Earth-Science Reviews 197 (2019) 102896

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

# The five deeps: The location and depth of the deepest place in each of the world's oceans

Heather A. Stewart[a,*], Alan J. Jamieson[b]

[a] British Geological Survey, Lyell Centre, Research Avenue South, Edinburgh EH14 4AP, UK
[b] School of Natural and Environmental Sciences, Newcastle University, Newcastle Upon Tyne NE1 7RU, UK

ARTICLE INFO

*Keywords:*
Bathymetry
Deepest places
Hadal zone
Oceanic trenches, five oceans

ABSTRACT

The exact location and depth of the deepest places in each of the world's oceans is surprisingly unresolved or at best ambiguous. Out of date, erroneous, misleading, or non-existent data on these locations have propagated uncorrected through online sources and the scientific literature. For clarification, this study reviews and assesses the best resolution bathymetric datasets currently available from public repositories. The deepest place in each ocean are the Molloy Hole in the Fram Strait (Arctic Ocean; 5669 m, 79.137° N/2.817° E), the trench axis of the Puerto Rico Trench (Atlantic Ocean; 8408 m 19.613° N/67.847° W), an unnamed deep in the Java Trench (Indian Ocean; 7290 m, 11.20° S/118.47° E), Challenger Deep in the Mariana Trench (Pacific Ocean; 10,925 m, 11.332° N/142.202° E) and an unnamed deep in the South Sandwich Trench (Southern Ocean; 7385 m, 60.33° S/25.28° W). However, discussed are caveats to these locations that range from the published coordinates for a number of named deeps that require correction, some deeps that should fall into abeyance, deeps that are currently unnamed and the problems surrounding variable and low-resolution bathymetric data. Recommendations on the above and the nomenclature and definition of deeps as undersea features are provided.

## 1. Introduction

Much of the world's ocean, in particular the open ocean, deep-sea and polar regions are profoundly inaccessible. Their great depths, remoteness and immense size also renders exploration and the mapping of undersea features an ongoing laborious process and as such only a small fraction has been bathymetrically mapped (Weatherall et al., 2015; Mayer et al., 2018). Yet humankind has always had great enthusiasm for not only discovering new territories and features but naming them in pursuit of cultural ownership and in order to establish their place within the known landscape. Therefore, in addition to the political and economic advantages associated with exploration, there is an underlying curiosity-driven, subjective appreciation of the Earths landscape. Furthermore, within sometimes arbitrary topographical categories, humans are intrinsically drawn to those at the ends of any given extreme. Fascination and inspiration is habitually drawn from the highest mountain, the longest river, the biggest ocean, the deepest trench, amongst many others at national, intercontinental or global levels. These world-record places are part of the heritage of humankind and not only tell us a lot about the planet in which we inhabit but provide the platform for awe and wonder.

Through relative ease of accessibility there is a far greater body of knowledge about the terrestrial landscape than that of our undersea landscapes, and indeed, the oceans are still often referred to as the last frontier on Earth. Yet looking at any large scale map of the seafloor, our knowledge regarding depth and morphology appears complete. However, much of the water depth information is derived from satellite altimetry rather than acoustic surveys (Smith and Sandwell, 1997; Becker et al., 2009) and as such there are dramatic variations in the resolution of our mapping of the seafloor. This variation is not only born from the difference in ever-evolving technological capability but the collation of information spanning very long timescales. The immense area occupied by the ocean makes a complete high resolution up-to-date map a long way off, but within the current body of marine geomorphological mapping it would be reasonable to assume we have as much of an understanding of where the deepest places are as we do the highest mountains, however, this has not been the case.

Satellite altimetry-derived global bathymetry datasets have represented a significant advancement in large-scale ocean mapping (Harris et al., 2014), yet only provide a generalised view of the shape of the seafloor (Smith and Sandwell, 1997; Becker et al., 2009), as they do not provide sufficient resolution to perform robust geomorphometric analyses (Lecours et al., 2016). They provide general estimates of water depths and coarsely fills gaps between sparse ship soundings (Smith and

* Corresponding author.
*E-mail address:* hast@bgs.ac.uk (H.A. Stewart).

https://doi.org/10.1016/j.earscirev.2019.102896
Received 18 July 2018; Received in revised form 5 July 2019; Accepted 7 July 2019
Available online 09 July 2019

Sandwell, 1997; Becker et al., 2009), but it is, however, less precise than single-beam echosounder-derived data and has far less resolution than multibeam echosounder systems.

A recent study (Mayer et al., 2018) reviewed the General Bathymetric Chart of the Oceans (GEBCO_2014; www.gebco.net) global compilations of bathymetric data and concluded that despite the appearance of complete global coverage of ocean depths, these datasets are deceptive as modern interpolation and visualization techniques produce apparently complete representations of ocean depth from apparently sparse data points. When the GEBCO_2014 dataset is interrogated and divided into its resolution of 30 arc-second grid cells (926 m at the equator), approximately 82% of the grid cells do not include a single depth measurement (Weatherall et al., 2015), in other words, the percentage of the seafloor that has been constrained by measured data or pre-prepared grids that may contain some interpolated values is < 18% (Weatherall et al., 2015; Mayer et al., 2018).

The most recent calculation of the ocean's mean and median depth is 3897 and 3441 m respectively (Weatherall et al., 2015), however, the average horizontal resolution at those water depths is about 8 km (Mayer et al., 2018). Depths > 3000 m account for 75.3% of the world's oceans, an area covering 230,910,385 km$^2$, of which 85% of it is uncharted (equal to 69% of the entire ocean; Mayer et al., 2018). This means asking simple questions like 'where are the deepest places in the world?' or 'what is the maximum depth of each ocean', very difficult to answer with confidence as the intricacies of seafloor morphology are largely unresolved and exacerbated at ever greater depths.

### *1.1. Peaks and troughs*

Mountains provide extremely topographically diverse high altitude environments (Ives et al., 1997) and are found on every continent culminating at the highest place on the earth, Mount Everest, at 8848 m above sea level (Gruen and Murai, 2002). It is widely recognised that mountains are of significant global importance in recognition of the interrelationships of high elevation ecosystems, the people who inhabit them, and as centres for biodiversity (Barthlott et al., 1996; Ives and Messerli, 1990).

From a human perspective, one of the great mountaineering challenges is to climb the 'seven summits', meaning the highest mountain on each of the seven continents. Alternatively there are the 'eight-thousanders' which are the 14 independent mountains > 8000 m above sea level. There are however slight variations in what are considered the highest points. The ambiguity arises in regards to the definition of a continent, for example, whether only mainland Australia is used or the larger region of Oceania. There are also ambiguities in relation to the exact altitude of some of these mountains, for example, when a mountain is situated a significant distance from the coast, sea level is often difficult to define. Even detailed surveys of Mount Everest range from 8840 m to 8850 m which emphasizes the uncertainties in the recorded heights and has remained problematic for some time (de Graaff-Hunter, 1955; Gruen and Murai, 2002; Mishra et al., 2015).

The highest summits of the world are analogous with the deepest places in the ocean. The maritime equivalent to the 'seven summits' include the deepest point in each ocean, or the 'five deeps' (Fig. 1), and similar to the 'eight thousanders', there are five locations that exceed 10,000 m water depth: the 'ten thousanders'. A common statement in popular marine science is that *"the Mariana Trench is so deep that Mount Everest would fit inside it with a mile to spare"*, but there are other similarities between these two unique places. The Himalayas are 2400 km long and the Mariana Trench is 2550 km long, scientists have had problems in both measuring the exact height above sea level of Mount Everest (Mishra et al., 2015) and the exact depth of the Challenger Deep in the Mariana Trench (e.g. Gardner et al., 2014; van Haren et al., 2017) and both are considered the ultimate 'end points' in exploration (Piccard and Dietz, 1961).

### *1.2. Underlying rationale*

The problems of defining these maritime end points in the pursuit of exploration based on unreliable data is exemplified by the 2011 announcement that the company Virgin Oceanic were constructing a full ocean depth manned submersible. *DeepFlight Challenger*, is anticipated to explore the deepest point in each ocean, a challenge akin to the 'seven summits'. The press release stated that they planned to dive the Mariana Trench (Pacific Ocean, 11,033 m), Molloy Deep (Arctic Ocean, 5608 m), Puerto Rico Trench (Atlantic Ocean, 8605 m), South Sandwich Trench (Southern Ocean, 7235 m) and the Diamantina Trench (Indian Ocean, 8047 m). However, by interrogating publically available global compilations of bathymetric data and peer-reviewed literature, it is concluded that none of these water depths are correct: Challenger Deep in the Mariana Trench is not > 11,000 m deep (10,925 m; van Haren et al., 2017), the Puerto Rico Trench and Diamantina Trench are somewhat shallower (8408 and 7090–7100 m respectively), and the South Sandwich Trench and Molloy Hole are deeper (8183 and 5669 m respectively), than the depths cited in the *DeepFlight Challenger* press release. Furthermore, the Diamantina Trench is not a trench, it is a fracture zone (as per guidelines for naming undersea features listed by the International Hydrographic Organization and the Intergovernmental Oceanographic Commission (IHO-IOC), see Holcombe, 1977), and is not the deepest place in the Indian Ocean which is actually located within the Java Trench (7290 m). Also, much of the South Sandwich Trench is in the Atlantic Ocean with the location for the deepest point in the trench recorded as being of a latitude of 55°S, and thus short of the 60°S boundary between the Atlantic and Southern oceans. Thus placing their South Sandwich Trench dive site in the South Atlantic Ocean and not the Southern Ocean as advertised.

The sources of these erroneous depths are not easily traced to the original citation and are often so widespread in literature and popular internet sites that they are difficult to correct (Table 1). The depth of 11,034 m for the Challenger Deep originates from the Soviet expedition on-board the ship *Vityaz* in 1957 although there is doubt surrounding the sound velocity correction for their echosounder data (discussed in Gardner et al., 2014). A 'deep' > 11,000 m water depth has never been found in subsequent surveys utilising more advanced technology (e.g. Nakanishi and Hashimoto, 2011), yet the depth record persists. Websites like Wikipedia complicate matters further, for example, the entry for the Diamantina Fracture Zone refers to it as a Trench and states it is *not* the deepest place in the Indian Ocean (7079 m) but directs the reader to the 'Diamantina Deep', apparently located within the Diamantina Fracture Zone and states it *is* the deepest point in the Indian Ocean at 8047 m water depth. Other entries state that the 'Litke Deep' (350 km north of Svalbard) is the deepest point in the Arctic Ocean (5449 m), while asserting that the Molloy Deep (5669 m) is not the deepest point in the Arctic Ocean as it is located in the Fram Strait, but does not cite any primary literature. However, the Fram Strait *is* within the Arctic Ocean, as stated when the reader is taken to the Arctic Ocean entry on the same website. These examples are given solely to illustrate the incongruences of data at the time of writing.

Furthermore, there are also discrepancies when global compilations of bathymetric data are interrogated. For example, using Geographic Information System (GIS) software to study large-scale trench topography derived from GEBCO_2014 can often lead to erroneous depths and locations. Examples of this include the Kuril-Kamchatka Trench, whereby GEBCO_2014 bathymetry places the deepest point at 44.07° N/150.18° E at 10,542 m (Jamieson, 2015) but a recent expedition on the RV *Sonne*, equipped with an EM122 multibeam echosounder failed to find depths > 9500 m (Brandt, 2016). Similarly, on the same vessel with the same multibeam echosounder system, an expedition transiting the Indian Ocean acquired data over the Wallaby-Zenith Fracture Zone with an estimated water depth of 7700 m (extracted from GEBCO_2014 data). However, the EM122 bathymetric data revealed the maximum water depth of the fracture zone to be a little over 6500 m (A. J.

