics can be provided at each MRCMP Level, and can be used depending on the analysis at stake. By-default statistics include surface areas of each geomorphological class, and the proportion of these geomorphological classes (normalized surface area) relative to the total surface area of the atoll. Typically for general inventories for instance at national scale, areal statistics have been provided at Level 3 (e.g., Andréfouët et al. 2008 for French coral reefs, or Andréfouët et al. 2009 for Indian Ocean coral reefs), but specificities between sites are better apparent when analyzing at Level 4 and especially Level 5 of descriptions (Gairin and Andréfouët 2021).

***Use of previous reviews and literature***

To achieve the present census, we used a number of references that provided useful starting points or information.

As a starting point, the most recent census by Goldberg (2016) was used to identify potential sites not previously mapped by MCRMP. In doing so, we kept track of sites classified as atolls by both Goldberg (2018) and MCRMP, and discrepancies as well. Indeed, we encountered frequently the cases of sites classified as atolls by MCRMP but not by Goldberg (2016), and vice-versa.

Other critical references to guide us included the listing of Indonesian atolls by Tomascik et al. (1997), the recent mapping work on China Sea atolls by Dong et al. (2019), and the Diaz et al. (2000) atlas of Colombia coral reefs. These references were also in some occasions useful in deciding which names had to be kept as reference. Indeed, many reef systems can have different names (typically colonial and local names). When the situation was confusing, if possible we used the most exhaustive and unambiguous source. For the China Sea and their disputed reefs, we kept three geographical, rather than national, subdivisions used by UNEP-WCMC (Spalding et al. 2001), namely China Sea, Spratly, and Paracel.

Then, a large number of references, not all cited here, have been useful to provide the various geological and eustatic regional contexts of the different archipelagoes where atolls are present. While not directly used to take decisions on the atoll (or non-atoll) MCRMP labelling, they were useful in identifying particular genetic processes or explaining remarkable features seen on Landsat images. These include for instance Hopley (1982), Purdy and Bertram (1993), Dullo and Montaggioni (1998), Flood (2001), Purdy and Winterer (2001), Gischler (2003, 2011), Vecsei (2003), Hopley et al. (2007), Andréfouët et al. (2009), Hutchison and Vijayan (2010), Hopley (2011), Terry and Goff (2013), Rowlands and Purkis (2015), Rankey (2016), Gischler and Hudson (2019), Wu et al. (2020) or Droxler and Jorry (2021), and many references within these references. In a way, all the information provided by geological studies on coral reef regions have helped the interpretation of MCRMP classes by providing the exact context of the documented reef complexes, yet, at some point, and this may be seen as a paradox, it is necessary to 'forget' all the precise genetic descriptions to be able to map and label all reef complexes worldwide consistently (as hinted with Figure 2) when using satellite images only with a limited number of geomorphological Level 4 classes. However, in doing this simplification while keeping a link to the relevant background literature, it is possible to backtrack from MCRMP maps to geology wherever it was documented, and explain the specific different choices.

**Results**

The new census based on MCRMP criteria and Landsat 7 & 8 data yielded 598 atolls worldwide (Table 1 and Figure 3). The list includes 494 and 104 oceanic and continental systems respectively, hence oceanic systems are dominant. As expected, the Pacific Ocean (including Japan here) has the highest abundance with 344 atolls, followed by atolls from the Indonesian waters (77), the China Sea (68) and the Indian Ocean (54). Australia had 29 atolls on its Coral Sea/Pacific and Indian Ocean sides. At nation-scale, France has the most, reaching 102 atolls spread in the Pacific and Indian oceans, including 78 in French Polynesia alone. Asia, with Spratly, Indonesia, Philippines, Paracel and China Sea summed up to 158 atolls.

The previous census by Goldberg (2016) identified 439 atolls. Here, we identified an additional 181 atolls not classified as such by Goldberg (2016). Conversely 22 sites identified as atolls by Goldberg (2016) did not meet the MCRMP criteria to be qualified as atolls in the present census, mostly due to the absence of lagoons.

