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A Typology for Reef Passages

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Coral reefs host exceptionally diverse and abundant marine life. Connecting coasts and sheltered lagoons to the open ocean, reef passages are important yet poorly studied components of these ecosystems. Abiotic and biotic elements 'pass' through these reef passages, supporting critical ecological processes (e.g. fish spawning). Reef passages provide multiple social and ecological benefits for islands and their peoples, but are so far neither characterized nor recognized for their multifaceted significance. This study investigated 113 reef passages across nine Pacific islands (Fiji, New Caledonia, Vanuatu). GIS-based visual interpretations of satellite imagery were used to develop criteria to define three distinct types, mainly based on distance to coastline and presence/absence of an enclosed water body. The discussion identifies ways to refine and augment this preliminary typology as part of a research agenda for reef passages. With these next steps, this typology will be extendable to other regions to better document reef passages and their various roles, supporting biodiversity conservation and sustainable fisheries management.

Keywords: reef passages, GIS (Geographic Information System), satellite imagery, visual interpretation, marine biodiversity, Fiji, New Caledonia, Vanuatu

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INTRODUCTION

Coral reefs play critical cultural, ecological, social, economic and physical roles in Small Island Developing States (Nurse et al., 2014). In these structurally complex ecosystems, reef passages "provide abrupt transitions between productive shallow benthic reef habitats and open ocean ecosystems" (Fisher et al., 2018: 1). In the absence of any established standard definition, a reef passage is defined here as any channel in the reef that connects the open ocean outside a reef with a confined water body or island.

Reef passages are essential to the renewal of water in lagoons and coastal areas, influencing energy balance and solute concentrations (von Arx, 1948; Gallagher et al., 1971; Schuhmacher, 1991; Hviding, 1996; Kench, 1998; Fourniotis et al., 2018), with potential implications for reducing bleaching stress, pollution intensity and funneling away water from the coast following heavy rain (Carilli et al., 2017). Reef passages may thus be the main 'arteries' for the energy supply of their adjacent waters (Skinner et al., 2021). Through their geomorphological characteristics and prevalent physical forces, reef passages can enhance ecosystem health and functionality in their vicinity by spatially dispersing produced nutrients into adjacent (micro)habitats, where they can be assimilated into local food webs (Hamner et al., 2007; Fox et al., 2014). Reef passages, like their surrounding reefs, may also be impacted by climate change, with their ecological and hydrodynamic characteristics strongly depending on the intensity of tides, wind and waves, as well as the temperature of the water flushed through (Sous et al., 2017).

This dynamic hydrography seems to foster an exceptionally diverse and abundant marine life within reef passages. Many reef fishes display migration behavior according to seasonal, lunar, diel or tidal cycles, moving between coral reefs and adjacent habitats such as seagrass beds but also among different reef zones and habitats (e.g. Krumme, 2009; Pittman and Olds, 2015; Filous et al., 2019). As 'arteries' of the reef system, passages are main connectors that concentrate individuals undergoing these movements, and fish migrating through the passages may play an important role in transporting nutrients to reef habitats (e.g. Francis and Côté, 2018). In coral reef ecosystems, fish spawning aggregation (FSA) sites often correspond to reef passages, and studies mention them implicitly (Moyer, 1989; Colin and Bell, 1991; Johannes and Hviding, 2000; Mourier et al., 2016; Fisher et al., 2018). FSAs are known to occur along promontories and reef channels (Johannes and Hviding, 2000; Claydon, 2004; Heyman et al., 2005; Nemeth, 2012; Colin, 2012; Kobara et al., 2013), although data on FSAs in proximity to reef passages are rare or hidden (Shcherbina et al., 2008). In addition to supporting FSAs, reef passages are known for hosting iconic, sometimes endangered, species such as giant groupers (Clua et al., 2015) and humphead wrasse (Sadovy et al., 2003), and they are used by migratory species such as cetaceans, mantas and sharks (Breckwoldt et al., in review; Anderson et al., 2011; McCauley et al., 2014; Mangubhai et al., 2019) or green turtles, which travel between distant reproduction areas and foraging areas located in lagoons (Read et al., 2014; Piovano et al., 2019). Distance from reef passage was found to be a clear predictor of whale shark presence at Ningaloo Reef (Anderson et al., 2014), and Takekawa (2000) documented the hunting of dolphins with the 'help' of a reef passage.