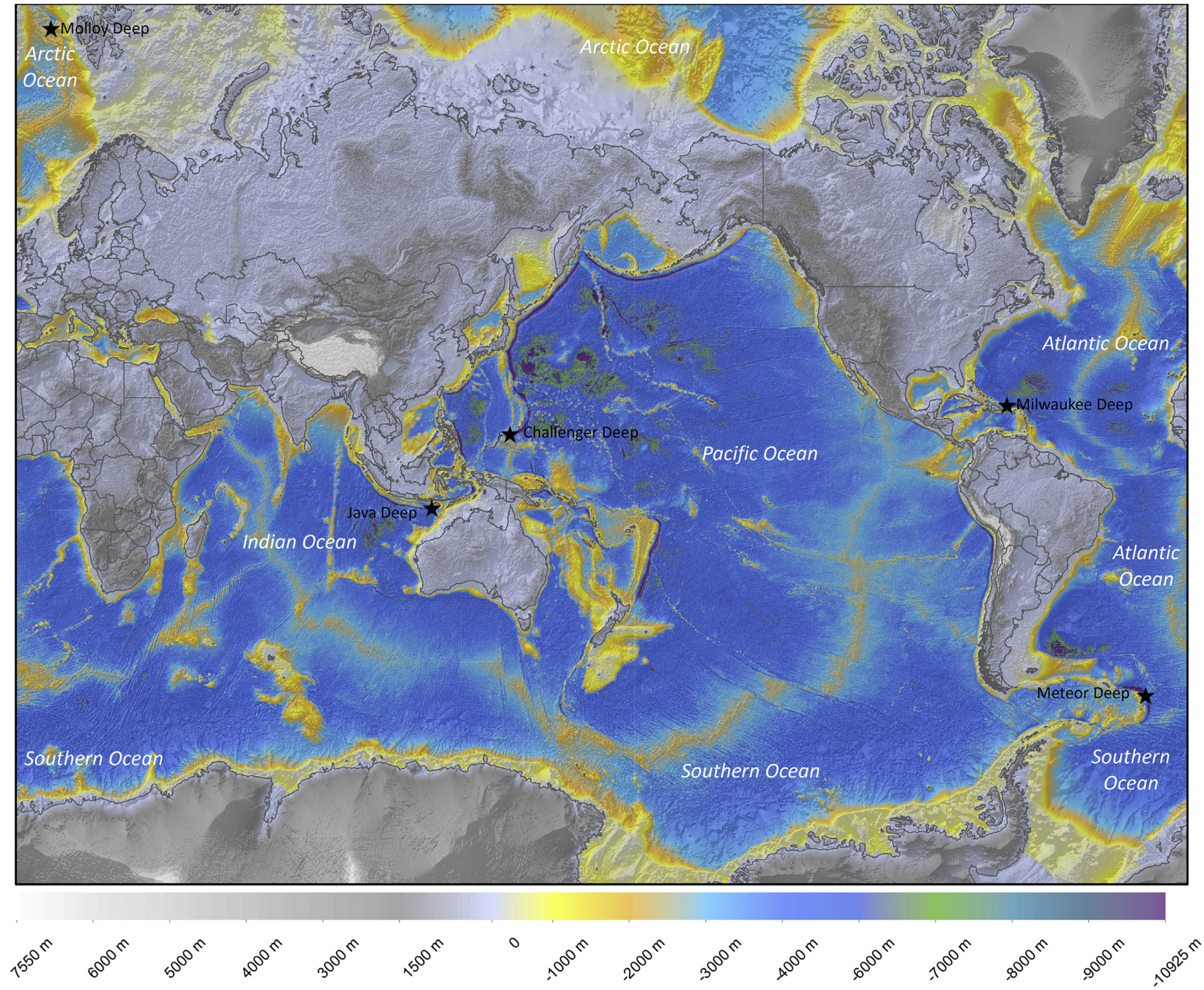


**Fig. 1.** Map showing the global location of the five deepest point of the five oceans. All data sourced from the Global Multi-Resolution Topography Synthesis (Ryan et al., 2009).

Jamieson personal observation; Werner et al., 2017). These examples demonstrate that global compilations, although include many areas of high-resolution, shipborne bathymetric soundings, also include areas where data are sparse and this must be taken into account during subsequent analyses.

The main objective of this study was to assess and locate the deepest points within the Arctic, Atlantic, Indian, Pacific and Southern oceans using the best data currently available via open access repositories. 'Deeps' are confined areas that represent the deepest point of a trench, fracture or basin. The focus of this study was to determine not only the location of these 'deep' points but to assess the quality of the data available and to assign a confidence value to those locations. The study was incentivised by the forthcoming '5-Deeps Expedition' (www.fivedeeps.com) on the Deep Submergence Support Vessel (DSSV) *Pressure Drop* to dive a new 11,000 m rated 2-man submersible, the Deep Submergence Vehicle (DSV) *Limiting Factor,* to the deepest point in each ocean.

## 2. Materials

### 2.1. Data sources

A data mining exercise was undertaken to search for publically available bathymetry data which included multibeam echosounder bathymetry acquired by scientific research cruises, single-beam echosounder bathymetry data acquired by both research and commercial vessels. Where no better data are available, global compilations from the GEBCO_2014, the International Bathymetric Chart of the Southern Ocean (IBCSO) and International Bathymetric Chart of the Arctic Ocean (IBCAO) were used. These latter three data sources utilised satellite altimetry in areas where data are sparse (e.g. the Shuttle Radar Topography Mapping 30 arc sec database (SRTM30_PLUS) altimetry-derived bathymetry (Becker et al., 2009)).

The most comprehensive publically available bathymetry were derived from the Global Multi-Resolution Topography (GMRT Synthesis; www.marine-geo.org) which comprises tiled, multiresolution, bathymetry datasets complete with source citations (Ryan et al., 2009). Each gridded tile set involves computing weighted averages of depth estimates at the nodes for each grid tile, designed to ensure preservation of

**Table 1**
List of the many published depths and location of potential sites for the deepest point in each ocean. For the deepest point in the Pacific Ocean the vessel and year of survey are given in italics where known. The precision in latitude and longitude is replicated from the source material cited although it should be noted that the accuracies of both modern and historical single-beam and multibeam echosounders and navigation systems, mean that a number of the positions published have an unreasonable level of accuracy (e.g. 0.000001 implies the position is known to one millionth of a degree, or 10 cm).

| Ocean | Feature | Latitude | Longitude | Depth (m) | Source |
|---|---|---|---|---|---|
| Arctic | Molloy Hole | 79.136667° N | 2.816667° E | 5669 | Klenke and Schenke (2002); Klenke and Schenke (2006a, 2006b) |
| | | 79.141° N | 2.798° E | 5573 | Jakobsson et al. (2012) |
| | | 79.166667° N | 2.833333° E | 5770 | Bourke et al. (1987) |
| | | 79.141667° N | 2.783333° E | 5669 | Thiede et al. (1990) |
| Atlantic | Milwaukee Deep (Puerto Rico Trench) | 19.58333° N | 66.5° W | 8740 | GEBCO Gazetteer |
| | | 19.6° N | 68.31667° W | 8710 | Lyman (1954) |
| | Puerto Rico Trench | 19.773° N | 66.928° W | 8526 | Stewart and Jamieson (2018) |
| Indian | Java Deep | 9.315193° S | 108.905716° E | 7725 or 7450 | GEBCO Gazetteer |
| | Java Trench | 11.1710° S | 118.4669° E | 7204 | Stewart and Jamieson (2018) |
| | Diamantina Deep (Diamantina Fracture Zone) | 35° S | 104° E | 8047 | GEBCO Gazetteer |
| | Dordrecht Deep (Diamantina Fracture Zone) | 33.42° S | 101.48° E | 7079 | GEBCO Gazetteer |
| | Diamantina Fracture Zone | 34.807° S | 102.567° E | 7324 | Stewart and Jamieson (2018) |
| Pacific | Challenger Deep (Mariana Trench) | 11.332417° N | 142.20205° E | 10,925 ± 12 | van Haren et al. (2017)<br>*RV Sonne 2016* |
| | | 11.329903° N | 142.199305° E | 10,984 ± 25 | Gardner et al. (2014)<br>*USNS Sumner 2010* |
| | | 11.326344° N | 142.187248° E | 10,994 ± 40 | Gardner and Armstrong (2011)<br>*USNS Sumner 2010* |
| | | 11.371° N | 142.593° E | 10,920 ± 5 | Nakanishi and Hashimoto (2011)<br>*Kairei 1998/99* |
| | | 11.373333° N | 142.591667° E | 10,920 ± 10 | GEBCO Gazetteer |
| | | 11.382° N | 142.4376° E | 10,744 | Fryer et al., 2003<br>*MR1 1997* |
| | | 11.3349° N | 142.1967° E | 10,896 | KAIKO remotely operated vehicle (ROV) (2002) cited in Todo et al. (2005) |
| | | 11.368333° N | 142.59° E | 10,903 | Bowen et al. (2009)<br>ROV Nereus |
| | | 11.3767° N | 142.5833° E | 10,989 | Taira et al. (2005)<br>*Hakuho-Maru 1992* |
| | | 11.3767e N | 142.5833° E | 10,890 | Taira et al. (2004) |
| | | 11.339° N | 142.22° E | 10,938 ± 10 | Fujioka et al. (2002)<br>*Kairei 1998* |
| | | 11.373337° N | 142.59167° E | 10,933 | Fujimoto et al. (1993)<br>*Hakuho-Maru 1992* |
| | | 11.373337° N | 142.59167° E | 10,920 ± 10 | *S/V Takuyo of the Hydrographic Department of the Japan Maritime Safety Agency (1984)* (Hydrographic Department, 1984) |
| | | 11.333° N | 142.197° E | 10,915 ± 10 | R.L. Fisher (pers comm. In Nakanishi and Hashimoto (2011)) Thomas Washington 1975 and 1980 |
| | | 11.333° N | 142.197° E | 10,915 ± 20 | Fisher and Hess (1963)<br>*Spenser F. Baird 1977* |
| | | 11.333° N | 142.197° E | 10,850 ± 20 | Fisher and Hess (1963)<br>*Stranger 1959* |
| | | 11.34833° N | 142.191667° E | 11,034 ± 50 | *Vityaz 1957* |
| | | 11.316667° N | 142.25° E | 10,863 ± 35 | Carruthers and Lawford (1952)<br>*Challenger VIII 1951* |
| | | 11.400° N | 143.267° E | 8184 | Thomson and Murray (1895)<br>*HMS Challenger 1875* |
| Southern | South Sandwich Trench | 56.243° S | 24.836° W | 8125 | Stewart and Jamieson (2018) |
| | Meteor Deep (South Sandwich Trench) | 55.6667° S | 25.9167° W | 8325 | Zhivago (2002) |
| | | 55.67° S | 25.92° W | 8428 | Allaby (2009) |
| | Unnamed Deep (South Sandwich Trench) | 60° S | 24° W | 7235 | Untraceable source but cited in Wikipedia (https://en.wikipedia.org/wiki/South_Sandwich_Trench) |

Note 'GEBCO Gazetteer' refers to the IHO-IOC GEBCO Gazetteer of Undersea Feature Names.

the data whilst avoiding introduction of data artefacts in the resultant Digital Elevation Model (DEM) (Ryan et al., 2009). The GMRT Synthesis also comprises gridded seafloor depths where multibeam bathymetry data are absent (30 arc sec resolution which equates to approximately 1 km) derived from GEBCO_2014 (Weatherall et al., 2015). Another source of bathymetric data is the National Oceanic and Atmospheric Administration National Centers for Environmental Information (NOAA-NCEI) (www.ncei.noaa.gov; NOAA National Centers for Environmental Information (2004)) which is the United States national archive for multibeam echosounder data with the ability to create binary grids of the data in an area of interest able to be imported into ArcGIS. ArcGIS grids of the bathymetry data were produced at the resolution of the dataset with additional layers of bathymetric contours, slope, and aspect derived from the bathymetry data and were generated in ArcGIS using the spatial analyst extension and Benthic Terrain Modeler (Walbridge et al., 2018).

### *2.1.1. Arctic Ocean*

The Arctic Ocean is the smallest and shallowest of the world's five major oceans. This water body is completely surrounded by the continents of Asia, North America, Europe and the island of Greenland. The Molloy Hole is located in the Fram Strait between Greenland and Svalbard, and is considered to represent the southern node of the Molloy seafloor spreading area (Freire et al., 2014). The 'deep' is broadly circular with a relatively featureless seafloor topography (Fig. 2). Terminal slide deposits from the Molloy Slide, the deepest

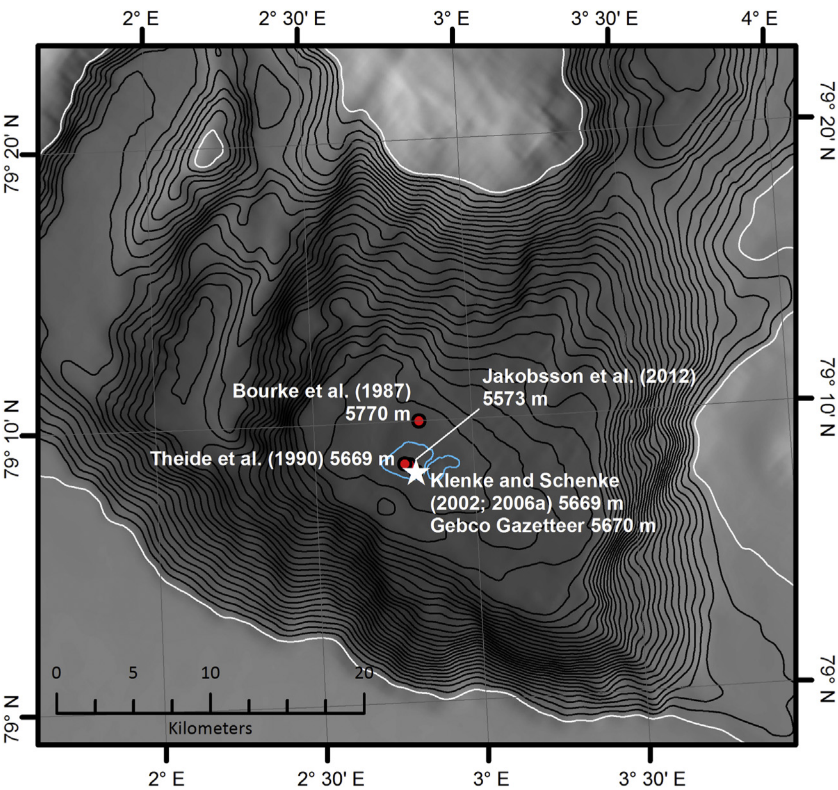


**Fig. 2.** Map of the Molloy Hole within the Fram Strait with the locations of published 'deeps' (red circles) and the deepest point determined by Klenke and Schenke (2002) (white star = 5669 m water depth) (Table 1). The outer rim of the Molloy Hole lies at 2700 m water depth (white contour). The deepest section of the Molloy Hole is defined by the 5600 m contour (blue contour). All other contours at 100 m intervals (between 2700 and 5600 m water depth). Illumination from 270° at an altitude of 35°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mass-wasting deposit in the northern Atlantic and Arctic Ocean, are present in the northern portion of the Molloy Hole marking the downslope limit of the slide (Freire et al., 2014). The headwall of the slide is located east of the Molloy axial rift valley to the north of the Molloy Hole (Freire et al., 2014). The Molloy Hole was previously known as the 'Molloy Deep', although it is noted here that in order to meet standardisation guidelines set by the Sub-Committee on Undersea Feature Names (SCUFN) feature name compilation of GEBCO the term 'Molloy Deep' was changed to 'Molloy Hole' (Klenke and Schenke, 2002). To comply with the SCUFN the term 'Molloy Hole' is used here.

