



# Hadal zones of the Southwest Pacific and east Indian oceans

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## Abstract

The hadal zone (water depths > 6000 m) are unlike the overlying shallower marine regions (bathyal and abyssal) as it does not follow a continuum from the continental shelves to abyssal plains, but rather exhibits a globally disjunct series of discrete deep-sea habitats confined within geomorphological features. From an ecological perspective, hadal communities are often endemic to individual or adjacent features and are partitioned and isolated by geomorphological structures. To examine the size, shape, depth and degree of isolation of features where hadal fauna inhabit, this study explores the broad seafloor geomorphology, and distinctly partitioned hadal areas, across the Southwest Pacific and East Indian oceans using global bathymetric datasets. This research revealed the area occupied by hadal depths to be 716,915 km<sup>2</sup> of which 58% are accounted for by trenches, 37% in basins and troughs, and 5% fracture zones. The largest feature in terms of area > 6000 m depth is the Wharton Basin with 218,030 km<sup>2</sup> spanning 376 discrete areas. The largest continuous hadal habitats were the Kermadec and Tonga trenches at 145,103 and 111,951 km<sup>2</sup> respectively, whereas features such as the Java Trench comprise two hadal components partitioned by a bathymetric high. Conversely, no physical barrier exists between the New Britain and Bougainville trenches thus any literature pertaining to hadal species or habitats from these trenches can be merged. This study highlights that the hadal zone mainly comprises two main geomorphological features (trenches and basins) that differ in size, depth and complexity. Hadal basins cover vast, generally shallower areas, comparable to abyssal plains, whereas trenches, despite a lesser footprint, represent greater depth ranges and complexity. As such, sampling designs and interpretation of ecological data must differ and hadal basins likely play an increasingly important role in understanding ecological shifts from abyssal to hadal ecosystems.

**Keywords** Hadal zone · Indian ocean · Pacific ocean · Subduction trench · Fracture zone · Oceanic basins

## Introduction

The hadal zone (water depths > 6000 m) poses a number of difficult research challenges beyond just the extreme depths that it represents (Jamieson 2018). For example, unlike the overlying shallower marine regions (bathyal and abyssal) it does not follow a bathymetric continuum such as those spanning large continental shelves and abyssal plains that are relatively well studied (Smith et al. 2008; Levin and Dayton 2009). Instead, areas exceeding 6000 m are represented by a number of negative bathymetric features, mainly subduction trenches and fracture zones, as well as troughs and basins (Jamieson 2015). The size, depth, shape and location of these features do not follow any consistent patterns relating to latitude, longitude or proximity to land (Stewart and Jamieson 2018). Trenches are associated with large-scale tectonic convergence zones, while basins tend to be located on abyssal plains, and fracture zones and troughs

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are predominantly associated with mid-ocean ridge spreading centres (Detrick et al. 1993; Stern 2002). From an ecological perspective, hadal communities are often endemic to individual or geographically adjacent features with cases of varying degrees of speciation with distance or isolation (Ritchie et al. 2015; Eustace et al. 2016; Linley et al. 2016; Jamieson et al. 2021a, b). Speciation and endemism are driven by the physical isolation of inhabiting depth greater than 6000 m as physical connectivity is greatly reduced relative to the abyssal plains < 6000 m deep. Knowing the extent of a biozone that comprises 45% of the total ocean depth range seems like an obvious starting point in relating observable patterns of biogeography, yet the prominence of the most conspicuous of these ultra-deep features is such that there is tendency to not think far beyond the large subduction trenches.

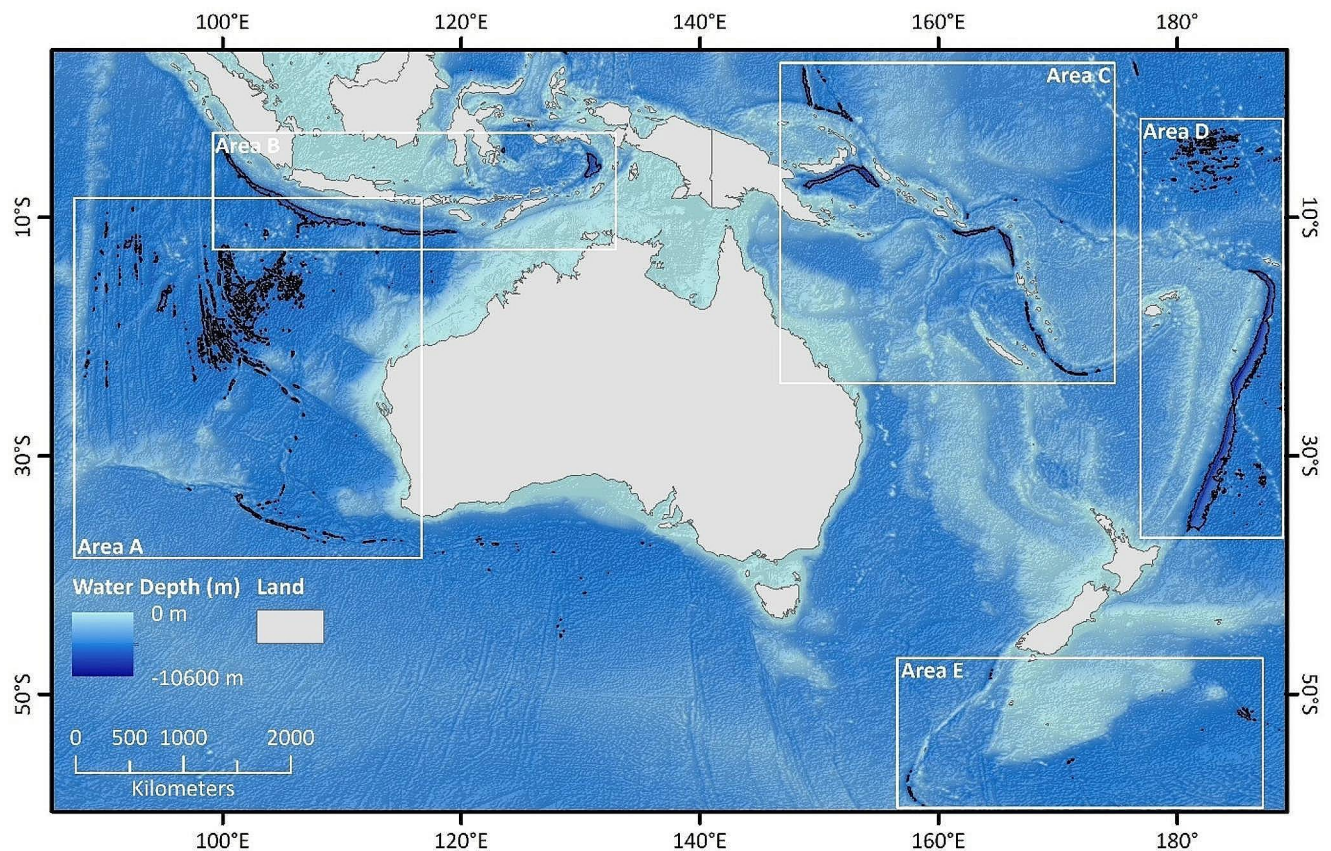
Jamieson and Stewart (2021) identified this problem and published a comprehensive study of the hadal zones of the Northwest Pacific Ocean. They concluded that the total area > 6000 m was 2,793,011 km<sup>2</sup>, which is considerably larger than the 686,114 km<sup>2</sup> accounted for by subduction

trenches alone and that the hadal ecosystem is likely to be far larger than previously anticipated.

In terms of the physical connectivity of these habitats, Jamieson and Stewart (2021) also found that the Mariana Trench comprised five hadal areas separated by bathymetric highs of < 6000 m depth, the Izu-Bonin, Japan, and Kuril-Kamchatka trenches represented one unabridged feature at hadal depths, highlighting the importance of seafloor geomorphology in understanding the distribution and genetic connectivity of endemic hadal species.

While the aforementioned study focussed on the Northwest Pacific Ocean as an area of particularly complex features, Jamieson and Stewart (2021) acknowledged the existence of an equally complex region; the trenches spanning the East Indian Ocean to the Southwest Pacific Ocean. This current study focusses on that area.

The objective of this study was to define the deep features, or distinctly partitioned areas therein deeper than 6000 m, from the Southwest Pacific and East Indian oceans (Fig. 1). We aimed to scrutinize features such as the New Britain and Bougainville trenches, and the San Cristobal and Santa Cruz



**Fig. 1** Bathymetry of the East Indian and Southwest Pacific oceans, white boxes relate to specific study areas described herein. Area A, the Wharton Basin, Wallaby-Zenith and Diamantina Fracture Zones; Area B, the Java Trench and Weber Basin; Area C, the Lyra Trough, West Melanesian, Massau, New Britain, San Cristobal, North New Hebrides and New Hebrides trenches; Area D, The Central Pacific Basin, Ker-

maDEC and Tonga trenches; Area E, the Puysegur and Hjort trenches and the Antipodes Fracture Zone. The black line represents the 6000 m depth contour. All elevation data sourced from the Global Multi-Resolution Topography Synthesis (Ryan et al. 2009; released CC BY 4.0 Deed | Attribution 4.0 International | *Creative Commons*). British Geological Survey © UKRI 2024

trenches, to clarify whether these trench complexes form one continuous or multiple separate hadal habitats. Likewise, we examined the larger subduction trenches (Java, Kermadec, New Hebrides and Tonga) in terms of whether they comprise continuous or partitioned habitats. Finally, we examined and quantified the seafloor geomorphology of the abyssal plains and basins of the region for inconspicuous areas > 6000 m deep that may expand the known footprint of the hadal zone, and potential for genetic connectivity between other larger hadal features.