In tropical regions such as the Southwest Pacific, these areas provide physical and biological processes linked to their specific geomorphological features (e.g. intermittent upwelling that retains nutrients, eggs and plankton; Wolanski and Hamner, 1988; Wilson et al., 2002; Ezer et al., 2011). If appropriately designed and managed, protection of reef passages that host FSAs and/or are frequently used by keystone species is hypothesized to have an umbrella-effect, supporting complex food-webs and predator-prey interactions that are crucial to maintain healthy ecosystem functions and services (Pauly et al., 1998; Heithaus et al., 2008). Yet, just like FSAs (Sadovy De Mitcheson et al., 2008; Sadovy de Mitcheson, 2016), reef passages and their potential roles remain relatively poorly documented and rarely integrated both in fisheries management and in conservation policies and practices (Bierwirth, 2021).

Beyond their ecological importance, the significance of these areas is reflected in the ontology of Indigenous Pacific Island communities, for whom the land-sea continuum is an eminently structuring concept (e.g. Degrémont and Sabinot, 2020). Reef passages are perceived both as transit areas toward the open ocean, and as areas through which everything from the outside world enters the island societies and affects them in some way (Hviding, 1996; Breckwoldt et al., in review).

It is thus suggested that reef passages are hotspots of connectivity, exchange, productivity and biodiversity (Erisman et al., 2017; Pittman and Heyman, 2020). Reef passages provide multiple invaluable benefits to the islands and their residents, which should justify their identification as priority areas where networks of fishers, scientists and conservation managers can help rehabilitate marine ecosystems. Such accelerated progress is necessary for reaching global policy targets, including the United Nations Sustainable Development Goal (SDG) 14 - Life below water. The 'conservation and sustainable use of marine resources for sustainable development' could be supported by enhanced knowledge on reef passages, therefore helping to develop sustainable fishing practices, management, and protection of coastal marine areas. This connection reinforces the relevance of working not only on physical or ecological aspects for sustainable development, but specifying how this relates to people, e.g. related to fishing resources and social community-related aspects. However, to date, little published research has targeted the uses and management of reef passages by local authorities including coastal communities, or has looked at which marine animals actually dwell in, visit or transit through these spaces, across temporal scales (with valuable exceptions, e.g. by Johannes and Hviding, 2000; Aswani and Hamilton, 2004).

As a first step, we will screen and characterize reef passages based on their physiography using satellite data, to develop a typology of reef passages, which can then be built on to assess how the different functions and roles of reef passages may vary according to their geographical and other characteristics (e.g. distance from coastline). Using remote sensing data does not require ground-truthing, which is relevant for ocean areas with many islands and reefs scattered over large areas (e.g. Andréfouët, 2014), particularly in the Pacific. Our approach is developed through a focus on reef passages in nine islands of the Southwest Pacific. As a future second step, the exploratory typology we propose can be augmented to account for additional physical and morphological criteria, as well as ecological and social aspects, in order to elucidate the complex web of reef passage uses, functions and roles at a larger scale. Despite its spatial limitations, this preliminary study can help researchers and managers use the same language about passages to enable more rigorous comparisons and interpretations in the future.

