An assessment of the offshore marine natural values of Australia's Indian Ocean Territories.

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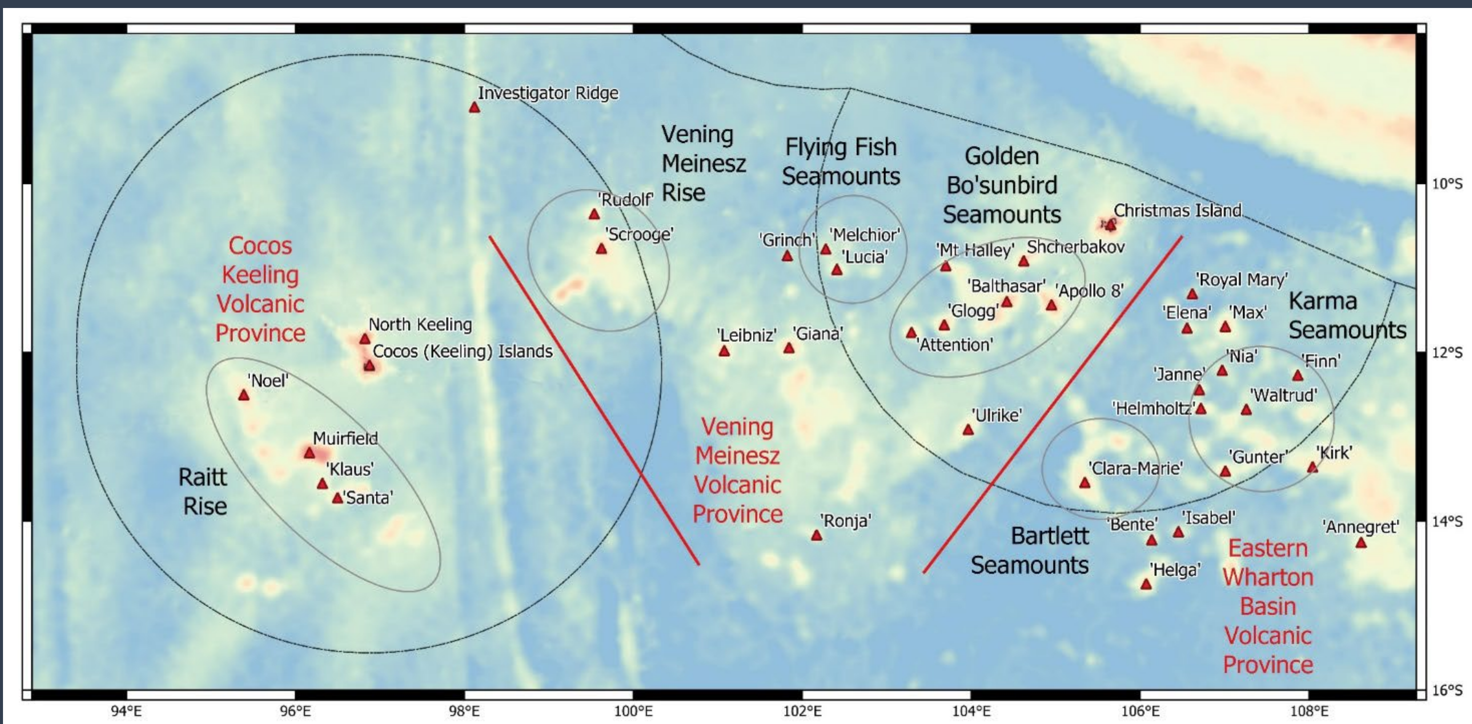

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Executive summary

Most of our knowledge of marine biodiversity of Australia's Indian Ocean Territories (IOT) is restricted to coastal waters around Christmas and Cocos (Keeling) Islands. However, we do know that the vast majority of the marine realm across the two territories is deep-sea, with seafloor consisting of seamounts and ridges, abyssal and hadal plains. These deeper habitats around Christmas Island were explored by a 12-day 2021 expedition of the RV Investigator (IN2021_V04). A subsequent expedition (IN2022_V08) surveyed seafloor habitats in the Cocos (Keeling) Islands Territory in 2022. This bio-assessment draws upon knowledge of the IOT shallow water fauna, the IN2021_V04 and IN2022_V08 expeditions, other observations from infrequent scientific voyages to the area, and from better-surveyed deep-sea habitats elsewhere.

Depth (and its oceanographic correlates temperature, salinity, oxygen, nutrients and carbonate dissolution) and surface primary production are major determinants of seafloor community composition at large scales. At smaller spatial scales, substratum type (rock vs soft sediment) and current velocity will also be important.

Different communities are likely to occur in coastal (0-30 m), mesophotic (30-200 m), upper bathyal (200-1100 m), mid bathyal (1100-1900 m), lower bathyal (1900-3500 m), abyssal (3500-6000 m) and hadal (>6000 m) depths. Although, the boundaries between these layers are only approximate and individual species may inhabit only a part of one depth layer or parts of two or more layers.

Primary productivity varies in a NE to SW direction across the IOT, with the highest productivity occurring near Indonesia and the lowest in the mid Indian Ocean. This will alter the abundance and diversity of benthic communities.

There are four seamounts in the IOT that support rare mesophotic and upper bathyal habitats (30-1100 m). These occur on the flanks of seamounts that underlie Christmas and Cocos Islands, and the upper flanks and plateau of the Muirfield Seamount. Upper bathyal habitats also occur on 'Green-eye' Seamount to the SW of Cocos that summits in ~440 m. Seamount biodiversity is generally structured by on-going or historical migration from surrounding regions that reflect predominant current patterns. As the currents at mesophotic and upper bathyal depths are similar in strength and direction to those at the sea-surface, it is probable that the biodiversity will reflect patterns seen in IOT coastal waters. Thus, the mesophotic and upper bathyal biological assemblages will be a mixture of Pacific and Indian Ocean species and populations characteristic of this depth, that arrive on the westward flowing South Equatorial Current from Indonesia and the South Java Current from the NE Indian Ocean. The biodiversity on these four seamounts are likely to be distinct, due to different primary productivity regimes and individual migration and environmental history.

Other seamounts, particularly in the Vening Meinesz and Cocos Keeling volcanic provinces, peak between 1100 and 1900 m (mid bathyal). These seamounts experience a mixture of intermediate-depth water originating from the south, north and east and so their community composition reflects this complex biogeography. The majority of other seamounts in the region, and the Investigator Ridge, peak between 1900-3500 m (lower bathyal) and experience deep-water masses originating in the south. The NE to SW gradient in primary productivity will alter benthic community composition and abundance. The Golden Bo'sunbird seamount chain (Christmas Island Marine Park) is in an area of relatively high productivity, while the Raitt seamount chain (Cocos (Keeling) Islands Marine Park) is in an area of relatively low productivity. The abyssal plain is very deep across the IOT, frequently below 5000 m and consists of siliceous sediments and manganese nodules. There is also some seafloor at hadal (> 6000 m) depths to the east and south of Christmas Island, and to the SE of Cocos

Islands. The fauna on and around manganese nodules has been found elsewhere to differ from that found on soft sediments.

A number of marine mammals, seabirds, turtles and fish feed in offshore waters. Species that breed on or around the islands typically forage in the surrounding waters, including the endemic Abbott's booby and Christmas Island frigatebird. Migrating predators such as tuna, mackerel, dolphins, sharks, and seabirds tend to aggregate in the open ocean around schools of small fish that are in turn reliant on patches rich in plankton. The spatial and temporal distribution of these aggregations is unknown. Pelagic planktivores such as manta rays and whale sharks are known to occur around the two island groups. Whale sharks are known to target the abundant larvae of the Red land crab around Christmas Island during summer. The entire Christmas Island Marine Park is part of the only known spawning site for Southern bluefin tuna.

The oceanic seamount and island communities (30-1900 m) in the IOT are rare examples of these habitats in the eastern tropical Indian Ocean and are of national to international conservation significance. The presence of rocky substrata at lower bathyal depths, manganese nodules at abyssal depths, and troughs at hadal depths are significant in a regional context.

1. Introduction

1.1. Context for this report

Prior to 2021, scientific knowledge of the marine biodiversity values of Cocos (Keeling) Islands and Christmas Island was largely restricted to inshore waters. From previous surveys and studies, we knew that the vast majority of the marine realm across the two territories is deep-sea, with seamounts and ridges, and abyssal and hadal plains. However, most areas had not been mapped with modern multibeam technology and only incidentally been surveyed by research vessels, which largely focused on geology or oceanography.

To gather more detailed knowledge, Museums Victoria led two RV *Investigator* voyages to the IOT to explore deep sea habitats—a 2021 voyage to Christmas Island and a 2022 voyage to Cocos (Keeling) Islands. In the context of establishing these waters as marine parks, Parks Australia supported these voyages and commissioned Museums Victoria to write this broad report about the offshore natural values of the IOT.

Three versions of this report have been produced to assist Parks Australia with the IOT marine parks planning process:

1. A first version relied on information available prior to the RV *Investigator* voyages.
2. A second version incorporated new information from the RV *Investigator* voyage to Christmas Island in 2021.
3. This third and final version incorporates new information from both the 2021 and 2022 RV *Investigator* voyages to the IOT.

This report is complemented by the report *Proposed offshore Key Ecological Features and Biologically Important Areas of Australia's Indian Ocean Territories*, also by Museums Victoria.

1.2. Background

Christmas Island (137.4 km^2) and the Cocos (Keeling) Islands (27 islands, 15.6 km^2) are two of Australia's remote offshore territories. They are surrounded by Territorial Sea (to 12 nm) and Exclusive Economic Zones (EEZs, 12-200 nm). The area of the Christmas EEZ is 325,021 km^2 and the Cocos EEZ is 463,371 km^2.

The marine environment is predominantly abyssal plain punctured by clusters of massive ancient seamounts that formed 120 to 47 million years ago. The two island groups (Christmas and Cocos) are both the summits of tall seamounts that rise over 5,000 m from the abyssal plain. One seamount, Muirfield, rises to within 17 m of the surface. Another at the SW edge of the Cocos territory (informally named here 'Green-eye' seamount) rises to 440 m. The others have summits at 1000 to 3000 m below sea-level. The Investigator Ridge runs south-north through the eastern Cocos (Keeling) Islands Marine Park at lower bathyal depths (< 2500 m).

These waters are managed by the Commonwealth of Australia, although some functions associated with the delivery of government services in the IOTs are outsourced to Western Australian state government agencies. In March 2022, two large new marine parks were created that extend across nearly all IOT waters. Offshore areas are National Park ('green') zones where fishing is prohibited, while inshore areas are Habitat Protection ('yellow') zones, allowing recreational and subsistence fishing. Some small areas of inshore waters continue to be protected by the long-established Pulu Keeling National Park and Christmas Island National Park. The existing national parks and new marine parks are managed by Parks Australia in accordance with the Environment Protection and Biodiversity Conservation Act.

A variety of names have been applied to seamounts, clusters of seamounts, rises and volcanic provinces within the IOT marine regions. To avoid confusion, this assessment uses the unofficial seamount names of Werner et al. (2009) placed in quotation marks (Fig. 1) as they refer to single identifiable features mapped using multibeam sonar. However, many seamounts are still unnamed (see Appendix 1 for more explanation).

1.3. IN2021_V04 expedition

A survey (IN2021_V04) of the Christmas Island Territory on the RV *Investigator* occurred between the 5th and 18th July 2021, which obtained detailed seafloor mapping data and biological samples from deep sea habitats. The voyage mapped 34,392 km^2 of seafloor (Fig. 2) including around Christmas Island (400-4800 m), over the large 'Max', Karma, 'Clara Marie', eastern Golden Bo'sunbird ('Apollo 8', Shcherbakov, 'Balthazar') and 'Ulrike' seamounts, numerous smaller unnamed seamounts, and sections of abyssal (3500-6000 m deep) and hadal (> 6000 m) seafloor. Representative biological samples were obtained from many of the larger seamounts and Christmas Island. As at March 2023, only some of this material has been identified on- or post-voyage, including the black corals, ophiuroids, and fish. Qualitative assessment of this material has been incorporated into this version of the report.

1.4. IN2022_V08 expedition

A second survey (IN2022_V08) of the IOT on the RV Investigator occurred between the 7th and 27th October 2022 as a replacement for lost days on the first voyage. This survey started in the west of the Christmas Is Marine Park (MP) and then traversed towards the centre and then south of the Cocos (Keeling) MP (Fig. 2). The IN2022_V08 voyage successfully mapped and surveyed a series of seamounts, including the 'Balthazar' complex, 'Glögg', 'Attention', 'Lucia' in the Christmas Island MP, and 'Scrooge', the 'Rudist' complex, the seamount underlying the Cocos (Keeling) Islands, 'Noel', Raitt Ridge, Muirfield, 'Klaus', and 'Santa Ridge', and the 'Green-eye' and 'Carcharocles' seamounts to the south-west of the Cocos (Keeling) Islands MP.

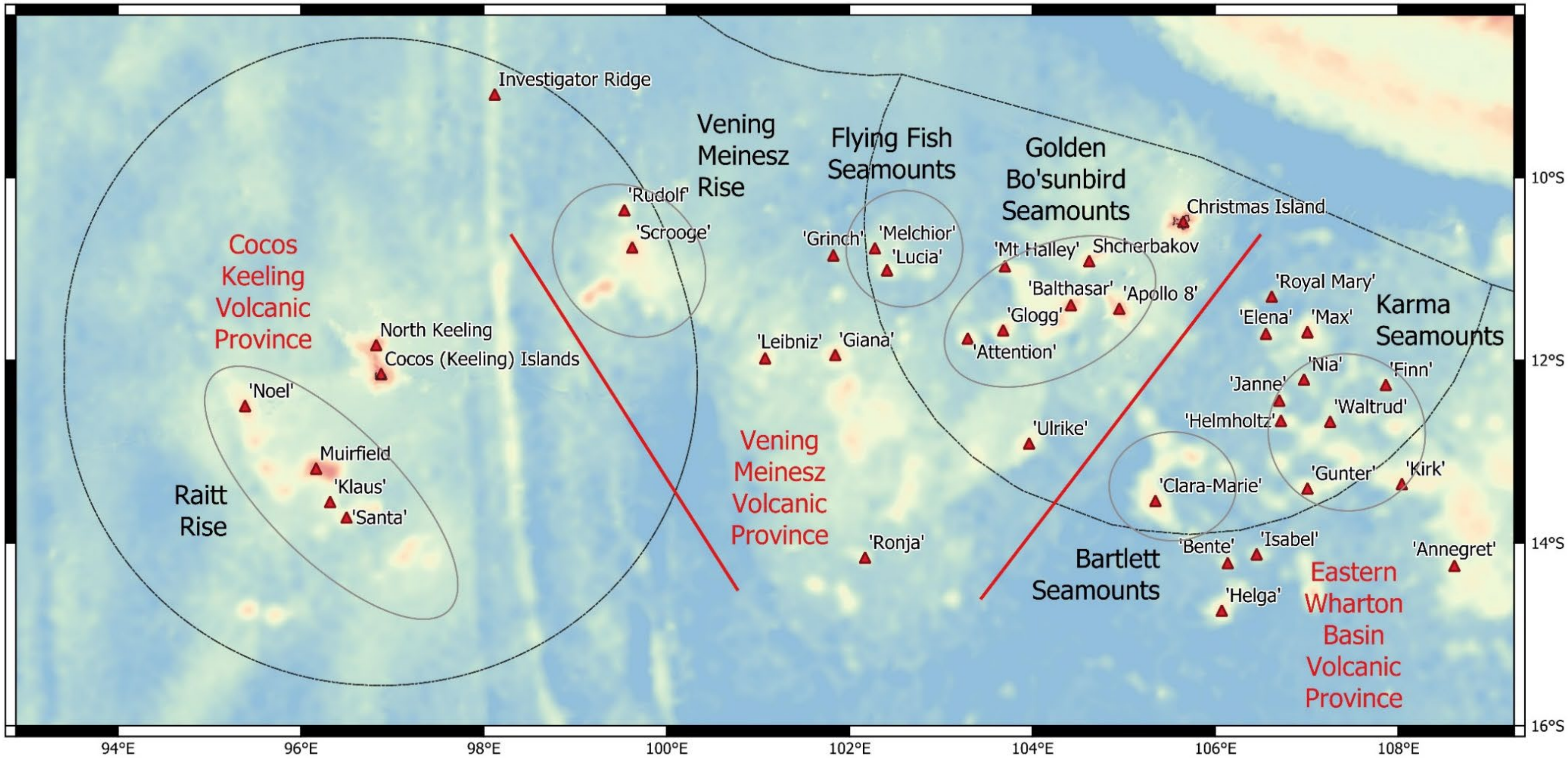

Figure 1. Topographical names given to features in the IOT. Volcanic Provinces follow Hoernle et al. (2011). The ellipses show approximate locations of seamount clusters named in the GEBCO gazetteer. The names in quotes are unofficial seamount names from Werner et al. (2009). The bathymetry is from AusSeaBed.

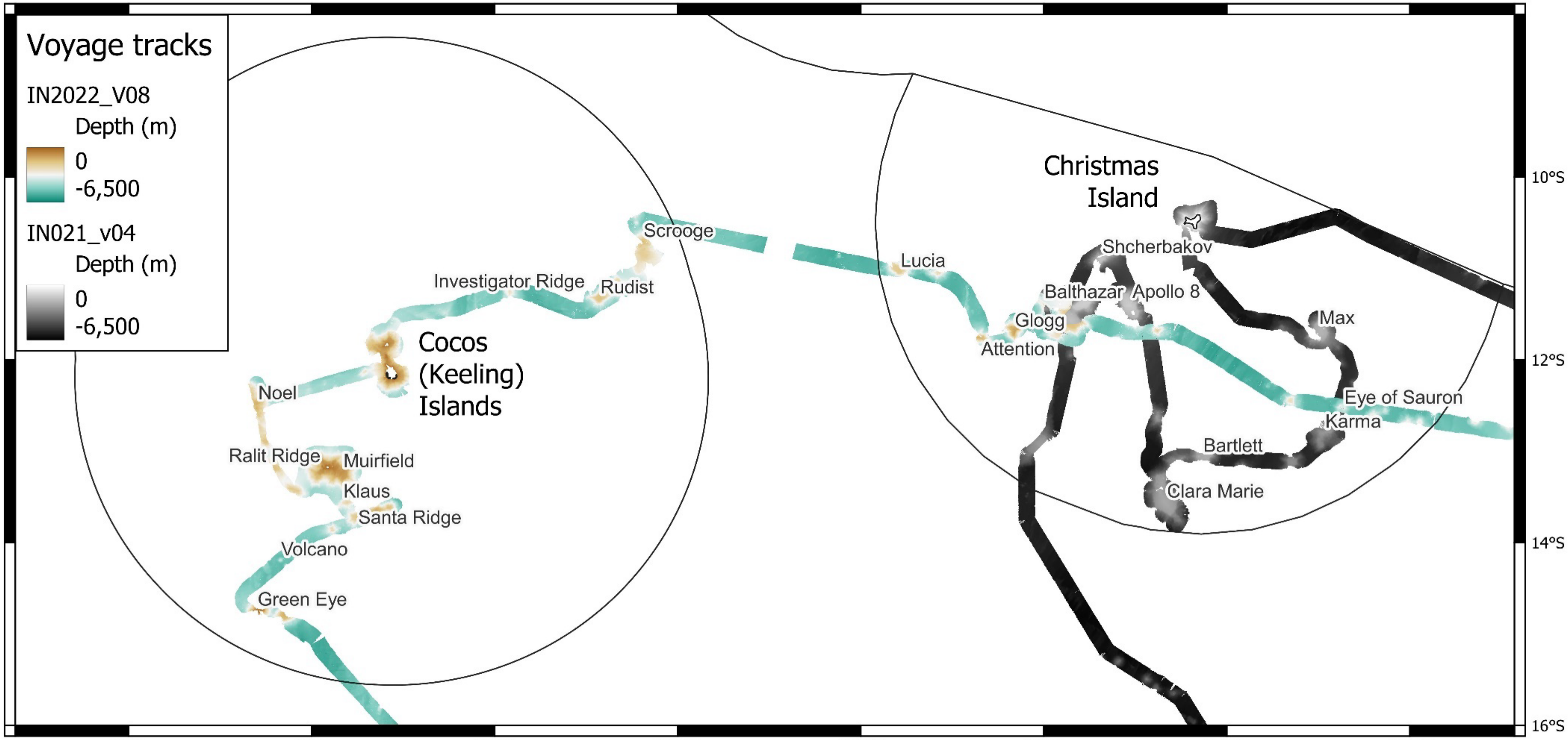

Figure 2. Voyage IN2021_V04 and IN2022_V08 of the RV Investigator through the Christmas Island and Cocos (Keeling) Islands Territory.

2. Physical Setting

The IOT sit in the Wharton Basin, part of the northward moving Indian-Australian plate that is slowly being subducted under the Eurasian plate in the Sunda Trench that occurs offshore of Java and Sumatra. But the Wharton seafloor and seamount clusters were formed long ago under different geological conditions. In general, the seamounts formed alongside a series of underwater ridges that have been subducted under the Eurasian plate over time. One hundred and forty million years ago, the Indian-Australian plate was part of Gondwana and much further south than today. The northern edge was bounded by a mid-ocean spreading (Neo-Tethyan) ridge that separated the westward rotating Gondwana from the northwards moving Meso-Tethys plate that formed the seafloor of the central section of the Tethys Sea [1]. The ancient seamounts of the Argo Basin (115˚E, east of the Christmas Island Marine Park) formed as off-ridge volcanos 136 mya [2]. Although new seafloor was continually laid down along the Neo-Tethyan Ridge, the Meso-Tethys plate was gradually reduced in size through subduction along its northern margin [1], until the Neo-Tethyan Ridge itself started to subduct (105 mya). Another cluster of seamounts (Eastern Wharton, Fig. 1) formed south of the ridge on the Australian plate (115-95 mya) [2]. A third cluster of off-ridge seamounts (Vening Meinesz) formed 95-64 mya [2]. Around 100-80 mya, Gondwana proceeded to break-up, India accelerated northwards and a new spreading (Wharton) ridge was formed between the Indian and Australian plates [1]. The final cluster of IOT seamounts was formed in the Cocos Basin (56-47 my) to the east of the Wharton Ridge [2]. The Meso-Tethys was largely subducted by 55 mya. The Australian Plate accelerated northwards, once again merging with the Indian Plate and extinguishing the Wharton Ridge (43-36 mya). These IOT seamount provinces formed much further south (at ~35-45˚S) than they are at present.

The Investigator Ridge is a ~1,800 km long north-south orientated ridge in the oceanic crust of the Wharton Basin, which is assumed to have formed prior to the plate tectonic reorganization of the circum-Indian area at 90 to 100 million years ago [3]. Due to the collision of India with Asia, the western part of the Indo-Australian Plate has been prevented from moving further northwards, while the eastern half of the plate is being subducted beneath Indonesia. This difference in movement is producing north-south aligned fracture zones in the ocean crust, part of a developing plate boundary. The younger crust to the west of the Ridge appears to be offset by ~900 km from the older crust to the east. There is a steep west-facing scarp along most of the fracture zone, which implies recent reactivation of older fractures [3].

Many of the IOT seamounts are massive, over 70 km in diameter, and rise 3-5 km above the seafloor. Some appear to have been at sea level at some point. They have flattened wave-formed summits [3] (called 'guyots') and are covered in Cretaceous (75-65 million years ago) limestones that contain shallow-water reef-building fossils, including (now extinct) rudist and *Inoceramus* bivalves [4]. However, the seamounts were heavier than, and gradually subsided into, the relatively young oceanic crust, and many now summit 1-3 km below sea-level.

There are two exceptions to this scenario of seamount subsidence. The seafloor of the Australian plate flexes upwards as it is forced to subduct into the Sunda Trench [5]. The Christmas Island seamount sits just trench-wards of the bulge and has been uplifted 361 m above sea-level. Several seamounts to the south-west of Christmas Island have risen to be now 1000-1500 m below sea-level. This flexing of the oceanic crust has led to secondary bouts of volcanic activity at Christmas Island during the Eocene (43 to 37 million years ago) and Pliocene (4.5 to 4.2) periods [5].