## Materials and methods

Bathymetry was derived from publically available data from the Global Multi-Resolution Topography (GMRT Synthesis; [www.gmrt.org](http://www.gmrt.org)). These bathymetric data comprise ten levels of spatial resolution composed of four fully complementary tiled sets complete with source citations (Ryan et al. 2009). This study utilised version 4 of the synthesis released in January 2022. To ensure preservation of the data whilst avoiding data artefacts in the resultant Digital Elevation Model (DEM), each gridded tile set involves computing weighted averages of depth estimates at the nodes for each grid tile (Ryan et al. 2009). Where no better resolution data exist, such as multibeam echosounder bathymetry (MBES), the GMRT Synthesis includes gridded seafloor depths from the global compilation GEBCO\_2014 (30 arc-second resolution which equates to approximately 1 km) (Weatherall et al. 2015) which utilises satellite altimetry in areas where data are sparse (Becker et al. 2009).

ArcGIS grids of the bathymetry data were produced at the resolution of the dataset with additional layers comprising bathymetric contours generated in ArcGIS Pro v.2.4.0 using the 3D Analyst extension. Polygons of areas exceeding 6000 m water depth were generated with surface area, and maximum and minimum water depths calculated for each polygon using the Functional Surface tool within 3D Analyst. All data and analyses were undertaken using the WGS84 Web Mercator (Auxiliary Sphere) projection.

This study does not attempt an in depth analysis of errors or limitations associated with DEMs generated from datasets of vastly differing resolution or derived from different acquisition methods (e.g. MBES, single-beam echosounders, and satellite altimetry), instead see Smith and Sandwell (1997), Becker et al. (2009), Weatherall et al. (2015) and Mayer et al. (2018). This study does however recognise that satellite derived altimetry data occasionally provide depths that can be inaccurate when compared to data recorded directly by ship-borne equipment. As such, there are multiple places in this study area where the mapping campaigns of the DSSV *Pressure Drop* have visited and more accurate

sounding by both MBES and in situ depth sensors have been acquired. These areas are the Diamantina Fracture Zone, Java and Tonga trenches (Bongiovanni et al. 2022) and the Massau, West Melanesian, New Britain, Bougainville, San Cristobal, Santa Cruz, North New Hebrides, New Hebrides and Kermadec trenches (Unpublished data, Caladan Oceanic, LLC). Where appropriate the maximum depths and coordinates of those features are reported.

All feature names were cross checked with [marineregions.org](http://marineregions.org) and where appropriate the name source is accredited to either IHO-IOC GEBCO Gazetteer of Under Sea Feature Names, or the US BGN Advisory Committee on Undersea Features (ACUF), referred to hereafter as ‘GEBCO’ and ‘ACUF’ respectively.

## Feature definitions

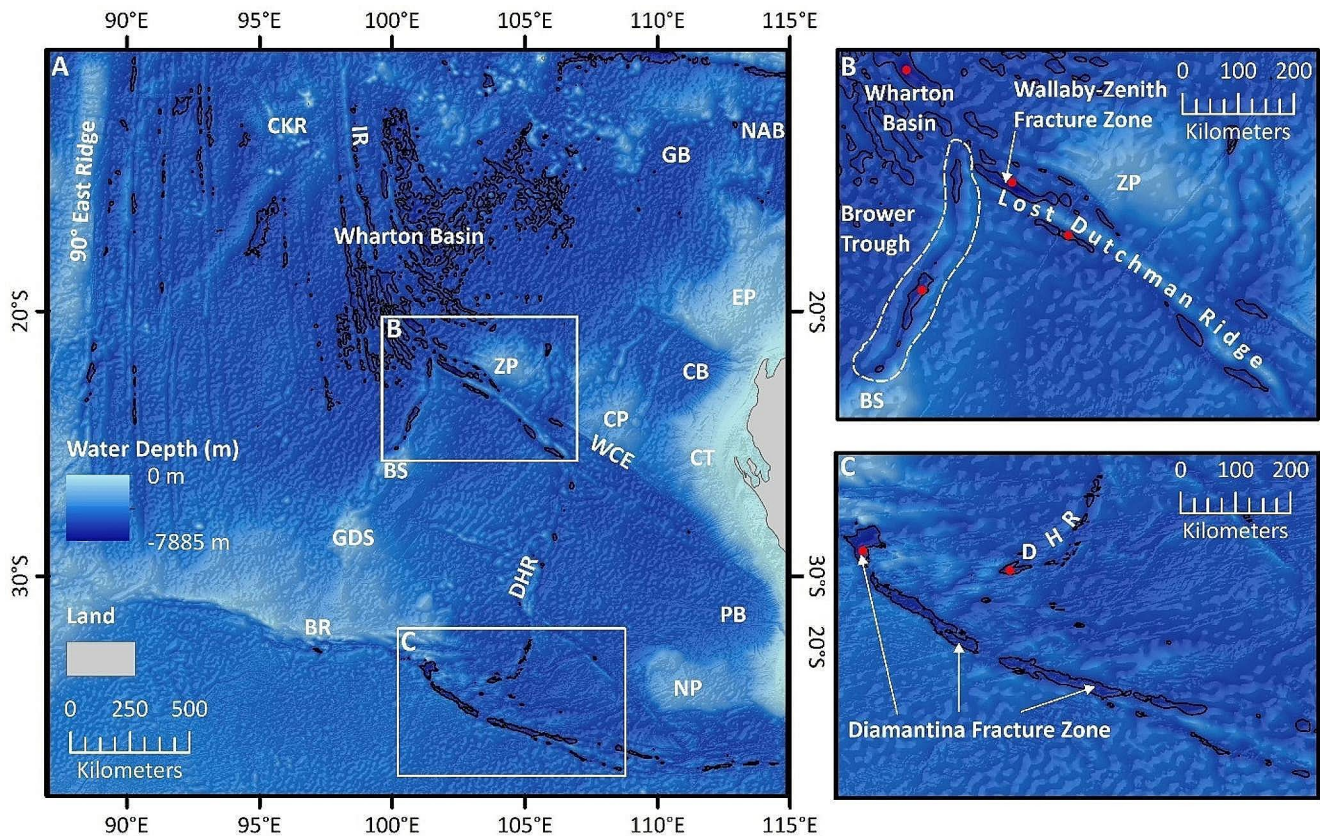
The definition of geological features referred to in this study follow IHO (2008) whereby a trench is “a long, deep, asymmetrical depression with relatively steep sides, that is associated with subduction”. A trough is “a long depression generally wide and flat bottomed with symmetrical and parallel sides”. A fracture zone is “a long narrow zone of irregular topography formed by the movement of tectonic plates associated with an offset of a spreading ridge axis, characterized by steep-sided and/or asymmetrical ridges, troughs or escarpments”. An escarpment is “an elongated, characteristically linear, steep slope separating horizontal or gently sloping areas of the seafloor”. A basin is “a depression more or less equidimensional in plan and of variable extent”. To be hadal they must host areas > 6000 m deep, and the surrounding abyssal plain are defined as “an extensive, flat or gently sloping region, usually found at depths greater than 4000 m”. The term ‘isolated’ is used in the scenario where a hadal feature is surrounded entirely by non-hadal depths (e.g., the abyssal plain), whereas a partitioned features is where two or more hadal areas of a larger features are closed off from one another by a partition < 6000 m, for example the Tonga and Kermadec Trench are the same convergence zone, but the hadal areas are partitioned by just one subducting seamount.

## Results

### Area A

Area A comprises several non-subduction hadal features located in the East Indian Ocean (Fig. 2). The East Indian Ocean was formed by the breakup, opening and seafloor spreading between the Indian, Australian, and Antarctic plates (Jacob et al. 2014). Approximately 130 Ma, India





**Fig. 2** A – Bathymetry of Area A comprising the Wharton Basin, Lost Dutchmen Ridge, Brouwer Trough and the Wallaby-Zenith and Diamantina fracture zones. White boxes indicate locations of inset maps B and C. Also labelled are the Batavia Seamount (BS), Broken Ridge (BR), Cocos-Keeling Rise (CKR), Cuvier Plateau (CP), Camarvon Terrace (CT), Dirck Hartog Ridge (DHR), Exmouth Plateau (EP), Gascoyne Basin (GB), Gulden Draak Seamount (GDS), Investigator Ridge (IR), Naturalist Plateau (NP), North Australian Basin (NAB), Perth Basin (PB), Wallaby Cuvier Escarpment (WCE) and the Zenith Plateau (ZP). B – Close up of the Wallaby-Zenith Fracture Zone, Brouwer

Trough, Zenith Plateau and Lost Dutchmen Ridge with selected feature boundaries indicated by dashed white lines. C – Close up of the deepest section of the Diamantina Fracture Zone (*Dordrecht Deep*) and the Dirck Hartog Ridge. The black lines represent the 6000 m depth contour. The red dots mark the deepest point in each feature discussed (see Table 1). All elevation data sourced from the Global Multi-Resolution Topography Synthesis (Ryan et al. 2009; released CC BY 4.0 Deed | Attribution 4.0 International | *Creative Commons*). British Geological Survey © UKRI 2024

separated from Antarctica and Australia and among other features created the Perth, Cuvier, and Gascoyne basins off Western Australia (Gibbons et al. 2012). Approximately 100 Ma, a major plate reorganization resulted in a  $\sim 40^\circ$  clockwise reorientation of the spreading direction, which among others formed the Wharton Basin (Jacob et al. 2014). Due to collision between the Indian and Eurasian tectonic plates  $\sim 40$  Ma, another  $\sim 50^\circ$  clockwise change in spreading direction occurred between India and Antarctica that ceased spreading in the Wharton Basin and formed a single “Indo-Australian” plate (Liu et al. 1983). The Wharton Basin is dissected by a series of north-south trending fracture zones, which divide it into eight compartments (Jacob et al. 2014). It is a deep basin comprising 376 distinct depressions  $> 6000$  m that combined total 218,030 km<sup>2</sup> of seafloor, occurring largely in the east of the basin coincident with smaller the Gascoyne Basin. The maximum

depth of the Wharton Basin is 7747 m located at  $20.328^\circ$  S /  $100.603^\circ$  E in a 6455 km<sup>2</sup> depression (Fig. 2B). Despite so many discreet depressions, on average they measure just 6126 m deep.