METHODS

This work focused on nine islands of different sizes and shapes in the Southwest Pacific, and belonging to the archipelagoes of Fiji, New Caledonia and Vanuatu (**Table 1**), study sites of the project SOCPacific (A Sea of Connections; socpacific.net; Fache and Breckwoldt, 2019). A number of the project scientists, and co-authors of this Brief Research Report, have field expertise on at least one of these islands, and presumably, rich local knowledge exists here on the importance of reef passages (e.g. Sadovy de Mitcheson, 2011; Gonson et al., 2017; Mangubhai et al., 2019. The locations of reef passages were determined using satellite imagery and GIS Software (QGIS version 3.16[1]). Criteria relevant to develop a first typology of reef passages were derived from GIS-based visual interpretations of satellite imagery (**Figure S1**, **Table S1**, see **Supplementary Material**). Island outlines from the Database of Global Administrative Boundaries (GADM) and basemaps within QGIS were used for visualization and analyses. Consistent with the definition of reef passages in the Introduction, these were identified as being all clearly visible breaks in the reefs surrounding each of the islands or island lagoons that could be detected and located by visual interpretation of Google Earth imagery. Their locations were then exported from GoogleEarth in KMZ format and imported as shapefiles into QGIS. QGIS maps were created to display the distribution of the identified passages on the islands.

The relevant island outlines were then selected from GADM data and measured. This allowed for comparing the number of reef passages around an island. The minimal width or minimum distance between the two sides of a passage was measured using the QGIS ruler tool and high resolution satellite imagery basemaps (Google Satellite Hybrid and ESRI Satellite tiles). In QGIS, the native tools, integrated SAGA tools, QuickMapServices and Point Sampling Tool plugins were used.

Apart from passage types, the minimal width of the passage and its calculated distance to the nearest coastline were added as attributes to the database [Nozik et al. (2022) to PANGAEA]. The complete attribute table of the reef passage shapefile was then imported into R (version 3.5.3., www.r-project.org), to plot parameters and their relationships and to compute descriptive statistics.

RESULTS

A total of 113 reef passages were found in the reefs surrounding the nine selected islands (**Table 1** and **Figures 1**, **2**). From the data, three types of reef passages were defined, mainly based on distance to coastline (**Figure 1**):

- **Type 1 ('Coast'):** Passages where the reef is adjacent to the coast (i.e. a fringing reef), with no water body between the passage and the coast;
- **Type 2 ('Lagoon'):** Passages where the reef builds a lagoon around the island (i.e. a barrier reef), with a passage between possibly different 'inside- and outside-reef' water bodies;
- **Type 3 ('Open Water'):** Passages in reefs located at larger distance from the coast (also barrier reef), with at least one of the reefs on either side entirely separated from the coast by deeper waters.

The highest densities of passages were found around the smallest islands of Gau, Yadua, Cicia and Makogai (**Table 1**). Here, on average, less than 10 km of coastline separated two passages. Around Malekula, the average distance between two passages was largest. Most reef passages (62) were found around Grande Terre (1860 km coastline), and the smallest amount (1) was detected on Kanacea Island (15 km coastline, **Table 1**). Between three and twelve passages were detected around the other seven islands.

Only around Grande Terre (NC) and Gau (FJ), all three reef passage types were found. Around Malekula, all reef passages belonged to Type 1 ('Coast'), while such passages were not found around Kadavu, Cicia and Makogai, and only one occured around Grande Terre. This reflects the fact that the reef around Malekula is a fringing reef along the coast, while the reefs around the other mentioned islands are barrier reefs further away from the coast. Type 2 ('Lagoon') reef passages were predominant around Kadavu, Gau, Cicia and Kanacea, in relation to the fact that the existing reefs around these islands form lagoons with partly enclosed water bodies. Only four of the nine islands, i.e. Grande Terre, Kadavu, Gau and Makogai, were surrounded by passages that belonged to Type 3 ('Open water'). In this case, the distance between the reef and coast was large, with a maximum distance of 59 km between the reef passage and the shore occuring north of Grande Terre. Although the reef around Kanacea was partly far from the island in open water, it did not have a single Type 3 passage, and only one Type 2 passage closer to the coast (**Figure 1**). Altogether, Type 2 passages were the most frequent (33.3% - 100%). The minimal width of the passages was smallest for the reef passages of Type 1 (median: 62.5 m) and largest for those of Type 3 (median: 450 m) (**Figure 2**). The largest island (Grande Terre) had the widest reef passages, while all the other islands showed lower values.