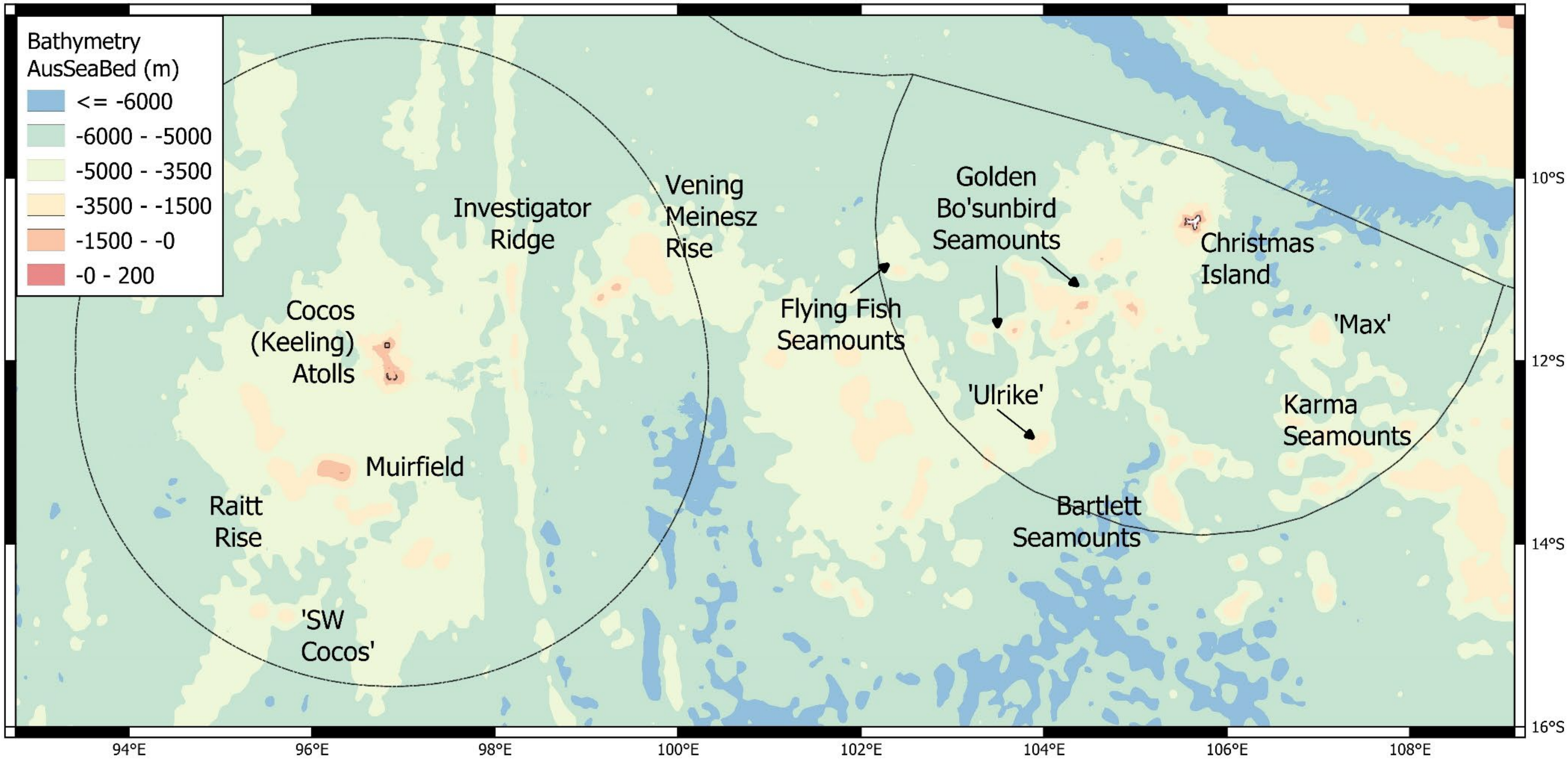

Figure 3 Seafloor bathymetry derived from the AusSeaBed dataset categorised into 6 depth layers. Topographical names follow the GEBCO gazetteer, informal names have single quotation marks.

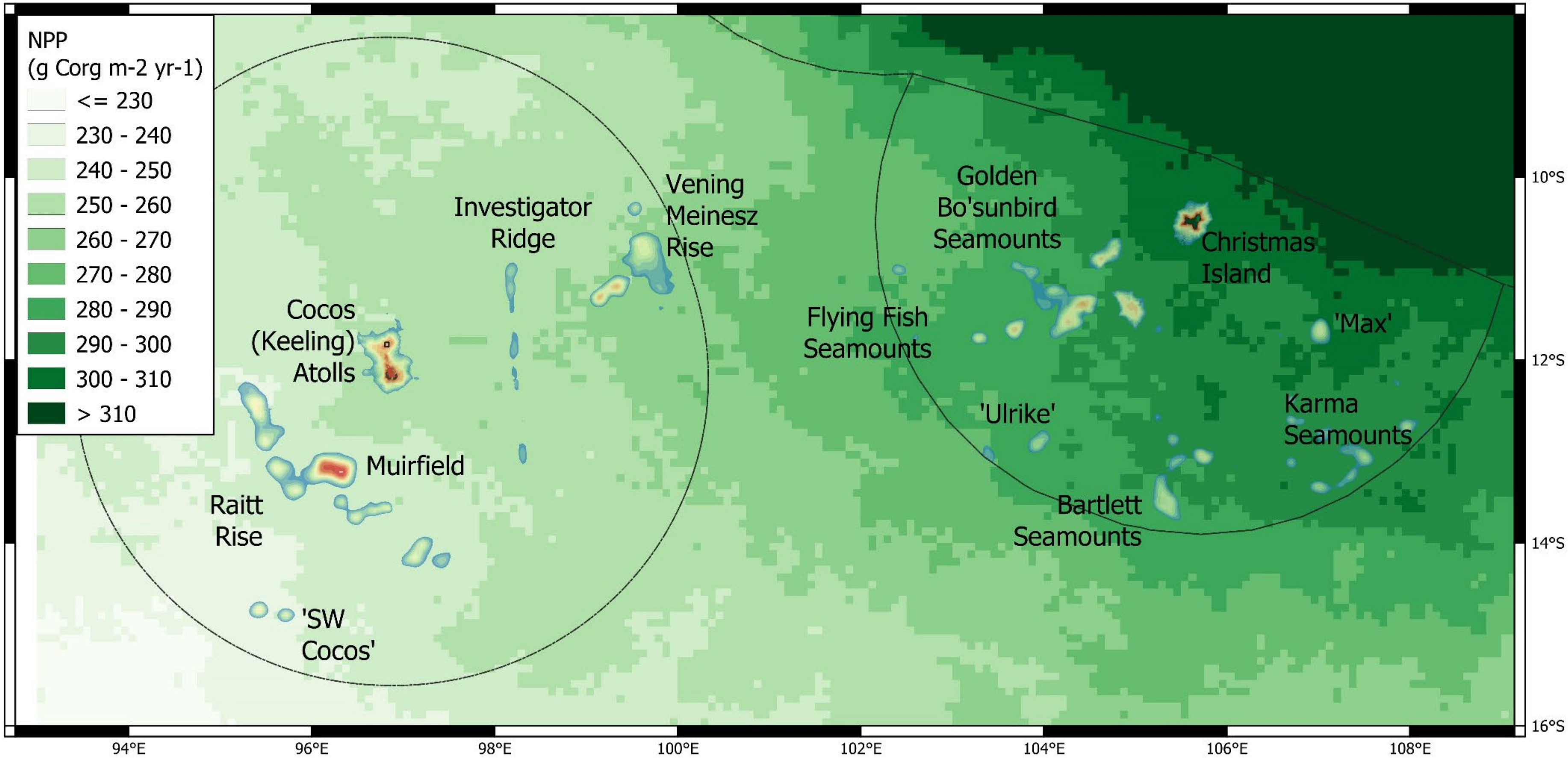

Figure 4. Annual Net primary productivity (NPP) as derived from a vertically generalized production model (VGPM) from 10 years of satellite-derived chlorophyll [23] showing a NE->SW gradient from a high near Indonesia (north of Christmas Island) to a low west of the Cocos (Keeling) Islands Marine Park. Seafloor bathymetry (3500-0 m, blue to red, from AusSeaBed) are superimposed over the NPP layer. Corg = organic particulate carbon. Topographical names follow the GEBCO gazetteer, informal names have single quotation marks.

The second anomaly affects seamounts in the Cocos (Keeling) Islands Marine Park. A magma plume to the SW [6] is hypothesised to be preventing the subsidence of the Muirfield seamount and slowing the subsidence of Cocos. The slowed rates of subsidence for Cocos has facilitated continuous coral growth and atoll development on the summit, and this seamount is now topped with 0.9-2.1 km of limestone [5]. The summits undergo Karst development during the lowered sea-levels of glacial periods and the centre is dissolved by rainwater and reduced in height. With rising sea-levels, the rim forms an atoll and the centre forms a lagoon [7, 8]. Muirfield appears to be a drowned atoll. It possibly shows signs of relatively recent volcanism near its summit [9] but that needs confirmation. There is no record of active volcanic activity today.

Overlaying the oceanic crust and flatter areas on seamounts, are layers of carbonate sediment formed from the skeletal remains of pelagic organisms that are gradually compressed to form clays or oozes [4]. The oozes shift from being of calcareous to siliceous origin below 5000 m [10]. These sediment layers are relatively thin compared to other seafloors [11], as the overlying water column has been relatively unproductive, from 150 m of sediment to the west of the Cocos (Keeling) Islands Marine Park [12] to over 450 m west of Christmas Island [13] nearer the Sunda trench. The summit of Muirfield also has areas of coarse unconsolidated rippled sand implying strong currents [9]. The sediment aprons around the seamounts also include quantities of volcanic debris [14].

Manganese nodules are known to occur on the surface of siliceous clays (4780-5888 m) to the south-west of Christmas Island [10] and southern part of the Cocos (Keeling) Territory. Ash from Indonesian volcanos may inhibit their formation further north [10]. Manganese crusts have formed on hard surfaces (e.g. bare rock or fossil sharks' teeth, Fig. 5) that are free of sediment [10]. Neither the nodules or crusts have minerals that are economically valuable enough to exploit [10].

Figure 5. Fossil Carcharocles *Shark tooth, collected off Cocos (Keeling) Islands, covered in a layer of manganese.*

3. Oceanography

The IOT are located in tropical latitudes in the eastern Indian Ocean. In winter the climate is dominated by SE monsoonal winds, and in summer by the western monsoon. Summer cyclones are common. The mixed-layer depth (the depth to which sea surface turbulence blends oceanographic conditions) is between 40-80 m depending on how this is calculated.

The IOT sits in the path of the South Equatorial Current (SEC), a jet-like flow that contains low saline waters from the Pacific that has traversed across central Indonesia and out into the eastern Indian Ocean. It contains two separate water masses, one flowing at the surface (Indonesian Through Flow waters, ITW) and one at 500-1100 m (Indonesian Intermediate Water, IIW) [15, 16]. During summer, the monsoon winds drives the surface Java Current to the northern IOT from the NW, before it retroflexes and gets entrained by the SEC [17]. Some mixing between the ITW/IIW and Central Indian Water (to the south of the IOT) is also likely to occur [14].

Below 1000 m the currents tend to originate from the south. Antarctic Intermediate water (1800-1500 m, AAIW), originating at subantarctic latitudes flows along the western Australian coast. However, this water starts shoaling just (to 1200 m) to the south of the IOT (18-20˚S) as it gains salinity and it also gets entrained by the SEC and pushed west [14-16]. The AAIW and IIW possibly interleave with each other in finger-like extensions [15].

Both the Indian Deep Water (IDW, 2-3,800 m) and the Antarctic Bottom Water (AABW, or Lower Indian Deep Water, below 3,800 m) flow north along the Ninety East Ridge (which is more like 89°E at IOT latitudes) [18]. Indian Deep Water appears to mainly originate in the Atlantic Ocean via the circumpolar current south of Africa. However, the IDW would also include bottom waters that have gradually warmed, lost oxygen and upwelled in the northern Indian Ocean. There must be some southerly flows of IDW to offset the northerly flows but its location is unknown.

Annual water temperatures at the surface to 50 m are about 27˚C, falling to 10˚C by 350 m and 5˚C by 1000 m. Deep water varies from 2.5˚C at 2500, 1.2˚C at 3800 m and 1.1˚C at 5000m. Oxygen-levels reach a minimum (~80 µmol kg^{-1}) at depths of 550-750 m, but never reach the low levels experienced elsewhere in a severe oxygen minimum zones (< 20 µmol kg^{-1}). Both surface waters and bottom waters are well oxygenated. There can also be a secondary peak of oxygen at 400-550 m due to the deep Indonesian ThroughFlow. Other oceanographic parameters such as salinity and silica also vary a little throughout the water column, but, although small differences in these values are used to characterise and track water masses, they are not likely to affect the function of benthic fauna.

Conversely, variation in Net Primary Productivity (NPP) has a marked effect on the biomass and richness of seafloor communities, from local [19, 20] to regional scales [21, 22]. The waters over the IOT are generally oligotrophic, except the nearest points to Indonesia (Fig. 4). Annual NPP declines in a gradient from the NE to the SW, however, phytoplankton production is seasonal. In winter (July-August) tongues of elevated phytoplankton extend to Christmas Island before being pushed westward by current over the northern half of the Cocos (Keeling) Islands MP. However, in early summer (November-December) phytoplankton is slightly elevated in the southern Cocos (Keeling) Islands MP [14].

4. Geomorphology and habitats

The fauna of the seafloor in the IOT was largely unknown prior to the RV *Investigator* expeditions. Previous faunal surveys have been focused almost exclusively on shallow water habitat (0-60 m) around Christmas and Cocos Islands. However, the vast majority of the IOT seafloor consists of deep-water habitats.

The biota will principally respond to depth (and environmental factors that correlate with it, such as light penetration, temperature, salinity, oxygen and nutrients), substrata (soft vs rocky seafloor surface), water flow, and primary productivity. Seafloor substrata (rock vs sediment) and water flow characteristics are very important in structuring marine faunas, but typically vary at too fine a scale to be mapped into bioregional units. The type of basement rock is often irrelevant unless it is exposed. There need only be a 10 cm covering of sediment over a rocky basement for the fauna to become a typical soft-sediment community.

Oxygen is not a limitation in the IOT as it is in other parts of the world, where oxygen minimum zones (OMZ) occur. These form at upper bathyal depths where circulation is poor and shallow water productivity is high (the decomposition of which uses up available oxygen), and oxygen falls to less than 20 µmol kg^{-1}. The IOT is on the southern margin of the North Indian OMZ, however, the powerful currents from the deep Indonesian Through-Flow ensure oxygen levels remain above 75 µmol kg^{-1} and hence are not hypoxic or anoxic.

Consequently, the assessment in this document categorises habitats along gradients (Fig. 3-4) of depth and net primary productivity (Table 1). Depth zones are based on water masses and typical faunal distributions. The evolutionary divergence between shallow (including the mesophotic zone, 0-200 m) and deep-sea animals can be in the order of hundreds of millions of years [24, 25]. To survive the cold, the immense pressures, the lack of light and limited food supply, deep-sea animal lineages may have to evolve a whole new biochemistry, physiology or anatomy. Change in community composition continues below 200 m, although this is not as dramatic as the change between shallow and deep. Ecologists have divided up the deep-sea into the bathyal (equivalent to continental slopes, 200-3500 m), the abyssal (plain, 3500-6000 m) and the hadal (trenches, below 6000 m) zones. Bathyal seafloors occur around continents, seamounts, ridges and volcanic plateaus. These zones are not uniform however, particularly the bathyal zone and there are very few organisms that can tolerate the range of conditions from 200 to 3500 m. It is convenient to divide the bathyal zone into upper, mid and lower strata that reflect differing water masses (Table 1). The boundaries between these layers can vary with location around Australia. A qualitative assessment of the brittle-star (ophiuroid) species found on the IN2021_V04 expedition (46 species) suggests the boundaries between these depth layers around Christmas Island occur broadly at 1100 m and 1900-2100 m (Fig. 6). Not enough data was collected to establish the boundary between the lower bathyal and abyssal faunas. However, the limited data available suggests that it would occur below 3300 m. Consequently we use the standard 3500 m as an interim limit. It is important to emphasise that these strata are just a convenient approximation. In reality, community composition changes continually through the bathyal region, with many species having overlapping bathymetric ranges [26].

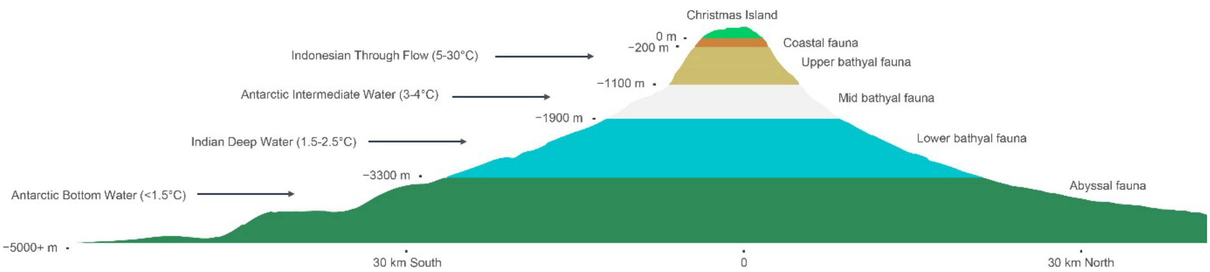

Figure 6. Proposed faunal depth layers mapped onto a South to North bathymetric profile of the Christmas Island Seamount.

The same depth layers on separate seamounts are linked by dispersal. Many organisms or their larvae/propagules can swim or be transported across the water to colonise similar depth ranges elsewhere. They don't descend, cross the abyssal plain, and re-climb the next seamount. The abyssal depths would kill them. A good way to visualise the connectivity of marine populations is to focus on colour similarities on a 3D topographic map (Fig. 7).

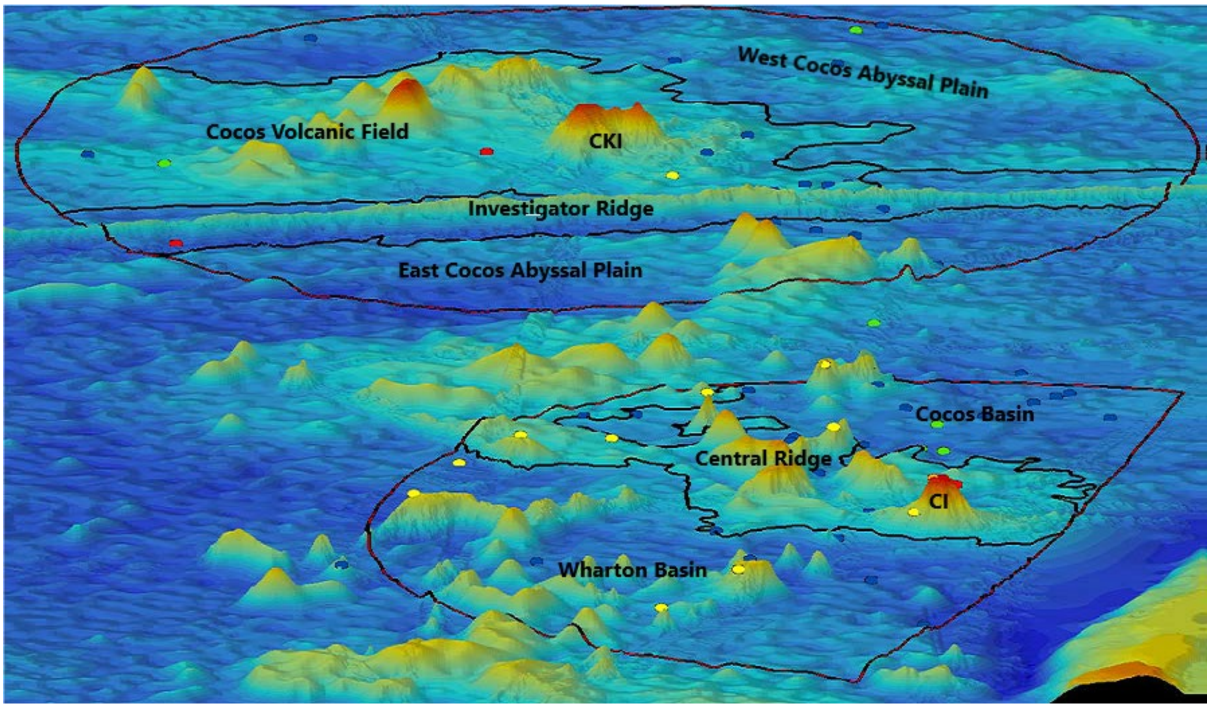

Figure 7. 3D visualisation of bathymetry from the IOT region – adapted from Brewer et al. 2009. Each colour represents a separate but connected biological community. The named areas within the EEZs are sub-regions identified by Brewer – see 4.4. below.

Ecosystem	Water mass	Type	High Productivity Examples (Christmas Is MP)	Low Productivity Examples (Cocos Is MP)
Oceanic mesophotic coral reef (30-200 m)	Shallow Indonesian Through Flow	Island flanks	Christmas	Cocos (Keeling)
		Seamount	-	Muirfield
Upper bathyal reef and sediments (200-1100 m)	Deep Indonesian Through-Flow/Central Indian Water	Seamount flanks	Christmas	Cocos (Keeling), Muirfield, 'Green Eye'
Mid bathyal reef and sediments (1100-1900 m)	Antarctic Intermediate Water	Seamount	Golden Bo'sunbird and Flyingfish seamounts, 'Max', 'Bartlett'	Vening Meinesz Rise, Raitt Rise and 'Santa' Ridge seamounts, 'Carcharocles'
Lower bathyal reef and sediments (1900-3500 m)	Indian Deep Water	Seamount and ridge	Karma Seamounts, 'Clara Marie', 'Ulrike',	Investigator Ridge
Abyssal reef and sediments (3500-6000 m)	Antarctic Bottom Water	Carbonate sediments (above 5000 m)	Plateaus and hills between seamounts, particularly in the central Christmas Is MP.	Plateaus and hills between seamounts, particularly in the central Cocos Is MP
		Siliceous sediments (below 5000 m)	Plain across Christmas Is MP	Plain across Cocos Is MP
		Gravel/ boulders	Seamount aprons, rises.	Seamount aprons, rises.
		Manganese nodule deposits	SW of Christmas Is MP	Unknown
Hadal sediments (below 6000 m)	Antarctic Bottom Water	Hadal plains	East and south of Christmas Is MP	SE of Cocos Is MP

Table 1. List of proposed offshore benthic habitat classifications. Many habitats will have communities on both exposed rock (e.g. on seamount flanks) and soft sediments (e.g. sand on seamount summits) depending on the slope of the feature. However, these are likely to vary at small spatial scales and cannot be mapped at present due to lack of comprehensive multibeam backscatter data.

A major driver of community composition is food availability. The biomass, abundance and diversity of seafloor communities will differ between areas of high and low productivity [27]. Annual NPP is distributed in a continuous NE->SW gradient across the IOT, but patterns can vary with season. However, the geographic separation of the Christmas and Cocos (Keeling) Is MPs provides a convenient break point in the gradient, dividing more productive waters in the Christmas Is MP from those of the more oligotrophic Cocos (Keeling) Is MP.

From a marine conservation perspective, it is important to protect several examples of each depth strata in each MP, and ensure that these examples contain a variety of substrata and water flow regimes. While the regional species pool is likely to be consistent across each MP (and perhaps across the IOT), there will be variation of assemblage structure within each of these habitats due to differences in colonisation history. Each seamount or feature will have a different subset of the regional species pool [28]. Any further subdivision of these MPs for marine conservation purposes should be along a NE to SW axis that would reflect the distance from the Indonesian continental margin, from which pulses of high productivity originate and which is likely to be the source of much migration to the IOT.

4.1 Shallow and mesophotic reef and sediments (30-200 m)

There are three shallow-water (less than 200 m deep) features within the IOT and all are very different from each other.

4.1.1. Christmas Island

Christmas Island is an uplifted seamount with a Cretaceous (87.5 to 75.2 million years ago) basalt base capped with a thick layer of limestone (mostly Late Eocene and early Miocene reef deposits, 43 to 17 million years ago [29]), with a few volcanic extrusions (Eocene, 43 to 37, and Pliocene, 4.5 to 4.2 million years ago [2]) at the surface and a covering of phosphate deposits (guano from seabird colonies from 4.5 million years ago). Thus the initial volcanic seamount was above sea-level during the Late Cretaceous and early Cenozoic, submerging by the late Eocene (43.6-37.0 million years ago) to form an atoll, submerging again during the mid-Miocene climatic optimum (17-14.5 million years ago), before being uplifted by flexing of the oceanic crust to become an island again during the early Pliocene (5.66-4.49 million years ago) [30].

