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DATA PAPER

High-resolution multibeam sonar bathymetry of the deepest place in each ocean

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Abstract

Over the course of 10 months, the global Five Deeps Expedition (2018–2019) mapped ~550,000 km^2 of seafloor of which 61% comprised new coverage over areas never before surveyed and ~30% was acquired from some of the ocean's deepest trenches and fracture zones. The deepest points of each ocean were mapped using a latest-generation, full-ocean depth Kongsberg EM 124 multibeam echosounder. These extreme depths were corrected using Conductivity, Temperature and Depth (CTD) data from sea surface to full ocean depth. The deepest place in each ocean were identified as the *Brownson Deep*, Puerto Rico Trench in the Atlantic Ocean (8,378 ± 5 m), an unnamed deep within the South Sandwich Trench in the Southern Ocean (7,432 ± 13 m), an unnamed deep within the Java Trench in the Indian Ocean (7,187 ± 13 m), *Challenger Deep* within the Mariana Trench in the Pacific Ocean (10,924 ± 15 m), and the *Molloy Hole* in the Arctic Ocean (5,551 ± 14 m). As part of the overarching mission of the Five Deeps Expedition, and to clarify beyond doubt the deepest point in the Indian, Pacific and Southern oceans, other sites were visited that had been postulated as potential deepest locations. This study has confirmed that the *Horizon Deep* within the Tonga Trench is the second deepest point in the Pacific Ocean (10,816 ± 16 m), the *Dordrecht Deep* within the Diamantina Fracture Zone is not the deepest point in the Indian Ocean (7,019 ± 17 m) and that in accordance with the guidelines of the Antarctic Treaty and International Hydrographic Organisation, although the *Meteor Deep* is the deepest point in the South Sandwich

Dataset

Puerto Rico Trench: https://doi.org/10.5285/7df163a1-30c6-40b6-844d-20fa0acffd18

South Sandwich Trench: https://doi.org/10.5285/143e304e-b9d5-43bf-b323-f2ab517bc18b

Diamantina Fracture Zone: https://doi.org/10.5285/1f13aa23-d413-44b6-a542-0f9ca41a8742

Java Trench: https://doi.org/10.5285/fb3425be-27e2-42b8-ad3e-1d880b9c7b97

Mariana Trench: https://doi.org/10.5285/7675c2f6-b32d-4a8b-854f-0ce2f953c4b2

Tonga Trench: https://doi.org/10.5285/1c642df0-905a-4936-97dd-81b50d7c3994

Molloy Hole: https://doi.org/10.5285/ee1600be-36d3-4e31-80ed-814d53029562

All bathymetric data collected by Caladan Oceanic were submitted to Seabed 2030 via the International Hydrographic Organization's Data Center for Digital Bathymetry (IHO DCDB) in October 2020. These data were submitted in both raw and processed data formats with the all processing and acquisition support files. Additionally, final grids of these data are made available through the National Geoscience Data Centre through the links cited here.

Trench (8,265 ± 13 m) it is located within the waters of the Atlantic Ocean and not the Southern Ocean.

KEYWORDS

Arctic Ocean, Atlantic Ocean, Indian Ocean, Pacific Ocean, Southern Ocean

1 | INTRODUCTION

In 2018, the Five Deeps Expedition (FDE; www.fivedeeps.com) embarked on an ambitious privately-funded year-long round-the-world expedition to dive a two-person full ocean depth submersible to the deepest point in each of the Worlds five oceans (Atlantic, Southern, Indian, Pacific and Arctic; Figure 1). There were considerable technical challenges in designing and constructing the submersible–the DSV *Limiting Factor*–and sourcing and refitting a dedicated research and deep-submergence support vessel named the DSSV *Pressure Drop* (Jamieson et al., 2019). In addition, one of the earlier challenges was to identify exactly where and the exact depth of the deepest point in each ocean. Stewart and Jamieson (2019) reported on the pre-expedition study into this very question using the most up-to-date publically available bathymetric datasets at that time (primarily the Global Multi-Resolution Topography Synthesis (Ryan et al., 2009) which included processed multibeam bathymetry data donated by the international research community, global compilations from the General Bathymetric Chart of the Oceans (GEBCO_2014, version 20,141,103, www.gebco.net; Weatherall et al., 2015), the International Bathymetric Chart of the Southern Ocean (IBCSO; Arndt et al., 2013) and International Bathymetric Chart of the Arctic Ocean (IBCAO; Jakobsson et al., 2012). They concluded that while the deepest parts of some oceans were relatively well known, others had multiple 'deeps' which may indeed be contenders for the deepest point in a particular trench or even ocean, while in other oceans due to a paucity of high-resolution data there was considerable doubt as to the exact location of the deepest point, let alone accuracy of that depth measurement.

In the Atlantic Ocean, the deepest feature is the Puerto Rico Trench (~19.6°N/67.8°W); an approximately 810 km long subduction zone oriented roughly parallel to the northern coast of Puerto Rico. The issues of exact depth and location of the deepest point were one of revisiting a number of named 'deeps' (mainly *Milwaukee Deep* and *Brownson Deep*) and determining whether these constituted real morphological features and to sound their exact depth. It was, however, determined by Stewart and Jamieson (2019), with some certainty, that the *Milwaukee Deep* did not exist as per the guidelines for naming undersea features listed by the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC), and that the *Brownson Deep* would host the deepest point.

In the Southern Ocean, the deepest feature is known to be the South Sandwich Trench although available bathymetric data was primarily derived from low-resolution satellite altimetry data (Stewart & Jamieson, 2019). The overall deepest point of the trench is the *Meteor Deep* discovered in 1926 (~55.2°S/26.2°W). However, the South Sandwich Trench extends from a latitude of around 54°40′S to 60°40′S, technically spanning the 60°S boundary between the Southern and South Atlantic oceans as defined by the IHO and The Antarctic Treaty System. Therefore, the *Meteor Deep* lies within the waters of the southernmost Atlantic Ocean and not the Southern Ocean. Stewart

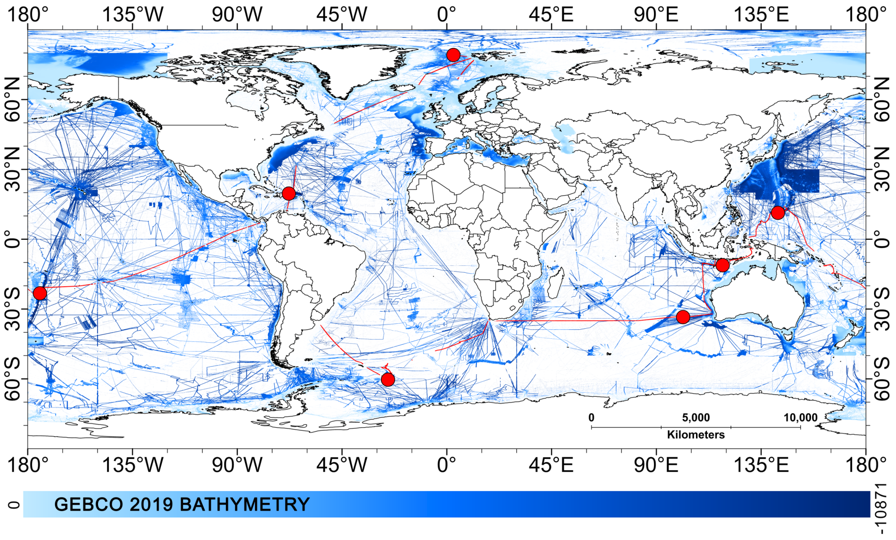

FIGURE 1 Using the GEBCO_2019 bathymetric data compilation's source information, all interpolated data sources were removed to show the true extent of publicly available global bathymetry. Red circles indicate the deepest points in the five oceans surveyed during the Five Deeps Expedition. Red line displays the ship's mapping route between dive locations

and Jamieson (2019) subsequently identified a depression at the southern-most extent of the South Sandwich Trench as potentially the deepest place in the Southern Ocean (~60.3°S/25.3°W). The FDE mapping objective was to survey the entire axis of the South Sandwich Trench, resolve the maximum depth and exact point of the *Meteor Deep,* and the deepest point south of 60°S.

The Indian Ocean hosts two candidates for the deepest point that were geographically distant, and were of seemingly very similar water depth, again primarily derived from low-resolution satellite altimetry data. The two locations were the *Dordrecht Deep* within the Diamantina Fracture Zone (DFZ) in the southeast Indian Ocean (~33.5°S/101.5°E) and the Java Trench in the eastern Indian Ocean (~11.2°S/118.5°E). Based on available data, the depths were found to be within ~200 m of each other; 7,100 and 7,290 m, respectively. Given the paucity of high-resolution data and the topographic complexity of both subduction trenches and fracture zones, the FDE objective here was to survey both the DFZ and the axis of the Java Trench to unequivocally determine the deepest point in the Indian Ocean.