An online database (see the *Online Information* section) provides areal statistics at Levels 4 and 5 of the MCRMP classification scheme. Latitude-longitude of the barycenter of each atoll are also provided to locate each site globally (Figure 3), as well as a GIS shapefile for each individual atoll from which the Level 4 and 5 surface areas were computed using the QGIS 3.10.7 software.

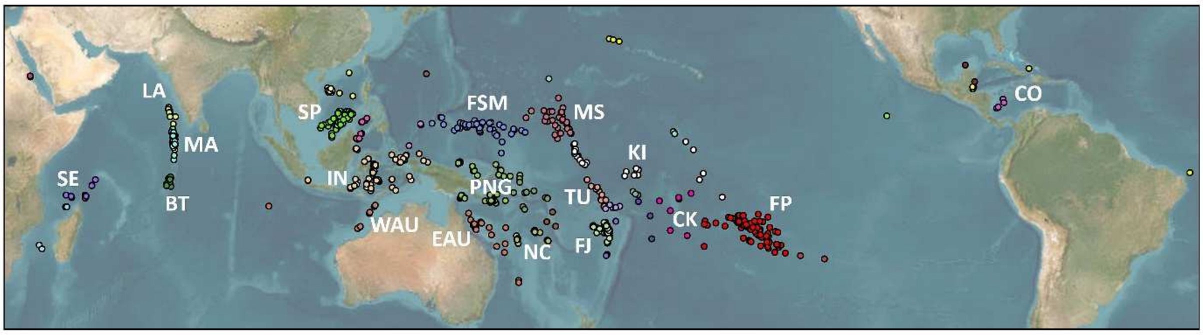


Figure 3: Distribution of the 598 MCRMP-defined atolls worldwide with indication of the main groups in the Pacific Ocean (CK=Cook Islands, FP=French Polynesia, FJ=Fiji, FSM=Federate States of Micronesia, KI=Kiribati, MR=Marshall Islands, NC: New Caledonia, PNG=Papua New Guinea, TU:

Tuvalu), Asia (SP=Spratly IN=Indonesia), Indian Ocean (BT: British Indian Ocean Territory, LA= Lakshadweep, MA=Maldives, SE= Seychelles), Western Australia (WAU), East Australia (EAU) and Caribbean (Co=Colombia).

Table 1: Numbers of atolls per country or region according to MCRMP. For the China Sea, the three subdivisions follow UNEP-WCMC (Spalding et al. 2001).

| **Region** | **Country or sub-area** | **Total** |
|---|---|---|
| ***Pacific Ocean*** | | ***344*** |
| | American Samoa | 2 |
| | Cook Islands | 7 |
| | Federate States of Micronesia | 46 |
| | Fiji | 50 |
| | France (Clipperton) | 1 |
| | French Polynesia (France) | 78 |
| | Japan | 1 |
| | Kiribati | 24 |
| | Marshall Islands | 29 |
| | New Caledonia (France) | 14 |
| | Niue | 1 |
| | Palau | 3 |
| | Papua New Guinea | 39 |
| | Solomon Islands | 15 |
| | Tokelau | 3 |
| | Tonga | 3 |
| | Tuvalu | 12 |
| | United Kingdom (Pitcairn) | 2 |
| | United States (Hawaii) | 3 |
| | United States (Outlier Islands) | 3 |
| | Vanuatu | 3 |
| | Wallis & Futuna (France) | 5 |
| ***Asia*** | | ***158*** |
| | Indonesia | 77 |
| | Philippines | 13 |
| | Paracel | 9 |
| | Spratly | 56 |
| | China Sea | 3 |
| ***Indian Ocean*** | | ***54*** |
| | British Indian Ocean Territory (UK) | 10 |
| | France | 4 |
| | Lakshadweep | 8 |
| | Maldives | 23 |
| | Seychelles | 9 |
| ***Australia*** | | ***29*** |
| ***Atlantic-Caribbean*** | | ***11*** |
| | Bahamas | 1 |
| | Belize | 3 |
| | Brazil | 1 |
| | Columbia | 4 |
| | Mexico | 2 |
| ***Red Sea*** | | ***2*** |
| | Sudan | 2 |