DISCUSSION

This report proposes a straightforward first working definition of reef passages - as any visible channel in the reef that connects the open ocean outside a reef with a confined water body or island - and applies this definition to geographical data derived from satellite-based imagery. Reef passages appear as cross-sectional water flows connecting inshore with offshore waters across a continuous reef system, and are visible in satellite-based images, and likely do not dry out during low tide.

By collating visually available information based on parameters from satellite imageries of nine islands, reef passages were characterized into three types according to geomorphological features, i.e. reef being connected/disconnected to the coast and presence/absence of an enclosed water body, with Type 3 passages being most distant and Type 1 passages being closest to the coast (**Figure 2**). Following Darwin's first classification (Darwin, 1842), the distance from the coast can distinguish three main types of reefs (i.e. fringing,

[1]QGIS Development Team (2021). QGIS Geographic Information System. Open Source Geospatial Foundation Project. Available at: http://qgis.osgeo.org. Accessed July 2021

TABLE 1 | The nine study locations of this report, ranked by size (island surface area), with length of coastline, number of reef passages identified by visual interpretation of satellite imagery, density of reef passages per 100 km coastline, and dominant reef passage type(s); in New Caledonia (NC), Vanuatu (VU), and Fiji (FJ).

Island name (country)	Surface area [km²]	Coastline length [km]	Number of detected reef passages	Density [reef passages per 100km coastline]	Dominant reef passage type(s)
Grande Terre (NC)	16461	1860	62	3.3	2 and 3
Malekula (VU)	2041	392	5	1.3	1
Efate (VU)	900	212	8	3.8	1
Kadavu (FJ)	411	296	12	4.1	2
Gau (FJ)	190	73	11	15.1	2
Cicia (FJ)	35	23	3	13	2
Kanacea (FJ)	13	15	1	6.7	2
Makogai (FJ)	8	22	6	27.3	3
Yadua (FJ)	1	37	5	13.5	1

Source for 'Surface area', 'Coastline length' and 'Density of reef passages per 100km coastline' values (calculated in QGIS): GADM database (gadm.org).

intermediate, barrier and atolls; Scoffin and Dixon, 1983; Sheppard, 2021), while other typologies include additional geomorphological criteria (e.g. Hopley, 2011; Andréfouët and Bionaz, 2021). In this study either fringing or barrier reefs had reef passages. The correlation between the width of the reef passages and distance from the coast showed Pearson correlation values of 0.48, 0.73, and -0.12 for Types 1, 2, and 3, respectively. As such, there is no relationship between these two parameters for Type 3, while they do correlate for Types 1 and 2 (Groß, 2010). Type 1 and 2 passages are more directly related to the coast by their geomorphological structure (see **Figure 2**), hence this observed distinction seems plausible.

The high density of reef passages per coastline found around the islands of Makogai, Gau and Yadua in particular indicates that the smaller islands in this study feature the highest 'relative connectivity' of land/inside-reef with outside-reef waters. Indeed, while bigger islands have more and bigger reef passages in absolute numbers, their distribution is less dense. Yet, the proportion of lagoon water that passes through a reef passage per tide cycle can determine the lagoon's flushing rate and possibly the passage's function. The main