In the Pacific Ocean, the deepest point is the well-known site of the *Challenger Deep* within the Mariana Trench (~11.3°N/142.2°E). Given the prestige of being the deepest, it had already undergone a degree of scrutiny not seen in other trenches (e.g. Gardner & Armstrong, 2011; Gardner et al., 2014; Nakanishi & Hashimoto, 2011; van Haren et al., 2017). The FDE goal was to revisit the site and refine the exact location and depth of the *Challenger Deep*. In addition, the neighbouring *Sirena* and *Nero* deeps located to the east of *Challenger Deep* (Fryer et al., 2003) were also to be mapped. There was also the opportunity to survey the *Horizon Deep* in the Tonga Trench (~23.3°S/174.7°E) in the SW Pacific that is known to be very close in maximum depth (~10,800 m) to that of *Challenger Deep*. As the Tonga Trench has only been subject to a small number of scientific expeditions it was pertinent that the *Horizon Deep* was also surveyed as part of the FDE mission to be certain of its status as the second deepest place in the World.

In the Arctic Ocean, the deepest point was identified as the *Molloy Hole* (previously known as the *Molloy Deep*; Klenke & Schenke, 2002) located in the Fram Strait between Greenland and Svalbard (~79.1°N/2.8°E). This is a relatively well known area (e.g. Freire et al., 2014; Klenke & Schenke, 2006). The FDE survey of the *Molloy Hole* would be one of simply refining the exact location and depth.

While over the course of the FDE, an extraordinarily large area of the Earth's seafloor and features therein were mapped, here we present the exact depth and location of the deepest point in each ocean, including the DMZ and Tonga Trench for context. We report on high-precision full-ocean depth multibeam echosounder data acquired using the Kongsberg EM 124 system, corrected with high-resolution, full-ocean depth Conductivity, Temperature and Depth (CTD) data to validate the greatest depths of our five oceans.

2 | MATERIALS AND METHODS

2.1 | Equipment

All hydrographic surveys were executed aboard the DSSV *Pressure Drop*, a refitted Stalwart class surveillance ship–formally the USS *Indomitable* of the US Navy–built for long endurance and with low ambient noise level. The vessel, built in 1985, is 68.28 m long by 13.11 m wide.

The DSSV *Pressure Drop* was fitted with a 1° × 2 Kongsberg EM 124 multibeam echosounder (MBES), the successor to the EM 122 system, designed to produce high-precision data to full ocean depth (11,000 m). The MBES System was mounted to the ship's hull on a gondola fixed ~20 m from the bow of the ship. The EM 124 has a nominal frequency of 12 kHz, with an operating frequency of 10.5–13.5 kHz. The EM 124 is a dual swath, 16 sector system with both Constant Wave and Frequency Modulation pulse capabilities. Positioning was determined by a Kongsberg Seapath 380+ (accurate to within 0.02° Route Mean Square (RMS) for Roll and Pitch, 0.075° RMS for Heading, and 5 cm for Heave) while sound velocity was collected by a fixed-mount Reson SVP70 at the transducer head (accurate to within ±0.05 m/s), and both were integrated real-time into the Kongsberg SIS 5 data acquisition software.

Lockheed Martin/Sippican T-5 expendable bathythermographs (XBTs) were used to collect depth and temperature data in the upper 1,800 m of water column. The XBTs had depth and temperature accuracies of +2% and +0.1°C, respectively. The XBT data were combined with World Ocean Atlas 2009 (WOA09) (Locarnini et al. 2010; Antonov et al. 2010) model salinity estimates to calculate sound velocity profiles subsequently extrapolated to full-ocean depth using Hydro Office's Sound Speed Manager (version 2018.1.50; Gallagher et al., 2017; HydrOffice, 2019; Masetti et al., 2017; Masetti et al., 2020).

In addition to the XBT data, the DSV *Limiting Factor* and the three supporting lander systems were equipped with a total of five CTD probes (two on the DSV *Limiting Factor* and one on each lander system) that recorded vertical profiles of salinity, temperature and depth during both the descent and ascent. These data were used to calculate full-ocean sound velocity profiles for the EM 124 and to validate the submersible dive depths. The Seabird Oceanographic SBE 49 FastCAT CTDs have a sampling speed of 16 Hz and conductivity, temperature and pressure accuracies of ±0.0003 S/m, ±0.002°C, and ±0.1% of full-scale range, respectively.

2.2 | MBES survey design and data processing

All MBES data acquisition was undertaken at a typical vessel speed of 8 knots, with a swath width typically 2–3 times water depth or ~15–20 km. Survey lines were spaced between 6 and 7 km to ensure 100% overlap over areas of interest. Each point of interest was positioned between 10° and 20° from nadir to limit the extent of outer-beam noise and the potential subsurface penetration in the beams nearest nadir. At each study area, an XBT was cast and integrated into the data acquisition system (SIS 5) and post-processed as needed. Full-ocean depth sound velocity profiles were determined after the deep submersible dives and applied during post-processing to ensure deviations in deep-water sound speeds were accounted for.

All raw bathymetry data were manually processed in QPS Qimera (version 1.7.5) and gridded to 75 m using CUBE (Combined Uncertainty and Bathymetry Estimator) algorithms. CUBE algorithms use the surrounding depth information and advanced statistical practices to determine the best estimate of depth while simultaneously calculating the uncertainty of those estimates (Calder & Mayer, 2003; Calder & Wells, 2006). The default Qimera CUBE calculation parameters were used to create these surfaces apart from the configuration setting which was set to 'Deep Water' and the CUBE Hypothesis Resolution Algorithm which was set to 'Number of samples & neighborhood'. All accuracy estimates for each acquisition system (as mentioned previously) were input into Qimera's total propagated uncertainty (TPU) estimator in the vessel file to calculate the uncertainty for each dataset during the CUBE surface creation and are the values used for all bathymetry uncertainties henceforth. These uncertainties represent a 95% confidence.

Final bathymetric grids for each survey were analysed in ESRI ArcGIS 10.7.1. The submarine and lander CTDs were analysed for depth and sound speed using Matlab. Final CTD depth values were based on the average of the two submarine CTD maximum depths and any lander CTDs deployed to the same location. The standard deviation of these values is used as the uncertainty.

2.3 | Additional sources of bathymetric data

For the purposes of figure production and to give context to the FDE study areas, bathymetric compilations were downloaded from the General Bathymetric Chart of the Oceans (GEBCO Compilation Group, 2019). The GEBCO_2019 dataset comprises gridded seafloor depths at 15 arc-second intervals with ArcGIS (version 10.7.1) grids of these data produced for this study. All figures were created using ESRI ArcGIS.

3 | DATA OVERVIEW

The total bathymetry collected over the ten-month expedition was about 550,000 km^2 with a significant amount acquired during transits between sites of interest. More than 330,000 km^2 (61%) represents areas never previously surveyed.

3.1 | Atlantic Ocean: Puerto Rico Trench

Nearly 4,000 km^2 of bathymetric data were collected within the *Brownson Deep* of the Puerto Rico Trench (Figure 2). The deepest point was identified as 8,378 ± 5 m uncertainty at 19.712°N/67.311°W. The maximum depth was verified by the subsequent submersible dive to the location as 8,376 ± 5 m (Table 1).

3.2 | Southern Ocean: South Sandwich Trench

Over 15,000 km^2 of bathymetric data were collected spanning the entire length of the South Sandwich Trench (Figure 3) with almost all of these data representing new coverage. The deepest point of the Southern Ocean was identified as 7,432 ± 13 m (60.479°S/25.542°W), with the deepest point in the entire trench observed in *Meteor Deep* as 8,265 ± 13 m uncertainty (55.230°S/26.173°W) (Table 1). The maximum depth of the unnamed deep south of 60°S was verified by the subsequent submersible dive to the location as 7,434 ± 3 m, ~15 km to the southwest of the GEBCO_2014-derived location identified by Stewart and Jamieson (2019).

Prior to the FDE, around 91% of the trench was unmapped with most available information coming from satellite altimetry. When the FDE MBES data are compared with the GEBCO_2019 dataset, the greatest surface differences can be found between 57.5°S and 59°S. Interrogation of the GEBCO_2019 data at *Meteor Deep* shows a value 804 m shallower than that determined by the FDE. Furthermore, the GEBCO_2019 dataset also indicated a depth 1,140 m shallower than the FDE data for the unnamed deep south of 60°S, the newly identified deepest point in the Southern Ocean.