It is bounded by cliffs with a few beaches with calcareous (chalky) sand [14]. The maximum height is 361 m. The subtidal environment is rocky and very steep, rapidly descending to 1000 m within 500 m of the coastline, with few areas of coarse sand [14]. There are no estuaries, mangrove beds, or lagoons.

The main winter shallow current through the area is the east to west flowing South Equatorial Current. This can change to a flow coming from the NW during the summer monsoon. Annual Net primary productivity over the IOT is greatest near the Indonesian coast, north of Christmas Island (Fig. 4). In winter (July-August) tongues of elevated phytoplankton extend to Christmas Island.

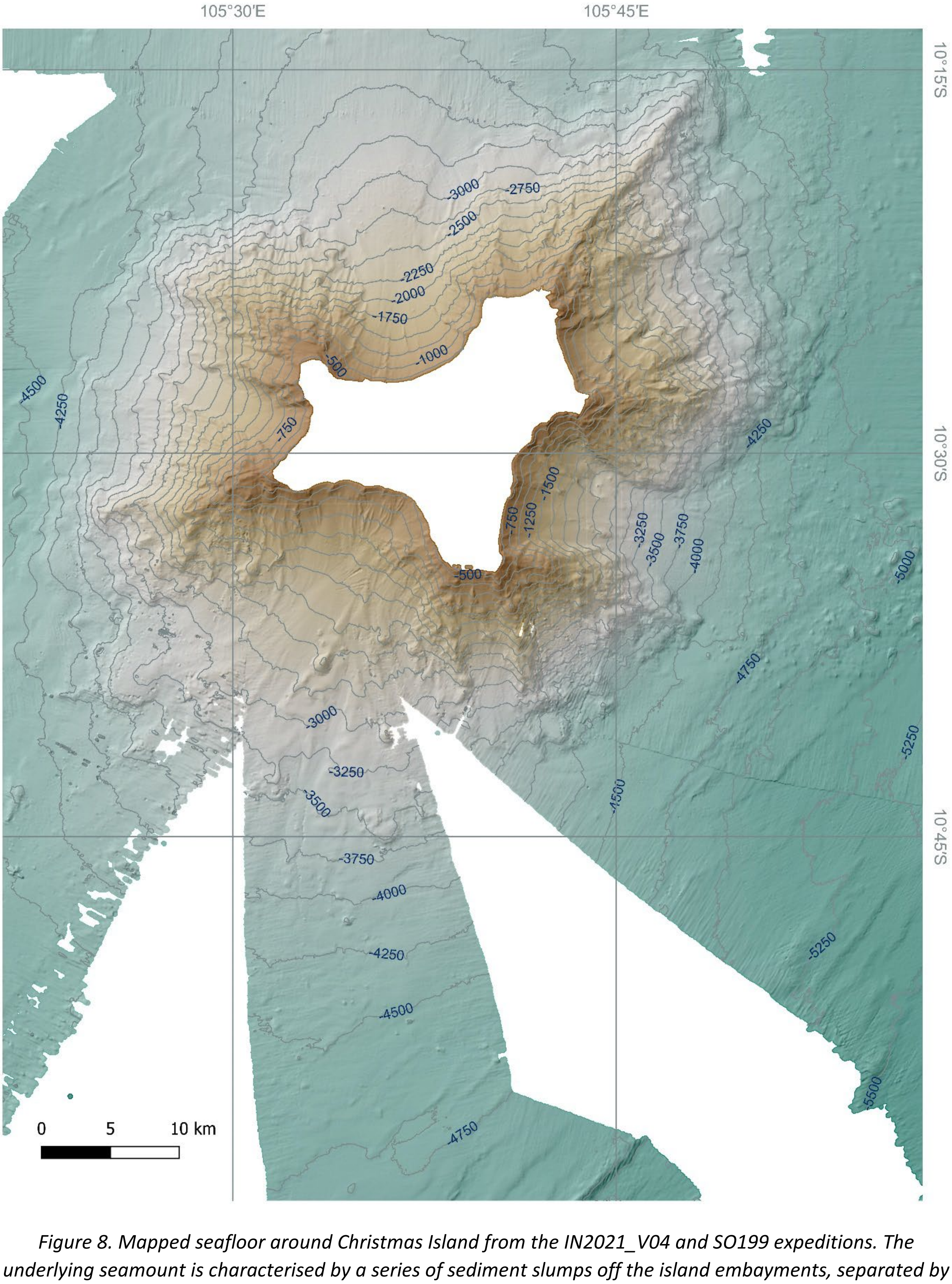

Figure 8. Mapped seafloor around Christmas Island from the IN2021_V04 and SO199 expeditions. The underlying seamount is characterised by a series of sediment slumps off the island embayments, separated by rocky spurs.

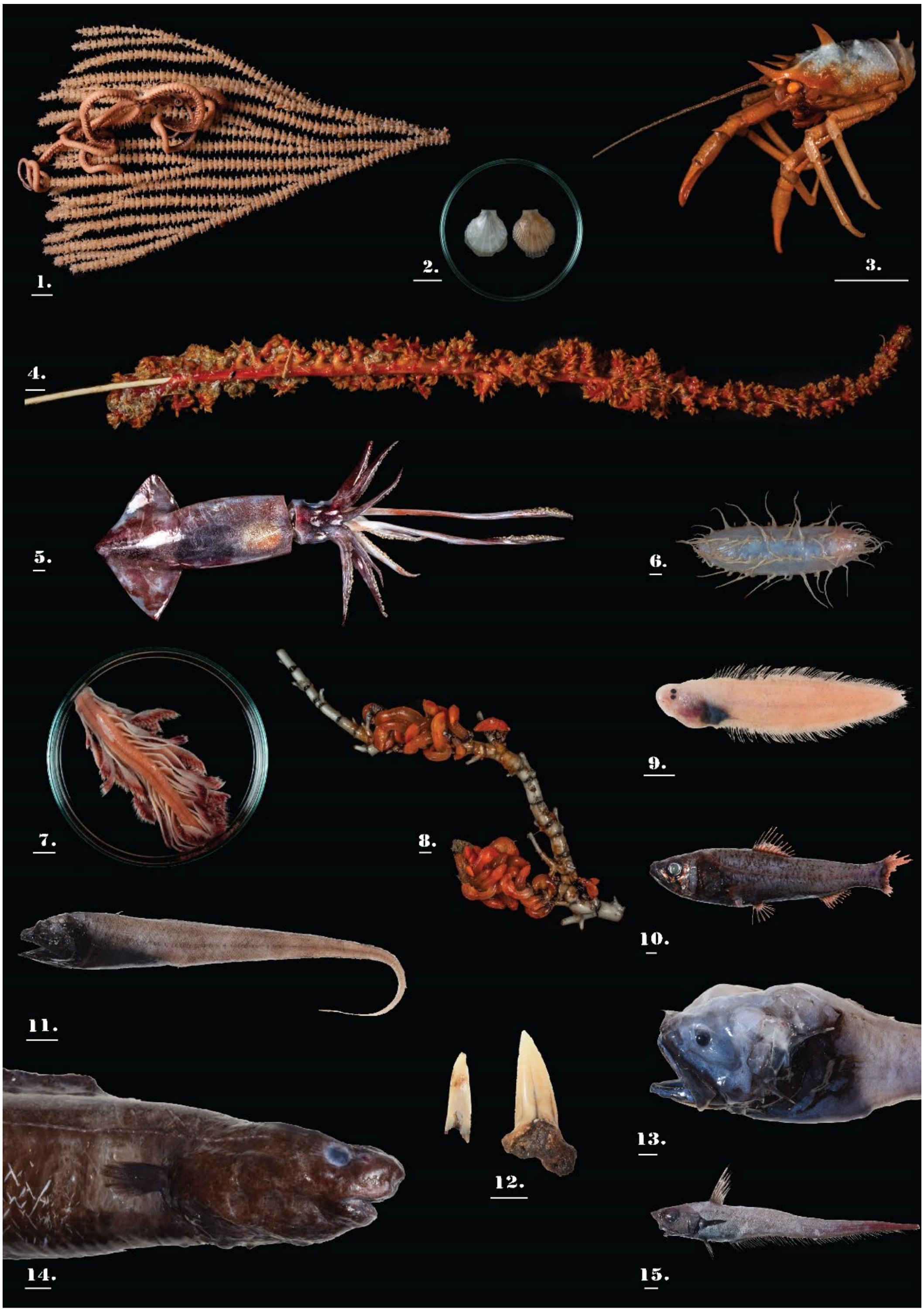

Figure 9. Seafloor fauna of Christmas Island seamount collected by the IN2021_V04 expedition. (1) brittle-star Asteroschema horridum *on primnoid coral. (2)* Propeamussium *bivalve. (3)* Galacantha *squat lobster. (4) Alcyonacea soft coral. (5)* Nototodarus *squid. (6)* Oneirophanta mutabilis mutabilis *sea-cucumber. (7) Pennatulidae coral. (8)* Heteralepas *barnacles on Isididae coral. (9)* Symphurus *sp. (10)* Neoscopelus macrolepidotus *large-scaled lantern fish. (11)* Bassozetus *sp. spongy rattail. (12) Fossil Lamnidae shark teeth of* Isurus hastalis*. (13)* Acanthonus armatus *bony-eared assfish. (14)* Promyllantor *congrid eel. (15)* Nezumia spinosa *sawspine whiptail. Scale bar under figure numbering = 10 mm.*

4.1.2. Cocos (Keeling) Islands

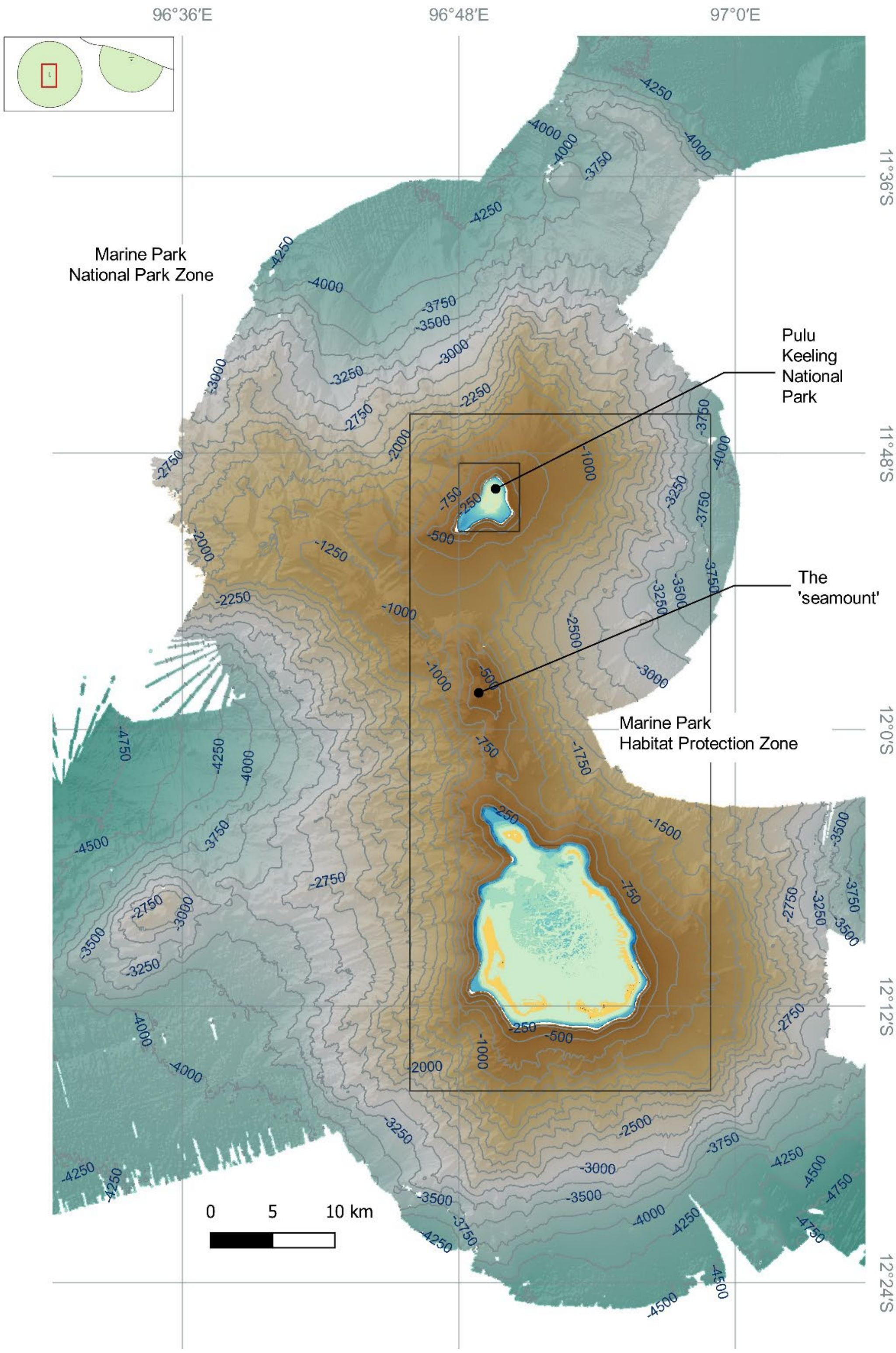

Figure 10. Bathymetric map of the Cocos (Keeling) seamount compiled from multibeam data from the IN2022_V08 and SO199 expeditions. The topography of the two summits that rise above sea-level, the multi-island South Keeling atoll and North Keeling Island, are compiled from AHO LIDAR (LADS) data.

The Cocos (Keeling) Islands form two groups of small sandy low-lying islands. To the south are 26 islands that form an atoll around a large shallow lagoon. North Keeling is a single island, a micro-atoll with a semi-enclosed lagoon. These island groups sit on separate volcanic peaks of the underlying seamount that are capped in 900-2,100 m of limestone (Fig. 10). Such atolls are likely to have developed on a flat Pliocene (5.3 to 2.8 million years ago) bank by seaward-growth of the outer rim during high-sea level interglacial periods and karst formation of the central lagoon-area during glacial low sea-level events [7]. Thus Cocos differs from Christmas in having areas of flat shallow-water seafloor with soft sediments and seagrass beds. There are no estuaries.

Figure 11. Hard and soft coral in the Cocos (Keeling) Lagoon. Photo by Sally Watson.

4.1.3. Muirfield seamount

The Muirfield seamount was comprehensively mapped for the first time by the IN2022_V08 expedition. The results show a large 50x70 km seamount bordered by a series of volcanic ridges separated by concave flanks, the latter resulting from coalescing sediment slumps, with avalanche debris sometimes obvious (as convex depth contours) at the seamount base. The domed summit rises from 1000 m to approximately 350 m, where it peaks in a cylindrical structure topped with what appears to be a small drowned atoll, trapezoid-shaped and 2.4x1.5 km in size. The rim of the atoll is at 17-20 m depth, with the centre 20-25 m deep. Another terrace surrounds the atoll at 40-45 m deep.

This data clearly shows that Muirfield is the shallowest seamount in the IOT, the only one (except the two islands) that is known to summit in less than 200 m depth, and so potentially supports a unique shallow water environment. It may be the most recent of all IOT volcanos, with basalt visible near the summit. There is also hyaloclastite boulders and debris (from undersea eruptions), and areas of calcareous sand on the western summit and the upper seamount flanks (to at least 885 m)

[9]. However, there are no reports of contemporary volcanic activity. The seamount summit experiences wave scour [9].

The FR07/99 expedition recorded sparse reef building corals above 25 m on the western summit and a band of gorgonian corals and sea-whips at 70 m [9]. Below that, sparse encrusting invertebrates, black corals, seastars, brittle stars, anemones and sea urchins were observed [9] (IN2022_V08 unpublished data).

A dome of reduced particulate organic carbon has been recorded over the summits of some other shallow seamounts (e.g. Melville Bank on the SW Indian Ocean Ridge, summit at 120 m) [31], which has been attributed to the seamount penetrating the euphotic zone and disturbing primary production. It is unknown whether this occurs at Muirfield.

The main winter shallow current through the area is the east to west flowing South Equatorial Current. This can change to a flow coming from the NW during the summer monsoon. Annual Net primary productivity around Cocos is less than around Christmas Island although in early summer (November-December) phytoplankton can be slightly elevated in the southern Cocos (Keeling) Is MP [14].

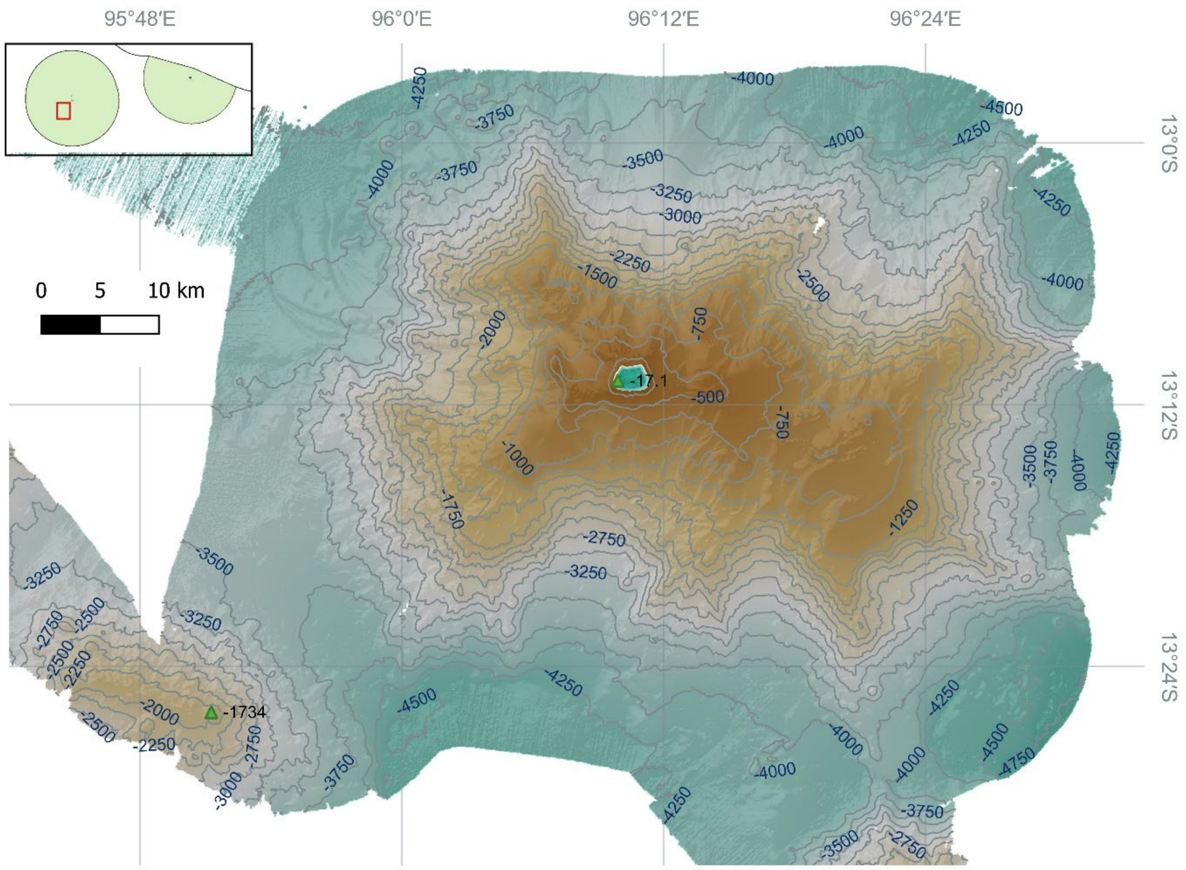

Figure 12. Bathymetric map of Muirfield seamount compiled from multibeam data from the IN2022_V08 expedition and LIDAR data of the summit area. The summit (17.1 m) appears to be a drowned atoll sitting atop a limestone plug.

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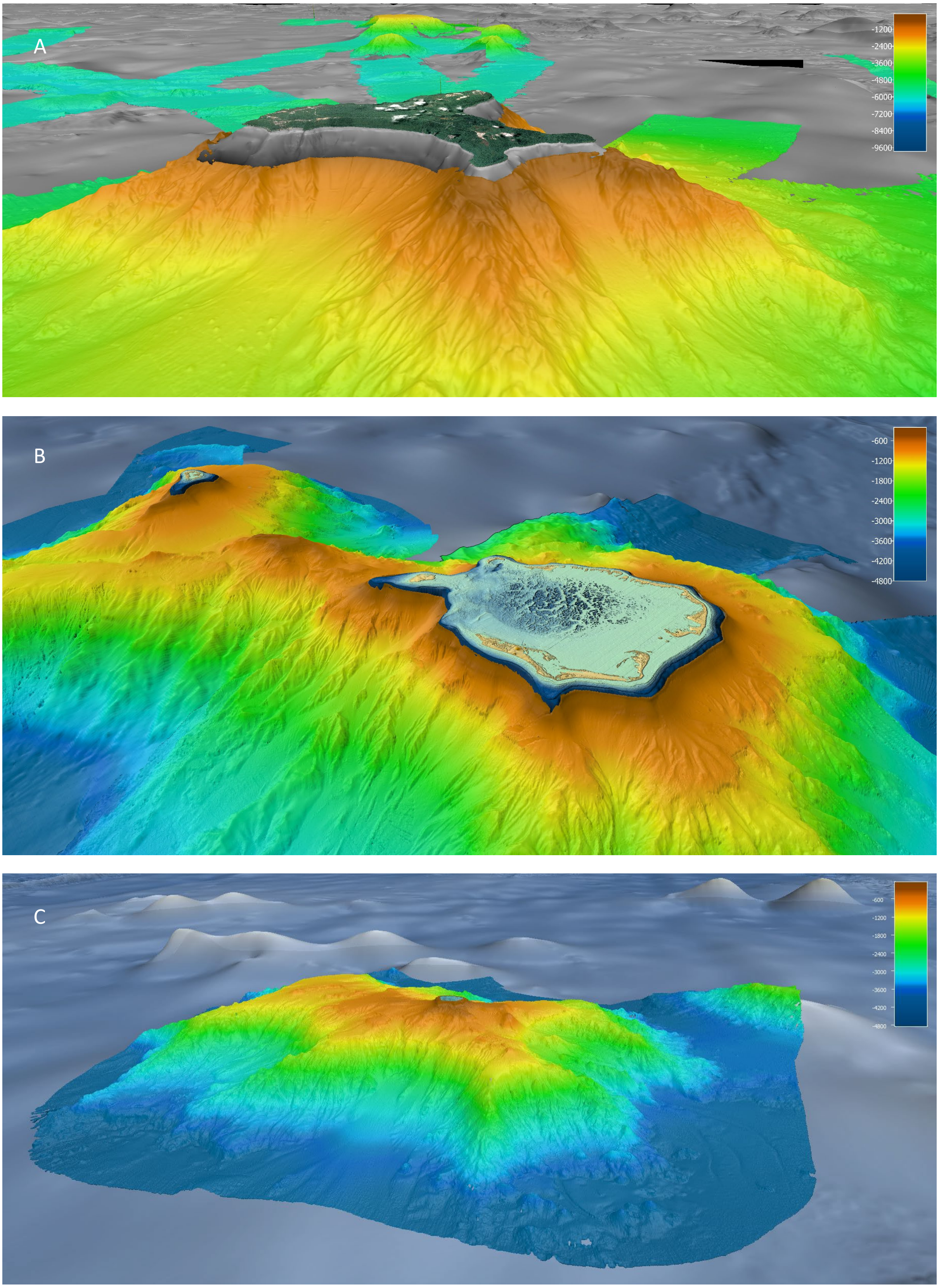

Figure 13. 3D bathymetric images of (A) Christmas Island (from the east), (B) Cocos (Keeling) Islands (from the SW), and (C) Muirfield Seamount (from the NE). Images produced by CSIRO using QPS Fledermaus software and background datasets AusSeabed (Geoscience Australia), GEBCO 2022 and AHO (LADS) Bathymetry.

4.2 Bathyal reef and sediments (200-4000 m)

4.2.1. Seamount reef and sediments (200-1100 m)

This depth layer only exists on the three shallow features listed in 4.1 and near the summit of the 'Green-eye' seamount.

The seafloor around Christmas Island drops rapidly on all sides. It is formed from the flanks of the seamount that underlies the island. There appears to be a series of sediment slumps (or landslides) down the seamount flanks, running from embayments on the coastline down to the abyssal plain at the base of the seamount, which have left behind a steep rocky seafloor (Fig. 8). These slumps are separated by a series of rocky spurs that continue underwater from topographical points around the island. The flatter sections (e.g. ridges, canyons) of these spurs are covered in sediment, the steeper sections by rock.