The first comprehensive bathymetric dataset of the Molloy Hole was published by Klenke and Schenke (2002) based on multibeam echosounder data acquired by the R/V *Polarstern* between 1984 and 1997. These data were gridded at 100 m resolution (Fig. 2) and formed the basis of an updated bathymetric chart of the Fram Strait (Klenke and Schenke, 2006a) and were available to download from the Pangaea world data centre (www.pangaea.de; Klenke and Schenke, 2006b). Subsequently Freire et al. (2014) published a study using processed multibeam echosounder data acquired in 2009 at a resolution of 30 m whereby the older data collated by Klenke and Schenke (2006b) was used to infill the gaps where the 2009 data were absent. The Freire et al. (2014) dataset was not available for this study from public repositories such as GMRT Synthesis, NOAA-NCEI or Pangaea. IBCAO version 3.0 (Jakobsson et al., 2012) includes the area of the Molloy Hole, comprising a base grid of 2 km resolution (from version 2.0; Jakobsson et al., 2008), with higher resolution datasets (mainly multibeam echosounder and Olex), merged onto the base grid at a resolution of 500 m (see Jakobsson et al., 2012 and references therein for detailed methodology). Using the IBCAO source identification grid it is revealed that multibeam echosounder data were included in the compilation covering the Molloy Hole and subsequently gridded at 500 m resolution. Multibeam echosounder data gridded at 100 m resolution as specified by Klenke and Schenke (2006b) were utilised for the purposes of this study.

Reported maximum water depths for Molloy Hole are 5573 m in the IBCAO compilation (Jakobsson et al., 2012), 5669 m as determined by Thiede et al. (1990) and Klenke and Schenke (2002, 2006a) (Fig. 2; Table 1), and 5770 m by Bourke et al. (1987) (Fig. 2; Table 1).

#### 2.1.2. Atlantic Ocean

The Atlantic Ocean is the second largest of the world's oceans, bounded to the north by the Arctic Ocean and by the Southern Ocean to the south. The continents of North and South America, and Africa and Europe bound the Atlantic Ocean to the west and east respectively. Harris et al. (2014) report the maximum water depth of the North Atlantic Ocean as 8620 m using Shuttle Radar Topography Mapping 30 arc sec database (SRTM30_PLUS, see Becker et al. (2009) for details). The deepest part of the Atlantic Ocean is thought to be the Milwaukee Deep within the roughly east-west oriented Puerto Rico Trench, located around 120 km north of the island of Puerto Rico (Lyman, 1954) (Fig. 3). The Puerto Rico Trench is around 810 km in length and has formed where the North American and Caribbean plates slide (strike-slip plate boundary) past each other with only a small component of subduction (on the eastern boundary resulting in the Lesser Antilles volcanic island arc). The Caribbean plate is drifting eastward at approximately 20 mm per year relative to the North American plate (De Mets et al., 2010). The small component of subduction has resulted in a wider and unusually smooth seafloor west of ~65° W underlain by normal fault bounded blocks (ten Brink, 2005) that manifest morphologically as a small number of elongated ridges along the trench bottom and an absence of confined 'deeps'. East of ~65° W the trench is narrower with the seafloor morphology revealing a number of escarpments descending stepwise into the trench axis (ten Brink, 2005). A complex interplay of faulting related to reactivation of an existing tectonic fabric and bend-related faulting of the subducting plate in the eastern section of the Puerto Rico Trench forms a network of trench-axis grabens, or confined 'deeps', as has been documented in other subduction settings (e.g. Masson, 1991; Stewart and Jamieson, 2018). Such features are absent in the western portion of the Puerto Rico Trench.

Data from both the GMRT Synthesis and NOAA-NCEI portal were compared to ensure the same surveys were included in both data compilations. Both compilations included multibeam echosounder data

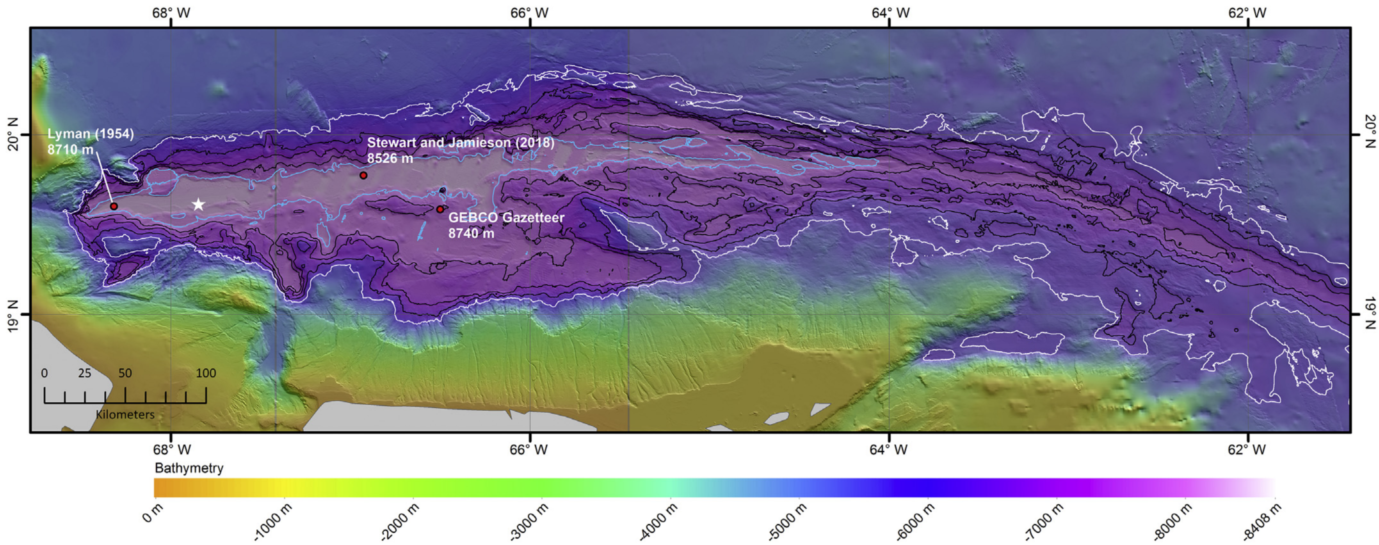


**Fig. 3.** Map of the Puerto Rico Trench with the published Milwaukee Deep locations (red circles) (Table 1) and the deepest point of the trench determined by this study (white star = 8408 m water depth). The 6000 m depth contour is shown in white. The deepest section of the trench is defined by the 8000 m contour (blue). All other contours at 500 m intervals (between 6000 and 8000 m water depth). Illumination from 20° at an altitude of 25°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from eight surveys between 1996 and 2015, with the resultant DEM gridded at 60 m resolution (Fig. 3). The DEM is infilled with data derived from the GEBCO_2014 global bathymetry dataset.

Documented maximum depths of the Milwaukee Deep vary from 8740 m as published in the IHO-IOC GEBCO Gazetteer of Undersea Feature Names, 8710 m as recorded by Lyman (1954), and 8526 m as determined by Stewart and Jamieson (2018) from analysis of the GEBCO_2014 global bathymetry dataset (Fig. 3; Table 1).

### 2.1.3. Indian Ocean

The Indian Ocean is bounded by the continents of Asia and Africa to the north and west respectively, Australia to the east and by the Southern Ocean to the south. There are two areas that have been historically claimed as the deepest point in the Indian Ocean; the Java (Sunda) Trench and the Diamantina Fracture Zone (e.g. Kopp et al., 2009, 2013; IHO-IOC GEBCO Gazetteer). Due to very similar estimated depths and the variation in those estimated depths, both the Java Trench and the Diamantina Fracture Zone are considered in this study.

The Java Trench, also known as the Sunda Trench, is located south and west of the islands of Java and Sumatra in the eastern Indian Ocean, and is in excess of 3200 km in length. The trench is formed as the Indo-Australian Plate subducts beneath the Eurasian Plate, at a rate of between 60 and 73 mm per year (De Mets et al., 2010).

The only publically data available covering the deepest portions of the Java Trench were the GEBCO_2014 global bathymetric compilation available at a resolution of 30 arc sec (Fig. 4A).

The documented maximum depths vary from 7725 m or 7450 m in the Java Deep as recorded in the IHO-IOC GEBCO Gazetteer of Undersea Feature Names, Harris et al. (2014) reporting the maximum water depth as 7318 m, and a maximum depth of 7290 m determined by Stewart and Jamieson (2018) from the GEBCO_2014 global bathymetry dataset (Fig. 4A; Table 1). These two locations are 1067 km apart therefore it can be concluded that there is still debate as to the location of the deepest point of the Java Trench.

The Diamantina Fracture Zone is located southwest of Australia and formed as the Australian and Antarctic continents separated and is in excess of 3400 km in length. Two data sources were available for the Diamantina Fracture Zone: multibeam bathymetry data available from Geoscience Australia and the GMRT Synthesis (Fig. 5A). Both datasets were interrogated for this review and were gridded at 110 m resolution with the Geoscience Australia data comprising single tracks of multibeam echosounder data. The GMRT Synthesis DEM incorporates the Geoscience Australia data as well as a survey from 2004 on-board the research vessel *Nathaniel B. Palmer* that runs along the axis of the fracture zone. The GMRT Synthesis DEM is infilled with data derived from the GEBCO_2014 global bathymetry dataset.

Documented maximum depths vary from 8047 m in the Diamantina Deep and 7079 m in the Dordrecht Deep as recorded in the IHO-IOC GEBCO Gazetteer of Undersea Feature Names and 7324 m as determined by Stewart and Jamieson (2018) from the GEBCO_2014 global bathymetry dataset (Fig. 5A; Table 1).

### 2.1.4. Pacific ocean

The Pacific Ocean is the largest of the world's five oceans and extends from the Arctic Ocean to the Southern Ocean and is bounded to the east by North and South American continents, and to the west by Australasia and the continent of Asia. The Mariana Trench is located southeast of the island of Guam and east of the Mariana Islands and is up to 10,925 m deep (van Haren et al., 2017), is 2550 km in length with a mean width of 70 km (Angel, 1982) (Fig. 6). The trench is formed as the Pacific Plate subducts beneath the Mariana Arc system, part of the Philippine Plate, to the west. This study encompasses only the westernmost portion of the Mariana Trench, oriented roughly west-east.

Two datasets, available from the NOAA-NCEI and the GMRT Synthesis, covering the southernmost area of the Mariana Trench were compared. The multibeam echosounder data includes three surveys undertaken by the U.S. Naval Oceanographic Office USNS *Sumner* in 2010, the RV *Melville* in 2001, and the *Thomas Washington* in 1986. GEBCO_2014 is used to infill areas where multibeam echsounder data are absent with ArcGIS grids of the multibeam bathymetry data produced at a grid size of 120 m for the Mariana Trench (Fig. 6).