3.3 | Indian Ocean: Java Trench and Diamantina Fracture Zone

The two potential locations for the deepest point in the Indian Ocean discussed by Stewart and Jamieson (2019) were located in the DFZ and the Java Trench. Only the northern portion of the DFZ, comprising the *Dordrecht Deep*, was surveyed during the FDE (Figure 4) as multibeam data had been collected along the

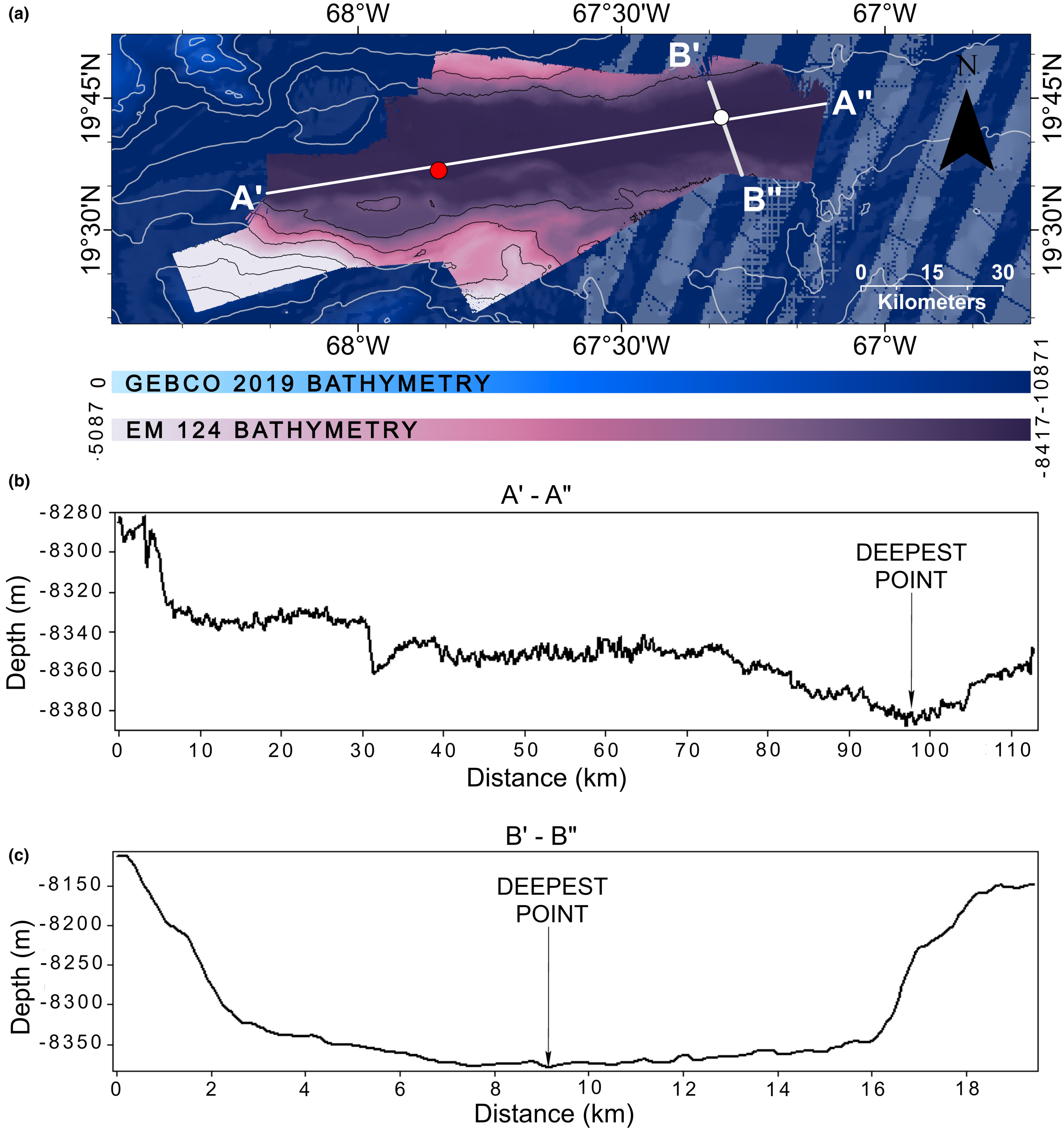

FIGURE 2 (A) Puerto Rico Trench multibeam bathymetry data gridded at 75 m acquired on-board the DSSV *Pressure Drop* overtop the GEBCO_2019 grid with interpolated sources removed (as shown in Figure 1) and the complete GEBCO_2019 grid with hillshade. EM 124 black contours at 500 m intervals, GEBCO_2019 grey contours at 1,000 m intervals. The white circle indicates the deepest point and submersible dive location, the red spot was the deepest point derived from the GEBCO_2014 gridded bathymetry. Bathymetric cross sections A'–A" oriented parallel to trench axis (B), and B'–B" oriented perpendicular to trench axis (C) over the deepest point

>3,400 km long fracture zone by Geoscience Australia (2017) and during the search for Malaysia Airlines flight MH370 (Picard et al., 2018). Stewart and Jamieson (2018, 2019) identified two discrete locations within the Java Trench that had the potential to be the deepest point with the FDE survey designed to cover both sites (Figure 5).

During the DFZ survey, more than 5,800 km^2 of bathymetric data were collected of which 2,607 km^2 was new coverage (Table 1). After an initial examination of these data, the deepest point was identified around 500 m southwest from the predicted location and a scientific lander was deployed equipped with only a pressure and temperature

TABLE 1 Study locations, and depths based on calibrated EM 124 multibeam bathymetry data and calibrated CTD data from the submersible DSV *Limiting Factor*

Ocean	Feature/Deep	Latitude	Longitude	EM 124 Depth (m)	Submersible CTD Depth (m)	Total Area/new area mapped (km^2)
Arctic	Mid Atlantic Ridge/*Molloy Hole*	79.194°N	2.706°E	5,551 ± 14	5,577 ± 23[a]	1,850/0
North Atlantic	Puerto Rico Trench/*Brownson Deep*	19.712°N	67.311°W	8,378 ± 5	8,376 ± 5	3,845/540
South Atlantic	South Sandwich Trench/*Meteor Deep*	55.230°S	26.173°W	8,265 ± 13	N/A	15,052/15,045
Indian	Java Trench/*Unnamed deep*	11.129°S	114.942°E	7,187 ± 13	7,192 ± 5	39,560/12,848
Indian	Diamantina Fracture Zone/*Dordrecht Deep*	33.631°S	101.356°E	7,019 ± 17	7,009 ± 7[b]	5,814/2,607
North Pacific	Mariana Trench/*Challenger Deep*	11.369°N	142.587°E	10,924 ± 15	10,925 ± 4	25,965/650
South Pacific	Tonga Trench/*Horizon Deep*	23.270°S	174.740°W	10,816 ± 16	10,817 ± 6	13,194/950
Southern	South Sandwich Trench/*Unnamed Deep*	60.479°S	25.542°W	7,432 ± 13	7,434 ± 3	Included in *Meteor Deep* above.

[a] Indicates uncalibrated submersible CTD value whereas the CTD calibration applied to the *Molloy Hole* EM 124 data is derived from a calibrated lander CTD.

[b] Denotes pressure sensor only data from lander (SBE-39, SeaBird Electronics, US).

sensor. Only XBT and synthetic sound velocity profiles were used during data acquisition as no submersible dive was undertaken at this location, therefore no full-ocean depth sound velocity profile was acquired. However, the lander's pressure sensor recorded a depth of 7,009 m, giving high confidence in the bathymetric data acquired. The data analysis revealed the deepest point in the DFZ as 7,019 ± 17 m at 33.631°S, 101.356°E (Table 1), 167 m deeper than and ~30 km southwest of the Stewart and Jamieson (2019) GEBCO_14-derived location.

The Java Trench survey acquired nearly 40,000 km^2 of bathymetric data of which 12,848 km^2 was new coverage (Table 1). The deepest location was found at 11.129°S, 114.942°E, 387 km west from the GEBCO_14-derived location (Stewart & Jamieson, 2019). After two submersible dives and seven lander deployments within the area, a final depth of 7,187 ± 13 m was determined from the EM 124 which correlated well with the 7,192 ± 5 m pressure readings from the submersible (Table 1). The significant difference in resolution between the GEBCO_2019 dataset (~900 m in this area) and the higher-resolution FDE dataset results in GEBCO_2019 registering a depth 487 m shallower than that determined using the EM 124 MBES.

As the depths from both the lander and the bathymetry fall outside the expected error term associated with the estimated Java Trench depths, the deepest point in the Indian Ocean was confirmed to reside in the Java Trench.

3.4 | Pacific Ocean: Mariana and Tonga trenches

Data acquisition in the Mariana and Tonga trenches (Figures 6 and 7) acquired 25,965 and 13,194 km^2 of bathymetric data, respectively of which 650 and 950 km^2 comprised new coverage (Table 1). The deepest point in the *Challenger Deep* was determined to be 10,924 ± 15 m, with the deepest point in *Horizon Deep* 10,816 ± 16 m.

The maximum depth of the Mariana Trench located at 11.369°N, 142.587°E was verified by four submersible dives to the location as 10,925 ± 4 m. Likewise, the maximum depth of the Tonga Trench located at 23.270°S, 174.740°W was verified by the subsequent submersible dive to the location as 10,817 ± 6 m.