The bathymetry around the Cocos atolls is more complex. The island groups are bordered by very steep drop-offs to 500 m which are likely to be exposed rock. Slopes between 500 and 1500 m on the south-eastern and northern sides are less steep and may be covered in pelagic sediments. A shallow (350-450 m) ridge like feature lies between the two island groups. It also may have soft sediments along the flattened ridge line.

Extended video tows were performed by the FR07/99 expedition [9]. They show mostly unconsolidated sands, volcani-clastic detritus, breccia, and outcrops of basalt. Steep slopes (~18°) continued to about 300 m, followed by more gentle slopes (6-8°) from 300-885 m. The volcanic debris and outcrops were more common near the summit, and sands more common at lower depths. A strong downward current produces asymmetrical sand ripples at 500-800 m. Sediment slumping can occur on slopes as gentle as 2° and may be responsible for the down slope occurrence of volcanic debris [9].

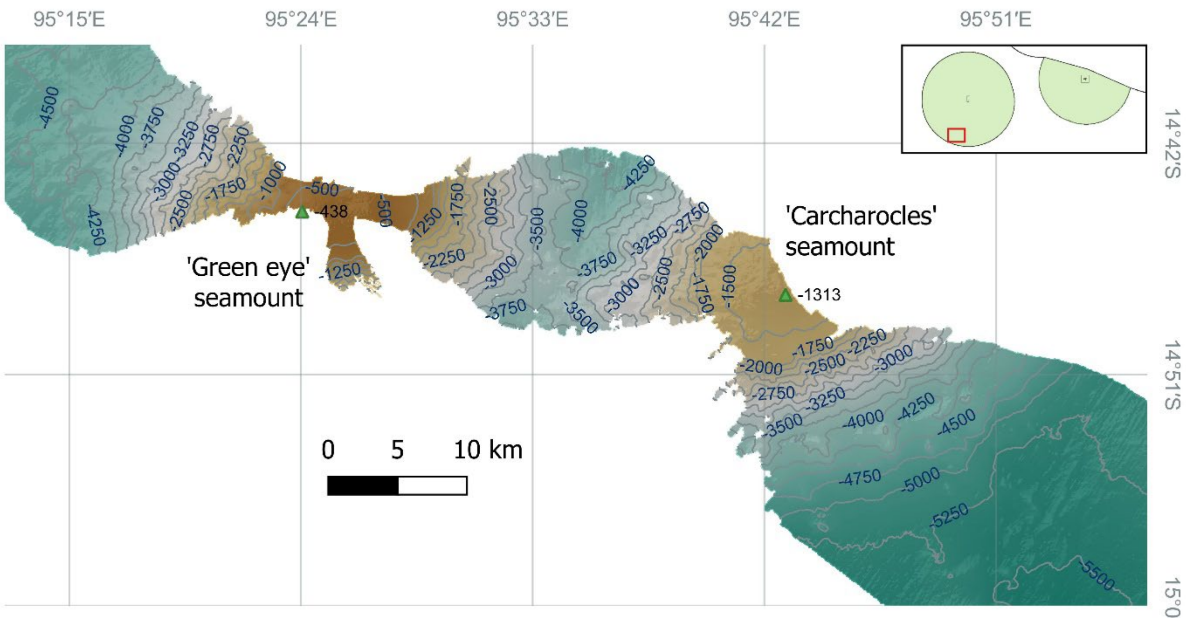

Figure 14. Bathymetric maps of the SW Cocos seamounts compiled from multibeam data from the IN2022_V08 expedition. 'Green-eye' is the only seamount in the Indian Ocean Territories that summits (green triangle) in the 200-1000 m range.

The "Green-Eye' seamount in the SW Cocos Marine Park is the only seamount in the IOT that has a peak at upper bathyal depths (438 m) (Fig. 14). This conical seamount rises 4000 m from the abyssal seafloor to form a slightly domed summit at 500-440 m depth. The echo sounders from the RV *Investigator* IN2022_V08 expedition showed dense aggregations of fish and zooplankton around the summit.

Upper bathyal depths in the IOT are still strongly influenced by the east to west flowing South Equatorial Current with waters originating from the deep Indonesian Through-Flow [17]. However, seasonal flows from the NW can also be important [32].

Seafloors at upper bathyal depths can interact with diurnal vertical migrators. Some types of pelagic migrators (e.g. euphausid krill) will boost predator numbers [33], but others have learned to avoid seamount flanks and will locally reduce predator biodiversity [34]. Seamounts are also known to alter bottom currents, such as reported for Muirfield.

4.2.2. Seamount reef and sediments (1100-1900 m)

There are eight seamounts in the Golden Bo'sunbird seamount cluster that have summits between 1100-1900 m (including Shcherbakov, 'Apollo 8', 'Balthazar' (north and south), 'Halley', 'Glogg', 'Attention' and an unnamed seamount, Fig. 16, 19). 'Max' (east of Christmas Island, Fig. 15), 'Bartlett' (south of Christmas Island), and 'Lucia' (Flyingfish seamount, Fig. 20) also peak in just under 2000 m. In the Cocos (Keeling) MP, there are another three on the Vening Meinesz Rise ('Scrooge', 'Rudist North' and 'Rudist South', Fig. 21), six on the Raitt Rise (including 'Noel', Fig. 22) and 'Santa' Ridge (including 'Klaus', Fig. 23), and 'Carcharocles' to the SW of the Cocos (Keeling) Is MP (Fig. 14).

Multibeam back-scatter and sub-bottom profiling data indicate that the summits of surveyed seamounts are generally covered in a thick (~100 m) layer of soft sediment (Fig. 28). The steep seamount flanks are covered in exposed rock with flatter ridges and canyons being covered in some sediment.

The 1100-1900 m depth range typically contains rocky seafloors that are most likely to form thick manganese crusts [10] and support colonial cold-water coral communities [35]. Manganese crusts have been shown to influence benthic community composition on seamounts elsewhere [36, 37]. Flat seamount summits are likely to have areas of soft sediment and carbonate rocks. The rims, steep flanks and associated volcanic cones will likely be exposed rock. Two video tows of the SO199 expedition showed a rocky surface supporting gorgonians and crinoids on the flanks of Shcherbakov and 'Balthazar' (Fig. 16) at 1800-2000 m. The mid-bathyal flanks of Christmas, Cocos and Muirfield seamounts will also support hard-and soft substrata habitats depending on the slope. Gentle slopes can occur where there has been sediment failure and debris flows and are more likely to retain subsequent pelagic sedimentation.

Water masses at this depth would include a mixture of Indonesian Intermediate Water arriving from the east, Antarctic Intermediate Water from the SE, and Indian Central Water from the south [18]. All these waters get entrained by the South Equatorial Current and flow to the west. Muirfield and Cocos are in more oligotrophic surface waters which may reduce seafloor biomass.

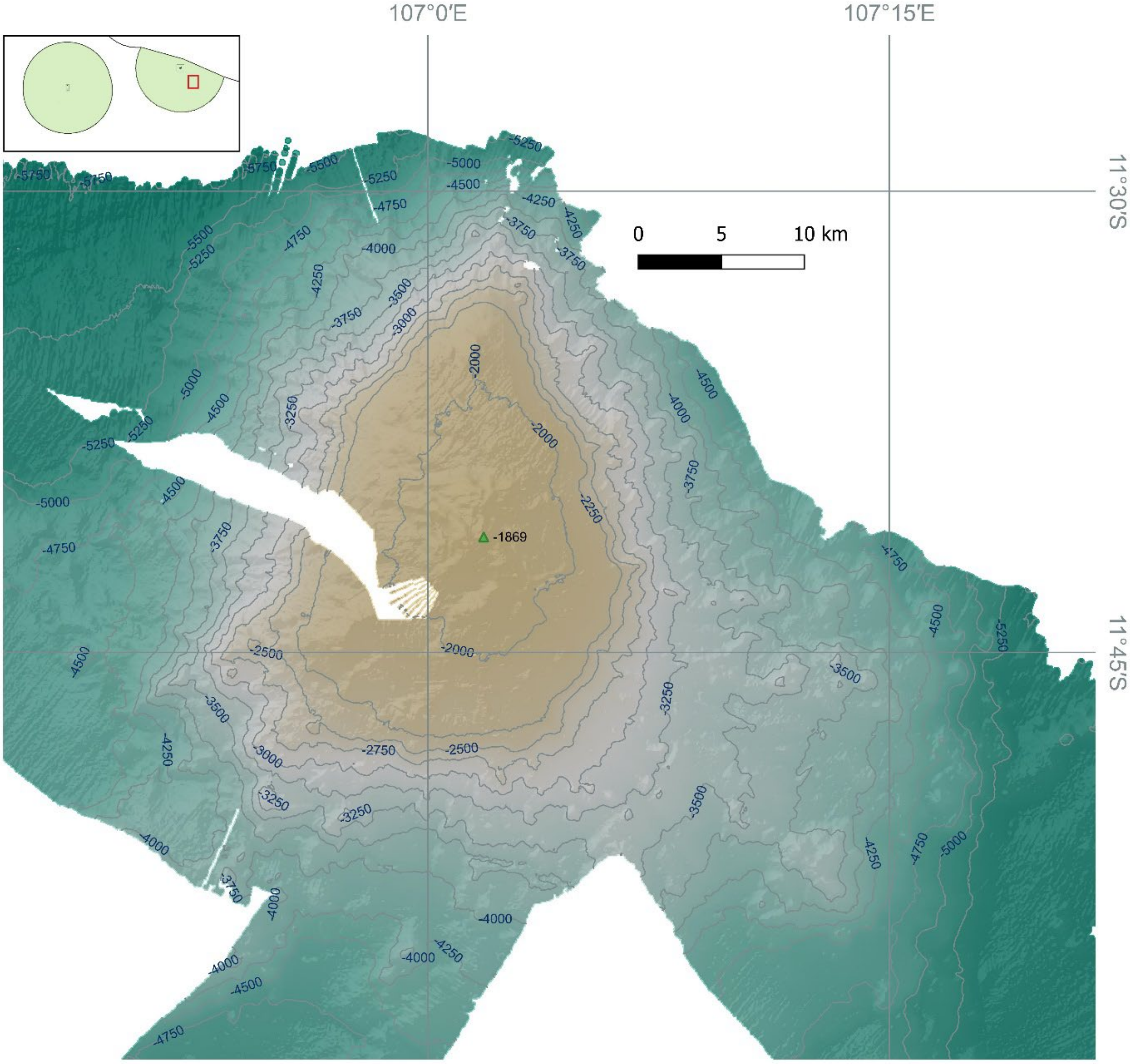

Figure 15. Bathymetric map of the 'Max' seamount, compiled from multibeam data from the IN2021_V04 and SO199 expeditions, showing a large guyot-like seamount that summits above 2000 m depth with evidence of sediment erosion on the southern boundary.

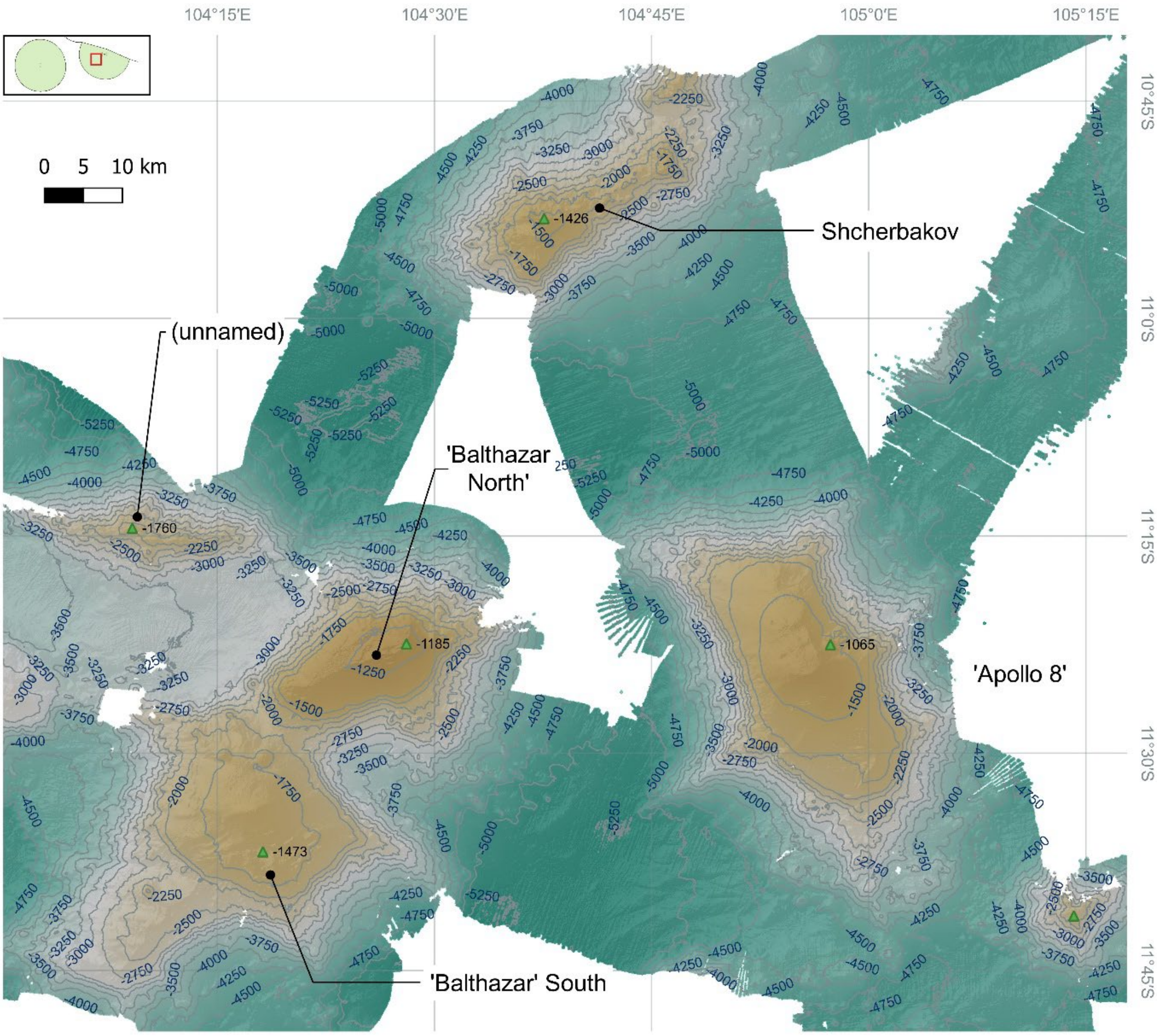

Figure 16. Bathymetric maps of the eastern Golden Bo'sunbird seamounts compiled from multibeam data from the IN2021_V04, IN2022_V08 and SO199 expeditions, showing a series of guyots and ridge like seamounts that summit (green triangles) in 1065-1760 m depth.

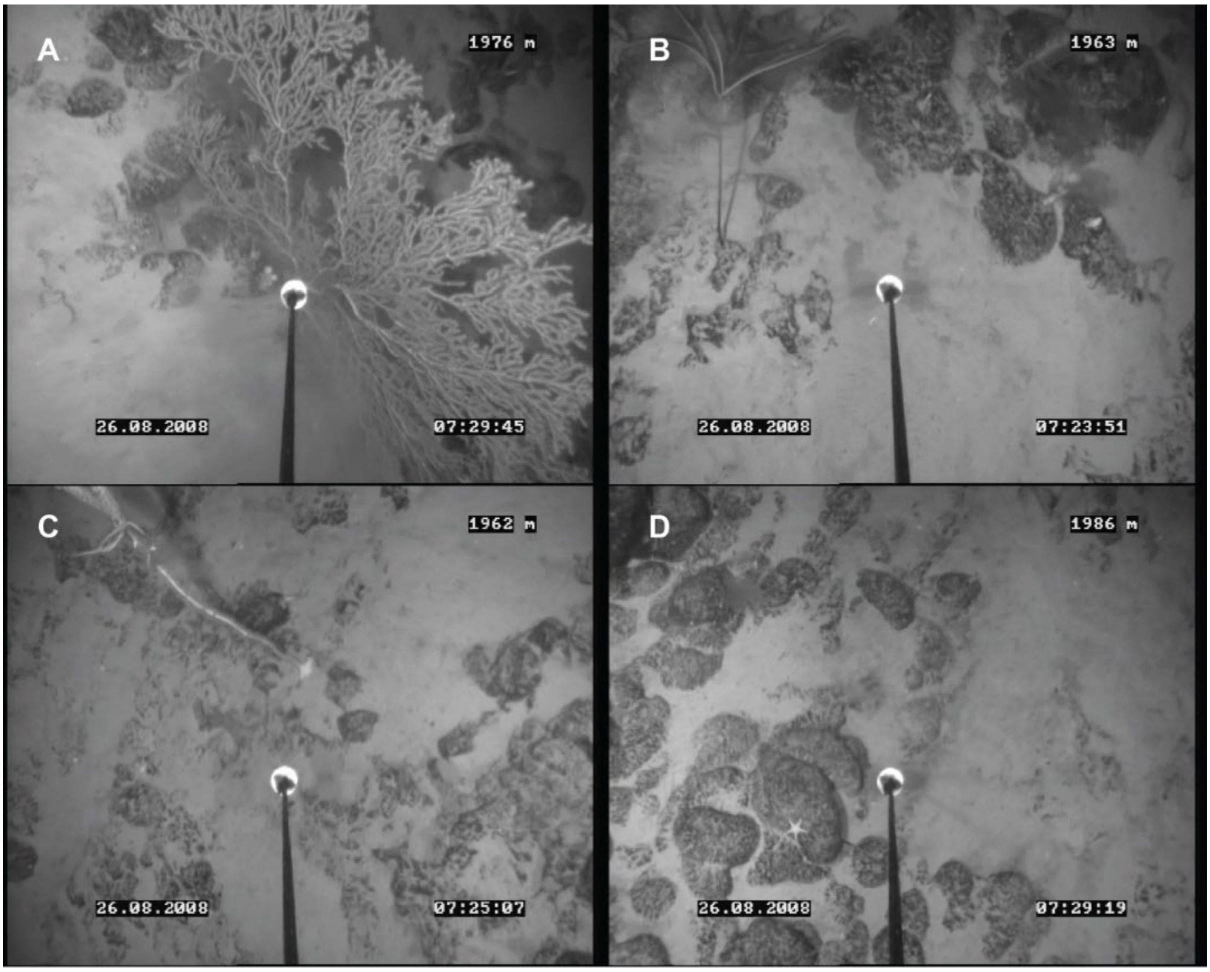

Figure 17. Video stills of a small volcanic cone on the NE flank of North 'Balthazar' seamount in 1800-2000 m depth taken by the Sonne SO199 expedition (courtesy of Carsten Lüter, Berlin Museum of Natural History). (A) Gorgonian coral. (B) stalked crinoid. (C) coral with epizoic brittle-star. (D) seastar.

Figure 18. Fauna of the Golden bo'sunbird seamounts collected by the IN2021_V04 expedition. (1) Glyphocrangon *shrimps ('Balthazar'. (2) Polychelidae blind lobster ('Apollo 8'). (3)* Galacantha *squat lobster ('Balthazar'). (4)* Etmopterus *lantern shark ('Apollo 8'). (5)* Desmophyllum *cup coral ('Balthazar'). (6) brittle-star on octocoral ('Balthazar'). (7)* Coelophrys *batfish ('Apollo 8'). (8)* Anoplogaster cornuta *fangtooth ('Balthazar'). (9)* Cerataspis *prawn ('Balthazar'). (10)* Chaceon *deep-sea crab ('Apollo 8'). (11)* Photostomias *barbeled dragonfish ('Apollo 8'). Scale bar under figure numbering = 10 mm.*

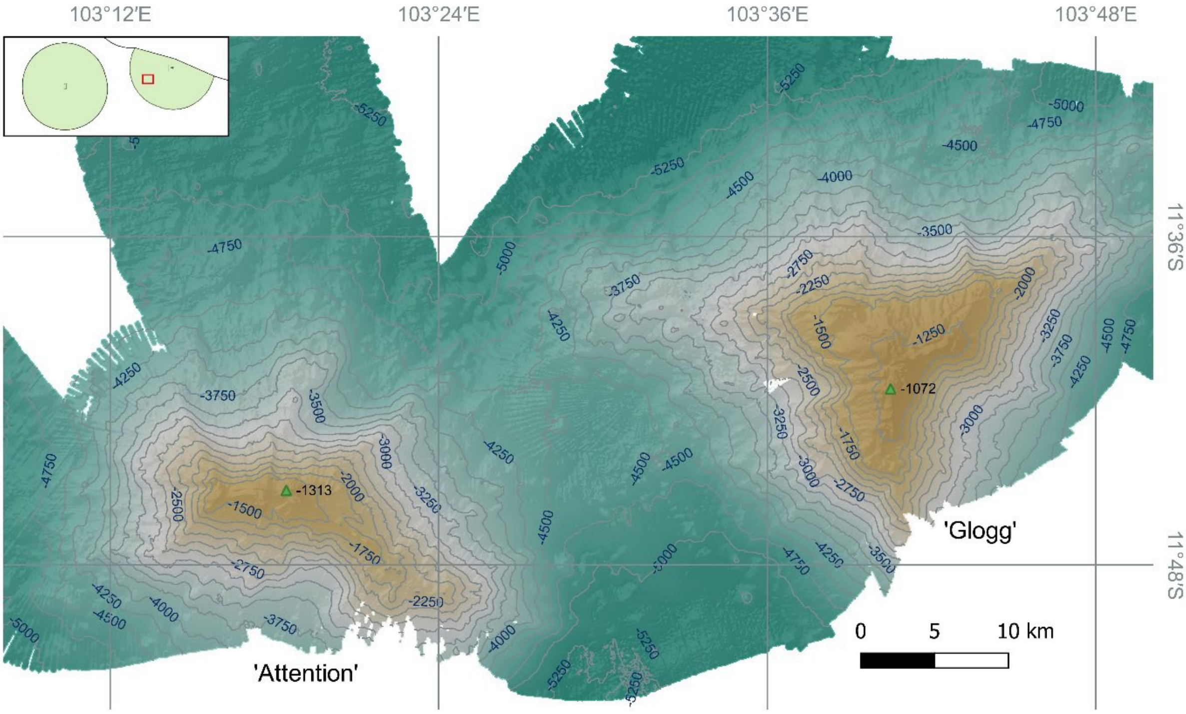

Figure 19. Bathymetric map of the western Golden Bo'sunbird seamount cluster, including 'Attention' and 'Glogg' seamounts, compiled from multibeam data from the IN2022_V08 and SO199 expeditions.