The ten largest atolls worldwide are listed in Table 2. Kwajalein (Marshall Islands), number 10 in our list, is often cited as the largest atoll worldwide. It is indeed the largest atoll but only if atolls with fully emerged or intertidal rims are taken into account. Otherwise the largest atolls are all partially, or largely drowned, complexes.

Table 2: List of the ten largest atolls worldwide according to MCRMP and their surface areas.

| Country/region | Name | Surface area (km$^2$) |
|---|---|---|
| *British Indian Ocean Territory* | Great Chagos Bank | 12811 |
| *New Caledonia* | Bellona | 8897 |
| *Spratly* | Liyue Antang Bank | 7813 |
| *China Sea* | Zhongsha | 5828 |
| *New Caledonia* | Chesterfield | 4118 |
| *Maldives* | Thiladhunmathee-Miladhunmadulu | 3787 |
| *Maldives* | Huvadhoo | 3280 |
| *Federate States of Micronesia* | Gray Feather Bank | 2975 |
| *Indonesia* | Pulau Sabalana | 2711 |
| *Marshall Islands* | Kwajalein | 2458 |

When counting the number of Level 5 classes per atoll (Figure 4), the most complex atolls are in Indonesia (20 Level-5 classes for Takabonerate, and 17 classes for Paternoster) and in Maldives (19 classes for Ari and North Male; 18 classes for Nilandhe; 17 classes for North Maalhosmadulu, South Male). The Great Chagos Bank comes close at 16 classes. The most complex French Polynesia atolls are Fakarava and Rangiroa with only 11 classes. The richness of Takabonerate and Maldives atolls is explained in particular by the different types of patch reef and faro units that are present in their lagoons, and the types of rim reefs, with often enclosed lagoons within. Conversely, the lowest complexity comes from 27 atolls or drowned atolls presenting only a subtidal/drowned reef flat for the rim and a deep/drowned lagoon, hence 2 Level-5 classes. In other words, they just meet the minimum number of criteria to be labeled as atolls. Examples, among others, include the Waterwitch Bank in Wallis and Futuna, the Sabine Shoal in Vanuatu, the Umzinto Bank in Seychelles, or the Zephyr Reef in Tonga.