3.5 | Arctic Ocean: Molloy Hole

A total of 1,850 km^2 of bathymetric data were collected over the feature named the *Molloy Hole* but did not acquire any new coverage as the area was already well mapped (Figure 8; Table 1). The relative swath width and line spacings were increased to maximize coverage in the comparatively shallower waters, specifically widening the swath from 55° to 65° on either side of nadir. An XBT was not collected at this site and synthetic sound velocity profiles

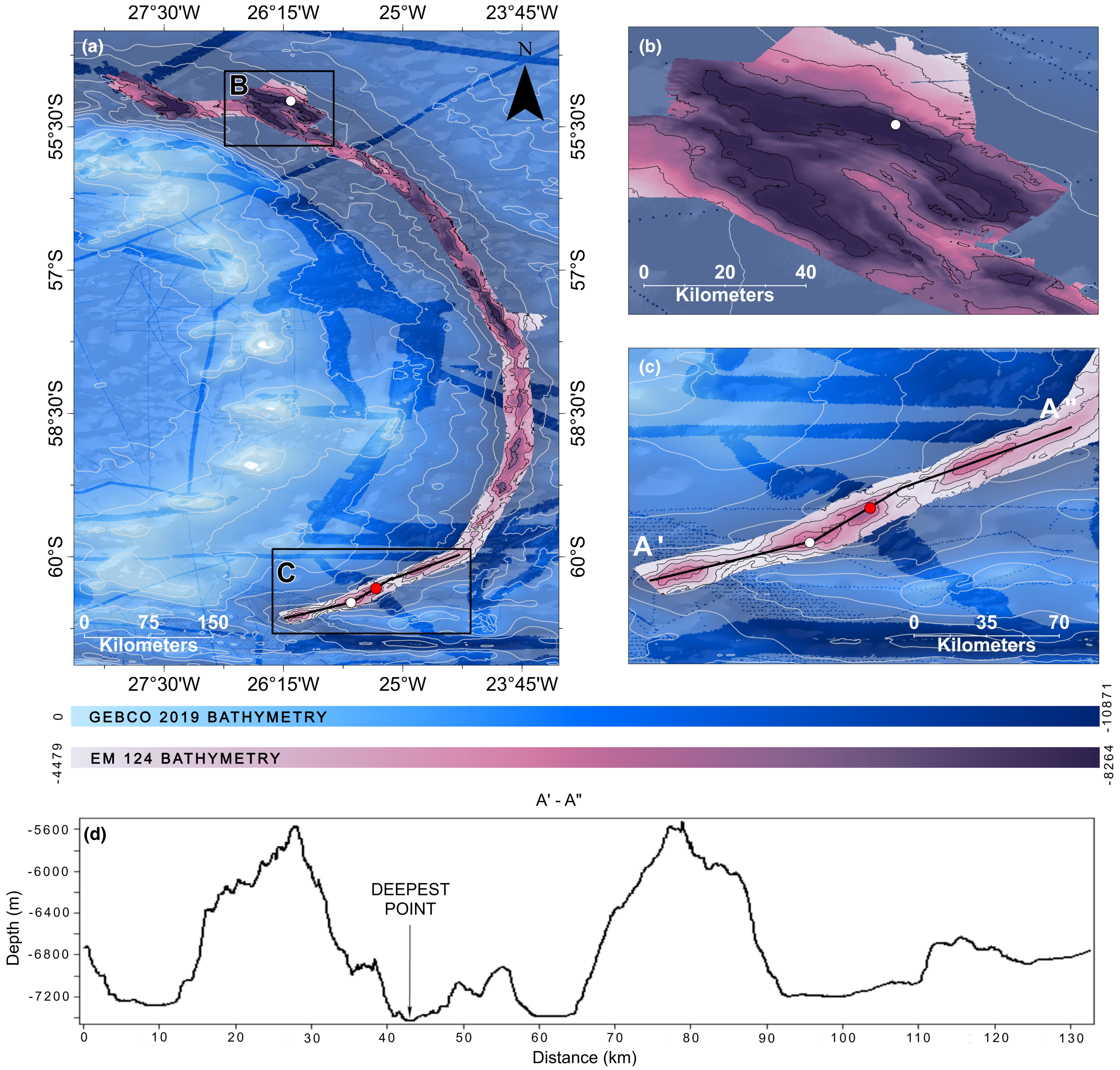

FIGURE 3 (A) South Sandwich Trench multibeam bathymetry data gridded at 75 m acquired on-board the DSSV *Pressure Drop* overtop the GEBCO_2019 source grid (as shown in Figure 1) and the complete GEBCO_2019 grid with hillshade. EM 124 black contours at 500 m intervals, GEBCO_2019 grey contours at 1,000 m intervals. The white circles indicate the deepest points north and south of 60°S, the red spot was the deepest point derived from the GEBCO_2014 gridded bathymetry. (B) *Meteor Deep* and the deepest point in the South Sandwich Trench. (C) The deepest point of the Southern Ocean and submersible dive location. (D) Bathymetric cross section A'–A" oriented parallel to trench axis over the deepest point in the Southern Ocean

were used exclusively during the survey. The deepest point was identified as 5,551 ± 14 m at 79.194°N, 2.706°E (Table 1), located almost 7 km NW of the point identified by Stewart and Jamieson (2019). However, the submersible and lander CTD readings of 5,577 ± 23 m (Table 1) deviate significantly from this final depth, which is attributed to calibration issues.

4 | QUALITY CONTROL AND VALIDATION

At such extreme depths, the small to moderate differences between modelled and measured sound velocity profiles can produce significant ray-tracing changes that resulted in large fluctuations in depths (Beaudoin et al., 2009).

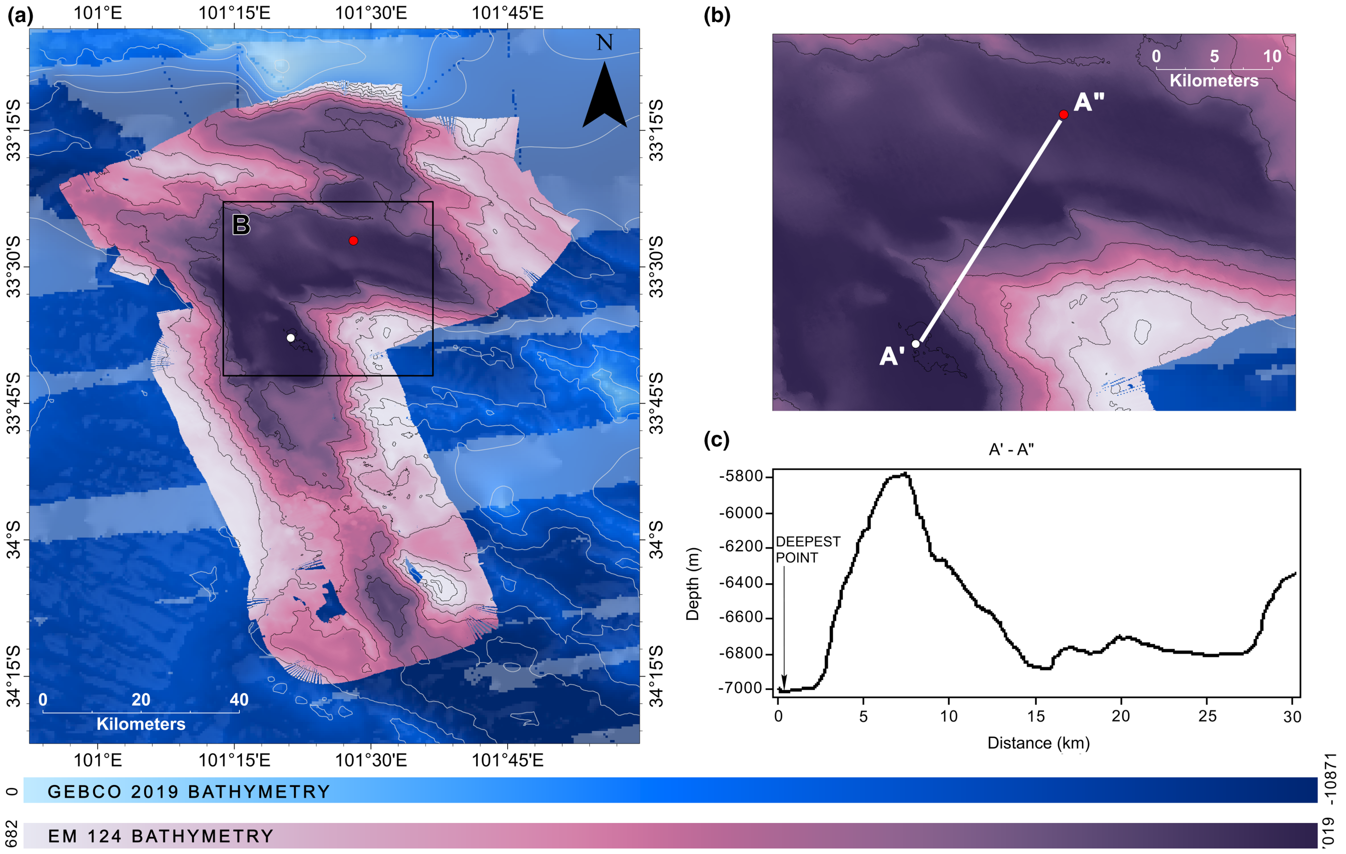

FIGURE 4 (A) Diamantina Fracture Zone (DFZ) multibeam bathymetry data gridded at 75 m acquired on-board the DSSV *Pressure Drop* overtop the GEBCO_2019 source grid (as shown in Figure 1) and the complete GEBCO_2019 grid with hillshade. EM 124 black contours at 500 m intervals, GEBCO_2019 grey contours at 1,000 m intervals. The white circle indicates the deepest point, the red spot was the deepest point derived from the GEBCO_2014 gridded bathymetry. (B) The deepest point in the *Dordrecht Deep*. (C) Bathymetric cross section A'–A" over the deepest point

Specifically, XBTs measure only temperature and depth in the upper, most variable portion of the water column, where wind, waves, biological mixing, and surface temperatures are most influenced by weather on the surface. XBTs are standardly combined with model estimates which provide information on the salinity and help extend the profile to full-ocean depth. Models are sufficient at greater depths because the temperature variations are minimal, with little to no outside influence apart from pressure (Beaudoin, 2010).