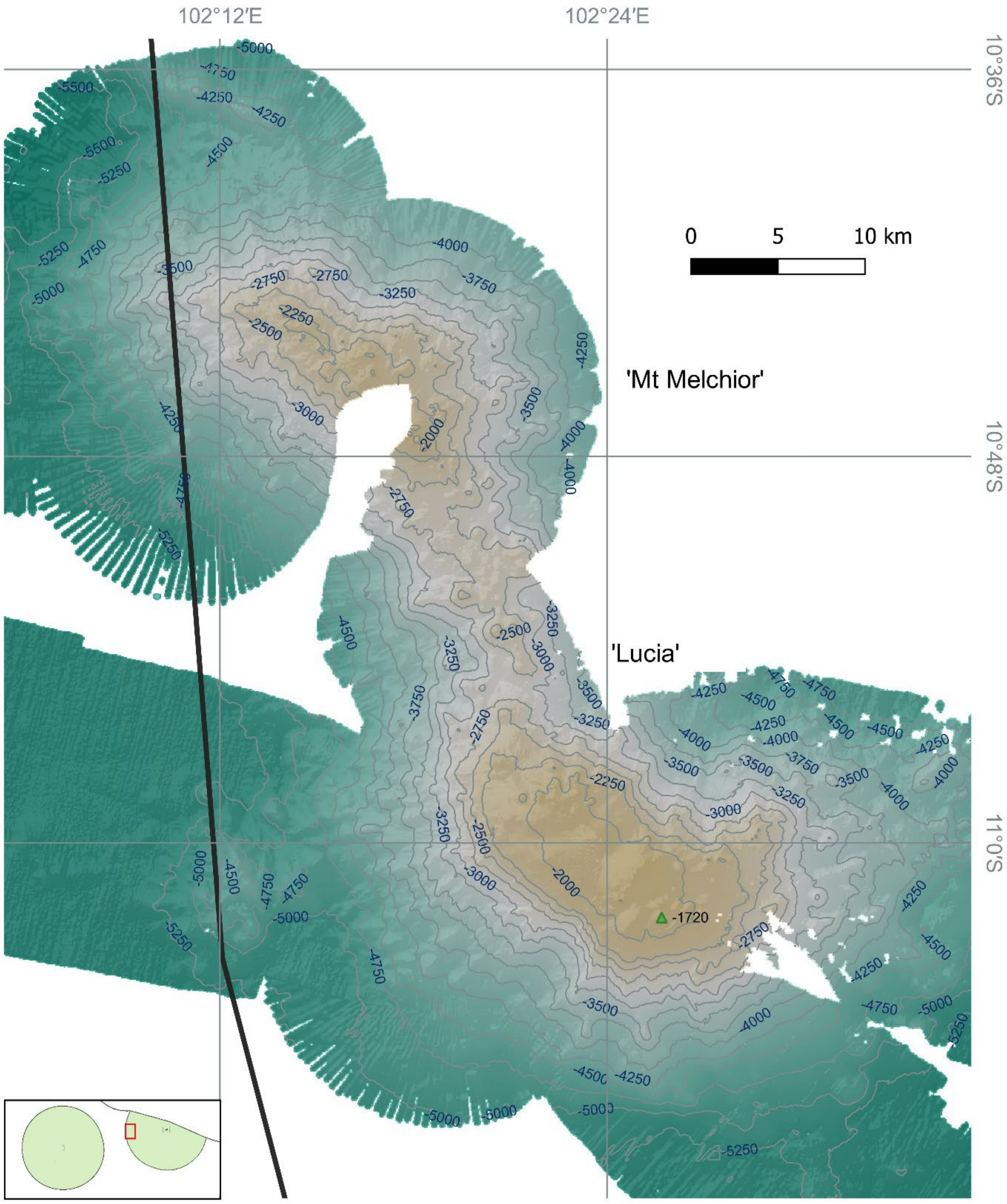

Figure 20. Bathymetric map of the Flyingfish seamount cluster, including 'Lucia' and 'Mt Melchior', compiled from multibeam data from the IN2022_V08 and SO199 expeditions.

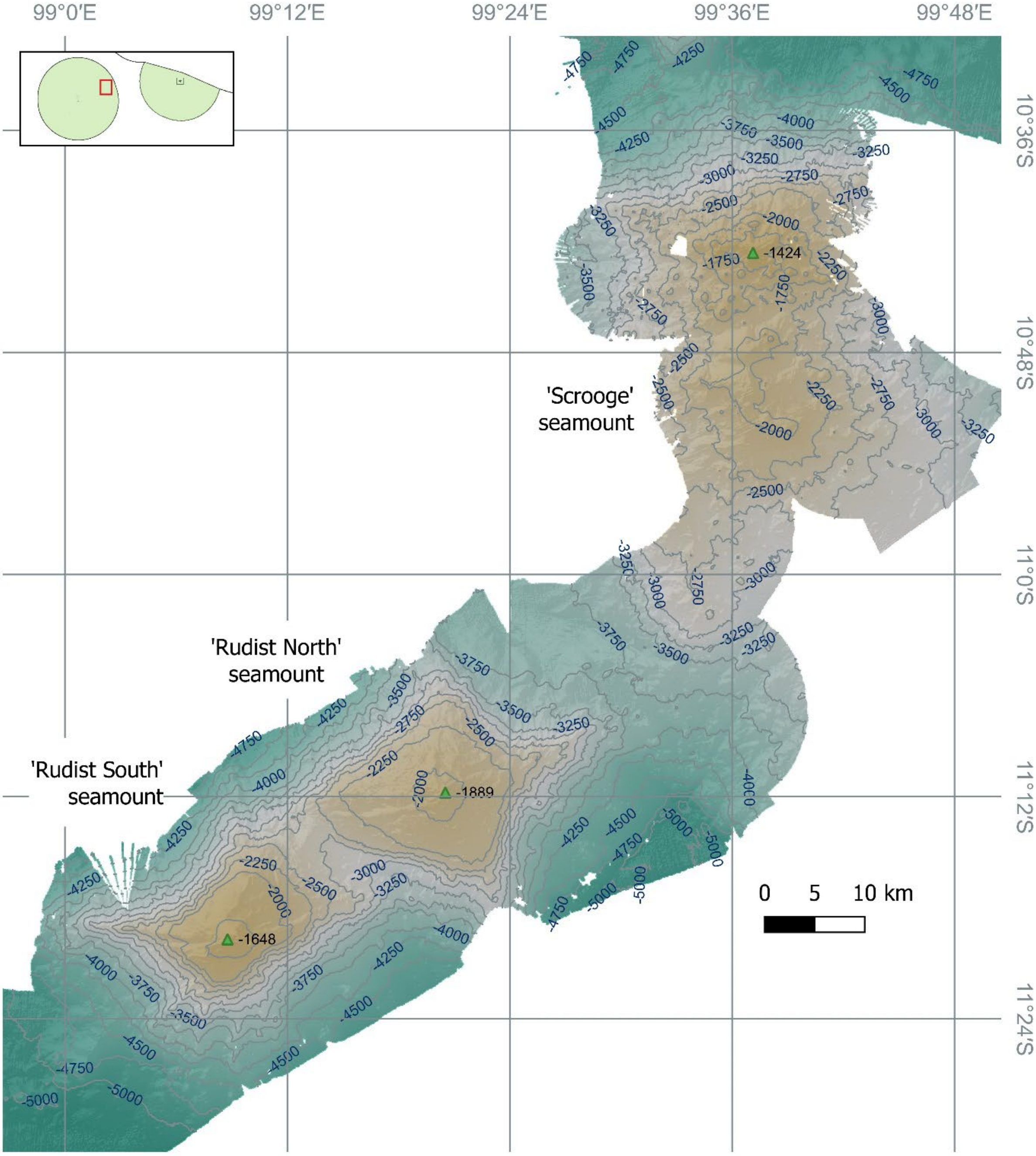

Figure 21. Bathymetric map of the Vening Meinesz Rise, including 'Scrooge' and 'Rudist' seamounts, compiled from multibeam data from the IN2022_V08 and SO199 expeditions.

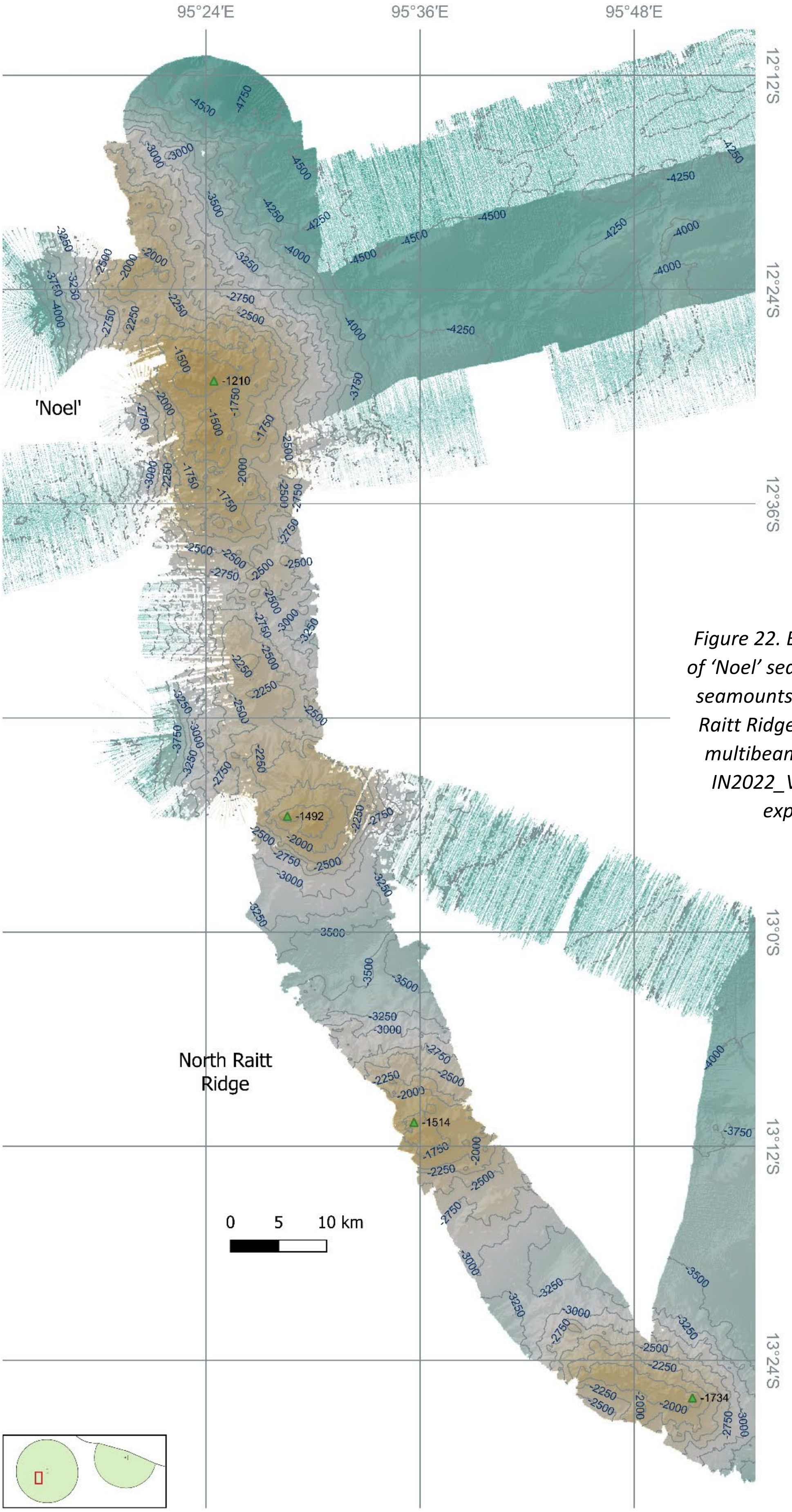

Figure 22. Bathymetric map of 'Noel' seamount and other seamounts on the northern Raitt Ridge, compiled from multibeam data from the IN2022_V08 and SO199 expeditions.

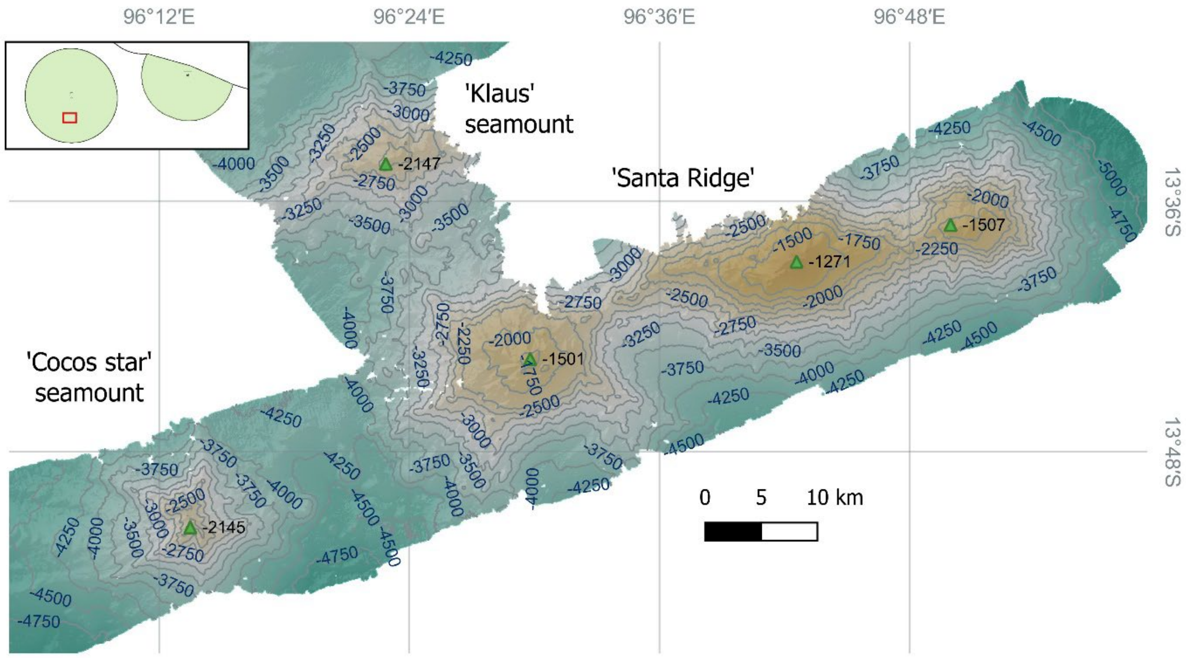

Figure 23. Bathymetric map of seamounts on and near the 'Santa Ridge' to the SE of Muirfield, compiled from multibeam data from the IN2022_V08 and SO199 expeditions.

4.2.3. Lower bathyal reef and sediments (1900-3500 m)

There are numerous seamounts that summit in 1900-3500 m spread around both Indian Ocean Territories Marine Parks. Some have flat or gently convex summits (e.g. 'Ulrike', Fig. 24; 'Erid Lithui', Figs. 25-27; 'Clara Marie', Fig. 28) indicating that they may have once been above water [5], however, they can also be covered in smaller volcanic cones (e.g. Fig. 28), which may have formed during later phases of volcanism [3]. Other seamounts have sharp peaks (e.g. 'Barad-dûr' in Fig. 25) and may never have been emergent [5]. There is a large caldera unofficially named 'Eye of Sauron' (Fig. 26-27) in the Karma cluster of seamounts, and a conical volcano-shaped feature in the SW of the Cocos (Keeling) Is MP (Fig. 30). Steep flanks are likely to have exposed rocky surfaces, and flatter surfaces (including the summits and extinct volcano craters) will be covered in sediment (Fig. 32). A video tow from the SO199 expedition showed a muddy substratum on 'Max' at 2740 m [3].

Rocks obtained from the lower sides of seamounts across the IOT have been generally basaltic in origin, often with a thin manganese crust [3]. The Karma seamount cluster (SE of Christmas Island) contains some of the oldest seamounts in the IOT [2]. The central section of the Investigator Ridge also contains several elevated peaks as shallow as 2700 m (Fig. 3) [3]. The steep sides of the Ridge, and especially the western side, are probably covered in exposed rock.

The main water mass at lower bathyal depths is Indian Deep Water (temperature 2°C, salinity 35.85, oxygen 4.7 ml/l), which is an extension of North Atlantic Deep Water mixed with upwelled Antarctic Bottom Water [18]. It flows northwards along the Ninety-East Ridge (to the west of the Cocos (Keeling) Is MP). Some southward movement across the IOT is possible, to compensate for the northerly water flows further west [18].

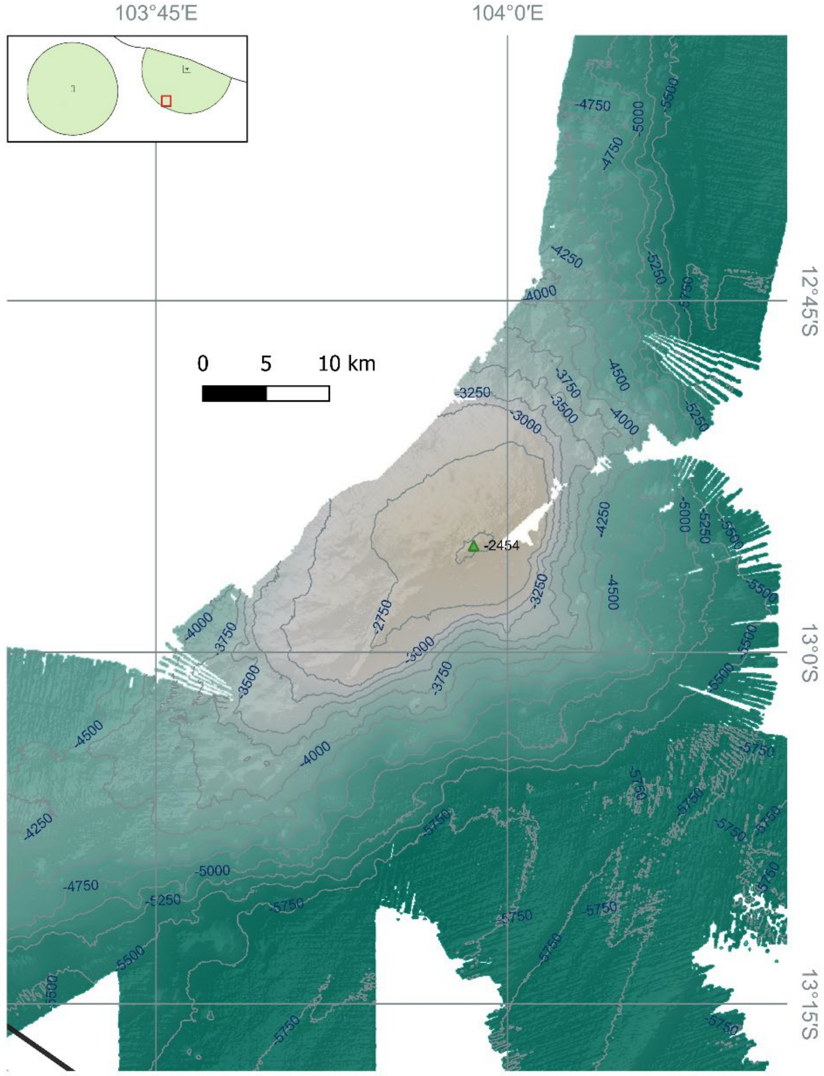

Figure 24. Bathymetric map of the 'Ulrike' seamount, compiled from multibeam data from the IN2021_V04 and SO199 expeditions.

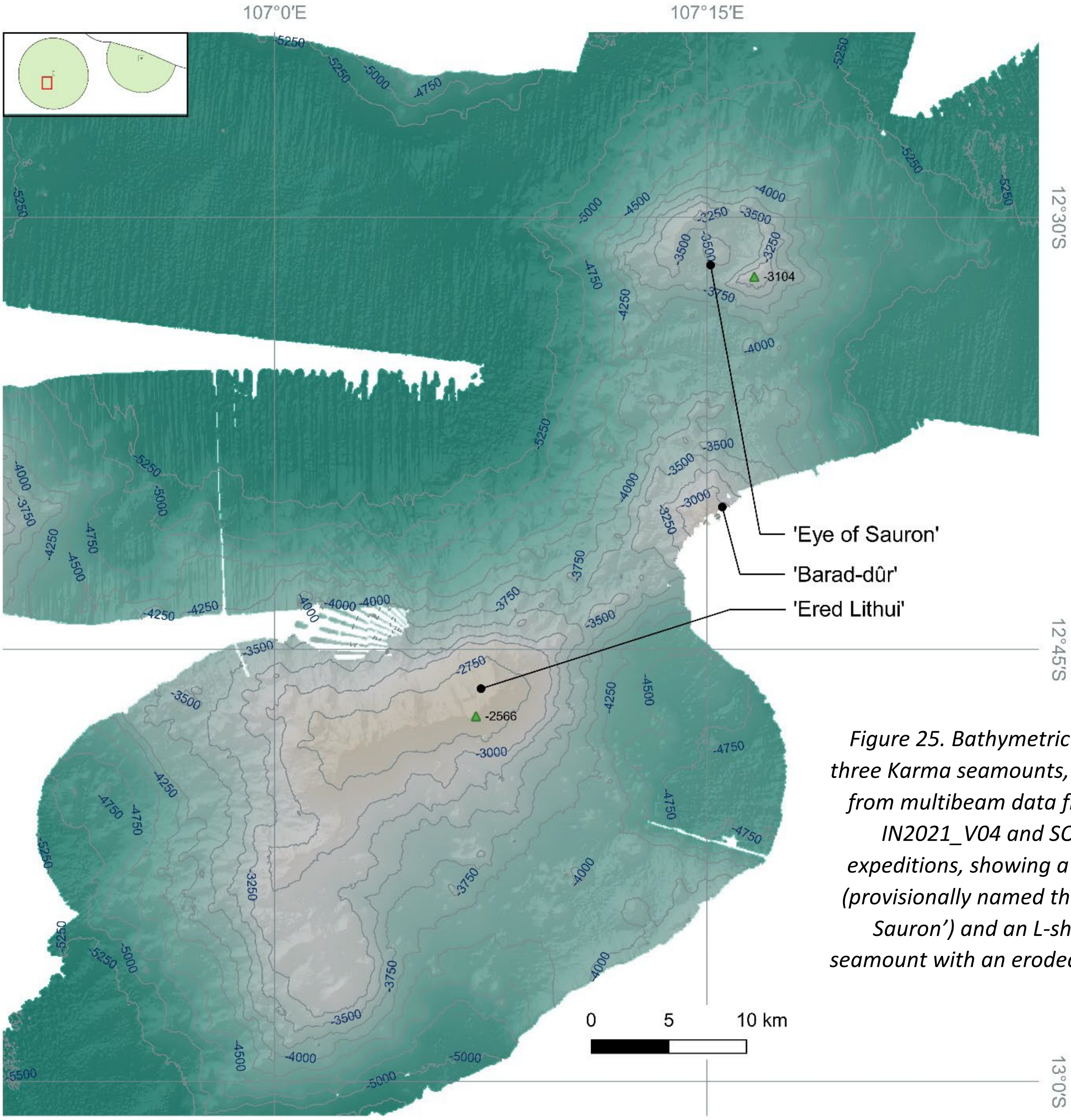

Figure 25. Bathymetric map of three Karma seamounts, compiled from multibeam data from the IN2021_V04 and SO199 expeditions, showing a caldera (provisionally named the 'Eye of Sauron') and an L-shaped seamount with an eroded summit.

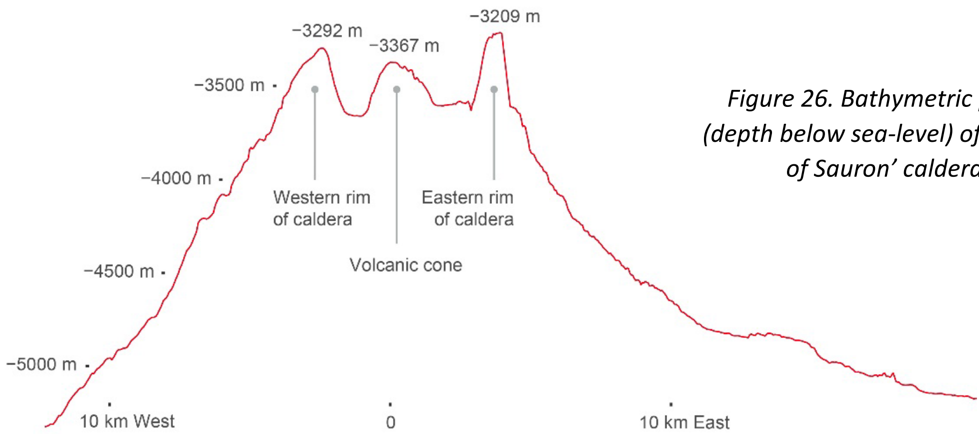

Figure 26. Bathymetric profile (depth below sea-level) of the 'Eye of Sauron' caldera.