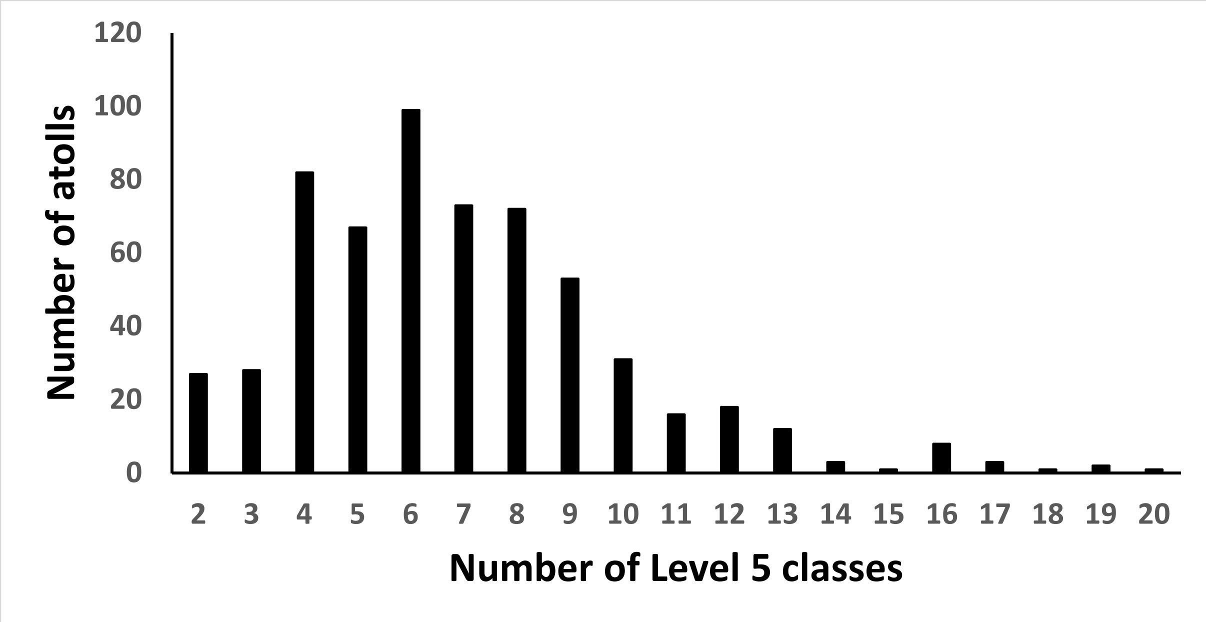


Figure 4: Global histogram of geomorphological richness (as defined as the number of Level-5 classes) from 598 atolls identified by MCRMP.

**Discussion**

Why a global mapping project is launched and what purposes the map products are supposed to serve is critical (Wyborn and Evans 2021, Andréfouët and Bionaz 2021). This is largely context-dependent, and can be based on priorities that can be short-lived. For MCRMP, the main initial goal more than twenty years ago was to conduct national-scale coral reef inventories (Andréfouët et al. 2006, Andréfouët and Bionaz 2021). However, in the early days of the MCRMP project it was decided to use the full potential of Landsat images and not oversimplify the types of information that could be inferred from high quality, high spatial resolution satellite images. Providing structural detail on each mapped reef would be also a major advance compared to the previously available global inventory (Smith 1978, Spalding et al. 2001). The focus was put on geomorphology because geomorphology is stable in time, at least across several decades, which ensure the long-term relevance of the products, unlike benthic coverage that can often change rapidly in few months and even days after for instance the passage of a hurricane (see Scopélitis et al. 2009, 2010, 2011 for remote sensing based change detection studies). Unlike geomorphological-level mapping, benthic biological information also require ground-truthing for training and accuracy assessment and this was not an option for all reefs worldwide (Andréfouët 2008). For these goals, a complex geomorphological classification scheme was designed for MCRMP, allowing simultaneously for a fine consistent geomorphological characterization of each reef complexes, the comparison between sites, and the quantification of their unique characteristics. The rich information allowed the customization of various types of research and management applications which would have been unattainable with simply a reef/non-reef description, or from a too simplistic classification scheme (Andréfouët and Bionaz 2021). This richness and the geomorphological descriptors explain why the products can still be used today for a variety of applications at various spatial scales (from large islands to archipelago to nations to oceans).

The definitions and criteria used to map atolls within the MCRMP framework obey both new and older qualitative considerations. The need to be a Level-2 reef system (Figure 1) is a fresh view imposed by the hierarchical classification system implemented by MCRMP. Conversely the presence of a lagoon surrounded by a peripherical rim system, even small and shallow, is not particularly original. The classification scheme used by MCRMP is not based on geological and reef genesis criteria, as shown here for atolls. It uses only topological and geomorphological criteria that can be inferred from Landsat satellite images (or higher resolution images), which ensures consistent decision and mapping, useful for present day applications in conservation, fishery management, reef ecology, or simply base mapping (Andréfouët and Bionaz 2021). As such, the variety of genetic processes that have led to the present forms and depths of present-day reefs and atolls as listed here are obliterated and very different structures regarding their origins may be merged within the same morphological groups. Conversely, reefs that probably have very similar origins can be separated into different groups (e.g., the reef complexes with dry lagoon present in the Tuamotu Archipelago, which were not considered here as atolls precisely due to their lack of lagoons). These choices may not be seen by some specialists as an advance, typically in coral reef geology that aims to characterize the present diversity of local and global reef formations through their detailed temporal evolution across geological and eustatic periods through coring analysis, datations or seismic surveys (see many examples reviewed in Hopley 2011). However, even if no geological genesis criteria were taken into account by MCRMP, the consistent mapping and the diversity of reef types that arise from MCRMP can be helpful for further geological studies to focus on poorly studied reef types after presenting them in a coherent exhaustive framework. This exercise was done for instance for New Caledonia (Andréfouët et al. 2009).