XBT profiling the upper layers and modelling thereafter is the standard practice for deep ocean mapping, as many operations do not have the time necessary to send a CTD to the seafloor. In the case of the FDE, the full-ocean CTDs on the submersible and scientific landers allowed for full-ocean sound velocity profiles to be derived from direct measurements at each location instead of relying on models.

Based on the sound velocity profiles for each dive location, the only two locations where the sub CTDs deviate drastically from XBT data and WOA09 estimates were at *Challenger Deep* and the *Molloy Hole* (Figure 9). These differences can be explained by the changes in surface water temperature from the deployment times of each instrument, the accuracy of each instrument, and the breadth of information included in the WOA09. Whichever the specific reason, the large differences between CTD and XBT/WOA09 profiles resulted in changes in bottom depth from the initial survey and the final surfaces.

At *Challenger Deep*, initial depth estimates for the deepest point were determined to be ~10,943 ± 20 m (11.369°N, 142.587°E). This was close in depth to a location ~42 km west (11.331°N, 142.205°E) that appeared only ~5 m shallower in depth but ultimately was determined to be nearly the same depth during post-processing application of the full-ocean depth CTD data (Figure 10A-B). Though five meters remains within the limitations of the sonar at almost any depth, it is particularly negligible in depths greater than 10,000 m as it represents less than 0.05% of the water depth.

The technological accuracy does not currently exist on low-frequency ship-mounted sonars required to determine which location was truly the deepest, nor does it currently exist on deep-sea pressure sensors. However, given the agreement between the CTD sensors of all five instruments after five full-ocean depth dives and multiple lander deployments

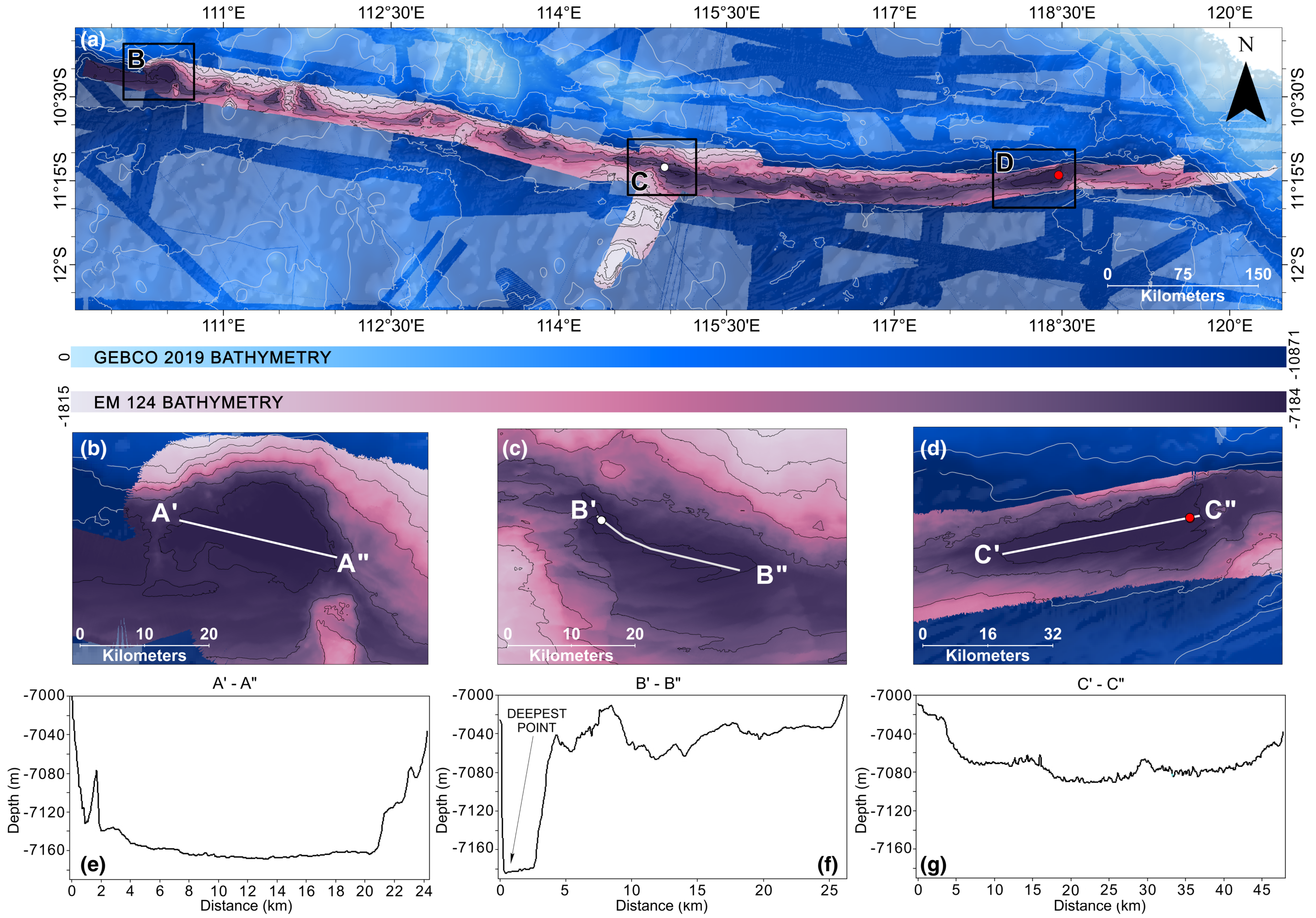

FIGURE 5 (A) Java Trench multibeam bathymetry data gridded at 75 m acquired on-board the DSSV *Pressure Drop* overtop the GEBCO_2019 source grid (as shown in Figure 1) and the complete GEBCO 2019 grid with hillshade. EM 124 black contours at 500 m intervals, GEBCO_2019 grey contours at 1,000 m intervals. The white circle indicates the deepest point and submersible dive location, the red spot was the deepest point derived from the GEBCO_2014 gridded bathymetry. (B), (C), and (D) show the deepest areas of the Java Trench. Bathymetric cross sections A'–A", B'–B", and C'–C" over the three deepest parts of the trench displayed in (E), (F), and (G), respectively

to the deepest parts of the Mariana Trench, we are certain that the depth achieved during this expedition is within the uncertainty of any future records of depth in *Challenger Deep*. More specifically, even if the western location is determined to be a meter or two deeper, the uncertainty associated with that measurement will encompass the depth achieved during the FDE, making them essentially the same. Readings of 1–5 m fluctuations on either CTDs or bathymetric maps at these depths do not necessarily correlate to actual observed changes of these amounts.

Despite being the shallowest location, the *Molloy Hole* in the Arctic Ocean proved to be the most challenging due to severe weather limiting the working window for survey. An XBT was not obtainable and synthetic profiles were therefore used exclusively for initial depth estimates. There were two potential locations for the deepest point following initial interrogation of the data (Figure 10C). These two points were the same depth of ~5,555 m, but the quality of acquired data over the Stewart and Jamieson (2019) point indicated significant outer beam noise from an additional pass and rough weather had influenced the depths rendering them unreliable. As such, the western point was chosen as the submersible dive location. However, the application of the full-ocean depth sound velocity profile during post-processing revealed the Stewart and Jamieson (2019) location was ~4 m deeper (Figure 10D).

This ~4 m difference in depth is within the limitations of the MBES sonar as it equates to ~0.07% of the water depth. Only one CTD cast was acquired, however, the readings were inconsistent. Despite remaining highly reliable throughout the FDE, the CTDs on the landers and submarine all provided depth readings ~30 m apart with no overlap resulting in a final average depth of 5,577 ± 23 m. This reading was almost exactly 23 m deeper than the calculated depth from the processed bathymetry and the difference is attributed to a calibration issue.