At  $\sim 22^\circ$  S /  $102^\circ$  E is the Wallaby-Zenith Fracture Zone (Fig. 2B), which is part of the larger Wharton Basin and Perth Basin complex and spans an area of 12,960 km<sup>2</sup> (Weston et al. 2021; Niyazi et al. 2024). It formed as a transform fault between 130 – 124 Ma with the opening of the Indian Ocean during the breakup of the Greater India and Australia along the northwest-southeast trending fracture zone (Oliero et al. 2015). The area exceeding 6000 m is 3609 km<sup>2</sup>, however, the depth recorded in the GMRT Synthesis data is 7884 m contrary to the depth measured directly by MBES of 6625 m at  $22.149^\circ$  S /  $102.311^\circ$  E (Weston et al. 2021). Extending southeast of the fracture zone is the Wallaby Cuvier Escarpment that extends for nearly 700 km to intersect the

**Table 1** Summary details of each hadal feature with each area examined with total number of discrete hadal areas, total area per features, mean depth where feature comprises multiple areas and maximum overall depth of that feature. The latitude and longitude positions are cited for the deepest points (from this study), updated depths and location from recent multibeam echosounder studies are cited where those data were available to produce a definitive table. \*Weston et al. (2021); \*\*Bongiovanni et al. (2022); \*\*\*Unpublished data, Caladan Oceanic, LLC

Feature	Number of Hadal Areas	Total Area > 6000 m (km <sup>2</sup> )	Depth (m)
<b>Deepest position</b>			
<b>Area A</b>			
Wharton Basin 20.328° S / 100.603° E	376	218,030	Mean Max: 6126 Max: 7747
Lost Dutchmen Ridge 23.005° S / 103.222° E	4	3483	Mean Max: 6386 Max: 6444
Brouwer Trough 23.896° S / 100.853° E	2	2805	Mean Max: 6522 Max: 6563
Wallaby Zenith Fracture Zone 22.149° S / 102.311° E*	4	3609	Mean Max: 6621 Max: 6625*
Diamantina Fracture Zone 33.631° S / 101.356° E**	50	19,435	Mean Max: 6221 Max: 7019**
Unnamed Fracture Zone 33.954° S / 103.760° E	26	1876	Mean Max: 6155 Max: 6905
Zenith Plateau 21.331° S / 105.887° E	7	2179	Mean Max: 6299 Max: 7022
<b>Sub Total</b>	<b>469</b>	<b>251,417</b>	
<b>Area B</b>			
Java Trench 11.129 °S / 114.942° E**	1	69,095	Mean Max: 7255 Max: 7187**)
Weber Basin 5.385° S / 130.918° E	1	15,969	Max: 7347
Unnamed Depressions (Banda Sea) 4.395° S / 123.488° E	2	812	Mean Max: 6402 Max: 6470
<b>Sub Total</b>	<b>5</b>	<b>85,876</b>	
<b>Area C</b>			
Massau Trench 0.106° S / 149.202° E***	1	7919	Max: 7240***
Lyra Trough 1.431° S / 151.959° E	7	4176	Mean Max: 6296 Max: 6438
West Melanesian Trench 0.835° S / 149.777° E***	3	2660	Mean Max: 6516 Max: 6691***
New Britain Trench 6.186° S / 153.597° E***	2	30,849	Mean Max: 7021 Max: 8921***
Cape Johnson Trough 9.786° S / 162.452° E	6	452	Mean Max: 6093 Max: 6185
Vityaz Trench 10.214° S / 170.118° E	1	181	Max: 6204
San Cristobal Trench 11.238° S / 163.129° E***	1	8884	Max: 8504***
Santa Cruz Trench 12.418° S / 165.901° E***	4	8689	Mean Max: 6923 Max: 9145***
New Hebrides Trench 23.115° S / 172.183° E***	22	11,886	Mean Max: 6479 Max: 7808***
<b>Sub Total</b>	<b>47</b>	<b>75,696</b>	
<b>Area D</b>			
Central Pacific Basin 4.294° S / 172.996° W	159	34,067	Mean Max: 6151 Max: 7016
Kermadec Trench 31.935° S / 177.317° W***	1	145,103	Max: 10,011***
Tonga Trench 23.270° S / 174.740° W**	1	111,951	Max: 10,816**
<b>Sub Total</b>	<b>161</b>	<b>291,121</b>	
<b>Area E</b>			

**Table 1** (continued)

Feature	Number of Hadal Areas	Total Area > 6000 m (km <sup>2</sup> )	Depth (m)
Deepest position			
Puyseger Trench 48.011° S / 164.457° E	7	459	Mean Max: 6208 Max: 6333
Hjort Trench 58.352° S / 157.654° E	9	4527	Mean Max: 6316 Max: 6614
Antipodes Fracture Zone 51.992° S / 174.041° W	9	7819	Mean Max: 6242 Max: 6339
<b>Sub Total</b>	<b>25</b>	<b>12,805</b>	
<b>Total</b>	<b>707</b>	<b>716,915</b>	

Australian continental shelf (Fig. 2A). Located parallel to, and south of the escarpment, is the 340 km long Lost Dutchmen Ridge which comprises four small hadal basins south of the bathymetric high of the ridge (Fig. 2B). From west to east, the largest three basins are 6444 m, 6394 and 6369 m deep with hadal areas of 1155, 1229 and 1100 km<sup>2</sup> respectively. The deepest point is located at 23.005° S / 103.222° E. The northerly point of the broadly north-south trending Brouwer Trough is located 27 km west of the most northerly point of the Wallaby Zenith Fracture Zone and extends south for 400 km to the Batavia Seamount (Fig. 2B). There are two main hadal basins in this trough, 6482 and 6563 m deep, spanning areas of 938 and 1867 km<sup>2</sup> respectively, with the deeper one in the south at 23.896° S / 100.853° E. These two basins are separated by a 149 km stretch of shallower seafloor that shoals at 3511 m depth. The Zenith Plateau (Fig. 2B) is an ~160 km wide plateau that reaches a high of ~1800 m depth (Olierrok et al. 2015). Hadal basins are located to the north-east and south-east of the plateau with respective depths and total areas of 7022 m and 704 km<sup>2</sup>, and 6267 m and 832 km<sup>2</sup>, with the deepest of these located at 21.331° S / 105.887° E. Five small depressions trend along the base of a steep escarpment to the south-west of the Zenith Plateau. These depressions total 643 km<sup>2</sup> and have a maximum depth of 6229 m.

The Diamantina Fracture Zone trends approximately east-west 1100 km south of the Wallaby Zenith Fracture Zone between 30° and 40° S southwest of Australia (Fig. 2A). It is > 3400 km in length and formed as the Australian and Antarctic continents separated (Stewart and Jamieson 2019). It is surrounded by the Cape Leeuwin manganese nodule field that extends to the base of the Naturalist Plateau to the east and may extend further north at depths > 4300 m (Frakes 1982). Bongiovanni et al. (2022) reported the deepest point in the fracture zone to be 7019 ± 17 m at 33.631° S / 101.356° E in a depression known as the *Dordrecht Deep* as measured by MBES, whereas the depth reported by the GMRT Synthesis is 7098 m. The fracture zone shallows eastward from the *Dordrecht Deep* with a total of 50 hadal basins averaging 6221 m deep covering an area of 19,435 km<sup>2</sup>, inclusive of *Dordrecht Deep*. The Diamantina Fracture

Zone is intersected at 34.449° S / 102.150° E by an unnamed fracture zone of which the most prominent feature is the parallel, high relief Dirck Hartog Ridge (Fig. 2C) (Halpin et al., 2017). This 480 km long feature comprises 26 discrete hadal basins, reaching a maximum depth of 6905 m at 33.954° S / 103.760° E. Note that GEBSCO recognizes the name Dirck Hartog Ridge whereas it is known as the Hartog Ridge by the ACUF.

In total, Area A is comprised of seven main hadal features that are collectively 469 distinct areas > 6000 m that combined total 251,417 km<sup>2</sup>.