A number of expeditions have visited the Mariana Trench in search of the deepest point with > 18 known published depths (e.g. Table 1) including the 1957 *Vityaz* recorded depth of 11,034 m (Taira et al., 2004). The first precise depth was published as 10,915 ± 10 m by Fisher and Hess (1963) using TNT charges and a controlled depth recorder during two expeditions to the region in 1959 and 1962 as many echosounders of the period could not operate in such deep water (Gardner et al., 2014). Over the following 25 years a number of expeditions determined the depth to be within 10,920 ± 10 m which is the value cited in the IHO-IOC GEBCO Gazetteer of Undersea Feature Names. More recently however, van Haren et al. (2017) have provided

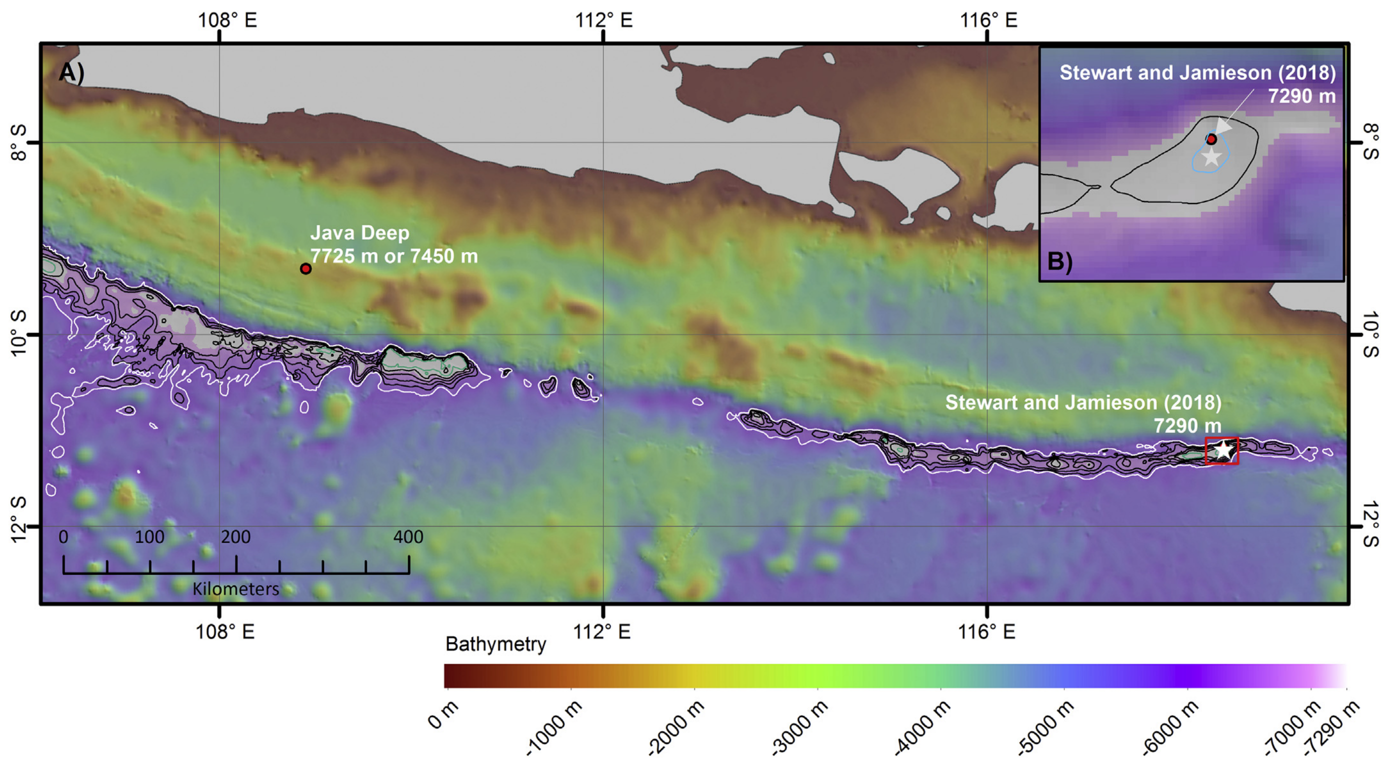


**Fig. 4.** (A) Map of the deepest section of the Java Trench with the locations of published 'deeps' (red circles) (Table 1). The 6000 m depth contour is shown in white. The deepest section of the trench is defined by the 7000 m contour (green). All other contours at 200 m intervals (between 6000 and 7200 m water depth) (B) Inset map of the identified deep within the Java Trench with the deepest point determined during this study (white star = 7290 m water depth) which is within 3 km of the published deepest point by Stewart and Jamieson (2018). The outer rim of the deep lies at 6900 m water depth (black contour). The 7200 m contour is coloured blue. For location of inset map see the red box in Fig. 4A. Illumination from 45° at an altitude of 35°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

an updated position and maximum depth for Challenger Deep, superseding that published by Gardner et al. (2014), using data acquired in 2010 with a Kongsberg EM122 multibeam echosounder, a deepest sounding of 10,925 ± 12 m (Table 2). The van Haren et al. (2017) study suggests that the observed discrepancy with the Gardner et al. (2014) depth is related to the application of the correct sound velocity profile, which is essential for accurate depth determination. Gardner et al. (2014) used Sippican Deep Blue Expendable Bathythermographs (XBTs) to determine the sound velocity for the upper 760 m, whereas van Haren et al. (2017) utilised a shipborne SBE911plus Conductivity Temperature Depth (CTD) that extended down to 8000 m below sea surface. Use of the XBTs whereby the sound velocity is extrapolated from 760 m below sea surface to 12,000 m water depth (as is required for the multibeam system used) is not equivalent to a sound velocity profile derived from 8000 m of data. Furthermore the van Haren et al. (2017) data are comparable to those acquired by Nakanishi and Hashimoto (2011) who although were operating a less accurate multibeam echosounder, also had CTD data to full ocean depth for determining the sound velocity.

### 2.1.5. Southern Ocean

The Southern Ocean extends from the northern coast of Antarctica to a latitude of 60° S as defined by the International Hydrographic Organization (IHO). The South Sandwich Trench, is a large arcuate subduction trench that spans both the South Atlantic and Southern oceans formed by the subduction of the southernmost section of the South American Plate beneath the South Sandwich Plate at a rate of 65–78 mm per year (Smalley et al., 2007). The South Sandwich Islands are the resultant volcanic arc, situated on the South Sandwich Plate. The trench is 965 km long and attains a maximum published depth in the Meteor Deep (Maurer and Stocks, 1933; Table 1). The Meteor Deep is located north of 60° S, around 100 km northeast of Zavodovski Island located at a latitude of between ca. 55.67° S and 56.24° S depending on which published location is believed. As has been highlighted in this paper previously, the South Sandwich Trench straddles the boundary between the Atlantic and Southern oceans. Therefore two respective 'deeps' were sought after during the course of this study, each side of the 60° S boundary (as per the recognised latitudinal boundary of the IHO). Examination of both the GMRT Synthesis and the NOAA-NCEI compilations revealed that few high-resolution datasets have been uploaded to public repositories (Fig. 7).

The IBCSO was initiated as a GEBCO regional mapping project with the goal of compiling the first bathymetric model covering the entire Southern Ocean south of 60° S. The first version was published in 2013 with a resolution of 500 m based on a polar stereographic projection with true scale at 65° S referenced to the WGS84 ellipsoid (Arndt et al., 2013). The dataset was compiled using data from hydrographic offices, scientific research institutions and data centres and includes single-beam and multibeam bathymetry data, regional bathymetric models, digitised soundings from nautical charts and satellite-based predicted bathymetry in the deep-sea where sounding data are sparse. Note that > 80% of the Southern Ocean is not yet mapped even at a resolution of 500 m (Arndt et al., 2013).

In addition, the British Antarctic Survey (BAS) have published a 1:750,000 bathymetry map compiled from a variety of different data sources (Leat et al., 2016). The BAS published map covers the area of the South Sandwich subduction system situated in the East Scotia Sea, South Atlantic, between ca. 55.1° S and 61.9° S, and 24° W and 32° W. The primary data are multibeam echosounder bathymetry collected from scientific cruises undertaken by BAS, Alfred Wegener Institute (AWI) and the Centre for Marine and Environmental Sciences (MARUM), University of Bremen. This is supplemented by older data

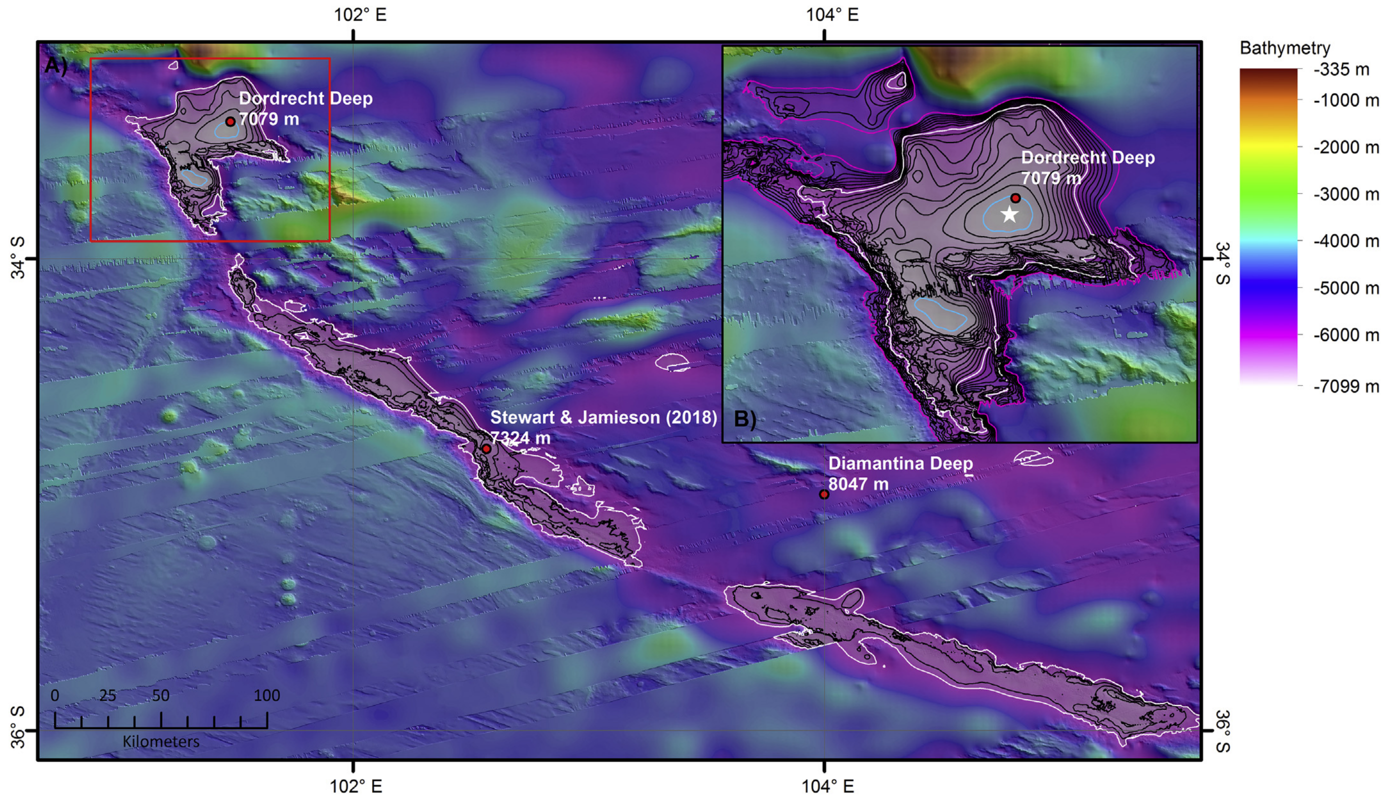


**Fig. 5.** (A) Map of the deepest section of the Diamantina Fracture Zone with the locations of published 'deeps' (red circles) (Table 1). The 6000 m depth contour is shown in white. The deepest section of the feature is defined by the 7000 m contour (blue). All other contours at 200 m intervals (between 6000 and 7000 m water depth) (B) Inset map of Dordrecht Deep with the deepest point determined during this study (white star = between 7090 and 7100 m water depth) which is within 4 km of the published GEBCO Gazetteer location for Dordrecht Deep. The outer rim of Dordrecht deep lies at 5300 m water depth (pink contour). The 7000 m contour is coloured blue. All other contours at 100 m intervals (between 5300 and 7000 m water depth). For location of inset map see the red box in Fig. 5A. Illumination from 45° at an altitude of 25°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from a BAS towed sonar survey (MR1) and single-beam data collected by scientific surveys and commercial fishing vessels. Where no data existed from these sources, global compilations from GEBCO_2014 and, below 60° S, the IBCSO were used; both these datasets use satellite altimetry in areas where data are sparse. Gridded datasets were resampled to 200 m resolution and then converted to point data with the final product produced via a weighted process given the variety of data resolutions available (Leat et al., 2016).

Even with the recent mapping effort and compilation exercises undertaken by both BAS and IBCSO, there are few high-resolution data available to robustly analyse from the South Sandwich Trench. Therefore the GEBCO_2014 data were interrogated for this area of interest. Note that the east-west trending fracture zone that intersects the southernmost extent of the South Sandwich Trench generally does not exceed around 6000 m water depth therefore was discounted as an area of interest in this study.

Published maximum depths in the Meteor Deep vary from 8428 m to 8325 m as reported in a number of publications (e.g. Allaby, 2009; Zhivago, 2002) although the original source of this sounding cannot be traced. Other published maximum depths for this trench include 8264 m (Maurer and Stocks, 1933; Heezen and Johnson, 1965) for "Meteor Depth", and 8125 m at a position to the south as determined by Stewart and Jamieson (2018) from the GEBCO_2014 global bathymetry dataset (Fig. 7; Table 1). The deepest point south of 60° S, located within the southernmost extent of the South Sandwich Trench attains a maximum depth of 7235 m (Fig. 7; Table 1).