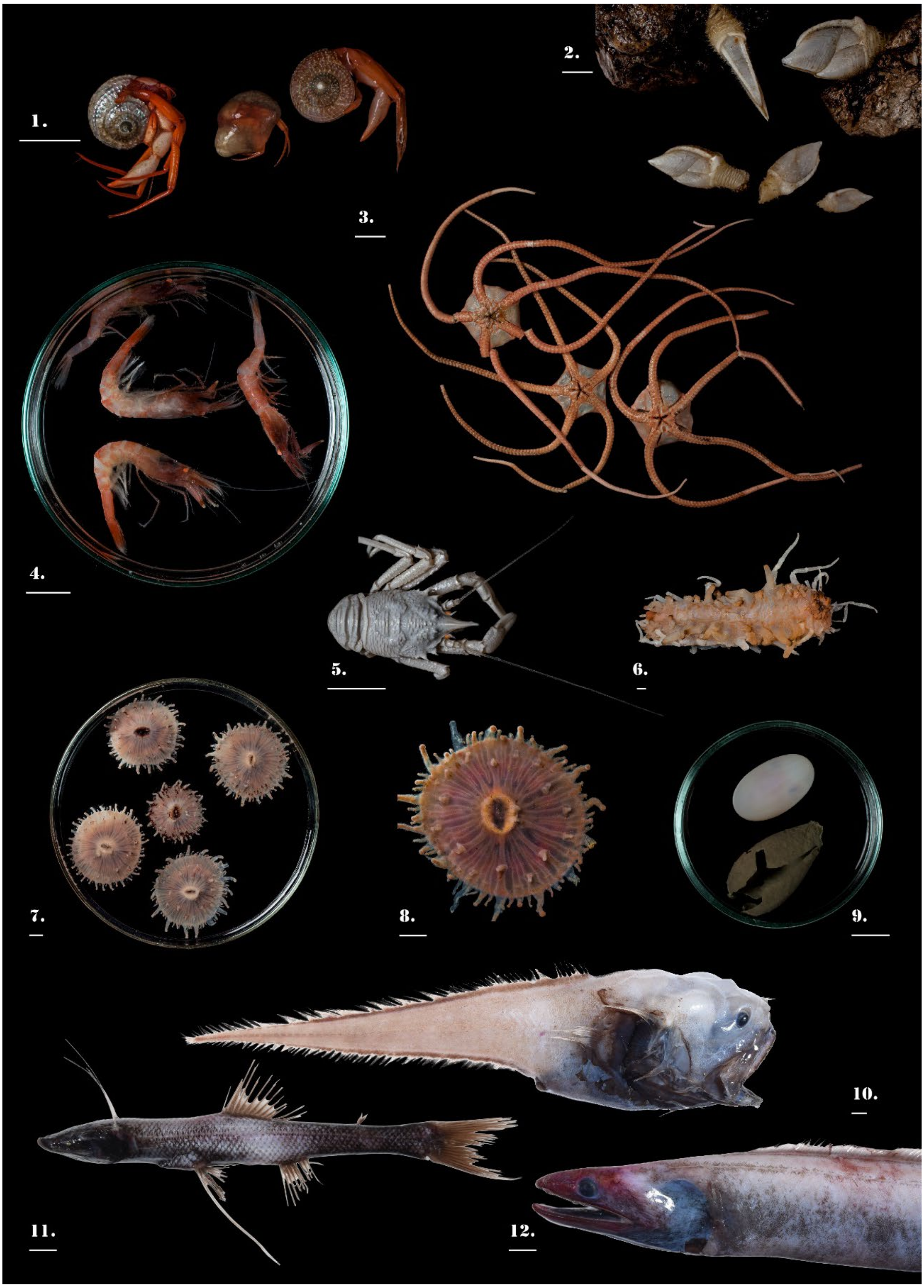

Figure 27. Selected animals from 'Max' and 'Ered Lithui' seamounts collected by the IN2021_V04 expedition. (1) Parapaguridae hermit crabs ('Max'). (2) Arcoscalpellum *barnacles ('Max'). (3) The ophiuroid* Bathypectinura heros *('Max'). (4) Crangonidae shrimps ('Max'). (5)* Munidopsis *squat lobster ('Ered Lithui'). (6)* Orphnurgus *cf* glaber *holothurian ('Ered Lithui'). (7-8)* Corallimorpharia *zooanthids ('Max'). (9) Cirrate octopod egg ('Max'). (10)* Acanthonus armatus *bony-eared assfish ('Ered Lithui'). (11)* Bathypterois *tripod fish ('Max'). (12)* Histiobranchus *sp. cut-throat eel ('Ered Lithui'). Scale bar under figure numbering = 10 mm.*

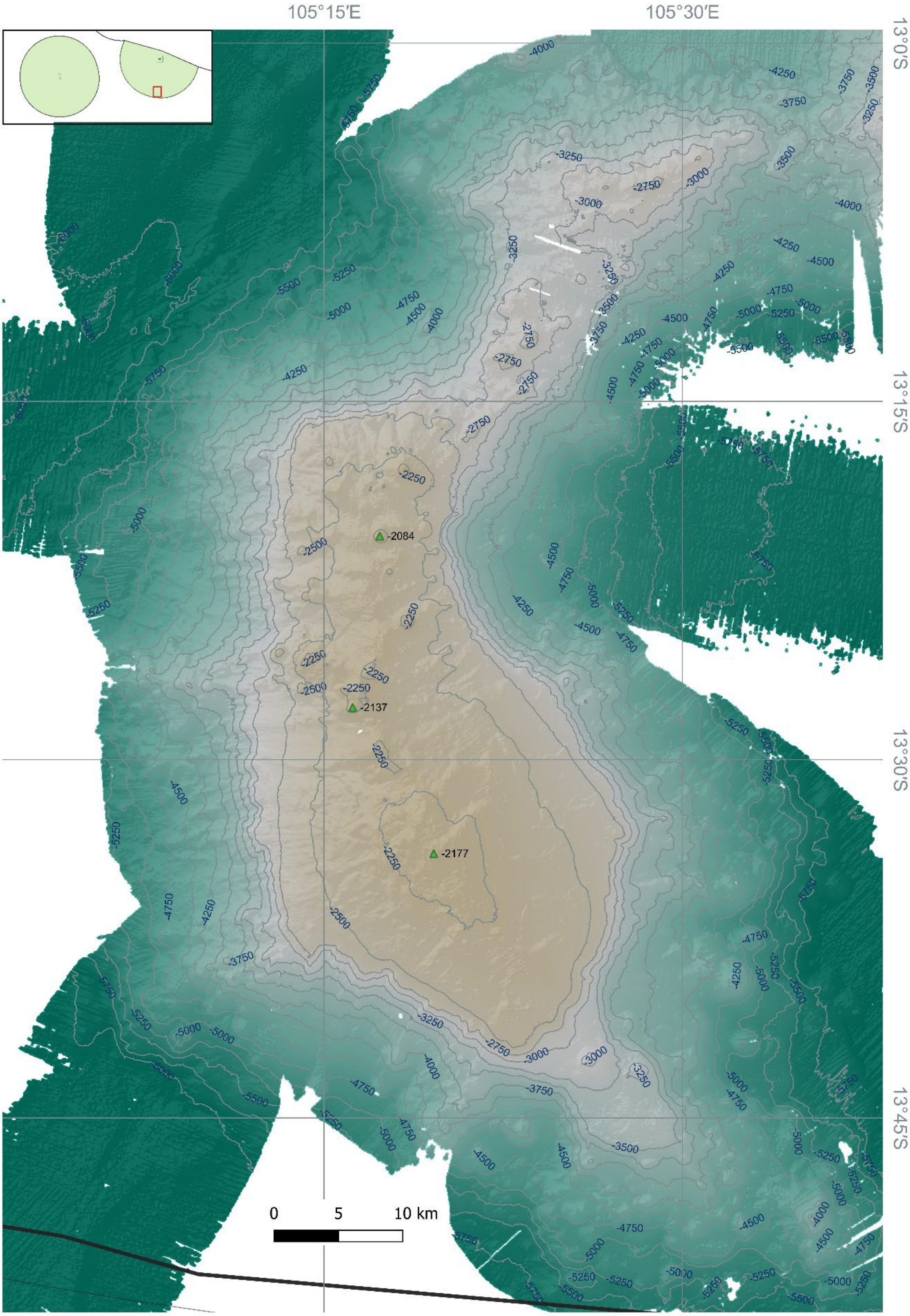

Figure 28. Bathymetric map of the 'Clara Marie' seamount, compiled from multibeam data from the IN2021_V04 and SO199 expeditions showing an elongated guyot with an eroded southern summit and the northern section dotted with small volcanic cones.

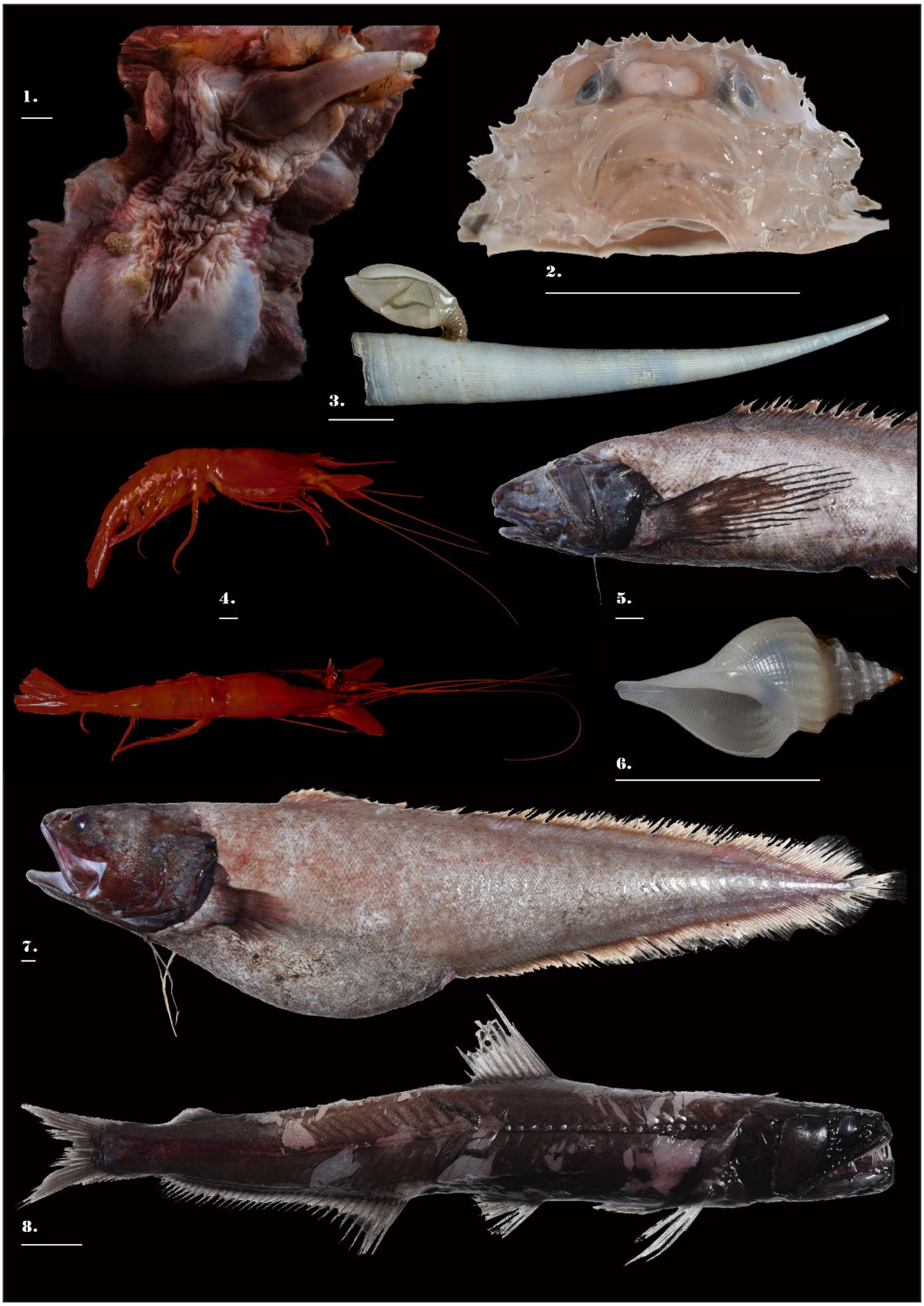

Figure 29. Animal examples from the 'Clara Marie' seamount collected by the IN2021_V04 expedition. (1) Psychropotes *holothurian. (2)* Halieutopsis *anglerfish. (3)* Teloscalpellum *barnacles on scaphopod mollusc. (4)* Cerataspis monstrosus deep-sea shrimp*. (5)* Holcomycteronus *cuskeel. (6)* Austrobela *gastropod. (7)* Spectrunculus *cuskeel. (8)* Odontostomops normalops *sabretooth fish. Scale bar under numbering = 10 mm.*

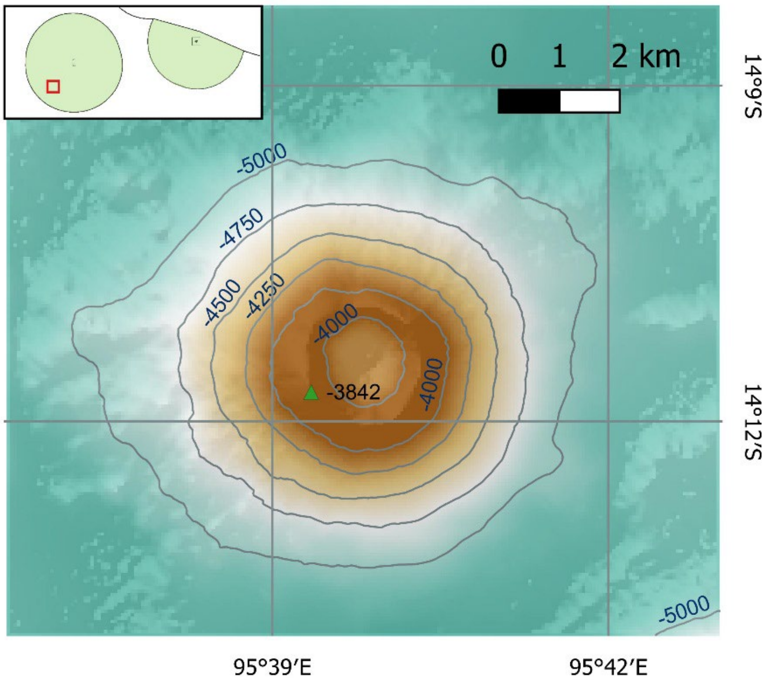

Figure 30. Bathymetric map of a conical volcano shaped structure in the SW Cocos (Keeling) Is MP, compiled from multibeam data from the IN2022_V08 expedition.

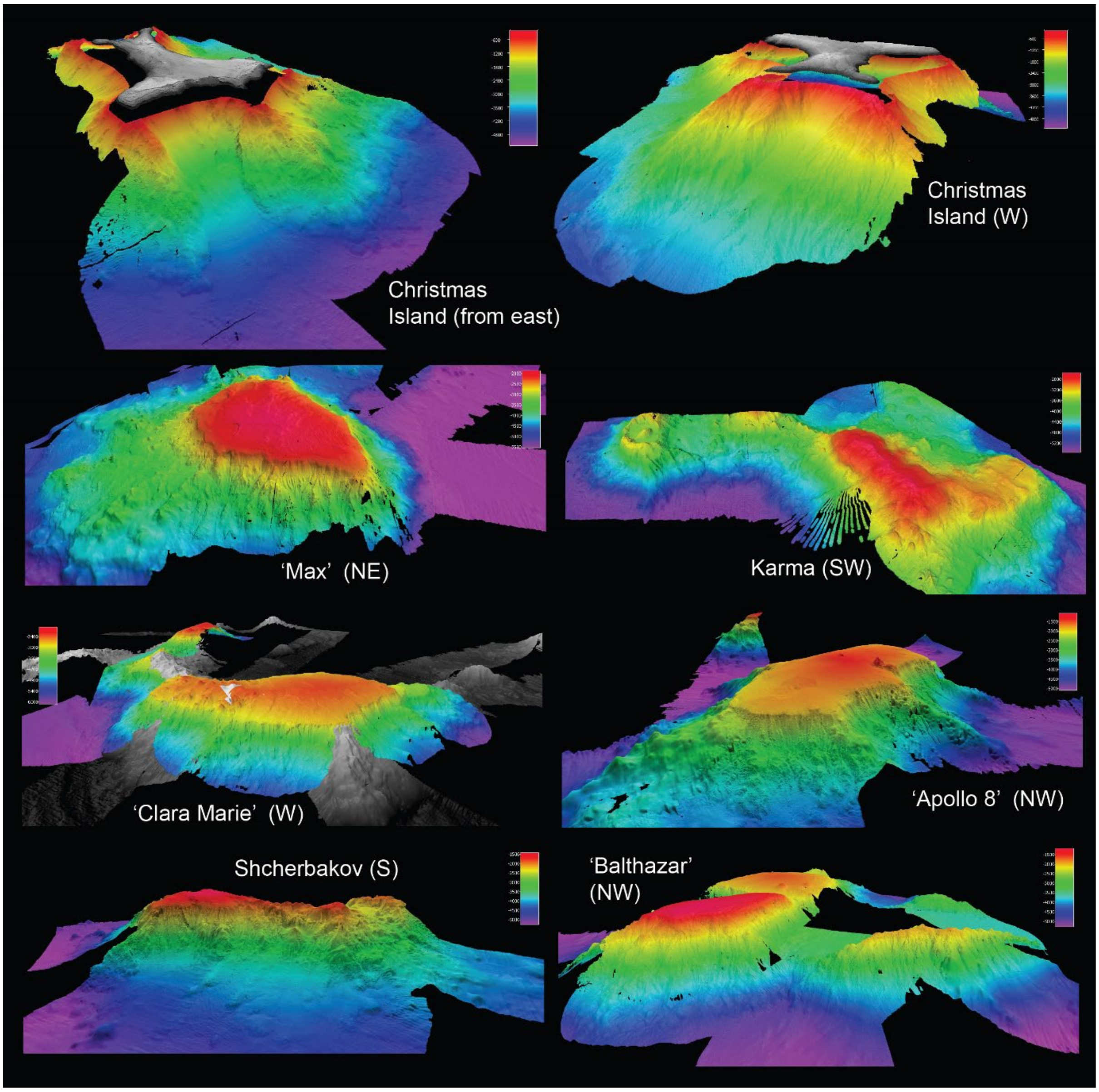

Figure 31A. 3d terrain representations of seamounts from the Christmas Island MP derived from IN2021_V04 expedition multibeam data. Images: GSM/CSIRO

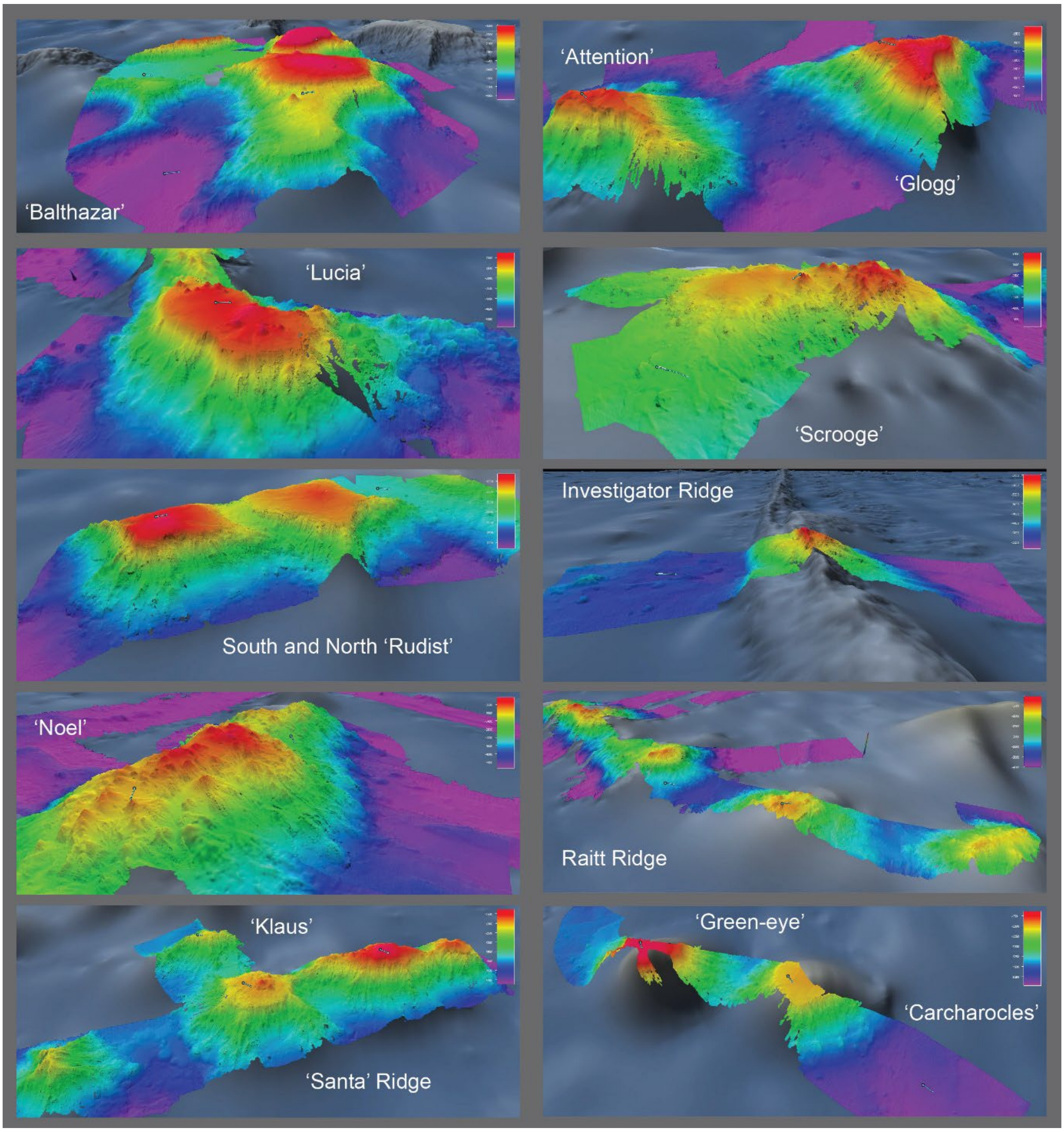

Figure 31B. 3d terrain representations of seamounts from the Christmas Island and Cocos (Keeling) Islands MPs derived from IN2022_V08 expedition multibeam data (colour) overlain on GEBCO 2022 modelled bathymetry data (in grey). All orientations are from the south. 2.5x vertical exaggeration. Images: GSM/CSIRO

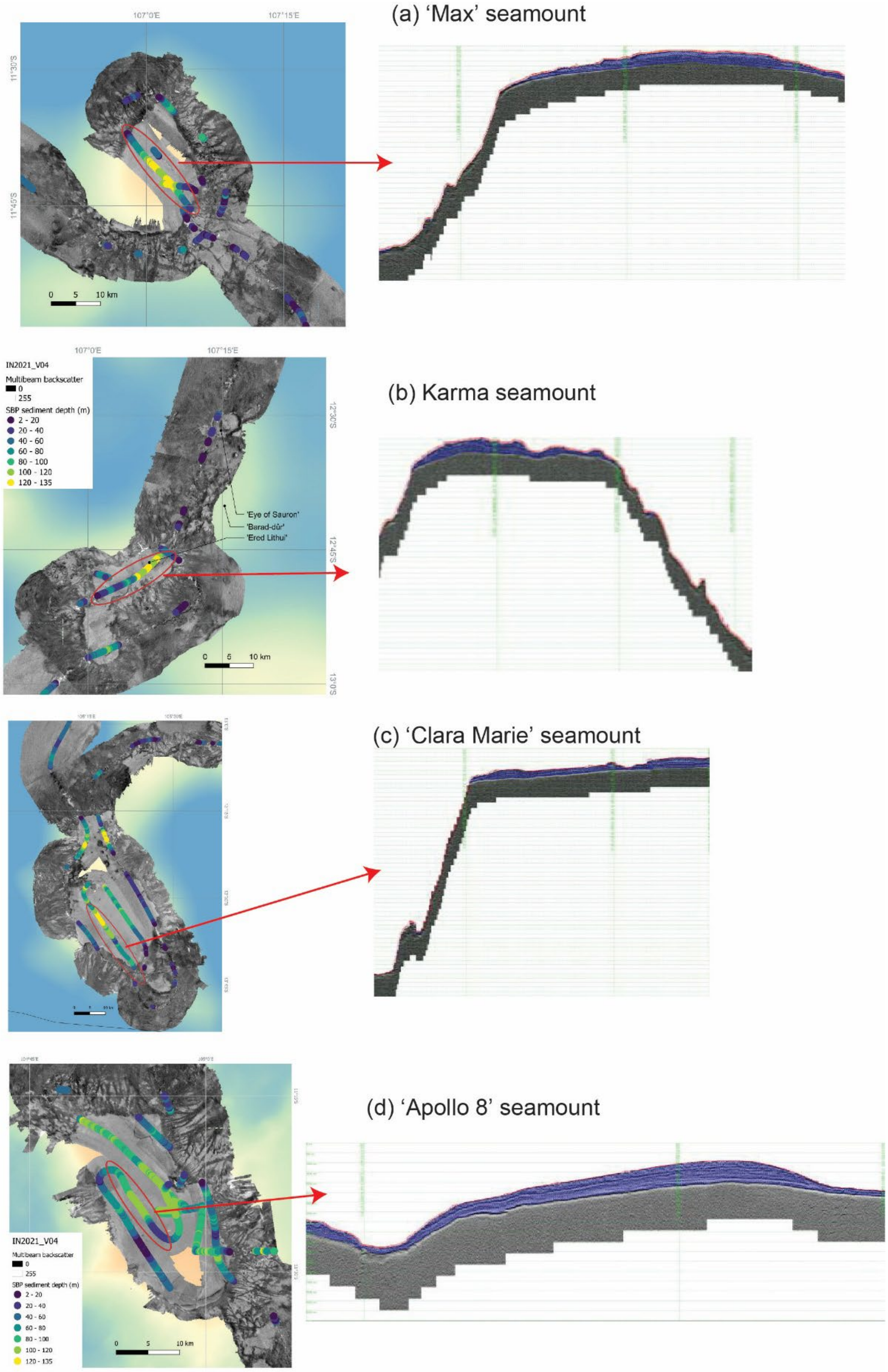

Figure 32. Sub-bottom profiles across selected seamounts in the Christmas Island Marine Park. The maps on the left show grey-scale multibeam backscatter data (black = relative hard, white = relative soft substrata) superimposed with coloured dots indicating the approximate depth of sediment. The sub-bottom profile of the transect within the red ellipses is shown on the right, with blue indicating depth of detectable sediment. Profile images GSM/CSIRO, maps MV.