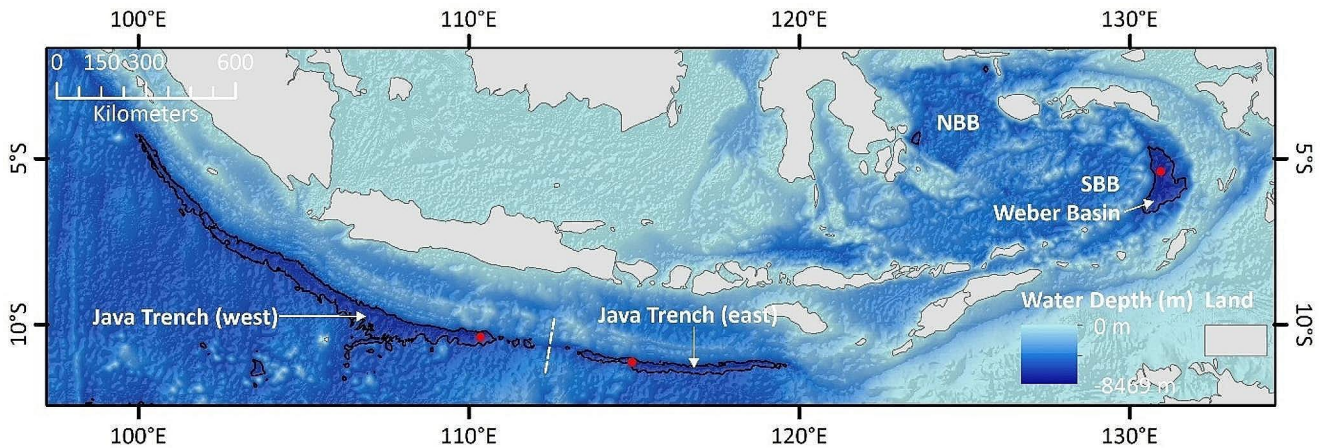
## Area B

Area B comprises the hadal zones around the coast of Indonesia. Here there are two main features to consider: the Java or Sunda Trench located in the East Indian Ocean, and the Weber Basin also known as the Banda Trench (Fig. 3).

The Java Trench stretches ~3200 km, follows the curve of the Indonesian islands of Sumatra and Java to the north, and extends easterly to the Lesser Sunda Islands. It was formed where the Indo-Australian plate subducts under a section of the Eurasian Plate (Moore et al. 1982). The trench is ~50 km wide in the northwest and gradually narrows to ~10 km to the southeast (Lemenkova 2020).

The ACUF recognises the name Java Trench while GEBSCO recognises the Sunda Trench. Furthermore, Priede (2018) split the Java Trench into two features, the 'Java East' and the 'Java West' which approximately mirror that of Lemenkova (2020) who defined 'Java' and 'Sumatra' segments of the feature. This study confirms two main hadal sectors within the Java Trench separated by a 279 km wide bathymetric high shoaling at 5202 m deep at 10.818° S / 113.138° E. The 15,687 km<sup>2</sup> eastern sector is the deepest with a maximum depth of 7187 ± 13 m at 11.129° S / 114.942° E (Bongiovanni et al. 2022), however, the regional bathymetric data states a maximum depth of 7269 m. This unnamed point, or 'deep' represents the deepest point in the Indian Ocean. The western sector is larger with an area of 53,408 km<sup>2</sup> and a maximum depth of 7241 m at 10.381° S / 110.362° E according to the regional bathymetric dataset





**Fig. 3 A** – Bathymetry of Area B comprising the Java Trench and Weber Basin, also known as the Sunda and Banda trenches respectively. The black lines represent the 6000 m depth contour. The white dashed line represents the abyssal partition in the Java Trench that divides the hadal area into west and east sections. The red dots mark the deepest point in each feature discussed (see Table 1). Also labelled

are the North Banda Basin (NBB) and South Banda Basin (SBB). All elevation data sourced from the Global Multi-Resolution Topography Synthesis (Ryan et al. 2009; released CC BY 4.0 Deed | Attribution 4.0 International | *Creative Commons*). British Geological Survey © UKRI 2024

used in this study. However, the MBES data acquired by Bongiovanni et al. (2022) reveal the western sector location to have a depth of only 6996 m.

The Weber Basin, also known as the Banda Trench (see Charlton et al. 1991 and Audley-Charles 2011 respectively), is a subduction feature rather than a ‘basin’ formed as the Australian plate subducts beneath the most south-easterly point of the Eurasian plate (Bird 2003). The ACUF recognises the name Banda Trench while GEBCO recognises Weber Basin. The Weber Basin is an arcuate trench running for 650 km east of the South Banda Basin between the Indonesian islands of Maluku and East Timor. It has a maximum depth of 7347 m at 5.385° S / 130.918° E and spans 15,969 km<sup>2</sup>. It is an isolated hadal feature contained within the Banda Sea as it is separated from the Java Trench by the island of East Timor and the shallow epicontinental Samu and Timor seas, and from the Philippine Trench to the north by the Molucca and Halmahera seas.

There are two further small depressions of >6000 m depth located in the Banda Sea. These two unnamed basins are on the northeast and southwest interior of the North Banda Basin (Fig. 3) and are 6335 m and 6470 m deep, with areas of 147 and 665 km<sup>2</sup> respectively. The deeper of the two is a point located at 4.395° S / 123.488° E.

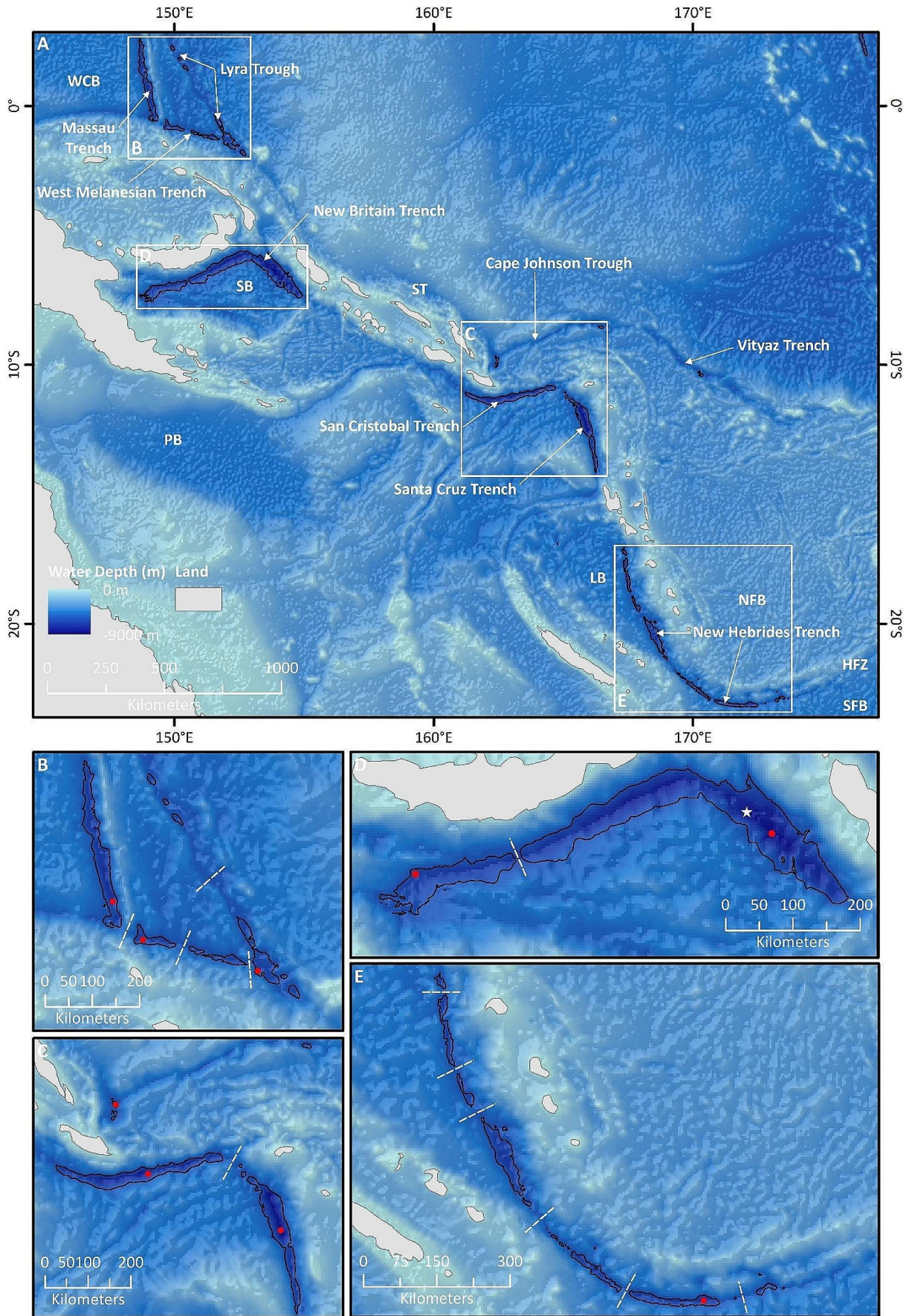
In summary, Area B is comprised of three broad-scale hadal features that are collectively five distinct areas > 6000 m that combined total 85,876 km<sup>2</sup>.