### 2.2. Confidence levels

With regard to the confidence assessment a value of '1' is given to a location with high confidence that has a suite of good quality multibeam echosounder bathymetry data as evidence to the accuracy of the location of the 'deep'. A value of '2' is given where either the multibeam echosounder bathymetry data is of poor quality containing a number of bathymetric artefacts, or the position is based on best available single-beam bathymetry data. A value of '3' is given where the location is based on global data compilations with low resolution data. A hydrographic survey will be essential to confirm the exact position and depth for the 'deep' should a confidence value of '3' have been assigned in this study.

Upon assessment of the data available for the five-deeps from data repositories and through global bathymetry compilations, the most comprehensive data available was over the Challenger Deep. Given the volume of high-resolution data available, and the in depth analysis on the error associated with soundings from depths exceeding 10,000 m (e.g. Gardner et al., 2014; van Haren et al., 2017), a confidence value of '1' is assigned to the van Haren et al. (2017) site which represents the most up-to-date location and depth for Challenger Deep. Conversely, a confidence value of '3' was awarded to the Java and South Sandwich trenches reflecting that these areas are only covered by low-resolution global bathymetry products. Data from the Puerto Rico Trench are awarded a confidence value of '2' as although the maximum depth recording is 8540 m within the available data, inspection of the data reveal that possible soundings > 8400 m water depth were individual data spikes extending > 100 m below the surrounding sea bed and no confidence value can be assigned to these points. Finally, data from the Molloy Hole in the Arctic Ocean were also assigned a confidence value of '2' reflecting the resolution of the multibeam data available (Klenke and Schenke, 2006a) and agreement between studies as to the location and depth of the deepest point (Thiede et al., 1990; Klenke and

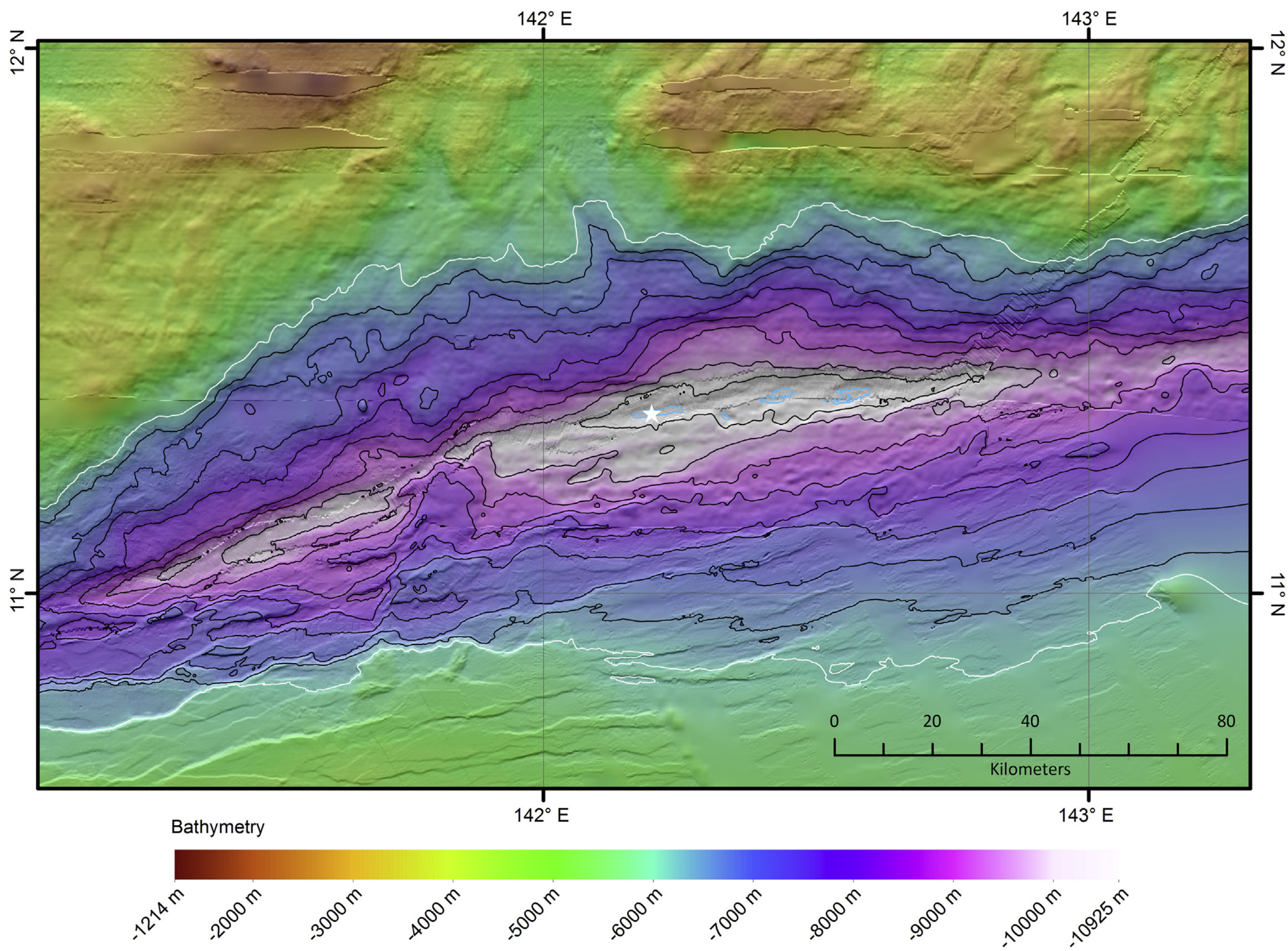


**Fig. 6.** Map of the deepest section of the Mariana Trench with the deepest point, located in Challenger Deep, determined by van Haren et al. (2017) indicated by the white star (10,925 m water depth). Note that due to clustering of the published 'deeps' locations it was not possible to display them all (Table 1). The 6000 m depth contour is shown in white. The 10,500 m contour is shown in blue with the deepest soundings located in the westernmost of the 3 basins. All other contours at 500 m intervals (between 6000 and 10,500 m water depth). Illumination from 350° at an altitude of 35°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 2**
List of locations that based on the best available data that constitute the deepest places in each ocean, the 'five-deeps'. Note that the deepest point in the South Sandwich Trench is south of 60° S and not the published location for Meteor Deep.

| Ocean | Area | Location | Latitude | Longitude | Anticipated Depth (m) | Confidence |
|---|---|---|---|---|---|---|
| Pacific | Mariana Trench | Challenger Deep | 11.332° N | 142.202° E | 10,925 ± 12 | 1 |
| Indian | Java Trench | Unnamed Deep | 11.20° S | 118.47° E | 7290 | 3 |
| Southern | South Sandwich Trench | Unnamed Deep South of 60°S | 60.33° S | 25.28° W | 7385 | 3 |
| Atlantic | Puerto Rico Trench | Milwaukee Deep | 19.613° N | 67.847° W | 8408 | 2 |
| Arctic | Fram Strait | Molloy Hole | 79.137° N | 2.817° E | 5669 | 2 |

Schenke, 2002, 2006a).

### 2.3. Uncertainty

The accuracies of both modern and historical single-beam and multibeam echosounders, as well as navigation systems, is an interesting subject although it is beyond the scope of this paper.

Multibeam echosounder systems are frequently tailored for each individual survey dependent on water depth, weather, whether there is a need to optimise the bathymetric data over backscatter intensity data or vice versa, and so on. Individual aspects such as beam angle (e.g. older systems were fixed beam and the operator could simply cut the outer beams compared to modern systems whereby you can alter the angle where you keep all beams but within a narrower angle), system calibration, and motion sensor and gyro accuracy (which are subsequently applied to the data). Many of these settings are not systematically recorded, or if they are, the information is contained in grey literature which is rarely available online. Aspects such as the application of an accurate sound velocity profile are crucial during data acquisition and any subsequent data processing. Sound velocity was one of the crucial differences between the Gardner et al. (2014) and van Haren et al. (2017) maximum depths for the Challenger Deep in the Mariana Trench.

Given the example parameters listed above and the fact that few of

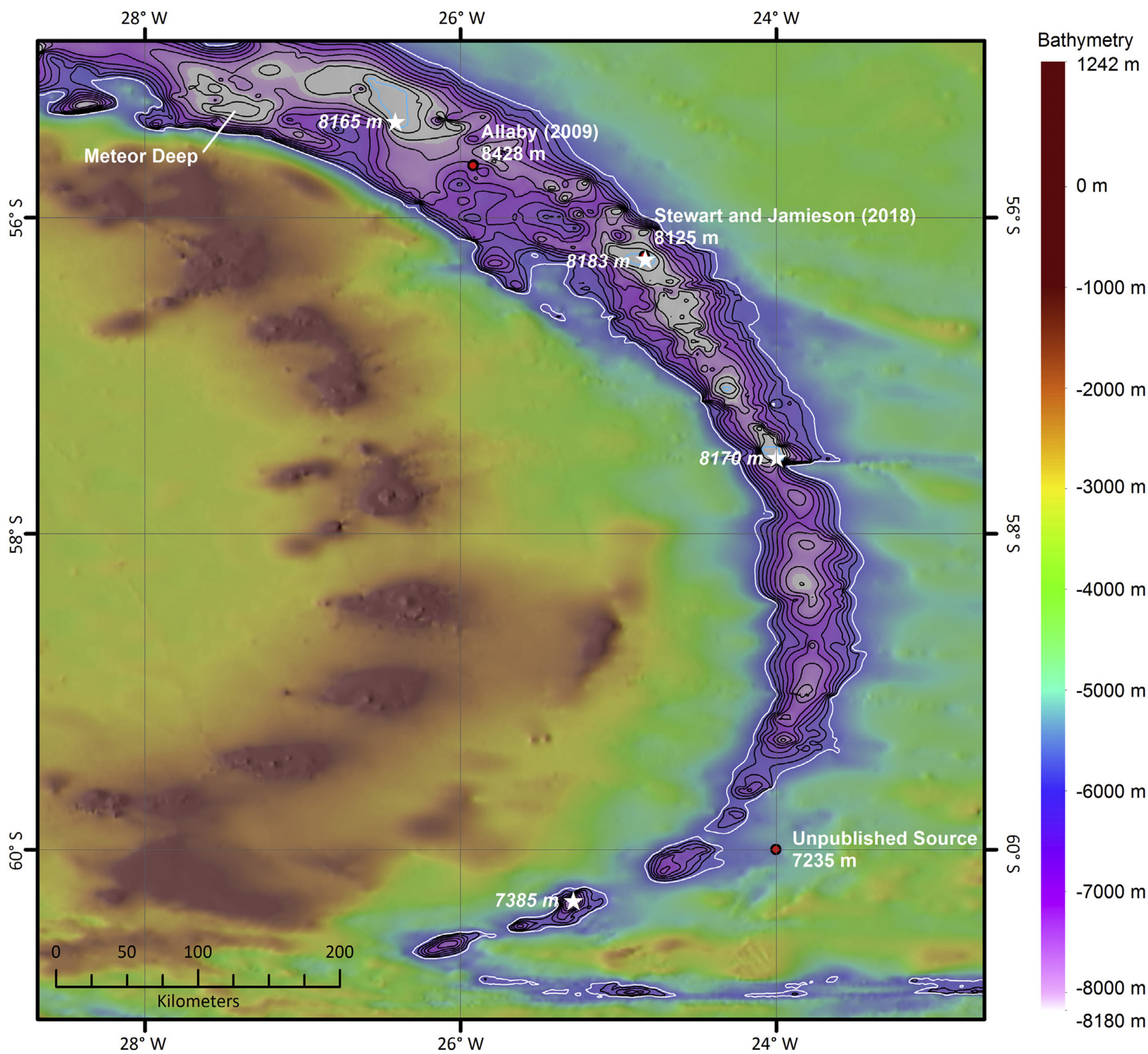


**Fig. 7.** Map of the South Sandwich Trench with the published 'deep' locations (red circles) (Table 1). 'Meteor Deep' is labelled with the deepest points of the trench determined by this study (white stars) with their associated depth in italics (Table 2 and Table 3). The 6000 m depth contour is shown in white. The deepest sections of the trench are defined by the 8000 m contour (blue). All other contours at 200 m intervals (between 6000 and 8000 m water depth). Illumination from 270° at an altitude of 35°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

these are recorded consistently for inclusion in a study such as this, a robust examination of system uncertainty for all published depths would be the subject of another review. Likewise, the accuracy of navigational systems, the impact of using different projections, datum and ellipsoids during data acquisition, processing and subsequent analyses are not addressed here.