In summary, it could be possible to provide the same list of 598 reef systems as here, but calling them differently than ‘atolls’, to avoid confusion and argument. They could be effectively and more rigorously called ‘Level 2 hydrodynamically open to closed annular reefs with lagoons’. The introduction of an all new class of reefs is unlikely however to close the debate on reef typology, as the ‘atoll’ label will clearly not be discarded, even if its use is inconsistent from places to places.

Consistent geomorphological mapping for atolls certainly helps bridging gaps between different scientific domains, namely geology, ecology and conservation. Indeed, it should help reef ecologists to be much more rigorous in the way reefs have been often described, sometimes by mixing different levels of reefal organizations with biological communities, geomorphologic and geological terms to describe field stations. Consistent hierarchical mapping also helps in realizing the diversity of coral reef units present in the field. Reef diversity (or richness) should be an integral part of biogeographic and comparative studies, but this has been generally overlooked in all recent biogeographic coral reef studies (but see Bakker et al. 2023). Indeed, overly simplistic reef type descriptions are still present in large-scale reef site categorizations at biogeographic scales. Often there are actually no categorizations at all, implying *de facto* that all reef types are considered equal, which is a strong, but poorly justified, assumption (e.g., Cinner et al. 2016). For scientific and management works that focus on atolls but also on other reef types described in MCRMP, it is always recommended to assess the representativity of the investigated sites, and one way to do it can be through the use of the MCRMP geomorphometric areal statistics.

It is also always possible to argue with some of the criteria used here. Indeed, while the first cut is based on qualitative criteria as it is necessary to start somewhere with one type of data source (i.e., satellite imagery), this first cut eventually provides quantitative data that can be useful for a second round of refined criteria. For instance, it is possible to wish to include other refined criteria, locally or globally, such as the sizes of the lagoon (absolute or relative to the total surface area of the reef complex), or the degree of aperture of the lagoon to the ocean (an atoll-like complex could be defined as an Atoll if at least 50% of the rim is closed to the ocean for instance). In any case, such refinements are possible through the use of the MCRMP geomorphic quantitative information, or through extra customized specific morphometric statistics that can be easily computed from the existing GIS files (Johnson and Ortiz 2023). Flexibility in definition and further analyses are possible from the set of 598 reef complexes identified here as atolls, and also from reef complexes classified differently in MCRMP (such as the Banks, not shown here). The utility of the quantitative surface area database is illustrated by Figure 5. It shows the result of a multivariate ordination analysis (multivariate dimensional scaling, or MDS) performed on the normalized surface areas at Level 4 for atolls in Maldives (n=23), French Polynesia (n=78) and Spratly Islands (n=56). From the resulting projections in the MDS 2D reduced space, outliers can be flagged, and a user has the flexibility to decide if these outliers are not 'true' atolls for his application. For instance, the group of Spratly atolls on the top of the MDS (atolls 2, 10, 23, 25, 41, 47, 52, 55, 56) and bottom (29, 48) are all atolls dominated by drowned rims and lagoons. The Maldives atoll Kaashidhoo (144 in Figure 5) at the far end of the Maldives group is characterized by a very small shallow lagoon, and lack of deep lagoon compared to other Maldives atolls. The atolls at the extremity of the French Polynesia cloud such as Niau (106), Tekokota (128), Pukapuka (111) and Anaa (79) are also peculiar atolls with the dominance of one geomorphological class. For instance, Anaa is dominated by its shallow uplifted lagoon in the Tuamotu Archipelago (Pirazzoli et al. 1988).