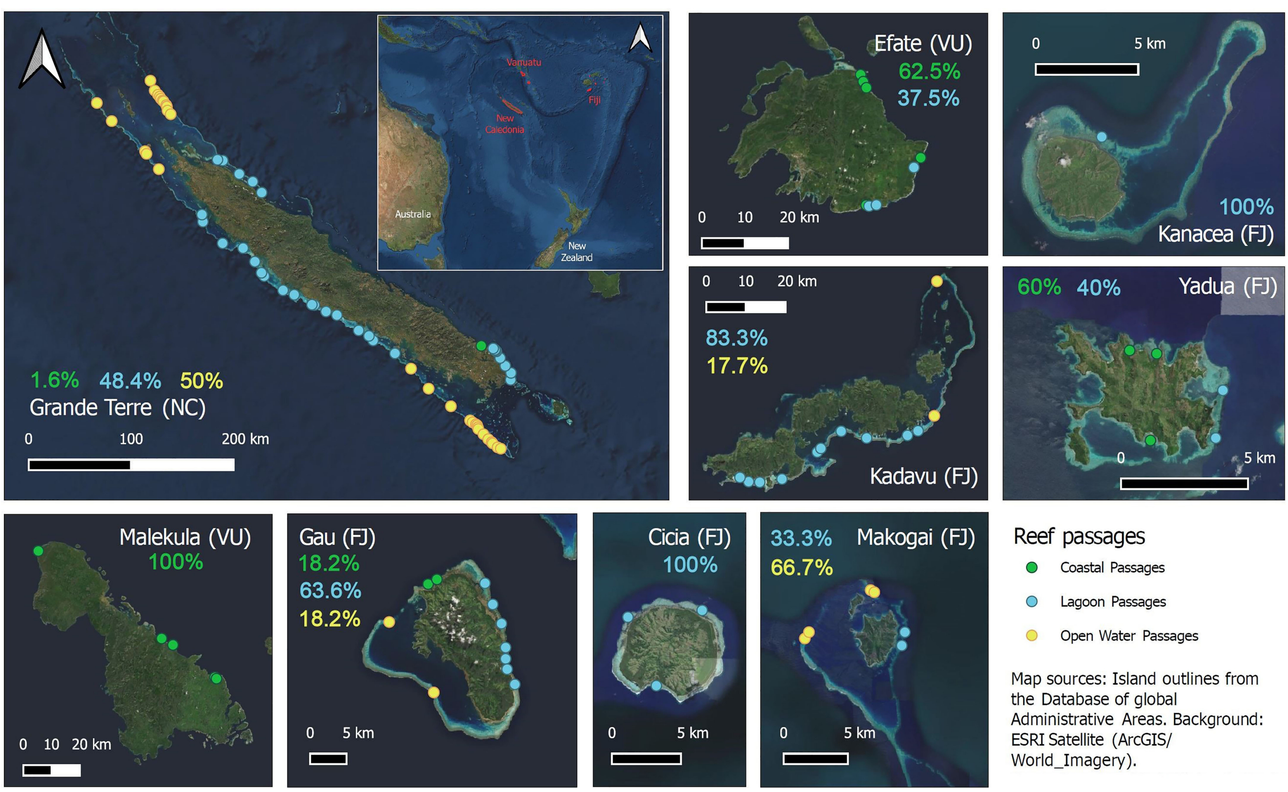

FIGURE 1 | Satellite images showing the locations of the three proposed reef passage types on the nine islands studied for this report, including their respective abundance for each of the islands; green=Type 1 'Coast', blue=Type 2 'Lagoon', yellow= Type 3 'Open Water', in New Caledonia (NC), Vanuatu (VU), and Fiji (FJ).