4.3 Abyssal (3500-6000 m) and hadal (>6000 m) reef and sediments

A thick layer of sedimentation will cover most abyssal and hadal seafloor habitats. Sediment thickness (measured using cores) is greatest near the Sunda Trench along the northern boundary of the Christmas Is MP (~435 m) [13] and least to the W of Cocos (Keeling) Is MP (~154 m) [12] due to the decline in surface productivity. The sediment is generally compacted into clays/oozes, with calcareous sediments being replaced by siliceous ones below 3800 m [10]. Another measurement of sediment depth comes from ship-board sub-bottom profiling, which illustrates the deepest detectable sediment horizon. On the IN2021_V04 expedition, sub bottom profiling measured sediment thickness up to ~200 m thick on the abyssal plains (Fig. 32c).

Oceanic depths below 6000 m are referred to as the hadal zone and animals require special adaptations to survive the extreme pressures, cold and lack of organic matter [41]. The deep seafloor (below 6000 m, as measured by satellite) of the Indian Ocean Territories total 12,834 km^2 in area and represent 93.2% of this depth zone across the Australian EEZ [14]. Satellite gravity measurements appeared to show that the IOT has some hadal seafloor troughs to the east of Christmas Island, to the NE of the 'Clara Marie' seamount, and to the SE and SW of the Cocos (Keeling) Is MP (Fig. 3). However, multibeam data from the IN2021_V04 expedition shows that the very deep areas east of Christmas Island (Fig. 33) and around the Clara Marie seamount to the south (Fig. 28), are better characterised as an abyssal-plain dissected by abyssal hills. The deep areas in the Cocos (Keeling) Is MP have not been similarly explored. The deepest point measured by the IN2021_V04 expedition east of Christmas Island was 6252 m (10˚30.32'S, 105˚53.76'E). The deepest point SE of the 'Clara Marie' seamount as measured by the SO199 expedition was 6256 m (13˚43.57'S, 105˚4.39'E). No biological samples are available from these hadal depths.

Multibeam sonar has revealed numerous abyssal hills across the IOT. At least some of these appear from sub-bottom profiling data to have exposed rocky substrata, including abyssal ridges to the east of Christmas Island (Fig. 32c). Studies elsewhere have shown that even if sediment covers the abyssal hills (and the aprons around seamounts), it generally has a greater gravel or boulder content, which in turn alters epibenthic community composition [39]. A comparison of ridges, plains and troughs in the Clarion-Clipperton Zone (NE Pacific, 3950-4250 m) found that although the nutrient content of the sediment was the same, the benthic assemblages in the troughs were different, in this case because of the increased density of manganese nodules [40].

Manganese nodules are known to occur at abyssal depths (4780 to 5888 m) to the SW of the Christmas Is MP, where they are most abundant in areas between seamounts [10]. The presence of nodules in the Cocos (Keeling) Is MP has not been quantitatively assessed [10]. Nodules form very slowly on the seafloor from a number of geochemical processes. Nodules influence the composition of the benthos as they provide hard substratum on a mainly sedimentary seafloor. The density of nodules will also affect community composition and biomass [38].

The ecology of the abyssal seafloor depends almost entirely on the downward flux of organic detritus from the productive surface waters. The gradient of net primary productivity from a high in the north of the Christmas Is MP to a low to the SW of Cocos (Keeling) Is MP (Fig. 4) will influence biomass and diversity of the benthic organisms. Antarctic Bottom Water temperature (1.1°C, salinity 34.7) slowly moves northwards across the Wharton Basin, although the strongest flows are west of the IOT along the eastern side of the Ninety-East Ridge, and gradually upwells into the Indian Deep Water [18]. There is little variation across the IOT at abyssal depths in temperature, salinity or oxygen [18]. However, we can expect some differences in abyssal-hadal benthic communities across the IOT based on differences in net primary productivity of overlying waters and proximity to the extensive Sunda Trench in Indonesia.

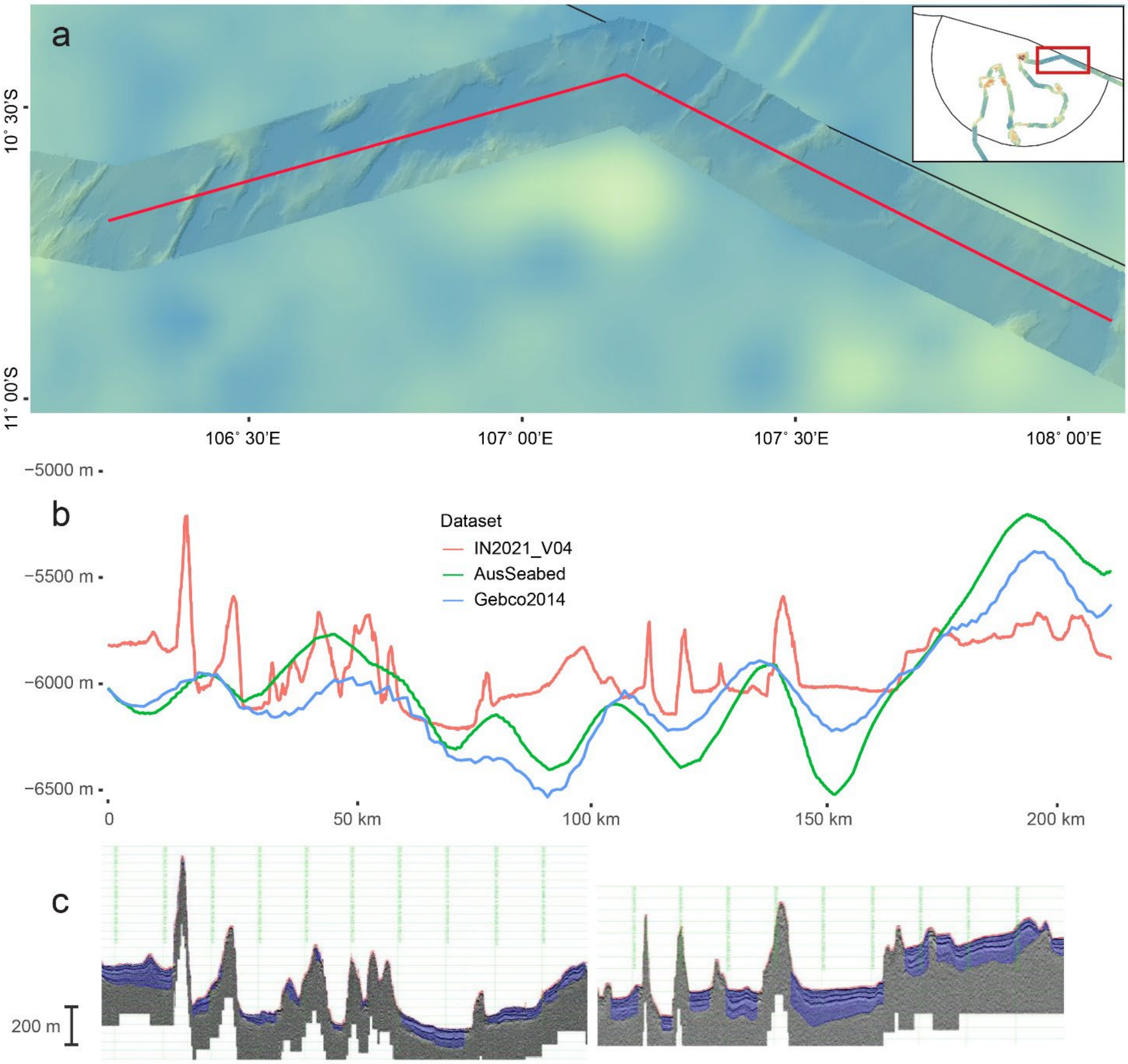

Figure 33. Transect of the IN2021_V04 voyage across the abyssal-hadal plain east of Christmas Island. (a) Multibeam bathymetry. (b) Profile of multibeam bathymetry (along red track in (a)) showing the considerable difference between the predicted seafloor bathymetry from satellite gravity measurements of the GEBCO 2014 and AusSeaBed datasets and the vessel based multibeam data. (c) Sub-bottom profiles showing the varying depth of the sedimentary layer (purple) on the plain and the abyssal hills (GSM/CSIRO).

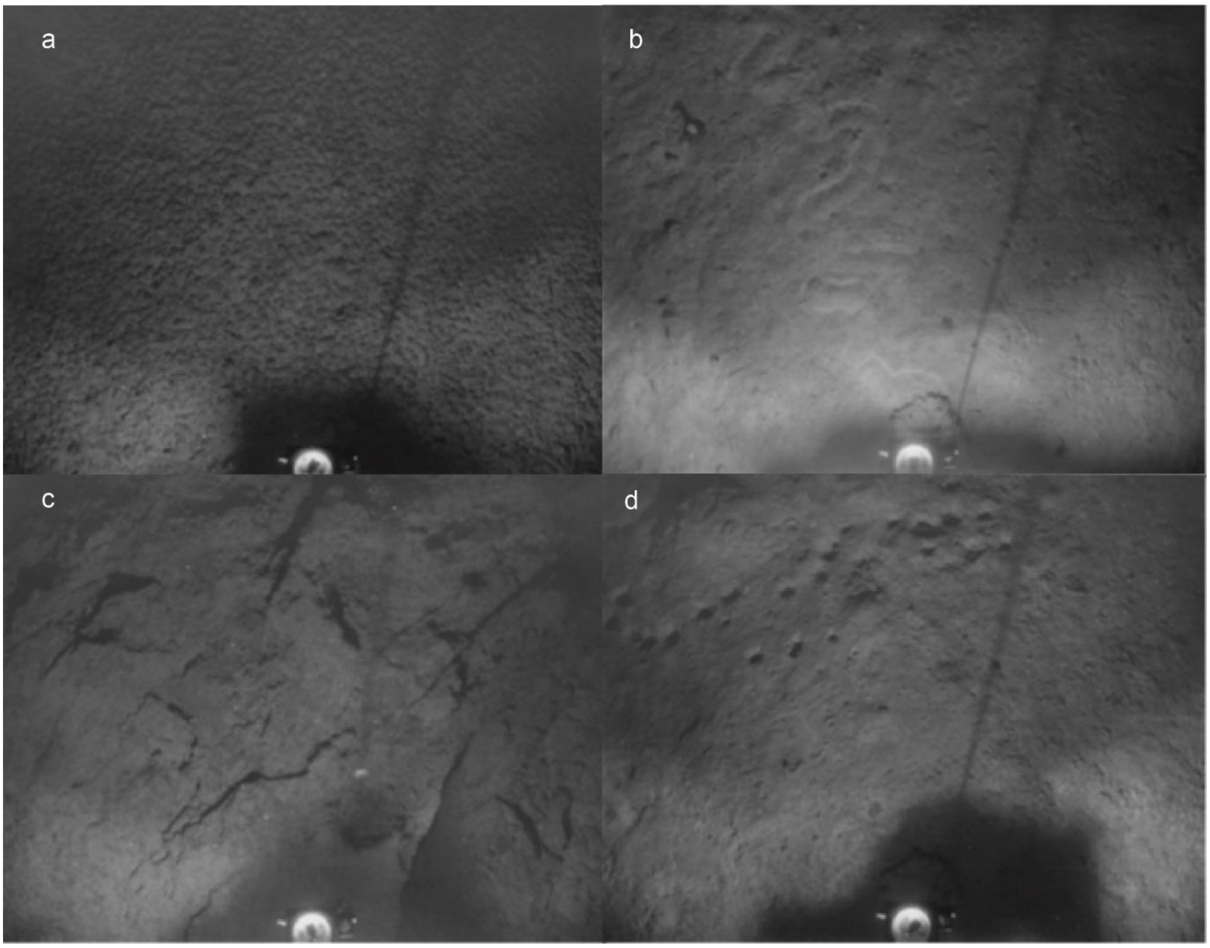

Figure 34. Photographs of benthic habitat showing (a) manganese nodules, (b) rock, and (c-d) soft sediment, at locations (a-b) VM33-005 (?2982 m, south Christmas Is MP) and (c-d) VM33-006 (3175 m, north Christmas Is MP), from Brewer et al (2009).

4.4. Comparison with the bioregionalisation in Brewer et al. (2009)

Brewer et al. [14] divide the IOT into seven bioregions, four in the Cocos (Keeling) Is MP and three in the Christmas Is MP. As biological data were lacking, the bioregionalsiation was based on a qualitative assessment of the geology and oceanography of the area. The seven bioregions are more or less placed east to west and so do capture the surface productivity gradient and predominant current flow of the IOT.

The area and boundaries of each of the Brewer bioregions reflect seafloor geomorphology, in particular the density and height of seamounts: 1) Wharton Basin has a sparse covering of deep old seamounts, 2) Christmas Central Ridge has a dense assemblage of seamounts on an 'uplifted block' , 3) Cocos Basin has relatively few seamounts and is mostly abyssal plain, 4) East Cocos Abyssal Plain is similar to the Cocos Basin but located in the Cocos (Keeling) Is MP, 5) Investigator Ridge includes a abyssal ridge and associated troughs, 6) Cocos Volcanic Field has a relatively dense covering of more recent seamounts, and 7) Western Cocos Abyssal Plain includes only abyssal habitat and has no seamounts of any size.

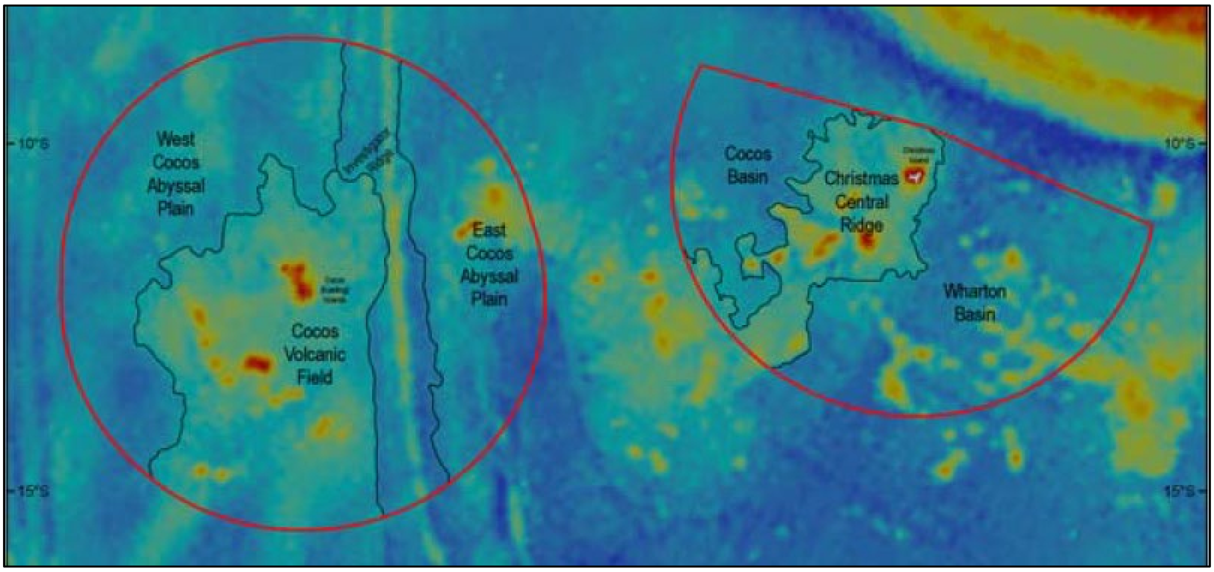

Figure 35. IOT bioregionalisation proposed by Brewer et al. [14].

The Brewer et al. report was written before the main geological findings of the Sonne SO199 expedition were published. Hoernle et al. [2] categorised the IOT seamounts into three volcanic provinces of different ages (Fig. 1) that have different boundaries than the Brewer bioregions. Their Vening Meinesz province extends from Christmas Island to the Investigator Ridge, thus includes Brewer's Christmas, Cocos Basin and East Cocos bioregions. The raised seafloor in the Christmas Central Ridge and Cocos Volcanic Field has also been interpreted differently, the former as a flexural bulge and the latter as a magma hotspot [5]. Moreover, seamounts are also surrounded by volcanic debris, sedimentary aprons and larva flows, which can be consolidated into single rise-like systems if the seamounts are close enough together.

While the use of geomorphology is intuitive from a landscape perspective, the sub-region boundaries of the Brewer classification are unlikely to reflect faunal distribution and diversity, as the fauna would be unlikely to differ on either side of the boundaries at similar depths.

5. The biogeographical significance of the area

The remoteness and location of the IOT, south-west of Indonesia in the eastern Indian Ocean, makes it unique within the Australian marine domain. The biogeography of the IOT benthic fauna is likely to be complex and differ between depth layers.

5.1. Shallow and mesophotic depths (0-200 m)

Surface waters of the IOT are part of the great Indo-West Pacific biogeographic province that stretches all the way from Africa to Easter Island. However, there is regional differentiation of fauna within the province. The islands of the IOT contain a mixture of species. Most are from 1) the Indonesian-N. Australian Archipelago (IAA) or coral triangle which contain the richest marine habitats on the planet, with some characteristic of 2) the western-northern Indian Ocean. The Cocos (Keeling) Islands are the westernmost distribution for many IAA species [42]. Sometimes both IAA and Indian Ocean species co-occur, especially around Christmas Island, leading to hybrids [43, 44]. The main (modern) migration routes for shallow water species would be via the South Equatorial Current from eastern Indonesia, or from the Indian Ocean coast of Sumatra via the South Java Current in summer [14]. For example, the seagrass (*Thalassia hemprichii*) appears to be genetically closer to populations in Eastern Indonesia than NW Australia or the Lesser Sunda Islands [45].

Our knowledge of the IOT's biogeography is likely to increase significantly as DNA is used to resolve the distribution of cryptic species (species that look very similar). For example, there are at least four Crown-Of-Thorns Seastar species with distinct regional distributions [46]. While the population off NW Australia is the Pacific species [46], the one at Christmas Island is the southernmost occurrence of a north Indian Ocean species, and the one at Cocos is the easternmost occurrence of a SW Indian Ocean species that also occurs at Chagos in the central Indian Ocean [47]. For fish, while Pacific and Indian Ocean sister species often overlap at Christmas Island, Cocos Islands can have both species [48] or just the Indian Ocean species [49, 50].

The remoteness of the islands has prevented many shallow water species from colonising from surrounding regions. For example, 160 coral species known from NW Australia are missing from Christmas Island but only eight species are known from Christmas Island but not Western Australia [51]. The fish fauna is described as a slightly impoverished Indo-Malay fauna with some notable absences [43, 52]. Equally, there are 50 fish species that do not occur elsewhere in Australia [14]. The species that do occur there tend to have pelagic adult or larval stages that can disperse over long distances [42]. Some species may have also arrived by rafting on debris or seaweeds.

The number of known endemic species is low, for example only 4 of 622 fish species are endemic to Christmas Island, and another three are shared with Cocos Islands [53]. Of the 602 fish currently recorded from the Cocos Islands, there are no endemic species [54]. There are five undescribed/unidentified coral species on Cocos that may turn out to be endemic or more widespread [55]. There are several mollusc populations from the IOT whose DNA differs from populations elsewhere and may be endemic species [56]. Endemic invertebrates have also been reported from marine and anchialine caves on Christmas Island [57-59] but other cave species have been found to be widespread, such as the patterned goby *Trimma fasciatum* [60]. The shallow water fauna on the Muirfield seamount is unknown [9].

Little is known about community composition at mesophotic depths.

5.2. Bathyal, abyssal and hadal depths (200-6300 m)

The bathyal and abyssal fauna of the IOT is poorly known. Although samples of seafloor fauna were collected on the IN2021_V04 expedition, most of the specimens (except the brittle-stars and some fish) have not been identified with precision and no DNA results are yet available. Our best alternative is to rely on knowledge from elsewhere, in particular from Indonesia and NW Australia, as a biogeographical surrogate.

It is likely that the upper to mid bathyal (200-1900 m) fauna of the IOT is related to similar faunas elsewhere in the Indo-West Pacific region [25, 61]. This fauna is ancient, its high diversity related to its age rather than bursts of more recent speciation [25]. It is likely to have been a long term refuge for marine lineages, avoiding the glacial/interglacial temperature and sea-level fluctuations of shallow water, and the periodic anoxic conditions of the abyss [25].

Biogeographies of the deep-sea fauna have tended to view the Indian Ocean as a single unit [62]. However, as in shallow water, DNA analyses have indicated that the enormous distances between suitable upper bathyal habitat across the central-southern Indian Ocean can act as an biogeographic barrier with cryptic species divided into eastern and western lineages [63]. The potential for deep-water species to migrate between the Pacific and Indian Oceans may have also decreased over time. Australia/Papua New Guinea collided with Indonesia 25-17 million years ago, cutting off the deep water inter-oceanic connection [64]. Indonesian Through-Flow water now has to rise over sills as shallow as 600 m depth. The implication is that, unless they can survive conditions south of Australia or their pelagic stages can vertically migrate over the Indonesian sills, Pacific Ocean deep-sea species may have been isolated from their Indian Ocean counterparts for tens of millions of years. Thus we can speculate that upper bathyal populations in the IOT will be evolutionarily distinct from those in the Pacific Ocean and those in the western Indian Ocean.

The IOT lies at the boundary of the northward flowing Antarctic Intermediate Water, and the mid-bathyal fauna may reflect this and have components that are related to southern Indian Ocean faunas.

The amount of available mid-ocean habitat increases with depth. The SW, SE and Central Indian Ocean Ridges radiate out from the Rodrigues triple junction like spokes across the Indian Ocean, providing habitat typically as shallow as 2500 m deep. Other volcanic or tectonic features occur as ridges, plateaus or seamounts scattered across the ocean. Thus it becomes more feasible for lower bathyal (1900-3500 m) animals to migrate horizontally across the Indian Ocean and we would expect less regional differentiation. There will still be dispersal barriers for some species, as the ridges are not always continuous and can be intersected by strong currents or other oceanographic barriers [65]. Although hydrothermal vent animals at this depth generally have good dispersal abilities, they too can have distribution limits or regional population structure [66]. Conversely, the animals of the abyssal basins and hadal trenches may experience the ridges as a dispersal barrier, although these barriers are likely to only reduce rather than prevent cross-ridge dispersal [67, 68]. The extreme oligotrophic conditions at the centre of the Southern Indian Ocean Gyre maybe a resource limitation for many benthic species, although this would not prevent migration around its periphery. The predominant flow across the IOT at mid bathyal to abyssal depths appears to be from the south, and latitudinal temperature gradients are minor, so we can expect some relationship of IOT and SE Indian Ocean faunas at these depths.

The 46 species of brittle-stars identified from the IN2021_V04 expedition are largely distributed elsewhere at tropical Indo-Pacific latitudes. This is particularly true of the fauna above 1900 m. However, DNA evidence is required to ascertain whether these populations are more similar to other Pacific or Indian Ocean populations. The lower bathyal and abyssal fauna are often widely spread, including the circum-global species (or species complexes) *Bathypectinura heros*, *Ophiomusa lymani*, *Ophiotypa simplex*, *Ophiuroglypha irrorata* and *Amphiophiura bullata* that also range into temperate latitudes off South Australia and New Zealand. In some cases (e.g. *Ophioplinthus* and *Stegophiura*), the species appear to be subtly distinct from the common Pacific Ocean form. Up to 10 species appear to be new to science and undescribed.