Given that these instruments were heavily used throughout the FDE, profiling a combined total of over 1 million meters vertically (up and down) in <10 months, it is likely the pressure sensors required recalibration. This was not only evident

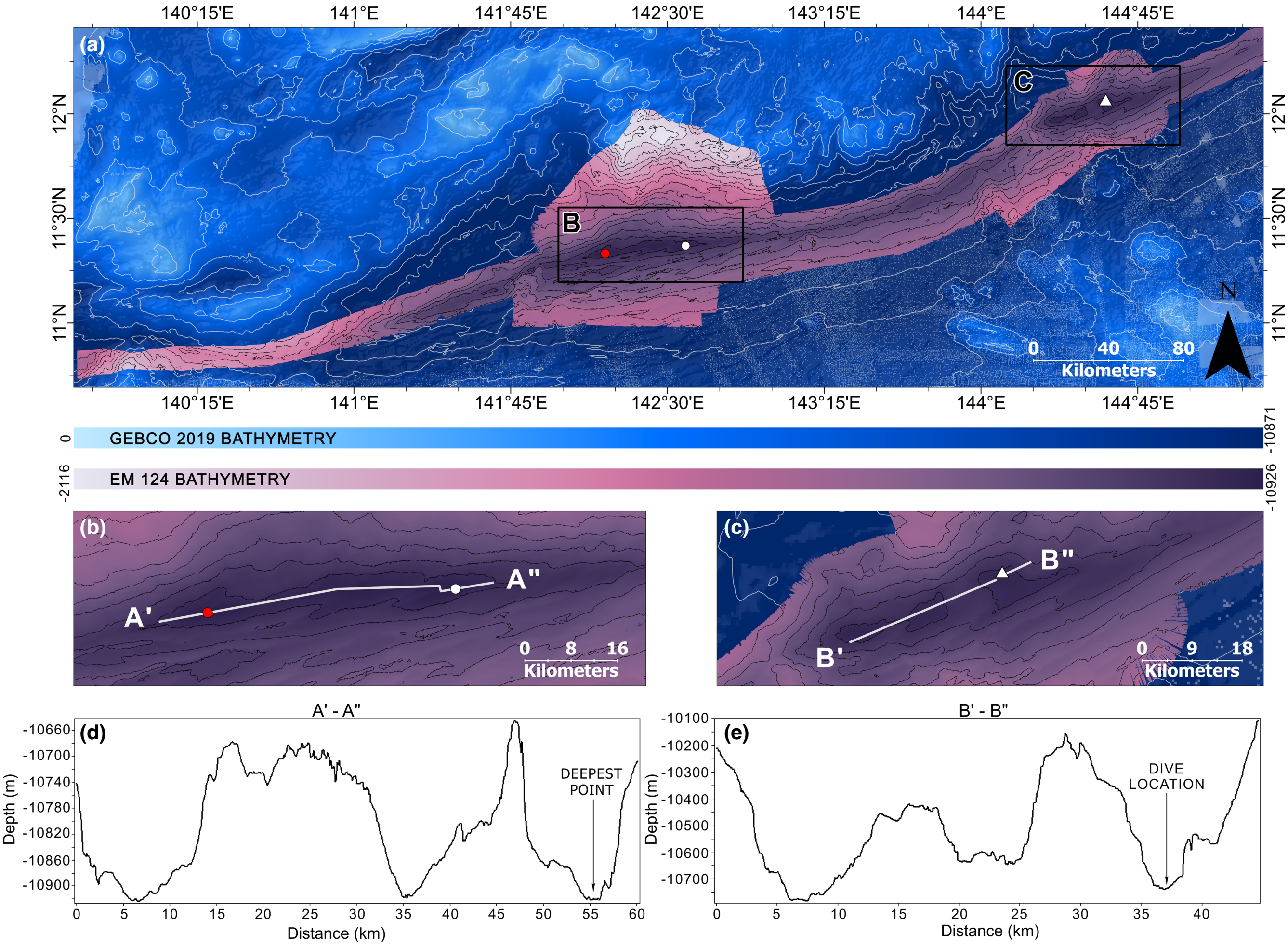

FIGURE 6 (A) Mariana Trench multibeam bathymetry data gridded at 75 m acquired on-board the DSSV *Pressure Drop* overtop the GEBCO_2019 source grid (as shown in Figure 1) and the complete GEBCO_2019 grid with hillshade. EM 124 black contours at 500 m intervals, GEBCO_2019 grey contours at 1,000 m intervals. The white circle indicates the deepest point and submersible dive location, the white triangle indicates the submersible dive location from *Sirena Deep*, the red spot was the deepest point derived by van Haren et al., (2017). (B) *Challenger Deep*. (C) *Sirena Deep*. Bathymetric cross sections A'–A" and B'–B" over *Challenger Deep* and *Sirena Deep* displayed in (D) and (E), respectively

in the discrepancies in depths but also when comparing the CTD sound speed profiles from the landers and submersible (Figure 11). Despite the year-long calibration certificate, the 23 m variability observed in the measurements taken at *Molloy Hole* are well outside the "±0.1% of full-scale range" pressure accuracies assured by the manufacturer (at these depths, it is expected to have ±5 m). As such, the more conservative depth from the processed bathymetry was used as the official depth of the dive since the agreement between the sonar and submersible depths had been consistent before the *Molloy Hole* survey (Table 1).

The combination of the state-of-the-art MBES sonar and the 5 full ocean depth CTD sensors on the submersible and landers allowed the FDE to not only accurately map some of the most remote and deepest trenches in the world, but also validate the depths observed by the EM 124. On average, with the exception of the *Molloy Hole*, the final bathymetric depths and those determined by the CTD only deviated by ~4 m, showing strong agreement and consistency between both platforms.

5 | COMPARISON AGAINST OTHER GRIDDED DATASETS

The FDE data were compared only to the datasets that directly contributed to the GEBCO_2019 compilation grid. The data illustrated in Figure 1 are true bathymetric datasets without interpolated, modelled, or satellite-derived data included and were the data used for comparisons. However, these data were bilinearly resampled in ArcGIS to be at the same 75 m grid resolution of the FDE data. The average difference among all seven datasets outlined in this paper and the GEBCO_2019 true dataset is ~14 m (Table 2).

The biggest variations were observed from the Puerto Rico, South Sandwich, Mariana and Tonga trenches. For