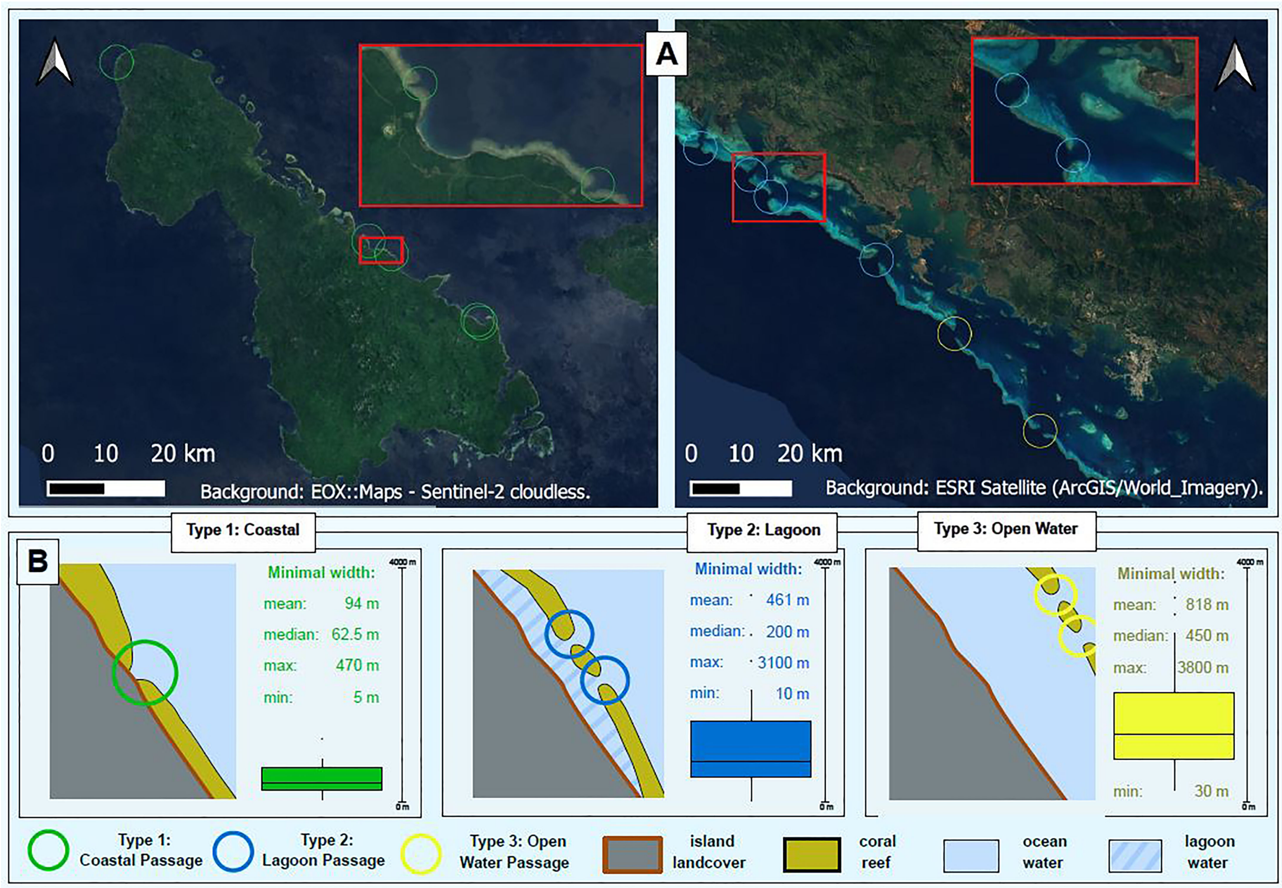

FIGURE 2 | **(A)** Satellite images of examples of reef passages from the study sites; Type 1 around Malekula on the left, and Types 2 and 3 around Grande Terre on the right; the circles represent the location of the reef passage, and the color of the circles the proposed reef passage type. **(B)** Conceptual image of the three types of reef passages proposed in this paper with boxplot images of minimal width values for each type; green=Type 1 'Coast', blue=Type 2 Lagoon', yellow= Type 3 'Open Water' (NC = New Caledonia, VU = Vanuatu).

difference between the types - and future research will have to investigate this - may therefore be the nature of the water bodies that are connected, and that ultimately also influence the functional relevance of the passage.

There are many other criteria which might be included next to help define different passages and strengthen our typology. We found the actual widths of a reef passage to be one important feature that requires more future research. We use widths in plural as we assume that the width at both ends, as well as the narrowest point of a passage will co-determine its functionality and characteristics. For example, a reef passage with a narrowest width of 1000 m can be assumed to be very different from a narrow reef passage of 20 m width (e.g. in terms of current strength). It will be necessary next to put this data in relation to both maximum passage width and passage depth (e.g., using simple bathymetric tools, Heyman et al., 2007; Shcherbina et al., 2008). A larger body of water requires larger reef passages to drain, while water from fringing reefs/coastal lagoons can run out to sea through smaller channels, resulting in different water velocities during tidal changes.