### Area C

Area C comprises a network of subduction trenches and troughs in the Western Pacific Ocean between 0° and 25°

S (Fig. 4A). The most northerly of these features is the ~400 km long Massau Trench that trends roughly north–south (Fig. 4B) north of Massau Island, part of the New Ireland Province of Papua New Guinea. It is located at the eastern boundary of the Caroline Plate but lacks active volcanoes and deep earthquakes, and is therefore not considered a subduction zone, although it may become one in the future (Bird 2003). The Massau Trench is sometimes referred to as the ‘Marceau Trench’ (e.g. Chan et al. 2020), but this appears to be a name used by only a small number of research institutions and is not listed by the ACUF or GEBCO. East of the Massau Trench is the northwest–southeast trending, ~700 km long depression named the Lyra Trough, sometimes spelled ‘Lira Trough’ (Fig. 4B). The Massau Trench has a maximum depth of 7240 m at 0.106° S / 149.202° E (Unpublished data, Caladan Oceanic, LLC) and the Lyra Trough has a maximum depth of 6438 m at 1.431° S / 151.959° E. Running perpendicular to the south of these two features is the West Melanesian Trench (formally the Manus Trench, e.g., Ryan and Marlow 1988), also known as the Admiralty Trench in older Russian Literature (e.g. Belyaev 1989) which forms the northern boundary to the North Bismark Plate (Zhang et al. 2018). The Massau Trench (Fig. 4B) contains one discreet hadal habitat totaling 7919 km<sup>2</sup>, within an otherwise abyssal feature. The southern end of the hadal boundary is separated from the West Melanesian Trench by a ~39 km wide bathymetric high that forms a connecting corridor between the two hadal areas which shoals at 4769 m water depth, although MBES data suggest this bathymetric high shoals at 5240 m water depth (Unpublished data, Caladan Oceanic, LLC). In comparison, the West Melanesian Trench is compartmentalised







**Fig. 4** A - Bathymetry of Area C comprising a network of trenches from the Massau Trench in the northwest to the New Hebrides Trench in the southeast. The black lines represent the 6000 m depth contour. White boxes represent areas shown in B-E, where B are the Lyra Trough, Massau and West Melanesian trenches, C – is the New Britain Trench, D – are the San Cristobal and Santa Cruz (North New Hebrides/Torres) trenches, and E – the New Hebrides Trench. All abyssal partitions indicated by white dashed lines. The red dots in B-E mark the deepest point in each feature discussed with the white star the location of the deepest point of the New Britain Trench (see Table 1). Other noted features are the West Caroline Basin (WCB), Papua Basin (PB), Solomon Basin (SB), Solomon Trench (ST), Loyalty Basin (LB), North Fiji basin (NFB), South Fiji Basin (SFB) and the Hunter Fracture Zone (HFZ). All elevation data sourced from the Global Multi-Resolution Topography Synthesis (Ryan et al. 2009; released CC BY 4.0 Deed | Attribution 4.0 International | *Creative Commons*). British Geological Survey © UKRI 2024

into two large and one small hadal depression situated between the intersections with the Massau Trench and Lyra Trough. Combined these total 2660 km<sup>2</sup>, with the easternmost hadal depression separated from the most southern of the seven hadal zones of the Lyra Trough by a narrow partition ~ 19 km wide and 4819 m deep although MBES data suggests a narrow hadal corridor may be present connecting these features shoaling at 6143 m depth (Unpublished data, Caladan Oceanic, LLC). The combined hadal area of the West Melanesian Trench and Lyra Trough is 6836 km<sup>2</sup>.

The West Melanesian Trench reaches a maximum depth of 6691 m at 0.835° S / 149.777° E (Unpublished data, Caladan Oceanic, LLC) and forms an arc almost 1400 km long connecting to the 829 km long Solomon Trench located north of Bougainville Island (Fig. 4A). The Solomon Trench does not exceed abyssal water depths and continues to the southeast where it intersects the approximately southwest–northeast trending Cape Johnson Trough, east of the Solomon Islands. This trough hosts two very small hadal areas at either end (Fig. 4A and C), with the westernmost area including an arc of six small depressions > 6000 m depth increasing in size to the east, with a maximum depth of 6185 m in a small area 142 km<sup>2</sup> at 9.786° S / 162.452° E. A single depression is located midway between the Cape Johnson Trough and Vityaz Trench covering 174 km<sup>2</sup> with a maximum depth of 6301 m. The Cape Johnson Trough meets the Vityaz Trench (also sometimes spelled ‘Vitiaz’) to the east (Fig. 4A) which reaches a maximum depth of 6204 m at 10.214° S / 170.118° E in a small depression 181 km<sup>2</sup>. The Cape Johnson Trough and Vityaz Trench combined form an arc convex towards the subducting Pacific Plate beneath the New Hebrides Microplate (Bird 2003). The West Melanesian Trench, Lyra Trough, Solomon Trench, Cape Johnson Trough and Vityaz Trench form a continuous feature of nearly 4000 km. This continuous feature, collectively known as the ‘Vitiaz Trench Lineament’, is a fossil subduction zone with no present-day movement, representing a

relic Australia-Pacific convergent boundary (Coleman and Packham 1976; Bird 2003; Calmant et al. 2003).

The New Britain Trench is located at the triple junction of the Australian, Caroline and Pacific plates. The arcuate trench comprises a sharp right-angle arc ~ 450 km off the south coast of New Britain where it abruptly changes to a southeast direction for ~ 350 km off the south coast of Bougainville, forming the northern boundary of the South Bismarck and the Solomon Sea plates (Fig. 4D) (Zhang et al. 2018). In the biological literature, particularly early Russian studies, this trench is often referred to as two trenches; the New Britain Trench (west-east sector) and the Bougainville Trench (north-south sector) (e.g. Birstein and Sokolova 1960; Birstein 1960; Kudinova-Pasternak 1965). GEBCO recognise the name New Britain Trench while the ACUF recognise the term ‘Bougainville–New Britain Trench’. Based solely on the regional bathymetric data, the eastern Bougainville sector is deeper, with a maximum depth of 9103 m at 6.476° S / 153.932° E, with a shallower depth of 8844 m observed in the New Britain sector at 7.023° S / 149.162° E (Fig. 4D). While the regional bathymetry data suggests there is no abyssal barrier between the ‘New Britain’ and ‘Bougainville’ trenches, instead they form one continuous hadal habitat through the apex of the two, this study did find that the New Britain sector is divided into two separate hadal areas (Fig. 4D). An 11 km wide bathymetric high with a minimum water depth of 5944 m is located at 6.811° S / 150.562° E dividing the feature into a 209 km long western portion spanning 6355 km<sup>2</sup> and reaching a maximum depth of 7028 m. When all sectors are taken as a complete feature, the New Britain Trench comprises two separate hadal habitats totalling 30,849 km<sup>2</sup>. However, unpublished MBES data (Caladan Oceanic, LLC) proves that no abyssal partition exists between the New Britain and Bougainville sectors with a maximum depth for the single hadal feature of 8921 m measured at 6.186° S / 153.597° E located in the Bougainville sector 49 km northwest of the position derived from the regional bathymetric data.

Southeast of the New Britain Trench is the hadal San Cristobal Trench, which extends 450 km westwards from the southern tip of San Cristobal to the Santa Cruz Island of Nendö (Fig. 4A and C). The tectonic convergence zone then alters from broadly east–west trending to south–trending for around 350 km delineated by the North New Hebrides Trench, also known as the Santa Cruz Trench, or Torres Trench. While the name San Cristobal Trench appears undisputed, the name North New Hebrides Trench is only recognised by GEBCO whereas the ACUF refer to the Torres Trench, additionally scientific literature refers to the feature the Santa Cruz Trench. The latter is a name used more recently to prevent confusion with the New Hebrides Trench immediately to the south (e.g., Jamieson and Linley

2021; Swan et al. 2021). The North New Hebrides/Torres/Santa Cruz Trench terminates off the north coast of Vanuatu. The San Cristobal and Santa Cruz trenches have maximum depths of 8504 and 9145 m at 11.238° S / 162.129° E and 12.418° S / 165.901° E, and hadal areas of 8884 and 8688 km<sup>2</sup> respectively. These hadal zones are partitioned from one another by a 74 km bathymetric high 4864 m deep. Additionally two smaller hadal basins are located near the apex of the North New Hebrides Trench.

South of the island of Malampa, 358 km south of the Santa Cruz Trench, the New Hebrides Trench, an arcuate trench runs for 1800 km south between the south islands of Vanuatu and New Caledonia and then to the east terminating at the southern islands of Fiji (Fig. 4E). The trench is formed at the convergent tectonic plate boundary where the Australian plate subducts beneath the New Hebrides and Conway Reef micro-plates and also marks the northern boundary of the South Fiji Basin with the easternmost section of the trench formed by a transform plate boundary rather than subduction zone (Bird 2003; Calmant et al. 2003). This transform fault is known as the Hunter Fracture Zone (Sigurdsson et al. 1993). This marks the easternmost end of a continuous subduction zone extending from the New Britain Trench ~4000 km to the northwest. The New Hebrides Trench has a maximum depth of 7808 m at 23.115° S / 172.183° E (Unpublished data, Caladan Oceanic, LLC). The New Hebrides Trench is comprised of 22 distinct hadal areas (Fig. 4E) spanning a total of 11,885 km<sup>2</sup>.

In total, Area C is comprised of nine formally named hadal features that are collectively 47 distinct areas > 6000 m with a combined total area of 75,694 km<sup>2</sup>.

### Area D

Area D comprises three areas of interest (Fig. 5A); including a sector of deep abyssal plain punctuated by a fragmented network of 159 depressions > 6000 m forming the southern sector of the large geographic area covered by the Central Pacific Basin (Fig. 5B) (see also Jamieson and Stewart 2021). These depressions average 6151 m deep, with a combined hadal area of 34,067 km<sup>2</sup> with a deepest point of 7016 m at 4.294° S / 172.996° W. The Central Pacific Basin is poorly studied as it forms a relatively small area of the vast abyssal plains that span much of the Pacific Ocean. Conversely, the Kermadec and Tonga trenches are among the better studied hadal trenches (e.g., Wright et al. 2000; Leduc et al., 2016; Jamieson et al. 2011; Lemenkova 2019; Jamieson et al. 2020).