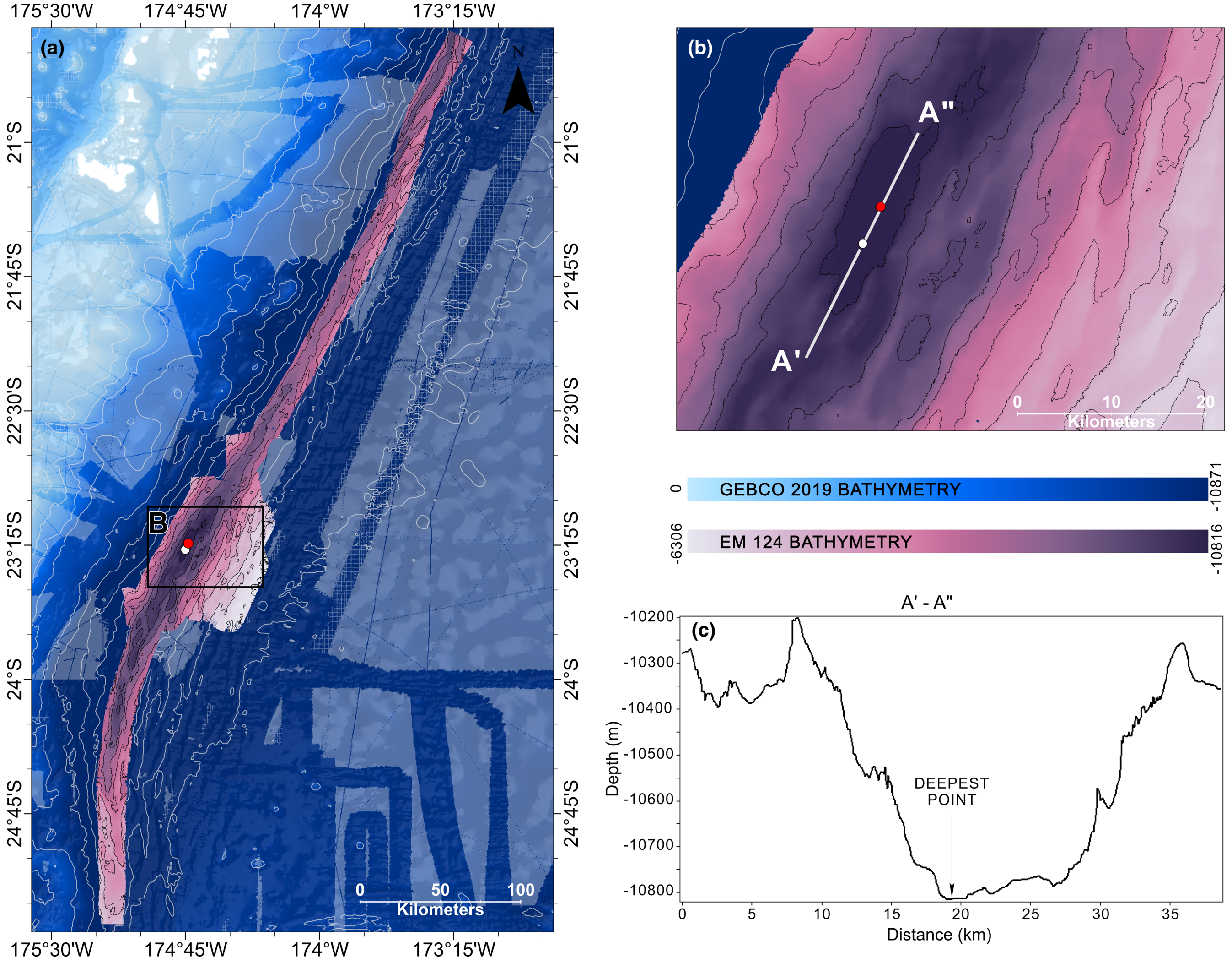

FIGURE 7 (A) Tonga Trench multibeam bathymetry data gridded at 75 m acquired on-board the DSSV *Pressure Drop* overtop the GEBCO_2019 grid with interpolated sources removed (as shown in Figure 1) and the complete GEBCO_2019 grid with hillshade. EM 124 black contours at 500 m intervals, GEBCO_2019 grey contours at 1,000 m intervals. The white circle indicates the deepest point and submersible dive location, the red spot was the deepest point derived from the GEBCO_2014 gridded bathymetry. (B) *Horizon Deep* and the deepest point in the Tonga Trench. (C) Bathymetric cross section A'–A" oriented parallel to trench axis over the deepest point

the most part, the larger differences can be attributed to a resolution contrast between the ~500 m resolution of the GEBCO_2019 grid and the 75 m grids produced during the FDE. Additionally, the geographic coverage of data contributing to the GEBCO_2019 grid plays a significant role in the differences observed. In the South Sandwich Trench, there were only three single beam transit lines coincident with the FDE survey area, making a true comparison difficult to perform. In comparison, the FDE survey area within the Puerto Rico Trench had good coverage in the western half of the study area compared with the eastern half, with previous mapping efforts there comprising individual multibeam lines.

The largest contributor to the average difference in the Mariana Trench survey comes from a singular multibeam line included in the GEBCO_2019 dataset. This line runs across the trench erratically with drastically different depths recorded (~300 m) in comparison to both the adjacent GEBCO_2019 data and the FDE data. It is unlikely that a consistent 300 m tall ridge the exact width of a multibeam swath is a true geologic feature and is more likely to be erroneous data unintentionally included in the compilation grid. To further this point, the FDE Mariana Trench survey was compared with the US Law of the Sea dataset (Armstrong, 2011) collected over the same area and the average difference was only 2 m.

6 | CONCLUSION

The contribution of the FDE to ocean mapping is somewhat unique, in both its focus on extreme water depths and its 10-month continuous survey campaign. The total bathymetry

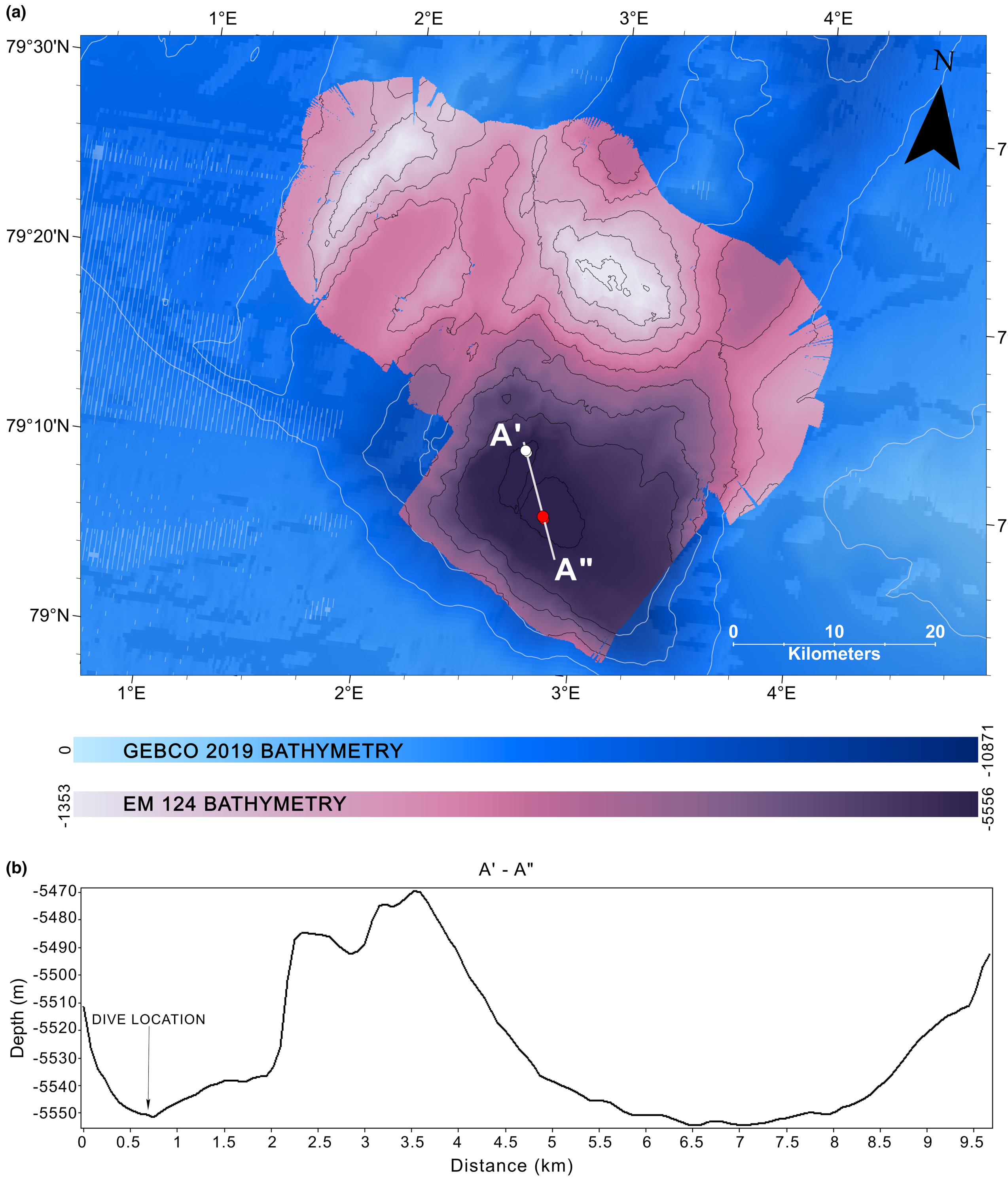

FIGURE 8 (A) *Molloy Hole* multibeam bathymetry data gridded at 75 m acquired on-board the DSSV *Pressure Drop* overtop the GEBCO_2019 grid with interpolated sources removed (as shown in Figure 1) and the complete GEBCO_2019 grid with hillshade. EM 124 black contours at 500 m intervals, GEBCO_2019 grey contours at 1,000 m intervals. The white circle indicates the deepest point and submersible dive location, the red spot was the deepest point determine by Klenke and Schenke (2002, 2006). (B) Bathymetric cross sections A'–A" over the deepest point

collected during that period was ~550,000 km^2 with over 160,000 km^2 of the total area mapped collected over trenches and fracture zones of interest while the remainder was acquired from transoceanic transits. More than 330,000 km^2 of the total comprise new data according to public bathymetric data repositories.

A significant contributor to ocean exploration is NOAA's exploration vessel the *Okeanos Explorer* which averages an