## 3. Results

Upon assessing the nominal location for each of the five-deeps there are some oceans that were treated slightly different from others. For example, there is no doubt that Challenger Deep in the Mariana Trench is the deepest point in the Pacific Ocean (Gardner et al., 2014; van Haren et al., 2017) and that the Puerto Rico Trench is the deepest place in the Atlantic Ocean. However, in the latter the exact depth of the deepest point, known as 'Milwaukee Deep' (Lyman, 1954), required reassessment. The deepest point in the Southern Ocean, the South Sandwich Trench, offered two locations: the deepest point in the trench, or 'Meteor Deep' (Allaby, 2009), which is north of the 60° S boundary and a currently unnamed deep which is the deepest point of the trench south of the 60° S boundary. In the Arctic Ocean, the Molloy Hole, in the Fram Strait (Bourke et al., 1987; Thiede et al., 1990; Klenke and Schenke, 2002, 2006a; Jakobsson et al., 2012) was investigated whereas online reports of the Litke Deep being the deepest point were discarded as data analysis revealed that the Litke Deep only achieves a maximum water depth of ~4000 m. The deepest point in the Indian Ocean is contentious as it is often reported as being either the Java Trench at 9° S to 11° S or the Diamantina Fracture Zone further south at 33° S to 35° S. To assess and establish which is indeed deeper than the other, both were included in this study, and in the Diamantina Fracture Zone two separate locations for the deepest place were investigated (Dordrecht Deep and Diamantina Deep).

### 3.1. Arctic Ocean

Klenke and Schenke (2002) compared multibeam echosounder bathymetry from their study (100 m grid) with that of an earlier version of the IBCAO (1 arc minute grid; Jakobsson et al., 2000) and found that the mean difference between the two datasets was around 52 m (about 2% of the depth) with the multibeam data registering systematically

**Table 3**
List of additional sites in the Indian and Southern Oceans that are of potential interest for future study to prove or refute the deepest point of those oceans.

| Ocean | Area | Location | Latitude | Longitude | Anticipated Depth (m) | Confidence |
|---|---|---|---|---|---|---|
| Indian | Diamantina Fracture Zone | Dordrecht Deep | 33.452° S | 101.468° E | 7090–7100 | 2 |
| Atlantic | South Sandwich Trench | North of 60°S - 1 | 55.39° S | 26.41° W | 8165 | 3 |
| Atlantic | South Sandwich Trench | North of 60°S - 2 | 56.26° S | 24.83° W | 8183 | 3 |
| Atlantic | South Sandwich Trench | North of 60°S - 3 | 57.52° S | 24.00° W | 8170 | 3 |

deeper primarily due to the difference between grid resolutions.

The fourth published maximum water depth for the feature (Bourke et al., 1987) is located ca. 3 km to the north of the other three points. Three published locations for the deepest point (Thiede et al., 1990; Klenke and Schenke, 2002; Klenke and Schenke, 2006a, 2006b; Jakobsson et al., 2012) are within 880 m of each other laterally. The fourth published location for the deepest point (Bourke et al., 1987) for the Molloy Hole plots around 3 km to the north of the other three points.

The position for the deepest point of the Molloy Hole is likely within the 880 m grouping of four published locations with the maximum water depth and geographic location reported by Klenke and Schenke (2002, 2006a, 2006b), based on multibeam bathymetry data, used in this study (Fig. 2; Table 2).

### 3.2. Atlantic ocean

The three published deepest points from within the Puerto Rico Trench are all located in the westernmost section of the trench, within 190 km of each other. The available data reveal depth soundings consistently shallower than those published with the deepest of those being 8740 m. This study report a significantly shallower depth of 7450 m for that coincident location, a median ridge within the trench axis. Lyman (1954) reports a depth of 8710 m, whereas this study reports a coincident depth of 8370 m for that location. Finally the Stewart and Jamieson (2018) maximum water depth of 8536 m coincides with an 8300 m depth in the dataset used in this study.

The differences between these water depths is largely a result of data availability at that particular time of publication and available technology. The Lyman (1954) depth pertains to soundings acquired on board the *Theodore N. Gill* in 1952 using an early echo-sounder system. The Stewart and Jamieson (2018) study utilised the GEBCO_2014 global compilation with a resolution of 30 arc sec. Subsequently, publically available multibeam echosounder data coincides with all three of these published geographic locations resulting in an improvement in the understanding of the morphology and bathymetry of this trench.

An area of relatively featureless, flat sea bed located west of 67.5° W, encompassed by the 8400 m contour was identified during this study using the multibeam echosounder data downloaded for this study. Unlike most other trenches, that culminate in a single localized deep, the deepest area of the Puerto Rico Trench presents more of an elongated depression, bounded by the 8400 m contour, around 13 km long by 3 km wide which makes identifying the deepest point difficult. This depression hosts a maximum water depth of 8408 m and is located approximately 40 km east of the Lyman (1954) position for the Milwaukee Deep (Fig. 3; Table 2).

### 3.3. Indian Ocean

The location of the two published Java Trench 'deeps', where the maximum depths are reported as 7725 m or 7450 m (depending on the source; Table 1) are incorrect. Furthermore, the location given for the Java Deep is located on the overriding plate, distal to the trench axis, with water depths of ~1910 m according to GEBCO_2014 (Fig.4A).

The maximum water depth in the Java Trench is 7290 m located in a confined deep 3 km south of the Stewart and Jamieson (2018) location (Fig. 4B; Table 2) that was derived from the GEBCO_2014 global bathymetry dataset. This currently unnamed deep is the deepest point of the Indian Ocean.

By plotting the location of these recorded depths against the GEBCO_2014 global bathymetry dataset it becomes obvious that the published location of the Diamantina Deep (IHO-IOC GEBCO Gazetteer of Undersea Feature Names), where the maximum recorded water depths are reported as exceeding 8000 m is incorrect due to positional inaccuracies and over-estimated water depths. Furthermore, the location given for the Diamantina Deep is outside the fracture zone entirely with water depths of around 5300 m at that location. It is clear that given the best resolution data available for this study, the deepest water depths will be found in the Dordrecht Deep.

Dordrecht Deep is a bathymetric depression approximately 80 km by 95 km in size located within the axis of the fracture zone. The 'deep' varies in water depth from 5300 m to 7099 m with two discreet basins that exceed 7000 m water depth with the data indicating the deepest point should be located in the northernmost depression (Fig. 5B; Table 3).

### 3.4. Pacific Ocean

Data from this study reveal three depressions that locally exceed 10,500 m water depth (Fig. 6). It is the westernmost one of these that is the deepest at 10,925 ± 12 m (van Haren et al., 2017; Table 2). Given the volume of high-resolution data available and the in depth analysis on the error associated with soundings from depths exceeding 10,000 m by authors such as van Haren et al. (2017) and Gardner et al. (2014) there is little doubt that this is the deepest point within the Mariana Trench.

### 3.5. Southern Ocean

Three 'deeps' were identified north of 60° S all within 18 m maximum water depth of each other (Fig. 7 and Fig. 8A–C; Table 3). One unnamed 'deep' was identified south of 60° S (Fig. 7 and Fig. 8D; Table 2). The most commonly reported depth for the Meteor Deep is 8428 m (Fig. 7; Table 1), however, when interrogating the GEBCO_2014 dataset the two geographic locations for that deep are 400 m distance apart and register as 7124 and 7145 m water depth based on the GEBCO_2014 compilation. This is a significant discrepancy and the published locations do not coincide with the three 'deeps' identified in this study (Fig. 7; Table 3). Similarly, the maximum water depth published for the section of the trench located south of 60° S, is documented as 7235 m (Fig. 7; Table 1). This is coincident with 5540 m water depth based on the GEBCO_2014 dataset with this inconsistency likely due to erroneously published coordinates plotting this position significantly distant from the trench axis.

## 4. Discussion

It is perhaps unsurprising that the site with the highest confidence is the Challenger Deep in the Mariana Trench as by the very prestige of being the deepest place in the world has led to extra scrutiny as to the exact depth and mapping effort. The review of efforts discussed in Gardner et al. (2014) and the refinement of van Haren et al. (2017)

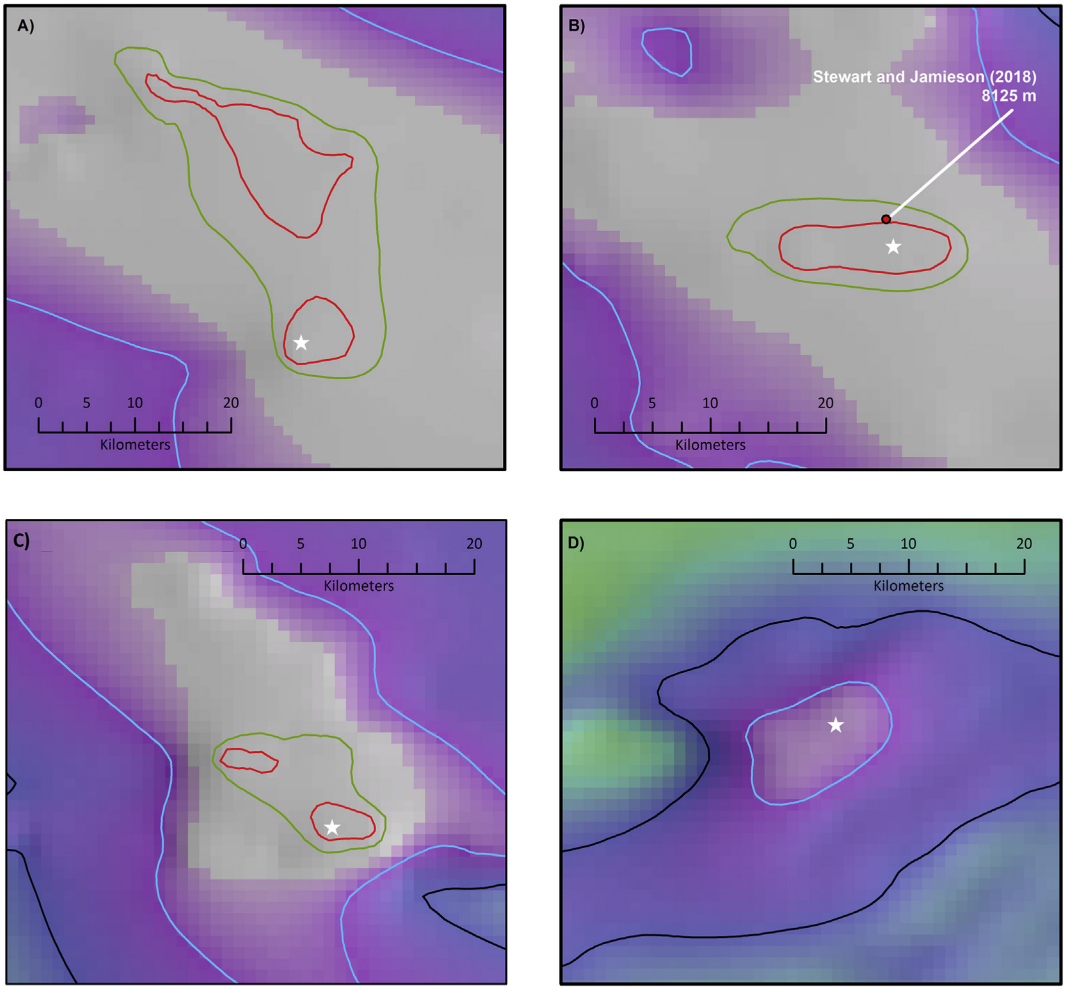


**Fig. 8.** Detailed maps of the 'deeps' identified within the South Sandwich Trench during this study from north to south. (A) The 8165 m 'deep'. (B) The 8183 m 'deep'. (C) The 8170 m 'deep'. (D) The 7385 m 'deep' located south of 60° S latitude. Selected contour lines are displayed for illustrative purposes (6000 m is black, 7000 m is blue, 8000 m is green, 8100 m is red). The deepest points determined during this study are indicated by the white stars. For bathymetry colour ramp and the geographic location see the corresponding white stars see Fig. 7. Illumination from 270° at an altitude of 35°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

places the deepest point in Challenger Deep, the Mariana Trench, the Pacific Ocean and indeed the world at 11.332° N/142.202° E with a depth of 10,925 ± 12 m. This has been realised through a high level of multibeam echosounder data acquisition carried out by researchers in the US and Japan (e.g. Fujioka et al., 2002; Fryer et al., 2003; Nakanishi and Hashimoto, 2011; Gardner et al., 2014; van Haren et al., 2017).

The Milwaukee Deep (Puerto Rico Trench), the Molloy Hole (Fram Strait) and the Dordrecht Deep (Diamantina Fracture Zone) were assigned a confidence value of '2' as the available bathymetry data is of lower quality and contain bathymetric artefacts (Table 2 and Table 3). In the case of the Milwaukee Deep, the current location is likely erroneous due there being no geomorphological distinction between this location and rest of the trench floor (known as Brownson Deep) and therefore requires correction, or rather the name simply falls into abeyance. However, this study confirms that the deepest area of this trench comprises an elongated depression, within the 8400 m contour of which the deepest point is approximately 40 km east of the Lyman (1954) position for the Milwaukee Deep.

In the case of the Molloy Hole, it appears the deepest point is in the vicinity of 79.137° N/2.817° E (Klenke and Schenke, 2002), the lower confidence level is purely a result of the resolution of the multibeam echosounder data publically available and not a reflection that another, deeper point lies elsewhere. The ambiguity in identifying the deepest point in the Molloy Hole is in part due to the relatively featureless topography of the seafloor of the deep. It is not a fracture zone or subduction trench, but rather a flat bottomed circular depression lacking in a compact, clearly confined 'deep'.