Whether or not these sites can remain within the atoll continuum regionally or globally can be at any user's discretion and his decision can be justified with quantitative criteria. Similar considerations can occur for instance for the inclusion, or not, of some reef complexes that are not part of Atolls in the MCRMP typology, for instance for some of the 'Bank' Level 2 entities.

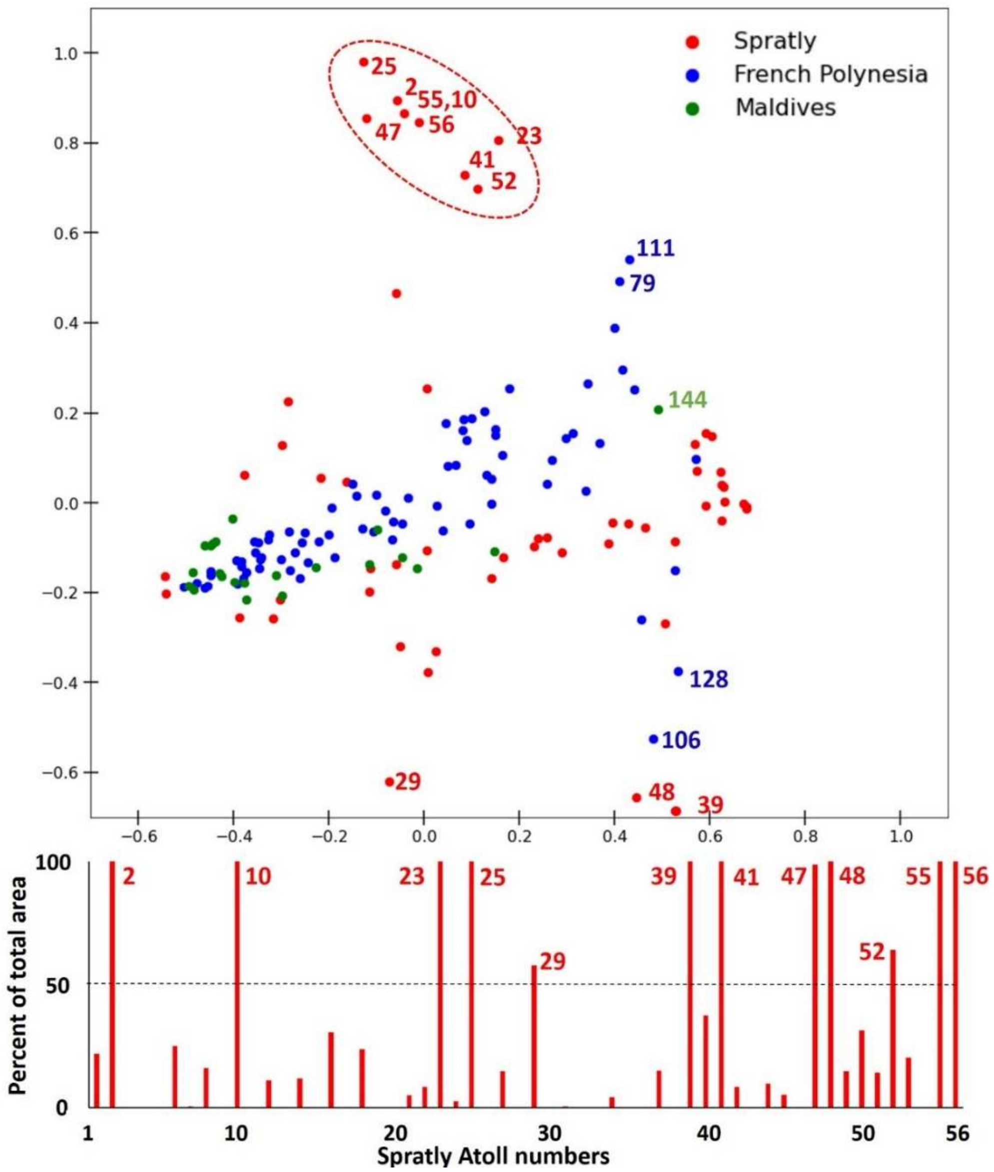


Figure 5: Top panel: results from a multivariate ordination performed using the Level 4 normalized surface areas for three regions (Spratly, Maldives, French Polynesia). For each region, outliers can be identified (e.g., atoll 144 for Maldives), but also outliers outside the main multi-region cloud of points, such as the Spratly atolls shown within an ellipse on the top of the ordination plot. Bottom panel: Among the 56 Spratly atolls, these outlier atolls, as well as atolls 29, 39 and 48 at the bottom of the ordination are all characterized by a very high percentage of drowned rim and lagoon structures. See text for the geomorphological specificities of atolls 79 (Anaa), 106 (Niau), 111 (Pukapuka), 128 (Tekokota), and 144 (Kaashidoo). Atolls 2, 10, 23, 25, 29, 39, 41, 47, 48, 52, 55, 56 in Spratly are respectively Ao'nan Shoal, Dayuan Bank, Lesi Shoal, Liue Antang Bank, Mengyi Shoal, Southern bank, Wan'an Bank, Xiwei Bank, Yongdeng Shoal, Zhongxiao Bank, Zi Bank and Zong Bank.

The Figure 5 shows a simple ordination for a range of selected atolls, only using MCRMP data. More complex multivariate classification work could combine MCRMP data with other types of ancillary databases, including biodiversity, socio-economical, fishery or climate data. Taken as explanatory or predictive variables, atoll MCRMP quantitative descriptors can help explaining biodiversity patterns, biogeochemical responses, assess conservation targets, and scale-up fishery yields (Adjeroud et al. 2000, Dufour et al. 2001, Dalleau et al. 2008, Bell et al. 2009, Hamel and Andréfouët 2012, Gairin and Andréfouët 2020, Bakker et al. 2023). There is still much comparative work to do along these lines with the full range of MCRMP descriptors (as in Bakker et al. 2023), including specifically for the 598 atolls worldwide identified here.