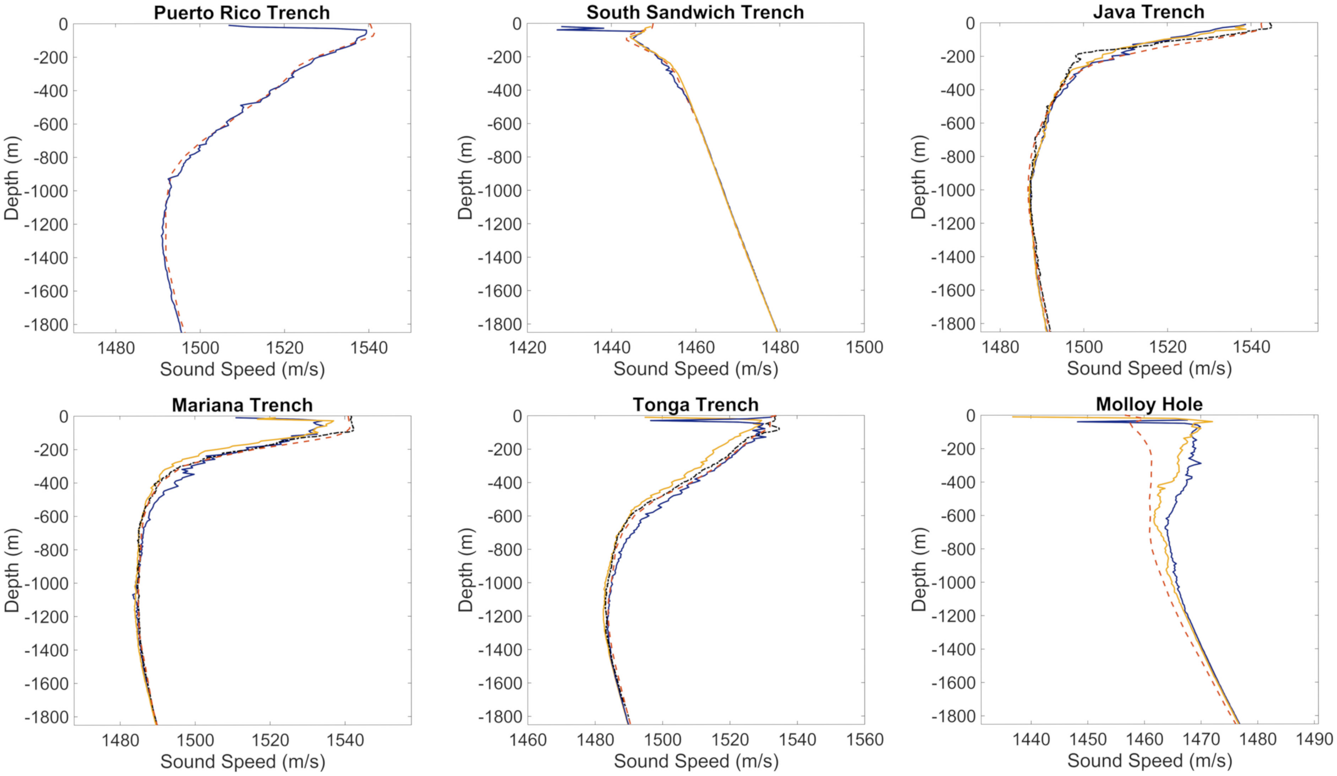

FIGURE 9 Sound velocity profiles generated from the two submersible CTDs in comparison with XBT profiles and World Ocean Atlas 2009 (WOA 09) modelled profiles for each dive location. CTD 1 and 2 are in blue and yellow solid lines, respectively, XBTs are in black dashed lines, and WOA 09 are in red dashed lines. Only the upper water column is shown (0–1,800 m depth) to highlight differences observed in the data sources

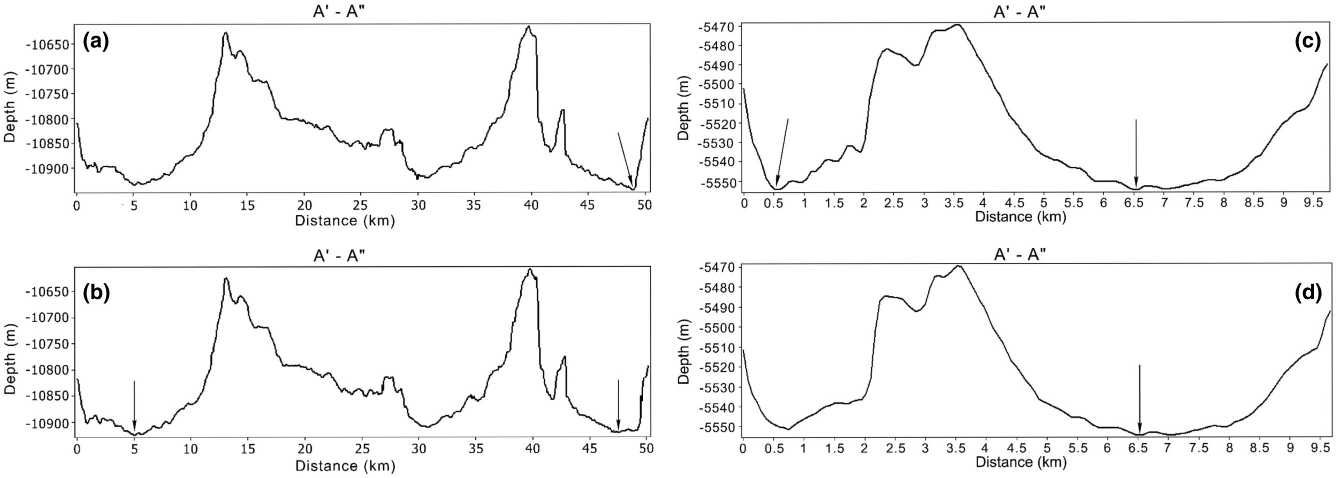

FIGURE 10 Bathymetric cross sections from *Challenger Deep* (Mariana Trench, Pacific Ocean) and *Molloy Hole* (Mid-Atlantic Ridge, Arctic Ocean). Black arrows indicate identified deepest points. (A) Profile across *Challenger Deep* (see Figure 6 for location) with only an XBT applied to the bathymetric data whereby one deep point is identified, and (B) following application of a full-ocean depth sound velocity profile where two points of the same depth are identified from the bathymetric data. (C) Profile across *Molloy Hole* (see Figure 8 for location) with only synthetic sound velocity profiles applied to the bathymetric data where two points of the same depth are identified, and. (D) following application of a full-ocean depth sound velocity profile whereby one clear deepest point is identified

unquestionably impressive ~190,000 km^2 of new bathymetry a year (NOAA, 2019). The non-profit Schmidt Ocean Institute's R/V *Falkor* which averages ~150,000 km^2 a year (Schmidt Ocean Institute, 2019) and the joint US Government and publicly run R/V *Nautilus* has a maximum annual mapping coverage record of over ~135,000 km^2 (Raineault & Flanders, 2020). While a direct comparison between these organizations and the FDE is impossible as those vessels also

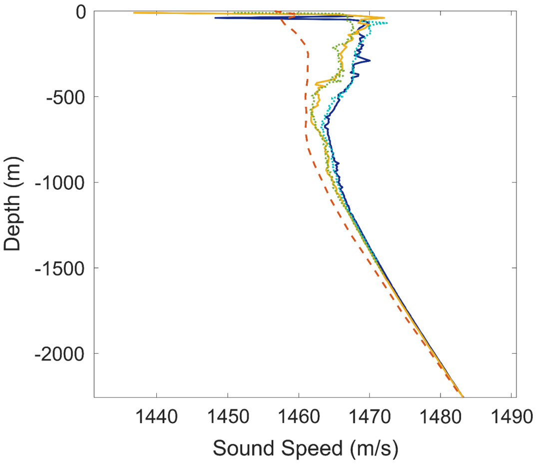

FIGURE 11 Sound velocity profiles from all CTDs collected during the *Molloy Hole* survey in August 2019. CTD 1 and 2 are in blue and yellow solid lines, respectively. The dotted green and blue profiles correspond to CTDs deployed on Landers 1 and 2, respectively. The red dashed profile is the WOA 09 modelled profile. All profiles deviate significantly from the WOA 09 modelled profile, but also deviate from each other. CTD 1 and 2 separate by ~5 m/s for almost 1,000 m despite both being deployed simultaneously on the DSV *Limiting Factor*. This separation is also observed by the CTDs deployed on the landers launched during submersible operations

TABLE 2 The average difference between the FDE bathymetric data and GEBCO_2019 grid and the percentage of new coverage collected in each study area

	PRT	SST	DFZ	Java	Mariana	Tonga	Molloy
Average difference FDE/ GEBCO_2019 datasets	18 m	35 m	2 m	5 m	13 m	20 m	1.5 m
New data coverage	14%	99%	45%	32%	3%	7%	0%

Abbreviations: DFZ, Dimantina Fracture Zone; PRT, Puerto Rico Trench; SST, South Sandwich Trench.

undertake non-mapping missions throughout the year, it is noteworthy to consider what a dedicated 'mapping' expedition could achieve in terms of coverage.

In conclusion, this study has determined the deepest point of the world's five oceans as the *Brownson Deep*, Puerto Rico Trench in the Atlantic Ocean (8,378 ± 5 m, 19.712°N/67.311°W), an unnamed deep within the South Sandwich Trench in the Southern Ocean (7,432 ± 13 m, 60.479°N/25.542°W), an unnamed deep within the Java Trench in the Indian Ocean (7,187 ± 13 m, 11.129°S/114.942°E), *Challenger Deep* within the Mariana Trench in the Pacific Ocean (10,924 ± 15 m, 11.369°N/142.587°E), and the *Molloy Hole* in the Arctic Ocean (5,551 ± 14 m, 79.194°N/2.706°S).

The FDE provided an unprecedented opportunity to contribute to the Seabed 2030 initiative (a collaborative project between the Nippon Foundation and GEBCO) that will bring together all available bathymetric data to produce the definitive map of the world's ocean floor by 2030. Given the sizeable Seabed 2030 goal and a focus on the deep sea as suggested by Mayer *et al*. (2018), perhaps a key contributor to success lies in privately funded expeditions such as the FDE. While it is not the only privately funded deep-sea exploration expedition, it does exemplify the contribution that private enterprises can make with the right vision and technology.

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CONFLICT OF INTEREST

No potential conflict of interest was reported by the authors.

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