Both the published depth and location for the Diamantina Deep appear to be erroneous, there are no areas indicated to be > 8000 m and given coordinates do not even fall within the fracture zone (and is only 5300 m when the underlying data were interrogated). Therefore, the location for the Diamantina Deep needs to be revised. In the Dordrecht Deep, it appears the deeper of the two interior depressions is the one to northwest (Table 3). The Dordrecht Deep is proposed here as the deepest site of the Diamantina Fracture Zone and is still included in this study given how close the estimated depths are to the Java Deep in the Java Trench (7100 and 7290 m respectively). Though, there is a note of caution given the similar water depths estimated for the Java and Dordrecht deeps therefore a multibeam echosounder survey will be required to settle this unequivocally thereby establishing the deepest point in the Indian Ocean. Also, within the Java Trench, the published 'deep' is instead located on the overriding plate rather than the trench axis. It is recommended that either the term 'Java Deep' falls into abeyance, or is corrected to a nearby depression (7258 m water depth at 10.38° S/110.35° E), or is reassigned the position reported in this study at 7290 m water depth. Furthermore, depending on the source, occasionally Java Deep means the deepest point, sometimes it refers instead to the whole of the Java Trench. Likewise other literature refer to this trench as the Java Trench (e.g. Southward et al., 2002), Sunda Trench (e.g. Nalbant et al., 2005), or the Sunda-Java Trench (e.g. Whittaker et al., 2007) and thus there is scope to clarify this by using the two terms for the trench and deep, perhaps Sunda for the trench after the larger biogeographical region of Sunda, and the Java Deep after the smaller Indonesian Island of Java.

Perhaps the most problematic site of all is the Southern Ocean's South Sandwich Trench. Firstly, to represent the deepest point in the Southern Ocean, technically the point must be south of 60° S, making the depression at 60.33° S/25.28° W (7385 m depth) the deepest point in the Southern Ocean, but by no means the deepest point of the South Sandwich Trench. Defining the deepest point of this trench is complicated, largely due to low quality bathymetric data but also in that there are three potential 'deeps' north of 60° S all within 18 m maximum water depth of each other (8165, 8170, and 8183 m). A modern multibeam echosounder system, if properly calibrated and with a proximal sound velocity profile, is capable of collecting accurate depth soundings with a minimum uncertainly of between 0.2% and 0.5% water depth dependent on signal-to-noise ratio and pulse length. Therefore, all three of the potential maximum depths within the South Sandwich Trench are within the uncertainty of a multibeam echosounder system and only acquisition of high-resolution data will determine the precise location of the deepest point of the trench. The published depths for the Meteor Deep is 8428 m, however, there were two locations given for this site, 400 m apart, with coincident depths from sourced data of 7124 and 7145 m respectively. Also, the published location for Meteor Deep does not coincide with any of the three unnamed 'deeps' identified in this study. Note that the identified depression south of 60° S that represents the deepest place in the Southern Ocean, is also unnamed.

## 5. Deeps as named features

According to the IHO-IOC guidelines for naming undersea features, 'deeps' are defined as "a localized depression within the confines of a larger feature, such as a trough, basin or trench". It used to be depth specific and defined as a "well defined deepest area of a depression of the deep-sea floor which applies when soundings exceed 3000 fathoms [5486 m]" (Wiseman and Ovey, 1953). The naming of 'deeps' was once thought to not offer anything useful scientifically and was simply spurred by the desire to name features and the British National Committee on Ocean Bottom Features suggested that the term should fall into abeyance (Wiseman and Ovey, 1954). As recent as 1990, the IHO-IOC committee reported that many named features such as 'cap', 'deep' and 'swell' have generally accepted historical usage, but do not recommend any wider use of such terms in new names (Bouma, 1990). Deeps are however back in the list of accepted names for undersea features by the IHO-IOC. In fact in 2014, a 5400 m deep depression in the Kermadec Trench was official accepted as the 'Crean Deep', despite it being nearly 5000 m shallower than the trench in which it resides.

Therefore, the tendency of naming deeps in general is perhaps still not completely resolved. For example, the Izu-Bonin and Tonga trenches have one clear deep each, the Ramapo Deep and the Horizon Deep respectively (Fisher, 1954) and the Kermadec has the single Scholl Deep (IHO-IOC GEBCO Gazetteer of Undersea Feature Names). However, the South Sandwich has one named, the Meteor Deep (Herdman et al., 1956), but clearly there are three other well defined 'deeps' of similar depth, size and morphology (Fig. 8A–C) without names, plus the issues of what constitutes the deepest point in the Southern Ocean as discussed above. In other instances there are multiple deeps within one large-scale topographic feature such as the Peru-Chile Trench with the Milne-Edwards, Krümmel, Haeckel and Richards deeps (Zeigler et al., 1957), and the Puerto Rico Trench with Brownson and Milwaukee deeps (Lyman, 1954) and a somewhat spurious Gilliss deep (George and Higgins, 1979). Albeit a number of these only appear informally in scientific literature and are seemingly not officially recognised (and are likely the source of dubious contributions that led to the sentiments of Wiseman and Ovey (1954) and Fisher (1987)). To the contrary, the Mariana Trench has, in addition to Challenger Deep, two other distinct deeps; the Sirena and the Nero deeps (Fryer et al., 2003). Interestingly, of all the deeps mentioned in this paragraph, only Challenger, Horizon and Scholl are recognised in the IHO-IOC GEBCO Gazetteer of Undersea Feature Names, furthermore, the Java Deep is recognised but represents the entire Java Trench, and not simply the deepest point or by the official definition of a deep.

To bring some clarity to this, the analogy with mountain summits can again be made. In the instance of mountains, there can be only one summit, the highest point, which in deep trenches should be mirrored in the naming of the 'deep'. This works well as a descriptor where a feature, in this case mostly trenches, have one clear deepest point. But in the terrestrial nomenclature for mountain summits, any other obvious protrusion that does not constitute the highest point is labelled a peak, to differentiate it from the summit (or 'parent peak'). A similar model could be used in the very deepest parts of the ocean to provide a coherent nomenclature between the very deepest points, and other distinct depressions that may be of interest to scientists or explorers. The current system of coining all depressions 'deeps' underwater is akin to calling every peak on a mountain range the summit.

In mountain ranges, topographic prominence is intuitively used to establish a single mountain or peak against what could be otherwise construed as a complex ridge system. This method distinguishes mountains from lesser peaks by the height above the highest saddle connecting it to a higher summit. A common definition of a mountain is having an altitude with a 300 m prominence (or ~ 7% relative prominence) over the surrounding ridge. Again a similar system of topographic prominence should be considered to clarify features such as those within some of the trenches in this study and others, where there is clearly a deepest point, but other shallower depressions and to confirm or refute the presence of more dubious 'deeps'.

## 6. Conclusions

Based on the best resolution bathymetric datasets currently available from public repositories, the deepest points in each ocean are the Molloy Hole in the Fram Strait (Arctic Ocean; 5669 m, 79.137° N/ 2.817° E), the trench axis of the Puerto Rico Trench (Atlantic Ocean; 8408 m 19.613° N/67.847° W), an unnamed deep in the Java Trench (Indian Ocean; 7290 m, 11.20° S/118.47° E), Challenger Deep in the Mariana Trench (Pacific Ocean; 10,925 m, 11.332° N/142.202° E) and an unnamed deep in the South Sandwich Trench (Southern Ocean; 7385 m, 60.33° S/25.28° W). The locations are located within the Exclusive Economic Zone (EEZ) of Norway, Dominican Republic, Indonesia, Federated States of Micronesia, and Britain (British Antarctic Territory), respectively. The Diamantina Fracture Zone is in an area beyond national jurisdiction (ABNJ).

There are however caveats to these conclusions. The deepest point in the Southern Ocean is not the deepest point in the South Sandwich Trench, but rather the deepest point south of 60° S. The location of the deepest point in that trench could be any one of three potential locations none of which coincide with the published location of the Meteor Deep, which is erroneously attributed to be the deepest point of that trench. The similarity in depth between the three contender deeps, combined with the poor quality of currently available data does not guarantee this would be the deepest overall point in the trench. Only acquisition of high-resolution bathymetric data would confirm this.

The deepest point in the Atlantic Ocean, the Milwaukee Deep, in the Puerto Rico Trench does not exist under the definition of the IHO-IOC guidelines. This trench actually comprises an elongated area of relatively featureless seafloor bounded by the 8400 m bathymetric contour. Furthermore, this elongated depression represents what has historically been sub-divided into the Brownson and the Milwaukee deeps (Lyman, 1954), and as such, these two names should be omitted given none of these form a defined topographic 'deep'. There is also no evidence to suggest the Gilliss Deep exists as a feature (George and Higgins, 1979).

In the Indian Ocean, if the Diamantina Deep is to remain a feature name, the location must be corrected to fall within the Fracture Zone although it is unclear as to where exactly to move this location to as the original reference has proven difficult to trace. This study has confirmed that the deepest point of the Diamantina Fracture Zone is the Dordrecht Deep with an updated geographic position at 33.452° S/ 101.468° E and a maximum water depth of between 7090 and 7100 m. Given the low quality of bathymetry data in this area, and that of the Java Trench, there is still a possibility that the Dordrecht Deep could be the deepest point in the Indian Ocean.

It is clear that many of these deeps identified are currently unnamed (particularly in the Southern and Indian Ocean), and there are a number that are either required to have their coordinates updated based on the data now available or indeed be omitted altogether (e.g. Meteor and Java deeps, and the Puerto Rico Trench deeps respectively). Furthermore we encourage the wider uptake of the correct name for the Molloy Hole in the literature and that IHO-IOC consider clarifying the Java/Sunda/Java-Sunda Trench nomenclature problem. Additionally, the IHO-IOC should consider resolving the ambiguity between the term 'deeps' being used to define the deepest point exclusively versus a collective term for all depressions regardless of depth.

The salient finding of this study is that at an inter-ocean level there is a reasonable grasp on where the deepest places in each ocean are. However, the detail remains elusive with exact coordinates and setting within a particular topographical feature poorly understood in the majority of cases with the exact depth also remaining ambiguous. It is hoped that initiatives such as the Seabed 2030 project (Mayer et al., 2018), high profile privately funded exploration, and the continuing upward trend in scientific work at such depths (e.g. Jamieson, 2018) will resolve these matters for future generations of explorers, scientists and everyone in between to engage.

## Acknowledgements

A.J.J. conceived the study incentivised by the forthcoming '5-Deeps Expedition' on the DSSV *Pressure Drop* financed by Caladan Oceanic LLC (USA). H.A.S. undertook data analysis and both authors contributed equally to the production of the manuscript. The authors thank two anonymous reviewers for their critical reviews of the manuscript. H.A.S. was supported in this research by the British Geological Survey (BGS) Ocean Geoscience Team and publishes with the permission of the Executive Director of the BGS (United Kingdom Research and Innovation). The authors declare no competing financial interests.