The Tonga Trench (Fig. 5C), oriented roughly north-northwest–south-southeast, is a linear feature where the Pacific Plate subducts westward beneath the Australian Plate (DeMets et al. 1990) with the northern sector converging at

a rate of 24 cm/yr, the fastest plate velocity known (Bevis et al. 1995). The trench terminates in the north at ~15° S at the Fiji Fracture Zone and back-arc extension in the northern Lau Basin (Wright et al. 2000). At approximately 26° S, the trench is intersected by the Louisville seamount chain; a chain of hotspot-related guyots and seamounts on the Pacific Plate (Watts et al. 1988). The trench is ~1300 km long and reaches a maximum depth of 10,816 ± 16 m at 23.270° S / 174.740° W in the *Horizon Deep* (Bongiovanni et al. 2022) as measured by MBES, making it the second deepest point on Earth. Regional bathymetry analysed for this study gives a slightly shallower maximum depth of 10,794 m. The hadal area of the Tonga Trench > 6000 m forms a single continuous habitat covering 111,951 km<sup>2</sup>.

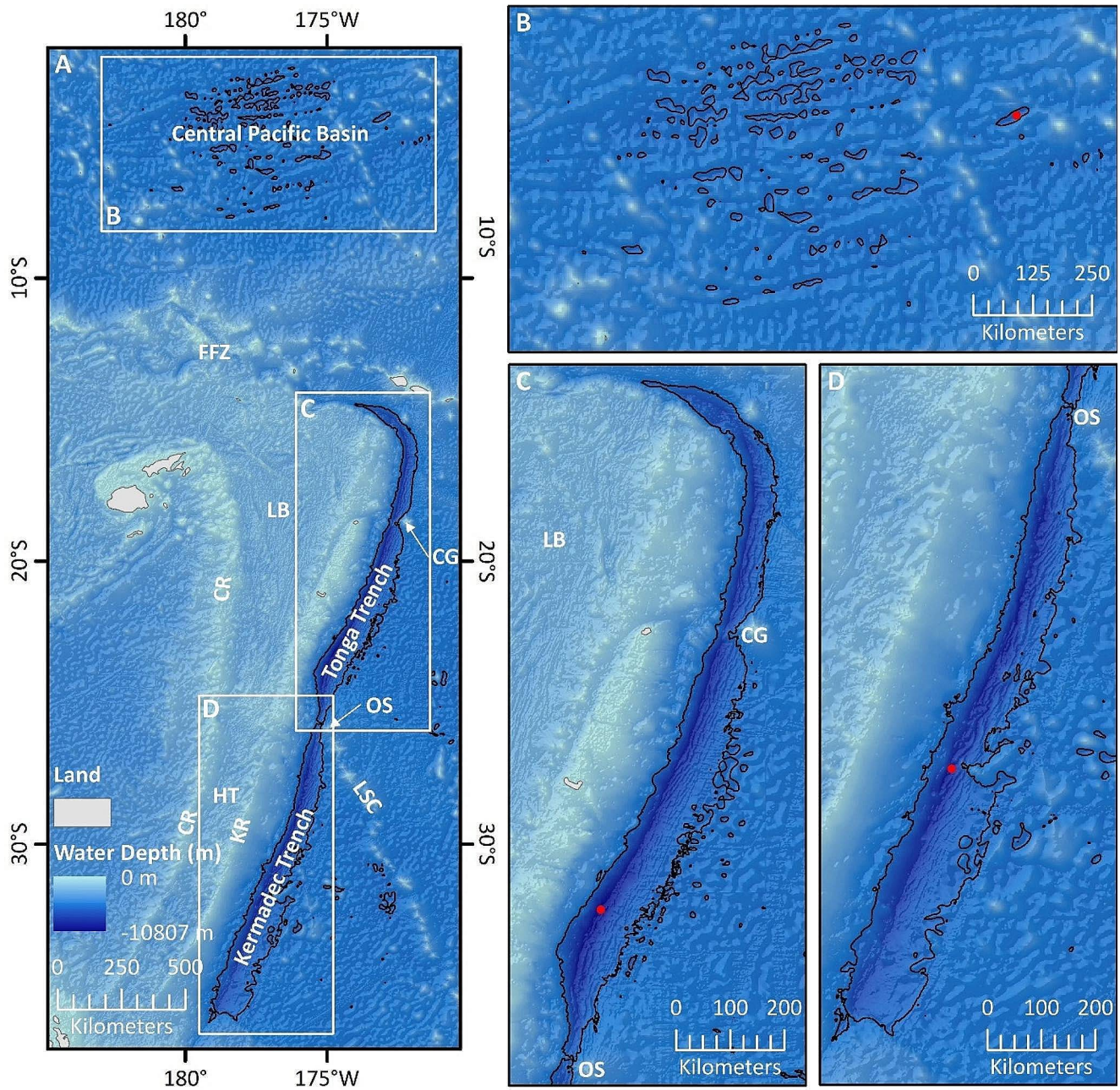
The Kermadec Trench is located on the same convergent boundary as the Tonga Trench, partitioned only by the subduction of the Osborn Seamount (Fig. 5D), forming an abyssal partition shoaling at 5331 m depth. The trench is approximately 1195 km in length and 120 km wide, narrowing northwards to ~80 km wide. The area of the Kermadec Trench > 6000 m spans 145,104 km<sup>2</sup> reaching a maximum depth ~10,106 m confined to a single, relatively small area (15.5 km<sup>2</sup>) at 31.935° S / 177.317° W known as the *Scholl Deep* (Jamieson et al. 2020). Recent unpublished MBES data acquired in 2021 onboard the DSSV Pressure Drop recorded an updated depth for *Scholl Deep* as 10,011 m (Unpublished data, Caladan Oceanic, LLC).

In total, Area D is comprised of three named hadal features that are collectively 161 distinct areas > 6000 m that combined total 291,121 km<sup>2</sup>.

### Area E

In Area E, located south and east of New Zealand's South Island, there are five features of interest comprising four trenches and one unnamed basin. Running southwest of the South Island are a series of four trenches: the Puysegur Trench, McDougall Trough, Macquarie Trench and the Hjort Trench (Fig. 6A) (Gurnis et al. 2019). These trenches are 430, 330, 260 and 460 km long respectively and form the Macquarie Ridge Complex (Massell et al. 2000). The deepest two are the Puysegur and Hjort trenches, with the latter being the only one typically mentioned in hadal literature. The Puysegur Trench, named after the nearby Puysegur Point in New Zealand, is an incipient subduction zone at an intermediate stage of transitioning to self-sustaining subduction between the Australian and Pacific plates (Gurnis et al. 2019). The geological setting in this region indicates strike-slip motion along the Macquarie Ridge Complex, however, the McDougall and southernmost Puysegur Trench show no evidence for past subduction whereas the Macquarie and Hjort trenches show evidence of past convergence, although





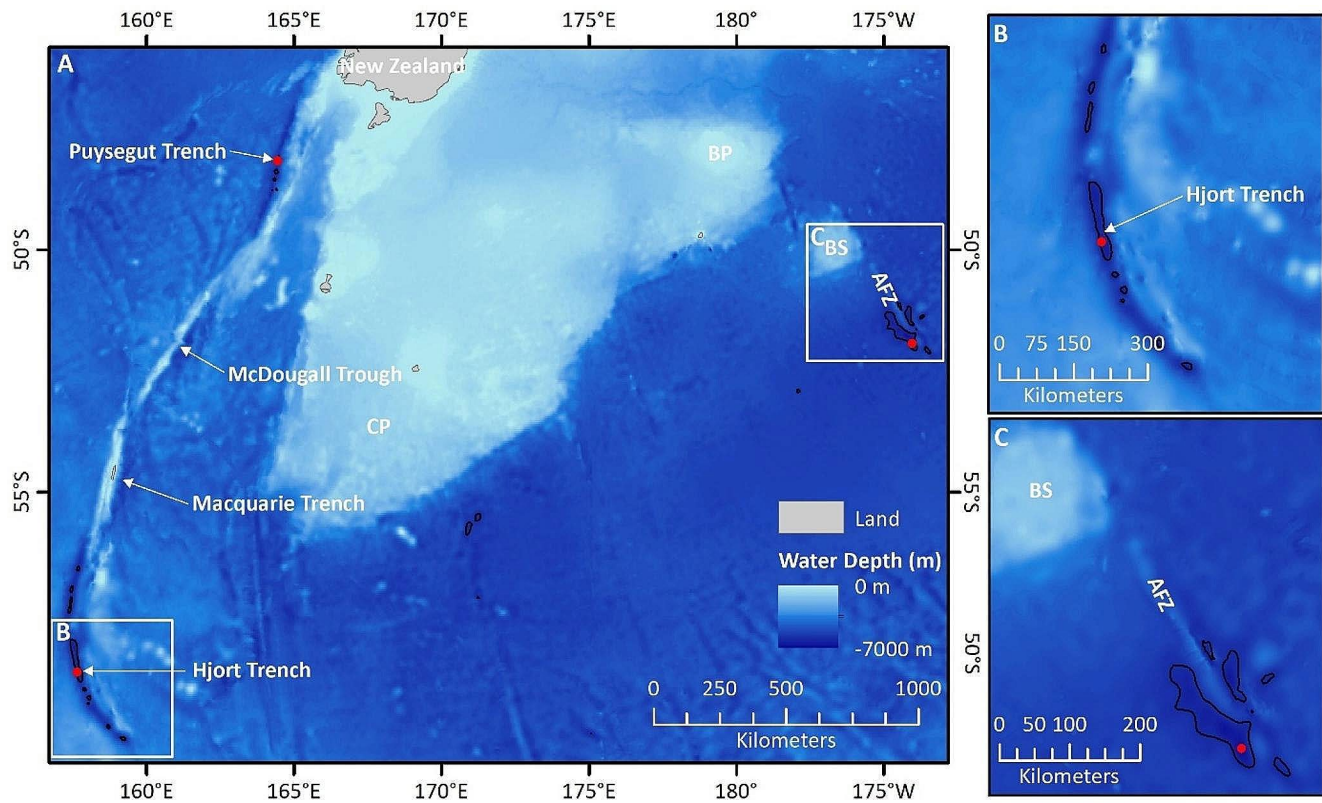
**Fig. 5** A - Bathymetry of Area D comprising the southern sector of the Central Pacific Basin, and the Kermadec and Tonga trenches, located north of New Zealand. The black lines represent the 6000 m depth contour. White boxes represent areas shown in B, C, and D. B – Close up of the Central Pacific Basin. C – Close up of the Tonga Trench. D – Close up of the Kermadec Trench. Other notable features are the Fiji Fracture Zone (FFZ), Lau Basin (LB), Colville Ridge (CR), Havre

Trough (HT), Kermadec Ridge (KR), Capricorn Guyot (CG), Osborn Seamount (OS) and the Louisville Seamount Chain (LSC). The red dots in B-C mark the deepest point in each feature discussed (see Table 1). All elevation data sourced from the Global Multi-Resolution Topography Synthesis (Ryan et al. 2009; released CC BY 4.0 Deed | Attribution 4.0 International | *Creative Commons*). British Geological Survey © UKRI 2024

the geomorphology of the latter is suggestive of present-day subduction (Massell et al. 2000). Meckel et al. (2003) argue that the Australian plate is actively under-thrusting the Pacific Plate along the Hjort Trench, but self-sustaining subduction does not yet appear to have commenced.