Some cases have been also difficult to label due to several types of ambiguity. For instance, we have not included in the MCRMP atoll list several drowned platforms in the Marquesas archipelago (French Polynesia), because these platform did not show clearly on remote sensing images a rim, but mostly a flat gently sloping structure, hence better qualified as Banks in the MCRMP typology. However, these decisions can be the consequences of a poor image quality with not so clear waters at the time of the satellite overpass and image acquisition. Less clear waters can impair the detection of the sometimes subtle depth variations that will highlight the presence of a rim. These problems for deep reef complexes were frequent when using the Landsat 7 images as many oceanic isolated sites could be imaged only once per year, sometimes less, and a very few number of times in total due to the acquisition strategy and scheduling put in place for this mission (Arvidson et al. 2001). The Landsat 8 image archive solved the issue as it can, generally, offer several cloud-free images for any given site. Nevertheless, cloud-free images quality can be systematically impaired by, for instance, windy conditions. It is therefore possible that additional atolls will be listed in the future, in particular for the guyots lying at the depth limit of optical detection, or simply missing on Landsat and optical satellite data coverage.

Other ambiguities can come from very unique sites, in particular those that are also major sites. For instance, Takebonerate Atoll in Indonesia (Figure 2), or the Great Chagos Bank in the British Indian Ocean Territory (Hamylton and Andréfouët 2013, Sheppard and Sheppard 2019) are both unique reef complexes that in fact present multiple atoll-like systems within one larger deep platform. The largest overarching platform was considered, following the MCRMP Level 2 criteria, as an atoll. But these complexes could be as well identified as something different than just an atoll, highlighting in doing so their uniqueness.