Equally important for characterizing a specific passage will be measurements of both its maximum depth and the depth of its respective edges (e.g. for those within submerged barrier reefs), as well as passage length. However, due to a lack of resolution, there are no reliable estimates for passage depth relative to reef depth in global satellite datasets. Many shelf systems may have a barrier reef on the outside that is largely submerged - and breaks within these sections of reef should also be considered a passage.

So far, only clearly visible features of passages surrounded by shallow reefs were included. With the widths of passages, their depths, and their (relative) length, hydrodynamic features such as speed (cf. tidal amplitude), amount and (relative) temperature of water passing (in both ways) could be used to refine the typology as a next step. Due to their huge influence on reefs (e.g. *via* sedimentation or freshwater input), another important characteristic to include in the typology next is the presence of rivers and built-up/inhabited areas, with ethnographic data collected on some of islands suggesting that some villagers perceived a direct connection between rivers and reef passages (Breckwoldt et al., in review). Given that some parameters that are important for characterizing passages cannot be sufficiently determined using satellite imagery, this highlights the need for complementary ground-truthed data (Breckwoldt et al., in review). Reliably detecting the potential influence of rivers, for example, requires actual fieldwork including a larger sample size. Likewise, the ecological roles of passages can only be assessed further with data collected on the ground. This should include, but not be limited to, information on the size, abundance and identity of fish species occurring at different locations throughout a passage, collected at high temporal resolution (i.e. over diel, tidal, lunar and seasonal cycles) and compared with other sections of the reef.

While substantiating and further identifying differences among reef passages in terms of their ecological functions and socio-cultural roles requires ground-truthed data, some initial hypotheses can be generated. For example, their role as access for boats will increase with the presence of human settlement behind a passage. A passage's ecological connectivity function is hypothesized to increase with the diversity and extent of habitats such as seagrass beds, mangroves and reef flats a passage leads to, and is likely lower for passages of Type 1 than for those of Type 2 and 3.

By providing identification of reef passages through satellite imagery, this Brief Research Report proposes a preliminary screening method to be built upon with extended future research involving the collection of *in situ* measurements and local knowledge. Based on our expertise in the study area, we listed a number of additional parameters and criteria that are relevant for further categorizing reef passages, such as water depth, including reef parts in different tidal conditions (**Table 2**).

For Grande Terre, some of the reef passages visualized in this report match with reef passages mentioned in qualitative interviews in the study of Breckwoldt et al. (in review), for example the Passe de Dumbéa (Type 3) or Passe Deverd (Type 2). These places offer themselves as starting points for some of the 'on the ground measurements' and ground-truthing mentioned for the next research steps. Future research should clarify next (1) when a distance from shore becomes too 'large' for connecting the passage to the coast, (2) when a Type 2 - Lagoon becomes a Type 3 - Open water passage, and (3) which additional parameters (**Table 2**) should be considered first for a broader application beyond the sites on which this preliminary study relied. With such ground-truthed parameters defining the reef passages types, future research could investigate machine learning methods for reef

TABLE 2 | Candidate parameters and criteria for characterizing reef passages, to be included for a more comprehensive typology of reef passages, with the data on parameters generated remotely being the only ones available at this stage, and those generated by 'on the ground measurements' and 'local interviews' largely not being available yet [(x) means 'possibly, yet not easy to measure at spatial scale of interest in this study'].