Of the 80 species of fish that were collected by the IN2021_V04 expedition, only 8 have been previously recorded before from the region. The new finds include the midwater Tube Eye (*Stylephorus chordates*) which is the first record of the taxonomic Order Stylephoriformes for Australian waters. Other likely new records are amongst the cuskeels, seabats, and halasaurs. The Andriashev's Seabat (*Halieutopsis andriashevi*) was previously only recorded from the Mascarene Islands in the Western Indian Ocean. The IN2022_V08 expedition discovered additional new species of fish including a deep-water blind-cusk-eel, and a green-eye that appears to be endemic to two seamounts in the SW of Cocos (Keeling) Is MP.

6. The ecological significance of the area

6.1. Shallow and mesophotic benthic biota (0-200 m)

The three shallow water features are ecologically unique within the IOT. Christmas Island is an emergent seamount, bounded by steep sides (except the occasional beach and caves), and a rim of coral growth.

The south Cocos group of islands is an atoll of low-lying sandy islands, with a shallow lagoon (including seagrass beds, a small area of mangroves, sand banks and coral reefs), and outer coral reefs (including an inner reef flat). North Keeling Island also has a shallow, largely closed, lagoon. There are no estuaries on any of the islands.

The southern atoll lagoon hosts Green and Hawksbill Turtles, which consume seagrass/algae and algae/sponge respectively [69]. Green turtles breed on both North Keeling and Christmas Island. Most of the green turtles foraging in the south Cocos lagoon appear to be from local breeding stock [70] although one tagged turtle originated at Ningaloo [71]. Five other tagged turtles only travelled on average 35.5 km (max. 66.5 km) after nesting at North Keeling [70]. The genetic diversity of nesting and foraging turtles is low compared to sites in NW Australia, with most sequenced green turtles belonging to widespread Indian Ocean or West Pacific lineages [72, 73]. Both the short foraging trips and low genetic diversity are indicative of an isolated population with the nearest alternative foraging area 1000s of km distant. The Hawksbill turtles also appear to be resident in South Cocos foraging grounds over multiple years at densities of 74-75 km^2 [74].

There is a high abundance (10 per Ha) of black-tip reef sharks (*Carcharhinus melanopterus*) and grey sharks (*C. amblyrhynchos*) in the lagoon at Cocos [75]. These animals are typically restricted to coastal habitats and bear live young [75]. There are numerous other fish and invertebrates typical of the reef and soft sediment habitats. Edible invertebrate species such as Beche-de-mer (*Holothuria* spp), giant clams (*Tridacna* spp), crabs, and Gong Gong gastropods (Common Spider Conch, *Lambis lambis*) are vulnerable to over-exploitation [75].

Muirfield is a submerged rocky seamount (summit at 17 m) with areas of exposed basalt, sparse coral cover, volcanic debris and coarse sand. While all three are in the path of the South Equatorial Current, the habitat nearest Indonesia (Christmas Island) experiences higher primary productivity and can be expected to support more abundant benthic and pelagic biota. The primary production over Muirfield may be even lower, as similar shallow seamounts elsewhere have been shown to have relatively low levels of dissolved particulate carbon [31].

Sometimes, the shallow water communities at Cocos and Christmas Islands have been described as slightly impoverished [52], however, for fish this has been attributed to the limited amount of reef area which is only 20 km^2 at Christmas and 110 km^2 at Cocos Islands [76], and coral species richness is similar to that at other offshore islands such as the Rowley Shoals [51].

There are fewer habitat types at Christmas Island, but the exposed nature of the coastline reduces dominance by a few common species and most species are rare [51]. Flying fish Cove was found to be the most sheltered and most diverse site for corals around the island [51]. The high diversity is around 20 m, below damaging waves but above the mesophotic zone [77]. The very exposed south coast is dominated by soft corals [51].

Each of these shallow water environments is also unique because of their isolation. Firstly, their biological communities have been assembled from long distance dispersal and so are biased to species that have reasonable dispersal capabilities [76]. Long distance dispersal always involves a degree of randomness and so every assemblage tends to be different. Five of the 169 species of shallow reef corals on Christmas Island have not been recorded anywhere else in Australia [51]. The currents arrive from both east and north-west directions, which ultimately has created a mixed fauna derived from both Pacific and Indian Oceans. This has facilitated hybridisation of closely related species, which is a key evolutionary process [43, 44]. Christmas and Cocos (Keeling) Islands are a global hotspot for fish hybridisation {Ng, 2022 #5299}.

The low rates of species migration to these isolated locations also mean that most species rely on self-recruitment of larvae. Larval self-recruitment can also facilitate the evolution of new endemic species. The number of endemic species on Christmas and Cocos is low (1.1 % and 0.4 % of fish species respectively), although their abundance can be relatively high [76].

Larval self-recruitment requires the on-going presence of an adult population. Recovery from long-distance dispersal is likely to be very slow after natural (e.g. cyclones) or anthropogenic (e.g. oil spill) disturbance events [75]. This could be catastrophic if it affected keystones species. In the Cocos southern atoll lagoon, seagrass (mostly *Thalassia hemorichii*) is the basis of a food chain that includes nesting green turtles [69] and the odd dugong [78], mangroves (mostly the small-leaved mangrove *Pemphis acidula*) function as a fish nursery, and coral colonies shelter many animals [79].

There are marine and anchialine caves around the coast of Christmas Island. The anchialine caves are crustacean dominated with endemic species (and genera) below the halocline (and therefore derived from marine taxa) [80]. At least one new species has also been described from the marine caves [58]. However, these types of caves are typically occupied by widespread species [80] and subterranean caves generally are very under-sampled [81], so such species may be discovered elsewhere in the future.

6.2 Bathyal-Abyssal benthic fauna

The seamounts that lie under these shallow features are massive structures that rise up to 5 km from the deep-abyssal plain, making them some of the tallest seamounts in Australia. Seamounts are rare in the Australian marine domain. Equivalent-sized seamounts that arise from the abyssal plain otherwise only occur in the Tasmantid chain off eastern Australia. Mid-oceanic shallow seamounts and islands are also very rare in the eastern Indian Ocean. The nearest are located at the south of the Ninety-East Ridge (1,950 km from Cocos). The nearest islands to the east are Chagos (2,800 km from Cocos) and Amsterdam (3,600 km away).

As well as shallow water environments, Cocos, Christmas, Muirfield and 'Green-eye' seamounts support the only upper bathyal habitat (200-1100 m deep) of the IOT. The upper bathyal habitat of the IOT also experiences a strong South Equatorial Current, this time bringing intermediate water from Indonesia.

There are more IOT seamounts at mid to lower bathyal depths (1000-3500 m) that are likely to support cold-water coral and sponge communities on their summit rims and steep flanks, and infaunal communities on flat muddy seafloors [3]. However, although IOT seamounts at these depths possibly share the same regional fauna, each seamount assemblage is likely to be different, due to contrasting histories of dispersal, colonisation and persistence [28]. The age of the seamounts varies from east (oldest) to west (youngest), although it is unclear what effect, if any, this will have on the fauna [2]. Manganese crusts can form on exposed rock, particularly on shallower seamounts (1000-1500 m), which can shape epifaunal community composition [36].

The 46 species of brittle-stars identified from the IN2021_V04 expedition formed overlapping bathymetric faunas extending approximately from 400-1100 m, 1100-1900 m, and 1900-3300 m, reflecting the differences in water masses (Fig. 6). No ophiuroids were collected under 3300 m. There was not a notable overall difference between different seamounts (except that the 400-1100 m fauna only occurred around Christmas Island as this was the only shallow seamount surveyed). The summits of each seamount had a soft sediment fauna but the dominant species could vary. For example, the small red species *Ophiura aequalis* dominated between 1200 and 1600 m on the Golden Bo'sunbird seamounts, *Ophiomusa lymani* at 1950 m on 'Max', *Bathypectinura heros* on

‘Clara Marie’ at 2200 m, *Stegophiura* sp on Balthazar at 2300 m, and *Ophiosphalma fimbriatum* on Karma at 2800 m.

The lower primary productivity in the Cocos (Keeling) Is MP may reduce biomass of the seafloor and bathypelagic fauna. Conversely, oceanographic anomalies like Taylor caps, tidal forcing or elevated currents can occur over seamounts and raise productivity. Other features such as Van Karman vortices can form in the lee of seamounts, which mix water masses, form eddies and also enhance productivity. This will be particularly true for seamounts that summit at depths traversed by the vertically migrating plankton (less than 1000m depth). Seamounts have been called the “stirring rods” of the ocean [82].

The Investigator Ridge has been proposed as a barrier to dispersal [14]. However, most of the ridge crests in 3,500 to 4,500 m of water, so it is only likely to affect the dispersal of the abyssal fauna. Moreover, bottom currents flow parallel to the ridge axis and some gaps exist in the south which would allow for some cross-ridge dispersal. The shallower peaks on the ridge (shallowest is 2,408 m) would function as elongated seamounts.

The steep western sides of the Investigator Ridge may provide rare exposed rock habitat at abyssal depths. Other rock habitat at abyssal depths is provided by the development of manganese nodules, particularly at very deep depths (4780-5888 m) in the southern sections of the Christmas Is MP (the Cocos (Keeling) Is MP is largely unexplored for nodules). Other hard substrata may occur near seamounts as recent volcanic debris or reworked flank slumps. However, most of the abyssal seafloor is covered in a thick layer of sediment. This sediment changes from being principally of calcareous origin above the calcite saturation horizon (~3800 m [83]) to being of siliceous origin below, including sediments below 6000 m.

6.3. Pelagic seabirds

Four species of booby breed in the IOT, Abbott’s booby (*Papasula abbotti*), Red-footed booby (*Sula sula*), Brown booby (*Sula leucogaster plotus*), and Masked booby (*Sula dactylatra*). The first is endemic, as it breeds only on Christmas Island (2500 breeding pairs), the second two breed both on Christmas and North Keeling [84], and a few pairs of the last species have started to breed on North Keeling [85]. Abbott’s booby used to breed on other western Indian Ocean islands but ceased by the early 20th century. The breeding colony of the Red-footed booby is one of the largest in the world [85]. Both Abbott’s and Red-footed booby tend to forage during the day and return to the nesting or roosting site at night. A tracking study of *P. abbotti* found that nesting birds tend to forage either to the NW or SE of Christmas Island, aligned with the prevailing wind (in August to October), and directly out to sea from the two nesting grounds [86]. Most foraging trips were less than 60 km out, with one as far as 550 km [86]. The foraging behaviour of *Sula sula* has also been tracked from Christmas Island, with an average maximum range of 164 km of up to 4 days in duration [87]. Most foraging trips were to the east, but longer trips tended to be to the NW or SE, and trips were correlated with chlorophyll α concentration rather than prevailing wind direction [87]. There has been no equivalent study of *S. sula* around North Keeling. This species probably identifies aggregated prey by tracking subsurface predators [88]. Breeding Brown booby at Swains Reef off the Great Barrier Reef foraged in relatively short trips (14.5±10.1 km range over 6.8±2.8 hours), with two-thirds of the trips during daylight hours [89].

Figure 36. Birds observed on the IN2021_V04 expedition in the Christmas Is Territory. (a) White-tailed tropicbird, Phaethon lepturus *(10.99 S, 105.63 E). (b) Abbott's Booby,* Papasula abbotti *(10.41 S, 105.46 E). (c) Juvenile frigatebird,* Fregata andrewsi*? (10.44 S, 105.58 E). (d) Immature Brown Booby,* Sula leucogaster *(10.44 S, 105.58 E). (e) Abbott's Booby,* Papasula abbotti *(10.39 S, 105.47 E). (f) Red-tailed tropicbird,* Phaethon rubricauda *(10.44 S, 105.58 E). (g) Red-footed booby (Brown Morph),* Sula sula *(10.76 S, 107.84 E). Photos Nish Nizar/MV.*

Three frigatebirds breed in the IOT, the Christmas Island frigatebird (*Fregata andrewsi*), the Greater frigatebird (*F. minor*) and the Lesser frigatebird (*F. ariel*). The former species is endemic, as it only breeds at Christmas Island, and the latter breeds almost exclusively at North Keeling where it forms the second largest breeding colony in the Indian Ocean [85]. Frigatebirds are special amongst seabirds in not being able to land on the sea as their plumage is not waterproof [90]. However, they expend little energy while flying and can remain in the air for up two months at a time, travelling 1000s km between roosting sites [90]. When not nesting, the Christmas Island frigatebird ranges across the Indian Ocean and South East Asia. Genetic analyses indicate that birds tend to return to the same nesting location. They predominantly feed on flying fish or by kleptoparasitism (robbing other seabirds of their food) or rarely scavenging on land. From breeding or roosting sites, such as on North Keeling or Christmas Islands, they forage shorter distances, up to 240 km. Consequently, although there are no data for foraging activities of frigate birds in the IOT, it is likely that the most important foraging area is nearby to each island.

Two tropic birds also breed both on Christmas and North Keeling, the Red-tailed tropic bird (*Phaethon rubricauda*) and an endemic subspecies of the White-tailed trophic bird (*P. lepturus fulvus*, known locally as the Golden Bosun). They are plunge divers, catching flying fish and squid, to a depth of 25.6 m [91]. Red-tailed tropic birds with chicks at Christmas Island have been recorded taking alternate short (3±4 hr) and long (57±41 hr) trips, with those incubating going on longer trips (153±47 hr) [91].

The Common noddy (*Anous stolidus*) breeds on both islands (550 pairs on Christmas Island) and the Lesser noddy (*Anous tenuirostris*) and Sooty tern (*Onychoprion fuscata*) on North Keeling [84, 85, 92]. The White tern (*Gygis alba*) breeds on a number of islands in the Cocos group [92]. A number of other petrels, gulls, terns and shearwaters are vagrants throughout the IOT [84, 92].

The IOT is part of one of four areas that are foraged by Sooty terns that breed on a small island in the Seychelles in the western Indian Ocean [93]. Non-breeding birds can forage up to 50,000 km on a single trip and the bird appears to sleep in flight. This species is the largest bird consumer of marine resources in the tropics. It forages in flocks by following tuna and mackerel, eating small fish and squid by 'dipping' and not settling on waters. The practice of 'facilitated foraging' by eating small fish chased to the surface by predatory fish is likely to be important for many seabirds [94].

Conversely, Lesser noddys and White terns do not stray that far from breeding colonies [95, 96]. The White tern's diet matches that of tuna and mackerel off Hawaii [96] suggesting that they too rely on facilitated foraging.

6.4 Pelagic mammals

Little is known about whale and dolphin activity in the IOT. Several whale species have been sighted around the islands or from marine observers, including Fin, Humpback, Blue and Sei whales, but many of these observations require validation [14].

Three dolphins are known to occur, Spinner (*Stenella longirostris*) and Short-beaked common dolphins (*Delphinus delphis*) around Christmas Island, and Bottlenose (*Tursiops truncates*) and Common dolphins around the Cocos Islands [14]. A pod of Common dolphins are occasionally seen around the south eastern corner of Christmas Island and an indented bay on the north coast of Christmas Island supports a population of approximately 200 resident Spinner dolphins [14].

Various dolphins and whales are known to associate with schools of tuna, particularly Yellowfin and Bigeye tuna, as they in turn follow schools of bait fish. This was originally reported from the eastern Pacific but also occurs in the western and central Indian Ocean [97]. Fishers have used this association to locate Yellowfin schools and set nets under feeding dolphins resulting in cetacean casualties [97]. Other cetaceans, such as false killer whales, have been recorded removing bait from tuna longlines [97].

A single male dugong ('Kat') has been reported from the north of the lagoon at the southern Cocos Islands, where it appears to seek the company of divers [78, 98].

6.5 Pelagic sharks and rays

Two species of manta rays have been recorded from the IOT, the Reef manta ray (*Mobula alfredi*) in and around the lagoon between the southern Cocos Islands, and the Oceanic mantra ray (*M. birostris*) around Christmas Island [99]. Reef manta rays appear to have long term affinity to foraging sites off Western Australia [100], with migrations generally less than 500 km and rarely up to 1150 km [99], so the population of this species at Cocos may be more or less resident to the IOT. The IN2021_V04 expedition sighted a devilray to the SE of Christmas Island (Fig. 37).

Figure 37. Devilray swimming around the RV Investigator over the Karma seamount cluster, SE of Christmas Island. Photo Nish Nizar/MV.

Whale sharks (*Rhincodon typus*) are regularly sighted along the north and east coasts of Christmas Island [14], including rarely seen juveniles [101]. They are seen mostly from December to April but can occur at the Island all year round [14]. Some animals have been tracked arriving from Ningaloo [14] and one animal tagged at Christmas Island swam past Timor into the Banda Sea [102]. The animals arrive at Christmas Island at the same time as the spawning of the Red-land crab (*Gecarcoidea natalis*) [101] and genetic evidence shows that the whale sharks consume a large amount of crab larvae [103]. However, Whale sharks regularly dive to 1000 m, and would consume other plankton in the deep water surrounding the island [14].

Pelagic sharks would also traverse the IOT but little information is available [14].

6.6 Pelagic fin fish.

Southern bluefin tuna (SBT, *Thunnus maccoyii*) is a single stock and the only known spawning ground is located between Java and NW Australia, including the Christmas Island MP. Adults (10-40 years old) arrive in September-October and February-March to spawn [104]. Spawning is largely late in the evening or early in the morning and occurs near the water surface [105]. Fish then regularly dive into deeper water to thermoregulate. SBT is a cold-water fish and cannot tolerate the warm waters of the spawning ground (24-30˚C) for extended periods. The location of a spawning ground outside its foraging range may reduce the risk of larval predation in the relatively oligotrophic waters [106] or because the larvae are endothermic [104].The timing of the spawning season occurs during the NW Monsoon which brings higher productivity and SE flowing currents to the region [14]. Females may have several spawning events and then rapidly migrate south again [106].

The larvae drift passively before becoming entrained in the southwards flowing South Java and Leeuwin Currents and carried down the coast of Western Australia [106]. One to two-year old juveniles then head east to the Great Australian Bight, or west to the waters off South Africa. They probably migrate by following older fish (‘adopted’ migration) [107] which decreases the chance of population recovery after over-fishing of adult fish. Historically, SBT was fished by Japanese longline fishers in waters now encompassed by the IOT, however, the meat of spawning fish is of poor quality [105] and from the 1960s fishing effort gradually moved southwards into the Southern Ocean [107].

Other pelagic fish also use IOT waters as a foraging or spawning ground. Tuna at equatorial latitudes are mainly Yellowfin (*Thunnus albacares*) and Bigeye (*Thunnus obesus*) [14, 108]. Yellowfin migrate through the IOT in the cooler months where they are caught by recreational fishers from the Islands [14]. Conversely Sailfish (*Istiophorus platypterus*) are caught mainly when waters begin to warm. Some pelagic species are commonly found associated with shallower reef and slope structures around the islands, such as Bluefin trevally (*Caranx melampygus*), Small-toothed jobfish (*Aphareus rutlians*) and Wahoo (*Acanthocybium solandri*), whose prey include demersal and benthic seamount species [14]. Wahoo appears to breed all year round [14]. Although, there is no genetic differentiation [109] across Wahoo’s global range, its morphology and parasite load shows regional differentiation [110], and it is likely to remain in a home range and be semi-resident [75]. Flying fish (Fig. 38) and small pelagic fish and squid are an important component of the pelagic food web in the IOT, especially during the spring upwelling when the water temperatures decrease [14].

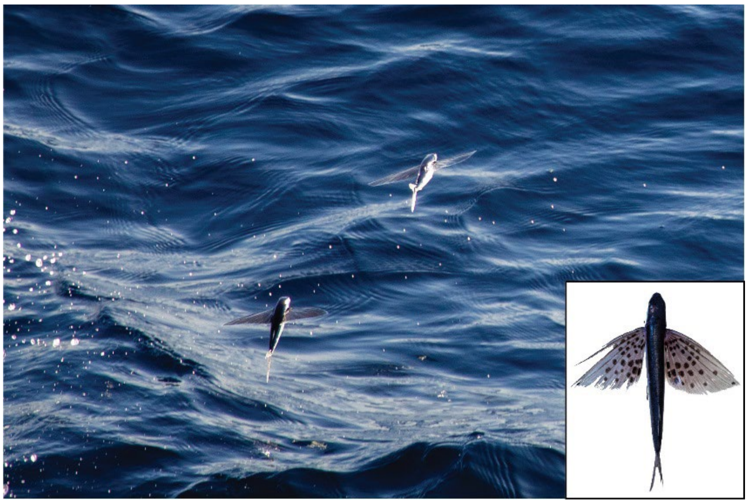

Figure 38. Flying fish in the IOT on the IN2021_V04. (a) Moving away from the RV Investigator’s bow wave. (b) Fish that landed on the vessel. Photos Rob French/MV.

7. Conclusion

The IOT contains a diverse range of benthic habitats ranging in depth from island coastal assemblages to hadal plains below 6000 m. There is a NE to SW gradient in sea-surface primary productivity that will influence benthic community composition and abundance. There is also a relatively high proportion of rocky substrata compared with the Australian continental margin.

The oceanic seamount and island communities (30-2000 m) in the IOT are rare examples of these habitats in the eastern tropical Indian Ocean and are of national to international conservation significance. Each of these seamounts is likely to have a distinct migration and environmental history leading to relatively unique combinations of the regional fauna at each location.

The presence of rocky substrata at lower bathyal depths, manganese nodules at abyssal depths, and seafloor at hadal depths are significant in a more regional context.

Appendix 1: IOT Seamount names

A number of names have been applied to seamounts, clusters of seamounts, rises and volcanic provinces within the IOT regions. The names in international gazetteers (eg GEBCO, Marine Regions) originated from discovery voyages of the International Indian Ocean Expeditions (IIOE, 1959-1965) or survey expeditions in the 1960-1980s when mapping technology was rudimentary. Consequently, many of these names refer to seamount clusters, rather than individual features (Fig. 1), and their geographic limits are unclear. These include the Raitt Rise to the SW of Cocos, the Vening Meinesz Rise to the east of the Investigator Ridge, the Flying Fish seamounts at the far NW of the Christmas Is MP, the Golden Bo'sunbird Seamounts to the SW of Christmas Island, the Bartlett Seamounts to the south of Christmas Island, and the Karma Seamounts to the SE. Confusingly, the name 'Vening Meinesz Seamounts' has also been given to 1) an overlapping group of northern Golden Bo'sunbird and Flying Fish Seamounts (but excluding Shcherbakov, 'Glogg' and 'Attention'), and to 2) a large volcanic province that stretches from Christmas Island all the way to the Investigator Ridge. The name 'Karma' was originally used for an "ill-defined tract of seafloor" before it was known to include seamounts. The utility of these names is debatable.

Hoernle et al. [2] divided the IOT seamounts into three volcanic provinces (Fig. 1): East Wharton Basin (south and southeast of Christmas Island), Vening Meinesz (Christmas Is and southwest to the Investigator Ridge) and Cocos (west of the Investigator Ridge) [2], although it is unclear on what basis this was done as the seamounts form a broad age gradient from east (oldest) to west [2].

Apart from the two island groups, the only individual features with official names are the Muirfield Seamount to the SW of Cocos islands and Shcherbakov Seamount (often misspelt Sherbakov or Scherbakov) to the west of Christmas Island. The voyage report by Werner et al. [3] of a geological expedition (SO199) of the RV Sonne in 2008 partially rectified this situation by unofficially naming numerous IOT seamounts that they discovered using multibeam sonar. However, these names have not been lodged in marine gazetteers or used in scientific literature. Instead Taneja & O'Neill [5] reused the seamount group names (listed above) to refer to a single seamount, including Golden Bo'sunbird for both 'Apollo 8' (Taneja & O'Neill Fig. 1) and 'Balthazar' seamount (Taneja & O'Neill Table 4), Flying Fish for 'Melchior', Vening Meinesz for 'Lucia', and Bartlett for a seamount NE of 'Clara Marie'.

The IN2021_V04 and IN2022_V08 expeditions also informally named several seamounts for operational clarity, including a caldera in the Karma cluster ('Eye of Sauron', Fig. 25), 'Rudist' seamounts (after the reef-building bivalves found as fossils on many IOT seamount summits) (Fig. 21), 'Green eye' (after the undescribed and dominant fish found there) and 'Carcharocles' (after the large haul of fossil white shark teeth found to the east) seamounts (Fig. 14).

To avoid further confusion, this assessment uses the unofficial names placed in quotation marks (e.g. Fig. 1) as they refer to single identifiable features. However, many seamounts are still unnamed.

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