The Puysegur Trench has three very small depressions of 6208 m average depth (with four peripheral minor depressions totalling 459 km<sup>2</sup>), and has a maximum depth of 6333 m at 48.011° S / 164.457° E. The McDougall Trough and Macquarie Trench do not reach hadal water depths.





**Fig. 6** A - Bathymetry of Area E comprising four trenches that run southwest of New Zealand, and an unnamed basin southeast of New Zealand. The black lines represent the 6000 m depth contour. White boxes represent areas shown in B and C. B – Close up of the Hjort Trench where white dashed line indicates major abyssal partition created by a subducting seamount. C – Close up of the Antipodes Fracture Zone (AFZ) located southeast of the Bollons Seamount (BS). Other

notable features are the Campbell Plateau (CP) and the Bounty Plateau (BP). The red dot in B mark the deepest point in each feature discussed (see Table 1). All elevation data sourced from the Global Multi-Resolution Topography Synthesis (Ryan et al. 2009; released CC BY 4.0 Deed | Attribution 4.0 International | *Creative Commons*). British Geological Survey © UKRI 2024

The Hjort Trench, named after Norwegian marine scientist Johan Hjort, has one relatively large and eight smaller hadal depressions located either side of an unnamed subducting seamount that splits the trench into two parts (Fig. 6B). The deepest point is 6614 m at 58.352° S / 157.654° E. This is contrary to previous studies using an earlier version of the GEBCO One Minute Grid (GEBCO Compilation Group 2008) which cite a maximum depth of 6727 m (Stewart and Jamieson 2018) indicating improvements in the resolution of global bathymetric compilations, although it should be noted that in the absence of MBES data, both of these depths and locations are potentially inaccurate.

The fifth feature of interest in this area are several unnamed small hadal basins located 200 km southeast of the Bollons Seamount within the northern Antipodes Fracture Zone (Fig. 6C). It is named after the nearby Antipodes Islands of New Zealand. The hadal areas comprise two large basins, located either side of the ridge with the three smaller ones. Combined they total 7819 km<sup>2</sup> with the deepest point being 6339 m at 51.992° S / 174.041° W.

In total, Area E is comprised of three hadal features that are collectively 25 distinct areas > 6000 m that combined total 12,805 km<sup>2</sup>.

## Discussion

Examination of the best available global bathymetric datasets from the Southwest Pacific and East Indian oceans revealed that the potential area occupied by depths exceeding 6000 m to be 716,915 km<sup>2</sup> of which 58% are accounted for by trenches, 37% in basins and troughs, and 5% fracture zones (Table 2). The largest feature in terms of area > 6000 m depth is the Wharton Basin with 218,030 km<sup>2</sup> spanning 376 discrete areas. While this basin has a maximum depth exceeding 7700 m, the average depth of the 376 depressions is just 6126 m. Therefore, as new and higher quality data becomes available, the hadal footprint of the Wharton Basin may change dramatically as these measurements are close in value to the 6000 m depth contour. As such, owing to the variation in quality of currently available data, some



**Table 2** Summary of total area and number of hadal habitats isolated within each feature type > 6000 m water depth

Feature	Number of isolated habitats > 6000 m	Total area (km <sup>2</sup> )
Subduction Trench	55	418,172 (58%)
Basins/troughs	563	266,004 (37%)
Fracture Zones	89	32,739 (5%)
Total	707	716,915

regions must be interpreted with caution. For example, the interrogated bathymetric data set has the Wallaby Zenith Fracture Zone as being 7885 m deep, whereas MBES data puts the maximum depth of the fracture zone 1260 m shallower at 6625 m (Weston et al. 2021). Other hadal features in the East Indian Ocean such as the Brouwer Trough and Lost Dutchman Ridge may therefore also be overestimated. However, to the south, in the Diamantina Fracture Zone, the dataset records 7098 m, whereas MBES survey records 7019 m (Bongiovanni et al. 2022), a difference of just 1%. The exact depths, particularly of the deepest point in each feature is perhaps not the salient point of scrutinization but rather the size and location of each feature and how that translates to future biological studies in terms of modern and historical connectivity.

### Features and areas of biological interest

This study represents an appreciation of the network of hadal habitats that span such large geographic areas. The largest single hadal features in the Southwest Pacific Ocean are the Kermadec and Tonga trenches at 145,103 and 111,951 km<sup>2</sup> respectively. In the Indian Ocean, the Java Trench represents the only subduction trench, and has an area of 69,095 km<sup>2</sup>, albeit partitioned by a bathymetric high into two hadal components. These three features represent perhaps the most 'classic' hadal features: large, relatively self-contained subduction trenches. Just as the Tonga and Kermadec trenches represent an ideal study site to examine adjacent hadal communities separated by a bathymetric high around 9 km wide named the Osborn Seamount, the Java Trench also provides such an opportunity as it too is split into east and west hadal sectors. Furthermore, as underriding plates subduct over geological time, the point which these hadal communities became separated can be calculated, hence putting a date whereby endemic hadal species began separate evolutionary trajectories.

The East Indian Ocean (areas A and B) represent perhaps the most interesting area in terms of examining connectivity between hadal features and the significance of non-trench/aseismic features. In the north there is the most traditionally conspicuous hadal feature, the Java Trench, south of this is the Wharton Basin with its network of 376 depressions that span > 10 degrees of latitude, to the cluster of features south

of the Zenith Plateau. These features, the Wallaby Zenith Fracture Zone, the Brouwer Trough and basins at the bases of the Lost Dutchman Ridge and the Zenith Plateau itself, form distinct negative topographies with isolated areas from 6400 to 7000 m water depth. The next 10 degrees of latitude to the south do not host many hadal areas except for a few very small depressions along the Dirck Hartog Ridge until it reaches the 1100 km long Diamantina Fracture Zone. In terms of testing and disentangling drivers of hadal diversity, the East Indian Ocean hosts hadal depths within a trench, trough, and basins and fracture zones, and all in relatively close proximity. Furthermore, some quintessentially hadal species, such as the Lysianassoid amphipod *Bathycallisoma schellenbergi* (Birstein & Vinogradov, 1958) are known from the Java Trench at 6935–7060 m (Dahl 1959), the Wallaby Zenith Fracture Zone at 6537–6546 m (Weston et al. 2021) and in the Diamantina Fracture Zone at 7019 m (Weston et al. 2022). *B. schellenbergi* is a species known only from hadal depths and whose globally isolated populations are on seemingly different trajectories, with the exception of the Wallaby-Zenith Fracture Zone and Java Trench populations (Weston et al. 2022). Weston et al. (2021) suggested that this fracture zone may host a spillover population from the Java Trench, that spread throughout the Wharton Basin. However, the lack of migration and high inbreeding suggests that these two populations are of incomplete lineage sorting with insufficient evolutionary time for genetic differences to accumulate. Unfortunately, the *B. schellenbergi* samples from the Diamantina Fracture Zone did not yield viable DNA sequences to test further species connectivity at hadal depths across the area.

The Weber Basin (or Banda Trench; Area B) represents a unique location for hadal research in other ways. Belyaev (1989) reported that the Banda Trench was the warmest trench in the world (3.43–3.63 °C at 6000–7293 m depth), has the lowest salinity (34.58 to 34.67 *psu*) and the lowest oxygen concentration (2.03–2.38 ml.l<sup>-1</sup> / 27–32% saturation). While many isolated trenches are bounded by often vast areas of abyssal plain, the Weber Basin and the two small depressions within the Banda Basin are encircled by depths of < 1000 m.

The area between the Massau and New Hebrides trenches (Area C) is an important area for hadal biological research in that it contains nine hadal features that that total 75,696 km<sup>2</sup> and represents the most intricate network of hadal ecosystems in the world. It hosts a complex network of trenches running from northwest to southeast spanning 30° of latitude. The largest hadal feature is the New Britain Trench (30,849 km<sup>2</sup>). The lack of any partition between the northern and eastern section of the arc confirms that the Bougainville Trench, as an individual hadal feature, does not exist and therefore any literature pertaining to hadal species or

habitats from the Bougainville Trench can be merged with that of the New Britain Trench (e.g., Birstein and Sokolova 1960; Birstein 1963; Kudinova-Pasternak 1965; species lists in Belyaev 1966, 1989). Conversely, other trenches of similar size and shape to the New Britain Trench - San Cristobal and Santa Cruz trenches - do represent two distinct hadal features with a 74 km shallow water divide 4864 m deep. Here there are opportunities to examine if and how trench populations are connected.