Criterion type	Passage Parameter	Remote sensing (incl. aerial and drone) imagery	On the ground measurements	Local interviews and observations
Morphological/Geophysical	Location	x	x	
	Distance from coast	x	x	
	Widths	x	x	
	Depths	(x)	x (and bathymetric maps)	
	Submersion at low tide (e.g.,falls dry or not?)	(x)	x	
	Length	x	x	
	Impacts of rivers	(x)	x	X (incl. perceptions)
	Geomorphological features	(x)	x	(x)
	Lagoon (e.g. water depth, enclosure by reef, to refine Type 2 categorization)	(x)	x	x
Physical/Oceanographic	Currents / tidal condition		x	(x)
	Wind and wave directions		x	x
	Water temperatures	(x)	x	x
	Salinity		x	(x)
	Soundscape		x	x
	Nutrient flow		x	x
Physical/Oceanographic & Socio-cultural	Pollution (e.g. plastic)	(x) (dispersing pollution)	x	x
Socio-cultural	Connectivity to inhabited areas (incl. accessibility)	(x)	x	x
	Cultural connections and roles			x
	Community uses/activities (based on location and type of reef passage)		(x)	x
	Other human uses (incl. management and conservation activities)		x	x
	Human History		x	x
Ecological	Natural history		x	x
	Frequenting marine fauna (size, abundance, identity, purpose (e.g. feeding))		x	x
	FSAs (yes/no; multispecies)		x	x
	Coral composition		x	(x)
	Other benthic habitats		x	x

passage detection in other coral reef structures - object-based remote sensing analysis methods applied in a specified radius around an island's outline are conceivable. Although this report focuses on reef passages around islands - as this is where people live and studies on socio-cultural aspects of reef passages can start - we also acknowledge the need to investigate other coral reef systems where passages are of potential importance (yet characterizing criteria will be different, like complex offshore reef and atoll systems, e.g. the Great Barrier Reef along Australia's east coast).

The definition of reef passages and their typology are a useful first step towards developing a common understanding (also for future research across different fields) to inform effective management and conservation strategies for these valuable reef places. In most of the case studies considered here, reef passages were not explicitly included in priority area planning, with the single notable exception being the legally gazetted Naiqoro Passage Spawning Aggregation Marine Reserve on Kadavu Island in Fiji.

In the next step, reef passages would then be characterized from the additional parameters and criteria proposed, enabling us to develop a consistent typology across the island states leading to comparable results for management and conservation planning at national or even regional scale. There are hence multifold, yet-unexplored perspectives and ways to characterize reef passages, calling for further multifaceted and multi-species research on reef passages, related to an array of interdisciplinary aspects, for example on the importance of their socio-cultural and ecological roles (Breckwoldt et al., in review). Different criteria involving distinct ways of knowing would then be integrated in a holistic typology. This study should stimulate both a discussion and a development of a typology of reef passages and their values at different scales (local, national, regional, global) for use in sustainable fisheries management and conservation planning, including the different roles reef passages potentially have in geological, social or ecological systems. Further developing the typology with and for the local communities or authorities who manage these places and their resources will improve its applicability in this respect - nationally, regionally or even globally.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, and the dataset on the 113 reef passages has been submitted to PANGAEA [Nozik et al. (2022)]. Further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

AB – contributed the idea of the manuscript based on SOCPacific research, its focus, and wrote first drafts. AN – contributed GIS analysis of the satellite imagery, determined reef passages' locations and parameters, prepared maps, tables and figures, and the final categorizations and types of passages. NM – contributed geological expertise into the design of the study as well as the writing of the manuscript. JB – contributed extensive literature review on reef passages, channels and FSAs in the international scientific and policy literature. EF - contributed with AB to the idea of the manuscript, contributed to writing and editing the manuscript. SF – contributed to discussing, structuring and writing of the manuscript. AF - contributed to discussing, structuring and writing of the manuscript. SM – contributed expertise on coral reefs in the region for discussing, structuring and writing the manuscript, including much needed insights on fisheries management and conservation aspects. DP – has worked extensively in the region and contributed much valuable experience and expertise into discussing, structuring and writing of the manuscript. SP – contributed extensive knowledge on marine ecosystems in the South Pacific and particularly the role of emblematic species into the discussing, structuring and writing the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.786125/full#supplementary-material

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