Other difficulties can came from the identification of Level 2 complexes themselves, and whether or not candidate atolls are indeed embedded within a Level 2 complex. This typically happens when candidate atolls are found on the continental shelf where other larger complexes are present nearby. The question of whether these nearby Level 2 complexes can be extended to the locations of the candidate atolls is not necessarily trivial to answer, hence, discarding them or not as atolls can be argued. By default, in this situation we omitted potential candidate reefs from the final atoll list, and in doing so we generally followed the previously established descriptions. Examples include the Capricorn-Bunker group where a series of individual reef complexes lining up mid-shelf of the southernmost Great Barrier Reef depth zone E (*sensu* Davies 2011) could qualify as continental atolls. But we have considered them to be part of the larger barrier reef shelf system (Hopley 1982, Hopley et al. 2007), and not as Level 2 reef complex on their own right. This certainly can be argued. Similarly, a large number of candidate atolls can be found on the southern east side of the Red Sea, along the Saudi Arabia coast (Rowlands and Purkis 2015), but they have been considered by MCRMP as part of a larger multiple barrier shelf Level 2 system (Figure 2).

Finally, to conclude, MCRMP mapped all types of reef structures worldwide, even if the global product is not completed in several places (Andréfouët and Bionaz 2021). Besides atolls, similar global or regional reappraisal as presented here could be performed for Banks for instance. We also suggest that a good candidate for reappraisal are Barrier Reefs (Andréfouët and Cabioch 2011), due to frequent confusions and mislabeling in the coral reef literature.

**Online information**

The data and related documentation that support the findings of this study are openly available in DataSuds repository (IRD, France), https://dataverse.ird.fr/dataverse/Atolls (accessed August 2023). Data reuse is granted under CC-BY-NC-SA license. Potential users are invited to contact the authors to assess the suitability of the products for a potential application (see also for general caveats on MCRMP products, Andréfouët and Bionaz 2021).

Online links and DOI per region or countries, and global statistics for the MCRMP Atoll GIS databaseare the following:

Asia : https://dataverse.ird.fr/dataset.xhtml?persistentId=doi:10.23708/ANJCRV (Andréfouët 2023a)
Australia : https://dataverse.ird.fr/dataset.xhtml?persistentId=doi:10.23708/JXNMFY (Andréfouët 2023b)
Caribbean-Atlantic : https://dataverse.ird.fr/dataset.xhtml?persistentId=doi:10.23708/6ZNSA3 (Andréfouët 2023c)
France : https://dataverse.ird.fr/dataset.xhtml?persistentId=doi:10.23708/LHTEVZ (Andréfouët 2023d)
Indian-Ocean and Red Sea : https://dataverse.ird.fr/dataset.xhtml?persistentId=doi:10.23708/OCEC0S (Andréfouët 2023e)
Pacific Ocean : https://dataverse.ird.fr/dataset.xhtml?persistentId=doi:10.23708/OS20O0 (Andréfouët 2023f)

Statistics : https://dataverse.ird.fr/dataset.xhtml?persistentId=doi:10.23708/OKTEFB (Andréfouët 2023g)


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Andréfouët, S., 2023d, Atolls of France: geospatial vector data (MCRMP project), https://doi.org/10.23708/LHTEVZ, DataSuds, V1

Andréfouët, S., 2023e, Atolls of Indian Ocean and Red Sea: geospatial vector data (MCRMP project), https://doi.org/10.23708/OCEC0S, DataSuds, V1

Andréfouët, S., 2023f, Atolls of Pacific Ocean: geospatial vector data (MCRMP project), https://doi.org/10.23708/OS20O0, DataSuds, V1

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