## References

Allaby, M., 2009. Oceans: A Scientific History of Oceans and Marine Life. Infobase Publishing.
Angel, M.V., 1982. Ocean trench conservation. Environmentalist 2, 1–17.
Arndt, J.E., Schenke, H.-W., Jakobsson, M., Nitsche, F.O., Buys, G., Goleby, B., Rebesco, M., Bohoyo, F., Hong, J., Black, J., Greku, R., Udintsev, G., Barrios, F., Reynoso-Peralta, W., Taisei, M., Wigley, R., 2013. The International Bathymetric Chart of the Southern Ocean (IBCSO) version 1.0-a new bathymetric compilation covering circum-Antarctic waters. Geophys. Res. Lett. 40, 3111–3117.
Barthlott, W., Lauer, W., Placke, A., 1996. Global distribution of species diversity on vascular plants: towards a world map of phytodiversity. Erdkunde 50, 317–327.
Becker, J.J., Sandwell, D.T., Smith, W.H.F., Braud, J., Binder, B., Depner, J., Fabre, D., Factor, J., Ingalls, S., Kim, S.H., Ladner, R., Marks, K., Nelson, S., Pharaoh, A., Trimmer, R., Von Rosenberg, J., Wallace, G., Weatherall, P., 2009. Global bathymetry and elevation data at 30 arc seconds resolution: SRTM30_PLUS. Mar. Geod. 32, 355–371.
Bouma, A.H., 1990. Naming of undersea features. Geo-Mar. Lett. 10, 119–125.
Bourke, R.H., Tunnicliffe, M.D., Newton, J.L., Paquette, R.G., Manley, T.O., 1987. Eddy near the Molloy Deep revisited. J. Geophys. Res. 92, 6773–6776.
Bowen, A.D., Yoerger, D.R., Taylor, C., McCabe, R., Howland, J., Gomez-Ibanez, D., Kinsey, J.C., Heintz, M., McDonald, G., Peters, D.B., Bailey, J., Bors, E., Shank, T., Whitcomb, L.L., Martin, S.C., Webster, S.E., Jakuba, M.V., Fletcher, B., Yound, C., Buescher, J., Fryer, P., Hulme, S., 2009. Field Trials of the Nereus Hybrid Underwater Robotic Vehicle in the Challenger Deep of the Mariana Trench. 2009. Marine Technology Society, OCEANS, Biloxi, MS, pp. 1–10.
Brandt, A., 2016. Cruise Report: RV Sonne SO-250 Kuril-Kamchatka Biodiversity Studies II Cruise Report. Tomakomai-Yokohama, Japan, pp. 174. 16.08–26.09.2016. https://repository.publisso.de/resource/frl:6401131.
Ten, Brink, U., 2005. Vertical motions of the Puerto Rico Trench and Puerto Rico and their cause. J. Geophys. Res. 110 (B06404).
Carruthers, J.N., Lawford, A.L., 1952. The deepest oceanic sounding. Nature 169, 601–603.
de Graaff-Hunter, J., 1955. Various determinations over a century of the height of Mount Everest. Geogr. J. 121, 21–26.
De Mets, C., Gordon, R.G., Argus, D.F., 2010. Geologically current plate motions. Geophys. J. Int. 181, 1–80.
Fisher, R.L., 1954. On the sounding of trenches. Deep-Sea Res. 2, 48–58.
Fisher, R.L., 1987. A proposal for modesty. Geology 15, 583.
Fisher, R.L., Hess, H.H., 1963. Trenches. In: Hill, M.N. (Ed.), The Sea. vol. 3. Wiley-Interscience, New York, pp. 411–436.
Freire, F., Gyllencreutz, R., Jafri, R.U., Jakobsson, M., 2014. Acoustic evidence of a submarine slide in the deepest part of the Arctic, the Molloy Hole. Geo-Mar. Lett. https://doi.org/10.1007/s00367-014-0371-5.
Fryer, P., Becker, N., Applegate, B., Martinez, F., Edwards, M., Fryer, G., 2003. Why is challenger deep so deep? Earth Planet. Sci. Lett. 211, 259–269.
Fujimoto, H., Fujiwara, T., Kong, L., Igarashi, C., 1993. Sea beam survey over the challenger deep revisited. In: Preliminary Report of the Hakuho-Maru cruise KH92–1. Ocean Research Institute, Tokyo, pp. 26–27 (unpublished).
Fujioka, K., Okino, K., Kanamatsu, T., Ohara, Y., 2002. Morphology and origin of the challenger deep in the southern Mariana Trench. Geophys. Res. Lett. 19, 1–4.
Gardner, J.V., Armstrong, A.A., 2011. The Mariana Trench: A New View Based on Multibeam Echosounding (Abs.). American Geophysical Union Fall Meeting, San Francisco, CA.
Gardner, J.V., Armstrong, A.A., Calder, B.R., Beaudoin, J., 2014. So, how deep is the Mariana Trench? Mar. Geod. 37, 1–13.
George, R.Y., Higgins, R.P., 1979. Eutrophic hadal benthic community in the Puerto Rico Trench. Ambio Spec. Rep. 6, 51–58.
Gruen, A., Murai, S., 2002. High-resolution 3D modelling and visualisation of Mount Everest. J. Photogramm. Remote. Sens. 57, 102–113.
Harris, P.T., Macmillan-Lawler, M., Rupp, J., Baker, E.K., 2014. Geomorphology of the oceans. Mar. Geol. 352, 4–24.
Heezen, B.C., Johnson, G.L., 1965. The South Sandwich Trench. Deep-Sea Res. 12, 185–197.
Herdman, H.F.P., Wiseman, J.D.H., Ovey, C.D., 1956. Proposed names of features on the deep-sea floor, 3. southern or antarctic ocean. Deep-Sea Res. 3, 258–261.
Holcombe, T.L., 1977. Ocean bottom features—terminology and nomenclature. GeoJournal 1 (6), 25–48.
Hydrographic Department, 1984. Japan maritime safety agency, Mariana Trench surveyed by the "TAKUYO". Int. Hydrography Bull. 351–352.
Ives, J.D., Messerli, B., 1990. Progress in theoretical and applied mountain research, 1973-1989, and major future needs. Mt. Res. Dev. 10, 101–127.
Ives, J.D., Messerli, B., Spiess, E., 1997. Mountains of the world: A global priority. In: Messerli, B., Ives, J.D. (Eds.), Mountains of the World: a Global Priority. Parthenon Publishing Group, New York, USA and Carnforth, UK, pp. 1–15.
Jakobsson, M., Cherkis, N., Woodward, J., Coakley, B., Macnab, R., 2000. A new grid of Arctic bathymetry: A significant resource for scientists and mapmarkers. EOS Transact. Am. Geophys. Union 81 (9) (89, 93, 96).
Jakobsson, M., Macnab, R., Mayer, L., Anderson, R., Edwards, M., Hatzky, J., Schenke, H.W., Johnson, P., 2008. An improved bathymetric portrayal of the arctic ocean: implications for ocean modeling and geological, geophysical and oceanographic analyses. Geophys. Res. Lett. 35, L07602.
Jakobsson, M., Mayer, L., Coakley, B., Dowdeswell, J.A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebesco, M., Schenke, H.-W., Zarayskaya, Y., Accettella, D., Armstrong, A., Anderson, R.M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M., Gardner, J.V., Hall, J.K., Hell, B., Hestvik, O., Kristoffersen, Y., Marcussen, C., Mohammad, R., Mosher, D., Nghiem, S.V., Pedrosa, M.T., Travaglini, P.G., Weatherall, P., 2012. The International bathymetric chart of the arctic ocean (IBCAO) version 3.0. Geophys. Res. Lett. 39, L12609.
Jamieson, A.J., 2015. The Hadal Zone: Life in the Deepest Oceans. Cambridge University Press, Cambridge, UK.
Jamieson, A.J., 2018. A contemporary perspective on hadal science. Deep-Sea Res. II Top. Stud. Oceanogr. https://doi.org/10.1016/j.dsr2.2018.01.005.
Klenke, M., Schenke, H.W., 2002. A new bathymetric model for the central Fram Strait. Mar. Geophys. Res. 23, 367–378.
Klenke, M., Schenke, H.W., 2006a. AWI Bathymetric Chart of the Fram Strait (BCFS) Sheet 581–21-4 Molloy Hole (Scale 1:100,000). Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.556370. PANGAEA.
Klenke, M., Schenke, H.W., 2006b. Digital Terrain Model (DTM) of the central fram strait. PANGAEA, https://doi.org/10.1594/PANGAEA.526589. Accessed November 2018.
Kopp, H., Hindle, D., Klaeschen, D., Oncken, O., Reichert, C., Scholl, D., 2009. Anatomy of the western Java plate interface from depth-migrated seismic images. Earth Planet. Sci. Lett. 288, 399–407.
Kopp, H., Flueh, E.R., Petersen, C.J., Weinrebe, W., Wittwer, A., Scientists, Meramex, 2013. The Java margin revisited: evidence for subduction erosion off Java. Earth Planet. Sci. Lett. 242, 130–142.
Leat, P.T., Fretwell, P.T., Tate, A.J., Larter, R.D., Martin, T.J., Smellie, J.L., Jokat, W., Bohrmann, G., 2016. Bathymetry and geological setting of the South Sandwich Islands volcanic arc. Antarct. Sci. 28, 293–303.
Lecours, V., Dolan, M.F.J., Micallef, A., Lucieer, V.L., 2016. A review of marine geomorphometry, the quantitative study of the seafloor. Hydrol. Earth Syst. Sci. 20,

3207–3244.
Lyman, J., 1954. The deepest sounding in the North Atlantic. Proc. R. Soc. Lond. A Math. Phys. Sci. 222 (1150), 334–336 (A discussion on the floor of the Atlantic Ocean (March 18, 1954). Published by the Royal Society).
Masson, D.G., 1991. Fault patterns at outer trench walls. Mar. Geophys. Res. 13, 209–225.
Maurer, H., Stocks, T., 1933. Die Echolotungen des Meteor. Wiss. Ergebn. Deut. Atlantic Expedition Meteor. 1925-27. pp. 1–309.
Mayer, L., Jakobsson, M., Allen, G., Dorschel, B., Falconer, R., Ferrini, V., Lamarche, G., Snaith, H., Weatherall, P., 2018. The Nippon foundation—GEBCO seabed 2030 project: the quest to see the world's oceans completely mapped by 2030. Geosciences 8, 63.
Mishra, S., Singh, S., Singh, P., Trikamji, B., 2015. Trigonometrical survey of India and naming of Peak XV as Mt. Everest. Indian J. Hist. Sci. 50, 642–645.
Nakanishi, M., Hashimoto, J., 2011. A precise bathymetric map of the worlds' deepest seafloor, challenger deep in the Mariana Trench. Mar. Geophys. Res. 32, 455–463.
Nalbant, S.S., Steacy, S., Sieh, K., Natawidjaja, D., McCloskey, J., 2005. Seismology: earthquake risk on the sunda trench. Nature 435 (7043), 756.
NOAA National Centers for Environmental Information, 2004. Multibeam Bathymetry Database (MBBDB), [Cruise]. NOAA National Centers for Environmental Informationhttps://doi.org/10.7289/V56T0JNC. (February 2018 and November 2018).
Piccard, J., Dietz, R.S., 1961. Seven Miles Down. Longman, London.
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.
Smalley, R., Dalziel, I.W.D., Bevis, M.G., Kendrick, E., Stamps, D.S., King, E.C., Taylor, F.W., Lauría, E., Zakrajsek, A., Parra, H., 2007. Scotia arc kinematics from GPS geodesy. Geophys. Res. Lett. 34, L21308.
Smith, W.H.F., Sandwell, D.T., 1997. Global seafloor topography from satellite altimetry and ship depth soundings. Science 277, 1957–1962.
Southward, E.C., Schulze, A., Tunnicliffe, V., 2002. Vestimentiferans (Pogonophora) in the pacific and indian oceans: a new genus from Lihir Island (Papua New Guinea) and the Java Trench, with the first report of Arcovestia ivanovi from the north Fiji Basin. J. Nat. Hist. 36, 1179–1197.
Stewart, H.A., Jamieson, A.J., 2018. Habitat heterogeneity of hadal trenches: considerations and implications for future studies. Prog. Oceanogr. 161, 47–65.
Taira, K., Kitagawa, S., Yamashiro, T., Yanagimoto, D., 2004. Deep and bottom currents in the challenger deep, Mariana Trench, measured with super-deep current meters. J. Oceanogr. 60, 919–926.
Taira, K., Yanagimoto, D., Kitagawa, S., 2005. Deep CTD casts in the challenger deep, Mariana Trench. J. Oceanogr. 61, 447–454.
Thiede, J., Pfirman, S., Schenke, H.-W., Reil, W., 1990. Bathymetry of Molloy Deep: Fram Strait between Svalbard and Greenland. Mar. Geophys. Res. 12, 197–214.
Thomson, C.W., Murray, J., 1895. Report of the Scientific Results of the Voyage of H.M.S. Challenger during the Years 1873–76, Narrative. vol. A(1) HM Stationary Office, London.
Todo, Y., Kitazato, H., Hashimoto, J., Gooday, A.J., 2005. Simple foraminifera flourish at the ocean's deepest point. Science 307, 689.
van Haren, H., Berndt, C., Klaucke, I., 2017. Ocean mixing in deep-sea trenches: new insights from the challenger deep, Mariana Trench. Deep-Sea Res. I Oceanogr. Res. Pap. 129, 1–9.
Walbridge, S., Slocum, N., Pobuda, M., Wright, D.J., 2018. Unified geomorphological analysis workflows with benthic terrain modeler. Geosciences 8, 94. https://doi.org/10.3390/geosciences8030094.
Weatherall, P., Marks, K.M., Jakobsson, M., Schmitt, T., Tani, S., Arndt, J.E., Rovere, M., Chayes, D., Ferrini, V., Wigley, R., 2015. A new digital bathymetric model of the world's oceans. Earth Space Sci. 2, 331–345.
Werner, R., Wagner, H.J., Hauff, F., 2017. RV Sonne cruise report SO258/1: INGON: the Indian-Antarctic break-up enigma, freemantle (Australia) to Colombo (Sri Lanka). In: GEOMAR Report No. 038, 187pp. Sonne cruise report. GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel, Germany.
Whittaker, J.M., Müller, R.D., Sdrolias, M., Heine, C., 2007. Sunda-java trench kinematics, slab window formation and overriding plate deformation since the cretaceous. Earth Planet. Sci. Lett. 255, 445–457.
Wiseman, J.D.H., Ovey, C.D., 1953. Definitions of features on the deep-sea floor. Deep-Sea Res. 1, 11–16.
Wiseman, J.D.H., Ovey, C.D., 1954. Proposed names of features on the deep-sea floor, 1. The pacific ocean. Deep-Sea Res. 2, 93–106.
Zeigler, J.M., Athearn, W.D., Small, H., 1957. Profiles across the Peru-Chile Trench. Deep-Sea Res. 4, 238–249.
Zhivago, A., 2002. Structural evolution of the Scotia Sea floor during the Paleogene-Quaternary period (West Antarctic). In: VII International Congress, . www.vitiaz.ru/congress/en/thesis/145.html.