South of New Zealand (Area D), the Puyseger Trench technically has a hadal footprint, but only comprising 459 km<sup>2</sup> across seven small depressions averaging just 6208 m. The main features in this area are the Hjort Trench and Antipodes Fracture Zone that have larger hadal areas of 4527 and 7819 km<sup>2</sup>, and maximum depths of 6614 and 6339 m respectively. These features are not only geographically isolated from other hadal systems with significant land masses or distances of > 1800 km between other identified hadal areas (Stewart and Jamieson 2018) but are also located very far south. In the case of the Hjort Trench, it is not only very close to the 60°S boundary latitude of the Southern Ocean but is also located within waters of the Antarctic Polar Front (Hodgson et al. 2014). This places the Hjort Trench as a lone Antarctic trench on the opposite side of the Antarctic continent to the only other Antarctic trenches at comparable latitudes: the South Orkney and South Sandwich trenches (Smirnov, 2000; Jamieson et al. 2021b) located over 7000 km away. Similarly, the Antipodes Fracture Zone is isolated from the Kermadec Trench to the north and the Hjort Trench to the southwest by 1800 km.

## Nomenclature

One complication in defining the exact number and extent of hadal habitats is perhaps simply inconsistent nomenclature. For instance, GEBCO and ACUF often recognise different names, for example the North New Hebrides and Torres trenches represent the same geological feature, however the term ‘Santa Cruz Trench’ is frequently used in scientific literature, making this issue difficult to resolve. To avoid confusion with the New Hebrides Trench immediately south of this feature, we suggest that the name North New Hebrides should fall into abeyance. Furthermore, the Anglo-French New Hebrides Condominium no longer exists and has been succeeded by the independence of Vanuatu in 1980, therefore it seems appropriate to discontinue use of the colonial name. The name Torres is also contentious as the Torres Island in the Torba Province of Vanuatu are located south of this trench at the north end of the New Hebrides Trench. Therefore, perhaps the Santa Cruz Trench moniker is the most appropriate as the trench lies to the west of the Santa Cruz Islands in the Temotu province of the Solomon Islands.

Furthermore, consideration should be given to renaming the San Cristobal Trench the ‘Makira Trench’ as the nearby island of San Cristobal is more commonly known as Makira. This would result in more geographically fitting names in the same manner as dropping the Admiralty Trench in favour of the West Melanesian Trench, although the former is not recognised by GEBCO or the ACUF. The ACUF does recognise the Manus Trench, while GEBCO recognises the West Melanesian Trench. However, given it runs for 1400 km east of Papua New Guinean province of Manus, the name West Melanesian Trench seems more appropriate. The Massau Trench is named after the Papua New Guinean island of Massau at its southern point, whereas the Lyra Trough is located near the remote submerged coral atoll of the Lyra Reef in the Bismark archipelago. The names Cape Johnson Trough and Vitjaz Trench are named after the American and Russian ships that discovered them but are both located with the EEZ of the Solomon Islands. Perhaps more geographically relevant names could be adopted for these two features.

The second largest hadal feature in this area is the New Hebrides Trench at 11,886 km<sup>2</sup>. The renaming of this trench to the Vanuatu Trench may be more appropriate to mirror the change in the name of the Islands. However, with the establishment of 200 nautical mile Vanuatu Exclusive Economic Zones in 1982, this trench now spans both the EEZ of Vanuatu and Nouvelle-Calédonie (New Caledonia), an overseas territory of France, with the easternmost end of the trench (and Hunter Fracture Zone) located in the EEZ of the Republic of Fiji.

## Feature definition

This study raises issues in quantifying the number of hadal features. For example, the number of hadal trenches reported ranges from 14 (Smith and Demopolous, 2003), 22 (Angel 1982), 32 (Vinogradova et al. 1993), 37 (Herring, 2002), 46 (Jamieson 2015), 55 (Belyaev 1989), 56 (Harris et al. 2014) to 95 (Priede 2018). These numbers vary greatly as a result of differing definitions of ‘hadal feature’. Within these lists are combinations of trench-only features, or lists including hadal troughs, basins, and/or fracture zones, and in some cases trenches that are not hadal.

The International Hydrographic Organisation have set definitions of each of these features (IHO 2008). For example, basins are “depressions more or less equidimensional in plan and of variable extent”, troughs are “A long depressions generally wide and flat bottomed with symmetrical and parallel sides”, Fracture Zones are “long narrow zones of irregular topography formed by the movement of tectonic plates associated with an offset of a spreading ridge axis, characterized by steep-sided and/or asymmetrical ridges,



troughs or escarpments”, and trenches are “long, deep, asymmetrical depression with relatively steep sides, that is associated with subduction.”

These definitions are to all intents and purposes good descriptors in geomorphology, it is arguably the ‘hadal’ component discussed in this analysis that complicates matters. Several troughs and basins may appear as one large geomorphological feature, but in a hadal context – truncated at the 6000 m contour – can appear fragmented, often over large distances. This bathymetric truncation between ‘abyssal’ and ‘hadal’ can give the impression of more trough like characteristics when in reality it might only be the deeper part of a more defined feature. For example, the Antipodes Fracture Zone described here, is represented at hadal depths by trough like depressions which are simply the deeper end of a much larger fracture zone. The definition of the term “fractures zone” is perhaps the most succinct as by the nature in which they form, are visible as discrete and isolated features, often presented parallel to one another along a ridge system. However, the definition of a trench does not easily mirror that which is considered common nomenclature. An example from this study is the Java Trench that in practical terms is one large trench but at hadal depths is partitioned into two parts by a subducting seamount. However, the physical partitioning by a subducting seamount between the Kermadec and Tonga trenches is taken as being the divide between two distinct features. This is why Priede (2018) defined Java Trench as ‘Java East’ and ‘Java West’. Conversely the only difference between the New Britain and Bougainville trenches is that the trench changes direction as there is no partition between them. However, the New Britain Trench does have a partition towards the west end, meaning technically (using the Kermadec-Tonga principle), the New Britain Trench could be considered only the west end depression and the rest of the ‘right-angled’ trench being the Bougainville Trench.

Whether any of these inconsistencies will ever be resolved is a matter for the Nations whose exclusive economic zone (EEZ) that encompass these features. The important point is that future studies are aware of such inconsistencies and factor physical partitions and connectivity into sampling designs.

## Conclusion

This study represents the second of two areas identified by Jamieson and Stewart (2021) as particularly complex with respect to defining the extent of the hadal zone. The other area, the northwest Pacific, was found to have 14 trenches, 15 basins and troughs, and four fracture zones (Jamieson and Stewart 2021). Respectively, these accounted for 32.4,

**Table 3** Total number of individual habitats > 6000 m deep, categorised as trench, basin or fracture zone and the total area > 6000 m (km<sup>2</sup>) of each from this study combined with the Northwest Pacific study of Jamieson and Stewart (2021)

Feature Type	Indo-Pacific	NW Pacific	Total area (km <sup>2</sup> ) [%]
	Hadal Features	Hadal Features	
Subduction Trench	13	14	1,104,286 [38.9]
Basins/troughs	9	15	1,584,127 [55.9]
Fracture Zones	4	4	147,843 [5.2%]
Total	26	33	2,836,256

62.2 and 5.4% of the 2,119,341 km<sup>2</sup> of hadal seafloor in the region. Combining those results with this study, therefore covering the entire West Pacific and East Indian oceans, the majority of the hadal zone is accounted for in basins and troughs (56%; Table 3) with trenches and fracture zones accounting for 38.9 and 5.2% respectively. This highlights that the hadal zone is largely made up of two main geomorphological features that differ in size, depth and complexity, and sampling designs and interpretation of ecological data must therefore differ in approach. The hadal basins are large sprawling areas but generally much shallower systems, likely more akin to abyssal plains, whereas trenches, despite a lesser footprint, represent much great depth ranges and more complex habitats in the interior (Stewart and Jamieson 2018). Although basins are perhaps best studied using methods typically adopted in abyssal plain studies, they do extend beyond the 6000 m hadal contour that is being increasingly recognised to observe a distinct shift in fauna (Jamieson 2015). Therefore, in the future it is perhaps the hadal basins that will play an increasingly important role in understanding the ecological shifts from abyssal to hadal ecosystems.

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**Author contributions** AJJ and HAS conceived the study. GTG led on bathymetric analyses of hadal zones. AJJ and HAS wrote the main manuscript text. HAS prepared all figures. All authors reviewed and edited the manuscript.

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**Data availability** Bathymetric datasets used in this study can be found through the open-access Global Multi-Resolution Topography Synthesis ([www.gmrt.org](http://www.gmrt.org)) released CC BY 4.0 Deed | Attribution 4.0 International | *Creative Commons*, which can be cited thus: Ryan, W.B.F., Carbotte, S.M., Coplan, J.O., O’Hara, S., Melkonian,

A., Arko, R., Weissel, R.A., Ferrini, V., Goodwillie, A., Nitsche, F., Bonczkowski, J., Zemsky, R., 2009. Global Multi-Resolution Topography synthesis. *Geochem. Geophys. Geosyst.* 10, Q03014, doi: <https://doi.org/10.1029/2008GC002332>.

## Declarations

**Ethics approval and consent to participate** Not Applicable. No human participants and/or biological material were used in this study. No geological or palaeontological material has been used in this study. The submitted work is original and has not been published elsewhere in any form or language.

**Competing interests** The authors declare no competing interests.

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